Research on high-temperature vibration measurement method using laser Doppler interferometry

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Abstract: High-temperature vibration measurement plays a critical role in the design and performance testing of equipment such as aero-engine and heavy-duty gas turbines. Due to its non-contact, high accuracy, and resolution, the laser Doppler method has become one of the most commonly used vibration measurement techniques. However, one of the main problems in high-temperature vibration measurement is that the surface of the measured objects is oxidized, thus resulting in a decrease of interference signal intensity and signal-to-noise ratio. Furthermore, the aforementioned may even cause measurement failure. In this paper, an all-fiber laser Doppler velocity measurement device using a fiber optic circulator is established. Its vibration measurement performance is experimentally validated at high temperatures. The results demonstrate that this device can achieve vibration measurement within the temperature range of 300°C-1200°C with a maximum vibration speed of 1 m/s and maximum vibration acceleration of 378.4 m/s². Relative deviation with Polytec vibrometer’s velocity results is within 1.95%. This model provides a viable solution for achieving accurate measurements of high-temperature vibration.

1. Introduction

High-temperature vibration measurement has received much attention in recent years due to its important applications in many fields. It is important for dynamic performances evaluation and tests conducted during the development and design process of major equipment, such as aero-engines, heavy-duty gas turbines, and coal-fired gas furnaces. Uludamar et al. analyzed the factors that cause vibration and noise in the engine created by the combustion of fuel in the combustion chamber. Moreover, the
The author studied related solutions to prevent their adverse effects\textsuperscript{[1-3]}, Gökhan observed that vibration has become one of the most important problems of diesel engines due to its direct relations with the fuel properties\textsuperscript{[4]}. LI et al. observed that the resonant frequency of the micro-cantilever decreases as the temperature increases. This research offers important guidance and reference for the design of MEMS (Micro-Electro-Mechanical-System) devices used in the high-temperature environment\textsuperscript{[5,6]}. According to the research of DAI J B et al., the natural frequency of engine turbine blades decreases with an increase in temperature. Moreover, the blade tip vibration shape becomes slightly distorted due to thermal stress\textsuperscript{[7]}. Contrary to the relatively complete development of room temperature vibration measurement technology, high-temperature vibration measurement is subjected to many difficulties due to the limitations of excitation, measurement equipment, and test methods\textsuperscript{[8]}. For example, due to air friction, the surface of a super-high-speed aircraft may reach 600℃-2000℃\textsuperscript{[9]} during the flight. Therefore, it is necessary to develop high-precision high-temperature vibration measurement methods.

Currently, the commonly used high-temperature vibration measurement methods are mainly the contact measurement technology utilizing the acceleration sensor and the non-contact measurement method employing the laser Doppler technology\textsuperscript{[8]}. Since the operating temperature of a high-temperature sensor is generally within the range of 80℃-200℃, conventional force sensors cannot be used in high-temperature environments. Craig A. Stephens et al. used PCB 218C sensor with the highest working temperature of 204℃ in the thermal modal test of a C/SiC elevator\textsuperscript{[10]}. The volume, weight, and installation method of the sensor have a significant impact on the original characteristics of the measurement structure\textsuperscript{[8]}. Wu D F et al. used ceramic stealth rods to install the acceleration sensor outside the heating zone and conduct the vibration test of hypersonic aircraft structure under the temperature range of 200℃-1200℃\textsuperscript{[11,12]}. On the other hand, as one of the most widely used vibration measurement techniques today, laser Doppler interferometry has great advantages of non-contact, high resolution, large speed range, and fast response. LI X K et al. built a high-temperature vibration system using OFV-534 produced by Polytec. The authors measured the MEMS micro-components at a high temperature of 500℃\textsuperscript{[6]}. DAI J B et al. carried out a three-dimensional model simulation of turbine blades. Moreover, the authors analyzed the hot-model of turbine blades with the temperature range from room temperature to 900℃ using three laser Doppler vibrometers\textsuperscript{[7]}. A classic laser vibrometer composed of He-Ne laser and discrete optical components is not suitable for measuring high-temperature vibration for the interference signal’s intensity. Furthermore, SNR (signal-to-noise ratio) decreases sharply when the temperature increases to a certain level. Moreover, with the rapid development of high-temperature devices and materials, the increasing structural complexity and precision demand brought about many difficulties to actual vibration measurement applications.

