Self-mixing frequency measurement using a liquid filled container with elastic bottom

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In this study, a method is proposed to measure vibration of absorbing, scattering, and rough surfaces where the self-mixing method is diffucult to apply. In the method, a liquid filled container with elastic bottom is used between the vibrating surface and the laser beam. Hence, the vibration of the surface was transmitted to the liquid. The vibration of liquid surface was measured at frequencies between 10-1000 Hz by using self-mixing method. The frequency of measured self-mixing signal was obtained by continuous wavelet transform based signal processing method. Maximum 1.5 Hz error was observed between the measured frequency and the frequency of the vibration source. The proposed method can expand the range of the applications of self-mixing method where compactness and low cost of the measuring devices are essential.

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1. Introduction

Many kinds of laser interferometry techniques have been developed to measure velocity, displacement and vibrations of devices in the industrial and laboratory environments [1]. In particular, the self-mixing technique has retained its importance for many years [2]. In self-mixing technique, there is no need for an external optical interferometer and a simple compact setup is provided. Also, it is highly sensitive, has some sort of coherent detection that easily reaches the quantum detection regime and it is possible to measure the path length under the nanometer scale [3]. Despite the simplicity of the layout of this technique, one of the challenges is the need of precise optical alignment to direct the reflected light from the surface to the laser diode's (LD) cavity. Specialy, this makes it difficult to take measurements on non-reflective, scattering and non-flat surfaces. To obtain self-mixing signal from the vibrating surface, the surface must be reflective and the laser beam must be perpendicular to the surface [4]. Another challenge is that the amplitude, velocity or frequency of the medium in interest cannot be extracted directly from the measured signal without signal processing in many cases [2, 4].

In this study, a new method is proposed for performing vibration frequency measurements by self-mixing method. In this method, a liquid-filled structure with an elastic base was designed. The purpose of this structure is to transmit the vibrations of surface to the liquid surface. These surfaces can be absorbing, scattering and rough surfaces. Thus, vibration frequency of the surface of the liquids can be measured relatively easily by self-mixing method.

2. Principle of operations

In this part, at first, the self-mixing technique and some of its challenges were summarized afterward the parts and setup of proposed system were presented. Finally, the method, used for signal processing and obtaining the frequency from self-mixing signal, were explained.

2.1. Self-mixing method

The self-mixing interferometry is a method that applied by measuring the change of laser intensity and spectrum depending on where the laser beam reflected back into the laser diode (LD) [5]. Many self-mixing interferometers do not require external dedector to monitor laser intensity change. A LD with a monitor photodiode, integrated into the same package, can be used to obtain self-mixing signal.

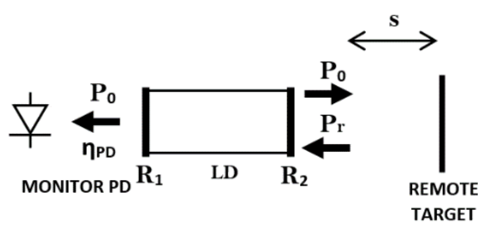

Fig. 1. Configuration of the self-mixing method

The principle of the self-mixing interferometer based on vibration measurement can be summarized as follows: The emitted rays from the laser and back reflected rays will take different paths during the vibration of the remote target. Thereafter, reflected beam interferes with the light already present in the cavity. Depending on the frequency alteration and phase of the back reflected light, the threshold condition of the LD changes. As a result, when the current pump is held constant, the emitted power changes [3,6]. The alteration in threshold value indicates a variation in the actual LD carrier density; as a result, the wavelength emitted by the LD subject to back reflections is also slightly varies [3].

