Fitting algorithm for interferometric spectrum of fiber Fabry-Perot cavity acoustic sensors

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Abstract. Fiber Fabry-Perot cavity acoustic sensors have been widely used in some fields recently due to its advantages such as high sensitivity, resistance to electromagnetic interference, etc. In order to control the performance of the sensors, it is necessary to precisely adjust the cavity length. In order to obtain the cavity length efficiently and accurately, a fitting algorithm for interference spectrum is proposed in this paper. The base of the algorithm is the principle of light interference and the key of the algorithm is to find the peaks and valleys of the interference spectrum. Experimental results show that the algorithm has a high fitting degree.

1. Introduction

As a new type of acoustic sensors, fiber acoustic sensors have the advantages of high sensitivity, resistance to electromagnetic interference, low transmission loss, corrosion resistance, small volume and lightweight. They have been widely used in environmental noise detection, noise source localization, photo-acoustic detection and other fields[1].

The fiber Fabry-Perot (F-P) cavity acoustic sensor is a kind of fiber acoustic sensor that is simple in structure and easy to implement. Its main features are high sensitivity, compact structure and excellent acoustic performance[2]. To obtain a fiber F-P cavity acoustic sensor, the cavity length needs to be adjusted to proper length[3]. So, it is important to obtain accurate cavity length through interference spectrum data. At present, there are some methods for solving cavity length, such as peak wavelength tracking measurement method[4, 5], fast Fourier transform demodulation algorithm[6], discrete cavity length transform demodulation algorithm[7], minimum mean error estimation[8], etc. but these methods have some shortcomings, such as low accuracy of cavity, high complexity of the algorithm, and limitation of the applicable conditions.

In this paper, a fitting algorithm of interference spectrum is introduced. By importing the test data, the exact cavity length value can be obtained, and the fitting result obtained at different fitting step length is compared.

2. Principle of fiber Fabry-Perot cavity acoustic sensors

The principle structure of the fiber F-P cavity acoustic sensor is shown in figure 1. The fiber F-P cavity consists of two reflectors, one is the fiber end face and the other is the diaphragm. Since the reflectance of the fiber end face is very weak, the interference of the structure can be equivalent to the two-beam interference[9].
Figure 1. The principle structure of fiber Fabry-Perot cavity acoustic sensors.

The intensity of the interference spectrum can be expressed by equation (1)[3]:

\[ I = I_0(1 + \gamma \cos(\varphi)) \]  

where \( I_0 = \frac{(I_{\text{max}} + I_{\text{min}})}{2} \), \( I_{\text{max}} \) and \( I_{\text{min}} \) represent the maximum and minimum of the interference spectrum intensity, respectively. \( \gamma = \frac{(I_{\text{max}} - I_{\text{min}})}{(I_{\text{max}} + I_{\text{min}})} \) is the interference contrast. \( \varphi = \frac{4\pi n L}{\lambda} \) is the initial phase, \( n \) is the refractive index of the medium, \( L \) is the length of the fiber F-P cavity, and \( \lambda \) is the wavelength of the working light.

When \( \cos(\varphi) = 1 \), the light intensity reaches the maximum value, as shown in equation (2):

\[ I_{\text{max}} = I_0(1 + \gamma) \]  

Dividing \( I \) by \( I_{\text{max}} \), taking \( A = 1/(1+\gamma) \), \( B = \gamma/(1+\gamma) \), and \( n \approx 1 \) for air, then the normalized spectrum intensity is shown in equation (3):

\[ I_{\text{normal}} = A + B \cos\left(\frac{4\pi L \lambda}{\lambda}\right) \]  

Equation (3) is the theoretical basis of the fitting algorithm introduced next. \( A \) and \( B \) can be obtained by experimental data.

3. Algorithm principle and analysis

The processing flow chart of the interference spectrum data is shown in figure 2:

3.1. Normalization of the interference spectrum

The spectrum of the ASE source used in the experiment is not flat, and interference spectrum will be modulated by that, as shown in figure 3(a):
Figure 3. Normalization of interference spectrum for removing the modulation.

In order to further process the data, it is necessary to remove the modulation of the ASE spectrum that is referred as reference spectrum. The specific processing method is employed to demodulate the interference spectrum, which is to divide the interference spectrum intensity \( I_{\text{test}} \) by the reference spectrum intensity \( I_{\text{ref}} \). Then we obtained the relative intensity \( I_r \), as shown in equation (4):

\[
I_r = \frac{I_{\text{test}}}{I_{\text{ref}}}
\]

Next, the demodulated interference spectrum was normalized. As a result, an interference spectrum similar to the standard cosine curve was obtained, as shown in figure 3(b). The method of normalization is shown in equation (5):

\[
I_{\text{normal}} = \frac{I_r}{I_{\text{max}}}
\]

3.2. Seeking of peaks and valleys

According to the previous derivation, we need to find the values of \( A \) and \( B \) first and then fit tested interference spectrum according to equation (3). \( A \) and \( B \) are the median and amplitude of the normalized interference spectrum curve, which can be obtained by equation (6) and equation (7):

\[
A = \frac{I_{\text{normal peaks}} + I_{\text{normal valleys}}}{2}
\]

\[
B = \frac{I_{\text{normal peaks}} - I_{\text{normal valleys}}}{2}
\]

where \( I_{\text{normal peaks}} \) and \( I_{\text{normal valleys}} \) represent the peaks and valleys of the normalized curve respectively. The valleys seeking algorithm has the same principle as the peaks seeking algorithm, so this paper will only introduce the peaks seeking algorithm.

