中國機械工程學刊第三十卷第二期第159~165頁(民國九十八年)
Journal of the Chinese Society of Mechanical Engineers, Vol.30, No.2, pp.159~165 (2009)

An Innovative Optical Fiber Flowmeter

Joe-Air Jiang*, Te-Yu Hsu**, Wen-Bin Liao***, and Cheng-Shiou Ouyang****

Keywords: Optical fiber flowmeter, Turbine flowmeter, Transmitting fiber, Collecting fiber

ABSTRACT

Optical fiber has been applied in sensing technology for years. Compared with conventional sensors, optical fiber excels in low cost, small size, free from electromagnetic interference, low transmission loss, etc. Hence it is very suitable for the environmental monitoring and measuring in various industries. An innovative optical fiber flowmeter combining optical fiber sensing technologies and turbine flowmeter is presented in this paper. The sensor head includes a precise propeller. The optical fibers are used to transmit and collect the light signals. The light injects on the blades of the propeller will be reflected and received by the collecting fiber. By calculating the reflected signal frequency, we can convert it into the flow velocity after appropriate calibration. A prototype was developed and verified in a simulated flow measuring system. The results show good linearity and accuracy which could be used for remote monitoring, especially in the hazard area under safety concern.

INTRODUCTION

Background

Flow measurement is necessary in many industrial applications such as water inventory control in municipal water market, leak etection in petroleum pipeline industry, corrosive bulk transport of industrial chemicals, low flow measurement in coatings industry, etc. which require the determination of the quantity of a fluid with the phase of gas, liquid, or steam, that passes through a check point. There are various types of flowmeters based on different technologies developed for different flow quantity to be measured. Besides electronic type to measure the acoustic wave or electromagnetic field and pressure type to measure the pressure difference, mechanical flowmeter are the most commonly used flow measurement devices. Beyond the primary disadvantage of employing moving parts to make them susceptible to wear, mechanical flowmeter excel in their inexpensive cost for manufacturing as well as the practicability and availability in nearly all applications. Among all mechanical flowmeters, turbine flowmeter provides the highest accuracy when properly installed and calibrated, especially when measuring clean, conditioned, steady flows of gases and liquids with low viscosities and is linear for subsonic and turbulent flow (Wadlow, 1998).

Motive of Research

Considering the increasing demand of flow measurement in various industries and the limitation for conventional sensors, optical fiber is an appropriate solution for sensor applications with many outstanding characteristics (Tai, 2004). In many countries, most of the waterworks are located in mountainous and thunderous area where serious electromagnetic interference (EMI) might happen easily. By using optical fiber as the signal carrier or sensing elements, the EMI issue could be eliminated (Culshaw, 1984). In addition to the foregoing, optical fiber sensors could be installed in the hazard districts for remote monitoring to decrease the possible harm to the workers.

In view of the merits and drawbacks of the conventional sensors and optical fiber sensors, we planned to develop an innovative flowmeter combining the advantages from both of them. We have designed the sensor head based on an existing mechanical turbine flowmeter with an in-line propeller. The optical fibers are used to transmit and collect the light signals modulated by flow velocities for analysis. Besides the wide applications and high accuracy could be expected from the current

Paper Received August, 2008. Revised October, 2008. Accepted March, 2009. Author for Correspondence: Joe-Air Jiang.

**Professor, Department of Bio-Industrial Mechatronics Engineering, National Taiwan University, Taipei 106, Taiwan.*

*** Ph. D., Department of Bio-Industrial Mechatronics Engineering, National Taiwan University, Taipei 106, Taiwan*

****Assistant Professor, Department of Electrical Engineering, Technology and Science Institute of Northern Taiwan, Peitou 112, Taiwan.*

*****Graduate Student, Department of Bio-Industrial Mechatronics Engineering, National Taiwan University, Taipei 106, Taiwan.*

understanding for turbine flowmeter, an essential feature of remote sensing can be reached with the inherent properties of optical fiber.

Literature Review

Turbine flowmeter has the highest accuracy in the mechanical type flowmeter, while it still has some limitations to the fluid to be measured and the restricted measurement range due to the non-linear properties. A study on the factors which influence the variability of turbine flowmeter signal characteristics had been raised by Cheesewright et al. (1998). Recently Li et al. (2006) also provided a method to extend the measurement range of turbine flowmeter. Another study (Sun et al. 2006) on turbine flowmeter's performance for measuring fluids with different viscosities was issued lately.

