Vorticity Measurements Using Calibrated Vane-Vorticity Indicators and Cross-Wires

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Vane-type vorticity indicators of various sizes have been constructed, calibrated, and used for direct and rapid measurement of local mean streamwise vorticity in several swirling flows. The dependence of the calibration factor, which relates the vane rotational speed to the local angular velocity of the fluid, on the freestream velocity, the fluid rotational speed, and the transverse vorticity gradient was determined. When the vanes were calibrated carefully and checked and maintained regularly, good agreement was achieved with vorticity profiles obtained using cross-wire data. Otherwise, a vane could be used only to give an indication of vorticity.

Nomenclature

N_f	= angular velocity of the fluid, rpm
N_v	= angular velocity of the vane-vorticity indicator, rpm
r	= radial distance measured from the center of the test section
U_∞	= freestream mean velocity
W	= vertical velocity in the fluid normal to the streamwise direction
x	= axial or streamwise distance
y	= lateral distance normal to streamwise direction and measured from the center of the test section
z	= vertical distance normal to streamwise direction and measured from the center of the test section
α	= half-angle setting between the airfoils
η	= vane indicator ratio
τ	= delay time in autocorrelation function
Ω_x	= vorticity in the streamwise direction

Introduction

THE streamwise vorticity component, i.e., the component of vorticity in the mean flow direction, can be measured using any one of several methods. Many of these methods rely on calculating the vorticity from measurements of the transverse velocity components and their spatial variations. One method that attempts to measure this vorticity component directly utilizes a mechanical device that we call the vane-vorticity indicator. Similar devices have been used by other experimenters for measurements and for demonstration purposes. However, it usually is not clear what calibration factors were involved in the determination of the magnitude of the vorticity and how these factors were established. Along with simple construction and measuring techniques, accurate determination of these factors and their dependence on some important parameters, such as freestream velocity, should provide a useful tool for the direct measurement of such an important but most difficult to measure quantity.

Recently, Zalay[1] presented a comparison between measurements of the circulation around wing trailing vortices based on the evaluation of vorticity by several methods including the vane-vorticity indicator, also called the vorticity meter. His comparison demonstrates that for some trailing vortices "the vorticity meter significantly underestimated the strength of the vortex field," e.g., as much as 65% difference. Zalay concludes that vorticity meters "behave in a nonlinear fashion in weak vortex fields" and notes that "no study has been done to compare the vorticity meter with other flow measuring devices." He also suggests that this information may help in explaining the low vortex circulations cited in references such as that of McCormick et al.[2] In most of the previous studies, including those of Zalay and McCormick et al., the vorticity meter was calibrated by positioning a "calibration collar," a fixed-vane-type swirl generator, upstream of the device. At best, this procedure can only reveal the dependence of the calibration factor on the freestream velocity, as evidenced by the results of these studies. In general, the calibration of a particular vane may depend as well on the fluid rotation velocity and the radial gradient of the angular velocity of the fluid.

In the present study, several vane-vorticity indicators are calibrated systematically, and the dependence of the calibration factors on various parameters is investigated. Next, they are used to measure the streamwise vorticity in several vortical flows, and the results are compared with data obtained by cross-wire anemometers. Finally, examples of the application of the vane-vorticity indicator for direct and rapid evaluation of streamwise vorticity are summarized.

Probe Construction and Instrumentation

The vane-vorticity indicator consists of four perpendicular blades and is designed to rotate about its axis on a high-speed steel shaft, as shown in the photograph and by the schematic of Fig. 1. Each vane is assigned a number that is listed in the table portion of the figure for identification purposes in the remainder of the paper. The vanes are milled from either brass or aluminum stock, with the dimensions as given. The blades of each vane are made very thin in order to minimize the moment of inertia and to make the vane as sensitive as possible to variations in the flow. The vanes also are balanced statically to account for any eccentricity or variation in the blade thickness. Initially, no teflon bushings or washers were used, but, during the calibration procedures, excessive friction and wear made this modification necessary. The teflon inserts are replaceable, making the lifetime of the vane unlimited. More recent modifications include vanes with even thinner blades and the use of jewel bearings for even longer bearing life and lower friction.

