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# Flow Measurements using a Simple Fiber Optic Technique

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## ABSTRACT

Fiber optic based flow measuring instrument is important in aerospace, wind and oil and gas industries as it simple, reliable and robust in extreme conditions etc. In the aerospace industry, fiber optics are used for stress monitoring instead of flow measurement and the pitot tube based airflow measurements can be replaced using optical fiber based sensors. A prototype with a mini bending fiber sensor is procured to measure the velocity of air. The fiber is placed into the flow stream such that the air flow across the fiber exerts a transverse force causing it to bend with finite curvature. The measured curvature in terms of voltage change can be related to the flow-rate. This working principle is similar to the work done by Schmitt *et al* and Rong *et al* however the equipment used for this work is relatively simple and hence it saves costs. The system uses low power light emitting diode to power up the fiber and the bending of the curvature results in a reduction in the light intensity at the receiver. The reduction in light intensity is proportional to the velocity of the air, hence it would be a reliable flow sensor for a range of 0 *m/s* to 14 *m/s*. Fiber length was small when compared with the radius of 1 mm such that it will not cause much disturbance to the flow field. Effect of end flaps on the fibers on the measurements sensitivity is explored.

## 1. INTRODUCTION

Over the past twenty years there have been many developments on fiber optic based flow velocimeter. Flow velocimeter is important in many industries such as petrochemical Peng(2004), medical and aeronautical industries Rong(2009); Culshaw(2008). Fiber based velocimeter system offer many advantages compared to other techniques such as pitot tube, hot-wire aneomometer, magnetic sensors etc Schmitt(1995); Nemoto(1998).

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Particularly for the aerospace industry, pitot tube is commonly used to measure the wind speed. Pitot tube requires regular maintenance as it is not dust resistant due to the tendency of choking therefore there is a need for the removal of a tag, protecting the pitot tube, before every flight which leads to an additional task to be completed by the flight crew. Fiber optics has been used progressively to monitor the stress on the wing instead of being used as a flow meter. Hence we would like to propose a simple methodology of developing such fiber based velocimeter to measure the wind speed on the aircraft so that aircraft crew members would no longer have to take the additional step of removing the tag covering the pitot tube before flight to measure wind speed. In addition, as it is a fiber based system, it is able to withstand high temperatures, electromagnetic resistant and also quite robust in weathering the harsh environment Amar(2011) therefore such approach is undertaken.

A few novel designs that use the concept of fiber based velocimeter has been developed recently Cipullo(2012);Amar(2011). One such method is fiber based sensors that incorporate a hinge joint in their design. It is able to detect the flow velocity by the rotation of the hinge that causes a bend on the fiber which produces a reduction in signal Anu(2008). Another flow meter uses the concept of a simple bluff body to pull the fiber which will cause the fiber was also demonstrated Rong(2009). One of the cantilever type makes full use of a Michelson interferometer where by the interference caused by the light path of two beams resulted by the bending of the fiber Libo(2008). The other cantilever uses an overlapping light spot to detect the displacement of the fiber. The amount of displacement displays the relation of the flow velocity with the bending curvature Amar(2011). Another system uses the principle of vortex generated by the fluid flow to determine the flow rate which requires complicated polarization technique Nemoto(1998).

The literature that was presented above mainly detects liquid flow velocities in the low velocity range Nemoto(1998); Libo(2008). In one particular work done, a similar technique was introduced, however in their technique; rubber cantilever beam was used as the supporting frame to join the fibers together. The fiber is joint to the cantilever via plastic rings and it has complicated system Schmitt(1995). Our team has developed a prototype with a mini bending fiber sensor that is able to measure the air without any support. The support that it requires comes from the fiber's own stiffness. Therefore system is cheap and comparatively simple to use and it does not require complicated equipment and has very low power consumption. To alter the sensitivity in the rubber cantilever work that was presented Schmitt(1995) uses grooves etching which can be costly due to intricate etching techniques. In the current prototype, to increase the sensitivity of the flow measurement, flap is attached at the free end of the fiber which is simple and cost-effective.

