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LASER DOPPLER VIBROMETER FOR MEASURING SMALL AMPLITUDE OF VIBRATION USING SYNTHETIC HETERODYNE INTERFEROMETRY

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Abstract

A new synthetic heterodyne laser Doppler interferometer based on homodyne interferometer is addressed in this work. Though the homodyne interferometer has the advantages of simple optical configuration and low cost, it requires caution in using an electronic filter such as high pass filter(HPF) to get rid of low frequency electronic noises of the photo diode electronic circuitry. When the vibration amplitude is smaller than at least $1/2$ of the wavelength of He-Ne laser, a serious problem of incorrect velocity measurement can be caused since there is non-zero crossing interference signal whose DC value can be eliminated in using the HPF. To solve this problem of using the HPF in the homodyne interferometer, a synthetic interferometer using a mechanical modulation method is proposed in this work by exciting a reference mirror with the displacement larger than the 1/2 of the wavelength. In this work, the analytical work is presented to show how the synthetic interferometer solves the problem of incorrect velocity measurement using the Fourier-Bessel function description of the interference signals. Simulation and Experimental works are also presented to validate the synthetic heterodyne interferometer proposed in the work.

1. INTRODUCTION

An optical interferometer is used to measure the velocity of the vibrating object using the Doppler effect. In the heterodyne interferometer, the interference signal is modulated to a several MHz by using the optical phase shifting modulation component such as AOM(acousto-optical modulator). Hence, the slowly varying disturbance signal can be easily removed by using the high pass filter (HPF) whose cutoff frequency is higher than that of low frequency disturbance signal. The heterodyne interferometer obtains the information of the bidirectional velocity by simply converting the interference signal to voltage.

The homodyne interferometer obtains the information of the velocity directly form the

Doppler effect without using the optical phase shifting modulation. When the velocity is very low, the frequency of the interference signal is almost zero. Hence, it requires caution to use the HPF in the photo diode electronic circuitry. When the vibration amplitude is smaller than at least $1/2$ of the wavelength of He-Ne laser, a serious problem of incorrect velocity measurement can be caused since there is non-zero crossing interference signal whose DC value is eliminated in using the HPF.

To solve this problem of using the HPF in the homodyne interferometer, a mechanical modulation method is proposed in this work. A reference mirror is mechanically excited by using a PZT element with the displacement larger than the 1/2 of the wavelength. This method generates a zero crossing interference signal whose DC value is not affected by the HPF. This method is called synthetic heterodyne interferometer.

Jackson and et. al [1] firstly introduced the pseudo-heterodyne demodulation, using ramp modulation technique in 1982. James suggested Synthetic-heterodyne interference demodulation using fiber optical interferometer [2] and active homodyne interferometer by Dandridge [3] in the same year. Recently, the synthetic-heterodyne demodulation method using wave-shape of PZT for reducing Flyback problem [4] or the digital synthetic-heterodyne demodulation [5] and digital heterodyne[6] for increasing measuring bandwidth of velocity were introduced.

In this work, the analytical work is presented to show how the synthetic interferometer solves the problem of incorrect velocity measurement using the Fourier-Bessel function description of the interferent signals. Simulation and Experimental works are also presented to validate the synthetic heterodyne interferometer proposed in the work.

2. SYNTHETIC HETERODYNE INTERFEROMETER

2.1 Optical interference signal

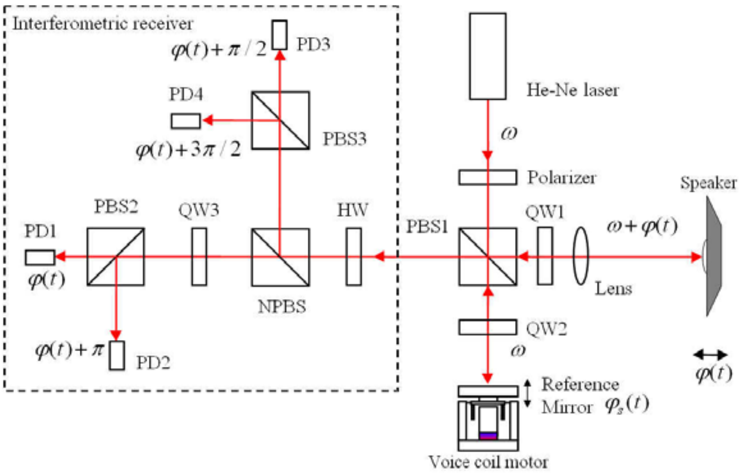


Figure 1. The homodyne optical interferometer

Fig. 1 shows the optical configuration of the homodyne laser interferometer. The laser beam emitted by the He-Ne laser source passes through the polarizing beam splitter 1 (PBS1), and is divided into two beams, the reference beam and the measurement beam, respectively. Quarter wave plate 1 (QW1) and 2(QW2) are used to prevent the laser beam from returning to the He-Ne laser source. The interference beam passing through PBS1 is divided into four beams and detected in the photo diodes, PD1 through PD4. Then, using the simple electronic operational technique, from the four interferometer signals, the in-phase interferometer signal,