As shown in Fig. 1, P_0 is the power of the beam emitting from the laser and $P_r = P_0/A$ is the power of the beam reflected from the moving object, A is the total optical power attenuation in the external cavity [3]. The analytical steady state solution of power emitted by LD can be expressed as:

$$P(\varphi) = P_0[1 + mF(\varphi)] \quad (1)$$

where P_0 is the power emitted by unperturbed LD, m is the modulation index, $F(\varphi)$ is the interferometric phase, $\varphi = 2ks$ is the optical phase shift, k is the wavevector, and s is the distance between target and LD mirror of R_2 [3, 7]. Therefore, the $F(\varphi)$ depends on modulation index and waveform swings over a full period as the target distance changes by $2k\Delta s = 2\pi$ for $m \ll 1$. The modulation index m and the function $F(\varphi)$ depend on the feedback parameter C:

$$C = \frac{\kappa s\sqrt{1+a^2}}{L_{las} n_{las}} \quad (2)$$

where a is the LD line width enhancement factor, L_{las} is the laser cavity length, and n_{las} is the refractive index of the cavity. The equation of k can be expressed as:

$$\kappa = \frac{\varepsilon}{\sqrt{A}} \frac{1-R_2}{\sqrt{R_2}} \quad (3)$$

where, R_2 is the reflectivity coefficient and $\varepsilon \leq 1$ explains mismatch between reflected and laser modes [3]. The C parameter is very important for obtaining the self-mixing signal because self-mixing can be affected when the value of the C parameter changes [8, 9]. When $0.1 < C < 1$, a self-mixing signal has a form without sharp peaks that are asymmetric or sinusoidal. When $1 < C < 4.6$, peaks will look like saw tooth and fringes exhibit hysteresis. When $C > 4.6$, saw tooth gradually disappear [3]. As can be seen in the equation (2) and equation (3), the beam that returns to the laser cavity changes the C parameter. Because the C parameter also affects the F (φ) function, the LD intensity so self-mixing signal strongly depends on the power level of the light entering into the cavity. It can be said that the C parameter changes when the self-mixing method applied to the rough and oblique surfaces. In this case, signal processing algorithms or circuits are needed to be improved to evaluate self-mixing signal [9]. This kind of complicated solutions does not necessary when the surface is flat and reflective like the designed apparatus used in our system.

2.2. Experimental setup

The designed experimental apparatus and mechanism of vibration transmission to the liquid surface were given in Fig. 2. The purpose of designed apparatus is to transfer vibration from oblique and rough surfaces to smooth, flat and reflective surface of the liquid instead of a mirror [10]. The apparatus was assembled from a cylindidrical container and an elastic membrane. The cylindidrical container has a radius of 15.4 mm and a height of 25.6 mm. The upper side of cylindrical container is open and the inner surface of the container was covered with a perforated plastic material which has an irregular pattern to decrease the effect of possible regular wave reflection from the surface of the container. This material is important to prevent possible modes that can occur by interaction of water waves with the cylindrical surface.

By the structure of the apparatus it is ensured that the surface where the vibrations are taken will always be flat and parallel to the ground which makes it easy to align the reflected laser beam to the cavity of LD. Here, a piezoelectric material, the underlying vibration source, will vibrate the membrane and this vibration will vibrate the water surface. The increase and decrease of the water height will turn into a swing motion (Fig. 2), which will lead to the formation of the self-mixing signal by focusing the part of reflected light into laser cavity and monitoring laser intensity changes.

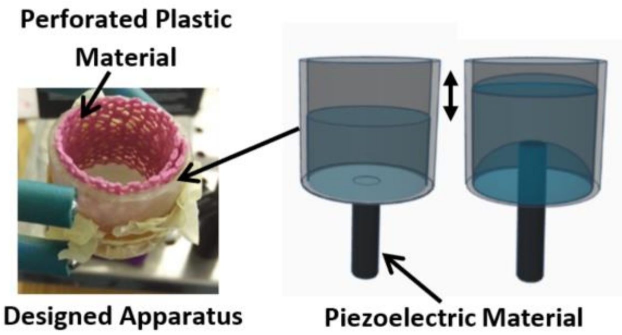

Fig. 2. Designed apparatus with perforated plastic material and illustration of liquid level change due to the piezoelectric material expansion

A piezoelectric material (PI P.820.30) was used as a vibration source in the experimental setup. The Gwinstek GFG-8015G signal generator were used for adjusting the vibration frequency and amplitude of the piezoelectric material. It is given in datasheet that this material (PI P.820.30) expands 45 μm when 100V is applied.