## 2. EXPERIMENTAL DETAILS

An experiment is setup to determine the feasibility of the prototype. The experiment is conducted in LW-3890 wind tunnel. The wind tunnel has its own limitations, in that it is only accurate in the region of more than 3 *m/s* and hence the experimental data of between 0 to 3 *m/s* is should not be considered. Therefore the test is being run from 0 to 15 *m/s* omitting the data up to 3 *m/s*.

*2.1. Optical Fiber*

The fiber is a single mode fiber with a center core of plastic fiber made up of polymethyl methacrylate (*PMMA)* which is encased in an epoxy adhesive material for the enhanced endurance and protection. Step like grooves are created only on the cladding. These steps-like grooves enable the fiber to have a higher reduction in light transmission when the fiber is bent at the particular region Lee(1994). When the fiber is bent, only the region of the fiber that have the step grooves would cause much higher the reduction of light intensity compared to the rest of the fiber. Therefore, other parts of the bent fiber would not affect the output voltage measurement.

Fig.1 shows the working principle. A light emitting diode transmits light into the fiber and the intensity of the light is reflected back by a mirror to the photo detector which can determine the amount of light loss. The signal is next amplified and fed into the NI-USB 6221 data acquisition system by an amplifier for analysis.

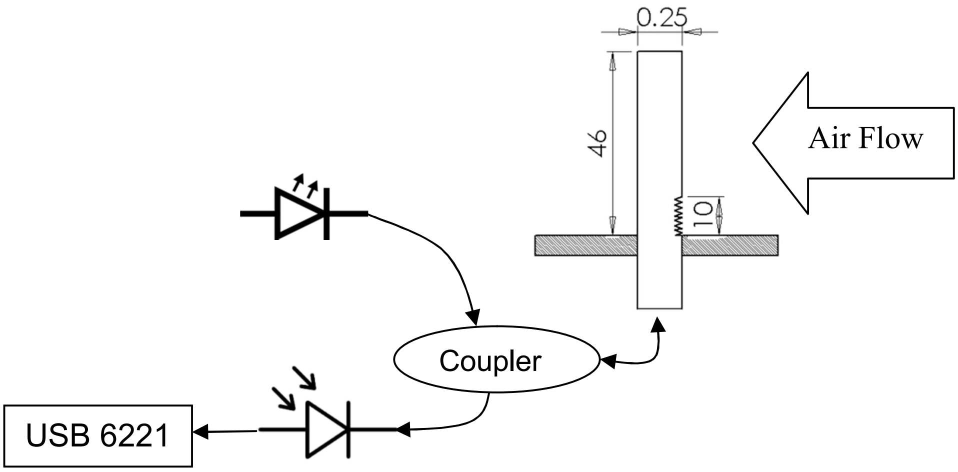



Fig. 1 Schematic of the optical fiber based flow sensing system (mm)

*2.2. Optical Fiber Holder*

To hold the optical fiber into the wind tunnel for testing, a fixture is needed to hold the fiber in place. A flat piece of aluminum is used to fabricate the fixture and holes are drilled for the insertion of the fiber. Adhesive are used to stabilize the bottom end of the hole. The section of the step grooves are carefully placed such that it lies at the fixed support on the flat plate. After the fiber is inserted the rest of components are placed together with the metal piece to be able to mount in the wind tunnel. Dimension of the optical fiber with the holder plate are depicted in Fig. 2.

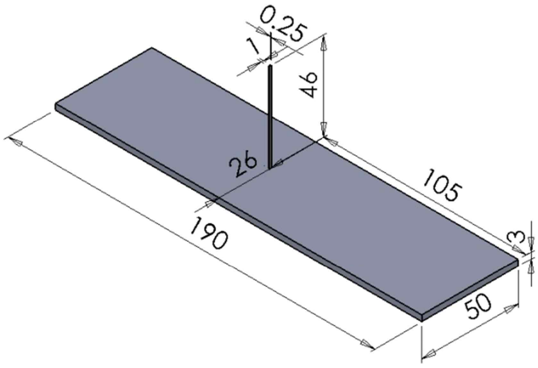



Fig. 2 Dimensions of the setup (mm)

## 3. PRINCIPLE OF OPERATION

The idea of the fiber system is taken from the observation of the hair on the human skin, on how it is able to “sense” the wind blowing across it. In the development of fiber sensor, for simplicity, it is just a cantilever beam sticking out into the free stream velocity without any additional tools similar to a human hair. As the wind blows across the cantilever, it creates a drag force which will push the fiber and hence causing the fiber to bend. The velocity of the flow can therefore be determined from the by the amount of deflection.