$\Phi_{m,i}$ and the quadratic interference signal, $\Phi_{m,q}$ are obtained and expressed as followings [7]

$$\Phi_{m,i} = A_1 + B_1 \cos(\varphi(t) + \varphi_0) \tag{1}$$

$$\Phi_{m,q} = A_2 + B_2 \sin(\varphi(t) + \varphi_0) \tag{2}$$

$$\varphi(t) = \hat{\varphi}\cos(\omega t) \tag{3}$$

A_i (i =1,2) is the DC offset due to the laser intensity. B_i (i = 1, 2) is the amplitude of the interference signals. $\varphi(t)$ is the phase difference caused by the harmonic motion of the vibrating object, φ_0 is the initial phase and $\hat{\varphi}$ is the maximum amplitude of the phase difference. Since $\Phi_{m,i}$ and $\Phi_{m,q}$ are conventionally obtained by using the analogue circuit, it is usual to use a high pass filter to get rid of the DC offset A_i and low frequency noise in the interference signal.

In order to investigate whether there is a problem about signal processing of obtaining velocity signal in using the HPF, $\Phi_{m,i}$ and $\Phi_{m,q}$ are expanded in terms of the Fourier-Bessel series, and rewritten as [8]

$$\Phi_{m,i} = A_1 + B_1 \left\{ \begin{aligned} &\left[J_0(\hat{\varphi}) + 2\sum_{n=1}^{\infty} (-1)^n J_{2n}(\hat{\varphi}) \cos(2n\omega t) \right] \cos(\varphi_0) \\ &- \left[2\sum_{n=1}^{\infty} (-1)^{n-1} J_{2n-1}(\hat{\varphi}) \cos((2n-1)\omega t) \right] \sin(\varphi_0) \end{aligned} \right\} \tag{4}$$

$$\Phi_{m,q} = A_2 + B_2 \left\{ \begin{aligned} &\left[J_0(\hat{\varphi}) + 2\sum_{n=1}^{\infty} (-1)^n J_{2n}(\hat{\varphi}) \cos(2n\omega t) \right] \sin(\varphi_0) \\ &- \left[2\sum_{n=1}^{\infty} (-1)^{n-1} J_{2n-1}(\hat{\varphi}) \cos((2n-1)\omega t) \right] \cos(\varphi_0) \end{aligned} \right\} \tag{5}$$

where, J_n is the Bessel function in n-th order. One thing to note here is that $\Phi_{m,i}$ and $\Phi_{m,q}$ contains the DC offset $B_1 J_0(\hat{\varphi})\cos\varphi_0$, and $B_2 J_0(\hat{\varphi})\sin\varphi_0$ in addition to A_1, A_2 when the

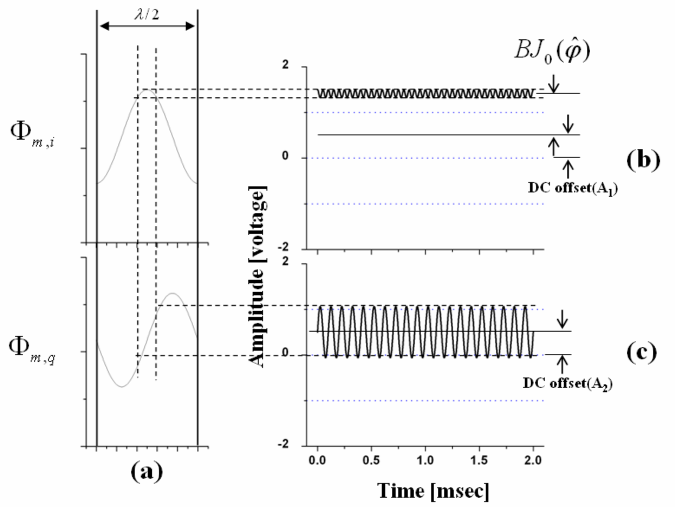


Figure 2. Interference signals, $\Phi_{m,i}$ and $\Phi_{m,q}$ when the vibration amplitude is smaller than at least $1/2$ of the wavelength of He-Ne laser.

