Design of twisted-pair type of frustrated total internal reflection passive fiber-optic liquid level sense measurement system

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Abstract: In order to meet the growing requirements of some national projects, such as the aerospace, monitoring of fuel liquid level, as a key parameter of the flight evaluation, directly affects the efficiency of all kinds of crafts. A liquid level sensor system, which can achieve both single-point discrete and multi-point continuous measurement, was designed based on the bending loss of the plastic optical fiber and the total internal reflection principle. After description of the theory, the actual equipment was used to test the theoretical analysis, illustrate the operating principle, systematical composition and the advantages of the technology were inustrated, simultaneously the feasibility of liquid level measuring experiments in theory was analyzed. Furthermore, both discrete and continuous liquid level sensing systems were finished. The verifying experimental system was also set up. The experimental results show the proposed liquid level sensor system not only can realize the measurement of the liquid level, but also has good consistency and simple implementation. The continuous liquid level sensing system can reach the test range of 450 mm with a sensitivity of 0.808 3 μW/mm, showing a significant reference for the engineering application.

Key words: fiber-optic liquid level sensor; optical fiber optics; bend; frustrated total internal reflection

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双绞式受抑全内反射无源光纤液位传感系统设计

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摘 要：为满足某些国家工程的发展需要，比如说航天领域内，液态燃料液位监测作为飞行指标考核的一个关键参数，检测精度直接影响到各类飞行器的指标实现效率。基于塑料光纤弯曲损耗和受抑全内反原理，设计了一种可实现单点离散与多点连续的液位传感系统。理论分析后，使用实际器材验证理论分析，阐述了操作原则、系统结构和技术优势，分析了进行液位测量的可行性。根据理论分析的结果，基于已有器材搭建了离散和连续式液位传感系统，同时设计了一套实验装置并利用该装置对传感系统进行了验证实验。实验结果表明：所提出的新型液位传感系统不仅可以实现液位的测量，而且具有较好的测量一致性和易实现性。其中连续液位测量系统达到了测试量程 450 mm，测试灵敏度为 0.808 3 μW/mm 的液位测量。对工程应用领域的具有较好的参考意义。

关键词：光纤液位传感；　光纤光学；　弯曲；　受抑全内反射

0 Introduction

Liquid fuel measurement and management system, as the largest airborne electromechanical system, has become the key parameter of the aerospace aircraft in the ground simulation and the actual flight[1-2].

Over the years, researchers in the field of the aerospace and other national projects are committed to the measurement of the liquid fuel level to improve the accuracy and the stability, having tried the methods of machinery, capacitance, ultrasonic, electron-magnetism, optical fiber, magnetostriction and so on. However, due to the complicated working condition of the aircrafts and rockets, the application of the above sensors in engineering is rare. Compared with the traditional sensors, fiber-optic sensor has the merits of compact structure, fast response, high sensitivity, strong resistance to electromagnetic interference and corrosion, and so on[3-8], which ensures it can be used in different occasions of the liquid level detection[9-10].

Aiming at the particularities in different liquid level measurement fields, a new method of testing the liquid level based on bending loss of the cladding mode of plastic optical fiber and the total internal reflection suppression effect is proposed in this paper.

1 Principle of the proposed measurement system

During the engineering application, the energy loss of the bending optical fiber was found. When bending the optical fiber, if curvature radius is smaller than a certain value, the transmission path of the light will change, with one part of the light infiltrating into the cladding and another going through the cladding and leaking to the outside. The surrounding environment of optical path will have an effect on the optical path, leading to different wastage of the light energy, which offers a possible mechanism to detect the liquid level. To be more specific, when surrounding medium of the bending optical fiber is gradually changing from air to liquid, the amount of the leaking light energy can also vary. Thus the measurement of the liquid level can be achieved by monitoring the various energy[11-13].

The numerical aperture of the optical fiber is often used to weigh its ability to capture light, being a dimensionless constant. The light reaching the input end of the optical fiber in a random angle may not all be transmitted in the optical fiber but in a certain range of angles of incidence. The sine of the angle value is defined as the numerical aperture of the optical fiber.

