A New Fiber Fabry-Perot Cavity Sensor

GAO Yingjun, ZHANG Zhilv, ZHAO Zhonghua, LUO Yufeng, ZHOU Mi, DING Tao
Optoelectronic Engineering Institute, Jinan University, Guangzhou 510632, PR CHINA

ABSTRACT

A new optical fiber Fabry-Perot (F-P) cavity sensor for liquid level detection was developed. The end of a flexible metal bellows, which can sustain a large strain displacement, is suggested to be one surface of the F-P cavity. Both electronic hardware and demodulation scheme in software were developed for fringes counting and direction discrimination of the liquid level. A scheme for temperature compensation was proposed. A prototype of the liquid level sensor was fabricated and the experiments for air pressure and water level measurement were carried out. Because the interference fringe counting technique was used for signal demodulation, the noise resistance capability of the sensor against optical power fluctuation and other disturbances is greatly improved.

Keywords: Fabry-Perot cavity, flexible metal bellows, optical fiber sensor, liquid level sensor, interference fringe

1. INTRODUCTION

Liquid level sensors have important and extensive applications in daily life and industry. There are lots of methods to detect the depth of liquid. With the features of high accuracy and inherent safety, fiber liquid level sensors are preferable for flammable and explosive environments [1-3]. Various configurations of fiber F-P cavity have been proposed to sense temperature, pressure, strain, and liquid level, and many discussions relevant to the output signal processing of fiber F-P interferometers have been reported[4-8]. Interference fringe counting technique is a basic method to demodulate the interference output signal [9-10].

A fiber F-P cavity liquid level sensor proposed in reference [7, 8], in terms of the principle of detecting the inner pressure to measure the liquid level, is inherent safety, and is convenient to install, simple to use, and easy to promote. This sensor, however, limits the change of the strain of the elastic sheet to 1/8 of the optical wavelength, in order to be worked in a single valued (not multivalued) and linear range. For this reason, it is not easy to extend its dynamic range. On the other hand, since the measurement result is determined by measuring the light intensity, it will be greatly affected by power fluctuation and external disturbances. The stability of the interference system, the light source, the driving circuit, and the data processing circuit has to be kept in a much higher standard.

In order to effectively settle these problems, interference fringe counting technique was proposed to demodulate the output signal from the optical fiber F-P cavity liquid level sensor. Therefore, all kinds of impacts caused by light intensity fluctuation and outside influences can be minimized, the mechanical structure of the sensor head can be simplified, the compensation and processing systems of the photoelectric signal can be predigested, and then the cost could be greatly reduced, practicability of the F-P cavity sensor may be improved, and more, the measurement range of the sensor may be theoretically unlimited..

Implementation of the interference fringe counting technique, however, leads up to the capability of a much larger strain measurement of the sensor tension structure, flexible metal bellows, which can sustain a large strain displacement, is suggested to be one part of the F-P cavity. Both electronic hardware and demodulation scheme in software were developed for fringes counting and direction discrimination of the liquid level.. A scheme for temperature compensation of the sensor head was suggested. The liquid level sensor was fabricated; the practical measurements were carried out both for the air pressure and the water level. Because the interference fringe counting technique was used for the signal demodulation, the noise resistance capability of the sensor against light source power fluctuation and other disturbances is greatly improved.

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2. PRINCIPLE AND STRUCTURE OF FIBER LIQUID LEVEL SENSOR

The relationship between liquid inner pressure and depth has a general form of

$$P = \rho g h \tag{1}$$

where P is the inner pressure of the liquid in depth h, ρ is the density of liquid, and g is the acceleration of gravity. Thus, the depth of the liquid h can be calculated when the inner pressure P is measured.

Fig.1 shows the structure of the fiber Fabry-Perot cavity liquid level sensor where the surface of metal bellows and the GRIN lens compose an F-P cavity. The other side of the bellows is sealed to the cavity body and connected through to the liquid vessel bottom. When the liquid level changes, the bottom pressure changes too, the bellows, therefore, will be pressed and elongated, then the length of the cavity varies accordingly. The optical fiber transmits the light into the F-P cavity via a GRIN lens, the GRIN lens collimates the light beam in the cavity as parallel one and ensures the interferometer can work properly. Part of the input light is reflected back from the lens surface, and the other irradiates the end surface of the bellows, and is reflected too. Then the two reflected light converge and interfere, and the output light intensity is related to the length of the F-P cavity which is related to the bellows elongation and thus the liquid level. The output light intensity changes periodically when the length of cavity varies. Detecting the output light intensity, by using the interference fringe counting technique, the change of the liquid pressure or the depth of the liquid can be estimated.

