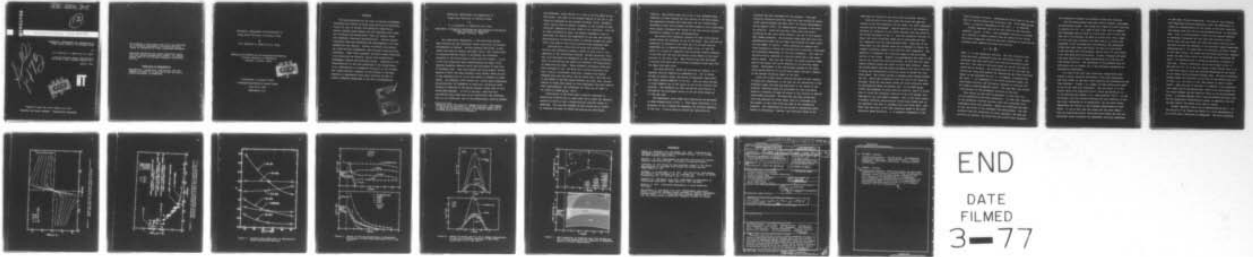


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GENERATION, MEASUREMENT AND SUPPRESSION OF  
LARGE SCALE VORTICITY IN INTERNAL FLOWS

by

R.A. Wigeland, M. Ahmed and H.M. Nagib

Interim Technical Report ARO-ITR-76-2  
IIT Fluids & Heat Transfer Report R76-5

August, 1976

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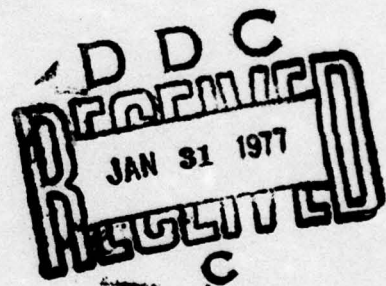
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Generation, Measurement and Suppression of  
Large Scale Vorticity in Internal Flows

by

R.A. Wigeland; M. Ahmed and H.M. Nagib

Mechanics and Mechanical and Aerospace Engineering  
Illinois Institute of Technology  
Chicago, Illinois 60616



"Turbulence in Internal Flows"

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## ABSTRACT

The main objectives are not only to develop recommended procedures for control of large scale swirling and secondary flows, but also to extract from empirical observations general concepts which design and test engineers could adapt for "tailoring and manipulating" their own special flows with different rotational characteristics. Several typical rotational flows were generated and superimposed on the flow through the test section. Careful calibration was carried out using hot-wire anemometers, and miniature vane-vorticity indicators. These flows represent the basic target conditions to be controlled by inserting various flow manipulators: honeycombs, screens and perforated plates. Comparison of the characteristics of the flow downstream of the manipulators (e.g., distribution of streamwise vorticity) to the original test flows provides a measure of the efficacy of the manipulators in suppressing large scale vorticity as well as clues to dominant mechanisms of the flow transformations.

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Generation, Measurement and Suppression of  
Large Scale Vorticity in Internal Flows\*

by

R. A. Wigeland, M. Ahmed and H.M. Nagib

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Illinois Institute of Technology  
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For wind-tunnel experiments, a flow which has uniform mean velocity and low turbulence levels along with low acoustic disturbances is desired. Various research activities, a more recent one being by Loehrke and Nagib (1972), have concentrated on attaining desired levels of uniformity and turbulence intensity in the free-stream of ducts and wind tunnels. In one of the flow conditions they studied, Loehrke and Nagib (1972) reported anomalous behavior which they attributed to some kind of secondary flow. Most wind tunnels and ducts exhibit various degrees of swirl and some secondary flows whether these are due to the propulsive fan or to the duct bends in presence of shear layers. As Carbonaro (1973) points out, curing these undesirable characteristics "is frequently an empirical cut-and-try study relying on ingenuity of the design engineer rather than on well established methods". At IIT in the past, such flow non-uniformities were taken care of by "overkilling" the condition, that is, by inefficient use of flow manipulators, such as screens

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\*Supported under ARO Grant No. DAHCO4-74-G-0160. The details of the study are available in an ARO Technical Report which is based on the Master's thesis of the second author and is included here as the first reference.

and honeycombs, which results in a loss in the top speed of the wind tunnel and often in the gradual heating of the air in the tunnel, as discussed by Tan-atichat and Nagib (1974). Carbonaro (1973) reports that no general treatment of the problem of such rotational components has been found in the literature. With all of these statements in mind, the present systematic study on techniques for control and suppression of the mean and unsteady characteristics of swirling flows in confined streams was undertaken, with some of the initial results being presented here.

Starting with a flow facility which has uniform mean velocity and turbulence intensity levels of from 0.6% to 1.0% depending on the free-stream velocity, various rotational flows had to be developed and documented so that controlled conditions exist for determining the effect of different flow manipulators on these swirling flows. Three different rotational flows have been developed so far, one which has a strong rotational core with a nearly irrotational outer part, another with angular momentum only near the walls, and the third with a swirling jet in the center of the duct which entrains the outer flow. Devices similar to those constructed for this experiment have been used by other experimenters, and references for these can be found in the report by Ahmed et al. (1976).

