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Frequency modulation method for a heterodyne laser interferometer

Hyunseung Choi*[1], Jongpil La[2], and Kyihwan Park[3]

[1]Intelligent Manufacturing Group, LG Production Engineering Research Institute
19-1 Cheongho-Ri Jinwuy-myun, Pyungtaik, Kyunggi-Do, 451-713, Republic of Korea
[2]Compressor Development Group, Samsung Gwangju Electronic Company
1119 Oryong-dong, Buk-gu, Gwangju, 500-712, Republic of Korea
[3]Dept. of Mechatronics, Gwangju Institute of Science and Technology,
1 Oryong-dong, Buk-gu, Gwangju, 500-712, Republic of Korea
khpark@gist.ac.kr (e-mail address of lead author)

Abstract

A heterodyne laser source can be generated by several methods. The method using the Zeeman effect is frequently used due to the simple construction and the small loss of a light. However, the low beat frequency of the laser in the zeeman method limits the velocity measurement. In this article, an electronical frequency modulation algorithm is proposed to overcome the drawback of the low velocity measurement capability by increasing the beat frequency electronically. The brief analysis, the measurement scheme of the proposed algorithm, and the experimental results are presented. It is demonstrated that the proposed algorithm is proven to enhance the measurable velocity limit.

INTRODUCTION

Heterodyne laser emits two linearly polarized beams whose frequencies are ω_1 and ω_2, respectively. They differ in frequency by a beat frequency, $\Delta\omega = \omega_2 - \omega_1$. When an object moves, the interferent signal, $\cos\{\Delta\omega t + \varphi(t)\}$ is varied by the Doppler effect.[2] In the heterodyne laser interferometer, the phase of the interferent signal, $\Delta\omega t + \varphi(t)$ should be larger than zero. Namely, the range of the phase variation is limited by the beat frequency, $\Delta\omega$. As the beat frequency increases, the range of the phase variation can be large. Therefore, the beat frequency should be high for high velocity measurement. However, it is not desirable to increase the beat frequency unlimitedly since it is difficult to design the electronic circuit of signal processing for the velocity measurement.

There are three kinds of methods for the heterodyne laser source generation. First method uses a He-Ne laser combined with an acousto-optic modulator (AOM). The heterodyne laser light is generated using the acousto-optic effect[3],[4] in the AOM method. The beat frequency is defined as the driving frequency of the AOM. This method has wide bandwidth since the beat frequency is several tens of MHz, and it is very stable and constant regardless of the laser source. However, the loss of light is large, the coherence length can be short.[4], and the signal processing for the high frequency modulation is hard to be implemented.

The second one uses two modes heterodyne laser. The two modes laser emits two oscillation frequencies, and polarization of these two adjacent modes are orthogonal due to mode competition. The two modes laser dose not need any peripheral equipments to make two frequencies. The maximum measurable velocity is not limited to the beat frequency since the beat frequency of the two modes laser is 600 $\sim$ 1000 MHz. Much research about the displacement measuring system using the beat frequency between the two modes has been introduced.[6],[7] However, the resolution is very low with mm order since it uses long wavelength light which is composed of two wavelengths. In order to overcome this drawback, S. C. Bartlett et al.[8] suggested the new system whose resolution is 0.5 nm by making a composed wavelength.

The third method uses the Zeeman frequency stabilized laser.[5] When a laser tube is placed in the transverse magnet field, two orthogonal linearly polarized intra-modes with different frequencies are emitted from the laser tube by the Zeeman effect.[2] The loss of the light is nearly zero and the construction is simple without additional devices in this method. The beat frequency between these two emitted lights of the Zeeman laser is dependent on the intensity of the magnetic field and the length of the laser tube. However, it is known that the maximum beat frequency is around 3 MHz.[1] This low beat frequency limits the velocity measurement.

In this article, in order to solve the disadvantage of the low velocity measurement capability in the Zeeman laser source method, an electronical frequency modulated algorithm is proposed. Analysis and experimental results are presented to validate the proposed method.

