Role of Wheatstone Bridge in Velocity Measurements with Tension Thread Flow Meter

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Abstract

This paper is concerned with the role of a Wheatstone bridge in velocity measurements with Tension Thread Flow Meter. The history of the Wheatstone bridge and the concept are reviewed in brief, and the role in the Tension Thread Flow Meter has been discussed. By using a prototype flow meter, how the system of structural, mechanical, and electrical components works harmoniously has been demonstrated. Several novel models of the present flowmeter have been proposed. It is realized that the Tension Thread Flow Meter possesses almost limitless potential to measure the instantaneous velocities ranging from nanometer/s to sound speed in air(gas) and water(liquid), together with the oscillating, boundary layer, channel and pipe flow. New development of the nanometer scale model for measuring the velocity in micro-fluid, and the application of Tension Thread Flow Meter to measure supersonic flow velocity are attractive research topics left for the future.

Keywords: Flowmeter, Wheatstone Bridge, Strain Gauge, Potentiometer, Drag

Introduction

Currently, the most fundamental of all electrical measuring instruments is the Wheatstone bridge, which historically takes precedence in the vast array of devices. Christie (1833) described a differential arrangement of conductors which formed a basis of Wheastone's application in his famous "Differential Resistance Measurer", published in his Bakerian Lecture (1943). In this lecture, Wheatstone unreservedly gave the credit for his idea to Christie, but he made so many practical additions so that the bridge became widely assigned to him solely.

At that stage of development, there was no accepted standard of electrical resistance, and so Wheatstone adopted one of his own which was the resistance of a copper wire of 30.48 cm in length having a diameter of 1.74 mm and weighing 6.48 g. He made up a number of resistance boxes which today are on display in the museum at King's College, UK.

Now let me introduce Wheatstone bridge in brief. Originally this bridge is an electrical circuit used to measure unknown electrical resistance by balancing two legs of a bridge circuit in terms of Ammeter and potentiometer, one leg of which includes the unknown resistor and there are other three different resistors, as depicted in Fig.1. The primary benefit of the circuit is its ability to provide extremely accurate measurements. In order to make a Wheatstone bridge, pick three different fixed resistors, R_1, R_2 and R_4 in the 10 kΩ range and combine with a 5 kΩ variable resistor or potentiometer Use the 12 volt as the electric potential until the ammeter reads zero current. Accordingly, referring Fig.1, we can immediately get the value of unknown resistor as

