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# Multi-point laser coherent detection system and its application on vibration measurement

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## ABSTRACT

Laser Doppler vibrometry (LDV) is a well-known interferometric technique to measure the motions, vibrations and mode shapes of machine components and structures. The drawback of commercial LDV is that it can only offer a point-wise measurement. In order to build up a vibrometric image, a scanning device is normally adopted to scan the laser point in two spatial axes. These scanning laser Doppler vibrometers (SLDV) assume that the measurement conditions remain invariant while multiple and identical, sequential measurements are performed. This assumption makes SLDVs impractical to do measurement on transient events. In this paper, we introduce a new multiple-point laser coherent detection system based on spatial-encoding technology and fiber configuration. A simultaneous vibration measurement on multiple points is realized using a single photodetector. A prototype16-point laser coherent detection system is built and it is applied to measure the vibration of various objects, such as body of a car or a motorcycle when engine is on and under shock tests. The results show the prospect of multi-point laser coherent detection system in the area of non-destructive test and precise dynamic measurement.

**Keywords:** Multi-point laser Doppler vibrometer, spatial-encoding, transient measurement, vibration analysis.

## 1. INTRODUCTION

Vibration is mechanical oscillations about an equilibrium point. It exists in almost every machining progress in today's industry. Conventional vibration test technique involves accelerometers or velocimeters in electric capacity or piezoelectric domain as vibration sensors in bulky structure measurement. However, these contact-type sensors have several disadvantages in high precision testing. With the development of optics and laser technology, laser Doppler vibrometry (LDV) became a popular non-contact vibration measurement technology [1]. The LDV is based on the Doppler Effect that occurs when the laser light scatter from a moving surface. The instantaneous velocity of the surface is converted to the Doppler frequency shift of the laser light which can be extracted by interference between object and reference beam. To avoid the directional ambiguity problem, the heterodyne as Mach-Zehnder (including one detector and one acousto-optic modulator) and the homodyne as Michelson interferometer (including two detectors and polarization components) are two typical configurations of LDVs. Most of the vibrometric systems offer point-wise measurement; this becomes a main disadvantage of LDVs. In order to measure vibration at different points, a scanning system containing two orthogonal mirrors is normally adopted to move the measurement point rapidly and precisely on testing surface [2]. This approach assumes that the measurement conditions remain invariant while sequential measurements are performed. Hence, it is only suitable to measure steady-state or well-characterized vibrations. However, most engineering applications do not satisfy these requirements. Transients, including impact or coupled vibrations, are commonly observed in real applications. This makes scanning LDVs impractical to generate a vibration image in these cases.

In recent years, several types of multi-channel and multi-point LDVs have been reported [3] by different research groups. This novel idea first appeared in a scientific paper where Zheng [4] proposed a multichannel laser vibrometer based on a commercial single-point Polytec vibrometer and an acousto-optic beam multiplexer. It is still a single point measurement system but with a switch among different channels instead of a scanning mechanism. Now some robust prototypes [5] and even customer-designed commercial products [6] can be found. However, these multi-beam versions are normally a combination of several sets of single-point vibrometer [7], or use multiple detectors or detector array, which still need synchronization. In our previous researches [8-10], we proposed a new method on generating a beam

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array with different frequency shifts, and realized a simultaneous vibration measurement on 20 points using a single photodetector. The results show the advantages of applying the spatially encoded LDV concept for multipoint vibration measurement using a single photodetector. Based on this research output, we developed a fiber-based 16-point laser Doppler vibrometer and used it for various applications of vibration measurements. In this paper, we will focus on this 16-point LDV system and its performance in steady-status and transient vibrations measurements.

## 2. 16-POINT LASER DOPPLER VIBROMETER

In multi-point LDV system, flexibility in measurement is always a concern. The measurement points can be on different surfaces and/or in arbitrary positions. However, the beam array generated by AOMs is a regular 1-D or 2-D pattern. This limits the flexibility of the measurement. Hence, fiber-based configuration will be a good selection in optical design. Figure 1 shows a typical single-point fiber-based LDV system. Laser beam is split by a fiber coupler. The frequency of the object beam is shifted by an AOM and output through a circulator. The adjustable beam expander can focus the laser beam on the object. The reflected beam is collected by the same expander and directed to the third port of the circulator. The object beam and the reference beam are combined by another fiber coupler and sent to the photodetector. The main concern in this system is the directivity of the circulator. A >60dB directivity is necessary. However, when the circulator is polarization maintained, low directivity is feasible. With this basic configuration, the system will be more flexible when measurement is executed.