PRINCIPLE OF OPERATION

Heterodyne interferometer

The heterodyne laser interferometer for the velocity measurement is shown in Fig.1 (a). The laser output, which consists of two orthogonal linear polarized beams with different frequencies of ω_1 and ω_2 (wavelength λ_1 and λ_2) is partially reflected by the beam splitter(BS). The reflected beam from the BS passes through the polarizer, which is oriented at 45^o to the polarization axis of the two orthogonal beams, and falls on the photo detector, PD_r. The output signal of the PD_r, Φ_r is called as a reference signal and expressed as the following,

$$\Phi_r = \hat{\Phi}\cos(\Delta\omega t) \tag{1}$$

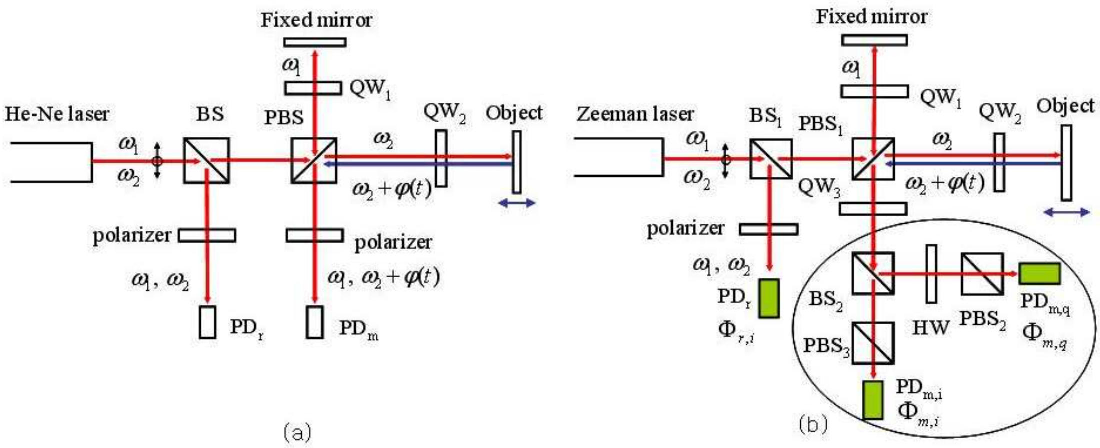

Figure 1: Heterodyne laser interferometer. (a) conventional configuration (b) proposed configuration

The two orthogonal polarized beams transmitted from the BS are divided at the polarized beam splitter (PBS) according to their polarization directions. one goes to the reference path to the fixed mirror and the other goes to the object path. The beams reflected from the fixed mirror and from the object mirror meet at PD_m. The Quarter waveplate1 (QW_1) and Quarter waveplate2 (QW_2) are the phase retarders and used to rotate the polarization directions of the returning beams from the fixed mirror and the object mirror. The output signal of the PD_m, Φ_m is called as a measurement signal and expressed as the following

$$\Phi_m = \hat{\Phi}\cos\{\Delta\omega t + \varphi(t)\} \tag{2}$$

where $\varphi(t)$ represents the phase varied according to the object movement.

Frequency modulation of the heterodyne signal

In this article, a frequency modulation algorithm is constructed to increase the beat frequency using an electronical modulation method. In order to perform this process, the optical signals from the laser interferometer and the electrical signals from the waveform generator are required. Equations (1) and (2) are called again as in-phase reference and measurement signals, respectively. The quadratic signals of Eq.(1) and Eq.(2) are required for the proposed frequency modulation process. The quadratic in-phase reference signal, $\Phi_{r,q}$ can be obtained by using a phase-shifting filter. The in-phase reference signal and its' quadratic signal are expressed for clarity respectively as

$$\Phi_{r,i} = \hat{\Phi}\cos(\Delta\omega t), \tag{3}$$

$$\Phi_{r,q} = \hat{\Phi}\sin(\Delta\omega t). \tag{4}$$

where the subscripts i and q mean the in-phase and the quadratic signals, respectively.

The quadratic measurement signal, $\Phi_{m,q}$ is obtained optically as shown in Fig.1 (b) for the sake of the measurement ease. Therefore, the additional optical components are added to the previous heterodyne optical system. The in-phase and the quadratic measurement signals from the interferometer are obtained at $PD_{m,i}$ and $PD_{m,q}$, respectively, and the in-phase and quadratic measurement signals are expressed as

$$\Phi_{m,i} = \hat{\Phi}\cos\{\Delta\omega t + \varphi(t)\}, \tag{5}$$

$$\Phi_{m,q} = \hat{\Phi}\sin\{\Delta\omega t + \varphi(t)\}. \tag{6}$$

The in-phase and the quadratic electrical signals, $\Phi_{s,i}$ and $\Phi_{s,q}$ are generated respectively from a waveform generator as

$$\Phi_{s,i} = \hat{\Phi}\cos(\omega_s t), \tag{7}$$

$$\Phi_{s,q} = \hat{\Phi}\sin(\omega_s t). \tag{8}$$

Hereafter, the electric signal which is expected to be shifted from the waveform generator is called as a shifting signal, and ω_s indicates the shifting frequency.