An expression for drag force $F_d$ per unit length, $l$ of the optical fiber is given by:

$$\frac{F_d}{l} = \frac{1}{2l} c_d \rho A u^2 \tag{1}$$

where $C_d$ is the drag coefficient assumed as 1 from Unicopter(2011); Engineering T.B. (n.d.) as it is cable which is perpendicular to the direction of the flow, $\rho$ is the density of air, $A$ is the frontal surface area of the fiber in direct contact to the air flow and $u$ is the mean flow velocity, see Fig. 3 below.

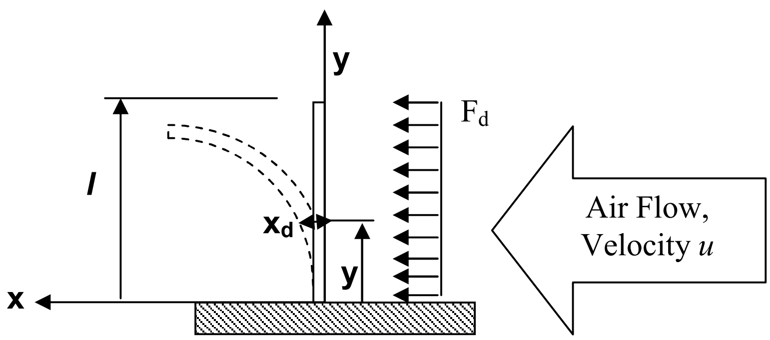



Fig. 3 Deflection of optical fiber under the application of drag forces of air flow

The deflection $x$ at a distance $y$ from the fixed end based on Euler infinitesimal beam deflection theory is given by:

$$x_d = \frac{F_d y^2}{24l(EI)_{eq}}\left(y^2 - 4ly + 6l^2\right) \qquad (2)$$

$x_d$ is the deflection of the beam at $y$. $y$ is the point on the fiber where the step grooves are located, see Fig. 1 and Fig. 3, $l$ is the length of the fiber. $(EI)_{eq}$ is the effective flexural rigidity of the optical fiber core and outer cladding system, with $E$ is the Young's modulus of the fiber material and $I$ is the second moment of area. $E$ can be obtained from the material property and it varies according to the fabrication of the fiber which can varies about 1GPa Kuzyk(2007) and from a literature source on strain sensor it is in the range of 0.248 and 3.367 GPa Luo(2010), hence the fiber material is assumed to have a $E$ of 1GPa. Multiplying Young's modulus and second moment of area gives the bending modulus and its equivalent is used in equation (2), as the fiber is made up of different material, an inner circular core of light transmitting medium *poly methyl methacrylate* (PMMA) and outer case made up of epoxy.

$$x_d = \frac{c_d \rho A u^2}{48l(EI)_{eq}}\left(y^2\left(y^2 - 4yl + 6l^2\right)\right) \qquad (3)$$

which can be represented simply as $x = \beta u^2$. Where $\beta$ is the constant which is obtained from the variables calculated from Eq. (3).

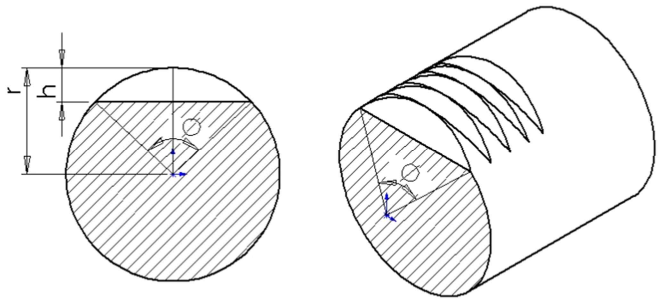



Fig.4 Area calculation of the fiber

Step like grooves are created on the fiber's cladding to promote power lost through bending, see Fig. 1 and Fig. 3. As schematically shown in Fig. 4, $r$ is the radius of the fiber and $h$ is the height of the segment which is the same as the depth of the groove(Lee 1994).

