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호모다인 간섭계를 이용한 레이저 진동 측정기의 개발

Laser Doppler Vibrometer using the Bulk Homodyne Interferometer

라종필* · 경용수* · 왕세명* · 김경석** · 박기환*

Jongpil La*, Yongsoo Young*, Semyung Wang*, Kyungsuk Kim, Kyihwan Park***

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ABSTRACT

The FM demodulation method for a bulk homodyne laser interferometer is presented. The Doppler frequency that represents the surface velocity of a vibrating object is obtained by using the bulk homodyne laser interferometer, and converted to the voltage signal by using the proposed analogue FM demodulation circuit. The DC offsets of the inteferent signals that are obtained from the bulk homodyne interferometer are eliminated by using a simple subtraction. The new method for compensation of the asymmetry of each channels is presented. The light power variation of the interferometer is normalized by using the Auto Gain Controller(AGC). The proposed FM demodulation algorithm is proved by the theoretical method, and validated by the experimental results. In experiments, the proposed FM demodulation algorithm is compared with the conventional demodulation methods.

1. Introduction

The displacement and velocity measurement techniques using laser interferometric sensors have been widely developed since Michelson invented Michelson interferometer in 1881. In general, laser interferometric sensors provide accurate, fast and non-contact measurements [1][2].

The demodulation scheme of the laser interferometer that converts the interferent signals to the displacement and/or velocity signal has been the main issue of the research during the past two decades.

In the simple Michelson interferometer, the displacement can be obtained by counting the interferent fringe. The resolution of the Michelson interferometer is half of the wavelength of the light. For example, He-Ne(λ =633.28nm) laser gives 316.64nm resolution. Hagiwara et. al. proposed the new method for improving the resolution of the Michelson interferometer by using the phase encoding method[3].

Charles et. al. proposed a symmetric analogue FM demodulator for the optical fiber interferometric sensors[4]. They assumed symmetry of the signals obtained in the optical fiber interferometer, which utilize a 3×3 symmetric optical fiber coupler. Three signals having $2\pi/3$ rad phase difference each were obtained from the laser interferometer and demodulated to the velocity and displacement signals by using the proposed FM demodulator. However, the existence of asymmetry causes the serious error signal in that kind of FM demodulator.

Zhiqian et. al. proposed asymmetric FM demodulation scheme for the optical fiber interferometer by compensating the asymmetry of the 3×3 optical fiber coupler[5]. They proposed algorithm for compensating the asymmetry of optical fiber coupler by the simple arithmetic operations of the obtained inteferent signals.

In this work, the analogue FM demodulator for the bulk homodyne laser interferometer is discussed. The DC offset signals of the interference signals are eliminated by the simple subtraction between two channels. The new algorithm for generating the quadratic signals from asymmetric interferometer is proposed. From those quadratic signals, the velocity signal can be obtained and displacement signal can be also obtained by integrating the velocity signal. Auto Gain Controller(AGC) for normalization of the velocity and displacement signal is added in the proposed FM demodulator.

* 광주과학기술원, 기전공학과
E-mail : khpark@nate.com
Tel : (062) 970-2391, Fax : (062) 970-2384
** 조선대학교, 기계설계공학과