Construction of the first swirl condition consisted of placing two airfoils next to each other and at equal but opposite angles of attack so that a strong wing-tip trailing vortex is generated. The size and strength of this vortex can be varied by changing the angle of attack and varying the free-stream

velocity. The airfoils span one of the 6 inch diameter ducts identical to those forming the test section of the wind tunnel. The separation distance and hinge point for the airfoils were optimized to give the strongest and most symmetric swirl conditions, which persist throughout the length of the test section without substantial changes in their characteristics.

The second swirl generator consists of eight slots equally spaced around the periphery of one of the ducts. The slots are as tangential as possible to the inner wall of the test section. Compressed air is supplied through these slots, so that the result is a series of tangential jets providing angular momentum to the flow near the wall and having little effect on the inner portions of the axial flow. This facility has been developed to provide jets which are as uniform as possible along each slot and among the eight slots.

The third facility, called the swirling jet ejector, is a separate facility supplied by compressed air. Air is forced through an annular region containing 18 adjustable vanes which can impart angular momentum to the air. This air exits through a 1-inch diameter jet in the center of one of the circular test sections. The remaining air flow through the test section is provided by the entrainment action of the jet which draws air in from the room.

The experiments using these swirl generators are performed as shown schematically in Fig. 1. With these facilities, it is necessary to have a method for measuring the swirling component of the flow. A device which is called the vane-vorticity

indicator has been developed for this purpose. Vane-type vorticity indicators have been used with some success by Barlow (1972) and by Holdeman and Foss (1975) for making measurements, and by Shapiro (1974), for demonstration purposes in his movie on vorticity. Since the vane has a more rapid and direct evaluation of the local fluid rotation, its use in this experiment seemed promising. The miniature vanes used here have four perpendicular blades and are made from aluminum for light weight and low moment of inertia. Teflon bushings and washers were found necessary to reduce the friction and to provide a consistent and repeatable measurement of the swirl component. This vane is mounted directly upstream of a hot-wire which has a very short sensor length. When the vane rotates, the wakes from the blades pass by the sensor and can be detected in the hot-wire output signal. Measurement of the time between passage of the wakes using autocorrelation of the hot-wire signal provides a measure of the average rotational speed of the vane.

Since the airfoil swirl facility provided the most variety of clean flow conditions, it was used for the calibration of the different vanes. The vane was positioned in the center of the airfoils' trailing vortex and calibrated for vane rotational speed as a function of angle of attack of the airfoils at several free-stream velocities. We found that the same calibration curve was obtained for three vanes, each of a different size and weight, so that this curve was used as the calibration standard. The independence of the curves on geometrical parameters is encouraging. However, the rotational speed of the

vanes must be related to the local fluid rotational velocity.

With the aid of an x-wire probe and using the same conditions as for the calibration of the vanes, the local tangential velocity can be determined. Typical profiles of the tangential velocity as a function of the radial distance from the center of the vortex are shown in Fig. 2. Once the tangential velocity is known, the local rotational speed can be calculated and used for comparison with the vane-indicator data. Using any of the vanes there are two methods which can be employed to obtain the "proper" rotational speed of the fluid for this comparison. One method is to determine the rotational speed of the solid body portion of the vortex. However, by superimposing the width of the vane on the tangential velocity profiles, we find that the vanes extend slightly beyond the region of solid body rotation. Hence, the second method uses the speed indicated at the tip of the vane as being the characteristic velocity, which is called the vane-width speed. The correct method is probably some average between the two. Taking the calibration curve for one of the vanes and plotting twice the vane speed versus the fluid rotational speed as calculated by these two methods (Fig. 133 of Ahmed et al. (1976)), the agreement is quite good for airfoils' angle of attack over  $5^\circ$ , since the rotational friction of the vane becomes less important as the vane speed increases. Even in the lower region, a slightly different multiplication factor would render most of the remaining vane data in agreement with the x-wire data. This shows that the ratio of the vane rotational speed to the fluid rotational speed, denoted by  $\eta$ , is somewhat independent of the

fluid rotational velocity. Comparing the x-wire data to the vane data for various free-stream velocities (Fig. 134 of Ahmed et al. (1976)), a similar independence of the ratio  $\eta$  is observed.

Another important test is for the effect of the vorticity gradient,  $\partial\Omega_x/\partial r$ . In Fig. 3 the streamwise vorticity is plotted as a function of radial distance from the center of the vortex. The x-wire tangential velocity data were converted to vorticity by assuming axial symmetry and using the relation

$$\Omega_x = \frac{W}{r} + \frac{\partial W}{\partial r},$$

where  $W$  is the tangential velocity. The vane vorticity indicator data were interpreted using the calibration curves. The corrected vane data agree quite well with the calculated x-wire data until the level of vorticity drops too low for the vane to rotate due to friction. The interpretation of the vane data was carried out using both methods for determining the fluid rotational speed, as was discussed for Fig. 2. In summary, it appears that the ratio  $\eta$  is independent of the fluid rotational speed, the free-stream velocity, and the spatial gradient of vorticity for the range of these parameters tested. The vane does then provide a good picture of the streamwise vorticity of the flow.

This device is then used to determine the test flow conditions generated by the swirl generators. In each case, changing of the parameters involved was done until flow conditions with reasonable swirls were obtained. These flow conditions are used to test the effect of the different flow manipulators. One flow condition from the tangential jet swirl generator, one from the swirling jet ejector, and seven from the airfoil swirl generator

with different strengths and different sizes were utilized.