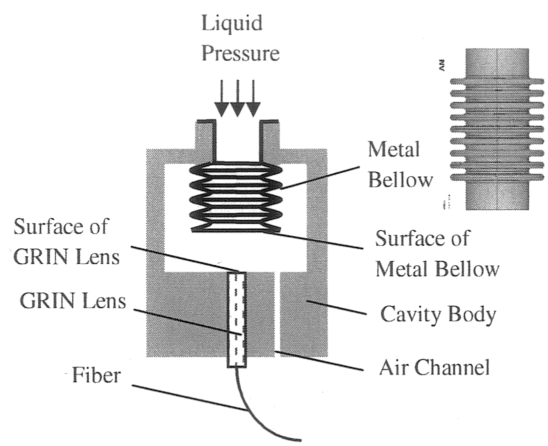

Fig.1 Schematic diagram of the liquid level sensor with optical fiber Fabry-Perot cavity

For ordinary F-P interferometers, surfaces with very high reflectivity (almost 100% reflection) are always to be chosen. The interference fringes are thin and sharp. It is unfavorable for fringe counting and direction discrimination. The reflectivity of the two surfaces should be properly designed in order to obtain a near sinusoidal output [7].

The relationship between the number of interference fringes (N) and the change of F-P cavity length ΔL is:

$$N = 2n\Delta L / \lambda \tag{2}$$

where n is the refractive index of the cavity material, and λ is the wavelength of the light source. The period of F-P interferometer cavity change is $\lambda/2$, it means that when the length of the cavity alters $\lambda/2$, the output varies one fringe. By counting the total number of fringes, the change of liquid level can be determined.

As shown in Fig. 1, there is a hole in the cavity body, which forms an air path connecting the F-P cavity to the atmosphere. Hence, the pressure in the cavity is the same as the atmosphere, which ensures the right pressure difference between the liquid and the atmosphere, and also eliminates the error due to pressure variation caused by temperature change.

With the use of the fringe counting technique, the adjustable length of the F-P cavity should be increased correspondently. For example, if the liquid level is 20 meters high, according to the common measurement accuracy of ±2mm required for industry, 5000 fringes have to be counted. If the operation light wavelength is 1310nm, the change of cavity length would be greater than 3.275mm. This spacing variation/displacement is very large and it is impossible to be achieved by the F-P sensor with the use of a conventional elastic sheet. It will also cause the problem of nonlinearity when the elastic sheet is operated in such large range even the stretchy limit is not being exceed.

Metal bellows has been chosen as a part of the F-P cavity structure to provide the capability of large strain measurement. Metal bellows is a pressure elastic element; its structure likes a thin corrugated metal pipe. The open side of the metal bellows is sealed to the cavity body, when a pressure is imposed on, the closed free bottom will stretch out. This peculiar structure of bellows will be able to provide a larger linear range within its stretching limit. Metal bellows not only possesses high sensitivity but also good anti-fatigue, and could endure high pressure, high or low temperature, and corrosive substance. The selections of the bellows material, structure and technical specific parameters are dependent on the dynamic measurement range and working environment.

3. INTERFERENCE FRINGE COUNTING METHOD

The interferential light intensity goes through photoelectric conversion, after the optoelectronic signal's pre-amplifying and trimming, the number of fringes can be counted. Here, two techniques for fringe counting are introduced.

1.1 Electronic hardware method for fringes counting

Schmidt circuit is used to convert the cyclical signals into rectangular pulses. The number of pulses represents the liquid level change. As shown in Fig.2, by choosing an appropriate threshold level, the triggering circuit will generate a high electrical output when the input signal voltage is higher than the upper threshold. The output voltage will be maintained until the input signal voltage falls below the lower threshold. In this way, the periodic input voltage signal will be converted to a pulse train with high or low states, say "1" and "0", which is the binary representation used in digital circuits. Thus, for one cycle of signal input, the circuit generates one trigger pulse, and then the numbers of these pulses were added up by the counting circuit. The electronic circuits applied in treating the interferential light are simple and almost under no influence of the fluctuations of the light source, temperature, and environmental vibration/ disturbance. The entire system stability can be greatly enhanced and the whole cost may be much reduced.

