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Optical fiber grating sensors for height measurement of liquid

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Abstract: A precision approach utilizing fiber grating as elements to measure height of liquid is presented and experimented and the basic issues of the sensor system design are discussed. This type of sensor can be used in precision measurement of medium measurement ranges. The sensitivity of 0.15mm/pm for measuring the height of water has been obtained.

Key words: measurement sensor optical fiber grating

用于测量液面高度的光纤光栅传感器

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摘要: 提出并实验了一种精密的用光纤光栅作为敏感元件测量液面高度的方法, 讨论了传感系统设计的关键问题。该传感器可用于中等深度的液面高度的精密测量, 其灵敏度可达 0.15mm/pm。

关键词: 测量 传感器 光纤光栅

Introduction

Compared with temperature and pressure measurement, the methods to measure the height of liquid are not good enough. In some circumstances, such as the liquid surface is fluctuating, the liquid is boiling and there are small floating materials on the liquid surface, it is difficult to measure the height of liquid precisely. Nowadays, there are several methods to measure the height of liquid. For example, using a rule to measure the height of liquid directly, measuring the height of liquid through the variation of the buoyant force or through the variation of liquid pressure or through the variation of electrical capacity induced by the liquid height variation. Because the precision of the transferring from these variations to electrical variation is not high, the sensitivity of measuring the height of liquid is not better than 1mm. Because of the immeasurable ranges, the technology of liquid height measurement needs to be developed a lot. It is a very important task to find more precision and higher resolution methods to measure the liquid height[1,2].

Recent years a number of papers have been reported on research of optical fiber grating sensors, most of which are used to measure strain, temperature and pressure[3~9]. In this paper, we experiment primarily and present an in-fiber grating application of measurement the height of liquid. This type of optical fiber grating sensors may be used in electron-magnetic interference or/and inflammable or/and corrosive or/and conducting or/and foaming surface liquids. Because a floating bar is used to transfer the liquid height to the strain of an in-fiber grating, the corresponding issues of design, including the measurement range, sensitivity, the diameter and length of the floating bar etc., are discussed. As the method we present is to embed the in-fiber grating element into the measured liquid, the fluctuation and the foam of the liquid surface will not influence the measurement precision and the immeasurable range can be reduced by using a short in-fiber grating. Our sensors fit with high precision of measurement range of a few hundred millimeters.

1 Experimental configuration

The experimental arrangement is shown in Fig. 1. A hollow floating bar FB is hung by spring SP so that the weight of FB is balanced. A broadband light source illuminates, through an isolator IS and a 3-dB coupler, the fiber with a in-fiber Bragg gratings G, of which the nominal reflecting wavelength is 1549nm. The reflecting signal from the grating is detected with a spectrum analyzer SA (or with other interrogative approaches), the height variation of liquid is measured with a ruler R. One end of the fiber grating G is mounted to the center of the round surface of the lower end of the bar while the other end of G is firmly fixed to the unmovable shelf. The spring supported on the shelf is so placed that it can be moved up and down to pre-strain G with a small quantity. We also employed a spring system consisting of a principal spring SP and 4 side-springs (four rubber ropes) to stabilize the floating bar (Fig. 2).

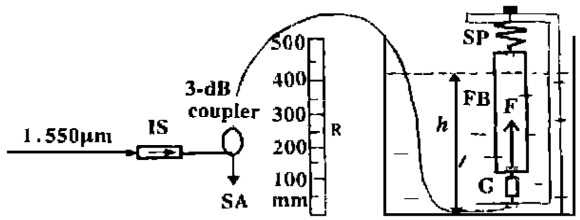

Fig. 1 Arrangement for liquid measurement utilizing fiber gratings

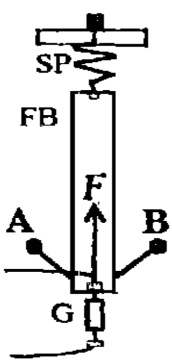

Fig. 2 Principal spring and four side-springs

The buoyant force F acting on the FB can be presented as

$$F = \pi r^2 \rho \Delta h \tag{1}$$

Where, r is the radius of the floating bar, ρ is the density of the liquid, Δh is the variation of liquid height, which can be measured with the ruler R. F increases with the increase of Δh, which induces the reflecting wavelength shift with a proportional quantity. During the experiments, the change of temperature of water is maintained within 0.1℃, the reflecting wavelength shift of G was measured with the spectrum analyzer and the water height was recorded with the ruler R as the water was poured into the vessel.

2 Experimental results

The experimental results are illustrated in Fig. 3, in which the curve A is for one spring SP and curve B is for the principal spring SP with the four side-springs together. Comparing the two curves, we see two parallel lines that have illuminated the same high linearity and sensitivity in the two cases, although the side-springs which protect the grating from breaking can strongly keep the floating bar stable. The sensitivity of 0.15mm/pm has been obtained for a fiber grating made of 145μm diameter KIST-1104 fiber and a floating bar with 36.0mm diameter. We can express the sensitivity as $K_w = 0.00619$ pm/mm·mm^2, which gives the reflecting wavelength shift against per mm of height change and per mm^2 of section area. With the spectrum analyzer in the lab, we were able to distinguish ~ 3mm water height change.

