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Abstract

The paper studied the noise elimination methods for the signals observed from a self-mixing-laser diode (SM-LD) based sensing system. The core part of the sensing system consists of a LD, a lens and an external vibrating target. The proposed noise elimination methods are applied on both the simulated and experimental sensing signals. The results presented in the paper show the noise contained in the sensing signals can be effectively eliminated. As a consequence, the vibration trace of the target can be reconstructed with high accuracy using this sensing system.

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Eliminating Noises Contained in Sensing Signals from a Self-mixing Laser Diode

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ABSTRACT

The paper studied the noise elimination methods for the signals observed from a self-mixing-laser diode (SM-LD) based sensing system. The core part of the sensing system consists of a LD, a lens and an external vibrating target. The proposed noise elimination methods are applied on both the simulated and experimental sensing signals. The results presented in the paper show the noise contained in the sensing signals can be effectively eliminated. As a consequence, the vibration trace of the target can be reconstructed with high accuracy using this sensing system.

Keywords: Laser diode, self-mixing interference, optical feedback self-mixing interferometry, noise reduction, digital filtering

1. INTRODUCTION

When a small fraction of light emitted by a laser diode (LD) is reflected or backscattered by an external target and re-enters the laser internal cavity, both the amplitude and the frequency of the emitted laser power can be changed[1-3]. In this case, the laser diode is called a self-mixing LD (SMLD) which can be used as a sensor for obtaining metrological quantities associated to the external target as well as the parameters of the LD. Experimental set-ups suitably oriented to such sensing have been devised, and theoretical analysis proposed accordingly [2-8].
A typical SMLD sensing system is depicted in Figure 1. The core part of the system consists of a LD, a lens and an external target. When the target moves or the injection current inside the LD changes, the emitted LD power will vary. The LD power, also called a SMLD sensing signal, is detected by a photodiode (PD), then is pre-processed by an analog detection circuit unit and finally acquired by a personal computer for the extraction of information carried by the sensing signal.

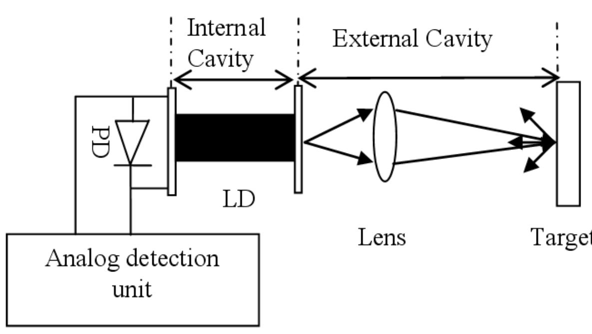

Figure 1: Schematic SMLD based sensing system

The sensing model used for above system is developed from Lang and Kobayashi (L-K) Equations [10], rewritten as follows [3-8]:

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$$\phi_F = \phi_0 - C \cdot \sin[\phi_F + \arctan(\alpha)] \tag{1}$$

$$g = \cos(\phi_F) \tag{2}$$

$$P = P_0 \left[1 + m \times g\right] \tag{3}$$

Equation (1) describes the laser phase variation due to the feedback light, with the variables defined as follows. $\phi_0 = 4\pi L / \lambda_0$, $\phi_F = 4\pi L / \lambda_F$, where ϕ_0 and ϕ_F are the external light phases at the location of the target for the LD without and with feedback respectively. λ_0 and λ_F are the laser wavelengths of the LD in the two situations, and L is the length of the external cavity.

Equation (2) is called interferometric function. Equation (3) gives the output power of the laser, denoted by P , where P_0 is the power emitted by LD without light feedback, m is modulation index of the laser power. As signal g can be obtained from signal P, we use g as a normalized SMLD sensing signal.

The parameters C and α in above model are the optical feedback level factor, and the line width enhancement factor respectively. The values of the two parameters are related to the design of the sensing system and can be determined using the method in [7].