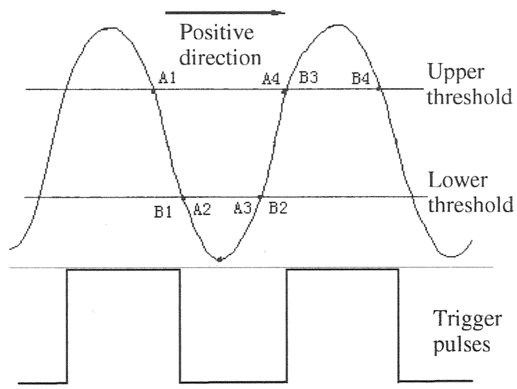

Fig.2 Signal conversion by the Schmitt circuit

1.2 Computer software method for fringes counting

After the optoelectronic signal's pre-amplifying and trimming, the signal can also be converted to digital one through an analog-to-digital (A/D) conversion circuit, and send to a computer to process with a computer program. Using software to count the fringes is much easier and more reliable because the thresholds can be set and modified easily.

The dynamic threshold values may be settled automatically according to the temporary highest and lowest output voltage of the detected signal in each period. Hence, the effect of signal fluctuation could be greatly reduced.

4. COUNTING AND DIRECTION DISCRIMINATION OF INTERFERENCE FRINGES

In order to count the fringe number accurately, the direction change of the fringes which related to the liquid level up or down change has to be discriminated correctly. A structure with dual optical channels for fringe counting was proposed, which is composed of two GRIN lenses A and B with exactly the same specifications. As shown in Fig.3, the two GRIN lenses were put together with the same orientation but were staggered with a distance of $\lambda/8$. When the light beams from these GRIN lenses are reflected by the same reflection surface, the optical path difference between these two channels is $\lambda/4$ (or phase difference $\pi/2$). With the intention of illustrating the relationship between the output light intensities of A and B and the direction of the fringe change, two series of points, A1 to A9 and B1 to B9, were marked on the output intensity curve with a phase difference spacing of $\pi/4$ for each series (as shown in Fig.4). The pairs, ($A1$, $B1$), ($A2$, $B2$),…, (A9, B9), represent the corresponding output signal detected from channels A and B and are in sequence. In terms of this direction discrimination setup with dual optical channels, one could not correctly make the direction change judgment at any point in an interference fringe cycle. But if we do it just when the signal gets to the threshold point, the result of the direction change distinguishing should be exclusive.

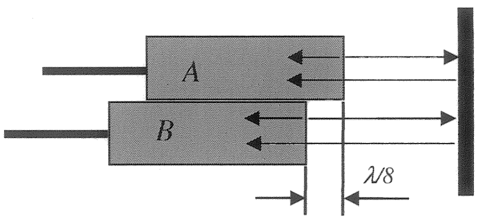

Fig.3 Direction discrimination with dual optical channels

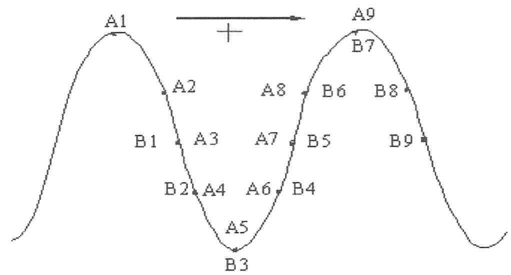

Fig.4 Principle analysis of direction discrimination with dual optical channels

In Fig.4, if the optical channel A is set as for fringe number counting, and optical channel B for direction change discrimination, when the signal detected from channel A increase and reach to the upper threshold (no matter from left or right), the fringe number will be counted; and at the same time, the fringe number counting pulse is applied as the trigger signal to activate the switch for the direction change sentencing, then the intensity change trend information (i.e. from low to high value or vice versa) of channel B is read, the combinations of the signals from the optical channels A and B hold unique, definite, logical corresponding relationship with the liquid level up or down, the output results from the channel B, therefore, could be used as the gist to distinguish the direction changing of the liquid level to be tested.

Table.1 Combinations of the two optical channel outputs

Positive direction		**Negative direction**	
Optical channel A (for counting)	Optical channel B (for direction discrimination)	Optical channel A (for counting)	Optical channel B (for direction discrimination)
$A2\downarrow$	$B2\downarrow$	$A2\uparrow$	$B2\uparrow$
$A8\uparrow$	$B8\downarrow$	$A8\downarrow$	$B8\uparrow$
The threshold value for counting is set at the level corresponding to $A2$ point.			

5. COMPENSATION OF TEMPERATURE INFLUENCE ON THE CAVITY LENGTH

Selecting suitable materials and related cavity parameters may compensate the impacts of temperature changes on the cavity length.