$$i_1R_1=i_2R_2 \quad (1)$$

$$i_1R_3=i_2R_4 \quad (2)$$

Dividing (1) by (2), we have

$$R_1/R_3=R_2/R_4 \quad (3)$$

Hence, we get

$$R_4=R_2/R_1\cdot R_3 \quad (4)$$

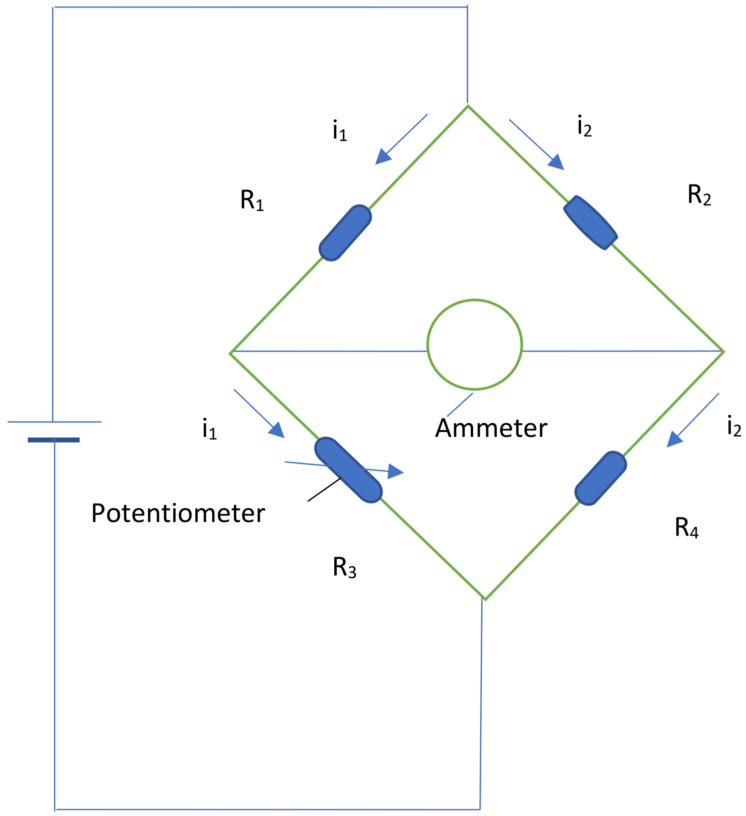

Fig. 1 Wheatstone bridge circuit

The four resistors of the Wheatstone bridge are set up practically in two forms. One is, the slide wire bridge, the place of the ratio arms is taken by a straight wire stretched along a meter scale divided at any point at will by a sliding contact connected to the ammeter.

In parallel with slide wire of potentiometer are stout metal bars with gaps and terminals for insertion of the resistance to be tested and of a standard resistance with which it is to be compared.

In the form which has been employed extensively so far, firstly for telegraph testing and later in all fields of electrical measurement, the standard resistance is divided into sub-divisions in the form of bobbins assembled in a portable box and connected to heavy brass plug terminals on a sleet of ebonite forming the cover.

Another early major contribution closely related to the Wheatstone bridge in form, is the potentiometer devised by Poggendorff (1841), in which a steady fall of electric potential is generated along a wire by a controlled current through it, and the wire calibrated in units of potential by connecting a standard cell in opposition so adjusted no current is drawn from the cell.

While so much interest is being aroused from the middle of the 19th century in the measurement of resistance a movement of great significance of the whole future of electrical engineering was started by Lord Kelvin to establish and co-ordinate electrical standards.

Until ca.1850 all units of resistance were based on arbitrary size and weight of a wire. Kelvin went into the inquiry with a will. During fundamental importance, revolving coil methods for the measurement of a resistance, apparatus of the measurement of current and special electrometers for the measurement of electromotive force.

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The report by Jenkin (1913), provided a remarkable record of the evolution of the C.G.S. system of units in electrical engineering and the experimental methods adopted for evaluating different units.

It had been shown by Kelvin in 1856 that metal wires carrying an electric current suffer a change of electrical resistances was directly proportional to the tensile strain in the wire. The method is to cement a grid of resistance wire between two thin pieces of paper, and then to fix one side with an adhesive bond directly to the metal surface where the strain is to be measured. The gauge can then be connected into an electrical circuit: Wheatstone bridge, where the change of electrical resistance give a quantitative measure of the strain (Appendix).

The main purpose of this study is to introduce the role of Wheatstone bridge in tension thread flow meter, and to propose new models of this flowmeter, to be developed in future.

Integration of Wheatstone Bridge into Tension Thread Flow Meter

In this section, state of art in research about tension thread flow meter（hereafter refer to TTFM）has been presented.

The TTFM uses a simple physical principle that the flow drag on a thread suspended in the flow depends on the velocity around it; as the velocity of the flow varies so does the drag and consequently, so does the tension in the thread. Thus, once the instrument is calibrated, the flow velocity either in the laboratory flume or in river, can be obtained by detecting the drag on the thread. Sharp(1964) and Sleath (1969) have designed instruments of this sort for use in two-dimensional flows in channel and oscillatory boundary layer, respectively. Then, Nakagawa (1983) have developed an elaborate version of earlier instruments for measuring three components of water particle velocity in breaking waves. Fig.2 shows a perspective of the flowmeter.

