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Double-Branched Vortex Generator

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NOMENCLATURE

P	static pressure
q	dynamic pressure
R	vortex radius
U, V, W	mean velocity components in Cartesian system
X, Y, Z	Cartesian coordinates for streamwise, normal, and spanwise directions.
Γ	circulation
ρ	density
ω	streamwise vorticity
$(\ )_{max}$	maximum value over the cross section

SUMMARY

In order to assess the suitability of using a double-branched vortex generator in parametric studies involving vortex interactions, an experimental study of the main vortex and secondary flows produced by a double-branched vortex generator has been conducted in a 20-by-40 cm indraft wind tunnel. Measurements of the cross-flow velocities were made with a five-hole pressure probe from which vorticity contours and vortex parameters were derived. The results showed that the optimum configuration consisted of chord extensions with the absence of a centerbody.

INTRODUCTION

Flows dominated by discrete vortices occur in a variety of situations which are of interest in aerodynamics. A classic example is the trailing wingtip vortex system behind a landing aircraft, leading to stability problems for a following aircraft. Smaller scale vortex interactions are an increasingly important consideration in the design of highly maneuverable aircraft, which use a canard or strake vortex that is designed to interact with the wing flow to sustain the necessary lift. In rotorcraft applications, the interaction of a rotor blade with the tip vortex shed by the preceeding blade is an important, yet poorly understood, aerodynamic and acoustic problem.

Experimental studies of vortex interactions, particularly those detailed enough to guide the development of calculations, illustrate the complexity of these flows. Recent flow visualization studies[1,2] of vortex/boundary layer and vortex/mixing layer interactions show that strong secondary motions can be induced by relatively weak vortices. Other investigations, designed to study longitudinal vortices embedded within turbulent boundary layers,[3,4] show that both the turbulence structure and the vortex characteristics are drastically altered by the interaction.

It has been traditional to use vortices generated by half-delta wings for experimental purposes, mainly because such generators are relatively easy to fabricate and install. Furthermore, these generators have been shown[4] to produce a vortex with minimal (undesirable) secondary flows. However, this generator produces a relatively weak vortex, and it is not possible to independently vary the vortex location and strength . For example, altering the semispan of a half-delta wing would move the vortex center and change the overall circulation. On the other hand, increasing the angle of attack not only increases the circulation, but also exacerbates the undesirable wing wake. These features make detailed parametric studies in areas such as vortex/boundary layer interactions difficult to design. In order to do more complete parametric studies of vortex interactions, a vortex generator is needed which is capable of producing a strong vortex that can be easily repositioned without altering its size and strength.

The objective of the present work was to study the performance of a double-branched vortex generator of the general type used by several previous investigators.[5–9] Our purpose was to assess the usefulness of this vortex generator for studies on vortex interactions. Although the previous investigations have indicated that strong vortices may be obtained, they have not provided information concerning possible undesirable secondary flows, and questions remain concerning the optimal design of the generator configuration. The basic configuration studied consisted of two adjacent, identical airfoils set at equal but opposite angles of attack. Cross-flow velocity fields, vorticity contours, and vortex parameters are reported here for five variations of the basic configuration. The authors would like to acknowledge the contributions of Charles Hooper in software development. RDM was supported by NASA Grant #NCC-2-294.

EXPERIMENTAL APPARATUS AND PROCEDURES

The experiments were carried out in the Unsteady Boundary Layer Wind Tunnel of the Fluid Dynamics Research Branch[10] at NASA Ames Research Center (see fig. 1), which has a test cross-section of 20-by-40 cm. The facility is of the suction type, with a vacuum compressor used to maintain a low pressure in the plenum downstream of the test section. A choked nozzle is used to accurately maintain a uniform free-stream flow. A unique feature of the facility is the use of a wedge in the sonic throat which can be moved using a motorized scotch yoke to produce a variable flow in the test section. The current experiments were run in the steady- flow configuration (wedge fixed) with a test speed of 13.5 m/sec and inlet free-stream turbulence of about 0.2%. A nominally constant streamwise pressure was achieved by diverging the tunnel walls in the flow direction. Probe access was provided through a sliding wall segment on the tunnel roof approximately 1.9 m downstream of the contraction exit.

The vortex under study was generated by a double-branched vortex generator, consisting nominally of two NACA 0012 wing sections of 15-cm chord and 33-cm span set at opposite angles of attack of $\pm 12\ ^\circ$ (see fig. 2a). The generator spanned the middle two-thirds of the wind tunnel settling chamber, and was mounted on the centerline of the settling chamber in a straight section located between the last screen and the contraction as shown in figure 2b. This produced two inboard trailing vortices of the same sign which rolled up together to form a single line vortex. Except for the near-field region close to the trailing edges of the wings, this flow can be approximated by a single rectilinear vortex with its axis parallel to the free stream.[8]

The configuration of the vortex generator was modified to include some or all of the following: a cylindrical centerbody between the wing sections, endplates at each wing-tip, and chord extensions at the trailing edges of the wings. Figure 2a shows the generator with all modifications installed. In all, five generator configurations were investigated (see table 1 for a description). Additionally, the undisturbed tunnel flow (without a vortex generator) was also documented.

A symmetric, cylindrical-tip (4-mm-diam) five-hole pressure probe was used to measure the cross-stream mean velocity components V and W. The five pressure taps, and a sixth total-pressure tapping , were scanned using a solenoid-actuated pressure scanning switch. The scanned pressure was connected to one port of a differential pressure transducer. The other transducer port was connected to a wall static-pressure tap located at the measurement station (X = 1.9 m). Calibration of the probe for pitch and yaw velocity components was done using an approximation of the method outlined by Treaster and Yocum,[11] simplified for the current case of small flow angle variation.

A dedicated laboratory computer (PDP 11/44) and software system was used to automatically control probe movement, pressure scanning, implementation of the calibration relations, and for on-line display of the cross-flow velocity vectors. The data acquisition system software is described in references 12 and 13. Vortex characterization and subsequent data analysis were performed after transferring the data to a larger computer system.

RESULTS

A regular grid of data was acquired for each case at the selected measurement station (X=1.9 m). Typically, a coarse-resolution set of data was initially acquired, using spanwise spacing of 1.5 cm and vertical spacing of 1 cm between measurement locations and extending over the central portion of the test section ($2 \leq Y \leq 16$ cm, $-18 \leq Z \leq 18$ cm). Additional data with finer resolution was then acquired in the central 5-cm-square region to improve definition of the main vortex core flow pattern (see figure 3). The total pressure was constant at all points on the measurement grid, obviating the need for any corrections to the probe data due to velocity gradient and finite probe size.

Streamwise vorticity was computed from the V and W measurements by first interpolating the measured data using cubic splines with natural end conditions, and then analytically evaluating the spline gradients (ref. 4). Integration of the computed vorticity field was performed to obtain the circulation. To provide some noise immunity in integrating the vorticity field, values of vorticity less than 10% of the maximum were neglected. Data within the central 10-by-10 cm region only was analyzed to obtain these parameters.