In general, the measured metrological quantities are connected to the sensing system through ϕ_0. The observed sensing signal from a SMLD system is P. For the detection of the quantities, the key is to extract ϕ_0 from P. The reconstruction of a vibration (or displacement) signal has been reported in [4, 11, 12]. [4] reconstructs an arbitrary displacement with a resolution of $\lambda_0 / 2$ by counting fringe pulse using analog circuit design. Following the work in [11], a digital signal processing based method for the reconstruction of displacement is reported in which the reconstruction accuracy is said on the order of tens of nanometers. However, this work does not discuss noise affection on the reconstruction algorithm. [12] presents an algorithm for displacement reconstruction with a resolution of $\lambda_0 / 50$ but only for weak feedback cases.

To achieve accurate sensing, we need to obtain P with high quality. Two ways can lead to improve the quality of the signal P. One is to optimize the optical and electrical setups for a SMLD system. Another one is to use advanced digital signal processing methods to remove the noises contained in the sensing signal P. This paper focuses on the later. We will firstly pre-processing the sensing signal obtained from a SMLD system by adaptive filtering, signal normalization, then, a phase unwrapping algorithm is developed for retrieving the vibration of the target.

2. NOISE REDUCTION AND VIBRATION RECONSTRUCTION

2.1 Principle of vibration reconstruction

Considering the case that the target is on simple harmonic vibration, we have:

$$s(t) = s_0 + A_s \sin(2\pi f t) \tag{4}$$

Where $s(t)$ and s_0 are respectively the instantaneous and initial positions of the target respect to the LD facet. A_s is the vibration amplitude, f is the vibration frequency. This vibration information is picked up by the SMLD sensing system through ϕ_0 represented as below.

$$\Phi_0(t) = \frac{4\pi s_0}{\lambda_0} + \frac{4\pi}{\lambda_0} A_s \sin(2\pi f t) \tag{5}$$

From equation (1), a time-varying phase ϕ_0 leads to a time-varying phase ϕ_F , and thus the laser power P is modulated. Using equations (1)-(5), the relationships between the signals $\phi_0(t)$, $\phi_F(t)$ and $g(t)$ can be plot and shown on figure 2.

