An impedance based method for acoustical absorption coefficient measurement and membrane health monitoring

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**AN IMPEDANCE BASED METHOD FOR ACOUSTICAL
ABSORPTION COEFFICIENT MEASUREMENT AND
MEMBRANE HEALTH MONITORING**

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ABSTRACT

Impedance, as one of frequency response functions, characterizes the dynamic behavior of the system and does not change with external excitations. Mechanical impedance is useful for applications such as modal testing, mechanical design and vibration monitoring, while acoustical impedance is closely related with the characterization of sound absorption material. However, measurement methods of acoustical/mechanical impedance are not as developed as for their theoretical counterparts due to lack of appropriate transducers to measure excitation or response variables.

In this thesis, based on the simultaneous sensing and actuating (SSA) capability of a dynamic microphone, the absorption coefficient of acoustical materials is measured and the state of health of a membrane is monitored at the end of a tube. In addition, a similar SSA technique is studied for a micro PZT cantilever transducer to measure mechanical impedance of micro structures.

The SSA capability of a dynamic microphone is firstly studied. With the calibrated transduction matrix, the dynamic microphone could perform well as a simultaneous sensor and actuator, which is validated by the measurement of mechanical impedance of point masses. Based on the SSA capability of the dynamic microphone, a

sensor-less method for measurement of specific acoustical impedance or absorption coefficient of materials in a standing wave tube is developed. The dynamic microphone-tube system is modeled as a two-port model, and the specific acoustical impedance is quantitatively expressed as a function of electrical impedance. Testing on different materials shows that through detecting electrical impedance of the dynamic microphone, specific acoustical impedance and, thus, the absorption coefficient of the material are accurately measured. Furthermore, the dynamic microphone is utilized for monitoring the damage level of an eardrum-like membrane based on its SSA capability. Taking the electrical impedance of the dynamic microphone as signature allows one to conveniently monitor the health of eardrum-like membrane and estimate the damage level.

Subsequently, a micro PZT cantilever transducer is designed to measure mechanical impedance of micro structures. The transduction matrix of the micro PZT cantilever transducer is numerically determined via finite element analysis. With the calibrated transduction matrix, the mechanical impedance of micro structure is numerically measured by the transducer. In addition, with the transduction matrix, it is demonstrated that the PZT cantilever transducer could be used to measure force and velocity of the micro structure. Finally, fabrication of the micro PZT cantilever transducer through MEMS technology is presented in detail.

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Chapter 1

Introduction

1.1 Background

Impedance is a frequency response function of a linear dynamic system defined as the ratio of excitation variable to response variable. It is the inherent characteristics of the system and does not change with the level and form of the external excitations. In general, impedance Z is a complex number and can be written in Cartesian form

$$Z = R + jX \quad (1.1)$$

or in the polar form

$$Z = |Z|e^{j\theta} \quad (1.2)$$

where j is the imaginary unit, the real part of impedance, R , is called resistance and the imaginary part of impedance, X , reactance. $|Z|$ is the amplitude and θ the phase. Impedance has been widely studied in electrical, mechanical and acoustical domains.

The electrical impedance is defined as the ratio of voltage applied to a circuit and the resulting current, which is described by the following equation

$$Z_e = \frac{E}{i} \quad (1.3)$$

where E is a complex excitation voltage, i is the resultant complex current.

Electrical impedance is easily measured. A setup including a voltage probe, current probe together with a two channel FFT analyzer is the most commonly used way to obtain electrical impedance.

Point mechanical impedance is defined as the ratio of the exciting force at one point to the velocity at the same point of a mechanical system, as described by the following equation

$$Z_m = \frac{F}{v} \quad (1.4)$$

where F is the complex driving force and v is the resultant complex velocity at the point where the force is applied. If the force and velocity are measured at the two different points, the ratio of force and velocity is called transfer mechanical impedance. In this thesis, only point mechanical impedance is studied, while transfer mechanical impedance is beyond our interest. Mechanical impedance characterizes the dynamic behavior of a mechanical system. It is measured for purposes such as material characterization, structural identification or health monitoring under dynamic excitations.

The most common way to evaluate the mechanical impedance of a structure is to excite it using an actuator and measure the excitation force and responded motion by a load cell and an accelerometer respectively [1]. In this conventional measurement system, three transducers including exciter, force sensor and accelerometer, are needed. In the process, the measurement accuracy is often affected by the loading

effects introduced by these devices. In addition, installing the exciter and the sensors onto structures on site and ensuring true driving-point measurement are another two big problems to be overcome. When measuring mechanical impedance of miniature or micro scale structures, conventional sensors introduce excessive loading effect which causes big errors. Besides these, the installation of the conventional transducers becomes very difficult or impossible due to the very limited available space. Although the availability of Laser Doppler Vibrometer (LDV) makes it easier to obtain the response of small systems, the space required for actuators and its associated force transducers remains a major obstacle to applying conventional dynamic testing techniques to miniature or micro scale systems.

In acoustical domain, several definitions of impedance are available for different application purposes. Among those impedances, the specific acoustical impedance is directly related with the characterization of sound absorption material. The specific acoustical impedance is the complex ratio of the effective acoustic pressure at a point of an acoustic medium or mechanical device to the effective particle velocity at the same point, i.e.

$$Z_a = \frac{p}{u} \quad (1.5)$$

where p is the complex pressure and u is the particle velocity. The particles mentioned here are not single gas molecules or anything like that. In acoustics, a particle is defined as a volume which is small compared to the dimensions of measuring devices or the wave length, but large compared to the molecular mean free

path ($\bar{l} = 5 \cdot 10^{-8} m$). In tubes, when considering only the plane wave mode, the particle velocity is the component along the direction of central axis of tube.

Actually, the difference between mechanical impedance and acoustical impedance lies in format more than in essence. In some research literature, acoustical impedance is considered as one sub-category of mechanical impedance. In this thesis, to state clearly, mechanical impedance is particularly for structures, while acoustical impedance is for sound waves in a compressible fluid, such as air or water.

The most straightforward way to measure acoustical impedance at a point is to measure the pressure and particle velocity at this point simultaneously. The measurement of the pressure is conveniently carried out using a microphone, but the measurement of particle velocity is much more difficult. Among the few researches about successful measurement of particle velocity, Pratt *et al* [2, 3] used a hot wire anemometer and Bree *et al* [4-8] invested a novel device to measure particle velocity, but they remain unusual. The second way to obtain specific acoustical impedance is to measure with two pressure microphones. As the particle velocity is locally proportional to the pressure gradient, it is possible to use the pressure difference measured by a pair of microphones to deduce the particle velocity, and then obtain the specific acoustical impedance [9]. However this method requires very precise amplitude and phase calibrations for each of the two microphones, otherwise the measuring error becomes unacceptable large [10].

As described above, existing methods and equipments are inconvenient and sometimes inaccurate in measuring mechanical/acoustical impedance. New transducers and sensing techniques for mechanical/acoustical impedance measurement are required. In the past decade, simultaneous sensing and actuating (SSA) technique has been developed for such purpose [11-14]. As people know, electromechanical actuators convert electrical into mechanical/acoustical power in order to drive an attached mechanical/acoustical system in the downstream of a power flow path. Because of internal electromechanical interaction, the voltage and current at the input ports of these actuators vary if the load driven by the transducer at the output port changes. If the relationship between the input variables and the output variables is made known, we then can obtain the output mechanical/acoustical variables by detecting the input electrical variables. Among the input electrical variables and the output mechanical/acoustical variables, four frequency response functions exist and together form a two-by-two matrix. This matrix completely characterizes the forward actuating and backward transduction functions of the actuator and thus is termed a transduction matrix.

The advantages of using transduction matrix for SSA are of two folds. Firstly, the difficult task of measuring output force (pressure) and velocity (particle velocity) is now replaced by the relatively easier probing of input voltage and current. The loading effect from the actuator is completely decoupled for impedance measurement and results in good measuring accuracy [15]. Secondly, since both potential and flow

variables are simultaneously measured, the mechanical/acoustical impedance at the output port of the transducer can now be calculated from the electrical impedance at the input port. An electromechanical transducer, therefore, performs both actuating and sensing simultaneously, eliminating or reducing the difficulties discussed earlier. In view of health condition monitoring and material characterization, impedance is far better than a potential or flow signal as the monitoring signature. This is because impedance is the inherent property of a system, and any change of the system will cause a change of the impedance.

1.2 Objective and Scope

The objective of the research work is to develop an impedance based method for measuring acoustical absorption coefficient and monitoring healthy state of membrane through a dynamic microphone. In addition, based on the same working principle, the transducer is miniaturized as a micro PZT cantilever for probing acoustical waves or micro structures. Hence, the scope of this thesis is:

1. Studying the simultaneous sensing and actuating capability of a dynamic microphone.
2. Measuring absorption coefficient of acoustical materials by the dynamic microphone in a portable tube.
3. Taking electrical impedance as signature to monitor healthy state of eardrum-like membrane at tube end.

4. Studying the simultaneous sensing and actuating capability of a micro PZT cantilever transducer to measure mechanical impedance for micro structures.
5. Fabricating micro PZT cantilever transducer through MEMS technology.

1.3 Outline of Thesis

In Chapter 2, existing methods for measuring specific acoustical impedance and absorption coefficient are reviewed first. Conventional methods and using active material for detecting mechanical impedance are reported, and their disadvantages or difficulties of these methods are discussed. Subsequently, literatures on taking electrical impedance as signature for non-destructive evaluation are summarized. Finally, SSA technique based on transduction matrix and its applications are briefly introduced.

Chapter 3 studies the SSA capability of a dynamic microphone. The dynamic microphone is modeled as a two-port model, which contains input electrical port and output mechanical port. A two-by-two transduction matrix is developed from both theory and experiment to relate the input electrical variables (voltage and current) and output mechanical variables (force and velocity). With the obtained transduction matrix, mechanical impedance of structures at the output port can be indirectly detected by probing electrical impedance. For experimental verification, mechanical impedances of a few point masses are measured by the proposed method.

In Chapter 4, a sensor-less method for measurement of specific acoustical impedance and absorption coefficient of materials mounted at the end of a standing wave tube is presented. The propagation of acoustic wave in standing wave tube is firstly introduced. The dynamic microphone-tube system is modeled as a two-port model, and the acoustical impedance is expressed as a function of electrical impedance with the help of three conditional impedances. After the conditional impedances are calibrated, the specific acoustical impedance of the material specimen is quantitatively evaluated by probing the input voltage and current to the dynamic microphone, and then absorption coefficient of the materials are calculated. Experiments on five different acoustic materials are carried out and the results are compared with those from classical transfer function method.

Chapter 5 describes a method taking electrical impedance as signature to monitor damage of eardrum-like membrane, and classifying damage severity through an artificial neural network. A dynamic microphone and an eardrum-like membrane are mounted at the two ends of an ear canal-like tube, respectively. Variation of electrical impedance from the dynamic microphone is observed for different damage levels of membrane. Features are extracted from the curves of electrical impedance and used to train an artificial neural network. The results obtained from the neural network for a few verification sets are identical with the real values, which validates the effectiveness of the proposed method for estimating damage levels of membrane.

In Chapter 6 the above methods are extended to measure mechanical impedance for

micro structures. A micro PZT cantilever transducer is developed in this case. The two-by-two transduction matrix for the transducer is numerically calculated via finite element analysis. Numerical measurement of mechanical impedance for micro structures by the transducer is presented. With the transduction matrix, measurement of force and velocity by the transducer is also discussed. Subsequently, this chapter presents the fabrication process of micro PZT cantilever through MEMS technology. A modified PZT thin film deposition technique is applied to the fabrication of micro piezoelectric cantilevers. Performances of PZT thin film by the modified process such as X-ray diffraction pattern and hysteresis loop upon polarization are characterized. Measurement of resonant frequencies for fabricated piezoelectric cantilever is performed to verify the self-excitation capability. The dynamic response of cantilever is also approximately checked via a simple primitive test.

Finally, the conclusions of the thesis and recommendations related to the current research topic are given in Chapter 7.

Chapter 2

Literature Review

In this chapter, the literature review is focused on five areas. Firstly, fundamental of acoustic waves in a standing wave tube is briefed to serve as a base for the development to be presented later. Secondly, the existing methods for measuring specific acoustical impedance or absorption coefficient using standing wave tube are introduced. This part provides comparisons for the new method proposed in this thesis to measure acoustic absorption coefficient. After that, the conventional methods for detection of mechanical impedance are summarized, and disadvantages or difficulties of those methods for measurement of mechanical impedance are discussed. Then, literature on taking electrical impedance as signature in application of monitoring structural health or estimating mechanical system is reviewed. Finally, the recently developed simultaneously sensing and actuating method based on transduction matrix is presented. Applications of this technique and newly developed transducers for such purpose are also surveyed.

2.1 Acoustic Waves in a Standing Wave Tube

2.1.1 Transfer Matrix for Acoustic Waves in a Standing Wave Tube

Assume that in a standing wave tube a plane wave propagates from $x = 0$ and

reflects at $x = L$, as shown in Figure.2.1. The characteristic property of a plane wave is that each acoustic variable has constant amplitude and phase on any plane perpendicular to the direction of propagation.

Fig.2. 1 Acoustic waves in a standing wave tube

In general, for a time-harmonic wave, the pressure in the standing tube is given by

$$\tilde{p}(x,t) = (Ae^{-jk(L-x)} + Be^{jk(L-x)})e^{j\omega t} = pe^{j\omega t} \quad (2.1)$$

where $k = \omega / c_0$ is the wave number with ω the frequency and c_0 the undisturbed speed of sound, p is the pressure amplitude (may be complex) at a single frequency of the pressure $\tilde{p}$, A and B are arbitrary complex numbers which represent the amplitude and relative phases of waves traveling in the positive and negative x direction respectively [16]. For one-dimensional acoustic wave along x direction, the linear Euler's equation is written as

$$\rho_0 \frac{\partial \tilde{u}(x,t)}{\partial t} + \frac{\partial \tilde{p}(x,t)}{\partial x} = 0 \quad (2.2)$$

where ρ_0 is the mean density of the medium (air), u is the particle velocity. From Equation (2.1) and (2.2), particle velocity associated with the pressure wave in the tube can be found

$$\tilde{u}(x,t) = \left(\frac{Ae^{-jk(L-x)}}{\rho_0 c_0} - \frac{Be^{jk(L-x)}}{\rho_0 c_0} \right) e^{j\omega t} = ue^{j\omega t} \quad (2.3)$$

where u is the amplitude of particle velocity $\tilde{u}$. Hereafter, unless otherwise mentioned, pressure and particle velocity are referred as their corresponding amplitudes. At $x = L$ and $x = 0$, pressure and particle velocity are respectively:

$$p_L = A + B \quad (2.4)$$

$$u_L = \frac{A - B}{\rho_0 c_0} \quad (2.5)$$

$$\begin{aligned} p_0 &= Ae^{-jkL} + Be^{jkL} \\ &= (A + B)\cos kL - j(A - B)\sin kL \\ &= p_L \cos kL - j\rho_0 c_0 u_L \sin kL \end{aligned} \quad (2.6)$$

$$\begin{aligned} u_0 &= (Ae^{-jkL} - Be^{jkL})/\rho c \\ &= \frac{(A - B)\cos kL}{\rho_0 c_0} - j\frac{(A + B)}{\rho_0 c_0}\sin kL \\ &= u_L \cos kL - j\frac{p_L}{\rho_0 c_0}\sin kL \end{aligned} \quad (2.7)$$

Equations (2.6) and (2.7) can be written in the matrix form

$$\begin{Bmatrix} p_0 \\ u_0 \end{Bmatrix} = \begin{bmatrix} \cos kL & -j\rho_0 c_0 \sin kL \\ -j/\rho_0 c_0 \sin kL & \cos kL \end{bmatrix} \begin{Bmatrix} p_L \\ u_L \end{Bmatrix} = [T] \begin{Bmatrix} p_L \\ u_L \end{Bmatrix} \quad (2.8)$$

The transfer matrix $[T]$ relates the acoustic variables at the two ends of the tube. It is easily found that the determinant of this transfer matrix $[T]$ is unity.

2.1.2 Acoustic Impedance in a Tube Ended with Absorbing Material

Assume that a one-dimensional acoustic field is generated with a sound source in a tube ended with absorbing material, as shown in Figure.2.2 [17]. The plane waves are reflected and absorbed by the absorbing material at the end of the tube ($x = L$). The

reflection coefficient R or the absorption coefficient $\alpha = 1 - |R|^2$ of the absorbing material for normal incidence can be calculated from the acoustic impedance Z_a .

Fig.2. 2 Tube ended with absorbing material

The specific normal acoustic impedance on the surface of the absorbing material relates the acoustic pressure p to the normal component of the particle velocity u according to

$$Z_a(\omega) = \frac{p}{u} \quad (2.9)$$

The surface can be porous or rigid and its impedance depends on the frequency ω (in rad/s). So, $R(\omega)$ and $\alpha(\omega)$ are also frequency dependent. The pressure as a function of the x coordinate can be written as

$$p(x) = \hat{p}(e^{jk(L-x)} + R(\omega)e^{-jk(L-x)}) \quad (2.10)$$

with $\hat{p}$ is the amplitude of the pressure and $R(\omega)$ the reflection coefficient. $e^{jk(L-x)}$ represents the forward traveling wave, i.e., in the positive x -direction and $R(\omega)e^{-jk(L-x)}$ the reflected wave.

From the Equations (2.10) and (2.2), the particle velocity in a tube can be derived:

$$u(x) = \frac{\hat{p}}{\rho_0 c_0} (e^{jk(L-x)} - R(\omega)e^{-jk(L-x)}) \quad (2.11)$$

with $\rho_0 c_0$ the characteristic acoustic impedance. Using the definition for the

impedance at $x = L$ one has

$$\frac{Z_a(\omega)}{\rho_0 c_0} = \frac{1 + R(\omega)}{1 - R(\omega)} \quad (2.12)$$

with $Z_a(\omega)/\rho_0 c_0$ the specific acoustic impedance ratio. From Equation (2.12), if the acoustic impedance is measured, the acoustic reflection coefficient $R(\omega)$ or absorption coefficient $\alpha(\omega) = 1 - |R(\omega)|^2$ for normal incidence can be calculated according to the following equations:

$$R(\omega) = \frac{Z_a - \rho_0 c_0}{Z_a + \rho_0 c_0} \quad (2.13)$$

and

$$\alpha(\omega) = 1 - \left| \frac{Z_a/\rho_0 c_0 - 1}{Z_a/\rho_0 c_0 + 1} \right|^2 \quad (2.14)$$

2.2 Measurement of Acoustic Absorption Coefficient

Acoustic absorption coefficient is directly related with specific acoustical impedance on the surface of material. According to the definition, to obtain specific acoustical impedance, the most straightforward way is to measure pressure and acoustic particle velocity on the surface of material. The measurement of pressure is conveniently carried out using a microphone, but the measurement of the particle velocity is much more difficult [18-20]. Usually the measurement of the sound absorption for normal incidence is usually done by means of a standing wave tube [21-25]. The apparatus can be described as a tube of circular or squared cross section whose terminations are equipped respectively with a loudspeaker on one hand and with sample to be tested on

the other. The waves impinging the sample at a normal incidence are assumed to be plane and the stationary field inside the tube can be described as the superposition of one or more standing waves [26]. To achieve the sound absorption coefficient of the material there are basically two methodologies known respectively as “standing wave ratio” and “transfer function method” [27, 28].