Placing one of these vanes in the flow so that the vane rotation axis is aligned with the mean flow direction, the vane rotates only when there is a rotating component of the flow in this direction. This rotation of the vane can be related to the corresponding vorticity component through careful

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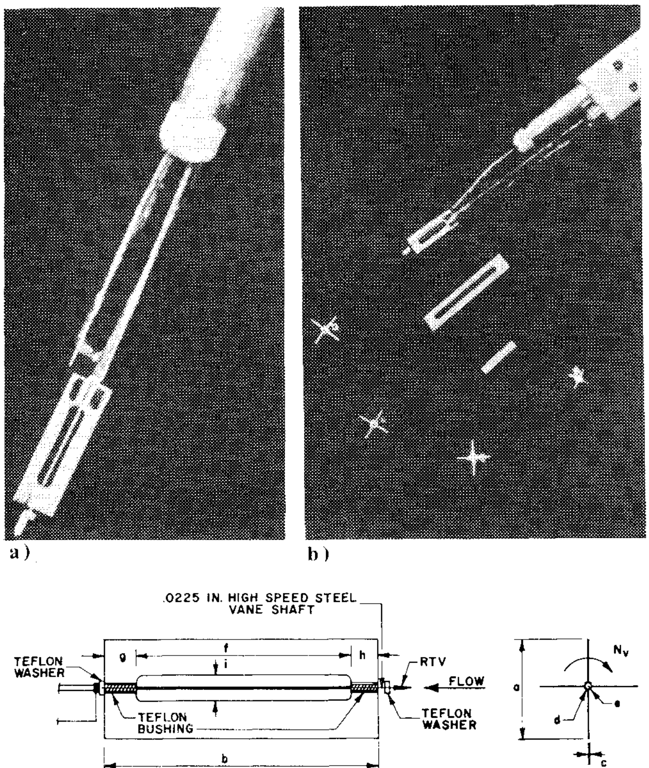

VANE NO.	a IN.	b IN.	c IN.	d IN.	e IN.	f IN.	g IN.	h IN.	i IN.
1	.25	.562	.012	.027	.0225	.37	.116	.077	.078
2	.375	.5	.017	.026	.0225	.37	.065	.065	.062
3	.25	.438	.015	.028	.0225	.3	.093	.045	.046
4	.375	.75	.014	.027	—	.5	.114	.136	.062

c)

Fig. 1 a) Vane vorticity indicator probe. b) Photographs of different-size vanes. c) Schematic of vorticity indicator vanes and dimensions.

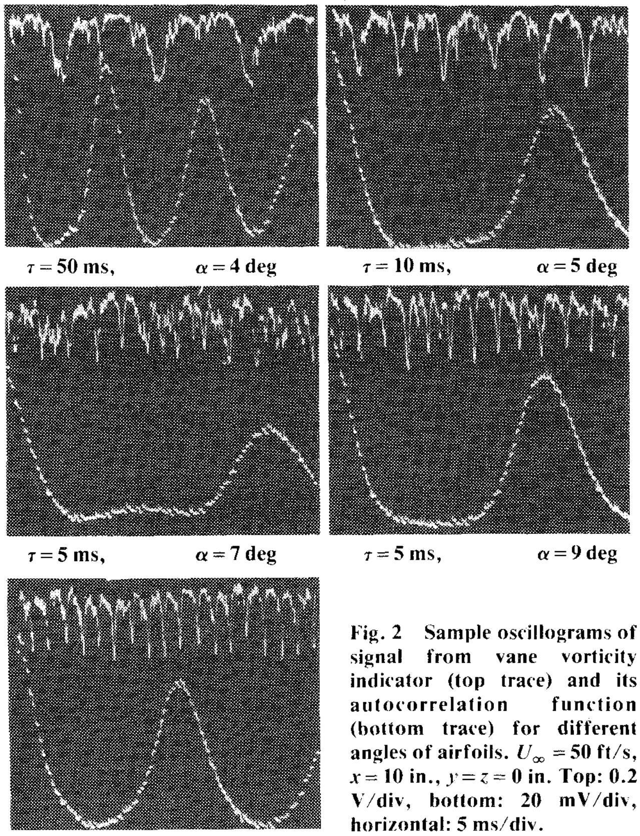

Fig. 2 Sample oscillograms of signal from vane vorticity indicator (top trace) and its autocorrelation function (bottom trace) for different angles of airfoils. $U_\infty = 50$ ft/s, $x = 10$ in., $y = z = 0$ in. Top: 0.2 V/div, bottom: 20 mV/div, horizontal: 5 ms/div.

calibration, as will be discussed later. One of the most important considerations is a means of measuring the rotation of the vane without imparting any load to the vane, so that its rotation is not inhibited. The method used in this experiment employs a hot wire located directly downstream of the vane and is similar to the method of Holdeman and Foss.[3] A photograph of the probe with the vane and hot wire in position also is shown in Fig. 1. As the vane rotates, the wake from each blade is detected when it passes over the hot wire. This is apparent in the top oscilloscope trace in every photograph in Fig. 2, where each one is taken for a slightly different flow condition. These traces of the hot-wire signal have spikes, caused by the passage of the vane-blade wakes, that are clearly visible because of the relatively low level of background turbulence. Autocorrelation of the hot-wire output provides a signal from which the average rotational speed of the vane can be calculated. The lower trace in each photograph in Fig. 2 is the corresponding autocorrelation function, where the time delay varies across the photograph from zero to the value listed in each case. The peak in the autocorrelation function occurs at the time delay corresponding to ¼ rev of the vane.