Regarding to the attractive features of remote sensing capability as well as immunity to electromagnetic interference, optical fiber has been applied to sensor applications for more than thirty years. In this application, a light beam was modulated and detected by photodetectors. These modulation algorithms include light intensity, optical phase, polarization, frequency and spectral distribution. However, the photodetectors are only capable of detecting light intensity; hence all these light properties have to be detected as a variation in the optical intensity.

Lyle et al. (1981) measured the fluid flow within a pipe by adopting the phase modulation of the light signal. The results showed good accuracy and reliability without using moving parts. However, there are still some limits and difficulties for implementation such as no obvious vortices are shed under the minimum flow velocity of 0.3 m/s. Besides, a single fiber is mounted transversely to the fluid flow within the pipe which will cause the lifetime issue for optical fiber and big challenge to water-resistant performance of the fillers in the holes for inserting the optical fiber. Recent studies of the determination of real-time vortex shedding frequency past a circular cylinder have been brought up by Lee (1998) and Hu (2006).

In addition, Takashime et al. (2004) have brought up an improved vertex flowmeter combining a cantilever fiber Bragg grating (FBG) sensor by using interferometric detection to measure the wavelength shift. With the characteristics of high sensitivity and accuracy for optical fiber interferometer, the minimum flow velocity to be measured could be lowered to 0 with the minimum detectable velocity of 0.05 m/s. Another idea of using a modal interferometer for flow measurement was published in 2007 (Frazão et al. 2007). The experiment results in this paper are very inspiring and convincing for the sensing mechanism, while in the practical applications such as borehole, the sensor package and reliability are two of the essential aspects to be taken into account carefully.

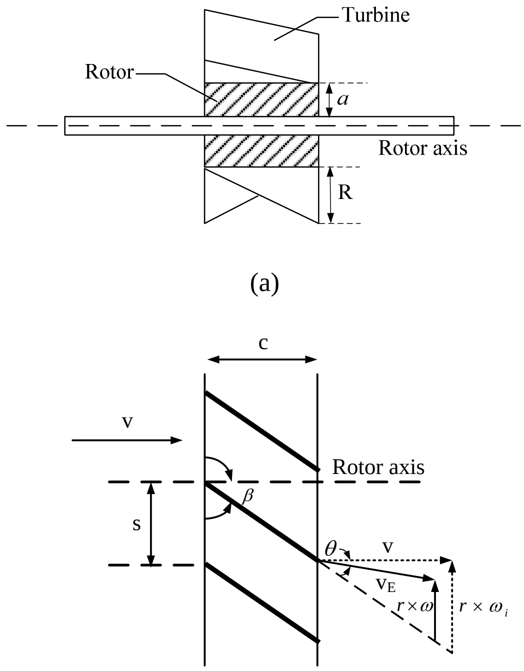
METHODOLOGY

Turbine Theory

The structure of an axial turbine is shown in Figure 1 (a). The tangent vector of the turbine rotor is shown in Fig. 1 (b). To simplify the derivation of the formula, we assume that the blades of the turbine are straight and thin. The radius of the rotor is a, the radius of the turbine is R, the width of the blades is c, and the distance between blades is s, respectively. The incoming flow with velocity v causes the turbine to rotate at angular velocity ω. If there is no velocity loss, the ideal angular velocity ω_i can be related to the flow velocity v by a simple trigonometric formula as Equation (1):

$$\bar{r}\,\omega_i = \mathrm{v}\tan\beta \quad \Rightarrow \quad \frac{\omega_i}{\mathrm{v}} = \frac{\tan\beta}{\bar{r}}, \tag{1}$$

where β is the angle between the pipe axis and the blades of the turbine, θ is exit flow swirl angle due to rotor retarding torques, $\bar{r}$ expressed in Equation (2) is the root-mean-square value of the inner and outer radii of blades.



(b)

Fig. 1. (a) Structure of an axial turbine; (b) Tangent vector of an axial turbine rotor.

$$\bar{r} = \sqrt{\frac{R^2 + a^2}{2}} \quad (2)$$

Considering the non-ideal case, flow velocity changes to v_E after it passes the turbine blades, as shown in Fig. 1. Due to this change of velocity vector, the flow applies a torque T to the turbine to make it rotate. The flow velocity can then be related to the angular velocity ω of the turbine:

$$\frac{\omega}{v} = \frac{\tan\beta}{\bar{r}} - \frac{T}{\rho A v^2 (\bar{r})^2}, \quad (3)$$

where ρ is the fluid density and A is the cross-section area of the pipe.