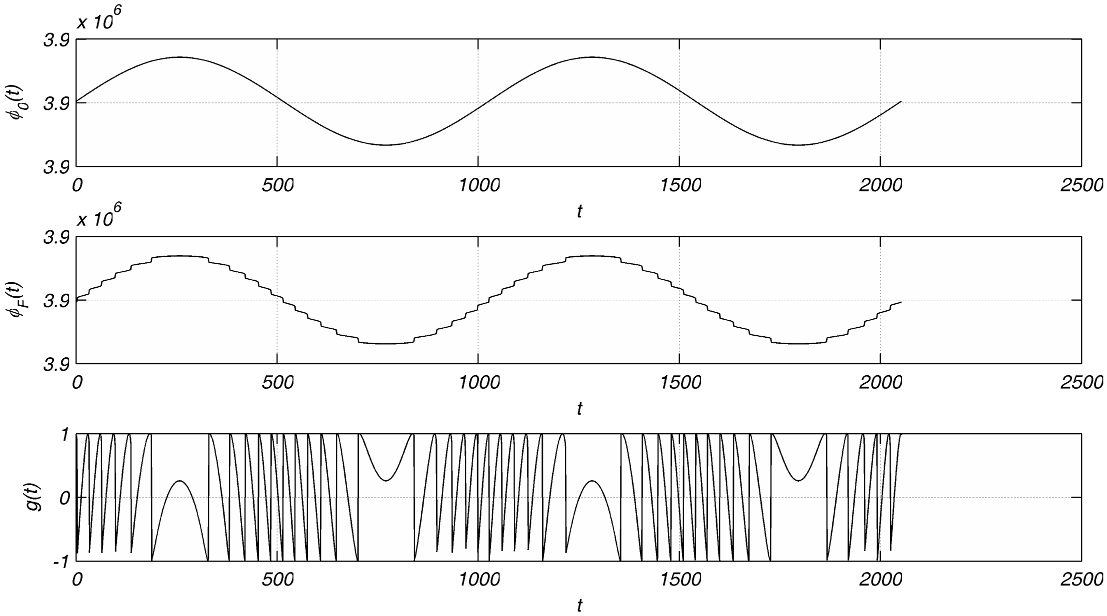

Figure 2: Relationships between ϕ_0 , ϕ_F and P , where $\phi_0(t) = 3.9\times10^6 + 11\pi\sin(390\pi t)$, C=1.5, $\alpha = 3$

The reconstruction of the vibration is to obtain ϕ_0 (t) using signal $g(t)$. The basic idea is to calculate the inverse function of *g(t)* using equation (2) to obtain its phase signal $\phi_F(t)$, then to reconstruct signal ϕ_0 (t) using equation (1) and finally the vibration signal *s(t)* according to equation (4). We will only discuss the reconstruction for the variable component in equation (4).

2.2 Reconstruction algorithm with noise reduction

Based on our observation, the SMLD based sensing accuracy is mainly affected by two disturbance factors. One is a low frequency fluctuation which brings an envelope in the sensing signal. The low frequency signal is mainly due to non-perfect rectifier circuit used for driving the LD. Another one is a white noise signal generated from electronic or thermal interference which obscures the characteristics of the sensing signal. The two factors seriously decrease the reconstruction accuracy of vibration signals.

To obtain ϕ_F (t) from signal *g(t)* , the key is to un-wrap the inverse function of *g(t)*. This requires to divide signal *g(t)* into segments. Each segment should be monotonic variation. The segments can be determined by some characteristic points shown on figure 3 (a). The points are called reverse points (indicated by R_k) and jumping points (indicated by J_i).

The characteristic points can be used to generate two control signals named control signal 1 and control signal 2. The control signal 1 (seen in figure 3(b)) generated from jumping points divides signal *g(t)* into short segments. Each short segment is marked by '$g(t)_i$'. The control signal 2 groups the short segments to form long segments according to the locations of reverse points. Each long segment is marked by '$\pm2\pi$ region'. The two control signals are jointly used to adjust the wrapped value of ϕ_F (t) for every short segment.