Vane Calibration

All of the traces in Fig. 2 were recorded in flow conditions typical of those used for calibration of the vanes, i.e., the trailing vortex generated by two adjacent airfoils hinged along the same axis at their quarter-chord position and set at equal but opposite angles of attack. By varying the angle of attack for a fixed freestream velocity, as in Fig. 2, curves were obtained relating vane rotational speed N_v to angle of attack α. During calibration, the vane rotational axis is aligned with the streamwise direction and positioned in the center of the trailing vortex with the vane located 10 in. downstream of the trailing edge of the airfoils. Careful probing of the trailing vortex at this position in several flow conditions demonstrated axial symmetry.[4,5]

Two curves for one vane (vane 1) and two freestream velocities are plotted in the top part of Fig. 3. For both velocities, the same trends are observed as the angle of attack of the airfoils is changed. The vane rotational speed generally increases as the angle of attack increases, but there are some regions where this is not the case, such as around 3 deg. Since these regions occur for different values of α and N_v as the freestream velocity is changed, they are believed to be a result of changes in the flow over the airfoils and not due to any mechanical difficulties related to the vane. (For further details, see Ref. 4.) In addition, the minimum angle of attack necessary for vane rotation, which is indicative of the threshold caused by friction in the bearings, decreases as the velocity increases. This is due to the increase in vortex strength with freestream velocity for a given angle of attack, with the result that the torque required to overcome the friction occurs at a smaller angle of attack for higher freestream velocities.

Results for three vanes of different sizes are plotted in the lower part of Fig. 3. The similarity of the results for all three vanes, along with the preceding observations, led to the designation of this level of performance by vanes 1 and 2 as the calibration conditions for any vane constructed using the teflon bushings. During the course of any experiment, the vane is checked periodically against these curves to insure the validity of the data. Typically, the teflon bushings have to be replaced and new ones broken in after 30 h of operation. This period depends on the fluid rotational speed in which the vane is used and varies from one bushing to another, so that frequent comparison to the calibration conditions is a necessity.

Since the rotational speed of the vane is known for various angles of attack and freestream velocities, data on the local

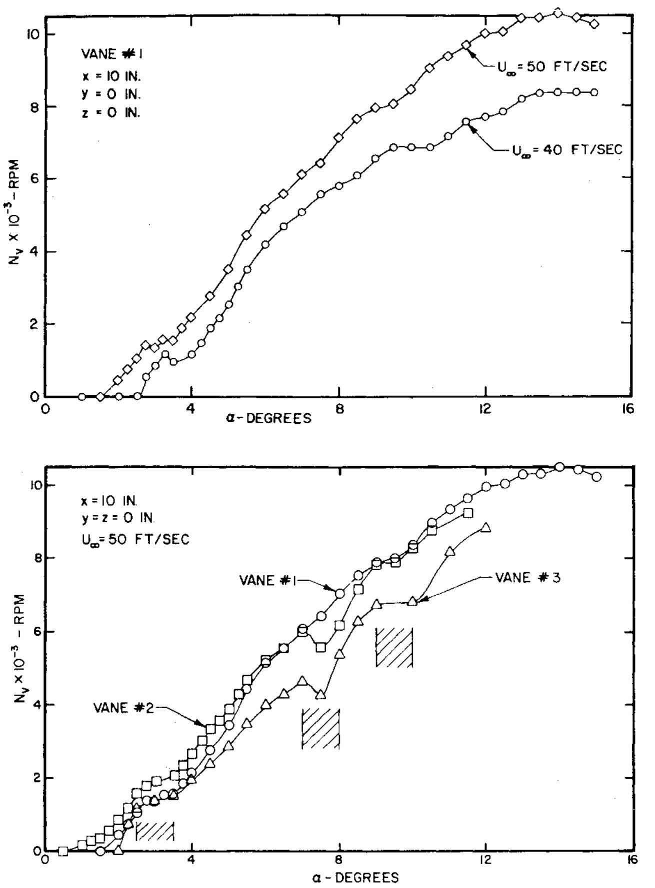

Fig. 3 Calibration of vorticity indicator rotational speed for vane 1 and comparison for vanes 1, 2, and 3 vs airfoil angle.