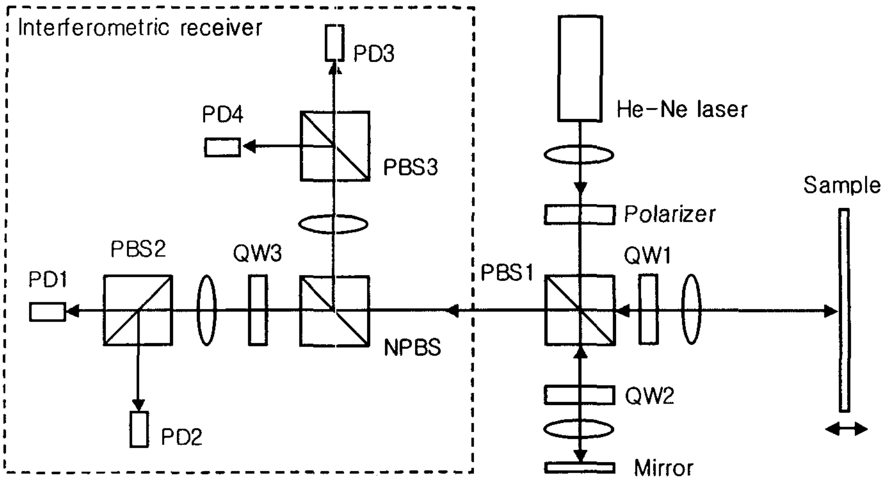

Figure 1. Schematic diagram of the Homodyne laser interferometer

2. FM demodulation circuit of a homodyne interferometer

Figure 1 shows the schematic diagram of the bulk homodyne laser interferometer [6]. The laser beam emitted by He-Ne laser source passes through polarizing beam splitter 1(PBS1), and divide into the two beams, the reference beam and the measurement beam, respectively. The quarter wave plate 1(QW1) and QW2 is used to prevent the laser beam return to the He-Ne laser source. The interferent beam passing through PBS1 is divided into 4 channels in the interferometric receiver as shown in Fig.(1). The interferent signals ϕ_i (i=1,2,3, and 4) obtained from the photo detectors can be expressed as Eq.(1).

$$\begin{aligned}\phi_1 &= A_1 + B_1 \sin\varphi(t) \\ \phi_2 &= A_2 + B_2 \sin\{\varphi(t) + \varsigma_1\} \\ \phi_3 &= A_3 + B_3 \sin\{\varphi(t) + \varsigma_2\} \\ \phi_4 &= A_4 + B_4 \sin\{\varphi(t) + \varsigma_3\}\end{aligned} \quad (1)$$

where A_i and B_i (i=1,2,3, and 4) are DC offsets of the inteferent signals obtained in the interferometer and the amplitudes of those interferent signals, respectively. The phase differences ς_i (i=1,2, and 3) are adjusted to have $\pi/2$, π, and $3\pi/2$, respectively. In actual, this symmetry hardly can be achieved by using the only optical treatments[5]. $\varphi(t)$ represents the optical path difference(OPD) between the reference beam and the measurement beam. The following sections address the method of compensating the asymmetry of the bulk homodyne laser interfermeter, and of demodulating the velocity and displacement signals from it.

2.1 Elimination of the DC offsets of the interferent signal

The proposed demodulation algorithm requires simple harmonic signals without any DC components. The DC offsets A_i (i=1,2,3,and 4) should be eliminated from the original interferent signals, which can obtained by the simple subtraction between two interferent signals as represented in Eq.(2).

$$\begin{aligned}\psi_1 &= \phi_1 - \frac{A_1}{A_2}\phi_2 \quad (2) \\ &= B_1 \sin\varphi(t) - \frac{A_1}{A_2} B_2 \sin\{\varphi(t) + \varsigma_1\} \\ &= B_1 \sin\varphi(t) - \frac{A_1}{A_2} B_2 \sin\varphi(t)\cos\varsigma_1 \\ &\quad - \frac{A_1}{A_2} B_2 \cos\varphi(t)\sin\varsigma_1 \\ &= (B_1 - \frac{A_1}{A_2} B_2 \cos\varsigma_1)\sin\varphi(t) \\ &\quad - \frac{A_1}{A_2} B_2 \sin\varsigma_1 \cos\varphi(t)\end{aligned}$$

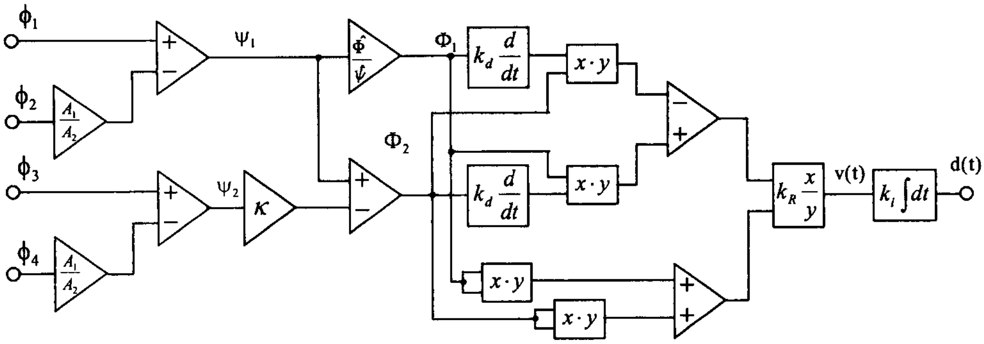

Figure 2. Block diagram of the proposed FM demodulation circuit of the bulk homodyne laser interferometer

Equation 2 can be expressed as Eq.(3) using the adding formula of Trigonometric functions.