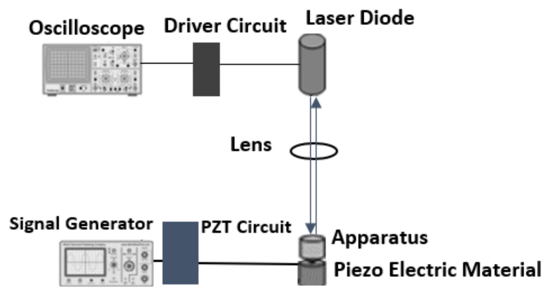

Fig. 3. Schematic of the experimental setup for self-mixing measurement

In the experiments, the piezoelectric material was driven with potential difference of 8 Vpp in the range of frequency 10-1000 Hz. A LD (Thorlabs-DL3147-060) that was used as a light source has a wavelength of 650 nm and a power of 7 mW. A digital oscilloscope is used to probe voltage changes of resistor connected to the photodiode of LD. Received datas are processed on the computer. Any external factors that might affect the result of experiments were tried to be removed while taking measurements. As an example, the test setup is built on a vibration isolating material so that the effect of external vibrations was minimized.

There are studies on the frequency response and modes that can occur on the surface of liquid filled cylindrical structures with flexible base [11]. In these studies, it has been shown that frequencies of surface waves may differ from the frequency of the vibration applied to the flexible base. We changed our system in order to determine whether such a situation exists in our designed system and validate previous results obtained with the system in Fig. 3. In the new experimental setup, an external photodiode (Thorlabs DET36A/M) was used as a detector instead of the photodiode in the LD. The laser beam was projected to the center of the water surface at an angle of 45 degrees with respect to the surface normal. It is expected that if there is no surface wave interference on the water, the reflection of the laser beam will move on an axis where photodiode placed and this motion will be monitored as a sine wave. If this is not the case, a sinusoidal wave form cannot be seen or signal with different frequency can be observed.

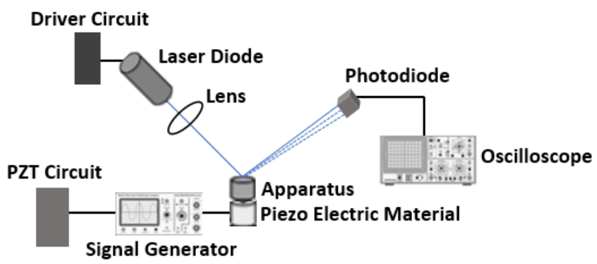

Fig. 4. Schematic of the experimental setup for validation

Signal with 50V amplitude was applied to the piezoelectric material in order to increase the response of the water surface. Experiments were performed at low frequencies (e.g. 1, 2, 3 Hz) and at relatively high frequencies (e.g. 400, 500, 1000 Hz).

2.3. Signal processing

Wavelet transform, a widely used multi-resolution signal processing method, was choosen for processing the measured self-mixing data. In wavelet transform, the analysis is performed at time-scale domain. While scale gives information about local regularity, time refers to the moment of the formation of wavelet. Basically, signals are decomposed into different scales in this method. Decomposition is realized by using short windows at high frequencies and long windows at low frequencies [12]. As a result, sharp transitions of the signals are preserved at the end of decomposition process which is an advantage for self-mixing signal analyses by using this method.

The continuous wavelet transform (CWT) is used to determine the frequency of the self-mixing signal by ridge detection in time-frequency analysis. The CWT is expressed as the sum of all times, multiplied by the scaled and shifted versions of the wavelet function [13]. The CWT of a signal $x(t)$ is expressed as:

$$wt(s,\tau) = \frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-\tau}{s}\right)dt \tag{4}$$

where s, τ, and $\psi^*(.)$ denote scaling parameter, shifting parameter, and complex conjugation of the base function, respectively.

The wavelet coefficients produced at different scales for different parts of the signal are obtained by decomposing the signal into 32 scales by CWT. In separating the self-mixing signal with CWT, 6th order complex Gaussian wavelet function is used as it is suitable for the signal structure. The low scales have fast changes and correspond to high frequencies whereas high scales have slow changes and correspond to low frequencies. In the case where a signal contains different scale characteristics over time, the scalogram provides a time-scale representation of a signal that is more useful than a time-frequency representation. In Fig. 5, a signal with different frequency components is given a time-scale representation with a scalogram. As can be seen from Fig. 5, the frequency information that the signal has over the scale information corresponding to each frequency can be obtained.