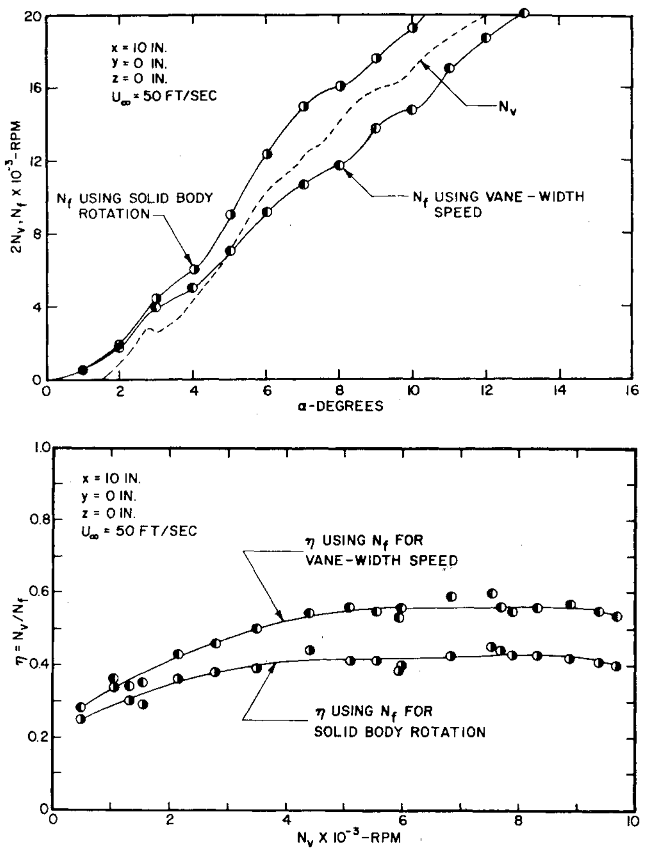

Fig. 5 Fluid rotational speed and vorticity indicator rotational speed using $\eta = 0.5$ as a function of airfoil angles at 50 ft/s, and variation of η with vorticity indicator rotational speed for vane 1.

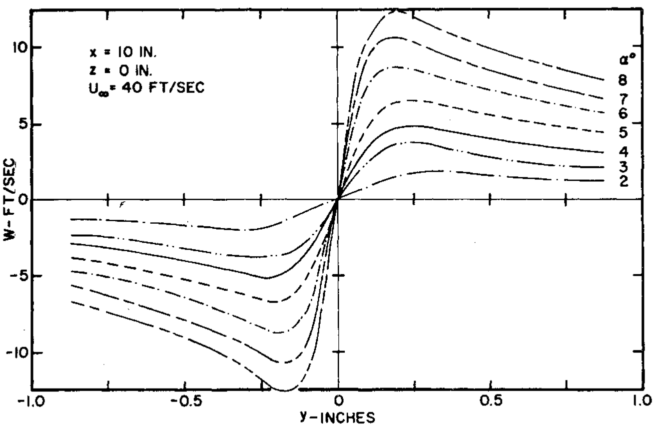

Fig. 4 Lateral profiles of vertical mean velocity through vortex of airfoil swirl generator for various angles of attack.

velocity components in these flow conditions provide the basis for determining how accurately the vane measures vorticity in the flow. The tangential velocity as a function of radius from the vortex center was measured with a cross-wire probe at the same downstream location as that of the vane during calibration. Samples of these traverses are given in Fig. 4 for several angles of attack. The solid-body core of the vortex is apparently of the same size for all of the cases shown. The slope of the velocity profile in this region is used to calculate the angular velocity of the core, called the solid-body rotation speed, which is one of the characteristic rotational speeds used in this investigation. However, reviewing the dimensions of the vanes, especially for vanes 2 and 4, we find the the vane extends beyond the region of solid-body rotation. Another rotational speed based on the tangential velocity at the tip of the vane is defined, assuming an equivalent solid-body rotation velocity profile across the vane, and is called the vane-width speed. Comparison of the rotational speed of the vane with these fluid rotational speeds provides a calibration factor that is used to convert the vane data. Depending on the size of the vane, the speed to be used in the calibration which accurately describes the vane behavior is probably somewhere between these two limits.

In general, the calibration factor may be at least a function of the fluid rotational speed, the freestream velocity, the radial vorticity gradient, and the physical dimensions of the vane. The calibration factor is equal to the ratio of the vane rotational speed N_v to the fluid rotational speed N_f, which is called the vane-indicator ratio η. It has two values for each N_v, depending on which N_f is used, i.e., either the solid-body rotation speed or the vane-width speed.

To demonstrate the effect of the fluid rotational speed on the value of η, the calibration curves of Fig. 3 can be used. Choosing $\eta = 0.5$, the comparison shown in the top part of Fig. 5 is obtained. This particular constant value of η causes most of the vane data to follow the cross-wire results except for low vane rotations. The agreement leads to the conclusion that η is somewhat independent of the fluid rotational speed, at least for the higher vane speeds. This is supported by the lower part of Fig. 5, where the detailed variation of η with vane rotational speed is plotted for the same two fluid rotational speeds. The value of η is almost constant for speeds over 3000 rpm and decreases nonlinearly for lower rotational speeds.