vibration amplitude is very small. Fig. 2 shows $\Phi_{m,i}$ and $\Phi_{m,q}$ where the DC offsets and BJo are indicated when the vibration amplitude is smaller than at least $1/2$ of the wavelength of He-Ne laser. Here, the high pass filter which is aimed to get rid of the DC offset A_i causes a problem of eliminating the $B_1 J_0(\hat{\varphi})\cos\varphi_0$ and $B_2 J_0(\hat{\varphi})\sin\varphi_0$, Therefore, the velocity measured from the high pass filtered interference signal results in the incorrect velocity signal.

2.2 Synthetic-heterodyne interferometer

In order to solve the velocity information loss problem generated by using the HPF, a synthetic heterodyne interferometer is proposed by using a mechanical phase modulation method. The reference mirror is excited by using a PZT element with the displacement larger than the 1/2 of the wavelength as shown in Fig.1. Fig.2 shows the configuration of the PZT. Then, the new interference signals, $\Phi_{m,i}$ ' and $\Phi_{m,q}$ ' from the phase modulation method are expressed as

$$\Phi'_{m,i} = A_1 + B_1\cos(\varphi(t) + \varphi_s(t) + \varphi_0) \tag{10}$$

$$\Phi'_{m,q} = A_2 + B_2\sin(\varphi(t) + \varphi_s(t) + \varphi_0) \tag{11}$$

where, $\varphi_s(t)$ is the phase difference due to the motion excited by the PZT actuator.

In order to show that the velocity information loss problem is not occurred in the phase modulation method, Equations (10) and (11) can be further expanded in terms of the Fourier-Bessel series again, and can be expressed as [7]

$$\Phi'_{m,i} = A_1 + B_1\left\{\begin{array}{l}\left[J_0(\hat{\varphi}) + 2\cos\varphi_s(t)\sum_{n=1}^{\infty} J_{2n}(\hat{\varphi})\cos(2n\omega t)\right]\cos(\varphi_s(t)+\varphi_0)\\ -\left[2\sin\varphi_s(t)\sum_{n=1}^{\infty} J_{2n-1}(\hat{\varphi})\sin\{(2n-1)\omega t\}\right]\sin(\varphi_s(t)+\varphi_0)\end{array}\right\} \tag{12}$$

$$\Phi'_{m,q} = A_2 + B_2\left\{\begin{array}{l}\left[J_0(\hat{\varphi}) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(\hat{\varphi})\cos(2n\omega t)\right]\sin(\varphi(t)+\varphi_0)\\ -\left[2\sum_{n=1}^{\infty}(-1)^{n-1} J_{2n-1}(\hat{\varphi})\cos((2n-1)\omega t)\right]\cos(\varphi(t)+\varphi_0)\end{array}\right\} \tag{13}$$

The resultant signal using the HPF can be described as

$$\left(\Phi'_{m,i}\right)_{HPF} = B_1\left\{\begin{array}{l}\left[J_0(\hat{\varphi}) + 2\cos\varphi_s(t)\sum_{n=1}^{\infty} J_{2n}(\hat{\varphi})\cos(2n\omega t)\right]\cos(\varphi_s(t)+\varphi_0)\\ -\left[2\sin\varphi_s(t)\sum_{n=1}^{\infty} J_{2n-1}(\hat{\varphi})\sin\{(2n-1)\omega t\}\right]\sin(\varphi_s(t)+\varphi_0)\end{array}\right\} \tag{14}$$

$$\left(\Phi'_{m,q}\right)_{HPF} = B_2\left\{\begin{array}{l}\left[J_0(\hat{\varphi}) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(\hat{\varphi})\cos(2n\omega t)\right]\sin(\varphi(t)+\varphi_0)\\ -\left[2\sum_{n=1}^{\infty}(-1)^{n-1} J_{2n-1}(\hat{\varphi})\cos((2n-1)\omega t)\right]\cos(\varphi(t)+\varphi_0)\end{array}\right\} \tag{15}$$

