Research of the vibrating infrasonic sensor based on Fiber Bragg Grating

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Abstract

Current research on infrasound more extensive and in-depth, the sensor is essential prerequisite for infrasonic detection, in order to overcome some lack of current infrasound sensor for detecting the infrasound, paper innovative design a vibrating wire sensor structure, and make it capable of receiving a full rang infrasound, range adjustable, easy installation, etc. and use fiber Bragg grating which has obvious advantages in terms of low-frequency detection as the sensing element. Test the performance of the sensor and the results show that the average of the sensor is 6.11%, within 1 Hz-20 Hz range, the sensor has good linearity and small error, has practical value.

Keywords: Fiber Bragg grating; vibration wire; infrasonic sensor

1 Introduction

In the acoustic frequency, frequency of less than 20Hz of the band called infrasonic wave. Infrasound has the particularity of low frequency, long wavelength, and has spread far, strong penetrating power, small interference characteristics. Infrasound exists widely, for example: the storm at sea, earthquake, volcano eruptions and other natural disasters are likely to produce infrasonic wave [1]. Our life is often accompanied by infrasonic wave, for example: Ohashi Ko, car racing, even audio and mixer at hone will produce [2] infrasound wave. At present there are many countries are devoted to the study of infrasonic wave, infrasound weapons, infrasonic wave exploration, infrasonic wave forecasting and warning are the recent hot, there must be foresee that future of infrasonic wave will have broader applications. Therefore, there will be great practical value and scientific significance to detect infrasound, existing for infrasound detection of infrasonic sensor have some shortcomings such as low sensitivity, frequency range is small, large volume, inconvenient installation and high demands on the environment, the fiber grating sensor has high sensitivity, wide dynamic range, without electromagnetic interference, corrosion resistance, small volume, light weight and other advantages [3]. Based on this, this paper designs a vibrating sound sensor based on fiber Bragg grating.

2 The measuring principle

2.1 THE SENSING PRINCIPLE OF FIBER BRAGG GRATING

Fiber grating wavelength of reflection or transmission peak concern with the refractive index modulation of the grating period and the core refractive index, and when a broadband light source is incident to the Bragg grating, refraction, transmission or reflection due to refractive index change occurs, the reflection need to meet Bragg condition, namely the reflection wavelengths of light to meet the optical [4] equations:

$$\lambda_B = 2\Lambda n_{neff} . \tag{1}$$

Type (1): λ_B as the center wavelength of fiber Bragg grating; n_{eff} as the core region of the fiber refractive index; Λ as the Bragg grating period.

By the Equation (1) shows, the Bragg center wavelength of fiber Bragg grating λ_B changes with the change of the n_{eff} and Λ, or change any physical quantity of n_{eff} or Λ will lead to reflection or transmission peak wavelength of fiber Bragg grating drift. Through the detection of Bragg wavelength reflection or transmission spectrum peak wavelength, also is the detection of the central fiber Bragg grating wavelength, can detect the corresponding variables.

When the fiber grating under strain and strain is uniform, on one hand, external strain induced grating period changes [5]:

$$\Delta\Lambda / \Lambda = \varepsilon . \tag{2}$$

On the other hand, photoelastic effect caused by the change of effective refractive index:

$$\Delta n_{eff} = \frac{n^3_{eff}[P_{12} - \nu(P_{11} + P_{12})]}{2}\varepsilon . \tag{3}$$

Type (3), P_{11} and P_{12} are the fiber optic strain tensor components, ν is the Poisson's ratio.

Changes of these two aspects led to the change of the wavelength of the fiber grating, by Equation (1) can be obtained:

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$$\Delta\lambda_B = 2n_{eff}\Delta\Lambda + 2\Delta n_{eff}\Lambda . \quad (4)$$

The types (2) and (3) into type (4) have

$$\Delta\lambda_B = 2n_{eff}\Lambda\{-\frac{1}{2}n_{eff}{}^2[P_{12} - \nu(P_{11} + P_{12})]\}\varepsilon + 2n_{eff}\Lambda\varepsilon . \quad (5)$$

Valid elastic optic constants of optical fiber P_e is defined:

$$P_e = \frac{n^2{}_{eff}}{2}[P_{12} - \nu(P_{11} + P_{12})] . \quad (6)$$

Then type (5) can be simplified as:

$$\Delta\lambda_B = (1 - P_e)\lambda_B\varepsilon = K_\varepsilon\varepsilon = K_\varepsilon\frac{\Delta\Lambda}{\Lambda} . \quad (7)$$