Since the turbine is rotating at a constant speed, the torque T must be counteracted by an equal amount of resistance torque. Neglecting all minor factors, the most important contributor to this resistance torque is the sum of the drag force on each blade. Through some mathematical derivation, the volume flow rate Q can be expressed in terms of the angular velocity of the turbine ω as Equation (4):

$$Q = vA = \frac{\omega (\bar{r})^2 A^2}{\bar{r} A \tan\beta - 0.037\, Re^{-0.2}\, n\, (R + a)\, s \sin\beta}, \quad (4)$$

where n is the number of blades and Re is Reynolds number which is used to describe the characteristics of a fluid and expressed as Equation (5):

$$Re = \frac{\rho v D}{\mu}, \quad (5)$$

where D is the pipe diameter and μ is the fluid viscosity.

In the turbine flowmeter, a magnetic transducer is mounted perpendicular to the shaft measures the passing of each blade. The relationship between flow and frequency is defined as K-factor. K-factor is expressed in pulses per unit volume and it can be used to electronically provide an indication of volumetric throughput directly in engineering units. In industrial applications, a K factor is commonly introduced to compensate for the neglected factors in the above derivations.

System Overview

Figure 2 shows the block diagram of the sensing system of the optical fiber flowmeter. In the sensing system, an 850 nm LED is adopted as the light source to transmit the light signal into flowmeter sensor head by the transmitting fiber. The light will then inject on the surface of the blades of the sensing element and be reflected and redirected through the collecting fiber to the detection circuit for analysis. Due to the

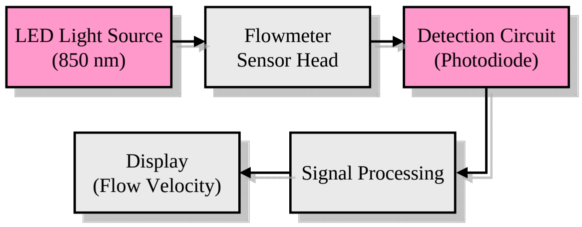


Fig. 2. Block diagram of the sensing system of the optical fiber flowmeter.

sensing element has a fan structure with several flat blades and it will rotate simultaneously with the propeller in the pipe while the flow passing through, so we will get a series of discrete signal with high and low in turn. This sensing mechanism is called intensity modulation. More detailed information of the sensor head mechanism will be described in next sub-section. A photodiode is used to detect the modulated light signal and converts it into voltage signal. The waveform of the signal and its frequency can be analyzed by an oscilloscope. According to our experiment results, the flow velocity is proportional to the frequency of the signal. By properly correlating the flow velocity to the signal frequency, we can then calculate the flow velocity from the measured signal frequency by the oscilloscope.

System Structure Design

LED Light Source: A commercial monolithic switching regulator of LM3402/02HV developed by National Semiconductor Corporation is a buck regulator derived controlled current source designed to drive LEDs at forward currents of up to 500 mA. In the flow measuring system we designed, the LM3402/02HV was used to deliver constant current to 850 nm LED light source. The LED driver circuit is shown in Figure 3.

Detection Circuit: A light-to-logarithmic-voltage conversion circuit shown in Figure 4 is used to detect the light signal from the collecting fiber and convert the light signal into voltage. The output voltage of this circuit is proportional to the logarithmic change

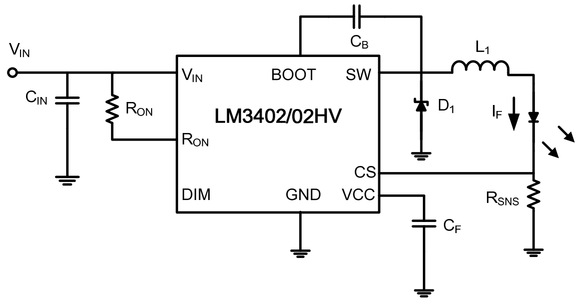
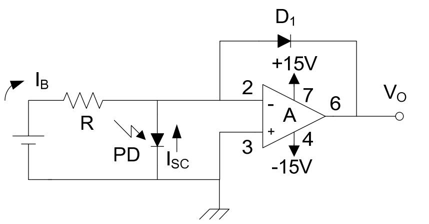


Fig. 3. LED driver circuit.

in the detected light level. A base-emitter junction of small signal transistors or a diode between the gate-source of junction FETs can be used as the log diode D_1. I_B is the current source that supplies the log diode with a bias current. If I_B is not present, the circuit will be unstable or latched up when I_{SC} by the incident light decreases to zero. The frequency of the V_o in Fig. 4 was shown to be proportional to the flow velocity described in the following sections.

