Novel techniques for laser doppler vibrometry for vibrating shiny and mirror surfaces

Kusuma Agusanto

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**NOVEL TECHNIQUES FOR LASER DOPPLER
VIBROMETRY FOR VIBRATING SHINY AND
MIRROR SURFACES**

KUSUMA AGUSANTO

**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

2020

NOVEL TECHNIQUES FOR LASER DOPPLER VIBROMETRY FOR VIBRATING SHINY AND MIRROR SURFACES

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School of Mechanical & Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

2020

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Assoc. Prof. Tran Anh Tuan

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The contributions of the co-authors are as follows:

- I proposed the idea. Prof. Lau Gih-Keong and I designed the experiments.
- Ting Liu and I conducted the experiments.
- The manuscript drafts were prepared by Prof. Lau Gih-Keong and I.
- The manuscript was revised by Prof. Lau Gih-Keong, Ting Liu, and Dr. Zhu Chuangui.

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Abstract

A laser Doppler vibrometer (LDV) is a versatile non-contact optical instrument used to measure the velocity at a single point on the surface of a moving object. The instrument works most efficiently when used for an object whose surface roughness is sufficient to allow scattered light to be received at the device sensor head. For an object with a mirror-like surface, which allows only specular reflection, precise alignment is a necessity, as a small tilt change can cause the light to diverge away from the sensor. Surface enhancements such as retroreflective tapes can mitigate the loss of light signal detection by improving the light scattering from the surface. This solution does not work for delicate or small objects, as altering them may change their measurement properties.

This study addresses these gaps in LDV-based methods by introducing novel external retroreflection techniques. These new methods allow recovery of the light signal lost due to a vibrating mirror with a large tilt or rotation angle. However, the Doppler-shifted frequency observed using this new method does not directly yield the target velocity without correction, because the oblique retroreflection itself also contributes to the Doppler frequency shift.

In this study, an equation describing the contribution of the oblique retroreflection to the detected Doppler frequency shift in the signal is derived. With the help of this equation and the oblique retroreflection method, a conventional LDV can be used to characterize a vibrating mirror with a large tilt angle. Furthermore, the new technique has also been used for unprecedented measurements of large deflections of a cantilever mirror with dynamic rotation.

For a scanning mirror with a large rotational angle, the oblique retroreflection model is inadequate as it does not consider the translation of the target point during the rotational motion. Therefore, an in-line velocity model is developed to overcome this limitation and enable the LDV with the external retroreflection

method to characterize the velocity of the dynamic target point of a scanning mirror along the direction of the laser beam. In addition, the in-line velocity model includes a unique trough-shaped retroreflector design, superior to the design used in the external retroreflection method. With the trough design, the retroreflector can recover reflected light from the mirror at a wider angle of rotation. This second technique has been used successfully to characterize a rotating mirror driven by a torsional spring at a large rotational angle (up to 30°), a performance beyond the capability of a conventional LDV by itself.

Additionally, an off-axis detection using an in-plane LDV is developed and tested to measure the in-plane motion vibration of shiny metallic samples, which a conventional in-plane LDV is not capable of doing. This off-axis detection method offers a great potential value for the in-plane motion characterization of micro-electro- mechanical systems (MEMS) devices with shiny metallic surfaces.

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Acronyms

AFM	Atomic Force Microscope
AOM	Acoustic-Optical Modulator
BRDF	Bidirectional Reflectance Distribution Function
DAQ	Data Acquisition
DHM	Digital Holographic Microscope
DHI	Digital Holographic Interferometry
DSPI	Digital Speckle Patterns Interferometry
FFT	Fast Fourier Transform
LDV	Laser Doppler Vibrometer (as an instrument)
LDV	Laser Doppler Vibrometry (as a technique)
MEMS	Micro-Electro-Mechanical Systems
NA	Numerical Aperture
SLDV	Scanning Laser Doppler Vibrometer
SNR	Signal to Noise Ratio

Dedicated to medical workers, doctors, nurses, cleaners, medical scientist and many others unsung heroes who battle against covid-19, those who survived, and those who passed away..

Chapter 1

Introduction

1.1 Background

Micro-electro-mechanical systems (MEMS) devices are used extensively in many consumer electronics such as tablets, smartphones, and mini projectors. As a small device with moving parts, it occupies less space and consumes less power than its competing non-MEMS devices, while delivering the same if not better performance. For example, a MEMS actuator stabilizes the image sensor of a camera phone five times faster than the speed of a voice coil actuator [1] (see Figure 1.1a). Another example is a micro-mirror for 3D sensing applications (see Figure 1.1b). The device is only a fraction of the cost of a conventional mirror but achieves high-speed scanning by operating at a resonant frequency [2]. Such excellent and reliable performance can be traced to the role of measurements in the device characterizations throughout the development and manufacturing phases [3]. Measurements confirm whether optimum parameters have been chosen by the designers, and help to monitor the process control on the production line. Thus, measurements are indispensable for MEMS during device characterization.

FIGURE 1.1: (a) A MEMS actuator for optical image stabilization function of a camera phone (source: MEMSDrive), (b) A micro-scanning mirror in a laser scanner (source: Chipworks).

Optical measurement techniques are often used for MEMS characterization. As these techniques use light energy for the measurement, they are physically non-contact and hence suitable for handling the fragile, minuscule movable parts. Static characterization provides straightforward information such as the dimension, shape, and profile of the device. For example, basic optical microscopy with digital image processing is used for dimensional analysis. Slightly more challenging is the dynamic characterization that measures dynamic attributes such as resonant frequency, settling time, and mode shapes.

An LDV is an optical instrument based on sensing the Doppler frequency shift of coherent light, primarily used to measure the velocity of a moving object [4]. It is one of the most popular devices utilized among the few available methods for dynamic MEMS characterization; it is commonly used to measure low to high resonant frequencies up to the gigahertz range. With added scanning capability, it is used to measure the vibration mode shapes for applications, such as confirming the failure modes of the device. Other advantages of an LDV are its real-time measurement capability (capable of transient response measurement), high resolution (displacement resolution down to picometers [5]), and high accuracy. Hence, this study largely focuses on utilizing an LDV-based optical technique for dynamic characterization.

Despite all these advantages, the issues faced when using an LDV when the measured object has a mirror surface are still unresolved. In order to understand

FIGURE 1.2: (a) a schematic setup of out-of-plane LDV measurement of a vibrating plate induced by a shaker, (b) an in-plane LDV measuring the speed of a conveyor belt. (c) Light scattering from a rough surface, (d) light scattering from a mirror surface.

these issues, a short introduction to how an LDV detects the light signal is first presented.

Like a laser pointer, an LDV is essentially a laser-based probe that emits and focuses a collimated beam on a solid surface, but unlike the pointer, an LDV has a sensor co-located with the laser source. Both the laser source and sensor share a common objective lens. Thus, the light returned by the object must travel to the LDV through the LDV collecting optics (i.e., the objective lens) for light signal detection to occur. Here, light detection is a prerequisite to the LDV's Doppler frequency shift signal detection, a topic that will be explained in Chapter 2.

Based on the types of object motion, there are two types of LDV instruments: out-of-plane and in-plane, for detecting the out-of-plane and in-plane motion, respectively (see Figure 1.2a and Figure 1.2b). From the light detection point of view, both types of LDVs rely on the surface of the target to scatter the light radiation back to the LDV sensor head. Modern commercial LDVs evolved from a laboratory setup into a portable device [6]; the present coaxial design of the sensor and laser source in the same LDV head unit is used because with it, the light signal detection remains optimum under various surface conditions [7].

They are intended to work with rough surfaces with a diffuse scattering such

FIGURE 1.3: Light detection failures using an LDV with specimen with shiny or mirror surfaces. An out-of-plane LDV with a mirror moving (a) with large rotation-translation coupling, (b) with pure large rotation. (c) An in-plane LDV with a smooth shiny surface moving with in-plane motion.

as paper, or those with shiny appearances such as brushed aluminum (see Figure 1.2c). However, when an LDV sensor does not receive the light reflected from moving shiny or mirror-like surfaces, it fails to detect light. Fig. 1.3 shows three such cases. An in-plane LDV designed to detect the backscattering of light is unsuitable for mirror surfaces [8]; it cannot measure the in-plane vibration from a shiny surface when the surface does not scatter light back through the center of the LDV collecting optics. An out-of-plane LDV can work with mirror surfaces but under limited conditions, such as the incident beam being normal to the surface (see Figure 1.2d). It also cannot measure a vibrating mirror with large rotation-translation coupling, or a vibrating mirror with pure rotation; in both cases, when the rotation angle of the mirror is greater than the limit of the angular detection of the collecting optics (the aperture) of the LDV, the mirror diverges the light away from the LDV sensor head. Essentially, a mirror surface can reflect most of the light to the sensor head, but its surface normal must be parallel to the optical axis of the LDV. A static tilt can be adjusted by manual alignment to restore normal reflection. However, the manual alignment method cannot work for a mirror with dynamic tilts, that rotates continuously between normal and oblique reflections. In summary, in all cases, the present standard LDVs cannot address the issue of inadequate object characterization for shiny or mirror surfaces.

FIGURE 1.4: (a) The Doppler effect of light in LDV. (b) The Doppler effect of sound wave in ultrasonography.

The Doppler effect is a shift in the frequency of waves due to the relative motion between the source and the receiver. A laser Doppler vibrometer uses the light-wave Doppler effect to measure vibrations in the same way that a medical ultrasound device uses the sound-wave Doppler effect to measure blood flow. Figure 1.4a illustrates this analogy. An LDV transmits an electromagnetic wave with an initial frequency f_t onto a target moving with velocity v in the direction of wave propagation. When the wave strikes the target surface, it is reflected back to the instrument with a new frequency f_r (in the reference frame of the LDV). The difference between these two frequencies is the Doppler frequency shift, which is proportional to the velocity of the object [9].

Similarly, an ultrasound probe transmits a sound wave at initial frequency f_t transcutaneously to the moving blood cells (see Figure 1.4b). The cells scatter back some sound waves to the probe at the Doppler-shifted frequency f_r (in the reference frame of the probe). The amount of frequency shift is proportional to the velocity of the blood cells. In this case, however, the velocity of the target is unlikely to be parallel to the propagation vector of the wave, and the Doppler relation must incorporate the angle θ between the probe and blood flow directions. In general, the observed Doppler frequency shift is sensitive to the direction as well as the magnitude of the target's velocity [10]. This angle correction is usually unnecessary with the LDV, which, in contrast to the ultrasound probe, is normally

operated by directly aiming the laser beam toward the target point along the direction of the velocity. However, the angle correction must be included whenever the laser beam is not aligned with the velocity of the target.

In some cases, it can be challenging to find the velocity of the object from the detected Doppler frequency shift alone. The light frequency measured by the LDV may contain information about other moving objects aside from the target. For example, any translational [11] or rotary [12] movement by the optical elements that participate in the transmission of the laser beam during the measurement will contribute to the Doppler frequency shift measured by the LDV; so will any motion of the base of the LDV due to ground vibration [13]. Therefore, it is necessary to make sure that the Doppler shift detected by the LDV comes from the motion of the target object, and to make appropriate corrections when it does not.

1.2 Motivation and Objectives

This study attempts to address the gap in LDV-based methods to measure an out-of-plane vibration from a mirror surface with a large tilt or rotation. The secondary objective is to address the limitation of an in-plane LDV, which cannot measure the in-plane motion of a shiny surface. These problems require solutions because many engineering applications require detection with shiny or mirror-like surfaces. For example, MEMS is fabricated from a polished silicon wafer that reflects like a mirror. Further examples include emerging applications such as a micro-lidar that uses a scanning mirror with a large rotation angle [14]. The conventional work-around method of using a retroreflective tape can improve the light backscattering, but this does not work for micro-devices because the added weight can alter the dynamics of the device. Other dynamic characterization methods do not have combined advantages and the industry standard

reputation of the LDV-based one. Hence, there is a need to develop LDV-based techniques for vibration measurement of shiny or mirror-like surfaces.

1.3 Novelty of the study

The ability of a conventional LDV to collect the oblique reflection from a deflecting mirror with a large rotation angle is limited by its lens aperture. For example, a conventional LDV with a focal length fixed at 50 cm can only measure the vibration of a tilted mirror with a less than 1.5° tilt angle. It would be extremely desirable to recover the light signal deflected beyond the detection range of the sensor head. This work has shown that the *oblique retroreflection* technique enables a conventional LDV to recover the deflected light when the vibrating mirror has a static tilt angle of up to 45° . Therefore, the light signal detection, which is the first step before obtaining the Doppler frequency shift signal, is fulfilled. However, the signal detected by the LDV also contains a frequency shift due to the oblique retroreflection itself.

In this work, we develop an analytical model showing the dependence of the measured velocity on the static tilt angle of the mirror. The model predicts correctly that the measured velocity is twice the cosine of the tilt angle of the mirror's velocity as measured by a standard LDV (i.e., one having the laser beam aligned to the mirror's normal). With this model, the LDV aided by the external retroreflection technique can measure the vibration of a mirror with a large tilt angle accurately.

The model can also be used to measure the velocity of a deflecting cantilever with a dynamic tilt angle. Successful measurements have been made on the cantilevered mirror with dynamic rotation-translation coupling and a maximum tilt angle of 2.5° , while the same experiment performed using a conventional LDV alone can only achieve accurate measurements up to a 1.8° tilt angle.

The analytical model of the external retroreflection method has the limitation of only considering a fixed target point (or a small translation within the diameter of the laser spot) during the dynamic tilting. For a pure rotational motion, such as that of a scanning mirror, the target point shifts further away from the initial point (at zero angle) as the mirror's angle of rotation becomes large; hence, the model becomes inaccurate. Thus, an analytical in-line velocity model is developed that considers the shifting of the target point during rotation so that the correct in-line velocity of the scanning mirror can be obtained.

The in-line velocity model employs a unique collector, a trough of retroreflective tapes. This design allows the LDV always to detect the light signal from a scanning mirror, even at large angles of rotation. For example, by this method the LDV can measure the velocity of a rotating mirror (driven by a torsional spring) with a dynamic rotation angle up to 30° ; the largest rotation angle of a scanning mirror measurable by a conventional LDV (even when assisted by a large lens aperture) has been found to be about 14° [15].

A standard in-plane LDV is designed to measure the in-plane motion of a target. For the device to be effective, the target must be a rough surface providing sufficient backscattering of light to the detector in the LDV sensor-head. In the case of a mirror-like surface, however, the light is instead reflected, and no light is returned to the sensor of the in-plane LDV. This study attempted to recover the reflected light by using the external retroreflection technique, but the measurement was noisy and inaccurate despite the successful collection of the light signal.

Here, an analytical model was developed to understand the failure of the external retroreflection method for the in-plane velocity measurement from the mirror surface. Instead, an off-axis in-plane LDV approach is proposed to measure a shiny in-plane vibrating target. An analytical model was developed to describe the in-plane velocity, and this work tested the new method on the shiny samples

from which the conventional in-plane LDV is unable to measure the sample's velocity.

An analytical model has also been developed to understand the failure of the external retroreflection method for the in-plane velocity measurement from the mirror surface. Instead, an off-axis in-plane LDV approach is proposed to measure a shiny in-plane vibrating target. An analytical model is developed to describe the in-plane velocity. This new method has been tested on shiny samples, the velocities of which conventional in-plane LDVs are unable to measure.

In summary, this study makes the following contributions:

1. A new external oblique retroreflection technique is developed to recover deflected light from a vibrating mirror with a large tilt angle.
2. A mathematical expression is derived giving the effect of the oblique Doppler frequency shift when using the new external retroreflection technique.
3. An analytical model of the in-line velocity for the scanning mirror with a large rotation angle is developed and verified. The model enables the characterization of such a scanning mirror for the first time by an LDV, using a unique trough-shaped retroreflector design.
4. An analytical model to show the zero Doppler frequency shift by the external retroreflection technique to measure in-plane velocity from the mirror surface target is developed and verified. An off-axis detection method is instead developed to measure the in-plane velocity from a shiny surface. The method was successfully verified through analysis and experiments.

1.4 Scope

The scope of this research work is limited to the following.

- Although the most likely real-world targets of the application will be microstructures, all our experimental demonstrations involved macroscopic target objects. Using a conventional LDV to measure the vibrations of a shiny object in the presence of large tilts is difficult at any size-scale.
- The assessment of the shininess of a surface is limited to the visibility of light from the viewpoint of the LDV sensor head. The study of the optical light scattering properties of the sample is not in the scope of our study.
- The proposed retroreflection method employs glass-beads-based retroreflective materials (3M Scotchlite™ 7610 Reflective Tape), commonly used in the LDV field to maximize the returned light intensity from the measurement target [16]. A limited study employing cube-corner reflector-based retroreflective material was briefly conducted to show that the proposed method also works on a different type of retroreflective film.

1.5 Thesis Organization

This thesis contains six chapters. The summary of each chapter is described as follows:

Chapter 1 provides a detailed introduction of the background and motivation for this study and discusses its novelty. Common applications of LDV-based measurement as well as a brief explanation of how an LDV detects the light signal are presented to provide a deeper understanding of the problems with conventional LDVs.

Chapter 2 reviews the literature on existing technologies of dynamic characterization, including LDV technology, for the specimen with shiny or mirror-like surfaces. The advantages and disadvantages of these techniques are discussed and compared. Lastly, the mechanism of an LDV is also explained as a basis for understanding its light signal detection process.

Chapter 3 presents an analysis of the effect of oblique retroreflection by a vibrating mirror on the laser Doppler frequency shift. A novel retroreflection technique for LDV measurement of a vibrating mirror with a large tilt is described and experimentally demonstrated. Finally, the limitation of this method for measuring a scanning mirror with a large rotational angle is also presented.

Chapter 4 presents the design and experimental demonstration of a retroreflective technique for out-of-plane LDV velocity measurement of a scanning mirror with a large rotation angle. The concept of in-line velocity is also explained, and its analysis by the proposed technique is discussed.

Chapter 5 briefly presents a technique of in-plane motion measurement using the retroreflection method, followed by a description of the off-axis technique of in-plane motion measurement by an in-plane LDV. The characterization of light scattering from different surfaces is also discussed.

Chapter 6 concludes the thesis with a look at the potential future directions and applications of this research work.

Chapter 2

Review and Theory

This chapter begins with a review of the literature regarding methods for the dynamic characterization of both in-plane and out-of-plane motions for small and micro-sized devices. Comparisons of laser Doppler vibrometry methods are also presented. Reviews of the working principle of the laser Doppler vibrometry and the light scattering from a solid surface are provided in the theory section. The third part discusses previous studies focusing on motion measurements from specimens with a shiny surface. Finally, a literature review and the applied principle are summarized.

2.1 Optical Dynamic Characterization

In this section, we first review the techniques applying microscopy and interferometry combined with stroboscopy. The second part provides a brief review of the laser deflection method.

2.1.1 Stroboscopic and Interferometric Methods

Stroboscopy is an illumination method used to view a fast-moving object by flashing a pulse of light lasting a fraction of a second onto the object. The motion of the object must be periodic, and thus by changing the rate of the flash, one can slow down or even freeze the moving object. This approach is commonly used to study rotating machinery parts, whereby flashing light using a strobe, the rotary part can appear stationary.

Stroboscopy enables other imaging techniques such as video microscopy or interferometry to be used in motion characterization. Video microscopy allows the recording of a magnified view of a vibrating specimen with the help of a microscope. The frame rate of the video limits how fast the vibrating motion can be recorded. Conversely, strobe video microscopy (SVM) can overcome such a limit using a stroboscopy method. For example, SVM has been steadily used to measure the in-plane vibrations of MEMS devices [15, 17, 18]. While SVM is useful for in-plane motion measurement, it is limited only to a two-dimensional (2D) image measurement. This restriction is because the video camera only records the 2D intensity image of the object but not its depth information.

In contrast, interferometric methods can capture the surface topography of an object [19, 20]. These techniques, in general, are using coherent light, which is split into two parts: the object beam and the reference beam, both having the same phase initially. The former illuminates the target object. Upon probing the target object, the wavefronts of the object beam changes. Then, the returned beam from the target is collected back to be combined with the reference beam. The superposition of the two beams results in an interference pattern, which is recorded as an interferogram, containing the phase difference between the two beams [21]. Finally, these phase distributions can be related to the height distribution of the specimen [22]. Digital speckle pattern interferometry (DSPI) and

digital holographic interferometry (DHI) are examples of coherent optical methods with diverse applications for the measurement of surface profiles [23–25], displacement [26, 27], and vibrations [28–30]. For small and microstructure dynamic testing, digital holographic microscopy (DHM) and white-light interferometry (WLI) can provide the methods for optical inspection at micro and nanoscales [28, 31, 32].

Among the examples, DHM is gaining some attention for MEMS dynamic testing in the industry. DHM works in two-step processes; first, it records the scattered wavefronts from the target object onto the image sensor digitally without imaging (being focused) [33]. Secondly, from the recorded hologram, it reconstructs the 3D phase and amplitude, as complex mathematical entities, of the wavefronts of the target object by numerical calculations [31]. Some examples of numerical reconstruction algorithms [33] are by solving the Fresnel diffraction equation [34], the convolution method [35], and the phase-shifting method [36]. Hence, a single-shot is typically sufficient to capture the full-topography of the target object [37]. On the other hand, two interferograms are required when the displacement is measured. One image is taken from the object before the mechanical loading, and another is after the loading. The phase difference from the two recorded wavefronts represents the displacement [29].

DHM does not just perform static characterization, it performs dynamic characterization, too. Some techniques that extend DHM capability for dynamic characterizations are such as time-averaging [38], stroboscopy [39], and high-speed camera [29] methods. While the time-averaging method is suitable only for a harmonic (sinusoidal) vibration measurement, the stroboscopic method can also measure non-sinusoidal but periodical vibrations. Lastly, the high-speed camera method can measure both periodical and transient vibrations, albeit the high-end camera with very high frame rates can be very expensive [40].

A laser Doppler vibrometer (LDV) is also an optical interferometer instrument primarily used for dynamic characterization in MEMS testing [41] but also found diverse uses in many other applications [4] such as structural health monitoring [42], clinical diagnosis [43], automotive [44], and even fruit quality testing [45]. As an interferometer, the light source of an LDV also is split into the target beam and reference beam. The target beam is used to probe the target surface on a single point. When the target surface is moving, the frequency of the probed beam changes due to the optical Doppler effect [46]. Then, the scattered beam from the moving object is picked up by the collecting optics of the LDV for further mixing with the reference beam on a high-bandwidth square-law photodetector [47]. Through the signal demodulation of the signal current from the photodetector, the Doppler frequency shift signal can be extracted as a voltage signal [48]. Furthermore, by adopting the optical heterodyning technique [49], one can resolve the ambiguity of the direction of motion by the LDV. Here, before the mixing, the reference beam undergoes an optical frequency shifter [46] to resolve the ambiguity of the direction of motion, resulting in an increase of the frequency from the original frequency. More details on the working principles are discussed in the later sections.

