Biomimetic whisker transducer for vibrissal tactile sensing

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**NANYANG
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**BIOMIMETIC WHISKER TRANSDUCER FOR
VIBRISAL TACTILE SENSING**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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ABSTRACT

The unique vibrissal tactile perception possessed by rats allows them to explore the surrounding environment actively with their whiskers, and helps them survive and thrive in hostile environments like underground tunnels, where vision becomes of little use. On the other hand, today most robots lack tactile sensing ability and rely on machine vision heavily. This seriously limits their survival chance and exploration performance in unstructured environments. In this thesis, a novel whisker transducer (WT) aiming to mimic the biological vibrissa system has been proposed, which can endow robots with vibrissal tactile sensing ability. The WT was developed based on a novel transduction matrix model, which characterizes the forward actuation and backward sensing functions of the transducer with a 2×2 matrix. As a result, the WT can perform active whisking and simultaneously sense the mechanical stimuli at its tip, just like what rat's whisker does. And the force, velocity and mechanical impedance at whisker tip are sensed from the input electrical signals, without using any additional sensors. The concept and functions of the WT were validated numerically using a finite element model and experimentally using a prototype. It can accurately measure mechanical impedance, force and velocity at whisker tip with errors of 1.28%, 0.88% and 1.55%, respectively. It also possesses features such as compact structure, good versatility and easy instrumentation, which facilitate its deployment on robots.

Vibrissal tactile texture sensing and object locating were first investigated. The texture sensing experiment showed that when the WT sweeps across a surface, the force and velocity sensed at whisker tip both have strong linear relationship with roughness (regression analysis $R^2 > 0.99$). And the damping property of the surface can be obtained from real part of WT-measured mechanical impedance. The WT was also used to study the mechanism of rat's vibrissal tactile texture perception in a biomimetic perspective. Then the object locating experiment was investigated with a miniaturized WT ($50 \times 50 \times 5000 \mu\text{m}$). A bio-inspired spatial-temporal-intensity triple-coding scheme was proposed and implemented using digital

signal processing and artificial neural networks. The WT can detect horizontal and radial locations of a contacting object with measurement uncertainties of 0.27 μm and 5.4 μm , respectively. And a WT array can enable object locating in the vertical axis.

Potential applications of WT were explored experimentally. First, the miniaturized WT can accurately measure geometry of high-aspect-ratio micro trenches and detect invalid tip contact caused by protrusion on the sidewall. Second, a modified WT with a sphere tip can sense both viscosity and density of a fluid online. The extracted viscosity and density were separated from each other, rather than in the form of product ($\eta\rho$) or quotient (η/ρ) as detected by existing viscosity sensors. The low working frequency (104 Hz) and large vibration amplitude (0.43 mm) of WT made its result more comparable to results of standard laboratory viscometers. Its measurement error is 1.4% for viscosity and 0.5% for density (water 25 $^{\circ}\text{C}$). And a wide measurement range of viscosity was achieved which is at least from 8.93×10^{-4} to 4.15×10^{-2} N s/m². The WT can also self-sense the fluid velocity without using any additional sensors. Finally, as a general transducer, the WT can also contribute to the broader field of dynamic testing especially in the micro-world, where room is extremely limited for installing additional sensors.

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Chapter 1

INTRODUCTION

1.1 Background

The history of biomimetics can be traced back to more than 3000 years ago, when Chinese attempted to make artificial silk inspired by nature [1]. In the 15th century, Leonardo da Vinci designed a flying machine inspired by the flight of birds, which finally led to the invention of aircraft in the 20th century. Robotics is one of the areas that have benefited most from biomimetics. Various robots have been designed by mimicking animals (e.g. insect, fish, snake, etc.) and humans. And many materials (e.g. gecko-inspired adhesive), components (e.g. artificial muscle) and algorithms (e.g. artificial neural networks) used in developing robots are also products of biomimetics.

In order to survive and perform tasks well in unstructured environments, autonomous robots need to imitate the five sensory modalities possessed by humans and many animals — vision, hearing, touch, taste and smell. The first two modalities have already been mimicked well by robotic vision and audio systems, which are now commercially available and widely equipped on robots. The remaining three modalities, however, are still in the early stages of development. The biomimetic tactile sensing, although being a hot research issue in robotics in the past two decades, is still in its infancy with the research emphasis remaining on the fundamental sensor development until now [2, 3]. The main reason of this slow development in biomimetic tactile sensing is the disperse nature of tactile sensory organ (skin) as well as its complex transduction compared with that of vision and hearing. Due to the absence of widely available tactile sensors, today most robots lack the sense of touch and rely on machine vision heavily. This is not only insufficient since vision cannot provide tactile information such as hardness and roughness, but also non-robust and even dangerous since the vision ability can be easily affected or even deprived in situations of poor/over illumination, smog, blind area of

vision, etc.

While most researchers are focusing on human's cutaneous tactile sensing, recently a unique tactile perception system possessed by some animals has been discovered and investigated extensively in neuroscience [4]. It has been found that rat performs tactile perception with its whiskers (also called vibrissae) in a way totally different from that of human. It actively sweeps its whiskers and palpates objects to extract tactile information with outstanding performance. This capability of vibrissal tactile perception allows them to survive and thrive in hostile environments like underground tunnels. Although neuroscience researches on this biological perception system are still going on, the existing knowledge about it can already serve as a rich source of inspiration for biomimetics. Compared with the cutaneous tactile perception, this vibrissal tactile perception is more suitable for robotic implementation due to its simple structure and localized nature. It also enables the robot to perform tactile sensing at a distance from the unknown object to avoid potential damage. If robots can be gifted with this vibrissal tactile perception, their survival chance and exploration performance in unstructured environments will be greatly enhanced.

The potential to imitate this biological vibrissal tactile perception has only recently begun to be exploited in robotics. Research projects are emerging and attracting funding and supports worldwide, such as the BIOTACT (BIOMimetic Technology for vibrissal ACtive Touch) project funded by the European Union FP7 Programme involving 9 research groups in 7 countries, and the AMOUSE (Artificial Mouse) project supported by the Swiss National Science Foundation and the Framework Programme of European Union. Previous researches in this area have resulted in a number of artificial whisker systems and revealed their potentials in vibrissal tactile sensing. However, most of these systems are too bulky and have some major technical drawbacks in actuation, sensing and implementation. Therefore their performance can hardly match that of the biological system.

On the other hand, remarkable advances have been made in transducer technology in

the past decade, among which is a novel technique called transduction matrix method. This technique allows an electromechanical actuator to act as a sensor simultaneously. And the mechanical quantities of interest are conveniently measured just from the input electrical signals. Therefore it is expected that this technique can serve as a good solution to aforementioned drawbacks in the development of biomimetic vibrissal tactile sensing.

1.2 Objectives and scope

This research aims to develop a whisker transducer for vibrissal tactile sensing, involving its basic principle, mathematical modeling, numerical validation with a finite element model, experimental calibration, experimental validation and testing. The developed whisker transducer will then be used in further investigations such as vibrissal tactile sensing, mechanical measurement and even studying the mechanism of the biological vibrissa system. The main objectives are:

- Developing a whisker transducer with the inspiration from rat's vibrissa system. The whisker transducer should have a compact structure and simplified actuation and sensing. It should also allow an accurate mathematical model for quantitative measurement of tactile stimuli. It should be easily implementable with simple and low-cost instrumentation, so that the use of a whisker array on a robot becomes feasible.
- Investigating vibrissal tactile sensing using the whisker transducer. Two desirable functions in robotic applications — texture discrimination and object locating — are to be implemented. They can be achieved by properly utilizing the whisker transducer's actuation and sensing abilities, as well as developing necessary algorithms for extracting tactile information.
- Exploring potential applications of the whisker transducer. In addition to robotic applications, the developed whisker transducer would also lend itself to the broader field of mechanical measurement including dynamic testing, metrology, viscometry, etc.
- Facilitating the neuroscience research of biological vibrissal tactile perception in a

biomimetic perspective.

The thesis focuses on the whisker transducer as well as its potential capabilities. It does not cover the construction of a robotic rat, nor does it include higher-level robotic tasks like navigation, manipulation and exploration, although they may benefit from the results of this thesis. The whisker transducer will be developed in the manner of biomimetics. Not only the morphology but also the functions and mechanisms of the biological vibrissa system will be imitated by the whisker transducer. Within this biomimetic process, the key issue is to create an artificial counterpart of the follicle-sinus complex (FSC) as the core of the vibrissa system. This will be addressed using the novel transduction matrix method.

1.3 Outline of the thesis

The thesis is organized as follows:

- Chapter 1 gives an introduction to the background, objectives and scope of the research.
- Chapter 2 begins with a brief overview of the biological vibrissal tactile perception. Then it reviews the state-of-the-art in biomimetic vibrissal tactile sensing, a novel technique called transduction matrix method, as well as potential applications of vibrissal tactile sensing.
- Chapter 3 proposes a whisker transducer inspired by the biological vibrissa system. Its working principle, mathematical model, calibration method, finite element model and numerical validation are then discussed.
- Chapter 4 presents experimental investigation with a prototype of the whisker transducer proposed in Chapter 3. It covers the implementation of electrical signal measurement and processing algorithms, experimental calibration and validation of transduction matrix, vibrissal tactile sensing of sandpaper specimens using the whisker transducer, and a study of the mechanism of the biological vibrissal tactile perception in a biomimetic

perspective.

- Chapter 5 implements the vibrissal tactile object locating ability of the whisker transducer by mimicking the triple-coding scheme of the biological vibrissa system. Its potential in geometry detection of high-aspect-ratio micro holes is also illustrated experimentally.
- Chapter 6 develops a novel technique for sensing fluid viscosity online with the whisker transducer. A method for extracting fluid properties from electrical signals of the whisker transducer is derived and also validated experimentally. Issues on miniaturization of the sensor are also discussed.
- Chapter 7 draws conclusions from the study and makes recommendations regarding future research.

Chapter 2

LITERATURE REVIEW

The sense of touch is one of the five major sensory modalities of humans and many animals. It allows us to acquire intimate and intrinsic information about an object. It becomes even more important than vision in certain environments like darkness, smog and murky water. And the tactile feedback also plays an important role in tasks like precision gripping and manipulation. Unfortunately, currently most robots lack the sense of touch or just have basic collision detection ability. As a result, their performance in exploration and manipulation is severely limited. Recently, a unique tactile perception system possessed by some animal species has attracted significant attention from the area of neuroscience as well as robotics. Outstanding tactile sensing performance of this biological tactile perception system has been revealed. The knowledge about this tactile perception system has the potential to contribute to robotic tactile sensing.

2.1 Vibrissal tactile perception

In the natural world, many mammals have long and stiff whiskers (vibrissae) which serve as tactile organs. For example, blind seals can hunt successfully without vision by detecting fish-generated water movement with whiskers [5]. After catching the prey, cat can detect whether it is still alive and decide where to make a precise killing bite based on whisker-collected information [6]. Many nocturnal animals like rats rely on the tactile information captured with whiskers for navigation in the darkness [7]. Recent studies showed that rats can even detect a rich variety of features of an object such as its shape, location and surface texture through active whisking [4] (see Figure 2.1).

Figure 2.1 A rat performing exploration in the darkness with its whiskers [8].

2.1.1 Structure of rat's vibrissa system

The whiskers of a rat are distributed in a regular grid form on each side of the snout [9] (see Figure 2.2a). Each row of the grid contains 5 to 9 whiskers whose length increases exponentially from rostral to caudal. Each whisker is supported by a follicle-sinus complex (FSC) beneath the skin (see Figure 2.2c), which can generate rhythmic sweeping motion of the whisker [10, 11] and simultaneously sense the mechanical stimulus applied on the whisker by converting mechanical energy into neural signals with mechanoreceptors [12]. The neural signals are then relayed and transmitted through brainstem and thalamus, and finally reach the somatosensory region of the cerebral cortex [4] (see Figure 2.2d). Each whisker is one-to-one mapped to a barrel in the barrel field of the cerebral cortex [13] (see Figure 2.2b and Figure 2.2d). Each barrel is responsible for processing the input from its corresponding whisker. Within this whisker-to-barrel pathway, features such as whisker deflection, velocity and amplitude are encoded, transmitted and extracted through neural processing [14].

Figure 2.2 Rat's vibrissa system.

(a) Grid distribution of whiskers [13]. (b) Barrel field of the cerebral cortex [13]. (c) Follicle [4, 11]. (d)

Whisker-to-barrel pathway [4].

2.1.2 Active whisking of vibrissa

Although many mammals and certain bird species have whiskers, most of them move whiskers only when needed (e.g. cat), and some do not even have the movement ability (e.g. horse) [15]. A prominent feature of rat's vibrissae is that they move back-and-forth rapidly in a rhythmic pattern, as shown in Figure 2.3. This vibrating movement of vibrissa is called "whisking" and explains the name "vibrissa" which comes from the Latin word "vibrio", meaning to vibrate [16]. This whisking behavior is involved in most exploration activities such as object locating [17] and texture discrimination [18].

Figure 2.3 Rhythmic whisking movement of vibrissa.

(a) Trajectory of whisker movement extracted from video images [18]. (b) Consecutive video frames of whisking [10].

The whisking of vibrissa is an active process controlled by follicular muscles. Figure 2.2c shows the anatomy of vibrissa follicles [11]. The small sling-like muscles that wrap around

the base of each follicle and attach to the pad surrounding the next caudal vibrissa are called intrinsic muscles. Another type of muscle that anchored to the skin is the extrinsic muscle. Figure 2.4 is the electromyogram (EMG) activity of these two types of muscle recorded during whisking [10]. It shows that they are alternately activated to create the rhythmic whisking. Based on this an approximate biomechanical model of the vibrissa system was proposed [10] and shown in Figure 2.5. In this model, contraction of the intrinsic muscle results in a forward rotation (protraction) of the vibrissa with respect to the pivot point. In contrast, contraction of the extrinsic muscle produces a force that moves the pivot point backward and leads to counter rotation (retraction) of the vibrissa. The alternating activation of the intrinsic and extrinsic muscles results in the rhythmic vibrissa movement (whisking). A recent study showed that these muscles mainly consist of a special type of fiber supporting high-speed contraction [19], therefore are able to generate high frequency whisking movement. The two springs in the model represent the elastic properties of the skin and the fibrous connective tissue.

Figure 2.4 EMG activity of intrinsic and extrinsic muscles recorded during whisking [10].

Figure 2.5 An approximate biomechanical model of the vibrissa system [10].

An interesting point about the whisking movement is that it is a voluntary behavior since rat can modify its whisking parameters to meet the functional demands of exploratory tasks [20, 21]. This is quite similar to the behavior of humans who choose optimal hand movements when evaluating different properties of an object [22]. The whisking frequency is tuned at a very pure value (frequency variability < 3%) within a single bout [10]. However, it changes between different bouts in the range of 5-25 Hz [18]. The amplitude of whisking, the spread of vibrissae as well as their initial position are also adjustable according to the task and circumstance [8, 10, 23, 24]. The reason for the changes in these whisking parameters between bouts is not clear, but it can be assumed that they will bring some benefits to the animal. For example, using large-amplitude low-frequency whisking can facilitate the exploration when rat is seeking for food [10]. After the initial contact with an object, it will switch to small-amplitude high-frequency whisking in order to extract fine features as well as to protect vibrissae [10, 25]. Changing the frequency allows the rat to sense the dynamic response over a wide frequency range. Changing the spread and initial position of vibrissae may allow it to access unapproachable places such as narrow gaps.

2.1.3 Vibrissa-mediated tactile location detection

Object locating is one of the most important functions of rat's whisker which is currently under extensive investigation in neuroscience. Rats are nocturnal animals living mainly in dark environments such as underground tunnels. Due to the absence of light, the

sense of vision becomes limited and unreliable, and the vibrissal tactile perception thus becomes an important means of exploration. Recent behavioral and neurophysiological evidences have revealed that rats can detect and locate objects in the 3-dimensional (3D) space with their whiskers [26]. For example, they accurately detect the gap between two platforms before they can safely cross it [4]. When they are running in a tunnel, they detect the proximity of the wall and use it to regulate the running direction and speed [7]. In addition, it is also believed that the locating ability plays an important role in detecting the shape of large objects [27].

The 3D space surrounding the snout of a rat can be geometrically described by a coordinate system consisting of three orthogonal axes (see Figure 2.6): a vertical axis, a horizontal axis and a radial axis. So a complete representation of the 3D location of an object requires three parameters: vertical location, horizontal location and radial location. The acuity of rat's locating ability is very fine and differs among axes. For example, they can discriminate the difference between horizontal locations as small as 0.24 mm [28]. And the acuity of radial locating is about 3 mm [29].

Figure 2.6 Coordinate system for representing the 3D space surrounding the snout of a rat [26]

Although the mechanism underlying this vibrissal object locating is not completely clear yet and to study it in awake and behaving rats remains a challenge, a plausible hypothesis is that object location is possibly encoded by a spatial-temporal-intensity

triple-coding scheme [26], as shown in Figure 2.7:

- *Spatial-coding for the vertical axis:* Since each whisker is one-to-one mapped to a barrel in the cortex (see Figure 2.2d), the vertical position is simply assumed to be encoded by the identity of the activated neuron in the barrel cortex which indicates the vertical location of the corresponding whisker in contact with the object.
- *Temporal-coding for the horizontal axis:* During the active whisking movement, the spiking activity of “whisking cells” located in the trigeminal ganglion (TG) (see Figure 2.2c) provides a temporal “whisking signal” (see Figure 2.8a) encoding the spatial position of the whisker over time. Once the whisker gets into contact with an object in the horizontal axis, another type of signal called “touch signal” encoding the onset time of contact will be generated by “touch cells” [30], as shown in Figure 2.8a. The horizontal location of the object is then detected from the concurrence of these two signals using a thalamocortical neuronal circuit [4, 17, 30], as illustrated in Figure 2.8b.
- *Intensity-coding for the radial axis:* The radial position is encoded by the firing intensity of TG neurons [31]. Contacting at a location closer to whisker base will increase the firing intensity, as shown in Figure 2.9.

Figure 2.7 A possible spatial-temporal-intensity triple-coding scheme for 3D object locating [26]

Figure 2.8 Temporal scheme for horizontal locating [30].

(a) Top: temporal signal of whisking movement. Bottom: temporal signal of neuron spiking activity of touch cells indicating the onset time of contact. (b) Decoding the horizontal location from the “whisking signal” and “touch/contact signal” by thalamic neurons.

Figure 2.9 Intensity scheme for radial locating [26, 31].

Such a triple-coding scheme allows for efficient multiplexing of 3D object location information and reduces ambiguity since different coding algorithms are used for different dimensions of the location.

2.1.4 Vibrissa-mediated tactile texture discrimination

Texture is one of the most important components of tactile sensation. Psychophysical studies have demonstrated that rats can discriminate surface textures with very high accuracy, efficiency and reliability by actively sweeping their whiskers across the surface [18, 32]. The acuity of this vibrissa texture sensing capability is remarkable ($< 100\text{ }\mu\text{m}$) and comparable to that of humans using their fingertips [33]. The time from first contact to the action of making choice is only several hundred microseconds [18, 34]. During the palpation process, whiskers are excited to vibrate in a rhythmic whisking motion at a frequency in the range of 5-25 Hz with mean amplitude of 32 degrees [10, 11, 18]. And the reliability of making correct choice is greater than 85% [18, 35, 36].

The underlying neural mechanism of this texture sensing capability is unknown and is currently under extensive investigation and debate. Two preliminary hypotheses are formed to explain how rats can transduce the mechanical stimuli into neural signals and subsequently encode them within the brain:

- The “resonance hypothesis” is proposed based on the passive whisking experiment conducted with anesthetized rats (see Figure 2.10a). It is found that the resonant frequencies of vibrissae on one face of rat vary systematically from posterior to anterior [37, 38] (see Figure 2.10b). When rat sweeps its vibrissae across a surface, the induced vibration will be amplified differently by different vibrissae. And the amplification is largest if the frequency is close to the resonant frequency of a certain vibrissa. Thus texture can be encoded as the spatial map of vibrissa frequency response across the face

[37]. This mechanism is similar to that used by human auditory system to encode acoustic frequencies.

Figure 2.10 The resonance hypothesis of vibrissal texture sensing [37].

(a) Passive whisking using a texture wheel to drive vibrissa motion. (b) Resonant frequencies of vibrissae distributed in a grid form on one mystacial pad of rat.

- The “kinetic signature hypothesis” states that texture features like the size of grains and the distance between them will induce a texture-specific high frequency component in the temporal profile of whisker velocity [39]. This unique “kinetic signature” is then encoded by neurons as a distinctive firing pattern [40] which is used in texture discrimination (see Figure 2.11).

Figure 2.11 The kinetic signature hypothesis [41].

Although there are not sufficient evidences to rule out the possibility of the first hypothesis, it is found to be less plausible than the second one [42]. The second hypothesis also needs more evidences to support it since it is just in the preliminary stage. The current research activities are mainly carried out with anesthetized rats, either by generating passive whisker vibration via moving the specimen or by generating electrical whisking via direct stimulation of the facial nerve. This is due to the difficulty in experimenting with awake and behaving rats [4]. So results from these studies may differ from that obtained from natural whisking by awake rats. Furthermore, the existence of other hypotheses is also possible. For example, rat may use multiple mechanisms and can shift the coding strategy under different conditions [39], just like humans using different strategies for detecting macro-texture and micro-texture.

2.2 Biomimetic vibrissal tactile sensing

It is amazing that a simple whisker could bring about so many functions with outstanding performance. Although the neural mechanism of this vibrissal tactile perception is not completely clear, the existing knowledge about it has already become a useful source of inspiration for developing artificial systems. It is hoped that artificial systems could achieve similar vibrissal tactile sensing capabilities by mimicking the biological vibrissa system.

2.2.1 Vibrissal tactile sensing vs. cutaneous tactile sensing

When people talk about tactile sensor, they usually refer to cutaneous sensor that measures the distribution of force over a large area, mimicking the function of human skin [2]. This type of tactile sensor is usually in an array form with simple resistive or capacitive sensing elements. It can be mounted on a robot as artificial skin for tactile sensing. So why do we need to develop a new type of tactile sensor if we already have the cutaneous sensor? The reason is that active vibrissal tactile sensing can provide some benefits over cutaneous tactile sensing. First, vibrissal tactile sensor allows a robot to explore the environment at a distance from the contact point. This can prevent the robot from being damaged in a harsh environment (high temperature, corrosion, wearing, etc.). It can also provide warning of collision so that the robot can take necessary actions such as deceleration before the collision happens. Second, the slender and flexible whisker allows the robot to access unapproachable places such as narrow gaps. Also its high compliance reduces the contact force and avoids damaging the object. Finally, different from the passive cutaneous sensing, vibrissal tactile sensor can work actively by sweeping the whisker. This active whisker movement facilitates the exploration by extending the sensing area. Active movement is also essential when sensing properties like texture and hardness. Even human sometimes may use a probe to detect texture by actively rubbing it across the surface [43]. In addition, active whisker movement enables hyperacuity in location sensing which means that rat can resolve spatial offsets that are smaller than the inter-vibrissal spacing [4, 26].

2.2.2 Whisker sensors and sensing systems

The biomimetics of the biological vibrissal tactile perception began in the early 1990s, but its progress was slow and intermittent in that decade with very few designs and papers reported [6, 44]. The past decade has seen an accelerating progress in this area. This is mainly due to the increasing knowledge about the biological vibrissa system as well as advances in a wide range of technologies such as sensing, fabrication, material and artificial intelligence. So far a number of whisker sensors and sensing systems have been developed mainly for robotic applications. These designs vary considerably in terms of whisker material (e.g. steel, superelastic Nitinol, glass-fibre composite, natural rat whisker, etc.), actuation (e.g. electric motor, shape memory alloy, etc.) and sensing (e.g. resistive, capacitive, Hall-effect magnetic, optical, etc.). And some of them are starting to be installed on robots, as shown in Figure 2.12. The typical designs are reviewed below and summarized in Table 2.1.

Figure 2.12 Robots equipped with whiskers for vibrissal tactile sensing.

(a) Khepera II robot [45]. (b) Koala robot [46]. (c) WhiskerBot performing texture sensing [47].

One of the earliest designs of whisker sensor was inspired by cat's whisker [6]. Its structure is shown in Figure 2.13. A curved stainless steel needle (length: 12.5 cm, diameter: 0.5 mm) is used as the whisker. The rotation angle of the whisker when it touches an object is measured by a potentiometer. And a spring is used to return the whisker to its initial position. The sensor itself works passively without whisking movement. However, it can be mounted on a robot arm to provide mobility. It is able to measure surface profile when scanning over a surface.

Figure 2.13 An early design of whisker sensor using potentiometer [6].

Figure 2.14a shows another design composed of a piano wire (length: 210 mm, diameter: 0.8 mm) as the whisker, a DC servo motor for actuation, an angular position sensor, and a torque sensor [44]. It is possible to sense the contact location between the whisker and an object, although some practical problems such as slip may deteriorate this capability. Later a new version was made by the same author by replacing the torque sensor with a CCD camera [48] (see Figure 2.14b). Both the contact force and contact position can be measured, so the stiffness of the object can be evaluated as well. However, the system becomes more complicated and larger, therefore is more difficult to deploy on a robot.

Figure 2.14 Whisker sensing system with torque and angular position sensing.

(a) Using torque sensor [44]. (b) Using CCD camera [48].

In another design, a whisker array was constructed with each element consisting of a natural rat whisker and a capacitive microphone [49] (see Figure 2.15a). The force applied on the whisker deforms the microphone membrane and generates a voltage signal. The whisker element cannot move by itself, so the whisker movement is performed by an additional servo motor as the actuator which is shared by all whiskers (see Figure 2.15b). The whisking frequency is approximately 0.7 Hz. Data are recorded when the whisker array sweeps across different textures. It showed that power spectral densities are different for different textures. Although this may be used as a basis for discriminating textures, the result is rather qualitative without a clear meaning. The nonlinear nature of the whisker as well as the complex structure of the system makes it difficult to interpret data.

Figure 2.15 Whisker array sensing system using microphone as sensor [49].

(a) Whisker sensing element. (b) Whisker array actuated by a motor.

Scholz and Rahn designed a whisker system for shape sensing [50]. The system is composed of a superelastic Nitinol whisker, a DC motor for actuation, and a six-axis mini load cell for force and torque sensing (see Figure 2.16). A nonlinear elastic model was used to predict the centerline displacement of the whisker from measured force and torque values by the load cell. A numerical algorithm was developed which can provide accurate solution only when proper initial value and tolerance are provided.

Figure 2.16 Whisker sensing system using load cell [50].

Kim and Moller designed a whisker system also for shape recognition [46]. This system has multiple steel whiskers sharing a single DC motor for angular movement (see Figure 2.17). A permanent magnet is attached to each whisker and a Hall-effect magnetic sensor is used to measure whisker deflection. Experimental results showed that the deflection angle or velocity provides the location information needed by shape recognition.

Figure 2.17 Whisker array sensing system using Hall-effect magnetic sensor [46].

Solomon and Hartmann [51] built a whisker array as shown in Figure 2.18. Each whisker is made of superelastic Nitinol and is quite thick and stiff (diameter: 1 mm). It is embedded in an aluminum block ($4 \times 4 \times 8$ mm) which has four strain gauges attached on its four faces for moment sensing (see Figure 2.18a). All whiskers are fixed on a vertical aluminum bar and share an AC servo motor for actuation (see Figure 2.18b). When the array scans across a surface, the moment sensed at the whisker base provides information about the contact location. Thus it is possible to reconstruct object shape by combining data from all whiskers [27]. However, friction and slip will cause error to the measurement result. In order to perform accurate sensing, knowledge about the friction coefficient between the whisker and the object is required [51].

Figure 2.18 Whisker array sensing system using strain gauge [51].

(a) Aluminum whisker base with strain gauges. (b) Whisker array fixed on a motor for actuation.

Recently, Fox et al. implemented a whisker sensing system actuated by a shape memory alloy (BioMetal) wire at a frequency of about 1 Hz [47] (see Figure 2.19). The artificial whisker is a 200 mm glass-fibre composite rod which can be rotated by heating the BioMetal wire. Strain gauges are installed at the base of each whisker for sensing. The system is able to perform rough-smooth discrimination with hand-picked features. However, additional knowledge of the object's position is required for finer discriminations.

Figure 2.19 Whisker sensing system using shape memory alloy and strain gauge [47].

Table 2.1 Whisker sensors and sensing systems

Year	Whisker	Actuation	Sensing	Measurand	Result	Reference
1992	Steel needle	Robot arm	Potentiometer	Surface profile	Quantitative	[6]
1998	Piano wire	DC motor	Angular position sensor Torque sensor	Contact location	Quantitative	[44]
2001	Piano wire	DC motor	Angular position sensor CCD camera	Contact location Contact force Stiffness	Quantitative	[48]
2003	Natural rat whisker	Motor	Capacitive microphone	Texture	Qualitative	[49]
2004	Superelastic Nitinol alloy	DC motor	Six-axis mini load cell	Contact location Shape	Quantitative	[50]
2007	Steel beam	DC motor	Hall-effect magnetic sensor	Contact location Shape	Quantitative	[46]
2008	Superelastic Nitinol wire	AC motor	Strain gauge	Contact location Shape	Quantitative	[51]
2009	Glass-fibre composite rod	Shape memory alloy wire	Strain gauge	Texture	Qualitative	[47]

2.2.3 Discussion

Above review shows that by mimicking the biological vibrissa system, it is possible to endow artificial systems with vibrissal tactile sensing functions like location/shape detection and texture discrimination. However, most designs in literature are still at a preliminary stage and their performance in terms of compactness, versatility, accuracy and efficiency is still

well below that of the biological system.

In the biological vibrissa system, both actuation and sensing is achieved with a highly compact follicle-sinus complex (FSC) at the base of each whisker, so that the structure of the system is very simple. In contrast, the artificial systems in literature are in the form of complicated systems with many components in order to achieve similar functionality. Due to the large size of some components such as the electric motor, the whole system becomes very bulky. In addition, since every sensor or actuator needs at least two electric wires, a single whisker element such as the one in Figure 2.14 may require more than six wires for operation. This wiring problem becomes more serious for a whisker array.

The review also reveals a common problem shared by most designs. Although a variety of sensors have been used, the choice of actuator is quite limited. All designs except the last one use electric motor as the actuator, which has several drawbacks. First, electric motor is usually very large (see Figure 2.18) and difficult to miniaturize. This makes the whole system very bulky and difficult to form a whisker array. As a result, all whiskers in a whisker sensing array have to share a single motor for actuation [49]. This seriously limits the versatility of the system since independent control of each whisker is found important in rat's vibrissal perception. For example, in some tasks rat adjusts the spread between whiskers as well as the direction of each whisker to facilitate the exploration [8]. Second, although an electric motor can run very fast in one direction, it cannot reverse its direction fast and frequently to generate back-and-forth motion of the whisker. This is also a problem faced by shape memory alloy actuators. As a result, most designs in literature are working at a frequency below 1 Hz [47, 49], which is much lower than that used by rat (5-25 Hz). The consequence is that the efficiency of these artificial systems is much lower than that of rat, which makes a decision within several hundred microseconds after contact [18, 34].

Finally, some designs cannot provide accurate and quantitative results due to the lack of an effective model for interpreting the sensed tactile data. Since these artificial systems

usually have complicated structures, the precise modeling is difficult especially when the whisker is made of a nonlinear material (e.g. natural rat whisker [49]) or it deflects beyond the linear regime [50]. In shape detection cases [51], accurate measurement requires the knowledge about the friction coefficient between the whisker and the object being known in advance, which is impossible when the system is used to explore an unknown environment. In texture discrimination cases [47, 49], even though the whisker moves at a very low speed in order to sense the roughness in a way more similar to that of a profilometer rather than rat's whisking behavior, it turns out that roughness is not simply converted as a high-frequency output signal. This makes the interpretation of the tactile data rather difficult. Although the authors claimed that it is possible to discriminate between different textures using hand-picked features, the measurement results are qualitative and subjective without a clear meaning.

In summary, there is still a long way to go before the performance of artificial systems can match that of the biological vibrissa system. Advances in technologies especially the developments of new transducers are welcome in order to overcome aforementioned limitations.

