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Improved transition detection algorithm for a self-mixing displacement sensor

Chunlei Jiang[a,b], Chengwei Li[a,*], Yuan Wang[b]

[a] School of Electrical Engineering and Automation, Harbin Institute of Technology, China
[b] College of Electrical and Information Engineering, Northeast Petroleum University, China

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ABSTRACT

An improved transition detection algorithm for a self-mixing interference (SMI) laser sensor is presented in this study. The proposed algorithm can correctly identify extreme points of SMI and can quickly and accurately locate determination thresholds, thus it can effectively reduce positioning deviation. The SMI laser sensor enables accurate reconstruction of the displacement information from a SMI signal. Displacement reconstructions performed by improved transition detection algorithm have been validated through simulations and experiments.

1. Introduction

In the last 20 years, researchers have spent considerable time and energy on the self-mixing interference (SMI) phenomenon [1–4]. The emitted optical beam is reflected into the laser cavity by an external moving target to form SMI effect, and the output power of the laser is altered once the optical path length changes. Laser output power changes an interference fringe when the external target moves by half a wavelength. Therefore, SMI exhibits the same sensitivity as that of the traditional double-beam interference. Because an SMI device shows the advantages of having a simple structure and being compact, easy to align, non-destructive, and smart, SMI technology has been widely used in speed, vibration, distance, and displacement, as well as in measuring fields [5–8].

Many algorithms can be used to process self-mixing signals and reconstruct target displacement information. The fringe counting and phase unwrapping algorithms are the most commonly used algorithms for self-mixing signals. The former has a low measurement precision with half a wavelength. The latter, which has high measurement accuracy, is the focus of this research. The phase unwrapping algorithm was proposed in Ref. [1]. This algorithm has an extremely high accuracy but requires a long time to estimate the optical feedback factor C and a preliminary experimental calibration to evaluate the linewidth enhancement factor α. Bes et al. [9] presented an auto-adaptive signal processing approach to reconstruct displacement. Their algorithm was divided into two steps. First, it would obtain a rough estimate in the feedback phase. Then, it would estimate the value of the optical feedback factor C and calculate the target displacement. Reconstruction accuracy was in the order of 40 nm. However, the algorithm only adapts to the moderate feedback regime and the application scope is limited. Zabit et al. [10] developed an adaptive transition detection algorithm to perform displacement measurements. This algorithm could automatically optimize the threshold level to detect all SMI fringes. But the method is too complicated

* Corresponding author.
E-mail address: lichengwei_hit@163.com (C. Li).

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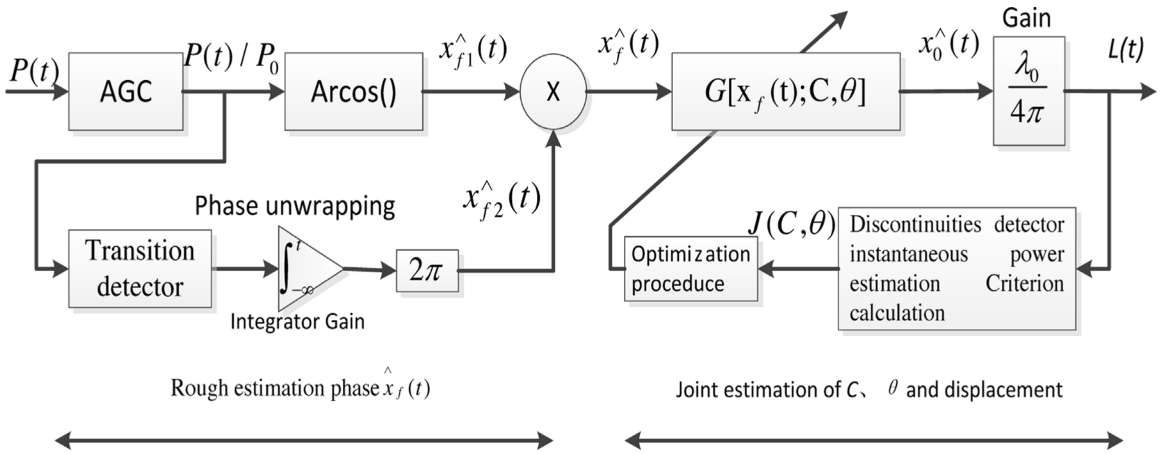

Fig. 1. Principle of displacement reconstruction.

to ascertain the presence of a transition. In Ref. [11], the characteristics of SMI signals were studied to estimate the value of C in real time. A new procedure was proposed to achieve an accurate estimation of the laser phase. But this algorithm needs high quality SMI signals, which is not conducive to practical application. In Ref. [12], a piecewise transition detection algorithm was developed. This algorithm could correctly detect self-mixing fringes at a low signal-to-noise ratio (SNR) in the presence of disturbances without filtering. In the previously described algorithm [9,10,12], they all detected the transition through the derivative of the arccos $[P(t)]$, $P(t)$ is the optical output power. It required a series of complicated judgments, especially for weak feedback regime [10]. In addition, the transitions detected by the algorithm is rough estimate, which have a identification error. Hence, transition detection is a critical aspect of the phase unwrapping algorithm. The identification errors directly affect the accuracy of displacement measurement.

This study focuses on the previously mentioned issues in transition detection and adopts a Double Differential algorithm to rapidly detect the extreme points of SMI and eliminate identification errors. Therefore, several aspects are addressed as follows. First, the principles of phase unwrapping are briefly explained. Second, improved displacement reconstruction process is explained in detail. And then, the Double Differential algorithm is proposed to address the determination threshold. Finally, the algorithm is validated through a numerical simulation and experimental data.

2. Algorithm description

SMI theory has been described by many researchers and is briefly described as follows [10]. Optical feedback induces a change in the optical output power of a laser. The optical output power $p(t)$ with feedback can be written as follows:

$$p(t) = p_0[1 + m\cos(x_f(t))] \tag{1}$$

where p_0 is the output power of the laser without feedback and m is the modulation index. $x_f(t)$ is the laser output phase with feedback, which is given by:

$$x_f(t) = \frac{4\pi L(t)}{\lambda_f(t)} \tag{2}$$

where $L(t)$ is the displacement of the laser to the target and $\lambda_f(t)$ is the laser output wavelength in the feedback case. The phase equation is expressed as [9]:

$$x_0(t) = x_f(t) + C\sin[x_f(t) + \arctan\alpha] \tag{3}$$

where α is the linewidth enhancement factor. $x_0(t)$ is the laser output phase without feedback, which can be expressed as:

$$x_0(t) = \frac{4\pi L(t)}{\lambda_0(t)} \tag{4}$$

Eq. (4) shows that $x_0(t)$ and $L(t)$ are linear relations. $L(t)$ is calculated based on $x_0(t)$ if the approximation of $x_f(t)$ is obtained.

2.1. Improved displacement reconstruction algorithm

A reconstruction algorithm of target displacement based on phase unwrapping has been reported in Ref. [9] and it was improved to show in Fig. 1. This algorithm consists of two parts. First, the rough estimation $\hat{x}_f(t)$ of the laser output phase $x_f(t)$ with feedback is obtained by the phase unwrapping algorithm. Second, the joint estimation of C and θ is performed