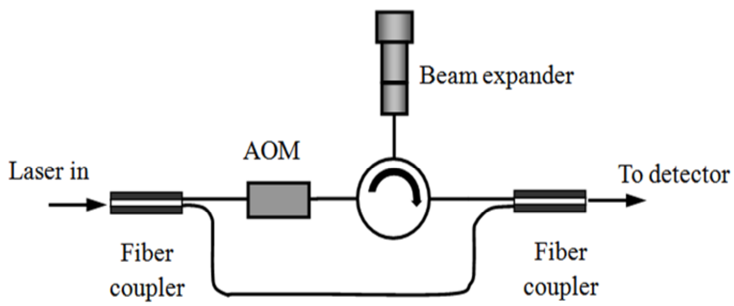


Figure 1. Schematic layout of fiber-based interferometer of each channel

Figure 2 shows the appearance of the 16-point laser Doppler vibration measurement system and the sensing head. The sensing heads are connected with optical system by stainless-steel projected PM fiber. The length of the fiber can be selected from 2m to 10m according to different applications. The standoff distance of each sensing head is from 20cm to 2m. The spot size of laser beam is from 15μm to 150μm. A red laser is applied as an aiming light source. The system is designed for large structure vibration measurement.

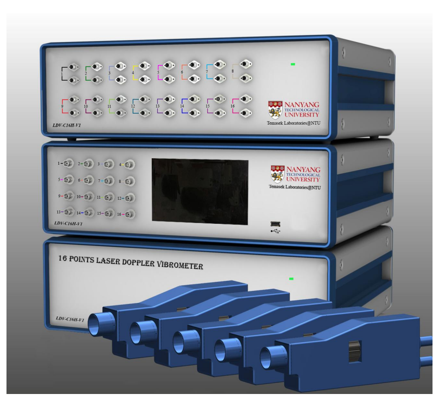


Figure 2. 16-point Laser Doppler vibration measurement system

## 3. APPLICATION 1: CAR BODY MEASUREMENT

The first application shown here is a simultaneous vibration measurement on a car body. Figure 3 shows the fiber-based 16-point laser Doppler vibration measurement system and its measurement on front door of a car. A 642nm laser is used as an aiming light. Figure 4 shows the displacement of 16 measurement points when the rear door is closing. This type of measurement cannot be done by normal scanning LDV, as it is a transient event. Figure 5 shows the displacement of same 16 measurement points when car engine is on. This can be considered as a steady-status vibration and can possible be done by scanning method.