2.3 Simultaneous sensing and actuating technique

Simultaneous sensing and actuating (SSA) is a novel technique for using a transducer as both actuator and sensor concurrently. It can offer many advantages including reduced number of devices, lower cost, simpler wiring and instrumentation, etc. Many actuators have the potential to be used reversely as sensors. For example, a loudspeaker can generate vibration when an electrical input signal is applied. It can also produce an electrical output signal when its diaphragm is excited by an external force. However, this example is still a little different from the SSA technique since the actuation and sensing capabilities of the loudspeaker are not concurrently utilized. The concept of SSA was initiated from the area of online motor monitoring and diagnosis [52]. It was found that the motion of motor can be

estimated from current and voltage measurements during its normal operation without using additional sensors. The similar idea was then applied to the magnetic bearing technology to control an active magnetic bearing in a self-sensing configuration using only the current signal [53]. The possibility of SSA using piezoelectric materials was investigated by Anderson and Hagood [54]. A PZT patch actuator bonded onto a one-dimensional cantilever beam was used simultaneously as a strain rate sensor by combining the applied voltage and charge. Another study by Liang et al. showed that it is possible to detect the mechanical impedance of a load by measuring the electrical impedance of a PZT actuator [55]. However, these methods can only qualitatively estimate dynamic behavior of the structure of interest and can hardly provide quantitative and accurate values. Therefore they are more suitable for condition monitoring rather than accurate measurement.

2.3.1 Transduction matrix method

In the past decade, Ling and his team put forward this SSA technique for accurate measurement of mechanical quantities using electromechanical transducers [56]. In their method, a two-by-two matrix is derived to describe the transduction process between the input electrical variables and output mechanical variables of a transducer. This matrix is thus termed “transduction matrix” which completely characterizes the forward actuating and backward sensing functions of the transducer. The transduction matrix can be derived analytically for a transducer with simple structure. For a complex transducer, its transduction matrix can be identified numerically or experimentally. With this transduction matrix being accurately determined, the mechanical quantities at the output port of a transducer can be accurately obtained through measuring electrical signals at the input port. Therefore direct measurement of mechanical quantities is avoided which is usually difficult in practice. This method is a true SSA solution since the actuation and sensing take place concurrently. It is particularly suitable for situations where both actuators and sensors are involved, such as the measurement of mechanical impedance. It also provides other benefits like online and *in situ* measurement, easy implementation and elimination of loading effect. Since then, a number of novel SSA

transducers have been developed which are reviewed below.

This transduction matrix method was first applied to develop a piezoceramic inertial actuator (PIA) for mechanical impedance measurement [56], as shown in Figure 2.20a. The transduction matrix of the PIA was derived analytically and also calibrated experimentally. Figure 2.20b shows the configuration for testing the mechanical impedance of a beam structure. The HP4192 impedance analyzer applies an AC voltage to the PIA to excite the structure at the test point. It also measures the electrical impedance at the same time. Using the identified transduction matrix, the mechanical impedance at the test point can be easily calculated from the measured electrical impedance. This transducer was also used in structural integrity monitoring to detect variations of the mechanical impedance caused by damages [57]. A further study revealed that this method is able to remove the loading effect and therefore increase the measurement accuracy [58].

Figure 2.20 A piezoceramic inertial actuator (PIA) for mechanical impedance measurement [56].

(a) Structure of the PIA. (b) Testing mechanical impedance of a beam using the PIA.

In 2004, an electromagnetic shaker with SSA capability was developed based on the transduction matrix method [59]. After experimental identification of its transduction matrix, the transducer is capable of *in situ* characterization of soft incompressible viscoelastic materials by measuring its mechanical impedance. It can be employed by biomedical applications such as testing mechanical properties of human skin *in vivo*.

Figure 2.21 An electromagnetic shaker for characterizing mechanical properties of human skin.

In 2005, a method for measuring the acoustic absorption coefficient of materials was proposed based on the transduction matrix method [60]. A loudspeaker is used as an acoustic driver and simultaneously as a sensor. The specific acoustic impedance of the material mounted perpendicularly at the end of the tube is indirectly measured through measuring the input electrical impedance of the loudspeaker, as shown in Figure 2.22. This method is particularly useful in situations where installing a microphone into an impedance tube is difficult.

Figure 2.22 Microphone-free measurement of acoustic absorption coefficient using a loudspeaker.

In 2006, the transduction matrix method was used to monitor the quality of ultrasonic welding of IC wires [61] or thermoplastics [62] driven by piezoelectric actuators (see Figure 2.23). After the identification of the transduction matrix, the welding force and velocity applied to the workpiece can be monitored via the input voltage and current. And the variation of the mechanical impedance during the process can also be obtained for studying the welding mechanism [63]. The proposed method is not only sensor-less, but also *in situ* and real-time, which means that the system can be implemented without affecting the normal operation.

Figure 2.23 Monitoring quality of ultrasonic welding.

In 2007, a novel bimorph impedance transducer (BIT) was designed for measuring both translational and rotational mechanical impedance of a structure [64, 65] (see Figure 2.24). It can be excited to generate translational or rotational motion by controlling the electrical signals input to the two PZT bimorphs. And the mechanical impedance can be simply achieved through measuring electrical signals, avoiding direct measurements of moment/force and translational/angular velocity. It is useful for characterizing linear viscoelastomers and magnetorheological elastomer.

Figure 2.24 A bimorph impedance transducer (BIT) for translational and rotational mechanical impedance measurement.

Besides the applications mentioned above, the transduction matrix method and the SSA technique were also applied to in-situ mechanical impedance measurement of air bearing in hard disk drive (HDD) [66], monitoring road surface condition through a mobile platform [67], in-situ quantification of soft tissue stiffness [68], on-line breakage monitoring in micro-drilling [69], and quality monitoring of resistance spot welding [70].

In brief, the transduction matrix method provides a neat and convenient way for dynamic measurement of mechanical quantities. With the feature of SSA, the instrumentation is simplified since no additional sensors are required, and the loading effect is completely eliminated. These advantages make it especially suited for space limited conditions such as the development of vibrissal tactile sensor.

2.4 Potential applications of vibrissal tactile sensing

Most of the whisker sensing systems in literature are designed for robotic applications including navigation, obstacle avoidance, object locating, shape detection, texture discrimination, etc. However, through the investigation of this thesis, another two potential applications of vibrissal tactile sensing have been recognized — geometry detection of high-aspect-ratio micro holes and online viscosity sensing. These two applications will be demonstrated in Chapter 5 and Chapter 6 respectively, using the whisker transducer developed in this thesis. Therefore a brief literature review on them is provided here.

2.4.1 Geometry detection of high-aspect-ratio micro holes

Currently an important and also challenging task in many industries is to detect geometry of high-aspect-ratio micro holes. Due to the advances in microfabrication technologies, today a large number of high-aspect-ratio micro components can be manufactured, such as fuel injector nozzles of combustion engines, ink-jet printer nozzles, micro-channels in microfluidic devices, laser drilled turbine blade cooling holes in aero-engines, small holes in aircraft wings, and medical syringes [71-74]. Their performance depends heavily on the precision of geometrical parameters of micro holes, including size, orientation, taper, circularity, surface roughness, blind hole depth, straightness, etc. For example, properly shaped fuel injector nozzle holes can improve the fuel flow and atomization characteristics as well as reduce engine exhaust emissions [74]. And taper of laser

drilled holes needs to be designed properly to increase the cooling efficiency of turbine blade as well as to improve the aerodynamic performance of aircraft wings [71].

However, current geometry detection technologies are not keeping up with the fabrication technologies. Although the probe of a conventional coordinate measurement machine (CMM) can be scaled down to 300 μm [72], it is still too large for detecting many micro features. In addition, its relatively large stiffness has the risk of damaging the workpiece, and its aspect ratio cannot be very high in order to maintain measurement accuracy [73]. Atomic force microscopy (AFM) is a common method for imaging surface profile at nanoscale. However, it is mainly designed for planar samples such as silicon wafers, so the aspect ratio of the probe is low and its measurement range is short. Furthermore, most AFM probes rely on an external laser source and detector for measuring the tip deflection during scanning. This configuration is difficult to implement when measuring high-aspect-ratio micro holes, since the laser beam will be obstructed by the sidewalls [75]. Optical methods such as laser reflectometry are possible to detect the depth and bottom profile of a blind hole [76, 77]. However, they cannot detect the geometry of the vertical sidewalls since light cannot be reflected back due to the high aspect ratio. Scanning electron microscope (SEM) is another instrument widely used for imaging surface topography of a sample with very high resolution. However, it can examine a high-aspect-ratio micro hole only when it is sectioned destructively [78]. And the produced image can only provide 2D information about the hole. Due to aforementioned limitations of conventional methods, manual inspection is still routinely carried out in some industries. For example, an operator detects the quality of a turbine blade cooling hole by manually passing a piano wire through it [76]. This process is error-free but labor-intensive.

To meet the increasing needs for non-destructive geometry detection of high-aspect-ratio micro holes, great efforts have been made in the past decade which have resulted in a consensus among many researchers that tactile probe with a high-aspect-ratio micro shaft may be the most promising solution. Various micro tactile probes have been

proposed which can be classified into two categories — static probe and vibrational probe. Static probes are based on the principle that mechanical contact force will cause static deflection of the probe which can be sensed by means of resistive sensor [73, 79], capacitive sensor [80, 81], optical sensor [72, 74], etc. Figure 2.25a is an example of a tactile probe with a micro silicon cantilever. The deflection is measured by an integrated strain gauge [73]. Figure 2.25b is a glass-fiber probe with a spherical tip [74]. A charge coupled device (CCD) optical sensor is used to measure the tip position. Figure 2.25c is another optical solution using a laser diode to illuminate the fiber shaft [72]. The shadow of the fiber is recorded by the camera and the image is then processed to extract probe deflection. Figure 2.25d is a triskelion probe with each of its three flexures being a capacitance sensor for displacement sensing [80].

Figure 2.25 Static tactile probes for high-aspect-ratio geometry detection.

Vibrational probes are based on the principle that mechanical contact will change the amplitude of a vibrating probe. The high-aspect-ratio microprobe is excited to vibrate usually by piezoelectric actuators. And the vibration amplitude is monitored using various methods such as electric conduction [82, 83], PZT strain sensor [75, 84] and capacitance sensor [85]. Masuzawa et al. developed a vibroscanning (VS) method for measuring inner dimensions of small holes [82]. In this method, a microprobe is excited to vibrate with small amplitude. A simple electric circuit is designed to detect the contact between the probe tip and a conductive object (see Figure 2.26a left). The voltage across the resistor is recorded as the output signal which changes with the variation of surface profile. Since this method is limited to conductive materials, a modified method using a twin-probe was proposed to solve this problem [83]. Contact with a non-conductive object will cause electric conduction between the two probe elements and generate a voltage output (Figure 2.26a right). However, the twin-probe is more difficult to fabricate and miniaturize. And the tiny gap between probe elements can be easily destroyed by dust or oxidation. Yamamoto et al. further modified this method into a resonance mode vibroscanning (RVS) method [75]. The microprobe is excited to vibrate at its resonance by a driving PZT (see Figure 2.26b). And the contact with an object is indicated by the change of strain value measured at the base of the probe using another detecting PZT. Using the similar principle, recently a triskelion microprobe was designed which can detect geometry of an object in three orthogonal axes [84]. However, its structure is very complicated since each of its three flexures is equipped with two PZT actuators and two PZT sensors.

Figure 2.26 Vibrational tactile probes for high-aspect-ratio geometry detection.

(a) Vibroscanning method [83]. (b) Resonance mode vibroscanning method [75].

In summary, although various principles have been tried for geometry detection of high-aspect-ratio micro holes, most designs are still in the conceptual stage with some drawbacks remained to overcome. Static probes especially the silicon MEMS probe have advantages such as high accuracy, simple structure, easy fabrication and miniaturization, and high scanning speed. However, they usually have large contact force and are more susceptible to adhesion and wearing. Vibrational probes can solve the problem of adhesion and reduce the contact force. However, they usually have complicated structure making the fabrication and miniaturization more difficult. Another important issue is the fabrication of the probe shaft. Common MEMS processes can produce very small and high-quality cantilevers. But their material is limited to silicon and their aspect ratio is not very high. The commonly used glass fiber is low-cost and its aspect ratio can be made very high by heating. But its quality is difficult to control. Probes of hard and tough material such as tungsten can be fabricated by μ EDM (Micro-Electrical Discharge Machining). However, it is not suitable for batch fabrication. Finally, the size of probes varies in a wide range. However, smaller ones are not always preferred since most practical micro holes such as fuel injector nozzle holes and laser drilled cooling holes have diameter of several hundred micrometers and length of several millimeters.

2.4.2 Online viscosity sensing

Viscosity is one of the most important properties of a fluid characterizing its fluid-mechanical behavior. It is a measure of the internal resistance or friction of the fluid to flow or shear. According to Newton's law of viscosity, when a fluid is sheared (see Figure 2.27), the applied shear stress τ is proportional to the resulting strain rate ($d\theta/dt$) or the velocity gradient (du/dy) [86]:

$$\tau = \eta \frac{d\theta}{dt} = \eta \frac{du}{dy} \quad (2.1)$$

where constant η is the absolute viscosity or dynamic viscosity. Its SI unit is N s/m^2 , Pa s , or kg/m s .

Figure 2.27 Shear deformation of a fluid element caused by applied shear stress.

The viscosity of a fluid can also be expressed in another form called the kinematic viscosity ν :

$$\nu = \frac{\eta}{\rho} \quad (2.2)$$

where ρ is the density of the fluid. This is the viscosity measured by many gravity type viscometers such as glass capillary viscometers. Its SI unit is m^2/s .

When the stress-strain rate relationship of a fluid follows Equation (2.1), it is termed a Newtonian fluid. The viscosity of a Newtonian fluid is independent of the applied shear stress. Water and many aqueous solutions are Newtonian. If a fluid does not obey the relation in Equation (2.1), it is termed a non-Newtonian fluid. Usually the viscosity of a non-Newtonian fluid depends on the shear stress rate. Many polymer solutions, solid suspensions and highly viscous fluids are non-Newtonian. The viscosity of Newtonian fluids also varies with pressure and temperature. Generally, the effect of pressure on viscosity is weak and negligible. The effect of temperature, however, is much stronger and should be taken into account when using or measuring viscosity.

2.4.2.1 Conventional viscometers and viscosity measuring techniques

The instrument for measuring the viscosity of a Newtonian fluid is called a viscometer. Relative motion between the fluid and an object is usually required which can be generated by keeping the fluid stationary and moving the object through it or vice versa. There have already been a number of conventional methods for measuring viscosity and some have been standardized by ASTM (D88, D445, D446, D1200, D1343-93, D2983-87, D4212, D5478-98, D7042, etc.) and ISO (2431, 2555, 2884, 3105, 3219, 12058, etc.). As a result, a variety of viscometers are now available commercially which can measure either dynamic viscosity (η) or kinematic viscosity ($\nu = \eta/\rho$), depending on the principle employed. They can be classified into the following types [87]:

- Capillary viscometers. They are the simplest and most common viscometers based on the principle that the time (t) required for a fixed volume of liquid to flow through a capillary between two graduation marks under gravity is proportional to the kinematic viscosity. The proportional factor (K) needs to be calibrated using a liquid of known viscosity and density. Once the value of K is known, the kinematic viscosity of the liquid can be obtained as $\nu = Kt$.
- Orifice viscometers. They are widely used in the oil industry due to the simplicity and convenience. The efflux time of a fixed volume of liquid passing through an orifice is measured. However, the time is not proportional to the viscosity and is generally not accurate. So it can only be used as an arbitrary measure of the kinematic viscosity.
- Falling ball viscometers. This type of viscometer measures the velocity of a sphere of known radius (R) and density (ρ_s) falling through a fluid of known density (ρ_f) under gravity. The sphere will reach a terminal velocity (V_t) when the gravitational force is balanced by the combination of drag force and buoyant force exerted by the viscous fluid. By measuring this terminal velocity, the dynamic viscosity of the fluid can be obtained as $\eta = 2R^2g(\rho_s - \rho_f)/9V_t$, where g is the gravitational acceleration. Although the result is in the form of dynamic viscosity, the fluid density should be known in advance.

- Rotational viscometers. This type of viscometer is based on the idea that the torque required to rotate an object at a known angular velocity is proportional to the dynamic viscosity of the fluid. It has the advantage of continuous measurement.
- Vibrational viscometers. This type of viscometer measures the damping of an electromechanical resonator oscillating in the test fluid using one of the following schemes: (i) measuring the power required to keep the resonator vibrating at constant amplitude; (ii) measuring the decay time once the external excitation stops; (iii) measuring the frequency change between the excitation and response waveforms. However, the measured damping value is density dependent. Therefore an independent test of the fluid density is required.

In summary, conventional viscometers are based on various standard methods and are well accepted in laboratories and industries. They can provide very precise results of the test fluid in a well controlled environment. However, most of them are bulky, complex and expensive. The procedure of capillary, orifice and falling ball methods is non-continuous and also requires a large sample volume and long measuring time. The rotational type is able to perform continuous measurement, but its complex structure (inner cylinder, outer cylinder, motor, torque/motion sensor) as well as difficult maintenance prevents it from being miniaturized and integrated into other systems for monitoring. The vibrational method has been recognized as the most promising technique for online monitoring due to advantages such as continuous reading, high sensitivity, wide range, small sample volume, having no moving parts, and less frequent maintenance and calibration. However, conventional viscometers of this type mainly measure the electrical power/decay time/frequency shift and empirically correlate it with the viscosity. More theoretical analysis of the underlying electromechanical interaction is required for better interpretation of the result. In addition, most of them can only provide the kinematic viscosity ($\nu = \eta/\rho$) which is dependent on the density. So an additional test of the fluid density is required for obtaining the dynamic viscosity (η) which will definitely complicate the measurement procedure.

2.4.2.2 Viscosity sensors

Viscosity sensors are devices having small or even micro size and can be deployed directly in a process line or integrated into a system for monitoring. Most of them are simply miniaturized versions of bulky viscometers. In terms of sensing principle, almost no sensor in the literature is based on falling ball or rotational technique since they involve complex structures and moving parts. Although there are a very few cases in which the capillary principle is employed through microfluidic technique [88, 89], these sensors are mainly miniaturized for saving the sample volume. They can hardly perform online measurement in a process vessel because the extremely small channel will block the flow. So the vibrational principle is the choice of the majority of sensors in literature due to aforementioned advantages.

Vibrational viscosity sensors can be further divided into two types depending on the sensor configuration and vibration mode. The most prevailing type is the thickness-shear mode (TSM) resonator. TSM resonators have been used for detecting a wide range of electrical, mechanical and chemical properties for a long time in an empirical manner without a precise analytical model, until Kanazawa and Gordan derived a simple analytical expression relating the resonant frequency to the fluid viscosity and density [90]. In their model, a quartz crystal plate or disk oscillates in the shear mode when an AC voltage is applied due to the piezoelectric effect. When it is immersed into a viscous liquid, the fluid-quartz interaction at the interface will change its resonant frequency as:

$$\Delta f = -f_0^{2/3} \left(\frac{\eta \rho}{\pi \mu_Q \rho_Q} \right)^{1/2} \quad (2.3)$$

where Δf is the shift of resonant frequency, f_0 is the resonant frequency of the quartz in air, η and ρ are the dynamic viscosity and density of the liquid, μ_Q and ρ_Q are the shear modulus and density of the quartz. Equation (2.3) shows that the shift of the resonant frequency (Δf) is proportional to the square root of the viscosity-density product ($\sqrt{\eta \rho}$) of the liquid.

Figure 2.28 Thickness-shear-mode viscosity sensor.

(a) The coordinate system [90, 91]. (b) Commercial TSM viscosity sensors [92].

This principle has been widely adopted to design viscosity sensors [91, 93, 94]. Some variant forms of this type also exist which are based on other excitation and sensing techniques rather than the piezoelectric effect, such as the electromagnetic sensor [95, 96] and thermal-driven membrane [97]. In addition, commercial products of this type are starting to enter the market in the form of solid-state viscosity sensors which are especially suitable for oil condition monitoring [92], as shown in Figure 2.28b. However, TSM resonator viscosity sensors are still facing some serious drawbacks hindering the commercialization process [98]. First, the working frequency of TSM resonators is in the MHz range which is much higher compared with that used by conventional viscometers (a few Hz). The consequence is that measurement result of TSM resonator is not correlated well with that of standard laboratory viscometers especially for liquids with non-Newtonian behavior. Second, the high frequency also causes a very small penetration depth in the submicrometer range which is much smaller than the millimeter range of conventional viscometers. This means that the sensor is only interacting with a very thin film rather than the macroscopic fluid. A severe consequence of this is that when testing emulsions or suspensions which have droplets larger than several micrometers, it will fail to give the correct apparent viscosity. Third, the sensitivity and

measurement range of TSM sensors are limited due to the mismatching of mechanical impedance between the resonator and the fluid load. Moreover, the measurement result is not viscosity alone but the viscosity-density product. This is a common problem faced by almost all viscometers and sensors [95]. Without solving it the applicability of TSM sensors will be limited to only those liquids with known density.

As a solution to the high working frequency problem of TSM viscosity sensors, flexural-mode resonating cantilevers with lower resonant frequency have been employed for viscosity sensing. In an early experiment, Oden et al. [99] tested the response of commercial microfabricated silicon AFM cantilevers when immersed in viscous liquids. The resonant frequency is below 100 kHz which — although is still very high — is lower than that of TSM resonators. Vibration was generated by ambient oscillating sources such as thermal fluctuations, acoustics, and structural vibrations. And cantilever motion was recorded optically by a focused laser spot and split photodetector. It was observed that the resonant frequency and quality factor both decrease with the increase of fluid viscosity. Hirai et al. [100] investigated the resonance characteristics of a microcantilever with thermal excitation and laser measurement. The resonant frequency is 10 kHz in air and decrease of resonant frequency was observed in water. In addition, they analyzed the frequency response of the cantilever using an approximate model called string of beads model. It was found that the drag force calculated with this model is overestimated for rectangular microcantilevers. A more precise analytical model for cantilever beams immersed in viscous fluids was developed later by Sader [101]. Comparing with TSM resonators, one problem of these silicon microcantilevers is that they need additional actuators to generate vibration. The ambient thermal excitation is not reliable and may cause signal-to-noise problem [102]. In another design, a conducting path like an Au-layer is created on the surface of the silicon microcantilever and Lorentz force is generated when an AC current flows through the conducting path to drive the microcantilever [103]. However, a large piece of permanent magnet is needed to create the magnetic field. Another common problem with silicon microcantilevers is that they rely on additional sensors for measuring the mechanical response. The commonly used optical motion sensors cannot operate properly in turbid liquids

like emulsions or suspensions. A possible solution to these problems is to use piezoelectric material based cantilevers which can perform both actuation and sensing, although they are difficult to microfabricate. Shih et al. [104] developed a piezoelectric unimorph cantilever with a PZT layer bonded on a steel beam which has a resonant frequency of only 334 Hz. The electrodes were uniquely designed into a dual-electrode form with one electrode for driving and the other for sensing (see Figure 2.29a). During the measurement, the free end of the sensor is immersed into the liquid for interaction. And the voltage response at the sensing electrode is recorded. The shift of resonant frequency and increase of damping were observed. However, since this sensor is more complex than a simple cantilever, there is no analytical model for relating the fluid properties to the sensor's response. The consequence is that the measurement result is qualitative and comparative. Recently, Takarada et al. [105] proposed a piezoelectric cantilever sensor for both viscosity and density sensing. This sensor also has a unique electrode layout which enables it to generate either tangential or normal vibration under different electrical input configurations (see Figure 2.29b). By combining the tangential mode and normal mode, the author claimed that it is possible to separate the dynamic viscosity and density from their product $\eta\rho$ by only measuring the shift of resonant frequency under different vibration modes. Its validity has been confirmed through numerical simulation but its actual performance needs to be tested experimentally.

Figure 2.29 Flexural-mode cantilever viscosity sensors.

(a) A dual-electrode unimorph piezoelectric cantilever sensor [104]. (b) A piezoelectric bimorph cantilever sensor using two vibration modes [105].

2.5 Summary

In this chapter, the unique vibrissal tactile perception of rat has been introduced. Rat sweeps its whiskers actively in a rhythmic pattern to explore the surrounding environment. The whisking movement is a voluntary behavior controlled by follicular muscles. The mechanical stimuli applied on the whisker are transduced into neural signals by mechanoreceptors in the follicle. These neural signals are then transmitted through the whisker-to-barrel pathway to the cerebral cortex, where information about the contacting object such as its location and texture can be extracted.

Although the mechanism of vibrissal tactile perception is not completely clear yet, the existing knowledge about it has already inspired a number of artificial systems aiming to mimic the biological counterpart. Their potentials in location detection and texture discrimination have been revealed. However, their performance is well below that of the

biological system due to technical limitations such as the poor actuation as well as the lack of effective models for accurate interpretation of tactile data.

A dynamic measurement technique called transduction matrix method has been proposed and validated in the past decade, which introduced a novel way of using an actuator as a sensor simultaneously. This method enables accurate measurement of mechanical quantities at the output point of an actuator simply through measuring the input electrical signals. It possesses features such as easy instrumentation, elimination of loading effect and *in situ* measurement, making it a potential method for vibrissal tactile sensing.

Finally, two potential applications of vibrissal tactile sensing have been recognized, namely geometry detection of high-aspect-ratio micro holes and online viscosity sensing. They are currently facing some shortcomings and may benefit from the investigation in this thesis.

Chapter 3

DEVELOPMENT OF WHISKER TRANSDUCER

The biological vibrissal tactile perception has recently aroused increasing interest in neuroscience and robotics. Several artificial whisker systems have been designed and their potentials in shape, location and texture sensing have been illustrated. However, as reviewed in last chapter, these systems are usually very bulky and complex so that they are impossible to be integrated into a robot as small as a real rat. They also have other shortcomings like difficult wiring and inaccurate measurement. In contrast, rats use a simple whisker-FSC structure to perform both actuation and sensing simultaneously. If an artificial counterpart of this structure can be developed, those whisker systems can be greatly simplified, miniaturized and improved.

In this chapter, a whisker transducer (WT) is proposed which captures the essence of the biological whisker-FSC system — simultaneous sensing and actuating (SSA). The SSA ability of WT is achieved with a novel technique called transduction matrix method. In this method, the forward actuation and backward sensing functions of an electromechanical transducer is characterized by a two-by-two matrix. Once this matrix is calibrated, the force, velocity and mechanical impedance at the whisker tip can be conveniently sensed through measuring the input electrical voltage and current, just during the course of active whisking. These mechanical quantities sensed at the whisker tip can be recorded as the vibrissal tactile data from which features of the contact object can be extracted.

3.1 Bio-inspired whisker transducer (WT)

In the biological vibrissal tactile perception system (see Figure 3.1), each whisker is

supported by a follicle-sinus complex (FSC) [4, 12]. The whisker is of inert material (keratin) therefore tactile information is transmitted through it mechanically, while the FSC is able to perform electromechanical transduction to give tactile sensitivity as well as motion to the whisker [12]. This whisker-FSC system functions as a transducer which can perform vibrissal tactile perception by actively sweeping the whisker and simultaneously sensing the mechanical stimulus applied on it.

Figure 3.1 Rat's whisker-FSC structure for vibrissal tactile perception [4]

An artificial counterpart of this whisker-FSC structure is highly demanded in robotics which can endow robots with the vibrissal tactile sensing ability. It can help robots improve their performance in numerous tasks like navigation, object recognition, collision detection, etc., by providing intimate and intrinsic tactile information of the contact object which is impossible to obtain by computer vision especially in an unknown or dark environment. However, compared with the highly developed biological whisker-FSC structure which is versatile, efficient and compact, the initial designs of artificial whisker sensing systems in the literature are bulky and complex with very low performance. This becomes the major obstacle hindering the implementation of vibrissal tactile sensing on robots and is mainly due to the limitations in traditional transducer technologies. In order to solve this problem, a biomimetic whisker transducer (WT) is proposed in this thesis which captures the essence of its biological counterpart based on a novel technique.

3.1.1 Working principles of the WT

The whisker transducer (WT) in Figure 3.2 is proposed based on the inspiration from rat's vibrissal tactile perception system. From a morphological point of view, it mimics the biological whisker-FSC system by using also two components: a slender steel wire and a cantilevered piezoelectric bimorph. The steel wire plays the role of the whisker, while the piezoelectric bimorph plays the role of the FSC. The piezoelectric bimorph is a multilayered structure consisting of two PZT layers and a middle conductive substrate layer of carbon fiber composite. It can excite the whisker to vibrate in y-direction when an AC voltage is applied. Due to the direct piezoelectric effect, a mechanical load applied on the transducer will produce an electrical response at the electrodes. In contrast, an applied electric field will produce a mechanical deflection of the transducer due to the inverse piezoelectric effect. These two effects are conventionally used separately therefore the transducer acts as either a sensor or an actuator at a time. However, with the aid of a novel technique called the transduction matrix method which will be presented in Section 3.2, the transducer can act as both the actuator and sensor simultaneously. This makes it possible to perform active vibrissal tactile sensing as efficiently as rats.

Figure 3.2 The whisker transducer.

The red arrow shows the direction of vibration when the WT is excited by an AC voltage.

From a functional point of view, the proposed WT mimics the biological vibrissal perception system to achieve basic vibrissal tactile sensing functions as reviewed in last

chapter: texture discrimination and location sensing. During operation, the whisker starts vibrating (whisking) in y -direction when an electrical sinusoidal input is applied to the WT. When it sweeps across the surface of an object, the texture will modulate its dynamic behavior which will be coupled into the electrical input signals due to the electromechanical coupling ability of the WT, as illustrated in Figure 3.3a. Then texture information can be extracted through measuring and processing the electrical signals. Similarly, if an object gets into contact with the whisker at a location d_x from the tip in the radial direction (x -direction) as shown in Figure 3.3b, the change of this contact location would cause a change to the boundary condition of the whisker which will also be reflected into the electrical signals. Finally, the whisker tip can be controlled by the applied electrical voltage so that it can move in the horizontal direction (y -direction) to explore the environment (see Figure 3.3c). When it touches an object, the occurrence of contact can be detected from the electrical signals. Therefore the location of the object (d_y) can be detected. These basic vibrissal tactile sensing functions can be combined to achieve more sophisticated functions like shape detection and object recognition.

Figure 3.3 Basic vibrissal tactile sensing functions.

(a) Texture discrimination. (b) Radial location sensing. (c) Horizontal location sensing.

Compared with those complex whisking systems reviewed in last chapter, this newly proposed WT has a simpler structure of only two components, similar to the biological whisker-FSC structure. Therefore it can be easily miniaturized into a small size, whereas this is impossible for those motor-actuated whisker systems in the literature. In addition, only two wires are required for each WT, so it is suitable to be used in an array form to achieve more sophisticated sensing functions. This can solve the wiring problem faced by those whisker systems in the literature. Moreover, the WT is able to work at a much higher frequency than the motor-actuated whisker systems (below 1 Hz). This enables it to work at a similar frequency

used by real rats, and also makes it more efficient during exploration. Finally, the WT can directly measure the exact force and motion at the whisker tip based on the transduction matrix method. This is impossible for those whisker systems in the literature since they cannot install sensors directly at the tiny whisker tip. Their measurements are usually at the base or in the middle of the whisker which are indirect and inaccurate.

3.2 Two-port system model and transduction matrix method

Just like rats rely on the well trained neural networks to extract the tactile information from the neural signals modulated by the mechanical stimulus on the whisker, our WT needs an accurate model to extract the mechanical quantities at the whisker tip from the measured electrical signals, which characterizes the underlying electromechanical transduction process. The transduction process of the WT can be completely described by a two-port system model. A two-port system is defined as one that exchanges energy with others only at its two ports. The concept of two-port system has been widely used in electrical circuit analysis where both ports are electrical. However, the two ports can also be in different energy domains such as electrical, mechanical, magnetic and thermal. In such cases, the two-port system becomes a transducer. Each port is associated with one effort variable and one flow variable. Their product gives the instantaneous power flowing through the port while their ratio gives the impedance at that port. Table 3.1 lists the pair of variables in different energy domains.