Equation (7) expresses the relationship between the wavelength shift and the external when the fiber Bragg grating strains uniformly. In Equation (7), K_ε is the strain sensitivity coefficient of fiber grating sensor. Its value is closely related to the size of the optical fiber material, by the decision of the effective refractive index of optical fiber, elastic-optic coefficient and Poisson's ratio. Therefore, When the materials of the fiber is determined, K_ε is a constant so the change of the fiber grating wavelength is determined by the change of the fiber Bragg grating period, in the other word, which is determined by fiber Bragg grating lattice spacing changes. When the lattice spacing changes at a high frequency, the change frequency of the center wavelength is also high. But the rapid changes of the center wavelength are not conducive to the detection. On the contrary, for small frequency strain, the change of the fiber Bragg grating lattice spacing frequency is small; its centre wavelength change frequency is also small, which is easier to be tested. Therefore, optical fiber Bragg grating has obvious advantages in detection of low frequency and ultra-low frequency.

2.2 WORKING PRINCIPLE OF THE SENSOR

As designed in this paper, the Vibration Wire infrasound sensor based on the fiber Bragg grating, using vibrating string as a receiving component, can receive a full range of infrasound and vibration. The vibration is transmitted to the elastic diaphragm through the string bridge. Elastic diaphragm produces strain due to the vibration, driven the fiber Bragg grating wavelength attached to the elastic diaphragm to shift.

At this point, the vibration is converted into the center wavelength shifting of the fiber Bragg grating. The center wavelength shift values of the fiber Bragg grating are obtained by the use of demodulation instrument, thus the corresponding relation of the vibration frequency and wavelength. In addition, the effective length of the vibrating wire is determined by two string bridges, one of the two can move within a certain range, so that the effective length of the vibrating string is adjustable, so the range of the designed sensor in this paper is adjustable.

3 Structure and design of the sensor

The structure of the sensor is shown in Figure 1, In order to be able to receive the full range of infrasound, this design uses a using vibrating string as a receiving component. Vibrating strings are fixed by the clamp device on both ends of the bracket. In order to make the range of the designed sensor adjustable, the effective length of the vibrating string must be adjustable. The vibrating wire length between the two string bridges is the effective length of the vibrating wire. So install a guide rail on the base plate of the right said of the fixed bracket to make the string bridge on the right side move on the guide rail to transform the effective length of the vibrating string. The string bridge on the left side can transmit the vibration of the vibrating wire. So, install the left side string bridge on center of the elastic diaphragm and paste the fiber Bragg grating under the elastic diaphragm then design a circular section on the left side of the fixed bracket to fix the elastic diaphragm.

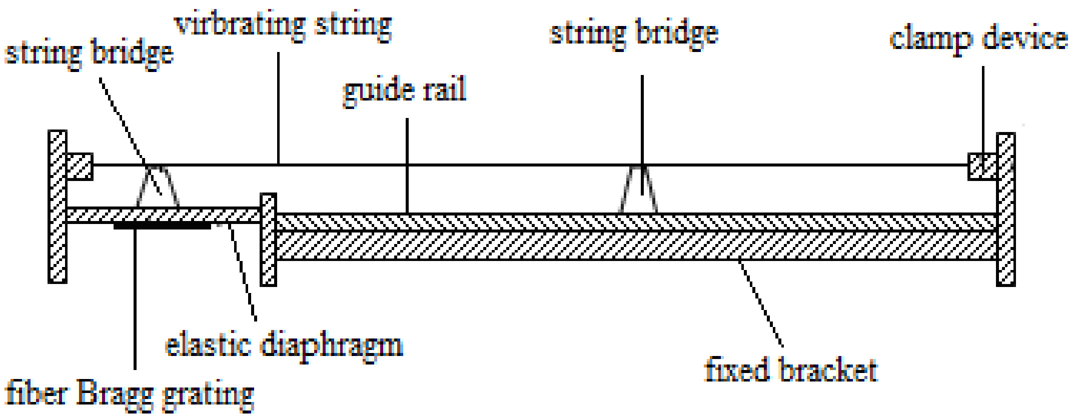

FIGURE 1 The structure of the vibrating wire infrasound sensor based on fiber Bragg grating

For the fixed strings at each end, the correspondent nth vibration displacement generated by receiving the infrasound of a series of frequencies is [6]:

$$y_n = B_n \sin\frac{n\pi}{l}x\cos(2\pi f_n t - \varphi_n) . \quad (8)$$

In Equation (8), B_n and φ_n are the correspondent undetermined coefficients of the n-th vibration. f_n is the frequency of the n-th vibration, and l is the length of the vibrating wire.