Meridional ray is the light spreading deviously in a plane, as shown in Fig.1. The typical feature of the meridional ray is that it intersects twice with the center of the optical waveguide axes in a cycle. This section mainly focuses on the propagating discipline of the meridian light in the bending waveguide based on the concept of numerical aperture, and the changes of the position of incoming light when

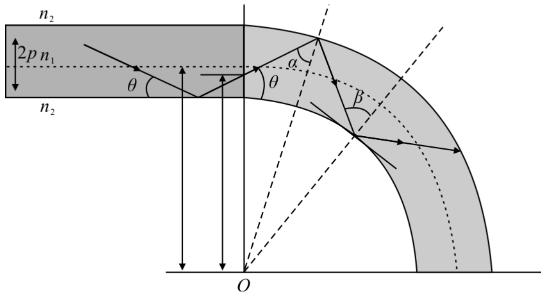

Fig.1 Transmission path graph of the meridional ray

the optical fiber bends. Assuming that when the external environment keeps constant, the limiting incident angle of the optical fiber is θ_c, the actual incident angle of the light is θ, thus we have:

$$-\theta_c\leqslant\theta\leqslant\theta_c\ (\theta_c=\arcsin\frac{n_1}{n_2})\tag{1}$$

Where n_1 and n_2 are the refractive index of the optical fiber core and cladding, R is the bending radius, α and β are defined as the inner and outer angles of the incident light , then the numerical aperture can be given as:

$$NA=n_1\sin\theta\leqslant\sqrt{n_1^2-n_2^2}\tag{2}$$

According to the geometry, we also have the relations as:

$$\frac{R+\rho}{\sin\left(\theta+\frac{\pi}{2}\right)}=\frac{r}{\sin\alpha\ \beta}\tag{3}$$

$$\frac{R-\rho}{\sin\alpha}=\frac{R+\rho}{\sin(\pi-\beta)}\tag{4}$$

According to the above formula, $n_1\sin\alpha\geqslant n_2$ and $n_1\sin\beta\geqslant n_2$ can be achieved. In Fig.1, we have and the is the diameter $-\rho\leqslant x\leqslant\rho$ range of $r=R+x$ incident light in the optical fiber core. Hence, in anormal air environment, the numerical aperture of the bending optical fiber can be given by:

$$NA_{\rm curve}=n_1\left[1-\frac{n_2^2}{n_1^2}\left(\frac{R+\rho}{R+x}\right)^2\right]^{1/2}\tag{5}$$

According to Eq.(4), the corresponding numerical aperture decrease with the decline of the bending radius R, causing the energy loss of the transmitting light[14-15].

2 Sensitive model of liquid level measurement system

According to the mentioned feature extraction method of the liquid level, the passive fiber-optic liquid level measurement system is constituted by twisted double optical fibers. As shown in Fig.2. The experimental setup diagram is shown in Fig.3.

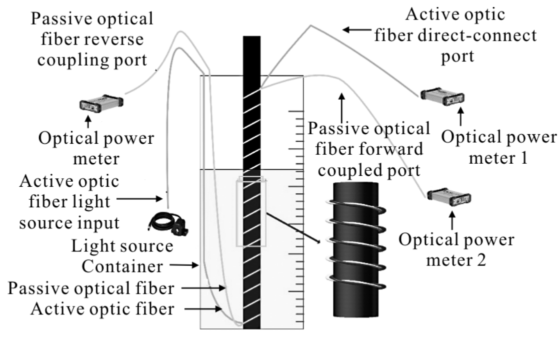

Fig.2 Schematic diagram of the experimental setup

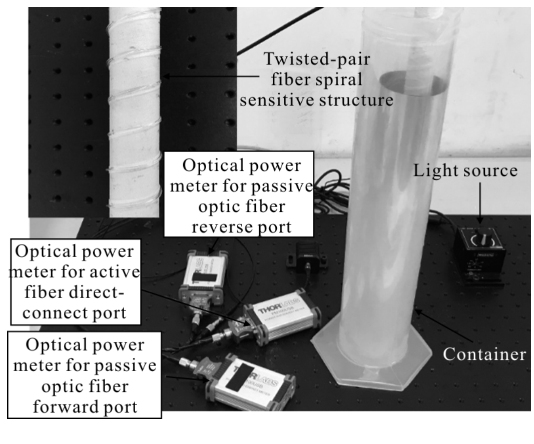

Fig.3 Physical diagram of the experimental setup

3 Liquid level measurement system and experiment process

According to the above content, light energy sensing loss can be effectively stimulated through two double-twisted plastic optical fibers.

The length of the two plastic optical fibers is 10 cm, bending diameter is 25 mm while winding. The power of the light source is 6 mW. The initial height of the liquid level is 137 mm. The measured medium flows at a speed of approximately 0.46 mm/s. Fiber optical ring is fixed at a distance of 45 mm to the bottom of the container. The experimental results are shown in Fig.4.