Table 3.1 Effort and flow variables in different energy domains

Energy domain	Effort variable	Flow variable
Electrical	Voltage	Current
Mechanical (translation)	Force	Velocity
Mechanical (rotation)	Torque	Angular velocity
Magnetic	Magnetomotive force	Flux rate
Thermal	Temperature	Entropy flow rate
Hydraulic	Pressure	Volume flow rate

3.2.1 Two-port system model of the WT

The two-port system model of the WT is shown in Figure 3.4. The electrical port on the left hand side represents the pair of electrodes of the WT with voltage (or electric potential) E as the effort variable and current I as the flow variable. The mechanical port on the right hand side represents the mechanical output point (whisker tip) of the WT with force F as the effort variable and velocity V as the flow variable. If electrical excitation is applied on the left hand side, the system behaves as an actuator and power flows to the right. If mechanical excitation is applied on the right hand side, it behaves as a sensor and power flows to the left.

Figure 3.4 Two-port system model of the WT

3.2.2 Transduction matrix of the WT

The electromechanical coupling relationship between the electrical port and the mechanical port of the WT can be expressed by Equation (3.1). Both the electrical and mechanical variables are in capital case as they are in the form of frequency spectrum. Each element $t_{ij}(\omega)$ of the 2×2 matrix $[T]$ defined in Equations (3.2)-(3.5) is the transduction function across the electrical and mechanical domains under two boundary conditions — boundary condition $V = 0$ physically means that the mechanical port is clamped and no movement is allowed, while boundary condition $F = 0$ represents that the mechanical port is allowed to move freely. The actual working condition of the WT is between these two extremes.

$$\begin{aligned} \begin{Bmatrix} E(\omega) \\ I(\omega) \end{Bmatrix} &= \begin{bmatrix} t_{11}(\omega) & t_{12}(\omega) \\ t_{21}(\omega) & t_{22}(\omega) \end{bmatrix} \times \begin{Bmatrix} F(\omega) \\ V(\omega) \end{Bmatrix} = [\mathbf{T}] \times \begin{Bmatrix} F(\omega) \\ V(\omega) \end{Bmatrix} \\ \text{or } \begin{cases} E = t_{11}F + t_{12}V \\ I = t_{21}F + t_{22}V \end{cases} \end{aligned} \quad (3.1)$$

$$t_{11} = \left. \frac{E}{F} \right|_{V=0}, \text{ transfer function of voltage to force if the mechanical port is clamped} \quad (3.2)$$

$$t_{12} = \left. \frac{E}{V} \right|_{F=0}, \text{ transfer function of voltage to velocity if the mechanical port is free} \quad (3.3)$$

$$t_{21} = \left. \frac{I}{F} \right|_{V=0}, \text{ transfer function of current to force if the mechanical port is clamped} \quad (3.4)$$

$$t_{22} = \left. \frac{I}{V} \right|_{F=0}, \text{ transfer function of current to velocity if the mechanical port is free} \quad (3.5)$$

Matrix $[\mathbf{T}]$ characterizes the transduction functions between electrical input and mechanical output variables. It is thus termed as “transduction matrix” [56].

3.2.3 Reciprocal property

Since all components of the WT are linear and bilateral, the system possesses the reciprocal property which is an important characteristic indicating that the system can transmit energy equally well in both directions [106]. The reciprocity theorem is stated that the effort response at port 2 due to a flow source at port 1 is equal to the effort response at port 1 with the same flow source now placed at port 2, as illustrated in Figure 3.5.

Figure 3.5 Graphical illustration of the reciprocity theorem

If we put both effort variables on the left hand side and both flow variables on the right hand side, Equation (3.1) can be rearranged as:

$$\begin{Bmatrix} E \\ F \end{Bmatrix} = \begin{bmatrix} t_{11} & t_{11}t_{22} - t_{12}t_{21} \\ t_{21} & t_{21} \\ 1 & t_{22} \\ t_{21} & t_{21} \end{bmatrix} \times \begin{Bmatrix} I \\ -V \end{Bmatrix} \quad (3.6)$$

A minus sign is added to V because Equation (3.1) considers the velocity generated by the transducer while Figure 3.5 considers the velocity applied to the transducer. The reciprocity theorem means that the two off-diagonal elements are equal, therefore:

$$\begin{aligned} \frac{t_{11}t_{22} - t_{12}t_{21}}{t_{21}} &= \frac{1}{t_{21}} \\ t_{11}t_{22} - t_{12}t_{21} &= 1 \\ |\mathbf{T}| &= 1 \end{aligned} \quad (3.7)$$

So the reciprocal property of the WT leads to the unity determinant of its transduction matrix. This is an important property used in Section 3.4.2 to develop the least-squares calibration method.

3.2.4 Extraction of force, motion and mechanical impedance

Due to its electromechanical coupling ability, the WT is able to perform both sensing and actuation. The transduction equation (3.1) shows that mechanical force and velocity are coupled into electrical voltage and current, therefore the WT can sense the mechanical

information through measuring electrical signals. An alternative form of transduction equation can be obtained by putting the mechanical variables on the left hand side and electrical ones on the right hand side, as shown in Equation (3.8). This equation expresses the actuation process that the applied electrical inputs generate mechanical outputs. If the four elements of the transduction matrix are known, the variables at one port can be easily converted to the variables at the other port with either Equation (3.1) or (3.8). And with the obtained $F(\omega)$ and $V(\omega)$ in frequency domain, the force $f(t)$ and velocity $v(t)$ as well as the displacement $u(t)$ in time domain can be reconstructed through inverse Fourier Transform as shown in Equation (3.9)-(3.11).

$$\begin{Bmatrix} F \\ V \end{Bmatrix} = [\mathbf{T}]^{-1} \times \begin{Bmatrix} E \\ I \end{Bmatrix} = \begin{bmatrix} t_{22} & -t_{12} \\ -t_{21} & t_{11} \end{bmatrix} \times \begin{Bmatrix} E \\ I \end{Bmatrix} \quad (3.8)$$

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{j\omega t} d\omega \quad (3.9)$$

$$v(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} V(\omega) e^{j\omega t} d\omega \quad (3.10)$$

$$u(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{V(\omega)}{j\omega} \cdot e^{j\omega t} d\omega \quad (3.11)$$

In addition, as mentioned earlier, the ratio between the effort variable and flow variable at each port is called impedance. Electrical impedance Z_e is a measure of how much a circuit resists the flow of current when a voltage is applied. It is defined in Equation (3.12) as the ratio of voltage to current and is usually represented as a complex quantity with its real part being the resistance R_e and its imaginary part being the reactance X_e . The measurement of electrical impedance is quite easy since both voltage and current can be easily measured. Similarly, mechanical impedance Z_m is a measure of how much a structure resists motion when a dynamic force is applied. It is defined in Equation (3.13) as the ratio of the applied

force to the resulting velocity. Its real part is called mechanical resistance R_m which is related to damping, while its imaginary part is called mechanical reactance X_m which is related to mass and stiffness. Since mechanical impedance characterizes the dynamic behavior of the structure under a given force load, it becomes an important factor in design and analysis of mechanical systems. However, in contrast to the easy measurement of electrical impedance, the measurement of mechanical impedance is more difficult. Figure 3.6 shows the configuration of traditional mechanical impedance measurement [106]. It requires an external exciter for generating the excitation force and two sensors for measuring the force and velocity (or acceleration). Whereas this configuration can be applied to bulky mechanical structures, it is impossible to be installed on a small structure like a whisker.

$$Z_e(\omega) = \frac{E(\omega)}{I(\omega)} = R_e + jX_e \quad (3.12)$$

$$Z_m(\omega) = \frac{F(\omega)}{V(\omega)} = R_m + jX_m \quad (3.13)$$

Figure 3.6 Traditional mechanical impedance measurement [106]

The proposed WT is able to greatly simplify the measurement of mechanical impedance based on the transduction matrix method. As the electrical power transmits forward to the mechanical port (whisker tip), the mechanical impedance at the mechanical port propagates backward to the electrical port. The relationship between electrical impedance Z_e and

mechanical impedance Z_m can be derived from Equation (3.1) or (3.8) as follows:

$$Z_e = \frac{E}{I} = \frac{t_{11}F + t_{12}V}{t_{21}F + t_{22}V} = \frac{t_{11}Z_m + t_{12}}{t_{21}Z_m + t_{22}} \quad (3.14)$$

$$Z_m = \frac{F}{V} = \frac{t_{22}E - t_{12}I}{-t_{21}E + t_{11}I} = \frac{t_{22}Z_e - t_{12}}{-t_{21}Z_e + t_{11}} \quad (3.15)$$

The above equations can be used to calculate the mechanical impedance from the electrical impedance measured at the electrical port, if the four transduction matrix elements are accurately known. Therefore it avoids the direct measurement of force and velocity involved in a traditional measurement configuration with only a single transducer.

Another point worth mentioning is the power efficiency, since the WT exchanges energy between electrical and mechanical domains. The WT can be used as an actuator to drive a mechanical load. It can also be used as an energy harvester to generate electrical energy from a mechanical vibration source. In both cases, power efficiency is a good indicator of the transducer's performance that usually needs to be optimized. Power efficiency can be calculated as the ratio of the output power to the input power. The electrical power P_e at the electrical port can be easily computed as the product of voltage and current which can be easily measured.

$$P_e = EI \quad (3.16)$$

Similar to the case of mechanical impedance measurement, the measurement of mechanical power also involves the sensing of force and motion which is traditionally difficult to implement. With our new technique, the mechanical power P_m can be computed also from the electrical voltage and current using the transduction matrix as follows:

$$\begin{aligned}
P_m &= FV \\
&= (t_{22}E - t_{12}I)(-t_{21}E + t_{11}I) \\
&= -t_{21}t_{22}E^2 + (t_{11}t_{22} + t_{12}t_{21})EI - t_{11}t_{12}I^2
\end{aligned} \tag{3.17}$$

If the WT works as an actuator, its power efficiency can be calculated as:

$$\begin{aligned}
\eta &= \frac{P_m}{P_e} \\
&= \frac{-t_{21}t_{22}E^2 + (t_{11}t_{22} + t_{12}t_{21})EI - t_{11}t_{12}I^2}{EI} \\
&= -t_{21}t_{22}Z_e + (t_{11}t_{22} + t_{12}t_{21}) - t_{11}t_{12} \frac{1}{Z_e}
\end{aligned} \tag{3.18}$$

So the measurement of force and velocity at the mechanical port is replaced by the easier task of electrical impedance measurement.

3.2.5 Simultaneous sensing and actuating

A unique feature of our technique is that Equation (3.1), (3.8) and (3.15) can be used concurrently to achieve simultaneous sensing and actuating (SSA). Conventionally, an electromechanical transducer acts as either a sensor or an actuator at a time. So in order to perform a dynamic testing, three transducers are required — one actuator for exciting the object, one sensor for measuring the force response and another sensor for measuring the displacement response. In our technique, only one transducer is required. When electrical excitation is applied to the WT, mechanical force and velocity will be generated at the mechanical port by Equation (3.8). In this manner, the WT acts as an actuator. At the same time, the mechanical interaction with the object will be coupled into the input electrical signals by Equation (3.1). Then the electrical voltage, current and impedance can be measured from which mechanical force, velocity and impedance can be calculated by Equation (3.8) and (3.15). In this manner, the WT acts as a sensor simultaneously. This SSA feature brings many advantages over traditional dynamic testing methods:

- The difficult task of measuring force and motion becomes much easier and more feasible since only the measurement of electrical voltage and current at the electrical port is required, without the installation of additional force and motion sensors at or nearby the mechanical port. And the force and velocity are measured concurrently therefore their ratio is the mechanical impedance of the object characterizing its dynamic properties.
- The number of devices as well as the cost, wiring and instrumentation involved in a conventional dynamic testing can be significantly reduced and simplified. And the robustness can be increased due to the reduced complexity of the measurement system.
- It is particularly suitable for situations where installation of sensors is impossible or difficult due to limited space, high operation frequency or harsh environment.
- It also makes it possible to perform *in situ* or online monitoring of product quality or the health of the transducer itself, since the measurement can be carried out during the course of a normal operation.

3.2.6 Elimination of loading effect

Another benefit of the transduction matrix method is the elimination of “loading effect”. Loading effect means that the measurement accuracy is affected by the load being measured. It is a common phenomenon involved in most measurements and may significantly jeopardize the measurement accuracy if not properly treated. It can affect the measurement both mechanically and electrically.

In a traditional dynamic testing such as the measurement of mechanical impedance shown in Figure 3.6, the structure under test is excited by an external exciter and the resulting force and motion are measured by an impedance head consisting of a force sensor and an accelerometer. Due to the attachment of the impedance head, the measurement result is actually the combination of the mechanical impedance of the structure and that of the impedance head. If the structure is much larger than the impedance head, the loading effect is

negligibly small so the measurement result can still be accurate. However, in case when the structure is not very large, the loading effect will become significant and the measurement result will have large deviation from its true value. As a result, the impedance head is not applicable to small structures and its scope of application is limited.

On the other hand, loading effect can also affect the measurement result in the electrical way. In the conventional use of electromechanical sensors, a single frequency response function is utilized as the transfer function for converting the electrical signal to the mechanical measurand, which cannot characterize the transduction process completely. Usually either the voltage or the charge signal of the sensor is used as a measure of force or displacement applied to the sensor. The transfer function between force/displacement and voltage output of a PZT sensor can be derived from Equation (3.1):

$$H_{FE}(\omega) = \frac{F(\omega)}{E(\omega)} = \frac{F}{t_{11}F + t_{12}V} = \frac{1}{t_{11} + \frac{t_{12}}{Z_L}} \quad (3.19)$$

$$H_{UE}(\omega) = \frac{U(\omega)}{E(\omega)} = \frac{V/j\omega}{t_{11}F + t_{12}V} = \frac{1}{j\omega \cdot (t_{11}Z_L + t_{12})} \quad (3.20)$$

Similarly, the transfer function between force/displacement and charge output of a PZT sensor can be derived from Equation (3.1):

$$H_{FQ}(\omega) = \frac{F(\omega)}{Q(\omega)} = \frac{F}{I/j\omega} = \frac{j\omega \cdot F}{t_{21}F + t_{22}V} = \frac{j\omega}{t_{21} + \frac{t_{22}}{Z_L}} \quad (3.21)$$

$$H_{UQ}(\omega) = \frac{U(\omega)}{Q(\omega)} = \frac{V/j\omega}{I/j\omega} = \frac{V}{t_{21}F + t_{22}V} = \frac{1}{t_{21}Z_L + t_{22}} \quad (3.22)$$

where $Z_L = F/V$ is the mechanical impedance of the load at the mechanical port. The existence

of Z_L in $H_{FE}(\omega)$, $H_{UE}(\omega)$, $H_{FQ}(\omega)$ and $H_{UQ}(\omega)$ shows that the transfer functions are depending on the load. It can be further derived that:

$$\lim_{Z_L \rightarrow \infty} H_{FE}(\omega) = \frac{1}{t_{11}} \quad (3.23)$$

$$\lim_{Z_L \rightarrow 0} H_{UE}(\omega) = \frac{1}{j\omega \cdot t_{12}} \quad (3.24)$$

$$\lim_{Z_L \rightarrow \infty} H_{FQ}(\omega) = \frac{j\omega}{t_{21}} \quad (3.25)$$

$$\lim_{Z_L \rightarrow 0} H_{UQ}(\omega) = \frac{1}{t_{22}} \quad (3.26)$$

This means that $H_{FE}(\omega)$ and $H_{FQ}(\omega)$ are exactly determined by t_{11} or t_{21} only when under ideal clamped boundary condition ($Z_L \rightarrow \infty$). While $H_{UE}(\omega)$ and $H_{UQ}(\omega)$ are exactly determined by t_{12} or t_{22} only when under ideal free boundary condition ($Z_L \rightarrow 0$). However, in most cases, the mechanical impedance of the load is between 0 and ∞ , therefore the loading effect is inevitable and the accuracy of measurement is limited.

The proposed WT can solve this problem since no additional sensor is attached to the structure under test — the actuator itself plays the role of a sensor. Therefore the mechanical loading effect is eliminated. And following equations illustrate that by using both voltage E and current I as independent variables and using four transduction elements as transfer functions, the force F and velocity V are completely decoupled from electrical signals.

$$\begin{aligned}
F &= t_{22}E - t_{12}I \\
&= t_{22}(t_{11}F + t_{12}V) - t_{12}(t_{21}F + t_{22}V) \\
&= t_{22}t_{11}F + t_{22}t_{12}V - t_{12}t_{21}F - t_{12}t_{22}V \\
&= (t_{22}t_{11} - t_{12}t_{21})F \\
&= |\mathbf{T}|F \\
&= F
\end{aligned} \tag{3.27}$$

$$\begin{aligned}
V &= -t_{21}E + t_{11}I \\
&= -t_{21}(t_{11}F + t_{12}V) + t_{11}(t_{21}F + t_{22}V) \\
&= -t_{21}t_{11}F - t_{21}t_{12}V + t_{11}t_{21}F + t_{11}t_{22}V \\
&= (t_{11}t_{22} - t_{21}t_{12})V \\
&= |\mathbf{T}|V \\
&= V
\end{aligned} \tag{3.28}$$

This “elimination of loading effect” feature ensures the measurement accuracy of the proposed WT and also makes it suitable for measuring the mechanical impedance of small or even micro structures.

3.3 Derivation of the transduction matrix

For a general piezoelectric-coupled system (such as a PZT bonded onto the surface of a structure), the following dynamic transducer equations can be derived using energy formulation and Ritz method [107]:

$$\begin{aligned}
(\mathbf{M}_s + \mathbf{M}_p)\ddot{\mathbf{r}}(t) + (\mathbf{K}_s + \mathbf{K}_p)\mathbf{r}(t) - \mathbf{\Theta}\mathbf{e}(t) &= \mathbf{B}_f\mathbf{f}(t) \\
\mathbf{\Theta}^T\mathbf{r}(t) + \mathbf{C}_p\mathbf{e}(t) &= \mathbf{B}_q\mathbf{q}(t)
\end{aligned} \tag{3.29}$$

where $\mathbf{M}_s$, $\mathbf{M}_p$, $\mathbf{K}_s$ and $\mathbf{K}_p$ are the mass and stiffness matrices of the structure and piezoelectric patch. Vectors $\mathbf{r}(t)$ and $\mathbf{f}(t)$ are the generalized coordinates for displacement and the external point forces, respectively. Vectors $\mathbf{e}(t)$ and $\mathbf{q}(t)$ represent the generalized coordinates for electric potential and the charge on the piezoelectric electrodes, respectively. $\mathbf{C}_p$ is the piezoelectric capacitance matrix. $\mathbf{\Theta}$ is the electromechanical coupling matrix. $\mathbf{B}_f$ and $\mathbf{B}_q$ are the forcing

matrices.

For a cantilevered beam with a single surface mounted PZT patch, a single value voltage throughout the electrode and a point force applied in one direction, $\mathbf{q}(t)$, $\mathbf{e}(t)$, $\mathbf{f}(t)$ and $\mathbf{C}_p$ reduce to scalars and $\mathbf{B}_q$ becomes an identity matrix. If the displacement $u(x,t)$ considered is at the location of the force application and the electric potential $E(x,t)$ considered is at the location of the charge application, the displacement and potential can be expressed as:

$$\begin{aligned} u(x_f, t) &= \mathbf{\Psi}_r(x_f) \mathbf{r}(t) = \mathbf{B}_f^T \mathbf{r}(t) \\ E(x_q, t) &= \mathbf{\Psi}_q(x_q) e(t) = \mathbf{B}_q^T e(t) = e(t) \end{aligned} \quad (3.30)$$

The time-domain transducer equations in (3.29) can be converted into frequency domain by taking Fourier Transform on both sides:

$$\begin{aligned} [-\omega^2(\mathbf{M}_s + \mathbf{M}_p) + (\mathbf{K}_s + \mathbf{K}_p)] \mathbf{R}(\omega) - E(\omega) &= \mathbf{B}_f F(\omega) \\ \mathbf{\Theta}^T \mathbf{R}(\omega) + \mathbf{C}_p E(\omega) &= Q(\omega) \end{aligned} \quad (3.31)$$

Then the displacement and charge represented in frequency domain can be obtained by solving Equation (3.31):

$$\begin{aligned} U(\omega) &= \mathbf{B}_f^T [-\omega^2(\mathbf{M}_s + \mathbf{M}_p) + (\mathbf{K}_s + \mathbf{K}_p)]^{-1} \mathbf{B}_f F(\omega) + \mathbf{B}_f^T [-\omega^2(\mathbf{M}_s + \mathbf{M}_p) + (\mathbf{K}_s + \mathbf{K}_p)]^{-1} E(\omega) \\ Q(\omega) &= \mathbf{\Theta}^T [-\omega^2(\mathbf{M}_s + \mathbf{M}_p) + (\mathbf{K}_s + \mathbf{K}_p)]^{-1} \mathbf{B}_f F(\omega) + \left\{ \mathbf{C}_p + [-\omega^2(\mathbf{M}_s + \mathbf{M}_p) + (\mathbf{K}_s + \mathbf{K}_p)]^{-1} \right\} E(\omega) \end{aligned}$$

or

$$\begin{aligned} U(\omega) &= \frac{1}{j\omega} \mathbf{B}_f^T \mathbf{Z}_m^{-1}(\omega) \mathbf{B}_f F(\omega) + \frac{1}{j\omega} \mathbf{B}_f^T \mathbf{Z}_m^{-1}(\omega) \mathbf{\Theta} E(\omega) \\ Q(\omega) &= \frac{1}{j\omega} \mathbf{\Theta}^T \mathbf{Z}_m^{-1}(\omega) \mathbf{B}_f F(\omega) + \left[\mathbf{C}_p + \frac{1}{j\omega} \mathbf{\Theta}^T \mathbf{Z}_m^{-1}(\omega) \mathbf{\Theta} \right] E(\omega) \end{aligned} \quad (3.32)$$

where $\mathbf{Z}_m = j\omega(\mathbf{M}_s + \mathbf{M}_p) + (\mathbf{K}_s + \mathbf{K}_p)$ is the mechanical impedance matrix of the transducer.

By denoting the scalar coefficients in equation (3.32) with the following:

$$\begin{aligned}
A(\omega) &= \frac{1}{j\omega} \mathbf{B}_f^T \mathbf{Z}_m^{-1}(\omega) \mathbf{B}_f \\
B(\omega) &= \frac{1}{j\omega} \mathbf{B}_f^T \mathbf{Z}_m^{-1}(\omega) \mathbf{\Theta} \\
C(\omega) &= \frac{1}{j\omega} \mathbf{\Theta}^T \mathbf{Z}_m^{-1}(\omega) \mathbf{B}_f \\
D(\omega) &= \left[C_p + \frac{1}{j\omega} \mathbf{\Theta}^T \mathbf{Z}_m^{-1}(\omega) \mathbf{\Theta} \right]
\end{aligned} \tag{3.33}$$

the matrix form of the transducer equations can be obtained:

$$\begin{Bmatrix} U(\omega) \\ Q(\omega) \end{Bmatrix} = \begin{bmatrix} A(\omega) & B(\omega) \\ C(\omega) & D(\omega) \end{bmatrix} \times \begin{Bmatrix} F(\omega) \\ E(\omega) \end{Bmatrix} \tag{3.34}$$

The following relationship between $B(\omega)$ and $C(\omega)$ can be found as the evidence of the reciprocal property of the system.

$$\begin{aligned}
\frac{1}{j\omega} \mathbf{B}_f^T \mathbf{Z}_m^{-1}(\omega) \mathbf{\Theta} &= \frac{1}{j\omega} \mathbf{\Theta}^T \mathbf{Z}_m^{-1}(\omega) \mathbf{B}_f \\
B(\omega) &= C(\omega)
\end{aligned} \tag{3.35}$$

Substituting current $I(\omega) = j\omega Q(\omega)$ and velocity $V(\omega) = j\omega U(\omega)$ into equation (3.34) and rearranging the equation will result in the following transduction matrix equation:

$$\begin{aligned}
\begin{Bmatrix} E(\omega) \\ I(\omega) \end{Bmatrix} &= \begin{bmatrix} -\frac{A(\omega)}{B(\omega)} & \frac{1}{j\omega} \cdot \frac{1}{B(\omega)} \\ j\omega \cdot \left[C(\omega) - \frac{A(\omega)D(\omega)}{B(\omega)} \right] & \frac{D(\omega)}{B(\omega)} \end{bmatrix} \times \begin{Bmatrix} F(\omega) \\ V(\omega) \end{Bmatrix} \\
&= \begin{bmatrix} -\frac{A(\omega)}{B(\omega)} & -\frac{1}{j\omega} \cdot \frac{1}{B(\omega)} \\ j\omega \cdot \left[C(\omega) - \frac{A(\omega)D(\omega)}{B(\omega)} \right] & -\frac{D(\omega)}{B(\omega)} \end{bmatrix} \times \begin{Bmatrix} F(\omega) \\ -V(\omega) \end{Bmatrix} \\
&= \begin{bmatrix} t_{11}(\omega) & t_{12}(\omega) \\ t_{21}(\omega) & t_{22}(\omega) \end{bmatrix} \times \begin{Bmatrix} F(\omega) \\ -V(\omega) \end{Bmatrix} \\
&= [\mathbf{T}(\omega)] \times \begin{Bmatrix} F(\omega) \\ -V(\omega) \end{Bmatrix}
\end{aligned} \tag{3.36}$$

where $-V(\omega)$ is the velocity generated by the transducer and $[\mathbf{T}(\omega)]$ is the transduction matrix of the system. The determinant of the transduction matrix is:

$$|\mathbf{T}(\omega)| = \frac{A(\omega)}{B(\omega)} \cdot \frac{D(\omega)}{B(\omega)} + \frac{1}{j\omega} \cdot \frac{1}{B(\omega)} \cdot j\omega \cdot \left[C(\omega) - \frac{A(\omega)D(\omega)}{B(\omega)} \right] = \frac{C(\omega)}{B(\omega)} = 1 \tag{3.37}$$

as a result of the reciprocal property of the system shown in Equation (3.35).

3.4 Methods for calibrating the transduction matrix

The transduction matrix of the WT needs to be determined before it can be used for vibrissal tactile sensing. Although the above direct derivation of the transduction matrix in the analytical form is possible for a simple piezoelectric system, it is usually difficult for complex ones in practice. In addition, for a practical piezoelectric-coupled system, most of its geometrical and material parameters are usually not accurately known due to the existence of tolerances — for example, the standard tolerance of piezoelectric constant of PZT is as much as $\pm 20\%$ — so it is impossible to obtain its exact transduction matrix analytically. Fortunately, the transduction matrix can be obtained experimentally through following calibration methods.

3.4.1 Direct methods

The four elements of the transduction matrix can be directly determined by setting the mechanical boundary condition (BC) as either free ($F = 0$) or clamped ($V = 0$) at the mechanical output point and applying electrical excitation, then measuring the four transfer functions based on their definitions in Equation (3.2)-(3.5). This method can be termed as the “free-clamped calibration method”. It is quite straightforward but has several implementation problems. One problem is the applying of the extreme boundary conditions. Although the free boundary condition is easy to achieve in practice, the implementation of ideal clamped boundary condition is rather difficult since no “perfectly rigid wall” is available in the real world. It becomes even more difficult at high frequency when all the motions become very small. Another obstacle is the measurement of force and velocity. Due to the small scale of the whisker tip, there is almost no room for installing force or motion sensors, not to mention the considerable loading error introduced by them.

Figure 3.7 Schematic diagram of direct calibration method 1.

(a) Free BC for calibrating t_{12} and t_{22} . (b) Clamped BC for calibrating t_{11} and t_{21} .

The elements of the transduction matrix can also be directly determined by setting the electrical boundary condition as either short-circuit ($E = 0$) or open-circuit ($I = 0$) and applying mechanical excitation at the mechanical output point, based on following alternative definitions derived from Equation (3.8):

$$t_{11} = \left. \frac{V}{I} \right|_{E=0}, \text{ transfer function of velocity to current if the electrical port is short} \quad (3.38)$$

$$t_{12} = - \left. \frac{F}{I} \right|_{E=0}, \text{ transfer function of force to current if the electrical port is short} \quad (3.39)$$

$$t_{21} = - \left. \frac{V}{E} \right|_{I=0}, \text{ transfer function of velocity to voltage if the electrical port is open} \quad (3.40)$$

$$t_{22} = \left. \frac{F}{E} \right|_{I=0}, \text{ transfer function of force to voltage if the electrical port is open} \quad (3.41)$$

Figure 3.8 Schematic diagram of direct calibration method 2.

(a) Open-circuit BC for calibrating t_{21} and t_{22} . (b) Short-circuit BC for calibrating t_{11} and t_{12} .

This method can be termed as the “open-short calibration method”. Unfortunately, it suffers from the difficulty to generate and measure force and velocity accurately. And the ideal electrical open condition is also difficult to achieve especially at high frequency.

3.4.2 Least-squares method

Applying or measuring electrical quantities is much more convenient and accurate than that of mechanical quantities. In order to avoid the force and velocity measurement as well as the extreme boundary conditions required by above direct calibration methods, the following indirect calibration method based on least-squares technique has been developed which requires only the measurement of electrical quantities.

(1) Calibration of Z_m - Z_e relationship

The relationship between mechanical impedance and electrical impedance is expressed by Equation (3.15) which can be further derived to obtain Equation (3.42) and (3.43):

$$Z_m = \frac{t_{22}Z_e - t_{12}}{-t_{21}Z_e + t_{11}} = \frac{Z_e - \frac{t_{12}}{t_{22}}}{-\frac{t_{21}}{t_{22}}Z_e + \frac{t_{11}}{t_{22}}} = \frac{Z_e - x_3}{x_2Z_e + x_1} \quad (3.42)$$

$$Z_mx_1 + Z_mZ_ex_2 + x_3 = Z_e \quad (3.43)$$

where x_1, x_2, x_3 are three unknown complex-value parameters to be determined and:

$$x_1 = \frac{t_{11}}{t_{22}}, \quad x_2 = -\frac{t_{21}}{t_{22}}, \quad x_3 = \frac{t_{12}}{t_{22}} \quad (3.44)$$

If a set of n mechanical loads with known mechanical impedances are available, the following system of simultaneous linear equations can be formed by applying each load to the mechanical port and measuring the corresponding electrical impedance at the electrical port as shown in Figure 3.9:

$$\begin{bmatrix} Z_{m_1} & Z_{m_1} Z_{e_1} & 1 \\ Z_{m_2} & Z_{m_2} Z_{e_2} & 1 \\ \vdots & \vdots & \vdots \\ Z_{m_n} & Z_{m_n} Z_{e_n} & 1 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \begin{Bmatrix} Z_{e_1} \\ Z_{e_2} \\ \vdots \\ Z_{e_n} \end{Bmatrix}$$

$$\mathbf{Ax} = \mathbf{b}$$
(3.45)

Figure 3.9 Schematic diagram of least-squares calibration method

The vector $\mathbf{x}$ of the three unknown parameters can be solved using the following equation:

$$\mathbf{x} = \mathbf{A}^+ \mathbf{b}$$

$$\mathbf{A}^+ = \begin{cases} (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T & \text{when } \text{rank}(\mathbf{A}_{m \times n}) = n, \\ \mathbf{A}^T (\mathbf{A} \mathbf{A}^T)^{-1} & \text{when } \text{rank}(\mathbf{A}_{m \times n}) = m. \end{cases}$$
(3.46)

where $\mathbf{A}^+$ is the Moore-Penrose pseudoinverse which can be efficiently achieved via singular value decomposition (SVD). The solution is a least-squares solution if the set of equations is overdetermined. And an underdetermined set of equations will result in a minimum-norm solution. So in order to get the least-squares solution, n should be greater than 3.

After the calibration of the $\mathbf{x}$ vector, the mechanical impedance of an unknown mechanical load can be calculated from measured electrical impedance using Equation (3.42).