Undisturbed Flow

The flow in the tunnel without the vortex generator was documented at the test speed of 13.5 m/sec. Cross-flow velocity vectors for this case are shown in figure 4. These results indicate that the flow in the tunnel without the vortex is of good quality; peak flow angles (measured with respect to the flow angle at the tunnel center) were everywhere less than 0.5 °, and the total pressure in the core flow was uniform to within 1%. Thus, in the results that follow, all indications of flow angularity are attributable to the vortex generators themselves, and are not manifestations of poor tunnel flow quality.

Flow due to Double-Branch Vortex Generators

Case A.- Figures 5a and 5b show velocity vectors and vorticity contours for Case A, which had a cylindrical centerbody added between the two wing sections. As might be expected, the two wingtip vortices are evident in addition to the main trailing vortex. The peak vorticity (normalized by the free-stream velocity) due to the primary vortex in this case, is about 0.044/cm. However, the outboard (secondary) vortices for this case were actually slightly stronger. Clearly, this case did not give good performance, in view of our desire for a strong vortex with relatively minimal secondary effects.

Case B.- Figures 6a and 6b show velocity vectors and vorticity contours for Case B, which employed the centerbody and wingtip endplates. The endplates reduced unloading from the wingtips such as observed in Case A, and produced a stronger primary vortex, as evidenced by a peak vorticity value of 0.061/cm. In both cases, the secondary flows do not seem to affect the shape or position of the primary vortex; the contours are still quite circular and the primary vortex maintains its position in the center of the tunnel.

Case C.- Figures 7a and 7b shows the data for Case C, which consisted of just the wingtip endplate modification. The centerbody was removed, and the wings were pushed against each other. The results show a primary vortex with a peak vorticity of 0.079/cm. The circulation in this case is slightly higher than in Case B. It appears that the centerbody had the effect of moving the virtual origin of the merged trailing vortex pair upstream, without greatly affecting the circulation of the resultant vortex.

Case D.- For cases D and E, chord extensions were added to the trailing edges of the wings; case E employed endplates but no centerbody. The purpose of the chord extensions was to vary the circulation along the span of the wings such that near the inner edges there was a sharp, nonlinear transition to the region of zero circulation at the axis. This steeper gradient in the circulation caused a region of higher vorticity, and a more tightly rolled-up vortex. Figures 8a and 8b show the results, indicating a much higher peak vorticity (0.131/cm) than in any of the other cases, with a circulation of 1.054 cm. Note, however, that the secondary flows are essentially unchanged from Case C, which had no chord extensions. Thus, the chord extensions had the desirable effect of producing a stronger vortex without affecting the secondary flows.

Case E.- To verify the earlier observation regarding the general effect of a centerbody to increase the vortex core diameter, a centerbody was added to the configuration of Case D to produce the Case E configuration. Results are shown in figures 9a and 9b; as before, the peak vorticity was reduced by adding the centerbody, but the overall circulation was not drastically changed. The results lend further support to the contention that the main effect of the centerbody was merely to move the virtual origin for the primary vortex upstream.

DISCUSSION

The double-branched vortex generator produced a strong, round primary vortex. Table 2 summarizes the scalar properties of the primary vortex for each of the five cases. Endplates were necessary to prevent excessively strong secondary vortices from being shed from the outboard wingtips. The addition of chord extensions near the center of the generator had the desirable effect of increasing the strength of the (primary) double-branched vortex, with no effect on the secondary vortices. Adding a centerbody decreased the observed peak vorticity while nearly maintaining the vortex circulation; this can be viewed as a change in virtual origin of the vortex. The optimal configuration studied was that of

Case D, which incorporated the wing extensions with endplates fitted to the wingtips.

The ideal configuration for many applications might have the wing sections extended all the way to the tunnel settling chamber walls, thus minimizing secondary flows as much as possible. Secondary flows could be further minimized by the use of larger end plates, or by twisting the airfoils so that the angle of attack is small near the outer ends. Our results clearly indicate that the use of chord extensions will generally provide the minimum secondary flow for a given desired circulation of the primary vortex.

The circulation of the primary vortex in the present investigation was approximately twice that obtained with half-delta wings used in previous studies.[1,3,4] Note that the circulation can be further increased by installing longer chord extensions or by using wing sections which produce a higher lift coefficient at relatively low Reynolds numbers.

CONCLUDING REMARKS

The double-branched vortex generator has been shown to produce a round primary vortex with higher circulation than typical delta wing vortex generators we have used in the past, while also providing flexibility in positioning of the primary vortex. Noticeable secondary flows were observed, and several means for controlling the relative strength of these undesired motions have been suggested. The double-branched vortex generator should prove useful for parametric studies involving independent variations in vortex position and strength.

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TABLE 1. Generator Configurations

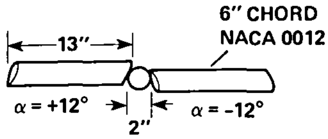
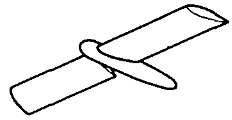
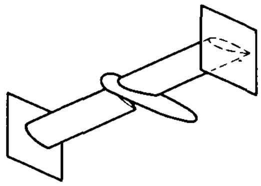
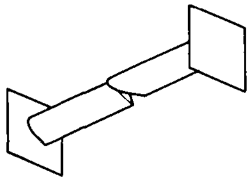
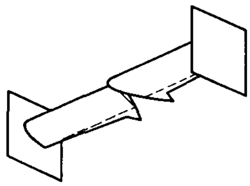
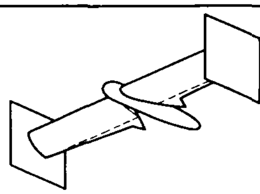
CASE	
A	 
B	
C	
D	
E	

TABLE 2. Scalar Properties of the Primary Vortex

case	maximum vorticity ω_{max}/U_o (cm^{-1})	circulation Γ/U_o (cm)
A centerbody only	0.044	0.711
B centerbody & endplates	0.061	0.727
C endplates only	0.079	0.779
D endplates & chord extensions	0.131	1.054
E centerbody, endplates & chord extensions	0.067	1.020