Technique	Lateral Resolution (typical)	Vertical Resolution (typical)	Static Shape	Dynamic Response	Starting Price *
SVM Strobe Video Microscopy	<0.01 μm	<1 μm	2D	Yes	USD 50K to 100K
WLI White Light Interferometer	<1 μm	<0.001 μm	3D	No**	USD 50K to 100K
DHM Digital Holographic Microscopy	<1 μm	<0.001 μm	3D	Yes	USD 50K to 100K
LDV	<1 μm	<10 ⁻⁶ μm	No	Yes	USD 10K to 50K

* Price is based on the year 2011

** Dynamic response possible using strobe technique

Table 2.1. Comparison of dynamic characterization methods for MEMS testing [50].

Among the methods discussed so far, LDV has some advantages for dynamics characterization in MEMS testing, as shown in Table 2.1. Measurements using LDV have high axial [51] and lateral resolutions [15]. The lateral resolution can achieve down to picometer resolution [41]. High lateral resolution helps to pick up the motion of the small structures more precisely, while more sensitivity in axial resolution allows LDV to characterize even smaller devices such as Nano-Electro Mechanical Systems (NEMS) [52]. Also, LDV has a high measurement frequency bandwidth up to the gigahertz range [53]. This high bandwidth allows LDV to measure fast events [54]. Furthermore, LDV can measure real-time transient response of moving structures via analog outputs [55], giving the instantaneous velocity measurement. This is in contrast to other full-field interferometric methods that rely on additional techniques (e.g., stroboscopy or high-speed camera). One drawback of the LDV method is that it only measures at a single point. For obtaining a full-field response of a structure, LDV needs to be equipped with X-Y scanning mirrors (i.e., two galvanometer mirrors setup orthogonal to each other) [56]. This system is known as a scanning LDV (SLDV) often used for measuring the mode shape of a mechanical structure [57].

Another strength of LDV is being a portable optical instrument [58] that can be suitable for use for testing on the production floor. As a heterodyne interferometer, it is not sensitive to the ambient lighting [59], nor sensitive to the floor vibration [52]. Also, with the help of beam steering optics [11], the LDV can measure some parts of machinery that are difficult to access.

In summary, the LDV method is still relevant and preferred choice for dynamic characterization in the MEMS industry. Hence, the relevance of the LDV motivates the research on the LDV method over other methods in our study. As a result, our subsequent review narrows to the discussion related to the LDV works.

2.1.2 Laser Deflection Method

A laser deflection method, or also known as optical beam deflection or optical lever method, is popular for measuring the displacement of cantilever tip in the atomic force microscopy (AFM) [60–63], and for measuring the rotation angle of a scanning mirror [64–67]. The principle is based on a triangulation method [68] whereby a laser beam is shone onto the target point, and the reflected beam is projected onto a target screen. The distances among the laser source, target point, and the projected point must be measured for triangulation from which the reflected angle of the laser to the incident beam can be calculated. The detected light intensity converted to the photodetector signal current is then calibrated to the position of the target point [69]. To measure the displacement motion of the target point, instead of a screen, a linear detector [14] or a quadrant photodetector [70] can be used for the real-time response measurement.

The advantage of the laser deflection method is its quick and straightforward setup. Also, this method is suitable for the specimen with reflective surfaces [62] as the light beam can be deflected toward the detector. The range of measurement angles can be scaled up by adjusting the projection distance to the screen. However, the size of the sensor can be a limiting factor regarding the maximum range of the projected trajectory [68]. Specifically, a commercial sensor, together with its receiving optics, typically requires a fixed working distance. Another drawback of this method is that it has poor sensitivity to the out-of-plane motion and is unsuitable for linear motion measurements owing to the cross-talk that occurs between angular and translation motions [71]. Here, we used this method for the measurement of the rotation angle of the scanning mirror. We shall discuss this application in Chapter 4.

2.2 Theory of LDV

2.2.1 The Doppler effects in LDV

In the present study, we frequently derive the frequency Doppler shifts, as observed by the laser Doppler vibrometer (LDV) used in our proposed techniques. Thus, it is helpful to review some theory related to the Doppler effects in the light waves.

FIGURE 2.1: An illustration of the principle of Doppler effect on a light wave.

Consider a point light source S emitting an omnidirectional light wave with a wavelength λ . Two stationary observers A and B , are facing toward the source. Both perceive the wavelength of the light similar to that of the source. When the source is moving at a velocity $\vec{v}_s$, toward an observer A and away from an observer B (see [Fig. 2.1]), the observer A perceives the light wave at a shorter wavelength λ_A . Conversely, observer B measures the light wave at a longer wavelength λ_B . Furthermore, if the observer A is moving at velocity $\vec{v}_a$ toward the light source S , the observer A will perceive even shorter wavelength. Given the speed of light c , the frequency of the light f_S is related to the wavelength with $f_S = c/\lambda$. In this study, we assume the target speed is much smaller than the speed of light ($v_A \ll c$). In general, this assumption is reasonable since many MEMS devices [72], including scanning mirrors [73], operate with a much smaller speed than

FIGURE 2.2: A diagram of an out-of-plane LDV measuring the velocity of a moving target.

the speed of light. This observation is also agreeable with speed required in many laser measurement applications in industry [74]. Thus, disregarding the relativistic effects, the observed frequency of the light by the observer A can be described [75] as:

$$f_A = f_S \left(\frac{c + v_A}{c - v_S} \right) \quad (2.1)$$

The sign convention for the speed is based on the relative motion between the observer and the source. When the observer is moving closer to the source, the observed frequency is higher; hence the sign for speed v_A is positive. Likewise, when the observer is moving away from the source, the observed frequency is lower; hence the sign for speed v_A is negative. Also, the sign for speed v_S is positive, when the source is moving toward the observer because the observed frequency is higher. Likewise, the sign for speed v_S is negative, when the source is moving away from the observer because the observed frequency is lower. A review of the derivation of the Doppler effect is discussed in more detail in Appendix A.1.

The preceding example also applies to the understanding of the Doppler effect on the LDV. Let us consider an out-of-plane LDV measuring the motion of a target moving with a speed of v at an angle of θ to the light path of as shown in Fig. 2.2. Here, the point S is fixed on the stationary LDV, and the observer A is the incident laser point on the target object. Also, we consider the target is moving toward the LDV; hence, the sign for the speed v is positive.

Now, let us consider a *single ray* from the light beam sent by the LDV on the

moving object. The ray is hitting on a single point, which is the observer A . The frequency of this light ray undergoes a Doppler frequency shift as A observes S moving with a relative speed of $v \cos \theta$. Using Eq. 2.1, the observed frequency f_{A1} by A is given as:

$$f_{A1} = f_S(1 + (v \cos \theta)/c) \quad (2.2)$$

Next, when the light ray is reflected by the target and received by the LDV, the detected frequency also undergoes the Doppler frequency shift and is given as:

$$f_A = \frac{f_{A1}}{1 - (v \cos \theta)/c} \quad (2.3)$$

Thus, the frequency of light sensed by the LDV contains two Doppler shifts, and by substituting Eq. 2.2 into Eq. 2.3, we obtain:

$$f_A = f_S \frac{1 + (v \cos \theta)/c}{1 - (v \cos \theta)/c} \quad (2.4)$$

By following the approach in [76], we can write the denominator of Eq. 2.4 in term of a Taylor series [77] as followings:

$$\frac{1}{1 - (v \cos \theta)/c} = 1 + \frac{v \cos \theta}{c} + \frac{(v \cos \theta)^2}{c^2} + \dots \quad (2.5)$$

By replacing the denominator in Eq. 2.4 with Eq. 2.5 and expanding the terms, we have the followings:

$$f_A = f_S \left(1 + \frac{2(v \cos \theta)}{c} + \frac{2(v \cos \theta)^2}{c^2} + \dots \right) \quad (2.6)$$

Considering that the speed of the target object is much smaller than the speed of light (i.e., $v \ll c$), we can drop the higher terms in Eq. 2.7 to be:

$$f_A \approx f_S \left(1 + \frac{2(v \cos \theta)}{c} \right) \quad (2.7)$$

Also, the frequency Doppler shift f_D is given as:

$$f_D = f_A - f_S \quad (2.8)$$

Finally, by substituting Eq. 2.7 into Eq. 2.8, we obtain the canonical LDV equation for the frequency Doppler shift as following:

$$f_D \approx \frac{2v}{c} f_S \cos \theta = \frac{2v}{\lambda} \cos \theta \quad (2.9)$$

Alternatively, the derivation of the Doppler effect observed by the LDV in vector notations is also presented in Appendix A.2.

FIGURE 2.3: A diagram of an observer O sensing the frequency Doppler shift on a light scattered from a moving target P illuminated by a light source S.

Let us consider a more general case in which a light source S shines a laser to a moving target P with a magnitude velocity v , as shown in Figure 2.3. Also, an observer O at the detector perceives the light scattered by the moving target P. In such a case, the light frequency detected at P is given as:

$$f_P = f_S + \frac{v}{\lambda} \cos \theta_1 \quad (2.10)$$

Additionally, the light frequency received by the detector O is given as:

$$f_O = f_P + \frac{v}{\lambda} \cos \theta_2 = f_S + \frac{v}{\lambda} (\cos \theta_1 + \cos \theta_2) \quad (2.11)$$

Finally, the frequency Doppler shift observed by the detector is given as:

$$f_D = f_O - f_S = \frac{v}{\lambda} (\cos \theta_1 + \cos \theta_2) \quad (2.12)$$

To understand the dependence factor of the angle dependence of θ_1 and θ_2 on Eq. 2.12, we plot the $(\cos \theta_1 + \cos \theta_2)$ term, as shown in Figure 2.4. One interesting observation here is that the term reduces to zero value along the isoline drawn on the top-view plot. This reduction happens when the target is moving in-plane (i.e., the velocity vector v is on the mirror plane) and is reflecting the light specularly, such that $\theta_2 = (\frac{\pi}{2} - \theta_1)$. This observation physically means that the Doppler shift increment in the light frequency of the incident beam cancels the Doppler shift decrement in the light frequency of the outgoing beam. We shall analyze more on this observation in Chapter 5.

FIGURE 2.4: An isometric plot and a top-view plot of the term $(\cos \theta_1 + \cos \theta_2)$ with θ_1 and θ_2 ranging from $-\pi$ to π (unit in radians). A thick blue isoline with the zero value is drawn on the top-view plot.

In a case of the target moving with an in-plane velocity, a differential scheme from dual illuminations of an LDV is commonly used for the velocity measurement. Figure 2.5 shows a schematic diagram of the setup for the dual illumination (of S_1 and S_2) on the in-plane moving target P. The frequency Doppler shift observed by O due to the light path from S_1 -P-O is obtained like the steps for

deriving Eq. 2.12, and given as:

$$f_{Ds1} = \frac{v}{\lambda} (\cos \theta_1 + \cos \theta_3) \quad (2.13)$$

Similarly, the frequency Doppler shift observed by O due to the light path from S_2 -P-O is given as:

$$f_{Ds2} = \frac{v}{\lambda} (\cos \theta_2 + \cos \theta_3) \quad (2.14)$$

FIGURE 2.5: A diagram of an observer O sensing the differential of the frequency Doppler shift on a light scattered from a moving target P illuminated by two light sources S_1 and S_2 .

The total frequency Doppler shift observed by O is the differential between the two frequency shifts [78], and is given as:

$$\begin{aligned} f_D &= f_{Ds2} - f_{Ds1} = \frac{v}{\lambda} (\cos \theta_2 + \cos \theta_3 - \cos \theta_1 - \cos \theta_3) \\ &= \frac{v}{\lambda} (\cos \theta_2 - \cos \theta_1) \end{aligned} \quad (2.15)$$

Using the trigonometric identity for $\cos \theta_2 - \cos \theta_1 = -2 \sin \frac{(\theta_2 + \theta_1)}{2} \sin \frac{(\theta_2 - \theta_1)}{2}$, and also defining $\alpha = \theta_2 - \theta_1$, and also defining $(\theta_2 + \theta_1)/2 = \theta_1 + \alpha/2 = \beta + \pi/2$, we can simplify Eq. 2.15 as the following:

$$f_D = 2 \frac{v}{\lambda} \cos \beta \sin \frac{\alpha}{2} \quad (2.16)$$

Here the angle α is the angle between the two illuminations, and β is the angle of the target plane to a plane perpendicular to the bisector of the two illuminations.

When the angle β is zero (i.e., the normal of the plane is along the bisector of the two illuminations), we obtain the standard formula for a standard in-plane LDV:

$$f_D = 2 \frac{v}{\lambda} \sin \frac{\alpha}{2} \quad (2.17)$$

So far, we use the single ray model to derive the Doppler frequency shift equation. In practice, the laser light is a light beam with a finite beam radius, often modeled as a Gaussian-beam [79], with a bundle of rays. Each ray is incident on many points, forming a laser beam spot, and hence sensing a group of velocity measurements. The detected beam on the sensor is averaged by the electronics into a single readout [80]. Hence, the actual velocity measurement from the LDV is *averaged* over the beam spot area [81]. It is essential to make the spot size as small as possible since it was observed that the heterodyne signal improved when the beam spot is reduced [82].

2.2.2 Common optical setups of LDV

The design of LDV has evolved from a laboratory optical setup [83–86] into a compact and portable optical instrument [56, 58, 87, 88], which can be found many in modern LDV instruments such as made by, for examples for some of the established makers, Polytec GmbH, Ono Sokki, MetroLaser Inc, and, recently joining the industry, Sunny Optical Technology, and Julight Srl. In the present study, we mainly used a standard commercial LDV (see Appendix C for more details). Herein, we examine two typical optical setups of standard LDV, namely, out-of-plane and in-plane LDV with a focus on its light signal detection.

Figure 2.6 shows an optical layout diagram of out-of-plane LDV. This setup is quite similar to a Mach-Zehnder interferometer [89]. In this setup, a He-Ne laser source emits a laser beam (632.8 nm wavelength). The beam is split into a target beam and a reference beam using a beam splitter (BS). The target beam

FIGURE 2.6: Diagram of an optical setup of out-of-plane LDV.

travels toward the target, whereas the reference beam is channeled to a Bragg cell, from which the frequency of the beam is modulated using a frequency f_B of typically 40 MHz. A portion of the target beam scattered by the vibrating target surface is collected by an objective lens L. At this instance, the frequency of the target beam is Doppler-shifted by the vibration motion of the target object. Finally, the target beam is recombined by the reference beam through an optical heterodyning process [90] at the photodetectors. Upon a conversion of the light signal into a current in the detectors, the electrical current output is ready for the signal demodulation. Here, the light signal detection process is completed.

FIGURE 2.7: Diagram of optical setup of in-plane LDV.

Figure 2.7 shows an optical layout diagram of in-plane LDV. In this setup, the laser beam emitted by the laser source is also split into a target and reference beam similar to an out-of-plane setup. The reference beam also undergoes frequency modulation using a Bragg cell. Here, unlike in an out-of-plane setup, the frequency-shifted reference beam is then, along with the target beam, focused onto the target object, and optically mixed on the object surface. Thus, optical heterodyning occurs outside the instrument. A portion of the interfered light is scattered back toward the LDV, and is collected by the objective lens L_1 and focused on the photodetector by the lens L_2 . The light signal is then converted into the current output signal for the signal demodulation.

Optical mixing between the target and reference beam is necessary for the process of light signal detection by the LDV. This enables the sensor and its electronics to detect the change in light frequency instead of directly measuring the absolute frequency of the light, which still exceeds the limit of the present sensing technology.

It is important that the mixing between the target and reference beam yields the optimum conversion of the optical beating signal. Thus, normally quarterwave plates are introduced in the interferometer arms to ensure that the object beam has the same polarization as that of the reference beam [91]. In addition, both target and reference beams must be parallel and of equal intensities [82].

For out-of-plane LDV, optical mixing occurs in the interferometer. Hence, the light scattering by the target object must be detected within the sensor head. Decoupling the detector from the sensor head to allow light signal detection outside the instrument can impose extra complexity in the optical design owing to the need to channel the reference beam onto the photodetector surface outside the instrument. Unlike with out-of-plane LDV, a decoupling of the detector for

in-plane LDV is possible because optical mixing occurs on the surface. As a drawback to optical mixing on the surface, however, the surface conditions can influence the SNR of the detected light [92].

2.2.3 Signal Demodulation

The output from the photodetector is a current signal, and according to [78], the current signal is described as follows:

$$i(t) \propto A \cos \left(2\pi \left(f_B - \frac{2v}{\lambda} \right) t + \delta\phi \right) \quad (2.18)$$

where A is a constant amplitude term, and $\delta\phi$ is the phase difference between the target and reference beam. The current signal is a frequency-modulated (FM) signal proportional to the target velocity v . Using an analog velocity FM-demodulation technique [5], the term $2v/\lambda$ can be extracted electronically to obtain a signal voltage proportional to the instantaneous velocity of the original object. In practice, the voltage output (in volts) from the demodulation is converted into the velocity (in m/s) using a constant scaling factor found through an instrument calibration.

In the present study, we use LDV through an analog velocity demodulation approach. One disadvantage of such a technique is that, in the absence of a target beam on the detector (i.e., signal loss), a demodulation process from the electronics still occurs. This incomplete signal demodulation causes random noises that fluctuate unpredictably. Therefore, failures in the light signal detection by the LDV do not translate to a zero-value measurement, and caution must be taken to interpret the origin of the noisy data.

2.3 Surface shininess

In this study, the target surfaces used for the measurements taken using LDV are mainly shiny and mirror-like. Figure 2.8 provides an overview of the types of surfaces with different levels of shininess and their respective reflection models [93]. These include surfaces with diffuse scattering, a glossy (shiny) surface, and a mirror-like surface. In a diffuse reflection model, incident light rays are scattered uniformly in many directions by a rough surface. Conversely, in a glossy reflection model, incident light rays are scattered dominantly toward the specular directions of the shiny surface. Finally, in a mirror-like reflection model, incident light rays are reflected in a specular manner by the mirror surface.

The scattering or reflection of light from a point on an opaque surface is described using a bidirectional reflectance distribution function (BRDF) [94]. This function is a ratio of the incoming irradiance to the outgoing radiance with a unit of 1/steradian. A common way to measure the BRDF of a surface is by applying a goniometer [95], which can provide an accurate measurement but is time-consuming. Faster but less accurate methods have also recently been developed using a camera phone [96], a dome-shaped LED device [97], and a laser scattering method [98].

In the present study, the BRDF can be a valuable tool to describe the specular lobe geometry (for example, the width of the spread of the rays) of the light reflected from a shiny surface. The lobe geometry and its directions can influence the amount of light entering the collecting optics of the LDV. However, it is not necessary to measure the full BRDF of our samples. In the case of a sample with a mirror surface, the distinction is straightforward. In the case of a sample with a shiny surface, the distinction is made through a laser scatter approach, which is discussed in Chapter 5.

FIGURE 2.8: Three types of surface reflections, from left-to-right: diffuse scattering, glossy, and mirror reflections. (Top row) Spherical objects with the appearance of the corresponding surface reflections [99]. (Bottom row) The corresponding surface reflection models.

2.4 Previous Studies

In this section, we review the previous works related to optical dynamic testing on the shiny surface target using the LDV technologies. This is followed by a review of the light signal recovery works. Finally, we also review the work related to the signal corrections due to the additional Doppler shift effect of the participating element that is not the target of the measurement.

2.4.1 Out-of-plane Motion Measurements

An early study [15] combined an out-of-plane LDV with a microscope objective lens having a magnification of 20x to investigate the out-of-plane vibration velocity from a scanning mirror. The dynamic response from the mirror scanning up to a maximum mechanical rotation of 14° [41] was reported to be successfully measured. The large numerical aperture (NA) of 0.46 increases the viewing extent of the LDV collecting optics such that the reflection off a mirror with a large tilt can be recovered. However, no subsequent studies have reported the use of

the same approach when applying an LDV to characterize a MEMS scanning mirror with a large scanning angle of beyond 14° . Interestingly, the development of scanning mirrors with a large scanning angle has increased [73]. In fact, the use of an LDV with a larger NA value can reduce the measurement accuracy [100]. For example, a maximum error of 5% in the measured vibration amplitude was shown to occur when a lens with a 60x magnification ($NA = 0.8$) is applied. In addition, using a lens with a larger NA also means a shorter working distance. This short focal length is generally undesirable for in-situ MEMS device measurements, however, because access to an electrical probe for the device is unavailable [64]. To provide a long working distance while maintaining as high NA as possible, albeit expensive, one can use a plano apochromatic objective lens instead (for example, a Mitutoyo infinity corrected lens [101]).

FIGURE 2.9: In an LDV design from [102], an incoming beam k_{in1} is scattered by glossy microstructures, and the scattered radiation is received by three collecting interferometers (no.3 is out-of-plane to the diagram), where two of the interferometers (2 and 3) are at an off-axis position from the incident beam.

Applying additional interferometers to a standard LDV allows the measurement of a three-dimensional (3D) vibration [102], as shown in Figure 2.9. Both extra interferometers are positioned off-axis from the optical axis of the LDV to collect additional scattering, from which the 3D velocities can be calculated. The use of this design to measure the dynamic response of a vibrating mirror surface with a

large rotation is unsuitable, however, because gaps between interferometers still remain, and thus the reflected light from the rotating mirror will be uncollected.

Scanning LDV (SLDV) can quickly acquire many points by changing the light beam directions with the help of the rotating X-Y mirrors either by point-by-point scanning [103, 104] or continuous scanning [105, 106]. Hence, a full-field measurement can be realized by the LDV [57, 107]. The drawback is that it has a limited angle measurement; furthermore, when the target surface has a reflective surface like a mirror, the angle restriction becomes more pronounced [9]. This limitation is because, at a large angle scanning, the incident beam is reflected away by the mirror target following the law of reflection, causing signal detection loss to the SLDV. Alternatively, one can achieve parallel scanning by moving the target on an X-Y linear stage so that the incident beam can be maintained almost always to be perpendicular to the target surface [108]. The other approach to allow greater flexibility to access the target point while maintaining a narrow incident angle from the LDV is by adopting multi-point LDV [109, 110] from which one can adjust the fiber optics head at proper alignment toward the target points. On the other hand, the preferred alignment of the LDV head can also be controlled by attaching the sensor head onto a robotic manipulator [111].