In the standing wave method, the pressure amplitudes at nodes and antinodes are measured with a microphone probe attached to a moving car, which slides along a graduated ruler, as shown in Figure 2.3. The ratio of the pressure maximum (antinodes) to the pressure minimum (node) is called the standing wave ratio. This ratio, which always has a value greater than or equal to unity, is used to determine the test material's absorption coefficient or specific acoustical impedance. The microphone is moved along the tube to find standing wave ratio and the procedure has to be repeated for each pure tone of interest. Obviously, this procedure was inherently time consuming.

Fig.2. 3 Standing wave method for measurement of absorption coefficient

The transfer function method (also called two-microphone method) is much faster and algorithms are easily implemented by FFT analyzers. The setup of transfer function

method is illustrated in Figure 2.4 A broadband random noise signal is generated from the FFT analyzer and amplified by the power amplifier. The speaker then produces a random noise sound wave. A test specimen is mounted at the end of the impedance tube. The sound field inside the tube depends on the test material. The sound pressures of the standing wave at two different locations are picked up and fed into a dynamic signal analyzer to identify the transfer function which in turn is used to derive the absorption coefficient. However, the transfer function method requires very precise transfer function measurement, which implies accurate amplitude and phase calibrations for each of the two microphone sensors.

Fig.2. 4 Transfer function method for measurement of absorption coefficient

Recently, de Bree *et al* [4-8] developed a new acoustic sensor which can measure the acoustic particle velocity. They named this sensor Microflown. The measurement principle of Microflown is based on the temperature difference between two resistive sensors which are 40 μm apart. A traveling acoustic wave causes movements of the air, and heat is transferred from one sensor to the other sensor through convection. This will cause a difference in temperature between the two resistive sensors, from which

particle velocity is in turn derived.

With the newly designed particle velocity sensor (Microflown), de Bree *et al* have developed several methods to measure specific acoustical impedance or absorption coefficient. First, they used two Microflown sensors to take place of two microphones to implement the transfer function method [29]. Second, they put a Microflown sensor and a miniature pressure microphone close together to constitute a pu-probe, which can measure the pressure and particle velocity simultaneously at the same point. With the pu-probe, specific acoustical impedance in a standing wave tube can be measured directly. Finally, they extended the pu-probe method for the measurement in a semi-anechoic room to determine the absorption coefficient in a fast way in-situ, real time oblique and without the use of a standing wave tube [30]. However, due to the complicated process of fabrication and calibration for the sensor, the Microflown remains unusual.

When the cross-sectional dimension is small and the tube is not straight, the assumption of planar waves is still valid. However, the difficulties of properly inserting microphones into such tubes jeopardize the practical use of the standing wave method or transfer function method. To overcome this problem, Peng and Ling [31] introduced a method of microphone-free to measure absorption. They reported such a method in which only the input voltage and current of the speaker, or the actuator in the acoustic system, are to be probed. In another words, the actuator is

used as a sensor simultaneously in the approach. But this method requires complicated and sophisticated experimental investigations to identify the parameters of a loudspeaker. Furthermore, the authors considered the wave near the speaker was planar, which will cause errors when applying the theory of plane wave to relate the acoustical impedance at the two ends of tube.

2.3 Measurement of Mechanical Impedance

2.3.1 Conventional Method

To measure mechanical impedance of dynamic structure, normally a powerful excitation to actuate the test structure and an accurate measurement of the excitation force and the response velocity at the point of interest are demanded [32-35].

The excitation applied to the structure can be basically classified into two types: contact and non-contact. Contact excitation involves the connection of an exciter which remains attached to the structure throughout the test. Mechanical exciters, electromagnetic shakers and electrohydraulic shakers all belong to this category. Each of them has its advantages and disadvantages. Non-contact excitation uses devices which are either out of contact throughout the vibration or which are only in contact for a short time period. Hammer, a popular and relatively simple exciter to create vibrations, belongs to this category.

In addition to a powerful excitation mechanism, sensors for measuring the excitation force and the motion response are essential for measurement of mechanical impedance. There are many other developed devices available to measure the force and the motion. Nowadays, piezoelectric transducers are widely used for both types of measurement in the form of load cell, accelerometer and impedance head. Recently, lasers also become commonplace to provide a non-contact response transducer in the form of Laser Doppler Velocimeter (LDV) [36]. In the following, only one of the most widely used setup is addressed here as an illustration Figure 2.5 A common electromagnetic shaker is employed to excite the structure under testing; a load cell and an accelerometer are utilized to detect the excitation and the response. The load cell and the accelerometer can also be encapsulated into one housing, forming an impedance head. While, the working principles are basically the same.

Fig.2. 5 General layout of FRF measurement system [1]

Shaker is utilized in this setup due to its easy availability. Its small size and high efficiency provides it with the capability to excite small structures at high frequencies [37-40]. One consideration concerning shaker is how to support or mount it on site. The general grounding requirement often poses inconvenience in experiments. In addition, although it seems that shaker is capable of applying a force in one direction only, due to the fact that the motion of most practical structures is generally complex and multidirectional, an unwanted secondary form of excitation often exists. The usual solution is to attach the shaker to the structure via a driving rod or stinger which is assumed to be stiff in one direction while flexible in all other directions. However, if the stinger is too long or too flexible, big errors will be introduced into measurement. To supply strong enough vibrations, power amplifier is often necessary for a shaker.

Due to the working principles of force and response transducers showed in Figure 2.5 the heavier and larger of the transducers, the higher the sensitivity. However, the addition of even small transducers imposes unwanted loading effects to the structure, changing its dynamic properties. Such loading effects, including inertia loading and local stiffening, can't be completely compensated.

Besides, as we aim to measure mechanical impedance at a given point, both force and response transducers should be at the same measurement point on the structure. Particular care is required to ensure that the measurement is the true mechanical

impedance at the point. However, this requirement is sometimes difficult to achieve.

2.3.2 Measurement Using Active Materials

In the past two decades, many researches have been devoted to developing transducers using piezoelectric materials. In 1994, an impedance method for dynamic analysis of active material systems has been developed by Liang, *et al* [41-44]. The impedance approach provides a straightforward approach to accurately determining the dynamic response of active material systems. In the impedance approach, the structural dynamic analysis and actuator electromechanical analysis are combined on the basis of matching structural and actuator impedance. To use the impedance model, one would only need the structural impedance at the actuator driving point (for single actuator cases), which may be calculated or measured without considering actuator-stiffening effect. On their work, variation of the mechanical impedance of the structure is detected by measuring the electrical impedance of PZT. A one-dimensional model governing the electro-mechanical coupling was successfully developed. The work proves the correctness of the concept.

Later, Liang *et al.* extended the impedance modeling of the PZT patch actuator to multi-degree-of-freedom systems by addressing the dynamic modeling of an active beam. A pair of piezoelectric patches was collocated on both sides of the host cantilever beam. The equations of motion of the beam were first analytically

developed and the corresponding solution was derived. The interaction between the host beam and the surface bonded piezoelectric actuators was then represented by pure line moments at the edges of the patches. Subsequently, the rotational impedance of the beam to line moments caused by the PZT patches was presented. Using similar procedure, Zhou *et al* [45] and Lalande [46, 47] applied the above approach to plate, shell and ring structures with surface bonded actuators.

In all the above papers by Liang and his team, it is important to note that to model the dynamic interaction between the surface-bounded PZT patch and the host structure, the impedance of the host structure has to be first determined by an analytical solution. In other words, this method relies on the closed-form analytical solutions of the structural impedance, which often needs a complex process to be determined. Therefore, in applications, the method introduced is not only difficult to apply, but most significantly, calibrating the measurement system is inherently impossible due to the constitution of the measurement system.

2.4 Electrical Impedance as signature for Non-destructive Evaluation

Input impedance, whether electrical or mechanical, characterizes the dynamic property of a linear dynamic system and its value is independent upon inputs and environment. This property of input impedance makes it an ideal signature for

monitoring, evaluation and diagnosis. Because detecting electrical impedance via probing voltage and current is much simpler than detecting mechanical impedance using force and motion sensors together with one or more actuators, electrical impedance-based structural health monitoring techniques have been developed as a promising tool for real-time structural damage assessment, and are considered as a new method for non-destructive evaluation (NDE).

A key aspect of electrical impedance-based structural health monitoring is the use of piezoceramic (PZT) material as collocated sensors and actuators. The theoretical development of the application of electrical impedance measurements to structural health monitoring was first proposed by Liang *et al* [48] and subsequently developed by Sun *et al* [49], Park *et al* [50-55], Giurgiutiu and Zagari [56-60], and Ling [6-7]. Their studies showed that the electrical impedance of the PZT is directly related to the mechanical impedance of the host structure, allowing the monitoring of the host structure's mechanical properties using the measured electrical impedance. Consequently, any changes in the electrical impedance signature can be considered an indication of changes in the structural integrity.

Experimental implementation of the electrical impedance-based structural health monitoring technique has been successfully conducted on several complex structures. Sun *et al* [49] pioneered the application of the impedance method to structural health monitoring by testing the truss structures. Chaudhry *et al* [61] monitor the integrity of

the tail section of a Piper Model 601P airplane. Two types of joint damage were induced in the structure: local and distant damage. The impedance sensors showed extreme sensitivity to the extent of damage for local area, and demonstrated insensitivity to far-field changes. Monitoring of a massive built-in bridge structure has been performed by Ayres *et al* [62]. The bridge model consists of steel angles, channels, plates, and joints connected by over 200 bolts. The size of this structure is 1.8 m tall and has a weight of over 250 kg. The same structure has been investigated by Park *et al* [50] under uncontrolled environmental conditions, which have varying mass loading, temperature, and operational vibrations. The capability of the impedance method to detect and distinguish incipient damage from these variations has been demonstrated. Giurgiutiu *et al* [63] present health monitoring results of spot-welded structural joints. The initiation and propagation of damage were successfully correlated with the impedance measurements. In addition, through the use of multi-site impedance measurements, the sensitivity to minor cracks, localization of damage, and rejection properties to far-field changes have been observed. Ling *et al* [64] used a piezoelectric inertial actuator affixed to a structure as a collocated sensor cum actuator for monitoring structural integrity through measuring electrical impedance. Their method can be implemented via a self-contained, integrated device, and their device can be conveniently attached to a structure on site indoor or outdoor through glue bonding or magnetic attraction and thus avoids the major inconvenience of mounting and dismounting actuators and sensors required in conventional modal testing methods when used for health monitoring.

Besides monitoring structural health, electrical impedance as signature for nondestructive evaluation can also be applied in manufacturing processes. Ling [64] extended their method to evaluating joining quality of welds in ultrasonic welding. They showed that input electrical impedance of the PZT drive of an ultrasonic welding machine is a good signature for the joining quality of a weld made by the machine. This is because the waveform of the input impedance of the welding machine is closely correlated with the thermo-mechanical behavior of the plastic work pieces at the joining interface and this thermo-mechanical behavior is fully responsible for the final quality. Fu *et al* [65] demonstrated that input electrical impedance of spindle motor is a useful signature for monitoring health conditions of micro-drills drilling process. Drill wear and variation of work-piece material are system properties and is explicitly revealed in the signature of electrical impedance. Furthermore, they confirmed that input electrical impedance is better than current in micro-drilling, because the disturbances inherently existing in supplied electrical power play more influential roles than drill breakage does in current signal. Xiao and Ling [66] took electrical impedance as signature to monitor the working condition of an electrical discharge machine (EDM). Through extracting features from electrical impedance and using fuzzy reasoning system as the classifier, they can effectively differentiate sparks and arcs in EDM process.

2.5 Simultaneous Sensing and Actuating (SSA) Method

Transducers may generally be divided into two classes: sensors and actuators [67].

Sensors are devices that detect or measure a parameter of a system, hopefully without disturbing that parameter. It has been thought for decades that any transducer in operation is functioning at any given moment either as a sensor or as an actuator. In real sensors it is not possible to achieve the ideal of a transducer, which monitors a parameter while having absolutely no affect on it, because the act of making a measurement requires either adding energy to the system or subtracting energy from the system. In order to minimize the loading effect of a sensor on the system, the size and energy exchange of the sensor usually must be minimized. On the counterpart, actuators are devices, which impose a state on a system, hopefully independent of the load applied to them. The ideal of a load-independent actuator can never be achieved for a transducer with finite energy, because there will always be a load exceeds its energy handling ability. The desire to minimize the loading effect of the load imposed by the system on the actuator performance usually leads to large and high-power actuators.

The distinctions between sensors and actuators also explain why it is so difficult to build a transducer which functions well, as both a sensor and an actuator. If the design is optimized for operation as a sensor, meaning low power and small size, then the device is not well suited to operating as an actuator. Similarly, if the transducer is

designed to function primarily as an actuator, with high power and large size, then it is not likely to make an adequate sensor. These distinctions have made people think that it is extremely difficult to build a transducer which functions well as both a sensor and an actuator. However, taking advantage of the loading from the test system to the actuator, it is possible to “sense” the properties of the system from the input variables of the actuator so that actuator functions both actuating and sensing simultaneously.

In early 2000s, Ling and his team developed a SSA method to measure mechanical impedance [11-15]. In their works, a two-by-two matrix is built and utilized to describe the relationship between the input electrical variables and output mechanical variables. As it completely characterizes the forward actuating and backward sensing functions of the SSA transducer, it is termed a transduction matrix. Utilizing such transduction matrix, the mechanical impedance at the output port can be evaluated from the electrical impedance measured at the input port. Thus, using this technique, measurement of mechanical impedance is converted to measurement of electrical impedance, which is easily to achieve. Besides, the output potential value and flow value are also quantitatively determined. Since then, the sensing capability of a number of newly designed transducers as well as existing actuators such as motors, speakers, and shakers, has been investigated.

In 1998, a Piezoceramic Inertial Actuator (PIA) was designed to measure mechanical impedance and monitor structural integrity without involving conventional sensors

like accelerometers, load cells or impedance heads [12]. The structure of the PIA is shown in Figure 2.6 The proof mass, the aluminum plate, the PZT patch, and other necessary frame works constitute a PIA.

Fig.2. 6 Structure of a piezoceramic inertial actuator

When the actuator is attached to a host structure, there is an electromechanical interaction between the host structure and the actuator. In experiments, the actuator generated a reaction force to excite the test structure by accelerating an inertial mass. At the same time, the mechanical impedance of the structure was “senselessly” detected. Therefore, PIA functioned both actuating and sensing at the same time. A two-port model can model the actuator as shown in Figure 2.7 since the PIA is a linear dynamic transducer without internal energy generation or consumption.

Fig.2. 7 Two-port model of PIA

The relationship between the input electrical voltage and current and the output mechanical force and velocity can be described by a transduction matrix,

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} F \\ v \end{Bmatrix} = [A] \begin{Bmatrix} F \\ v \end{Bmatrix} \quad (2.15)$$

$[A]$ is named transduction matrix of the PIA and its four elements are complex transduction functions. In their research, they identify $a_{11}, a_{12}, a_{21}, a_{22}$, which are related with system parameters and frequency successful by experiment method. As we know that E and i are easy to measure compared with that of F and v . With the known E , i and the transfer matrix, F and v are easily calculated.

Figure 2.8 is schematic of measurement of mechanical impedance using PIA. In this experiment, the mechanical impedance of the beam at a point which is 1/6 of the beam span from the left end is first picked-up by an impedance head while a PIA serves as the exciter only at the same point [12]. Afterwards, the mechanical impedance at the same point is detected via the PIA as actuator and sensor simultaneously using above method. The measured and the “detected” mechanical impedance of the beam at the given location are compared and agreement is found between the two results. The validity of the above method “transduction matrix” and feasibility of PIA for mechanical impedance measurement are confirmed. A further study about the PIA [15] demonstrated the role of the transduction matrix in decoupling the loading effect of the actuator when conducting SSA.

Fig.2. 8 Mechanical impedance detection by using a PIA

Furthermore, in 2001, the use of a PIA affixed to a structure as a collocated sensor cum actuator for monitoring structural integrity is also studied [11]. It's well understood that variations of the mechanical impedance directly indicates changes of structural properties, such as stiffness changes due to cracking, mass changes due to wearing, or changes of boundary conditions due to malfunctions of a coupling machine element. As revealed above, the input electrical impedance of a PIA attached to a structure is a sensitive function of the mechanical impedance of the structure at the attaching point. Therefore, any change of structural conditions due to problems of structural integrity, changes of supporting conditions, etc, can be detected by comparing the records of input electrical impedance of a PIA attached to a structure.

Fig.2. 9 Material characterization using a shaker as a sensor cum actuator

A study for utilizing electromagnetic shaker as SSA transducer is investigated by Yin *et al* [13]. A small electromagnetic shaker together with an indenter fixed at its output end forms an electromechanical actuator which takes in ac electrical power and exerts dynamic indentation to the material specimen under testing as illustrated in Figure 2.9. When supplied with ac electrical power, a dynamic force was exerted to the specimen, indenting the ball to the specimen. At the same time, the input voltage and current of the shaker were measured, which contained information of the elastomer's vibration. A transduction matrix relating the input electrical voltage and current and the output force and velocity is calibrated experimentally. Since this transduction matrix neatly relates the mechanical impedance of the material with the electrical impedance measured at the input port of the actuator, the electromechanical transducer senses impedance simultaneously when actuating. Because no direct measurement of motion

and force are required, this method possesses advantages in testing miniature samples in situ and development into a low cost handy tool for characterization of soft tissues, such as human skin is in progress.

Since 2002, Hou and Ling designed a new Bimorph Impedance Transducer to accurately and conveniently measure both translational and rotational mechanical impedance [68, 69]. The schematic of the newly designed Bimorph Impedance Transducer (BIT) is shown in Figure 2.10. It consists of a pair of identical piezoelectric bimorphs, an insulating layer, and a supporting block. The two bimorphs have same material characteristics and geometric dimensions and are attached to the insulating layer at their inner ends. Each bimorph consists of two piezoelectric elements, which are electrically connected in series and have opposite polarization directions. A center metal shim is inserted between the two piezoelectric layers to improve the strength of the bimorph.

Fig.2. 10 Structure of bimorph impedance transducer

When ac electrical power is supplied to the left and right bimorphs in the BIT,

harmonic forces and moments are generated at their inner ends. If the electrical signals applied to the two bimorphs are identical in both amplitude and phase, the resulting moments are same in magnitude but opposite in phase, therefore they offset each other; while the forces are doubled as they possess same magnitude and phase, as shown in Figure 2.11 (a). The resulted force then sets the test structure into harmonic vibrations. In contrast, if the electrical excitations are same in magnitude but opposite in phase, the forces offset each other and the moments are doubled and exerted to the structure, as illustrated in Figure 2.11 (b).

Fig.2. 11 Working Principles of the BIT for impedance measurement

For either force or moment excitation, during actuation, the vibration behavior of the

tested structure at the measurement point is embedded in the input electrical parameters of the transducer due to electro-mechanical interaction. Therefore in both translational and rotational measurement, the Bimorph Impedance Transducer functions as both an actuator and a sensor simultaneously. With the calibrated transduction matrix, the measurement of translational/rotational impedance is simply performed by measuring the input electrical impedance of BIT. Furthermore, this transducer can be utilized for characterizing linear viscoelastomers and magnetorheological elastomer.

A method of making use of PZT-coated cantilevers as both vibration exciters and sensors simultaneously to measure the point mechanical impedance of structures was proposed by Ling *et al* [14]. The schematic of the designed PZT cantilever is shown in Figure 2.12. Piezoelectric patch is bonded on one side of a cantilever, and a point at the free end was defined as the output port where a stinger was installed in the testing.