The flow manipulators used were various screens, honeycombs, and perforated plates. The screen has a mesh of 0.0357 inch with a solidity of 0.35, i.e., made of wire 0.007 inch in diameter. The honeycombs were #3 which is 1-inch long, with a 0.257 inch mesh and 0.014 solidity; #2 which is 2-inch long, with a mesh of 0.135 inch and a solidity of 0.008; and #1, a 2-inch long honeycomb, 0.068 inch mesh and 0.03 solidity. The perforated plates were both 0.063 inch thick, #2 with 0.14 inch holes, 0.188 inch mesh and 0.49 solidity, and #3 with 0.25 inch holes, 0.313 inch mesh and 0.42 solidity. Figure 4 displays the pressure drop coefficient of these manipulators as a function of free-stream velocity. The importance of the pressure drop coefficients will be brought out in the following discussion on manipulator performance.

For each of the test flow conditions, manipulators were placed a certain distance downstream of the swirl generators, and their effect on the swirl flow condition was determined by the vane indicator. Figure 5 is a sample of some typical data taken in two of the test flow conditions. The top figure is in the airfoil swirl flow condition "V-2-1", while the bottom one is in the swirling jet ejector, i.e., flow condition "SJ-1". In the top figure, the vane rotation defining the flow condition is the top curve, designated as no manipulator, and the other curves demonstrate the effects of the different manipulators as indicated. It can be seen that the screen has the least effect, then the perforated plates, which have more effect and then the honeycomb, which eliminates the measurable vorticity completely

at some small distance downstream. The drop in vane rotation with downstream distance immediately after the manipulator is viewed as a homogenization of the pieces of the swirl condition that emerge from each cell of the perforated plate or the honeycomb. Only in the manipulator itself can the angular momentum be absorbed; afterwards the flow from each cell must rejoin. Notice that even the screen can take some torque from the flow, and does not show the decrease in the rotational speed immediately downstream due to its small mesh, low solidity, and short length. In the lower figure, the screen and perforated plate have approximately the same effect while the honeycomb again eliminates the swirl. We conjecture that a different mechanism is working in this case. Further elaboration can be given based on Fig. 6. The peak for P.P. #3 in the top figure is much flatter than it is in the lower figure, while the profiles downstream of the screen do not exhibit much difference between them. The major difference between these two conditions is the size of the swirling part of flow; i.e., the swirl in the lower figure is about 3 times larger. When the size of the swirl is compared to the characteristic mesh size of the manipulator, there is not much change for the screen between the two cases but there is for the perforated plate. It becomes apparent that a scaling between the swirl size and the manipulator characteristic length is important, and for the best effect, the proper ratio must be chosen.

Another important result can be demonstrated by Fig. 7. In the top part of the figure the effect of a given manipulator on all of the swirl conditions is summarized. The swirl reduction

ratio presented here is one minus the ratio of vane rotational speed in the flow downstream of the manipulator to that in the flow at the same position when there is no manipulator present. As outlined in the figure, a range is defined which bounds the reduction in swirl of the conditions employed. Using the dashed marks to indicate this range, and taking similar results from the other manipulators, a composite map of the effect of the different manipulators can be drawn, as is shown in the lower part of the figure. An important thing to notice in this composite plot is that the same reduction in swirl can be achieved using any one of several manipulators, as indicated by the overlapping regions. This makes it possible for the design engineer to select a certain manipulator with a known level of performance which may have other desirable characteristics for his case, where another manipulator with the same swirl reduction ratio may not have them. Another, probably more important result is that the selection can be optimized with respect to the total pressure drop, an important parameter in wind tunnel design. In particular, note that honeycomb #3, which eliminates the swirl completely, also has the lowest pressure drop coefficient, as presented in Fig. 4. Given a certain swirl condition, it should be possible to choose the best manipulator for the job based on the other factors involved. It is perhaps better to work on the swirl reduction first when modifying a given flow, and then to operate on the turbulence, rather than the other way around. It may also be possible to achieve better results with combinations of manipulators as far as both of these items are concerned.

