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Multi-beam laser Doppler vibrometer with fiber sensing head

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Abstract. Laser Doppler vibrometry (LDV) is a well known technique to measure the motions, vibrations and mode shapes of structures and machine components. Photodetector-based LDV can only offer a point-wise measurement. However, it is possible to scan the laser beam to build up a vibrometric image. 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 method of generating multiple laser beams with different frequency shifts. The laser beams are projected on different points, and the reflected beams interfere with a common reference beam. The cross-talk among object beams can be bypassed with a proper selection of frequency shifts. A simultaneous vibration measurement on multiple points is realized using a single photodetector. Based on the proposed spatial-encoding technology, a self-synchronized prototype of fiber-based multipoint laser Doppler vibrometer at 1550nm wavelength is developed. An addition red pilot laser is used for aiming purpose. It has the flexibility to measure the vibration of different points on various surfaces. The prototype is used to measure the vibration of different points on a cantilever beam and a plate. The measured results match well with simulation results using finite element method (FEM).

Keywords: Laser Doppler vibrometry, multiple-beam, spatial encoding, fiber, simultaneous measurement.
PACS: 42.25.Gy, 42.79.Jq, 24.62.Cf, 42.25.Kb, 42.82.Bq.

1. INTRODUCTION

Vibration refers to mechanical oscillations about an equilibrium point. It exists in almost every machining processes in today's industry and significantly affects the precision of the surface finish and hence the performance of the fabricated parts. Conventional vibration test technique involves accelerometers or velocimeters as vibration sensors in bulky structure measurement. These contact-type sensors, however, 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 scatters 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 optical interference between object and reference laser beams. Most existing vibrometric systems offer point-wise measurement. In order to measure vibration at different points, an optical system containing two orthogonally scanning 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, 4] by different research groups. This novel idea first appeared in a scientific paper where Zheng [5] proposed a multichannel laser vibrometer based on a commercial single-point Polytec vibrometer and an acousto-optic beam multiplexer. It is still a pointwise measurement but with a mechanism to switch among different channels instead of scanning. Now some robust prototypes [6] and even customer-designed commercial products [7] can be found. However, these multi-beam versions are normally a combination of several sets of single-point vibrometer [8], or use multiple detectors or detector array [3-4, 6-9], which still need synchronization. Recently some simultaneous multi-point measurements [10-12] using one laser source and one detector have been reported in the akin technique ------ Laser Doppler velocimetry, which has widely been used in experimental fluid mechanics area for flow measurement. These

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techniques use at least two acousto-optic devices to generate various frequency shifts at spatially-separated points, and resolve the signals in frequency domain. However, the results presented are limited in the measurement on two or three points, where cross-talk region can be easily separated in the spectrum. The same approach suffers when it is applied in laser Doppler vibrometry, as all object beams will interfere with a common reference beam, and the object beams will also interfere with each other. Resolving the measurement signals from cross-talk region is difficult when the number of measurement points increases.

In our previous researches [13, 14], we proposed a new method on generating a beam array with different frequency shifts, and realized a simultaneous vibration measurement on 20 points using a single photodetector. A 5×4 beam array with various frequency shifts is generated by a 1.55 μm laser and four acousto-optic devices, and illuminating different points of two vibrating cantilever beams. The reflected beams are collected by a pigtailed collimator and interfere with a reference beam. The signal output from a high-speed photodetector is amplified and then digitized by a high-speed A-D convertor with a sampling rate of 1GS/s. The cross talk among twenty object beams can be bypassed in experiment and signal processing stages. The results show the advantages and potential of applying the spatially encoded LDV concept for multipoint vibration measurement using a single photodetector.

In this paper, we focus on the engineering development of a multi-point LDV prototype. A fiber-based four-point LDV has been built for performance testing. It has been applied to do a simultaneous vibration measurement of four points on a cantilever beam and the experimental results are compared with the simulation results obtained by finite element method (FEM). The results show the prototype performs well in simultaneous vibration measurement on any points of different surfaces.

