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Design and Development of a Low-Cost Cantilever-Based Flow Sensor

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Abstract: Measuring fluid flow rate in a precise manner plays a vital role in process engineering with important objectives, including monitoring and controlling of process operations to improve productivity and ensure safety. Flow sensing is a well-studied problem to the extent, even there exist many sophisticated sensors. Despite the vast developments, there are matters of concern, particularly in residential and irrigation sectors. The existing sensors are expensive, unidirectional, and less efficient in measuring low flow rates. Hence, the development of low-cost, robust and accurate flow sensors with the simplicity in operation is highly demanded. This work presents a novel low-cost flow sensor based on the principle of cantilever deflection. The proposed flow sensor uses a stainless steel strip as the sensing element and measures the flow based on the angle of deflection of the cantilever through an image analysis technique. A calibration model that relates the flow rate to the angle of deflection is developed from experimental data. The results are subsequently non-dimensionalized in terms of Reynolds number, thereby extending its applicability to other fluids and accommodate pipes of different dimensions. In addition, a simplified theoretical model based on the cantilever deflection mechanism is presented in support of the working principle. The developed cantilever flow sensor is cost-effective, simple, reliable, and capable of measuring even moderate flow rates in the pipeline. Experimental results are presented to demonstrate the precision and accuracy of the proposed flow sensor.

Keywords: Cantilever-based flow sensor, cost-effective, calibration model, image processing technique.

1. INTRODUCTION

Measurement of fluid flow is carried out in almost every industrial and commercial applications including in the process analysis of bulk fluid flows in open channels or inside closed pipes. The objective of a flow process is primarily to control the flow rate. Monitoring and control of the process is the vital requirement for obtaining the efficacy. To have a sound productive and safe process, with information about governing factors like the knowledge about the process, the properties of the measurable fluid, accuracy, robustness and simplicity in usage helps in developing essential sensors. The underlying sensing principle is generally based on differential pressure or velocity associated with the fluid flow and crucial to consider the type of flowmeter, whether measurements expressed as volumetric or mass flow.

In an epoch of water deficiency and limited supply, an effort needs to be made to understand actual water requirement and consumption. The residential and irrigation sector are particularly in need of smart, low-cost sensor for the measurement of flows. Although many flow sensors exist, affordable solutions are yet to be developed for the two areas, as mentioned earlier. In residential applications, especially in water-scarce areas, it is essential to monitor and regulate the water consumption, flow rate, create timely awareness and related cost for the consumers. One of the desirable factors is accuracy, but in this scenario, cost-effectiveness, ease of implementation, simplicity of usage and consistency are the essential criteria to be considered for developing a flow meter for the above applications.

A precise meter is a high-quality flow meter, carefully produced with excellent reproducibility, adaptable design and high-quality materials to avoid fatigue characteristics. An essential factor for developing a sensor along with the economy, ease of implementation and accuracy is known as the turndown ratio (Baker, 2005). Any flow meter should have a specified range over which its performance is valid and determined by upper and lower range values. The ratio of high range value to lower range value is termed as turndown ratio. Development of different types of analog flow sensors like differential pressure sensors, turbine, variable area flowmeter were reported in the early 1700s. Ad-

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vancements in technology have provided improved sensor designs and measurement methods (Pereira, 2009). Some of them are Coriolis, magnetic, and ultrasonic flow meters and thus started the era of digital flow meters. Developments provided any flow meter can exist as a smart flow meter version with the help of wireless sensor networks for collaborative and real-time sensing applications. They increasingly gained the market due to several advantages, like the low-pressure loss, no moving parts, and long term performance.

Water meters used in residential and commercial buildings use a public water supply system. These meters are designed to quantify how much water is consumed by a particular household with moderate accuracy compared to expensive and highly accurate flow meters used in industries. For residential water metering, the pipe diameter is usually 20 to 50 mm. The typical permanent flow rate of a residential water meter for a 20 mm diameter pipeline is 4.0 m^3ph. Similarly, in irrigation applications, flow meters are needed for measuring water usage during scheduled irrigation, manual watering, identifying high flow conditions, slow leaks, and collecting data for water budgeting and compliance purposes. Existing electronic water meters, such as ultrasonic and electromagnetic flow meters, are limited in their capabilities for measurement at low flow rates. Mechanical meters can have higher turndown ratio, but due to wearing of moving parts, their performance decreases over time. Even though many high-quality flow sensors and measurement techniques exist, there is always a need for the development of the low-cost, possibly nonintrusive, precise and accurate sensor.