The common practice to reduce the unwanted specular reflection from the shiny target is by spray painting the surface to make them diffusive [56, 112], or by adhesively pasting the retroreflective film [113, 114]. However, some cautions must be taken when using these solutions on the finished product so as not to contaminate them [115]. Similarly, the use of spray diffusive coating is also not suitable for the microstructures like MEMS. In particular, if the solution is temporary and not part of the design feature as the MEMS fabrication process is complex and expensive [116]. Also, the extra weight of the coating can influence the dynamics of the device.

2.4.2 In-plane Motion Measurements

An in-plane LDV is related to a laser Doppler anemometer (LDA) used for a fluid flow measurement. In 1964, Yeh and Cummins developed an early LDA [117] with a forward-scatter design in which the photodetector is placed facing the two incident beams along the optical axis of the objective lens, and arranged to collect forward-scattered light from particles that pass through a focal region, which is also known as a probe volume. The design of the LDA for use in a solid surface motion adopts a backscattering optical setup because such a design is more robust and portable. This design has become the standard in-plane LDV we presently know.

An in-plane LDV optical design works well for most non-contact speed measurements in an industrial process, such as rolled steel, paper, metal sheets, wire, timber, plastic, and laminates. Most of the surface conditions of the materials used can backscatter the incident laser beams owing to a surface roughness.

Conversely, the use of in-plane LDV for a MEMS device with a shiny surface has not been widely reported. Zhong [118] and Zhang [119] demonstrated a successful measurement on an in-plane moving MEMS device. However, they took advantage of a comb-structure, which can act as a diffuser to backscatter the light to the sensor. The LDV design in [120] was developed for a dynamic characterization of the MEMS device with a certain degree of surface roughness (through a coating or comb-like structure).

An out-of-plane LDV has also been used to measure the in-plane motion of a slider of a hard-disk drive (HDD) [121], as depicted in Fig. 2.10. The slider, attached to a suspension, moves along the plane above the disk platter. By aiming at the side of the slider, the in-plane motion can be measured as an out-of-plane vibration using an axial LDV, which is an interesting design choice.

FIGURE 2.10: Left: Axial LDV used to measure the in-plane motion of an HDD slider [121]. Right: A typical modern HDD slider based on a thermal actuator as viewed under a scanning electron microscope (SEM) [122].

This method has a few limitations: First, because the slider is thin and suspended freely in air, it is difficult to aim the laser spot onto it. The average size for a laser spot is approximately 0.5 mm with a working distance of 20 cm, whereas the slider thickness can be less than 0.02 mm. As another problem, some HDD slider designs have a protecting frame that can block the laser from reaching the moving slider component.

Recent works from [123] and [124] offer interesting approaches to measure the angular velocity or acceleration of a target moving perpendicularly to the incident beam from a modified Mach-Zehnder interferometer. Here, the laser beam has been modified by a spatial light modulator (SLM) to have the desired phase profile such that the interaction of the modified beam to the target surface causes the change to the original phase. The change itself is related to the rotational Doppler shift [125], which is proportional to the angular velocity. Although the techniques have not been shown to the smooth and shiny surface object, it is promising if the methods work because, at the normal incidence, the specular reflection problem would not occur in this case.

2.4.3 Light Signal Recovery Works

Using a reflector to recover a light signal reflection loss by itself is not new. In work done by [126], a laser Doppler velocimeter employed an external flat mirror that redirects the specular reflection from an in-plane rotating disk with its tiltable rotational axis (see [Fig. 2.11]). The recovered signal from the mirror was used to deduce the tilt angle of the rotating disk. The calculated angle assumed a small tilt angle value but not useful for a large tilt angle condition. This limitation is because the specular reflection is not retroreflected but specularly reflected for the second time by the mirror, adding an extra unknown angle-dependent factor in the calculation.

FIGURE 2.11: A laser Doppler velocimeter by [126]

Recent work from Song et al. [127] provides a method to enable DSPI to measure the deformation of a shiny surface target. Here, this method introduced a rough reference surface in the interferometer arm of the reference beam path so that the mixing between the scattered reference beam and object beam from the smooth surface forms the speckle patterns on the detector. The approach to work around the constraint of not modifying the target surface property by employing an external object seems interesting for our study.

Instead of modifying the target surface, one can adopt a cube corner retroreflector and a flat mirror that are placed externally facing toward the target object.

Menq et al. built a laser interferometer that measures the linear and angular displacement of a mirror target [128]. To improve the angular tolerance, they adopted the corner reflector and the mirror without which the interferometer can lose the specular reflection when the tilt angle of the target is large. Caution needs to be taken to consider this solution for our study; the involvement of additional optical elements in their setup (e.g., wedge prism, corner reflector, and flat mirror) can reduce the returned light intensity, and hence the required laser power for the optical mixing.

FIGURE 2.12: Surface inspection using D-Sight method [129]. The diagram is reproduced from [130]

Reynolds et al. [129] developed an optical surface inspection method to reveal surface defects by illuminating the surface with a laser light illumination (see [Fig. 2.12]). His solution adopts a retroreflective screen sheet to make the camera insensitive to the specimen position. The scattering effect of the retroreflective glass beads [131, 132] also helped in the visualization of the defects. This solution offers an interesting idea for the work of light signal recovery from a shiny surface.

2.4.4 Doppler shift correction

Johnson and Burgess in 1968 [133] used a laser Doppler method to measure a high projectile velocity. To recover any diverged light from the tilted surface of

the target during the motion, they adopted a folding mirror and a corner cube reflector. An equation that describes the velocity was also provided. Although it correctly described that the velocity is of multiple of the Doppler shift frequency, it did not provide any details of derivation. Instead, the extra Doppler shift was counted from how many times the light was reflected by the mirrors.

Lomenzo [134] developed a self-tracking LDV allowing the LDV to track a target point of blades vibrations from a rotating structure. One interesting aspect from this work is that it employed a vertex mirror attached to the rotating shaft from which the incident beam from LDV, with the help of a static fold mirror, is always reflected toward the rotating target point. Under an ideal condition, the contribution of the detected Doppler signal arises only from the vibrations of the blade. However, when there is a misalignment in the rotating shaft (e.g., causing the mirror to tilt periodically), there is an additional contribution of the Doppler shift that must be accounted for in the measurement [135].

Various supporting accessories are often employed when the LDV is used in the field. For example, a beam steering mirror can be used to guide the laser beam to access difficult locations in complex machinery. Another example is that a tripod is often used to provide stable support for an LDV during a measurement. Often in a challenging measurement environment, like the production floor, the vibrations can influence the instrument in the case of the tripod or the deflected laser beam in the case of the beam steering mirror. Recent works by Halkon et al. [11, 13] studied this issue and also provided methods and analysis to correct the measurement. These corrections are needed because the uncorrected signal contains the additional Doppler frequency shifts either at the light source (e.g., for the LDV on the tripod), or the steering mirror.

Finally, when the supporting optical element is placed on the target object, it is also moving together with the object being measured. For the users of LDV, they often place an adhesive retroreflective film on the surface of the target in order to

improve the backscattering of the laser beam from the object. A more detail discussion on the retroreflective film is given in Section 2.5. Several works extended this approach by placing two cube-corner retroreflectors on the target object for the linear and angular motion measurement using a laser heterodyne interferometer [136–138]. Zhang et al. [136] placed two cube-corner retroreflectors fixed on the target object. Their instrument shined two laser beams onto the reflectors to measure both linear displacements from the two points. By finding the difference between the two displacements together with the fixed distance separating the two points, one can obtain the angular displacement. A similar work of using two LDVs to measure the dynamic angular displacement is also presented by [139]. The drawback for this approach is that the need for additional laser beam (or LDV) to obtain the differential measurement.

2.5 Retroreflective technologies

This section reviews briefly the retroreflective film technology as this solution is used in our proposed methods for the light signal recovery, as further discussed in Chapter 3 and 4. Retroreflective film is a sheet of material that is used to reflect illuminations back preferably toward the directions close to the opposite of the direction from which the illuminations come [140]. Often the film comes with adhesive property and this adhesive film is known as retroreflective tape. The main applications for the retroreflective film are for road safety as often found in traffic signs, and pavement markings [140, 141].

There are two kind of retroreflective technologies: retroreflection from cube corners, and retroreflection from glass beads. The former is known to be more efficient than the latter in terms of the amount of light being retroreflected (i.e., minimum loss). However, prismatic retroreflector performs well only for a narrower angle of incident of light, while glass bead retroreflector can maintain its

performance well over a wider acceptance angle [141]. The latter advantage suggests that the glass bead technology provides greater flexibility for anticipating the reflected light from a reflective surface for the light recovery in our study. In terms of the structure of the retroreflective film, there are three types: exposed lens, encapsulated lens, and enclosed lens. The last two types have a protective coating layer to provide more durability but weaker response of the returned intensity than the first type [142]. The example of the glass bead retroreflector with exposed lens is 3M retroreflective tape 7610, which, according to the manufacturer, is primarily used for tracking, measurement, security, and safety with laser and polarised light [142]. Furthermore, this product is widely used in industry and research works using LDV [4, 16, 143–145]. We also use this product in our study (see Appendix B for the specifications).

FIGURE 2.13: Left: a drawing of a retroreflection on a glass bead embedded partially in a reflective substrate and Right: a retroreflective tape under a laser illumination at 10x magnification (right).

Figure 2.13 shows the schematic drawing and photograph of the glass bead (microsphere) retroreflector. A study from [131, 132] shows that there are some light scattering from the glass bead retroreflective tape; mainly, the light is scattered from the front bead surface and the exposed surface of the substrate in the gaps. This finding suggests that some signal loss could still happen from the retroreflective tape. Finally, Furthermore, the surface roughness of the retroreflective tape [7] contributes to the formation of speckles [146], which can influence the measurement uncertainty by the LDV. Hence, careful analysis must be taken to

interpret the measurement result if the noise is due to signal loss or due to speckles.

2.6 Discussions

From the survey of optical dynamic characterizations, LDV is still the preferred method for use in MEMS testing, in particular where the measurement speed and frequency bandwidth matters [147]. Despite the advantages, LDV has certain drawbacks. One critical drawback is its limitation when used to measure large vibrations from shiny and mirror-like surfaces under tilted conditions. With such a measurement, a large tilt may deflect the incident beam away from the sensor head. Based on a review of the working principle of LDV, it is clear that the optical design of an LDV requires the light to be scattered back to the sensor head. By contrast, a shiny and mirror-like surface does not scatter the light diffusely. Furthermore, a tilted mirror surface reflects the light obliquely. In addition, based on a literature review, no previous studies have addressed the gap in the signal loss when applying LDV in measurements from a vibrating mirror under the presence of large rotational angles.

The literature study has shown that a flat mirror reflector [126] placed externally can help to recover the signal loss. This approach is, however, sensitive to the changes in the vibrating mirror's tilt, especially a large tilt that can still cause the signal loss during the measurement. A better approach would be a combination of a cube-corner retroreflector and a flat mirror from [128, 133]. The solution provides a greater tolerance in positioning the reflector in the setup with respect to the mirror target. Also, the reflector can detect incoming reflections from the vibrating mirror with tilts at a broader angular range. Though this approach improves the angular tolerance, it has yet to be demonstrated to work with a large

tilt displacement. The finite size of a corner-cube reflector suggests the limit of the angular range the reflector can recover.

Meanwhile, a solution to use a retroreflective film from [129] provides an attractive idea. The continuous sheet contains arrays of microspheres acting as small retroreflectors, providing a continuous retroreflection from the cone of a beam reflected from the defective surface. This solution gives us an idea to recover the diverged light from a largely vibrating mirror by the LDV method. Furthermore, the glass-bead retroreflective tape is already commonly adopted in many LDV works [143]. However, given some imperfections of the glass-bead retroreflective tape that may still cause some light scattering [130, 132], hence some signal loss, we need to study further how this factor influences the detected signals by the LDV. Also, due to the surface roughness of the tape [7], speckles may be expected in the detected signal when using this approach, hence a proper study is also needed to mitigate such an effect. Finally, the flat shape in the original work may be sufficient for retroreflecting the scattered light patterns to find the surface defects. However, the flat shape of the reflector may not provide optimum signal detection for the LDV due to the finite depth of field of the LDV outside, which can affect the accuracy of the measurement [148, 149]. Therefore, investigating these challenges becomes compelling in this study.

This study starts with the focus on investigating techniques to recover the signal loss from the specular surface for the LDV methods. Now, it becomes clear that a proper study for the contribution of the Doppler frequency shift to the measured velocity needs to be done when we change the setup of the LDV to achieve our first goal. From the literature survey, we also learned that the additional Doppler frequency shifts could be contributed to the measurement signal due to the introduction of the supporting accessories of LDV measurement [11, 13] or the external reflectors [128, 133]. In the case of supporting accessories, the extra signal is not due to the influence of environmental vibration. In the latter case, it

is due to the multiple reflections between the reflectors and the target. Also, any changes of the incident beam or the reflected beam toward the LDV system that has an angle to the vibration velocity [120] would introduce angle dependence factor to the Doppler frequency shifts. In all these cases, a proper analysis must be carried out to investigate the contribution of the extra Doppler shift factor or the angle factor and apply the correction to get the actual displacement or velocity of the target. Hence, if we also introduce some reflectors in the light path of the measurement system, we also expect the canonical equation describing the out-of-plane LDV (Eq. 2.9) or the in-plane LDV (Eq. 2.17) is no longer applicable to the new setup. Therefore, there is a need to develop the analytical Doppler frequency shift model in our new setup.

2.7 Summary

In this Chapter, we start the review of the optical dynamic characterization methods for small and microstructure like MEMS devices. Some optical methods such as DHM and WLI can capture full-field measurement, while the LDV methods are only capable of a single-point measurement. However, in some testing, a single-point measurement is sufficient to provide critical information such as frequency response, and the instantaneous velocity. This is the LDV strength, and additionally, the evidence that LDV is still widely adopted by the industry gives us the motivation to use the LDV method as our focus on the present study.

Next, we review the theory of the LDV to understand better the working principle as later we develop our solutions. This includes the review of the derivation of the Doppler frequency shift for both out-of-plane and in-plane LDV, the optical setup, and the signal demodulation process. Aside from the theory, a brief review of the BRDF is introduced. This helps to categorize a shiny (gloss) surface and a mirror surface in our study.

A review of the previous works is also presented systematically. Here, we divide the previous works into the relevant study related to the out-of-plane and in-plane LDV. This is followed by a review of the light signal recovery works. Finally, we review the study related to the correction of the unwanted signal in the measurement. This unwanted signal is due to the disturbance by the environment to the optical setup. Or it can be due to the novel design of the system. Finally, we end the Chapter with the discussions and the summary.

Chapter 3

Oblique Retroreflection Technique

A laser Doppler vibrometer (LDV) fails to measure a large out-of-plane vibration of a rotating mirror when the mirror obliquely reflects the laser beam away, causing a signal loss from being detected. To solve this problem, we used an external retroreflective tape to recover the oblique reflection. However, the reading of LDV obtained from the recovered signal is not right because the retroreflection adds extra Doppler frequency shifts to the oblique reflection. Here, we first derive the relationship of Doppler shift to the oblique angle of retroreflection. For the first time with the help of retroreflection, a standard LDV can measure the largely vibrating mirror as good as a high-speed camera, except without the need for intensive computation.

3.1 Introduction

A laser Doppler vibrometer (LDV) is extensively used for non-contact vibration measurement [76, 150] in the industries of micro-electro-mechanical system [41,

64, 66, 151–153], automotive [56], manufacturing [115], medical diagnosis [154], and even vehicle navigation [155]. An LDV can measure a translational velocity of a vibrating object. This velocity measurement follows the principle of the Doppler effect of light [76]. During operation, an LDV sends a light beam on a vibrating target and simultaneously receives the reflected light. Superimposed of the original and the reflected light wave signals yield an interference pattern and the determination of the Doppler frequency shift [156, 157]. Because the LDV sensor head has a laser source and a photodetector sharing the same objective lens, the best signal detection is achieved by focusing the light beam on a moving target and collecting most of the reflected light. Signal detection of LDV is sensitive to the surface finish of the target [158]. A shiny surface such as a mirror, or a polished metal, with normal reflection, yields a clear signal, whereas a diffuse surface yields omnidirectional reflections and thus an average level of signal detection.

FIGURE 3.1: The mirror motion effects on reflected signals to LDV sensor: (a) a normal reflection on a translating mirror, (b) an oblique reflection on a translating mirror, (c) an oblique reflection on a rotating mirror, and (d) an oblique reflection on a deflecting mirror (translation-and-rotation coupling).

Figure 3.1a shows that a standard LDV sensor head can measure the pure translation of a vibrating mirror M from the normal reflection. A static tilt θ of the

vibrating mirror causes an oblique reflection, diverging the signal away from the detection (Fig. 3.1b). Specifically, this happens when the tilt angle θ is greater than the angle δ , which is defined as the maximum tilt angle detectable by the collecting optics:

$$\delta = \frac{1}{2} \tan^{-1}\left(\frac{r}{f_c}\right) \quad (3.1)$$

where r is the radius of the objective lens and f_c is the focal length as shown in Fig. 3.1a.

This tilt can be manually adjusted to restore the normal reflection. However, this manual alignment method does not help in the presence of dynamic rotation of a mirror that tilts continuously between oblique and normal reflections. For example, LDV fails to correctly measure the out-of-plane vibration of a rotating mirror, or a deflecting cantilevered mirror (Fig. 3.1c and Fig. 3.1d). When the dynamic tilt causes the oblique reflection beyond the LDV's view angle, the LDV signal detection is lost [9, 41].

The maximum detectable tilt angle of a vibrating mirror-surface target is limited by the numerical aperture (NA) of the objective lens (of the LDV sensor head) [159]. An objective microscope lens with a large NA lens (with a small focal length) can widen the angle of detection for an LDV [66, 151, 153]. For example, an LDV with a 20x microscope objective lens can measure 12 degrees dynamic rotation of micromirror [153]. However, this approach only works for small micro-mirrors. Also, the small focal length limits the working access by probes [64]. Unfortunately, a higher NA microscope lens (>20x) compromises the accuracy of the measured vibration amplitude; for example, a 60x (NA=0.8) lens causes a maximum error of 5% [100].

Diffuse coatings can be applied on a vibrating mirror to improve the signal detection by an LDV. For example, a removable paint was applied on a shiny car body [56] to help modal testing by an LDV, or powder coatings were sprayed on a fan

blade [112] to help strain measurement by an LDV. However, the diffuse coating is not always feasible and practical. It needs to be removed [115] from the finished product of mirrors after the sampling check. Furthermore, the diffuse coating adds extra mass and may alter the dynamics of micro-mirrors. Similarly, a retroreflective tape [160] was applied on a rotating shaft for measuring the radial vibrations, but it introduces cross-axis noises [161]. While measuring the vibration of a rotating shaft, a tangential motion of the micro-rough retroreflective surface can be mistaken as the radial vibration.

An external retroreflective tape can solve the problems mentioned above by recovering the oblique reflection. However, the velocity reading of LDV from the recovered signal is wrong because retroreflection adds extra Doppler frequency shifts to the oblique reflection. In this Chapter, we first derive the dependence of the Doppler shift on the oblique angle of retroreflection. Besides, we showed that a standard LDV with the help of external retroreflection could measure the large vibration of a cantilevered mirror, which undergoes dynamic tilt or rotation. The subsequent sections describe in detail the method and the results of this LDV with retroreflection.

3.2 Principle

3.2.1 Theory

A standard LDV can measure the out-of-plane motion of a moving object. Figure 3.2a shows that an object M is moving obliquely at velocity $\vec{v}$ by an angle α off the incident laser beam at point p . The LDV sensor at point o measures a total Doppler frequency shift f_D proportional to the projected velocity along the direction of the beam with [76]:

$$f_D = 2 \frac{v \cos \alpha}{\lambda} \quad (3.2)$$

FIGURE 3.2: The oblique retroreflection effects on the Doppler frequency shifts (see **Visualization 1**). Standard method: (a) a normal reflection as observed by a standard LDV, (b) an oblique reflection undetected by the LDV sensor. Proposed method: (c) a retroreflection of the light to the LDV sensor. (d) the light path and the Doppler frequency shifts, f_D and Δf_D in oblique and retroreflections.

where v is the magnitude of the object velocity $\vec{v}$, and λ is the optical wavelength of the laser beam. This frequency shift is twice the Doppler shift, as observed by the moving object. This equation is similar to the derived Eq. 2.9.

In a particular case that the object moves along the laser beam ($\alpha = 0^\circ$), the magnitude of the measured velocity v_m by the standard LDV is defined as:

$$v_m = \frac{\lambda}{2} f_D \quad (3.3)$$

However, if the moving object is shiny (like a mirror) and tilted with $\theta > \delta$ (see Fig. 3.2b), the oblique reflection (at an angle θ off the surface normal $\hat{n}$) will miss from being detected by the LDV sensor head.

Figure 3.2c shows a simple setup devised by using an external retroreflective tape to recover the diverged laser beam (i.e., oblique reflection). The incident laser beam from a standard LDV is obliquely reflected by the moving *flat* mirror M .

The outgoing light hits the retroreflective tape at point q . By retroreflection from spherical glass beads partially embedded in a reflective substrate on the tape, the divergent laser beam returns to the sensor at point o . In this way, the LDV sensor can always detect the oblique reflection off the moving mirror even in the presence of a large tilt angle.

However, the retroreflection from q to p causes additional Doppler frequency shifts Δf_D :

$$\Delta f_D = 2 \frac{v \cos \beta}{\lambda} \quad (3.4)$$

where β is the angle between the object velocity $\vec{v}$ and the retroreflected beams (i.e. $\beta = 2\theta - \alpha$). This frequency shift is twice the Doppler shift as observed by the retroreflective tape q . Again, this equation is according to Eq. 2.9.

Let us now analyze the details of the Doppler frequency shift among the sources and the targets. Figure 3.2d shows the light path and the Doppler frequency shifts, f_D and Δf_D in oblique and retroreflections. There are three local observers, namely: point o on the LDV, point p on the moving target M , and point q on the retroreflective tape. Let us first consider that target M is moving closer toward o and q with a velocity $\vec{v}$ by an angle α off the incident laser beam at p .

