

Resolution Improvement in Fabry-Perot Displacement Sensor Based on Fringe Counting Method

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Abstract

This paper presents an improved Fringe Counting Method (FCM) technique in order to enhance the displacement resolution of a Fabry-Perot Displacement Sensor (FPDS). A simulation model of a FPDS based on the improved FCM has been developed and simulated for nanometer displacement range by using MATLAB mathematical software. Unlike conventional FCM that analyzed the number of fringes produced over one time period, the improved FCM analyzed the number of fringes for one largest Free Spectral Range (FSR). In this work, the initial length of Fabry-Perot Interferometer (FPI) cavity has been set at 75 μm due to limitation of the machining precision equipment. For the displacement analysis, the improved FCM technique is used as an algorithm. The research results prove that this FPDS could detect displacement at 10nm resolution over a working range of 40 nm. It showed that the improved FCM technique managed to enhance the capability of the conventional FCM in detecting nanometer displacement.

Keywords: fringe counting method, fabry-perot displacement sensor, fabry-perot interferometer

1. Introduction

Displacement as one component in vibration can be detected by a variety of displacement sensors working based on different principles. These sensors work based on capacitive, inductive, piezoelectric and most recently using optical technology [1]-[2]. Displacement sensor based on optical technology has drawn increasing attention from manufacturers and researchers since it can give remarkable performances in high sensitivity, lightweight, fast response and immunity to electromagnetic interference (EMI) [3]-[4]. There are three types of optical based displacement sensors which are Intensity-Based Sensors (IBS), Fabry-Perot Interferometer (FPI), and Fiber Bragg Grating (FBG). Among these three methods, FPI is more preferred since it provides high displacement resolution [5]. This type of sensor is also called as Fabry-Perot Displacement Sensor (FPDS).

In evaluating the FPDS performance, sensor's resolution has been analyzed. This resolution represents the smallest change that can be detected by the sensor. High displacement resolution of FPDS allows the sensor to detect displacement caused by the moving object precisely. In order to provide FPDS with a high resolution, algorithm used to process the detected interference signal should be carefully chosen. This is because the preferred algorithm will determine the resolution limit of the FPDS. Several algorithms have been proposed for the past few years. This includes wavenumber spacing method [6], combination of Fourier transform method and minimum mean square error estimation (MMSE)-based signal processing method [7], control and phase demodulation technique [8], and frequency modulated phase generated carrier (FMPGC) demodulation scheme based on the arctangent (Arctan) algorithm [9], and Fringe Counting Method (FCM) [10]-[12]. Nevertheless, all these methods have their own shortcomings. The wavenumber spacing method managed to achieve resolution about 16 nm but requires accurate data analysis on the wavenumber spacing. Other methods such as Fourier transform method and MMSE-based signal processing method, the control and phase demodulation technique, and the FMPGC-Arctan technique contribute very high resolution, up to sub nanometer displacement resolution. However, these techniques need a complex data processing. In contrast, FCM technique offers an algorithm with less complex data processing in displacement detection. Despite the simplicity of the

system, this technique is limited to displacement detection up to micrometer range only. It is only possible to reach nanometer displacement detection with some modification in FCM technique [13]-[14]. Therefore, in this paper, a new fringe counting mechanism has been developed in order to enhance the FPDS resolution and called as the improved FCM technique. This technique is discussed in details in the following section. The developed FPDS based on the improved FCM simulation model is analyzed in terms of number of fringe for a specific displacement.

2. Working Principle of FPDS

FPI is a passive optical structure that used multiple-beam interference in a cavity between two semi reflective surfaces [15]. This FPI configuration is used for nanometer displacement detection in this project. Figure 1 shows the FPDS configuration in detecting displacement. Reference beam in this figure is the reflection from fiber-air interface at the front of the cavity while sensing beam is the reflection of fiber-air interface at the back of the cavity. Mirror M_2 that attached to the moving object will move backward and also forward, hence changes the length of FPI cavity, d . This changes lead to significant alteration of phase difference (φ) between reference reflection and sensing reflection in FPDS operation as stated in (3). These two beams signal interfere with each other and resulted in the variations of FPI interference signal as presented in (1).

