Measurement of streamwise vorticity using a vane vorticity meter

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A vane vorticity meter to measure streamwise vorticity was designed, constructed and calibrated. To obtain low bearing friction influence on the rotational speed of the meter, a relatively large vane span was chosen. A new method of data fitting is presented which gives an accurate description of vortex strength and diffuseness even when the characteristic radius of the vortex is nearly equal to or smaller than the vane span.

Keywords: *vorticity, flow measurement, streamwise vortex*

Introduction

Streamwise vorticity is an important fluid flow parameter. In research fields dealing with vortex generators for boundary layer control[1] and trailing vortices of wings, it is desirable to measure the streamwise vorticity.

The conventional method of measuring vorticity by measuring the velocity fields is indirect and often time consuming. The results are often inaccurate on account of its indirect nature.

One of the direct streamwise vorticity measurement methods is the vane vorticity meter[2,3]. This method, however, has never been accepted as a reliable quantitative tool because of the difficulty in determining the calibration ratio η, which is less than 1. This is because of the existence of the bearing friction torque, which is a function of vorticity w and the side wind load which is caused by the circumferential velocity when the centres of meter and vortex do not coincide. Such uncertain factors will make the calibration very difficult if η is far less that 1. However, if the vane span R is larger, the bearing friction will play a smaller role in decreasing the value of η, If the vane span is large enough and η is nearly 1, the calibration becomes easier because in this situation the objective in the calibration is to make sure that η is very near to 1, and the uncertain influences of friction on η can be ignored.

However, if the vane span R is large and the characteristic radius r_s of the vortex to be measured is small, it would be difficult to use the meter to evaluate the strength and diffuseness of the vortex.

In this study, a new concept of data fitting is used so that the actual vortex strength and diffuseness can be determined from the measured data even if the vane-span : vortex-radius ratio θ is near to or greater than 1.

The vorticity meter and its calibration

The vorticity meter is shown in Fig 1. A 0.4 mm diameter shaft and jewel bearings are used, which result in a very small friction torque. Relatively large vanes are used. The vane span is 5 mm with a chord of 3 mm.

As shown in Fig 1, the rotational speed of the meter is obtained by using a light source which transmits to a phototransistor through a small slice fixed on the shaft of the meter. The electric pulses produced by the phototransistor, which indicate twice the rotational speed of the meter, are amplified by an amplifier and counted by an electronic counter.

A 300 mm x 300 mm free jet wind tunnel was used for the calibration. The velocity of its potential core was approximately 39 m/s. A trailing vortex was generated by a small wing with a span of 150 mm and a chord of 30 mm. The wing was fixed on the side of the wind tunnel as shown in Fig 2.

The calibration procedure was as follows. A number of planes were chosen which were perpendicular to the z axis (flow direction). The readings of the vorticity meter at different points on each of these planes were obtained by scanning the meter on these planes. The location of the vortex centre and the vorticity meter reading at the vortex centre were determined by carefully changing the position of the vorticity meter until the reading was maximized. After that, the circumferential velocities of the vortex, as shown in Fig 3, were measured by a 3-hole yaw probe which scanned along the directions of the x and y axes, respectively, via the centre of the vortex.

According to Dosanjh *et al*[4], for a laminar trailing vortex the lateral distribution of its vorticity is Gaussian:

$$w = w_0 \, e^{-\beta^2 r^2} \tag{1}$$

Dosanjh[4] and other authors[5] also found that the velocity distribution of the turbulent trailing vortex is nearly Gaussian, though not exactly. In the present study, a circumferential velocity distribution of the Gaussian vortex,

$$v = \frac{w_0}{2\beta^2} \frac{(1 - e^{-\beta^2 r^2})}{r} \tag{2}$$

was used to fit the data of the 3-hole yaw probe according to the 'best fit' principle, and the values of w_0 and β were determined.