The first incremental Doppler shift in oblique reflection happens to the emitted light traveling along the path $\overline{op}$ as observed by p [76]:

$$f_{D_{op}} = \frac{v \cos \alpha}{\lambda} \quad (3.5)$$

where v is the absolute velocity of $\vec{v}$. The sign in the above expression is positive. It is because the observer p is moving closer toward the stationary source of light at o . The second incremental Doppler shift in oblique reflection happens to the reflected light along the path $\overline{po}$ as observed by o :

$$f_{D_{po}} = \frac{v \cos \alpha}{\lambda} \quad (3.6)$$

Again, the sign in the above expression is also positive because the source of light at p is moving closer toward the stationary observer at o . We can observe that the sum of $f_{D_{op}}$ and $f_{D_{po}}$ is equivalent to the Doppler shift f_D as measured in normal reflection in Eq. 3.3, and write this as:

$$f_D = f_{D_{op}} + f_{D_{po}} = 2 \frac{v \cos \alpha}{\lambda} \quad (3.7)$$

The first incremental Doppler shift in retroreflection happens to the reflected light traveling along the path $\overline{pq}$ as observed by q :

$$f_{D_{pq}} = \frac{v \cos \beta}{\lambda} \quad (3.8)$$

where β is the angle between the reflected light along the path $\overline{pq}$ and the velocity vector $\vec{v}$. The sign in the above expression is positive because the source of light at p is moving closer toward the stationary observer at q . The second incremental Doppler shift in retroreflection happens to the retroreflected light along the path $\overline{qp}$ as observed by p :

$$f_{D_{qp}} = \frac{v \cos \beta}{\lambda} \quad (3.9)$$

The sign in the above expression is also positive because the observer at p is approaching the stationary observer at q . And the sum of the $f_{D_{pq}}$ and $f_{D_{qp}}$ is expressed as Δf_D to denote the total Doppler shifts due to retroreflection, and is written as:

$$\Delta f_D = f_{D_{pq}} + f_{D_{qp}} = 2 \frac{v \cos \beta}{\lambda} \quad (3.10)$$

Our derivation remains the same in the case of the target M moving away from o and q . In such a case, the sign in the expression Eq. 3.5-3.10 becomes negative.

As a result of the oblique retroreflection, the LDV observes a sum of Doppler frequency shifts f_D' from both oblique and retroreflections:

$$\begin{aligned} f_D' &= f_D + \Delta f_D \\ &= 2 \frac{v}{\lambda} (\cos \alpha + \cos \beta) \end{aligned} \quad (3.11)$$

This Doppler frequency shift is more than the one measured from normal reflection (see Eq. 3.2). Alternatively, the derivation of the Doppler frequency shift in vector notations is also presented in Appendix A.2. The magnitude of the measured velocity v_m' by the LDV with retroreflection is defined as:

$$v_m' = \frac{\lambda}{2} f_D' \quad (3.12)$$

Hence, the measured velocity by LDV needs to be corrected by substituting Eq. 3.11 into Eq. 3.12 to yield the mirror (object) velocity using the following relationship:

$$v = \frac{v_m'}{(\cos \alpha + \cos \beta)} \quad (3.13)$$

In the case that the object velocity is normal to the surface ($\theta = \alpha = \beta$), Eq. 3.13 reduces to:

$$v = \frac{v_m'}{2 \cos \theta} \quad (3.14)$$

3.2.2 Geometric shape of the retroreflector

In this subsection, we discuss the theoretical two-dimensional (2D) shape of the retroreflector in the proposed method. Glass-beads-based retroreflective materials can return a large amount of light to the original light source. However, the retroreflective tape also scatters small portions of light, causing the reductions of the intensity of the light received by the detector. To maximize the signal detection, the LDV focuses the laser beam on the surface of the reflective tape instead of the target point on the mirror surface. For a vibrating flat mirror with a static tilt (e.g., Fig. 3.1b), the reflected incident laser beam from the LDV is localized to a small spot on the tape. On the other hand, for a rotating mirror (e.g., Fig. 3.1c), the reflected beam traces a line on the tape. Therefore, the retroreflective tape, when used for the vibration measurement with the dynamic rotation, must have the shape whose surface coincides with the focal points of the laser beam as formed by the rotational motion of the mirror.

FIGURE 3.3: Traces of the path of the reflected points from a mirror rotating at an angle of: (a) $\theta = 10^\circ$, (b) $\theta = 20^\circ$, and (c) $\theta = 30^\circ$.

The motion path of the focal points of the laser beam can be traced by performing a ray-casting analysis [162]. In the analysis, an LDV shines a laser beam on a target point s of a rotating mirror. The LDV is at a horizontal distance d and a vertical distance h to the mirror (from the vertical line passing through the mirror's center of rotation). Here, the LDV is set to have a fixed focal length of f whose value is always greater than the horizontal distance of the LDV to s .

Figure 3.3 shows the snapshots of the motion of the rotating mirror at a different rotational angle of 10° , 20° , and 30° . At each rotational angle, the mirror reflects the laser beam to be in focus at point p , q , and r . By repeating the analysis at a smaller step of rotational angles, more focal points can be obtained. Finally, a polynomial curve-fitting on the focal points gives a function describing the 2D-shape of the retroreflective tape.

Alternatively, we can use a geometric analysis to derive the radius curvature of the curve and its center of curvature (see Appendix D). Both analytical and simulation approaches can describe the shape of the curve of the retroreflective tape. In practice, the LDV operates with the laser beam using a single transverse mode, having a Gaussian beam [163], which has a depth of focus that can be precisely estimated [79]. The depth of focus of the laser beam allows some deviations of the actual shape of the retroreflective tape from the simulation and analytical results.

FIGURE 3.4: A test setup of LDV to measure the vibration of a mirror (top view): (a) at normal reflection ($\theta = 0^\circ$), and (b) at oblique reflection ($\theta > 0^\circ$) with oblique retroreflection method.

3.3 Experiments with vibration calibrator

The objective lens of a standard LDV has a limited view angle to detect oblique reflection from a vibrating mirror. Here, we measure the limit of view angle of the LDV. Subsequently, we investigate the method of external retroreflection to recover the oblique reflection. Then, we correct the measured mirror velocity from the obliquely reflected signals at various tilt angles.

Figure 3.4a shows the test setup using an out-of-plane LDV (LV-S01, Sunny Instruments Singapore - see Appendix C for more details) method to measure the velocity v_m of a vibrating mirror mounted on a vibration calibrator. The LDV has a vari-focal objective lens of radius $r = 2.4$ cm. The laser beam was focused on the target of the vibrating mirror at a focal length of $f_c = 50$ cm. In this setup, the numerical aperture is calculated as $\text{NA} = \sin\delta = 0.048$ [159], where $\delta = \frac{1}{2} \tan^{-1}(\frac{r}{f_c})$. The controller of LDV indicates the level of the detected light signal.

FIGURE 3.5: The instruments used in the experiment.

Figure 3.4b shows the experiment setup of a retroreflection-assisted LDV. In this setup, the laser beam is incident obliquely ($\theta > 0^\circ$) to the vibrating mirror. To return the oblique reflection to the LDV sensor head, we introduced a retroreflective adhesive tape along the light path (3M Scotchlite™ 7610 Reflective Tape - see Appendix B for more details). The retroreflective tape was mounted externally

on a support column (Fig. 3.5). The retroreflective tape with a wide entrance angle [164] can always return the incident light to the source, without the need for precise angular adjustment. However, the laser beam needs to be focused on the retroreflective tape instead of the target by adjusting the focus of the vari-focal lens of the LDV to maximize signal detection. The signal level indicator can help to confirm when the returned signal is optimum. Here, the measured velocity using the retroreflection method is denoted as v_m'

FIGURE 3.6: (Left) The influence of the tilt angle θ to the measured velocity using LDV with a standard method and retroreflection method. (Right) The zoom plot of the bounded region on the left plot.

3.3.1 View angle of LDV measurement

To measure the maximum view angle of an LDV sensor (see Eq. 3.1), we turn a vibrating mirror at angular increment until the signal detection (from oblique reflection) was lost. A rotary measuring stage was used to turn at angular increments below: $\theta = 0, \pm 1, \pm 1.5, \pm 2, 3, 4, 5, 10, 22.5, 30$ and 45 degrees. A vibration calibrator (VC110, Metra Mess-und Frequenztechnik) was used to drive the mirror. The vibration calibrator (with a piezo stack actuator) generates a sinusoidal acceleration of 1 m/s^2 constant amplitude. When the mirror is excited by the calibrator at 220 Hz, its velocity amplitude is 0.72 mm/s.

Figure 3.6 shows the view angle within which the LDV can accurately measure the mirror velocities of a vibrating mirror on the rotary stage. The experiment shows that this LDV can accurately measure the mirror velocity when the mirror is positioned nearly normal to the laser beam not more than 1.5° tilt. This maximum detectable tilt angle δ is close to the predicted value of 1.4° tilt from Eq. 3.1.

In contrast, we showed that an external retroreflective tape could recover the oblique reflection from a vibrating mirror over a wide range of tilt angles. Interestingly, the tilt angle can be as wide as 45° , and the retroreflective tape can help recover the signal for LDV measurement. The corrected velocity is identical to the driving velocity of the calibrator. It is noted here although the test for the new method only considers small negative angular values (-1.5 , -2 , and -3 degrees) and was shown to be working as expected, it skipped the test for the larger negative values of the corresponding other angles (4 to 45 degrees). Here, the focus of the test was not to find the angular range of the tilt angles from which the new method can respond well; instead, it is to show the advantage of the new method over the conventional method.

FIGURE 3.7: Tilt angle θ dependence of controlled mirror vibrations.

3.3.2 Correction of the measured velocity

Here, we correct the LDV measured velocities by substituting the tilt angle into Eq. 3.14. The correction test is conducted over a range of driving frequencies. The vibration calibrator is tuned to drive a mirror from 150Hz to 250Hz. Given a constant acceleration amplitude, the amplitude of calibrator velocity is inversely proportional to the driving frequency. Figure 3.7 shows that the velocities measured by LDV from oblique and retroreflected signals are different from the true velocities of the vibrating mirror. The measured velocity is equivalent to the velocity measured by the LDV (unassisted by the retroreflective tape) when the mirror is tilted to cause normal reflection ($\theta = 0^\circ$); here, we call this velocity as V_{ref} .

Figure 3.8a shows that the deviation between the measured velocity to the true one is frequency independent (i.e., at constant proportionality). The differences between the measured velocities at $\theta > 0$ and V_{ref} is given as $|\Delta_1| = |V_{m'} - V_{ref}|$. In this test, we collected 10 measurements for each measured velocity data point. The average value of the standard deviations for the measurements is 0.0027 mm/s. Upon angular correction, Eq. 3.14 yields the correct velocity as shown in Fig. 3.8b. The differences between the corrected velocities at $\theta > 0$ and V_{ref} is given as $|\Delta_2| = |V - V_{ref}|$. The errors $|\Delta_2|$ are found to be below 0.02 mm/s.

3.4 Measurement of a cantilevered vibration

A cantilevered mirror translates and rotates when excited by a shaker at the cantilever base. The translation of the cantilevered mirror is large, but its rotation is small. However, the vibrating mirror with a small rotation can deflect a laser beam like a scanning mirror [66]. An out-of-plane LDV cannot correctly measure the large translation of a cantilevered mirror in the presence of a small rotation. To illustrate this problem and feasible solution, we measure the vibration

FIGURE 3.8: (a) (Left) Tilt angular dependence of the LDV measured velocities from oblique retroreflection at different frequencies. (Right) The error $|\Delta_1|$ of the measured velocities at $\theta > 0$ to V_{ref} . (b) (Left) Tilt angular correction of the LDV measured velocities from oblique retroreflection at different frequencies. (Right) The error $|\Delta_2|$ of the corrected velocities at $\theta > 0$ to V_{ref} .

of a cantilevered mirror using three different methods. These methods are: 1) a standard out-of-plane LDV (LV-S01), 2) a retroreflection-assisted LDV, and 3) imaging method using a high-speed camera.

3.4.1 Setup and methodology

The sample under test is a cantilevered mirror (see Fig. 3.9a). The cantilever is a ruler of 135 mm long, and 7.9 grams in weight. On the tip of the cantilever is a silicon mirror (of $8 \times 20 \text{ mm}^2$ in size and < 0.3 grams in weight) attached adhesively.

FIGURE 3.9: (a) A front view of the cantilevered ruler (the measuring ruler is inserted for visualization purpose). (b) The setup (top-view) for the measurement of large deflection of a cantilevered mirror using a standard out-of-plane LDV (see **Visualization 2**).

The cantilever base is mounted on an electrodynamic shaker (TK2004E01, The Modal Shop, USA). In the test, vibration levels of shaker were increased until a dynamic tilt of the cantilevered mirror exceeds the detection angle of a standard LDV. Moreover, the driving frequency input signal was set at 14 Hz. The base motion x_{base} caused by the shaker excitation is described as:

$$x_{base}(t, u) = X(u) \sin(2\pi ft) \quad (3.15)$$

where t is the time, and f is the frequency of the periodic input signal, X is the vibration amplitude (in mm), and u is the applied voltage to the shaker. Meanwhile, the translation of the cantilever tip (mirror), y is described as:

$$y(t, u) = A(u) \sin(2\pi ft) \quad (3.16)$$

where A is the amplitude.

In the test, we used a high-speed camera (FPS1000, Imagetec, UK - see Appendix E) to capture the video of the cantilevered vibration. The camera has an image resolution of 1280 x 720 at 550 frames per second. To assist in our measurement,

we attached a needle acting as a pointer on the cantilever tip. While the cantilever vibrates, the tip (pointer) scans over a measuring ruler beneath it. Tracker software [165] was used to process the video frame-by-frame. This computation yields the displacement waveforms, y_h , over the time, and thus the velocity waveforms, v_h as the time derivative $v_h = dy_h/dt$. The displacement amplitude A_h is taken as half of the peak-to-peak value of the periodic waveforms. The inset in Fig. 3.9b) shows an example of the captured image of the pointer.

FIGURE 3.10: (a) The setup (top-view) for the measurement of large deflection of a cantilevered mirror using a retroreflection-assisted LDV ($\theta = 20^\circ$) (see **Visualization 3**). (b) The relative position of the retroreflective tape to the cantilevered mirror.

The neutral orientation of the vibrating mirror needs to be adjusted to suit to the measuring methods. To achieve normal reflection detectable by a standard LDV, we positioned the mirror surface to be normal to the incident light from LDV (as seen in Fig. 3.9b). To show the recovery of oblique reflection by the retroreflective tape, we oriented the mirror surface at an angle, say $\theta=20^\circ$ (as shown in Fig. 3.10a). A retroreflective tape of 50 mm long, mounted on a vertical column, was placed at a distance of 35 mm away from the target mirror (Fig. 3.10b) to cover the scanning range of the mirror's reflection.

Moreover, the laser beam was focused on the retroreflective tape, instead of the

vibrating target, to maximize the signal detection by LDV. The focus can be readily done at a point on the tape, say near the pivotal mount of an angularly adjustable column. To ensure the scan line at the extremes in focus, we turned and bent the retroreflective tape by trial-and-error.

The LDV acquires raw data in the form of velocity waveforms (time-domain). Here, a Fast Fourier Transform (FFT) function was used to transform the time varying-signal data into frequency spectrum data. The peak value in the spectrum curve is the velocity amplitude V . Here, V_m denotes the value obtained by the standard LDV method, and V_r denotes the value obtained by the retroreflection method using Eq. 3.13 with $\theta=20^\circ$. Time integrals of the LDV's measured velocity yield the displacement waveforms, y_m and y_r from the standard and retroreflection method, respectively. Ideally, the amplitudes A of the harmonic displacement can be calculated in terms of velocity amplitudes following: $A = V/(2\pi f)$.

3.4.2 Results of measurements

The high-speed camera can capture the cantilever tip's vibration from low (1.5 mm amplitude) to high (6.1 mm amplitude) while the voltage driving the shaker was raised from 0.1 V to 0.34 V. Images in Fig. 3.11a show the extreme positions of the vibrating cantilevered mirror (as indicated by the pointers above the measuring ruler) when a shaker excites the base of the cantilever at 14 Hz under 0.34 V input. The displacement waveforms obtained from the processed images appear harmonic with a displacement amplitude A_h is found to be at 6.1 mm (see Fig. 3.11a). The velocity waveforms as the derivative of the displacement's (v_h) are also harmonic. However, the velocity obtained by out-of-plane LDV is full of noises due to signal truncation beyond the LDV's view angle. These noises lead to anharmonic displacement waveforms with inaccurate amplitude A_m . On

FIGURE 3.11: Measurement results (see **Visualization 2** and **Visualization 3**): (a) Snapshot of high-speed camera showing pointer's position at Left: minimum amplitude, Right: maximum amplitude, giving $A_h = 6.1$ mm (b) Time plots of the mirror vibration measurement as measured by a high-speed camera, a standard LDV (see **Visualization 4**) and an LDV with retroreflection (see **Visualization 5**)

the other hand, our retroreflection method avoids the problem by fully recovering the obliquely reflected signals. Full recovery of the signal yields the accurate measurement of the large vibration of the cantilevered mirror.

Figure 3.12a shows the base excitation X and the vibration amplitudes of the cantilevered mirror increase when the driving voltage to the shaker was ramped up. Figure 3.12 show the limit of a standard LDV to measure the large vibration amplitudes. Below the limit (vibration amplitude of 4.7 mm, and tilt angle of 1.8 degrees), the standard LDV works well. Beyond the limit, the measurement becomes inaccurate, being about 21% lower than the "true" value as measured by the high-speed camera method and the retroreflection method.

FIGURE 3.12: (Top) The measured vibration amplitudes of the cantilevered tip, and the corresponding tilt angles ($\Delta\theta$) as a function of the voltage input to the shaker. (Bottom) The equality plot for the vibration amplitude measurement from a high-speed camera and two methods of LDV. The line of equality concerns the measurement from the high-speed camera, A_h .

Next, we further tested the velocity measurement of the deflecting cantilevered mirror at different excitation frequencies of the driving input signal. Here, instead of using the high-speed camera method, we used the standard LDV method assisted by a reflective tape pasted on the cantilever tip (tape on a ruler). The retroreflective tape on the tip allows the recovery of the diverged signal when the tip is deflecting at a large angle. The detail of the experimental setups is discussed in Section F.1 of Appendix F.

FIGURE 3.13: (a) The velocity waveforms excited by the driving signal frequency of 50 Hz (top), and 60 Hz (bottom). (b) The peak amplitude velocity vs. the excitation frequency. (c) The difference $|\Delta|$ of the peak amplitude velocities between the LDV methods.

Figure 3.13a shows the peak velocity v_m measured at the tape on the tip of the ruler and the corrected peak velocity v measured at the mirror on the tip of the deflecting cantilevered mirror. Here, we used 10 samples to obtain the average value of the peak velocity for each data point with the average standard deviations of 0.079 and 0.117 mm/s, respectively. Furthermore, the difference between the two results is expressed as $|\Delta| = |v_m - v|$ whose plot is shown in Fig. 3.13b. Examples of the velocity waveforms are also presented for clarity (see [Fig. 3.13c] and Appendix F for more results).

The error plot suggests that the influence of the frequency variations to the accuracy of the external retroreflection method is not significant (i.e., the maximum error is below 3%). These measurement errors are possibly caused by the signal from the out of focus laser beam. This defocused laser beam can take place when the amplitude of the deflection changes upon the change in the driving signal frequency.

Here, the laser spot size increases when the laser beam is defocused. Few things can happen. First, since the velocity is an average over the spot area, this size increment reduces the mean velocity [81]. Secondly, the increased spot area gives rise to the chance of the signal drop-out from the speckles [166] and also some diffuse scatterings from the tape [132]. As a result, the lower signal level of the detected beam increases the noise [148]. Finally, the imperfection in bonding between the tape and the substrate can also affect the accuracy of the measurement at a higher frequency range [143].

3.5 Microprismatic retroreflector test

Lastly, a different kind of retroreflective film for the retroreflection method was tested in measuring the deflection of the cantilevered mirror. The retroreflective

film is a 3M™ Diamond Grade reflective sheeting which is based on the microprismatic technology (see Section B.2). This test compared the performance of the microprismatic retroreflector to that of the glass bead retroreflector using the same off-axis setup as described in Section F.1 (see [Fig. 3.14a]). Here, the shaker drove the cantilevered mirror at a fixed vibration level at 0.1 V, and a driving frequency of 15 Hz.

FIGURE 3.14: (a) The retroreflection method using the microprismatic tape. (b) The velocity waveforms v_m' as measured by the LDV using the glass bead retroreflector and the microprismatic retroreflector. (c) The structure of the retroreflective film under optical microscope with 5x magnification. (d) The structure of the microprismatic retroreflector under optical microscope with 5x magnification.

Figure 3.14b shows the velocity waveforms obtained by the retroreflection methods using the glass bead and the microprismatic tape. The velocity waveform obtained by the method using microprismatic tape can overall return the diverged

light signal from the deflecting cantilever and does not suffer from a significant loss of signal (e.g., unlike the one obtained by the standard method in Fig. 3.11b). However, there are discrepancies in the peak amplitudes of the two results. The calculated average peak velocities are 287.1 mm/s and 271.5 mm/s from 10 samples with a standard deviation of 0.31 mm/s and 0.73 mm/s, respectively. Furthermore, the difference in the peak velocity from these two results is about 5.4%, which is significant.

Generally, the prismatic retroreflector performs better than the spherical retroreflector in terms of the retroreflection (i.e., it is much brighter when lit close, parallel direction), but it performs worse at wider angles of incidence [141]. In other words, the relative positioning of the glass bead tape is less sensitive to the level of the signal returned to the LDV in comparison to that of the microprismatic tape. A closer look at the microstructure of the retroreflective films also can reveal the possible reasons for the discrepancy (see [Fig. 3.14c and 3.14d]). From the magnified view, although the glass beads appear to be irregularly distributed, they are densely packed. On the other hand, although the microprismatic retroreflectors are arranged in a regular array, there are significant gaps (i.e., X-shaped region in the image) delineating the arrays into some groups. Here, these gaps could cause a reduction of the peak amplitude in the detected velocity signal.

3.6 Discussions

We have demonstrated that the oblique retroreflection method can be useful for the measurement of the out-of-plane velocity of the largely vibrating mirror. The method can recover the diverged light signal from the tilting mirror. Besides, it can remove the extra Doppler shift introduced in the measured signal by applying Eq. 3.14 such that the correct velocity measurement can be obtained. The results

of the experiment of the vibrating mirrors over a wide range of tilting angles confirm this — the corrected velocity can be viewed as *equivalent* to the out-of-plane velocity of the vibrating mirror measured by the LDV with a standard setup (e.g., the incident beam is set up to be perpendicular to the target surface).