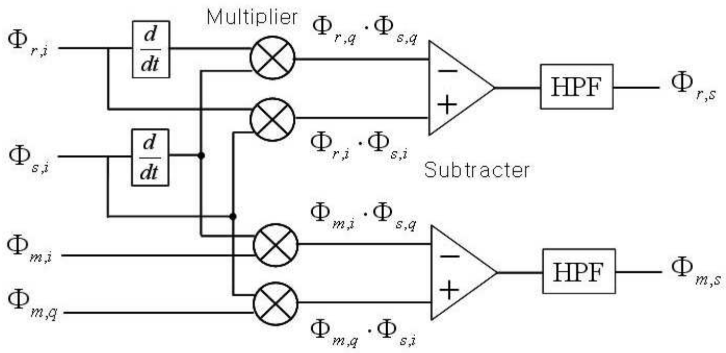

Figure 2: Signal processing algorithm of the frequency modulation

Figure 2 shows the process of the frequency modulation algorithm to explain how the modulated reference signal, $\Phi_{r,s}$ and the modulated measurement signal, $\Phi_{m,s}$ are obtained. $\Phi_{r,s}$ can be obtained by using $\Phi_{r,i}$, $\Phi_{r,q}$, $\Phi_{s,i}$ and $\Phi_{s,q}$ as following

$$\begin{aligned}\Phi_{r,s} &= \Phi_{r,i}\cdot\Phi_{s,i} - \Phi_{r,q}\cdot\Phi_{s,q} \\ &= \hat{\Phi}\cos(\omega_f t)\end{aligned} \tag{9}$$

where $\omega_f(=\Delta\omega + \omega_s)$ indicates the final beat frequency which is shifted by ω_s from the original beat frequency, $\Delta\omega$. In the same way, $\Phi_{m,s}$ can be obtained by using $\Phi_{m,i}$, $\Phi_{m,q}$, $\Phi_{s,i}$ and $\Phi_{s,q}$ as following

$$\begin{aligned}\Phi_{m,s} &= \Phi_{m,q}\cdot\Phi_{s,i} - \Phi_{m,i}\cdot\Phi_{s,q} \\ &= \hat{\Phi}\cos\{\omega_f t + \varphi(t)\}\end{aligned} \tag{10}$$

Frequency demodulation using an one-shot F/V converter

Once the interferent signals, $\Phi_{r,s}$ and $\Phi_{m,s}$ are obtained, the velocity can be obtained using several demodulation algorithms. In this article, a frequency demodulation algorithm using an one-shot F/V converter[9] is used. 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 the F/V converter. The one-shot process is occurred when the interferent signal crosses the zero voltage. The zero crossing is not dependent on the amplitude but only on the period of the interferent signal. Therefore, the one-shot is more robust to the noise and the amplitude variation of the interferent signal than the other methods. Two one-shot F/V converters are used to demodulate the modulated reference signal, $\Phi_{r,s}$ and the modulated measurement signal, $\Phi_{m,s}$.

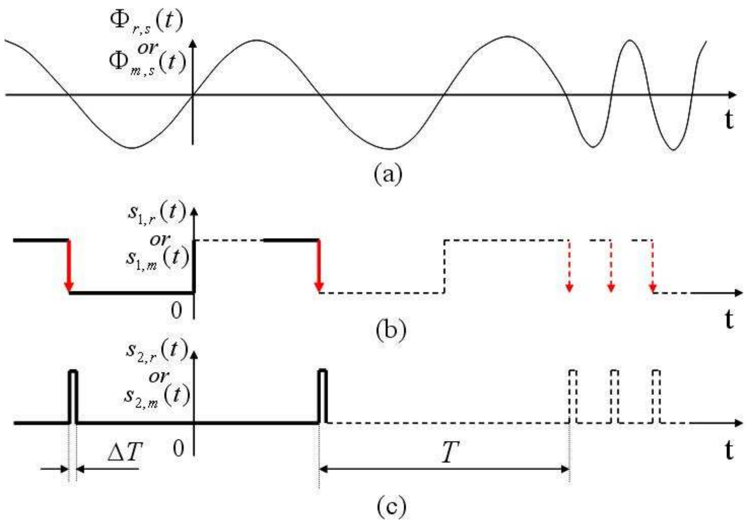

Figure 3: Principle of the one-shot F/V converter. (a) frequency modulated interferent signal, (b) square wave of the interferent signal, and (c) one-shot pulse signal

