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Automatic gain control for the measurement of a flexible body motion using a laser Doppler vibrometer

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Abstract

The amplitude variation of the interferent signal can be caused in the flexible body motion since the object surface is uneven and the reflection angle can be varied according to the object motion. The amplitude variation causes an error in the signal processing algorithm. This error distorts the output signal. In order to eliminate this dependence of the interferent signal on the amplitude variation, an automatic gain control (AGC) is proposed. Electronic circuit is constructed to implement the AGC algorithm. The brief analysis, the measurement scheme of the system, and the experimental results of the AGC using a laser Doppler vibrometer are presented. They demonstrate that the proposed AGC is proven to make the system robust to the amplitude variation of the interferent signal in the flexible body motion.

INTRODUCTION

The laser Doppler vibrometer has been used to measure the velocity of the moving object using an optical interference. The velocity signal can be obtained from the interferent signal by using various demodulation algorithms.

The interferent signal is generated by the interference effect when the object beam scattered from the object falls on the photodiode(PD) with the reflected beams from the reference path. Though the path of the reference signal to the PD is not varied, the path of the object signal to the PD can be changed due to the object motion. Hence, the amplitude of the interferent signal can vary when there is a small misalignment between the two reflected beams. The amplitude of the interferent signal also can be varied by the variation of the focusing spot size of the object beam. Especially, the amplitude variation can be large when the vibration amplitude of the object is excessively large, because the focal length of the beam in the object path to the PD much varies according to the object motion.

A homodyne laser interferometer is relatively sensitive to the amplitude variation of the interferent signal since its amplitude is usually used in the frequency demodulation of the interferent signal. It is difficult to use the amplitude varying interferent signal for the demodulation algorithm, especially in the linear frequency demodulation methods. In order to solve the problem, the demodulation algorithm[1] which is robust to the amplitude variation of the interferent signal were reported.

An automatic gain control(AGC) is introduced to minimize the error which is caused by the amplitude variation of the interferent signal for the application of the homodyne laser interferometer. The AGC has been used to regulate an arbitrary input signal to some specified level. A very common and typical example is the AGC used in AM radio. Such a receiver is essentially linear - that is, the output is proportional to the input. This is a necessary requirement because the information content of the signal is carried by the changes of amplitude of the carrier frequency. In other applications, L. Eisenberg et al.[2] applied the AGC to correct the fluctuation of the light source in the spectrofluorometer. E. J. Tacconi et al.[3] reported the AGC with wide range and high speed in the radio frequency(RF) range. D.N. Green[4] improved the linear tracking properties of phase-locked loops(PLL) by being less sensitive to the input waveform parameters using the AGC. N. K. Abdulaziz[5] also improved the performance of the PLL system in the presence of a large interfering signal. All of these method use the AGC using feedback loops. W. Wenzhao et al.[6] compared the analog AGC and digital AGC, and implemented the AGC with mixed feedback/feedforward analog and digital method.

In this article, a feedforward AGC algorithm which has more simple structure and higher bandwidth than that of the feedback method is proposed. The proposed AGC algorithm is applied in the homodyne laser Doppler vibrometer to reduce the velocity error by regulating the amplitude variation of the input interferent signal. The brief analysis and experimental results are presented to validate the proposed method.

PRINCIPLE OF OPERATION

Laser Doppler vibrometer

The homodyne laser Doppler vibrometer used in this work is shown in Fig.1. The laser beam emitted from a He-Ne laser source has a frequency of ω (wavelength λ), amplitude of $\hat{E}$ as following

$$E = \hat{E}\exp[i\{\omega t\}] \tag{1}$$

The laser beam passes through a polarized beam splitter (PBS1), and divided into two paths, a reference path and an object path, respectively. The Quarter waveplate1(QW1) and QW2 are phase retarders and used to rotate the polarization direction of the returning beams from the fixed mirror and object, respectively. Since a typical mechanical object surface is not always