Fig.2. 12 Schematic of PZT driven beam

Fig.2. 13 Schematic of system for mechanical impedance measurement

Supplied with electricity, the cantilever vibrated and exerted forces to test a structure connected to its tip (Figure 2.13). Due to the load from the test structure, the PZT patch of the cantilever undergoes variations of input electrical impedance. Probing the input electrical impedance quantitatively detects the mechanical impedance imposed at the output port of the cantilever transducer provided that its transduction matrix is known. As a further study, Wang [70] carried out an optimization that decides the dimensions and system parameters of the transducer, which provides the optimal compromise between the sensing and actuating capability.

Chapter 3

Simultaneous Sensing and Actuating (SSA) Capability of a Dynamic Microphone

In this chapter, a dynamic microphone is studied for its simultaneous sensing and actuating (SSA) capability. Firstly, coupling between the electrical field and mechanical field in a voice coil transducer is modeled and analyzed. As a voice coil transducer, the dynamic microphone is modeled as a two port model, and a transduction matrix is used to relate the electrical variables and mechanical variables. The transduction matrix is obtained via both theory and experiment respectively. Through the transduction matrix, the mechanical impedance at output port can be measured by detecting the input electrical impedance. Finally, for validation, mechanical impedance of three point masses is evaluated by measuring the electrical impedance of the dynamic microphone.

3.1 Voice Coil Transducer (VCT)

3.1.1 Motion of Current-Carrying Wires in Magnetic Field

When current passes through a wire placed in a magnetic field, a force F proportional to the current i and the magnetic flux density B is produced

$$F = Bli \quad (3.1)$$

where l is the length of the wire. When a wire moves in a magnetic field, a voltage E is generated in the wire:

$$E = -Blv \quad (3.2)$$

where v is the velocity of the wire relative to the magnetic field, and the minus sign exists by convention and clearly depends on the definition of potential ground.

Equations (3.1) and (3.2) are known as Ampere's force law and Faraday's induction law, respectively. They are constitutive equations for the energy transformation in an electromechanical transducer based on the motion of current-carrying wire in a magnetic field. They suggest two types of transduction relationships: relating force and current, and relating voltage and velocity in a magnetic field.

An electromechanical transducer couples the electrical field and the mechanical field. For a transducer in which the coupling is based on the motion of a current-carrying wire in a magnetic field, we can write

$$F = Bli + Z_m^i v \quad (3.3)$$

and

$$E = Z_e^v i - Blv \quad (3.4)$$

Here Z_m^i is the mechanical impedance, measured with no current in the transducer and Z_e^v is the electrical impedance measured with no velocity of the current-carrying wires. Z_m^i is often referred to as the open circuit mechanical impedance and $Z_m^i v$ is

a measure of the force required to move the wire in the absence of a current. Z_e^v is referred to as the clamped electrical impedance and $Z_e^v i$ is a measure of the voltage drop induced by a current in the absence of motion [65].

3.1.2 Loudspeaker and Dynamic Microphone

Fig.3. 1 Cross-section of loudspeaker

An example of a common transducer which uses the motion of current-carrying wire in a magnetic field for transduction is loudspeaker, as shown in Figure 3.1. The magnetic flux density is established by a permanent magnet. A solenoid, usually referred to as a voice coil, is positioned so that the current flow is perpendicular to the magnetic flux direction. Current running through the coil produces a force on it in the direction orthogonal to both the current flow and magnetic flux. The force produces motion of the speaker diaphragm attached to the voice coil and the motion causes a

sound wave to propagate. Obviously, loudspeaker is a generator which converts power from electrical field to mechanical field. Typically a voltage signal is supplied to the speaker. The voice coil is modeled as a lumped electrical resistance and inductance. Taken together these items are the components that would be included in Z_e^v . The diaphragm and coil mass are the primary elements included in the mechanical impedance, Z_m^i .

Fig.3. 2 Cross-section of dynamic microphone

The strict reciprocal of the loudspeaker is dynamic microphone, as shown in Figure 3.2. This device is quite similar to the loudspeaker, but instead of a voltage drive producing a velocity, a velocity is used to generate a voltage. When the diaphragm vibrates in response to incoming sound waves, the coil moves backwards and forwards past the magnet. This creates a current in the coil which is channeled from the microphone along wires. Therefore, a dynamic microphone is basically a loudspeaker in reverse, except that some geometric designs are changed to obtain

good performance as a sound sensor.

There are a number of transducers which exploit the same transduction mechanism as that of the loudspeaker and dynamic microphone. Because of this, these transducers typically are referred to as voice coil transducers (VCT). VCT is one kind of electromechanical transducer, and it is capable of transferring energy from electrical to mechanical domain as a loudspeaker, or from mechanical to electrical domain as a dynamic microphone.

3.2 Simultaneous Sensor and Actuator

As indicated by the Equations (3.3) and (3.4), within a VCT electrical and mechanical fields are coupled: when the VCT is supplied with ac power, according to Equation (3.1), it generates a force and causes vibration of the coil and the diaphragm. If there is a structural or fluidic loading on the diaphragm, the reaction force of the motion of the diaphragm is exerted to the structure or fluid. In this process, the voice coil transducer serves as an actuator. During actuating, the response of the structure or fluid affects the motion diaphragm and results in additional deformations of the diaphragm, and then changes the velocity of the coil. As a result, the input electrical impedance is changed accordingly according to the Equation (3.2). In this process, the VCT functions as a sensor. Therefore, a voice coil transducer can simultaneously function as actuator and sensor. If the electromechanical interaction taking place in a

VCT is properly modeled, the mechanical impedance at its output port can be evaluated from the measured electrical impedance at the input port.

Fig.3. 3 Structure of dynamic microphone

In this report, a one-inch dynamic microphone is employed to study the sensing and actuating capability of a voice coil transducer. Figure 3.3 shows the structure of dynamic microphone under study. A coil is mounted on the back of the diaphragm and located in the magnetic field of a permanent magnet. The diaphragm is a circular shell and is made of a plastic film, and its rim is fixed at the frame. The place where the coil connects with the diaphragm is named as “coil-diaphragm joint point”. It is assumed that there is no relative motion between the turns of the coil, i.e., the coil moves as a whole piece, so the force or velocity of the coil is equal to the ones at coil-diaphragm joint point. The dynamic microphone can be viewed as a two port electromechanical transducer. In this model, the input port is the two electrodes of the coil, and the output port is the center point of diaphragm. When carrying out

experiment, electrical power is applied on the input port, and a mechanical structure is connected with the dynamic microphone at the output port.

The dynamic microphone used for our experiment is purchased from Guangdong Guanxing Electronic Co. Ltd, and the type is SE-V3. Figure 3.4 shows the photograph of the dynamic microphone.

Fig.3. 4 Photograph of dynamic microphone

Since the dynamic microphone is a linear dynamic transducer without internal energy generation or consumption, it can be characterized by a two-port model as shown in Figure 3.5. The model correlates the complex voltage and current at the electrical port with the complex force and velocity at the mechanical port of the transducer.

Fig.3. 5 Two-port model of dynamic microphone

The frequency response functions (FRFs) among the voltage and current at the input port and the force and velocity at the output port together form a two-by-two matrix:

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} F \\ v \end{Bmatrix} = [A] \begin{Bmatrix} F \\ v \end{Bmatrix} \quad (3.5)$$

Because this matrix characterizes the forward actuating and the backward sensing function of an electromechanical transducer, it is called transduction matrix. From Equation (3.5), it is obvious that the matrix elements could be determined by imposing conditions at the output port of the transducer as follows:

$a_{11} = \frac{E}{F} \Big|_{v=0}$ Transfer function of voltage to force when the output point is clamped.

$a_{21} = \frac{i}{F} \Big|_{v=0}$ Transfer function of current to force when the output point is clamped.

$a_{12} = \frac{E}{v} \Big|_{F=0}$ Transfer function of voltage to velocity when the output point is free.

$a_{22} = \frac{i}{v} \Big|_{F=0}$ Transfer function of current to velocity when the output point is free.

In words commonly used in vibration, they are the four frequency response functions between the input and output variables of the system respectively. Because the electromechanical transducer is a linear system, reciprocity theorem is applicable and thus the determinant of the transduction matrix is unity (proof of reciprocity theorem is shown in Appendix A), i.e.

$$|A| = a_{11}a_{22} - a_{12}a_{21} = 1 \quad (3.6)$$

3.3 Theoretical Derivation of Transduction Matrix

To theoretically derive the transduction matrix, mathematical formula must be found to relate the input electrical variables (voltage and current) and output mechanical variables (force and velocity). Equations (3.3) and (3.4) give out the relationship between the electrical variables and mechanical variables, however, the force and velocity in the two equations are for the coil, not for the center point of diaphragm (output port). Therefore, two transduction matrices will be derived: one is to relate the electrical port and the coil-diaphragm joint point, denoted as $[C]$, and the other is to relate the coil-diaphragm joint point and the center point of diaphragm, denoted as $[T]$. The two two-port models are cascaded in series, as shown in Figure 3.6. Obviously, the whole transduction matrix for the dynamic microphone $[A]$, which relates the electrical port and the center point of diaphragm, is equal to $[C]$ multiplied by $[T]$:

$$[A] = [C][T] \quad (3.7)$$

Fig.3. 6 Cascaded two-port model

Firstly, let us consider the first transduction matrix, which relates the electrical port and the coil-diaphragm joint point. Equations (3.3) and (3.4) can be rewritten to arrange electrical variable at one side and mechanical variable at the other side, and become

$$i = \frac{1}{Bl} \cdot F_{coil} - \frac{Z_m^i}{Bl} \cdot v_{coil} \quad (3.8)$$

$$\begin{aligned} E &= \left(\frac{1}{Bl} \cdot F_{coil} - \frac{Z_m^i}{Bl} \cdot v_{coil} \right) \cdot Z_e^v - Bl v_{coil} \\ &= \frac{Z_e^v}{Bl} \cdot F_{coil} - \left(\frac{Z_m^i}{Bl} Z_e^v + Bl \right) \cdot v_{coil} \end{aligned} \quad (3.9)$$

A subscript “coil” is added to indicate that the force or velocity is for the coil. Similarly, Z_m^i is referred to the mechanical impedance of the coil-diaphragm joint point, not for the center of the diaphragm. The Equations (3.8) and (3.9) can be rewritten in the compact matrix form

$$\begin{aligned} \begin{Bmatrix} E \\ i \end{Bmatrix} &= [C] \begin{Bmatrix} F_{coil} \\ v_{coil} \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{Bmatrix} F_{coil} \\ v_{coil} \end{Bmatrix} \\ &= \begin{bmatrix} \frac{Z_e^v}{Bl} & -\left(\frac{Z_m^i}{Bl} Z_e^v + Bl \right) \\ \frac{1}{Bl} & -\frac{Z_m^i}{Bl} \end{bmatrix} \begin{Bmatrix} F_{coil} \\ v_{coil} \end{Bmatrix} \end{aligned} \quad (3.10)$$

where

$$c_{11} = \frac{Z_e^v}{Bl}, \quad c_{12} = -\left(\frac{Z_m^i}{Bl} Z_e^v + Bl \right), \quad c_{21} = \frac{1}{Bl}, \quad c_{22} = -\frac{Z_m^i}{Bl}$$

The magnetic flux density of permanent magnet is $B = 0.4T$, which can be found

from the specification of dynamic microphone [71]. Z_e^v is the electrical impedance when the coil is fixed. It includes two items: resistance and inductance, i.e.

$$Z_e^v = R + j\omega L \quad (3.11)$$

where R is the resistance, j is the imaginary unit, ω is the frequency, and L is the self-inductance of the coil. For the dynamic microphone under study, the resistance is measured as $R = 675 \text{ ohm}$, and inductance $L = 0.0035 \text{ H}$.

Because the diaphragm of dynamic microphone is a circular shell structure of irregularly shaped cross section, and connected with a coil, it is complicated to derive a mathematical expression of Z_m^i for the diaphragm. Therefore, Z_m^i is obtained via finite element method, which is conducted in the finite element package ANSYS. ANSYS is equipped with well-developed pre-processor and post-processor and interactive graphing working environments, the time consuming tasks of model generation and solution extraction can be significantly reduced.

Table 3.1 provides the physical properties and element types used in the finite element model, which is shown in Figure 3.7. For the diaphragm, since the diameter is hundreds of times larger than the thickness, solid elements are not appropriate to model it because that will produce huge element numbers and consequently long calculation time. In order to achieve both accurate simulation and short calculation time, structural elastic four-node shell element, SHELL63, is chosen as the modeling element for the following three reasons: (1) SHELL63 has bending capability, and

both in-plane and normal loads are permitted; (2) SHELL63 has four nodes and each node has six degrees of freedom: translations in the nodal x , y and z directions and rotations about the nodal x , y and z axes; (3) Stress stiffening and large deflection capabilities are included in SHELL63 element. Regarding the coil, it is assumed that no gap exists between the turns, so that the coil can be modeled as a cylindrical shell. Again, SHELL63 is chosen as the modeling element for the coil.

Table 3. 1 Physical properties and modeling elements of the dynamic microphone

Component	Diaphragm	Coil
Material	polystyrene	copper
Density (kg/m ³)	910	8960
Young's Modulus (GPa)	3	103
Poisson's Ratio	0.33	0.34
Diameter (mm)	25.5	10.2
Thickness (mm)	0.020	0.041
Turn		40
Finite Element Type	SHELL63	SHELL63

(a)

(b)

(c)

Fig.3. 7 FEM model of diaphragm and coil of dynamic microphone (a) top view (b) bottom view (c) cross-section view

For boundary conditions, the rim of the diaphragm is fixed, i.e. the values of all the six degrees of the nodes located at the rim are set zero. All of the nodes at the coil-diaphragm joint points are coupled together so that they have the same velocity. During simulation, these nodes are subjected to a unit force along z direction, and the responding velocity along this direction is picked up, then the z -directional mechanical impedance is calculated. Harmonic analysis is carried out to obtain the curve of Z_m^i versus frequency, which is shown in Figure 3.8.

Fig.3. 8 FEM result of Z_m^i

Next, let us consider the second transduction matrix $[T]$, which relates the coil-diaphragm joint point and the center point of diaphragm. The force and velocity at the two points are expressed as

$$\begin{Bmatrix} F_{coil} \\ v_{coil} \end{Bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{Bmatrix} F_{center} \\ v_{center} \end{Bmatrix} = [T] \begin{Bmatrix} F_{center} \\ v_{center} \end{Bmatrix} \quad (3.12)$$

Similar to the previous section, the four elements of $[T]$ are defined as

$$\begin{aligned} t_{11} &= \left. \frac{F_{coil}}{F_{center}} \right|_{v_{center}=0} & t_{12} &= \left. \frac{F_{coil}}{v_{center}} \right|_{F_{center}=0} \\ t_{21} &= \left. \frac{v_{coil}}{F_{center}} \right|_{v_{center}=0} & t_{22} &= \left. \frac{v_{coil}}{v_{center}} \right|_{F_{center}=0} \end{aligned} \quad (3.13)$$

It is difficult to derive close forms for these four elements, so they will be obtained by FEM using the finite element model shown in Fig 3.7. In finite element analysis, a unit force F_{coil} is applied along z direction at the coil-diaphragm joint point. To get t_{11} and t_{21} , the center point is clamped to realize $v_{center} = 0$, and then the responding velocity at the coil-diaphragm joint point v_{coil} and the reaction force at the center point F_{center} are obtained. According to the left side of Equation (3.13), t_{11} and t_{21} can be calculated. Following the similar steps, to get t_{12} and t_{22} , the center point is free to realize $F_{center} = 0$, and the responding velocity at the coil-diaphragm joint point v_{coil} and the velocity at the center point v_{center} are picked up. According the right side of Equation (3.13), t_{12} and t_{22} can be calculated. The results of the four elements of matrix $[T]$ from FEM are shown from Figure 3.9 to Figure 3.12.

Fig.3. 9 Transduction element t_{11}

Fig.3. 10 Transduction element t_{21}

Fig.3. 11 Transduction element t_{12} Fig.3. 12 Transduction element t_{22}

From Equations (3.10) and (3.12), the electrical port and the mechanical port at the center point of diaphragm can be related through one transduction matrix

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} F_{center} \\ v_{center} \end{Bmatrix} = [A] \begin{Bmatrix} F_{center} \\ v_{center} \end{Bmatrix} \quad (3.14)$$

where

$$[A] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = [C][T] \quad (3.15)$$

With the detailed parameter in Table 3.1, the four elements of matrix $[C]$ can be calculated according to Equation (3.10). Subsequently, with the obtained matrix $[T]$, the four elements of matrix $[A]$ can be calculated and shown as follows:

Fig.3. 13 Theoretical result of transduction element a_{11}

Fig.3. 14 Theoretical result of transduction element a_{12}

Fig.3. 15 Theoretical result of transduction element a_{21}

Fig.3. 16 Theoretical result of transduction element a_{22}

Fig.3. 17 Theoretical result of determinant of $[A]$

As shown from Fig.3.13 to Fig.3.16, the resonant frequency is found around 150 Hz. The determinant is calculated and shown in Figure 3.17. It is found the determinant is close to unity in magnitude and close to zero in phase, which indicates the correctness of the transduction matrix $[A]$.

3.4 Experimental Calibration of Transduction Matrix

3.4.1 Calibration Method

In experiments, direct identification of $a_{ij}(i, j = 1, 2)$ is impractical. For calibrating a_{11} and a_{21} , which should be identified under clamped condition, output force F_{center} is required to be measured. However, clamp boundary condition is difficult or impossible to realize in laboratory. Furthermore, the diaphragm of dynamic microphone is so flexible that it is difficult to install a force transducer at the center point of the diaphragm. To overcome these problems, a new method is put forward to indirectly identify $a_{ij}(i, j = 1, 2)$ from a set of the measured voltage, current, velocity of the vibrating diaphragm when various known masses are applied to its output port. Output force can be calculated according to the Newton's second law after mass and velocity have been known.

For simplicity, from now on we will ignore the subscript "center" in F and v . At a

specified frequency, Equation (3.14) can be written separately as two equations.

$$\begin{Bmatrix} F & v \end{Bmatrix} \begin{Bmatrix} a_{11} \\ a_{12} \end{Bmatrix} = E \quad (3.16)$$

and

$$\begin{Bmatrix} F & v \end{Bmatrix} \begin{Bmatrix} a_{21} \\ a_{22} \end{Bmatrix} = i \quad (3.17)$$

where F and v are both complex variables, and $e^{j\omega t}$ is ignored because it exists on both side of the equations.