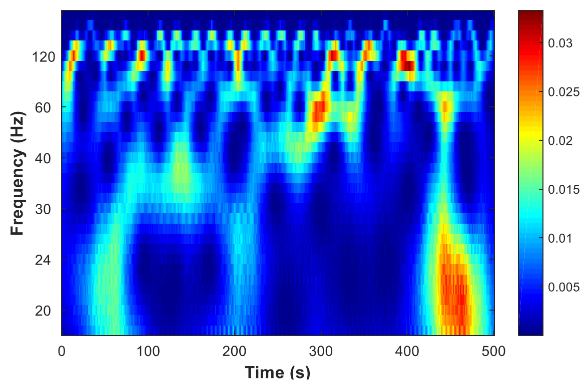

Fig. 5. The scalogram representation of a self-mixing signal with a frequency of 25 Hz

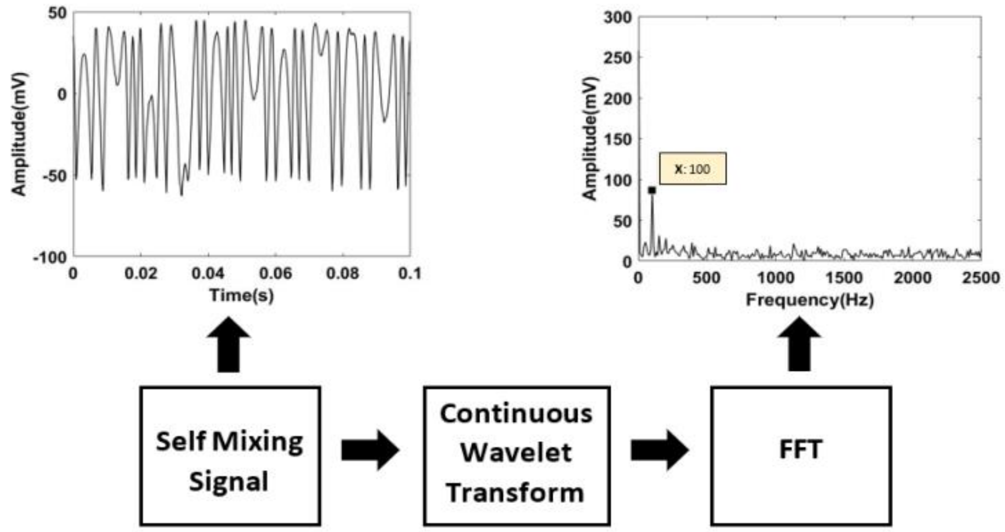

Fig. 6. Flow chart diagram of signal processing and FFT result of self-mixing signal with frequency of 50 Hz

In the scalogram representation, the frequency of a signal is calculated from the scales in equation (5) considering that high frequencies are resolved at low scales and low frequencies are resolved at high scales.

$$F_a = \frac{F_c}{a\,\Delta} \tag{5}$$

where F_a is the relative frequency of a scale in Hz, F_c is the center frequency of a wavelet, a is a scale and Δ is the sampling rate.

In order to obtain the frequency of the signal, a constant threshold value is applied to the wavelet coefficients of the first scale. The threshold values are chosen as the average of the absolute values of the wavelet coefficients of the respective self-mixing signal. After applying a threshold value, Fourier transform of thresholding wavelet coefficients is used to obtain frequency of measured signal (FFT in Fig. 6). The value of obtained frequency should be two times of the given frequency since the wavelet coefficients get the highest value twice in full oscillation. Another reason is the laser diode which is used is not suitable to differentiate the up and down direction of surface movement at full oscillation of applied signal. As an example self-mixing signal with a frequency of 50 Hz is shown in Fig. 6 and FFT result with 100 Hz is obtained as expected.

3. Results and discussion

Self-mixing measurements were taken by using the designed system shown in Fig. 3 in the frequency range of 10 to 1000 Hz. In the experiments, water was used to fill the container given in Fig. 2. The reflectance of water surface is around 0.02 (refractive index, 1.33) at 20 ^{o}C while the incident ray strikes to the surface perpendicularly. In this case, only 2% of the emitted light is reflected. The fluids like paraffin which have larger refraction index can be used in situations where more reflected intensity is required.