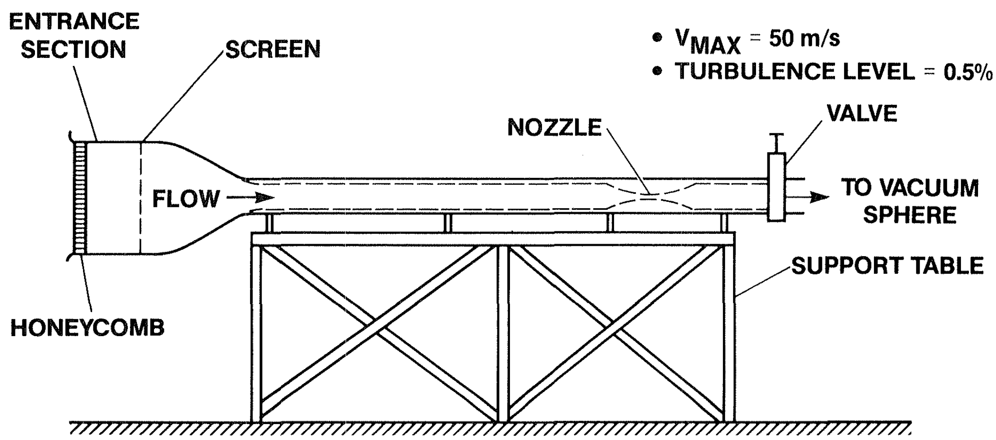


FIGURE 1. Schematic of the NASA-Ames Unsteady Boundary Layer Tunnel

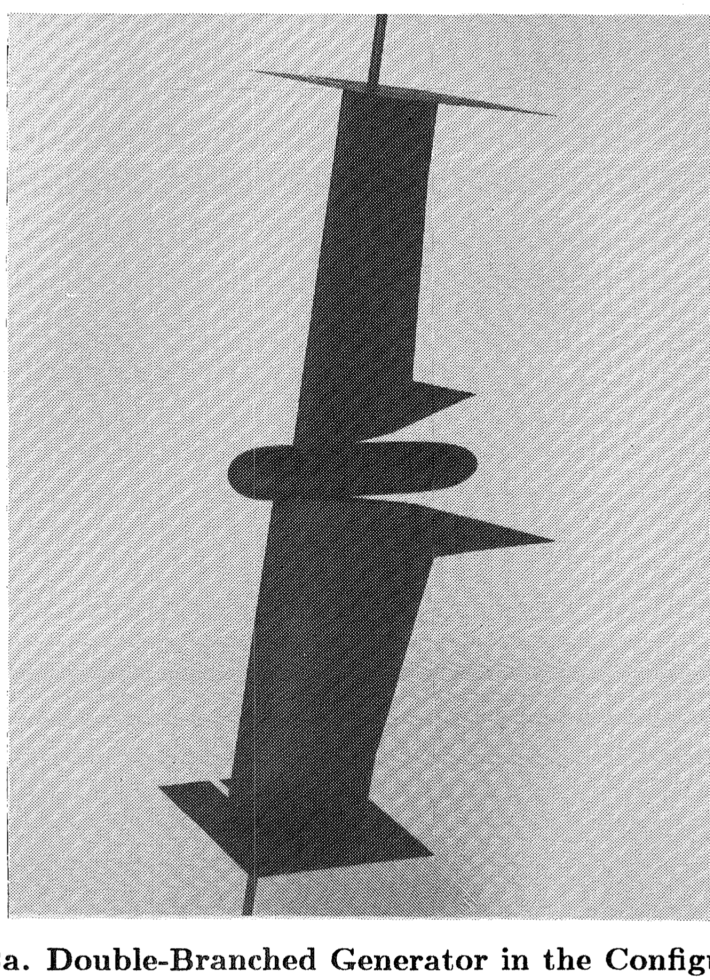


FIGURE 2a. Double-Branched Generator in the Configuration of Case E

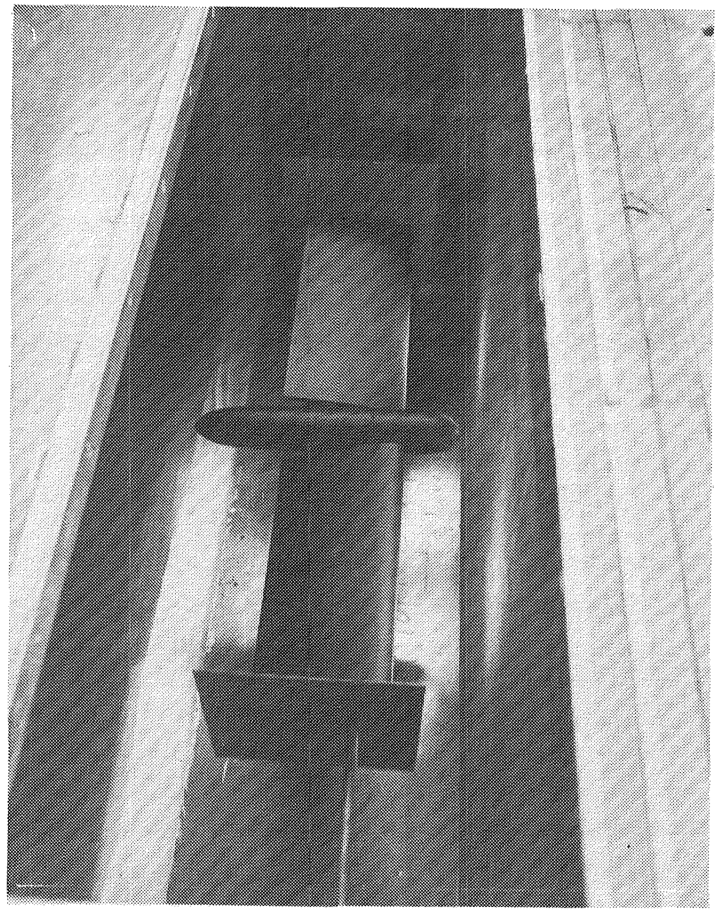