Some of the improved sensor designs and measurement methods reported in the literature have received considerable attention. Dijkstra and Uittenbogaard (2010) experimentally found validation for numerical simulation model with the help of observations of flexible plastic strips positions and the forces subjected to the flow. The physically measurable input parameters provide a handy and generic tool in studying flow and exchange processes in the fields of flexible vegetation. Eswaran and Kumar (2012) found a conceptual design of automated water distribution and metering system for residential buildings. Current water distribution and the metering system uses mechanical or electronic water meters, which do not have any control over the consumption of water. To address this issue, the authors implemented a closed-loop water metering system along with the development of GUI (graphical user interface), which gives uniform distribution irrespective of pressure variation in the pipelines and geographical elevation, conservation on water consumption.

Evans et al. (2004) and Dinardo et al. (2013) describes a procedure for improving the measurement of fluid flow rates in pipes through the analysis of vibrations with the help of an accelerometer. The sensor is non-intrusive, low-cost and reliable flow rate measurement methods without load errors. Wei et al. (2007) proposed a novel 2-D capacitive silicon flow sensor that is anchored by a spring-like beam which can detect both airflow velocity and direction. The flow-induced drag force makes the disk shift and eventually changes the capacitance. Lu and Chen (2008) developed a new fibre-optic sensor system consisting of a fibre Bragg grating cantilever to realize the simultaneous measurement of fluid flow rate and direction with stainless steel and spring steel cantilever as substrates. The authors found that a change in the water flow rate gives rise to a monotonic shift in the Bragg resonance wavelength of the grating and also evaluated the flow direction. Yang and Yi (2015) implemented a novel and compact optical vortex flow meter. The sensor monitors the open area liquid flow velocity based on the von Karman vortex street and floating fibre ring vortex sensor to measure the vortex shedding frequency in the liquid flow.

This work presents the possibility of developing a low-cost flow sensor based on a cantilever beam inserted vertically inside a pipe. The critical sensing element of the proposed sensor is made of stainless steel. The sensor bends in the direction of flow due to force induced. The deflection of the sensor associated with fluid force can be quantified. Cost-effectiveness, size of the sensor and repeatability are the advantages of the proposed sensor. The developed sensor is capable of obtaining the fluid flow rate and the flow direction at the same time.

The remaining section of the paper is organized as follows. Section 2 lays down the underlying sensing principle for the designed sensor. Section 3, along with three subsections, explains the sensor design, experimental prototype and the technique used for flow sensing. The results and discussion, along with the comparison using theoretical and measured data, is showcased in section 4. The paper ends with the conclusion in section 5.

2. WORKING PRINCIPLE

Analysis of cantilever deflection is of great importance in structural design. Extending the utility into fluid mechanics helps in resolving the problems related to fluid flow measurements. A structural member whose length is considerable in comparison to its thickness and impacted by transverse loads that produce significant deflection is known as a beam. A uniformly loaded cantilever is fixed at one end and free at other end thereby carrying a uniformly distributed load. The principle for the proposed sensor is based on cantilever deflection subjected to a uniformly distributed load. Deflection is measured from the normal force induced by the flow over the sensor.

The normal force F, acting on the cantilever with drag coefficient C_D (dimensionless), the solid area A_p (m^2) projected on the vertical plane perpendicular to the flow, as shown in Fig. 1 is given as:

$$F = \frac{C_D \rho A_p V^2}{2}, \tag{1}$$

where, ρ is the fluid density (kg/m^3) and V is the velocity of fluid (m/s) (Pritchard and Mitchell, 2016). C_D is used to quantify the resistance of an object in a fluid environment. Due to the effect of force, the deflection in the sensing element of length L (m) can be calculated from (2):

$$D = \frac{qL^4}{8EI}, \tag{2}$$

where, q = F/L is the uniformly distributed load (N/m), E is the modulus of elasticity (Pa) and I is the moment of inertia (m^4). Finally, the angle of deflection is defined as the ratio of deflection to the length of the cantilever, given as (3).