$$\psi_1 = \hat{\psi}_1 \sin\{\varphi(t) + \alpha_1\} \tag{3}$$

where, $\alpha_1 = \tan^{-1} \dfrac{-(A_1/A_2)B_2 \sin\varsigma_1}{B_1 - (A_1/A_2)B_2 \cos\varsigma_1}$

$$\hat{\psi}_1 = \sqrt{(B_1 - \frac{A_1}{A_2}B_2 \cos\varsigma_1)^2 + (\frac{A_1}{A_2}B_2 \sin\varsigma_1)^2}$$

As represented in the Eq.(3) the subtraction of two signals obtained from detectors is still harmonic function. DC offsets and the fluctuations due to the external noises that have the same frequency and phase are eliminated. Another pure harmonic signal ψ_2 can also be obtained by subtraction ϕ_4 from ϕ_3 as the same way.

2.2 Generation of the quadratic signal from the interferent signal

The pure harmonic signals obtained in the previous section can be expressed as Eq.(4).

$$\psi_1 = \hat{\psi}_1 \sin\{\varphi(t) + \alpha_1\} \qquad (4)$$
$$\psi_2 = \hat{\psi}_2 \sin\{\varphi(t) + \alpha_2\}$$

For simplicity, Eq.(4) can be expressed as Eq.(5) by letting $\beta = \alpha_2 - \alpha_1$.

$$\psi_1 = \hat{\psi}_1 \sin\{\varphi(t) + \alpha_1\} \qquad (5)$$
$$\psi_2 = \hat{\psi}_2 \sin\{\varphi(t) + \alpha_1 + \beta\}$$

Equation 5 gives exactly the same result with Eq.(6) when those signals are continuously given.

$$\psi_1 = \hat{\psi}_1 \sin\varphi(t) \qquad (6)$$
$$\psi_2 = \hat{\psi}_2 \sin\{\varphi(t) + \beta\}$$

Here, β is not always $\pi/2$. To be quadratic signals, a new signal that has $\pi/2$ phase difference with respect to ψ_1 or ψ_2 is required. It is simpler to obtain the signal that is quadratic to ψ_1, because the phase of ψ_1 is zero. To obtain the quadratic signal of ψ_1, the new signal ψ_3 generated by using ψ_1 and ψ_2 is proposed as

$$\psi_3 = \psi_1 - \kappa\psi_2 \tag{7}$$

Equation 7 has the same form with Eq.(2). Therefore, the resultant equation is expressed as represented in Eq.(8).

$$\psi_3 = \hat{\psi}_3 \sin\{\varphi(t) + \gamma\} \tag{8}$$

where, $\gamma = \tan^{-1} \dfrac{-\kappa\hat{\psi}_2 \sin\beta}{\hat{\psi}_1 - \kappa\hat{\psi}_2 \cos\beta}$

$$\hat{\psi}_3 = \sqrt{(\hat{\psi}_1 - \kappa\hat{\psi}_2 \cos\beta)^2 + (\kappa\hat{\psi}_2 \sin\beta)^2}$$

To be a quadratic signal with respect to ψ_1, γ in ψ_3 must be $\pi/2$, that is,

$$\tan^{-1} \frac{-\kappa\hat{\psi}_2 \sin\beta}{\hat{\psi}_1 - \kappa\hat{\psi}_2 \cos\beta} = \frac{\pi}{2} \tag{9}$$

From Eq.(9), κ can be obtained as Eq.(10).

$$\kappa = \frac{\hat{\psi}_1}{\hat{\psi}_2 \cos\beta} \quad (10)$$

Therefore, ψ_1 and ψ_3 satisfy quadratic condition. That is,

$$\psi_1 = \hat{\psi}_1 \sin\varphi(t) \quad (11)$$
$$\psi_3 = \hat{\psi}_3 \cos\varphi(t)$$

These two quadratic signals have different amplitudes. If these two quadratic signals are normalized to have $\hat{\Phi}$ which has the same value with $\hat{\psi}_3$, for simplicity, Eq.(12) can be obtained.

$$\Phi_1 = \frac{\hat{\Phi}}{\hat{\psi}_3}\psi_3 = \hat{\Phi}\cos\varphi(t) \quad (12)$$
$$\Phi_2 = \frac{\hat{\Phi}}{\hat{\psi}_1}\psi_1 = \hat{\Phi}\sin\varphi(t)$$

Using the conventional arctangent method, $\varphi(t)$ can be easily obtained by using the following relationship,

$$\varphi(t) = \tan^{-1}\frac{\hat{\Phi}_2}{\hat{\Phi}_1} \quad (13)$$

It is reported that the homodyne laser interferometer using the arctangent method has below 0.1nm resolution. However, the inverse tangent calculation is a time-consuming operation that this method cannot be used for the very fast interferent signal. The result from the proposed FM demodulation algorithm will be compared with the arctangent method in experiments.