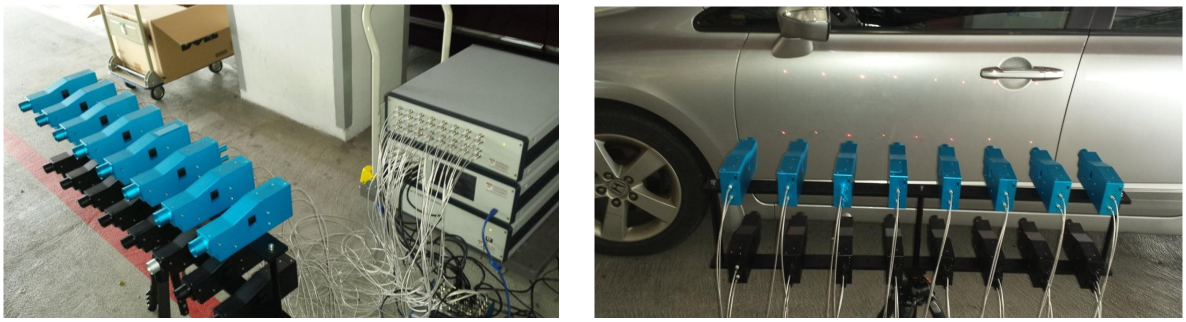

Figure 3. 16-point LDV on car body vibration measurement

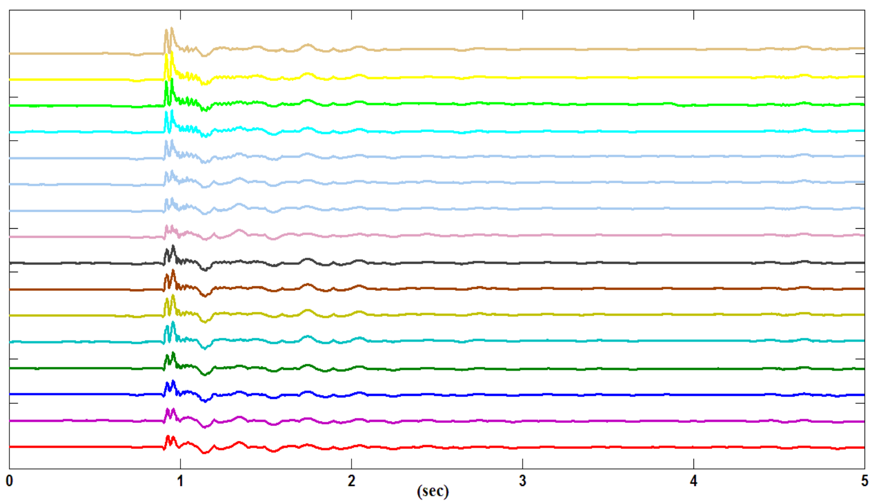


Figure 4. vibration measurement when rear door is closed (Transient event)

## 4. APPLICATION 2: CRACK DETECTION

The structural damage, such as a crack, will lead to a variation in the vibration properties, such as the resonance frequency and mode shape[11]. As a inverse problem, finding the crack location and severity from the change of vibration properties, has attracted the scientific and technical community over the past few decades. Compared with frequency, mode shape is more sensitive to the damage and more robust to environmental conditions, thus is more feasible in practice, but the globally distributed mode shape is more complicated to be measured exactly. The electrical measuring method is most popular, but it is a contact measurement, in which the additional sensor mass restricts density of sensor placing and influences metrical precision. The asynchronous sampling is more sensitive to noise. An instantaneous holistic rigid move of structure or metrical system can be eliminated in synchronous sampling, but probably engender a perturbation in asynchronous sampling. Moreover, unlimited sampling points are unnecessary in respect that the quality of damage detection is not always improved with the increase of sampling in practice [12].

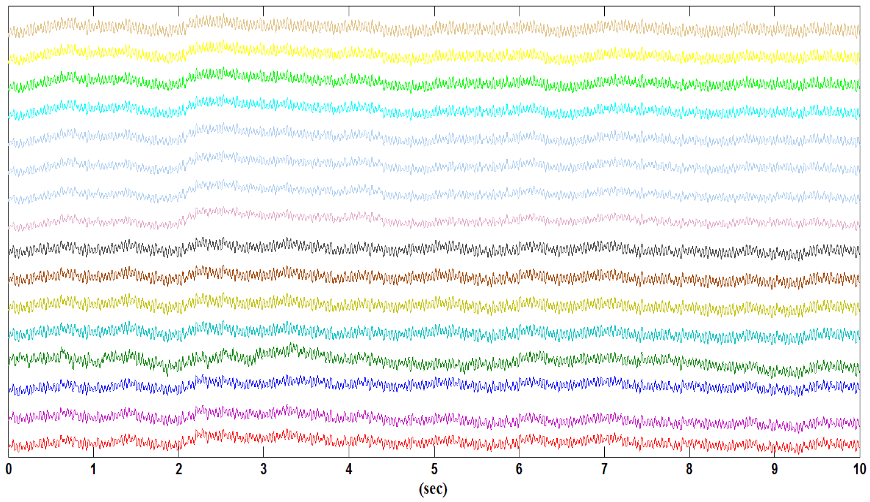


Figure 5. Vibration measurement when engine is on (steady-status vibration)