As earlier described, the Doppler shift observed by the LDV in Eq. 3.11 can be reduced to depend only on the mirror's tilt angle θ by strictly assuming the motion of the mirror is a pure out-of-plane motion (i.e., $\alpha = \beta = \theta$). As a result, any change in the tilt angle of the rigid mirror causes the change in the velocity direction; thus, the change in the Doppler frequency shift. The change in the tilt angle can happen when the tilt angle varies with time. For example, the tip of a vibrating cantilever undergoes a dynamic translation and rotation with respect to its base.

In our experiment with the cantilevered mirror, the tilt angle was determined before the measurement. In fact, it was the angle of the optical axis of the LDV to the mirror's surface normal when the cantilever is at its initial resting position. In theory, for an accurate measurement, the changes of the tilt angle should be accounted in our calculation to obtain the corrected velocity. Although it is possible to measure the angle change using the triangulation method [71, 167], it is not necessary in our case for two reasons. First, it is noted that the Doppler shift is related to the tilt angle by the cosine function; thus, a small change $\Delta\theta$ of the tilt angle causes a negligible change to the existing Doppler shift (i.e., $\cos(\theta + \Delta\theta) \approx \cos\theta$). On the other hand, when $\Delta\theta$ is substantial, the change in the Doppler shift Δf_D can be significant. In our setup, the initial tilt angle θ is 20° and the maximum deflection angle is about 2.5° , thus the error of excluding the tilt angle change in the corrected velocity is about 1.68%. The error analysis of the effect of $\Delta\theta$ to the corrected velocity is discussed in Chapter 4.

Secondly, the vibration response of the cantilevered mirror follows the excitation input force [168]. Here, the response was a sinusoidal velocity response

whose maximum velocity occurs when the cantilevered mirror is at the equilibrium. This maximum velocity happens when the change of the tilt angle $\Delta\theta$ is zero. Thus, the formula is accurate at this resting position.

In general, the oblique retroreflection method can measure the out-of-plane velocity of a deflecting cantilevered mirror or a scanning mirror under the assumption that the time-varying angular rotation is small. Under such a condition, the target point (e.g., the laser spot) remains on the same location on the mirror surface. However, as the angle of rotation starts to increase, we shall observe that the laser spot on a deflecting cantilevered mirror starts to shift from its original spot. As the angle of rotation becomes increasingly large, the shift of the laser spot also becomes further. The shift of the target point contributes to the additional tangential and radial velocity components to the detected laser Doppler frequency shift by the LDV. These velocity contributions are not considered by the oblique retroreflection method. We shall discuss the analysis of these velocity contributions in Chapter 4.

Finally, the external retroreflective tape in the setup of the oblique retroreflection method is limited by the initial tilt (off-axis) angle in the setup. Let us consider the optical axis of the LDV is initially set up with the off-axis angle α to the surface normal of the mirror at resting position. Here, in the working condition, the incident beam on the target point is reflected toward the external retroreflective tape and then retroreflected by the tape to the mirror and finally returned to the LDV. At a large rotation angle beyond the critical angle θ_{crit} , the mirror does not reflect toward the external tape but directly returns the light to the LDV. In such a situation, the detected light signal by the LDV is a mix of the oblique retroreflection signal and the normal reflection signal. The analysis treatment for this mixed signal is discussed in Chapter 4. The critical angle of rotation is given by the following equation:

$$\theta_{crit} = \alpha - \delta \quad (3.17)$$

where δ is described by Eq. 3.1.

3.7 Summary

We presented that an oblique retroreflection method could recover oblique reflection from a large vibration of a mirror. However, the reading by a standard LDV deviates from the true velocity because the oblique retroreflection introduces extra Doppler frequency shifts to the detected signal. Here we successfully derived the contribution of oblique retroreflection to the extra Doppler frequency shifts. In this way, we correct the measured velocity of a vibrating mirror from the recovered signal, even in the presence of large deflection. For the first time with the help of retroreflection, a standard LDV can measure the largely vibrating mirror as good as a high-speed camera, albeit without the need for intensive computation.

We also presented that the oblique retroreflection method is limited to work for the largely vibrating mirror with small rotations. For a rotating mirror with large rotation angles, the effect of the radial and tangential velocity due to the shifting of the laser spot is not considered by the method. This limitation is addressed by the method introduced in the next Chapter.

Chapter 4

In-line Retroreflection Technique

A laser Doppler vibrometer (LDV) is precise and fast in measuring the translational velocity of a vibrating diffuse surface. However, it could fail to measure the tangential velocity of a rotating mirror. While the specular reflection away from the mirror can be recovered by a retroreflective collector, the recovered LDV reading is found to deviate from the true tangential velocity of the probed scanning mirror. This happens because the probed spot shifts radially along the rotating mirror surface and thus introduces extra Doppler shift, while the laser beam was aimed at a constant height on the scanning mirror. Here, we derive an analytical relationship between the laser Doppler shift and the tangential velocity of the measured spot. With the input of the prescribed scan profile, we recovered the true reading of the tangential velocity of the scanning mirror even at the large rotational angle. This corrected LDV reading is as precise as the measurement by a high-speed camera.

4.1 Background

Scanning mirrors can control the light path [169–171]; they are widely used for barcode readers and display projectors. Recently, miniaturized scanning mirrors have found new applications in micro-lidar devices [172–175] and optical coherence tomography micro-scanners [176, 177]. However, micromirrors are susceptible to deformation when being driven towards resonance [152]. Dynamic characterization is crucial to quality check [178] of scanning mirrors. There are a few non-contact optical methods to characterize the dynamic behavior of the scanning mirror. First, the triangulation method [64] can measure the scan angles and estimate the out-of-plane velocity of a scanning mirror over a permissible displacement range. Second, stroboscopic interferometry [179] can extract the out-of-plane profile from the interferograms (i.e., patterns of the coherent light-wave interference) [180] while a stroboscope flashes short light pulses to freeze a periodic motion. Third, a laser Doppler vibrometer (LDV) can measure the real-time velocity of a vibrating target at high precision by using the effect of laser Doppler frequency shift [150]; it is fast to identify the resonant frequency of a scanning mirror under the excitation by a frequency sweep [5, 153, 181].

FIGURE 4.1: a) A standard LDV with a normal reflection from a vibrating mirror M. v_m is the measured velocity at the probe spot along the laser direction of the LDV. b) The mirror's oblique reflection (see Visualization 1). v_t is the tangential velocity, and v_r is the radial velocity at the probe spot.

Fig. 4.1a shows a standard setup of LDV to measure the translation velocity (out-of-plane) of a vibrating mirror. It managed to measure the tangential velocity v_t caused by a small rotation δ of a scanning mirror, for example, 1.8° as limited by the aperture of the collecting optics (see Fig. 4.1b). Despite its wide adoption, LDV fails to measure the out-of-plane velocity of the rotating mirror when the mirror's reflection diverges the light beyond the viewing optics of the LDV sensor, causing the loss of signal detection.

FIGURE 4.2: a) The oblique retroreflection technique [182]: the LDV is setup at an off-axis angle α to a scanning mirror (seen from the top) with rotation angle $\theta \approx 0$. b) The error of the oblique retroreflection method when $\theta > 0$ with $\alpha \gg \theta$.

Few ad hoc methods are developed for the solution. First, an objective lens with a high numerical aperture (NA) can be used to extend the detection range of LDV for the measurement of a scanning mirror. For example, a $NA=0.46$ ($20 \times$ magnification) microscope lens was used to measure a mirror scanning up to 14° [181]. However, the measurement accuracy can be compromised by a higher numerical aperture of the lens [100]. Secondly, diffusive coatings, such as a retroreflective tape, can back-scatter some parts of the laser beam incident on a tilted mirror. This solution is potentially useful to return the specular light reflection, which would otherwise diverge away from the LDV sensor. However, the extra weight of a retroreflective tape may alter the dynamics of a small mirror under test. The

third solution is the recent work we developed by using the oblique retroreflection method [182] (see Fig. 4.2a) to send the diverged signal back to the LDV sensor head.

Figure #	Method	Measurement	Signal Direction	Add-on to Setup	Off-Axis α	Max Mirror Tilt θ	Remarks	Ref.
1a	Standard Method	V_m of mirror due to translation	direct in-line reflection	nil	0°	0°	zero radial speed V_r	-
1b	Standard Method	V_t of mirror due to rotation	direct oblique reflection	nil	0°	1.8°	N.A=0.048 negligible V_r	[20]
-	Standard Method	V_t of mirror due to rotation	direct oblique reflection	nil	0°	14°	N.A=0.46 neglect V_r	[17]
1d	Off-axis Method	V_t of mirror due to rotation	indirect oblique reflection	external retro-collector (one flank)	20°	2.5°	negligible V_r	[20]
3a	Standard Method	V_t of mirror due to rotation	direct retroreflection	tape on mirror	0°	$>16^\circ$	account for radial speed, add-on mass	this work
3b	In-line Method	V_t of mirror due to rotation	indirect inline reflection	external retro-collector (two flanks)	0°	$>16^\circ$	account for radial speed	this work

Table 4.1 Various adhoc methods

FIGURE 4.3: Various adhoc methods for standard LDV to measure the tangential velocity (v_t) of a rotating mirror. Here, *direct* means the light from the mirror goes directly to LDV, while *indirect* means the light from the mirror is reflected to the external reflector first before going to the LDV.

Even if the diverged signal is recovered by the retroreflector, the Doppler frequency shift in the detected signal is not *purely* coming from the tangential velocity component of the rotating mirror. It is mixed by the radial velocity component v_r of the probed spot (e.g. as shown in Fig. 4.2a and 4.2b, the point Q with radius $r = h$ at zero angle, shifts away to point Q' with radius $r = h / \cos \theta$ at angle θ). Clearly, the Doppler frequency shift is dependent on the mirror's angle. Without the time profile of the angle, the tangential velocity v_t cannot be related correctly to the Doppler frequency shift during a cycle of the mirror's rotation. This problem is negligible at a small angle but critical at a large angle. In this work, we analyze the kinematics of the mirror's rotation with reference to the detected probe spot to relate to the Doppler frequency shift.

This study is organized as follows. Here, we first describe the limitation of our recent work in Section 4.2. Then, we describe the analysis of the effect of the radial and tangential velocity in the in-line velocity model in Section 4.3. The

setup of the experiments is presented in Section 4.4. The results and discussions are presented in Section 4.5. And finally, the conclusions are presented in Section 4.6.

4.2 Limitation of the recent work

Recently, we use an external retroreflective collector to recover the diverged light from a scanning mirror. In the setup, the LDV was positioned at a large off-axis angle α with reference to the normal of the mirror at a neutral position. The diverged light was retroreflected and eventually reflected at an oblique angle back to the LDV sensor. The previous setup of this method had an off-axis of 20° to measure the tangential velocity of a rotating mirror up to a maximum tilt angle of 2.5° . This measurement was proper to pick up the maximum tangential velocity of a *harmonic oscillation* where the peak happens at the neutral position ($\theta = 0^\circ$) of the mirror, but it fails to account for the extra velocity component dependant on $\alpha + \theta$. This contributes to the error of the right tangential velocity reading, shown in Figure following [182]:

$$\Delta v_t = \frac{v_m}{2} \left| \frac{1}{\cos \alpha} - \frac{1}{\cos(\alpha + \theta)} \right| \quad (4.1)$$

where α is the off-axis angle, and the θ is the rotation angle. Figure 4.4 shows the plot of the error. Further, this off-axis setup of laser probing does not just pick up the tangential velocity of a rotating mirror but also the radial velocity of the probe motion on the rotated mirror. As such, the equation above for extracting tangential velocity from the off-axis setup become inaccurate in the presence of mirror tilt θ of the same order magnitude as the off-axis angle α .

FIGURE 4.4: The normalised error of the oblique retroreflection model.

4.3 Theory and Principle

When a scanning mirror rotates harmonically, the tangential velocity v_t is maximum at its neutral position. As such, one should aim the laser beam of LDV in the same direction as the maximum velocity so that the off-axis angle α is zero between the probing laser beam and the direction of mirror's maximum velocity. However, a mirror tilt θ from its neutral position will diverge the light. Here, two retroreflection methods are devised to recover the diverged reflection from the scanning mirror, namely: (1) direct application of retroreflective tape onto the mirror, as shown in Figure (a)-(b), and (2) a collector trough based on two stripes of retroreflective tapes. In the second method, the collector is located between an LDV and a moving target; it has a small slit (between two tapes) to pass the incident and reflected laser beam between the sensor and target. In this way, the LDV can probe a point on the mirror for tangential velocity measurement.

An LDV measures the velocity component of a moving target along the direction of the probing laser beam (i.e., optical axis). Here, the in-line velocity is defined as the velocity component along the direction of the probing laser beam, v_m . Usually, during the measurement, the laser beam probes at one spot of a constant

height offset from the axis of the mirror's rotation. For a small mirror's rotation, the probed spot is roughly the same material's spot at a prescribed distance from the axis of the mirror's rotation. However, for a large mirror rotation, the probe spot is scanning radially along the mirror surface. Hence, the reading of in-line velocity is not exactly the tangential velocity. The following derivation will relate the tangential and radial velocities to the mirror kinematics and, ultimately, their influence on the Doppler frequency shift in the detected signal.

Let us first analyze the kinematics of a mirror scanning in a prescribed angular time profile. In this setup, the target, i.e., a scanning mirror is positioned neutrally such that the mirror surface normal $\hat{n}$ is parallel to the incident light beam (of LDV) (along the horizontal x-axis). An angular displacement of θ of the mirror plane is defined with reference to the vertical y-axis or neutral position ($\theta = 0^\circ$). As a laser beam is probing a scanning mirror at a height h off the axis of rotation, the target spot Q on the mirror keeps shifting. At $\theta = 0^\circ$, the reflected laser beam is parallel to mirror's surface normal; then, the target point Q moves out of the plane of mirror at an angular speed $\dot{\theta} = d\theta/dt$ and a tangential velocity: $v_{t(\theta=0)} = h\dot{\theta}$. Then, the velocity reading v_{m0} by LDV is in-line to the laser beam and happens to be out of the plane to the mirror.

4.3.1 Oblique Reflection

Figure 4.1b shows the mirror rotating by an angle θ off a neutral plane such that the LDV detects the in-line signal. Then, the target point shifts to Q' at a distance $r = h/\cos\theta$ off the axis of rotation. This yields a radial velocity $v_r = dr/dt = r\dot{\theta} \tan\theta$, parallel to the mirror plane in addition to a tangential velocity $v_t = r\dot{\theta}$ normal to the mirror plane. Also, the mirror rotation causes an oblique incidence and reflection of the laser beam. The incident laser beam SQ' leaves the laser source at a fixed point S and hits on a moving point Q' on the rotating mirror. Meanwhile, the reflected laser beam $Q'P$ returns from the rotating mirror to a

point P on the LDV's photodetector. The detected signal by the LDV is modulated by two parts of Doppler frequency shift: first being $f_{D_{SQ}}$ as observed by the point Q' moving away from the source point S , and second being $f_{D_{QP}}$ as observed by the point P moving away from the point Q' on rotating mirror. In total, the sensed Doppler frequency shift f_{D_0} by the LDV is given as:

$$\begin{aligned}
 f_{D_0} &= f_{D_{SQ}} + f_{D_{QP}} \\
 &= -[v_t \cos \theta + v_r \sin \theta + v_t \cos \theta + v_r \cos(\pi/2 - \theta)] / \lambda \\
 &= -2[v_t \cos \theta + v_r \sin \theta] / \lambda = -2h\dot{\theta}(\tan^2 \theta + 1) / \lambda
 \end{aligned} \tag{4.2}$$

where λ is the wavelength of the laser source. At a small angle $\theta \approx 0^\circ$, this frequency Doppler shift reduces to $-2h\dot{\theta}/\lambda$ and this corresponds to the velocity $v_{m_0} = h\dot{\theta}$. However, at a large angle $\theta \gg 0^\circ$ of mirror rotation, the reflection of the laser beam diverges beyond the detection range of the LDV sensor head.

FIGURE 4.5: (a) In-line retroreflection from a tape on a mirror (see Visualization 2). (b) A photograph of the retroreflective tape on a scanning mirror.

4.3.2 Direct Retroreflection

Figure 4.5a and 4.5b show a retroreflection tape being applied directly on a scanning mirror to ensure in-line reflection instead of the mirror's oblique reflection. Then, the retroreflected laser beams $Q'S$ always return parallel to the incoming

Figure 4.6a shows an external retroreflective collector recovering the oblique reflection off a mirror scanning over a large angle. In this new in-line measurement setup, an LDV was placed behind the collector. The LDV probes a moving target in front of the collector by sending a laser beam through a slit in the collector. While the mirror rotation change from small to large angles, the LDV sensor receives a piecewise signal of normal reflection and recovered in-line reflection (see

Fig. 4.7a). The Doppler frequency shift due to normal reflection is the same as derived in Eq. 4.2. The recovered in-line signal is a mix of oblique reflection $Q'W$ (off the scanning mirror towards the point W on the collector) and oblique retroreflection WQ' (returning to the same point Q' on the scanning mirror). After passing a light path, $S - Q' - W - Q' - S$, a total Doppler frequency shift f_{D_2} sensed by the LDV, is:

$$\begin{aligned}
 f_D &= f_{D_{SQ}} + f_{D_{QW}} + f_{D_{WQ}} + f_{D_{QS}} \\
 &= -2[v_t \cos \theta + v_r \sin \theta + v_t \cos \theta + v_r \cos(\pi/2 - \theta)] / \lambda \\
 &= -4(v_t \cos \theta + v_r \sin \theta) / \lambda = -4h\dot{\theta}(\tan^2 \theta + 1) / \lambda
 \end{aligned} \tag{4.4}$$

This corresponds to a velocity reading being twice the in-line velocity: $v_{m_2} = 2v_{m_0}(\tan^2 \theta + 1) = 2v_{m_1}$. Figure 4.7b shows the Doppler frequency shift $f_D/(h\dot{\theta})$ with respect to in-line velocity being a function of mirror angle. The angle dependence increases rapidly beyond 10° . This equation provides a means to relate the in-line velocity v_{m_2} to the tangential velocity v_{m_0} .

FIGURE 4.7: (a) Waveforms of the angular displacement θ , velocity $\dot{\theta}$, and the mixed-signal v_{mix} obtained from the collector. (b) A plot of the normalized Doppler frequency shift to the increasing angle θ .

FIGURE 4.8: The setup of the LDV with the proposed method for the measurement of a scanning mirror (see Visualization 3).

4.4 Experimental Setup and Methods

Figure 4.8 shows an experimental setup to measure the tangential velocity of a large-angle scanning mirror. This in-line setup of laser Doppler vibrometer is equipped with a retroreflective collector. The vibrometer used is a standard out-of-plane commercial LDV (LV-S01, Sunny Instrument Singapore) with a varifocal objective lens (24mm radius). The target to be measured is a galvanometer with a 1-dimensional scanning mirror (OSST8161, Sintec Optronics). The LDV sensor head aimed a laser beam at a point Q on the scanning mirror at a distance $h=3.4$ mm off the axis of mirror rotation. Before actual measurement by LDV, a rotating stage was used to orientate the mirror to a neutral position where the mirror surface is normal to the laser beam. The retroreflection collector consists of two pieces of curved retroreflection tapes (3M, Scotch-lite) and a spacing (slit) to allow the passing of a laser beam between the sensor and target, which were separated by the collector. The curved shape of the retroreflective tapes was formed manually by trial and error such that the level of retroreflected signal detection by the LDV sensor was maximized.

FIGURE 4.9: (a) The setup of the optical deflection beam method for calibrating the maximum scan angle to the voltage input (driven by a sine wave signal). (b) Photograph of the setup. (c) The calibration plot of the maximum scan angle of 2θ versus voltage input (peak-to-peak value).

4.5 Results and Discussions

4.5.1 Angular characterization of galvanometer

First, we characterize the scanning angle θ of a galvanometer under harmonic excitation. A signal generator (DG5000, Rigol) was used to provide the desired voltage waveform. In this calibration, the galvanometer under harmonic excitation shows a harmonic scan profile: $\theta = \Theta \sin 2\pi ft$, where f is a constant driving frequency, say 40Hz here, and Θ is the amplitude of angular displacement. As the amplitude V was ramped up stepwise (at a 2.5V step) from 2.5V to 15V, the scan angle 2Θ increases linearly with respect to the peak-to-peak value V_{pp} . An optical triangulation method was used to measure the scan angle. As the mirror scans harmonically to and fro, the laser beam was projected into a scan line (with an envelope width $2w$) on a screen, as shown in Fig. 4.9. The scan angle is then calculated as $\Theta = 0.5 \tan^{-1}(z/d)$, where d is the distance between the screen and parallel neutral plane of the scanning mirror.

4.5.2 Tangential velocity measurement of galvanometer

We investigated the angular dependence of the Doppler shift in the LDV signal recovered from a scanning mirror. Fig. 4.10 shows a triangular (see-saw) voltage

Algorithm 1: v_{m3} recovery from v_{mix}

Input: v_{mix} : measured velocity (mixed with normal and oblique reflection)

Output: v_{m3} : the tangential velocity after correction

Apply signal smoothing filter: $v_{p1} = \text{smooth}(v_{mix})$.

Find the jump points: $pts_1 = \text{threshold_and_mark}(v_{p1})$.

Extract the oblique reflection signal: $v_{m2} = \text{extract}(v_{mix}, pts_1)$.

Apply correction on oblique reflection signal: $v_{m3} = v_{m2}/2$.

FIGURE 4.10: (a) Snapshots of the mirror scanning at: (i) maximum, (ii) neutral, and (iii) minimum positions (top-view). (b) The triangle input signal and its gradient signal. (c) The velocity measurement waveforms by the LDV methods and the high-speed camera method.

wave being supplied to switch the galvanometer between positive and negative constant speeds. As a reference, a high-speed camera (FPS1000, Imagetec, UK) was used to take the top-view video of the scanning mirror. The video taken has a frame rate of 1500/s and an image resolution of 640×360 . The target of a scanning mirror was marked with a dot at the top side at a distance h from the axis of rotation. Image tracking of the marker helps retrieve the tangential velocity at the spot. High-speed video shows that the motion of the scanning mirror is not a pure rotation at a constant speed but coupled with a bit of translation. Hence, the image-tracked tangential velocity is nearly constant, with little fluctuation.