Flowmeter Sensor Head: Figure 5 (a) shows the sensor head mechanism of the optical fiber flowmeter we have developed. The axis of the propeller is connecting to a sensing element in the vertical direction with the flow pipe. The sensing element has a fan structure with several flat blades. We can improve the sensitivity of the flowmeter by increasing the numbers of blades. An optical fiber probe with two-fiber configuration shown in Fig. 5 (b) is mounted perpendicular to the surface of the sensing element. The one for transmitting the light signal is called transmitting fiber. The other one to receive the reflected light is called collecting fiber. Light injects through the transmitting fiber on the surface of the blades will be reflected and received by the collecting fiber. The intensity of the reflected light will depend on the reflectivity of the blade surface.

When the flow passes through the pipe, the propeller will be driven to rotate at a speed proportional to the flow rate. At the same time, sensing element will also rotate synchronously with the propeller. Due to there are gaps between each blade of the sensing element, so the light will pass through the gaps without being reflected. That's why a series of discrete signals with high and low will be obtained in turn and its frequency is proportional to the flow rate accordingly. In addition, the intensity difference of the high signal and low signal is quite



D_1 : Diode of low dark current and low series resistance

I_B : Current source for setting circuit operation point, $I_B << I_{SC}$

I_{SC} : Short circuit current of the photodiode

R : 1 G to 10 GΩ

I_O : D_1 saturation current, 10^{-15} to 10^{-12} A

A : FET input Op-amp

$$V_O \approx -0.06 \log\left(\frac{I_{SC}+I_B}{I_O}+1\right) \quad [V]$$

Fig. 4. Detection circuit.

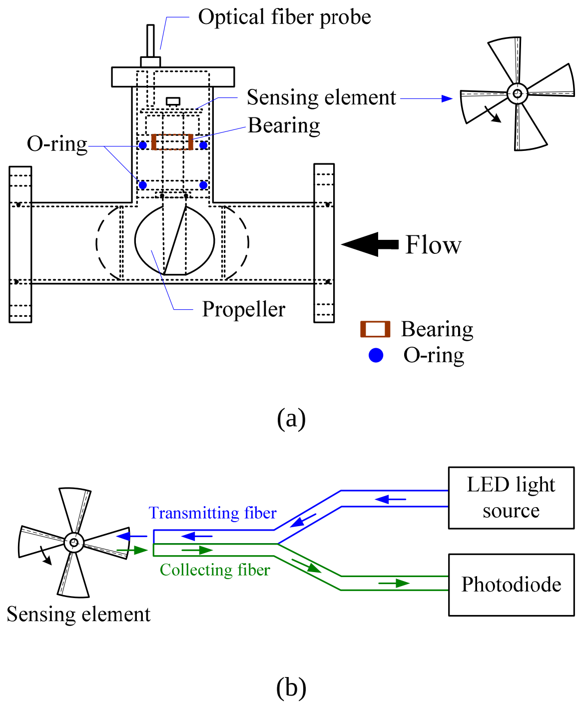


Fig. 5. (a) Mechanism of the flowmeter sensor head; (b) Optical fiber probe.

distinct, so we can easily set a threshold for identifying the high signals to neglect the reflectivity variance between each blade. All the signals over the threshold will be treated as "One", otherwise it will be treated as "Zero". This concept is very practical and easy to be implemented in the industrial application.

In the vertical tube of the sensor head accommodating the sensing element and optical fiber probe, there are O-rings installed between propeller and sensing element. The O-rings are used for sealing to prevent the flow penetrating from the pipe into the vertical tube, so we won't get the fouling problem on the blades of the sensing element. Even the wall of flowmeter or blade tip are not clean, it won't induce much impact on the rotation rate of the sensing element and the accuracy of the sensor. The transparency of the flow won't be an issue neither. These distinguishing features make our optical fiber flowmeter breaks through the limitation of traditional turbine flowmeter whose accuracy will be reduced by the blades contamination addressed by Anabtawi (2000).