FIGURE 2b. Double-Branched Vortex Generator Mounted in Wind Tunnel

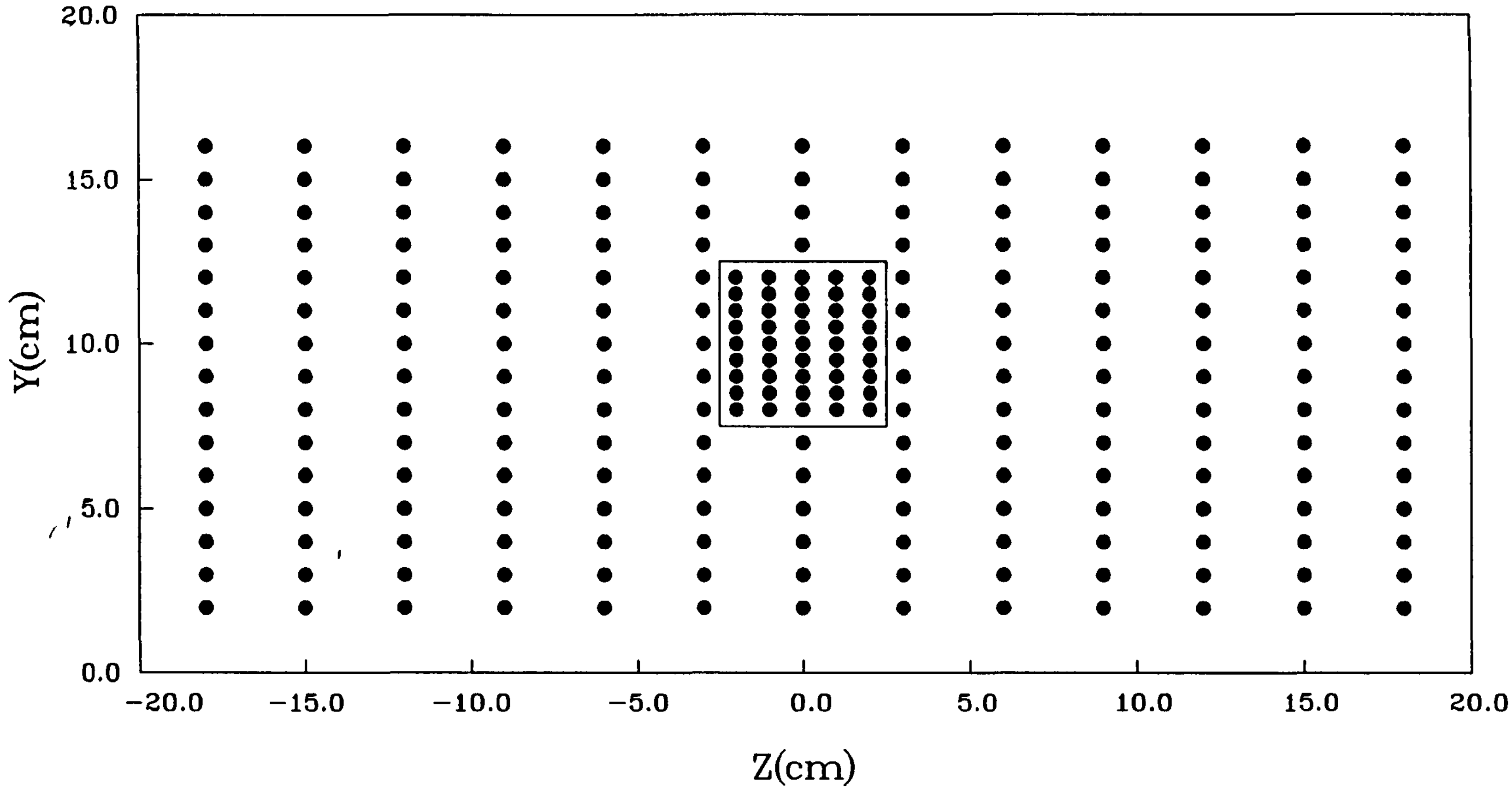


FIGURE 3. Schematic of Measurement Grid

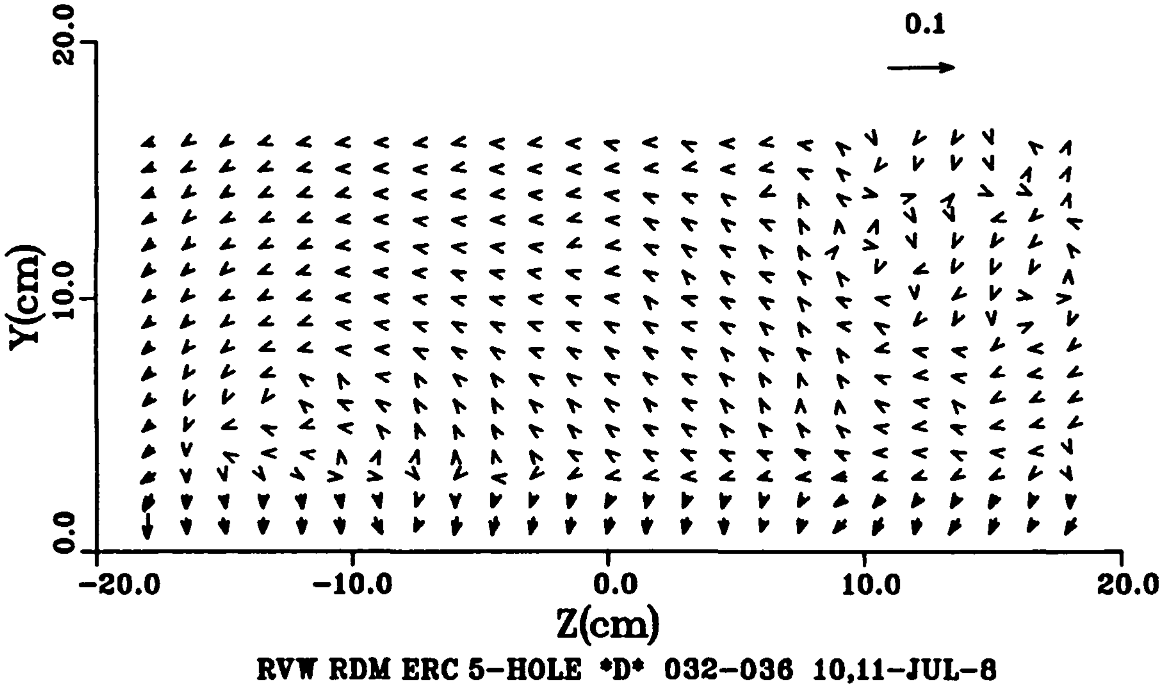


FIGURE 4. Velocity Vectors, Undisturbed Flow