(2) Determination of the transduction matrix elements

With the calibrated $\mathbf{x}$ vector, it is only able to calculate the mechanical impedance rather than the separate values of force and velocity. Fortunately, the four elements of the transduction matrix can be derived from the $\mathbf{x}$ vector using the unity-determinant property of the transduction matrix as follows:

$$\begin{aligned}
|\mathbf{T}| &= t_{11}t_{22} - t_{12}t_{21} = 1 \\
\frac{t_{11}}{t_{22}} - \frac{t_{12}}{t_{22}} \frac{t_{21}}{t_{22}} &= \frac{1}{t_{22}^2} \\
x_1 + x_2x_3 &= \frac{1}{t_{22}^2} \\
t_{22} &= \frac{1}{\sqrt{x_1 + x_2x_3}} \\
[\mathbf{T}] &= \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \begin{bmatrix} x_1t_{22} & x_3t_{22} \\ -x_2t_{22} & t_{22} \end{bmatrix} = \frac{1}{\sqrt{x_1 + x_2x_3}} \begin{bmatrix} x_1 & x_3 \\ -x_2 & 1 \end{bmatrix}
\end{aligned} \tag{3.47}$$

With the four elements of the transduction matrix determined, the force and velocity values at the mechanical port can be calculated from the measured voltage and current at the electrical port using Equation (3.8).

3.5 Finite element model of WT

A finite element (FE) model for numerical simulation is built in ANSYS and shown in Figure 3.10. The piezoelectric bimorph is composed of two PZT layers ($46 \times 2.1 \times 0.2$ mm) and a middle conductive substrate of carbon fiber composite ($46 \times 2.1 \times 0.15$ mm). The whisker is a 61 mm long steel wire with a radius of 0.15 mm. One end of the bimorph is fixed while the other end is connected with the whisker through a tiny ($3 \times 2.1 \times 0.5$ mm) epoxy adhesive block. The PZT layers are meshed with 8-node coupled-field SOLID5 element. The middle layer is meshed with 8-node SOLID45 element. The steel whisker and adhesive block are meshed with 20-node SOLID95 quadratic element. The material properties are listed in Table 3.2 and Table 3.3.

Figure 3.10 Finite element model of the WT

Table 3.2 Material properties of PZT

Density (kg/m^3)	ρ	7500
Piezoelectric charge constant (m/V)	d_{31}	-2.74E-10
	d_{33}	5.93E-10
	d_{15}	7.41E-10
	s_{11}^E	1.65E-11
Compliance (m^2/N)	s_{33}^E	2.07E-11
	s_{12}^E	-4.78E-12
	s_{13}^E	-8.45E-12
	s_{44}^E	4.35E-11
	$\epsilon_{11}^S/\epsilon_0$	3130
Relative dielectric constant (unitless)	$\epsilon_{33}^S/\epsilon_0$	3400

Table 3.3 Material properties of the substrate, whisker and adhesive

		Substrate (carbon fiber composite)	Whisker (stainless steel)	Adhesive (epoxy)
Young's modulus (GPa)	E	20	185	3.5
Poisson's ratio (unitless)	ν	0.3	0.29	0.4
Density (kg/m^3)	ρ	7600	7900	1000

During the simulation, a harmonic response analysis will be performed with a sweep sine (1-100 Hz) voltage signal as the input. The electrical field will be applied in the y-direction. The two PZT layers have the same poling direction but opposite electric field directions, this will

result in extension in one layer and contraction in the other so vibration will be generated in y-direction. The voltage and current signals will be recorded simultaneously and their ratio is the electrical impedance.

The electrical impedance under free load ($F = 0$) is first simulated and plotted in Figure 3.11. The sharp notch near 53 Hz is the resonant frequency. This frequency is much higher than that used by rat. In order to make it lower, a concentrated mass element MASS21 (2.3338 g) is added to the model at 41 mm from the fixed end. Then the electrical impedance under free load is simulated and plotted again after adding mass, as shown in Figure 3.12. This time the resonant frequency is reduced to around 36 Hz. Following simulations are all based on the model with this added mass.

(a)

Figure 3.11 Electrical impedance under free load without the added mass. (a) Z_e vs. frequency. (b)

Voltage and current in time domain at 10 Hz. (c) Voltage and current in time domain at 50 Hz. (d)

Voltage and current in time domain at 100 Hz.

Figure 3.12 Electrical impedance under free load with the added mass

3.5.1 Numerical identification of transduction matrix of the FE model

The transduction matrix of the WT needs to be determined before it can be used for vibrissal tactile sensing. The three calibration methods introduced in Section 3.4 will be used to determine the transduction matrix and their performances will be compared.

(1) Direct method 1 (free-clamped method)

This method is to directly determine the four transduction matrix elements based on their definitions in Equation (3.2)-(3.5). The whisker tip is first kept under free boundary condition ($F = 0$) and a sweep sine voltage signal is applied on the electrical port as input. During the excitation, the voltage E , current I and velocity V signals are recorded simultaneously to calculate t_{12} and t_{22} . Then the whisker tip is clamped ($V = 0$), and the excitation voltage E , current I and reaction force F signals are recorded to calculate t_{11} and t_{21} . The determined four elements of the transduction matrix are plotted in Figure 3.13, as functions of frequency.

Figure 3.13 Four elements of the transduction matrix by direct method 1 (free-clamped method)

If the transduction matrix is properly calibrated, its determinant should be unity as described in Equation (3.7) and (3.37). This is checked in Figure 3.14 which shows that the determinant is exactly unity as expected. Therefore reciprocal property of WT is confirmed.

Figure 3.14 Determinant of the calibrated transduction matrix

(2) *Direct method 2 (open-short method)*

Similar to direct method 1, this method is to directly determine the four transduction matrix elements based on their alternative definitions in Equation (3.38)-(3.41). The electrical port of the WT is kept under electrical open condition ($I = 0$) and a sweep sine velocity signal is applied on the whisker tip as input. During the excitation, the velocity V , reaction force F and voltage E signals are recorded simultaneously to calculate t_{21} and t_{22} . Then the electrical port is set to electrical short condition ($E = 0$), and the excitation velocity V , reaction force F and current I signals are recorded to calculate t_{11} and t_{12} . The determined four elements of the transduction matrix are plotted in Figure 3.15, as functions of frequency. They are just the same as those determined by the direct method 1.

Figure 3.15 Four elements of the transduction matrix by direct method 2 (open-short method)

(3) *Least-squares method*

In this method, a set of 5 mechanical loads consisting of mass, stiffness and damper are chosen and listed in Table 3.4.

Figure 3.16 Mechanical load

Table 3.4 Five mechanical loads used in the least-squares calibration method

No.	Mass m (kg)	Stiffness k (N/m)	Damping c (Ns/m)
1	0	0	0
2	6.10E-05	2.5	1.00E-02
3	6.20E-05	2.6	1.10E-02
4	6.30E-05	2.7	1.20E-02
5	6.40E-05	2.8	1.30E-02

The theoretical mechanical impedances of these loads can be calculated with the following equation:

$$Z_m = c + j\left(\omega m - \frac{k}{\omega}\right) \quad (3.48)$$

During each run, one of the loads is created and connected to the whisker tip of the model using a pair of MASS21 (Structural Mass) and COMBIN14 (Spring-Damper) elements. The sweep sine voltage excitation is applied to the electrical port and both the voltage E and current I signals are recorded simultaneously. The electrical impedance Z_e is then calculated as their ratio. The electrical impedances under five loads are simulated and plotted in Figure 3.17. Although the curves for load 2-5 are quite similar, slight differences can be observed among them. These five electrical impedances together with their corresponding theoretical mechanical impedances calculated using Equation (3.48) are used to form the system of simultaneous linear Equations (3.45). The solution of this set of equations is the $\mathbf{x}$ vector which relates the mechanical impedance to the electrical impedance with Equation (3.42). The three elements of the $\mathbf{x}$ vector are plotted in Figure 3.18, Figure 3.19 and Figure 3.20, as functions of frequency.

Figure 3.17 Electrical impedance curves under five mechanical loads used in least-squares method

Figure 3.18 x_1 by least-squares method

Figure 3.19 x_2 by least-squares method Figure 3.20 x_3 by least-squares method

After the calibration of the $\mathbf{x}$ vector, the four elements of the transduction matrix are determined using Equation (3.47) and plotted in Figure 3.21, as functions of frequency. They are compared with the results determined by direct method 1 and 2.

Figure 3.21 Four elements of the transduction matrix by least-squares method

Above simulation results show that the three calibration methods are equivalent and any of them can give the same result. So the ease of implementation becomes the most important criterion when choosing among them in practical applications. As described in Section 3.4, the least-squares method requires only the measurement of electrical quantities which is much easier to implement. Therefore it is more preferable than the two direct methods.

3.6 Numerical study of vibrissal tactile sensing with WT

3.6.1 Sensing mechanical quantities at whisker tip

In order to test the proposed vibrissal tactile sensing ability of the WT, a test mechanical load (mass $m = 6 \times 10^{-5}$ kg, stiffness $k = 2.5$ N/m, damping $c = 0.01$ Ns/m) is connected to the whisker tip of the FE model in y -direction and a sweep sine voltage excitation is applied to the electrical port (see Figure 3.22). Both the input voltage E and current I are recorded simultaneously from which force F , velocity V and mechanical impedance Z_m are extracted with Equation (3.8) and (3.15). The actual values of F , V are also recorded and the theoretical Z_m is calculated with Equation (3.48). Both the measured and actual values are plotted in Figure 3.23 and Figure 3.24 for comparison.

Figure 3.22 Sensing force, velocity and mechanical impedance at whisker tip caused by a mass-spring-damper load

Figure 3.23 Comparison between the actual and WT-measured values of force and velocity at the whisker tip under a test load

Figure 3.24 Comparison between the theoretical and WT-measured values of mechanical impedance at the whisker tip under a test load

The results of this test show that after the determination of the transduction matrix, the

force F , velocity V and mechanical impedance Z_m at the whisker tip can be accurately sensed through measuring the input voltage E and current I . The actuator itself performs the role of a sensor simultaneously, just like what the rat's whisker-FSC structure does in the active vibrissal tactile perception. This means that it is possible to replace the motor, force sensor, motion sensor etc. in a traditional whisker system with only a single WT. As a result, the size of the robotic rat can be greatly reduced to even as small as a real rat. More importantly, the F , V and Z_m measured with the WT are the exact values at the whisker tip. And the loading effect affecting the measurement accuracy of traditional sensors is completely eliminated. And it is believed that these F , V and Z_m values are closely related to the texture properties of the object such as roughness, friction and hardness. Moreover, the simulation also shows that the WT works over a wide frequency range (1-100 Hz), while traditional whisker systems can only work at a frequency lower than 1 Hz. This is very important since it is known that rats can purposely modify the whisking frequency to meet the functional demands of exploration tasks.

3.6.2 Radial location sensing

To simulate the radial location sensing, the whisker is fixed in the y -direction (y -displacement of the whisker is constrained to be 0) at a radial distance d from the tip (see Figure 3.3b). Forty five simulations are carried out with d increasing from 9 mm to 53 mm. The electrical impedance Z_e is recorded in each simulation and plotted against the radial contact position d in Figure 3.25 and Figure 3.26.

Figure 3.25 Real part of electrical impedance vs. radial contact position d Figure 3.26 Imaginary part of electrical impedance vs. radial contact position d

The results show that the electrical impedance of the WT is sensitive to the radial contact

position. And the effect on real part is different from that on imaginary part. Although both curves are nonlinear, the curve of real part is quite linear when d is relatively small, while the curve of imaginary part is quite linear in the higher range of d . Therefore the radial contact position can be estimated using one of them according to the detection range.

For a better understanding of the relationship between the radial contact position d and the electrical impedance Z_e , let's consider the case of a simple cantilevered steel whisker shown in Figure 3.27. According to Euler–Bernoulli beam theory, the bending stiffness k of the whisker at a distance d from its free end is:

$$k = \frac{3EI}{(L-d)^3} = \frac{3E\pi r^4}{4(L-d)^3} \quad (3.49)$$

where E is the elastic modulus, I is the area moment of inertia, L is the length of whisker, and r is the radius of whisker. And the effective mass is approximately:

$$m = \frac{\mu(L-d)}{3} + \mu d = \mu \left(\frac{L}{3} + \frac{2d}{3} \right) \quad (3.50)$$

where μ is the linear mass density. So the mechanical impedance of the whisker at a distance d from its tip is:

$$Z_m = j \left(\omega m - \frac{k}{\omega} \right) = j \left[\frac{\omega \mu L}{3} + \frac{2\omega \mu d}{3} - \frac{3E\pi r^4}{4\omega(L-d)^3} \right] \quad (3.51)$$

Equation (3.51) shows that the relationship between the mechanical impedance Z_m of the whisker and the radial contact position d is nonlinear. Therefore when the contact position changes, the mechanical load applied to the PZT bimorph changes nonlinearly with respect to d . Since the relationship between the applied mechanical impedance Z_m and the electrical impedance Z_e of the PZT is also nonlinear as shown in (3.14), the relationship between Z_e and d becomes nonlinear as well, as illustrated by the simulation results.

Figure 3.27 A cantilevered steel whisker with a force load applied at a distance d from its free end

The accurate determination of d from measured Z_e is an inverse problem. And direct calculation of d from Z_e requires the nonlinear relationship between them being known accurately. This may be difficult since the WT is more complicated than a simple whisker and most of its parameters are not accurately known in a practical case. In contrast, rat solves this inverse problem in a completely different manner. The relationship between the contact position and neural response is obtained by learning from many training cases. After the establishment of this relationship with neural networks, it can reliably extract the contact position from the neural response with high efficiency and robustness. This biological way to solve inverse problem can be mimicked and implemented with artificial neural networks (ANN) and may facilitate the use of WT for radial location sensing.

3.6.3 Horizontal location sensing

As introduced in Chapter 2, the whisker-based horizontal location sensing function of rat is based on the sensing of two different signals — “whisking signal” and “touch/contact signal”. “Whisking signal” is caused by the active sweeping movement of whisker and is continuously sensed by “whisking cells” so that rat knows its whisker position at any moment. “Contact signal” is generated by “touch cells” upon contact with an object. Once rat detects the occurrence of contact, it immediately detects the position of the whisker at that moment and knows the location of the object. Similarly, the WT can be controlled to perform active whisking and its position at any moment can be determined from the electrical voltage signal. In order to detect the location of an object, it needs the ability to detect the occurrence of contact which is studied in the following simulation.

To illustrate the contact detection ability of the WT, simulations are carried out under non-contact (free, $F = 0$) and contact ($V = 0$) boundary conditions. The measured electrical impedances Z_e under these two conditions are plotted and compared in Figure 3.28. Then the corresponding mechanical impedances Z_m are calculated with Equation (3.15) and plotted in Figure 3.29.

Figure 3.28 Electrical impedance curves under non-contact (free) and contact conditions

Figure 3.29 Mechanical impedance curves under non-contact (free) and contact conditions.

(Some points cannot be plotted with a logarithmic scale since they reach 0 or ∞ as they should be.

Others are able to be plotted due to truncation errors in calculation.)

The results show that the occurrence of contact will change the electrical impedance curve. The change is most significant near the resonance which shifts to the right after contact (see Figure 3.28). And with the aid of the transduction matrix, the two curves of Z_e can be converted to two extreme mechanical impedance values — 0 and ∞ (see Figure 3.29). So the WT is able to differentiate these two conditions by setting a reasonable threshold between 0 and ∞ . And this contact detection ability can be utilized together with the whisking ability of the WT to achieve horizontal locating of an object, as illustrated in Figure 3.3c.

3.7 Potential applications of WT

Although this research starts with the motivation to develop an artificial counterpart of the biological whisker-FSC system to be used as a tactile sensor in robotic applications, the proposed concept of WT as well as the underlying sensing technique is quite general and can

be applied to a wide range of areas such as:

- Tactile sensing. The utilization of WT on robots can provide them with the tactile information which can facilitate tasks like manipulation and exploration. The proposed WT is a better solution than existing whisker systems since it can provide more quantitative and accurate tactile data which directly reflect the mechanical quantities at whisker tip. More importantly, it performs all the actuation, force sensing and motion sensing with a single compact device.
- Dynamic measurement. The technique can be directly adopted by many existing electromechanical actuators and endow them with the simultaneous sensing and actuating ability, so that one transducer can perform a complete dynamic measurement which conventionally needs at least three transducers.
- High-aspect-ratio metrology. The slender shape of the whisker makes it suitable for tactile sensing at very narrow and deep locations such as high-aspect-ratio holes which are difficult to access with conventional sensors.
- MEMS characterization. The performance of MEMS structures is highly related to their mechanical properties such as stiffness and friction. The characterization of them usually requires both actuators and sensors. Due to the extremely small scale of the structure, the installation of conventional transducers on the structure is almost impossible. Our research provides a possible solution to this problem. Since the tip of the whisker can be easily miniaturized to be several micrometers, the WT can conveniently probe the mechanical properties of the MEMS structure by simply touching it with the whisker tip, just like we probing the electrical voltage at a certain node in an electrical circuit with a voltage probe. The procedure is non-destructive and can be used as a routine online testing of MEMS product quality.
- Cell mechanics. Due to the tiny tapered tip of the whisker, the WT is able to apply mechanical force to an individual cell and detect the resulting motion without additional sensors. It can also monitor the mechanical properties of the cell which are related to its biological functions. And the simultaneous sensing and actuating feature of the WT will

greatly simplify the conventionally complex experimental setup.

- Neuroscience. The proposed WT mimics the biological whisker-FSC system from both morphological and functional aspects. Due to the high similarity between them, it is possible to increase our understanding of the underlying mechanism of rat's vibrissa system through the use of the WT. For example, it can be used to test hypotheses that are difficult or even impossible to implement in the biological way. On the other hand, new hypotheses may also initiate from the investigation of the WT which may be confirmed on the biological system later.

3.8 Summary

In this chapter, a bio-inspired whisker transducer (WT) which captures the essence of the biological whisker-FSC system has been proposed. It has a simple and compact structure with only two components. It is proposed to perform basic vibrissal tactile sensing functions — texture discrimination, radial location sensing and horizontal location sensing.

The WT is mathematically modeled as a two-port system based on a novel technique called the transduction matrix method. In this method, a two-by-two transduction matrix is used to characterize the forward actuation and backward sensing functions of the WT. Once this matrix is calibrated, the force, velocity and mechanical impedance at the mechanical output point can be conveniently sensed through measuring the input electrical voltage and current, just during the course of excitation. Three experimental methods for calibrating the transduction matrix of the WT have been presented, among which the least-squares method is much easier to implement in practical applications.

Numerical study of the WT has been conducted on a finite element model. The validity of the three calibration methods is confirmed. The calibrated WT is then used to simulate the vibrissal tactile sensing of mechanical quantities at the whisker tip under a test load. Another

two simulations also reveal the potential of the WT in radial location sensing and horizontal location sensing.

This WT has many advantages over those complicated whisker systems as well as traditional transducers. The simultaneous sensing and actuating (SSA) ability reduces the number of transducers required in a dynamic test as well as the cost and complexity of the measurement system. It is particularly suitable for situations where installation of sensors is impossible or difficult. It can also perform *in situ* or online monitoring during the course of a normal operation. And the elimination of loading effect solves the problem of inaccurate measurement suffered by traditional sensing techniques. It is hoped that the proposed WT and sensing technique can contribute to a wide range of areas such as tactile sensing, dynamic measurement, high-aspect-ratio metrology, MEMS characterization, cell mechanics as well as neuroscience.

Chapter 4

EXPERIMENTAL INVESTIGATION OF WHISKER TRANSDUCER FOR VIBRISSAL TACTILE SENSING

In last chapter, a bio-inspired whisker transducer (WT) has been proposed for vibrissal tactile sensing and its validity has been confirmed numerically. In this chapter, experimental investigation will be conducted with a prototype of the proposed WT. Its transduction matrix will be calibrated based on the method discussed in last chapter. This will be followed by validation experiments to check its performance. The calibrated WT would then be used to perform vibrissal tactile sensing on sandpaper specimens and to study the mechanism of rat's vibrissal tactile perception in a biomimetic perspective. The results of this chapter would be of interest to both researchers developing artificial whisker sensing in robotics and those investigating the biological vibrissal tactile perception system in neuroscience.

4.1 Prototype of WT

A prototype of the proposed whisker transducer (WT) which has the same configuration as the one in simulation has been fabricated and a picture of it is shown in Figure 4.1. The PZT bimorph consisting of two PZT layers ($46 \times 2.1 \times 0.2$ mm) and a middle carbon fiber composite layer ($46 \times 2.1 \times 0.15$ mm) is made by APC International, USA. It is fixed on a thick aluminum bar for handling. A 61 mm long stainless steel wire with a radius of 0.15 mm is glued to the free end of the PZT bimorph using 3M DP-460 Epoxy Adhesive. A small aluminum clamp which has the mass of 2.3338 g is added to the transducer at 41 mm from the fixed end in order to reduce the resonant frequency.

Figure 4.1 A prototype of whisker transducer.

(a) Steel whisker. (b) PZT bimorph. (c) Added mass. (d) Aluminum bar.

The electrical impedance of this prototype under free load condition is first checked in the frequency range of 1-100 Hz, using a SI 1260 Impedance/Gain-phase Analyzer (Solartron Analytical). Figure 4.2 and Figure 4.3 show that the resonant frequency is reduced from 54 Hz to around 36 Hz by adding the small piece of mass. This agrees well with the simulation result shown in Figure 3.11 and Figure 3.12.

Figure 4.2 Electrical impedance of the WT before adding mass

Figure 4.3 Electrical impedance of the WT after adding mass

4.2 Electrical signal measurement and processing

The operation of WT requires the measurement of voltage, current and electrical impedance. Although the Solartron Impedance Analyzer in our lab can measure electrical impedance easily, it cannot give the separate signals of voltage and current. In addition, the maximum AC voltage provided by the Impedance Analyzer is only 3 V which may not be sufficient for some applications. As a result, a dynamic measurement system was built up with a PXI-1042 Chassis, a PXI-8106 Embedded Controller and a PXI-4461 Dynamic Signal Acquisition and Generation Module (24-Bit, 204.8 kS/s, 2-Input/2-Output), all from National Instruments (Austin, TX). This system is more flexible than the Solartron Impedance Analyzer since it can measure the voltage and current separately. It can also connect to a power amplifier to boost the output voltage. In addition, it is programmable using the NI LabVIEW development environment so that more complex functions such as digital signal processing can be achieved through programming.

Figure 4.4 is a block diagram of the entire measurement system. The LabVIEW

software on the computer controls the NI DSA system to generate a voltage excitation signal from its output channel. Since the maximum output voltage of the DSA system is 10 V, a power amplifier may be used to boost the voltage up to 200 V in case when high voltage is needed. The voltage is applied to the WT to generate whisking movement of the whisker. Due to the mechanical interaction with the mechanical load, the electrical voltage and current signals of the WT will be changed through electromechanical coupling. The input voltage is directly measured by one of the input channels of the NI DSA system. The current signal needs to be converted into a voltage signal so that it can be measured by another input channel of the DSA system. An I-V convertor circuit was designed to perform this task based on the method that will be discussed in Section 4.2.1. These two signals are then transmitted back to LabVIEW for further processing and calculation.

Figure 4.4 Block diagram of the dynamic measurement system

4.2.1 Electrical impedance measurement

According to [108], there are a number of methods for measuring electrical impedance which can be differentiated by technical factors such as frequency range, measurement range, measurement accuracy and ease of implementation. Table 4.1 summarizes the advantages and disadvantages of six common electrical impedance measurement methods: bridge method, resonant method, I-V method, RF I-V method, network analysis method and auto-balancing bridge method. By comparing their frequency ranges, four of them — resonant method, I-V method, RF I-V method, network analysis method — are quickly excluded since they are for relatively high frequency (> 10 kHz) measurement while our WT is mainly working at a

frequency less than 1 kHz. In the remaining two methods, the bridge method is not easy to use since it needs to be manually balanced. In addition, its working principle requires the input voltage to be divided so the actual voltage applied on the device under test (DUT) is much lower. Now the only remaining method is the auto-balancing bridge method, which is illustrated in Figure 4.5.

Table 4.1 Common electrical impedance measurement methods [108]

	Frequency range	Advantages	Disadvantages
Bridge method	DC to 300 MHz	<ul style="list-style-type: none"> • High accuracy • Low cost 	<ul style="list-style-type: none"> • Manual balancing • Narrow frequency range with a single instrument
Resonant method	10 kHz to 70 MHz	<ul style="list-style-type: none"> • Good Q accuracy 	<ul style="list-style-type: none"> • Needs to be tuned to resonance • Low impedance measurement accuracy
I-V method	10 kHz to 100 MHz	<ul style="list-style-type: none"> • Grounded device measurement • Probe-type test 	<ul style="list-style-type: none"> • Frequency range limited by transformer used in probe
RF I-V method	1 MHz to 3 GHz	<ul style="list-style-type: none"> • High accuracy • Wide impedance range 	<ul style="list-style-type: none"> • Frequency range limited by transformer used in test head
Network analysis method	300 kHz and above	<ul style="list-style-type: none"> • High frequency range • High accuracy when the unknown impedance is close to the characteristic impedance 	<ul style="list-style-type: none"> • Needs recalibration when changing measurement frequency • Narrow impedance range
Auto-balancing bridge method	20 Hz to 110 MHz	<ul style="list-style-type: none"> • Wide frequency range • High accuracy over a wide impedance range • Grounded device measurement 	<ul style="list-style-type: none"> • Higher frequency ranges not available

Figure 4.5 Principle of the auto-balancing bridge method for electrical impedance measurement [108]

The auto-balancing bridge method in Figure 4.5 is based on the basic idea of measuring the voltage across the DUT and the current flowing through it. The potential V_x at the “high” terminal can be measured by a voltmeter. Since the potential at the “low” terminal is maintained at 0 V due to the virtual ground, V_x also represents the voltage across the DUT. In order to sense the current signal, an I-V converter circuit (an operational amplifier with a negative feedback resistor) is used to convert the current signal into a voltage signal that can be input to the NI DSA. The current I_x flowing through the DUT is balanced by the current I_r through the feedback resistor R_r so:

$$I_x = I_r \quad (4.1)$$

The current I_r can be easily measured as the ratio of the output voltage V_r to the resistance R_r of the feedback resistor:

$$I_r = \frac{V_r}{R_r} \quad (4.2)$$

Using Equation (4.1) and (4.2), the electrical impedance Z_x of the DUT can be derived as:

$$Z_x = \frac{V_x}{I_x} = \frac{V_x}{I_r} = R_r \frac{V_x}{V_r} \quad (4.3)$$

By implementing this method in our measurement system, the measurement of the electrical impedance becomes the measurement of two voltage signals V_x and V_r which can be directly input to the NI DSA in Figure 4.4.

4.2.2 Analytic signals of voltage, current and electrical impedance

The electrical signals acquired by the NI DSA system in Figure 4.4 are in the form of time-domain sinusoidal signals. However, in the transduction matrix equation (3.1), all electrical and mechanical variables (E , I , F , V) are complex quantities. So a conversion from sinusoidal signal to complex number representation should be carried out on the measured electrical signals before they can be used in the transduction matrix method. It is implemented in the LabVIEW development environment on the computer through programming, based on following theories and algorithms.

A time-domain sinusoidal real-valued signal can be represented as a cosine function of time t in the following form:

$$x(t) = A \cos(\omega t + \phi) \quad (4.4)$$

where A is the amplitude of the signal, ω is the angular frequency and ϕ is the phase angle. In electric circuit analysis, the AC voltage and current are usually represented in the complex number form called “phasor” which encodes the amplitude and phase information as follows:

$$X = Ae^{j\phi} = A \angle \phi \quad (4.5)$$

According to Euler’s formula, the actual signal $x(t)$ can be obtained by multiplying its phasor representation by $e^{j\omega t}$ and taking the real part, so:

$$x(t) = \text{Re}(Xe^{j\omega t}) \quad (4.6)$$

The sampling of the continuous time signal $x(t)$ by the analog-to-digital converter (ADC) in the NI DSA system will result in a discrete signal $x(n)$ in the following form:

$$x(n) = A \cos(\omega n t_s + \phi) \quad n = 0, 1, \dots, N-1 \quad (4.7)$$

where t_s is the sampling period. If the signal is time-invariant in terms of amplitude and frequency, its phasor representation can be easily obtained through spectrum analysis. Both the amplitude spectrum and phase spectrum can be calculated from the fast-Fourier Transform (FFT) of the signal $x(n)$ as follows:

$$A(f) = \frac{|\text{FFT}[x(n)]|}{N}$$

$$\phi(f) = \arctan\left(\frac{\text{Im}\{\text{FFT}[x(n)]\}}{\text{Re}\{\text{FFT}[x(n)]\}}\right) \quad (4.8)$$

The amplitude and phase of the original signal can be extracted from its spectra by finding the peak in the amplitude spectrum. And the phasor representation of the signal can be formed with this peak amplitude and its corresponding phase using Equation (4.5). Figure 4.6 is an example of obtaining complex representation of a time-invariant sinusoidal signal from its amplitude and phase spectra.

Figure 4.6 Obtaining complex representation of a time-invariant sinusoidal signal $x(t)$ from its amplitude spectrum $A(f)$ and phase spectrum $\phi(f)$.

If the original signal $x(t)$ is not time-invariant, for example its amplitude, phase or frequency changes with time, the above method becomes inapplicable since it can only

provide information in the frequency domain. In this case, a generalization of the phasor termed “analytic signal” can be used. An analytic signal represents the original signal in the complex number form and varies with time. It can provide the instantaneous amplitude and frequency information of the original signal. The analytic signal of a real-valued signal can be obtained from the original signal and its Hilbert transform (HT) as:

$$X(t) = x(t) + j\hat{x}(t) \quad (4.9)$$

where $X(t)$ is the analytic signal, $x(t)$ is the original signal and $\hat{x}(t)$ is the HT of the original signal defined in Equation (4.10) as:

$$\hat{x}(t) = \text{HT}[x(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau \quad (4.10)$$

The HT can be implemented either in the frequency domain or in the time domain [109]. In the frequency domain, it can be calculated based on the FFT of the discrete signal $x(n)$ as:

$$\hat{x}(n) = \text{IFFT}\{-j \text{sgn}(f) \cdot \text{FFT}[x(n)]\} \quad (4.11)$$

where IFFT is the inverse Fourier transform, and the sign function $\text{sgn}(f)$ is defined as:

$$\text{sgn}(f) = \begin{cases} 1 & f > 0 \\ 0 & f = 0 \\ -1 & f < 0 \end{cases} \quad (4.12)$$

Alternatively, the HT can be implemented in the time domain using a finite impulse response (FIR) filter in the following form:

$$\hat{x}(n) = \sum_{k=-\infty}^{\infty} h(k)x(n-k)$$

where $h(k)$ is the k th filter coefficient. These two implementations have their own advantages and disadvantages under different situations. The frequency domain implementation can give more accurate result but is computationally more expensive for real-time processing. The time domain implementation is more suitable for real-time processing but its result is less accurate

due to the limited length of the FIR filter. Finally, the complete process to generate analytic signal from the real-valued signal $x(n)$ is illustrated in Figure 4.7.

Figure 4.7 Analytic signal generation using Hilbert transform

Figure 4.8 is an example of generating analytic signal $X(t)$ of a time-variant signal $x(t)$ using Hilbert transform. It should be noticed that both the plotted amplitude and phase of the resulting analytic signal $X(t)$ are in time domain. And the change of amplitude at $t = 0.5$ s can be clearly observed from the amplitude signal.

Figure 4.8 Generating analytic signal $X(t)$ of a time-variant sinusoidal signal $x(t)$ using Hilbert transform.

4.3 Experimental calibration of the transduction matrix

As discussed in Section 3.4, there are three methods for calibrating the transduction matrix of the WT. However, the two direct methods require the measurement of force and

velocity at the mechanical output point. Although this may be possible for a big transducer by using equipments like accelerometer and laser vibrometer, it is almost impossible for our WT since the whisker tip is very small. In addition, it is also difficult to clamp the whisker tip firmly without damaging it. In order to circumvent these problems, the least-squares calibration method is employed which avoids the direct measurement of force and velocity.

4.3.1 Least-squares calibration

The least-squares calibration method requires a set of mechanical loads with known mechanical impedances (see Figure 3.9). The mass-spring-damper system used as mechanical load in the simulation in last chapter is difficult to implement in practice. In addition, due to the small size of the whisker tip, the application of pure mass loads is also impractical. As a result, a cantilever beam ($82 \times 1 \times 0.3$ mm) made of precision AISI 304 stainless steel (Hasberg-Schneider GmbH, Germany) is chosen as the mechanical load, which can be modeled as a mass-spring system with its effective mass and stiffness values. Figure 4.9 is the schematic diagram of the calibration experiment. The load steel cantilever is placed perpendicular to the vibrating whisker. The vibration is generated in the y -direction upon the application of electrical voltage. All the measurements (E , I , Z_e) are carried out at the electrical port when the mechanical load is applied at the mechanical port.