Experimental Set-up of Flow Measuring System

The experimental set-up of the flow measuring system is shown in Figure 6. We use a water tank with a partition in the middle to divide into two separate spaces for water storage. Some control valves and water pump are used to provide a simulated low system. A calibrated flowmeter is installed before the optical fiber flowmeter to deliver

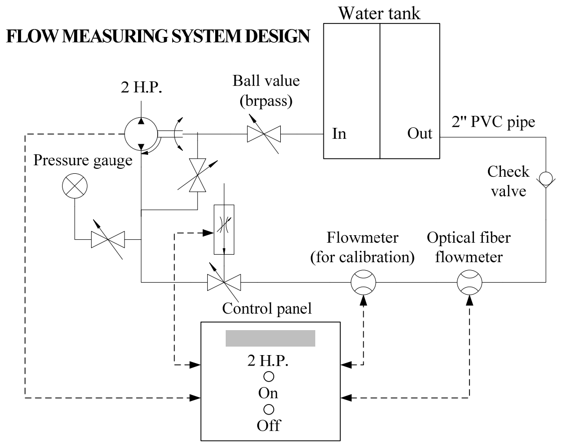


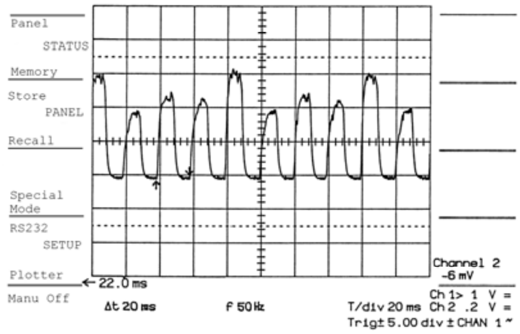
Fig. 6. Experimental set-up of flow measuring system.

an accurate measurement of the flow velocity which is used to compare the data obtained from the optical fiber flowmeter we developed.

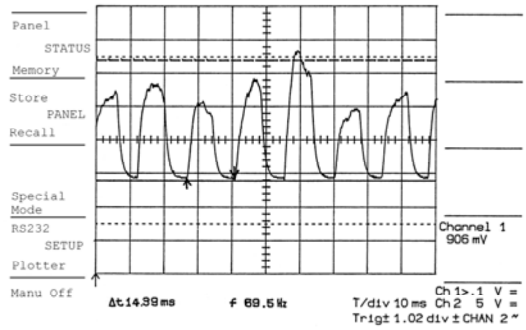
RESULTS & DISCUSSIONS

Frequency Spectrum of the Detected Signals

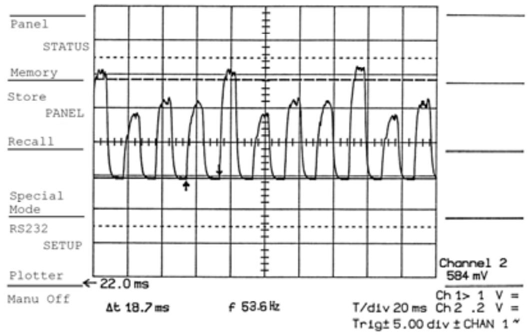
We use the flow measuring system described above and an oscilloscope to measure the frequency of the detected voltage signal. The material of the sensing element we adopted is stainless steel 304 which has many excellent properties in mechanical strength, heat resistance, corrosive resistance in a wide variety of environments, etc., so a more stable reflectivity of the blades surfaces could be expected. We had made two types of structures of the sensing element with 4 blades and 6 blades respectively to verify the system sensitivity. The frequency spectra obtained from 4-blade and 6-blade sensing elements at the flow velocity of 0.2 m/s are shown in Figure 7 (a) and Fig. 7 (b) individually. Fig. 7 (c) and (d) shows the results from 4-blade and 6-blade structures at the flow velocity of 0.4 m/s. Because of the reflectivity variances of the blades surfaces, the magnitude of amplitude will be different for each high signal. While it is distinct between the high signals and low signals, therefore we can set a proper threshold to treat the signals as “One” or “Zero”. Then the sensor will act like a counter to calculate the frequency of the high-low signals and correlate the frequency to the flow velocity. Moreover, the spectra obtained by the oscilloscope show good stability and repeatability.