Figure 3 shows how $\Phi_{r,s}$ or $\Phi_{m,s}$ are converted to the series of pulse using one-shot F/V converter. To demodulate the interferent signal, $\Phi_{r,s}$ or $\Phi_{m,s}$ as shown in Fig. 3 (a), the sinusoidal interferent signal is converted to the square wave. The square wave can be obtained by using a comparator. The square wave signal, $s_{1,r}(t)$ or $s_{1,m}(t)$ is derived from $\Phi_{r,s}$ or $\Phi_{m,s}$, respectively as shown in Fig. 3 (b). At the falling edge(or rising edge) of $s_{1,r}(t)$ or $s_{1,m}(t)$, the one-shot generates very short pulse having the same period regardless of the input frequency as shown in Fig. 3 (c). Since the output of the one-shot is zero except the short pulse, the average value of the one-shot output is inversely proportional to the period of the input signal of the one-shot. The one-shot pulse signal $s_{2,r}(t)$ from $s_{1,r}(t)$ can be averaged by using a low pass filter as

$$\hat{s}_2 \Delta T/T = 1/T \int_{-T/2}^{T/2} s_{2,r}(t)dt. \tag{11}$$

where, T is the period of the $\Phi_{r,s}$. Since $\hat{s}_2$ and ΔT are constant, $\hat{s}_2\Delta T$ can be assumed to be 1 for the simplicity. Therefore,

$$\omega_f = 1/T \int_{-T/2}^{T/2} s_{2,r}(t)dt \tag{12}$$

As the similar way, the frequency of the modulated measurement signal, $\Phi_{m,s}$ can be obtained as

$$\omega_f + \dot{\varphi}(t) = 1/T \int_{-T/2}^{T/2} s_{2,m}(t)dt \tag{13}$$

where, $s_{2,m}(t)$ is the one-shot signal of the modulated measurement interferent signal, $\Phi_{m,s}$.

The derivation of the phase which is related to the Doppler frequency can be obtained by subtracting Eq.(12) from Eq.(13) as following

$$\dot{\varphi}(t) = 1/T \int_{-T/2}^{T/2} s_{2,m}(t)dt - 1/T \int_{-T/2}^{T/2} s_{2,r}(t)dt. \tag{14}$$

Then, the velocity of the object can be calculated from the following relationship

$$\upsilon(t) = \dot{\varphi}(t)\lambda/4\pi n \tag{15}$$

where, n is the refractive index of the medium along the laser path.

EXPERIMENT

A Zeeman-type frequency-stabilized He-Ne laser is used as the coherent light source which emits the two linearly polarized beams. The beat frequency, $\Delta\omega$, of the heterodyne laser used in this work is nearly 450 kHz. Since $\Delta\omega$ is 450 kHz in the experiment, the maximum frequency of the interference signal is 900 kHz. Therefore, the maximum measurable velocity is ± 0.14 m/s by Eq.(15). In the experiment, the electronically modulated beat frequency, ω_f is shifted up to 900 kHz. The maximum measurable velocity is increased to ± 0.28 m/s. The electronical frequency modulation algorithm for the increase of the beat frequency is implemented by using high speed operational analog amplifiers, AD8056, and Multipliers AD734. The developed electronical frequency modulation system has a wide bandwidth enough to modulate the interferent signal.

Figure 4 (a) shows the interferent signal, $\Phi_{m,i}$ or $\Phi_{m,q}$ and the velocity signal without the electrical frequency modulation when the excitation velocity of the object is lower than the maximum measurable velocity, ± 0.14 m/s. The velocity signals obtained from the system without using the electrical frequency modulation and the commercial product are expressed as $\upsilon_{wo}(t)$ and $\upsilon_c(t)$, respectively. The velocity in this experiment is ± 0.11 m/s which is obtained by vibrating the light rectangular plate at 800 Hz. No distorted signals are observed in velocity signal. Figure 4 (b) shows the interferent signal and the velocity signal without the