$$\tan\theta = \frac{D}{L}, \quad (3)$$

The main focus of our work is to build a relationship between the angle of deflection and the flow rate. The idea is further extended to non-dimensionalise the relation in terms of Reynolds number, thereby providing its potential utility in any fluids and pipes of other dimensions. Reynolds number (Re) helps in visualizing the flow patterns as laminar or turbulent. C_D is a function of Re, and in this work, it is considered as a constant because the flow is turbulent. It helps in examining the relationship between the velocity and behaviour of the fluid flow and is given by:

$$Re = \frac{d\rho V}{\mu} \quad (4)$$

where, μ is the viscosity of the fluid and d is the diameter of the pipe Here, the method of measurement of angle is by image processing technique (Gonzalez, 2004). Above equations demonstrate that the fluid flow rate is proportional to the squareroot of angle of deflection.

3. PROPOSED FLOW SENSOR

This section comprises of the design of the sensor, validating it with the help of experimental prototype and the techniques used in measuring the flow rate.

3.1 Sensor design

A schematic diagram of the proposed flow sensor (45 x 15 mm) consists of a cantilever with a fixed top section and an adequate length of 45 mm is inserted into the pipe section of diameter, $\phi = 63$ mm. The cantilever-based sensor arranged will deflect with an angle, θ, corresponding to the flow, as shown in Fig. 1. Several techniques can

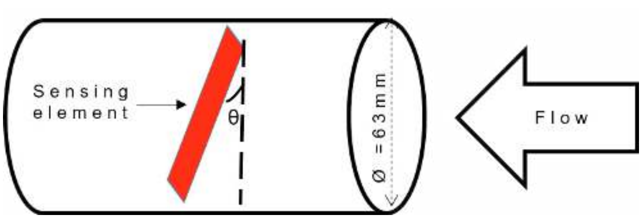

Fig. 1. Simplified schematic diagram of the proposed sensor

be used to measure the angle. In this study, we have used a camera-based approach. A transparent window made of acrylic glass is grooved into the pipe with the proposed cantilever and a camera is placed outside the duct to monitor its deflection concerning the flow. An LED (light-emitting diode) strip with IP68 (having the same area of that of the cantilever) is attached on to the steel cantilever for visibility as shown in Fig. 2. Stainless steel is selected because of its durability, safe to use in a water environment, and hence it ensures public health.

3.2 Experimental prototype

The hydraulic system developed for evaluating the sensor consists of one reservoir (100 litres), a pump of 746 W,

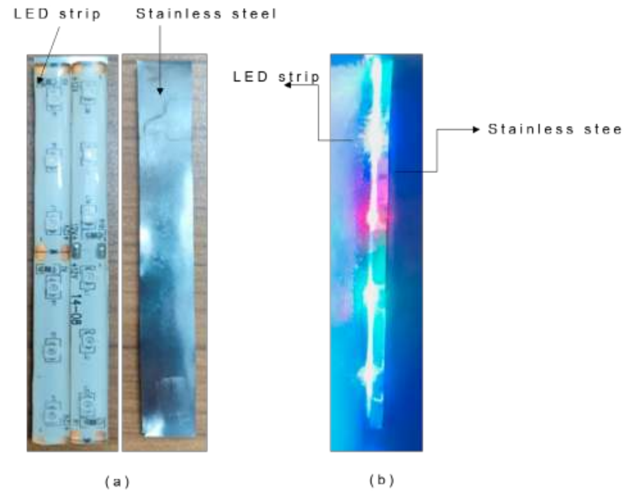

Fig. 2. Stainless steel cantilever sensor : (a) sensor unit with front and reverse view; (b) side view of sensor inserted inside pipe. LED strip and camera are used to capture the deflection of the strip as a function of the flow to evaluate the proposed cantilever based scheme.

two valves one for regulating (globe valve) and the other for bypassing (gate valve), electromagnetic (MAG650) flow meter (2-35 m^3ph) as flow instrument for calibration. The flow test section is a horizontal PVC pipe with a nominal diameter of 63 mm with an inserted cantilever of length 45 mm and width 15 mm and a high definition camera (Logitech c920) for analyzing the image as shown in Fig. 3.