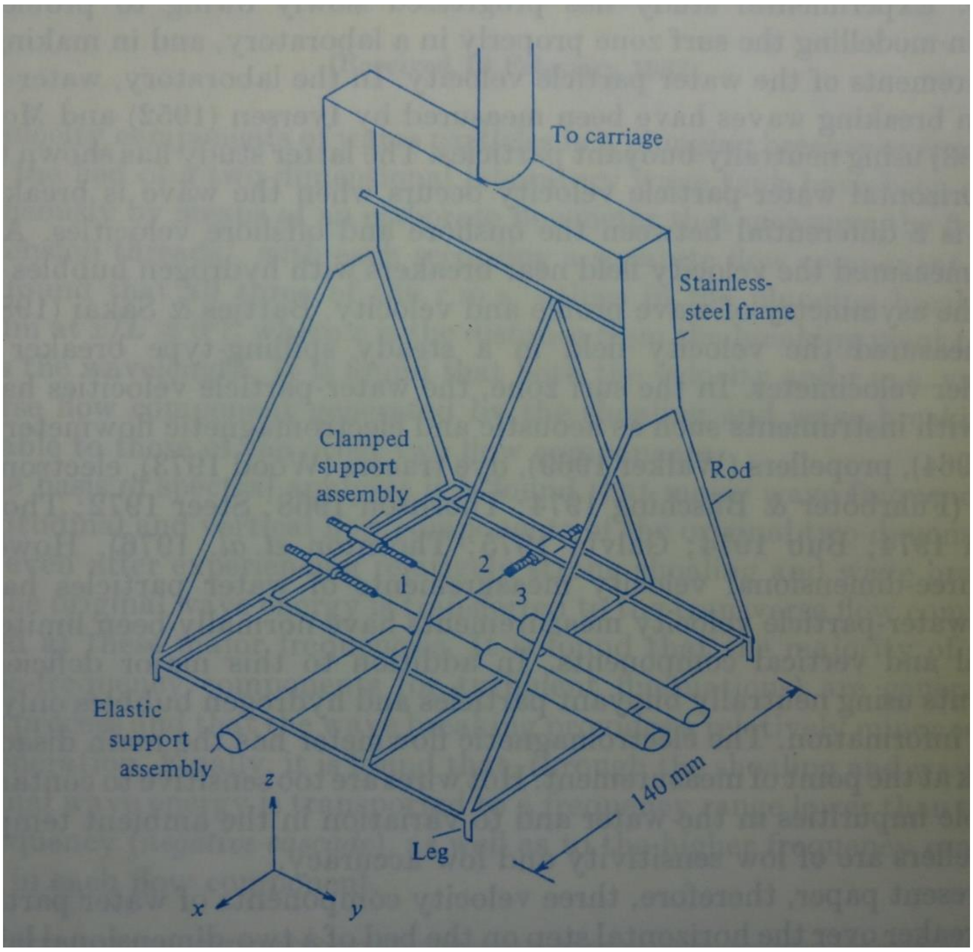

Fig.2 Perspective of Tension Thread Flow Meter.

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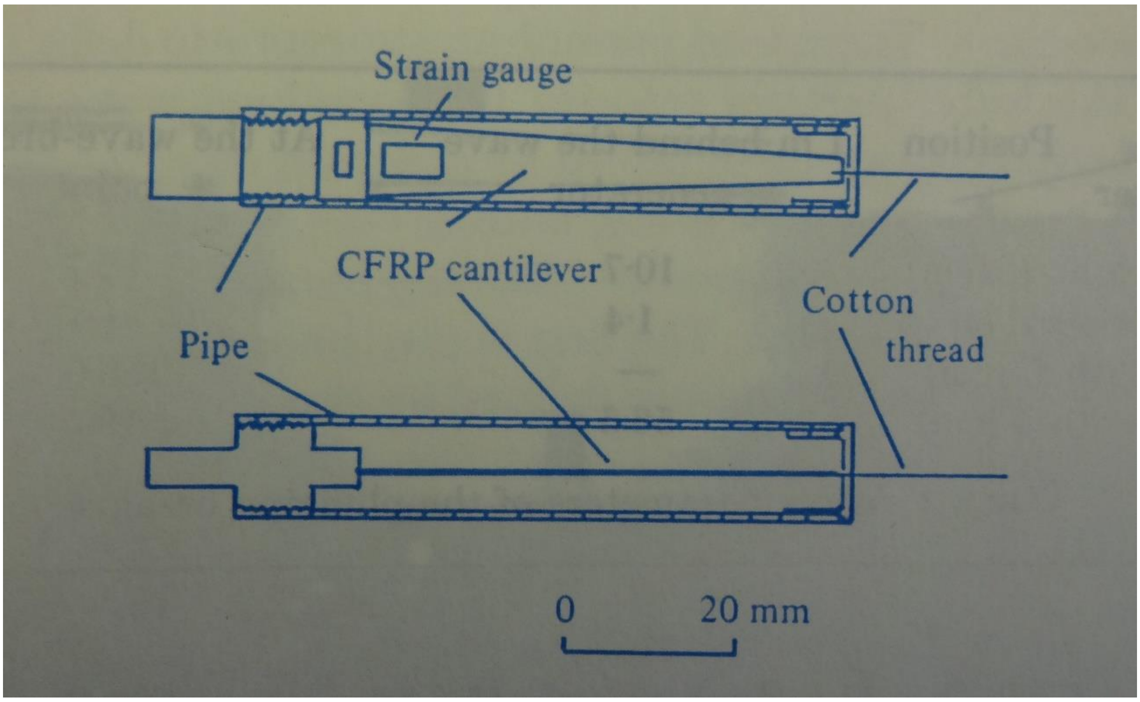

Fig.3 Cross-sections of the elastic support assembly.

