Optical-fiber Vortex-shedding Flowmeter Based on White-light Interference

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ABSTRACT

Optical-fiber vortex-shedding flowmeter is prospective in its application in the measurement field not only for the merits up from vortex-shedding flowmeter but also those in optical fiber sensor such as flexibility, strong endurance, anti electromagnetic interference capacity and adaptation in the flammable explosive environment. A new optical-fiber vortex-shedding flowmeter based on white-light interference principle is introduced in this paper. Because of only responding on dynamic disturbance, the all-fiber white-light interferometric flowmeter not only holds the high-sensitivity of interferometric sensors, but also overcomes the instability of the traditional interferometric sensors, which tend to being affected from the external environmental condition such as temperature fluctuation. At last, some experimental curves are presented in this paper.

Key words: Vortex-shedding, Flowmeter, Optical fiber, White-light interference, Sensor

1. INTRODUCTION

Flowmeters based on the principle of vortex shedding is an important class of devices among the many techniques for fluid flow velocity, which offer a number of advantages over conventional designs without rotating or reciprocating mechanisms and produce a frequency output linearly related to mean flow velocity over a wide range of Reynolds numbers.

Optical fibers are becoming increasingly important as not only remote information channels but also sensing organs in transducers. With the merits such as high sensitivity, flexibility, strong endurance, optical fibers become an excellent choice as sensing elements in vortex streets [1-5]. And moreover, with immunity to electromagnetic interference and without emitting electromagnetic radiation, the optical-fiber vortex-shedding flowmeters are inherently safe to explosive and inflammable fluids such as oils.

Monomode fiber optic interferometric sensors have been used in the measurement of a wide range of physical variables. The optical-fiber vortex-shedding flowmeters based on phase modulation have higher accuracy and sensitivity than the early ones based on intensity modulation. However, the traditional interferometric principles used in vortex-shedding flowmeters, such as Michelson, Mach-Zehnder and Fabry-Perot, tend to make the flowmeters disturbed by the environmental perturbations such as temperature fluctuations [3-5].

In this paper, an all-fiber vortex-shedding flowmeter based on white light interference and phase compression is introduced, which is expected to be more stable and suit remote transinformation.

2. PRINCIPLE AND STRUCTURE

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A nonstreamlined body sited in a fluid flow will, above a threshold, cause the phenomenon of Karmen vortex street: a regular stream of vortices formed in the fluid downstream. As shown in figure 1, an optical fiber may be sited transverse to the fluid flow. There are two conditions: (1) Fiber sited as a cylindrical bluff body and sensing element at the meantime; (2) Fiber sited down the vortex street only as a sensing element after a bluff body, in this condition a more effective bluff body such as triangular prism may be selected. Over a wide range (about Reynolds number $Re=10^2 \sim 10^6$ corresponding to the shape of the bluff body), vortices shed alternately from each side of the bluff body, giving rise to a periodic force on the optical fiber. The rate at which vortices are shed is dependent on the mean flow velocity and the size of the bluff body. The shedding frequency f is approximately proportional to the flow velocity:

$$f = \frac{sv}{d} \tag{1}$$

where s is the Strouhal number (a dimensionless constant), v is the mean flow velocity and d is the transverse diameter of the bluff body. Eq. 1 provides the basis for all the vortex-shedding flowmeters, that is, measurement of the vortex shedding frequency f will indicate the fluid velocity v.

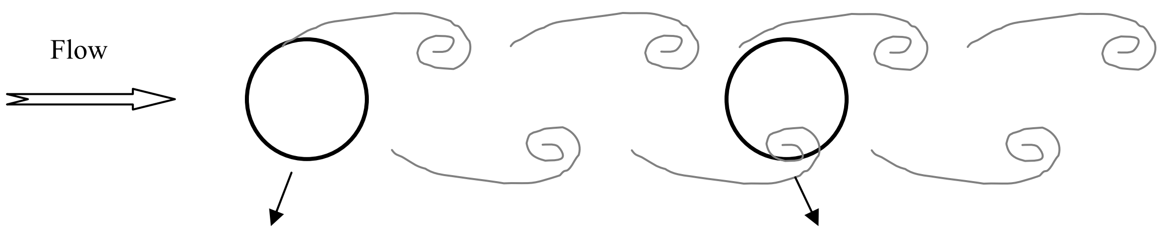

Fig.1 Illustration of vortex shedding and optical fiber

Vortex shedding induces an oscillating strain on the sensing fiber, which periodically modulates the phases of the light beams in fiber. The white-light interference measurement in Fig.2 was employed to check the phase changes. As illustrated in Fig.2, the introduced system includes a white-light source, two detectors, a 2×2 coupler, a 3×3 coupler, a fiber delay arm and direct arm, a sensing fiber with a reflection end, and some connection fibers. A beam from the white-light source is split equally into three by the 3×3 coupler, and two of them propagate delay arm and direct arm, respectively. After arriving at the reflection end, the two beams are reflected, split by the 2×2 coupler, and then route through delay arm and direct arm again. So between the source and the detectors, there are actually four beams as follows:

Beam 1: Source → 3×3 coupler → delay arm → sensing fiber → 2×2 coupler → delay arm → detectors
Beam 2: Source → 3×3 coupler → delay arm → sensing fiber → 2×2 coupler → direct arm → detectors
Beam 3: Source → 3×3 coupler → direct arm → sensing fiber → 2×2 coupler → direct arm → detectors
Beam 4: Source → 3×3 coupler → direct arm → sensing fiber → 2×2 coupler → delay arm → detectors.

Attribute to the wideband spectrum of the white-light source, It can be seen that only the beam 2 and 4 are picked out as interfering beams, which would have the same optical path length when the sensing fiber is static. Other beams just contribute to the DC components, because the optical path difference between them is much longer than the coherence length of the white-light source.

In the following calculations, we assume that the splitting ratio of two fiber couplers is symmetrical and other additional losses in the circuit are neglected. Assume that *a(t)* is the intensity initially launched from the source, so the signals at D1 and D2 are given by

$$P_1 = \frac{1}{36}\left[a^2(t) + a^2(t-\tau) + a(t)a(t-\tau)\cos\left(\varphi + \frac{2\pi}{3}\right)\right] \tag{2.1}$$

$$P_2 = \frac{1}{36}\left[a^2(t) + a^2(t-\tau) + a(t)a(t-\tau)\cos\left(\varphi - \frac{2\pi}{3}\right)\right] \tag{2.2}$$

Where τ is the time delay introduced by delay arm, and $2\pi/3$ is the nonreciprocal phase bias induced by the symmetrical 3×3 coupler [6-8].

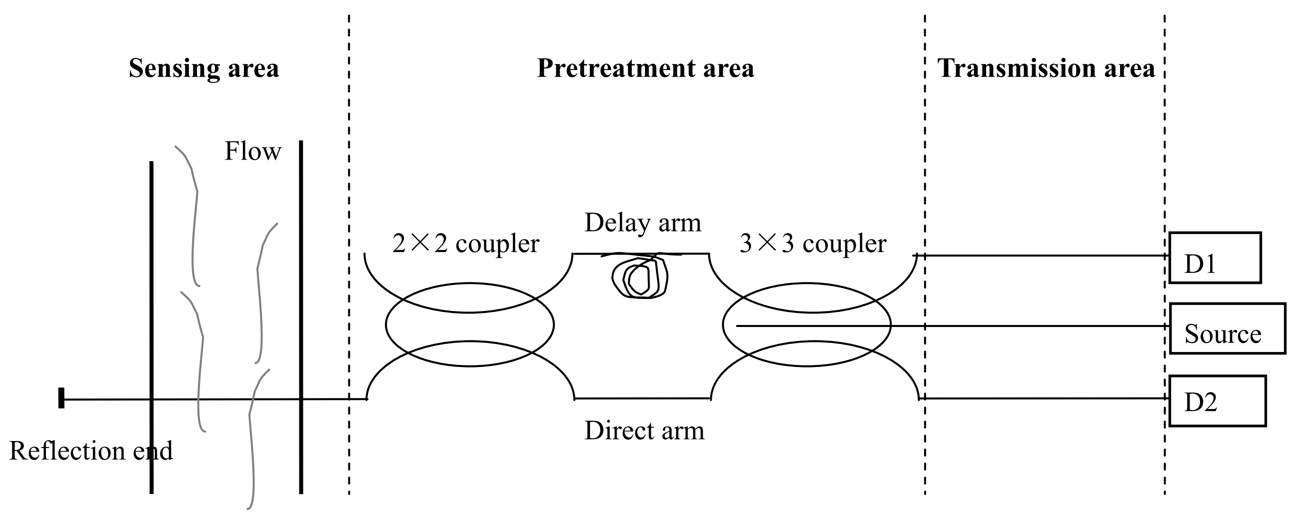

Fig.2 Schematic diagram for the all-fiber vortex-shedding flowmeter

The changes of the static or quasi-static parameters such as temperature fluctuations, whose change frequency is far less than $1/\tau$, will not make interference phenomenon arising in this system. The optical structure in Fig.2 may be divided into three areas by broken lines: sensing, pretreatment, and transmission area. The sensing area, which is sensitive to dynamic parameters, should be closed into the measured tube. The pretreatment area, which is potential to be affected by dynamic environmental perturbations, should be protected. The transmission area, which is immune to environmental perturbations, can transfer the measured information to a long distance, where the electronic terminal would be far away from the measured site.