Figure 4.9 Schematic diagram of least-squares calibration using a precision cantilever beam as the mechanical load.

The red arrow shows the direction of vibration.

In order to obtain more than 3 different mechanical impedances required by the least-squares calibration method from a single cantilever beam, the contact location (d mm from the base of the cantilever beam, see Figure 4.9) is changed to create a different mechanical load. A set of 6 mechanical loads ($d = 71, 73, 75, 77, 79, 81$ mm) together with the free load are used for calibration. Their theoretical mechanical impedances can be calculated with the material properties in Table 4.2.

Table 4.2 Material properties of the steel beam

Young's modulus (GPa)	E	185
Poisson's ratio (unitless)	ν	0.29
Density (kg/m^3)	ρ	7900

A sinusoidal voltage signal (10 V, 36 Hz) is used as the excitation to the WT. Since the WT is working at a single frequency, the transduction matrix to be identified is a 2×2 matrix with each element being a single point on the curves in Figure 3.21. Both the electrical voltage and current signals are acquired and processed by the dynamic measurement system

in Figure 4.4 to generate their complex number representations. Then the electrical impedance is calculated as the ratio of voltage to current.

The electrical impedances of the WT under the calibration loads are measured and plotted in Figure 4.10. Their corresponding theoretical mechanical impedances are calculated and plotted in Figure 4.11 as blue circles. Now the transduction matrix can be determined using Equations (3.45) to (3.47). The calibrated transduction matrix is plotted in Figure 4.12 as “square” to compare with the simulation results in Chapter 3. Since the WT is working at a single frequency of 36 Hz, the identified transduction matrix is a 2 by 2 matrix with each element being a single point on the curve in Figure 4.12. The good agreement between experimental result and FE simulation results confirms the validity of the WT. With this transduction matrix successfully calibrated, the force, velocity and mechanical impedance at the whisker tip can be converted from measured electrical signals using Equations (3.8) and (3.15). And the WT can be used as an actuator and a sensor simultaneously.

Figure 4.10 Measured electrical impedances under calibration loads.

Figure 4.11 Theoretical mechanical impedances and measured mechanical impedances under calibration loads.

Figure 4.12 Experimentally calibrated transduction matrix of WT compared with simulation results.

4.4 Experimental validation of the transduction matrix

4.4.1 Validation of mechanical impedance measurement

The performance of the calibrated transduction matrix is first checked on the calibration loads. The measured electrical impedances in Figure 4.10 are converted to the measured mechanical impedances with Equation (3.15) and plotted in Figure 4.11 as red crosses for comparison with their theoretical values. The measurement error is evaluated with the following equation and listed in Table 4.3.

$$\text{Error} = \left| \frac{\text{Measured } Z_m - \text{Theoretical } Z_m}{\text{Theoretical } Z_m} \right| \times 100\% \quad (4.13)$$

The good agreement between the measured mechanical impedances and their theoretical values indicates that the transduction matrix is successfully and accurately calibrated. And the measurement error is less than 0.67%.

Table 4.3 Measurement errors of mechanical impedances of calibration loads

Test location d (mm)	WT-measured Z_m (Ω)	Theoretical Z_m (Ω)	Error
71	$3.75 \times 10^{-6} + j9.99 \times 10^{-4}$	$0 + j9.95 \times 10^{-4}$	0.54%
73	$-3.51 \times 10^{-6} + j9.13 \times 10^{-4}$	$0 + j9.18 \times 10^{-4}$	0.67%
75	$-3.66 \times 10^{-6} + j8.47 \times 10^{-4}$	$0 + j8.50 \times 10^{-4}$	0.54%
77	$-6.92 \times 10^{-7} + j7.89 \times 10^{-4}$	$0 + j7.89 \times 10^{-4}$	0.11%
79	$2.60 \times 10^{-6} + j7.37 \times 10^{-4}$	$0 + j7.34 \times 10^{-4}$	0.54%
81	$2.57 \times 10^{-6} + j6.87 \times 10^{-4}$	$0 + j6.85 \times 10^{-4}$	0.46%

In order to evaluate the reliability and repeatability of the WT, each measurement was repeated five times. The electrical impedance Z_e under different loads is plotted in Figure 4.13 and Figure 4.14. In addition, measurement uncertainty was estimated at 95% confidence level and also plotted. The Z_e data are consistent with each other and the measurement uncertainty is small. The Z_e data were then converted to measured Z_m data using the calibrated transduction matrix and plotted together with the theoretical Z_m in Figure 4.15 and Figure 4.16. Both small measurement error and low measurement uncertainty are observed.

Figure 4.13 Repeated measurement data of real part of electrical impedance under different calibration loads (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is load number (1 — free, 2 — 81 mm, 3 — 79 mm, 4 — 77 mm, 5 — 75 mm, 6 — 73 mm, 7 — 71 mm).

Figure 4.14 Repeated measurement data of imaginary part of electrical impedance under different calibration loads (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is load number (1 — free, 2 — 81 mm, 3 — 79 mm, 4 — 77 mm, 5 — 75 mm, 6 — 73 mm, 7 — 71 mm).

Figure 4.15 Repeated measurement data of imaginary part of mechanical impedance of different calibration loads (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is load number (1 — free, 2 — 81 mm, 3 — 79 mm, 4 — 77 mm, 5 — 75 mm, 6 — 73 mm, 7 — 71 mm).

Figure 4.16 Repeated measurement data of real part of mechanical impedance of different calibration loads(left) and estimated measurement uncertainty at 95% confidence level (right). “n” is load number (1 — free, 2 — 81 mm, 3 — 79 mm, 4 — 77 mm, 5 — 75 mm, 6 — 73 mm, 7 — 71 mm).

To further check the validity and performance of the calibrated transduction matrix, another independent set of 6 mechanical loads ($d = 70, 72, 74, 76, 78, 80$ mm) are used for validation. The electrical impedances under these loads are measured and plotted in Figure 4.17. They are converted to mechanical impedances with the calibrated transduction matrix

using Equation (3.15) and plotted in Figure 4.18 as red crosses. The theoretical values are also calculated and plotted in Figure 4.18 as blue circles for comparison. The measurement errors calculated with Equation (4.13) are listed in Table 4.4. Close agreement is observed between them with the measurement error being less than 1.28%, which confirms that the transduction matrix has been properly calibrated.

Figure 4.17 Measured electrical impedances under validation loads.

Figure 4.18 Theoretical mechanical impedances and measured mechanical impedances under validation loads.

Table 4.4 Measurement errors of mechanical impedances of validation loads

Test location d (mm)	WT-measured Z_m (Ω)	Theoretical Z_m (Ω)	Error
70	$6.11 \times 10^{-6} + j1.05 \times 10^{-3}$	$0 + j1.04 \times 10^{-3}$	1.28%
72	$-3.46 \times 10^{-6} + j9.47 \times 10^{-4}$	$0 + j9.55 \times 10^{-4}$	0.95%
74	$-3.54 \times 10^{-6} + j8.76 \times 10^{-4}$	$0 + j8.83 \times 10^{-4}$	0.89%
76	$-3.29 \times 10^{-6} + j8.15 \times 10^{-4}$	$0 + j8.19 \times 10^{-4}$	0.61%
78	$1.31 \times 10^{-7} + j7.62 \times 10^{-4}$	$0 + j7.61 \times 10^{-4}$	0.16%
80	$1.87 \times 10^{-6} + j7.13 \times 10^{-4}$	$0 + j7.09 \times 10^{-4}$	0.58%

The measurement was repeated five times. The repeated Z_e and Z_m data were plotted in Figure 4.19 to Figure 4.22 together with the measurement uncertainty estimated at 95% confidence level. Both small measurement error and low measurement uncertainty can be observed.

Figure 4.19 Repeated measurement data of real part of electrical impedance under different validation loads (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is load number (1 — 80 mm, 2 — 78 mm, 3 — 76 mm, 4 — 74 mm, 5 — 72 mm, 6 — 70 mm).

Figure 4.20 Repeated measurement data of imaginary part of electrical impedance under different validation loads (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is load number (1 — 80 mm, 2 — 78 mm, 3 — 76 mm, 4 — 74 mm, 5 — 72 mm, 6 — 70 mm).

Figure 4.21 Repeated measurement data of imaginary part of mechanical impedance under different validation loads (left) and estimated measurement uncertainty at 95% confidence level (right). “ n ” is load number (1 — 80 mm, 2 — 78 mm, 3 — 76 mm, 4 — 74 mm, 5 — 72 mm, 6 — 70 mm).

Figure 4.22 Repeated measurement data of real part of mechanical impedance under different validation loads (left) and estimated measurement uncertainty at 95% confidence level (right). “ n ” is load number (1 — 80 mm, 2 — 78 mm, 3 — 76 mm, 4 — 74 mm, 5 — 72 mm, 6 — 70 mm).

4.4.2 Validation of velocity measurement

Although above results are already sufficient to confirm the validity of the calibrated transduction matrix, the ability of the WT to measure force and velocity has not been illustrated. By using optic methods, non-intrusive measurement of velocity can be achieved to check the performance of our WT-based velocity sensing. It is implemented by capturing

images of the whisker movement with a high speed camera and then extracting the vibration parameters through image processing. This is also a popular method used by many neuroscientists when studying the whisker movement of real rats [18, 40].

A FASTCAM (Photron USA, Inc.) high speed camera has been chosen for capturing the movement of our WT. It has a maximum resolution of 1024×1024 and a maximum frame rate of 109500 fps which is much higher than the vibration frequency of the WT (36 Hz). The camera is equipped with an Optem Zoom 70XL lens (Qioptiq USA, Inc.) for magnification. Figure 4.23 is the schematic diagram of the velocity validation experiment. The camera is mounted above the WT and focused on the whisker tip. Lens magnification is adjusted so that best spatial resolution can be obtained. The WT is working under the free load condition at a frequency of 36 Hz. The camera captures its movement at a speed of 6000 fps for 0.8 second so that 4800 frames are recorded. At the same time, the voltage E and current I are measured to compute the vibration velocity using the calibrated transduction matrix.

Figure 4.23 Schematic diagram of velocity validation using a high speed camera.

The red arrow is the direction of vibration.

Figure 4.24 shows examples of images of the vibrating whisker tip captured by the high speed camera. They are processed in MATLAB using a series of image processing algorithms shown in Figure 4.25 so that the movement of whisker tip can be extracted accurately. The vibration amplitude is obtained from the extracted whisker movement signal. The amplitude of velocity is then calculated from the vibration amplitude $|U|$ using following relationship:

$$|V| = \omega|U| \quad (4.14)$$

The result is presented in Table 4.5 as $|V_{CAM}|$. The velocity is also computed from the voltage and current measured by the WT using Equation (3.8) and listed in Table 4.5 as $|V_{WT}|$ for comparison.

Figure 4.24 Examples of the vibrating whisker image captured by the high speed camera

Figure 4.25 Image processing for extracting the whisker movement

Table 4.5 Velocities measured by WT and high speed camera under free load

$ V_{WT} $ (m/s)	$ V_{CAM} $ (m/s)	Error
0.789	0.796	0.88%

The measurement was repeated ten times and consistent results were obtained which are listed in Table 4.6. The measurement uncertainty was estimated to be ± 0.007 (m/s) at 95% confidence level.

Table 4.6 Repeated measurement of velocity by WT

No.	$ V_{WT} $ (m/s)
1	0.784
2	0.792
3	0.793
4	0.793
5	0.785
6	0.787
7	0.787
8	0.786
9	0.787
10	0.786

It can be found from Table 4.5 that the velocities measured by WT and high speed camera coincide with each other and the measurement uncertainty of WT is small. Therefore the validity of the WT to measure velocity at its whisker tip has been confirmed.

4.4.3 Validation of force measurement

The validation of the force measured at the whisker tip is more difficult than that of the velocity since it is almost impossible to install a force sensor at the tip. However, since there are only two independent variables among force F , velocity V and mechanical impedance as $F = Z_m V$, the validation of the force measurement is unnecessary and the measurement error of force can be estimated using the rules of error propagation [110]. Suppose the measured mechanical impedance Z_m and velocity V have uncertainties δZ_m and δV respectively, the uncertainty δF in the force measurement can be expressed as:

$$\frac{\delta F}{|F|} = \sqrt{\left(\frac{\delta Z_m}{Z_m}\right)^2 + \left(\frac{\delta V}{V}\right)^2} \quad (4.15)$$

By using the measurement errors in mechanical impedance (1.28%) and velocity (0.88%) obtained in previous validation experiments, the measurement error of force is estimated to be 1.55%.

In addition, the measured force at whisker tip should be 0 under free load condition. It is computed from the measured voltage and current using the calibrated transduction matrix and Equation (3.8). The result presented in Table 4.7 shows its order of magnitude is only 10^{-6} which is very close to the theoretical value. Therefore the validity of force measurement using WT has been confirmed as well.

Table 4.7 Comparison of WT-measured force and its theoretical value under free load

$ F_{WT} $ (N)	Theoretical $ F $ (N)
1.90×10^{-6}	0

The measurement was repeated ten times and results were listed in Table 4.8. It appears that the repeated data are not very consistent. However, if compared with the data in Figure 4.28, each value in Table 4.8 is just zero plus a small deviation. So they are still consistent. The measurement uncertainty was estimated to be $\pm 4.90 \times 10^{-6}$ (N) at 95% confidence level.

Table 4.8 Repeated measurement of force by WT

No.	$ F_{WT} $ (N)
1	6.18×10^{-6}
2	6.45×10^{-6}
3	8.34×10^{-6}
4	8.55×10^{-6}
5	5.33×10^{-6}
6	1.20×10^{-6}
7	1.48×10^{-6}
8	5.06×10^{-6}
9	6.82×10^{-6}
10	6.39×10^{-6}

4.5 Vibrissal tactile sensing using WT

After calibration and validation of its transduction matrix, the WT is capable of performing vibrissal tactile sensing by actively sweeping across the surface of a specimen, just like what rats do with their whiskers. In the following tactile sensing experiment, five pieces of sandpapers of different roughness levels are used as specimens. Each roughness level is evaluated in mean grain size and labeled with a corresponding P-value [111], as listed in Table 4.9.

Table 4.9 Roughness levels of sandpaper specimens used in vibrissal tactile sensing experiment

P-value	Mean grain size (μm)
P1200	15.3
P800	21.8
P400	35.0
P320	46.2
P280	52.2

4.5.1 Experiment setup

The experiment setup is shown in Figure 4.26. The WT attached to an aluminum handle is fixed on a linear stage system (Physik Instrumente GmbH, Germany) which can position the WT in y - and z -axes so that the whisker tip can be located at the center of the specimen. The specimen is clamped on a rotation stage for controlling the contact angle to be 10° . The force between the whisker tip and specimen in the direction perpendicular to the surface is controlled to be 3.3×10^{-4} N. After positioning, the linear stage system stops moving. Then the electrical excitation signal (10V, 36 Hz) is applied to make the whisker sweep across the surface (see Figure 4.27). The excitation voltage E as well as the current I are measured simultaneously.

Figure 4.26 Experiment setup for vibrissal tactile sensing of sandpaper texture.

(a) WT. (b) Aluminum handle. (c) YZ-linear stage. (d) Sandpaper specimen. (e) Rotation stage.

Figure 4.27 Whisker tip sweeps across the specimen when the WT is electrically excited.

4.5.2 WT-measured force, velocity and mechanical impedance

The force, velocity and mechanical impedance at whisker tip are calculated from measured electrical voltage and current with Equations (3.8) and (3.15). Figure 4.28 is the plot of the force at whisker tip vs. roughness of specimen. An increasing relationship is found between them which means the increase of specimen's roughness will cause an increase in the

force sensed at whisker tip. Figure 4.29 is the plot of whisker tip velocity vs. roughness. The relationship is decreasing so the velocity sensed at whisker tip will decrease as the roughness increases. Linear regression analyses are also carried out and both relationships are quite linear since R^2 is greater than 0.99. Therefore they can be used as indicators of the texture from which roughness can be estimated. And the measurement process is non-intrusive, so the measured force and velocity are their exact values at the whisker tip. This is impossible to achieve with other sensing techniques (e.g. strain gauge, magnetic sensor, etc.).

Figure 4.28 The force (F_y) sensed at whisker tip when the roughness of the specimen changes.

Figure 4.29 The velocity (V_y) sensed at whisker tip when the roughness of the specimen changes.

The real part and imaginary part of the mechanical impedance measured at whisker tip are plotted in Figure 4.30 and Figure 4.31, respectively. It can be observed that the real part will increase when the roughness increases. Regression analysis shows that the relationship is quadratic rather than linear. This real part of mechanical impedance is a direct measure of the damping or frictional property of the surface texture that resisting the relative motion between the whisker tip and surface. In contrast, the imaginary part of mechanical impedance shows little sensitivity to the change of roughness. And the magnitude of the imaginary part is much lower than that of the real part. So it can be concluded that the mechanical impedance of sandpaper specimen is dominated by its real part which is sensitive to the change of roughness.

Figure 4.30 Real part of the mechanical impedance (Z_m) sensed at whisker tip when the roughness of the specimen changes.

Figure 4.31 Imaginary part of the mechanical impedance (Z_m) sensed at whisker tip when the roughness of the specimen changes.

Above experiment shows that the force, velocity and real part of mechanical impedance

measured at the whisker tip are sensitive to the change of surface texture. They can be used as raw data for further processing such as texture discrimination or characterization. This kind of tactile information is critical to robots when they are performing tasks like manipulation and exploration. In addition, due to the simultaneous sensing and actuating (SSA) feature of WT, it provides a good technique for non-destructive tribology study of micro structures. As the size of a structure reduces to the micro scale, surface forces like friction becomes more and more important. However, conventional friction sensing methods are difficult to implement on the micro structure since they usually have complex configurations involving several actuators and sensors. In contrast, our WT has a very simple structure and both actuation and sensing are achieved with a single device. It can easily measure the real part of mechanical impedance which is directly related to the frictional property of the surface, as illustrated in our experiment.

4.6 Studying the mechanism of rat's vibrissal tactile perception with the WT

As introduced in the literature review, there are currently two hypotheses about the mechanism of rat's vibrissal tactile perception. The "kinetic signature hypothesis" is becoming more popular over the "resonance hypothesis" since some new evidences against the later have been found. However, the former also needs more supporting evidences since it is just in the preliminary stage. The current experiments are mainly carried out on anesthetized animals, so the result may differ from that obtained from awake and behaving animals. Unfortunately, it has been proved difficult, if not impossible, to record neural signals in awake rats and at the same time accurately monitor whisker movement [4]. Our WT can facilitate this in a biomimetic perspective due to its high similarity to the biological system.

4.6.1 Testing the kinetic signature hypothesis

Recently there is a popular hypothesis about the mechanism of rat's vibrissal tactile perception called "kinetic signature hypothesis" [39]. In this hypothesis, it is believed that features of the surface texture such as the size of grains will induce texture-specific high frequency vibrations to the temporal profile of the whisker velocity. These high frequency vibrations are then transmitted to the sensory neurons in cerebral cortex as texture-specific firing patterns with which different textures are discriminated. In order to test this hypothesis, the WT is excited to sweep across the sandpaper specimen and the waveforms of electrical signals are recorded simultaneously. Both temporal signals and frequency spectra of the electrical signals are recorded simultaneously. Both temporal signals and frequency spectra of the electrical signals are plotted in Figure 4.32 and Figure 4.33. Although the change of temporal signal is not very obvious, the spectrum clearly shows that the interaction with texture does generate high frequency components in the electrical signals of WT.

Figure 4.32 Voltage signal obtained when the WT sweeps across different sandpaper specimens.

(a) Free load. (b) P1200 sandpaper. (c) P800 sandpaper. (d) P400 sandpaper. (e) P320 sandpaper. (f) P280 sandpaper.

(a)

(b)

(c)

(d)

(e)

Figure 4.33 Current signal obtained when the WT sweeps across different sandpaper specimens.

(a) Free load. (b) P1200 sandpaper. (c) P800 sandpaper. (d) P400 sandpaper. (e) P320 sandpaper. (f) P280 sandpaper.

Now let's consider the “kinetic signature hypothesis”. Assuming each sand grain will cause a high frequency event on the whisking motion, the frequency of the induced vibration when the whisker sweeps across a piece of sandpaper of d μm grain size at a speed of v $\mu\text{m/s}$ is approximately:

$$f = \frac{v}{d} \quad (4.16)$$

With Equation (4.16), the frequency of the texture-induced high frequency vibration can be estimated using the measured velocity in Figure 4.29 as well as the mean grain size of sandpaper in Table 4.9. The results are listed in Table 4.10.

Table 4.10 Estimation of the frequency of texture-induced vibration under different sandpaper loads

Specimen	Whisking velocity v_{RMS} ($\mu\text{m/s}$)	Grain size (μm)	Frequency of induced vibration f (Hz)
P1200	3.61×10^5	15.3	23.6 k
P800	3.35×10^5	21.8	15.4 k
P400	2.93×10^5	35.0	8.4 k
P320	2.42×10^5	46.2	5.2 k
P280	2.13×10^5	52.2	4.1 k

Table 4.10 shows that based on the “kinetic signature hypothesis”, the frequency of the

texture induced vibration will decrease when the roughness increases. If this is true, there should be a peak value in the spectrum of the electrical signal (see Figure 4.32) whose frequency changes with the roughness of the specimen. Since there is more than one peak value in each spectrum plot, the frequencies of all peak values are extracted and listed in Table 4.11 for comparison. It is obvious that the first peak represents the operation frequency of 36 Hz. And it is expected that some other peaks will change with the roughness. However, the frequencies of all other peaks are almost constant with respect to the roughness change. Therefore they are just higher order harmonics of the operation frequency rather than the texture-specific vibration.

Table 4.11 Peak frequencies extracted from each spectrum plot in Figure 4.32b-f

Specimen	1st peak (Hz)	2nd peak (Hz)	3rd peak (Hz)	4th peak (Hz)	5th peak (Hz)	6th peak (Hz)	7th peak (Hz)	8th peak (Hz)
P1200	36	360	1066	2080	3440	5112	7116	9388
P800	36	360	1073	2087	3436	5114	7109	9375
P400	36	360	1066	2084	3436	5109	7111	9379
P320	36	357	1065	2074	3443	5123	7116	9383
P280	36	367	1071	2084	3442	5095	7101	9396

Above results cast doubt on the “kinetic signature hypothesis” from a biomimetics point of view. It appears that texture or roughness of the specimen is not coupled into the whisking signal in a straightforward and faithful way. Although there is evidence that the spectrum of the electrical whisking signal changes significantly between the free load and sandpaper load, this change has no direct relationship with roughness.

On the other hand, in the earliest and also most important research study on rat’s vibrissal tactile discrimination, Carvell and Simons [18] carried out biometric analyses on hundreds of texture discrimination cases and found that the whisking behavior is not strictly stereotyped since its major parameters such as whisking frequency, amplitude and velocity all vary over a fairly broad range both within-subject and across-subject, as shown in Table 4.12.

Interestingly, rat made the correct choice in each case despite these significant differences in the whisking behavior. This finding challenges the “kinetic signature hypothesis” since the whisking velocity varies in such a wide range that it will result in a significant variation of the induced vibration frequency even for the same texture roughness. How could the rat always make correct choice with this variant kinetic signal?

Table 4.12 Parameters of whisking behavior during discrimination tasks [18]

Parameter	Average	Range
Whisking frequency (Hz)	8	5~25
Contact duration (ms)	684	333-1100
Whisking amplitude (°)	31.6	16.9-46.3
Contact distance (mm)	15	10-20
Angular velocity (°/s)	800	150-1500
Velocity (mm/s)	210	40-390

Finally, from the neurophysiological point of view, the mechanical stimuli applied on the whisker are transduced into neural signals by mechanoreceptors in whisker follicles [4]. Among all types of mechanoreceptors, even the rapidest Pacinian corpuscle can only respond to vibration up to a few hundred Hz. Using the data from [18], it can be calculated that the texture induced vibration has a frequency higher than 2 kHz. It is doubtful whether rat can perceive such a high frequency vibration and use it to discriminate textures. This again questions the suitability of the “kinetic signature hypothesis”.

4.6.2 Suggestion on neuroscience investigation

Above experiment and analysis suggests that the “kinetic signature hypothesis” may be oversimplified since the texture is not directly coupled into the electrical signal of WT. It also cannot explain the invariant discrimination performance of rat when the whisking parameters change significantly. According to our vibrissal tactile sensing experiment results in Section 4.5, the amplitudes of force and velocity have clear relationships with roughness. And their

ratio is the mechanical impedance whose real part is also sensitive to roughness. Although the force and velocity can vary significantly, the mechanical impedance is relatively invariant and texture-specific. Therefore it is a better indicator of the texture than the velocity alone. It is known that the mechanoreceptors in whisker follicle encode information about both displacement and torque [4]. And there is evidence that rat can perform higher level processing to extract the deflection amplitude and velocity of the whisker [14]. Therefore a new hypothesis can be proposed here on rat's vibrissal tactile perception — rat utilizes both the force and velocity information sensed by mechanoreceptors in the whisker follicle and calculates the mechanical impedance through higher level processing and uses it as an invariant indicator for texture discrimination.

4.7 Summary

A prototype of the proposed whisker transducer (WT) has been fabricated in this chapter. Its electrical impedance is first checked with a commercial Impedance Analyzer and the result agrees well with that of numerical simulation. Since the Impedance Analyzer has some limitations such as the inability to measure separate signals of voltage and current as well as the limited output voltage level, a more flexible dynamic signal measurement system has been built up based on the auto-balancing bridge impedance measurement method. Digital signal processing algorithms are implemented on this measurement system to generate analytic signals of voltage and current required by the transduction matrix method.

The transduction matrix of the WT has been calibrated experimentally using the least-squares method. A subsequent validation experiment shows that the measurement error of mechanical impedance using the calibrated WT is less than 1.28%. In order to further verify the WT's velocity sensing ability, the velocity at whisker tip is non-intrusively measured by a high speed camera and compared with WT-measured velocity. It is found that the measurement error of velocity is as small as 0.88%. Although the force measurement is not directly validated due to the difficulty caused by the small scale of the whisker tip, its

measurement error is estimated to be 1.55% using error propagation. And the WT-measured force under free load is also checked which is close to its theoretical value (0 N).

A vibrissal tactile sensing experiment has been carried out using the calibrated WT. The force, velocity and mechanical impedance at whisker tip are simultaneously sensed when the WT sweeps across the surface of sandpaper specimens. Regression analysis results show that the force, velocity and real part of mechanical impedance are all sensitive to the roughness change. Therefore they can be used as indicators for texture discrimination.

Finally, the WT has been used to study the mechanism of rat's vibrissal tactile perception from a biomimetic point of view. It has been found that texture is not directly coupled into the electrical whisking signal as a high frequency component. This finding indicates that the current "kinetic signature hypothesis" proposed by some neuroscientists may be oversimplified. According to our experimental results, it is suggested that mechanical impedance is a better indicator of texture than velocity alone since it is more invariant to the variations of whisking parameters.

Chapter 5

VIBRISSAL TACTILE LOCATION DETECTION WITH WHISKER TRANSDUCER

The tactile sensing experiment in last chapter has illustrated that texture information can be extracted from electrical signals of WT. In this chapter, it will be shown that the electrical signals of WT also contain rich information about the location of a contacting object. A three-dimensional (3D) object locating scheme using WT will be developed by imitating the mechanism of the biological vibrissa system. In addition, it will be demonstrated through the use of a miniaturized WT that the WT-based object locating would become a potential solution to the challenging problem of geometry detection of high-aspect-ratio micro holes.

5.1 Miniaturization of the WT

Vibrissal tactile location detection will be studied using a miniaturized WT. The reason to miniaturize the WT is that it will be used to illustrate the geometry detection of high-aspect-ratio micro holes later in this chapter. This miniaturized WT is fabricated by adding a micromachined steel whisker ($50 \times 50 \times 5000 \text{ }\mu\text{m}$) to the end of a thin PZT bimorph ($0.5 \times 0.5 \times 32 \text{ mm}$), as shown in Figure 5.1.

Figure 5.1 The miniaturized WT.

(a) WT. (b) Micromachined whisker.

5.1.1 Fabrication of the micro whisker using μ EDM

Due to its micro size and high aspect ratio, the micro whisker cannot be fabricated by conventional machining processes such as turning, milling and grinding. Among all microfabrication technologies, photolithography on silicon substrate is one of the most popular processes to fabricate micro structures. However, it has some major limitations such as the quasi-three-dimensional structure, low aspect ratio and limited type of working material [112], making it not suitable for fabricating the micro whisker. Another popular microfabrication technology LIGA (Lithography, Electroplating, and Molding) can produce high-aspect-ratio and three-dimensional micro structures. However, it requires special facilities such as the synchrotron radiation source, and its procedure is relatively complex and time-consuming. μ EDM (Micro-Electrical Discharge Machining) is a micromachining technology for efficient fabrication of micro structures. It is an electro-thermal material removal process making use of a series of discrete electrical sparks generated between a micro-wire electrode and the workpiece immersed in a dielectric fluid to melt and evaporate material from the workpiece's surface [113]. Due to its high temperature (8000 – 12000 °C) and non-contact features, μ EDM is able to machine almost any conductive material regardless of its hardness. In addition, the non-contact feature also results in very small process forces

and good repeatability which have made μ EDM the best method for creating high-aspect-ratio micro-features [114].

The μ EDM technology has been chosen to fabricate the micro whisker. The process is carried out on a MG-ED72W μ EDM machine (see Figure 5.2). A 50 μ m thick steel sheet is used as the workpiece. A 300 μ m tungsten wire is used as the micro electrode whose diameter can be further reduced down to 5 μ m using the wire electrical discharge grinding (WEDG) process. The whisker is fabricated by engraving the surface of the thin steel sheet following a designed path. The use of the 300 μ m electrode rather than a thinner one can facilitate the forming of the T-shaped tip as shown in Figure 5.3. Finally, the whole whisker is fabricated and shown in Figure 5.4. It has the size of 50 $\times$ 50 $\times$ 5000 μ m and aspect ratio of 100:1.

Figure 5.2 MG-ED72W μ EDM instrument

Figure 5.3 Creating the T-shaped tip of the micro whisker using a 300 μm electrode

Figure 5.4 Micro whisker fabricated using μEDM

5.1.2 Calibration of transduction matrix

The electrical impedance of the miniaturized WT under free load is first checked in the frequency range of 1-1000 Hz, using the Solartron Impedance Analyzer. The result plotted in

Figure 5.5 shows that its resonant frequency is at around 400 Hz.

Figure 5.5 Electrical impedance of the miniaturized WT

As indicated by the simulation result in Section 3.6.3, it is better for the WT to work at a frequency near its resonance since sensitivity is higher in that region. In addition, the magnitude of the electrical impedance reduces to a very low value at the resonant frequency. This will increase the level of sensed electrical signals so that higher signal-to-noise ratio can be obtained. Therefore the operation frequency is decided to be 420 Hz. The WT is calibrated at this frequency based on the least-squares method using a configuration similar to the one shown in Figure 4.9, except that a cantilevered precision tungsten wire (5.2 mm long, 50 μm diameter, Alfa Aesar) is used as the mechanical load. A set of 9 mechanical loads ($d = 5200 - i \times 324 \mu\text{m}$, $i = 0, 1, \dots, 8$, see Figure 4.9) together with the free load are used for calibration. The electrical impedance Z_e under each load is measured and the theoretical mechanical impedance Z_m is calculated. Then equations (3.45) to (3.47) are used to obtain the transduction matrix. The performance of the calibrated transduction matrix is checked on the calibration loads and shown in Figure 5.6.

Figure 5.6 Performance of the calibrated transduction matrix tested on the calibration loads

The measurement was repeated five times. The repeated Z_m data were plotted in Figure 5.7 and Figure 5.8 together with the measurement uncertainty estimated at 95% confidence level. It can be found that the measurement error between WT-measured Z_m and theoretical Z_m is very small and the measurement uncertainty is low, therefore the transduction matrix is accurately calibrated.