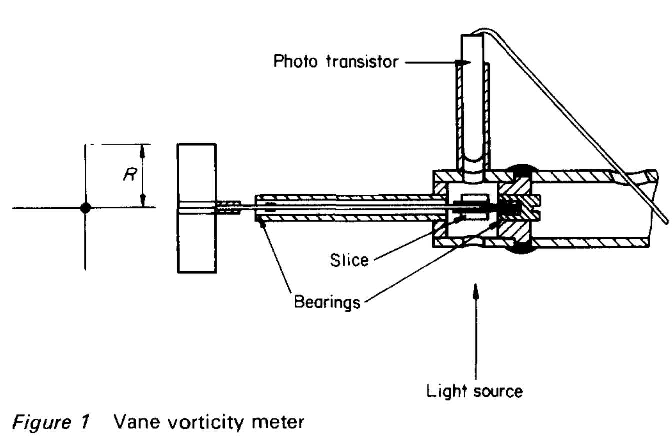

Figure 1 Vane vorticity meter

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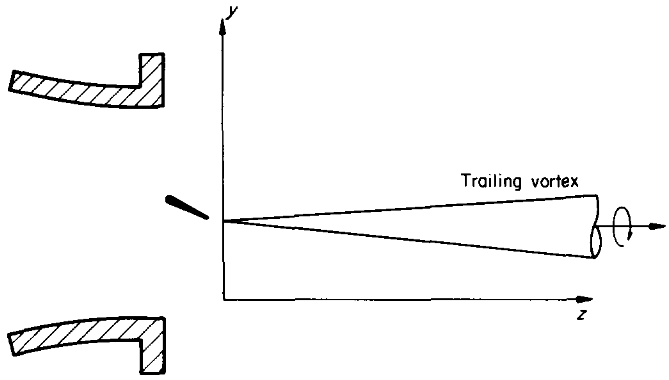

Figure 2 Coordinates for the calibration flow

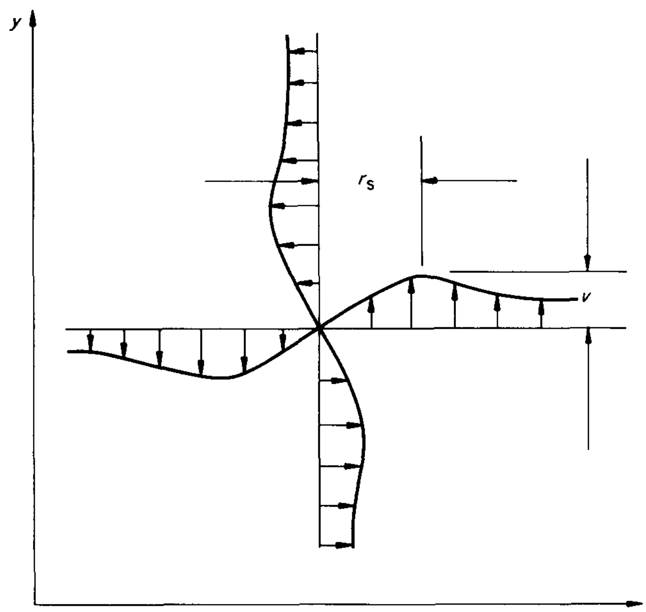

Figure 3 Circumferential velocity distribution in a vortex

Because the actual vortex is not exactly axisymmetric, values of w_0 and β determined by fitting velocity data may be slightly different in the x and y directions. The average values were used to describe the vortex.

Knowing w_0 and β, the average vorticity over the rotational area S of the meter vanes when positioned at the vortex centre can be determined:

$$\bar{w}_{\text{centre}}=\frac{1}{\pi R^2}\int_{r=0}^{R} w_0\, e^{-\beta^2 r^2}\, 2\pi r\, dr=\frac{w_0}{R^2}\frac{(1-e^{-\beta^2 r^2})}{\beta^2} \qquad (3)$$

$\bar{w}_{\text{centre}}$ obtained from Eq (3) is used to calibrate the vorticity meter reading at the centre of the vortex.

Fig 4 shows the result of the calibration. η is almost 1 except when w is very large or small, where η is larger than 1. This may be attributable to factors such as the errors in circumferential velocity measurements, the approximate nature in the assumption of a Gaussian vorticity distribution for a turbulent vortex, the assumption that the vortex used in the calibration is axisymmetric, and the assumption that the vorticity meter reading indicates the arithmetic average vorticity on the rotational area S of the vanes. The vortex is not axisymmetric very near the wing, where axisymmetry has not yet been fully established, and far downstream from the wing, where the vortex is very diffuse and the interaction of the vortex with the shear layer of the free jet becomes visible. The present result of calibration suggests that η is very near to 1 and we can assume that $\eta=1$.