3. EXPERIMENTS

Experiments were carried out on a transparent plastic tube, in which any changes could be observed. The experimental arrangement was shown in Fig. 3. The inside diameter of flow tube is 13 mm, in which pure water was flowing. All the fibers used in experiments were G652 monomode fibers. A sensing fiber, which was formed from a commercial tight buffer jumper with 0.9mm diameter, was positioned along a diameter at the centre of the tube. The sensing fiber was held vertically between a clamp and a box, and sealed in place by flexible filler. The clamp could adjust the initial axial tension of the sensing fiber. A 2×2 coupler, a 3×3 coupler and some delay fibers are sealed in a box called pretreatment box. The pretreatment box was mounted in the tube walls. One of the sensing fiber ends was aluminized, the other end was connected to the 2×2 coupler in box. Tree long fibers, called transmission fibers, joined the 3×3 coupler in box and light source and detectors. The beams were emitted by a superluminescent diode (SLD) and detected by two PIN photodiode. It can be seen that the sensing area, pretreatment area and transmission area in Fig.3 were corresponding to the ones in Fig.2. By sealing the sensing fiber into the tube and enhancing the protection to optical elements in box, the experimental flowmeter was working stably.

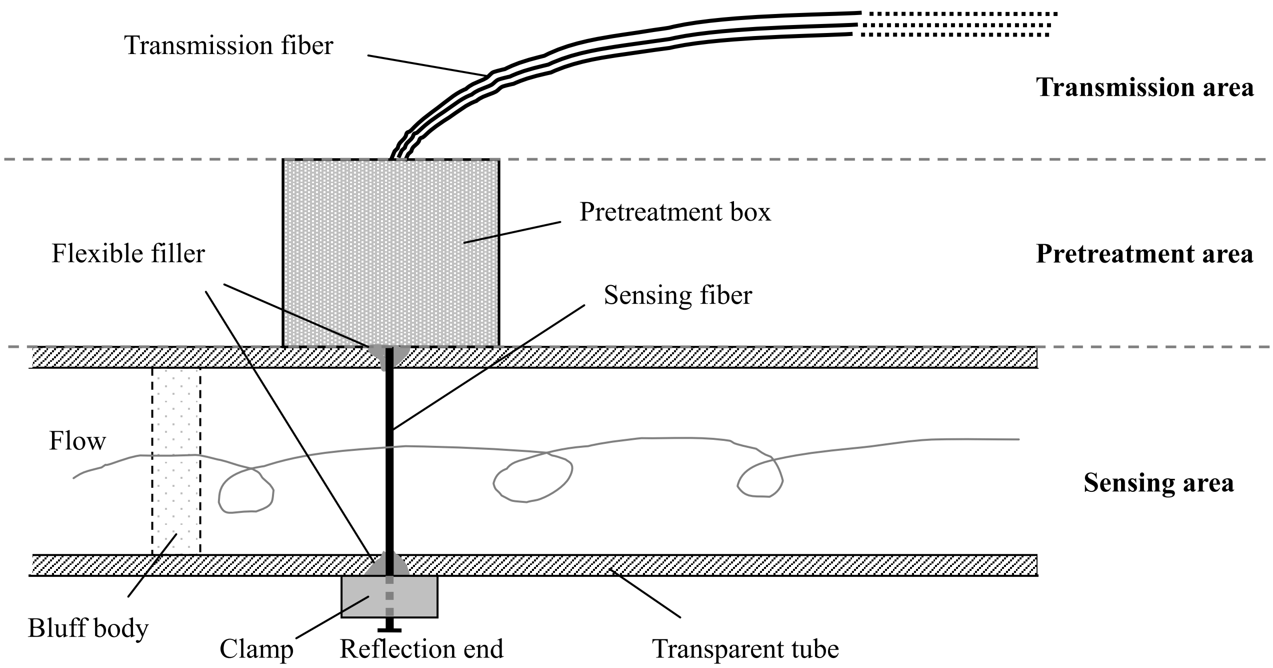

Fig.3 Experimental arrangement

Two experiments were carried out. Firstly only a fiber was located in flow, as a cylindrical bluff body and a sensing element at the same time. Secondly a triangular prism with 3.5 mm transverse diameter, which is an outstanding bluff body, was put in front of the sensing fiber. The output signals in first case were shown in Fig. 4 and second case in Fig. 5, in which the above graphs were time-domain curves and the blow ones were frequency-domain curves. By comparing the peaks of frequency spectra, it can be seen that the results in Fig. 5 are better than Fig. 4. Though the structure of only one sensing fiber in flow is simpler, the strain from vortex-shedding is also weaker.