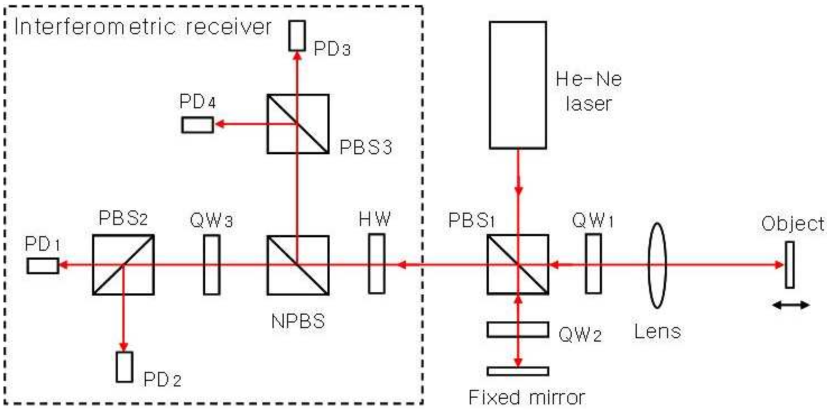

Figure 1: System configuration of the homodyne laser Doppler vibrometer

well reflective, the lens are used to focus the object beam reflected from the vibrating object to the photo detectors. The electromagnetic waves returning from the reference path and object path are expressed as followings

$$E_r = \hat{E}_r \exp[i\{\omega t\}] \tag{2}$$
$$E_m = \hat{E}_m \exp[i\{\omega t + \varphi(t)\}] \tag{3}$$

where, $\varphi(t)$ represents the phase according to the object movement by the Doppler effect.[7] Each electromagnetic wave described in Eq.(2) and Eq.(3) goes to the interferometric receiver to make the interferent beam as shown in Fig.1. Then, the interferent beam is written as following

$$\begin{aligned} \phi &= |E_r + E_m|^2 = (E_r + E_m) \cdot (E_r + E_m)^* \\ &= \hat{E}_r^2 + \hat{E}_m^2 + 2\hat{E}_r\hat{E}_m \cos\varphi(t) \\ &= A + B\cos\varphi(t) \end{aligned} \tag{4}$$

If nonlinearity errors are not considered, the interferent signals ϕ_i(i=1,2,3, and 4) obtained by the photo detectors(PD) can be expressed as followings

$$\begin{aligned} \phi_1 &= A + B\cos\varphi(t) \\ \phi_2 &= A + B\cos\{\varphi(t) + \pi\} = A - B\cos\varphi(t) \\ \phi_3 &= A + B\cos\{\varphi(t) + \pi/2\} = A + B\sin\varphi(t) \\ \phi_4 &= A + B\cos\{\varphi(t) + 3\pi/2\} = A - B\sin\varphi(t) \end{aligned} \tag{5}$$

The interferent signals, Φ_i(i=1 and2) for the velocity measurement can be easily obtained by subtracting each interferent signal described in Eq.(5), and expressed as followings

$$\Phi_1 = \phi_1 - \phi_2 = \Phi\cos\varphi(t) \tag{6}$$
$$\Phi_2 = \phi_3 - \phi_4 = \Phi\sin\varphi(t) \tag{7}$$

where, $\Phi = 2B$. The frequency demodulation algorithm to obtain the velocity is shown in Fig. 2. The demodulation algorithm begins with defining the demodulated signal $f(t)$ as

$$f(t) = \Phi_1\dot{\Phi}_2 - \Phi_2\dot{\Phi}_1 \tag{8}$$

By using Eq.(6) and Eq.(7), $f(t)$ is expressed as

$$\begin{aligned} f(t) &= \Phi^2\{\cos^2\varphi(t) + \sin^2\varphi(t)\}\dot{\varphi}(t) \\ &= \Phi^2\dot{\varphi}(t) \end{aligned} \tag{9}$$

The velocity which is proportional to the Doppler frequency can be expressed as

$$\begin{aligned} v(t) &= \frac{\lambda}{4\pi}\dot{\varphi}(t) \\ &= \frac{\lambda}{4\pi}\frac{f(t)}{\Phi^2} \end{aligned} \tag{10}$$