Figure 5.7 Repeated measurement data of imaginary part of mechanical impedance under different calibration loads. “n” is load number.

Figure 5.8 Repeated measurement data of real part of mechanical impedance under different calibration loads. “n” is load number.

In order to further evaluate the performance of the calibrated WT, a silicone MEMS cantilever (Veeco Instruments Inc.) was used as test specimen. It has dimension of $400 \times 29 \times 2 \mu\text{m}$, resonant frequency of 18 kHz and nominal stiffness of 0.157 N/m. Its mechanical impedance was measured by the WT using the configuration in Figure 5.9 at the excitation frequency of 420 Hz. The imaginary part of mechanical impedance is related to both the mass m and stiffness k of the cantilever as follows:

$$\text{Im}(Z_m) = \omega m - \frac{k}{\omega} \quad (5.1)$$

Since the operation frequency is much lower than the resonant frequency of the cantilever, the contribution of the mass part is negligible. So the stiffness can be calculated from the imaginary part of mechanical impedance with following equation:

$$k \approx -\omega \text{Im}(Z_m) \quad (5.2)$$

Figure 5.9 Measuring stiffness of a MEMS cantilever using WT.

The stiffness was measured with the WT and listed in Table 5.1. The measurement was repeated five times and measurement uncertainty was calculated at 95% confidence level to evaluate its reliability and repeatability. The WT-measured stiffness is 0.153 ± 0.019 N/m. It agrees with the nominal value but the measurement uncertainty is a little bit large which is 12.1% of the nominal value. This may be due to the mechanical impedance Z_m of this cantilever is too small compared with those of calibration loads in Figure 5.6. Therefore it is close to the lower limit of the WT's measurement range.

Table 5.1 WT-measured stiffness of the MEMS cantilever.

No.	Stiffness (N/m)
1	0.166
2	0.161
3	0.152
4	0.143
5	0.146

Above validation and evaluation experiments confirm that the WT has been properly calibrated. It has high accuracy as well as high repeatability, although its performance may degrade when the load is out of its measurement range.

5.2 Horizontal location detection with WT

The biological temporal-coding scheme introduced in Chapter 2 can be adopted by the WT to achieve horizontal locating. The implementation of this scheme requires two distinctive signals — “whisking signal” and “touch signal”. In the biological system, they are generated by “whisking cells” and “touch cells” respectively. In an artificial whisker system, this can be implemented by using two different sensors, one detecting the whisker position and the other detecting the contact event. However, this will make the system very complicated and cause wiring problem. In our solution, both “whisking signal” and “touch signal” are generated by the actuator itself. This is implemented by exciting the WT with a special input signal. The temporal signals of voltage and current are measured from which the “whisking signal” and “touch signal” are obtained using digital signal processing.

5.2.1 Whisking signal

Due to the inverse piezoelectric effect, the application of an electrical voltage to the WT will generate a responding displacement of the whisker tip. If the WT is working at a frequency much lower than its resonant frequency, the relationship between the generated displacement and applied voltage is linear. The transfer function $H_{UE}(f)$ between the generated displacement U and applied voltage E is simulated with a FE model of the miniaturized WT and plotted in Figure 5.10. It can be observed that the value of $H_{UE}(f)$ is almost constant when frequency is below 100 Hz. This means that the whisker tip movement can be easily reconstructed from the voltage signal by multiplying a constant factor $K = H_{UE}(0)$. Therefore this low frequency voltage signal plays the role of the “whisking signal” encoding the whisker position over time.

Figure 5.10 Simulation result of the transfer function $H_{UE}(f)$ between generated displacement and applied voltage of the miniaturized WT

An experiment has been carried out to determine $H_{UE}(0)$. The static displacement of the whisker tip is measured optically using an OMIS II Vision Measurement System (RAM Optical Instruments, Inc.). The value of $H_{UE}(0)$ is obtained by dividing the static displacement by the applied voltage and the result is $1.20 \mu\text{m/V}$.

5.2.2 Touch signal

The “touch signal” in rat’s vibrissal system encodes the onset time of the mechanical contact with an object. As illustrated by the numerical simulation in Figure 3.29, the contact with an object will cause a significant change to the mechanical impedance at the whisker tip. If the mechanical impedance at whisker tip is continuously sensed by the WT during whisking and recorded as a temporal signal $Z_m(t)$, the contact event will be represented as a rising edge in the magnitude of $Z_m(t)$ waveform while the detachment event will be represented as a falling edge. Then the onset time of contact can be extracted from this rising edge and used to

determine the horizontal location of the object based on the following decoding scheme.

5.2.3 Decoding the horizontal location

An object locating scheme (see Figure 5.11) has been proposed using above “whisking signal” and “touch signal”. An electrical voltage signal $e(t)$ consisting of two sinusoidal components in the following form is used as the excitation to the WT:

$$\begin{aligned} e(t) &= e_L(t) + e_H(t) \\ &= A_L \cos(\omega_L t + \phi_L) + A_H \cos(\omega_H t + \phi_H) \end{aligned} \quad (5.3)$$

where $e_L(t)$ is the low frequency component serving as the “whisking signal”, while $e_H(t)$ is the high frequency component involved in the generation of the “touch signal”. The WT starts whisking under the excitation of this signal. The amplitude of the high frequency component is set to be much smaller than that of the low frequency signal, so whisker movement is dominated by the low frequency component. Both waveforms of electrical voltage $e(t)$ and current $i(t)$ are measured at the electrical port of the WT. Since the two components are playing different roles, they are separated using filters. The low frequency component of voltage signal is used to reconstruct the temporal signal of whisker movement using the following equation:

$$u(t) = e_L(t) \cdot H_{UE}(0) \quad (5.4)$$

And the high frequency components of both voltage and current signals are transformed into analytic signals using Hilbert transform (HT):

$$\begin{aligned} E_H(t) &= e_H(t) + j \cdot \text{HT}[e_H(t)] \\ I_H(t) &= i_H(t) + j \cdot \text{HT}[i_H(t)] \end{aligned} \quad (5.5)$$

where $E_H(t)$ is the analytic signal of voltage and $I_H(t)$ is the analytic signal of current. Both of them are temporal signals in complex number representation. They are used to calculate the

temporal signal of mechanical impedance $Z_m(t)$ which serves as the “touch signal”, using following equation based on the transduction matrix method:

$$Z_m(t) = \frac{t_{22}E_H(t) - t_{12}I_H(t)}{-t_{21}E_H(t) + t_{11}I_H(t)} \quad (5.6)$$

The transduction matrix elements t_{11} , t_{12} , t_{21} and t_{22} in Equation (5.6) are four complex constants calibrated at the frequency ω_H of the high frequency component. Now the onset time t_c of mechanical contact can be extracted from the rising edge in the waveform of $Z_m(t)$. And the horizontal position $u(t_c)$ of whisker tip at the moment of contact can be obtained from Equation (5.4), which is also the horizontal location of the object.

Figure 5.11 Proposed scheme for extracting object horizontal location from measured temporal signals of electrical voltage and current at the electrical port of the WT

A test experiment has been carried out to detect the horizontal location of an aluminum object using the WT, as illustrated in Figure 5.12. This is similar to the case that rats detect the location of the tunnel wall for navigation when moving underground. The distance from whisker tip to the object surface is controlled by a linear stage. The excitation signal is chosen to be the combination of a 1 Hz 9.5 V low frequency sinusoidal signal $e_L(t)$ and a 420 Hz 20 mV high frequency sinusoidal signal $e_H(t)$. The WT starts whisking upon the application of this excitation signal and the whisker tip contacts with the object intermittently.

Figure 5.12 Schematic diagram of the horizontal locating experiment.

The red arrow shows the direction of vibration.

Both waveforms of the voltage and current signals are sampled and plotted in Figure 5.13 and Figure 5.14, respectively. Figure 5.13 represents 2 cycles of whisking and each cycle is divided into 2 phases — protraction and retraction. Protraction means that the whisker is moving towards the object while retraction means that the whisker is moving away from the object. Since the high frequency component $e_H(t)$ has negligible amplitude compared with that of the low frequency component, it is not discernible in the voltage waveform. However, both components can be clearly observed in the current waveform. This is because the electrical impedance of the WT at high frequency is much smaller than that at low frequency (see Figure 5.5). So even though $e_H(t)$ has much smaller amplitude, the amplitude of $i_H(t)$ is not much smaller than that of $i_L(t)$.

Figure 5.13 Waveform of the voltage signal $e(t)$ Figure 5.14 Waveform of the current signal $i(t)$

The low frequency component and high frequency component are separated by processing the original temporal signal using digital FIR (finite impulse response) filters. All filters are designed with the same length so that they can have the same delay time to maintain synchronization. The separated low frequency component $e_L(t)$ of voltage, high frequency component $e_H(t)$ of voltage, and high frequency component $i_H(t)$ of current are shown in Figure 5.15, Figure 5.16 and Figure 5.17, respectively. They will be used for different purposes in subsequent steps.

Figure 5.15 Low frequency component $e_L(t)$ of voltage separated from the original signal $e(t)$ using a FIR filter

Figure 5.16 High frequency component $e_H(t)$ of voltage separated from the original signal $e(t)$ using a FIR filter

Figure 5.17 High frequency component $i_H(t)$ of current separated from the original signal $i(t)$ using a FIR filter

The low frequency component $e_L(t)$ is the “whisking signal” from which whisker movement can be reconstructed using Equation (5.4). The reconstructed waveform of whisker

movement $u(t)$ is shown in Figure 5.18.

Figure 5.18 Temporal signal of whisker movement reconstructed from the “whisking signal” $e_L(t)$

The high frequency components $e_H(t)$ and $i_H(t)$ are converted into analytic signals $E_H(t)$ and $I_H(t)$ using Hilbert transform according to Equation (5.5). The results are plotted in Figure 5.19 and Figure 5.20. The magnitude of $E_H(t)$ is almost constantly 20 mV. In contrast, the magnitude of $I_H(t)$ changes dramatically with time.

Figure 5.19 Analytic signal $E_H(t)$ of the high frequency component $e_H(t)$ of voltage signal obtained using Hilbert transform

Figure 5.20 Analytic signal $I_H(t)$ of the high frequency component $i_H(t)$ of current signal obtained using Hilbert transform

The temporal signal of mechanical impedance $Z_m(t)$ at whisker tip is then calculated using $E_H(t)$ and $I_H(t)$ based on Equation (5.6) and plotted in Figure 5.21. This $Z_m(t)$ is the “touch signal” from which the onset time of contact can be extracted. In Figure 5.21, initially the whisker moves forward freely in the air therefore the mechanical impedance $Z_m(t)$ is close to 0. At the moment of 165 ms, it gets into contact with the object so the magnitude of mechanical impedance increases to a higher value of about 2×10^{-3} Ohm. The contact is maintained for 510 ms, within this period the mechanical impedance remains at the high value. At the moment of 675 ms, the whisker is detached from the object and a falling edge can be observed in the $Z_m(t)$ waveform. The starting time of the rising edge is thus extracted as the onset time of contact t_c .

Figure 5.21 Temporal signal of mechanical impedance $Z_m(t)$ used as the “touch signal”

Since the temporal signal of whisker movement $u(t)$ (see Figure 5.18) reconstructed

from the “whisking signal” $e_L(t)$ is in synchronization with the “touch signal” $Z_m(t)$, the horizontal position of the whisker tip at the moment of contact can be extracted from Figure 5.18 as $u(t_c)$, which is also the horizontal location of the object.

A set of 15 horizontal locations are used to check the performance of the WT. The measured horizontal locations are plotted against their corresponding actual values in Figure 5.22. The measurement was repeated three times to evaluate its repeatability. A linear regression analysis is carried out on the data and it is found that the linearity is reasonably good since R^2 is 0.9981. In addition, the measurement uncertainty is also estimated and the result is as small as 0.27 μm . So the repeatability of the measurement is good.

Figure 5.22 Experimental test of the performance of the WT in horizontal locating

5.3 Radial location detection with WT

In the biological system, the radial contact position is encoded as the firing intensity of neurons which increases when the contact is closer to the whisker base. In order to use our

WT for radial locating, it is necessary to find a variable that is sensitive to the change of radial position. The simulation result in Section 3.6.2 shows that the electrical impedance Z_e of WT is sensitive to the radial position d of the contact object. However, the relationship between Z_e and d is not linear. In this section, it is experimentally illustrated using the miniaturized WT. And two approaches are proposed for decoding the radial position from measured electrical impedance of the WT.

5.3.1 Electrical impedance response to the change of radial contact location

Figure 5.23 is the schematic of the experiment setup. An aluminum object with a very sharp edge (see Figure 5.24) is used to contact with the whisker at different radial locations (d μm from whisker tip). The WT is working at a frequency of 420 Hz and its electrical impedance is recorded when d changes from 0 to 3200 μm . The real part $\text{Re}(Z_e)$ and imaginary part $\text{Im}(Z_e)$ are plotted against d in Figure 5.25 and Figure 5.26, respectively. Similar to the simulation results, both of them are sensitive to d but not linear. As described in Section 3.6.2, this nonlinearity is caused by the nonlinear relationship between d and the mechanical impedance Z_m of WT, as well as the nonlinear relationship between Z_m and the electrical impedance Z_e of WT.

Figure 5.23 Schematic diagram of the radial locating experiment.

The red arrow shows the direction of vibration.

Figure 5.24 Examples of WT contacting with the object at different radial locations.

Figure 5.25 Real part of electrical impedance vs. radial position d

Figure 5.26 Imaginary part of electrical impedance vs. radial position d

5.3.2 Decoding the radial location by a polynomial model

The application of WT for radial locating requires the determination of d from measured Z_e . The most direct approach is to establish an accurate mathematical model of the nonlinear relationship between d and Z_e . However, this is difficult since the WT has a relatively more complicated structure than a simple beam. A more practical method to solve this problem is to use a high-order polynomial model to approximate the nonlinear relationship:

$$f(x) = c_0 + c_1x + c_2x^2 + \cdots + c_{n-1}x^{n-1} + c_nx^n \quad (5.7)$$

where c_i ($i = 0, 1, \dots, n$) are parameters of the model. Figure 5.27 is a 9th degree polynomial model of the relationship between d and $\text{Re}(Z_e)$ obtained using the data in Figure 5.25. Even through using such a high-order polynomial, the error is still quite large (RMSE = 167.3 μm). Figure 5.28 is the model of the relationship between d and $\text{Im}(Z_e)$. The performance of this model (RMSE = 25.9 μm) is much better than the model in Figure 5.27, however it still shows

large error when d is near 0. Either of these two models can be used for roughly calculating the radial position d from measured electrical impedance Z_e .

Figure 5.27 Polynomial model of the relationship between d and $\text{Re}(Z_e)$

Figure 5.28 Polynomial model of the relationship between d and $\text{Im}(Z_e)$

5.3.3 Decoding the radial location by an artificial neural network (ANN)

An alternative way to determine the radial location d from measured electrical impedance Z_e is to mimic the biological way used by rats. Rats establish the relationship between d and neural response signal by learning from many training cases. The relationship is not explicitly expressed by a mathematical function but is distributed in numerous neurons of its neural network. Due to its features like parallel processing and high nonlinearity, neural network is good at dealing with information that is fuzzy, nonlinear, noisy, etc. Its unique architecture also makes it highly efficient, flexible and robust. Artificial neural network (ANN) is a generalized and simplified model of the biological neural network. It has certain characteristics in common with the biological neural network therefore also possesses above advantages. One important application of ANN is nonlinear function approximation [115]. Consider a nonlinear function in the following form:

$$\mathbf{y} = \mathbf{f}(\mathbf{x}) \quad (5.8)$$

where $\mathbf{x}$ is the input vector, $\mathbf{y}$ is the output vector, and $\mathbf{f}(\cdot)$ is an unknown nonlinear function representing the system model. In our case, $\mathbf{x}$ is the radial distance d therefore is only 1-dimensional. And $\mathbf{y}$ is the resulting electrical impedance Z_e of WT which can be represented as a 2-dimensional vector $\{\text{Re}(Z_e), \text{Im}(Z_e)\}$. Instead of the function $\mathbf{f}(\cdot)$ in Equation (5.8), we are looking for its inverse function $\mathbf{f}^{-1}(\cdot)$ that produces the vector $\mathbf{x}$ in response to the vector $\mathbf{y}$. The inverse system is thus described by:

$$\mathbf{x} = \mathbf{f}^{-1}(\mathbf{y}) \quad (5.9)$$

Although we lack the knowledge about function $\mathbf{f}^{-1}(\cdot)$, given a sufficient number of examples of input-output pair:

$$\{\mathbf{x}_1, \mathbf{y}_1\}, \{\mathbf{x}_2, \mathbf{y}_2\}, \dots, \{\mathbf{x}_N, \mathbf{y}_N\} \quad (5.10)$$

it is possible to train an ANN to approximate the unknown function $\mathbf{f}^{-1}(\cdot)$ such that the actual input-output relationship $\mathbf{F}^{-1}(\cdot)$ realized by the ANN is close enough to $\mathbf{f}^{-1}(\cdot)$ in a Euclidean sense over all inputs, as shown by:

$$\|\mathbf{F}^{-1}(\mathbf{y}) - \mathbf{f}^{-1}(\mathbf{y})\| < \varepsilon \quad (5.11)$$

where ε is a small positive number. The learning scheme of ANN is shown in Figure 5.29. The system output $\mathbf{y}_i$ which is the electrical impedance in our case is used as the input to the ANN. While the system input $\mathbf{x}_i$ which is the radial location d in our case is used as the desired output of the ANN. The error vector $\mathbf{e}_i$ between $\mathbf{x}_i$ and the actual output $\mathbf{x}_i'$ of the ANN is used to adjust the network parameters so that the error can be minimized over the training set to meet the criterion described by Equation (5.11).

Figure 5.29 Block diagram of inverse system modeling using ANN

A multilayer feed-forward neural network has been designed to solve our problem of determining radial location d from measured electrical impedance Z_e . According to the universal approximation theorem [116], any continuous nonlinear function can be approximated arbitrarily well by a feed-forward neural network having only a single hidden layer of sufficient neurons. Complex networks with more hidden layers are more susceptible to overfitting which leads to poor generalization. So a three-layer neural network is employed whose architecture is shown in Figure 5.30. It contains an input layer of 2 neurons, a single hidden layer of 10 neurons and an output layer of 1 neuron. The input layer does not perform any computation and just distributes the input vector to the hidden layer. The hidden layer and

output layer contain computational neurons. Each neuron receives inputs from the layer to its left, calculates the weighted sum and generates an output value using an activation function. A nonlinear sigmoid function in the following form is used as the activation function.

$$\varphi(v) = \frac{1}{1 + e^{-v}} \quad (5.12)$$

The variable v in Equation (5.12) is the weighted sum of inputs:

$$v = \sum_{i=0}^m w_i x_i \quad (5.13)$$

where x_i is the input from the i th neuron in the previous layer, and w_i is the weight for the i th input.

Figure 5.30 Architecture of the 3-layer feed-forward ANN

The ANN is trained using the back-propagation (BP) algorithm [115]. This algorithm contains two passes of computation. In the forward pass, all neuron weights remain unchanged, and the input signals propagate forward through the network on a neuron-by-neuron and layer-by-layer basis, and emerge at the output layer as the output signal. In the backward pass, the error signal is computed at the output layer, propagates backward layer-by-layer, accompanied by the recursive calculation of the local gradient for each neuron

which enables the adjustment of neuron weights. The training process is iteratively performed by presenting epochs of training samples to the network until the stopping criterion is met.

The data in Figure 5.25 and Figure 5.26 are used as training samples. The input vector is $\{\text{Re}(Z_e), \text{Im}(Z_e)\}$, and the target output vector is the radial location d . The training samples are randomly divided into three sets: a training set (60% samples), a validation set (20% samples), and a test set (20% samples). The training set is for iteratively updating neuron weights. The validation set is for monitoring the generalization performance of the network to prevent overfitting. The test set is not used during training, but provides an independent test of the network's generalization to the data that it has never seen. The stopping criterion is set as $MSE = 1 \times 10^{-5}$, which is the mean square error between the network output and the target. After 9 epochs of training, the stopping criterion is met and the training history of the network is plotted in Figure 5.31. The result shows a good generalization of the network since the performances on both the validation set and test set are quite close to that on the training set. And no evidence of overfitting is observed.

Figure 5.31 Training history of the ANN

In order to further check the performance of the network, the entire data set is presented to the trained network and a linear regression analysis is carried out between the network output and the corresponding target (d). The result is shown in Figure 5.32. A strong linear relationship is found between the output and the target, with the correlation coefficient being 0.99999. This means that the network performance is good in terms of both accuracy and generalization on the entire data set.

Figure 5.32 Linear regression analysis of ANN output values and target values

Finally, the error between the network output and the corresponding target value is calculated. The maximum error is $11.9 \mu\text{m}$ which is 0.0037% of the measurement range. And the root mean square error (RMSE) is only $5.4 \mu\text{m}$ which is 0.0017% of the measurement range. This performance is much better than that of the polynomial models in Section 5.3.2.

The overall response of the ANN within the range of the input vector is plotted in Figure 5.33. With this accurately trained ANN, the radial contact location of an object can be extracted easily by inputting the measured electrical impedance to the ANN and obtaining the

output from it.

Figure 5.33 Overall response of the ANN within the range of the input vector

In order to evaluate the repeatability and reliability of the WT and the trained ANN, the electrical impedance of the WT was repeatedly measured five times. The data plotted in Figure 5.34 and Figure 5.35 show that the WT has high repeatability and small measurement uncertainty over the whole range of radial position d . The repeated Z_e data were then input to the ANN to decode the radial position. Consistent performance of the ANN was observed from the result plotted in Figure 5.36.

Figure 5.34 Repeated data of real part of electrical impedance vs. radial position d (left) and estimated measurement uncertainty at 95% confidence level (right).

Figure 5.35 Repeated data of imaginary part of electrical impedance vs. radial position d (left) and estimated measurement uncertainty at 95% confidence level (right).

Figure 5.36 Performance of the trained ANN on repeated measurement data.

5.4 Vertical location detection with WT

Each whisker of rat is only allowed to move within a certain horizontal plane [26]. Similarly, a single WT can only move in the x - y plane shown in Figure 5.37. Some neuronal evidences show that rats may use a spatial (or identity) coding scheme in order to detect the vertical location of a contacting object [4]. The whiskers of a rat are distributed in the form of an array (see Figure 2.6). Whiskers in different rows have different elevations. Since each whisker is one-to-one mapped to a barrel in the cerebral cortex, the contact with the object by a certain whisker will cause its corresponding barrel to be activated. Then the vertical location of the object can be easily extracted from the identity of the activated barrel which contains the spatial information of the whisker. This spatial coding scheme can be adopted by our WT to achieve vertical locating. As proposed in Figure 5.37, an array of WT can be constructed by placing several WTs at different vertical locations in the z -axis. These WTs work independently and their mechanical impedances are monitored. If a certain WT gets into contact with an object, its mechanical impedance will be changed which can be used to represent its contact state (contact or non-contact). Then the vertical location of a contacting object can be encoded as a vector composed of the states of all WTs, as shown in Table 5.2.

Figure 5.37 Vertical locating using an array of WT

Table 5.2 Spatial (or identity) coding scheme of vertical location

Vertical location	WT states (1: contact, 0: non-contact)		
	WT a	WT b	WT c
1	1	0	0
2	0	1	0
3	0	0	1

5.5 Geometry detection of high-aspect-ratio micro holes

As mentioned in Chapter 2, geometry detection of high-aspect-ratio micro holes is currently an important and also challenging issue in many industries. For example, taper is one of the most important geometrical parameters that need to be measured when inspecting the quality of laser drilled small holes (0.1-0.8 mm diameter) [117]. Traditional technologies such as CMM, AFM, SEM and optical methods are suffering from many drawbacks caused by the high aspect ratio. Therefore the development of new technologies suitable for non-destructive detection of high-aspect-ratio micro holes is in great demand. Our WT provides a possible solution to this problem. Since the whisker has a micro-scale cross section ($50 \times 50 \mu\text{m}$) and a high aspect ratio (100:1), it can enter a high-aspect-ratio micro hole to perform vibrissal tactile sensing. In the following experiment, the WT will be employed to detect geometrical features of high-aspect-ratio micro trenches based on the vibrissal tactile object locating ability described in previous sections.

5.5.1 Fabrication of specimens

The high-aspect-ratio micro trenches to be inspected by the WT are shown in Figure 5.38a. These specimens are fabricated in a 3 mm thick aluminum plate by μEDM process. The first specimen is a $300 \times 5000 \mu\text{m}$ zero-taper trench made by surface engraving using a tungsten wire electrode of $300 \mu\text{m}$ diameter (see Figure 5.39). The other two specimens have positive taper created by two steps as illustrated in Figure 5.39b. First, a zero-taper slot is

made using the 300 μm wire. Second, the specimen is rotated by a small angle θ and another slot is made. Since the rotation angle is small, the two slots merge into one which has a taper angle of θ . The reason to use surface engraving rather than drilling to create specimens is that in this way one side of the specimen is open therefore it is possible to monitor the detection process from that side. In real cases such as the detection of a laser drilled hole, all sides of the hole are closed and only the entrance of the hole is visible, as illustrated in Figure 5.38b.

Figure 5.38 High-aspect-ratio micro trenches.

(a) Side view. (b) View from entrance when the open side is closed.

Figure 5.39 Fabrication of high-aspect-ratio micro trenches using μEDM .

(a) Surface engraving by μEDM . (b) Paths of electrode movement for making specimens.

5.5.2 Experiment setup

The experiment setup is shown in Figure 5.40. The 3 mm aluminum plate containing micro trenches is placed in the x - y plane. It is fixed on a PI linear stage (not shown) that can move in the x -axis. The WT with an acrylic handle is fixed on another linear stage system for y - z axis positioning. The two wires of the WT are connected to the NI DSA system (see Figure 4.4) for both actuation and sensing. A digital microscope (iCamscope, Sometech Inc.) with a wide range of magnification is placed in the z -axis above the specimen for monitoring the detection process. Figure 5.41 shows example images obtained by the microscope during the detection.

Figure 5.40 Experiment setup for tactile geometry detection of high-aspect-ratio micro trenches.

(a) WT. (b) Specimen. (c) Linear stage. (d) Digital microscope.

Figure 5.41 Microscope view of the geometry detection process.

(a) 50X magnification. (b) 500X magnification.

5.5.3 Geometry detection

Before starting the geometry detection, the WT is positioned by the linear stage system so that the whisker tip is located at the entrance of the trench (location A in Figure 5.41a). Then the other linear stage controls the specimen to move in the x -direction until the whisker tip reaches location B (see Figure 5.41a) which is near the bottom of the trench. After fixing the stages at the position, the detection starts based on the horizontal locating scheme proposed in Section 5.2. The excitation signal is the combination of a 0.5 Hz 100-200 V low frequency sinusoidal signal $e_L(t)$ and a 420 Hz 200 mV high frequency sinusoidal signal $e_H(t)$. The WT starts vibrating upon the application of this excitation signal. The vibration amplitude is set to be larger than the width of the trench, so the whisker tip contacts with the sidewalls intermittently during detection. Both the electrical voltage and current waveforms are recorded from which the horizontal locations of the two sidewalls are extracted following the

algorithm in Figure 5.11. Then the WT stops detection and the linear stage controls the specimen to move in the $+x$ direction for a distance of 687 μm . This is equivalent to moving the WT in the $-x$ direction towards the entrance in Figure 5.41a. The detection procedure is then repeated until the whisker tip exits the trench. A total of 7 detections are performed at 7 locations along the length of the trench.

The detected geometries of the 3 specimens are plotted in Figure 5.42 to Figure 5.44 and compared with their microscope images. They are in close agreement with each other. The reconstructed geometry also allows us to estimate the taper of each specimen, which is the most important parameter of laser drilled holes. The taper of each specimen is obtained by fitting two linear curves for the two sidewalls and calculating the angle between them. It is also measured optically using the OMIS II Vision Measurement System. The comparison in Table 5.3 shows that the taper values measured by these two methods coincide with each other and the difference between them is less than 0.1° . This difference may be caused by the measurement errors in both methods. However, it is believed that our WT-based tactile method would provide more reliable result than the optical method. This is because the optical method is easily affected by a lot of factors like illumination, magnification, image quality, etc. Also the optical method is limited to measure the geometry of the trench only at its surface while our tactile method is measuring at a z -location below the surface. This may be another cause of the difference between their results. More importantly, in the real case of geometry detection of micro and even blind holes, it is impossible to use the optical method since all sidewalls of the hole are closed as illustrated in Figure 5.38b. Then the advantage of our WT-based tactile method becomes more obvious.

Figure 5.42 Detected geometry of specimen 1.

(a) Detected geometry. (b) Microscope photo of the specimen.

Figure 5.43 Detected geometry of specimen 2.

(a) Detected geometry. (b) Microscope photo of the specimen.

Figure 5.44 Detected geometry of specimen 3.

(a) Detected geometry. (b) Microscope photo of the specimen.

Table 5.3 Comparison of taper values measured by WT and optical method

No. of specimen	WT-measured (°)	Optical (°)	Error (°)
1	0.12	0.11	0.01
2	1.59	1.66	-0.07
3	2.74	2.78	-0.04

5.5.4 Invalid contact detection

A potential problem in geometry detection of high-aspect-ratio micro holes that has been seldom studied in the literature is the detection of invalid contact. Our detection scheme assumes that the contact only occurs at the whisker tip. This assumption holds when the sidewall is relatively smooth and straight. However, in a real case the sidewall may not be very smooth or straight. Figure 5.45 shows a typical hole made by laser percussion drilling [71]. It can be found that there are a lot of protrusions on the sidewall. These protrusions may

be created by the non-uniform distribution of laser power on the sidewall. They can also be produced by the spatter of melted material. Due to the T-shaped tip of our WT, small protrusions will not affect the measurement. However, large protrusions will cause the whisker shaft rather than the whisker tip to be in contact with the sidewall, therefore result in invalid measurements. The detection of this kind of invalid contact should be a basic requirement when designing sensors for geometry detection of high-aspect-ratio holes.

Figure 5.45 Typical hole made by laser percussion drilling [71].

(a) Cross section of the hole. (b) Close-up view of the entrance wall.

Due to its radial locating ability, our WT is able not only to detect the presence of the invalid contact but also to locate it. In order to illustrate this, a high-aspect-ratio micro trench with a large protrusion on its sidewall is fabricated using μ EDM process, as shown in Figure 5.46. The distance from whisker tip to the location of the protrusion is labeled as d . Three test cases are carried out when d is set to 0.5 mm, 1.5 mm and 2.5 mm, respectively. The electrical impedance of the WT in each case is measured and input to the ANN trained in Section 5.3.3. The network output is compared with the actual value of d in Table 5.4. The small error between them shows that the proposed method for detecting and locating invalid contact is valid and accurate.

Figure 5.46 Example of invalid contact caused by a protrusion on the sidewall

Table 5.4 Comparison of WT-detected protrusion location and its actual value

WT-detected location (mm)	Actual location (mm)	Error
0.509	0.500	1.8%
1.505	1.500	0.33%
2.497	2.500	0.12%

To evaluate its repeatability, the protrusion location detection was repeated five times and consistent results were obtained which are listed in Table 5.5. The measurement uncertainty values estimated at 95% confidence level for the three locations are ± 0.002 (mm), ± 0.006 (mm) and ± 0.006 (mm), respectively.

Table 5.5 Repeated measurement of protrusion location detection.

No.	Location 1 (mm)	Location 2 (mm)	Location 3 (mm)
1	0.511	1.507	2.494
2	0.511	1.505	2.499
3	0.510	1.500	2.501
4	0.511	1.500	2.498
5	0.508	1.501	2.502

Another important issue when detecting the geometry of a blind hole is axial loading. In a real application, due to the high aspect ratio of the hole, it is difficult to use visual assistance during the detection process. If the depth of the blind hole is not known in advance, any movement inside the hole may cause axial loading to the whisker tip which will further lead to buckling or even failure of the whisker. Our WT provides a possible solution to the detection of axial loading before buckling occurs. When the WT is moving inside the hole in the x -direction (see Figure 5.41a), the mechanical impedance at its tip is continuously monitored using its transduction matrix. The initial contact between the whisker tip and the bottom of the hole will cause an increase of the mechanical impedance due to friction. Due to the high sensitivity of the WT, it is able to detect a very small change of mechanical impedance before the axial loading reaches the critical value for buckling. The x -position at the moment of this initial contact can then be used to calculate the depth of the blind hole.