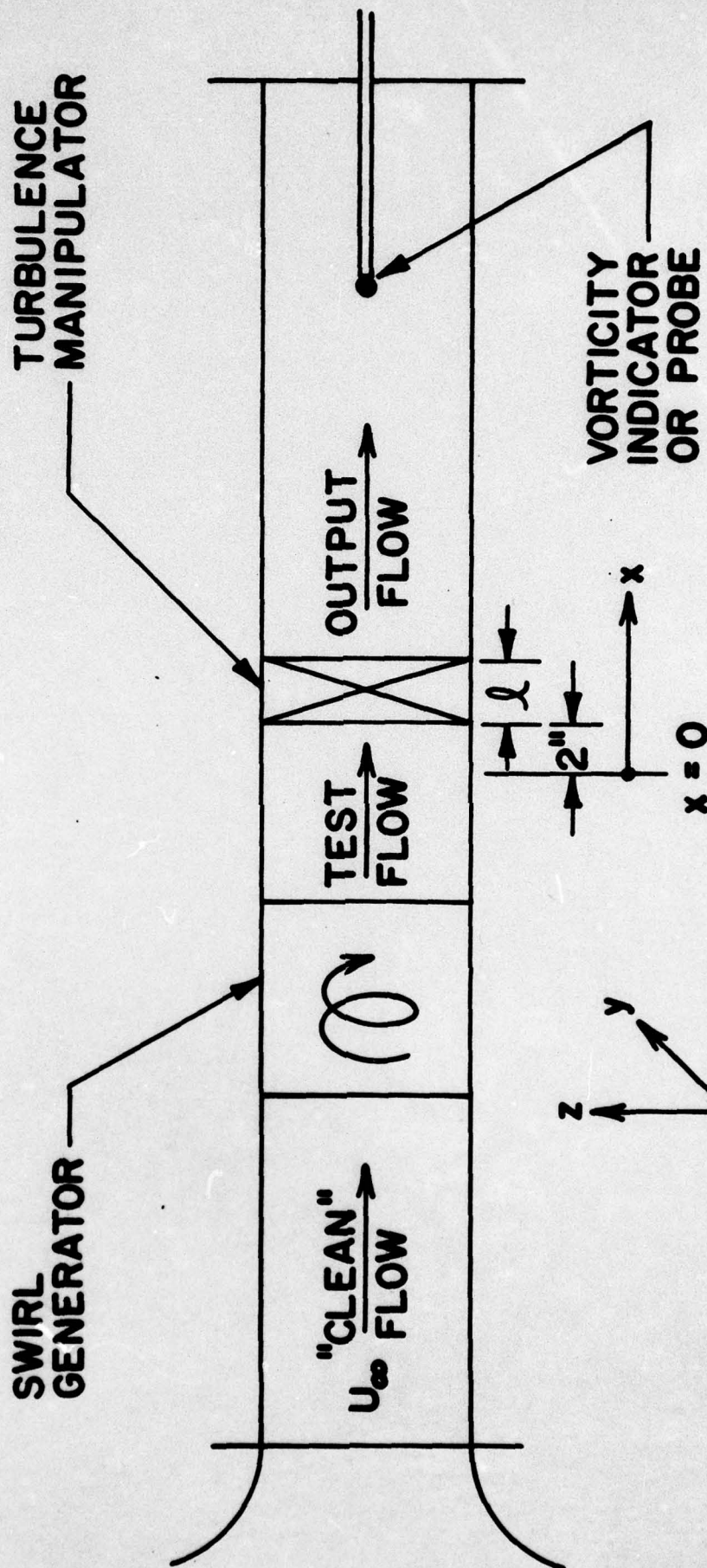


Figure 1. Schematic of Test Section Arrangement.

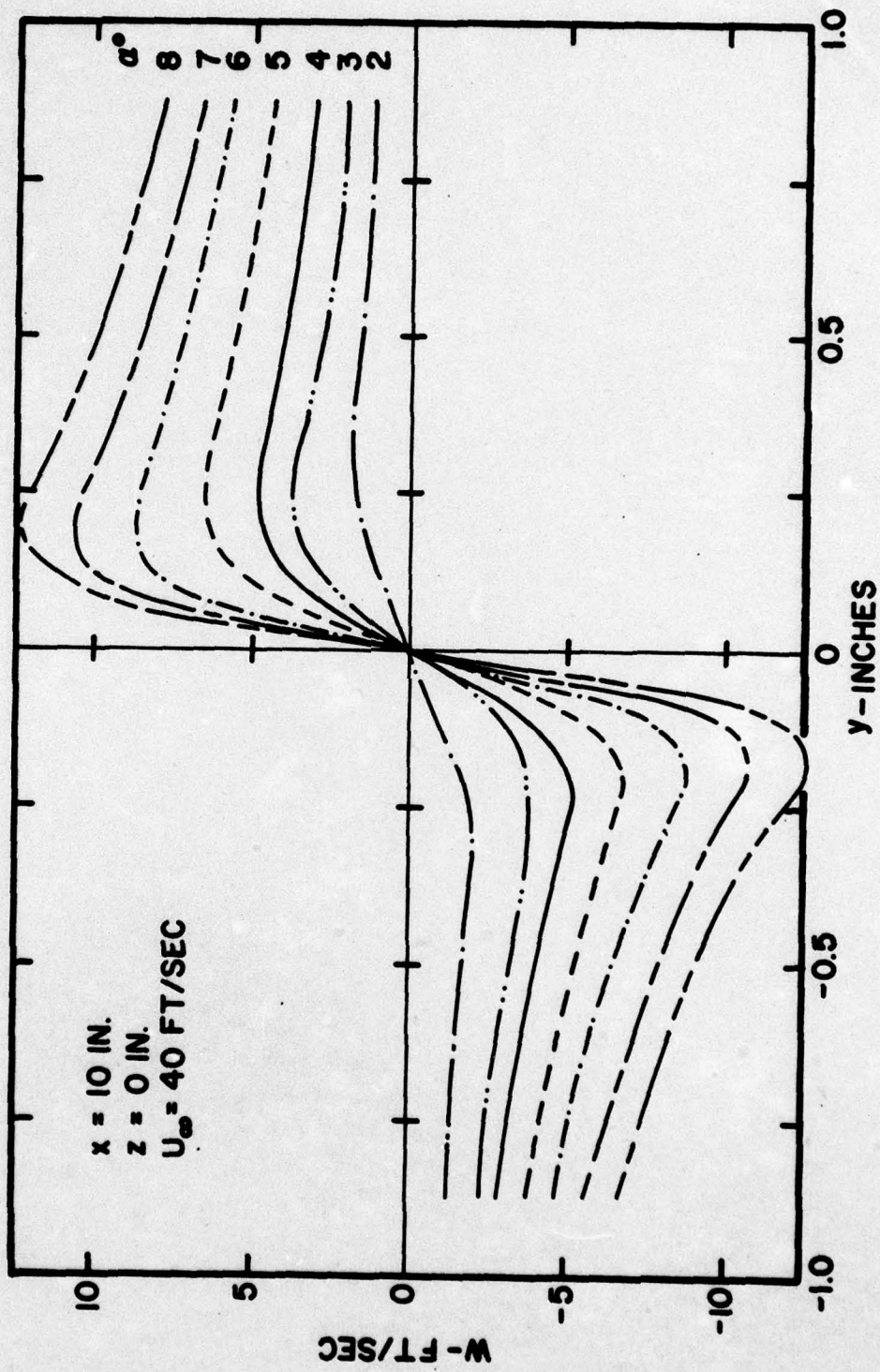


Figure 2. Tangential Velocity Profiles Across Vortex of Airfoil Swirl Generator for Various Angles of Attack.