The flow sensor is placed vertically inside the pipe with silicone tubing for the LED strip that houses it with an insulated as well as waterproofed cross-section. Different types of LEDs are available, but for the current application we use RGB LEDs consisting of one red, green, blue LED, and are colonized in a flexible circuit board known as an LED strip light. "IP" is the abbreviation for Ingress Protection. IP67, given by number 6 and 7 means that it is dust tight and offers complete protection against contact and also protects against the ingress of water in harmful quantity. The deflection of the sensor concerning each flow rate is captured by the camera for image analysis with a frame per second of 15, as shown in Fig.4.

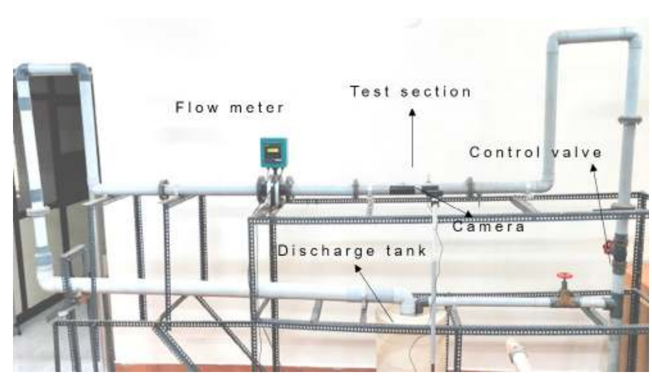

Fig. 3. Experimental system with the prototype flow sensor and a flow meter to compare the results.

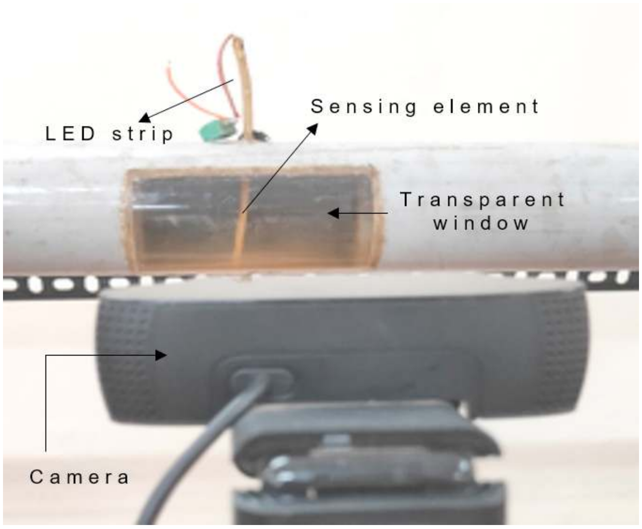

Fig. 4. Photograph of the test section

3.3 Flow sensing by image analysis techniques

Image analysis methods extract information from an image by using automatic or semiautomatic techniques. There are different techniques used in automatically analysing images and the main technique used here is image segmentation. Image segmentation is the process of partitioning a digital image into multiple segments. The simplest method of image segmentation is called the thresholding method. Thresholding is a non-linear operation that converts a gray-scale image into a binary image where the two levels are assigned to pixels that are below or above the specified threshold value. In order to extract the information from image, edge detection tool is used. It is a set of mathematical methods which aim at identifying points in a digital image at which the image brightness changes sharply or, more formally, has discontinuities. The points at which image brightness changes sharply are typically organized into a set of curved line segments termed edges.

An image processing technique transforms the edge data of the image into a parametric transform space, known as Hough transform, which is used for determination of the angle of the sensor. Shapes are characterized by the parameters associated with the curves that form the boundary of the object with the help of edge detection (Gonzalez, 2004). Mohammad et al. (2014) commented on different edge detection algorithms, and the popular Sobel edge detection method considered in this work. The main advantage of this edge detection method is that it has some smoothing effect on the random noise in the image by introduction of an average factor. Also, it takes differential of two rows or two columns, so the elements of the edge on both sides has been enhanced, so that the edge seems thick and bright. The Hough transform proposed by Hough[1962] was initially developed to recognize lines. Consider a point (x, y) in the xy-plane and the general equation of a straight line in slope-intercept form is,

$$y = ax + b \tag{5}$$

Infinitely many lines pass through (x, y), satisfying (5) for varying values of (a, b). However, rewritting (5) as (6) and considering the ab-plane (also called parameter space) yields the equation of a single line for a fixed pair (x, y).