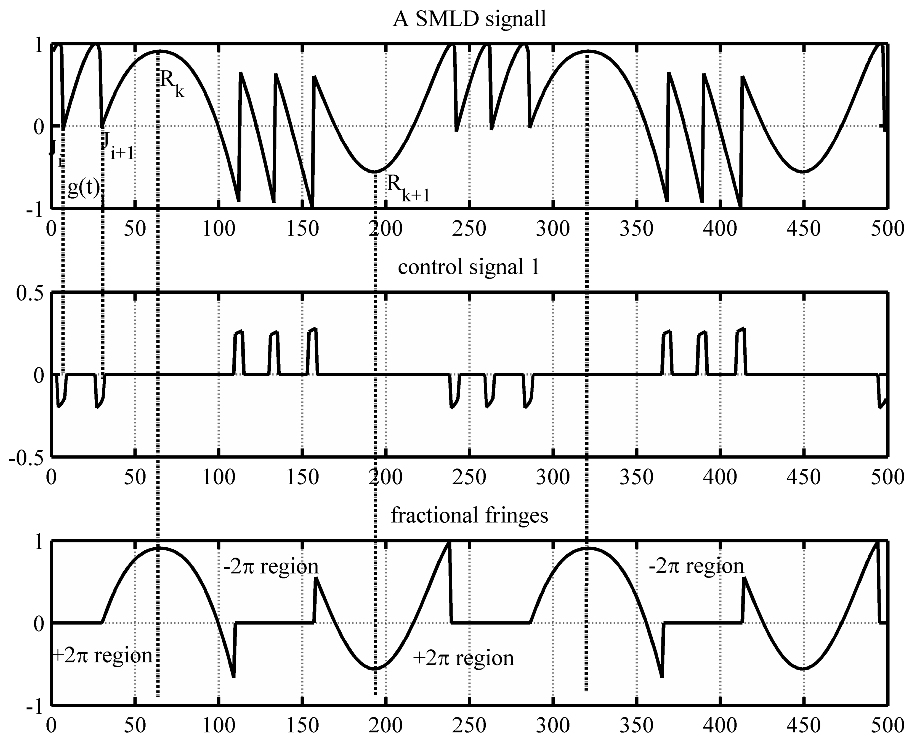

Figure 3: SMLD signal and its characteristic points

In practice, an experimental signal g(t), unlike the ideal signal g(t) plot on figure 2 , often exhibits an envelop. And those characteristic points are often buried in noise. Only after we remove the envelop and clearly recognize the characteristic points, the wrapped ϕ_F (t) can be unwrapped correctly. An adaptive filter system shown in figure 4 is designed for this aim. The filter includes two input channels. The corrupt SMLD sensing signal from the sensing system is entered the upper channel. The bottom channel is used to receive a reference signal which is used to reduce the noise contained in the SMLD signal. The reference signal can be obtained from the driving source of the LD. H(z) is the transfer function of the adaptive filter, Y(t) is the output of the adaptive filter and g(t) is the difference of the corrupt signal and the output of the adaptive filter. The least mean square (LMS) algorithm is employed by the adaptive filter. The weights of the filter are updated using this algorithm.

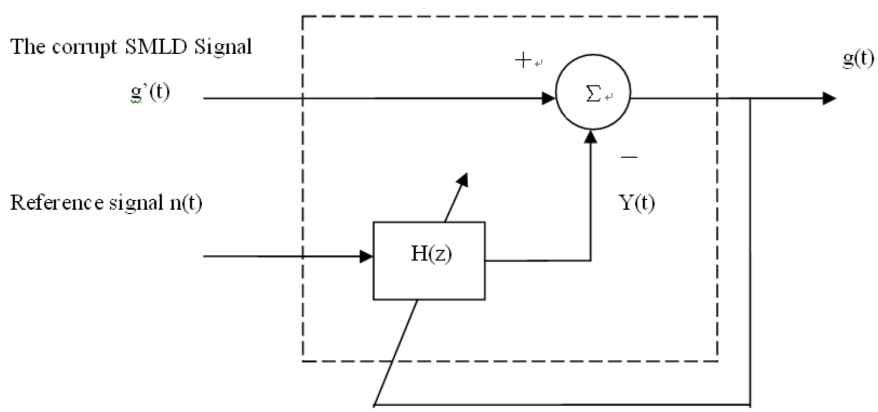

Figure 4: Adaptive filter scheme used for noisy SMLD signals

After the SMLD sensing signal is processed by above adaptive filtering scheme, we can indentify those characteristic points. We firstly need to obtain the differential signal of a SMLD signal, from which the jumping points can be located. This differential signal can be further processed and used for extract fractional fringe parts shown in figure 3(c). The fractional fringes are used to locate the reverse points and generate control 2. Due to noises, around some characteristic points, there are narrow pulse sequences. We remove the noise pulses by detecting pulse width and generate a revised differential signal as control 1. This control signal can accurately divide the SMLD signal into short segments. Each segment signal can be directly used for calculating $\phi_{Fi}(t)$ as below

$$\phi_{Fi}(t) = a\cos(g_i(t)) \tag{6}$$

As the values of $\phi_{Fi}(t)$ are wrapped, they should be adjusted by adding $\pm 2\pi$ under the control of control signal 2. The adjustment is done by

$$\phi_{Fi}(t) = a\cos(g_i(t)) + 2i\pi \quad g(t) \in (R_{2k-1,} R_{2k)} \tag{7}$$

$$\phi_{Fi}(t) = a\cos(g_i(t)) - 2i\pi \quad g(t) \in (R_{2k,} R_{2k+1)} \tag{8}$$

Up to now, the proposed reconstruction algorithm with noise elimination can be summarized as following steps.