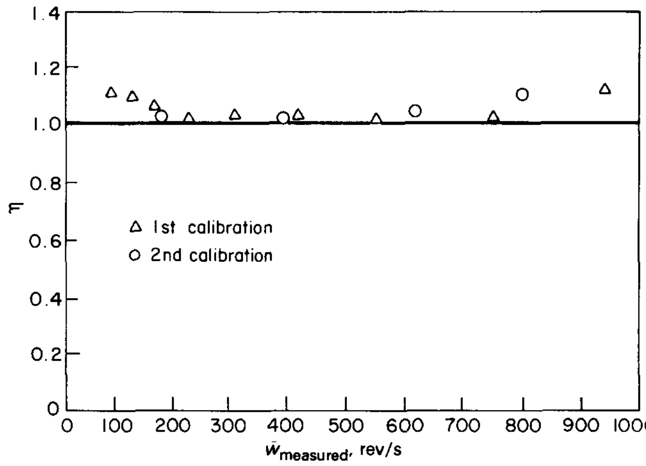

Figure 4 Calibration results without side wind

The calibration result indicates that when no side wind load is presented, ie at the vortex centre, the friction torque effect on the rotational speed of this vorticity meter can be neglected within the vorticity range of the calibration. This range of about 84–950 rev/s or about 530–6000 rad/s. Because the rotational speed of the meter is half of $\bar{w}$, the maximum rotational speed of the meter in the calibration is about 500 rev/s or 30000 rev/min.

When the meter is displaced from the vortex centre, the circumferential velocity or the side wind is present, causing an additional load to the bearings. It is difficult to estimate the exact influence of the side wind on η. However, if friction torque without side wind plays only a negligible role in reducing η it may not play a significant role even with a side wind. With the assumption that $\eta=1$ even when the meter is displaced from the vortex centre, a comparison of the results of vorticity meter measurement with the results obtained by the 3-hole yaw probe measurement will be used to justify the assumption indirectly.

A new concept of data fitting and the comparison of the measured results

Because the vorticity reading indicated by the vorticity meter represents an average quantity of vorticity on the meter rotational area S, there may be large errors if a conventional

Notation

r	Distance from the vortex centre
R	Vane span of the vorticity meter (Fig 1)
r_s	Characteristic radius of the vortex, where the circumferential velocity reaches its maximum
S	Rotational area of the meter vanes $\equiv \pi R^2$
v	Circumferential velocity of the vortex
w	Vorticity
$\bar{w}$	Average vorticity on the area S
w_0	Maximum vorticity at the vortex centre when using the Gaussian vorticity distribution model
x, y, z	Cartesian coordinates
β	Parameter representing the diffuseness of the vortex when using the Gaussian vorticity distribution model $=1.1209/r_s$
Γ	Total circulation of the vortex when using the Gaussian vorticity distribution model $\equiv \pi w_0/\beta^2$
η	Calibration ratio (vorticity indicated by the meter actual average vorticity)
θ	Ratio of vane span to vortex radius $\equiv R/r_s$

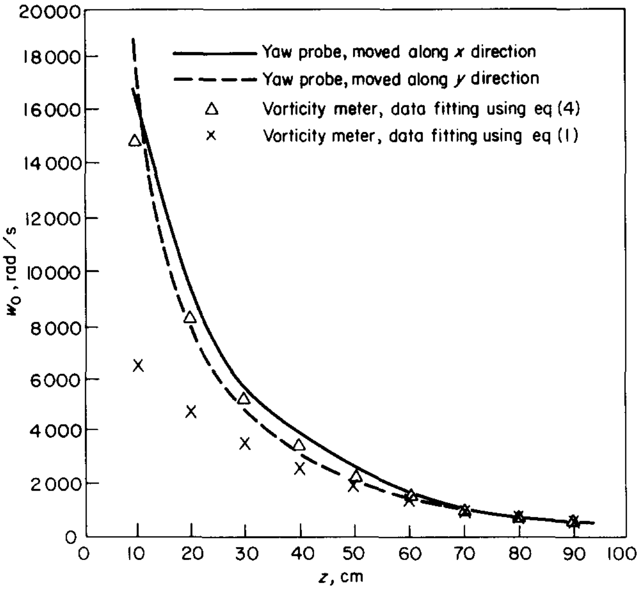

Figure 5 Measured values of w_0 of a vortex, assuming a Gaussian distribution of vorticity

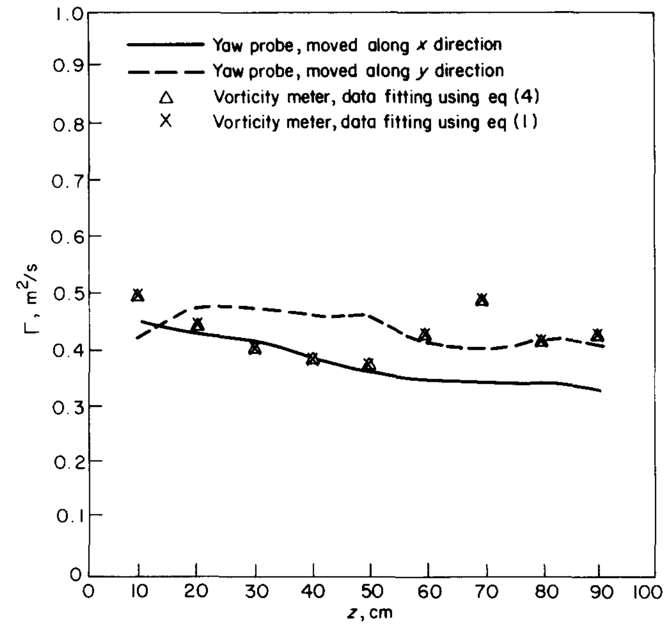

Figure 7 Measured values of Γ of a vortex, assuming a Gaussian distribution of vorticity