The flow velocity is measured by the three cotton threads [1], [2] and [3], which measure velocities in the x-, y- and z-directions, respectively.

The cross-sections of the elastic support assembly through the pipe axis are shown in Fig.3. The upper cross-section includes the plane of the cantilever of thickness 0.5mm, whereas the lower cross-section is normal to the cantilever. One end of the thread is fixed rigidly to the head of the screw rod, while the other end is knotted at the free end of the cantilever, so that it is supported elastically. Initial tension in the thread is controllable within a certain limit by adjusting the horizontal position of the screw rod. A semiconductor strain gauge of 120 Ω(Appendix) is glued on each surface of the cantilever, which is made of CFRP (Carbon Fiber Reinforced Plastic) of specific weight 1.7 and Young modulus $1.96{\cdot}10^5$ N/mm^2. The length and the diameter of all the threads are 55mm and 0.01mm, respectively. Threads [1] and [3] are suspended in the same horizontal plane, and are parallel with each other and separated by 20mm. Thread [2] is in a horizontal plane at 15mm below the plane including threads [1] and [3], but it is normal to them. It is, therefore, clear that the velocity measured by the flowmeter is an integrated mean velocity in the small space, where the three threads are suspended: In the data analysis, however, the geometrical center of the three midpoints of the threads is assumed as the measuring point.

An increase of the thread tension due to the flow produces a small deflection of the cantilever and thus a strain in the gauges. Each of the threads can measure a separate velocity component normal to the respective plane of the cantilever, because the ratio of the width to the thickness is sufficiently large: The ratio is 6 and 16 at the tip and base of the cantilever, respectively. In general, the flow drag on a thread is not linearly proportional to the velocity, but is proportional to square of the velocity weakly, as being elucidated by Nakagawa & Nakagawa (2020) theoretically.

For each of the three threads, two strain gauges are glued on the surface of a cantilever and a bridge box constitute an AC Wheatstone bridge as depicted in Fig.4 , and the unbalanced electrical signal is amplified by a dynamic amplifier and is recorded on magnetic tape.

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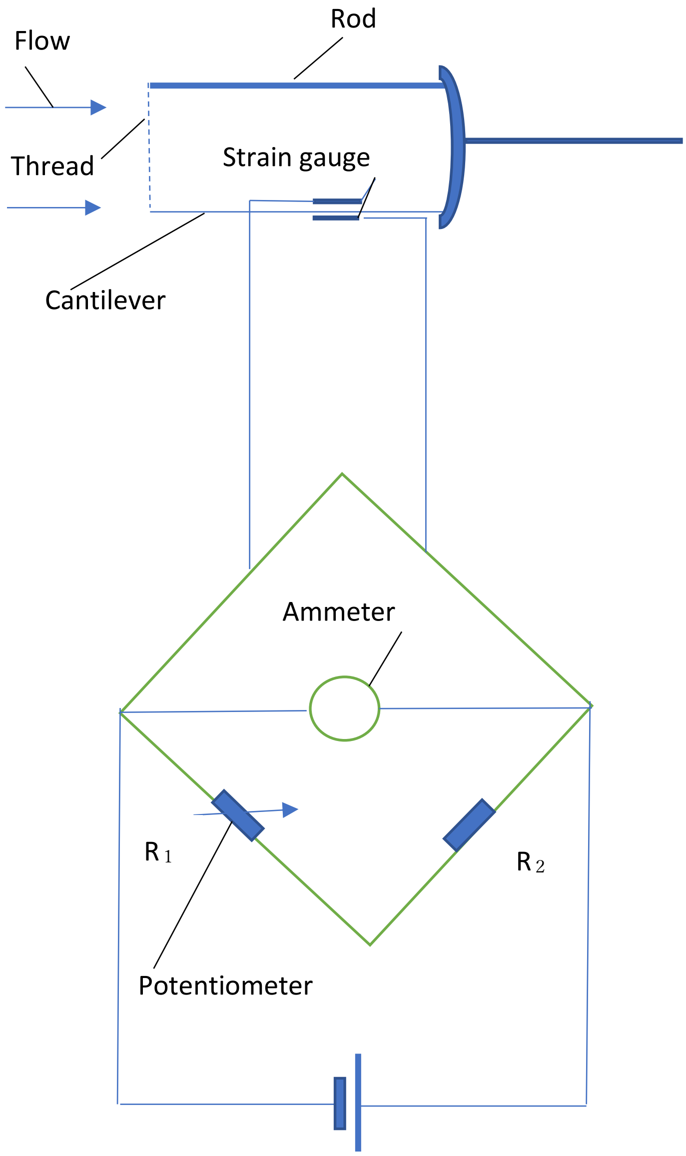