Let us consider a_{11} and a_{12} first. Dividing E on both sides of Equation (3.16), we have

$$\begin{Bmatrix} F/E & v/E \end{Bmatrix} \begin{Bmatrix} a_{11} \\ a_{12} \end{Bmatrix} = 1 \quad (3.18)$$

For a given point mass as a load of transducer under calibration, force can be calculated according to the Newton's second law when velocity has been measured ($F = m\dot{v}$, where m is mass, $\dot{v}$ is acceleration). Thus, F/E , v/E can be obtained by measuring voltage and velocity. We can build a group of simultaneous equations based on a set of a_{11} and a_{12} obtained by adding various masses to the mechanical port of the transducer.

$$\begin{Bmatrix} (F/E)_1 & (v/E)_1 \\ (F/E)_2 & (v/E)_2 \\ \dots & \dots \\ (F/E)_n & (v/E)_n \end{Bmatrix} \begin{Bmatrix} a_{11} \\ a_{12} \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ \dots \\ 1 \end{Bmatrix}_{n \times 1} \quad (3.19)$$

n is the number of experiment times of loading different masses. Let

$$H = \begin{Bmatrix} (F/E)_1 & (v/E)_1 \\ (F/E)_2 & (v/E)_2 \\ \dots & \dots \\ (F/E)_n & (v/E)_n \end{Bmatrix}, \quad A = \begin{Bmatrix} a_{11} \\ a_{12} \end{Bmatrix}, \quad C = \begin{Bmatrix} 1 \\ 1 \\ \dots \\ 1 \end{Bmatrix}_{n \times 1}$$

Equation (3.19) can be rewritten as

$$HA = C \quad (3.20)$$

a_{11} and a_{12} can be identified by solving these over-determined simultaneous equations. The least square solution of the Equation (3.20) can be derived as follows:

$$\begin{Bmatrix} a_{11} \\ a_{12} \end{Bmatrix} = A = [H^T H]^{-1} H^T C \quad (3.21)$$

The other two elements a_{21} and a_{22} can be obtained by applying the same process as above, except replacing voltage E with current i . Therefore, to calibrate all the elements $a_{ij}(i, j = 1, 2)$ of the transduction matrix, totally four types of frequency response function need to be measured or calculated: F/E , v/E , F/i , v/i .

3.4.2 Experimental Setup

The experimental setup for calibration of transduction matrix for dynamic microphone is shown in Figures 3.18. The schematic view of calibration system is shown in Figure 3.19. The signal of voltage is measured by voltage probe (Tektronix P5205) and the current is measured by the current amplifier (Keithley 428). Velocity is picked up by Laser Doppler Vibrometer (Polytech OFV056), and force is calculated according to the Newton's second law. In testing, swept sinusoidal signals from dynamic signal

analyzer are sent to actuate the dynamic microphone. The measured voltage, current and velocity signals are fed into the dynamic signal analyzer (HP35670A) for processing and analysis.

Fig.3. 18 Experimental setup for calibration of transduction matrix

Fig.3. 19 Scheme of experimental setup for calibrating transduction matrix

As mentioned above, in order to calibrate the four elements of transduction matrix, several masses are needed for the calibration. The mass is a thin copper film, one side of which has glue so that it is able to be attached well on the diaphragm of dynamic microphone. The dimension of the copper film is very small compared to the diameter of diaphragm, so that the attached copper film can be viewed as a point mass, which means the internal structure of the copper film can be neglected, and it can be treated as if its mass were rigidly concentrated at one point. Totally eight masses are used in the calibration, their weights are listed in Table 3.2.

Table 3. 2 Masses used for calibration

Mass Number	1	2	3	4	5	6	7	8
Weight (10^{-6} kg)	6.314	12.124	19.795	26.150	31.596	36.774	42.898	48.505

The measured FRF v/E corresponding to different calibration masses are overlay vs. frequency in Figures 3.20 and 3.21. The enlarged view around the first resonance is depicted in Figures 3.22 and 3.23. In the figures, from the left to right, each curve represents the FRF v/E of the dynamic microphone when it is loaded with a different mass. It is found that the curves of v/E directly reflects the properties of the mechanical load attached to the transducer. The greater the calibration mass, the lower the resonance. The other three types of FRF (F/E , F/i , v/i) are shown from

Figure 3.24 to 3.29, in which similar discrepancy can be found for different mechanical loads.

Fig.3. 20 Magnitude of v/E

Fig.3. 21 Phase of v/E

Fig.3. 22 Magnitude of v/E around 1st resonance

Fig.3. 23 Phase of v/E around 1st resonance Fig.3. 24 Magnitude of F/E

Fig.3. 25 Phase of F/E

Fig.3. 26 Magnitude of v/i

Fig.3. 27 Phase of v/i

Fig.3. 28 Magnitude of F/i

Fig.3. 29 Phase of F/i

Through the measured four types of FRF, the four elements of transduction matrix ($a_{ij}(i, j=1,2)$) are easily calculated from Equation (3.21). These experimentally determined $a_{ij}(i, j=1,2)$ are compared with the theoretical results and shown from Figure 3.30 to 3.33. It is observed that $a_{ij}(i, j=1,2)$ obtained from experiment are comparable with the theoretical ones, which validate the practicability of the present calibration method using adding masses. As expected, the determinant of transduction matrix $[A]$, as shown in Figure 3.34, is very close to unity in magnitude and zero in phase, which indicates the correctness of the $a_{ij}(i, j=1,2)$ obtained from experiment.

Fig.3. 30 Experimental result of transduction element a_{11}

Fig.3. 31 Experimental result of transduction element a_{12}

Fig.3. 32 Experimental result of transduction element a_{21} Fig.3. 33 Experimental result of transduction element a_{22}

Fig.3. 34 Experimental result of determinant of $[A]$

3.5 Measurement of Mechanical Impedance of Point Masses

It is obvious that, from Equation (3.12), the mechanical impedance Z_m loaded at the output port of the transducer can be expressed as a function of the four transduction elements and the measured input electrical impedance Z_e :

$$Z_m = \frac{F}{v} = \frac{a_{22}Z_e - a_{12}}{a_{11} - a_{21}Z_e} \quad (3.22)$$

where $Z_e = E/i$. Equation (3.22) expresses the working principle of dynamic microphone being used simultaneous sensor and actuator. When the load at the output port of the dynamic microphone changes, the input electrical voltage, current and thus electrical impedance change correspondingly. Furthermore, this change is a function

of the dynamic characteristics of the transducer which is fully expressed by the four elements of transduction matrix.

For point mass, the mechanical impedance is known as

$$Z_m = j \cdot 2\pi f M \quad (3.23)$$

where f is the frequency, M is the mass. From Equations (3.21) and (3.22), we have

$$M = \frac{1}{j \cdot 2\pi f} \frac{a_{22}Z_e - a_{12}}{a_{11} - a_{21}Z_e} \quad (3.24)$$

As indicated by the Equation (3.22) or (3.24), mechanical impedance or mass can be detected by measuring the input electrical impedance.

For experimental verification, three arbitrary copper films with different masses (9.622, 25.470 and 40.082mg) are respectively loaded on the output port of the dynamic microphone. The measured input electrical impedances Z_e corresponding to these three different loadings are depicted in Figure 3.35. Figure 3.36 displays the same set of data for the frequency range around the first resonant frequency to amplify the discrepancies. As shown in the figure, the electrical impedance corresponding to different loadings distinguishes with each other. The larger of the loadings, the curves shift more towards left.

With the obtained transduction matrix $[A]$ and the measured electrical impedances, the weight of masses can be calculated from Equation (3.24). Comparing the

calculated result with the real value, very good coincidence is found in Figure 3.37 for each of the three loadings. Therefore, it is concluded that once the transduction matrix is properly calibrated, the mechanical impedance loaded at the output port of dynamic microphone can be detected through the measured input electrical impedance.

Fig.3. 35 Electrical impedances under different loadings

Fig.3. 36 Electrical impedances around 1st resonance under different loadings

Fig.3. 37 Comparison of the calculated masses and the true values

3.6 Summary

In this chapter, simultaneous sensing and actuating (SSA) capability of a dynamic microphone is studied. The dynamic microphone is modeled as a two-port model, which contains input electrical port and output mechanical port. A two-by-two transduction matrix is developed from both theory and experiment to relate the input electrical variables (voltage and current) and output mechanical variables (force and velocity). With the obtained transduction matrix, mechanical impedance, which is generally difficult to measure, can be indirectly detected by detecting electrical impedance. For experimental verification, mechanical impedance of point masses is measured by the proposed method. The experimental results show good coincidence with the real values, which verify that a dynamic microphone is of SSA capability with the developed transduction matrix.

When the transducer (here dynamic microphone) is used to measure mechanical impedance of an external structure (here point mass), the input electrical impedance of transducer changes accordingly to the mechanical impedance of the external structure. The measured electrical impedance is actually an outcome of the coupling of the transducer and external structure. Therefore, the electrical impedance contains mixed information of the transducer and the external structure. If one wants to detect the mechanical impedance of the external structure separately from the measured

electrical impedance, he must firstly decouple the transducer and the external structure, which is a complicated process. However, with the mentioned transduction matrix in this chapter, the coupled problem is easily solved. As shown in the above results, following Equation (3.22), the mechanical impedance calculated from the measured electrical impedance is definitely of the external structure, and independent on the transducer. In other words, when the transducer conducts SSA, the transduction matrix can decouple the interaction between the transducer and the loading structure. Through this decoupling capability of transduction matrix, quantitative dynamic measurement is thus made possible in SSA technique.

Chapter 4

Measurement of Absorption Coefficient of Acoustical Materials

From Chapter 3, it is seen that a dynamic microphone can be employed as a transducer to simultaneously perform sensor and actuator. Similar to mechanical impedance, acoustic impedance can also be related with the electrical impedance through a transduction matrix. As external loading of dynamic microphone, acoustical impedance differs from mechanical impedance in format more than in essence. In this chapter, a dynamic microphone is inserted at one end of a tube to measure the acoustic impedance of the absorbing material at the other end of the tube. When the dynamic microphone is supplied with ac power, the diaphragm vibrates and radiates acoustic waves. In this process, the dynamic microphone acts as an actuator. The outgoing wave propagates in the tube and impinges upon the surface of a test specimen mounted at the other end of the tube, and is partially reflected to create a standing wave that uniquely characterizes the acoustic impedance of the test specimen. The standing wave exerts load and thus causes additional deformation of the diaphragm of dynamic microphone and result in a change of the input electrical impedance. In this process, the dynamic microphone serves as a sensor. Similar to the case in Chapter 3, the relationship between the input electrical impedance and output acoustical impedance can be expressed in terms of the elements of a two-by-two

transduction matrix. This transduction matrix is an inherent property of the dynamic microphone-tube system, thus, once it is properly calibrated, the acoustical impedance of different material specimens mounted at its output port can be evaluated from the measured electrical impedance.

4.1 Behavior of a Combined Driver-Tube System

A more realistic investigation of acoustics in a tube must account for the mechanical driver which is used for generating a sound wave in the tube [17]. The driver has its own mechanical impedance, so that when a force is applied to the driver-tube system the mechanical resonances of the combined system involve the mechanical behavior of both driver and tube.

Fig.4. 1 Schematic representation of a driver-tube system

Let the driver be simplified as a damped harmonic oscillator of mass m , mechanical resistance R_m , and stiffness s , as shown in Figure 4.1. Suppose the oscillator excited with the externally applied force $F = F_0 \exp(j\omega t)$. Newton's second law for the motion of the mass is

$$m \frac{d^2 \xi}{dt^2} = -R_m \frac{d\xi}{dt} - s\xi - Sp(0,t) + F \quad (4.1)$$

where ξ is the displacement of the mass to the right, S is the cross area of the mass, and $p(0,t)$ is the pressure in the tube at $x=0$. The complex speed of the mass is $u = d\xi/dt$, the particle speed of the fluid in the tube at $x=0$, so that Equation (4.1) becomes

$$\left[R_m + j \left(\omega m - \frac{s}{m} \right) + \frac{Sp(0,t)}{u(0,t)} \right] u(0,t) = F \quad (4.2)$$

The input mechanical impedance Z_{md} of the sound driver is

$$Z_{md} = R_m + j(\omega m - s/m) \quad (4.3)$$

And the input mechanical impedance of the tube ($x=0$) is

$$Z_{m0} = \frac{Sp(0,t)}{u(0,t)} \quad (4.4)$$

Thus Equation of (4.2) show that the mechanical impedance Z_m of this system is the series combination of Z_{md} and Z_{m0} , so that

$$F = Z_m u(0,t) = (Z_{md} + Z_{m0}) u(0,t) \quad (4.5)$$

The driver alone would resonate when its reactance vanishes, $\omega_0 = \sqrt{\omega/m}$, and the tube alone would resonate when $\text{Im}\{Z_{m0}\} = 0$. When the combined system is driven, however, the input impedance seen by the applied force is the sum of the impedance of the driver and tube, so that the frequencies of mechanical resonance of the system are found from

$$\text{Im}\{Z_{md} + Z_{m0}\} = 0 \quad (4.6)$$

From reference [17], we know that for a stiff driver, most of the resonances occur

approximately for $k_n L = n\pi$. Therefore, when $L = n\lambda/2$, i.e. the length of tube is an integer multiple of half wavelength of sound, there is a standing wave peak. However, in the vicinity of the driver resonance, the standing wave peaks are affected and will not appear at $L = n\lambda/2$ any longer. Indicated by Equation (4.6), how the standing wave peaks are affected is depend on the mechanical resonance of the driver.

4.2 Two-Port Model of a Dynamic Microphone-Tube System

In this report, a dynamic microphone is used as a sound driver. It is mounted in a tube to constitute a dynamic microphone-tube system: when it is supplied with ac power, the diaphragm vibrates and generates sound wave propagating in the tube. At the end of tube, the acoustic wave is planar because the diameter of tube is far smaller than the sound wavelength. The dynamic microphone-tube system involves two sub-systems: dynamic microphone and tube, as shown in Figure 4.2.

Fig.4. 2 Dynamic microphone-tube system

Under AC power, the diaphragm of dynamic microphone vibrates. The power is transformed from electrical format to mechanical format. The motion of the diaphragm generates acoustic wave from the surface of diaphragm to the air in tube.

Mechanical variables can be easily related with acoustical variables: for plane wave in a tube, force is equal to pressure times the cross area of tube, and acoustic particle velocity on the surface of diaphragm is identical with the vibrating velocity of the diaphragm. In this process, mechanical power is transformed to acoustical power. Therefore, the dynamic microphone actually converts electrical power to acoustical power. Since the dynamic microphone and tube are both linear systems, their combination, the driver-tube system, is certainly also linear. A two-port model is built to describe the relationship between the electrical port and acoustical port of the dynamic microphone-system, as shown in the Figure 4.3. In this model the input electrical port is referred to the two electrodes of dynamic microphone, and the output acoustical port is at the terminal of the tube. The dynamic microphone transfers energy from electrical to acoustical domain, and the tube plays a role of relating the acoustical variables at the two ends of tube. In experiment, the surface of the testing material is installed at the position of the output port. Absorption coefficient of the material can be measured by detecting acoustic impedance on the surface of material.

Fig.4. 3 Two-port model of dynamic microphone-tube system

The relationship between the input electrical variables and output acoustical variables

are given by:

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} p \\ u \end{Bmatrix} \quad (4.7)$$

where E voltage and i current are power conjugate variables in electrical domain, and p pressure and u particle velocity in acoustical domain. The four elements of the transduction matrix are defined as:

$$a_{11} = E/p|_{u=0}; \quad a_{21} = i/p|_{u=0}; \quad a_{12} = E/u|_{p=0}; \quad a_{22} = i/u|_{p=0}$$

The particle velocity being zero ($u = 0$) is called clamp boundary condition, which means that the acoustic particle is clamped. Generally, when a normally incident wave is totally reflected back on the surface of a rigid wall, the particle velocities in positive and negative traveling directions have equal magnitude but 180° out of phase, so that the superposed particle velocity is zero. The pressure being zero ($p = 0$) is called free condition or pressure release, which is impossible realized in laboratory. From Equation (4.7), the acoustical impedance at the output port can be calculated from the measured input electrical impedance:

$$Z_a = \frac{p}{u} = -\frac{a_{22}Z_e - a_{12}}{a_{21}Z_e - a_{11}} \quad (4.8)$$

where $Z_a = \frac{p}{u}$ is the acoustic impedance, $Z_e = \frac{E}{i}$ is the electrical impedance.

To get a_{ij} ($i, j = 1, 2$) of the transduction matrix through experiment, we must impose free and clamp conditions to the output port of the tube. Clamp condition of acoustic is easy to realize by letting output port be rigid wall. However, free boundary condition of acoustic ($p = 0$) is impossible to realize in laboratory. Furthermore,

calibrations of a_{12} and a_{22} require measurement of acoustic particle velocity. Unfortunately, so far there is no reliable acoustic particle velocity sensor available in market. Therefore, the calibration method mentioned in the Chapter 3 is not applicable to get $a_{ij}(i, j = 1, 2)$ for acoustic impedance measurement.

To overcome the above experimental difficulties, an alternative calibration method is developed to characterize the transducer. Some conditional impedances are defined as:

$$Z_{ao} = \left. \frac{p}{u} \right|_{i=0} \quad (4.9)$$

$$Z_{ef} = \left. \frac{E}{i} \right|_{p=0} \quad (4.10)$$

$$Z_{ec} = \left. \frac{E}{i} \right|_{u=0} \quad (4.11)$$

where

Z_{ao} = acoustical impedance when the transducer is electrically open-circuited;

Z_{ef} = electrical impedance of the transducer when the pressure at the output port is zero;

Z_{ec} = electrical impedance of the transducer when the particle velocity at the output port is zero;

From Equation (4.7), if we let i , p , u equal to zero respectively, the following equations can be derived

$$Z_{ao} = -\frac{a_{22}}{a_{21}} \quad (4.12)$$

$$Z_{ef} = \frac{a_{12}}{a_{22}} \quad (4.13)$$

$$Z_{ec} = \frac{a_{11}}{a_{21}} \quad (4.14)$$

Considering Equations (4.8), (4.12), (4.13) and (4.14), the acoustical impedance can be expressed as:

$$Z_a = Z_{ao} \frac{Z_e - Z_{ef}}{Z_e - Z_{ec}} \quad (4.15)$$

As discussed above, two sets of functions could be utilized to describe the system dynamics: transduction elements as Equation (4.8) and conditional impedances as Equation (4.15). In practice, the conditional impedances Z_{ao} , Z_{ef} , Z_{ec} are much easier to measure. After they are identified, as illustrated in Equation (4.15), acoustic impedance at the output port can be evaluated from the input electrical impedance of the transducer. However, the difficulties in measurement of $a_{ij}(i, j = 1, 2)$ still exist in calibration of Z_{ao} and Z_{ef} . To solve the problem, a new method is put forward to indirectly identify Z_{ao} and Z_{ef} from a set of the measured Z_{ec} and Z_e of the dynamic microphone when various calibration materials with known Z_{ao} are applied to the output port.

We can rewrite Equation (4.15) as follows:

$$a \frac{1}{Z_{ao}} + b Z_{ef} = c \quad (4.16)$$

where $a = Z_a(Z_e - Z_{ec})$; $b = 1$; $c = Z_e$.

For a given absorbing material, its acoustic impedance Z_a is first measured by transfer function method conducted in a commercial impedance tube, which is relatively accurate for measurement of acoustic impedance in tube. Subsequently, corresponding Z_e for this material is measured by mounting it at the output port of the dynamic microphone-tube system. Z_{ec} is the electrical impedance for the condition of rigid wall at output port and is easily obtained. Thus, a and c in Equation (4.16) can be calculated or measured. We can build a group of simultaneous equations based on a set of Z_e and Z_a obtained by applying various absorbing materials to the acoustical output port of the dynamic microphone-tube system. This group of equations is written as matrix form:

$$\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \\ \dots & \dots \\ a_n & b_n \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{Z_{ao}} \\ Z_{ef} \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \dots \\ c_n \end{bmatrix} \quad (4.17)$$

where $a_{(k)} = Z_{a(k)}(Z_{e(k)} - Z_{ec})$; $b_{(k)} = 1$; $c_{(k)} = Z_{e(k)}$; $k = 1, 2, \dots, n$. n is the number of experiment times of applying different absorbing materials to the acoustical output port the dynamic microphone-tube system.

