Demodulation of Fabry-Perot Pressure Sensor based on Radial Basis Function Network

Wu Jing , Wang Ming*,Dai Xiajuan
Opto-electronic Technology Key Lab, School of Physical Science and Technology,
Nanjing Normal University, 210097, Nanjing, China
*corresponding author: Tel:+ 86-25-83598685; fax: +86-25-83598685
Email: wangming@njnu.edu.cn

ABSTRACT

In this paper, we present a demodulation of Fabry-Perot pressure sensor method based on radial basis function network(RBF). RBF network is a kind of three layers frontal feedback neural network with single connotative layer. It is proved that RBF is able to approach random continuous function with random precision. The cavity length variation is simulated from 473 to 483 μm with the step of 0.5 μm and the simulation result shows that the relative error of this new method is less than 0.02% and the maximum absolute error is less than 0.1 μm. The MEMS Fabry-Perot pressure sensor is also demodulated by the experiment. In the experiment, we change the pressure from 0 to 2 MPa with the step of 0.1 MPa. The experimental result shows that its linearity of the cavity length versus pressure achieves 0.98858 and the standard deviation between measured pressures and real pressures is less than 0.05 Mpa. By the experiment we can see that, this RBF network method can obtain upper precision and can reach the practice demand. This new method adapts to the practice demand with its higher resolution and less calculation time.

Key words: demodulation of Fabry-Perot pressure sensors, radial basis function network

1. INTRODUCTION

The characteristics of minitype, wide response frequency, high sensitivity, low cost, anti-jamming ability to adapt to harsh environment which Fiber MEMS pressure sensors have, make it become the hot spot in optical sensor .In fiber Fabry-Perot sensor system, demodulation technology is the key to achieving system. Signal demodulation is mainly segmented into strength and wavelength demodulation. And wavelength demodulation is also segmented into a variety of methods , such as tracking peaks, frequency Fourier transform, and the like.

Tracking peaks demodulation is tracking the peak in one or more specific intervention levels of interference spectrum to achieve demodulation of cavity length. The advanced technology of tracking peaks demodulation are signal peak measurement and bimodal measurement. Signal peak measurement has the advantage of high resolution, but in order to

2008 International Conference on Optical Instruments and Technology: Advanced Sensor Technologies and Applications,
edited by Anbo Wang, YanBiao Liao, AiGuo Song, Yukihiro Ishii, Xudong Fan, Proceedings of SPIE Vol. 7157, 71570L
 · doi: 10.1117/12.808072

avoid fuzzy peak levels, its dynamic range is limited; bimodal measurement has the advantage of greater dynamic range to achieve absolute measurement of cavity length, however, with low resolution. In this paper, a RBF neural network-based peak tracking demodulation way is presented to avoid the illegbility of peak levels, tracking a number of peaks continuously to achieve a large dynamic range of measurement.

2. PRINCIPLE OF RBF NETWORK

Radial basis function network is a structure of neural network put forward by J.Moody and C.Darken in later 1980s. It is a three-layer feed-forward network which has single hidden layer. It is proved that the radial basis function network is able to approach any continuous function with any precision. To achieve the same function, the neuron number of RBF network is possibly more than BP network, however, necessary training time of RBF is less than BP.

Radial basis function network is a three-layer feed-forward network made up of input, hidden and output layer. Take single output neuron as an example, hidden layer use radial basis function as activation function, which is commonly Gaussian, as shown in Figure 1. The distance between weight vector $\omega 1_{ij}$ each hidden layer neurons connected with input layer and enter vector x_i^q is multiplied by the threshold $b1_i$ as their own input, as shown in Figure 2.