According to the thermal property of materials, for a temperature change ΔT, the length change Δl of the material with length l can be written as:

$$\Delta l = \alpha \, \Delta T \, l \tag{3}$$

where α is the linear thermal expansion coefficient of the material.

Supposing at the temperature t_0, the effect depth of the cavity is l_{01}, the thermal expansion coefficient of the cavity body is α_1; and the effective length of the bellows is l_{02}, the axial thermal expansion coefficient of the bellows is α_2, and then, the actual spacing of the F-P cavity d_0 is:

$$d_0 = l_{01} - l_{02} \tag{4}$$

Assuming the temperature changes ΔT and reaches to t, then the effective depth of the cavity is altered to l_{t1}:

$$l_{t1} = l_{01} + \alpha_1 \Delta T l_{01} \tag{5}$$

the axial effective length of the bellows l_{t2} now:

$$l_{t2} = l_{02} + \alpha_2 \Delta T l_{02} \tag{6}$$

Therefore at the temperature t, actual length d_t of the F-P cavity can be written as:

$$\begin{aligned} d_t &= l_{t1} - l_{t2} \\ &= d_0 + (\alpha_1 l_{01} - \alpha_2 l_{02})\Delta T \\ &= d_0 + c\Delta T \end{aligned} \tag{7}$$

Choosing proper cavity body and bellows materials and structures, and their axial expansion coefficients and initial lengths make the following equation maintained, i.e.:

$$c = \alpha_1 l_{01} - \alpha_2 l_{02} = 0 \tag{8}$$

then, within a certain scope, for any temperature change, it holds

$$d_t = d_0 \tag{9}$$

Thus the F-P cavity length would not be affected by the temperature variation. Practically, the temperature change scope ΔT should not be unreasonably large.

6. AIR PRESSURE SIMULATION AND WATER LEVEL TEST EXPERIMENTS

To evaluate the performance of the system with the proposed sensor head, experiments for air pressure and water level measurement were conducted respectively.

Varying air pressures were applied by a pressure calibrator which has the full scale of 0~100KPa (equivalent to about 10 meter high water), and the precision of 0.05% FS. The output pulses from the sensor were recorded and processed by a Labview program. During the experiments, for every 10 pulses (i.e. 10 fringes), the pressure indicated by the calibrator will be recorded. Fig.5 shows the number of pulses detected as a function of applied air pressure, where the data points correspond to the experimental results, while the solid line represents the curve fitting result. The experiments were also carried out for the climbing up and falling down cycles, revealing a good consistency. The experiment results show that the linearity and repeatability is quite satisfied in the full scale measurement. The actual minimum resolution of 2mm was observed.

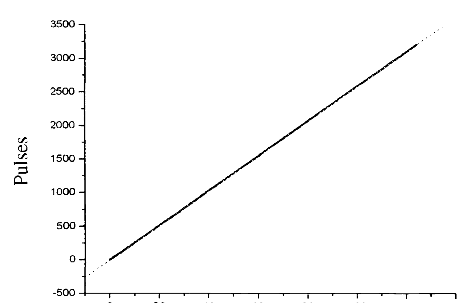

Fig.5 Results for air pressure measurement

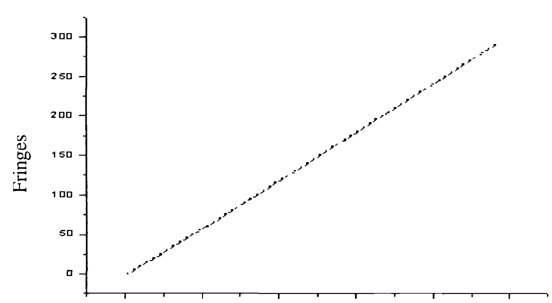

Fig.6. Results for water level measurement

Water level measurements were performed with varying water depth. For every 5 pulses output, the water level was measured, the full scale of the test is about 1 meter. Fig.6 shows the test results.

7. CONCLUSIONS

In order to solve the problems encountered in the interferometric liquid level sensor based on light intensity measurement, the fringe counting technique was proposed and a sensor structure sustained with large strain/displacement was presented. Flexible metal bellows was used as the elastic element to provide a large axial strain. Both electronic hardware and software demodulation scheme were developed to count the fringes and distinguish the up or down of the liquid level. A scheme of temperature compensation for the sensor head was discussed. A prototype of the liquid level sensor was fabricated and the experiments for air pressure and water level measurement were carried out. The experiments showed that the sensor system may have a bright future application. Because the interference fringe counting technique was used for the signal demodulation, the noise resistance capability of the sensor against optical power fluctuation and other disturbances was greatly improved.

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