$\frac{1}{Z_{ao}}$ and Z_{ef} can be identified by solving these over-determined simultaneous

equations. The least square solution of the above mentioned equations can be derived as follows:

$$Z = [A^T A]^{-1} A^T C \quad (4.18)$$

where

$$Z = \begin{bmatrix} \frac{1}{Z_{ao}} \\ Z_{ef} \end{bmatrix};$$

$$A = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \\ \dots & \dots \\ a_n & b_n \end{bmatrix};$$

$$C = \begin{bmatrix} c_1 \\ c_2 \\ \dots \\ c_n \end{bmatrix}.$$

With Z_{ao} and Z_{ef} known, we can mount arbitrary specimen at the output port of the tube, by measuring the input electrical impedance Z_e of the dynamic microphone, acoustical impedance Z_a of the specimen under testing can be calculated according Equation (4.15). Finally, reflection coefficient and absorption coefficient can be calculated according to the Equations (2.13) and (2.14)

4.3 Experimental Setup

The photo and schematic view of experimental setup are shown in Figure 4.4 and 4.5

respectively. The simple straight tube is 320mm in length and 28mm in diameter. The wall thickness of tube is 5mm. The material of tube is stainless steel, whose damping is several times than that of lightly damped materials such as aluminum. The tube is massive and sufficiently rigid to avoid (1) transmission of noise into the tube from outside and (2) vibration excitation by the sound source or from background sources (e.g., doors closing). The whole tube is fixed by a clamp to insure no vibration while measurement.

Fig.4. 4 Experimental setup for measurement of acoustic absorption coefficient

Fig.4. 5 Schematic view of experimental setup

A one-inch dynamic microphone is mounted in an equal-diameter tube and sealed with silica gel. It serves as an actuator to generate sound waves. A front cover is mating with the tube to protect the dynamic microphone as well as prevent sound leakage. The material specimen under testing is carefully mounted at the terminal of tube in order that the surface of specimen is perpendicular to the propagation direction of acoustic wave. All the material specimens under testing are cut with 20mm in thickness and same cross area with the tube. A back cover is tightly screwed with the tube in order that no sound leaks into or out of the tube where the back cover and the tube meet. In addition, this back cover functions as a back wall for the specimen, so it is also massive and rigid for totally reflecting acoustic wave. It is important to ensure that no air gap exists between the specimen and the back cover, i.e. the specimen is on rigid backing, otherwise the results from the proposed method can not be comparable with those from transfer function method conducted in impedance tube. Compared with the impedance tube in the classical transfer function method, the tube used in this method is relative small and portable.

In testing, swept sinusoidal signals from dynamic signal analyzer (HP35670A) are sent to activate the dynamic microphone. A standing wave pattern that uniquely characterizes the acoustic impedance of the test specimen is created in the tube. When acoustic impedance on the surface of diaphragm changes due to different absorbing materials, corresponding change of the electrical impedance of dynamic microphone are detected. The signal of voltage is measured by voltage probe (Tektronix P5205) and the current is measured by the current amplifier (Keithley 428). The measured voltage and current are picked up and fed into the dynamic signal analyzer for calculating the input electrical impedance. Table 4.1 lists the parameters used in the experiment.

Table 4. 1 System parameters in experiment

Parameters	Description	Value
L	Length of tube	320 mm
D	Diameter of tube	28 mm
f_1	Fundamental resonance frequency of dynamic microphone	130 Hz
ρ_0	Air density (in room temperature)	1.202 kg / m ³
c_0	Sound speed in air	343 m / s

4.4 Calibration of Conditional Impedances

4.4.1 Measurement of Z_{ec}

Calibration of Z_{ec} requires the particle velocity at output port is clamped to be zero.

This condition can be realized by mounting a steel block at the output port of the tube.

The steel block functions as a rigid wall to totally reflect the acoustic wave so that the particle velocity on the surface of steel is zero. Utilizing the experimental setup introduced in the previous section, the electrical impedance for clamp boundary condition is measured and shown in Figure 4.6 and 4.7.

Fig.4. 6 Magnitude of electric impedance for clamp boundary condition

Fig.4. 7 Phase of electric impedance for clamp boundary condition

In the figures of electrical impedance for clamp boundary condition, the first peak at 130Hz is the resonance of dynamic microphone, and the other peaks are caused by the standing wave pattern in the tube. The electrical impedance varies cyclically in the frequency domain, which reflects the fact that the acoustical impedance on the surface of diaphragm reaches a maximum value when the length of the tube is an integer multiple of the half wavelength of the sound. In theory, for those peaks far away from the resonance of dynamic microphone, the frequency difference between two neighboring standing wave peaks is

$$\Delta f = f_n - f_{n-1} = c_0 / 2L \quad (4.19)$$

Substituting the values $c_0 = 343 \text{ m/s}$ and $L = 0.32 \text{ m}$, we can get $\Delta f = 536 \text{ Hz}$, which is identical with the experimental result. However, in the vicinity of the

resonance of dynamic microphone, Equation (4.19) is not valid any longer. How Δf is affected by the resonance of dynamic microphone depends on the mass and stiffness of the diaphragm.

4.4.2 Calibration of Z_{ao} and Z_{ef}

Six materials with different absorption coefficients are selected for calibration of conditional impedance Z_{ao} and Z_{ef} . Acoustical impedance of these materials is measured by transfer function method conducted in the B&K 4206 impedance tube. The results are shown in Figure 4.8, from which we can observe that different calibration materials have different acoustic impedance. In theory, a material with high acoustic impedance will have high reflection coefficient.

Fig.4. 8 Acoustic impedance for the calibration materials

Then these six calibration materials are mounted at the output of the dynamic microphone-tube system, respectively. Through the experimental setup shown in Figure 4.4, the electrical impedance for these calibration materials are measured and shown in Figure 4.9 and Figure 4.10.

Fig.4. 9 Magnitude of electrical impedance for the calibration materials

Fig.4. 10 Phase of electrical impedance for the calibration materials

From Figure 4.9, we observe that the standing wave peaks are much weaker than those in the case of rigid wall. The reason is that the acoustic wave is almost totally reflected back at the surface of rigid wall, which means that less energy loss for the rigid wall. However, within absorbing materials most acoustic energy is absorbed and converted into heat. Thus the resonance peaks of the standing wave for absorbing materials are not as obvious as the case of rigid wall, i.e. clamp boundary condition. Even more, for those materials with high absorption coefficient, some standing wave peaks disappear.

Having obtained Z_a and Z_e for the six calibration materials, as well as Z_{ec} for clamp boundary condition, we can calculate Z_{ao} and Z_{ef} according to Equation

(4.18). The results of Z_{ao} and Z_{ef} are shown in Figures 4.11 and 4.12, respectively.

Fig.4. 11 Magnitude and phase of Z_{ao}

Fig.4. 12 Magnitude and phase of Z_{ef}

4.5 Extreme Acoustical Conditions at Tube End

4.5.1 Fully-Reflected Condition

As mentioned in the previous section, steel block is used to realize rigid wall boundary condition, and the acoustic wave can be considered perfectly totally reflected by the steel. There are other hard materials, such as aluminum, which are not as rigid as steel, but is hard enough to reflect most energy of acoustic wave. Therefore, it is expected that the reflection coefficient of the hard materials is close to unity. To check this point, an aluminum block of 20 mm in thickness is mounted at the output port of the dynamic microphone-tube system, and the electrical impedance is measured and shown in Figure 4.13.

Fig.4. 13 Electrical impedance of aluminum

Fig.4. 14 Specific acoustic impedance ratio of aluminum

According to Equation (4.15), acoustic impedance can be calculated from the measured electrical impedance. The specific acoustic impedance ratio is shown in Figure 4.14. The real part and imaginary part of acoustic impedance are called acoustic resistance and acoustic reactance respectively. From the result, the acoustic resistance is close to zero at the frequency range above 1500 Hz, which demonstrate that little energy dissipation happens at the hard materials. However, the acoustic resistance is not equal to zero at the frequency range below 1500 Hz. It may be due to the following reasons: (1) there are losses in the tube wall. (2) it is possible that some sound is leaking out from the end. (3) there is vibration of the tube itself, and any vibration will remove energy from acoustic field. Comparison between the acoustic

reactance and acoustic resistance disclose that their difference in magnitude is up to 10 times, which means that the acoustic reactance makes obvious the active role of the mass and stiffness of hard materials. After calculating the reflection coefficient, which is shown in Figure 4.15, we can observe that the reflection coefficient of aluminum is very close to unity as expected in a wide frequency range.

Fig.4. 15 Reflection coefficient of aluminum

4.5.2 Anechoic Condition

If we connect a long pipe to the experimental tube, and plug some high absorptive material at the terminal end of the long pipe, then the sound energy will not be reflected back because the acoustic energy are almost consumed in its way to the end of the whole pipe. This means an anechoic boundary condition for a standing wave. In

this case, the acoustic impedance is equal to the characteristic impedance

$$Z_{\text{anechoic}} = \rho_0 c_0 \quad (4.20)$$

Replace $Z_a = Z_{\text{anechoic}}$ into Equation (2.14), the absorption coefficient will be

$$\alpha = 1 \quad (4.21)$$

which means all the energy has been absorbed.

The experimental realization of this boundary condition is not easy because it requires a very long and it is hard to ensure no wave is reflected back. In our experiment, a long PVC pipe is used to connect to the experimental tube. The PVC pipe is 1.3 meters in length, which is about four times of the length of the experimental tube. To reduce sound reflection and disturbance from outside, some cotton are plugged at the end of the PVC pipe.

The electrical impedance for this condition is shown in Figure 4.16. Due to the imperfect anechoic condition, a small part of acoustic wave is reflected back to form a weak standing wave pattern. Therefore, some resonance peaks of standing wave can still be observed when the length of the tube plus PVC pipe is an integer multiple of the half wavelength of the sound.

Fig.4. 16 Electrical impedance for anechoic boundary condition

Subsequently, the acoustic impedance ratio and absorption coefficient for the anechoic condition are calculated and shown in Figures 4.17 and 4.18. The anechoic boundary condition in experiment is not close to ideal description and the indirect method is not so sensitive because some middle calculated results are not accurate enough and will then influence the final results greatly because some mathematical operation like division may induce big difference. Those two reasons explain why the experimental results don't agree so well with theoretical results. Nevertheless, the result of absorption coefficient shows that the value is near to unity in the most part of the frequency range. On the whole, the results are reasonable and this method reflects the change trend of absorption coefficient versus frequency.

Fig.4. 17 Specific acoustic impedance ratio for anechoic boundary condition

Fig.4. 18 Absorption coefficient of anechoic condition

4.6 Experimental Results of Absorbing Materials

After successfully verifying the absorption coefficient for the two extreme boundary conditions, it is necessary to test the method for other boundary conditions with various different sound absorbing materials. Various acoustic materials are available. Porous materials used for noise control are generally categorized as fibrous medium or porous foam. Fibrous media usually consists of glass or rock wool, which have high acoustic absorption, and are fireproof. Therefore, they are widely used materials in the noise control engineering. So, some porous materials will be tested in this experiment.

The result graphs for porous materials are shown and then compared with the result from transfer function method conducted in the commercial B&K 4206 impedance tube. In the experiment, five different materials are tested and compared with other results for method verification purpose. The test examples are 20 mm in thickness and 28mm in diameter and backed by rigid end. For each test specimen, swept sine with frequency range from 10 to 5000Hz is firstly generated by the source of analyzer. The electrical impedance of the dynamic microphone is then measured for each frequency. The surface specific acoustic impedance and the corresponding absorption coefficient are calculated and compared with the result from transfer function method. The result graphs are shown from Figure 4.19 to 4.33. For each material, the graphs are arranged in the following sequence: First is the measured electrical impedance versus

frequency. Second is the calculated surface specific acoustic impedance ratio ($Z_a/\rho_0 c_0$) versus frequency. And the third is the absorption coefficient versus frequency for both the proposed method and transfer function method.

Material 1

Fig.4. 19 Electrical impedance for material 1

Fig.4. 20 Acoustical impedance ratio for material 1

Fig.4. 21 Absorption coefficient for material 1

Material 2

Fig.4. 22 Electrical impedance for material 2

Fig.4. 23 Acoustical impedance ratio for material 2

Fig.4. 24 Absorption coefficient for material 2

Material 3

Fig.4. 25 Electrical impedance for material 3

Fig.4. 26 Acoustical impedance ratio for material 3

Fig.4. 27 Absorption coefficient for material 3

Material 4

Fig.4. 28 Electrical impedance for material 4

Fig.4. 29 Acoustical impedance ratio for material 4

Fig.4. 30 Absorption coefficient for material 4

Material 5

Fig.4. 31 Electrical impedance for material 5

Fig.4. 32 Acoustical impedance ratio for material 5

Fig.4. 33 Absorption coefficient for material 5

In the frequency range above 1500 Hz, the contribution from standing wave to electrical impedance becomes smaller compared to that contributed from the internal electrical impedance of dynamic microphone. Therefore, the resonance peaks in the electrical impedance plots become more and more insignificant as frequency increases. Comparing electrical impedance of the absorbing materials to the one of the hard materials, we observe again that the resonance peaks of standing wave for the absorbing materials are much weaker than those for the hard materials. Even more, some standing wave peaks for absorbing materials can not be found because a great part of acoustical energy has been absorbed.

The experimental results from the five sound absorbing materials show that the calculated absorption coefficient agrees with the result from the transfer function method tube in the frequency range of interest. In the frequency range lower than 100Hz, the error is big due to the fact that in low frequency the acoustic energy generated by the dynamic microphone is very weak, and then the acoustic wave is greatly dissipated during propagation, which makes it difficult to cause enough change of electrical impedance for sensing. In other words, the signal-to-noise ratio of the measurement system is low at the low frequency range.

From the experimental result of absorption coefficient, we can find some fluctuations of the curve in some frequencies. This is caused by the standing wave pattern: when the length of tube is an integer multiple of half wavelength of sound, a resonance peak

is created by the standing wave. In theory, these fluctuations should only exist in the result of electrical impedance, and when we use electrical impedance to calculate absorption coefficient, the fluctuations will be counteracted by the standing wave pattern lying in Z_{ao} , Z_{ef} and Z_{ec} . However, due to the errors from experiment and mathematical operation like division, these fluctuations can not be totally smoothed during the calculation of absorption coefficient. Therefore, in the results of absorption coefficient, some fluctuations, which are the imprint of standing wave pattern, can be observed at the frequencies where the length of tube is an integer multiple of half wavelength of sound.

4.7 Summary

A method for measurement of acoustic impedance or absorption coefficient of materials was developed and presented. In this method, a dynamic microphone mounted in a tube is used as an actuator to generate sound waves and simultaneously performs as a sensor to probe acoustical impedance. The specific acoustic impedance of materials at the terminal of the tube is indirectly measured through detecting the input electrical impedance of the dynamic microphone. Different from the transfer function method, the proposed method doesn't require two identical microphone sensors inserting in the tube for detecting pressure, which make it possible to fabricate the tube small enough to be portable. The dynamic microphone-tube system is modeled as a two-port model, in which the input electrical port is the two electrodes

of dynamic microphone, and the output acoustic port is at the position of absorbing material. A two-by-two transduction matrix is used to relate the variables of the two ports, so that the acoustic impedance can be expressed as a function of electrical impedance with the help of the conditional impedances, i.e. Z_{ao} , Z_{ef} and Z_{ec} . Utilizing the calibrated Z_{ao} , Z_{ef} and Z_{ec} , probing the input voltage and current to the dynamic microphone alone allows quantitative evaluation of the specific acoustical impedance of the material specimen. Testing on five different materials shows that the method can correctly identify the absorption coefficient of acoustic materials in the frequency range of interest. The experimental results verify the sensing capability of the dynamic microphone, which is used to be an electro-acoustic actuator simultaneously.

In this method, the use of microphone sensors for measuring sound pressure in conventional methods is unnecessary and replaced by a voltage and a current probe for detecting electrical impedance of the dynamic microphone. The microphone-free feature of the method is of particular use in situations where inserting a microphone sensor into an impedance tube is difficult. An example is measurement of the specific acoustic impedance of a material specimen at the end of a curved duct with small diameter. However, due to the difficulties of inserting microphone sensors, transfer function method are impractical to implement, and the presented method could become a useful tool.

Chapter 5

Health Monitoring of Membrane at the End of a Tube

Structural health monitoring is an important process in the quality control process of engineering systems. One of the important aspects of structural health monitoring is that the technique provides information on the life expectancy of structures, as well as detects and locates structural damage [72-75]. In general, structural health monitoring requires knowledge of the model of structures in great detail, which is not always possible. In addition, dynamic systems usually present non-linear characteristics, which impose practical difficulties on the model-based damage detection techniques [76]. Figure 5.1 presents the typical steps of a pattern recognition process: a sensor transforms the physical state into a measured signal. The processor removes unnecessary or corrupting information from the signal. The feature extractor computes the features required for classification. The pattern classification yields a decision regarding the class membership of the pattern being analyzed, i.e., achieve the pattern-recognition goal [77].

Fig.5. 1 Schematic of a pattern recognition process

Eardrum perforation can be viewed as one kind of structural damages occurring in human being. Eardrum is a membrane in ear canal, as shown in Figure 5.2. The membrane

vibrates when sound waves hit it and helps transfer sound energy into the inner ear which allows us to hear. An eardrum perforation is simply a hole or rupture in the eardrum. A perforated eardrum is often accompanied by decreased hearing and occasional discharge. Generally, the larger is the perforation, the greater the loss of hearing. Therefore, it is necessary to detect the perforation of eardrum even when the damage is incipient.

Fig.5. 2 A perforated eardrum [78]

Since mechanical impedance is an inherent property of structure, any damage of structure will cause variation of mechanical impedance. From this point, mechanical impedance should be a good signature for detecting structural damage. Unfortunately, mechanical impedance is difficult to measure in most time. In Chapters 3 and 4, it has been proved that mechanical/acoustical impedance can be related with electrical impedance, so it is naturally considering detecting structural damage by measuring electrical impedance instead of mechanical impedance. This chapter will describe a concept to monitor healthy state of an eardrum-like membrane by measuring the variation of electrical impedance. Furthermore, a method based on neural networks is presented to estimate the severity of damage.

5.1 Experimental Setup

The experimental setup is similar to the one used for measurement of acoustic absorption coefficient: a dynamic microphone is installed at one end of a tube, and a membrane is attached at the other end. The front part of the tube is like a cone and the back part is uniform, as shown in Figure 5.3. At the end of tube, the acoustic wave is planar because the diameter of tube is relative smaller than the sound wavelength. Since the objective of this experiment is providing a preliminary concept to detect membrane damage by measuring electrical impedance, two simplifications are made. Firstly, a true eardrum can not be obtained for experiment, so a thin polymer membrane is used as a substitute. Secondly, because the dimension of ear canal is too small to install a one-inch dynamic microphone, the dimension of tube for experiment is scaled up so that the dynamic microphone can be mounted in the tube. The detailed dimension of tube and its photo are shown in Figure 5.3 and 5.4 respectively.

Fig.5. 3 Dimension of tube for measurement of membrane damage

Fig.5. 4 Photo of tube for monitoring membrane damage

The polymer membrane is 10mm in diameter and 0.1 mm in thickness, and is carefully attached at the terminal of tube to ensure no sound leakage from the rim. In testing, the dynamic microphone is supplied with ac power, and a standing wave pattern is created in the tube. If the membrane is damaged with a hole, just like the perforated eardrum, the standing wave pattern will change, which accordingly causes a change of electrical impedance of dynamic microphone. Therefore, measuring variation of electrical impedance allow us to monitor the healthy state of the membrane.