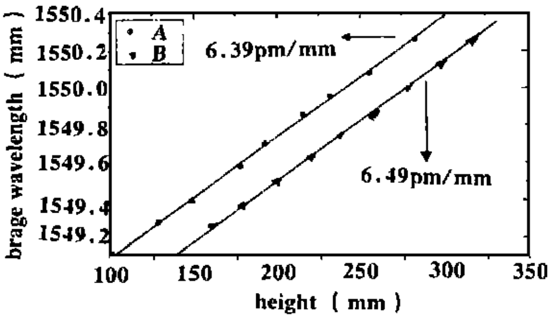

Fig. 3 Curve of wavelength shift against the water height

3 Considerations in design

Five issues have to be considered to design an in-fiber grating liquid height sensor: the maximum limitation of the reflecting wavelength shift $\Delta\lambda_{max}$, which is dependent on the force stretching the optical fiber safely; measurement range Δh_{max}; length L and section area A of the floating bar; sensitivity K and resolution. The relation of these parameters can be expressed by

$$K_w \rho A h = \Delta\lambda < \Delta\lambda_{max} \quad (2)$$

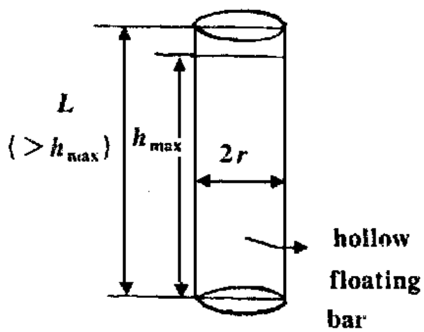

Fig. 4 Floating bar: length and diameter

Where, $K_w\rho$ is the sensitivity of liquid, $\Delta\lambda$ is the reflecting wavelength shift which can not be greater than $\Delta\lambda_{max}$, A is the section area of the floating bar. For a bar with a round section (Fig. 4), Eq. (2) can be rewritten as $K_w \rho \pi r^2 h = \Delta\lambda < \Delta\lambda_{max}$ (3)

Where, r is the radius of the floating bar, and

$$S = K_w \rho A = K_w \rho \pi r^2 = \Delta\lambda_{max} / h_{max} \quad (4)$$

is the sensitivity of measurement which is directly proportional to ρ and A. $\Delta\lambda_{max}$ varies with different types of fiber. Wang has indicated that ~ 7800pm reflecting wavelength shift can be induced by stretching a fiber of ~ 130μm diameter with 7N force, the corresponding strain is 7860μstain beyond which the fiber will be snapped[10]. These are the maximum limitation of the wavelength shift, strain and stretching force acting on the optical fiber. In order to be safe, it is appropriate to limit the greatest wavelength shift to $\Delta\lambda_{max} \cong 5000$pm which correspond − 5nm to a ~ 5nm wavelength shift. One can use the given measurement range h_{max} to calculate r then S, or on the contrary use the given S to calculate h_{max} and r. The measurement ranges of traditional types are 0~ 300mm and 0~ 2000mm et al. We chose $h_{max} = 500$mm as a measurement range of the example design, which needs the length of floating bar $L > 500$mm (for example 550mm). From Eq. (3) the diameter of the floating bar in water height measurement can be calculated as below

$$\Delta\lambda_{max} = K_w \rho h_{max} \pi r^2 \quad (5)$$

As discussed above we take that $\Delta\lambda_{max} = 5000$pm, $h_{max} = 500$mm, $\rho = 1$g/cm^2 and $K_w =$

0.00619pm/mm·mm^2, thus $5000\text{pm} \cong (0.00619\text{pm/mm} \cdot \text{mm}^2) \times 500\text{mm} \times \pi r_w^2$

Which means $r_w \cong 22.68\text{mm}$ and the diameter is 45.36mm

In a word, it is safe for a fiber grating of ~ 140μm diameter stretched by a floating bar of 45.36mm diameter to measure the water height of 500mm.

For other liquids, $r = r_w/\sqrt{\rho}$

From Eq.(4), we know that the sensitivity $S = 10\text{pm/mm}$.

The resolution varies with the interrogative approaches because they have different wavelength shift resolution. For the given example, 10pm wavelength shift is against 1mm water height change. The ordinary resolutions are: 10mm for a spectrum analyzer with a wavelength resolution of 0.1nm; 0.4mm for a fiber Fabry-Perot filter with 4pm wavelength resolution; and 0.1mm for the approach of length-tuning reference fiber grating.

4 Conclusion and discussion

A novel approach to measure water height was presented and demonstrated. As the in-fiber grating is embedded into the measured liquid, the measurement precision is immune to the fluctuation of the liquid surface and the foam on the liquid surface. The sensitivity of 6.49pm/mm of water height measurement has been obtained for a floating bar of 36mm diameter (or $K = 0.00619\text{pm/mm} \cdot \text{mm}^2$). The sensitivity of the technology of interrogating wavelength shift has achieved 1pm. The sensitivity of 6.49pm/mm means the sensitivity of 0.15mm of liquid height. During the experiments, we maintained the variation of temperature less than 0.1℃. A general design consideration fitting for various liquids was given. By calculating, the influence of the wavelength shift induced by water pressure under 500mm depth is small, at an order of 0.015pm, therefore it can be negligible. The temperature variation can be compensated by some methods and using a shorter in-fiber grating can reduce the minimum measurable height.

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