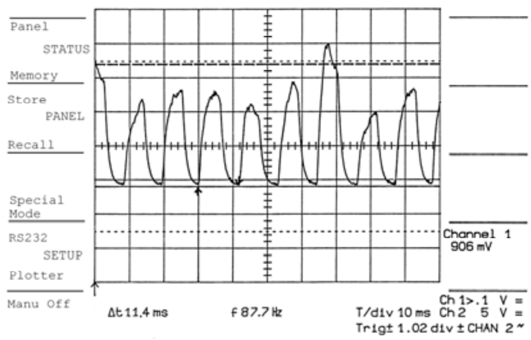
(a)



(b)



(c)



(d)

Fig. 7. Frequency spectra of the sensing signals obtained from (a) 4-blabe structure at v = 0.2 m/s; (b) 6-blade structure at v = 0.2 m/s; (c) 4-blabe structure at v = 0.4 m/s; (d) 6-blade structure at v = 0.4 m/s.

Calibration of the Sensor Signals

For calibrating the sensing system, we adjusted the flow rates from 0.2 m/s to 2.0 m/s and measured the signal frequencies for both 4-blade and 6-blade sensing elements. The calibrated data are shown in

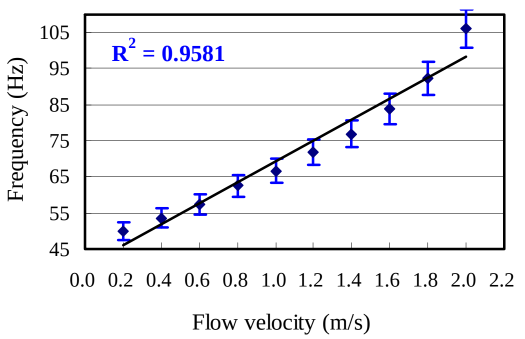
Figure 8. From the test results, we obtained the data with good linearity and observed that the sensitivity of the sensing system is improved by increasing the numbers of the blade. The R-square in both Fig. 8 (a) and (b) shows a reasonable variation of the measurement.

CONCLUSIONS

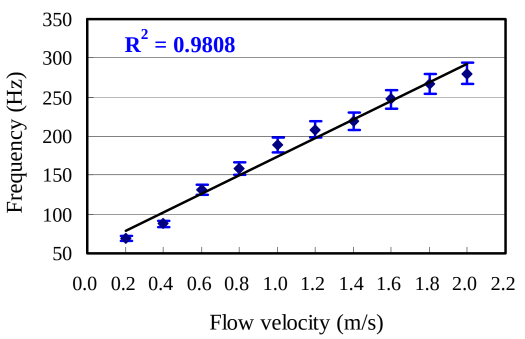
In this study, we successfully developed a prototype of flowmeter adopting the innovative idea to combine both of the merits of mechanical flowmeter and optical fiber flowmeter. Besides the advantages we expected to get from the precise turbine flowmeter, a more beneficial idea we raised in this paper is to use the excellent characteristics of optical fiber for remote monitoring in the hazard area with strong electromagnetic interference. By the unique design of sensor head mechanism, the optical fiber probe is installed in a space with good sealing to prevent the flow penetrating into it. This design had solved the fouling issue which will limit the applications or optical sensor. Somehow, it also breaks through the limitation of traditional turbine flowmeter whose accuracy will be reduced by the blades contamination.

From our experiments and test results, we obtained good linearity of the sensing system for the flow velocity ranging from 0.2 m/s to 2.0 m/s with both 4-blade and 6-blade structures of the sensing element. The sensitivity of the sensing system is improved obviously by increasing the numbers of blade. The R-square of the measured data also shows a reasonable variation of our measurement.

In the future, further studies on both hardware and software of the sensing system are worth while for extending the measuring range, enhancing the stability and sensitivity of the optical sensing system and its application fields.



(a)



(b)

Fig. 8. Calibrated flow velocity with (a) 4-blade sensing element; (b) 6-blade sensing element.

ACKNOWLEDGMENT

This work was supported in part by the National Science Council, Taiwan, under for financially contracts no.: NSC 96-2218-E-002-015 and NSC 96-2628-E-002-252-MY3.

REFERENCES

Anabtawi, A. L., and Howlett, R. J. "Detection of blade contamination in turbine flowmeters using neural networks", *Proceedings of Fourth International Conference on knowledge-Based Intelligent Engineering Systems & Allied Technologies*, Aug, 30th – Sep. 1st (2000).