If the cutoff frequency of the HPF is lower than that of $\varphi_s(t)$, the DC offsets are only eliminated with $B_i J_0(\hat{\varphi})$ being left since it is modulated by $(\cos\varphi_s(t)+\varphi_0)$ and $(\sin\varphi_s(t)+\varphi_0)$ respectively. Hence, $\Phi'_{m,i}$ and $\Phi'_{m,q}$ are expressed from Eq(10) and (11) as

$$\left(\Phi'_{m,i}\right)_{HPF} = B_1\cos(\varphi(t)+\varphi_s(t)+\varphi_0) \tag{16}$$

$$\left(\Phi'_{m,q}\right)_{HPF} = B_2\sin(\varphi(t)+\varphi_s(t)+\varphi_0) \tag{17}$$

3. SIMULATION

In order to validate the proposed S-H technique, a simulation using MATLAB was performed. Fig.3 shows the block diagram of LDV demodulator. Once the interference signals, are obtained, the velocity can be obtained using several demodulation algorithms. In this article, in order to distinguish a direction of velocity, the electrical modulating algorithm [6] is applied. Because the velocity always has just a positive value since homodyne laser has a single frequency. Moreover, a frequency demodulation algorithm using an one-shot F/V converter [9] is used. Therefore, the principle of the one-shot F/V converter is based on the fact that the frequency is inversely proportional to the period of a signal. The frequency of a signal is directly converted to voltage using F/V converter. Two one-shot F/V converters are used to demodulate the modulated reference signal, and the modulated measurement signal.

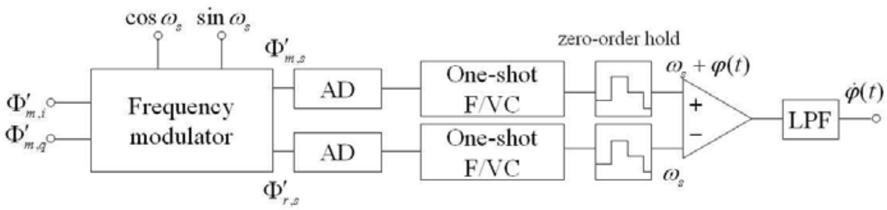
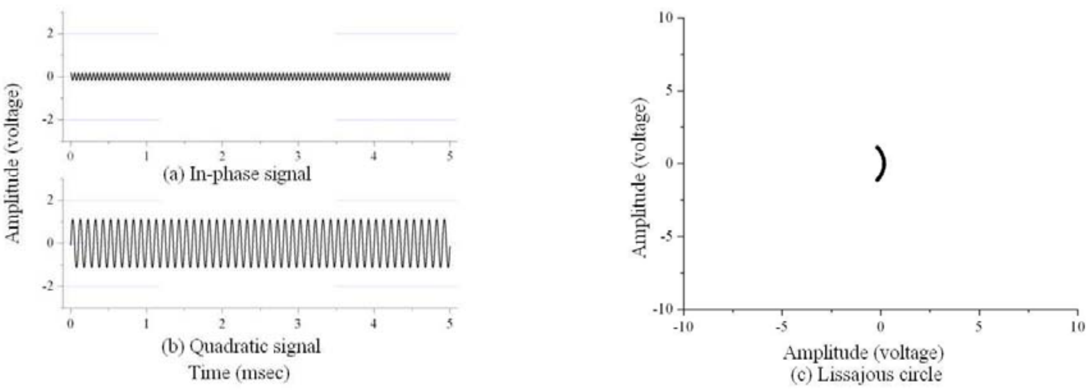


Figure 3. Velocity demodulation circuit

3.1 Interferometer without using synthetic-heterodyne technique

Fig.4 shows signals obtained from the demodulation circuit passing through the HPF without using S-H technique. Fig.4(a), (b) and (c) show the in-phase interference signal $\left(\Phi_{m,i}\right)_{HPF}$, the quadratic signal $\left(\Phi_{m,q}\right)_{HPF}$ and noncontinous Lissajous circle when the DC component and the DC offset are eliminated by the HPF. Fig. 4(d) shows the interference signals that are shifted by ω_s as represented in (22). The amplitude of the interference signal is excessively fluctuated by