In this paper, a set of high-temperature vibration measurement systems using an all-fiber laser Doppler Vibrometer is presented. The vibration measurement tests are completed within the temperature range of 300℃-1200℃. The results are experimentally validated by employing a maximum vibration speed of 1 m/s and a maximum vibration acceleration of 378.4 m/s\textsuperscript{2}. The relative deviation with the Polytec vibrometer’s velocity results is within 1.95%. This model offers a viable alternative non-contact method of high-temperature vibration measurement.

2 Materials and methods
2.1 Laser Doppler principle

Laser Doppler vibrometer is based on the principle of the Doppler effect. In Figure 1, a classic heterodyne interferometer is shown. The light emitted by a He-Ne laser (with the frequency \(f\)) is divided into two beams by the polarization beam splitting prism 1: the measurement light and reference light. The reference beam is modulated by an acoustic-optic modulator with a driving frequency of 40 MHz, and the output frequency is \(f\pm40\) MHz. The measuring light reaches the surface of the vibrating object to cause diffuse reflection. The frequency of the reflected light changes by \(\Delta f\) due to the velocity, where \(\Delta f\) is the Doppler frequency shift. The reference light and the measurement light interfere passing the polarization beam splitter 3, when the frequency is 40 MHz\(\pm\Delta f\). The vibration speed can be obtained according to the relationship between the Doppler frequency shift and the vibration speed \(\Delta f = \frac{2V}{\lambda}\).

![Figure 1. The measurement principle of heterodyne laser Doppler velocity](image)

When measuring vibration under high temperatures, the main problem that traditional heterodyne laser vibrometers face is that the measured target is oxidized or even becomes red at high temperatures. This seriously affects the intensity and quality of the measured return light, particularly because He-Ne laser with lower power is employed as the light source in a traditional system. Consequently, a reduction in the SNR of the interference signal occurs. More significantly, demodulation failure or loss of the interference signal may occur. Therefore, the aforementioned problem has to be investigated by increasing the laser power, improving the interference efficiency, or via similar methods.

2.2 Methods and experimental investigation

In this paper, a set of all-fiber photon Doppler vibration measurement systems based on the structure of the Fizeau interferometer is established to adapt to the high-temperature vibration measurement. These systems are shown in Figure 2.
This vibration measurement is carried out using the homodyne interference principle. The light from the fiber diode laser enters the circulator. At port 2, part of the light is reflected by the end face of the fiber probe. This light is called the reference light, and the transmitted part of the light is reflected on the surface of the measured object. The other part of the reflected light returns to port 2. Then, it interferes with the reference light. Amplitudes of the reference light and measurement light can be described as follows\(^\text{[13,14]}\):

\[
E_1 = E_{10} \exp \left\{ i \left[ \omega_1 t + \varphi_1 (t) \right] \right\} \quad (1)
\]

\[
E_2 = E_{20} \exp \left\{ i \left[ \omega_2 t + \varphi_2 (t) \right] \right\} \quad (2)
\]

where \( \omega_1 , \varphi_1 , \omega_2 , \) and \( \varphi_2 \) represent the angular frequency and phase of the reference light and the measurement light in Eqs. (1) and (2), respectively.

The amplitude of the interference light is the sum of \( E_1 \) and \( E_2 \):

\[
E = E_1 + E_2 \quad (3)
\]

According to the square-law detection principle of the detector, the light intensity of the interference light \( I \) can be expressed as:

\[
I = E^2 = \frac{1}{2} (E_1^2 + E_2^2) + E_1 \cdot E_2 \cos \left( \omega_1 t + \varphi_1 - \omega_2 t - \varphi_2 \right) \quad (4)
\]

The difference between the angular frequency of the reference light and the measurement light corresponds to the Doppler shift \( \Delta f \). If the intensity of the reference light is \( I_1 \), then the intensity of the measurement light is \( I_2 \). Therefore, the total intensity of the interference light is equal to:

\[
I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \cos \left( \frac{2\pi}{\lambda} \cdot \Delta f + (\varphi_1 - \varphi_2) \right) \quad (5)
\]

The photodetector converts the light intensity signal into an electrical signal output. Since the value of \( \Delta f \) can be obtained, the corresponding vibration velocity can be modulated from \( \Delta f \):

\[
v(t) = \frac{\Delta f \lambda}{2 \cos \theta} \quad (6)
\]

In Figure 2, the all-fiber interference high-temperature vibration measurement system designed based on the aforementioned principles is shown. The center wavelength of the light source used in this device is 1550 nm. Thus, the influence of red light generated by the target under high temperatures can be effectively avoided. The line width of the laser is less than 100 kHz, and the power is 20 mW. The
fiber circulator and other components applied in the system are of single-mode types. Thorlab APD430C/M photodetector is used for the device. In addition, to collect more reflected measurement light, a fiber zoom collimation probe with a large-aperture was designed. Then, the all-fiber laser Doppler interferometer was built, which is shown in Figure 3.