Area of the shaded segment, Fig. 4 is obtained by subtracting the sector segment circle from the area of the circle and expressed as

$$A = \pi r^2 - \frac{r^2}{2}\left(\theta - \sin\theta\right) \qquad (4)$$

The sector subtended angle $\theta$ is related to the height $h$ as:

$$\theta = 2\cos^{-1}\left(1 - \frac{h}{r}\right) \tag{5}$$

Since the deflection of the fiber, x is equal to the change in height *h* which gives the relation such that $x_d = dh$.

Subsituting eqn (5) into (4) and $x_d = dh$ , which enables the substitution of $x=\beta u^2$ into (4) gives.

$$dA = \pi r^2 - \frac{r^2}{2}\left(2\cos^{-1}\left(1 - \frac{\beta u^2}{r}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{\beta u^2}{r}\right)\right)\right) \tag{6}$$

It is to be noted that the cross-sectional area change is related directly to the intensity of led light *P*, we can expresses their differential normalised change as

$$\frac{dP}{P} = \frac{dA}{A} \tag{7}$$

As the voltage feedback is sensed by the photo-detector and gives the following relationship, where *k* is proportional gain in the amplifier.

$$V = k\frac{dP}{P} \tag{8}$$

Finally, the voltage can be expressed as:

$$V = \frac{k}{2\pi}\left(2\pi - 2\cos^{-1}\left(1 - \frac{\beta u^2}{r}\right) + \sin\left(2\cos^{-1}\left(1 - \frac{\beta u^2}{r}\right)\right)\right) \tag{9}$$

Equation 9 shows the relationship between the voltage drop and the flow speed. The only variable that is affecting the deflection would be the surface area, the length of the fiber and the flow velocity. The length of the fiber is fixed at $l$, due to the fabrication of the fiber bending system. The surface area effect on voltage would be investigated in this setup by employing a flap on the tip of the fiber and is discussed further.

In all the previous work that was done, most of the simplest design measured small velocity scale of up to 3 *m/s*. Although the design proposed is similar in principle to the work done by Schmitt *et al* Schmitt(1995) and Rong *et al* Rong(2009), the proposed design was found to be able to measure air flow velocities up to 15 *m/s* with certain linearities in the measured region. And the proposed design does not require any complicated interferometery design or equipment or any high power laser system. It uses low power light emitting diode to power up the fiber and the change in the curvature results in a reduction in the light returning back to receiver. The power requirement is small compared to other systems. There is certain amount of correlation between the reduction in the voltage due to the bending and the flow velocity hence it would be able to produce a reliable flow sensor for a range of 0 *m/s* to 14 *m/s*. The fiber length is 46 mm in length and the overall width of the fiber together with the encasement is 1 *mm* which is small in relation to the magnitude of the application, in this case would be the wings of the aircraft. So that it will not cause much disturbance to the flow field and hence trying to obtain accurate results.

## 4. RESULTS AND DISCUSSION

The experiment was conducted on the fiber and inclusive of the flaps from flow velocity of 0 to 15 *m/s*. The raw voltage output recorded using the data acquisition system for a typical applied flow rate is shown in Fig. 5. The setup has a data collection frequency of 1000 data points per second. In the current experimentation, voltage is captured for a period of 100 seconds.