- Step 1, Apply LMS algorithm to remove the envelop
- Step 2, normalize the amplitude of the SMLD signal
- Step 3, identify the jumping points to get control signal 1
- Step 4, extract the fractional parts and locate reverse points to generate control signal 2
- Step 5, the control signal 1 divides the SMLD signal into segments denoted by $g_i(t)$, equation (6) is applied on each segment to obtain its phase segment $\phi_{Fi}(t)$.
- Step 6, all the segments $\phi_{Fi}(t)$ are adjusted using equation (7) and (8)
- Step 7, reconstruct $\phi_0(t)$ using equation (1) cooperating parameters *C* and α
- Step 8, convert $\phi_0(t)$ to vibration signal *s(t)* using equation (5)

2.3 Verification of the Reconstruction algorithm

Supposing $\phi_0(t) = 3.9\times10^6 + 11\pi\sin(390\pi t)$, we use the SMLD sensing model described by equation (1)-(3) with parameters C=1.5, $\alpha = 3$ to generate a SMLD sensing signal shown in figure 5(a). 10dB white noise is added to the sensing signal. According to the proposed algorithm, we reconstructed the signal $\phi_F(t)$ shown in Figure 5 (b), and then $\phi_0(t)$ is obtained using equation (1) shown in figure 5 (c). It can be seen that the vibration signal can be reconstructed correctly from the simulated SMLD sensing signal with 10dB noise. Note that the constant phase in $\phi_0(t)$ can not be obtained in practice. Actually, we do not need to know the constant part for a practical vibration.

Figure 6 shows the reconstruction result using an experimental SMLD sensing signal. The vibration information $\phi_0(t)$ is calculated using parameters C=1.5 and α =3. Not that there is small fluctuation appearing on the reconstructed result $\phi_0(t)$. This is due to non-accurate values of above two parameters. The result can be improved by obtaining accurate values for the two parameters by referring to [7].