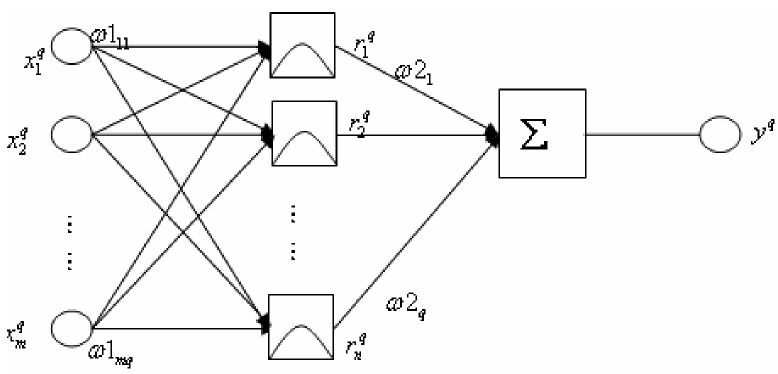

Fig.1 Structure of RBF network

Thereout the input of the ith hidden layer neuron is:

$$k_i^q = \sqrt{\sum_j (w1_{ji} - x_j^q)^2} \times b1_i \tag{1}$$

The output is:

$$r_i^q = \exp(-(k_i^q)^2) = \exp(\sqrt{\sum_j (w1_{ji} - x_j^q)^2} \times b1_i) = \exp(-(\| w1_i - X^q \| \times b1_i)^2) \tag{2}$$

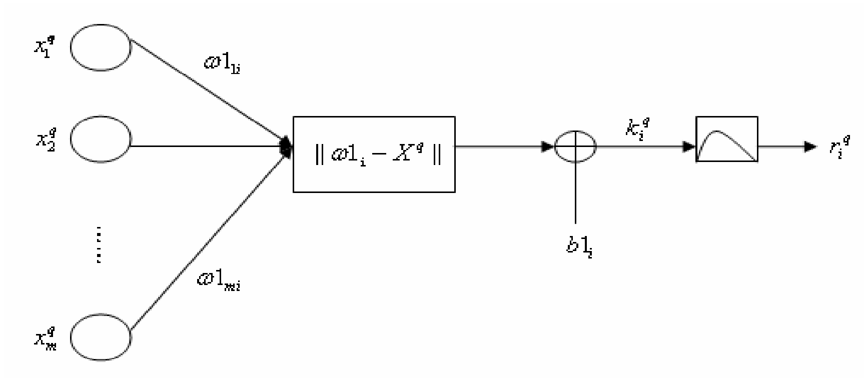

Fig.2 Input and output of hidden layer neuron of RBF network

The threshold of radial basis function $b1$ can be used to regulate the sensitivity of the function, but actually another parameter C is in common use. There are many methods to confirm the relation between $b1$ and C. In the neural network toolbox of MATLAB, the relationship is $b1_i = 0.8326 / C_i$, now the output of hidden layer neurons become:

$$g_i^q = \exp\left(\frac{\sqrt{\sum_j (w1_{ji} - x_j^q)^2} \times 0.8326}{C_i} \right) = \exp(-0.8326^2 \times (\frac{\| w1_i - X^q \|}{C_i})^2) \tag{3}$$

Thereout the value of C actually reflect the output response width to the importation. The greater the value of C, the wider the responding range of hidden layer neuron to enter vector, and the better the smoothness among neurons.

The input of the output layer is the sum of output of each hidden layer neurons. As activation function is pure linear function, the output is:

$$y^q = \sum_{i=1}^{n} r_i \times w2_i \tag{4}$$

The training process of RBF network is segmented into two steps. The first step is leaning without teachers, to confirm threshold between input layer and hidden layer $\omega 1$ for training. The second step is leaning with teachers, to confirm threshold between hidden layer and output layer $\omega 2$ for training. Before training, input vector X, corresponding target vector T and expansion constant of RBF C are provided. The purpose of training is to strike the final weight $\omega 1$ 、 $\omega 2$ and threshold $b1$ 、 $b2$ between two layers.