To determine the effect of the freestream velocity on the value of η, the freestream velocity is varied for a fixed angle of attack, as shown in Fig. 6. Here the value of η is again 0.5, as indicated by the vertical axis scale. The converted vane data follow the calculations of N_f from the cross-wire measurements based on the vane-width speed, with only a

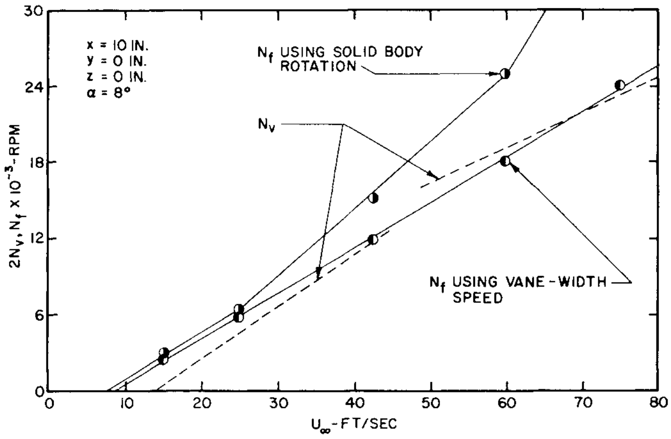

Fig. 6 Fluid rotation speed and twice the vorticity-indicator rotational speed as a function of freestream velocity.

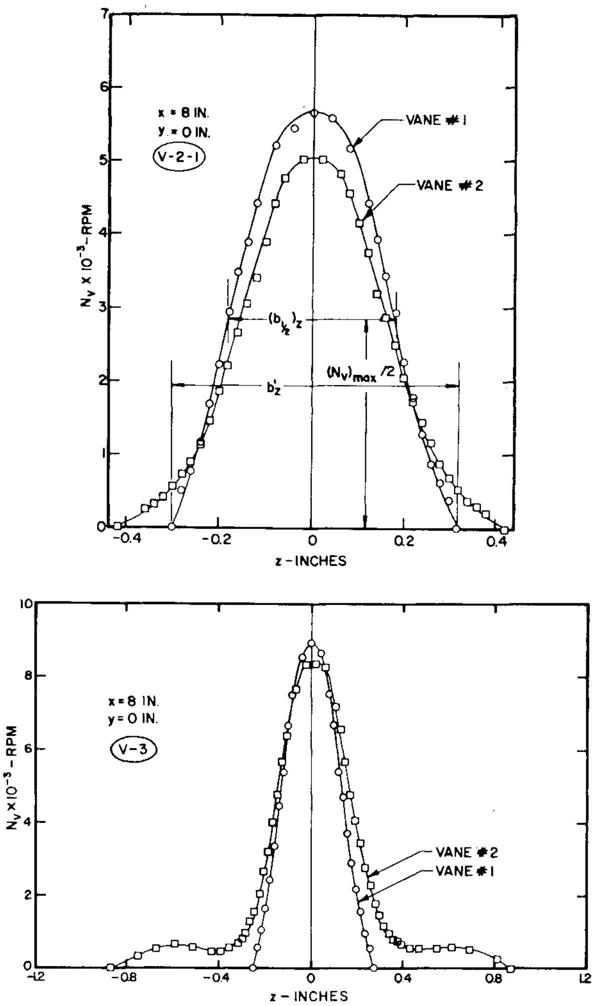

Fig. 7 Radial distribution of vorticity indicator rotation in test flow conditions V-2-1, and V-3 for vanes 1 and 2.