The fundamental frequency vibration is the most stable form of vibration. That is, in Equation (1), when n=1, the frequency is:

$$f = \frac{1}{2l}\sqrt{\frac{T}{\delta}} = \frac{1}{2l}\sqrt{\frac{E\varepsilon}{\rho}} . \tag{9}$$

In Equation (9), T - vibrating string tension, δ - vibrating wire density, $\delta = \rho s$, ρ means the vibrating wire material density, s means the cross-sectional area of the vibrating string, t - time, l - vibrating string length, E - vibrating wire elastic modulus; ε - the internal stress of vibrating. By increasing the length of the vibrating string, increasing the radius of vibrating strings can reduce the frequency of vibrating wire, thereby increasing sensor's sensitivity to low-frequency. At the same time, we can also know that the bigger elastic modulus of the material is helpful to improve the sensitivity of the sensor, Therefore, we chose the experimental calculated Young's modulus of E=200Gpa, a density of ρ=$OCr_{18}Ni_9$ 7.93g/cm3, the chord diameter of 1.20mm, the chord length is 1000mm stainless steel vibrating string.

By the Equation (9) shows that the longer vibrating wire means the better characteristics of low-frequency, but it is represented by the Equation (8) shows that the longer vibration string will get very small strain when receiving the low frequency infrasound. So it is not suitable for the fiber Bragg grating pasted directly on the vibrating string, In this paper an innovative structural design makes vibrating accept vibration, the vibration through the bridge to the elastic diaphragm. This put the vibration focus on the elastic diaphragm, the diaphragm can produce relatively large strain, to facilitate detection.

While the elastic diaphragm not only played the role of isolation and protection, but also increase the damping effect of sensor system. An ideal sensor should be an ideal linear time invariant system, namely the sensor output can be linear to truly reflect the input signal. Specifically, should make the output amplitude is to maintain a constant for all the frequency of the measured signal, to ensure that the harmonic components are the same amplification, and the output phase is linear to the all measured frequency, to ensure the phase shift that each harmonic component is directly proportional to the frequency. This requires sensors with larger bandwidth, and the bandwidth depends largely on the system's natural frequency and damping ratio. When the damping ratio is too large, with the increase of frequency amplitude frequency characteristic curve decreased rapidly, while the damping ratio is too small, with the increase of frequency amplitude frequency characteristic curve will rise, in the above two cases, the amplitude frequency characteristics flat areas are narrow, therefore, appropriate damping ratio can make the sensor has a wide operating frequency range. The sensor is designed in this paper, and the effective length of string vibration adjustable makes the sensor range adjustable, thus the need for a larger operating frequency range. After testing, this design uses the polyester film as diaphragm can enable the sensor has the appropriate damping ratio and wide operating frequency. The elastic diaphragm is round, the radius of R=120mm, thickness of h=0.3mm. The bridge is made of wooden materials, the bottom surface of radius r0=30mm.

According to the principle of the elastic mechanics, when the uniform pressure of perpendicular to the circular diaphragm clamped films, film will produce bending deformation. The center (R=0) of the maximum deformation, the deformation of the diaphragm can be expressed as a Equation:

$$Y_{\max} = \frac{3(1\text{-}\mu^2)\mathrm{P}}{16Eh^3}R^4 . \tag{10}$$

In the Type (10), E, μ, h and R respectively refers to Young's modulus of the polyester film, Poisson's ratio and thickness and the effective radius.

Analysis of elastic diaphragm were carried out by the finite element software ANSYS [7, 8], circular flat diaphragm radial strain distribution in the diameter direction of the Figure 2:

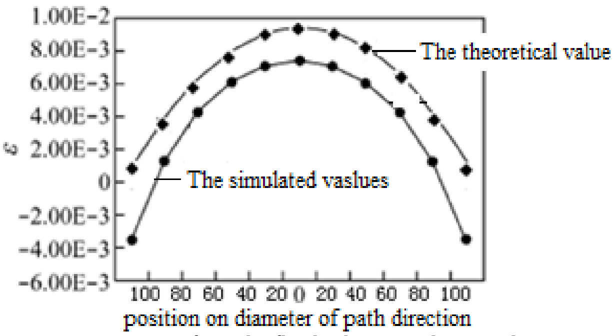

FIGURE 2 Strain of circular flat diaphragm in diameter direction

We can see from Figure 2 strain at the center of the diaphragm is maximum, and at about 1/2 in radius radial strain have another turning point, combine type (10), so as to determine the paste position of fiber Bragg grating on the membrane should be at 1/2 in the diaphragm to the radius of the center. Figure 3 is the schematic diagram of circular flat diaphragm sticking position of fiber Bragg grating.