2. MULTI-BEAM LASER DOPPLER VIBROMETRY

2.1 Theory

In a single-beam LDV, a laser beam with wavelength of λ is projected on an object moving with velocity *V*, the shifted frequency f_D of the reflected laser beam is proportional to the velocity of the object due to the Doppler effect, and can be expressed as

$$f_D(t) = \frac{V(t) \cdot S}{\lambda} \tag{1}$$

where $S = e_i - e_o$ is the sensitivity vector given by the geometry of the setup, *S* can be considered as 2 when the illumination and observation are approximately in right angle. In order to avoid the directional ambiguity in frequency shift, the most common solution is the heterodyne interferometer where an optical frequency shift is introduced into one arm of the interferometer by an acousto-optic modulator (AOM) to obtain a virtual velocity offset. The intensity fluctuation at the detector can be expressed as [15]

$$I = I_{DC} + I_{RO} \cos\left(2\pi\left(f_D + f_{AOM}\right)t + \Delta\phi\right) \tag{2}$$

where f_D and f_{AOM} are Doppler frequency shift and carrier frequency introduced by AOM, respectively. $\Delta\phi$ is the phase difference between the reference beam and object beam. The modulation factor I_{RO} is determined by $\sqrt{I_R I_O}$, the product of the square root of object and reference beam intensities. Photodetector will convert the intensity fluctuation to a current signal for later analog or digital decoding.

In this paper, we propose a spatially encoded 4-beam laser Doppler vibrometer. Four laser beams with different frequency shifts are projected onto a vibrating object. The reflected beams interfere with a reference beam. The detected interference signal can be expressed by

$$I = I_{DC} + \sum_{i=1}^{4} I_{M(i)} \cos\left(2\pi\left(f_{D(i)} + f_{AOM(i)}\right)t + \Delta\phi_{(i)}\right)$$

$$+\sum_{m=1}^{3}\sum_{n>m}^{4} I_{mn}\cos\left(2\pi\left[\left(f_{D(m)}-f_{D(n)}\right)+\left(f_{AOM(m)}-f_{AOM(n)}\right)\right]t+\Delta\phi_{mn}\right) \tag{3}$$

where $i = 1, 2, \ldots 4$, m and n are integers; $f_{AOM(i)}$ are the central frequencies of four object beams; The second term is the interference signal between four object beams and reference beam, from which the useful vibration information of four points can be extracted. The third term is the sum of the cross talk between any two object beams, which has to be bypassed when the interference signal is decoded. In order to extract the vibration information of four points from the second term, central frequencies of laser beams have to be elaborately designed so that the useful signals can be separated from cross-talk regions in frequency spectrum or temporal-frequency spectrogram. Once it is achieved, it is possible to extract the vibration information of four points from a single one-dimensional using conventional signal processing algorithms, such as Fourier analysis after digitization; or using analog or digital demodulation system for real-time decoding. The results demonstrated in this paper are processed by LABView of National Instruments (NI) after the signal is digitized by a high-speed digitizer (NI, PXI5154, 8-bit, 2GS/s, 256MB on-board memory) with a rate of 1G sampling points per second.

2.2 Design and Generation of Four Laser Beams

In the proposed spatially encoded laser Doppler vibrometer, a beam array with different carrier frequencies is generated and projected on different points of a vibrating specimen. Obviously it is not reasonable to use one AOM for each channel. Hence, a combination of different types of AOM in Bragg and Raman-Nath regimes [16, 17] with some optical components is proposed to generate a beam array cost-effectively. The details can be found in Refs [13] and [14]. In this paper, we use one pigtailed AOM with 50MHz frequency shift (Brimrose, AMF-50-1550-2FP+) and one frequency shifter in Raman-Nath regime (Brimrose AMF-20-1550, separation angle = 12mrad, RF power tunable, aperture 2mm) to generate a four-point beam array. Fig 1(a) shows the frequency shifts of five laser beams after Raman-Nath AOM. Four beams with -20MHz, 0MHz, +20MHz and +40MHz frequency shifts are selected. Figure 1(b) shows the final frequency shift of selected four beams when the 50MHz pigtailed AOM is connected in series.