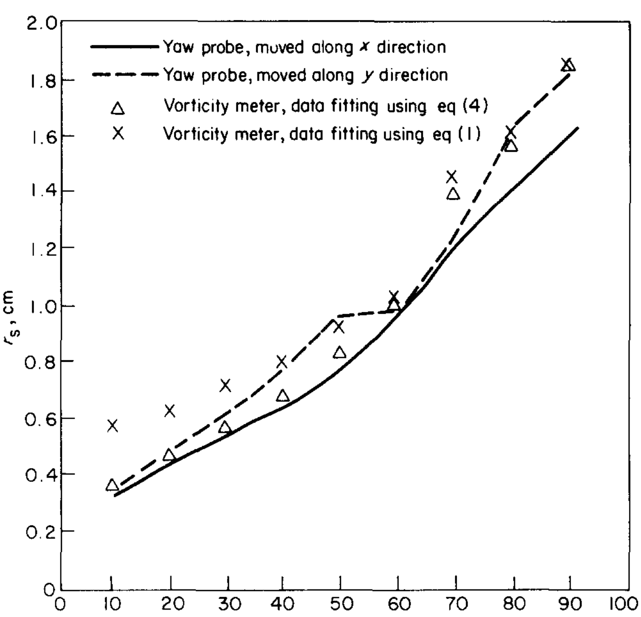

Figure 6 Measured values of r_s of a vortex, assuming a Gaussian distribution of vorticity

method, ie Eq (1), is used for data fitting when the ratio of vane span to vortex radius, θ, is large. This is represented by an underestimated w_0 and an overestimated r_s. This tendency becomes more serious when θ is near to or greater than 1. So the results are dependent on vane span. To reduce the influence of vane span size on the measured results, we use

$$\bar{w}=\frac{1}{\pi R^2}\iint_S w_0\,e^{-\beta^2 r^2}\,dS \tag{4}$$

instead of Eq (1) to fit the experimental data. Eq (4) represents the average vorticity on the meter rotational area S. If the centre of the area S coincides with the vortex centre, Eq (4) then becomes Eq (3). With a specially developed computer code of optimization, including numerical integration, the 'best' w_0 and β can be found using Eq (4) to fit the experiment data according to the 'best fitting' principle.

Figs 5, 6 and 7 show the parameters w_0, r_s and Γ of the Gaussian vortex obtained using the vane vorticity meter. They are compared with the 3-hole yaw probe results. In these figures, the 3-hole yaw probe results are presented in two curves: one for which the probe was moved along its x direction, and the other for which the probe was moved along its y direction. The inconsistency of the two curves may be attributable to the fact that the vortex is not exactly axisymmetric. From these figures it can be seen that most of the results of the vane vorticity meter measurement are located between the two curves. The comparisons are satisfactory. Fig 6 shows that vortex radius can be as small as 0.37 cm, ie θ can be as large as 1.35, while a good comparison still exists. This is not necessarily the upper limit of θ. Figs 5 and 6 also show that when vortex radius r_s is less than 1 cm, ie θ is greater than 0.5, serious errors in w_0 and r_s exist when the conventional data fitting method is used. The comparisons also indicate that the assumption that the side wind has a negligible effect on η holds true; if not so, the results, especially r_s which represents the diffuseness of the vortex, could not be correct. It is interesting to notice from Fig 7 that the total circulation Γ remains unchanged whether the new or conventional data fitting method is used.

Conclusions

A vane vorticity meter was developed. The influence of its bearing friction torque on the rotational speed was decreased by suitable design. Its calibration without the influence of the side wind was performed by using a 3-hole yaw probe within a vorticity range from 530 to 6000 rad/s. The calibration shows that the calibration ratio η under the calibration conditions can be considered as 1.