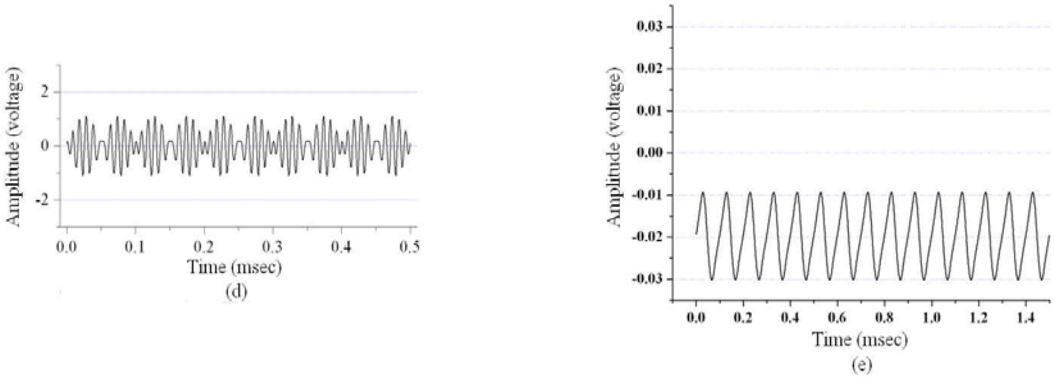


Figure 4. Signals obtained from the demodulator without using S-H technique
(a) in-phase signal, (b) quadratic signal, (c) Lissajous circle,
(d) mixed interference signal(mixing frequency : 1MHz) and (e) velocity signal

periods. So the velocity signal can not be normally obtained. Fig. 4(d) shows the demodulated velocity signal which has the DC error and the unbalance distortion with no corresponding sinusoidal signal.

3.2 Interferometer with using synthetic-heterodyne technique

Fig.5 show signals obtained by the demodulation circuit passing through the HPF with using S-H technique. Fig. 5(a), (b) and (c) show the in-phase interference signal, the quadratic signal and continuous Lissajous circle when the DC offset is just eliminated by the HPF. Fig. 5(d) shows the interference signals that are shifted by ω_s as represented in (18). The amplitude of signal is kept constantly without the fluctuation. So, when the S-H technique is used, a distort-

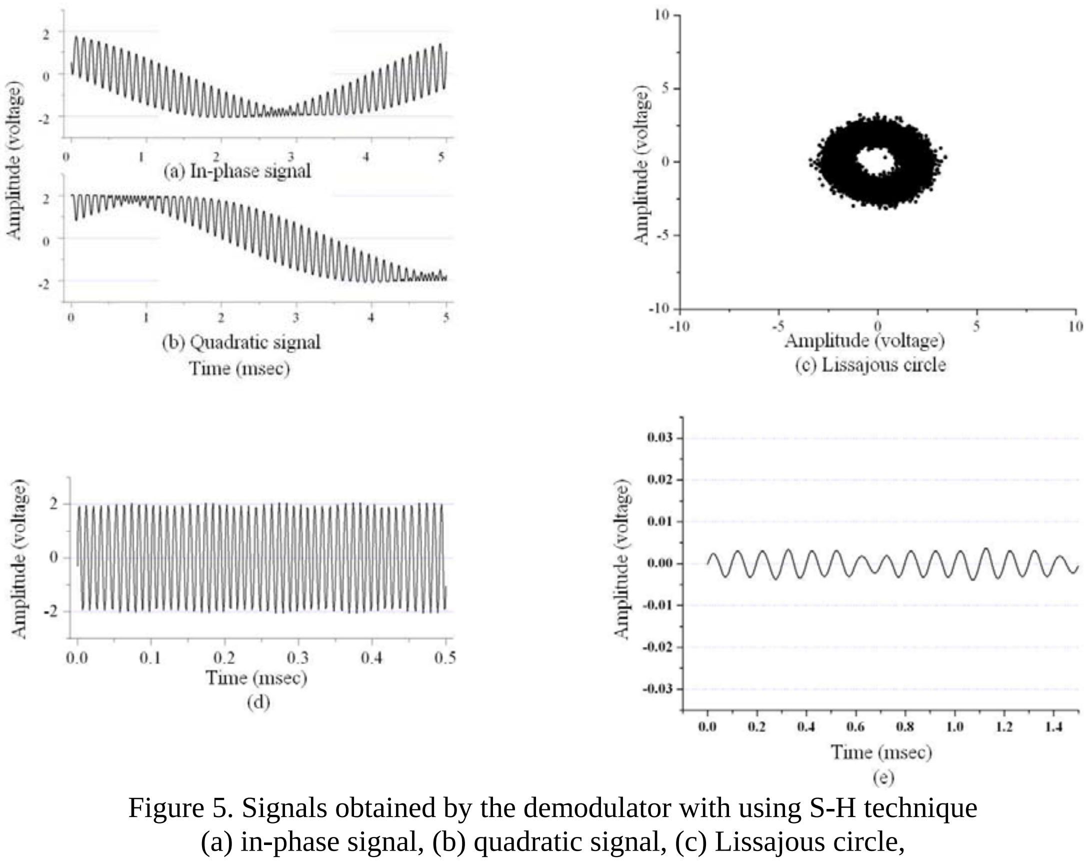


Figure 5. Signals obtained by the demodulator with using S-H technique
(a) in-phase signal, (b) quadratic signal, (c) Lissajous circle,
(d) mixed interference signal(mixing frequency : 1MHz) and (e) velocity signal