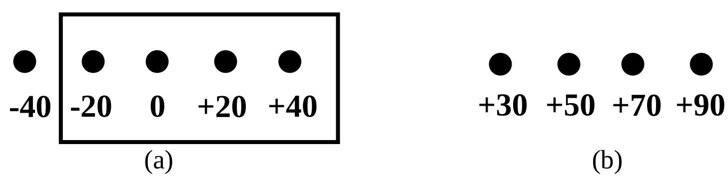


FIGURE 1. (a) Beam array with different frequency shift after Raman-Nath AOM; (b) final frequencies shifted of four beams when a 50MHz pigtailed AOM is connected in series.

The cross-talk between two object beams has to be bypassed when the frequency shifts are designed. In this application, assuming the Doppler frequency shift on each point is within the range of ±3.3MHz (equivalent to ±2.55m/s in velocity when a 1550nm laser is used), the vibration signals on different carriers are limited in the spectrum regions of 30±3.3MHz, 50±3.3MHz, 70±3.3MHz and 90±3.3MHz, and the cross-talk region among twenty object beams are limited in the region of 20±6.6MHz, 40±6.6MHz and 60±6.6MHz. Hence, when the measurement range is set as ±3.3MHz, four signals can be separated with cross-talk regions in spectrum.

3. DESIGN OF FIBER-BASED OPTICAL SYSTEM

In a multi-point LDV system, measurement flexibility is a key concern. There are often requirements for the measurement points to be on different surfaces and/or at arbitrary positions. However, the beam array generated by AOMs is a regular 1-D or 2-D pattern [13,14]. This limits the flexibility of such measurement. To enhance measurement flexibility in this multi-point LDV prototype, we split the various frequency encoded beams and couple them into individual fiber sensing head. Figure 2 shows the equivalent of an individual fiber sensing head to a single point fiber-based LDV system. The laser beam is further split by a fiber coupler 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.

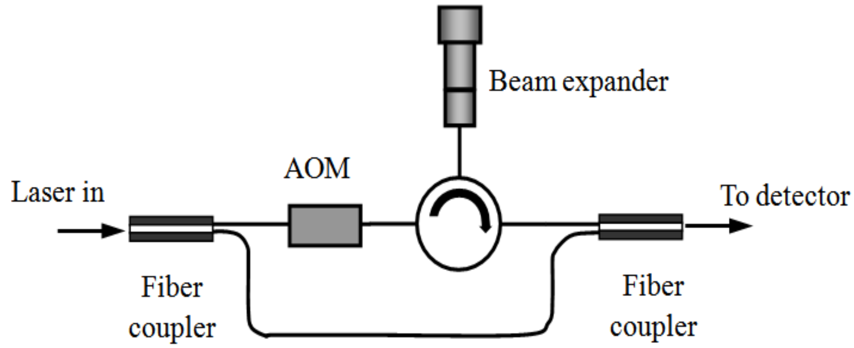


FIGURE 2. Schematic layout of fiber-based interferometer of each channel

Figure 3 shows the schematic layout of our 4-point LDV system. Four fiber sensing heads are connected with the main optical system and focus the laser beams on different points of various surfaces. The wavelength of laser for measurement is in C-band (1550nm). As it is invisible, a 650nm pilot laser is used for aiming. Hence, the sensing head is achromatic for both wavelengths. A 4-channel demodulation system will be connected to the optical system for real-time decoding.