During the process of training RBF network, to confirm the number of hidden layer neurons is the key point, traditional method is to make it equal to the elements of input vector. It is clear that too many numbers of hidden layers are unacceptable when there are a lot of input vector. Therefor we propose an improving method, the basic principle is that to start training from 0 neuron, and increase neurons automatically by examining the output error. Each cycle, make the corresponding import vectors of the greatest error which the network create as the weight vector $\omega 1_i$, resulting in a new hidden layer neurons and then check the error of new network, repeat the process until reaching the required error and maximum number of hidden layer neuron. This shows that the RBF network have characteristic of adaptive determine structure, output and initial weight have nothing to do and so on.

3. RBF NETWORK BASED METHOD OF PROCESSING INTERFERENCE SPECTRUM

F-P pressure sensors can be similar to two-beam interference when reflectivity of the fiber end is low. The light reflection can be expressed with formula as this:

$$I_r / I_0 = 2R[1\text{-}cos(\frac{4\pi}{\lambda}L)] \tag{5}$$

Thereinto R is the reflectivity of fiber end, I_0 is the light incident, L is the length of F-P cavity.

From the fomula can be seen that cavity length have something to do with light intensity and wavelength. Bring the sensor to bear a stated pressure, optical spectrum analyzers can get a set of wavelength data corresponding with light intensity. Change the pressure continuously, you can get many group of spectral data. The change of pressure result in the change of cavity length. So demodulation of cavity length can be achieved from these spectral data.

Set up a RBF network and take eigenvalue of spectrum signal and corresponding cavity length as training set. Take all the peak value as the eigenvalue, orientation of peak value is achieved by wavelet de-noising and least squares method. Finally test the trained network, take a group of spectral data arbitrarily, the network can calculate the cavity length automatically.

Interference signal in wavelength domain is not a band limited signals with limited frequency components. Finite impulse response (FIR) low-pass filter is not suitable for achieving noise reduction. Wavelet transform is an effective method to realize noise reduction of non-band-limited signals.

Process wavelet de-noising to spectrum signal. First choose a wavelet basis function, determine wavelet decomposition level N and carry out N level wavelet decompose to signal. The useful interference signal is distributing in low-frequency, while the noise is in high-frequency. To high frequency coefficient of every level got from wavelet decomposition, apply certain statistical method to make sure a threshold. Select right rule, carry out resetting and minishing properly to high frequency coefficient under threshold bounds. According to the Nth level low frequency coefficient from wavelet decomposition and high frequency coefficient by threshold processing, use restructuring algorithm to carry through restructuring and gain the signal after de-noising.

After wavelet de-noising, we get smooth normalization interference spectrum signal. First in effective spectrum band, get maximum point of interference spectrum as estimation value of the peak through simple comparison. After confirming the estimation value of the peak, to several points near the estimation, use least square fit to get a quadratic polynomial curve $I(\lambda)=a_1+a_2\lambda+a_3\lambda^2$.Take the maximum point of the fitting polynomial curve as the exact location of the peak.

4. EXPERIMENT AND RESULT

4.1 Experiment system

In order to test the feasibility of the algorithm, establish the experiment system shown in Figure 3. Wide light source export from sensing analyzer Si720 pass through one end of 2:2 coupler and is joined with FP pressure sensors, and the other end hang in the air. The reflected light is imported to Si720 through coupler. The spectrum of reflected light is scanned by Si720 transport to PC through reticle. Then process the spectrum data by PC.

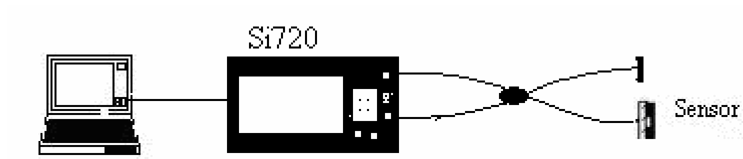

Fig.3 Experiment system

Over here FP pressure sensors adopt fiber MEMS pressure sensors developed by Opto-electronic Technology Key Lab of Nanjing Normal University. The structure is shown in Figure 4.