Following the same procedure of the measurement as mentioned in the last chapter, swept sinusoidal signals from dynamic signal analyzer are sent to activate the dynamic microphone. The signal of voltage is measured by voltage probe and the current is measured by the current amplifier. The measured voltage and current are picked up and

fed into the dynamic signal analyzer for calculating the input electrical impedance.

5.2 Effects of Tube Shape and Hole Position

To check whether the tube shape affects the measured electrical impedance of the dynamic microphone, two tubes with different shapes, one straight and one curved, as shown in Figure 5.5, are respectively used in the experiment for comparison. The two tubes have the same diameter and effective length. The measured electrical impedance is shown in Figure 5.6. It is seen that the results for the two tubes are identical with each other, which indicates that the tube shape does not affect the measured electrical impedance. Therefore, using the straight tube to simulate the true ear canal, which is non-straight, is reasonable for the investigation presented in this chapter.

Fig.5. 5 (a) The straight tube and (b) curved tube

Fig.5. 6 Electrical impedance for the straight and curved tubes

In the actual situation of eardrum perforation, the holes may occur at any position of the membrane. As known that the acoustic wave in tube is planar, the pressure or particle velocity at a cross section of tube is the same, so that the position of hole in membrane does not affect the standing wave pattern in tube. Therefore, for the membranes with holes in the same size but at different position, the corresponding electrical impedances should be identical with each other. To check this point, three membranes with holes in the same diameter but at different positions, as shown in Figure 5.7, are mounted on the tube respectively for experiment. The electrical impedances for these three cases are shown in Figure.5.8, from which we can observe that they are identical with each other as expected. Since the position of hole in membrane does not affect the measured electrical impedance, hereafter we will only study the case that holes locate at the center of the membrane.

Fig.5. 7 Membranes with holes in the same size but at different positions

Fig.5. 8 Electrical impedance for equal-size holes at different positions

5.3 Classification of Damage

The damage severity of the membrane is classified into four levels: Undamaged situation, Damage 1, Damage 2 and Damage 3. Larger the hole size, the greater the damage. Table

5.1 lists the detailed information for each damage level.

Table 5. 1 Damage levels of membrane

Damage level	Undamaged situation	Damage 1	Damage 2	Damage 3
Description	without damage	slight damage	medium damage	heavy damage
Size of hole	without hole	1mm	3mm	5mm
Illustration				

During the experiment, firstly, an undamaged membrane is mounted at the end of tube, and then the electrical impedance of dynamic microphone is measured by the experimental setup introduced in the previous section. Secondly, without taking down the membrane, a hole with diameter of 1 mm is carefully drilled in the membrane, and electric impedance is measured again. The same procedure is repeated for holes with diameter of 3mm and 5mm, respectively. The real part and imaginary part of electrical impedance for these four damage levels are shown in Figure.5.9 and Figure.5.10 respectively.

Fig.5. 9 Real part of electrical impedance for different damage of membrane

Fig.5. 10 Imaginary part of electrical impedance for different damage of membrane

As can be seen from the real and imaginary parts of electrical impedance, when damage is progressing, three phenomena occur: (1) resonance peaks shift, (2) some resonance peaks split, (3) new resonance peaks appear. The resonances shift towards right when the damage becomes heavier, and the values of peak is different with each other.

When the damage is slight, the difference between the undamaged spectrum and the damage spectrum are noticeable but slight, whereas when the damage is severe, the differences are very intense. One challenge in the spectral classification is to detect not only the intense differences, but also the slight differences. Thus, the better the detection method is, i.e., the better the detection sensitivity, the sooner one would be able to detect incipient damage.

As shown in Figures 5.9 and 5.10, electrical impedance is very sensitive to minor damages of the membranes. Taking the resonance peak around 2000 Hz as example, the frequency shifts 60Hz per 1 mm size of hole in the membrane, and the real part of electrical impedance has a change of 20 Ohm. Although the difference between spectra is apparent, quantification of this difference is neither obvious nor immediate. One cannot correlate a change in electrical impedance directly with the severity of damage. Hence, a method based on neural networks is used to estimate the severity of damage.

5.4 Features Selection

Before utilizing the neural network for pattern classification, features as the input to

neural network should be selected. Features extraction can reduce the problem dimensionality and separate essential information from non-essential information. As the shapes of the impedance spectrum reflect the health of membrane, features of the spectrum are naturally taken into condition. In impedance spectral analysis, the features-vector approach recognizes that the number and characteristics of resonance peaks play a major role in describing the dynamic behavior of the structure. By considering the essential features of the spectrum, i.e., the peaks at resonance frequencies, meaningful information corresponding to the particular state of structural health can be extracted. This information can be organized in a vector of features, which represents a certain structural healthy state. Since both real part and imaginary part of impedance spectrum can reflect the healthy state of membrane, features are selected from the two curves in the frequency range of 10Hz-4000Hz, as shown in Figure 5.11 and 5.12 respectively.

Fig.5. 11 Feature extraction from real part of electrical impedance

Fig.5. 12 Features extraction from imaginary part of electrical impedance

As can be seen from the real part of electrical impedance, five peaks are selected for features extraction. The peaks will shift as the damage severity progresses. In the selected peaks, the first peak is the mechanical resonance of diaphragm and the other four peaks are the resonance of the standing wave pattern. Each resonance peak contains two features: the position and value. Thus, ten features are extracted from the curve of real part of electrical impedance. Considering the curve of imaginary part of impedance together, 20 features are selected in total. The small peak at around 780 Hz is not selected because it will disappear at other damage levels.

5.5 Pattern Recognition via Artificial Neural Networks

Artificial neural networks (ANNs) has recently emerged as a promising tool for monitoring and classifying damage of structures and machines [79-84]. This technique is well suited for solving inverse variational problems in the context of monitoring and damage detection because of their pattern recognition and interpolation capabilities. ANN may also successfully classify the problems associated with non-linearity, and this approach can avoid the complexity introduced by conventional computational methods.

Artificial neural networks are information processing models that are inspired by the way biological nervous systems, such as the brain, process information. The models are composed of a large number of highly interconnected neurons working together to solve specific problems [85]. Each neuron is a simple mathematical processing unit that, when combined with other neurons, produces complex networks that can be trained to recognize defined patterns. During the process of ANN, input information, which could be a series of numbers, is received at the input neurons. Then the information is transferred through subsequent neurons to the end. As the data travels through the network, the information is modified, and mathematical operations are performed. At the end, the output neurons will show a series of simple numbers, which indicate the result of classification. Figure 5.13 shows the pattern architecture of one ANN with one hidden layer [76].

Fig.5. 13 Architecture of neural network with one hidden layer

The input to the ANN are the variables, $(x_1, x_2, \dots, x_N)$, which are weighted by $w_{j,i}^h$ and bias b_j^h and the output results, $(y_1, y_2, \dots, y_N)$, feed the hidden layer. The output of the j th-hidden unit can be described by

$$y_j^h = F_1 \left(b_j^h + \sum_{i=1}^N W_{j,i}^h \cdot x_i \right) \quad (5.1)$$

where the superscript (h) means that the quantities pertain to the hidden layer and $F_1(\cdot)$ is a sigmoid nonlinear function. The output of the ANN is biased and weighted by sum of the hidden layer outputs:

$$y_l = F_2 \left(b_l^o + \sum_{j=1}^H W_{j,l}^o \cdot y_j^h \right) \quad l = 1, 2, \dots, k \quad (5.2)$$

where the superscript (o) refers to the output unit. H is the number of units in the hidden layer and $F_2(\cdot)$ is a linear activation transfer function. The ANN is trained starting with a random set of weights and biases and the output is calculated for every input set. Then, the error E is computed from the output layer backwards, which has historically been called the backpropagated error. This learning algorithm is called backpropagation. The error E is given by

$$E = \sum_i (\{y_i\} - \{T\})^2 \quad (5.3)$$

where $\{T\}$ is the desired output. The error E is formulated as a function of the weights and biases and then, the minimization is performed by means of the usual descent algorithm.

The training of the network uses a set of inputs for which a specified output is known and in this case, the process finishes when the error E becomes lower than a pre-specified threshold or when the maximum specified number of iterations is exceeded. In the latter case, the training set is considered unsatisfactory. The output indicates the answer of the problem, could be a combination of simple numbers which indicate the result of pattern classification, or prediction of the measured variable.

5.6 Results of ANN

Using the selected features as input, we constructed an ANN to detect the damage severity of the membrane using the neural network toolbox in MATLAB. The ANN consists of a three-layer feed forward structure with an input layer, a hidden layer, and an output layer. The input layer has 20 nodes which receive the 20 features extracted from the electrical impedance curve as mentioned earlier. The output layer has one node which indicates the level of damage severity. The number of nodes in the hidden layer is 16 which is selected after comparisons of the results of a few ANN with a different number of nodes. The activation functions used in the hidden and output layer are sigmoid and

pure linear function, respectively. The parameters of the ANN including weights among neurons are obtained by standard back propagation training.

The ANN is trained to map the training data to the corresponding damage levels. The output range of the ANN for this step is from 0 to 3, which corresponds to the undamaged situation, Damage 1, Damage 2 and Damage 3, respectively. 20 sets of data are collected for each damage level, so totally 80 sets of data are used to train the neural network. Training target corresponding with each training set of data is input for training ANN. The training is stopped when the output error falls below the pre-specified convergence threshold (for example, $1e^{-10}$). The training time is short since the structure of neural network is a simple net with only one hidden layer with 16 neurons. After the completion of training process, in order to check the accuracy, an additional 20 sets of data (5 for each of damage level) are tested as a set of verification data. Table 5.2 summarizes the information for training and verification in ANN.

Table 5. 2 Training and verification of ANN

Size of hole	0	1 mm	3 mm	5 mm
Damage level	Undamaged situation	Damage 1	Damage 2	Damage 3
Training target	0	1	2	3
Training set (Totally: 80)	20	20	20	20
Verification set	5	5	5	5

(Totally: 20)				

Fig.5. 14 ANN output of training and verification sets

Figure 5.14 shows the ANN output results obtained for different damage levels. Because the convergence threshold is $1e^{-10}$, the ANN output for training sets are almost identical with the training target, i.e., 0 for undamaged situation, 1 for Damage 1, and so on. The ANN output for verification sets are so close to the target values that it is easy to judge the damage level for every verification set. Table 5.3 lists the ANN output for verification sets, as well as the average error and maximum error. The maximum error for all the verification sets is 0.1174, which indicates that ANN output result is accurate enough to

be used to estimate the damage level. Therefore, it is concluded that the proposed method is able to reliably identify the severity of damage.

Table 5. 3 ANN output and errors for verification sets

Damage level	ANN output of verification sets (y_i)	Average error $\bar{e} = \frac{1}{N} \sum_{i=1}^N y_i - y_{\text{target}} $	Maximum error $e_{\text{max}} = \max(y_i - y_{\text{target}})$
Undamaged situation ($y_{\text{target}} = 0$)	0.0361	0.0626	0.0982
	-0.0723		
	-0.0337		
	-0.0982		
	0.0725		
Damage1 ($y_{\text{target}} = 1$)	1.1037	0.0632	0.1037
	1.0129		
	0.9223		
	0.9646		
	1.0861		
Damage2 ($y_{\text{target}} = 2$)	1.9251	0.0567	0.0832
	1.9363		
	2.0832		
	1.9528		
	2.0147		
Damage3 ($y_{\text{target}} = 3$)	2.8826	0.0929	0.1174
	2.9241		
	3.1037		
	2.9075		
	3.0752		

In the technique for damage detection based on neural network, it is almost an impossible task to train the neural networks for all possible size of holes in membrane. Here, only three sizes of holes are drilled to represent the different damage levels. Because neural network is a nonlinear process, we have no way to obtain the exact size of hole from the output of neural network, but can only estimate the damage level. It is reasonable to assume that if we train ANN by the electrical impedance for every size of hole, then we can predict the size of an arbitrary hole. However, this way is not implemented because it is extremely time-consuming and the report is only a preliminary verification of a method to estimate damage severity. The situation of multiple holes in a membrane is not included in this report either.

Table 5. 4 Rule to classify the damage level

ANN output (y)	$y < 0.5$	$0.5 \leq y < 1.5$	$1.5 \leq y < 2.5$	$y \geq 2.5$
Classification	Undamaged situation	Damage 1	Damage 2	Damage 3

Table 5. 5 Classification of several sizes of holes

Size of hole	1.5 mm	2 mm	3.5 mm	4 mm	5.5 mm
ANN output	1.1817	1.7123	2.1576	2.7852	3.1194
Classification	Damage 1	Damage 2	Damage 2	Damage 3	Damage 3

If the sizes of holes in membranes are not exactly 1 or 3 or 5 mm, the output for these

sets may deviate farther from the target values than the ANN output for training and verification sets do. To estimate damage level for any size of hole, a rule is given in Table 5.4. Through this rule, any size of hole can be classified into one of the damage levels according to the corresponding output of neural network. Some holes (1.5, 2, 3.5, 4, 5.5 mm), which are not exactly 1 or 3 or 5 mm, are used for experiment and the corresponding features vectors are input to the trained ANN. Table 5.5 lists the output of neural network for these holes, as well as the result of classification for each case. For example, when the size of hole is 2 mm, the corresponding ANN output value is 1.7123, and we can conclude that the damage level is close to Damage 2, i.e. medium damage. When the hole is 5.5 mm, the ANN output value is 3.1194, and it can be considered that the damage level is stronger than Damage 3, i.e. very heavy damage. The above experimental results demonstrate the usefulness of the proposed method for monitoring the healthy state of structure and estimating the damage severity.

5.7 Summary

This chapter describes a non-model based method to detect membrane damage, just like an eardrum perforation, and classify damage severity through an artificial neural network. In the proposed method, damage of membrane is divided into four levels: undamaged situation, slight damage, medium damage and heavy damage. The resonance peaks in electrical impedance curves are used as data features to monitor the healthy state and estimate the damage severity. Totally 20 features are extracted from the real and imaginary part of electrical impedance for each damage level. 80 sets of data are used to

train the neural network and 20 sets of data are used for verification. The ANN output for verification sets are close to the target values, which indicates the proposed method can successfully estimate the damage level.

In this chapter, three major tasks are completed successfully. First, electrical impedances for different damage levels of membrane are measured and compared. Second, features are extracted from the resonance peaks in real and imaginary part of electrical impedance to train the neural network. Third, for arbitrary sizes of holes in membrane, the damage levels can be estimated according to the corresponding ANN output.

The method is unique in a few aspects. First, it is sensorless. No sensors are needed to measure the pressure and particle velocities, and thus the mechanical/acoustical impedance on the surface of membrane. Second, the electrical impedance represents the dynamic characteristics of the system, and is very sensitive to minor damages of the membrane structure. Third, this method is in situ, and can be applied to the practical detection of eardrum perforation.

In summary, this chapter provides a preliminary verification of the method to detect healthy state of structure by measuring electrical impedance. Without prior knowledge of the model of structures, the methodology is able to monitor minor changes in structural healthy state and to estimate the damage level, even in its early stage. For further application, this method can be extended to predict the transmission loss of muffler, or monitor healthy state of musical instruments, such as trumpet.

Chapter 6

SSA Capability of a Micro PZT Cantilever Transducer and Its MEMS Realization

When measuring mechanical impedance of a structure, the most common way is to excite the test structure using a shaker and measure the excitation force and the output motion by a conventional force transducer and an accelerometer. The loading effects and calibration errors introduced by these devices often affect the measurement accuracy. In addition, installing the exciter and the sensors onto structures on site and ensuring the true driving-point measurement are another two big problems to be overcome. In the measurement of mechanical impedance of mini/micro structures, the above problems become more serious. The decoupling ability of the transduction matrix mentioned in the previous chapters allows an actuator used simultaneously as a sensor, which can overcome the problems discussed above.

In principle, employing piezoelectric material for dynamic sensing and actuating simultaneously is also feasible. In this chapter, we will study the simultaneous sensing and actuating (SSA) capability of a micro PZT cantilever transducer, and use it to numerically measure mechanical impedance of micro structures via FEA. First, a two-port model is built for the transducer to describe the relationship between electrical and mechanical variables. Second the four elements of transduction matrix

are numerically calibrated through FEA, and then numerical simulation is carried out to use the transducer to measure mechanical impedance, velocity and force of Micro Structures. Finally, fabrication and characterization of micro PZT cantilever transducer is addressed.

6.1 Piezoelectric Material and Its Applications in MEMS

By applying a mechanical stress to a piezoelectric material, a charge can be generated on the surface of the material. This is known as the piezoelectric effect. The application of a voltage to the piezoelectric material causes deformation of the material, which is known as the converse piezoelectric effect. The constitutive equations for piezoelectric material are described as:

$$\begin{aligned}\{S\} &= [s^E]\{T\} + [d]^T\{E\} \\ \{D\} &= [d]\{T\} + [\varepsilon^T]\{E\}\end{aligned}\tag{6.1}$$

where $\{S\}$ is strain, $\{T\}$ stress, $\{E\}$ electric field, $\{D\}$ charge density field, $[s^E]$ compliance matrix with fixed electric field, $[d]$ piezoelectric coefficient, $[\varepsilon^T]$ electric permittivity with fixed stress. The second equation of Equation (6.1) describes the direct piezoelectric effect and shows that a charge density field results from not only an electric field, but also a stress in material. The first equation of Equation (6.1) describes the converse piezoelectric effect and shows that a strain will result from an electric field in the material as well as stress.

In recent years, rapid development of thin-film deposition and micromachining technology has enabled us to drive extensive research on micro-electro-mechanical system (MEMS) devices. Among all of the piezoelectric materials, PZT is most widely used because of its large remanent polarization, high piezoelectric coefficients and ease integration into micro systems[86-93]. PZT cantilevers fabricated by MEMS technology have been applied in various fields, which include self-excited oscillator [94, 95], resonance sensor [96, 97], micropump[98], acoustic transducer [99], as well as active slider for hard disk drives [100, 101], etc.

6.2 Two-port Model of Micro PZT Cantilever Transducer

The micro PZT cantilever transducer studied here is composed of a PZT cantilever and a rigid supporting block, as shown in Figure 6.1, and will be fabricated through MEMS technique. The PZT cantilever has two layers: PZT film and silicon cantilever structure. In MEMS technique, PZT film is coated on a silicon wafer by chemical solution deposition, so it is considered that PZT film is perfectly bonded on the cantilever. The cantilever structure and supporting block are formed by etching the substrate of silicon wafer, thus, the cantilever is well clamped on the supporting block. Figure 6.1 depicts the PZT cantilever transducer under study.

Fig.6. 1 Front and top view of micro PZT cantilever transducer

During measurement, the supporting block of PZT cantilever is affixed on the test structure, and the output port of the transducer is the center of the bottom of the supporting block. When ac power is supplied to the PZT cantilever, it extends and contracts in x-y plane due to converse piezoelectric effect; this causes the transactional bending of the cantilever, which in turn accelerates the supporting block. The reaction force of the motion of the supporting block is exerted to the test structure. In this process, PZT cantilever serves as an actuator. During actuating, the response of the test structure affects the motion of the supporting block and results in additional deformations of the PZT film. As a result, the input electrical impedance is changed accordingly due to the direct piezoelectric effect. If the electromechanical interaction taken place in PZT cantilever is properly modeled, the mechanical impedance at its output port can be evaluated from the measured electrical impedance at the input port.

Similar to the dynamic microphone, the micro PZT cantilever transducer can be characterized by a two-port model since it is linear without internal energy generation, as shown in Figure 6.2.