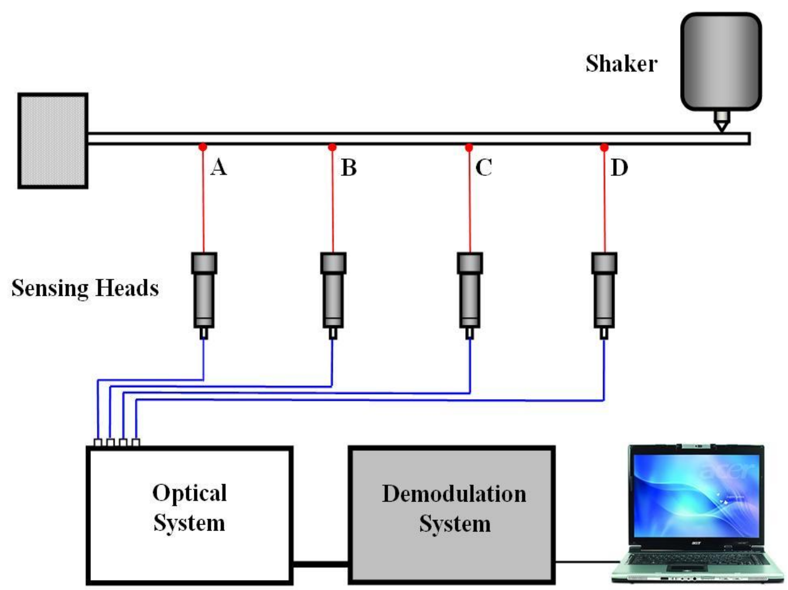


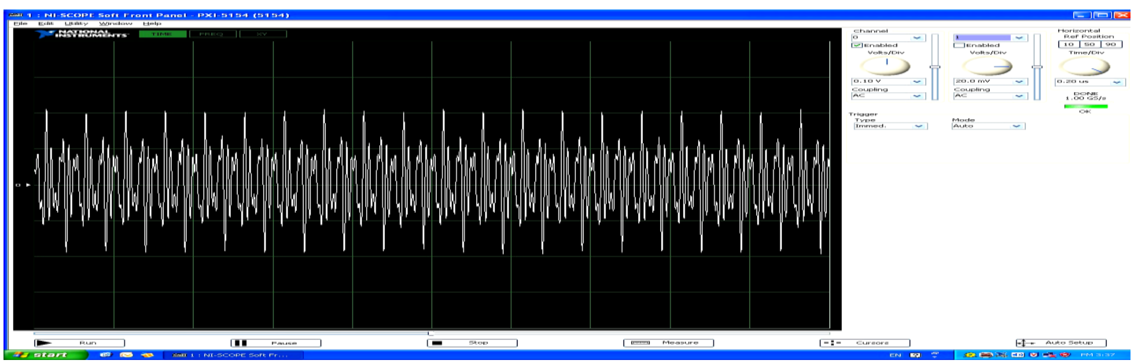
FIGURE 3. Schematic layout of four-point laser Doppler vibrometer

4. MEASUREMENT RESULTS AND DISCUSSION

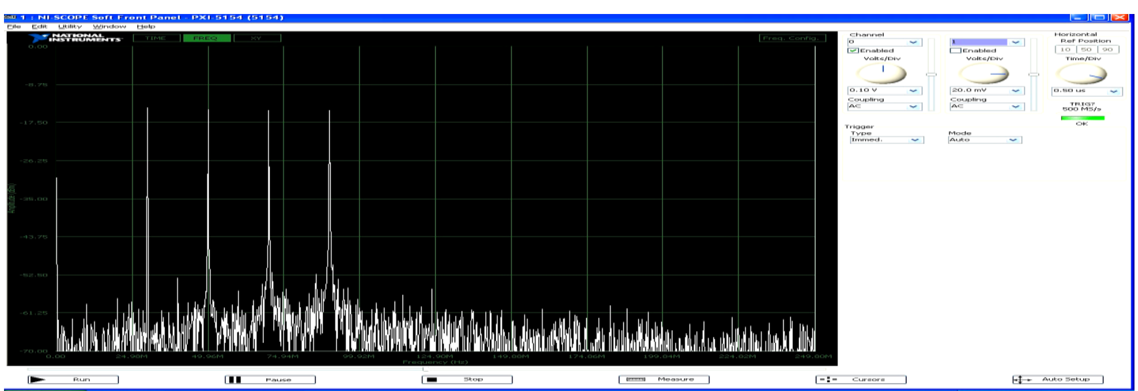
Figure 3 shows the schematic layout of the experimental setup. An aluminum cantilever beam is excited by a shaker at the position of 10mm to the free end. The length, width and thickness of the cantilever beam are 270mm, 20mm and 4mm, respectively. Four points (point A, B, C and D) on the beam are measured. The distances of these four points to the clamping end are 50mm, 100mm, 150mm and 200mm, respectively. The stand-off distance of sensing head is around 1.5m. Considering the laser safety of human eyes, the power of measurement laser (1550nm) emitted from each sensing head is capped at around 3mW, and the power of red pilot laser (650nm) is around 0.2mW. The results presented in this paper are obtained by computer-based demodulation system. The signal is digitized by a high-speed digitizer (NI, PXI5154, 8-bit, 2GS/s, 256MB on-board memory) with a rate of 1G sampling points per second, and processed by NI PXI-8108 embedded controller.