Figure 4.10c shows the LDV reading obtained in the test of the galvanometer under the excitation by a triangular (saw-tooth) voltage wave. Though the scan rate (i.e., the gradient of driving voltage) was piecewise constant between direction reversal, the velocities probed on the rotating mirror, however, varies with the mirror rotation angle. Angular correction by Eq. 4.3 of the directly retroreflected signal (by a pasted retroreflective tape on the scanning mirror) yields a linearly sloped profile of the tangential velocity due to the radial shift of the probed spot. This observation shows the complications of measuring the tangential velocity from a scanning mirror, undergoing a large rotation. Next, it is noted that the uncorrected signal obtained from the collector is double the actual velocity. A notch down in the signal happens near the neutral angular position, and it corresponds to the actual velocity. Algorithm 1 was used to match the laser Doppler shift during the transit from direct reflection to multiple passes of retroreflection. Subsequently, the angular correction of the collector-recovered signal by Eq. 4.4 yielded the true velocity, which has the same linearly sloped profile.

The recovered signal from the retroreflective collector shows a notch, instead of the given input waveform. Algorithm 1 was developed to extract the tangential velocity from the recovered signal. First, a low-pass smoothing filter was applied to the recovered signal to remove the speckle noises [144] introduced by the roughness of retroreflection tape. Second, we map a batwing waveform into separate pieces, which corresponds to direct reflection of oblique retroreflection, respectively. According to Eq. 4.3 and 4.4, the Doppler frequency shift in the recovered signal of oblique retroreflection is twice the value in the directly reflected (or retroreflected) signal from the scanning mirror. Together with the angular information obtained from the harmonic calibration, Algorithm 1, equation 4.3 and 4.4 can retrieve the true velocity.

Next, we measured the harmonic forced oscillation of the scanning mirror. In this test, as shown in Figure 4.11, the galvanometer with a 1D scanning mirror was

FIGURE 4.11: (a) The driving signal input and its gradient signal. The measurement results from the scanning mirror: (b) The time-varying velocity waveforms by the standard LDV method (see Visualization 1). (c) The normalized time-varying velocity waveforms by the retroreflector-assisted LDV methods (see Visualization 2 and 3). (d) The peak-to-peak velocity values at different optical scan angles as measured by the LDV methods.

driven by a sinusoidal waveform of voltage at 15V amplitude. Figure 4.11b shows that a standard LDV cannot correctly measure the tangential velocity from the pristine scanning mirror because the large specular reflection goes outside the LDV view angle. Hence, the obtained LDV reading was noisy despite being expected in a sinusoidal waveform. On the other hand, the retroreflective methods, either a direct paste or an external collector, help the LDV recovered the diverged specular reflection and obtained a signal in a bat-wing profile. Correction of the bat-wing profiled signal yield the true reading and harmonic waveform of the mirror's tangential velocity. During each cycle of the free oscillation, the peak velocity happens at its resting position (zero degrees); the null velocity happens at the extreme position. Angle dependence of the radial scan is not apparent in the harmonic waveform.

Furthermore, the amplitude of the extracted tangential velocity agrees closely with the one measured from direct retroreflection. The corrected LDV readout is 240mm/s at $f=40\text{Hz}$ when the mirror scans at an angular amplitude of $\Theta = 16.4^\circ$. This corrected reading also agrees with the calculated tangential velocity of $2\pi f h \Theta$ (Fig.4.11d). The standard deviations based on 5 sets of measurement

are: 0.96 mm/s for the corrected collected signal (v_{m3}) and 0.83 mm/s for the corrected directly retroreflected signal (v_{m1}) respectively. In short, the deviation of the corrected velocity is not more than 0.4% of the true tangential velocity.

FIGURE 4.12: (a) Schematic drawing of the setup for a free torsional scanning motion measurement (top-view). (b) A photograph of the setup (see Visualisation 4). (c) Snapshots of the mirror scanning at: (i) maximum, (ii) neutral, and (iii) minimum positions (top-view). (d) The velocity measurement waveforms by the LDV methods and the high-speed camera method.

4.5.3 Large-angle free oscillation of a torsional-hinged mirror

Last but not least, we measure large free oscillation of a torsional-hinged mirror by using either an LDV or a high-speed camera. Figure 4.12a shows this torsional-hinged mirror on the support by a fan axle. The laser beam is positioned to probe a point on the vibrating mirror at a distance of $h = 10\text{mm}$ off the axis of rotation. The elastic restoring force to the axle support comes from two rubber bands, which are attached to the quarter-span position of fan blades. While the fan blade was perturbed at a large angle of $\theta = 30^\circ$, one rubber band is stretched, and the other is relaxed. Upon releasing the fan from its perturbed position, a damped free vibration with decaying amplitude follows. During each cycle of the free oscillation, the peak velocity happens at its resting position (zero degrees);

the null velocity happens at the extreme position. Though angle dependence was expected from the LDV measurement, it is not apparent in the measured velocity, as shown in Figure 4.12d, except for some initial differences in the reading between LDV and high-speed camera measurements.

4.6 Conclusion

The tangential velocity measurement of a scanning mirror by an LDV is more complex than it was thought. The mirror rotation can diverge the probing laser beyond detection. It even introduces a radial velocity component to the probing spot on the mirror while the probe spot is kept at a constant height from the axis of rotation. This results in a slope reading of tangential velocity with respect to the mirror's angle even though the rate of scan is prescribed constant. Here, we developed the external collector always to recover the diverged light signal as the in-line reflection. We also analyzed the kinematics of the scanning mirror and related to the tangential and radial velocity components of the probed spot with respect to the mirror's angle. In this way, we can extract the tangential velocity from the total Doppler frequency shift from the in-line reflection. This technique makes LDV capable of fast dynamic characterization of a scanning mirror as good as a high-speed camera.

Chapter 5

In-plane Motion Measurement Techniques

This chapter describes the techniques for measuring the in-plane motion of vibrating shiny and mirror surfaces. This chapter is divided into three parts. The first part discusses the analysis of an off-axis setup with a standard in-plane LDV using the retroreflection method. The analysis shows that this method fails to detect the frequency Doppler shift in the collected light signal.

The second part discusses the off-axis technique for measuring the in-plane motion of shiny and rough surfaces exhibiting a significant specular reflectance with a dual illumination LDV. A method for quantifying the gloss of surfaces is discussed, and the results of the experiment are presented. Finally, a summary is provided at the end of the chapter.

FIGURE 5.1: (a) Out-of-plane and (b) in-plane LDV setups off-axis to the surface normal of a target mirror moving in-plane with velocity v . Both setups adopt a retroreflection technique to recover the oblique reflections.

5.1 Off-Axis In-plane LDV Technique

Figure 5.1a shows a schematic diagram of an out-of-plane LDV setup off-axis to the surface normal of a target mirror moving with velocity v . The setup uses an external retroreflective tape to recover the light reflected from the mirror. Here, the objective is to calculate the total Doppler frequency shift f_{D1} detected by the LDV owing to the in-plane motion of the target. Accordingly, three local observers are introduced: S at the LDV, P at the target, and Q at the retroreflective tape. The LDV observes the Doppler frequency shift due to the contribution of the light paths S-P-Q and Q-P-S. Consequently, the total Doppler frequency shift f_{D1} is as follows:

$$\begin{aligned}
 f_{D1} &= f_{D-SP} + f_{D-PQ} + f_{D-QP} + f_{D-PS} \\
 &= [-\cos(\pi/2 - \theta) + \cos(\pi/2 - \theta) + \cos(\pi/2 - \theta) - \cos(\pi/2 - \theta)]v/\lambda \quad (5.1) \\
 &= 0
 \end{aligned}$$

Here, the total frequency shift is zero. The negative sign on the term f_{D-SP} indicates that the observer P is moving away from the light source S. Conversely, the

negative signs on the term f_{D-PS} indicate that the light source P is moving away from the observer S.

Figure 5.1b shows a schematic diagram of an in-plane LDV setup off-axis to the surface normal of a target mirror moving with velocity v . The setup uses an external retroreflective tape to recover the deflected light from the mirror. Here, an additional target point P' is introduced such that the reflected light from both P and P' are focused at Q on the tape. There are two reasons for the choice of this setup. One is to allow the light scattered at the tape to travel back to the LDV sensor head. The beams Q-P and Q-P' are the envelope of the light scattered from the tape. However, the scattered light is expected to be minimal as scattering from the tape is an imperfection rather than a design feature. The second reason is to maximize the returned light energy from the tape to the LDV, which is useful given the low power of the laser used in our experiment.

To derive the total Doppler frequency shift f_{D2} , we can follow the approach from the previous derivation, by treating the light paths S-P-Q-P-S and S-P'-Q-P'-S as separate. The total frequency shift is the difference of the Doppler shift detected in the light signals from both light paths. From Eq. 5.1, the signals in the light paths to-and-fro an in-plane-moving mirror surface do not have any frequency shift. Thus, the frequency shifts in the light signals from both light paths are also zero, giving $f_{D2} = 0$. This finding suggests that the proposed off-axis in-plane method is not suitable for our study.

Regardless of the analysis result, several experiments were conducted for verification. The setup and the experimental results are described in Appendix G. The conclusion from the experiments supports the conclusion that the off-axis in-plane LDV cannot be used to detect frequency Doppler shifts proportional to the in-plane motion of the target mirror sample.

5.2 Off-Axis Dual Illumination Technique

A standard in-plane LDV is designed to work with a target object with a surface that scatters sufficient light back for signal detection by the photodetector located in the sensor head along the axis of the LDV optics. Here, we propose a signal detection setup off-axis to the target point surface normal. The photodetector is separated from the LDV and is placed along the main direction of the scattered light. For optimal signal detection, the ideal BRDF of the target surface must be determined theoretically. Here however, the detection along the average specular direction seems sufficient to take the measurements.

5.2.1 Principle

Figure 5.2a shows a schematic diagram of a dual illumination LDV setup off-axis to the surface normal of a target mirror moving with in-plane velocity v . The detector of the LDV is placed externally along the direction of the reflected light. To analyze the Doppler frequency shift detected by the LDV, we introduce the local observers S_1 and S_2 at the LDV, P at the target, and Q at the detector. The LDV detects the Doppler frequency shift f_{D3} due to the contribution of the frequency shifts from the light signals in light paths S_1 -P-Q and S_2 -P-Q. These light paths can be treated individually, similarly to the off-axis in-plane LDV method. By following the same steps followed to derive Eq. (5.1), the total Doppler frequency shift is also found to be zero. In other words, the off-axis dual illumination technique cannot detect the Doppler shift for the target mirror surface.

In the setup in figure 5.2b, the moving target is a shiny surface. The detector is placed along the direction of the average specular reflections from the sample. In this case, the total Doppler frequency shift f_{D4} is due to the frequency shifts from the signal in the light paths S_1 -P-Q and S_2 -P-Q. Unlike in the case of the mirror

FIGURE 5.2: Diagram of a dual illumination LDV with its detector placed externally along the direction of the light reflected from (a) a target mirror surface and (b) a shiny target surface moving with in-plane velocity v .

target, the light path P-Q is the average of the scattered light, and its average direction is along the optical axis of the detector. Hence, the frequency shift f_{D4} is as follows:

$$\begin{aligned} f_{D4} &= f_{D-S1P} + f_{D-PQ} - f_{D-S2P} - f_{D-PQ} \\ &= [-\cos(\pi/2 - \theta_1 - \theta_2) + \cos(\pi/2 - \theta_1 + \theta_2)]v/\lambda \end{aligned} \quad (5.2)$$

By using the trigonometry identity $2 \sin a \sin b = \cos(a - b) - \cos(a + b)$, and the angle relationship $\alpha = 2\theta_2$ and $\beta = \theta_1$, we obtain the simplified equation:

$$f_{D4} = 2[\sin(\alpha/2) \cos(\beta)]v/\lambda \quad (5.3)$$

The corresponding velocity measured by this LDV v_m is given by

$$v_m = v \cos \beta \quad (5.4)$$

where the $\lambda f_{D4}/[2 \sin(\alpha/2)]$ is equal to v_m from the instrument calibration. The result from Eq. (5.2.1) suggests that the measured velocity depends on the off-axis angle.

FIGURE 5.3: Photograph of the laser scattering setup.

5.2.2 Sample Characterizations

The shininess of the surface can be determined from the laser light scattering from such a surface [98]. Here, our interest is to see if the sample is able to scatter or reflect the light to the LDV sensor head. Secondly, there should be minimum radiant energy of the collected light that would produce a successful signal detection (in the case of out-of-plane LDV, this is after the optical mixing) by the photosensor of the LDV. When the two conditions are satisfied, the signal level indicator on the LDV controller will show the excellent signal level, indicating that signal demodulation is successful. Hence, this is the common practice to survey the sample characteristics quickly. An alternative approach is by visualizing the scattered laser beam from the captured image (see Appendix H).

In this test, we tried another approach and used a simple setup (see [Fig. 5.3]) instead, to test the *visibility* of the LDV by the CCD camera (which is supposed to see from the same point of view of the LDV photodiode). Here, the visibility means if the LDV is able to *see* the light reflected or scattered by the sample. We expected that besides the sample characteristics, the lens aperture also becomes the limiting factor. In the setup, an objective lens with an NA of 0.25 was used.

In the test, we used four specimens: two samples from pieces of a silicon wafer with different grain orientations (silicon-1 and silicon-2), a piece of silicon wafer coated with Nitride, and a piece of retroreflective tape. The sample was mounted on a rotary stage and was initially positioned with its surface normal parallel to the optical axis of the objective lens. During the test, the samples were rotated by 0° , 5° , 10° , and 15° and pictures were taken by the camera at each angle, as shown in Figure 5.4. The test results show that the laser spot was not visible for the first two samples at angles greater than 15° . These results are consistent with the manufacturer specification of the NA (14°).

FIGURE 5.4: Pictures of (a) silicon-1, (b) silicon-2, (c) silicon nitride, and (d) retroreflective tape samples taken at various angles between 0° and 15° (left to right).

The results confirm that bare silicon wafer (uncoated) behaves like a mirror from the LDV point of view. Conversely, a silicon nitride surface can be treated as

a shiny surface because it returns light beyond the instrument's aperture limit, albeit the amount of light (relative) returned is lower.

In the following experiment with the off-axis dual illumination technique, we prefer to use the first approach instead to immediately test (using a standard in-plane setup) if the illuminated sample would trigger a good signal level to the LDV system. Although this method seems somewhat imprecise, together with the surface roughness (R_a) of the samples, the combined information would be sufficient for our test.

FIGURE 5.5: Four samples of different surface shininess used in the experiment. From left to right, in order of increasing shininess: retroreflective tape, aluminum, polished steel, and polished silicon. Top-row: picture taken at an oblique angle. Bottom-row: pictures taken approximately perpendicular to the samples.

5.2.3 Experimental Setup

This section describes the measurement tests conducted, which had two objectives. The first was to verify whether a standard in-plane LDV is unsuitable for the characterization of the shiny target. The second was to investigate whether our method can measure the in-plane motion of a shiny target surface accurately.

Accordingly, both LDV methods were used in the experiment. As the target surface, we used four samples with different surface shininess. The samples, in order of increasing relative shininess are slabs of retroreflective tape, aluminum, polished steel, and polished silicon (Fig. 5.5).

In the tests, we used an electrodynamic shaker (TK2004E01, The Modal Shop, USA) to excite the sample attached to a stinger. A short stinger was deliberately chosen (4.5 cm) to minimize the transverse vibration of the sample. The shaker induces a sinusoidal in-plane vibration in the test surface, which is measured by the LDVs at three frequency values: 100, 200, and 300 Hz.

FIGURE 5.6: Experimental setup using (a) a standard method with an in-plane LDV and (b) our proposed method.

Figure 5.6 shows a schematic diagram of the LDV methods setups, where the sample is excited by the shaker. An out-of-plane LDV was used to measure the velocity of the shaker's axial vibration. This velocity is assumed to be equal to the actual in-plane velocity of the target surface. Here, the angular separation between the dual illumination from the in-plane LDV $\alpha = 14.5^\circ$, while that of the off-axis LDV method is $\beta = 26^\circ$.

FIGURE 5.7: Photographs of the off-axis dual illumination setup.

5.2.4 Results and Discussions

As expected, the measurements of the retroreflective tape and aluminum samples obtained with the two methods agree. However, only the off-axis method was able to measure the in-plane velocity (v_m) of the polished steel (see [Fig. 5.8]). The result of the measurements with the standard in-plane method consisted mainly of noise due to the light signal detected by the LDV. Furthermore, both methods failed to measure the velocity from the polished silicon.

FIGURE 5.8: Time-varying velocity waveforms measured with the standard in-plane and off-axis in-plane methods at 100-Hz driving frequency.

Lastly, Figure 5.9 shows the comparisons between the results from both methods with those from the out-of-plane LDV. The results were computed from the average peak amplitude of the vibration velocity (v) waveforms. The difference between the in-plane methods and the reference LDV method is prominent at a 200-Hz frequency 200 Hz for all samples. The measurement condition was not satisfied at this data point for the reference LDV.

FIGURE 5.9: Plot of the peak amplitudes for all samples obtained with the in-plane methods and the reference LDV method.

In the present study, we proposed the off-axis dual illumination method for the shiny surface but not for the mirror surface. In theory, the application to the shiny surface is also applicable to the off-axis in-plane method combined with a retroreflection technique. However, this approach is not suitable for two reasons. First, it requires a strong laser power source to ensure that sufficient light intensity returns from the retroreflector. Second, the off-axis in-plane method detects the frequency Doppler shift owing to the out-of-plane component twice as accurately as the off-axis dual illumination method. Hence, with an out-of-plane motion component, the motion is no longer pure in-plane owing to the cross-talk.

5.3 Summary

This chapter presents two approaches for addressing the problem of in-plane motion measurement from a mirror and shiny surfaces. The first technique is a standard in-plane LDV with an off-axis setup. To recover the diverged specular reflection from the shiny target, we used an external retroreflective tape. Then, the correction scheme to account for the effect of the oblique retroreflection from the tape is derived. It is shown, however, that the result of the Doppler frequency shift is zero. This analysis result is further validated by the experiment. Although

the result is negative, this work provides a complete understanding of the approach to apply oblique retroreflection for the in-plane LDV method.

We have also shown the principle of the dual beam off-axis detection for measuring the in-plane velocity of shiny target surfaces. While a standard in-plane LDV is unable to recover the specular reflection, with the proposed method, this light can be recovered by placing the detector along the direction of the dominant reflection off the surface. From the recovered light, the off-axis LDV method can measure the in-plane velocity comparable to the equivalent out-of-plane velocity measured by the out-of-plane LDV.

Chapter 6

Conclusion and Future Works

6.1 Conclusion

A conventional LDV cannot be used to measure a shiny and mirror surface vibrating with the presence of large tilts. By design, an LDV can measure an out-of-plane vibration from a diffuse rough surface. The surface must backscatter enough light to the LDV sensor head for sensing to take place. Although a mirror surface can reflect most of the light to the sensor head, its surface normal must be parallel to the optical axis of the LDV. A small tilt of the mirror is acceptable provided the reflected light off the mirror is within the extent of the viewing optics of the LDV. However, a large tilt of the mirror can reflect the light away from the LDV viewing optics. When this happens, the light signal is not detected by the LDV, and the measurement is no longer accurate.

This thesis has presented solutions to the major issues faced in the implementation of LDVs as a method of characterizing objects with mirror-like surfaces, as presented in Chapter 1. There are essentially three problems: 1) LDV measurement of the out-of-plane velocity of a vibrating mirror with a large tilt (translation coupled with rotation), 2) LDV measurement of the out-of-plane velocity

of a scanning mirror (pure rotation), and 3) LDV measurement of the in-plane vibration velocity of a shiny or mirror-like surface (in-plane motion).

Chapter 3 has provided a solution to the first problem. By introducing a retro-reflection technique to a conventional LDV, a proper and accurate measurement can be done on the vibrating mirror with a large tilt angle. The external retro-reflection method provides a method to recover the divergent beam obliquely reflected by the mirror. Once the light is recovered and detected to the LDV, the Doppler frequency shift can be extracted by the conventional signal demodulation approach of the LDV. However, due to the effect of the oblique reflection on the Doppler shift, an extra frequency shift that is angle-dependent must first be corrected, as shown in this study. For the first time, we have demonstrated the measurement of a large deflection from a cantilevered mirror with a maximum tilt angle of 2.5° , while in the same experiment performed using a standard LDV alone can only obtain accurate measurements up to a 1.8° tilt angle.

Chapter 4 has proposed a solution to the second problem. On the other hand, the second problem cannot be addressed by the solution from Chapter 3. It is because when the scanning mirror is rotating at a large angle, the incident beam on the mirror is also sliding. Besides the tangential velocity component, the radial velocity of the probed spot also adds up to the sensed Doppler frequency shift by the LDV. Furthermore, the analysis shows the presence of a strong angle dependence on the detected Doppler shift of the recovered light. The dependence angle has a form of the tangent function. This analysis also provides the means to correct this angle-dependent factor on the recovered signal. For the first time, we have demonstrated a conventional LDV, assisted by the retroreflection collector, capable of obtaining the time-varying waveform of the scanning mirror with a mechanical rotation angle beyond 30° .

Finally, Chapter 5 has discussed the off-axis dual illumination technique to address the third problem. From the analysis, an off-axis detection method is unable to detect the Doppler frequency shift from a mirror surface. The Doppler shift component in the specular reflection is canceled out by the component in the incident beam. Conversely, the off-axis technique allows the in-plane motion measurement from a shiny moving surface. As a proof of concept, we demonstrated the measurement on a polished steel surface successfully from which the standard LDV is unable to obtain the successful measurement.

In summary, the scientific contributions from the study can be summarised as followings:

1. The effect of the extra Doppler frequency shift from oblique retroreflection is successfully analyzed. A new equation to correct the effect from the measured velocity signal is derived. With this equation, which is not found in existing literature, the LDV users can use the oblique retroreflection method to perform measurement confidently on cantilevered-mirror with a large deflection angle.
2. The presence of the radial component from the measured velocity signal by the LDV on a rotating mirror with a large angle is identified through kinematic analysis. The amount of this component is successfully analyzed, such that the desired velocity of the scanning mirror (which is the tangential velocity) can be correctly obtained. With this analysis of the extra radial component, which was not thought previously, the LDV users can accurately measure the full profile of the tangential velocity of a scanning mirror with a large rotational angle up to 16.4° for the scanning mirror.
3. The Doppler frequency shift equation model for the off-axis LDV methods is successfully derived. This equation shows that the Doppler frequency shift is zero from the measurement by the off-axis LDV methods on the mirror surface

moving in-plane. The equation agrees with the experiments. With this finding, this analysis provides further confirmation for the researcher tackling the same problem.

