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Directional-sensitive differential laser Doppler vibrometry for in-plane motion measurement of specular surface

Kusuma Agusanto^{a,b}, Gih-Keong Lau^a, Kun Wu^b, Ting Liu^b, Chuangui Zhu^b, and Ling Yuan^b

^a*Nanyang Technological University, Singapore*

^b*Sunny Instruments Singapore, Pte. Ltd., Singapore*

ABSTRACT

A new method for measuring in-plane vibration velocity of glossy and specular surface using differential laser Doppler vibrometer (LDV) is proposed in this work. A standard tangential LDV using similar differential configuration is only able to measure in-plane velocity of objects with rough surface, due to its inherent on-axis optical design that collects backscatter light along its optical axis. The proposed method adopts an off-axis detection scheme, in which the photodetector is decoupled from LDV, and placed along the dominant direction of the scattered light. For optimal placement, the bidirectional reflectance distribution function (BRDF) of the sample must be considered ideally, but in our measurement tests, the off-axis detection along the direction of specular reflection is sufficient to obtain good measurement results. Another advantage with this setup is that it also works with the objects with rough surface. Experimental works using the standard tangential LDV and a prototype of this method were conducted to measure the in-plane motion of four different samples representing rough, glossy and mirror-like surface. An electrodynamic shaker was used to provide the in-plane motion of the samples at three different frequencies. A single point axial vibrometer was used to validate the in-plane velocity of the measurement from both in-plane LDVs. Some preliminary results showed that the in-plane motion of the object with glossy and specular surface can be measured using the proposed method.

Keywords: in-plane motion, laser Doppler vibrometry, surface condition, BRDF

1. INTRODUCTION

An in-plane or tangential laser Doppler vibrometer (LDV) has been steadily gaining acceptance into research and industry communities as a tool to measure in-plane or tangential vibration motion of a solid surface. It measures the instantaneous velocity of a point on a surface with a motion perpendicular to its optical axis. A differential configuration with an on-axis detection is commonly adopted. In this setup, two coherent beams at an equal angle with respect to the optical axis are intersected and focused on the measured point. Since the detector is placed along the optical axis, it relies on the surface roughness of the sample to scatter the incident beams back. When the surface is shiny, the incident beam is not scattered diffusely but dominantly along its specular reflection as shown in Figure 1. This causes not enough light (or even none for highly reflective surface) to be measured by the photodetector, as a result, noisy and distorted measurements are produced. Therefore, a standard tangential LDV are typically applied in in-plane motion measurement of objects with sufficient surface roughness such as paper, and rolled metal sheet [1].

However, many important device and structure such as MEMS, and hard-disk drive sliders have highly reflective surface, and reliable in-plane motion measurement is critical for their characterization and testing. Applying standard technique to improve surface roughness such as retroreflective tape or by varnishing is not possible due to small sample size or

sample contamination. Zhong et al adopted inductive coupled plasma (ICP) etching in which high density plasma and ion are bombarded on the test substrate - silicon bulk-machined resonator - during fabrication, resulting in high degree of surface roughness [2].

Figure 1. Problems with LDV on specular or glossy surfaces. (a) in-plane LDV on diffuse surface is OK. (b) in-plane LDV on glossy surface is not good (NG). The detector, for illustration, is lit up for enough scattered light.

In this work, a new method based on off-axis differential LDV is developed and studied. Early works on off-axis differential LDV have been reported by Stein et al [3] and Penney [4]. Both works were carried out at early stage of LDV development in 1970s and focused on measuring objects with rough surface and did not restrict how the detector is placed. The proposed method firstly requires the sample be tilted such that the surface normal is at an angle with respect to the symmetrical axis of the two incident beams from LDV, so that the reflected beams can be detected off-axis. The detector, which is a photodiode with an optical set of collecting and focusing lens, is placed along the direction of the optimum scattered light from the sample. Ideally, when the BRDF of the sample is available, or can be measured, it can be used to determined such optimum direction. In this work, it is argued that the direction of specular reflection is sufficient for such an off axis detection.

In addition, two optical designs are considered in this method in measuring sample with different sizes. For large sample size (the length is greater than 5 mm), a single focusing lens can be used to guide the two beams to a target point on the sample. For small-and-micro structures, the two beams are decoupled, and focused separately using objective lenses. In doing so, it allows a narrower angle separation of the two incident beams with longer working distance so that there is enough optical access for the off-axis detector. Also, it makes the overlapped incident beams smaller to fit on the required target point on microstructure samples. In this work, only large samples are discussed and used for the experiment.

2. MEASUREMENT PRINCIPLE

The schematic diagram of the proposed method is shown in Figure 2. The source of coherent light LS uses HeNe laser having wavelength λ of 632.8 nm with power less than 5 mW. The light beam is splitted into two beams by a polarizing beam splitter, PBS, one of which is reflected by triangular mirror, TM and go through an acousto-optic modulator (AOM) or also known as Bragg cell, BC. A frequency shift of 40 MHz (f_B) is added to this beam for discriminating the direction of the velocity. Eventually, both beams are focused by a focusing lens L_1 onto the target point on an object P vibrating at

velocity $v(t)$. As in the case of shiny surface, the incident beams are reflected in the direction of specular reflection along which the detector D is placed. The reflected beams are collected and focused by group lenses GL onto the detector unit. It is noted here that the sample surface normal $\mathbf{n}$ is tilted at an angle of α with respect to optical axis of the L_1 . Therefore, the Doppler effect sensed by the detector is directional sensitive.