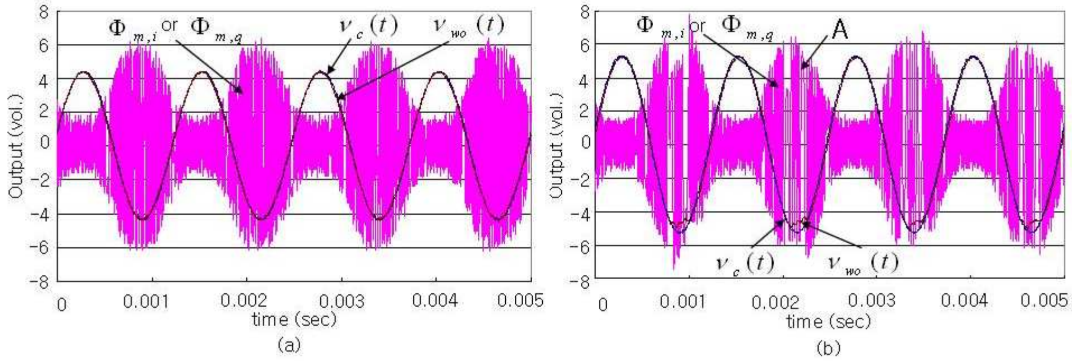

Figure 4: Interferent signal and velocity signal without the frequency modulation. (a) under maximum measurable velocity, and (b) over maximum measurable velocity.

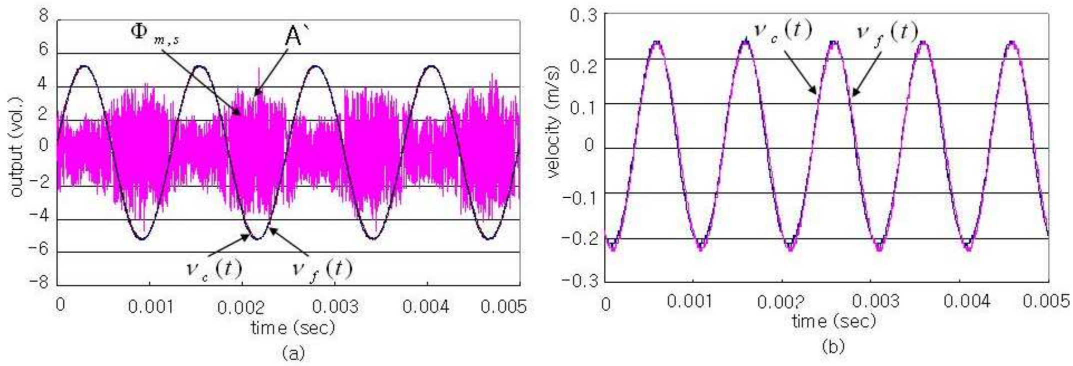

Figure 5: Interferent signal and velocity signal using the frequency modulation. (a) at the velocity of 0.14 m/s, and (b) at the velocity of 0.24 m/s

electrical frequency modulation when the excitation velocity of the object is higher than the maximum measurable velocity. The interferent signal,$\Phi_{m,i}$ or $\Phi_{m,q}$ and the velocity signal, $v_{wo}(t)$ are distorted at the maximum velocity point 'A'. Each velocity signal is compared with that of the commercial laser Doppler vibrometer, OFV3001 made in Polytec Co.. The output voltage indicates the 0.025 m/s/vol..

Figure 5 (a) shows the frequency modulated interferent signal, $\Phi_{m,s}$ and the velocity signal using the proposed frequency modulation algorithm. No distorted velocity signal is observed even at the point of 'A''. Figure 5 (b) shows the velocity, $v_{fm}(t)$ when the proposed frequency modulation algorithm is used. The maximum velocity in this experiment is 0.24 m/s which is obtained at 1 kHz excitation. It is higher than the maximum velocity, 0.14 m/s which is obtainable from using the original beat frequency of 450 kHz. The proposed method is verified that the velocity measurement can be increased through the experiment.

DISCUSSION

The electronical frequency modulation algorithm to increase the maximum measurable velocity by increasing the beat frequency is proposed. The proposed algorithm overcomes the drawback of the Zeeman type laser which has a relatively low beat frequency, while taking the advantages of simple construction and high efficiency. This method can shift the beat frequency electronically. The electronic circuit for the frequency modulation is designed to have the bandwidth over 3 MHz. For the high speed signal processing, whole electronic components are selected seriously. The one-shot F/V converter method is used to demodulate the modulated interferent signals since the method is robust to the amplitude variation of the interferent signals. The theoretical analysis and the experimental results demonstrate that the proposed algorithm is proven to enhance the measurable velocity limit by increasing the beat frequency of the heterodyne laser. The velocity result using the developed system is compared with that of the commercial laser Doppler vibrometer experimentally.

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