2.3 Estimation of the velocity signal

The velocity proportional to the Doppler frequency can be expressed as represented in Eq.(14).

$$v(t) = \dot{\varphi}(t) \quad (14)$$

The new FM demodulation method proposed in this work can be expressed as represented in Eq.(15).

$$f(t) = \Phi_1\dot{\Phi}_2 - \Phi_2\dot{\Phi}_1 \quad (15)$$

The first term of Eq.(15) is expressed as represented in Eq.(16).

$$\Phi_1\dot{\Phi}_2 = \hat{\Phi}^2\cos^2\varphi(t)\dot{\varphi}(t) \quad (16)$$

The second term of Eq.(15) is expressed as represented in Eq.(17).

$$\Phi_2\dot{\Phi}_1 = -\hat{\Phi}^2\sin^2\varphi(t)\dot{\varphi}(t) \quad (17)$$

Therefore, the velocity signal $f(t)$ is represented as Eq.(15).

$$\begin{aligned} f(t) &= \Phi_1\dot{\Phi}_2 - \Phi_2\dot{\Phi}_1 \\ &= \hat{\Phi}^2\{\cos^2\varphi(t) + \sin^2\varphi(t)\}\dot{\varphi}(t) \\ &= \hat{\Phi}^2\dot{\varphi}(t) \end{aligned} \quad (18)$$

2.4 Auto gain controller(AGC)

As represented in Eq.(18), the obtained velocity signal is proportional to $\hat{\Phi}^2$ which is variable according to variation of laser power and reflectivity condition of measuring objects. The role of AGC is to eliminate this dependence of the velocity signal on $\hat{\Phi}^2$. The FM demodulated signal $f(t)$ contains undesirable $\hat{\Phi}^2$ term that varies with respect to power variation of laser source. If $\hat{\Phi}^2$ can be calculated by some electronic operation, this dependency can be reduced or even eliminated. The amplitude signal $A(t)$ can be obtained as

$$\begin{aligned} A(t) &= \Phi_1^2 + \Phi_2^2 \\ &= \hat{\Phi}^2\{\cos^2\varphi(t) + \sin^2\varphi(t)\} \\ &= \hat{\Phi}^2 \end{aligned} \quad (19)$$

The surface velocity of a vibrating object that is proportional to the instantaneous frequency of quadratic signal is obtained as represented in Eq.(20) by using Eq.(18) and Eq.(19).

$$v(t) = \frac{\Phi_1\dot{\Phi}_2 - \Phi_2\dot{\Phi}_1}{\Phi_1^2 + \Phi_2^2} \quad (20)$$

Therefore, the displacement of the object $d(t)$ can be obtained by Eq.(21).

$$d(t) = \int_0^t v(\tau)d\tau + d_0 \qquad (21)$$

Here, d_0 represents the initial position of the surface of a vibrating object.

3. Experimental setup and experimental results

The proposed FM demodulation scheme is validated by the experimental results. Figure 1 shows the bulk homodyne laser interferometer used in the experiments. He-Ne laser(Melles Griot Co. Ltd.) whose wavelength is 633nm is used for coherent laser source. All optical components are coated a 633nm AR(anti-reflective) material. The object to be measured is coated by well-reflective material that enables the laser beam to be well reflected at the surface of the vibrating surface. The exciter driven by a function generator and a power amplifier excites the vibrating object.

Figure 2 shows the block diagram of the proposed FM demodulation circuit of the bulk homodyne laser interferomter. All the linear algebra operation such as subtraction and addition is achieved by using OP27(manufactured by Analog Device Co. Ltd). This OP-amp has 126dB common mode rejection ratio (CMRR), and very low noise characteristics given by $3.5nV/\sqrt{Hz}$. AD633(manufactured by Analog Device Co. Ltd.) with ± 0.1\% nonlinearity is used for the multipliers. Division process is obtained by inverse transform of multiplication using AD633. OP27 is also used for the inverse process of AD633. Derivative process is achieved by using OP27. Here, the differentiating constant k_i in the two differentiators as shown in Fig.(2) should have the same value. If the two differentiating constants are not equal, carrier signals that are generated by the interferent signals obtained in the interferometer will not be eliminated as represented in Eq.(18). That means that additional $\sin\varphi(t)$ or $\cos\varphi(t)$ terms will be appeared in Eq.(18). To make the two differentiating constants be the same, each capacitors and each resistors in the differentiators are chosen to have the same value within 0.01% difference.