Fig.6. 2 Two-port model for micro PZT cantilever transducer

Similar to the case of dynamic microphone, the relationship between the electrical and mechanical variables is given by

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} F \\ v \end{Bmatrix} = [A] \begin{Bmatrix} F \\ v \end{Bmatrix} \quad (6.2)$$

where

$$a_{11} = \left. \frac{E}{F} \right|_{v=0}, \quad a_{21} = \left. \frac{i}{F} \right|_{v=0}, \quad a_{12} = \left. \frac{E}{v} \right|_{F=0}, \quad a_{22} = \left. \frac{i}{v} \right|_{F=0} \quad (6.3)$$

Here, F and v are both the components along z direction. The four elements are frequency response functions under clamped and free boundary conditions, which have been introduced in the previous chapters. Similarly, because the PZT cantilever transducer is reciprocal, the determinant of transduction matrix is unity, i.e.

$$|A| = a_{11}a_{22} - a_{12}a_{21} = 1 \quad (6.4)$$

6.3 Numerical Calibration of Transduction Matrix

To numerically calibrate transduction matrix through finite element analysis which is conducted in software the ANSYS, finite element model of the transducer is first built, as shown in Figure 6.3. The properties of PZT cantilever transducer are shown in Table 6.1.

Fig.6. 3 Finite element model of PZT cantilever transducer

Table 6. 1 Properties of micro PZT cantilever transducer

Component	PZT film	Cantilever structure	Supporting block
Dimension (μm)	$500 \times 50 \times 1$	$500 \times 50 \times 10$	$150 \times 200 \times 100$
Material	PZT	Silicon	
Density (kg / m^3)	7800	2330	
Young's Modulus($\times 10^9 \text{ N} / \text{m}^2$)		130	
Poisson's Ratio	0.3	0.4	

In ANSYS, the piezoelectric elements are modeled with 3-D Coupled-Field Solid Element SOLID5. Three matrices are utilized to define material properties. The

piezoelectric matrix $[e]$ is a 6×3 matrix relating the electric field to the mechanical stress; the elastic coefficient matrix $[C]$ is a 6×6 symmetric matrix specifying the stiffness coefficients. These two matrices, together with the permittivity matrix $[\epsilon^s]$, are listed below in a format required by ANSYS:

The piezoelectric matrix

$$[e] = \begin{bmatrix} 0 & 0 & -7.3 \\ 0 & 0 & -7.3 \\ 0 & 0 & 17.2 \\ 0 & 0 & 0 \\ 0 & 14.5 & 0 \\ 14.5 & 0 & 0 \end{bmatrix} \cdot C/m^2$$

The elastic coefficient matrix

$$[C] = \begin{bmatrix} 12.3 & 7.7 & 8.0 & 0 & 0 & 0 \\ & 12.3 & 8.0 & 0 & 0 & 0 \\ & & 11.2 & 0 & 0 & 0 \\ & & & 2.3 & 0 & 0 \\ & & & & 1.9 & 0 \\ & & & & & 1.9 \end{bmatrix} \cdot 10^{10} N/m^2$$

The permittivity matrix under constant strain

$$[\epsilon^s] = \begin{bmatrix} 1039 & 0 & 0 \\ & 1039 & 0 \\ & & 749 \end{bmatrix} \epsilon_0$$

The cantilever and the supporting block are modeled with SOLID45, which is widely used for three-dimensional modeling of solid structures. It has eight nodes, each node has six degree of freedom: translations in the nodal x , y and z directions, and rotations about the nodal x , y and z axes.

To calibrate the four elements of transduction matrix, clamp and free boundary conditions are set at the output port respectively. The clamp boundary condition is often difficult to achieve in experiments, whereas it can be easily simulated in the numerical studies by setting the nodal displacement of the node at the output port to be zero. Free condition is also easily realized in numerical study by not applying any constraint at the output port.

For PZT film, the top and bottom surfaces are set as top and bottom electrodes, respectively. The electric potential in the same electrode surface is equivalent. To simulate this condition, all voltage degree of freedoms (DOFs) of nodes on each electrode surface is coupled together. Transducer is a lightly damped structure, so structural damping is included in the simulation and set to be 0.1%.

When a sinusoidal electrical wave with amplitude of 1 volt is supplied to the PZT film, the electrical current can be determined using $i = \frac{dQ}{dt}$ through harmonic analysis. To get a_{11} and a_{21} , the output port is clamped, and the corresponding force along z direction at the point is obtained. According to first two of the Equation (6.3), a_{11} and a_{21} can be calculated. To get a_{12} and a_{22} , the output port is set as free condition, and the corresponding velocity along z direction at the point is obtained. According to last two of the Equation (6.3), a_{12} and a_{22} can be calculated. The FEA results of a_{ij} are shown in Figures 6.4 and 6.5.

Fig.6. 4 Magnitude and phase of a_{11} and a_{21} Fig.6. 5 Magnitude and phase of a_{12} and a_{22}

Figure 6.6 presents the determinant of the transduction matrix obtained from FEA. The results are unity in magnitude and zero in phase, which matches expectation and reflects the reciprocity property of the transducer.

Fig.6. 6 Determinant of transduction matrix

6.4 Measurement of Mechanical Impedance of Micro Structures

According to Equation (6.2), mechanical impedance can be measured by detecting the electrical impedance, as indicated in Equation (6.5).

$$Z_m = \frac{F}{v} = \frac{a_{12} - a_{22} \cdot Z_e}{a_{21} \cdot Z_e - a_{11}} \quad (6.5)$$

where $Z_e = E/i$ is electrical impedance. Because F and v are the components along z direction, Z_m is the z -directional mechanical impedance of the test structure at the point affixed with the transducer.

A beam in micro scale clamped at one end is chosen as the test structure to study the effectiveness and feasibility of the micro PZT cantilever transducer. The test beam is also made of silicon and is $3000 \mu\text{m}$ in length, $600 \mu\text{m}$ in width, $100 \mu\text{m}$ in thickness. The transducer is affixed at the tip of the test beam. The resonant frequencies of test beam and transducer are well separated in the frequency range. Finite element models of the transducer & test beam system is depicted in Figure 6.7 and 6.8. The test beam is modeled with SOLID 45. After a sinusoidal voltage with amplitude of 1 volt is supplied to the PZT cantilever, the input impedance of the transducer Z_e is calculated via harmonic analysis (Figure 6.9). The mechanical impedance of the test beam is then calculated using Equation (6.5), as shown in Figure 6.10.

Fig.6. 7 Finite element model of the transducer & test beam system

Fig.6. 8 Finite element model of the transducer & test beam system (enlarged view)

Fig.6. 9 Input electrical impedance of the transducer

Fig.6. 10 Mechanical impedance of the test beam

To check the results obtained by PZT cantilever, the mechanical impedance of the test beam is evaluated by constructing finite element model of the beam directly (Figure 6.11). Here, a sinusoidal force is applied to the measurement point (Figure 6.12). By calculating the response linear velocity at the point through harmonic analysis using ANSYS, the mechanical impedance is obtained ($Z_m = F / v$).

Fig.6. 11 FEA model of the test beam

Fig.6. 12 Setup for determining Z_m from its definition

Now, for the test beam, we have two sets of mechanical impedance determined through two different numerical ways. One set is assessed via PZT cantilever transducer, and the other set is calculated according to the definition of mechanical impedance. As shown in Figure 6.13, they coincide with each other very well in both amplitude and phase. It is therefore concluded the transduction matrix correctly relates with the input electrical port and output mechanical port.

Fig.6. 13 Comparison of Z_m

6.5 Measurement of Velocity and Force

Equation (6.1) can be rewritten as

$$\begin{Bmatrix} F \\ v \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}^{-1} \begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{Bmatrix} E \\ i \end{Bmatrix} = [B] \begin{Bmatrix} E \\ i \end{Bmatrix} \quad (6.5)$$

where matrix $[B]$ is inverse of $[A]$. The velocity and force can be expressed as

$$v = b_{21}E + b_{22}i \quad (6.6)$$

$$F = b_{11}E + b_{12}i \quad (6.7)$$

Here, F is the force exerted by the transducer to the test structure, and v is the vibration velocity of the test structure under the force. From the above two equations, we can see that with the help of transduction matrix, by probing electrical voltage and

current, the PZT cantilever can be used as velocity or force transducer.

Using the finite element model of the transducer & test beam system (Figure 6.7), there are two methods to obtain velocity via FEA. First, by measuring voltage and current of the PZT cantilever transducer, velocity can be calculated through Equation (6.6). Second, velocity value can be directly picked up from the nodal result in FEA solution. These two results are compared in Figure 6.14, which shows that they match well with each other.

Fig.6. 14 Comparison of velocity

Following the same procedure in the first method for velocity, by measuring voltage

and current of the transducer, force can be calculated through Equation (6.7). To check the correctness of the result from transducer, we seek another method to obtain force for comparison. Because the force here is an internal one for the transducer & test beam system, it is impossible to pick up the force directly from nodal result. However, since the velocity and mechanical impedance have been obtained, F can be calculated from definition of impedance ($F = Z_m \cdot v$). Figure 6.15 compare the forces from the above two methods and good coincidence is found.

Fig.6. 15 Comparison of force

Because the PZT cantilever transducer is designed in micro scale and fabricated through MEMS technique, by measuring the voltage and current, it can be used as a micro velocity or force sensor, whereas, by applying voltage and current on the PZT

cantilever, it can be used as a micro force actuator.

6.6 Realization of Micro PZT Cantilever Transducer

In the fabrication of micro PZT cantilever through MEMS technique, the actual structure of the cantilever is composed of Pt/Ti/PZT/Pt/Ti/SiO₂/Si multimorph (Figure 6.16). Platinum (plus titanium as the bottom adhesion layer) is used as the electrode and barrier layer to prevent the diffusion between PZT and the silicon substrate. The thickness of electrodes is very thin and can be ignored during the theoretical calculation. The silicon is used as the supporting structure of the cantilever because of its rigidity and stiffness. Silicon dioxide (SiO₂) is used to fasten the bottom electrode to the silicon substrate.

Fig.6. 16 Top view and cross-section of the micro PZT cantilever

6.6.1 Flow of Fabrication Process

The fabrication process includes four main steps: (i) The bottom electrode is deposited by sputtering and patterned by a lift-off process. (ii) A PZT thin film is deposited by sol-gel spin coating with commercial Mitsubishi E-Series solution and patterned by wet etching. (iii) The top electrode is deposited and patterned by the same method as used on the bottom electrode. (iv) Cantilever structure is released by using a double side deep reaction ion etching (DRIE) process. The fabrication process flow is listed in the table 6.2 and series of cross-section diagrams are shown in Fig.6.17. All of the fabrication steps are performed in the Micro Machines Center of the School of Mechanical and Aerospace Engineering in Nanyang Technological University. The fabrication details will be introduced in the next section.

Fig.6. 17 Fabrication process of micro PZT cantilever

Table 6. 2 Main process flow in the fabrication of micro PZT cantilever

No.	Layer	Thickness	Deposition method	Etching method
1.	SiO ₂ deposition	0.5 μm	Thermal oxide	
2.	Bottom electrode	Ti (50nm)/ Pt (150nm)	Sputtering	Lift-off
3.	PZT	0.7 μm	Sol-gel	PZT etching solution
4.	Top electrode	Ti (50nm)/ Pt (150nm)	Sputtering	Lift-off
5.	SiO ₂ etching	0.5 μm		Wet etching
6.	Front side Si etching	10 μm		DRIE
7.	Back side bulk Si etching	400 μm		DRIE

6.6.2 Details of Fabrication

Design of Mask

The first work for fabrication is designing masks according cantilever's structure and dimensions. Many types of software can be used to design masks, such as AutoCAD and L-Edit. Here we choose the MaskEditor of the IntelliSuite software package for its convenient operation. The design drawing is shown in Fig.6.18. There are totally five masks used in our fabrication: Mask #1 is for patterning bottom electrode, shown here in yellow; Mask #2 is for patterning PZT layer, shown here in red; Mask #3 is for top electrode, shown here in light blue; Mask #4 is for etching from the front side, shown here in green; Mask #5 is for bulk etching from the back side, not shown here. The masks are printed on glass with chrome, and are used for the patterning of the wafer by photolithography technique.

Fig.6. 18 Masks design for micro PZT cantilever

Photolithography and pattern transfer

Lithography in the MEMS context is typically the transfer of a pattern to a photosensitive material by selective exposure to a radiation source such as UV (ultraviolet). A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If we selectively expose a photosensitive material to radiation (e.g. by masking some of the radiation) the pattern of the radiation on the material is transferred to the material exposed, as the properties of the exposed and unexposed regions differ [102].

In lithography for micromachining, the photosensitive material used is typically a photoresist. When photoresist is exposed to a radiation source of a specific wavelength, the chemical resistance of the photoresist to developer solution changes. In our fabrication, AZ9260 is chosen as the photosensitive material. The process step of photolithography is described in detail as follows :

The cleaning of the silicon substrates and dehydration bake (on a hotplate at 110°C for 10 min) are carried out first, to remove any dirt and moisture adsorbed onto the wafer. This is followed by the coating of HMDS, which is used to promote adhesion. Subsequently the wafers are spin coated with AZ9260 photoresist at 2000rpm, for 60s. After the wafers are soft baked at 110°C for 4 min and left aside for a minimum of 5 min for the resist to cool down. This is followed by UV exposure for 30s. Subsequently, the wafers are developed in the developer AZ421K for approximately 2

min and rinsed in the de-ionized water for another minute. The patterned wafers are then dried and hard baked for 15 min at 120°C on a hotplate.

There are two methods for patter transfer: etching and lift-off [103]. In the process of etching, a photoresist layer is used as a temporary mask when etching an underlying layer, so that the pattern is transferred to the underlying layer, as shown in Figure 6.19(a). In the process of lift-off, photoresist is used as a template for patterning material deposited after lithography, as shown in figure 6.19(b). The photoresist is subsequently etched away, and the material deposited on the resist is lifted off.

Fig.6. 19 Pattern transfer by (a) etching and (b) lift-off

Deposition of electrodes

The electrodes consist of a thin layer of titanium for adhesion and a platinum layer.

Platinum is used as the bottom electrode in order to facilitate the correct crystal

structure of PZT to be grown onto the surface. Sputtering is used to deposit the bottom and top electrodes in our fabrication. During sputtering, the target (here titanium and platinum material), at a high negative potential, is bombarded with positive argon ions created in plasma. The target material is sputtered away mainly as neutral atoms by momentum transfer ejected surface atoms are deposited onto the substrate placed on the anode.

The lift-off is carried out using acetone in an ultrasonic bath for 1 hour. Subsequently, after immersed in isopropyl alcohol (IPA) to wash away acetone, the wafers are rinsed in de-ionized water and then put into spin drier for drying.

Deposition of PZT thin film and etching

Deposition of PZT thin films is the most critical technique to successfully fabricate micro piezoelectric devices. A number of methods for PZT thin film deposition have been reported, such as RF magnetron sputtering, metal organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), metal organic decomposition (MOD) and sol-gel process. Among them, sol-gel method has attracted considerable interest because its better integration with circuit (IC) fabrication, easier composition control, lower cost, better reproducibility and shorter fabrication cycle.

However, sol-gel process consists of several phases of heat treatment such as solution drying after spin coating, gel pyrolysis and post-annealing treatments for

crystallization. The heat treatments often cause severe PZT film cracking, especially on the areas without Pt buffer layer (bottom electrodes). The cracking occurs due to several reasons. First, during pyrolysis at about 350°C, organic materials are being driven off from the PZT. This process causes the PZT layer to slightly shrink which results in stress between the PZT thin film and the underlying substrate. Also PZT goes through a phase change to the pyrochlore state at this temperature. This change in crystal structure can also create stress in the films. Secondly, more stress is induced during post-annealing treatment for the film crystallization at about 700°C, due to the PZT changing its crystal state to the perovskite phase for obtaining piezoelectricity. Finally, mismatching of thermal expansion coefficients between PZT thin film and substrate could also cause cracks. The cracks at the edge of Pt bottom electrodes can easily extend to the device areas in the subsequent wet etching process of PZT thin film, which will lead to the short-circuit of fabricated devices in the later deposition process of top electrodes. In addition, diffusion of PZT to the silicon substrate (areas without Pt bottom electrodes) during high temperature annealing will also degrade the substrate properties and may hinder further micromachining processes on these surfaces.

Fig.6. 20 Flow diagram of modified sol-gel process for PZT deposition

To overcome the above problems, a modified PZT deposition technique based on sol-gel process is presented and applied in the fabrication of micro piezoelectric cantilevers [104]. The flow diagram of modified PZT thin films deposition technique based on sol-gel process is shown in Figure 6.20. A lead titanate (PT) seeding layer with thickness of about 70 nm is coated and pyrolyzed before PZT thin film deposition. The deposition of seeding layers can improve the quality of ferroelectric films and the interfaces between the ferroelectric films and electrodes⁷. The 15% PZT (115/52/48) sol-gel solution is composed of 18wt% of lead acetate

($\text{Pb}[\text{CH}_3\text{CO}_2]_2 \cdot 3\text{H}_2\text{O}$), 8wt% of Zirconium-tetra-n-butoxide ($\text{Zr}[\text{n-OC}_4\text{H}_9]_4$), 6wt% of Titanium-tetra-iso-propoxide ($\text{Ti}[\text{i-OC}_3\text{H}_7]_4$), and 58wt% of 1- Butanol ($\text{C}_4\text{H}_9\text{OH}$), 10wt% of Propylene Glycol ($\text{CH}_3\text{CH}[\text{OH}]\text{CH}_2\text{OH}$). First, PZT sol-gel solutions were deposited on Pt/Ti/SiO₂/Si substrate by spin coating at 500 rpm for 3 seconds and then at 3000 rpm for 30 seconds. These films were then baked at 350 °C for 5 min on a hot plate for pyrolysis. The processes of spin coating and pyrolysis were repeated for 3 times before the films were patterned and wet etched. To etch the PZT film, thick photo resist AZ9260 was employed as etch mask, and a mixture of HF (40%), HCL (36%) and DI water with a volume ratio of 1.5:10:30 was used as the PZT film etchant. The etch time was about 10 seconds for 3 layers films with fresh etching mixture. The patterned PZT films were annealed at 700°C using a 3-zone quartz tube furnace (ST55666C) for 15 minutes. During the annealing process, oxygen (O₂) was flowed to keep the pure perovskite forms precisely at O₂ stoichiometry. The above PZT sol-gel deposition process was repeated for 3 to 4 times, yielding a PZT multi layer of about 0.72 μm to 0.96 μm thick. Further spin coating may result in film cracking when the critical film thickness is reached. Finally, another PT seeding layer was deposited on the PZT layer and pyrolyzed.

In the conventional sol-gel process, PZT thin films are patterned after post-annealing and only for one time. However, in this modified process, we pattern the pyrolyzed PZT thin films by wet etching before every treatment of post-annealing for crystallization. This modification is based on the consideration that the cracking of

films and diffusion of PZT to uncovered substrate mainly occur during the post-annealing treatment at high temperature (700°C). Due to the unwanted PZT films are removed before sintering, the modification brings two advantages over the conventional process: One is reduce of thin film stress by cutting down the areas of individual films, which will release the residual stress in the remaining films. Another is surface cleaning effect for the substrate without Pt electrodes, and therefore no PZT diffusion to substrate during the high-temperature annealing phase.