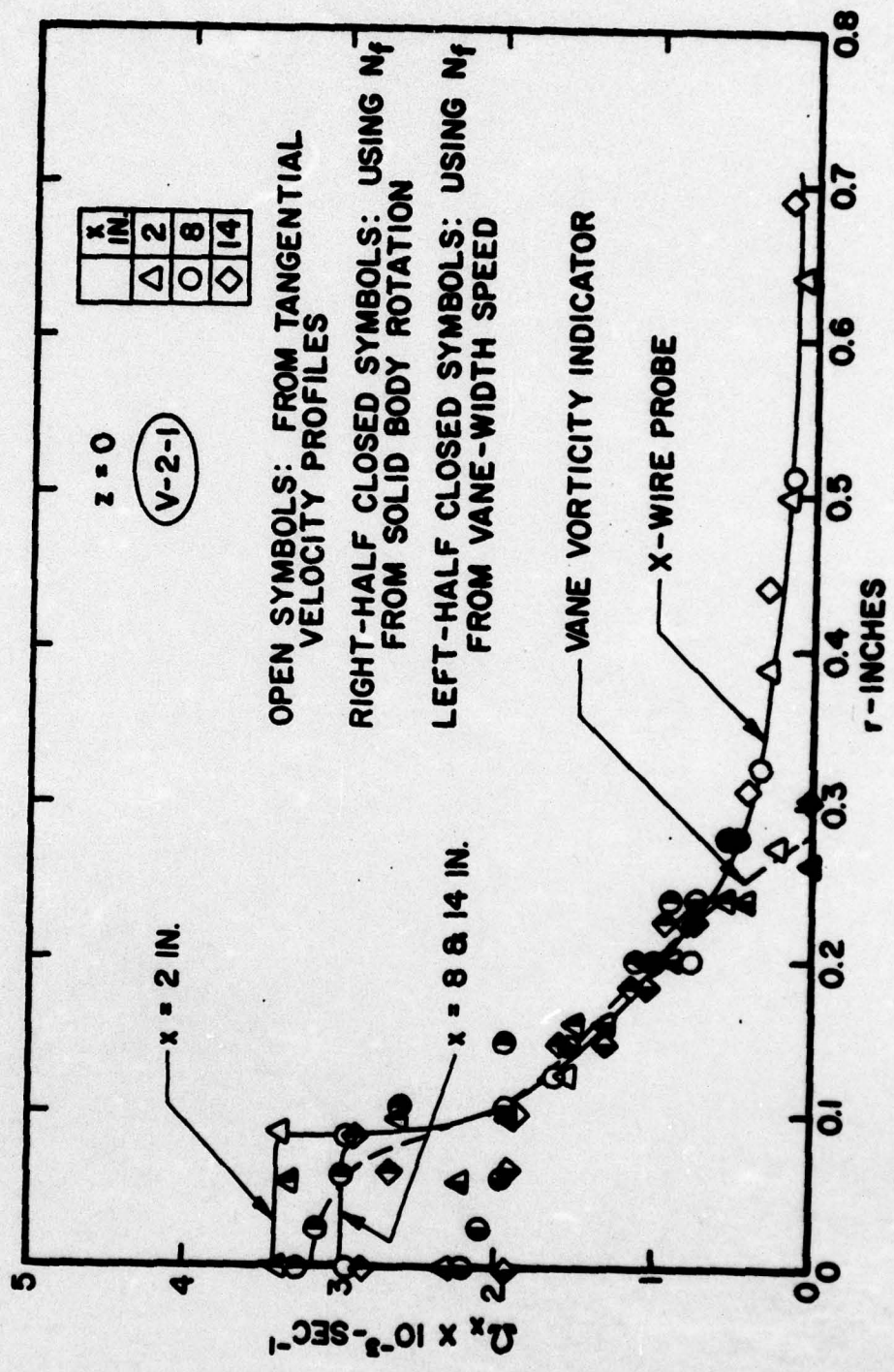


Figure 3. Comparison of Radial Distribution of Local Streamwise Vorticity Obtained From X-Wire and Vane-Vorticity Indicator Measurements in Test Flow Condition "V-2-1".