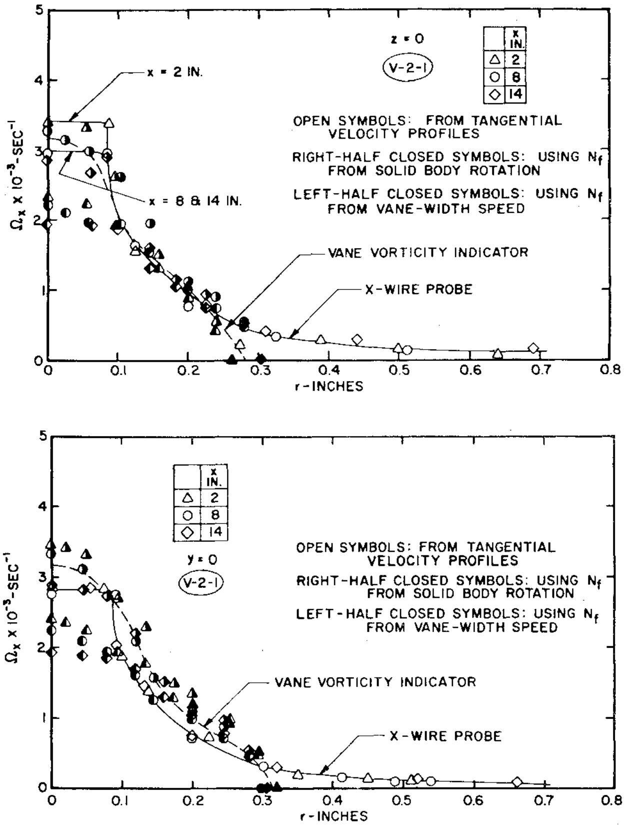

Fig. 8 Comparison of local streamwise vorticity as obtained from cross-wire data and from vane vorticity indicator measurements for lateral and vertical distributions in test flow condition V-2-1.

small dependence on freestream velocity. If a slightly different value of η is used, the vane results follow the data for solid-body rotation. In either case, the ratio η appears to be only a slight function of freestream velocity over this range.

Before examining the effect of the radial velocity gradient, a further discussion on the effect of vane size is needed. As mentioned earlier, calibration curves for three different vanes are presented in the lower part of Fig. 3. Vane 2 is 50% wider and almost the same length as vane 1, while vane 3 is the same width as vane 1 but is about 25% shorter. The agreement between vanes 1 and 2 is quite good, as noted earlier, but vane 3 rotates at slightly slower speeds. This discrepancy is attributed to construction differences with resulting additional friction. Data also were obtained using vane 4, which is the same one used by Holdeman and Foss,[3] but are not shown here. After balancing and other minor modifications, the performance of this vane was similar to the other vanes constructed by us. Figure 3 demonstrates that the ratio η is essentially independent of the width and probably also independent of the length for the range of calibration conditions and vane sizes used. Details of the calibration curves, particularly over the ranges of α indicated by the hatched areas in Fig. 3, also are repeated for the different-size vanes at the same angle of attack, i.e., fluid rotational speed of the vortex. This emphasizes the lack of dependence of the value of η on the size of the vane and supports the earlier conclusion that these areas are caused by changes in the flowfield. However, the vane was always in the vortex center for all of these results.

An effect of the vane width can be demonstrated by using radial profiles of the vane rotational speed across the vortex as shown in Fig. 7. In the top part of this figure, the profile for vane 2 is similar to that for vane 1, except at the base. The value for the half-width $(b_{1/2})_z$ is the same for the two vanes. The extra width at the base is due mainly to the larger size of vane 2, and to a lesser extent to the different thresholds of rotation observed for these two vanes in Fig. 3.

A more graphic display of the effect of vane width and friction is shown in the bottom part of Fig. 7. Obviously the difference in size between vanes 1 and 2 cannot account for the discrepancy at larger distances from the center of the vortex. However, considering the rotational speed of vane 2 in this area, and comparing with the aid of the calibration curves, we find that the amount of rotation for vane 2 corresponds to an angle of attack α for which vane 1 does not

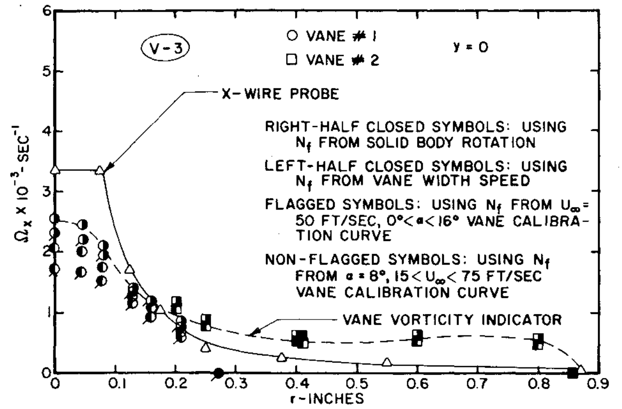

Fig. 9 Comparison of vertical distribution of local streamwise vorticity as obtained from cross-wire data and from measurements of vorticity indicator with vanes 1 and 2 in test flow condition V-3.

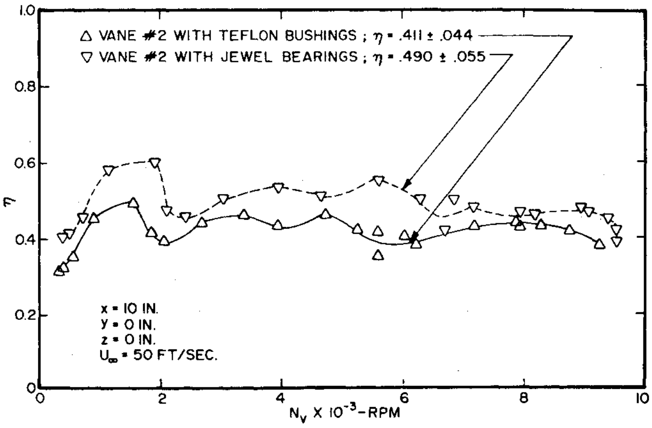

Fig. 10 Comparison of the vane indicator ratio for teflon bushings and jewel bearings for vane 2.

rotate. Whether this is an effect of friction alone, size alone, or a combination of lower friction and increased size is not known, but it appears that the larger vane is more useful for measuring low values of vorticity.