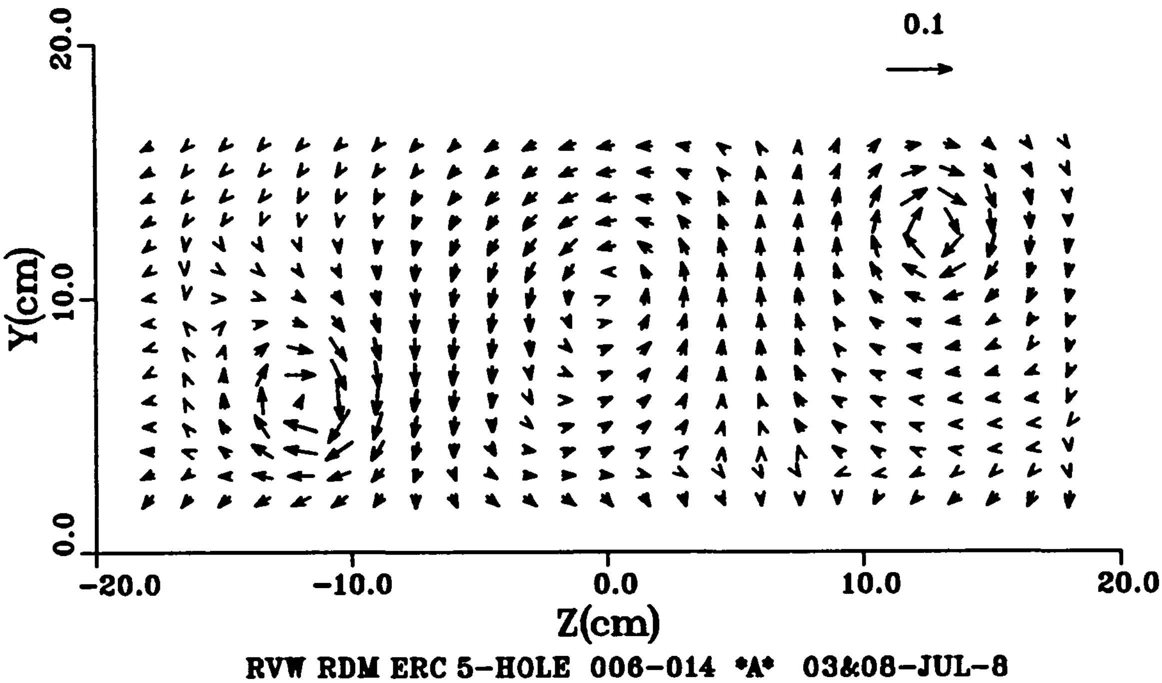


FIGURE 5a. Velocity Vectors, Case A

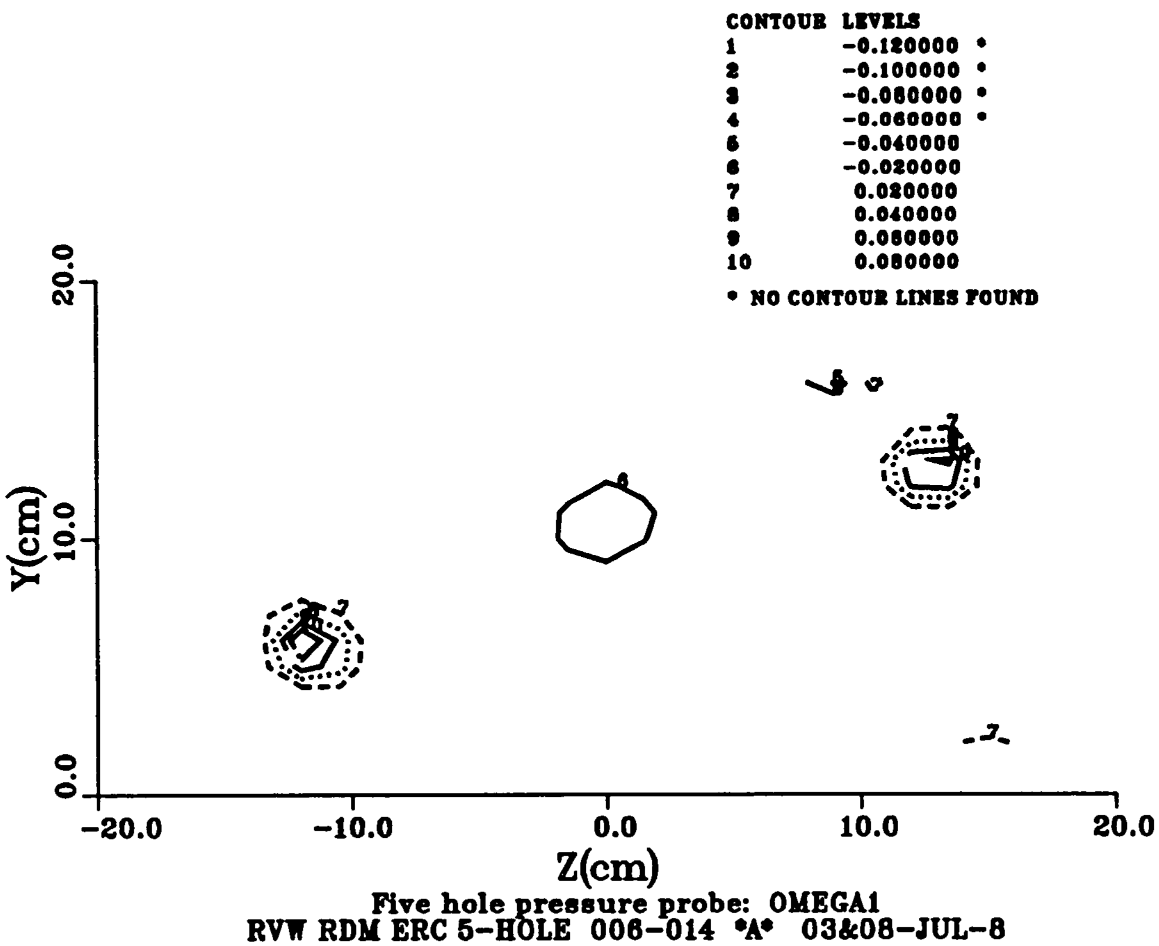


FIGURE 5b. Vorticity Contours, Case A

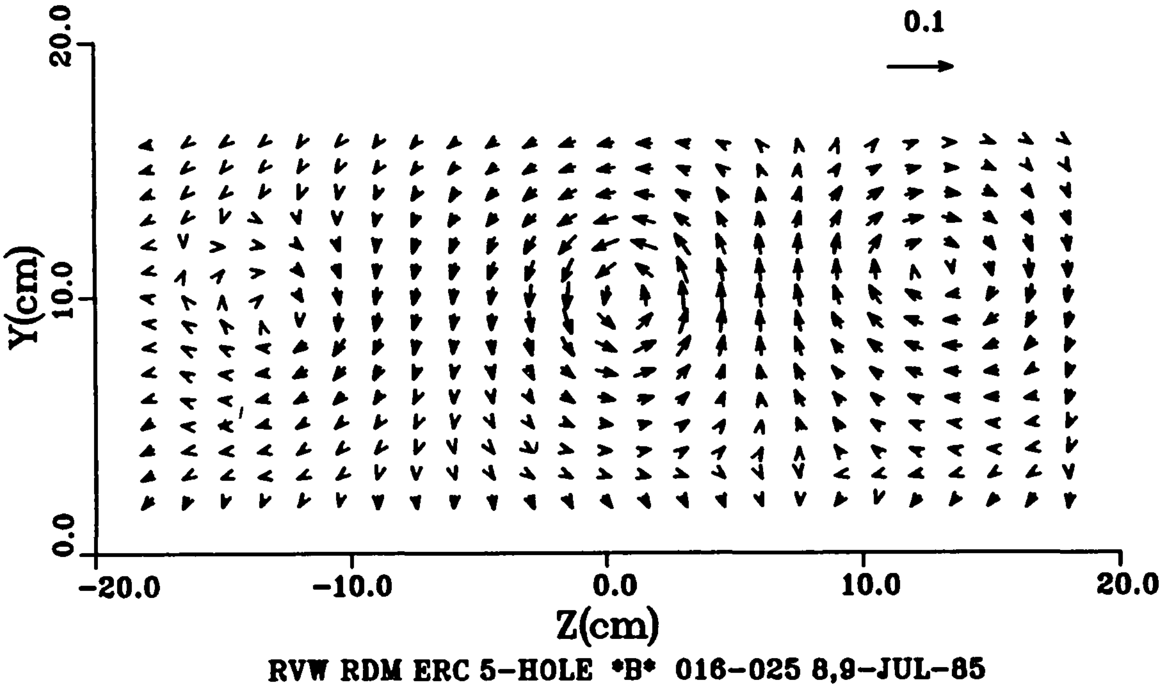


FIGURE 6a. Velocity Vectors, Case B