Figure 6.21 shows the results of existing and presented processes for PZT thin films deposition. Obviously, the conventional sol-gel process causes severe PZT film cracking on the substrate which is not covered by Pt buffer layer (bottom electrodes), and remains a layer of brownish substance after wet etching of the thin film. The substrate surface where PZT is removed from is entirely impaired with the remaining trace of PZT cracks. The edges of some patterned PZT films are also damaged due to the over-etching along the cracks. However, in the modified process, the PZT thin films are uniformly deposited and patterned with tidy edges, and the PZT removed substrate surfaces are left clean and intact. Although the modified process is a bit time consuming due to the increase of times of PZT patterning, the phenomena of film cracking and PZT diffusion to substrate have been effectively eliminated, and the quality of PZT thin film deposition has been greatly improved.

Fig.6. 21 Piezoelectric cantilevers fabricated by (a) conventional process and (b) modified process

Releasing cantilever structure

The definition and release of the cantilever structure are finished by DRIE of silicon with the photo resist as etching mask. To create a cantilever beam, three sides of this diaphragm are etched away in the DRIE system, leaving only one side still fixed. To protect the beams, a thick layer of photoresist is slowly spin coated onto the wafers. The etch selectivity of silicon to photo resist is larger than 80. An etch rate of about $2.6 \mu\text{m} / \text{min}$ is achieved with the uniformity better than 2% over a 4-inch wafer. The thickness of the cantilever $20 \mu\text{m}$ in thickness is defined by the DRIE from the front side of the silicon. The bulk silicon $400 \mu\text{m}$ in thickness on the backside of the wafers is etched by DRIE process to release the cantilever structure. After the cantilever structure is cut from the wafer, the photoresist is then removed by soaking in acetone followed by isopropyl alcohol.

About 80 piezoelectric cantilevers with different dimensions have been successfully fabricated on one wafer. The yield rate of fabricating piezoelectric cantilevers is close

to 100%, which is attributable to the reduction of film cracking and short-circuiting due to the improvement of sol-gel process for PZT deposition. Figure 6.22 shows different dimensions and patterns of fabricated microcantilever by SEM photograph.

Fig.6. 22 SEM photograph of fabricated micro PZT cantilevers

6.7 Characterizations and Testing

One method used to determine whether the deposited PZT is in the correct crystal phase, the perovskite structure, is x-ray diffraction (XRD). The perovskite structure for PZT will have a characteristic XRD pattern. As X-rays are emitted through the PZT crystal, the rays are diffracted. The intensity of the x-rays emitted through the crystal is measured as a function of the diffraction angle. At certain diffraction angles, a peak in the intensity will be observed. These peaks are indicative of the crystal planes for the structure being analyzed. In our investigation, the deposited PZT thin film by sol-gel process is analyzed before top electrode deposition by glazing incidence X-ray diffraction. The results (shown in Figure 6.23) indicate that most of the intensity peaks are for PZT and only one for Pt (bottom electrode). The results also show a perovskite phase PZT structure with (111) peak as the main peak, which proves that the film has a (111) preferential structure [105].

Fig.6. 23 XRD analysis results of PZT films (all are PZT peaks, only one for Pt)

The most common technique used to determine the piezoelectric properties of PZT thin film is through performing charge vs electric field hysteresis by using a ferroelectric test system that supplies an oscillating voltage to the device and measure the charge density as a function of the voltage. The particular system used for our experiments is the RT6000HVS Ferroelectric Test System manufactured by Radiant Technologies. For our tests, a voltage of -18 to $+18$ volts at 1KHz is applied to each device under test. The RT6000HVS displays the hysteresis loop along with the pertinent values (P_r , P_s , P_{sat}) and the relative dielectric constant. One of the hysteresis loops obtained from one of our tests is shown in Figure 6.24.

Fig.6. 24 Hysteresis loop of PZT thin film

Four parameters are observed from the hysteresis loop: remanent polarization (P_r), saturation polarization (P_{sat}), spontaneous polarization (P_s) and coercive field (E_c). The remanent polarization, P_r , is a measure of the degree of ferroelectricity in the

poled material and is given as the amount of charge in the material when zero electric field is applied. Typically, high P_r values indicate that the material has an adequate degree of piezoelectricity. The saturation polarization, P_{sat} , is a measure of the largest change that can be produced in the material. The value of P_{sat} is dependent upon the value of the peak field. The spontaneous polarization, P_s , is determined by extrapolating P_{sat} along a tangent back to zero electric field. The coercive field, E_c , is taken as the field required to obtain a zero net charge in the material.

For our PZT microcantilever shown in Figure 6.24, one can see the remanent polarization (P_r) is $22.2 \mu C / cm^2$, the saturation polarization (P_{sat}) is $42.8 \mu C / cm^2$, the spontaneous polarization (P_s) is approximately $35 \mu C / cm^2$. The coercive field (E_c) can be calculated: $2.15V / 0.7 \mu m = 30.7 kV / cm$. The remanent polarization and coercive field are the most popular values to be reported to and provide a good indication of the quality of the piezoelectric material being tested. A higher value for P_r indicates a higher degree of polarity in the material, which correlates well to the piezoelectric activity of the material. A lower value of E_c generally indicates a lower operating voltage required. A higher electric field used for testing will produce a higher remanent polarization [106]. Therefore, for comparisons, the voltage or electric field used to excite the piezoelectric thin film should be cited in addition to the respective ferroelectric values that are measured. Table 6.3 lists the properties of PZT thin films by different deposition processes and the electric field used. The remanent polarization and the coercive field of modified sol-gel PZT film are comparable to

previously reported values by other deposition processes. The comparison indicates that the PZT thin film deposited by the modified sol-gel method has the same composition and crystalline structures as the PZT deposited by other methods.

Table 6. 3 Properties of PZT thin films by different deposition methods

Deposition methods	+Pr ($\mu C / cm^2$)	+Ec (kV / cm)	Electric field (kV / cm)
Sputtering[107]	15.1-22.0	65-81	+/-200
MOCVD[108]	21.5	33.8	+/-150
MOD[109]	11.4	57.9	+/-200
Sol-gel[110]	18-26	28-77	+/-150
Modified sol-gel	22.2	30.7	+/-250

To verify the self-excitation capability of fabricated piezoelectric cantilever, the frequency response of the cantilever was measured by a Laser Doppler Vibrometer (Polytec, model PSV-300F). A fabricated piezoelectric cantilever with 500 μm in length, 50 μm in width and 20 μm in thickness is chosen for the testing. The first mode resonant frequency was observed at 223125Hz by the variations of tip displacement and velocity, shown in Figure 6.25. The same object is measured by an impedance analyzer (SI 1260) and found at 223156Hz as shown in Figure 6.26. The two values are very close to each other. This indicates that complex impedance analysis can provide an effective and convenient way to evaluate the resonant behavior of piezoelectric cantilevers used as micro sensors and actuators.

Fig.6. 25 Resonant frequency measured by laser vibrometer

Fig.6. 26 Resonant frequency measured by impedance analyzer

Since the piezoelectric cantilever was designed to be a component in a sensor for dynamic motion and/or force measurement, a simple test was carried out to roughly tell about the sensitivity of resonance frequency to a change of the environment. In the test, the beam is subjected to wind blowing. Figure 6.27 shows that the resonant

frequency changes quite significantly when the distance of fan is changed slightly.

Fig.6. 27 Resonant frequency shift with change of wind loading

6.8 Summary

This chapter introduces a micro PZT cantilever transducer which is used to measure mechanical impedance of micro Structures. The transducer is modeled as a two-port model, and the input electrical and output mechanical variables are related by a transduction matrix. The transduction matrix is firstly numerically calibrated via FEA. After that, the transducer is utilized to numerically measure the mechanical impedance of a micro test beam. To verify the results obtained by the transducer, mechanical impedance of the test beam is obtained by definition. The comparison leads to the conclusion that the micro PZT cantilever transducer can accurately measure the mechanical impedance of the micro structure. Furthermore, it is

numerically proved that by probing electrical voltage and current, the PZT cantilever can also be used as micro transducers for measurement of velocity and force.

Subsequently, this chapter presents the fabrication process of micro PZT cantilever. In the sol-gel process for PZT thin film deposition, film cracking always causes low yield rate of fabrication of piezoelectric devices. In this chapter, the reasons for thin film cracking are analyzed and a novel PZT thin film deposition technique has been proposed to eliminate these problems. By applying it to the fabrication of micro piezoelectric cantilevers, a comparison has been made to the conventional process. Performances of PZT thin film by the new technique such as X-ray diffraction pattern and hysteresis loop upon polarization are characterized. Measurement of resonant frequency for fabricated piezoelectric cantilever is performed to verify the self-excitation capability. The dynamic response of cantilever is also roughly checked via a simple primitive test. All experimental results show that the performances of the piezoelectric cantilevers fabricated by the modified process are the same as those by the conventional processes. Most importantly, with this modified process, the quality and yield rate of fabrication of piezoelectric cantilevers are tremendously increased.

After numerically proving the feasibility to use a micro PZT cantilever transducer to measure mechanical impedance of micro Structures, and having successfully fabricated micro PZT cantilevers with high quality, the remain work is to conduct experiments to validate the proposed method.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

This thesis reports the investigation of a commercially available dynamic microphone and an in-house made micro PZT cantilever transducer to characterize acoustic property of materials and monitor health condition of structures based on the concept of transduction matrix. Through the calibrated transduction matrix, simply by measuring the input electrical impedance, the dynamic microphone can measure specific acoustic impedance of material and absorption coefficient, while the micro PZT cantilever transducer can measure mechanical impedance for micro structures. Consequently the direct measurement of force/pressure and velocity/particle velocity, which are usually difficult to conduct in experiment, is avoided. The method possesses two features in usage: 1) it is sensor-less and free of loading effect, and 2) capability of measuring actuating impedance in-situ and almost real-time. Besides, taking impedance (which is a system property) as signature, monitoring of a mechanical system is made more accurate compared with the conventional methods using other output signals. The investigation validates the method with a number of cases, which are summarized in the following.

To study the simultaneous sensing and actuating (SSA) capability of a dynamic microphone, a two-by-two transduction matrix is proposed to relate the input electrical variables (voltage and current) and output mechanical variables (force and velocity). The transduction matrix is obtained from theory and experiment, respectively. Through the transduction matrix, mechanical impedance at output port could be expressed as a function of the corresponding electrical impedance. For experimental verification, mechanical impedances of some point masses are measured by the dynamic microphone. The experimental result matches well with the real value, which indicates that dynamic microphone could perform well simultaneous sensor and actuator.

Based on the SSA capability of dynamic microphone, a sensor-less method for measurement of specific acoustical impedance or absorption coefficient of materials in a standing wave tube is presented. A dynamic microphone is mounted in a portable tube to constitute the dynamic microphone-tube system, which is modeled as a two-port model. Derived from the model, three conditional impedance functions (Z_{ao} , Z_{ef} and Z_{ec}) are defined to characterize the dynamic behavior of the system. Through these conditional impedance functions, the specific acoustical impedance could be quantitatively expressed as a function of electrical impedance. Due to the practical difficulties in directly identifying Z_{ao} and Z_{ef} , new calibration methods have been developed, in which the calibration is performed simply by measuring the input electrical impedance of dynamic microphone when the tube terminal is mounted

with some calibrated materials, whose specific acoustical impedances have been known from the classical transfer function method ahead of time. Testing on five different materials shows that the method can accurately identify the specific acoustical impedance or absorption coefficient of materials in the frequency range of interest. The microphone-free feature of the method is of particular use in situations where inserting a microphone sensor into an impedance tube is difficult.

Another investigation utilizing the SSA capability of dynamic microphone is monitoring the health condition of membrane. A dynamic microphone is mounted in an ear canal-like tube and the eardrum-like membrane is attached at the other end of tube. Taking electrical impedance from the dynamic microphone as signature, we are able to monitor the healthy state of membrane and evaluate the damage level. The electrical impedance of dynamic microphone is directly related to the mechanical impedance of the membrane, and any changes in the electrical impedance can be considered an indication of changes in the membrane integrity. For different damage levels of membrane, variation of electrical impedance from the dynamic microphone is observed. Features are extracted from the curves of electrical impedance and used to train an artificial neural network. Through the trained neural network, damage in membrane can be monitored even in its incipient stage, and damage level can be easily estimated, which indicates electrical impedance is a good signature for non-destructive evaluation.

Besides dynamic microphone, a micro PZT cantilever transducer is also studied for its SSA capability, and is employed to measure mechanical impedance for micro structures. The two-by-two transduction matrix for the micro PZT cantilever transducer is numerically calibrated via finite element analysis. With the calibrated transduction matrix, mechanical impedance for micro structure is numerically measured by the transducer. Furthermore, with the transduction matrix, it is numerically validated that the PZT cantilever transducer could be used to measure force and velocity. Finally, fabrication of micro PZT cantilever transducer through MEMS technology is presented in detail. A modified PZT thin film deposition technique is developed and applied to the fabrication of micro piezoelectric cantilevers. Performances of PZT thin film by the modified process such as X-ray diffraction pattern and hysteresis loop upon polarization are characterized. Measurement of resonant frequency for fabricated piezoelectric cantilever is performed to verify the self-excitation capability. The dynamic response of cantilever is also roughly checked via a simple primitive test. All experimental results show that the performances of the piezoelectric cantilevers fabricated by the modified process are the same as those by the conventional processes. Most importantly, with this modified process, the quality and yield rate of fabrication of piezoelectric cantilevers are tremendously increased.

7.2 Recommendations

After validating the SSA capability of dynamic microphone and micro PZT cantilever transducer, it is necessary to examine the possibility of improving their actuating and sensing performance. For such transducer which performs simultaneous sensor and actuator, so far there is not a well-accepted criterion defining its optimal performance. However, it is safe to say that such a “good” transducer should have high actuation efficiency to effectively generate acoustic wave or excite test structure, and simultaneously high sensing capability to detect even small variations of the test variable. For dynamic microphone, dimension and material of vibrating membrane, coil and permanent magnetic are key parameters for optimization. Due to the complex geometry of dynamic microphone, the optimization work can only be done through finite element analysis. For micro PZT cantilever transducer, dimension of cantilever and supporting block, piezoelectric coefficient of PZT and thickness of PZT thin film are most important to lead good performance of the transducer. Since the geometry of PZT cantilever transducer is not very complex, doing optimization through closed-form analytical solution or finite element analysis is both feasible.

So far, in the mentioned method for measuring absorption coefficient of materials, a piece of material must be cut down as a sample installed in the standing wave tube, which means this method can be only implemented in laboratory. However, measurement of absorption coefficient in situ is more important in practical engineering. The advantages of the method, such as portable tube and sensor-less feature, make it possible to measure absorption coefficient in situ. One difficulty to

realize in situ measurement is ensuring no sound leakage from the place where the tube presses on the material. Any sound leakage will lead the result of absorption coefficient larger than the real value. The other difficulty is keeping the tube absolutely stable during measurement because any vibration of tube will affect the standing wave pattern and in turn cause unacceptable error of the result of absorption coefficient.

Regarding the experiment of taking electrical impedance to monitor healthy state of eardrum-like membrane, this thesis only provides a preliminary verification of the method. To apply the technique to practical detection of damage of eardrum, two aspects need to be improved. First, the size of dynamic microphone should be small enough to be installed in human's ear without sound leakage, and the generated sound pressure should be strictly controlled under the level human ear can endure, but large enough for sensing purpose. Second, a large number of data sets corresponding to different damage levels should be collected in situ with real human eardrum, so that the artificial neural network can be trained with high accuracy for actual measurement. Besides detection of eardrum damage, the proposed method may also be applied to monitor healthy state of musical instrument or predict transmission loss of muffler.

The research reported in the thesis is to develop a novel and simple method for dynamic measurement of acoustical absorption coefficient and membrane health monitoring. Simulations and experiments were designed and conducted to develop the

method and validate the concepts and measures. The dynamic microphone utilized was conveniently chosen from commercial products available in the market. It is obviously not the perfect “transducer” we were looking for, yet it serves the purpose properly – validate the concept and develop the method. Uncertainty ought to be concerned and investigated in order to ensure the accuracy of the measurement results. This is an important work to be carried when a measurement device is developed according to the method. It, however, is not a concern in the stage of developing the innovative method.

To convincingly prove that micro PZT cantilever transducer is a good tool for detection of mechanical impedance for micro structures, not only numerical simulation but also experimental validation need be conducted. Before we can use the fabricated micro PZT cantilever transducer to measure mechanical impedance for micro structures, some work must be completed firstly, such as wire bonding, package and installation of transducer, which may be difficult and complicated because micro transducer is very fragile and easily broken during operation. To improve performance of the transducer, a new design can be considered that two identical PZT cantilevers are symmetrically fixed on the supporting block. With this new design, rotation moment to the supporting block will be totally eliminated, and the transducer may have higher actuating and sensing capability, but the fabrication of the transducer will become more difficult. Since the micro PZT cantilever transducer can measure mechanical impedance for micro structures, it is expected to be widely applied into

the fields of micro mechanics and micro biomedicine, such as improving operation efficiency of atomic force microscope (AFM), distinguishing cancer cell and measuring blood viscosity through measuring their mechanical impedance.

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Appendix A

Reciprocity Theorem

For the reciprocity theorem in this thesis, suppose the transducer is passive where the one energy can flow in either direction, i.e., which can function as either a sensor or an actuator. Such a transducer can be regarded as a reciprocal transducer. As we know, for the linear system, the relationships between the input variables e_{in} and f_{in} and the output variables e_{out} and f_{out} can be written as

$$\begin{Bmatrix} e_{out} \\ f_{out} \end{Bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{Bmatrix} e_{in} \\ f_{in} \end{Bmatrix} \quad (a1)$$

where, the matrix containing b_{11} , b_{12} , b_{21} and b_{22} is the transduction matrix of the transducer.

Selecting the output port of the transducer as the input port and the input port as the output port, and then rewriting the above equation, we have the following equations:

$$\begin{aligned} \begin{Bmatrix} e_{in} \\ f_{in} \end{Bmatrix} &= \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} e_{out} \\ f_{out} \end{Bmatrix} \\ &= \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{Bmatrix} e_{in} \\ f_{in} \end{Bmatrix} \\ &= \begin{bmatrix} a_{11}b_{11} + a_{12}b_{21} & a_{11}b_{12} + a_{12}b_{22} \\ a_{21}b_{11} + a_{22}b_{21} & a_{21}b_{12} + a_{22}b_{22} \end{bmatrix} \begin{Bmatrix} e_{in} \\ f_{in} \end{Bmatrix} \end{aligned} \quad (a2)$$

Identify the last matrix in the above equation as the identity matrix leads to the following relations:

$$\begin{aligned}
a_{11}b_{11} + a_{12}b_{12} &= 1 \\
a_{11}b_{12} + a_{12}b_{22} &= 0 \\
a_{21}b_{11} + a_{22}b_{21} &= 0 \\
a_{21}b_{12} + a_{22}b_{22} &= 1
\end{aligned} \tag{a3}$$

The relations might seem difficult to solve, being a set of four nonlinear algebraic equations in eight unknowns. However, there is a unique, easily verified solution, which is given below:

$$\begin{aligned}
a_{11} &= b_{22} \\
a_{12} &= -b_{12} \\
a_{21} &= -b_{21} \\
a_{22} &= b_{11}
\end{aligned} \tag{a4}$$

According to the above relations, the elements of the transduction matrix are not independent, and related by the following equation:

$$a_{11}a_{22} - a_{12}a_{21} = 1 \tag{a5}$$

The above equation is called the reciprocity relation, which is the characteristic of the reciprocity.