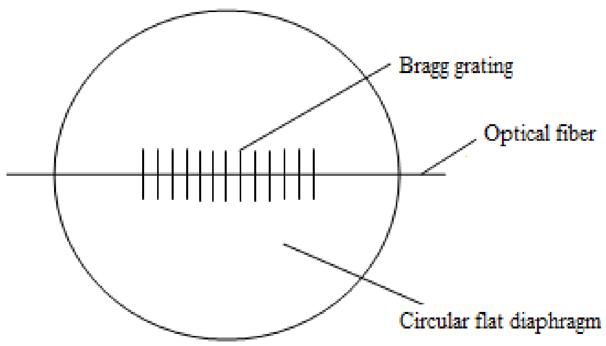

FIGURE 3 Paste position of fiber Bragg grating in the round flat diaphragm

4 Test data and analysis

Produce 0-20Hz sine excitation signal by signal generator, amplified by the power amplifier and speaker produce infrasound wave, the cut-off frequency to the 21Hz test will be low pass filter, 10 tests were carried out for each test frequency, test results, by the Equations (11) and (12) to calculate the average value, the result in Table 1.

$$\bar{f} = \frac{1}{n}\sum_{1}^{n} f_i , \quad (11)$$

$$\bar{\lambda} = \frac{1}{n}\sum_{1}^{n} \lambda_i . \quad (12)$$

TABLE 1 Output frequency of the sensor and fiber Bragg grating center wavelength with Different input frequency

The given input frequency M(Hz)	**The average value of measured output f(Hz)**	**The center wavelength of fiber Bragg $\lambda(\mu m)$**	**The given input frequency M(Hz)**	**The average value of measured output f(Hz)**	**The center wavelength of fiber Bragg $\lambda(\mu m)$**
0	0	1.137236	5.00	5.42	1.137236
0.01	0	1.137205	6.00	6.44	1.137241
0.05	0.04	1.137206	7.00	7.56	1.137244
0.10	0.09	1.137207	8.00	8.36	1.137247
0.20	0.19	1.137208	9.00	9.47	1.137251
0.30	0.25	1.137208	10.00	10.21	1.137255
0.40	0.37	1.137209	11.00	11.17	1.137258
0.50	0.52	1.137211	12.00	11.56	1.137261
0.60	0.63	1.137214	13.00	12.53	1.137265
0.70	0.74	1.137216	14.00	13.80	1.137270
0.80	0.83	1.137218	15.00	14.55	1.137274
0.90	0.94	1.137220	16.00	15.69	1.137279
1.00	1.12	1.137223	17.00	16.42	1.137283
2.00	2.32	1.137226	18.00	17.79	1.137289
3.00	3.35	1.137230	19.00	18.80	1.137294
4.00	4.16	1.137233	20.00	19.74	1.137298

From Table 1 can draw the diagram of the relationship between each given frequency and the correspond center of fiber Bragg grating wavelength, as shown in Figure 4:

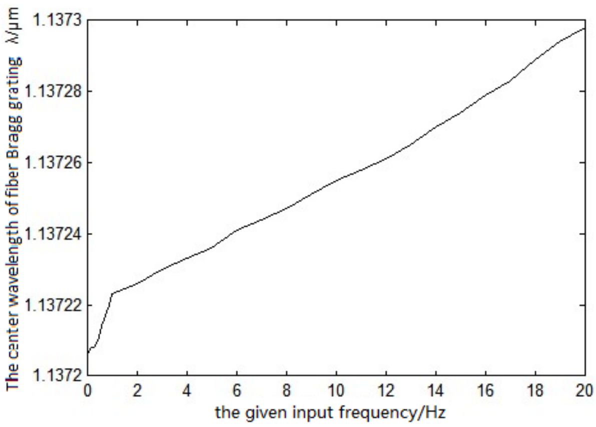

FIGURE 4 Corresponding relations between the given input frequency and the center wavelength about fiber Bragg grating

We can see from Figure 4, in the range of 0 Hz-1 Hz relationship of wavelength and frequency is relatively large, and in the 1 Hz-20 Hz range, relationship between wavelength and frequency are g in a straight line that in this range the sensor has good linearity.