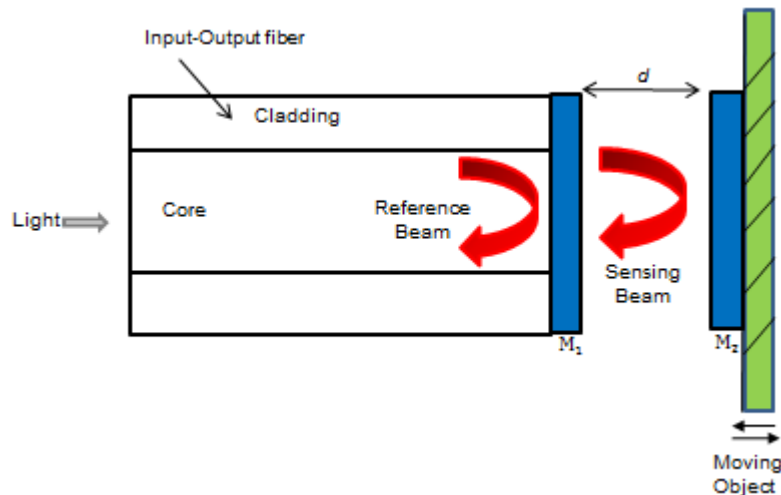


Figure 1. FPDS Concept in Displacement Sensing

According to the multi-beam interference principle, the normalized transfer function of the reflected interference spectrum at wavelength λ is given by the well-known Airy function. It can be expressed as below [16].

$$I_{FP}(\lambda) = \frac{1}{1 + M \sin^2(\varphi/2)} \quad (1)$$

$$\text{Where } M = \frac{4R}{(1-R)^2} \quad (2)$$

$$\text{and phase difference, } \varphi = \frac{4\pi nd}{\lambda} \quad (3)$$

R is reflectivity of the mirror, n is refractive index of the FP cavity, d is length of FPI cavity, and λ is light center wavelength in vacuum. By utilizing (1), the displacement of the M_2 can be detected from the reflected interference spectrum.

3. FPDS Based on the Improved FCM Technique

3.1. FPDS Simulation Model

As afore mentioned, the improved FCM is developed to enhance resolution of conventional FCM for nanometer range displacement detection. In order to evaluate performance of the new improved method, a simulation model based on equations (1-3) is developed using MATLAB mathematical software. Several important parameters in FPDS structure are analyzed in 2-dimensional analysis which are length of the FPI cavity and mirror reflectivity.

Figure 2 shows the illustration of the developed FPDS model. The initial length of FPI cavity, d_0 is chosen to be at $75 \mu\text{m}$ due to limitation in precision machining equipment. Length of FPI cavity is increased by nanometer variation for each simulation. Hence, the length of FPI cavity undergoes a continuous change with a certain displacement, D , thus resulting in a new d . This displacement variation analysis is needed in order to obtain displacement resolution of the sensor. The other parameters involved in this simulation are as tabulated in Table 1.