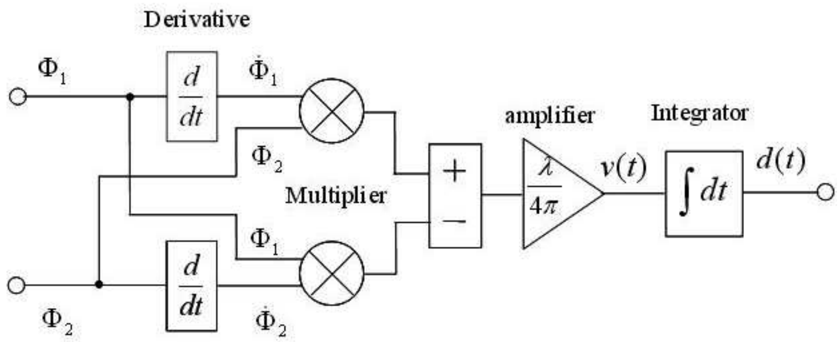

Figure 2: Frequency demodulation algorithm for the velocity measurement

As represented in Eq.(6) and Eq.(7), the interferent signals, Φ_1 and Φ_2 are proportional to the amplitude, Φ which is variable according to the variation of laser power and the reflectivity condition of the moving objects.

In a flexible body motion, the various vibration mode shapes can be observed on the object surface since the object is not a rigid body. The path of the reflected object signal to the PD can be changed due to the flexible body motion and the focusing spot size of the reflected object beam can be varied. Then, the amplitude of the interferent signal can vary by the misalignment between the reflected reference beam and the reflected object beam. If the amplitude of the interferent signal is large to saturate or very small, the errors can be caused in the mathematical calculations such as a differentiation, multiplication, and square rooting, etc.. Then, this errors distort the output signal.

Automatic gain control(AGC)

In order to reduce the errors which are caused by the amplitude variation of the interferent signal, an AGC is proposed. The AGC is constructed with feedforward structure instead of the feedback structure which is used in general applications since the small variation of the amplitude does not matter in the signal processing and the feedforward structure gives the high bandwidth. Since the amplitude of the interferent signal, Φ is variable with respect to time, Eqns (6) and (7) are rewritten as followings

$$\Phi_1(t) = \Phi(t)\cos\varphi(t) \quad (11)$$

$$\Phi_2(t) = \Phi(t)\sin\varphi(t) \quad (12)$$

The frequency of magnitude, $\Phi(t)$ is relatively lower than that of $\Phi_1(t)$ or $\Phi_2(t)$. If $\Phi(t)$ can be obtained, the interferent signals, $\Phi_1(t)$ and $\Phi_2(t)$ are normalized by dividing them with $\Phi(t)$ using the RMS(root mean square) circuit as shown in Fig.3.

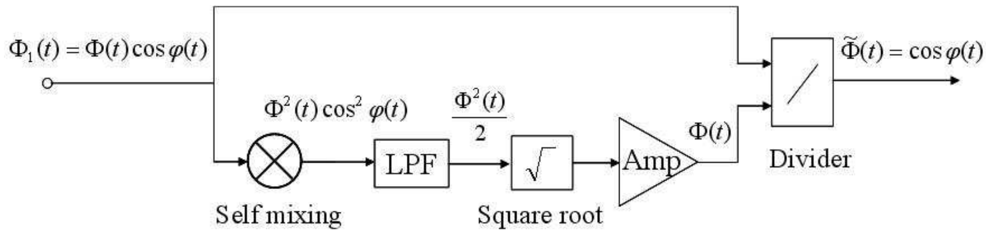

Figure 3: Schematic diagram of the proposed feedforward AGC algorithm

The signal after the self mixing is expressed as following

$$\begin{aligned}\Phi_1^2(t) &= \Phi^2(t)\cos^2\varphi(t) \\ &= \frac{\Phi^2(t)}{2}\{1-\cos 2\varphi(t)\} \quad (13)\end{aligned}$$

