A Novel Low Frequency Vibration Measurement Method Based on Single Camera

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Abstract. In recent years, low frequency vibration measurement is being widely concerned in many applications, because low frequency vibration usually introduces a strong influence. The low frequency vibration is commonly measured by the laser interferometry, requiring a complicated system and a high cost laser interferometer, and its flexibility in field vibration measurement is poor; or the method using vibration transducer, requiring a transducer with known sensitivity, and its measurement precision is not high. In this paper, we propose a novel method based on single camera, which achieves low frequency vibration measurement via collecting and processing sufficient frame sequence images. The proposed method is compared with the heterodyne interferometry by measuring the vibration displacements of a long-stroke shaker simultaneously. Experimental results show the proposed method realizes <1% vibration displacement measurement precision at frequencies between 0.05 Hz-5 Hz.

1. Introduction
Low frequency vibration measurement is widely used in the applications of precision manufacturing, seismic monitoring, precision calibration, etc [1, 2]. The inaccurate vibration measurement will result in a significant influence on these applications, and further decreases their reliability. Therefore, it is significant to take a research on low frequency vibration measurement.

The heterodyne interferometry with a heterodyne laser interferometer is usually used to measure low frequency vibration because of its high-precision displacement measurement [3]. However, the laser interferometer price is high, and its measurement system is usually complicated, which decreases its flexibility in field vibration measurement. Although the method using vibration transducer has the advantages of low cost and high flexibility, its measurement precision is affected by the sensitivity calibration precision and measurement range of this transducer.

The measurement method with a single camera has the advantages of briefness, flexibility, efficiency, etc [4]. Therefore, we propose the method based on single camera to measure low frequency vibration by the collection and processing of vibration sequence images. Furthermore, this method is easily implemented by a simple measurement system with a low frame rate camera, its flexibility is high, and its price is usually low cost.

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2. The vibration measurement principle based on single camera

Figure 1 shows the sketch of low frequency vibration measurement system based on single camera. The horizontal long-stroke shaker provides low frequency vibration. The feature mark is fixed on the shaker working surface, making a feature edge that has the same vibration with the working surface is existed, as the red dotted line shown in figure 1. The camera is fixed above the working surface, which records the working surface vibration by collecting sequence images during its vibration, and the camera optical axis is perpendicular to the working surface. The computer stores and processes the collected sequence images.

![Sketch of low frequency vibration measurement system based on single camera.](image)

The long-stroke shaker is actuated by the standard sinusoidal signal, and thereby the working surface vibration is sine. We use the camera to collect the sufficient frame sequence images which accurately reflect the spatial vibration displacement characteristics of the working surface.

Additionally, the calibration of camera had been completed before the vibration measurement [5, 6], i.e., the relation between the pixel coordinates on the image and the corresponding world coordinates were established. The Zernike moment sub-pixel edge detection method described in [7] was used to detect the feature edges of the collected sequence images.

We specify the 1th frame image feature edge position as the reference zero displacement, and afterwards calculate the displacements between the subsequent frame images and the 1th frame image. Take the calculation of the displacement between the i th frame image and the 1 th frame image for example, we select the midpoint \((u_{i,0}, v_{i,0})\) of the i th frame image feature edge and its perpendicular point \((u_{i,p}, v_{i,p})\) on the 1 th frame image feature edge. Then we obtain their corresponding world coordinates \((x_{i,0}, y_{i,0})\) and \((x_{i,p}, y_{i,p})\) by the camera calibration established relation. Finally, we take the related distance calculated by formula (4) as the spatial vibration displacement between the i th frame image and the 1 th frame image.

\[
d_i = \sqrt{(x_{i,0} - x_{i,p})^2 + (y_{i,0} - y_{i,p})^2}
\]

(1)

where \(i = 0, 1, \cdots, N-1,\) and \(N \geq 5.\) Because the working surface vibration displacement is sine, the sine approximation method (SAM) described in [8] was used to fit the measured displacements \(\{d_i\}\), as follows:

\[
d_i = A\cos(\omega_s t_i) - B\sin(\omega_s t_i) + C t_i + D
\]

(2)

where \(\omega_s\) is the vibrational angular frequency, \(t_i\) is the sampling time. Parameters \(A, B, C,\) and \(D\) can be calculated by solving the over-determined equations that consist of \(N\) equations shown in formula (2) based on the least squares method. Thus we get the working surface vibration displacement peak
by the following formula:

\[ s_{p,V} = \sqrt{A^2 + B^2} \]  

(3)

3. Experimental results

To validate the precision of the proposed method for low frequency vibration measurement, we set up the low frequency vibration measurement experimental system according to the sketch shown in figure 1. This system is composed of an ESZ185-400 air bearing long-stroke shaker (maximum vibration displacement 360 mm and frequency range 0.05 Hz-5 Hz), an AVT Manta G-125B camera (maximum resolution 1292x964 pixels and maximum frame rate 30 fps). Additionally, a Polytec OFV-5000 heterodyne interferometer for laser interferometry whose measurement precision can be ensured to be better than 0.1%, was also used to measure the same low frequency vibration.

The shaker working surface produced different vibration displacements at different frequencies, and the camera with different frame rates (satisfy Nyquist sampling theorem) collected 60 frame sequence images during the working surface vibration. The detected partial frame sequence images feature edges were shown in figure 2, at frequency 0.5 Hz.

![Figure 2](image_url)

*Figure 2. The detected partial frame sequence images feature edges.*

Figure 3 shows the vibration displacements at frequency 0.5 Hz measured by the proposed method (frame rate 10 fps) and the heterodyne interferometry, respectively. The solid red circles shown in figure 3 were the measured vibration displacements relating to each frame images.

![Figure 3](image_url)

*Figure 3. The vibration displacements measured by the proposed method and the heterodyne interferometry, at frequency 0.5 Hz.*

Table 1 lists the vibration displacement peaks measured by the proposed method and the heterodyne interferometry at different frequencies. The results of the proposed method were consistent with those of the heterodyne interferometry. In the frequency range from 0.05 Hz-5 Hz, the calculated \( RE \)
according to formula (4) were less than 0.544%.

\[
RE = \left( \frac{s_{p,v} - s_{h,l}}{s_{p,l}} \right) \times 100\%
\]

(4)

where, \(s_{p,l}\) is the vibration displacement peak measured by the heterodyne interferometry at the same frequency.

| Frequency (Hz) | The proposed method (mm) | The heterodyne interferometry (mm) | \(RE\) (%) |
|---------------|--------------------------|-----------------------------------|---------|
| 0.05          | 179.95                   | 179.60                            | 0.195   |
| 0.08          | 169.99                   | 169.07                            | 0.544   |
| 0.1           | 157.30                   | 156.80                            | 0.319   |
| 0.2           | 130.13                   | 129.88                            | 0.192   |
| 0.4           | 100.26                   | 100.58                            | -0.318  |
| 0.5           | 90.297                   | 90.536                            | -0.264  |
| 0.8           | 70.434                   | 70.441                            | -0.010  |
| 1             | 60.633                   | 60.379                            | 0.421   |
| 2             | 30.205                   | 30.196                            | 0.030   |
| 4             | 15.852                   | 15.816                            | 0.228   |
| 5             | 10.335                   | 10.289                            | 0.447   |

4. Conclusions
This paper proposed a new method based on single camera for low frequency vibration measurement. The proposed method with a low frame rate camera obtained the vibration measurement precision similar to laser interferometry at frequencies between 0.05 Hz-5 Hz. Additionally, the proposed method with the advantages of low cost and high flexibility. Further works will concentrate on researching the vibration measurement for lower frequency and larger displacement.

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