$$b = -ax + y \tag{6}$$

A practical difficulty with this approach is that the slope of line, approaches infinity as the line approaches the vertical direction. An effective way to overcome this difficulty is to use the standard representation of line and considering (ρ, α). The new parameter space is known as Hough space, where α is the angle of the line and ρ the distance from the line to the origin.

$$\rho = x \cos\alpha + y \sin\alpha \tag{7}$$

A horizontal line has $\alpha = 0^o$ with ρ being equal to the positive x-intercept. Similarly, a vertical line has $\alpha = 90^o$ with ρ being equal to the positive y-intercept. Each sinusoidal curve represents the family of lines that pass through a particular point (x, y) in the xy-plane. The obtained images from the camera were processed in MATLAB using image processing toolbox. MATLAB builtin functions like 'hough' that performs the Hough transform on a binary edge image, and returns the accumulator. Lines are detected by interpreting the accumulator with the help of 'houghpeaks' and 'houghlines' which converts infinite lines to finite lines. From the image, the longest line segment is extracted to obtain the angle with respect the horizontal axis, which is indeed the deflection angle as shown in Fig. 6.

4. RESULTS AND DISCUSSION

The results and analysis are presented, starting with the comparison between the observed model from experimental data and a simplified cantilever model to show that the data follows the expected trend. Subsequently, a calibration model is developed with the measured data that provide the relation between the angle of deflection and the flow rate.

The cantilever model, as described in section 2, is a simplified version of the actual structural mechanism. One of the objectives is to find a similar trend between observed and the cantilever model, and there exists a qualitative match. However, a quantitative difference can be expected due to the approximations involved in the sensor design. This claim is demonstrated by performing a comparison study between the angle from the cantilever model and the observed model. The experimental deflection of the cantilever induced by the water flow and the theoretical deflection from the cantilever principle as a function of Reynolds number is shown in Fig. 5

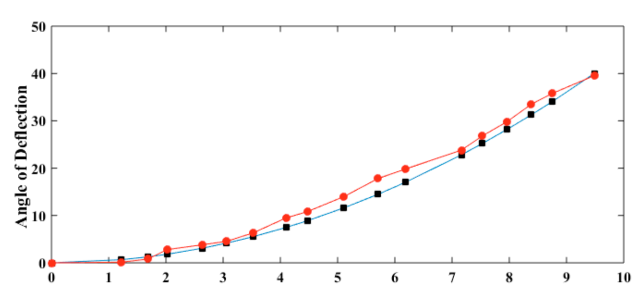

Fig. 5. Comparison between observed and cantilever model at different Reynolds number values: red- experimental; blue- theoretical

The system on which the experiment is performed consists of a LED stainless steel cantilever, with fixed top section (5 mm) and the remaining section (45 mm) was impacted by the water flow as shown in Fig. 6. During the experiment, when the flow rate was increased from 0 to 15.5 m^3ph, the corresponding images were recorded and processed to get the angle, θ for each flow rate.

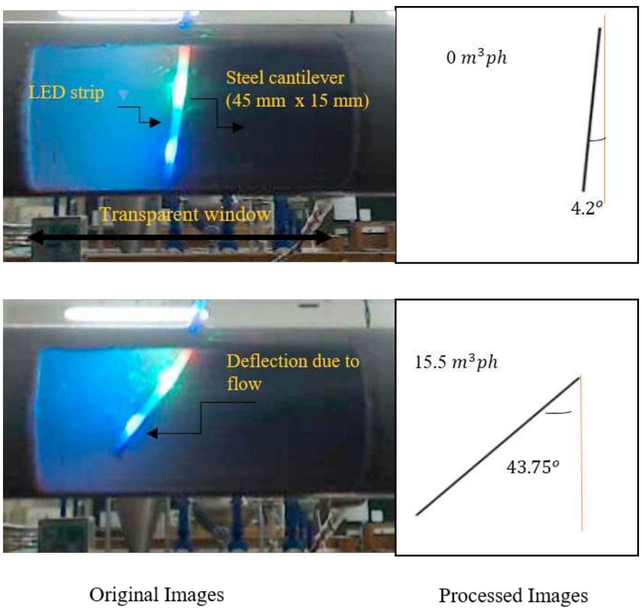

Fig. 6. Original images captured from the camera and processed images with angle from the algorithm. 4.2 ^{o} offset is present in the prototype, due fixed the mechanical misalignment.