Observed self-mixing signals were asymmetric and saw tooth in our experiments. If we consider the reflectance of water and self-mixing data shape, it can be said that the C parameter given in Eq (2) is in the range of $0.1 < C < 1$. The frequency of vibration was determined from the obtained self-mixing signal by the CWT based signal processing algorithm. The obtained data showing the frequency of the vibration against the measured frequency is given in Fig. 7. The results are consistent with the given frequency values. However, maximum 1.5 Hz differences were observed in the measured frequency range. The average error margin for 200 measurements made between 10 and 1000 Hz was around 0.3 Hz (total frequency difference / number of measurements). There may be several causes of this kind of frequency difference like signal processing errors, some mismeasurement originating from data acquisition and usage of not perfectly isolated system from the mechanic vibrations. However, in following part it is shown that the measurement of the frequency is possible by using external photodiode and FFT method. This indicates that main cause of measured error was due to the signal processing of self-mixing signal. In addition, the non-filtered self-mixing signal is a time dependent pulsating AC signal with DC offset and there are several articles about frequency deduction from self-mixing signal [2, 9]. The method we used is relatively simpler and different than these methods but it is error-prone.

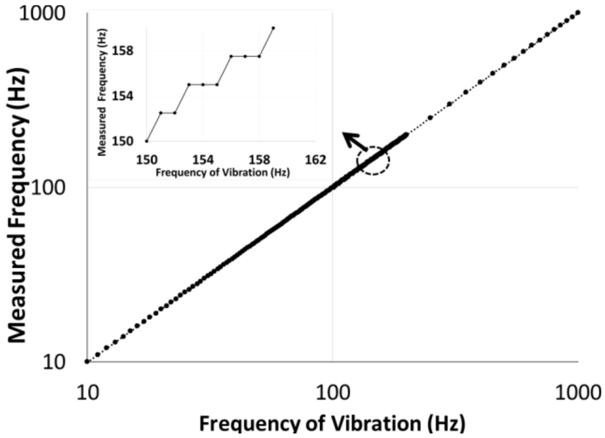

Fig. 7. Measured frequency by using self-mixing method and the frequency of the vibration

The data obtained from the experimental setup, which was established to observe whether the water surface modes were formed, was processed by using FFT and frequencies of sinusoidal signals were determined. The frequencies of the signals which are applied to piezoelectric material are in accordance with the frequencies of the measured signals as shown in Fig. 8. Based on the results of this experiment, it is seen that the fluctuations on the surface of the water transmits the frequency of vibration applied from the elastic bottom.

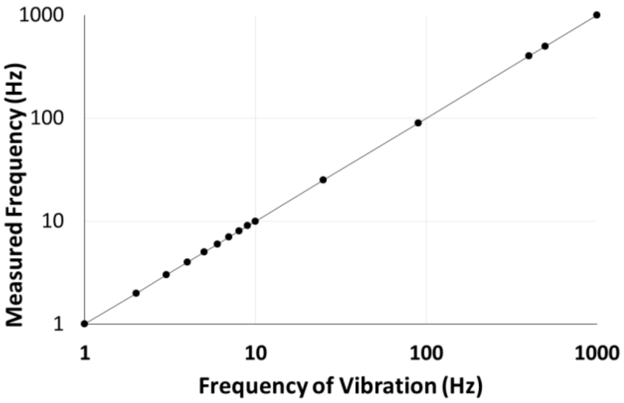

Fig. 8. Measured frequency by using an external photodiode and vibration frequency

4. Conclusions

A water filled container with elastic bottom, was designed to measure vibration frequencies of surfaces. This container was used for transferring applied vibrations to the liquid surface that ensures an easy optical alignment for self-mixing technique. A self mixing setup was built and a piezo electric material was placed under the bottom of the apparatus as a vibration source. The frequency of the measured self-mixing signal was obtained by CWT signal processing. The maximum error was around 1.5 Hz in the frequency range of 10-1000 Hz. In addition, the incident light to the liquid surface was reflected to an external photodiode and the vibration frequency was measured correctly. Consequently, the frequency transmission feature of the apparatus was confirmed. These results show that the proposed system can be used for frequency measurement on the surfaces where self-mixing method is difficult to apply.

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