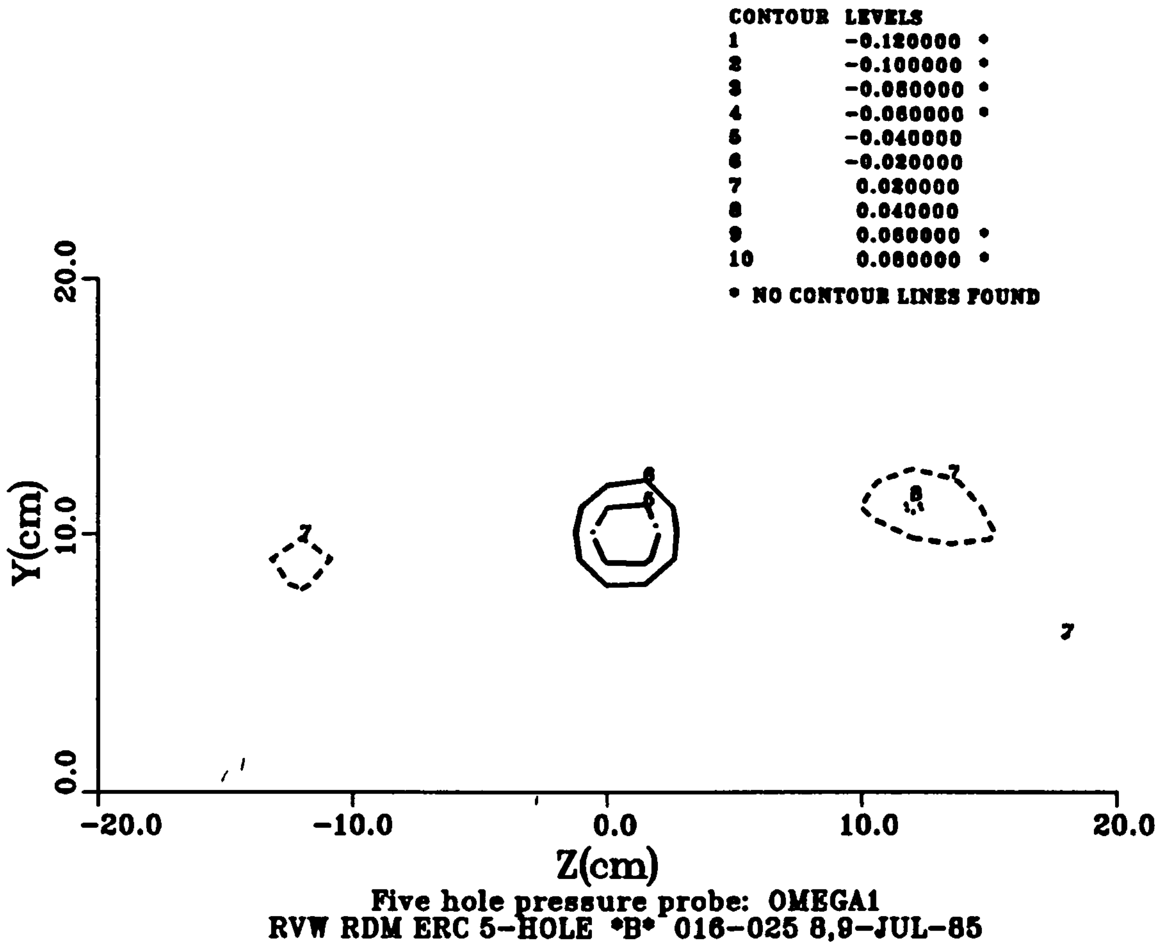


FIGURE 6b. Vorticity Contours, Case B

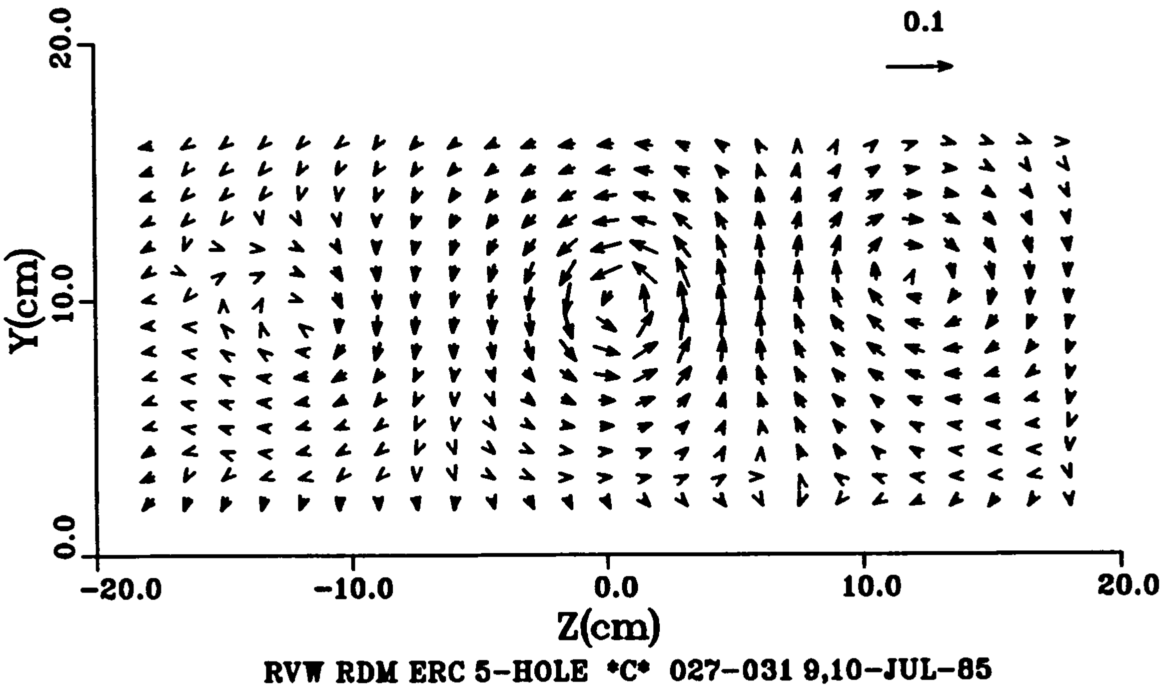


FIGURE 7a. Velocity Vectors, Case C

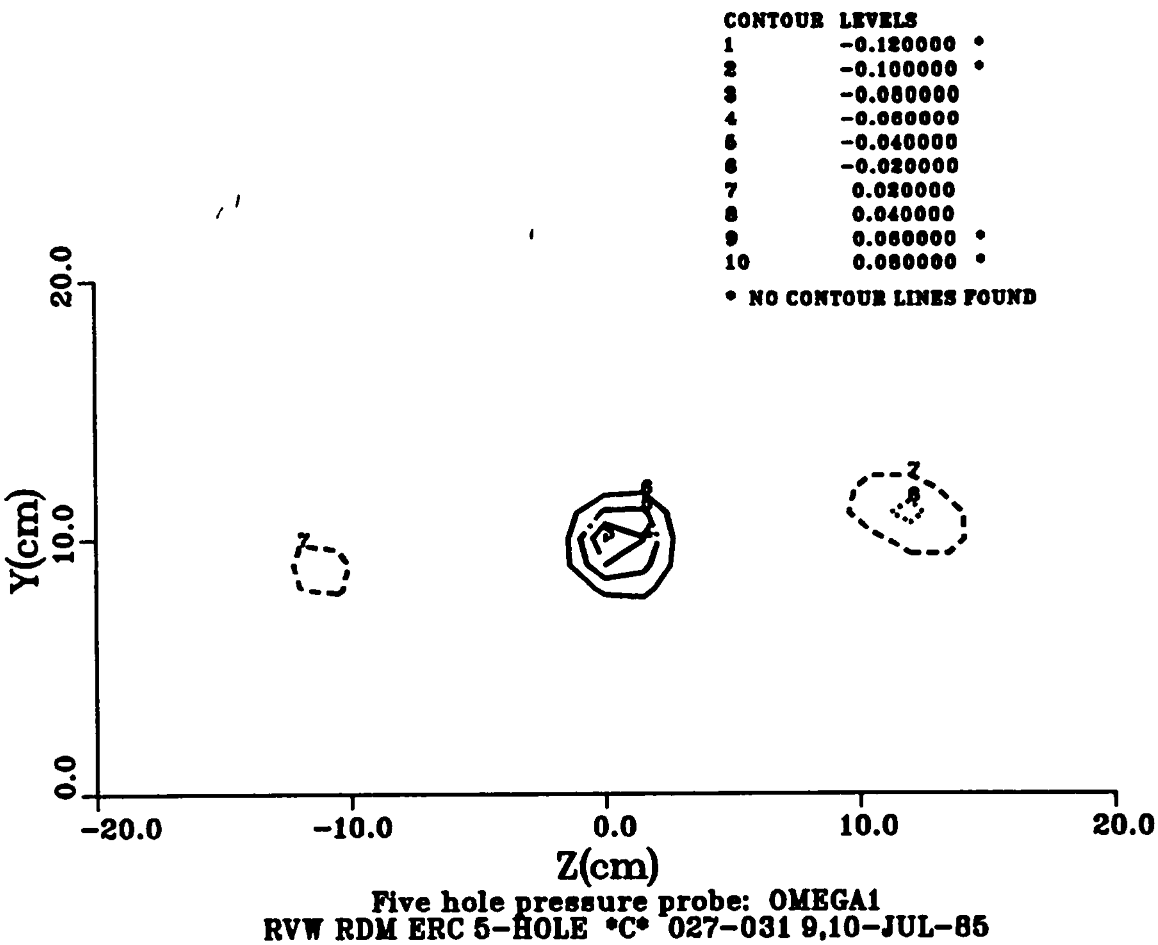


FIGURE 7b. Vorticity Contours, Case C