Fig.4 Sketch of electrical, structural and fluid dynamical system of Tension Thread Flow Meter.

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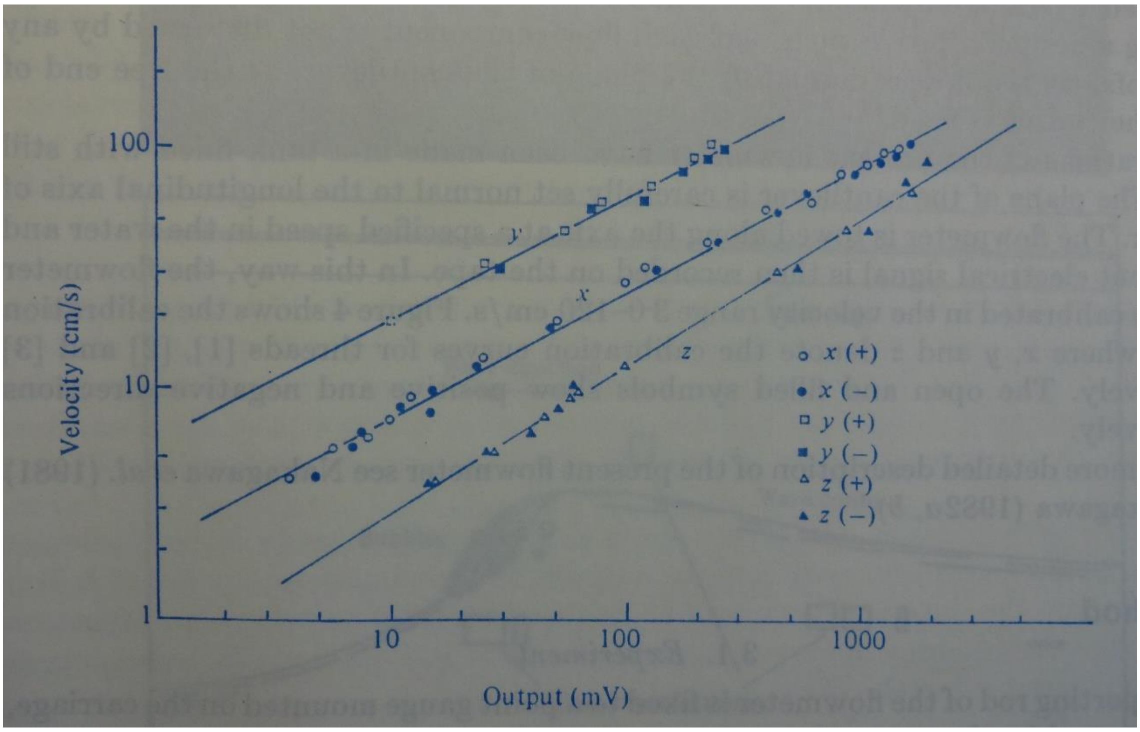

Fig.5 Velocity calibration curves.

Figure 5 shows the velocity calibration curves for threads [1], [2] and [3], respectively.

The plane of the cantilever is carefully set normal to the longitudinal axis of a calibration flume. The flowmeter is towed along the axis at a specified speed in the water and the output electrical signal is then recorded on the tape. In this way, the flowmeter has been calibrated in the velocity range 3.0~120 cm/s. The open and filled symbols denote positive and negative directions, respectively.