Since the frequency of $\Phi(t)$ is much lower than that of $\Phi_1(t)$, the DC term of Eq.(13) remains after the low pass filter which has a higher corner frequency than the frequency of $\Phi(t)$. The amplitude of the interferent signal, $\Phi(t)$ is obtained by using a square root and amplifier. The normalized interferent signal, $\tilde{\Phi}(t)$ is obtained by dividing $\Phi_1(t)$ by $\Phi(t)$, and expressed as following

$$\tilde{\Phi}(t) = \cos\varphi(t) \quad (14)$$

The amplitude of the normalized interferent signal is idealy constant regardless of the amplitude of the interferent signal. However, the amplitude of $\tilde{\Phi}(t)$ is not actually constant because there is a phase delay between $\Phi(t)$ and low pass filtered signal. This phase delay results in non-constant amplitude of $\tilde{\Phi}(t)$.

The simulation results using the AGC are shown in Fig. 4. The vibration frequency of the object is 100 Hz. The cutoff frequency of the LPF is 2 kHz. $\Phi_1(t)$ or $\Phi_2(t)$ is the simulated interferent signal. $\Phi(t)$ is the low pass filtered signal which is caused by the flexible body motion. $\tilde{\Phi}(t)$ is normalized interferent signal of the $\Phi_1(t)$ or $\Phi_2(t)$ using the AGC. $v(t)$ is the velocity signal from the normalized interferent signal by using demodulation algorithm as described above. The periodic short peak signals of the $\tilde{\Phi}(t)$ are appeared due to the

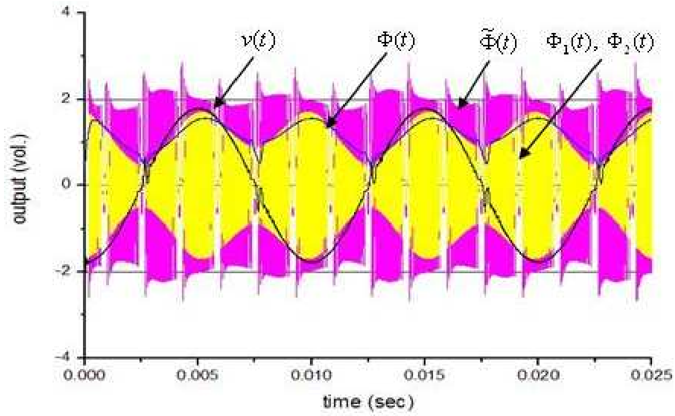

Figure 4: Simulation results when the object vibrates with 100 Hz oscillation with using the AGC

characteristics of the LPF at zero frequency. The simulation results show that the proposed feedforward AGC can normalized the interferent signal and reduce the error which is caused by the amplitude variation of the interferent signal.

EXPERIMENT

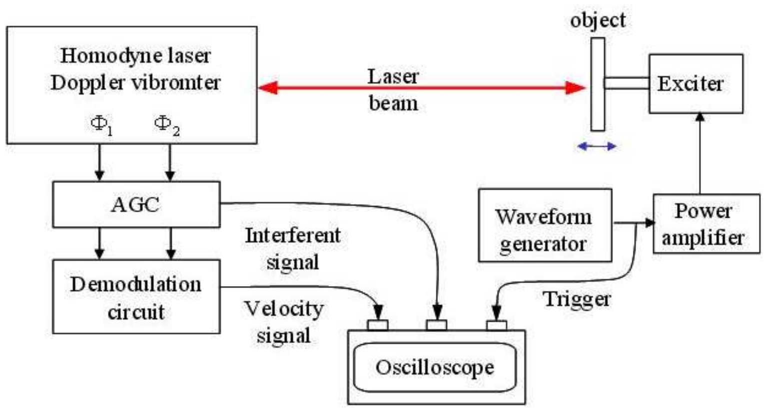

Figure 5: Experimental setup with using the AGC

To verify the proposed method explained above, the homodyne laser Doppler vibrometer using the AGC circuit is set up as shown in Fig. 5. The system is composed of the laser interferometer, the phase demodulation circuit with AGC, and the object which is fixed on the exciter. The exciter is vibrated by using a waveform generator. When the object vibrates with the exciter, the interferent signals are obtained at the photo detector. The interferent signals go to the phase demodulation circuit with AGC. Then, the velocity or displacement can be obtained.