4. Finally, the methods of oblique and in-line external retroreflectors, as proposed in Chapter 3 and 4, provides a practical solution for light-recovery, even if they are only used to measure the static tilt vibrations. This solution is only a fraction of the cost of the more sophisticated methods, such as the use of robots [111] or multi-point LDVs [109, 110].

6.2 Future Works

This study presented techniques for laser Doppler vibrometry to measure the vibration of a shiny and mirror surfaces. However, there are a few improvements that can be made. These areas of improvements are discussed as follows:

- Presently, we used the proposed method using the method of retroreflection. This method relies on the use of retroreflective tape. We have tested extensively with 3M Scotchlite. The retroreflective tape has some surface roughness [7] causing some signal loss and even contributes to speckle noises and signal dropout [183]. One mitigation is to have more power for the laser source. Another mitigation is to reduce the distance of the tape to the target point. These approaches are workarounds in this study. A proper study is to test with different kinds of retroreflectors, such as cube corner retroreflectors. In principle, the retroreflection returned by the cube corner reflector should provide the same outcome but perhaps different efficacy in terms of the acceptance angle by the retroreflector. Future work involves the study of a different kind of retroreflector for the retroreflection technique presented in this study.

- The design of the retroreflector by far follows a trial and error approach. By the large depth field of the LDV vari-focal lens mostly used in our retroreflection techniques, the imperfection of the shape of the collector is not revealed. However, for a narrow depth of field of a different kind of lens, a more precise shape of the collector is needed. A proper ray tracing simulation of the shape of a trough and geometrical optic analysis can help to confirm.
- For in-plane measurement, we have demonstrated the measurement on a reflective surface target using the off-axis dual illumination method. Future works can be extended to test the method on a micro-device to further show the practical value of the method for the industry. A preliminary has been shown in Appendix I.
- Lastly, we briefly show an alternative method for the in-plane method using the retroreflection technique with an out-of-plane LDV assisted by a prism mirror in Appendix J. Future work can test the method in an experiment for the validation purpose.

Appendix A

The Doppler Effect

A.1 Basic equation

Here, we show the derivation of the classical Doppler effect, following [8]. Let us consider a stationary light source emitting a light wave with a wavelength λ and frequency f_0 . The time taken for the waveform with a length λ to arrive at the stationary observer is $T_0 = 1/f_0$. When the observer travels away from the light source at speed v , the wave train takes a slightly longer time T_1 to reach the observer. The total distance cT_1 of the wave traveling in time T_1 can be thought as the sum of the distance λ and the distance vT_1 traveled by the observer, and is given as:

$$\begin{aligned} cT_1 &= \lambda + vT_1 \\ (c - v)T_1 &= \lambda \end{aligned} \tag{A.1}$$

Since $f_1 = 1/T_1$ and $\lambda = c/f_0$, and also considering that for the traveling observer, the period of the wave observed by the moving observer is T_1 , we have the followings:

$$(c - v)/f_1 = c/f_0 \tag{A.2}$$

And, the observed frequency f_1 is given as:

$$f_1 = f_0(c - v)/c = f_0(1 - v/c) \quad (\text{A.3})$$

Hence, if the observer moves away from the light source ($v > 0$), the observed light frequency is smaller. Likewise, if the observer moves toward the light source ($v < 0$), the observed frequency is bigger. Again, the assumption in this classical derivation is that the velocity v is much smaller than the velocity of light c . As pointed out by [75], the general Doppler effect equation is given in Eq. 2.1.

A.2 Derivation with vector notation

Here, we briefly show the steps for deriving the Doppler effect using the vector notation by adapting the approaches from [83, 90]. Let us consider the target object moving with velocity $\vec{v}$ toward the LDV but not necessarily in the direction of the incident light beam. And, the LDV shines the laser with the incident light with direction $\vec{k}_1$ and the light is reflected in the direction $\vec{k}_2$. Hence, the observed frequency shift at the target point is:

$$f_{D_1} = -\frac{\vec{v} \cdot \vec{k}_1}{\lambda} \quad (\text{A.4})$$

Here, the sign is negative because vector $\vec{k}_1$ is in the opposite direction to $\vec{v}$. When the light is reflected by the target, the observer at the LDV perceives the frequency shift as followings:

$$f_{D_2} = \frac{\vec{v} \cdot \vec{k}_2}{\lambda} \quad (\text{A.5})$$

Finally, the total Doppler frequency shift is the sum of the two Doppler frequency shifts:

$$\begin{aligned} f_D &= f_{D_1} + f_{D_2} \\ &= \frac{(\vec{k}_2 - \vec{k}_1) \cdot \vec{v}}{\lambda} \end{aligned} \quad (\text{A.6})$$

To extend this derivation further on the oblique retroreflection method, let us consider the setup as shown in Fig. 3.2c in particular. Now, we consider the target is a tilted mirror such that it reflects the incident light obliquely. The addition of the retroreflective tape allows the reflected light from a tilted mirror to be diverged to the LDV. Here, we introduce $\vec{k}_3$ as the vector of the reflected light from the mirror to the tape. And $\vec{k}_4$ is a vector of the retroreflected light from the tape to the mirror. By following the steps to obtain the Doppler shift frequencies in Eq. A.4 and Eq. A.5, we can also obtain the same frequency shift as observed by the tape as followings:

$$f_{D_3} = \frac{\vec{v} \cdot \vec{k}_3}{\lambda} \quad (\text{A.7})$$

And, similarly, we can obtain the Doppler frequency as observed by the mirror due to the reflection from the tape as follows:

$$f_{D_4} = -\frac{\vec{v} \cdot \vec{k}_4}{\lambda} \quad (\text{A.8})$$

Here, we add a negative sign because the vector $\vec{k}_4$ is in the opposite direction to the velocity direction $\vec{v}$. And, the total Doppler frequency shift by the oblique retroreflection is the sum of the four Doppler frequency shifts:

$$\begin{aligned} f_{D_o} &= f_{D_1} + f_{D_2} + f_{D_3} + f_{D_4} \\ &= \frac{(\vec{k}_2 - \vec{k}_1 + \vec{k}_3 - \vec{k}_4) \cdot \vec{v}}{\lambda} \end{aligned} \quad (\text{A.9})$$

where this result is equivalent to the scalar notation in Eq. 3.11. The difference is that this approach can handle the case of the reflected light which is not in the

orthogonal plane of the coordinate system (i.e., we need to describe with 3 angles instead of 2 angles if we use the scalar approach).

Appendix B

Specifications of the retroreflective films

B.1 Microsphere retroreflector

Below are the technical specifications of the 3M Scotchlite™ High Gain Reflective Sheeting 7610 (the glass bead retroreflector) as obtained from the reference [184]:

Physical Characteristics

Characteristic	Value
Film Color	Light gray
Retroreflection Definition	<p>The typical coefficient of retroreflection defined is measured at a -4° entrance angle and a 0.2° observation angle. It is expressed in candlepower per foot-candle per square foot (candela/lux/square meter) per ASTM E810.</p> <p>The entrance angle is formed by a light beam striking the surface at a point and a line that is perpendicular to the surface at the same point.</p> <p>An observation angle is formed by the light beam striking the reflective surface and returning to the observer. From 800 feet (249 meters), a motorist normally views a graphic at a 0.2° angle.</p>
Thickness	<p>Without liner: 0.004 in (0.010 cm)</p> <p>With liner: 0.006 in (0.015 cm)</p>
Typical Luminance Factor	<p>-4° reading: 900X</p> <p>Skewed 45° reading: 700X</p>
Temperature Resistance	<p>Continuous exposure: 175°F (79°C)</p> <p>Intermittent exposure: 250°F (121°C)</p>
Available Sizes*	<p>Widths: 1/2 in (1.27 cm); 3/4 in (1.90 cm); 1 in (2.54 cm); 2 in (5.08 cm); 24" (60.96 cm)</p> <p>Lengths: 50 yds. (45.7 m)</p>

* Custom widths and lengths are available on request, subject to minimum order requirements.

FIGURE B.1: Specifications of 3M Scotchlite™ Tape 7610 [184].

B.2 Microprismatic retroreflector

Below are the technical specifications of the 3M™ Diamond Grade™ DG3 Reflective Sheeting Series 4000 (an equivalent to the prismatic tape used in our experiment) as obtained from the reference [185]:

Adhesive Type	Pressure-sensitive, Solvent free
Application	Regulated Rigid Traffic Signs
Brand	Diamond Grade™
Color	Brown, White, Blue, Brown, Green, Red, Translucent White, White, Yellow
Construction	Full-cube prismatic, Microprismatic
Dimensions	12" x 50 yds, 12-3/4" x 50 yds, 18" x 50 yds, 2" x 50 yds, 24" x 50 yds, 30" x 50 yds, 36" x 50 yds, 40" x 50 yds, 48" x 50 yds, 6" x 50 yds, 9" x 50 yds
For Use On	Aluminum, Plywood, Polyethylene
Overall Length (Metric)	45.72 m, 91.44 m
Overall Width (Metric)	1016 mm, 1219.2 mm, 152.4 mm, 228.6 mm, 304.8 mm, 323.85 mm, 457.2 mm, 50.8 mm, 609.6 mm, 762 cm, 914.4 mm
Performance Level	Diamond Grade
Performance Tier	DG3
Product Code	4090, 4090T, 4091, 4092, 4095, 4097, 4099
Product Series	4090
Size	Sheets
Specifications Met	All ETA Class 3 tables, ASTM D4956 Type XI
Substrate	Aluminum, Metal, Polyethylene Devices

B.3 List of suppliers

Based on a literature survey [141, 142] and internet search, including 3M™ company, the lists of manufacturers of the retroreflective films with comparable performance to the model used in this research work are:

3M™	Scotchlite high gain reflective sheeting 7610
Avery-Dennison	High intensity grade reflective sheeting T5500
Nippon Carbide Industries	Nikkalite J8112
Orafol	ORALITE® Photoelectric Sheeting

As indicated in [142], the application of 3M 7610 product includes "the measurement, tracking, security and safety with laser and polarised light". Therefore, this product is, admittedly, the most suitable retroreflective film for use with LDV applications at the moment.

Appendix C

Specifications of the LDV system

Below is the technical specification of the LDV system, LV-S01, as obtained from the reference [186]:

Operation Temperature	3°C 45°C
Operation Humidity	<90%
Power Source	220 240Vrms 50-60hz
Laser wavelength	He-Ne laser 632.8nm
Safety Class of Laser	Class IIIa
Work distance	0.35m 20m (Depend on object surface under test)
Velocity range	50mm/s, 100mm/s, 500mm/s, 1m/s, 5m/s, 10m/s
Output Voltage Range	±10V
Max. Linearity Error	1.00%
Filter	High-Pass Filter, Low-Pass Filter

Velocity Resolution	1µm/s
Frequency Range	DC to 25KHz, to 100KHz, to 1MHz/2.5MHz
Displacement Resolution(@500hZ)	0.32nm
Displacement Resolution(@20KhZ)	0.008nm

In most of our experiments, we placed the object at the distance about 50 cm, which is set to be the focal length of the lens. We can use the following equation [82] to estimate the diameter of the laser spot on the target object:

$$d = \frac{2\lambda F}{\sigma} \quad (\text{C.1})$$

where λ is the wavelength of the He-Ne laser of 632.8 nm, F is the focal length of the lens, and σ is the original of the incident beam's diameter on the objective lens. Here, σ value is estimated about 1.2 cm, and by substituting these values we have the following estimated diameter of the laser spot **d = 0.05 mm**.

Furthermore, from this result, we can also estimate the depth of field of the LDV system in the experiment. Here, for the Gaussian beam laser, we use the Rayleigh length (or Rayleigh range) [79] definition for the depth of field of the laser beam. The Rayleigh length is the distance from the smallest beam spot (beam waist) where the beam radius is changed by a factor of the square root of two [187], and is given by the following formula:

$$z_R = \frac{\pi w_o^2}{\lambda} \quad (\text{C.2})$$

where w_o is the beam spot radius (i.e., $d = 2w_o$). Here by substituting the value of w_o , we obtain $z_R = \mathbf{3.45 \text{ mm}}$.

The calibration of the LDV controller unit has been certified by the Singapore National Metrology Center (NMC).

FIGURE C.1: The label of the calibration status of the LDV audited by NMC.

Below is the product information of an equivalent laser source used in the LDV (i.e., the exact detail of the actual part is not available) [188]:

Wavelength (nm):	632.8	Pointing Stability (mrad/°C):	From Cold Start, 25°: <0.1
Pointing Stability after Warm Up (mrad/°C):	N/A	Output Power (mW):	2
Beam Diameter (mm):	0.63	Beam Divergence (mrad):	1.30
Polarization:	500:1	Static Alignment:	Centered to Outer Cylinder: $\pm 0.01''$ Parallel to Outer Cylinder: ± 1.0 mrad
Beam Diameter Tolerance (%):	± 3	Beam Divergence Tolerance (%):	± 3
Color:	Red	Model Number:	1103P
Diameter of Laser Head (inches):	1.245	Laser Class - CDRH:	IIIa
Length of Laser Head (inches):	9.50	Longitudinal Mode Spacing, Nominal (MHz):	730
Manufacturer:	Lumentum	Maximum Drift:	Mean Power over 8 hrs: ± 2.5
Minimum Output Power, TEM ₀₀ (mW):	2.0	Mode Purity (TEM ₀₀):	>95%
Operating Humidity:	0 to 100%, non-condensing	Operating Temperature (°C):	-40 to +70
Output Type:	Free Space	Power Supply:	#11-380 (110/220V AC), #11-384 (12V DC), #11-385 (24V DC), #11-387 (110/220V AC)
RMS Noise:	30 Hz - 10 MHz: 0.1%	Spatial Mode:	TEM ₀₀
Storage Temperature (°C):	-40 to +150	Type of Laser:	HeNe
Warm-Up Time (minutes):	10	Weight (lbs):	0.54

FIGURE C.2: Specifications of an equivalent laser source model (Model 1103P) [188].

Below is the product information of an equivalent detector used in the LDV (i.e., the exact detail of the actual part is not available) [189]:

Absolute maximum ratings

Symbol	Parameter	Min	Max	Unit
T_{STG}	Storage temp	-40	100	°C
T_{OP}	Operating temp	-20	70	°C
M_{max}	Gain ($I_{P0} = 1$ nA)	200		
I_{PEAK}	Peak DC current		0.25	mA

Schematic

Spectral response ($M = 100$)

Electro-optical characteristics @ 23 °C

Symbol	Characteristic	Test Condition	Min	Typ	Max	Unit
	Active area		diameter 230			μm
	Active area		0.04			mm^2
I_D	Dark current	$M = 100$		0.2	0.5	nA
C	Capacitance	$M = 100$		0.6		pF
	Responsivity	$M = 100; \lambda = 800$ nm	45	50		A/W
t_R	Rise time	$M = 100; \lambda = 905$ nm; $R_L = 50$ Ω		0.18		ns
	Cut-off frequency	-3dB		2		GHz
V_{BR}	Breakdown voltage	$I_R = 2$ μA	80		120	V
	Temperature coefficient	Change of V_{BR} with temperature		0.45		V/K
	Excess noise factor	$M = 100$		2.2		
	Excess noise index	$M = 100$		0.2		

FIGURE C.3: Specifications of an equivalent detector (AD230-8 SMD) [189].

Below is the product information of the data-acquisition (DAQ) unit NI-6251 USB BNC (from National Instruments) used in the LDV system [190]:

Number of channels	8 differential or 16 single ended
ADC resolution	16 bits
Sample rate	Single channel maximum 1.25 MS/s
Sample rate	Multichannel maximum (aggregate) 1.00 MS/s
Timing resolution	50 ns
Timing accuracy	50 ppm of sample rate
Input coupling	DC
Input range	± 0.1 V, ± 0.2 V, ± 0.5 V, ± 1 V, ± 2 V, ± 5 V, ± 10 V
Small signal bandwidth (-3 dB)	1.7 MHz
Input FIFO size	4,095 samples
Scan list memory	4,095 entries

Finally, the LDV system used in-house data acquisition software (developed by the author) called QuickSA (version 2.0) that supports the data collection and its real-time plot. This software has also been used by other researcher groups [45, 191–193].

Appendix D

Geometric analysis of the retroreflector

In this appendix, we derive *the radius curvature* of the reflector geometry and describe *the position* of the reflector relative to the center rotation $\mathbf{m}$ of the mirror. Fig. D.1 shows the geometry of the curved reflector in our setup. The origin coordinate $\mathbf{o}$ is at the center of LDV objective lens. The laser beam is incident on a rotating mirror at point $\mathbf{p}$ and is reflected toward a curved reflector at point $\mathbf{q}$. The mirror is tilted at an angle of θ with respect to y-axis. The center of rotation of the mirror is at point $\mathbf{m}$.

FIGURE D.1: Geometry of the reflection

In this setup, the LDV has a fixed focus distance at $\mathbf{f}$, which is defined as:

$$f = \overline{op} + \overline{pq} = w + s$$

where w is the length of line segment $\overline{op}$ and s is the length of line segment $\overline{pq}$. When $\mathbf{p}$ coincides with $\mathbf{m}$, the values of w and s are constants, otherwise they varies with θ .

Specifically, we can describe w and s as followings:

$$w = k + v \sin \theta \quad (\text{D.1})$$

$$s = f - w \quad (\text{D.2})$$

where k is the x-coordinate of point m and v is the y-coordinate of point m .

The point $\mathbf{q}$ can be described as

$$q_x = w - s \cos 2\theta \quad (\text{D.3})$$

$$q_y = s \sin 2\theta \quad (\text{D.4})$$

The radius curvarture R is defined parametrically as [194]:

$$R = \left| \frac{ds}{d\varphi} \right| = \left| \frac{(\dot{x}^2 + \dot{y}^2)^{\frac{3}{2}}}{\dot{x}\ddot{y} - \dot{y}\ddot{x}} \right| \quad (\text{D.5})$$

where where $\dot{x} = \frac{dx}{dt}$, $\ddot{x} = \frac{d^2x}{dt^2}$, $\dot{y} = \frac{dy}{dt}$, and $\ddot{y} = \frac{d^2y}{dt^2}$.

Let us define q'_x and q''_x as the first and second derivatives of q_x with respect to θ .

$$q'_x = \frac{dx}{d\theta} = 2s \sin 2\theta \quad (\text{D.6})$$

$$q''_x = \frac{d^2x}{d\theta^2} = 4s \cos 2\theta \quad (\text{D.7})$$

Similarly, we also define q'_y and q''_y as the first and second derivatives of q_y with respect to θ .

$$q'_y = \frac{dy}{d\theta} = 2s \cos 2\theta \quad (\text{D.8})$$

$$q''_y = \frac{d^2y}{d\theta^2} = -4s \sin 2\theta \quad (\text{D.9})$$

Now, the radius curvature R formula is given as followings:

$$R = \left| \frac{(q'^2_x + q'^2_y)^{3/2}}{q'_x * q''_y - q'_y * q''_x} \right| \quad (\text{D.10})$$

$$= \left| \frac{(4f^2 - 8fk - 8fv \sin(t)^3 + 4k^2 + 8kv \sin(t)^3 + 12v^2 \sin(t)^4 - 12v^2 \sin(t)^2 + 4v^2)^{3/2}}{\frac{3v^2 \cos(4t)}{2} - 16fk + 8f^2 + 8k^2 + \frac{13v^2}{2} - 15fv \sin(t) + 15kv \sin(t) + fv \sin(3t) - kv \sin(3t)} \right| \quad (\text{D.11})$$

The center of the curved reflector can defined as:

$$c_x = R \cos 2\theta + q_x \quad (\text{D.12})$$

$$c_y = R \sin 2\theta - q_y \quad (\text{D.13})$$

Appendix E

Specifications and Setup of the high-speed camera

E.1 Specifications

The model of the high-speed camera is FPS1000 Platinum. The camera is made by Imagetec, UK. Below are the technical specifications of the camera, as obtained from the reference [195]:

Maximum Resolution	2560 x 2048
Bandwidth	5.75 Gbits/sec
Frame Rate @ 1280 x 720 (HD)	500 fps
Frame Rate @ 640 x 360	1500 fps
Pixel Color Depth	10 bits
Video Memory Capacity	64 GBytes
Recording time at max frame rate	1 minute
Responsivity (V/Lux.s)	7.7
Pixel Size (micron)	4.8
Format	2/3"

To match the working distance at about 60 cm in the experiments, a telephoto zoom lens (Fujinon, Fujifilm) was used.

FIGURE E.1: (a) Setup of the displacement measurement with the high-speed camera. (b) The top-view of the rotating mirror as seen by the camera.

E.2 Setup and methods

Here, we describe the setup and the procedures of using the high-speed camera in the experiments explained in Section 4.4 of Chapter 4. Specifically, we used the high-speed camera to measure the time-varying displacement response of the rotating mirror with an angular speed of $\dot{\theta}$. The target point of interest is the intersection point of the mirror to a vertical axis L whose distance is chosen at $h=3.5$ mm to the center (rotation axis) of the mirror (see [Fig. E.1a]). For example, the intersection point of the mirror is the point Q when the mirror surface is perpendicular to L ; this position is the neutral position of the mirror when the angle of rotation is $\theta = 0$. Here, we position the camera to view the top side of the mirror. Due to the optical magnification, only a portion of the mirror is

visible in the captured image. Therefore, it is not straightforward to determine the center of rotation. Hence, when the mirror is initially resting at its neutral position, we marked a point Q' on the top side of the mirror also at a distance h to the center of rotation. This marker is always visible to the camera during the measurement (see [Fig. E.1b]).

The high-speed camera records the motion of the rotating mirror during the measurement. To process the captured images, we used the software *Tracker*, a video image analysis software [165]. Here, in the captured images, we tracked the point Q' to establish the center of rotation and thus the reference frame. Then, we tracked the target points (e.g., point p_1 , p_2 , or p_3), which are the intersection points of the line L to the mirror. We further used the software to calculate the displacement of the target points. Also, we used the software to obtain the velocity of the target points (the in-line velocity) from the derivatives of the displacement with respect to the time.

Few factors are contributing to the uncertainty in the displacement measurement using the high-speed camera method. For example, the temporal aliasing is present in the captured images (at 1500 frames per second) whose intensity fluctuates due to the target object was illuminated under the room lighting with 60-Hz alternating current (AC). Another more important factor is the difficulty in determining the exact tracking point from the marker in the captured images. Due to the magnification, the marker appears as a region of pixels rather than a pixel point. The image processing can transform this region area as a blob by image thresholding, and then the centroid of the blob can be used as the tracking point. Although the software can automate this process, it can fail in some instances when the intensity variation of a particular frame is outside the thresholding range. Hence, manual centroid identification must be performed. The manual method is not reliable and prone to error. Thus, this contributes to the errors in the measurement.