Having noted the effects of angular velocity, freestream velocity, and physical size, only the effect of radial gradient of vorticity still has to be demonstrated. This involves comparing the vane data to the cross-wire data in terms of vorticity using results similar to those of Fig. 7.

Vorticity Comparisons

The radial profiles of streamwise vorticity for the calibration flow conditions are calculated using the cross-wire data for the tangential velocity, as presented in Fig. 4, assuming axial symmetry and taking derivatives graphically. The radial profiles of vane rotation obtained from the vane vorticity indicator, such as those shown in Fig. 7, are converted to the equivalent fluid rotational speeds using curves similar to those in the lower part of Fig. 5. Since the vorticity is twice the angular velocity of the fluid, the vorticity measured by the vane can be obtained easily. However, the calibration curves for the vanes were taken when the vane was in a region of almost constant vorticity, i.e., in the solid-body core of the vortex. The vane is located in such a region only in the center of the vortex; at other radial positions, the vorticity is varying across the vane. If the gradient of vorticity has an effect on the value of η, the agreement should not be very good between the vorticity profile obtained using the converted vane data and that from the cross-wire results.

Some of the comparisons are shown in Fig. 8, where both the lateral and vertical radial distributions are given. The converted vane data follow the vorticity calculations from the cross-wire measurements very well in the region from the center of the vortex out to a radius where the vorticity is too low for the vane to rotate because of frictional effects. In particular, conversion of the vane data using the values of η determined from the solid-body rotation speed gives better results in the center of the vortex, while either fluid rotational speed can be used outside the core region. This good agreement demonstrates that the value of η is independent of the vorticity gradient, at least for vane 1 and the range of the present calibration conditions, and that the vane gives a good measure of the vorticity in the flow.

While discussing the lower part of Fig. 7 in the last section, it was noted that the larger vane might be more effective for measurements of low levels of vorticity. To demonstrate this, the same profiles of vane rotational speed were converted to vorticity and are compared to cross-wire results in Fig. 9.

Although the larger vane provides information far away from the center of the vortex, there are several errors in the comparison with cross-wire results. In particular, the magnitude of the vorticity from the two methods does not agree anywhere. Part of this error is caused by using extrapolated values for η, since flow condition V-3 is outside the range of calibration conditions available for this vane. Even though the value of η is only a slight function of velocity, as shown in Fig. 6, errors still can be appreciable if the flow condition is far enough outside the range of calibration. This is a very important result that must be considered when using any vane-vorticity indicator. The vane can only be used to measure vorticity when it is operating within the range of calibration. Outside of this range, it can be used only to give indications of vorticity.

In addition to errors in the magnitude of vorticity, there is also a discrepancy in the vorticity profiles. As the cross-wire results show, the vorticity decreases steadily with increasing radius. However, the vane data show a slight increase as the radius increases at a large distance from the center. This is caused mainly by errors in measuring very small values of vorticity, as has been noted by other experimenters[1] as well. It is not known yet whether this error is due to the large size of the vane, some nonlinearity and hysteresis effects near the threshold of rotation (see Figs. 3 and 5), or some other undetermined cause.

Recent Improvements and Applications

As mentioned previously, in an effort to reduce the bearing friction and extend the useful range of the vane-vorticity indicator, jewel bearings were installed instead of the teflon bushings. An example of the resulting improvement in performance is given in Fig. 10. Here the vane indicator ratio η is plotted for vane 2 with teflon bushings and with jewel bearings. The value of η is increased for every value of N_v, and the average value of η is increased from 0.411 to 0.490, which indicates a significant reduction in the bearing friction. At low vane speeds, the nonlinear behavior of η with N_v is the same for either type of bearing, which means that this behavior is characteristic of the vane itself. This also can be demonstrated by contrasting the shape of the η vs N_v data for vane 2 in Fig. 10 with the data for vane 1 in Fig. 5. With the increase in the vane-indicator ratio η, the jewel bearings should extend the range of measurements in weak vortex flows, especially for the smaller vanes. However, care must be taken to keep errors to a minimum through proper calibration.