Figure 4(a) shows the digitized signal captured by the photodetector. The spectrum of this signal is shown in Fig. 4(b). Four peaks at 30MHz, 50MHz, 70MHz and 90MHz are observed. Lower peaks of cross-talk signals at 20MHz, 40MHz and 60MHz are also observed. Band-pass filters are applied at 30MHz±3MHz, 70MHz±3MHz, and 90MHz±3MHz.

Figure 5(a) shows the vibration amplitude, frequency and relative phase direction obtained at point A, B, C and D when the exciting frequency is 1400Hz. It can be observed that point B is very close to a nodal point, as the amplitude is quite low compared with other three points.



(a)



(b)

FIGURE 4. Signal in (a) time domain and (b) frequency domain

In order to generate comparative results, Finite Element method (FEM) software ANSYS is used to simulate the cantilever beam under different excitation frequencies. The material properties of the beam have been tested before simulation. The Beam188 element is chosen in the analysis. It is a linear (2-node) or a quadratic beam element in 3-D and has six or seven degrees of freedom at each node. Figure 5(b) shows the vibration shape of the cantilever beam with 1400Hz excitation frequency. Two nodes are found at 104nm and 186mm from the fixed end. The points at the left and right sides of the node will have different direction of vibration. Figure 5(c) shows the simulated vibration amplitude of points A, B, C and D. Compared with the experimental results, the overall error is within 10%.