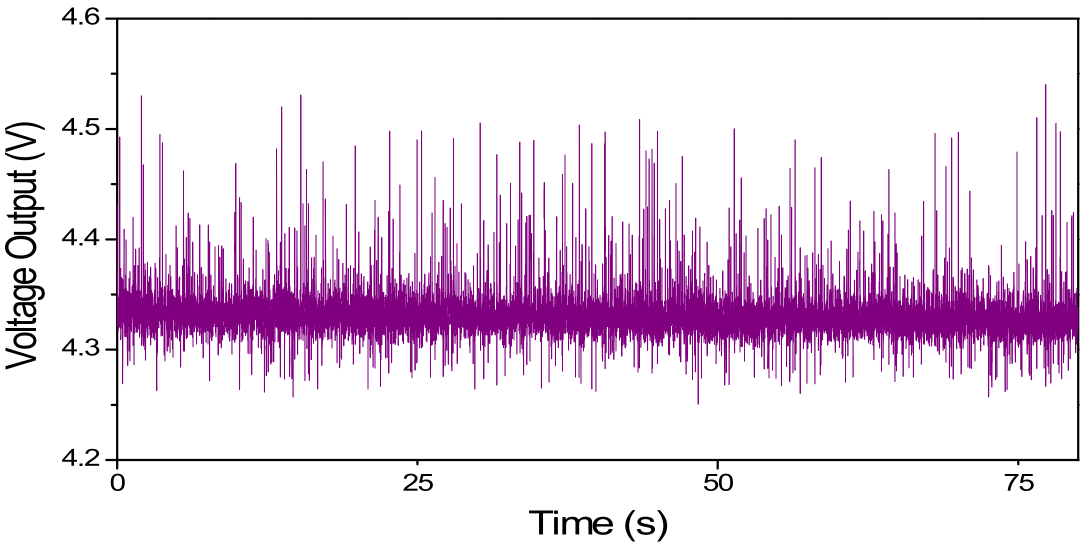



Fig. 1 Voltage output data for flow rate of 10 m/s

As shown in Fig. 5, since it is in a real time monitoring, there would be fluctuations due to environmental factors and there is little damping from the fiber itself. Hence there is a need to plot the normalized or the average values and the standard deviation plot. It is thus plotted in Fig. 6 which demonstrates the standard deviation measure at different flow rate. The centre is the plot of the averaged values. The start of the experiment begins at 5 Volts where there are no flow rate to cause any voltage drop as there is no bending of the fiber. As the flow rate increases, the fiber bends which will results in the voltage drop as seen in Fig. 6 and for comparison the theoretical voltage drop with external air flow given by Eq. (9) is shown.

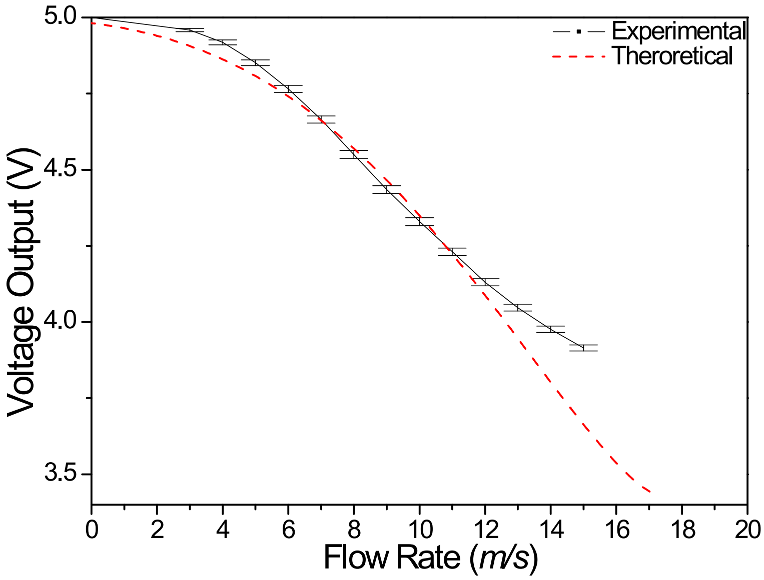


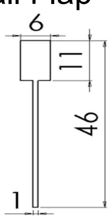
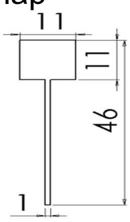
Fig. 2 Experiment data of no flap and theoretical

Observation from Fig. 6 reveals that there is a difference between theoretical values and experimental measurements. The reasons for the deviation are (i) the power loss is assumed to be linear to the change in area and as there are a many grooves which are affected by the bending, it may not cause a direct change in power density, (ii) the bending model of the fiber does not take into account large deflection. However from the theoretical formula, the graph shows a similar trend as the experimental measurement data. Despite the difference between the theoretical data and the experimental data, it is able to give clear values of the different flow rate based on the voltage drop and it can be used effectively as a flow rate velocimeter at the linear region from 0 *m/s* to 14 *m/s* with a sensitivity of -0.0922 *Vs*/*m.*

Besides the application in the aerospace industry, this technique is had been investigated to see if it is able to customize the current sensitivity to the different job requirements and hence we are determined to investigate on improving the current sensitivity by the addition of a flap. So a piece of flap was suggested to be added to the tip of the fiber whereby in Eq. (1), the drag force is increased by increasing the area. However by increasing the area might have an additional effect on the disturbance cause which is a compromise of the increase sensitivity.