Figure 3 shows the pure harmonic interferent signals, which satisfy the quadrature condition as represented by Eq.(12). These two signals have $\pm\pi/2$ phase difference each other according to the moving direction of the vibrating object. The DC offsets and the phase nonlinearity are eliminated by using the proposed algorithm. These quadratic signals are demodulated as shown in Fig.(4). The dot products of the derivative of one quadratic channel with the other that is $\Phi_1\dot{\Phi}_2$ and $\Phi_2\dot{\Phi}_1$ are plotted as shown in Fig.(4). The simple subtraction of those two signals eliminates the same phase carrier signal. As a result, the only velocity signal is remained as shown in Fig.(4).

Figure 5 shows the difference between the result from the proposed FM demodulation algorithm and the conventional arctangent method. The two plots show almost the same result within sub-nanometer scale. Note that, the result from the proposed FM demodulation algorithm is obtained in real-time calculation performed by the analogue processing circuit. In contrast, the result from the conventional arctangent method is obtained by calculating in computer after saving the signal. The conventional arctangent method cannot be used in the very high frequency signal such as a vibration analysis.

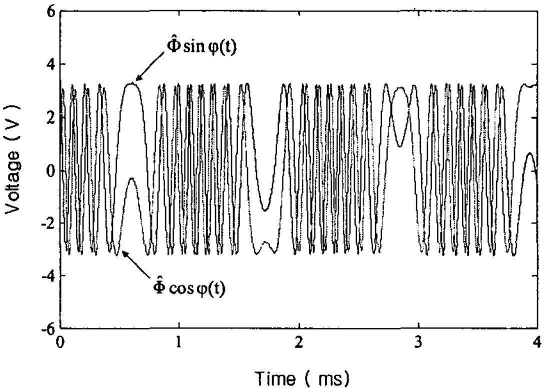

Figure 3. Pure harmonic interferent signals that satisfy the quadrature condition

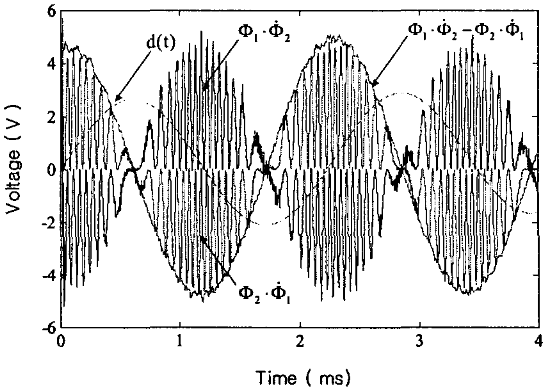

Figure 4. Signals measured at each nodes of the proposed FM demodulator

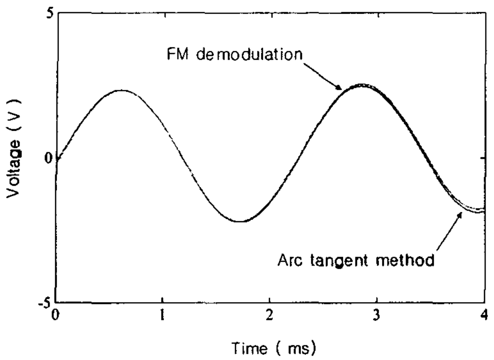

Figure 5. Comparison between the output of the proposed FM demodulation algorithm and that of the conventional arctangent method

The results shows that the proposed FM demodulation algorithm is very fast enough to calculate the velocity signal, and very accurate within sub-nanometer scale.

4. Conclusions

The bulk homodyne laser interferometer utilizing the dual beam polarization interferometer is discussed, and whose FM demodulation algorithm that converts the Doppler frequency to the velocity signal is proposed in this work. The undesirable DC offsets and the nonlinearity of phases are eliminated by the proposed algorithm, which is proved by the mathematical and the experimental approach. For experiments, the analogue type signal processing circuit is manufacture. The experimental results show that the proposed FM demodulation algorithm is very fast enough to cover several hundreds kHz interferent signal and very accurate compared with the conventional arctangent method.

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