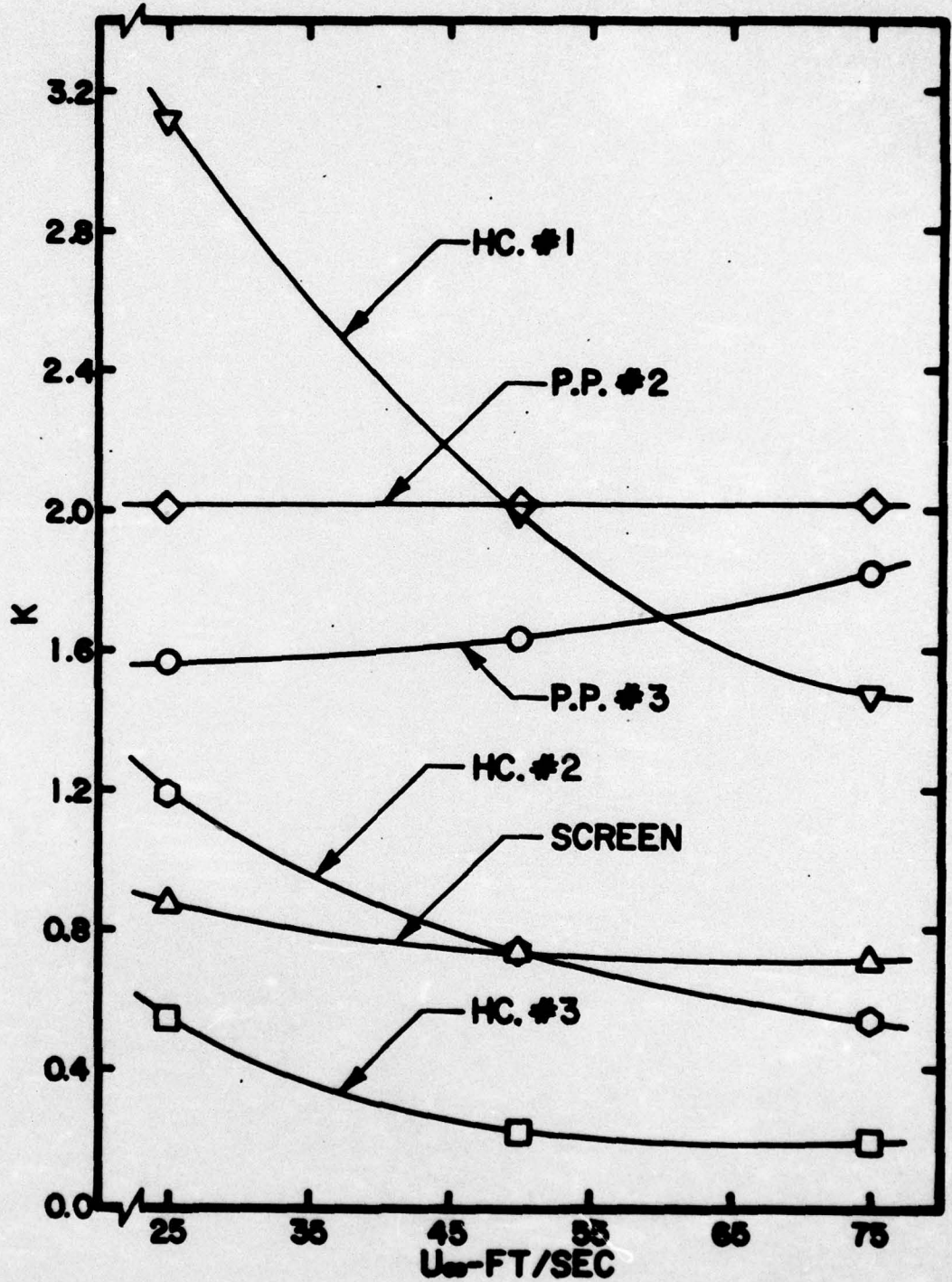


Figure 4. Pressure Drop Coefficient of Manipulators Versus Free-Stream Velocity.