Since the interference spectrum is discrete data, the peaks can be determined by second-order difference. Due to existing noise during the test, the peaks obtained will contain spurious peaks. The normalized interference spectrum is mathematically approximated as a cosine function, so the peak intensity must be greater than the mid-value of the normalized curve amplitude that is 0.5, as shown in equation (8):

\[
I_{\text{normal}}(\text{Index}_{\text{peaks}}) > 0.5
\]

where \( \text{Index}_{\text{peaks}} \) is the index of each peak in the spectrum.

At this moment, there may still be spurious peaks that are close to the true peaks. These peaks are grouped by setting threshold. The maximum value of each group is the peak.
The peaks $I_{\text{normal, peaks}}$ and the valleys $I_{\text{normal, valleys}}$ can be reliably determined by the seeking algorithm. The result is shown in figure 4, where “+” signs represent peaks and “o” signs represent valleys.

![Figure 4. The peaks and valleys of normalized spectrum.](image)

### 3.3. The fitting of interference spectrum and the solution of cavity length

After obtaining the peaks and valleys of the normalized interference spectrum, the cavity length of the fiber F-P cavity can be determined by fitting. First of all, the period $T$ of the tested interference spectrum need to be determined. It can be expressed by the index of peaks and valleys, as shown by equation (9),

$$T = \frac{\text{mean}(\text{diff}(\text{Index}_{\text{peaks}})) + \text{mean}(\text{diff}(\text{Index}_{\text{valleys}}))}{2}$$

where $\text{Index}_{\text{peaks}}$ and $\text{Index}_{\text{valleys}}$ represent the index of the peaks and valleys respectively, $\text{mean}$ and $\text{diff}$ are matlab function.

In the process of fitting, an initial cavity length $L$ is presupposed at first and then a fitting curve is generated according to equation (3), and the period $T_{\text{temp}}$ of the fitting curve is calculated according to equation (9). If $T_{\text{temp}} = T$, the corresponding $L$ is the desired cavity length. In general, $T_{\text{temp}}$ and $T$ are not equal. So a loop is employed to search the cavity length $L$. If $T_{\text{temp}} > T$, $L$ needs to increase, and a flag A is set to 1. If $T_{\text{temp}} < T$, $L$ needs to decrease, and another flat B is set to 1. To reduce the calculating number of loop, a dynamically adjusting algorithm is adopted. Since the period $T$ of interference spectrum is related to the cavity length, the dynamically adjusting algorithm is expressed as equation (10):

$$\begin{align*}
L &= L + \left[ T_{\text{temp}} - T + 1 \right], & T_{\text{temp}} > T \\
L &= L - \left[ T - T_{\text{temp}} + 1 \right], & T_{\text{temp}} < T
\end{align*}$$

(10)

When the flag A and B are both 1, the loop is terminated. At this time, the $L$ is an approximate value close to real cavity length. Next, the accuracy of fitting cavity length $L$ needs to be further improved by calculating the fitting degree $R$ according to equation (11) [10] in a range of several micrometers by a linear step,

$$R = 1 - \sqrt{\frac{\sum(l_{\text{normal}} - l_{\text{temp}})^2}{\sum(l_{\text{normal}})^2}}$$

(11)

For different $L$, different $R$ is obtained. The maximum of $R$ is obtained, and the corresponding $L$ value is the exact cavity length value. To get the most precise $L$, a loop program is employed to calculate the $R$ in an appropriate length range, such as $L \pm 2 \mu m$, by step. By continuously calculating and comparing $R$, the maximum of $R$ can be obtained, and the corresponding $L$ should be the exact cavity length value.
4. Experimental results and analysis
The results of the algorithm operation as shown in figure 5. In the experiment, the reference spectral data and the test spectral data measured by the spectrometer are imported. To investigate the fitting step on the accuracy of the fitting results, three steps of 10nm, 1nm, 0.1nm are set in fitting program.

![Figure 5. Fitting results at different fitting step lengths.](image)

It is not difficult to find that the fitting degree with the step size of 1 nm is higher of about 0.5 than that of 10 nm. However, when the step size is further reduced to 0.1 nm, the improvement of fitting accuracy can be ignored. So, within a certain range, the fitting degree will increase as the step length decreases. However, as the step length further reduces, the improvement of the fitting accuracy is almost negligible and the fitting time will greatly increase.

5. Conclusion
A cavity length fitting algorithm for fiber Fabry-Perot cavity acoustic sensors is proposed. The algorithm is also suitable for sensors based on fiber F-P cavity structures. The advantage of this algorithm is high resolution and can process spectral data in batches, but it is not suitable for systems with high real-time requirement. The key of the algorithm is to find the peaks and valleys of the interference spectrum. The cavity length obtained by this algorithm has higher precision. Additionally, it should be noted that the fitting step length will affect the fitting accuracy and the calculating time.

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