5.6 Summary

In this chapter, the object location detection ability of WT has been investigated based on the inspiration from rat's vibrissal tactile object locating. A spatial-temporal-intensity triple-coding scheme has been developed for detecting the location of a contacting object in the 3D space. The horizontal location is detected from the temporal signal of whisker movement and the temporal signal of mechanical impedance sensed at the whisker tip using transduction matrix method. The radial location is detected from the electrical impedance of the WT using a multilayer feed-forward neural network as the inverse model. And the vertical location can be detected simply from the identity (spatial location) of the activated WT in a WT-array. This triple-coding scheme allows for efficient multiplexing of 3D object location information. In addition, the simultaneous sensing and actuating feature of the WT reduces the complexity of its implementation in practical applications.

The vibrissal tactile object locating ability as well as the high aspect ratio of the

whisker makes the WT a potential solution to the challenging problem of geometry detection of high-aspect-ratio micro holes. In order to demonstrate this experimentally, the WT is miniaturized using μ EDM process and then used to detect the geometries of three high-aspect-ratio micro trenches. The result shows that it can accurately detect the taper of each specimen which is the most important geometrical parameter of laser drilled holes. And the abilities of the WT in detecting invalid contact and detecting depth of blind hole have also been studied.

Chapter 6

SENSING FLUID VISCOSITY WITH WHISKER TRANSDUCER

Vibrissal tactile sensing is also a surviving tool of many marine mammals, such as sea lion and harbor seal. In order to survive, they need to hunt in the ocean's murky water where vision becomes of little use. Although some species of dolphins and whales have evolved the ability of echolocation with their ears, others without this biosonar system rely on their whiskers for hunting [118]. In this chapter, the ability of WT to perform vibrissal tactile sensing in fluids will be demonstrated. Instead of object locating, it will be used to solve a more challenging problem — fluid viscosity sensing. Traditionally, the measurement of viscosity requires actuation as well as sensing of force and velocity. This can be greatly simplified by our WT due to its simultaneous sensing and actuating feature. A transduction matrix model will be established for extracting not only the dynamic viscosity but also the density of the fluid accurately from measured electrical signals of the WT. Other issues such as non-Newtonian fluid characterization and sensor miniaturization will also be studied. The result of this chapter would contribute to a wide range of areas such as petroleum industry, microfluidics and biomedicine.

6.1 Online sensing of fluid viscosity

Fluid viscosity is one of the most important parameters that need to be monitored or controlled in numerous industries and areas. In the petroleum related industries, viscosity is a critical parameter during both production and use of petroleum products [92]. In medicine, blood viscosity is directly related to some circulatory system diseases [119]. Using a miniaturized viscosity sensor in diagnosis can reduce the required blood sample volume and

lessen the pain of patients. In food industry, viscosity data are needed when determining ingredient functionality, controlling final product quality, testing shelf life as well as evaluating food texture [120].

Standard laboratory viscometers, although accurate, are usually not suitable for online viscosity sensing due to the large size, non-continuous measurement, long measurement time, large sample volume, difficult maintenance and high cost. Because of the complex nature of viscosity as well as the limitations in sensing technology, existing viscosity sensors cannot provide satisfactory results which are comparable to standard viscometer measurements. Therefore the increasing demand in aforementioned industries is continuously driving the development of new viscosity sensors.

6.2 Sensing fluid properties with WT

As mentioned in Chapter 2, vibrational viscosity sensing is currently facing several major drawbacks and inherent limitations preventing them from obtaining accurate and separate value of dynamic viscosity that is comparable to the results of standard laboratory viscometers. The thickness-shear mode (TSM) resonator viscosity sensor has a very high working frequency (MHz) and a very small penetration depth (submicrometer) causing large deviations from results of standard viscometers. Micromachined silicon cantilevers can reduce the working frequency by vibrating in the flexural mode. However, they require external actuators for excitation and external sensors for sensing the response. And their working frequency is still very high (hundred kHz). Piezoelectric cantilever sensors can further reduce the working frequency into the hundred Hz range, but their relative complex structure and electromechanical coupling make it almost impossible to derive a precise analytical model for relating the electrical response to fluid properties.

In this section, a novel viscosity sensing technique using the WT and transduction matrix method will be proposed aiming to solve above problems. As shown in Figure 6.1, the WT is

placed in the y -direction with its whisker being perpendicular to the fluid surface. The upper end of the WT is clamped while the whisker is partially immersed in the fluid. A sphere is attached to the whisker tip for three important reasons — enhancing the interaction with the fluid, reducing the working frequency, and facilitating the interpretation of the fluid loading with an analytical model. In order to make the transduction matrix method work, an assumption is made that the fluid loading acting on the sphere is dominant while that on the whisker shaft is negligible. This requires either the diameter of whisker being much smaller than that of sphere, or the depth of immersion being small enough.

Figure 6.1 Principle of fluid property sensing using WT.

The red arrow shows the direction of vibration.

Unlike those techniques in literature estimating fluid viscosity by measuring shift of resonant frequency, our WT operates in a more direct manner (see Figure 6.1). When an AC voltage is applied to the WT, it will excite the sphere to oscillate in the x -direction due to the inverse piezoelectric effect. The interaction with the fluid will affect the mechanical response of the sphere which will be coupled into the electrical excitation signals due to the direct

piezoelectric effect. Since the transduction process between the electrical port and the mechanical port is completely characterized by the transduction matrix, the force, velocity and mechanical impedance of the fluid loading on the sphere can be directly calculated from measured electrical signals, from which fluid properties can be extracted.

This new technique is expected to solve the major drawbacks of existing viscosity sensors as mentioned above. It can also provide additional benefits like easy instrumentation due to its simultaneous sensing and actuating (SSA) feature, and the ability to measure fluid velocity for studying non-Newtonian fluids which is impossible for other techniques.

6.3 Fluid-sensor interaction

In order to gain some insights into the problem, the interaction between the fluid and the sensor will be discussed. First, the fluid-sphere interaction will be studied analytically. Then, the fluid-sphere-WT interaction will be estimated based on an approximate single degree-of-freedom (SDOF) model. Finally, a transduction matrix model of the fluid-sphere-WT interaction will be established which can be used as the basis for extracting fluid properties accurately from electrical signals of the WT.

6.3.1 Effect of fluid loading on sphere tip

When a sphere immersed in a viscous fluid executes translational oscillation as shown in Figure 6.2a, the surrounding fluid will exert a drag force on it which is analytically expressed by the following equation [121]:

$$f = 6\pi\eta R \left(1 + \frac{R}{\delta}\right) \frac{dx}{dt} + 3\pi R^2 \sqrt{(2\eta\rho/\omega)} \left(1 + \frac{2R}{9\delta}\right) \frac{d^2x}{dt^2} \quad (6.1)$$

where f is the drag force, $x = x_0 e^{j\omega t}$ is the displacement, R is the radius of the sphere, ρ is the

density of the fluid, η is the dynamic viscosity of the fluid, ω is the angular frequency of oscillation, and $\delta = (2\eta/\omega\rho)^{1/2}$ is the depth of penetration (over a distance δ , the wave amplitude decreases by a factor of e). This drag force is the combination of two forces — a dissipative force proportional to the velocity caused by the viscous damping and an inertial force proportional to the acceleration which is induced by a small portion of fluid mass trapped by the sphere during its oscillation. So the fluid loading acting on the sphere can be represented by a mass-damper model shown in Figure 6.2b, with following parameters:

$$\begin{aligned} c_f &= 6\pi\eta R \left(1 + \frac{R}{\delta}\right) = 6\pi R \eta + 3\sqrt{2}\pi R^2 \sqrt{\omega} \sqrt{\eta\rho} \\ m_f &= 3\pi R^2 \sqrt{(2\eta\rho/\omega)} \left(1 + \frac{2R}{9\delta}\right) = \frac{2\pi R^3}{3} \rho + \frac{3\sqrt{2}\pi R^2}{\sqrt{\omega}} \sqrt{\eta\rho} \end{aligned} \quad (6.2)$$

where c_f is the effective damping of the fluid load and m_f is the effective mass. Both of them are related to the dynamic viscosity and density of the fluid.

Figure 6.2 Effect of fluid on an oscillating sphere.

(a) A sphere executing translational oscillation in a viscous fluid. (b) A mass-damper model representing the fluid loading.

Take the example of a sphere with a radius of 1 mm immersed in water at a temperature of 25 °C. Water has dynamic viscosity of 8.9×10^{-4} Pa s and density of 1.0×10^3 kg/m³. The fluid induced damping and mass are then calculated using Equation (6.2):

$$\begin{aligned} c_f &= 1.68 \times 10^{-5} + 1.26 \times 10^{-5} \sqrt{\omega} \\ m_f &= 2.09 \times 10^{-6} + 1.26 \times 10^{-5} \frac{1}{\sqrt{\omega}} \end{aligned} \quad (6.3)$$

Both of them are functions of the oscillating frequency. Equation (6.3) appears that damping dominates in the high frequency range while mass dominates in the low frequency range. However, more careful analysis concludes differently. Since mass affects the motion in the form of $j\omega m_f$, when $\omega \rightarrow 0$, the damping term would approach a constant value of 1.68×10^{-5} while the effect of mass becomes negligible. While ω increases, both effects of mass and damping become significant but the $j\omega m_f$ changes more rapidly. And at a high frequency, damping is dominated by its second term while mass is dominated by its first term.

6.3.2 Effect of sphere tip and fluid loading on the WT

The direct derivation of the analytical motion equation for the WT with a sphere tip under fluid loading is difficult due to its relative complex structure as well as the electromechanical coupling. However, by assuming that the WT is a pure mechanical structure and the working frequency is not too high compared with its first resonant frequency, it can be approximated by a second order SDOF system with effective parameters. If the sphere tip can be considered as a point mass attached to the tip of the WT, the motion equation of the sensor becomes:

$$(m_w + m_s) \frac{d^2 x}{dt^2} + c_w \frac{dx}{dt} + k_w x = F_0 e^{j\omega t} \quad (6.4)$$

where $F_0 e^{j\omega t}$ is the forcing function defined by amplitude F_0 and angular frequency ω , x is the displacement response at the tip, m_w , c_w and k_w are the effective mass, effective damping and effective stiffness of the WT, respectively. And m_s is the mass of the sphere tip.

The attachment of the sphere tip to the WT will decrease its natural frequency as:

$$\omega_n = \sqrt{\frac{k_w}{m_w + m_s}} \quad (6.5)$$

And the damping ratio will also decrease:

$$\zeta = \frac{c_w}{2\sqrt{k_w(m_w + m_s)}} \quad (6.6)$$

which means that the maximum vibration amplitude will increase.

Now considering the effect of the fluid loading as a combination of induced mass and damping exerting on the sphere tip as described in Equation (6.2), the motion equation of the system becomes:

$$(m_w + m_s + m_f) \frac{d^2 x}{dt^2} + (c_w + c_f) \frac{dx}{dt} + k_w x = F_0 e^{j\omega t} \quad (6.7)$$

The natural frequency will be further reduced compared with that in the case without fluid loading:

$$\omega_n = \sqrt{\frac{k_w}{m_w + m_s + m_f}} \quad (6.8)$$

However, since the induced mass m_f itself is a function of frequency, Equation (6.8) is not a constant value. Similarly, the damping ratio becomes:

$$\zeta = \frac{c_w + c_f}{2\sqrt{k_w(m_w + m_s + m_f)}} \quad (6.9)$$

The damping ratio depends on both values of c_f and m_f which are functions of frequency. Assuming the fluid induced damping is much larger than the structure damping of the WT and the fluid induced mass is much smaller than the total mass of the WT and sphere, the damping ratio will increase after applying the fluid loading. Thus the maximum vibration amplitude will decrease.

Take the finite element model of WT in Chapter 3 as an example. Under open-circuit

boundary condition, its effective stiffness is 0.988 N/m, resonant frequency is 38.0 Hz, and effective mass is 1.73×10^{-5} kg. The damping ratio is 0.005, and the structure damping is 4.14×10^{-5} N s/m. The response of this WT under a 1 N harmonic force excitation is simulated and plotted in Figure 6.3 as the blue curve. Now if an aluminum sphere with a radius of 1 mm is attached to the tip of the WT whose mass is 1.13×10^{-5} kg, the natural frequency will decrease to 29.6 Hz according to Equation (6.5). And the damping ratio will decrease to 0.004 according to Equation (6.6). As a result, the maximum vibration amplitude will increase slightly. This is confirmed by the simulation result plotted in Figure 6.3 as the green curve. Finally, when the sphere tip is immersed in water of 25 °C, the fluid loading is calculated using Equation (6.3). However, since the induced mass itself is a function of frequency, Equation (6.8) cannot be used directly to calculate the changed natural frequency. So the response of the system is simulated across the frequency range of 1-50 Hz and plotted in Figure 6.3 as the red curve. The natural frequency is found to be 28.1 Hz from the simulation, which is reduced compared with that in the free load case. At this frequency, the fluid induced damping is 1.84×10^{-4} N s/m and the fluid induced mass is 3.04×10^{-6} kg. Then the damping ratio is calculated to be 0.020, which is significantly larger. So a significant decrease of the vibration amplitude is found in Figure 6.3.

Figure 6.3 Simulation of the response of the WT with an aluminum sphere tip (1 mm radius) immersed in water (25 °C) under a harmonic force excitation of 1 N.

6.3.3 Transduction matrix model of the fluid-sphere-WT interaction

The above approximate second-order SDOF model only considers the mechanical interactions of fluid, sphere and WT. It only qualitatively estimates the effect of fluid loading on the mechanical response of the sensor. It is hardly usable for accurately extracting fluid properties from the electrical response of the WT, since it does not include the electromechanical coupling. As mentioned earlier, the derivation of an analytical equation to relate the fluid loading and electrical response of the WT is difficult due to the complex structure of the WT as well as the presence of uncertainties in its geometry and material parameters. This has become the major obstacle hindering the development of vibrational viscosity sensors. Fortunately, it can be circumvented by our transduction matrix method.

According to transduction matrix method, the electromechanical transduction process of a transducer can be accurately modeled as a two-port system model with a 2×2 transduction matrix as shown in Equation (3.1). After the determination of the transduction matrix, the mechanical force, motion and impedance at the mechanical port can be faithfully reconstructed through measuring the input electrical voltage and current simultaneously at the electrical port. No additional sensors or actuators are required therefore it is a true simultaneous sensing and actuating technique especially suitable for online or *in situ* measurement.

As is a little different from the WT used in previous chapters, the sensor proposed in Figure 6.1 has introduced an additional sphere tip to enhance the interaction with the fluid and facilitate the interpretation of fluid properties. The whole system can be represented as a chain of two-port systems in series such that the output of one is the input of the next, as shown in Figure 6.4.

Figure 6.4 Cascaded two-port system representation of the fluid-sphere-WT system

The transduction matrix $[\mathbf{T}]_w$ of the WT can be derived theoretically using Equation (3.36). However, this is not necessary as it can be determined easily and accurately in practice using the calibration methods described in Section 3.4. With this matrix available, the following transduction equation can be obtained:

$$\begin{Bmatrix} E \\ I \end{Bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}_w \times \begin{Bmatrix} F_1 \\ V_1 \end{Bmatrix} = [\mathbf{T}]_w \times \begin{Bmatrix} F_1 \\ V_1 \end{Bmatrix} \quad (6.10)$$

where F_1 and V_1 are the force applied on the sphere by the WT and the resulting velocity, respectively. The sphere tip connects the output port of the WT and the input port of the fluid load with its own transduction matrix $[\mathbf{T}]_s$. It can be considered as a rigid body therefore the following relationship can be obtained:

$$\begin{aligned} F_1 &= F_2 + j\omega m_s V_2 \\ V_1 &= V_2 \end{aligned} \quad (6.11)$$

where m_s is the mass of the sphere. So the relationship between its input and output ports can be expressed as:

$$\begin{Bmatrix} F_1 \\ V_1 \end{Bmatrix} = \begin{bmatrix} 1 & j\omega m_s \\ 0 & 1 \end{bmatrix}_s \times \begin{Bmatrix} F_2 \\ V_2 \end{Bmatrix} = [\mathbf{T}]_s \times \begin{Bmatrix} F_2 \\ V_2 \end{Bmatrix} \quad (6.12)$$

In Equation (6.12), F_2 is the force acting on the fluid load and V_2 is the resulting velocity. Their ratio is the mechanical impedance of the fluid load relating to the induced damping and mass in Equation (6.2) as follows:

$$\begin{aligned}
\frac{F_2}{V_2} &= Z_m \\
&= c_f + j\omega m_f \\
&= 6\pi R\eta + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho} + j\left(\frac{2\pi R^3}{3}\omega\rho + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho}\right)
\end{aligned}
\tag{6.13}$$

Now the electrical voltage and current at the electrical port of the WT can be related to the fluid loading by combining Equation (6.10) and (6.12) as:

$$\begin{aligned}
\begin{Bmatrix} E \\ I \end{Bmatrix} &= [\mathbf{T}]_w \times [\mathbf{T}]_s \times \begin{Bmatrix} F_2 \\ V_2 \end{Bmatrix} \\
&= \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}_w \times \begin{bmatrix} 1 & j\omega m_s \\ 0 & 1 \end{bmatrix}_s \times \begin{Bmatrix} F_2 \\ V_2 \end{Bmatrix} \\
&= \begin{bmatrix} t_{11} & j\omega m_s \cdot t_{11} + t_{12} \\ t_{21} & j\omega m_s \cdot t_{21} + t_{22} \end{bmatrix} \times \begin{Bmatrix} F_2 \\ V_2 \end{Bmatrix}
\end{aligned}
\tag{6.14}$$

And the dynamic viscosity η and density ρ are electromechanically coupled into the electrical impedance as:

$$\begin{aligned}
Z_e &= \frac{E}{I} \\
&= \frac{t_{11}Z_m + (j\omega m_s \cdot t_{11} + t_{12})}{t_{21}Z_m + (j\omega m_s \cdot t_{21} + t_{22})} \\
&= \frac{t_{11}(6\pi R\eta + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho}) + t_{12} + j \cdot t_{11}\left(\frac{2\pi R^3}{3}\omega\rho + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho} + \omega m_s\right)}{t_{21}(6\pi R\eta + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho}) + t_{22} + j \cdot t_{21}\left(\frac{2\pi R^3}{3}\omega\rho + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho} + \omega m_s\right)}
\end{aligned}
\tag{6.15}$$

6.4 Extracting fluid properties from electrical impedance of WT

Equation (6.15) directly relates the dynamic viscosity and density of the fluid to the

measured electrical impedance of the WT. If the transduction matrix is known and the electrical impedance is measured, then the two unknown variables η and ρ can be solved. This can be achieved in two steps. First, the mechanical impedance Z_m of the fluid load can be calculated from the electrical impedance Z_e of the WT using calibrated transduction matrix. Second, the following set of equations can be formed:

$$\begin{cases} 6\pi R\eta + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho} = \text{Re}(Z_m) \\ \frac{2\pi R^3}{3}\omega\rho + 3\sqrt{2}\pi R^2\sqrt{\omega}\sqrt{\eta\rho} = \text{Im}(Z_m) \end{cases} \quad (6.16)$$

where $\text{Re}(Z_m)$ and $\text{Im}(Z_m)$ are the real part and imaginary part of the mechanical impedance of the fluid load, respectively. This set of equations contains two unknown variables η and ρ which can be analytically solved as:

$$\eta = \frac{1}{\pi R} \left(\frac{5}{84} \text{Re}(Z_m) - \frac{3}{28} \text{Im}(Z_m) + \sqrt{\frac{9}{784} \text{Re}(Z_m)^2 - \frac{10}{784} \text{Re}(Z_m) \cdot \text{Im}(Z_m) + \frac{9}{784} \text{Im}(Z_m)^2} \right)$$

$$\rho = \frac{1}{\pi R^3 \omega} \left(-\frac{27}{28} \text{Re}(Z_m) + \frac{15}{28} \text{Im}(Z_m) + \sqrt{\frac{729}{784} \text{Re}(Z_m)^2 - \frac{405}{392} \text{Re}(Z_m) \cdot \text{Im}(Z_m) + \frac{729}{784} \text{Im}(Z_m)^2} \right) \quad (6.17)$$

Thus the dynamic viscosity and density of the fluid are obtained in the separate form at the same time.

A major advantage of our WT is that it can not only measure the dynamic viscosity and density of the fluid, but also the fluid condition (velocity) under which the measurement is taken. This is of particular importance when characterizing fluids with non-Newtonian behavior such as blood. Equation (6.14) can be inversed as:

$$\begin{Bmatrix} F_2 \\ V_2 \end{Bmatrix} = \begin{bmatrix} j\omega m_s \cdot t_{21} + t_{22} & -j\omega m_s \cdot t_{11} + t_{12} \\ -t_{21} & t_{11} \end{bmatrix} \times \begin{Bmatrix} E \\ I \end{Bmatrix} \quad (6.18)$$

And the fluid velocity can then be calculated from the electrical voltage and current as:

$$V_2 = -t_{21}E + t_{11}I \quad (6.19)$$

Due to this ability, accurate monitoring of fluid velocity can be achieved without using any additional sensors. The WT acts as a viscosity sensor, a density sensor and a velocity sensor simultaneously. This can facilitate the characterization of non-Newtonian fluids under different fluid conditions.

6.5 Experimental study

Figure 6.5 is the experiment setup for calibrating the transduction matrix and testing fluid properties. The sensor is composed of a PZT bimorph (46×2.1×0.6 mm), a steel whisker (length: 21 mm, radius: 0.3 mm) and a glass sphere (radius: 1.9 mm). One end of the PZT is clamped on an aluminum bar which is further fixed on a XYZ linear stage (Newport, resolution: 0.0001 mm) for precise positioning. The electrical measurement instrumentation is the same as before (see Figure 4.4). Figure 6.5b is a precision steel cantilever beam (82×1×0.2 mm) used as the mechanical load in least-squares calibration of transduction matrix. After calibration, the sensor can be immersed into a test fluid to measure its viscosity and density, as illustrated in Figure 6.5c. The temperature is controlled to be 25 °C.

(a)

(b)

(c)

Figure 6.5 Fluid property sensing experiment setup.

(a) WT fixed on a XYZ linear stage. (b) A steel cantilever beam used in calibration. (c) Testing properties of a fluid in the beaker.

6.5.1 Calibration and validation

Before doing the calibration, the electrical impedance of the transducer under free load is checked within a wide frequency range (5-1000 Hz) in order to decide the optimal working frequency. The result is plotted in Figure 6.6 and two resonant frequencies at around 100 Hz and 500 Hz are found. As discussed in Chapter 2, lower working frequency is more preferable for obtaining results comparable to standard viscometer measurements. So the working frequency is chosen to be in the vicinity of the first resonance (100 Hz) under free-load

condition. Also at this frequency the vibration amplitude is much larger so the interaction with fluid will be stronger.

Figure 6.6 Electrical impedance of the WT under free load.

Now the working frequency range has been narrowed down to 90-120 Hz. In order to calibrate the transduction matrix, more than three mechanical loads with known mechanical impedances are required. In addition to the free load, the steel cantilever beam ($82 \times 1 \times 0.2$ mm) in Figure 6.5b is used to create three more mechanical loads. This is achieved by measuring the steel cantilever at three different locations (0, 10, 20 mm from its tip) along its length, as shown in Figure 4.9. A 3V sweep sine signal with frequency increasing from 90 Hz to 120 Hz is input to the WT to generate vibration. At each test location, the input voltage and current are measured simultaneously and their ratio is the electrical impedance. The electrical impedances under the calibration loads are plotted in Figure 6.7.

Figure 6.7 Electrical impedances under calibration loads.

With the material properties of the steel cantilever precisely known in Table 4.2, the theoretical mechanical impedances can be easily calculated, which are plotted in Figure 6.8 as blue circles. Then Equations (3.45)-(3.47) are used to calibrate the transduction matrix which is shown in Figure 6.9.

(a)

(b)

Figure 6.8 Comparison of theoretical and WT-measured mechanical impedances of calibration loads.

(a) Imaginary part. (b) Real part.

Figure 6.9 Calibrated transduction matrix in the frequency range of 90-120 Hz.

To check the performance of this calibrated transduction matrix, the electrical impedances in Figure 6.7 are converted into mechanical impedances using Equation (3.15). The results are plotted in Figure 6.8 as red crosses to be compared with their theoretical values. The comparison shows good agreement between theoretical and WT-measured values for the imaginary part. However, the real part curves have relative large deviations except for the frequency of 100, 102 and 104 Hz.

In order to check the validity of Equation (6.17) for extracting fluid viscosity and density from measured electrical impedance, water at 25 °C is used as the test fluid. The fluid is placed in a beaker as shown in Figure 6.5c. The linear stage controls the WT to move downwards until the sphere tip is completely immersed in the fluid. Then the electrical impedance of the WT under the fluid load is measured in the frequency range of 90-120 Hz and plotted in Figure 6.10. Compared with that in the free load condition, it can be observed that the resonant frequency under water load decreases to 96 Hz due to the inertial component of the fluid loading, and the

peak value of the curve also decreases due to the dissipative component of the fluid loading, as predicted in Section 6.3.2. Both measurements were repeated three times and the results are consistent with only minor variations.

Figure 6.10 Comparison of electrical impedances under free load and water load (25 °C).

The mechanical impedance of the fluid load is then calculated with the calibrated transduction matrix from which the fluid viscosity and density are solved using Equation (6.17). The measured values at different frequencies are plotted in Figure 6.11 and Figure 6.12. The theoretical values of dynamic viscosity and density are $8.93 \times 10^{-4} \text{ N s/m}^2$ and $9.97 \times 10^2 \text{ kg/m}^3$ for water at 25 °C, respectively. They are also plotted in Figure 6.11 and Figure 6.12 for comparison. It can be found that the measured results are more accurate near the resonant frequency (100-104 Hz) but have larger deviations at other frequencies. The main reason is that the calibration error is relatively larger at other frequencies which can be observed in Figure 6.8b. The error also comes from other sources including the electrical noise and mechanical perturbation. Since the measurements are made one frequency by one frequency, the vibration

response in one measurement is easily affected by the waves generated by the previous measurement. At the resonance the electromechanical coupling and mechanical vibration both become strongest therefore the noise is suppressed and the signal-to-noise ratio is enhanced. So the sensor measures more accurately near the resonance. The performance at other frequencies may be improved by calibrating the transduction matrix each time at only one frequency rather than in a frequency sweep manner to eliminate the interference.

Figure 6.11 Comparison between WT-measured viscosity of water (25 °C) and its theoretical value.

Figure 6.12 Comparison between WT-measured density of water (25 °C) and its theoretical value.

Finally, it is found that at the frequency of 104 Hz both the measured viscosity (9.05×10^{-4} N s/m²) and density (1002 kg/m³) have minimum errors of 1.4% and 0.5% compared with their theoretical values, respectively. So it is chosen as the optimal working frequency of the WT for fluid property sensing.

6.5.2 Testing glycerol-water mixtures

In order to test the sensor in a wide range of viscosity value, glycerol-water mixture is chosen as the test fluid due to its easy availability. Glycerol and water can be mixed at any ratio and the viscosity of the mixture varies from 8.93×10^{-4} to 9.06×10^{-1} N s/m². Also the viscosity of glycerol-water mixture is well documented in the literature with several databases available for comparison [122, 123].

In the following experiment, specimens of glycerol-water mixture with various volume concentrations ($C_v = 0\%, 25\%, 30\%, 38\%, 50\%, 60\%, 67\%$ and 75%) are used as test fluids. The experiment setup is shown in Figure 6.5c and the temperature is controlled at $25\text{ }^{\circ}\text{C}$. In each measurement, the sensor is controlled by the linear stage to move downwards slowly until the sphere tip is completely immersed in the fluid. Then a $3\text{V } 104\text{ Hz}$ electrical voltage signal is applied to the WT and the sphere tip starts oscillating in the fluid. In order to increase the accuracy, the measurement is not started until the steady state is achieved by setting a delay time of 10 seconds. Then electrical voltage, current and impedance are measured simultaneously, from which the dynamic viscosity and density of the fluid are extracted using Equation (6.17).

The WT-measured dynamic viscosity values of various test fluids are plotted as the bar chart in Figure 6.13. They are compared with the values in the literature. The two results agree well with each other. The measurement error and uncertainty are estimated and listed in Table 6.1. It is found that the measurement error varies within $0.38\text{-}11.60\%$, and for most cases its value is less than 7% . And the uncertainty is less than 0.5% for all specimens.

Figure 6.13 WT-measured dynamic viscosity values vs. literature data.

Table 6.1 Error and uncertainty in viscosity measurement

Specimen C_v	η_{WT} (N s/m)	$\eta_{literature}$ (N s/m)	Error	Uncertainty
0%	9.05E-04	8.93E-04	1.37%	0.20%
25%	2.21E-03	2.10E-03	5.18%	0.53%
30%	2.84E-03	2.57E-03	10.16%	0.10%
38%	4.02E-03	3.60E-03	11.60%	0.54%
50%	7.36E-03	6.88E-03	6.98%	0.56%
60%	1.34E-02	1.28E-02	4.83%	0.48%
67%	2.06E-02	2.07E-02	0.38%	0.35%
75%	4.11E-02	4.15E-02	0.84%	0.32%

Similarly, the WT-measured density data are plotted in Figure 6.14 and good agreement is found with the literature data. The error and uncertainty are estimated and listed in Table 6.2. The relative error for all specimens is less than 4% and the uncertainty is less than 0.2%.

Figure 6.14 WT-measured density values vs. literature data.

Table 6.2 Error and uncertainty in density measurement

Specimen C_v	ρ_{WT} (kg/m ³)	$\rho_{literature}$ (kg/m ³)	Error	Uncertainty
0%	1.00E+03	9.97E+02	0.52%	0.03%
25%	1.05E+03	1.08E+03	1.95%	0.20%
30%	1.05E+03	1.09E+03	3.87%	0.05%
38%	1.11E+03	1.11E+03	0.21%	0.10%
50%	1.10E+03	1.14E+03	3.50%	0.09%
60%	1.16E+03	1.17E+03	1.22%	0.08%
67%	1.17E+03	1.19E+03	1.66%	0.06%
75%	1.22E+03	1.21E+03	1.60%	0.04%

In order to evaluate the reliability and repeatability of the WT in viscosity and density measurement, each specimen was measured ten times and the repeated measurement data were plotted in Figure 6.15 and Figure 6.16. In addition, the measurement uncertainty was estimated at the confidence level of 95% and also plotted. It was observed from the figures

that the WT has good repeatability and low uncertainty.

Figure 6.15 Repeated measurement data of viscosity (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is specimen number (1 — $C_v = 0\%$, 2 — 25%, 3 — 30%, 4 — 38%, 5 — 50%, 6 — 60%, 7 — 67% and 8 — 75%).

Figure 6.16 Repeated measurement data of density (left) and estimated measurement uncertainty at 95% confidence level (right). “n” is specimen number (1 — $C_v = 0\%$, 2 — 25%, 3 — 30%, 4 — 38%, 5 — 50%, 6 — 60%, 7 — 67% and 8 — 75%).

In conclusion, this experiment confirms that the proposed sensor is able to measure the dynamic viscosity and density of a fluid. It also shows that the sensor is sensitive in a wide range of viscosity which is at least from 8.93×10^{-4} to 4.15×10^{-2} N s/m². Within this range, most

results have small measurement error and uncertainty. A few results have relative large deviations from the literature data, which may be due to the inaccuracy within the volume ratio during the preparation of specimens. In addition, the literature data may also contain error which is claimed to be less than 5% by the authors.

6.6 Monitoring and controlling fluid velocity

The WT has the ability to sense the fluid velocity at its tip using Equation (6.19). This has been checked with a laser vibrometer using a configuration similar to the one in Figure 4.23. The WT-measured velocity under free load is 0.283 m/s, which has close agreement with the laser vibrometer result of 0.277 m/s.