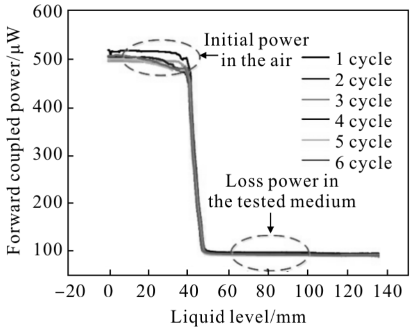

Fig.4 Experiment curve of the discrete liquid level measurement

We further improve sensitive components of the measurement system to achieve continuous dynamic liquid level measurement.

The sensitive structure is built through twisted-pair plastic optical fiber winding on the base with fixed diameter. The value of the light power meter in the active fiber is 5.19 mW with core diameter of the plastic optical fiber being 1 mm, the winding pitch being 23 mm, base diameter being 20 mm, level measurement being 450 mm. The measure d medium velocity is about 2.12 mm/s. The test results are shown in Fig.5, the test results of 6 consecutive measurements of the forward port of passive optical fiber are shown.

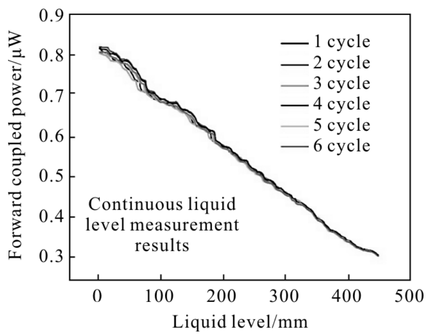

Fig.5 Continuous level measurement experiment curve

4 Analysis of experimental results

According to the variation of cladding external environment medium, the transmission of light energy in cladding mode will change. Based on bending total internal reflection suppression effects of plastic optical fiber, the liquid level sensitive system has been formed.

During the discrete level measurement experiment, the output of the active fiber, the direct and reverse passive optical fiber coupling power output are measured, and the normalization comparison of three curves are shown in Fig.6. Thus, we can see that the reverse coupling power has a rising trend in the process of level falling

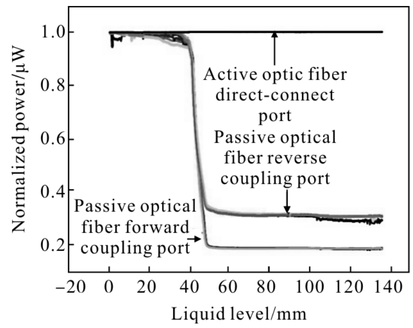

Fig.6 Normalized curve discrete level measurement

with time going in the above curve, but in comparison with the direct coupling end, the change magnitude is relatively weak. The output value of the port on active fiber is almost constant. Through the experimental curve of discrete measurement, we could obtain the following conclusions:

(1) The energy was not change suddenly at the testing point. The reason is that the medium around the sensitive part does not change suddenly, but changes slowly along with the liquid level, and due to the liquid tension, there would be measured liquid residue on the surface of the sensitive part, which leads to measurement hysteresis and brings test error.

(2) In the air, the residual liquid on plastic optical fibers surface each time is different. Similar to the discrete level measurement experiment, there is difference between the coincidence of low liquid level and high liquid level. Optical power meter resolution can reach 0.1 nW. According to the data fitting results, as

shown in Fig.7, the theoretical resolution of the continuous liquid level measurement system can reach 0.084 5 mm. But it needs improving the measurement accuracy to a certain range to have practical significance. The average error within the scope of liquid measurement can reach 4.24 mm, the test sensitivity is 0.808 3 μW/mm in the diagrammatic curve.

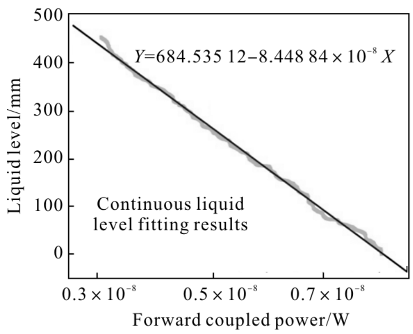

Fig.7 Continuous level measurement curve fitting

5 Conclusion

This article studied the transmission light energy influenced by the structure deformation aiming at the liquid sensing requirements of high security and simple implementation in engineering application field. A novel method based on frustrated total internal reflection in the optical fiber cladding is proposed to build the liquid level sensor according to the feasibility of the plastic optical fiber in bending. Two plastic optical fibers twisted around to constitute a level sensitive component. The discrete and continuous liquid level detection methods were realized respectively. Thus the study in this article provided good references for simple liquid level measuring system in relevant fields.

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