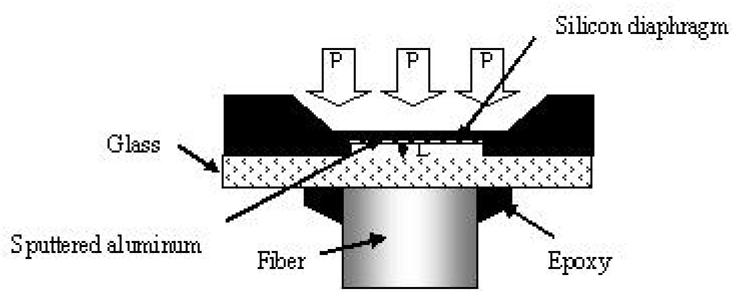

Fig.4 The sketch of optical fiber MEMS pressure sensor

The light enter into the sensor from a single-mode fiber, reflected in optical fiber-borosilicate glass, borosilicate glass-the air cavity, air cavity-Al-media interface. Reflected light interfere each other, finally reflected to fiber is interference signal of composite cavity which is made of borosilicate glass and air cavity. When the silicon film come in for pressure, it have a deformation, which result in reduction of the length of Fabry-Perot cavity.

Using standard piston gauge to plus press to fiber MEMS pressure sensors, plus from 0MPa to 2MPa in an interval of 0.1MPa. In this way, sensing analyzer gain 21 group data, we carry through character distill to every group of spectrum.

4.2 Simulation analysis

Get the first group of data, and carry through wavelet de-noising to it. Shown in Figure 5 and 6.