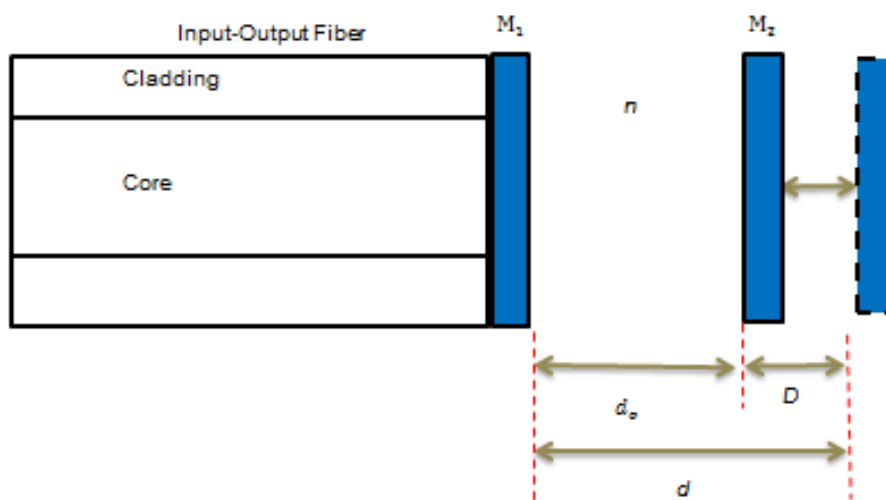


Figure 2. Modelling of FPDS in MATLAB Software

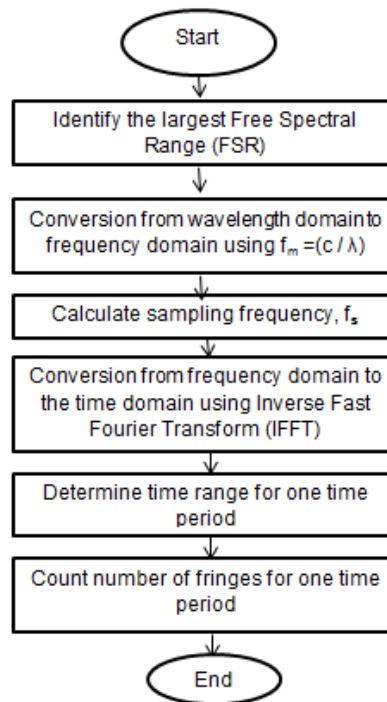
Table 1. FPDS Simulation

| Parameters | Values |
|-------------------------------------|------------------|
| Initial length of FPI cavity, d_0 | $75 \mu\text{m}$ |
| Mirrors reflectivity, R | 98% |
| Refractive index of FP cavity, n | 1.0 |
| Light incident angle at M_1 | 0° |

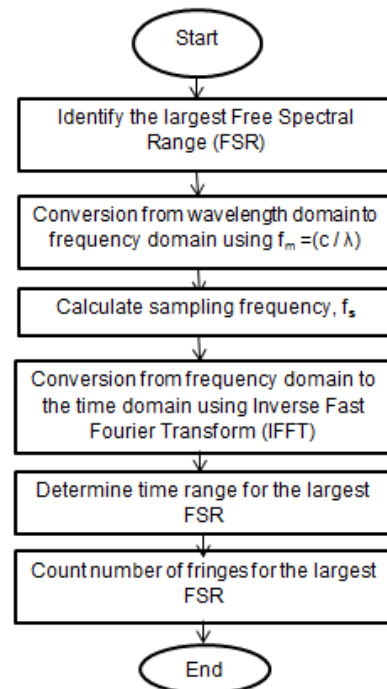
3.2. The Improved FCM Technique

Based on FCM technique, a large number of counted fringes produced will improve resolution of the FPDS. Therefore, this paper presents an improved fringe counting method that considers total number of fringes in the largest FSR instead of one time period in conventional FCM. Process steps for both counting methods are illustrated in flow charts in Figure 3.

In this work, the simulated light source is ranging from 600 nm to 1700 nm wavelength. Accordingly, the largest FSR is examined within this wavelength range. Without displacement ($D = 0 \text{ nm}$), the largest FSR is found to be 200 nm as shown in Figure 4. This FSR value will be used in the proposed algorithm. Varying the displacement value will varies the FSR range, thus will change the number of fringes produced.



(a) Conventional FCM Technique



(b) Improved FCM Technique

Figure 3. Process Steps of the Conventional FCM and the Improved FCM Technique

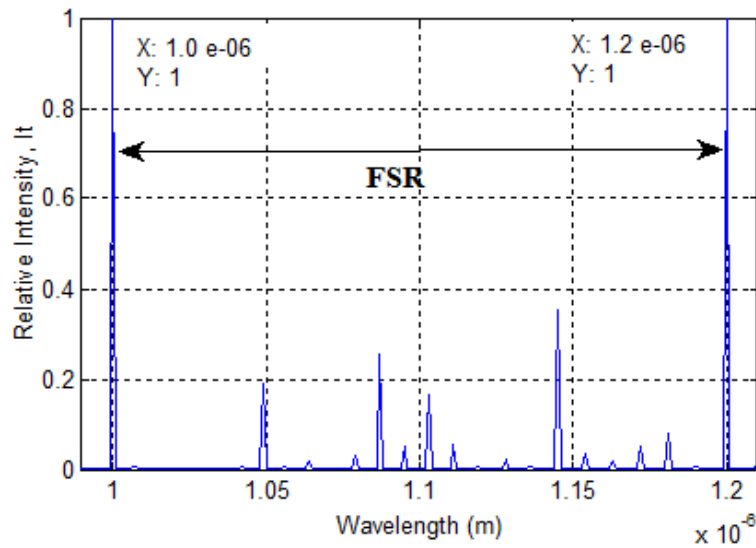


Figure 4. Relative Output Intensity of FPDS in Wavelength Domain Representation ($d_0 = 75 \mu\text{m}$)

Fringe calculation in both FCM techniques is done in time domain analysis. Hence, the optical spectrum needs to be transformed into time domain representation. The following equations are used for the transformation process.