The thread (or cotton string) senses the flow drag. Strain gauges cemented on the front and back sides form a Wheatstone bridge with resistors R_1 and R_2, as shown in Fig.4. By keeping the value of ammeter zero, the potentiometer may detect the unbalanced electrical voltage due to the two strain gauges, and it will be amplified by the dynamic amplifier. Using Fig.5, these data will be converted by using the calibration curves into the flow velocity.

Proposition of novel Models of Tension Thread Flow Meter and Discussion

In this section, several novel models of TTFM will be proposed.

a. Velocity measurement for one component ranging from 0 to sound speed in air and water.

To accomplish this aim, it is necessary to select scales and materials of each components of the flowmeter: Scale of the thread will ranges from nanometer to 1.0 mm, and its material may be cotton, silk, or platinum, whereas material of cantilever can be CFRP, PTFE, platinum, or brass. It is, particularly, important that the Reynolds number based on the thread diameter and the velocity must be limited within 1.0, to avoid any disturbance due to the vortex shedding from the thread.

a. Alternating oscillatory flow measurement near solid surface

In this case, the thread must be closed enough to the surface, so that when one design the flowmeter this factor must be considered seriously. Moreover, since flow direction varies from positive direction to negative direction alternatively, the supporting rods must be arranged so as not to disturb the flow.

b. Boundary layer flow measurement.

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The thread should be changed stepwise from near the solid surface to the ambient flow covering the whole thickness of the boundary layer. It may be critical to guarantee the precise setting of the measuring point in order to get reliable data.

Since the flow is turbulent in general, three threads are required to measure three velocity components x, y, and z, respectively, but some modification of the supporting rods is required to make it possible that the threads measure velocities much closer to the surface.

c. Velocity measurements in channel and pipe flows.

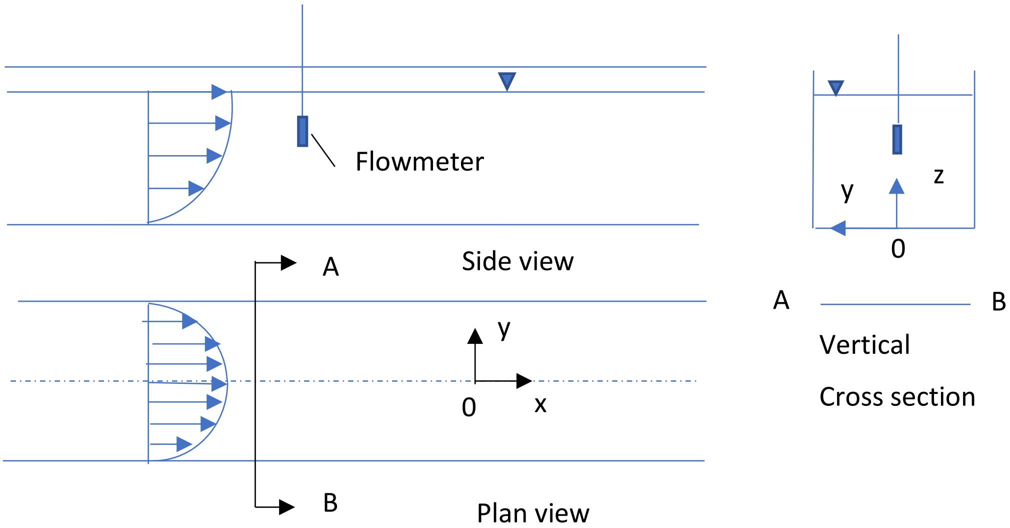

Fig.6 Sketch of the way how to measure the velocity in a channel by the flowmeter.

Firstly, design and construct a small scale flowmeter comparing with the scale of channel, which provides a detail velocity profile. Similarly to the case in a channel, the velocity distribution in a pipe could be obtained.

d. Weathercock type TTFM for measuring two velocity components.

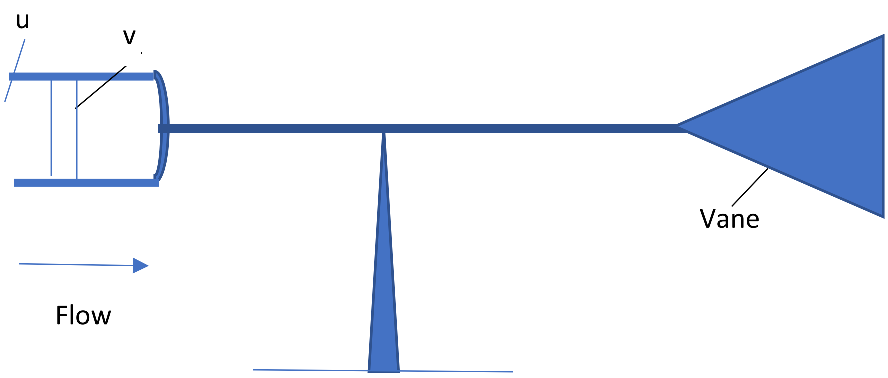

Fig.7 Sketch of weathercock type Tension Thread Flow Meter.