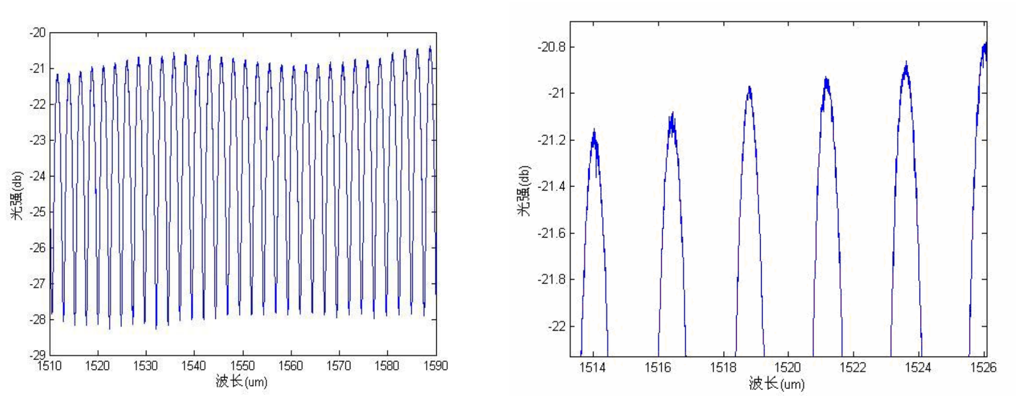

Fig.5 Spectrum before wavelet de-noising

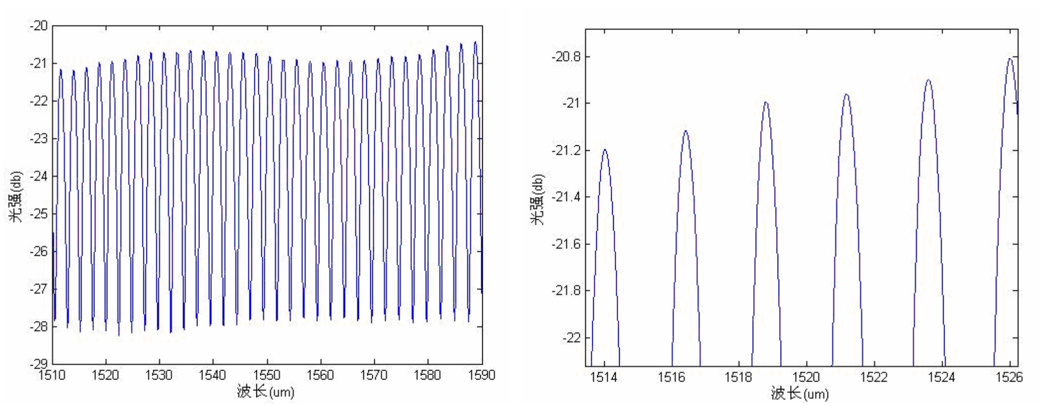

Fig.6 Spectrum after wavelet de-noising

We can see that the spectrum is very smooth after wavelet de-noising, and without any obvious distortion compare to the spectrum before de-noising.

Through simple comparison, find estimate value of the peak, to the few points nearby using least squares fitting, get a fitting curve as follows, take extremum point of the curve as exact position of peak.

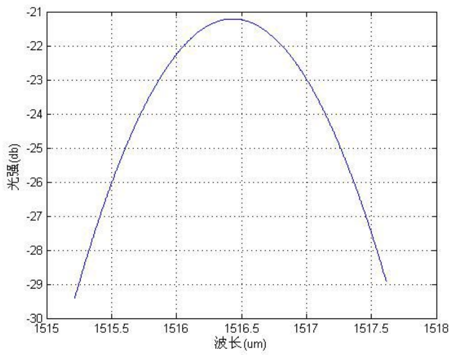

Fig.7 Least squares fitting curve

Then, a group of spectrum data can get 30 peak value. 21 groups of data can get 21*30 array.

We take corresponding wavelength of peak value as the eigenvalue of every spectrum. A group of wavelength is corresponding to a spectrum, namely corresponding to a cavity length. Use empirical formula to get a group of cavity length. 30 wavelength and 1 cavity length make up of a group of input and output data. Choose 1-18 groups as training set, and 19-21 groups as testing set. Use newrbe function to create a precise neural network, which function in creation of RBF network, automatically select the number of hidden layer, making the error of 0.

In MATLAB, there is a RBF distribution density SPREAD, whose value impact on the forecast accuracy of network. The greater the value of SPREAD, the smoother the function fitting. However, excessive SPREAD means an awful lot of neurons to adapt to rapid changes of the function. If SPREAD is set too small, it means that many neurons is needed to adapt to slow changes of the function, then the performance of designed network would not be very good. So in the design process of network, we need to try different value of SPREAD to determine an optimum value. We take SPREAD=0.1,0.2,0.3,0.4,0.5 to compute the forecast accuracy of network and found that when SPREAD=0.2, the relative accuracy is highest.

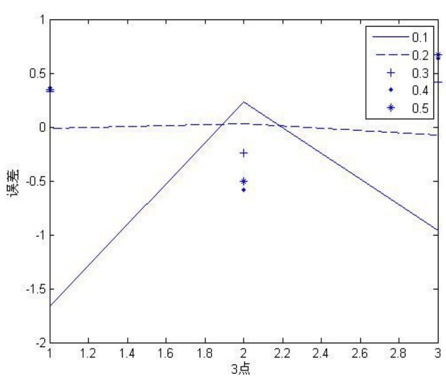

Fig.8 Error of different SPEARD

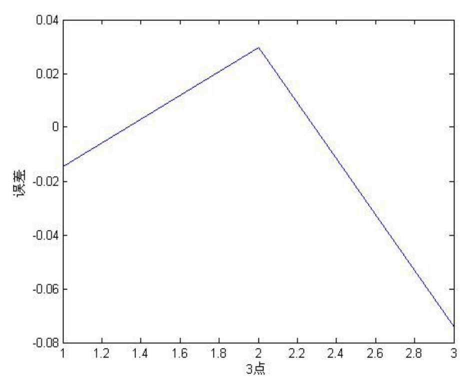

Fig.9 Error when SPREAD=0.2

It is obvious from Figure 9 that forecast accuracy of RBF network is good. However, because of limited amount of data, the predict number is small. Expand the number of testing set, the forecast number will increase accordingly.