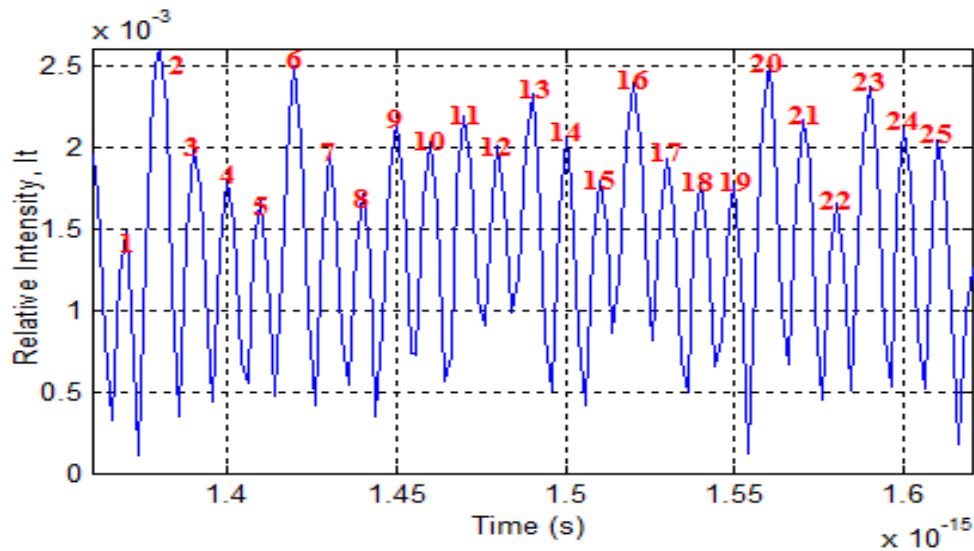
$$\text{Operating frequency, } f_m = \frac{c}{\lambda} \quad (4)$$

$$\text{Sampling frequency, } f_s = 2 f_m \quad (5)$$

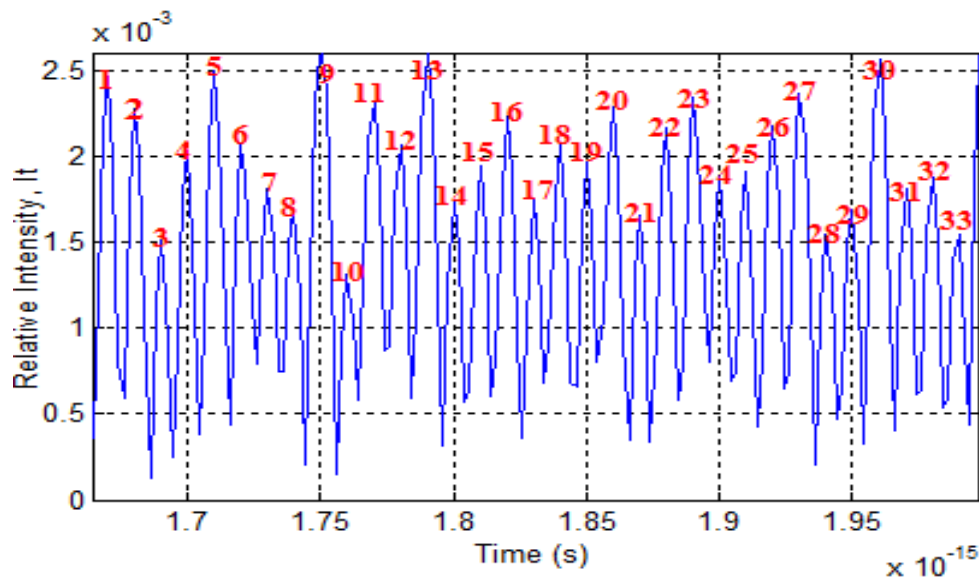
$$\text{Time, } t = \frac{L-1}{L} \left(\frac{1}{f_s} \right) \quad (6)$$

Where c is speed of light, λ is operating wavelength and L is length of the signal.

As stated before, the conventional FCM technique analyzes number of fringes for one time period. In contrast, the improved FCM counts the number of fringes exists within the largest FSR. Figure 5 shows the fringe patterns obtained by using the conventional FCM and the improved FCM technique. The improved FCM technique produced 33 fringes for the largest FSR while the conventional FCM produced only 25 fringes for one time period. Higher counted number of fringes resulted in a better resolution of FPDS.