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Currently, to measure wind velocity, weathercock type propeller has been often used, but it only provides us average velocity for a certain time period, say 10 seconds. It is, therefore, preferable to develop a flowmeter which gives us instantaneous velocities continuously. Indeed, the proposed Weathercock type TTFM gives us the instantaneous two velocity components u and v, where u is the velocity in the main flow direction, while v is the velocity in the transverse direction.

Regarding to design of the vane in Fig.7, there are several alternatives, e.g. horizontal airfoil, vertical airfoil, archery feather and so forth. But, an interesting device called "wind lens" has been proposed by Ohoya & Karasudani(2010), who succeeded to increase wind power output. The wind lens is sketched in Fig.8: this lens consist of two major ideas to accelerate the wind speed, viz. the diffusor pipe, whose cross section increases in the downstream direction, and the brim at the diffusor end. It is reported that by adopting the wind lens, they could obtain more than a few times the original power output, together with its better directional stability of wind turbine. Hence, it is suggested that the directional stability of Weathercock type Tension thread flow meter could be improved by integrating the concept of wind lens into the design of vane.

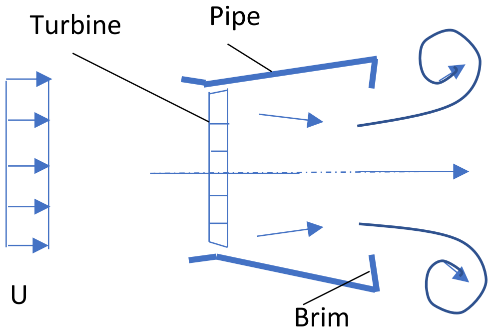

Fig. 9 Conceptual sketch of wind lens.

4 Conclusions

In this section, new knowledge and insights obtained through the present study have been summarized:

1. The history of Wheatstone bridge and the concept are reviewed in brief, and the role in the Tension Thread Flow Meter have been discussed.
2. By using a prototype flow meter, how the system of structural, mechanical and electrical components works harmoniously has been demonstrated.
3. Several novel models of the present flowmeter have been proposed.
4. It is realized that the Tension Thread Flow Meter possesses almost limitless potential to measure the instantaneous velocities ranging from nanometer/s to sound speed in air(gas) and water(liquid), together with oscillating, boundary layer, channel and/or pipe flows.
5. New development of the nanometer scale model for measuring the velocity in micro-fluid, and the application of Tension Thread Flow Meter to measure supersonic flow velocity are attractive research topics left for the future.

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Appendix: Strain Gauge

Various types of strain gauge had been used to measure the strain at selected parts of machines or structures under load, but the idea of cementing small pieces of resistance wire onto the surface of members under load was developed in USA during or just before the second World War Ⅱ, and it resulted in one of the most important changes in the practice of mechanical and electrical engineering.

By this means, the working stress in any part of a design can be checked by gluing a gauge no larger than a postage stamp to the surface of materials such as metal, CFRP (Carbon Fiber Reinforced Plastic), PTFE(Poly Tetra Fluoro Ethylene) and/or glass. .

It had been shown by load Kelvin in 1956 that metal wires carrying an electric current suffer a marked change of electrical resistance when subjected to a tensile load and that the change of electrical resistance was directly proportional to the tensile strain in the wire, but it was not until this period that the phenomena was used to obtain direct measurements of the strain of parts of machines and structures while under operation or test conditions of loading. The method used was to cement a grid of resistance wire between two thin pieces of paper.

The strain gauge was then connected into an electrical circuit, Wheatstone bridge, where the change of electrical resistance gives a quantitative electrical measure, viz. current or voltage. This method had been used for the rapid weighting of an aircraft on landing in an air field or for the detailed experimental analysis of the stresses, both static and dynamic, in all parts of a machine under load, and for many other purposes.

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