Cheesewright, R., Bisset, D., and Clark, C., "Factors Which Influence the Variability of Turbine Flowmeter Signal Characteristics", *Flow Measurement and Instrumentation*, Vol. 9, pp. 83-89 (1998).

Culshaw, B., *Optical Fibre Sensing and Signal* Processing, Peter Peregrinus Ltd(1984).

Frazão, O., Caldas, P., Araújo, F. M., Ferreira, L. A., and Santos, J. L. "Optical Flowmeter Using A Modal Interferometer Based on A Single Non-adiabatic Fiber Taper", *Opt. Letters*, Vol. 32, pp. 1974-1976 (2007).

Hu, C.C., Miau, J.J., and Chen, T.L., "Determination of Real-time Vortex Shedding Frequency by a DSP", *Journal of the Chinese Society of Mechanical Engineers*, Vol.27, No.3, pp. 335-342 (2006).

Lee, W.T., Wu, S.J., and Chen, Y.M., "Phase-Resolved Investigation of Vertex Shedding in Flow Past a Circular Cylinder by Using Laser Doppler Anemometry", *Journal of the Chinese Society of Mechanical Engineers*, Vol.19, No.5, pp. 465-473 (1998).

Li, G., Li Q.Z., and Dong, F., "Study on Wide-Range Turbine Flowmeter", *Proceedings of the*

Fifth International Conference on Machine Learning and Cybernetics, Dalian, Aug, 13th － 16th (2006).

Lyle, J.H., and Pitt, C.W., **"**Vortex Shedding Fluid Flowmeter Using Optical Fibre Sensor", *Electronics* Letters, Vol. 17, Issue 6, pp. 244-245 (1981).

Sun, L., Zhang, T., and Zhou, Z.Y., "Experimental Study on Turbine Flowmeter's Performance Measuring Fluids with Different Viscosities", *Proceedings of the 6th World Congress on Intelligent Control and Automation*, Dalian, June 21th － 23th (2006).

Tai, H.M., Chou, J.T., Huang, H.C., and Cheng, K.Y., "Optical Fiber Position Sensor with Phase Tuning and Interpolation Circuits", *Journal of the Chinese Society of Mechanical Engineers*, Vol.25, No.5, pp. 417-421 (2004).

Takashima, S., Asanuma, H., and Niitsuma, H., "A Water Flowmeter Using Dual Fiber Bragg Grating Sensors and Cross-Correlation Technique", **Sensors** *and Actuators A: Physical*, Vol. 116, Issue 1, pp. 66-74 (2004).

Wadlow, D., *The Measurement, Instrumentation and Sensors* Handbook, Boca Raton, FL: CRC Press (1998).

NOMENCLATURE

a	radius of the rotor
A	cross-section area of the fluid pipe (in Eq. (3) and (4))
A	FET input Op-amp (in Fig. 5)
c	width of the blades of the turbine
D	pipe diameter
D_1	Diode of low dark current and low series resistance
I_o	D_1 saturation current
I_B	current source for setting circuit operation point
I_{SC}	short circuit current of the photodiode
n	number of blades of the turbine
$\bar{r}$	the root-mean-square value of the inner and outer radii of blades
R	radius of the turbine
Re	Reynolds number
s	distance between blades of the turbine
T	torque applied to the turbine by the flow
v	flow velocity
v_E	flow velocity after passing through the turbine blades at non-ideal case

Greek Symbols

ω	angular velocity of the rotating turbine
ω_i	ideal angular velocity without velocity loss
θ	exit flow swirl angle due to rotor retarding torque
β	the angle between the pipe axis and the blades of the turbine
μ	fluid viscosity
ρ	fluid density

新型光纖流量感測器之研製

江昭皚
國立台灣大學生物產業機電工程學系/生機所

許德瑜
國立台灣大學生物產業機電工程學系/生機所

廖文彬
北台灣科學技術學院電機工程學系

歐陽丞修
國立台灣大學生物產業機電工程學系/生機所

摘要

流量量控在工業上佔有極重要的地位，而光纖優越之抗電磁干擾及低傳輸損耗特性，在感測領域之應用已行之多年。本論文提出一種新型光纖流量感測器原型製作，以高精度傳統渦輪流量計為主體，並將感測信號轉為光調變信號以光纖進行傳輸。由於光纖傳輸損耗低，因此適用於偏遠地區之遙測監控，而抗電磁干擾特性則可望應用於落雷區之水庫或水廠中。