Appendix F

Cantilevered mirror experiment

F.1 Setup and methods

FIGURE F.1: The setup (top-view) for the measurement of large deflection of a cantilevered mirror using: (a) an oblique retroreflection-assisted LDV ($\theta = 25^\circ$), (b) a standard out-of-plane LDV assisted with the retroreflective tape on the cantilever tip.

Figure F.1 shows the experimental setups for the measurement of the deflections of a cantilevered mirror using two methods: the oblique retroreflection (external tape) method and the retroreflective tape on the ruler (tape on ruler) method. The off-axis angle θ of the external tape method is set at 25° . In this test, the sample is a cantilevered ruler of 135 mm long, and 7.9 grams in weight. A silicon mirror (of $8 \times 20 \text{ mm}^2$ in size and < 0.3 grams in weight) is attached adhesively at the tip of the ruler. At the backside of the tip, a retroreflective film is pasted. The

cantilever base is mounted on an electrodynamic shaker (TK2004E01, The Modal Shop, USA). In the test, we fixed the vibration levels of the shaker at 0.1V but varied the driving frequency of the input signal. The driving frequencies used in the tests were from 20 Hz to 60 Hz with an increment of 10 Hz. The base motion x_{base} caused by the shaker excitation is described by Eq. 3.15. Moreover, the translation of the cantilever tip (mirror), $y(u)$ is by Eq. 3.16. Finally, in the test, the LDV obtained the velocity waveforms v_m , and v'_m from the deflecting cantilever at each different frequencies. The velocities v'_m were corrected by using Eq. 3.14.

F.2 Additional results

Figure F.2 shows the comparisons of the velocity waveforms as acquired by the external-tape method and the tape-on-ruler method at different frequencies of 20 Hz, 30 Hz, and 40 Hz. The plots are the additional results supplementing the test results in Section 3.4 of Chapter 3. By and large, the velocity waveforms obtained from both methods show good agreements.

FIGURE F.2: The velocity waveforms of the deflection of cantilevered ruler by the external-tape and the tape-on-ruler method at the driving signal with the frequency of 20 Hz (top), 30 Hz (middle), and 40 Hz (bottom).

Appendix G

Off-axis In-plane Experiment

In this Appendix, we describe the measurement tests of the in-plane motion of a shiny and mirror samples by using the off-axis in-plane LDV method described in Chapter 5. The experimental setup generally follows the principle discussed in Section 5.1. Figure G.1 shows our first experimental setup. A mirror sample was attached to a sample holder supported by a stinger attached to an electrodynamic shaker (TK2004E01, The Modal Shop, USA). Upon a sinusoidal driving input to the shaker, the shaker excites the sample to vibrate harmonically at a frequency of 100 Hz. In this test, the main focus was to find out if the recovered light signal from the retroreflective tape contains the Doppler-shifted frequency proportional to the in-plane motion of the vibration.

FIGURE G.1: The experimental setup from the first test

Figure G.2 shows the result of the first experiment. The measured time-varying vibration waveforms appeared to be sinusoidal waveforms with a vibration frequency of 100 Hz. This test result does not agree to the analysis from the theory (Eq. 5.1) that suggests the Doppler-shift frequency, from an incident beam and its specular reflection from a moving mirror, cancel each other, yielding zero value. Also, we expected from the method should not be able to measure the in-plane motion from the mirror sample.

FIGURE G.2: The time-domain waveform and spectral plots of the first test

We hypothesized that the result from the first experiment was mainly due to the out-of-plane component of the vibration from the sample. Here, in the second experiment, a piezo stack actuator (FPST150, Piezomechanik, Germany) was used to provide the excitation for the in-plane motion of the sample. The piezo actuator was expected to provide little or no transverse force that may induce the out-of-plane vibration of the sample. Figure G.3 shows the setup of the second experiment.

FIGURE G.3: The experimental setup from the second experiment

Figure G.4 shows the result of the measurement test. The test shows that the LDV with the off-axis in-plane method cannot measure the in-plane vibration velocity of the polished silicon sample properly. The out-of-plane LDV confirmed the absence of the out-of-plane vibration in the in-plane moving sample. This result supports our hypothesis. The finding from the two tests indicates that the off-axis in-plane LDV could not measure the in-plane motion. Instead, the method can pick up the out-of-plane vibration of the sample. Furthermore, the detected Doppler frequency shift from the off-axis in-plane method is more than twice proportional to the out-of-plane vibration component. Therefore, the theory predicting that zero Doppler frequency on the in-plane motion measured by the LDV with this approach is correct.

FIGURE G.4: The time-domain waveform and spectral plots of the second test

Appendix H

Visualization of the laser scatterings

Visualizations of a laser beam on a solid surface can help to confirm if the surface is optically rough, or shiny. This visualization means being able to see the propagation path of the laser both the incident and reflected or scattered on the propagation medium. This is different from viewing the projected scattered laser beam on the image sensor plane or a screen [16, 115].

Some works visualized the path by passing the laser beam onto a liquid medium. Shian et al. [196] used a colloidal silica dispersion in water to visualize the thickness of a green laser beam at the focal point. Hullin et al. proposed to use a fluorescent liquid for a direct view of the light propagation [197]. These solutions gave stable and useful visualizations of the laser path. However, the use of liquid medium provides some logistics challenge, and more importantly, the interface of the glass container may influence the light path from the actual scattering from the surface object.

Here, we proposed a simple method commonly used in troubleshooting of the laser beam alignment by using a white-card. The method is by scattering the light beam with the white paper card manually and taking a picture in the process with a long exposure camera setting enabled. Fig. H.1 shows the setup which adopting the in-plane LDV as the light source. The camera is placed on a stable tripod,

looking almost perpendicularly to the plane where the two beams from the LDV illuminate the sample. As the camera is triggered, the white card is moved up and down manually, traversing the area surrounding the light path propagation. This manual process must be done within the camera exposure time. At the moment, the optimum exposure time is obtained by trial and error.

FIGURE H.1: Setup of the image capture of the laser scatterings.

Fig. H.2 shows the captured image from a rough metallic sample.

FIGURE H.2: A photograph of scattered laser from a rough sample.

Fig. H.3 shows the captured image from a smooth aluminum sample.

FIGURE H.3: A photograph of scattered laser from a smooth aluminum sample.

From the captured photograph, it appears that the rough sample scattered more beams than the smooth sample. The two photographs, however, were taken at different exposure times; hence, it is unwise to make quantitative comparisons from the results (e.g., comparing the pixel intensity of the beam from the image). Finally, it is noted here what is captured by the camera is the integration over the exposure time of the light energy scattered by the card. Since this was operated manually, to get repeatable results could be challenging. However, for the qualitative measure of the optical shininess of the sample, this approach seems sufficient for our study.

Appendix I

In-plane MEMS Testing

This chapter discusses the development of MEMS in-plane actuators and the in-plane motion characterization using in-plane LDV. The chapter is divided into several parts: 1) design and simulation, 2) fabrication and characterization, 3) experiment, and 4) discussion. The future work is briefly discussed in the last section.

I.1 Design and simulation

The underlying principle of the MEMS in-plane actuators developed is based on electro-thermal micro-actuation following the work from [198]. It is reported that the design allows an in-plane rectilinear stroke at the center due to very high stiffness in the orthogonal directions to the stroke of the beam. With a non-out-plane component of motion, this design is suitable for the validation of the proposed method.

For this work, two types of design are developed. The first design adds the center part of the original design with a probe beam. The probe beam has some various surface conditions: a plain polished silicon part and a glossy part from the heater, as shown in Figure I.1. The second design features a planar stage supported by

FIGURE I.1: A schematic diagram of MEMS electro-thermal actuator (design 1 & 2) that can provide precise rectilinear in-plane motion, indicated by red vertical arrows.

two-pair actuators that can be activated independently to provide bidirectional motion. There are two variations on the planar stage for the second design, one design is with a smooth surface, and another design is with a grid of through-holes to simulate surface roughness.

FIGURE I.2: A simulation of the design 1 (left) and design 2 (right) for the maximum displacement under operating temperature. The simulated maximum displacement is about $35.6 \mu\text{m}$ and $32.9 \mu\text{m}$, respectively.

For the simulation, we use finite-element modeling (FEM) analysis and use the ANSYS software. The simulation is developed to predict the possible stroke that

can be achieved. The result of the simulation is for the maximum displacement is about $35.66 \mu\text{m}$. The result is shown in Figure I.2.

I.2 Fabrication and characterization

Figure I.3 shows the micro-fabrication process for the device which follows the work from [198].

FIGURE I.3: The fabrication process for the MEMS device for the design 1 and 2. (credit: Mr. Chong)

The first step involves low-pressure chemical vapor deposition (LPCVD) and followed by a series of photolithography (step 2 to step 4). A bulk-machining process is carried out for step 5 to remove some material at the back of the silicon wafer. The aluminum or oxide layers are grown to protect the base layer for the following step at step 6 and then followed by the photolithography process. The aluminum or oxide etching is carried out in step 9. Finally, the release process is done either by laser cutting or manual process.

Basic device characterizations are carried out to validate the design performance of the device in particular for design 1. One example of the characterization result of device number 4 of design 1 is shown in Figure I.4. The plot shows the resistance change in the time given a step input of driving voltage of 4 V. The initial resistance is at $232\ \Omega$ and the peak resistance is at $258\ \Omega$. The second plot shows the consumed power during the same step input of 4 V which shows the peak value of 62 mW. For the same step input of 4 V, the maximum stroke measured is about $38\ \mu\text{m}$.

FIGURE I.4: Device number 4 of design 1 characterization: a) the resistance plot under step input of driving voltage 4V b) The consumed power under the same input as in (a).

Fig. I.5 shows the design 1 and design 2 (variation 2 with a grid of holes) device taken by a microscope from a MEMS probe station. For design 2, from initial basic characterization, it was discovered that the actuator is unable to move the stage at the center although the thermal actuators are responsive under the step input (shown by the small deformation of the SU-8/Si structures).

From further analysis, it is discovered that there is an incorrect design assumption that the size of the stage is sufficient to prevent heat energy from one of the active actuators going to the passive actuator. From the observation, however, it is apparent that when the actuator is activated (heated), the heat energy leaks to the passive actuator causing it to be activated too. As a result, the two pairs of the actuator are activated together, causing the resultant of motion to cancel each other at the center. This was a significant setback.

FIGURE I.5: The MEMS device for design 1 on the left and design 2 (with grid hole variation) on the right.

To remedy the adverse effect of the cross-talk for the heat transfer for design 2, manual mechanical removals done by the author were carried out. The removal works were to remove one of the actuators by hand with the help of a microscope. The result of this work is shown in Figure I.6

FIGURE I.6: The design 2 devices after some remedial works. Left: design 2 variation 1 in color, Right: design 2 with variation 2 in black and white image.

The next step to enable the devices to be tested under the LDV workstation is to mount the device on a PCB (printed circuit board) so that the device can be wire-bonded. For this purpose, two methods have been adopted: one is to use wire-bonding to attach wires to the bond pad, and another approach is to use a conductive epoxy that glues the wire to the bond pad. Both works were carried out. Figure I.7 shows the result.

FIGURE I.7: Left: wire-bonded design 1 device (grayscale), Right: a color image of design 2 device glued with conductive epoxy

I.3 Experiment

The first conducted experiment is to validate the MEMS device with a conventional differential LDV.

FIGURE I.8: The setup of the microscope in-plane LDV test station.

I.3.1 Setup

The dynamic characterization for the MEMS device is carried out at the LDV test station. The setup is shown in Figure I.8. The test station is equipped with several stations. The in-plane LDV is positioned vertically and secured with a linear stage that is attached to an anti-vibration table. The LDV is equipped with a microscope objective lens of 5x magnification that allows the two laser beams to be focused onto the microstructure sample. The sample itself is mounted on a vertical stage with adjustable height, and its base is secured. A camera with a zoom lens is positioned such that the laser spot on the sample can be viewed. It helps during alignment and getting the right focus. An LED light source is used to illuminate the sample as viewed by the camera. The wires soldered to the PCB connected to the bond pad is plugged to a signal input generator. The LDV is connected to its controller and a DAQ system, which is connected to the PC system.

FIGURE I.9: The sample for the test. Left: design 2 device, and Right: design 1 device.

I.3.2 Samples

Figure I.9 shows the sample used in the first measurement. The left sample is a MEMS device of design 2 with a smooth surface; the sample on the right is a

MEMS device of design 1. Another sample of design 2 with a simulated rough surface is also used.

I.3.3 Velocity characterization

To understand the MEMS device in-plane motion velocity, we measured the sample of design 1. One point of measurement is located on the heater surface, which gives an excellent signal level (the signal is sufficient for the LDV controller to perform demodulation). Interestingly, this point is at the heater, which is coated with a gold layer, which was expected to have a shiny surface and less backscattered light to the LDV.

FIGURE I.10: (Left) Plot of the average of root-mean-square in-plane velocity in $\mu\text{m/s}$ against the driving voltage (V) at the laser spot shown in Figure I.9. (Right) The plot of the average of root-mean-square in-plane velocity in $\mu\text{m/s}$ against the frequency of the input sinusoidal signal at 8 Vpp input.

Figure I.10 shows the test plot of the measurement at the laser spot, as shown in Fig. I.9. On the left plot of the Figure, the plot shows the relationship of the in-plane velocity against the driving input voltage of the signal generator. The input signal is of sinusoidal type fixed at 20 Hz. The voltage is set as the Vpp (peak-to-peak) mode. At each data point on the plot, several measurements are collected from the reading of the RMS (root-mean-square) peak magnitude at

frequency 20 Hz in frequency domain plot from the DAQ (data acquisition) software. The several collected data is then averaged to get the measured data point. The process is repeated for different V_{pp} values. From this plot, it can be shown the device is working as expected within the input voltage range, that is to say, as the voltage input is increased, the in-plane velocity (average of RMS in-plane velocity) is increased.

FIGURE I.11: Plot of time series of the in-plane velocity. The plot shows 3 snapshots in time of data point on a measured point overlaid on top of each other. Band-pass filtering is applied to remove very low and high-frequency noise.

The second plot on the right shows the relationship of the average in-plane velocity against the change in the frequency of the driving input signal. The same input signal type is used - sinusoidal input signal with a fixed driving voltage at 8 Vpp. Similar to the first plot, at each data point, several measurements are collected from the reading of the RMS peak magnitude from frequency domain plot from the DAQ software. The measured data points are then averaged. The typical example of corresponding time series data is given in Figure I.11. From this plot, what can be learned is that it shows a trend that as the frequency of the

input signal is increased, the in-plane velocity is increased at some range of frequency, but it starts going down around the frequency above 30 Hz. So far, this does not say much about the device performance as no specific design criteria are set for this device (i.e., what frequency range is expected for this design to work optimally, and what range of driving voltage is required to operate this device to work optimally).

I.3.4 Signal detection test

The next step is to show that the conventional design of differential LDV would have challenges for the point in the flat and smooth area, as shown in our previous experiment with the macro-scale sample.

Figure I.12 shows the laser spot from LDV on two different surface conditions on a device with design 2, the left image is on the smooth surface, and the right image is on the simulated rough surface. The two beams are focused on a point on the stage with the help of a microscope objective lens, and the size of the spot is about $20\text{ }\mu\text{m}$.

FIGURE I.12: The signal detection test on different surface conditions: (Left) The sample for the rough surface, (Right) The sample for the smooth surface. The laser spot is about $20\text{ }\mu\text{m}$.

For this test, we rely on the signal level from the LDV controller. The signal level indicates if the incident of both reference and object beams (both beam) are

backscattered to the photodetector. If the detector receives both beams, interference takes place at the vicinity of the photodetector's plane, and when this happens, the LDV controller demodulates the signal, and from this result, it shows the level of signal content the photodetector receives.

From the test, it is observed that the signal level for a smooth surface is below 5%, which is not sufficient for proper signal detection for the LDV. The resulting time series plot for this condition is random signals. On the other hand, for the rough surface, the signal level can achieve above 70%, which is sufficient even though they are not ideal (which is above 90% for this instrument).

I.4 Discussions

For the velocity measurement test, both test results validate the basic in-plane velocity characterization of the MEMS device. It shows a few things: firstly, the MEMS in-plane thermal actuator device can be actuated according to driving periodic input signal over time, and this process is repeatable. The second observation is that the in-plane LDV is able to measure the in-plane velocity of the device. It means it can detect the Doppler signal from this device at the measured point described above. The test results, however, does not say much about the accuracy of the measurement at this point. Supporting evidence is required to show if the in-plane LDV is accurate for the velocity range measurement in μm . This is one of the tasks to be done to provide calibration for the LDV against a reference calibrator working at μm range or compared the measured value against the reference equipment. Both tasks pose challenges for the author at the moment for the reasons described in the later section. In summary, the first step is to find a method to verify the measurement of LDV is reliable for velocities at the range of micron-scale.

I.5 Future Works

The next step first is to validate the LDV with a reference instrument. One candidate is to use an imaging method with a high-speed camera. However, the measurement with the imaging method poses some interesting problems. The imaging method requires the sample to have displacement that is discernible under microscope magnification, and usually, this happens at static displacement or frequency around 1 to 2 Hz. LDV has not been tested successfully under this very low frequency for the current MEMS device. One reason is the influence of the environment vibration is quite significant even though the anti-vibration table has been activated.

We have not set up the proposed method as described in Chapter 5 for the in-plane LDV system in the LDV test station. The second step is to modify the setup and apply the proposed off-axis dual illumination method with the in-plane LDV (see Section 5.2) to test on the sample with a smooth surface. When the results are obtained, and if they agree with the previously observed measurement on the macro-scale object, we can put them together into a publication journal which is done for the next step. In summary, we need to repeat the proposed method for the MEMS device measurement.

I.6 Acknowledgement

Prof. Lau provides the basis of the source code for FEM simulation for the design of the device. For the MEMS in-plane development work, the author contributes to the initial design and simulation with ANSYS (finite-element simulation software), with a later update from Dr. Cao Xinping, and the primary focus work on

the experiment with LDV. Mr. Liu Ting helped with the final device design, including the device layout design for creating the photo-mask for the photolithography process. Mr. Chong Nyok Boon assisted by Mr. Lim Cheng Yi assisted in the process of MEMS fabrication and device characterization (static displacement test and resistivity variation with temperature plot in section I.2). Dr. Han Lin provides the help for surface roughness and surface profile measurement with a confocal microscope instrument.

Appendix J

In-plane Retroreflection Technique

An oblique retroreflection technique can recover a deflected light beam from a moving target mirror. The recovered light contains the Doppler frequency shift induced by the velocity of the moving target. Only the velocity component projected along the direction of the light is detected by the LDV. The velocity of the target can be in any directions relative to the surface normal at the target point. Therefore, the velocity may not be parallel to the surface normal. By exploiting this fact and making use of Eq. (3.5), it is possible to measure the in-plane motion of the moving target with an out-of-plane LDV. Here, we propose an external retroreflection technique that recovers the obliquely reflected light from a mirror attached to the in-plane-moving target (see [Fig. J.1a]). This method is called an in-plane retroreflection technique.

Figure J.1b shows a schematic diagram of the working principle of the proposed method. An LDV shines the laser beam along the x-axis toward the target point P on a mirror M moving with a velocity v along the y-axis. The mirror is tilted at a fixed angle θ to the y-axis. Therefore, the beam incident from the LDV is reflected obliquely. If the tilt angle θ is greater than the maximum detectable tilt angle δ defined in Eq. (3.1), an external retroreflective tape is needed to recover

the deflected light outside the viewing range of the LDV optics. In such a case, the LDV can detect the Doppler frequency shift from the moving mirror.

FIGURE J.1: (a) An in-plane retroreflection technique for in-plane motion measurement by an LDV. (b) A diagram of the in-plane-retroreflection-assisted LDV, measuring a mirror M moving with velocity v perpendicular to the optical axis of the LDV. The surface normal of the mirror M is tilted at an angle θ relative to the optical axis of the LDV.

To understand the Doppler frequency shift f_D as detected by the LDV, we introduce local observers O at the LDV, P at the target point, and Q at the tape. The total Doppler frequency shift f_D is due to the light paths O-P-Q and Q-P-O. By following the same step as those followed to derive the Eq. (3.5) in Chapter 3 and substituting α with $\pi/2$, we obtain the following:

$$f_D = 2v(\cos(\pi/2) + \cos \beta)/\lambda = 2v(\cos \beta)/\lambda \quad (\text{J.1})$$

Eq. (J) is similar to Eq. (2.16), which indicates that the standard method of LDV measurement combined with a retroreflective tape attached to the target object can achieve similar measurement results.

$$v'_m = v \cos(\beta) = v \sin(2\theta) \quad (\text{J.2})$$

Eq. (J) suggests that v_m' depends only on the tilt angle θ . When the tilt angle is 45° , the measured velocity v_m' is equal to v . Accordingly, it is possible to use a standard 45° prism mirror for the attachment to the target object and a retroreflective tape (or a flat mirror) with the surface normal parallel to the x-axis as

the reflector. In practice, instead of attaching a prism mirror to the target object, one can consider incorporating a design feature in the target device, for example, a 45° silicon-based micro-reflector [199].

List of Author's Awards, and Publications

Journal Articles

- **Agusanto, K.**, Lau, G. K., Liu, T., and Zhu, C. (2019). Effect of oblique retroreflection from a vibrating mirror on laser Doppler shift. *Applied Optics*, 58(9), 2277-2283. DOI: 10.1364/AO.58.002277.
Awarded **Editor's Pick**.
- **Agusanto, K.**, Lau, G. K., Liu, T., Zhu, C., (2020). Radial and tangential velocity effects of a probed scanning mirror on laser Doppler frequency shift. *Applied Optics*. 59(12). DOI: 10.1364/AO.387267.

Conference Proceedings

- **Agusanto, K.**, Lau, G. K., Wu, K., Liu, T., Zhu, C., and Yuan, L. (2015, March). Directional-sensitive differential laser Doppler vibrometry for in-plane motion measurement of specular surface. In *International Conference on Experimental Mechanics 2014* (Vol. 9302, p. 93020V). International Society for Optics and Photonics.

Poster

- **Agusanto, K**, Liu, T., Zhu, C., (2014). Least Square Landmarks Registration for Automatic Scanning Laser Doppler Vibrometer. In 9th International Conference on Optics-photonics Design & Fabrication.

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