To investigate the effects of area, an adhesive tape is used as the flap to increase the area. Two different areas are cut to size and are attached to the tip of fiber. The thickness of the tape is approximately 0.01 mm and hence we assumed that it does not affect the stiffness of the fiber. Different flap sizes used are listed in Table 1.

Table 1 Different flap sizes

| Flap | a)No Flap | b) Small Flap | c) Big Flap |
|---|---|---|---|
| |  |  |  |
| Area | 46 $mm^2$ | 101 $mm^2$ | 156 $mm^2$ |

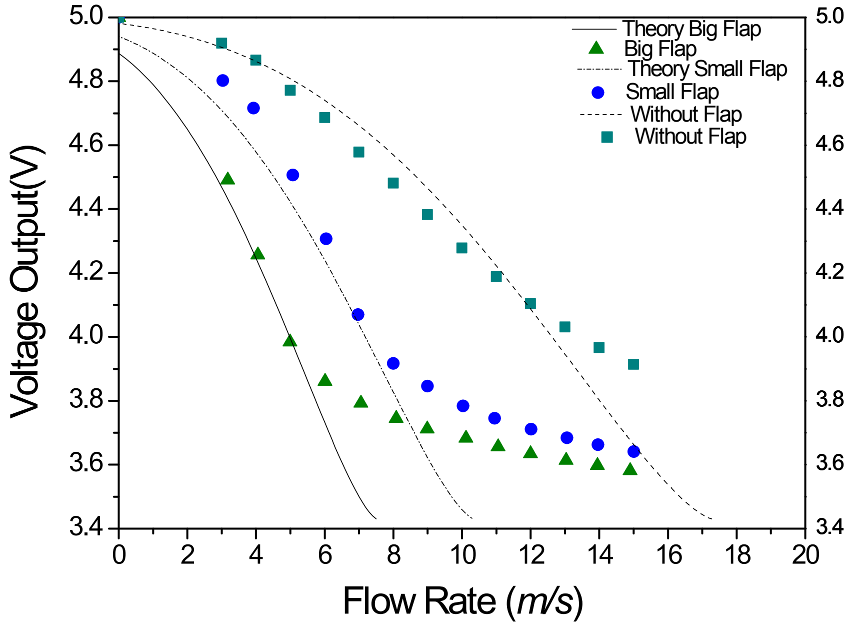



Fig. 7a Different flap Voltage output with theoretical data

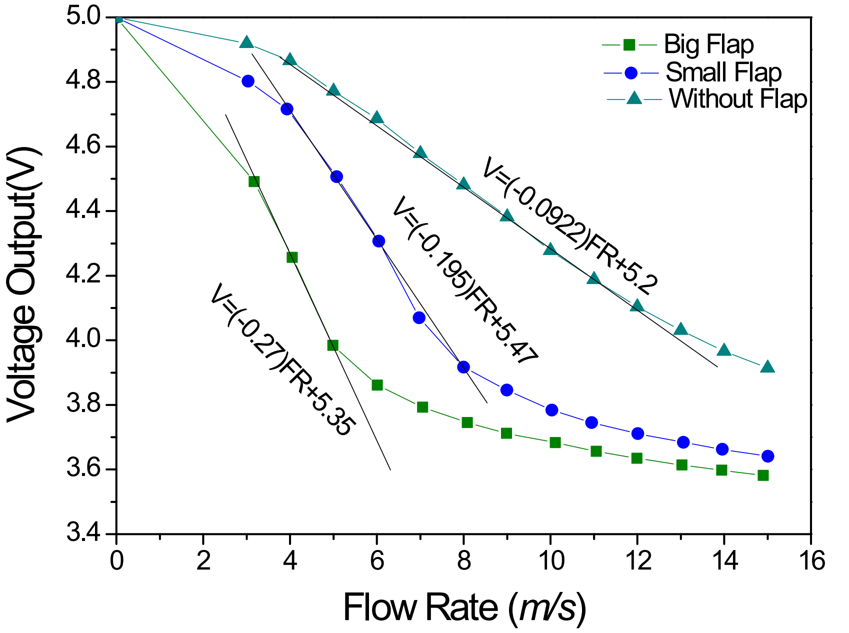



Fig. 7b Different flap Voltage Output with linear equations

With the addition of the flap, the voltage output against the flow rates are shown in Fig. 7a and 7b: It is to be noted that with flaps the voltage saturates to a constant value at a much lower flow rate. The range of flow detectability reduces. The small flap produces a linear region from 4 *m/s* to 8 *m/s* with a sensitivity of -0.195 *Vs/m.* The big flap produces a linear region from 3 *m/s* to 5 *m/s* with a sensitivity of -0.27 *Vs/m.* It reveals that the increase of the area of the flap would bring about an increase in the sensitivity but will also cause a decrease in the range of linear region.

It is to be noted that equation 1, the increase in the contact area, *A* would bring a increase the coefficient $\beta$ and thus affecting the final equation 9. Increasing $\beta$ has brought about the increase of the graph and it does follow the trend of reduction in range but with an increase in sensitivity which is similar to the trend observed in the experimental results.

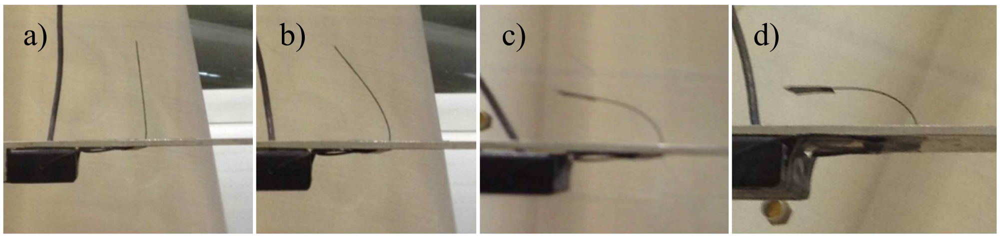



Fig. 8 Photographs of optical fibers in the wind tunnel: a) No flap, 0 *m/s;* b) No flap, 15 *m/s;* c) Small flap, 15 *m/s and* d) Big flap 15 *m/s*

Fig. 8 shows the deflection profile of the optical fiber at 0 and 15 *m/s* with different flap size. The inherent material property of the fiber is able to upright the fiber when there is no fluid flow hence from Fig. 5a it can be seen that there is no bending of the fiber at 0 *m/s* and hence it is able to have zero voltage drop. At a flow rate of 15 *m/s* the bending of fiber without flap