From the experimental data, a calibration model is developed between the fluid flow rate and the observed angle from the proposed sensor as shown in Fig. 7. From the analysis, it is evident that, the fluid flow rate is proportional to squareroot of the observed angle of deflection. The maximum flow rate is 15.5 m^3ph for a maximum angle of 43.75^o from the stainless steel cantilever.

Coefficients of the model equation given in (8) for Fig. 7 is listed in Table1.

$$f(z) = uz^v \tag{8}$$

Table 1. Coefficient of the polynomial models

Coefficient	Value	f(z)	z
u	0.77	Flow rate	Observed angle
v	0.79		

In order to use these results for pipes of other dimensions and different fluids, a non-dimensional approach is helpful. For this purpose we have done the analaysis in terms of Reynolds number as shown in Fig. 8. Similarly, Table2 lists the coefficients of the model equation given in (9) for Fig. 8.

$$g(k) = pk^q \tag{9}$$

The cost of the prototype sensor developed is about 35 USD which is much less compared to the equivalent commercially available sensors. Validation is done to test the efficiency of the model obtained with test data which provides necessary accuracy for the usage in flow applications. The results obtained are valid for a PVC pipe of 63 mm diameter. Repeated measurements on the sensor indicated that the sensing response is reproducible with a standard deviation of 2^o for mid-scale range. The process was repeated five times leading to an accuracy of 2 %. The change in the forward flow rate yielded a threshold value of 2 m^3ph. Under zero flow conditions, the cantilever has an offset angle of 4.2^o and is due to the physical arrangement inside the pipe. The issue can be rectified by proper surface mounting. From Fig 7 is it evident that the LED stainless steel cantilever is an effective low-cost sensor to realize simultaneous sensing of the water flow both for its rate and direction.

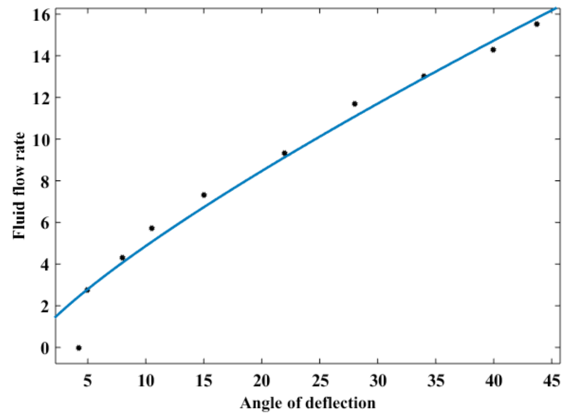

Fig. 7. Calibration model for flow rate and angle of deflection.

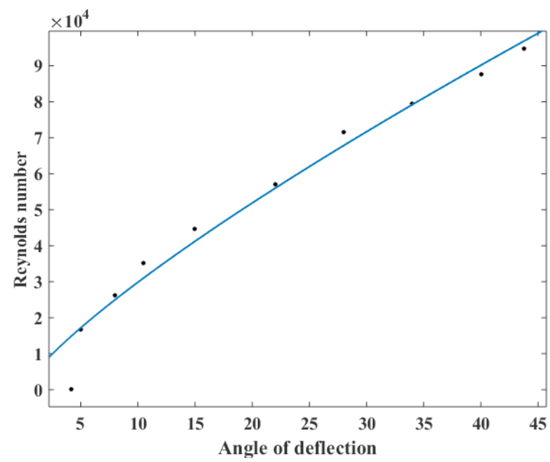

Fig. 8. Non-dimensional plot of angle of deflection vs Reynolds number

Table 2. Coefficient of the polynomial models

Coefficient	Value	f(k)	k
p	4760	Reynolds number	Observed angle
q	0.79		

5. CONCLUSIONS

In this work, the design and demonstration of a novel low-cost flow sensor for flow measurement and the indication of flow direction is presented. The results presented in this work have shown that the proposed sensor is an effective way for flow measurement and also efficient in terms of cost, size, adaptability, and precision. The experiments were tested with a low-resolution camera also provided excellent results. A proper surface mounting can rectify the mechanical misalignment of the sensor, and zero offset can be eliminated. The sensor is 45 mm in length and 15 mm in width and flow up to a velocity of 2 m/s can be measured. Therefore, the cantilever sensor presented in this work is well suited for meeting the demands of fluid flow measurements.

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