Figure 2 Schematic diagram of proposed off-axis differential LDV method, where LS is the laser source, PBS is the polarizing beam splitter, TM is triangular mirror, BC is Bragg Cell, f_B is central band frequency at 40 MHz, GL is focusing group lenses, D is detector, and P is the target object moving at $v(t)$ velocity.

Using a similar approach from Paone et al in [5], the Doppler frequency shift of this optical setup can be derived - in this case the fluid particle flow is replaced by a vibrating target with a backward scatter setup (the detector is placed in front of the target). It can be shown that the measured Doppler shift f_D is as followings:

$$f_D = 2 \frac{v}{\lambda} \sin \frac{\beta}{2} \cos \alpha \quad (1)$$

Two things can be observed from equation (1) that the Doppler shift is proportional to the projected velocity v to the plane orthogonal to the optical axis, and it is independent from the detection angle θ . This equation assumes for the case when the reflected beam follows mostly along the direction of angle θ .

3. EXPERIMENT AND RESULTS

In the experiment, both a standard tangential LDV and an off-axis differential LDV were used to collect a measurement dataset from 4 different samples representing: rough, glossy and mirror-like surface at 3 different frequencies of 100, 200 and 300 Hz. The samples are: aluminum - (surface roughness $R_a \sim 0.3 \mu\text{m}$), retroreflective tape - ($R_a \sim 12 \mu\text{m}$), polished steel ($R_a \sim < 0.1 \mu\text{m}$), and silicon (mirror-like surface) as shown in Figure 3a. To validate the measurement accuracy, a single point axial LDV (from Sunny Instruments Singapore) was used. An electrodynamic shaker (SmartShakerTM from ModalShop, Inc.) was used to provide the vibrational in-plane motion of the sample which is attached to a short cantilever (about 4.5 cm long) by means of double-sided glue tape.

The experimental setup with off-axis differential LDV is shown in Figure 3b. In this setup, it is assumed that the incident beam from axial LDV is along the *outplane* velocity of the cantilever, hence the measured Doppler shift f_{Do} is given as followings:

$$f_{Do} = 2 \frac{v}{\lambda} \quad (2)$$

Therefore, to compare the axial LDV results with those of differential LDVs, the correction factor must be of $\sin(\beta/2)$ and $\cos(\alpha)$ must be applied to (2) to arrive at (1). In the case of standard in-plane LDV, there is only one correction factor of $\sin(\beta/2)$ with β is about 14.5 degree, since $\cos(\alpha) = 1$. For the case of off-axis method, there are two correction factors: $\sin(\beta/2)$, similar to that of standard method, and the other one is $\cos(\alpha)$, with α is about 26 degree from the normal vector $\mathbf{n}$ of the sample surface. Subsequently, the difference between the axial and differential LDVs results were computed to get the error of the measurements as presented in Figure 4.

Figure 3 (a) Left: The samples in the experiment from left-top clockwise direction: aluminum, retroreflective tape, silicon, polished steel. (b) Right: Experimental setup for the off-axis differential LDV method.

Figure 4 shows the results measured by the two methods, namely: standard in-plane LDV and off-axis differential LDV methods for the four different samples at three different frequencies.

Figure 4 (a) Left: Results from standard in-plane LDV, (b) Right: results from off-axis LDV.

In the results from Figure 4a, only the result from sample aluminum and retro-tape are presented with the error less than 10% of the velocity measured by the axial LDV. The results from polished steel and silicon are not available as they are not detectable by the in-plane detector (the photodetector are not lit up, as indicated by the modulation control box of the system).

Meanwhile, the results from Figure 4b, firstly with the off-axis method, it can be confirmed that it can detect the signal well from all the four samples. Secondly, for the other first three samples, they show consistent trends with error less than 4% for frequency 100 Hz, 23 % for frequency 200 Hz, and 10% for frequency 300 Hz. The result for silicon sample has less error about 8% and 6% at 200 Hz and 300 Hz respectively.

Figure 5 (a) Top-Left: Steel sample measured by standard in-plane LDV, (b) Top-Right: Steel sample measured by off-axis LDV, (c) Bottom-Left: Silicon sample measured by standard in-plane LDV, (d) Bottom-Right: Silicon sample measured by off-axis LDV.

In this experiment, there some factors that contributed the errors in off-axis measurements, those are: the environment noise, generated by the shaker which shared the same table as the LDV system. Secondly, it is observed that there is an outplane component perpendicular to the in-plane motion (the vibration is not in pure in-plane) at particular frequency (e.g. 200 Hz), and the off-axis setup may detect more sensitively in comparisons to the standard in-plane LDV. Thirdly, poor repeatable setup that occurs when the sample is replaced to another one by means of glue.

4. CONCLUSIONS

In this work, a new method to measure in-plane vibration of specular surface has been reported. The method is able to detect the vibration of specular object including mirror-like surface with good signal-to-noise ratio (SNR) in the result.

The method is based on an off-axis differential LDV in which the detector is decoupled and placed along the dominant direction of the scattered light off the sample. Unlike a standard in-plane LDV, this method can measure samples with rough surface as well as specular surface including mirror-like surface such as silicon, an important material in semiconductor industry. Further works are required to understand the source of errors reported in the experiments, to improve the design to obtain more accurate results, and to experiment with wider range of frequencies.

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