It has been demonstrated by all of these results that the vanes provide a good method for direct and rapid measurement of the streamwise vorticity in the flow when the data are interpreted using appropriate calibration conditions. An example that shows the useful range of the signal processing scheme described earlier is presented in Fig. 11. The autocorrelation functions show not only the uniformity of the vane rotation, as depicted by the many peaks when the range of τ is increased, but also that it is possible to obtain

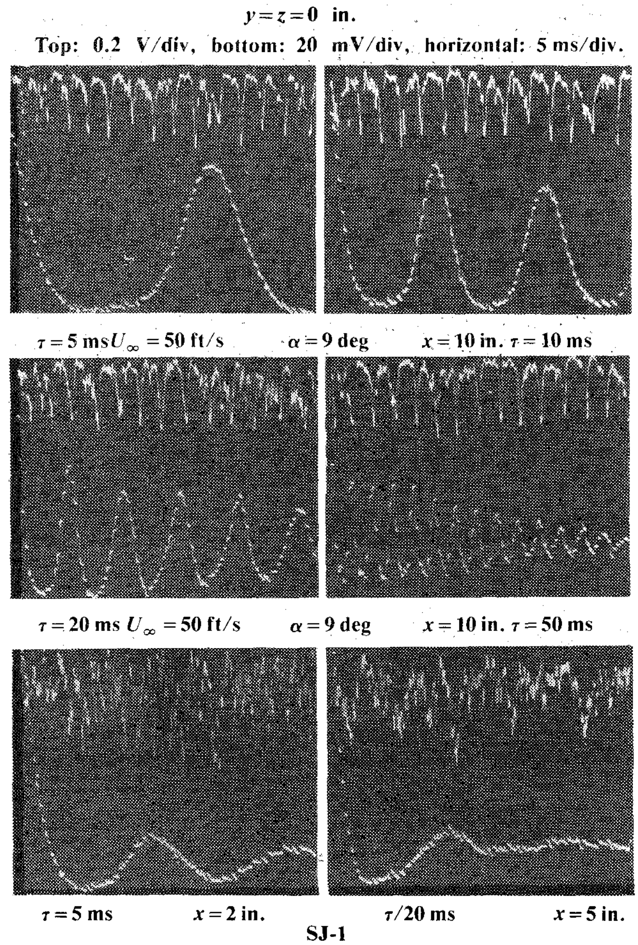

Fig. 11 Sample oscillograms of signal from vane vorticity indicator (top trace) and its autocorrelation function (bottom trace) using various correlation time constants and different flow conditions.

information even when the spikes from the blade wakes are not visible in the hot-wire output trace, as in the high-turbulence flow condition SJ-1. (For the detailed description of flow condition SJ-1, the reader is referred to Ahmed et al.[4,5])

This versatile means of measuring the streamwise vorticity was used extensively in experiments on the control of swirling and secondary flows in ducts and wind tunnels. The objective was to determine the effect of standard flow manipulators, such as screens and honeycombs, on different types of swirling flows. After documenting the rotational characteristics of each test flow condition using the vane-vorticity indicator, traverses downstream of any flow manipulator inserted in the test flow condition provided data for calculating the amount of swirl removed from the flow. The results not only demonstrated the relative effectiveness of the manipulators but also provided insight into some of the mechanisms involved in removing the swirl. In particular, the reader is referred to Figs. 6-8 and the section on "Results and Discussion" in Ref. 5. Detailed information on this subject can be found in Ahmed et al.[4,5] In all of these studies, extensive measurements were made possible due to the rapid evaluation of the streamwise vorticity by calibrated vane-vorticity indicators.

Conclusions

Miniature vane-vorticity indicators are very useful tools for the direct and rapid evaluation of streamwise vorticity. Utilizing advanced signal processing techniques, the vanes can be used in turbulent flows, even those with high turbulence intensities. For carefully constructed and balanced vanes, the calibration factor η relating the vane rotation to the local rotation of the fluid is only a slight function of the angular velocity of the fluid (except at low vane rotations), the freestream velocity, the physical dimensions of the vane, and the radial gradient of vorticity for the range of vane sizes and calibration conditions used here. However, the value of η does not increase monotonically with freestream velocity, as others have reported.[1,2] It appears to reach a maximum around the middle of the velocity range considered in these experiments. Also, the values of η are lower than those found in these references and have a nonlinear dependence on low fluid rotational speeds.

These vane characteristics emphasize the need for extensive calibration as presented in this paper. Any vane must be calibrated in flows that have known rotational characteristics determined by some other accurate means of measurement, such as cross-wire probes. The performance of the vane also must be checked frequently with some calibration conditions to insure the validity of the data. Further information on the calibration of the vanes and the methods used can be found in the report by Ahmed et al.[4]

In summary, when using proper calibration curves, the vanes accurately determine the streamwise vorticity in the flow. Without these calibration curves, or outside their applicable ranges, the vane can only be used to provide an indication of the vorticity, and the circulation inferred from the measurements may contain substantial errors.[1]

Acknowledgments

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