ion of velocity is reduced obviously. Fig. 5(d) shows a stable velocity signal without the DC error.

4. EXPERIMENT

Velocity can be obtained more stable when $\varphi_s(t)$ has large amplitude and low frequency. Therefore, Voice coil motor(VCM) that has long stroke and low vibration impact on interferometer is used for synthetic-heterodyne technique as shown in Fig.1. Fig.6 shows frequency modulated interference signal with and without using synthetic-heterodyne technique respectively. The amplitude of modulated interference signal with using synthetic-heterodyne technique is smaller than 1/5 of modulated signal without synthetic-heterodyne technique and is variable periodically. However, the amplitude of modulated interference signal with the synthetic-heterodyne technique is constant.

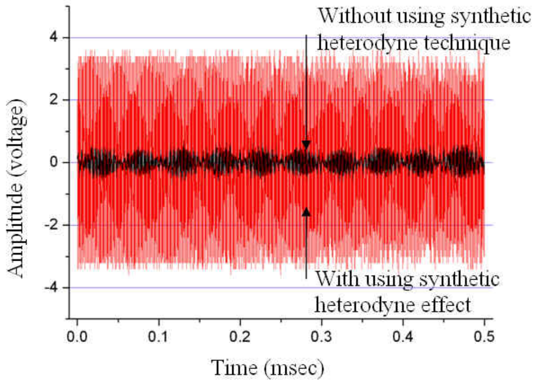
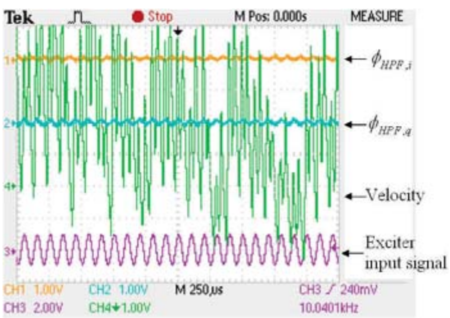
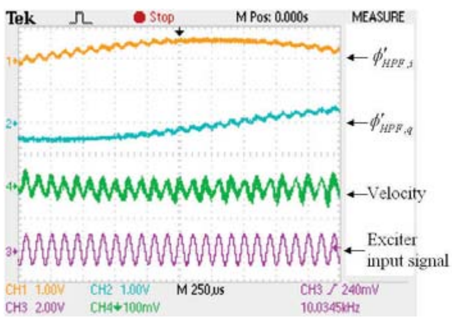


Figure 6. Modulated interference signals

Fig.7(a) shows the velocity and interference signals without the synthetic-heterodyne technique. The velocity signal shows several instability and distortion. When the reference mirror is moved using VCM of frequency near 2Hz along the horizontal axis, fig.7 (b) shows the interference signal passing through the HPF is crossing the zero axis since the DC component is not eliminated by using the synthetic-heterodyne technique. So the velocity of vibration object can be stably obtained.



(a) Without S-H technique



(b) With S-H technique

Figure 7. Velocity signals and interference signals

Therefore, the amplitude of modulation interference signal is variable periodically. So we have proven by experiment that this variable of amplitude have an effect on velocity signal.

Moreover, a loss of measured information is not incurred by using the synthetic-heterodyne technique, the amplitude of modulated interference signal is kept constantly. Therefore, the velocity signal of vibration object can be obtained consistently.

5. CONCLUSION

The synthetic interferometer using the mechanical phase modulation method is applied to measure small vibration of an object for homodyne interferometer. The analytical work is presented why there is a problem of distorted velocity measurement in homodyne interferometer for small amplitude of vibration. This work shows theoretically how the synthetic interferometer solves the problem of incorrect velocity measurement using the Fourier-Bessel function description of the interference signals. Simulation and Experimental works are also presented to validate the synthetic heterodyne interferometer proposed in the work.

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