Demodulate peak of reflect spectrum under different pressure and calculate cavity length. Fit the pressure and cavity length, shown in Figure 10. The fitting equation is: $L = 485.2131 - 6.21366 \times P(\mu m)$,reached 0.98858 fit.

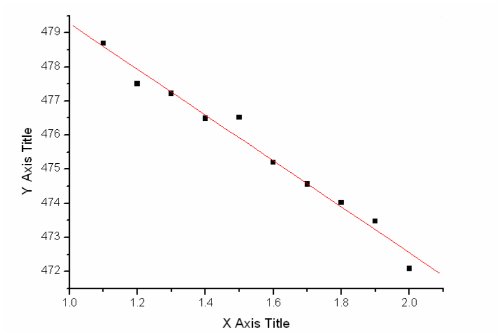

Fig.10 Cavity length versus pressure

5. CONCLUSION

Analyze the principle of muli-peak measurement method based on RBF network, and achieve demodulation of cavity length of sensor through experiment, to some extent resolve the problem of dynamic range and resolution, reducing the amount of calculation.

Acknowledgement

This work was supported by Jiangsu provinc science and technology support project (BE2008138)

REFERENCE

[1] Don C. Abeysinghe, Samhita Dasgupta, Joseph T.Boyd et al.. A novel MEMS pressure sensor fabricated on an optical fiber [J] .IEEE Photonics Technology Letters. Vol.13, No.9, September, 2001:993-995

[2] Jie Zhou, Samhita Dasgupta, Hiroshi Kobavashi et al.. Optically interrogated MEMS pressure sensors for propulsion applications [J]. Opt. Eng., 2001, 40(4):598-604

[3] Jing Zhenguo, Yu Qingxu, Zhang Guiju, Song Shide, A Novel Wavelength Demodulating Method for White Light Optical Fiber Sensor System, Acta Optical Sinica,2005,10(25):1347-1351

荆振国，于清旭，张桂菊，宋世德，一种新的白光光纤传感系统波长解调方法，光学学报 2005，10

（25）:1347-1351

[4] The principle of neural network and realize with MATLAB, Publishing house of electronics industry,2006:116-120

神经网络理论与 MATLAB7 实现，电子工业出版社，2006:116-120

[5] Wang Xiaodong, Application of RBF Neural Networks in Sensor Calibration, Chinese Journal of Scientific Instrument,2003,2(24):96-98

汪晓东，RBF 神经网络在传感器校正中的应用，仪器仪表学报 2003，2（24）:96-98

[6] Yang Guangxue, Yin Lijing, Kang Shouqiang, Reconstruction of FBG spectrum based on radial basis function network, Transducer and M icrosystem Tecnologies,2007,26(10):12-14

杨广学 ,尹丽静 ,康守强 ,基于径向基函数网络的 FBG 传感光谱的重构 ,传感器与微系统 2007 ,26(10):12-14

[7] A.Wang, H.Xiao, R.G. May, et al. Optical fiber sensors for harsh environments, SPIE,2000,4077:2-6

[8] B.Qi, G.Pickrell, J.Xu, et al. "Novel data processing techniques for dispersive white light interferometers", Opt. Eng.42(11),3165-3171(2003)

[9] Abdeq M. Abdi and Steve E. Watkins, Demodulation of Fiber-Optic Sensors for Frequency Response Measurement, IEEE Sensors Journal, Vol.7, No.5, May 2007:667-676

[10] Nie Yongjun, Yan Huiming, Du Yanli, Zhang Xiuda, New data processing method of white light interference spectrum, Journal of Zhejiang University, Vol.40 No.1 Jan.2006:38-40

聂永军，严惠民，杜艳丽，张秀达，一种新的白光干涉谱数据处理方法，浙江大学学报，Vol.40 No.1 Jan.2006:38-40