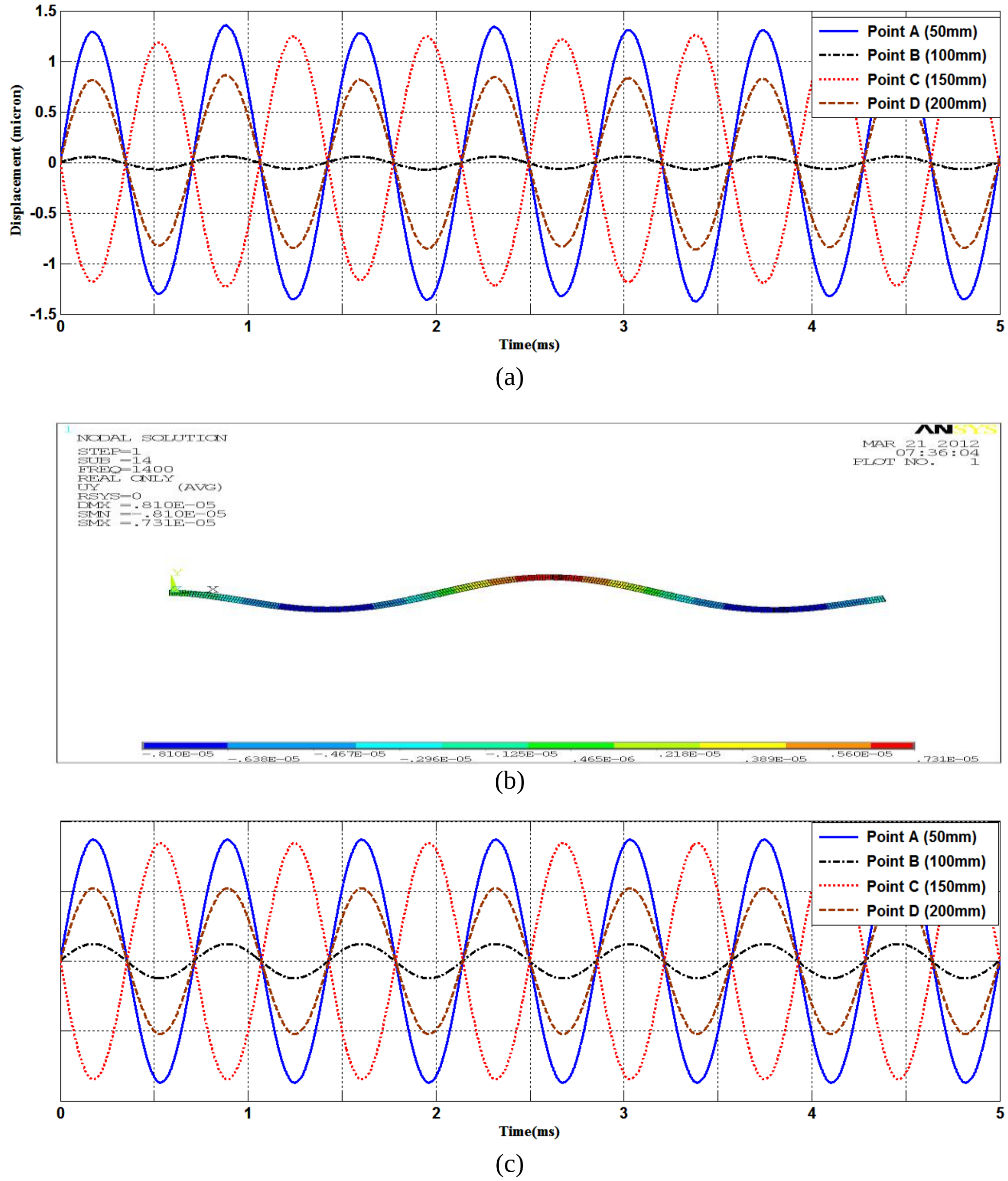


FIGURE 5. (a) Vibration measurement results of points A, B, C and D on cantilever beam using four-point LDV system; (b) FEM simulation result using ANSYS; (c) The simulated vibration on points, A, B, C and D.

5. SPECIFICATIONS OF THE SYSTEM

The proposed multi-point laser Doppler vibrometer has been commercialized by LightHaus Photonics Pte. Ltd., Singapore. The specifications of the system are listed as follows:

(1)	Number of measurement point:	4, 8, 16 or 32.
(2)	Laser used:	Single frequency diode laser (1550nm, eye-safe); Visible aiming laser (650nm, Class II).
(3)	Stand-off distance of sensing head:	0.05m – 20m (depend on object surface and the size of sensing head)
(4)	Length of fiber:	2m, 5m, 10m;
(5)	Velocity measurement range:	30mm/s or 2.5m/s
(6)	Frequency measurement range:	1Hz-100kHz (real-time measurement) 4Hz-100MHz (post-processing by computer)
(7)	Decoding system:	Analog or digital (real-time output) Computer post-processing (for high frequency measurement)
(8)	Velocity resolution:	1µm/sec (analog decoder); 0.1µm/sec (digital decoder)
(9)	Data communication:	USB interface or 16-bit wireless (>30m)
(10)	Power supply:	110V-240V, 50Hz-60Hz
(11)	Software:	Windows-based interface for display, analyze and record results.

6. CONCLUDING REMARKS

In this paper, we present a four-point laser Doppler vibrometer with a new technology ------ spatial encoding technology. Only one high-speed photodetector is used to capture the signal that contains vibration information of four points. Compared to a scanning laser Doppler vibrometer and multichannel LDVs using detector array, the proposed technique has an advantage in simultaneous measurement of transient events with a relative simple setup. The optical system is mainly integrated by fiber components. The pigtailed fiber sensing heads ensure the flexibility of the measurement. The laser of 1550nm wavelength is used for measurement, while a laser of 650nm is applied as a pilot laser for aiming. Hence the optical system is designed for two wavelengths. The measurement results coincide with those from FEM simulation. The specifications of the proposed system can meet the requirements of most industrial applications.

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