appears to have more room for bending. For the small flap, it can be observed from the 0 *m/s* to 10 *m/s* it have a very observable change in the deflection. But beyond 10 *m/s* the change in the deflection is hardly noticeable. In the case of the big flap, the change in deflection is significant up to 6 *m/s*. However from observation, an increase of flow rate from 6 *m/s* does not create much change in the deflection which compiles to the experimental measurements.

The use of flaps has brought about a huge deflection in which would be inaccurate in using the Euler beam deflection equation. Hence to have a more accurate approximation, large deflection equation or finite element method is required. Besides the deflection, the addition of the flap also causes the beam to be subjected to an additional load on the tip of the fiber. Hence for a more accurate approximation, computational fluid dynamics with fluid structure interaction should be implemented to investigate the effect of drag forces and fiber geometry on the deflection profile of the optical fiber.

## CONCLUSION

In the experiment carried out, it can be shown that it is possible to use the simple optical fiber based instrument to obtain an indirect relationship with the flow velocity. Employing different flap area allows the user to customize the range of measure and control on the sensitivity. The benefits of this prototype is that it is relatively cost effective and with the advantage of having low power requirement as the equipment used is just led and photo detector. It is also rugged as the fiber is encased in its protective cladding.

## FUTURE WORK

As mentioned earlier, the fiber was manufactured to a fixed length, which imposes a limitation. The effect of optical fiber length along with the groove geometry, their number on the power drop or voltage drop has to be explored. The analytical model in the deflection of the cantilever shall be refined with large deflection theory.

Material properties of the fiber can be modified to obtain the required range of application.

Parametric studies of the flap area can also be done to optimize the sensitivity and range that is required by the user for the required application domain.

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