![Figure 3. All-fiber laser Doppler interferometer for high-temperature vibration measurement](image)

A high-temperature vibration measurement system based on the previously described all-fiber laser Doppler interferometer is established (Figure 4). The vibration exciter adopted in our system is B&K 4808 with the vibration frequency range of 5 Hz-10 kHz. The target to be tested is fixed on the vibrating table surface by settling. To minimize the impact of high temperature on the vibrating table during the test, a ceramic adapter block is used to connect the alloy steel column and the vibrating table surface. Moreover, the electromagnetic induction heating method shown in Figure 5 is adopted. The high-temperature vibration measurement performance of the fiber laser vibrometer is validated by comparing the velocity results with the Polytec OFV-400 interferometer. It should be pointed out that, since the stability and intensity of the interference signal decrease in temperatures higher than 750°C, the OFV-400 interferometer is not suitable for high-temperature vibration measurements. Thus, the OFV-400 interferometer is employed to measure the surface of the vibration exciter. In addition, the all-fiber interferometer is employed to measure the end face of the alloy steel column sample. Since the measuring points of the two interferometers are different, it is necessary to measure the initial difference of the two interferometers before the high-temperature vibration test. This will serve as a reference for calculating the speed deviation in the subsequent test.
2.3 Signal modulation method

The main problem of the proposed device is that the direction of the velocity cannot be obtained directly from the velocity signal demodulation result as a result of the homodyne laser Doppler interference principle. Therefore, it is necessary to do speed reversal processing during the vibration demodulation procedure, as shown in Figure 6. However, the obtained speed signal often contains a significant amount of noise such as peak noise appearing near the inflection point. This results in inaccurate evaluation at the inflection point position. Thus, significant interference and measurement errors may be obtained. As
a result, a speed signal automatic reversal method is proposed. The method is based on the autocorrelation detection frequency estimation method and initial phase estimation method. Cross-correlation is utilized combined with the least square principle. Hence, local optimization and automatic flip of the homodyne photoelectric signal modulated by simple harmonic vibration are achieved. The specific processing process is shown in Figure 7.

![Figure 6. The velocity signal reversal of a homodyne interferometer](image)

![Figure 7. The velocity signal reversal processing algorithm](image)

3 Results
The vibration measurement experiment in the temperature range of 300°C-1200°C and the frequency response tests were completed. The results indicate that the all-fiber vibration interferometer proposed in this paper can achieve a maximum measurement speed of 1 m/s with the amplitude linearity of the speed sensitivity of 0.43% and maximum vibration acceleration of 378.4 m/s². According to Figure 8, the absolute deviation of the speed measurement is within 19 mm/s while the relative deviation is less than 1.95%. The frequency range of 0-2 kHz can be achieved in the test with the results described in Figure 9.
Figure 8. Relative speed deviation for the temperature of 300°C-1200°C

Figure 9. Frequency response measurement results for the temperature of 600°C and 1200°C

4 Conclusions and outlook
The proposed all-fiber laser Doppler interferometer showed a good performance in periodic vibration measurement for the temperature range of 300°C-1200°C and frequency response range of 0-2 kHz. This paper represents a preliminary exploration of high-temperature vibration measurement based on fiber circulator interference and laser Doppler principle. The experimental foundation for the high-temperature vibration measurement in aeroengine and other fields is provided.

In future works, more research will be focused on the improvement of methods, fiber probe optimization, and environmental compensation. Moreover, eliminating the zero drift of the homodyne
interferometer and random vibration measurement under complicated environments with higher temperatures will be also investigated. The heterodyne interferometry is significant for avoiding the zero drift. Therefore, to achieve direction discrimination and to obtain higher anti-interference ability, future investigations may concentrate on the inquiry of heterodyne all-fiber photon Doppler, as shown in Figure 10.

Figure 10. Principle of an all-fiber laser Doppler heterodyne interferometry

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