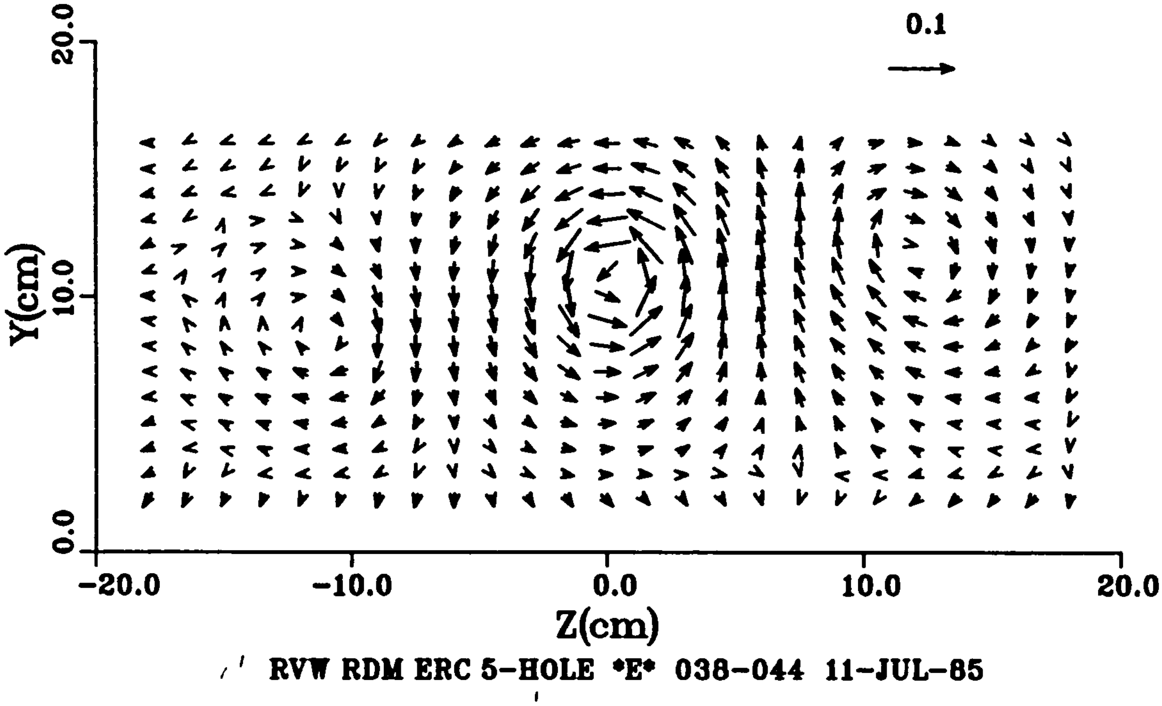


FIGURE 8a. Velocity Vectors, Case D

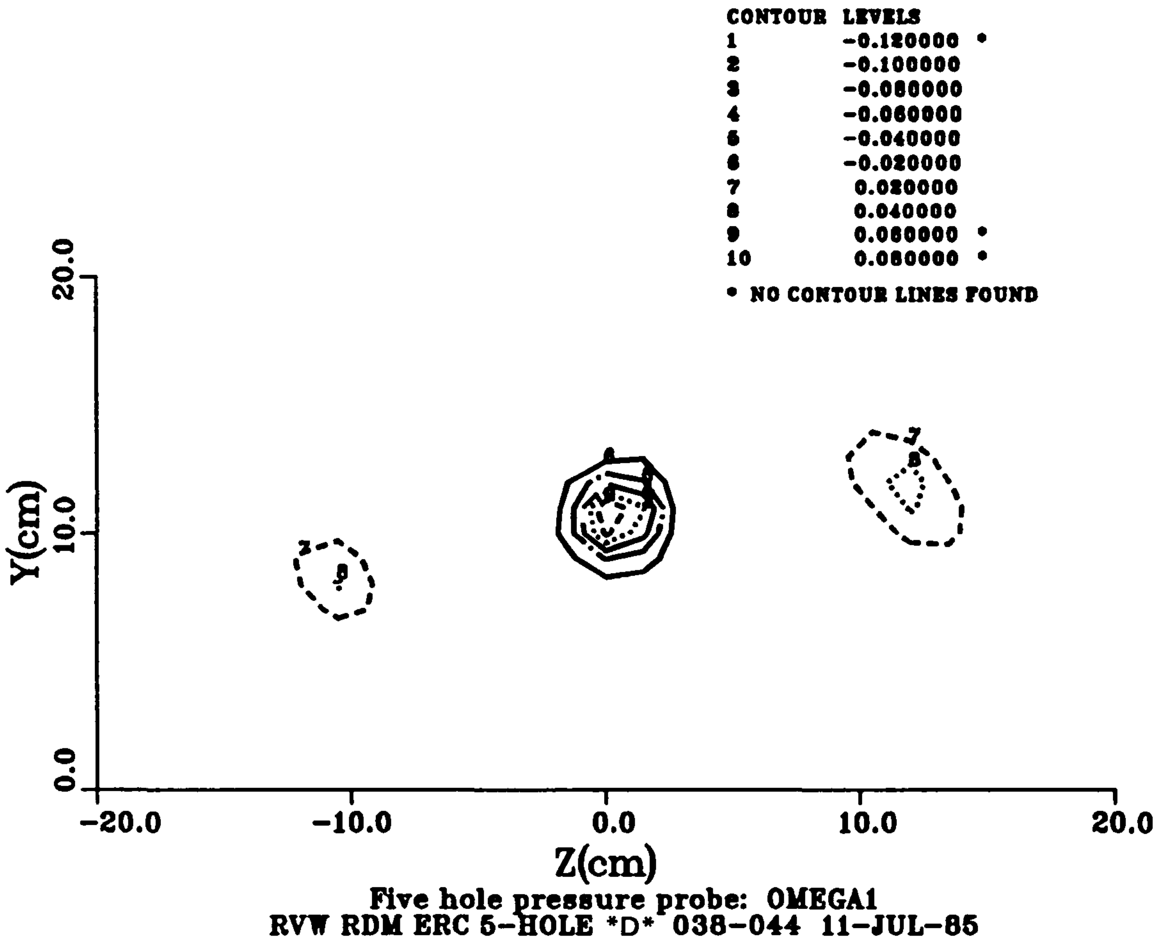


FIGURE 8b. Vorticity Contours, Case D

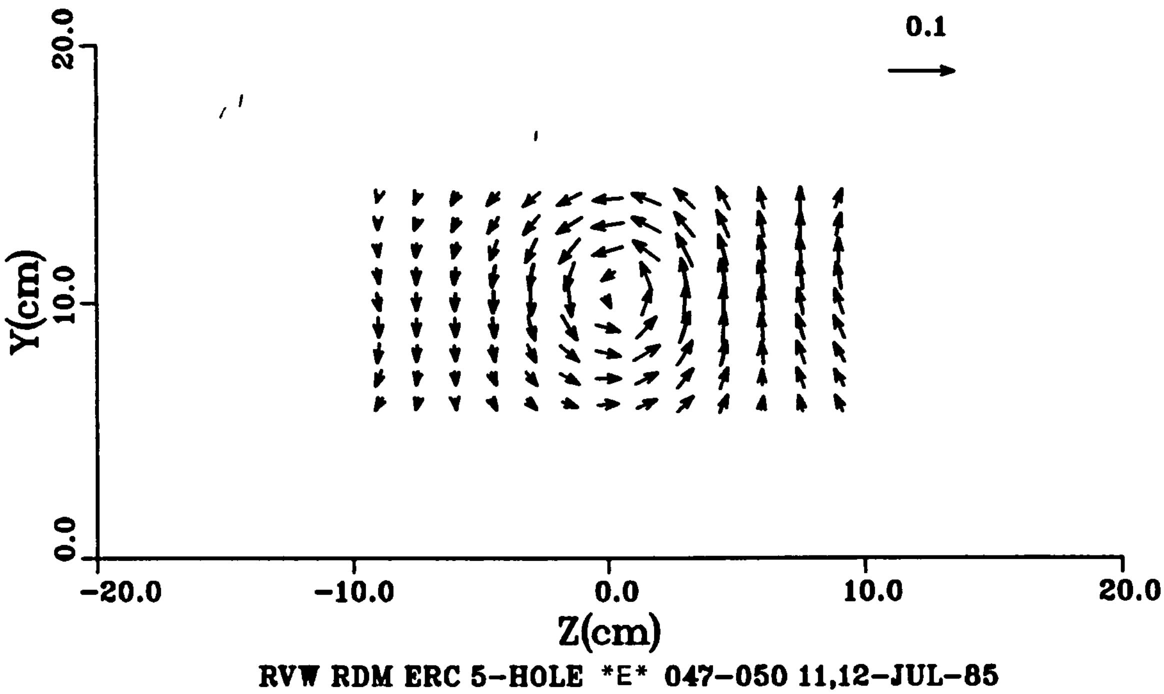


FIGURE 9a. Velocity Vectors, Case E

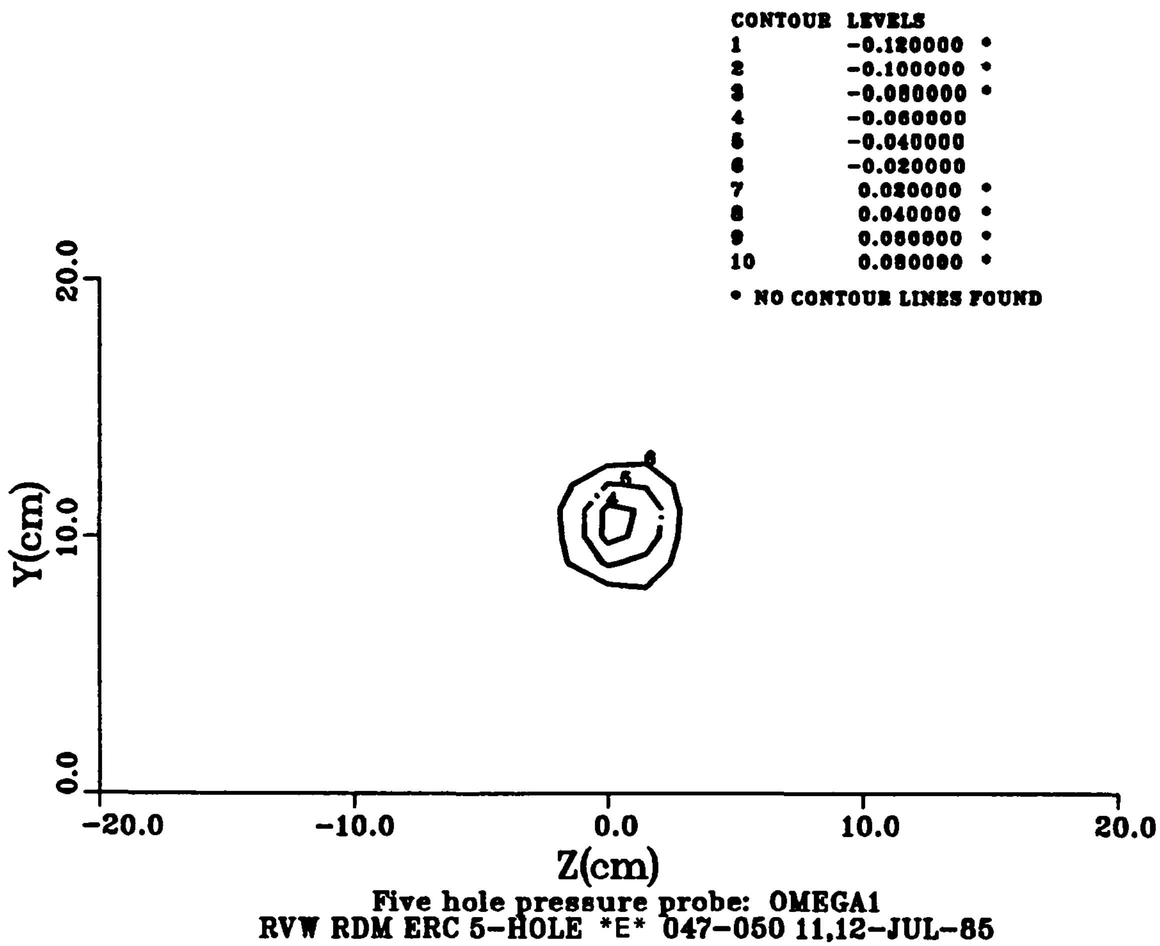


FIGURE 9b. Vorticity Contours, Case E

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15 Supplementary Notes

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16 Abstract

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