Our home-developed self-synchronizing multipoint LDV is able to overcome above mentioned disadvantages of SLDV. An experiment is conducted on cantilever beams to validate the feasibility and accuracy of crack detection by the multipoint LDV. An undisturbed and two cracked aluminum cantilever beams with the same dimensions of 270 mm×10 mm×10 mm and material properties are manufactured. An artificial single edge crack with a depth of 4 mm and a width of 0.2 mm is made on each cracked beam, as shown in Fig.6. That means the relative crack depth $\alpha=r/H=0.4$. The cracks on the two beams are at position of 108 mm and 135 mm to the clamping end, respectively, hence the relative crack location $e=l/L$ are respective 0.4 and 0.5. The beam is subjected to an exciting force with sinusoidal configuration by an electro-mechanical shaker at position of 10 mm to the free end. Frequency of the force is the corresponding second resonance frequency of the beam, thus the vibratory response is approximately the second mode shape. Fourteen equal-spaced sample points are measured along the central-line, as shown in Fig.7. The distances of sampling points to the clamping end are $70+(i-1)\times10$ mm, respectively, where $i=1, 2, 3, \ldots, 14$.

The indicator based on spatial derivative of mode shape is testified to be more sensitive to crack than displacement mode shape itself. Hence in the data processing stage, after a cubic spline interpolation applied to the measured 14-point mode shape to enhance the number of sampling points, the curvature of mode shape, which is the second derivative, is extracted by the windowed Fourier transform algorithm. The normalized 14-points mode shapes and their interpolated versions are shown in Fig.8(a) and (b), where the abscissa is the relative location. The left, middle and right columns are intact beam, cracked beam with $e$=0.4 and $e$=0.5, respectively. The curvature is shown in Fig.8(c). Then, the absolute difference of curvature squares before and after the crack appearance is calculated, as shown in Fig.8(d), of which the maximum value indicates the location of artificial crack precisely.

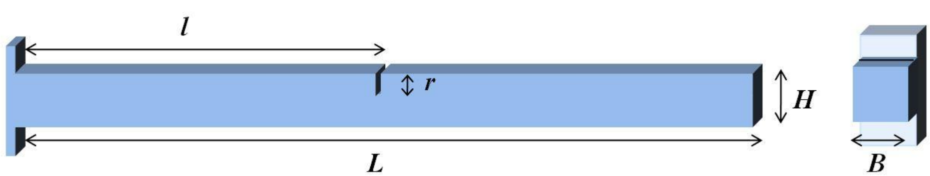


Figure 6. An Euler-Bernoulli cantilever beam model with a single edge open crack

Primarily, the localization depends on the sampling interval. The number of sampling points provided by the proposed LDV is still small. Since the approach to remove cross-talk has been established, the number of measurement points is mainly restricted by the range of frequency and velocity of vibration to be measured. Considering that almost entirely the low-frequency vibration in a small scale is adopted in defect diagnoses, the number of measurement laser beams can be developed to be more. In that case, the inspection performance can be enhanced significantly. Besides, gradually zooming out the searching range is a good solution since the fiber-based system can adjust the spatial interval of measurement points conveniently.