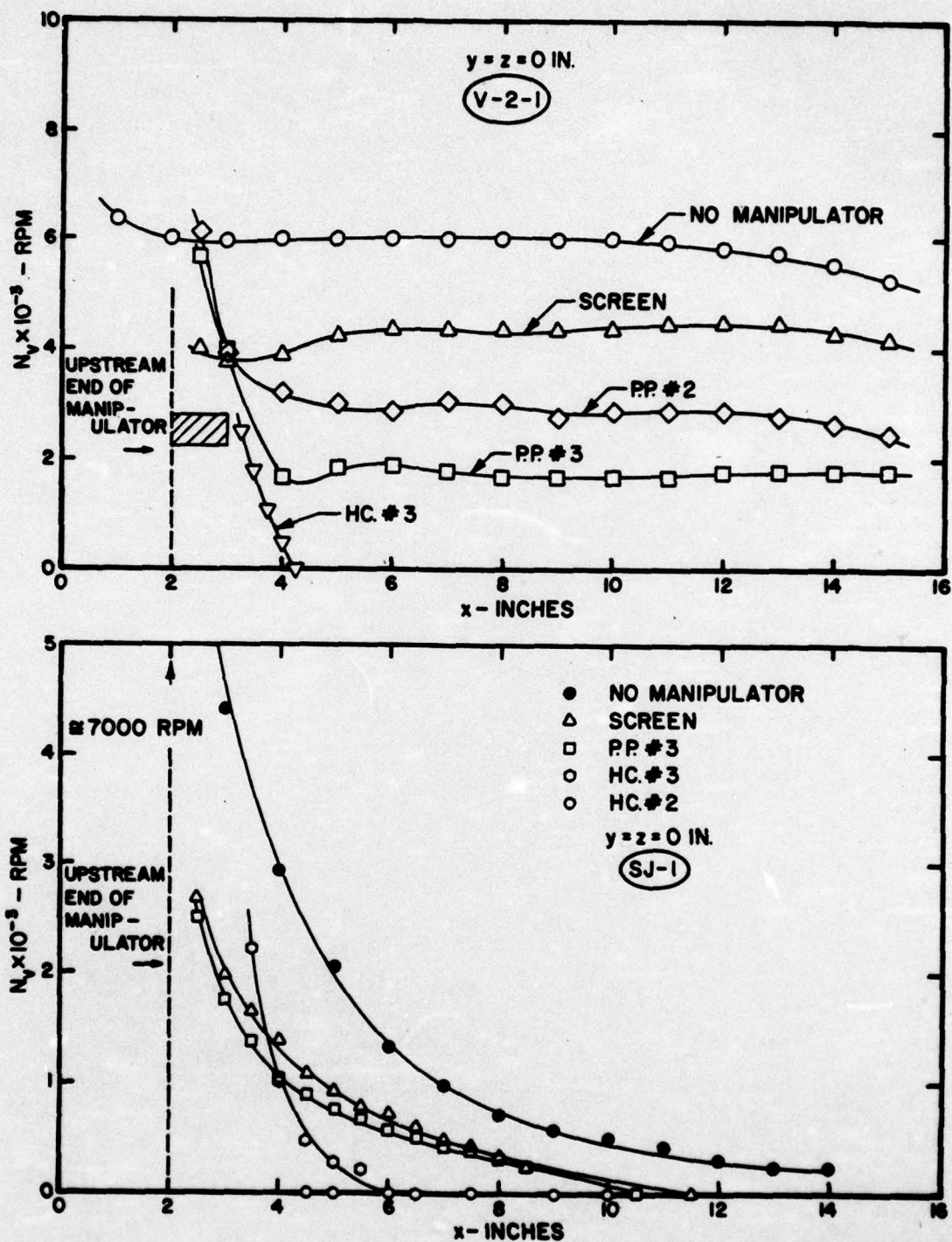


Figure 5. Effect of Various Manipulators on Downstream Development of Test Flow Conditions "V-2-1" and "SJ-1".

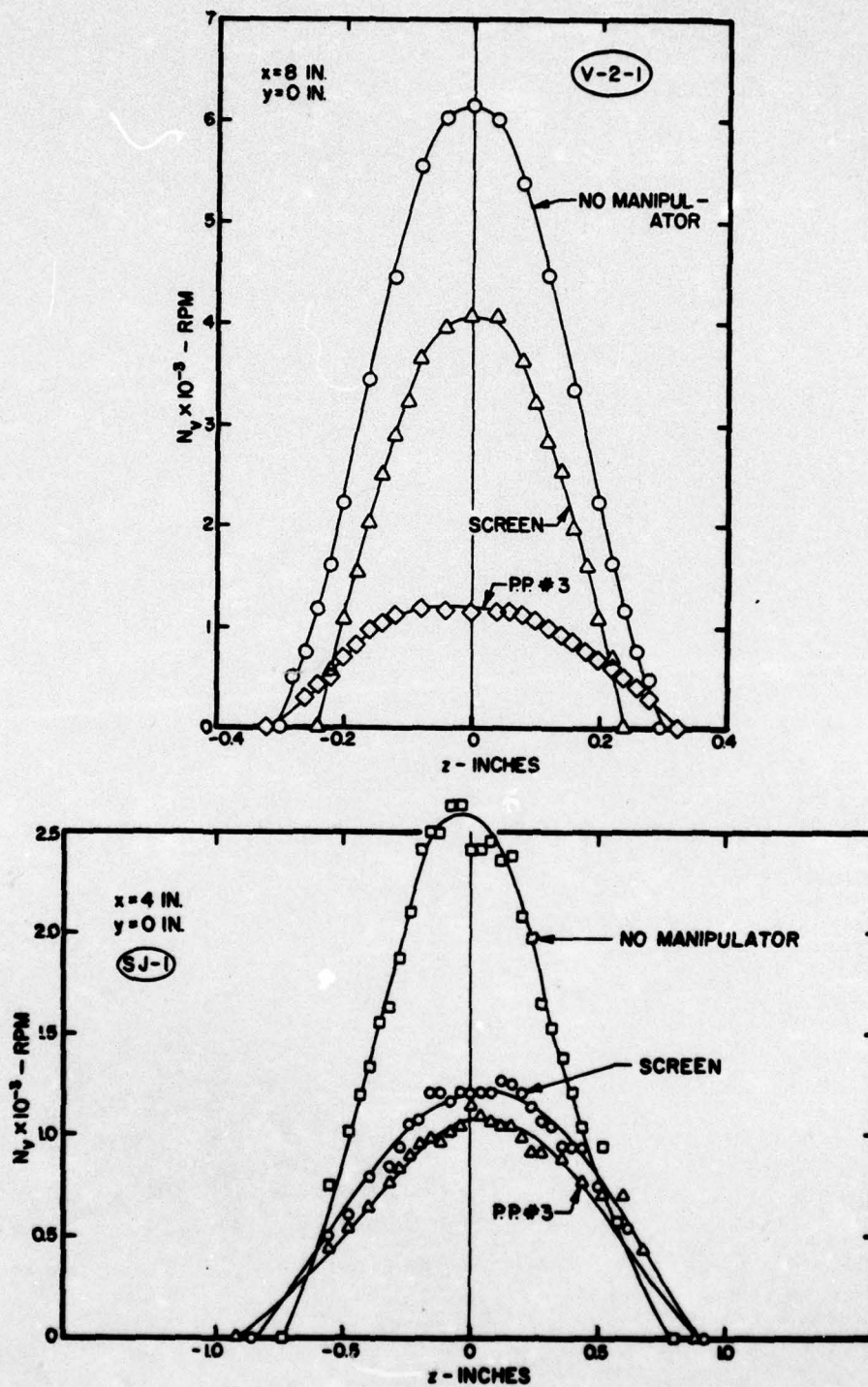


Figure 6. Effect of Screen and P.P. #3 on Radial Distribution of Vorticity Indicator Rotation in Test Flow Conditions "V-2-1" and "SJ-1".