According to Table 1 can also draw the input frequency and the measured output frequency contrast diagram, as shown in Figure 5:

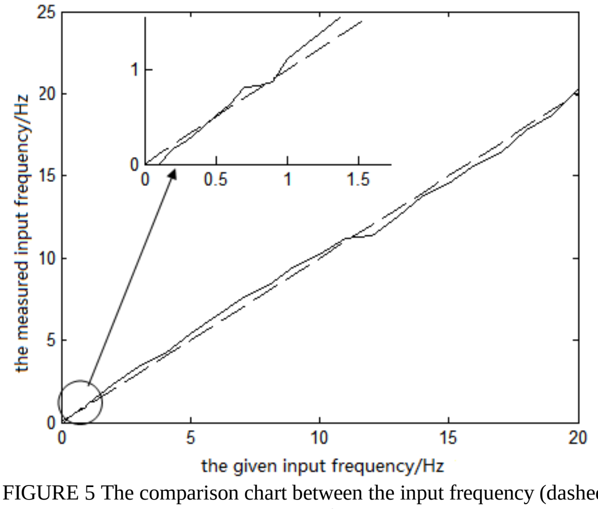

FIGURE 5 The comparison chart between the input frequency (dashed line) and the actual output frequency (solid line)

The Equation of relative error of E:

$$e_i = \frac{f_i - M_i}{M_i} \cdot 100 . \quad (13)$$

Relative errors of given input frequency and the measured frequency is shown in the table below:

TABLE 2 The relative error of the given input frequency and the measured output frequency

The given input frequency M(Hz)	The average value of measured output f(Hz)	Relative error (%)	The given input frequency M(Hz)	The average value of measured output f(Hz)	Relative error (%)
0	0	--	5.00	5.42	0.084
0.01	0	--	6.00	6.44	0.073
0.05	0.04	-0.200	7.00	7.56	0.080
0.10	0.09	-0.100	8.00	8.36	0.070
0.20	0.19	-0.050	9.00	9.47	0.045
0.30	0.25	-0.167	10.00	10.21	0.021
0.40	0.37	-0.075	11.00	11.17	0.015
0.50	0.52	0.040	12.00	11.56	-0.037
0.60	0.63	0.050	13.00	12.53	-0.036
0.70	0.74	0.057	14.00	13.80	-0.014
0.80	0.83	0.038	15.00	14.55	-0.030
0.90	0.94	0.044	16.00	15.69	-0.019
1.00	1.12	0.120	17.00	16.42	-0.031
2.00	2.32	0.160	18.00	17.79	-0.012
3.00	3.35	0.117	19.00	18.80	-0.011
4.00	4.16	0.040	20.00	19.74	-0.013

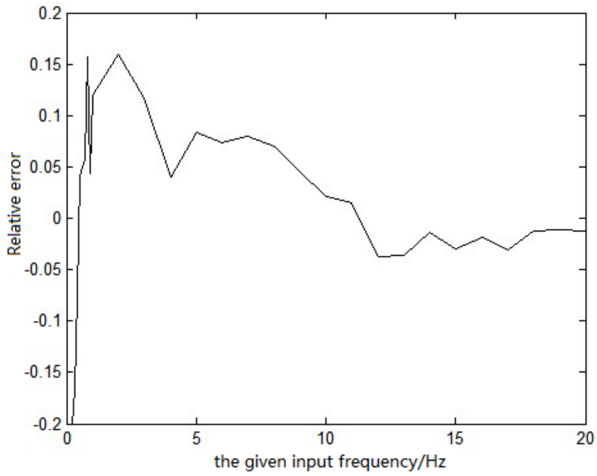

FIGURE 6 Curves of relative error

According to the Equation (13), using the data in Table 2 dawn relative error curves plotted as in Figure 6. We can see from Figure 6, with the increase of the test frequency, the error will be gradually reduced, the average error is E=6.11%. According to Figure 4 and Figure 6 shows, the sensor in the range of 0 Hz-1 Hz designed in this paper, the measurement results is not very stable, the error is large, but in the 1 Hz-20 Hz range, the sensor has good linearity and small error, the result show that the design of the sensor is of practical value.

5 Conclusions

This paper design the vibrating string type infrasonic sensor based on fiber Bragg grating, the sensor using optical fiber Bragg grating as the sensitive element and structure design innovation make the sensor has the advantages of convenient installation, electromagnetic interference resistance, suitable for high temperature, corrosive environment, also can receive infrasound in full range, the measuring range can be adjusted according to the actual situation, so as to improve the sensitivity of the sensor, avoid reducing the sensitivity by using the same range to measuring different frequencies , analysis the test data, and the results show that the sensor error is small, high precision, and has great practical value.

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