The transfer function $G(s)$ between the output velocity $V(s)$ and input voltage $E(s)$ of WT can be derived from Equation (6.14) as:

$$G(s) = \frac{V(s)}{E(s)} = \frac{1}{t_{11}(s)Z_m(s) + m_s t_{11}(s) \cdot s + t_{12}(s)} \quad (6.20)$$

where $Z_m(s)$ is the mechanical impedance of the fluid load related to its dynamic viscosity and density. For a Newtonian fluid, its viscosity is a constant therefore $Z_m(s)$ is also a constant. So the relationship between the output velocity and the input voltage is linear and a feed-forward controller can be used to control the velocity based on Equation (6.20). For a non-Newtonian fluid, its viscosity changes with the fluid velocity therefore $Z_m(s)$ is an unknown function of $V(s)$. So the relationship $G(s)$ between the output velocity and the input voltage is nonlinear and unknown. In this case, a feedback controller is required to control the output velocity, such as the one shown in Figure 6.17.

Figure 6.17 Feedback control of fluid velocity for characterizing non-Newtonian fluid.

Figure 6.17 is a block diagram of a feedback control scheme for controlling fluid velocity when characterizing a non-Newtonian fluid with WT, where $R(s)$ is the reference input of velocity, $\Delta(s)$ is the error between the reference and the output, $C(s)$ is the controller, $E(s)$ is the voltage applied to the WT, $V(s)$ is the output fluid velocity. A unique feature of this control system is that the WT itself plays the role of a velocity sensor providing the feedback, as shown in Equation (6.19). Therefore the control system is greatly simplified. Following relationships can be identified from Figure 6.17:

$$\begin{aligned} V(s) &= G(s)E(s) \\ E(s) &= C(s)\Delta(s) \\ \Delta(s) &= R(s) - V(s) \end{aligned} \quad (6.21)$$

Solving for $V(s)$ in terms of $R(s)$ gives:

$$\begin{aligned} V(s) &= \frac{G(s)C(s)}{1 + G(s)C(s)} R(s) \\ &= H(s)R(s) \end{aligned} \quad (6.22)$$

where $H(s)$ is the closed-loop transfer function of the system. If the open-loop gain $|G(s)C(s)| \gg 1$, $H(s)$ becomes approximately 1. Therefore the output velocity $V(s)$ is approximately equal to the reference $R(s)$ which is the desired fluid velocity for characterizing the non-Newtonian fluid.

6.7 Issues on miniaturization of the sensor

Although the technique of WT-based fluid property sensing proposed in this chapter is

demonstrated through a macro-size sensor, its sensing principle is also applicable to a micro-size version. The dimensions of the sensor can be shrunk through some microfabrication processes. The miniaturization can enable the sensor to be used in microfluidic applications to save the sample volume. It also allows the sensor to be used as a biosensor in biomedical applications, such as being implanted into a human body for monitoring the blood viscosity *in vivo*. A miniaturized sensor is also desired in tribology for measuring viscosity of the thin film of lubricant. Some important considerations regarding the challenges, techniques as well as the effect of miniaturization will be discussed in the following.

6.7.1 Miniaturization techniques

The fabrication of a micro-size version of the sensor requires the miniaturization of the PZT cantilever, whisker and sphere. The PZT cantilever can be miniaturized by depositing a thin film of PZT on the substrate through well developed MEMS fabrication processes such as sol-gel deposition or sputtering. This has been investigated and realized by this same research group previously [124]. And the miniaturization of whisker has also been realized in Chapter 5 of this thesis using the μ EDM process. So the remaining problem is the miniaturization of the sphere.

Although MEMS processes can be used to fabricate various micro structures, they are not suitable for fabricating a micro-sphere on the whisker tip. Recent investigations have revealed that μ EDM is potentially an excellent technology for making micro-spherical probes [125]. The fabrication procedure includes two steps, as shown in Figure 6.18a. First, a 300 μ m tungsten wire electrode is micromachined by the WEDG (wire electrical discharge grinding) process to reduce its diameter to 20-30 μ m. Second, an OPED (one pulse electrical discharge) process is conducted to melt the tip of the tungsten wire instantaneously due to the electrical discharge energy. The melted part will then shrink into a sphere due to surface tension. This technology can be used to make probes with very small sphere tip (15 μ m) and high aspect ratio. The surface of the micro-sphere is also very smooth and the procedure is very efficient.

Figure 6.18b is an example of micro-spherical probe fabricated using μ EDM technology.

Figure 6.18 Fabrication of a micro-spherical probe using μ EDM [125].

(a) Fabrication procedure. (b) Micro-spherical probe (diameter of sphere: 50 μm).

Another potential method for fabricating micro-sphere is to melt the tip of a glass fiber using a commercial fiber fusion splicer, as shown in Figure 6.19a. The 125 μm thick glass fiber is clamped on the fiber holder. The XY stage aligns the fiber to the proper location. Then the splicer starts to generate arc discharging to melt the tip and form the micro-sphere. Micro-spheres with diameter of about 300 μm can be fabricated, as shown in Figure 6.19b. The major advantage of this method is the very low cost. However, the produced spheres have large errors in roundness and center offset, which need to be improved by further investigations.

Figure 6.19 Fabrication of micro-sphere using a fiber fusion splicer [126].

(a) Fabrication setup. (b) Images of the micro-sphere viewed at four angular positions.

Above two methods can produce both the whisker and sphere at the same time. However, the quality of the sphere is difficult to control. Alternatively, a micro-assembly method can be adopted to fabricate micro-spherical probes with commercially available high-quality micro-spheres. For example, a micro-sphere (75 μm) is glued to the end of a glass fiber (50 μm diameter) with the assistance of a microscope and a three-axis stage [72]. More recently, a FIB/SEM (Focused Ion Beam and Scanning Electron Microscope) machine is used to manipulate a glass sphere (70 μm), assemble it onto a tungsten-carbide shaft (diameter <100 μm), and monitor the process [127] (see Figure 6.20). Although the assembly is not completely successful, difficulties involved in this task have been recognized through initial trials, such as the long operation time (several days), the requirement of high operation skill and the limited strength of the bond.

Figure 6.20 Assembly of a micro-sphere (70 μm) onto the shaft using a FIB/SEM machine [127].

6.7.2 Effect of scaling on the fluid load

According to Equation (6.2), both the fluid induced damping and mass are functions of the radius of the sphere. Considering the case when the sphere is scaled by a factor of α as shown in Figure 6.21, the new radius R' becomes:

$$R' = \alpha R \quad (6.23)$$

Figure 6.21 Scaling of the sphere

Substituting the radius R in Equation (6.2) with R' will result in the induced damping c'_f and mass m'_f after scaling as:

$$\begin{aligned} c'_f &= \alpha \cdot (6\pi R \eta) + \alpha^2 \cdot (3\sqrt{2}\pi R^2 \sqrt{\omega} \sqrt{\eta \rho}) \\ m'_f &= \alpha^3 \cdot \left(\frac{2\pi R^3}{3} \rho \right) + \alpha^2 \left(\frac{3\sqrt{2}\pi R^2}{\sqrt{\omega}} \sqrt{\eta \rho} \right) \end{aligned} \quad (6.24)$$

It can be found that the effect of scaling on the induced damping is different from that on the induced mass. In addition, the two terms in each expression are affected by the scaling differently. When the working frequency is very low ($\omega \rightarrow 0$), it can be approximated that:

$$\begin{aligned} \frac{c'_f}{c_f} &\approx \alpha \\ \frac{m'_f}{m_f} &\approx \alpha^2 \end{aligned} \quad (6.25)$$

On the other hand, if the working frequency is very high ($\omega \rightarrow \infty$), the following relationship can be obtained:

$$\begin{aligned} \frac{c'_f}{c_f} &\approx \alpha^2 \\ \frac{m'_f}{m_f} &\approx \alpha^3 \end{aligned} \quad (6.26)$$

The comparison between Equation (6.25) and (6.26) shows that the scaling effect is more significant in the high frequency range. It is also obvious that in either of the above cases, the effect of scaling on the mass is much stronger than that on the damping. As a result, the fluid loading will be dominated by the damping and more energy will be dissipated into the fluid.

6.7.3 Effect of scaling on the sensor

Now let's consider the effect of scaling on the sensor which is composed of the PZT cantilever, the whisker and the sphere tip. If all dimensions are scaled by a factor of α as shown in Figure 6.22, both the effective mass and stiffness of the sensor will change therefore the resonant frequency will also change.

Figure 6.22 Scaling of the sensor

The mass of the sphere tip is in the form of:

$$m_s = \rho_s \frac{4\pi R^3}{3} \quad (6.27)$$

So the mass after scaling is:

$$m'_s = \alpha^3 m_s \quad (6.28)$$

which is scaled by a factor of α^3 .

The PZT can be treated as a rectangular cantilever whose effective stiffness and mass are:

$$k = \frac{Ewt^3}{4l^3}$$

$$m = \frac{\rho wtl}{3} \quad (6.29)$$

where E is the elastic modulus, w , t and l are the width, thickness and length of the cantilever beam, respectively. While the whisker can be treated as a circular cantilever with effective stiffness and mass being:

$$k = \frac{3E\pi r^4}{4l^3}$$

$$m = \frac{\rho\pi r^2 l}{3}$$
(6.30)

where r and l are the radius and length of the beam, respectively. If all dimensions are scaled by a factor of α , the effective stiffness and mass of the WT will become:

$$k'_w = \alpha k_w$$

$$m'_w = \alpha^3 m_w$$
(6.31)

Substituting Equations (6.28) and (6.31) into Equation (6.5), the resonant frequency of the sensor in air after scaling can be calculated as:

$$\omega'_n = \sqrt{\frac{k'_w}{m'_w + m'_s}} = \sqrt{\frac{\alpha k_w}{\alpha^3 m_w + \alpha^3 m_s}} = \frac{1}{\alpha} \sqrt{\frac{k_w}{m_w + m_s}}$$

$$= \frac{1}{\alpha} \omega_n$$
(6.32)

This means that the new resonant frequency is proportional to the original resonant frequency with a factor of $1/\alpha$. In the case when the sensor is miniaturized, the scaling factor $\alpha < 1$, so the resonant frequency will increase.

Finally, when the new sensor is immersed into a fluid, its electrical impedance will be changed which can be evaluated by the shift of resonant frequency. According to Equation (6.8), the new resonant frequency under fluid loading is:

$$\omega'_n = \sqrt{\frac{k'_w}{m'_w + m'_s + m'_f}} = \sqrt{\frac{\alpha k_w}{\alpha^3 m_w + \alpha^3 m_s + \alpha^2 m_f}}$$

$$= \frac{1}{\alpha} \sqrt{\frac{k_w}{m_w + m_s + \frac{m_f}{\alpha}}}$$
(6.33)

Equation (6.33) assumes that the sensor's resonant frequency is still low so the fluid induced

mass is approximated by Equation (6.25). In the case when the sensor is miniaturized, the scaling factor $\alpha < 1$, so the following inequation holds:

$$\begin{aligned}
 \sqrt{\frac{k_w}{m_w + m_s + \frac{m_f}{\alpha}}} &< \sqrt{\frac{k_w}{m_w + m_s + m_f}} \\
 \frac{\omega'_n|_{fluid}}{\omega'_n|_{air}} &< \frac{\omega_n|_{fluid}}{\omega_n|_{air}} \\
 \frac{\omega'_n|_{air} - \omega'_n|_{fluid}}{\omega'_n|_{air}} &> \frac{\omega_n|_{air} - \omega_n|_{fluid}}{\omega_n|_{air}} \\
 \frac{\Delta\omega'_n}{\omega'_n|_{air}} &> \frac{\Delta\omega_n}{\omega_n|_{air}}
 \end{aligned} \tag{6.34}$$

This indicates that the extent of resonant frequency shift will become greater after scaling. In other words, the sensitivity of the sensor will become higher.

6.7.4 Numerical study of the scaling effect

A finite element model of the sensor used in experiment is built in ANSYS for simulating the scaling effect. Three scaling factor values ($\alpha = 1, 0.1, 0.02$) are used which correspond to the original sensor, a 10-times smaller one, and a 50-times smaller one, respectively. The simulations are carried out with a 1 V sweep sine input voltage over a wide frequency range. The displacement responses as well as electrical impedances of the sensors under both the free load and the water load are simulated and plotted in Figure 6.23 and Figure 6.24. First, an interesting thing is that for the same input voltage, the maximum vibration amplitude under free load remains the same for all the three cases, although the third sensor is 50 times smaller than the first one. The reason is that when the sensor is scaled by a factor of α , its thickness becomes smaller therefore the electrical field becomes larger. Since the strain of a PZT material is proportional to the applied electrical field rather than the voltage, it will increase by a factor of $1/\alpha$ which cancels out the effect of scaling on the vibration amplitude.

Figure 6.23 Simulation results of the displacement response of the sensor with various scaling factors ($\alpha = 1, 0.1, 0.02$) under free load (blue) and water load (red).

Figure 6.24 Simulation results of the electrical impedance of the sensor with various scaling factors ($\alpha = 1, 0.1, 0.02$) under free load (blue) and water load (red).

Second, the resonant frequency of each sensor under free load is extracted from the blue curves in Figure 6.23 and listed in Table 6.3 as $f_n|_{air}$. The result shows that when the scaling factor decreases, the resonant frequency increases with a proportional factor of $1/\alpha$ as predicted in Equation (6.32). Then the resonant frequencies under water load are also extracted from the red curves and listed in Table 6.3 as $f_n|_{fluid}$. It is found that $f_n|_{fluid}$ also increases when the scaling factor decreases, but not proportionally. The change of the resonant frequency between the two load conditions is calculated and listed in Table 6.3 in a percentage form. This relative shift of resonant frequency increases when the sensor is shrunk, as indicated in Equation (6.34). This means that the sensor becomes more sensitive after miniaturization. The similar trend is also observed in the damping behavior in Figure 6.23

since the response curve is more significantly dampened when α becomes smaller.

Table 6.3 Resonant frequency of the sensor with various scaling factors ($\alpha = 1, 0.1, 0.02$) under free load and water load

	$\alpha = 1$	$\alpha = 0.1$	$\alpha = 0.02$
$f_n _{air}$	98	980	4900
$f_n _{fluid}$	89	870	4150
$\frac{\Delta f_n}{f_n _{air}} \times 100\%$	9.2%	11.2%	15.3%

As illustrated by the simulation result, the major problem of miniaturization is that it will cause the resonant frequency of the sensor to increase. This is an undesirable side effect of scaling which will make the measurement result less comparable to that of standard viscometers. A solution to this problem is to make the whisker thinner as this will reduce the stiffness of the WT so that the resonant frequency of the sensor can remain unchanged according to Equation (6.32). This may also increase the sensitivity of the sensor since the mass of the WT in Equation (6.33) will become smaller. Alternatively, the resonant frequency can also be lowered by increasing the mass of the sphere tip by means of using heavier material.

6.8 Experimental study using a miniaturized WT

Although a miniaturized WT was successfully fabricated in Chapter 5, it has a T-shaped tip rather than a spherical tip. As described earlier in this chapter, a spherical tip is important since it can enhance the interaction with the fluid, reduce the working frequency, and facilitate the interpretation of the fluid load with the analytical model in Equation (6.2). In order to meet this requirement, a miniaturized WT with spherical tip was fabricated which has similar dimensions to the one in Chapter 5. It is composed of a thin PZT bimorph ($0.5 \times 0.5 \times 32$ mm),

a thin tungsten whisker (50 μm radius, 3.2 mm long) and a plastic sphere tip (340 μm radius), as shown in Figure 6.25.

Figure 6.25 Miniaturized WT with a sphere tip.

The electrical impedance of the miniaturized WT under free load condition was checked in the frequency range of 1-1000 Hz using the Solartron Impedance Analyzer and plotted in Figure 6.26. The resonant frequency of the WT was found at around 400 Hz. The operation frequency range was thus chosen to be 350-450 Hz in the following experiment since the sensitivity of the WT is high in this range.

Figure 6.26 Electrical impedance of the miniaturized WT with sphere tip.

The experiment setup for fluid sensing using the miniaturized WT is shown in Figure 6.27. The upper end of the WT is fixed on an acrylic handle which is further fixed on a linear stage system (Physik Instrumente GmbH, Germany) for precise positioning. The fluid specimen is placed in a beaker which is placed on another linear stage system for rough positioning. The two electrodes of the WT are connected to the Solartron Impedance Analyzer for electrical excitation and measurement. A 3V sweep sine signal in the frequency range of 350-450 Hz is used as the excitation. A digital microscope (iCamscope, Sometech Inc.) is used to monitor the sensing process (not shown in Figure 6.27). The temperature is controlled to be 25 °C.

Figure 6.27 Experiment setup for fluid sensing using the miniaturized WT.

Specimens of glycerol-water mixture with various volume concentrations ($C_v = 0\%$, 25%, 38%, 50%, 67% and 75%) were used as test fluids. In each test, the WT was controlled by the linear stage to move downwards slowly until the sphere tip was completely immersed in the fluid. Then electrical excitation was applied and electrical impedance of the WT was measured. The measured electrical impedances under the test fluids as well as free load are plotted in Figure 6.28. The measurement was repeated five times and the results are highly repeatable with low measurement uncertainty which can be found from the zoom-in view in Figure 6.28. It can be found that the WT is very sensitive to the change of load since its

impedance is different for different loads. Compared with the Z_e curve under free load, the Z_e curves under fluid loads are shifted to the left mainly due to the mass component of the fluid in Equation (6.2). And their peak values decrease due to the dissipative component of the fluid load. According to Equation (6.2), when the dynamic viscosity and density of the fluid load increase, the effective mass and damping of the fluid load will also increase. Thus the resonant frequency and peak value of Z_e curve under fluid load of higher concentration C_v will become smaller. This can also be observed in Figure 6.28.

Figure 6.28 Electrical impedance of the miniaturized WT under different loads.

Above observations are mainly qualitative. In order to analyze the result more quantitatively, we need to convert the electrical impedance in Figure 6.28 into mechanical impedance of the fluid load. This requires the transduction matrix of the WT to be calibrated. In this experiment, instead of using a precision cantilever beam to create mechanical loads, the test fluids themselves were used as the loads for calibration. Their theoretical mechanical impedances were calculated using Equation (6.2) and plotted in Figure 6.29 in the frequency

range of 350-450 Hz. If the calibration can be successfully achieved, it will prove that the proposed transduction matrix-based fluid sensing technique is also applicable to this miniaturized WT.

Figure 6.29 Theoretical mechanical impedances of fluid loads and free load.

The Z_e data in Figure 6.28 and the theoretical Z_m data in Figure 6.29 were used to form Equation (3.45)-(3.47). Then least-squares solution of the transduction matrix in the frequency range of 350-450 Hz was obtained and plotted in Figure 6.30.

Figure 6.30 Calibrated transduction matrix of the miniaturized WT with sphere tip.

To check the validity of the calibrated transduction matrix, the Z_c data in Figure 6.28 were converted to “WT-measured” Z_m data and plotted in Figure 6.31. The theoretical Z_m data were also plotted in Figure 6.31 for comparison. Figure 6.31 shows that the WT-measured Z_m data approximately agree with the theoretical Z_m data for all loads across the whole frequency range. However, similar to the result in Figure 6.11, the accuracy is different at different working frequencies. As indicated in Figure 6.31, the most accurate result is achieved at 402 Hz. This frequency is close to the resonance of the WT therefore sensitivity is high and noise is suppressed. The deviation of WT-measured Z_m from its theoretical value at 402 Hz was calculated for each fluid load and plotted in Figure 6.32. It shows that measurement error is less than 5% for all cases. Therefore at this frequency the transduction matrix was accurately calibrated. This frequency can be chosen as the optimal working frequency for the miniaturized WT. The successful calibration of transduction matrix also proves that the fluid sensing technique proposed early in this chapter is applicable to miniaturized WT which can be potentially applied to microfluidic and biomedical applications.

Figure 6.31 Comparison between WT-measured Z_m and theoretical Z_m .

Figure 6.32 Deviation of WT-measured mechanical impedance from theoretical value for fluid loads of different volume concentrations.

6.9 Summary

In this chapter, the ability of the WT in sensing fluid's dynamic viscosity and density has been revealed. A sphere tip is added to the WT for three important reasons — enhancing the interaction with the fluid, reducing the working frequency, and facilitating the interpretation of the fluid loading. A transduction matrix model of the fluid-sphere-WT interaction has been established based on the transduction matrices of the WT and sphere tip, as well as the analytical model of the fluid loading. This model directly relates the fluid properties to the electrical signals of the WT therefore can be used as the basis for accurate sensing of fluid's dynamic viscosity and density. In addition, the fluid condition (velocity) under which the measurement is taken can also be obtained easily from measured electrical voltage and current of the WT without using any additional sensors. This can facilitate the characterization of non-Newtonian fluids.

A prototype has been fabricated to test the proposed methodology. The transduction matrix of the WT is calibrated using the least-squares method. By comparing its performance within a wide range of working frequency, the optimal working frequency is found to be 104 Hz. At this optimal frequency, the sensor reaches both good accuracy and strong interaction with fluid (vibration amplitude: 0.43 mm). The testing result of water (25 °C) shows small measurement errors for both dynamic viscosity (1.4%) and density (0.5%). A further test with various glycerol-water mixtures of different volume concentrations shows that the sensor has a wide measurement range of viscosity which is at least from 8.93×10^{-4} to 4.15×10^{-2} N s/m².

The velocity sensing ability of the WT has been confirmed using a laser vibrometer. This ability allows the monitoring and controlling of fluid velocity without using any additional sensors. Based upon this, a feedback control scheme has been proposed for accurate control of fluid velocity which is important for characterizing non-Newtonian fluids.

In order to facilitate the potential application of the sensor in microfluidics and

biomedicine, issues regarding the miniaturization of the sensor have been studied. Three microfabrication techniques have been found in the literature for fabricating the micro-spherical probe. However, none of them are well developed therefore research efforts are still required in this direction in the future. In addition, the effect of miniaturization is evaluated both on the fluid load and on the sensor. It is found that the effect of miniaturization is more significant on the induced mass of the fluid load. So after miniaturization, the fluid load will be dominated by the damping part. On the other hand, the miniaturization has a good effect on the sensor since it will increase its sensitivity. However, the miniaturization will cause the resonant frequency of the sensor to increase proportionally to the scaling factor. This is an undesirable side effect of miniaturization which will make the measurement result less comparable to that of standard viscometers. It can be solved by reducing the stiffness of the WT or increasing the mass of the sphere tip.

Chapter 7

CONCLUSIONS

This thesis focuses on the development of a biomimetic whisker transducer (WT) as well as the investigation of its potential applications. Through the research, several important results and findings have been achieved which can contribute to a wide range of areas. This chapter summarizes the conclusions and contributions of the thesis and also provides possible directions for future research and development.

7.1 Conclusions

(1) A novel biomimetic whisker transducer (WT) featuring simultaneous sensing and actuating (SSA) has been developed.

A WT was proposed based on the inspiration from rat's vibrissal tactile perception system. Morphologically, it mimics its biological counterpart with a steel wire as the whisker and a piezoelectric bimorph as the follicle-sinus complex (FSC). Functionally, it performs active whisking and simultaneously senses mechanical stimuli applied on the whisker, also similar to the biological system. This SSA feature was achieved by a novel transduction matrix model which completely characterizes the forward actuation and backward sensing functions of the transducer with a 2×2 matrix. Thus the force, velocity and mechanical impedance at the whisker tip can be conveniently and accurately sensed just from the electrical input signals, without using any additional sensors.

The validity of the proposed WT was confirmed numerically using a finite element model. Then a prototype of WT was fabricated. Its transduction matrix was calibrated experimentally using the least-squares method. Subsequent validation experiments showed that the calibrated WT can accurately measure mechanical impedance, force and velocity at

whisker tip with error being as small as 1.28% for mechanical impedance measurement, 0.88% for velocity measurement, and 1.55% for force measurement.

Compared with existing whisker sensing systems in literature, this newly developed WT has very compact and simple structure, which facilitates its installation and miniaturization. It is also very versatile since it acts not only as an actuator to perform whisking, but also as a force sensor, a motion sensor and a mechanical impedance sensor concurrently. Due to the accurate transduction matrix model, the sensed mechanical quantities are their exact values at whisker tip, which are more desirable than the values at whisker base measured by those whisker sensing systems in literature. In addition, the WT can work at a high frequency similar to that used by rats, making it more efficient than those motor-actuated whisker systems. Finally, its implementation and instrumentation are very easy. Each WT requires only a pair of electric wires for both actuation and sensing. This solves the wiring problem faced by whisker array systems in the literature. The measurement of voltage, current and electrical impedance can be implemented easily with the measurement system and digital signal processing algorithms developed in Section 4.2. Many common dynamic signal acquisition modules can meet this requirement by simply adding a self-designed I-V converter circuit at the cost of several dollars.

(2) Vibrissal tactile texture sensing and object locating have been achieved with the WT.

From a vibrissal tactile texture sensing experiment with sandpaper specimens, it was found that the force, velocity and real part of mechanical impedance sensed by the WT are all sensitive to the change of specimen roughness. Regression analyses showed that the relationship between WT-measured force and roughness is increasing linear ($R^2 > 0.99$), while that between WT-measured velocity and roughness is decreasing linear ($R^2 > 0.99$). Therefore they can be used as indicators for texture discrimination. In addition, an increasing quadratic relationship was found between real part of WT-measured mechanical impedance and roughness. This real part of mechanical impedance is a direct measure of the damping or frictional property of the surface texture. Thus the WT can be potentially used as a convenient

tool for tribology study especially in the micro-world. Also the availability of all these WT-measured force, velocity and mechanical impedance is beneficial to robotic applications such as manipulation and exploration. Finally, it was found that the manner (e.g. angle, normal force, etc.) in which the whisker contacts the surface should be controlled since it would affect sensing results. Rat does this with a combination of head and body movement [4]. This strategy can be adopted by robots to facilitate vibrissal tactile sensing.

The vibrissal tactile location sensing was investigated with a miniaturized WT fabricated using μ EDM process. A spatial-temporal-intensity triple-coding scheme has been developed for detecting the 3D location of a contacting object. The horizontal location is detected from the concurrence of the temporal signal of whisker movement and the temporal signal of mechanical impedance sensed at the whisker tip, with measurement uncertainty of $0.27\ \mu\text{m}$. The radial location is detected from the electrical impedance of the WT using a multilayer feed-forward neural network as the inverse model, with measurement uncertainty of $5.4\ \mu\text{m}$. And the vertical location can be detected simply from the identity (spatial location) of the activated WT in a WT-array. This 3D location sensing ability allows the detection of object shape by combining locations of multiple points on the object contour. In addition, the high aspect ratio of WT (100:1) makes it a potential solution to the challenging problem of geometry detection of high-aspect-ratio micro holes. It was experimentally demonstrated that the WT can accurately detect taper of high-aspect-ratio micro trenches using its horizontal locating ability. And its radial locating ability can be used to detect invalid contact to avoid invalid measurement of geometry.

(3) A novel technique for online sensing of fluid viscosity and density using WT has been developed.

A modified WT with a sphere tip can sense both dynamic viscosity η and density ρ of a fluid through vibration. A transduction matrix model was established which accurately describes the relationship between the fluid load and electrical signals of the WT. An equation for extracting fluid's η and ρ from measured electrical impedance of the WT was also derived.

The extracted η and ρ are separated from each other rather than in the form of product ($\eta\rho$) or quotient (η/ρ) as detected by many viscometers and viscosity sensors in the literature. With its SSA feature, the WT is also able to self-sense the fluid velocity without using any additional sensors. This can facilitate the characterization of non-Newtonian fluids. Due to the added sphere tip, the working frequency is reduced to 104 Hz which is much lower than that of TSM viscosity sensors (MHz) and microcantilever viscosity sensors (hundred kHz) in the literature. And the interaction with fluid is enhanced so that vibration amplitude is in the millimeter range. These improvements enable the WT to generate results more comparable to results of standard laboratory viscometers. In addition, due to the accurate modeling of the fluid-sphere-WT interaction by transduction matrix method, the result of WT is not only quantitative but also accurate, with measurement error being as small as 1.4% for dynamic viscosity and 0.5% for density (water 25 °C). And a wide measurement range of viscosity is achieved which is at least from 8.93×10^{-4} to 4.15×10^{-2} N s/m². Finally, issues about its miniaturization were discussed and simulated. It was found that after miniaturization the fluid load will be dominated by its damping part. And miniaturization will increase the sensitivity of WT. However, it will increase its resonant frequency which is undesirable.

(4) The mechanism of rat's vibrissal tactile perception has been investigated with the WT. And a new hypothesis has been suggested.

The WT was used to test the “kinetic signature hypothesis” proposed by some neuroscientists in a biomimetic perspective. It was found that texture is not directly coupled into the whisking signal as a high frequency component. Therefore this hypothesis may be oversimplified. Based on the texture sensing experiment with WT, it was suggested that mechanical impedance is a better indicator of texture than the texture-induced high frequency component, since it is more invariant to variations of whisking parameters.

7.2 Summary of contributions

The WT developed in this thesis contributes directly to robotic tactile sensing. On the other hand, as a general transducer, it can also contribute to a wide range of areas such as metrology, tribology, viscometry as well as the broader field of dynamic testing. Several contributions of the most importance are summarized as follows:

- This thesis contributes to robotic tactile sensing by providing a novel vibrissal tactile sensor featuring simultaneous sensing and actuating (SSA), compact structure, high versatility, high efficiency, accurate mathematical model and easy implementation.
- A bio-inspired triple-coding scheme for 3D location sensing using WT has been developed which can potentially solve problems like object shape detection and geometry detection of high-aspect-ratio micro holes.
- It also contributes to online fluid viscosity sensing by providing a new sensing technique which is quantitative, accurate and easy to implement. And more importantly, it can obtain separated values of dynamic viscosity and density that are difficult to separate by existing viscosity sensors.
- The testing of the possible mechanism of the biological vibrissal tactile perception conducted in this thesis helps neuroscientists view the problem from a different angle. And the new hypothesis suggested based on experimental results using WT can be a good option for them to check biologically.
- The calibration method of transduction matrix has been simplified by introducing a precision cantilever beam load which is tested at different locations. This facilitates the implementation of the transduction matrix method in the micro-world.

7.3 Recommendations

Despite the successful development and novel application of the WT in this thesis, there

is still room for improvement in the future. First, the parameters of the WT such as its materials and dimensions need to be optimized. Currently they are chosen empirically therefore the WT may not be working in an optimal condition. For example, the reduction of the resonant frequency of the WT was achieved by adding a small piece of mass to it in Chapter 4. However, this can be achieved in a better way by optimizing the dimensions of the steel whisker and PZT bimorph, without adding anything. In addition, it was found that a stiffer whisker would increase the sensitivity of the WT. This can be achieved by increasing its thickness and elastic modulus which, however, may lead to a loss of its merits such as high aspect ratio and flexibility. Therefore a compromise should be made through optimization of its parameters to achieve optimal performance.

Second, advanced techniques and algorithms need to be developed in robotics to make the performance of a robot equipped with WTs match that of a real rat. Currently the vibrissal tactile sensing abilities of the WT were demonstrated in a well-controlled environment. For example, the contact angle and the normal force were controlled in texture sensing. And in location sensing, the assumption of single-point contact condition was made. However, a real rat uses its whiskers more freely and its performance is very robust even under different contact conditions. There is also evidence that rat can integrate signals from different whiskers to achieve better performance. These behaviors and strategies may be learned by robots through the use of artificial intelligence to improve their performance.

Third, although some potential applications of the WT were illustrated, other potential applications mentioned in this thesis still need to be studied in the future. For example, the proposed application of WT in characterizing non-Newtonian fluids needs further experimental verification. The application of object shape detection can be studied by building a WT-array and installing it on a rat robot. And applications in microfluidics and biomedicine can be carried out with the miniaturized WT, such as *in vivo* blood viscosity monitoring and cell mechanical property characterization.

Finally, although reliability and repeatability of the WT were considered and evaluated in this thesis, more testing and characterization are still needed before the WT can be commercialized and used in real applications. For example, the glycerol-water mixture used as fluid specimen in viscosity and density sensing is not a standard reference system, and it is difficult to properly prepare solutions of exact composition. More standard reference systems such as those recommended by IATP (International Association for Transport Properties) may be considered in future testing. In addition, since temperature has significant effect on fluid viscosity, the WT needs to be characterized within a wide temperature range so that it can be used in temperature-varying environments.

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