Analog operational amplifier, LT1280 from Linear technology co. and multiplier, AD734 from Analog devices Inc. are used in analog circuit. The bandwidths of these chips are over 3 MHz in an actual application. The low frequency of the amplitude variation of the interferent signal is not over 1 kHz actually. Therefore, the cutoff frequency of the LPF is set to about 3 kHz.

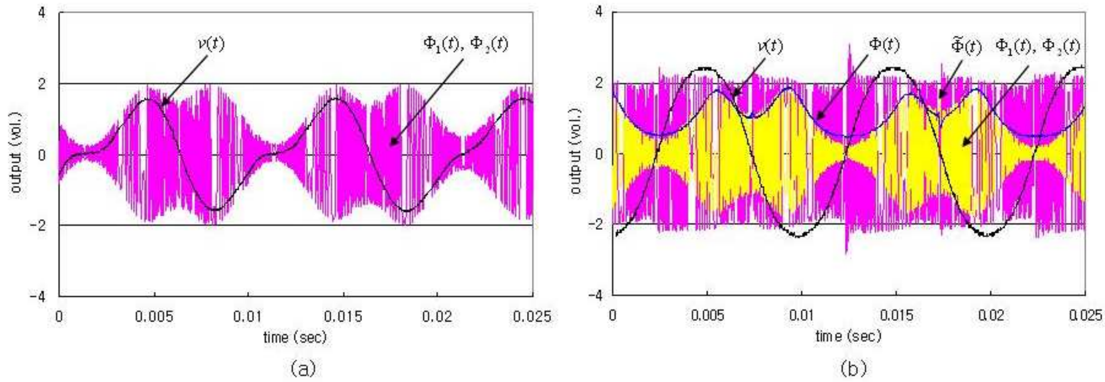

Figure 6: Experimental results when the object vibrates with 100 Hz oscillation (a) without using the AGC, and (b) with using the AGC

Figure 6 shows the experimental results when the object vibrates with 100 Hz oscillation. Figure 6(a) shows the interferent signal and the velocity signal without using AGC. The amplitude variation of the interferent signal is large. The velocity signal is distroted when the amplitude of the interferent signal is small. Figure 6(b) shows the interferent signal, low pass filtered signal of the interferent signal, revised interferent signal after passing the AGC, and velocity signal when the results when the AGC is used. As it is predicted that the low pass filtered signal follows the amplitude shape of the interferent signal since the frequency of the interferent signal is relatively higher than that of the amplitude variation. The amplitude of the revised interferent signal is nearly constant regardless of the amplitude of the input interferent signal. Then, the velocity signal is not distorted even in the points where the amplitude variation is large.

The AGC gives the revised interferent signals with constant amplitude regardless of the amplitude of the input interferent signal. The proposed method can be verified that the velocity of the moving object can be obtained without any distortion even in the flexible body motion with severe amplitude variation of the interferent signal through the experiment.

DISCUSSION

In this article, the AGC is suggested to reduce the error due to the amplitude variation of the interferent signal in the laser Doppler vibrometer. The amplitude variation of the interferent signal due to the flexible body motion, and the velocity signal distortion after passing through the demodulation signal processing circuit are observed by the experiment. The mathematical modeling of the interferent signal of the flexible body motion, and the brief analysis of the AGC are done. The electronic circuits are constructed to implement the AGC algorithm. The bandwidth of the proposed feedforward AGC is higher than that of the other feedback system since the proposed AGC has more simple structure, while most of other AGC adopt the feedback structure. The experimental results verify that the proposed feedforward AGC makes the demodulation system of the laser Doppler vibrometer robust to the amplitude variation of the flexible body motion.

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