A new concept of data fitting is presented. The distribution of the average vorticity on the meter area S assuming a vortex with Gaussian vorticity distribution, instead of Gaussian vorticity distribution itself, is used as the fitting function for the experimental data. In this way, the results are much less dependent on the vane span size. In this study, the vane-span:vortex-radius ratio θ can be increased from 0.5 to 1.35 without evident influence on the evaluation of the vortex strength and diffuseness. This is not necessarily the upper limit.

The comparisons of the vorticity meter measurement results with those of the 3-hole yaw probe are satisfactory, showing that the assumption of $\eta=1$ holds true when the meter is moved away from the vortex centre and, therefore, under the side wind effect.

An adequately designed vane vorticity meter with its η value very near to 1, after careful calibration and incorporated with the new data fitting method of the present study, can be an accurate, quantitative instrument for measuring streamwise vorticity.

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Conference report

International conference on laser anemometry: advances and application

16–18 December 1985, Manchester, UK

The UK LDA Users Group held its first international conference on laser anemometry at the University of Manchester in December 1985. The conference was organized by the UK LDA Users Group, sponsored by the University of Manchester and co-sponsored by the Institution of Mechanical Engineers, the Royal Aeronautical Society and the British Hydromechanics Research Association. A large field of papers of a high standard had been received and of the 38 papers presented at the conference, 16 were by overseas authors, with a similar proportion of overseas delegates. There were no parallel sessions and the quality of the papers and enthusiasm of the delegates could be judged by the high attendance levels at all sessions. The atmosphere of the conference was amicable and workmanlike and the local organizers must be congratulated both on the quality of the social and domestic arrangements and on running the proceedings to time!

The technical sessions of the conference were structured around five invited papers by internationally recognized authorities who had each been asked to address a particular aspect of laser anemometry. Mike Fingerson's introduction to fibre optics in LDA applications was the springboard for a group of papers demonstrating the considerable potential of fibre optics in radically altering our concept of optical systems design in terms of both miniaturization and the use of fibre optic phase modulators. Two authors described multipoint measurements using fibre optics to deliver and collect light at many points in the flow simultaneously. Preben Buchhave considered the design of 3D measurement systems and described the often conflicting requirements of a real example. A number of papers addressed the problems of making measurements in 3D and rotating flows and presented results from a variety of rotating flow structures. Les Drain discussed laser anemometry and particle sizing, providing an overview of the combined field of size and velocity measurement and describing the range of techniques that have been developed. LDA measurements in two-phase flows were presented by various authors who had examined water sprays in air, solid particles in a spouted bed and wet steam flows. Franz Durst's paper on turbulence quantities and Reynolds stresses in a pipe flow of polymer solutions discussed measurements in turbulent boundary layer flows and described the use of refractive index matching techniques to permit detailed study of the near wall region. This paper acted as the focus for a group of papers which considered a wide range of special applications varying from turbulent confined jets with recirculation to natural convection flows, from bluff body wakes to ribbed wall channel flow. Jim Whitelaw described a wide range of applications of laser anemometry to engine flows, both combustion studies for gas turbines and in-cylinder measurements in reciprocating IC engines. He also addressed the difficulties of making measurements of fuel droplet size in such flows. Other authors presented measurements made in furnaces and in motored reciprocating engines.

The LDA Users Group has broadened its field of interest, dropping the word Counter from its title and this was demonstrated by the large number of paper presenting aspects of instrumentation, signal processing and interpretation using frequency trackers, transient recorders, photon correlators and filter banks. The emphasis of this conference was on advances and application and the papers presented show the wide front of the advance. Although three papers were presented specifically on the topic of comparison between theoretical prediction and experimental measurement it does still seem that there is no general feedback into computational modelling of data obtained from turbulent flows using LDA. Perhaps this is a topic that will be addressed by authors at the next conference in this series.

The quality of the technical sessions was repeated in the excellent exhibition of instrumentation and equipment which included displays by the major manufacturers. The exhibitors had obviously taken a great deal of trouble to present the current state of their art and the stands were manned with the standard of erudition one has come to expect.

Copies of the Conference volume containing the invited papers and contributed papers may be obtained from Publications Sales, BHRA, Cranfield, Bedford, M43 0AJ, UK, at a price of £44.00 UK and EEC – £47.00 elsewhere.

Encouraged by the success of this first international conference, and the previous national symposium in 1982, the LDA Users Group has decided to hold the second international conference at the University of Strathclyde between 21 and 23 September 1987. A preliminary announcement has been made and a call for papers will follow very soon. The UK LDA Users Group continues to hold meetings several times yearly, acting as a forum for researchers concerned with the application of LDA. Further details can be obtained from UK LDA Users Group, c/o Department of Engineering, University of Manchester, Oxford Road, Manchester.

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