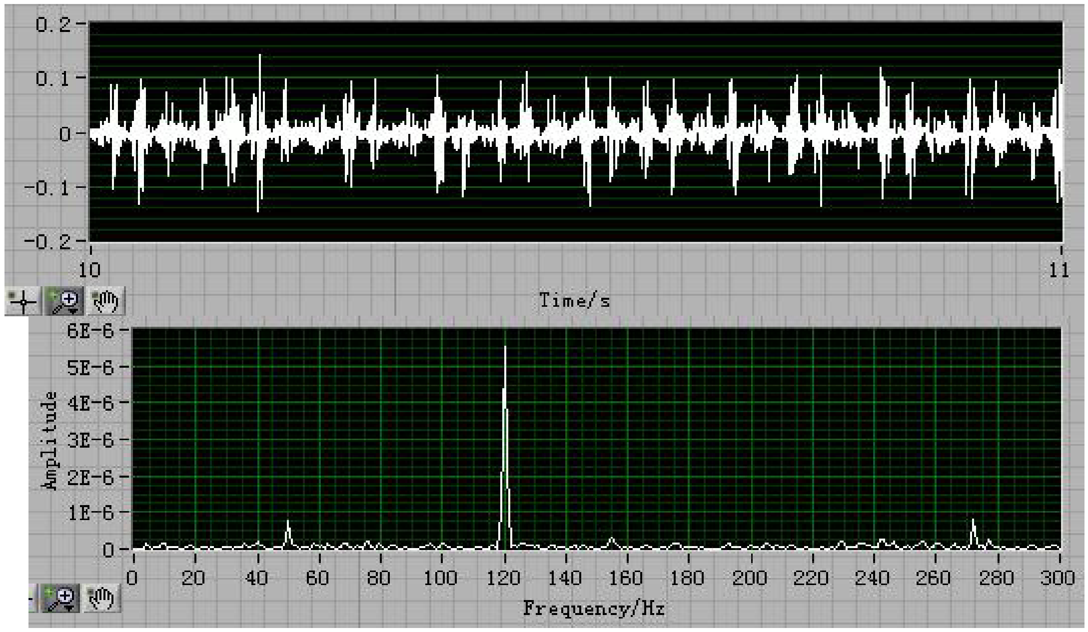

Fig.4 Output frequency spectrum in the case of only the sensing fiber in flow

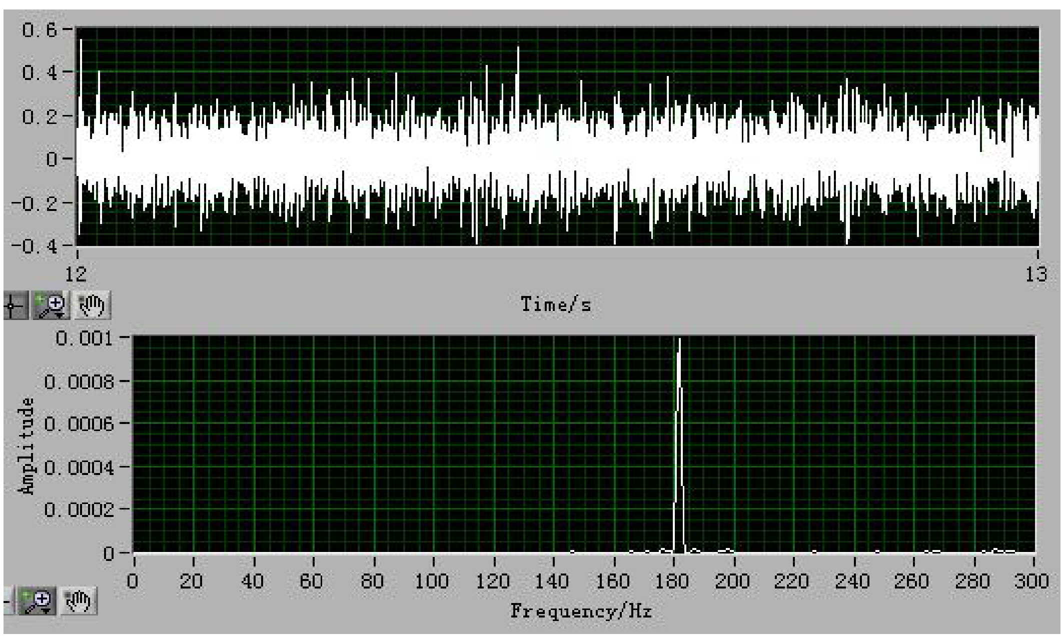

Fig.5 Output frequency spectrum in the case of a triangular prism in front of the sensing fiber

4. CONCLUSION

A vortex-shedding flowmeter based on white light interference and phase compression principle is introduced in this paper. The designed optical structure is only sensitive to dynamic parameters such as oscillating vortex shedding, and is immune to static and quasi-static parameters such as temperature fluctuations. The designed experimental system works stably from environmental perturbations. The laboratory results show that the method is potential in its future application in flow velocity measurement field. The higher sensitivity and SNR are expected be acquired in the next experiments with bare fibers as sensing elements.

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