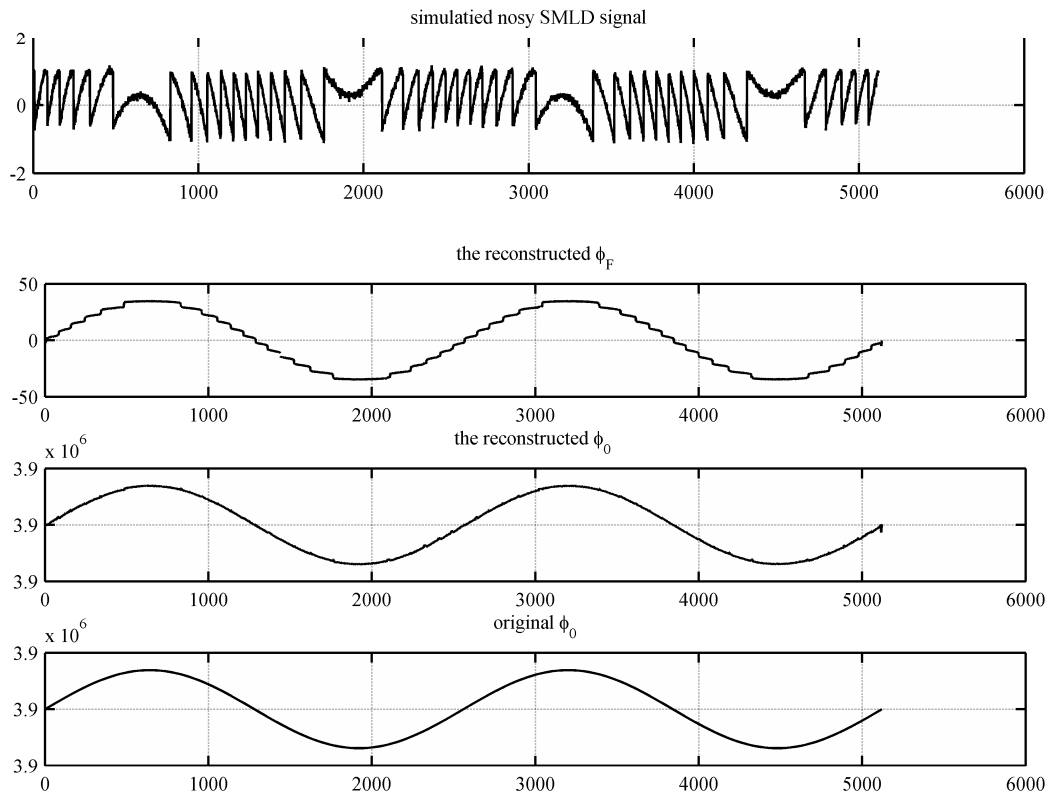

Figure 5: Vibration reconstruction from a simulated SMLD sensing signal with 10dB noise

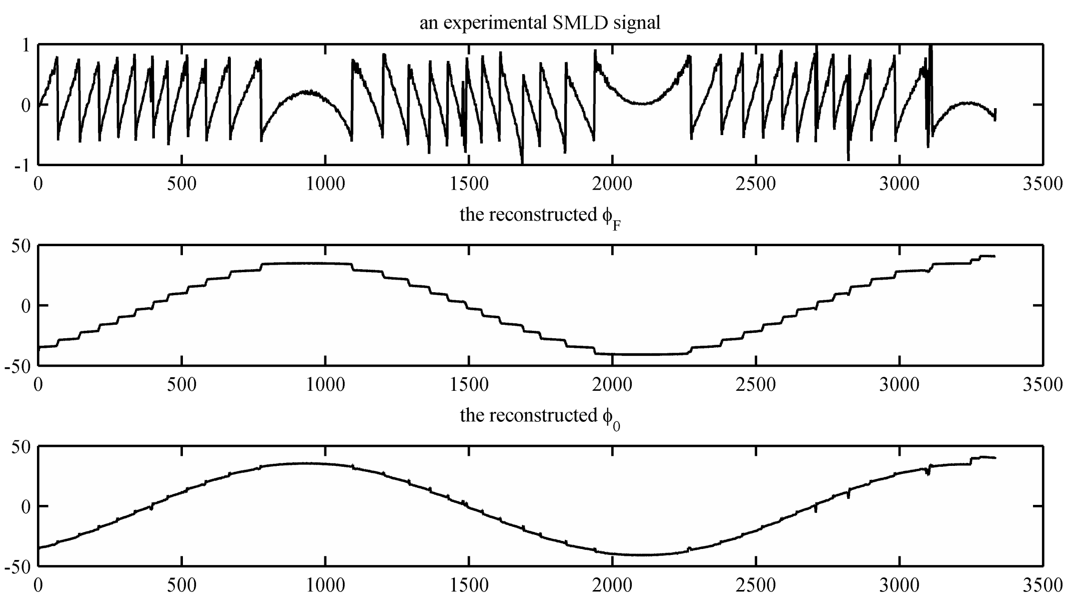

Figure 6: Reconstruction result for an experimental SMLD sensing signal.

3. CONCLUSIONS

The paper proposes a reconstruction algorithm used for obtaining the vibration of the target using a SMLD based sensing system. The algorithm has been verified by both simulation and experimental data. The results presented in the paper show that the noise affection can be effectively eliminated and the vibration information can be retrieved correctly from a SMLD sensing signal.

4. ACKNOWLEDGMENT

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