(a) Conventional FCM Technique



(b) Improved FCM Technique

Figure 5. Relative Output Intensity of FPDS in Time Domain Representation for Both Techniques ($d_0 = 75 \mu\text{m}$)

4. Results and Discussion

In this section, relationship between the number of fringes and displacement of FPDS based on the improved FCM technique is presented. This relationship provides information on the displacement resolution and working range of the developed FPDS simulation model. Graph depicted in Figure 6(a) illustrates that number of fringes are varied according to the value of displacement. Number of fringes decrease steadily starting from $75 \mu\text{m}$ to $75.04 \mu\text{m}$ length of FPI cavity. Beyond $75.04 \mu\text{m}$, the number of fringes starts to increase again due to incoherent superposition [17]. This pattern shows that the developed FPDS based on the improved FCM technique is able to detect the displacement up to 40 nm . The relationship between the length of FPI cavity and the displacement is illustrated in Figure 6(b). The FPDS resolution is identified as 10 nm since the number of counted fringes less than this value is not linear in pattern.

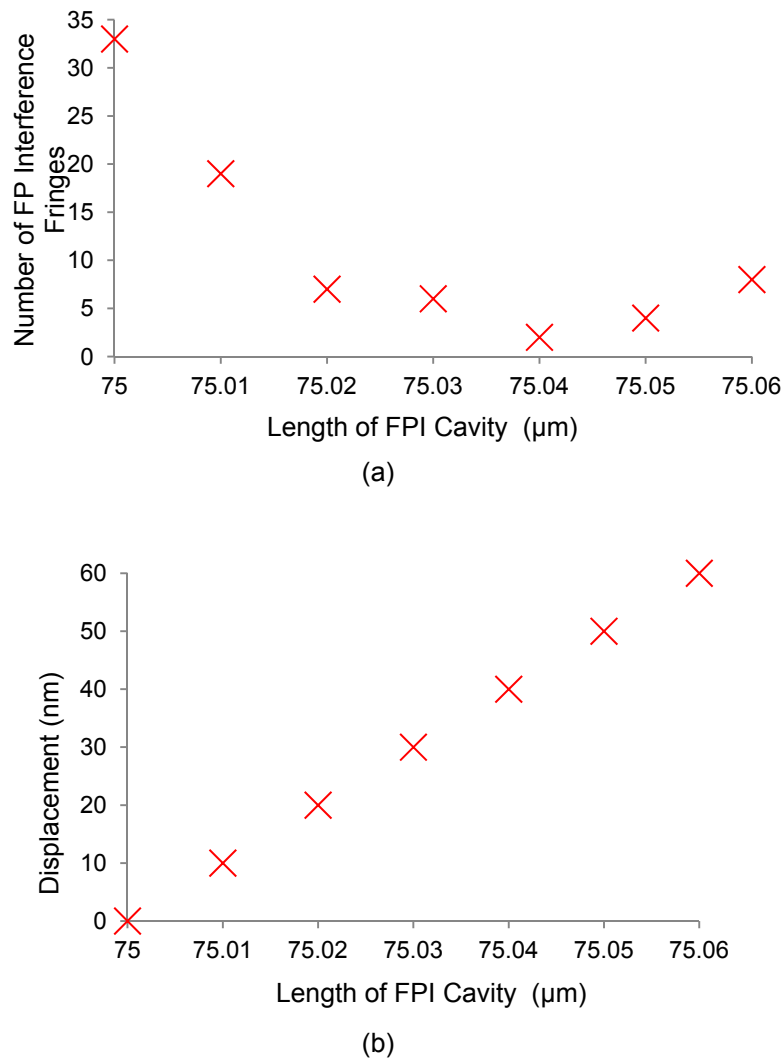


Figure 6. (a) Counted Number of FP Interference Fringes for a Specific Length of FPI Cavity and (b) Detected Displacement for a Specific Length of FPI Cavity

5. Conclusion

FPDS based on the improved FCM technique is developed and presented in this paper. Analytical model of FPDS is simulated by using initial length of the FPI cavity of $75 \mu\text{m}$. From the simulation, FPDS with a displacement resolution of 10 nm and working range of 40 nm are realized with the used of the improved FCM technique. These results are obtained for $75 \mu\text{m}$ initial length of FPI cavity with a light source ranging from 600 nm to 1700 nm wavelength. The proposed FPDS configuration is targeted for applications that require a nanometer displacement detection such as microscope, telescope, and also disk slider. The application of this FPDS can be extended to many other applications since it offers the immunization to EMI, lightweight and also ease of implementation.

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