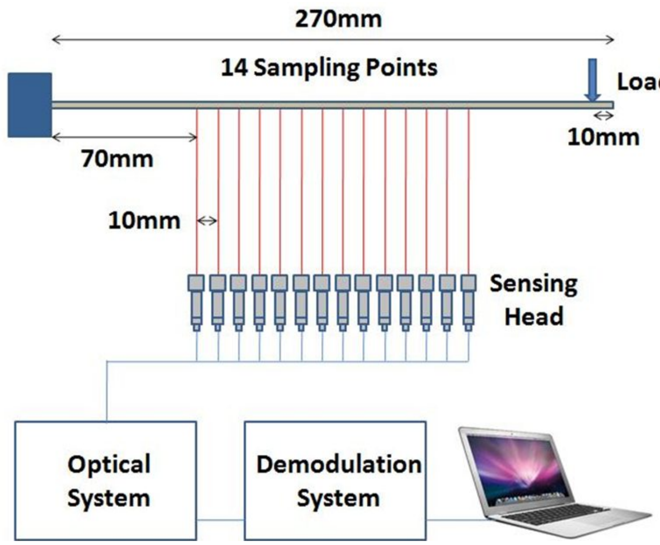


Figure 7. Experimental layout of the vibration measurment

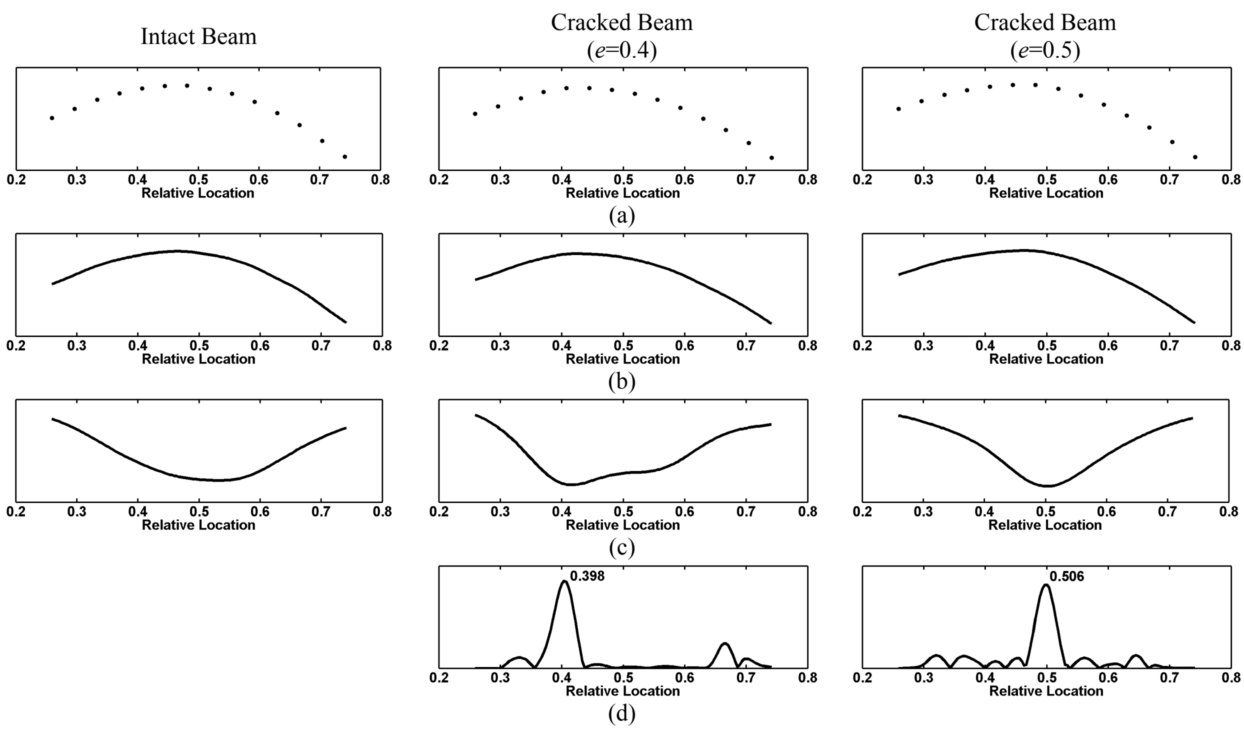


Figure 8. (a) Normalized 14-point mode shapes; (b) Interpolated mode shapes; (c) Curvatures; (d) Absolute difference of curvature squares of the intact and cracked beams.

## 5. CONCLUSIONS

This paper presents several applications of our home-developed laser Doppler vibrometer for steady-status and transient vibration measurement. Several designs are attractive to certain applications: (1) Self-synchronized; (2) flexibility of fiber based system (3) real-time output. The multi-point laser Doppler vibration measurement system has been commercialized by HoloBright (S) Pte Ltd and we hope it can meet the requirements of most industrial applications.

## 6. ACKNOWLEDGEMENT

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