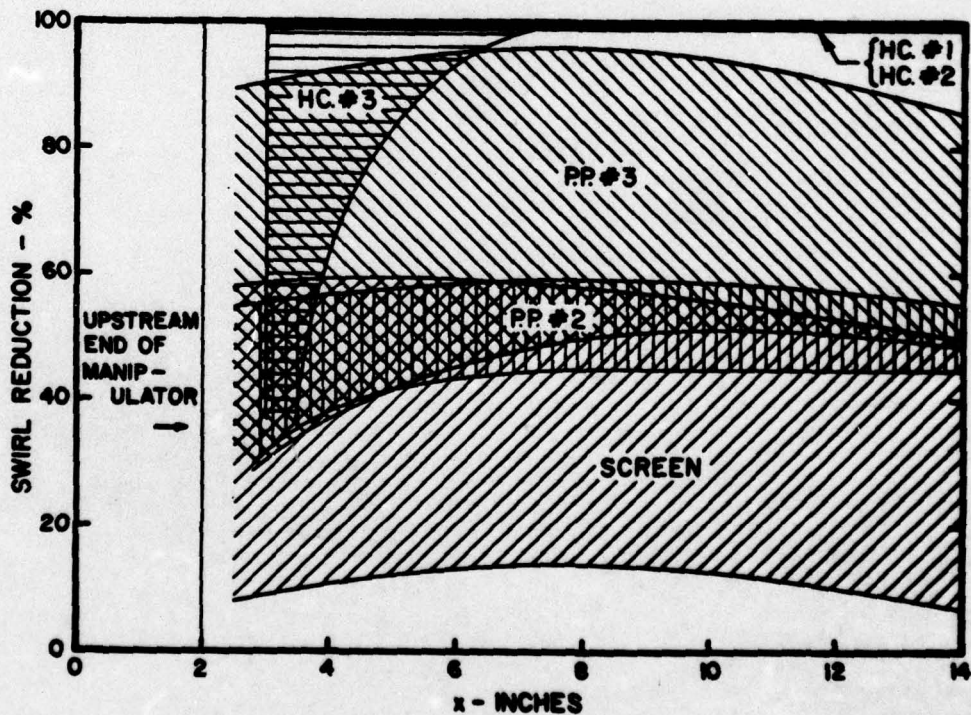
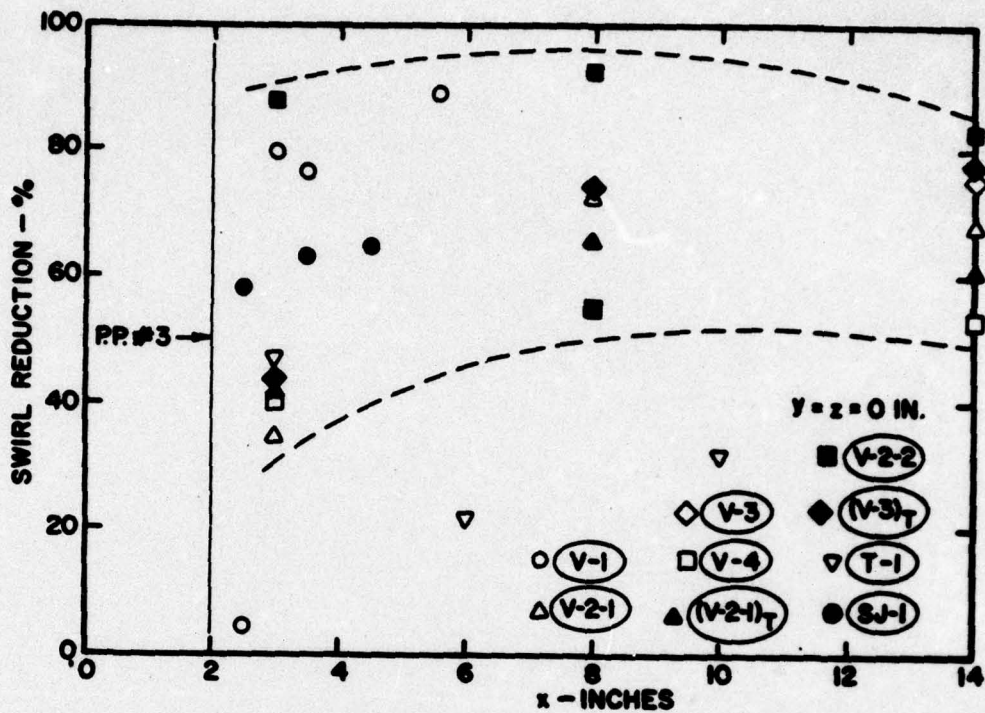


Figure 7. Swirl Reduction in Different Test Flow Conditions for One Flow Manipulator and Composite of Reduction Range for Several Manipulators.

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20. ABSTRACT - continued

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