AIAA 96-2013 Fluid Dynamics Conference, June 1996

# ROTOR TIP-VORTEX / AIRFRAME COLLISION FEATURES

Raghav Mahalingam* and Narayanan Komerath+
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

## ABSTRACT

This paper describes progress towards understanding the basic test case of the interaction between a vortex-dominated wake from a two-bladed rotor, and a solid cylinder surface. Prior work had taken prediction capability in this test case to a level where the trajectories of the tip vortex and the associated surface pressure were predictable until the actual collision between the tip vortex core and the surface. The substantial role of the core axial velocity, postulated from pressure data on the airframe, is now confirmed by direct velocity measurements. Both the tip vortex core and the inboard vortex sheet, which have opposite signs of vorticity, have substantial wake-like velocities: further evidence that the axial velocity arises from the no-slip condition at the blade edges. The vortex shows interior structure: outside the core, there are multiple thin regions of jet-like velocity, attributed to the induced effect of the rolling-up vortex sheets. This appears to resolve the contradiction between Euler results (jet-like axial velocity) and experiments (wake-like core). During the collision, the axial velocity at the top of the airframe persists even after the flow has stagnated on the advancing blade side, further evidence of the blade-wake genesis of this flow. Suction peaks on the retreating blade side stay for a long duration. The levels of suction observed exceed those explainable by potential flow theory.

## NOMENCLATURE

| | |
|---|---|
| ABS | The side of the cylinder under the advancing-blade side of the rotor disk. |
| $Cp_{unsteady}$ | $(P_{uns} - P_\infty) / q_\infty$ |
| H | Vertical spacing between rotor hub center and airframe centerline |
| $P_{uns}$ | Unsteady surface pressure |
| $q_\infty$ | Free stream dynamic pressure |
| R | Rotor radius |
| RBS | The side of the cylinder under the retreating-blade side of the rotor disk. |
| Xb | Distance parallel to tunnel axis from cylinder nose |
| Zb | Vertical distance from cylinder top surface |
| $U_\infty$ | Tunnel freestream velocity. |
| $\phi$ | Circumferential location of points on the surface of the airframe cylinder, measured from the top of the airframe |
| $\mu$ | Rotor advance ratio, $U_\infty/\Omega R$ |
| $\Psi$ | Rotor azimuth in degrees, measured from downstream position |
| $\Omega$ | Rotor angular velocity. |

* Graduate Fellow. Student Member, AIAA.
† Professor. Associate Fellow, AIAA.



## INTRODUCTION

Progress in the last few years has enabled us to understand and compute many of the features of the interaction between a rotor wake and solid bodies. With this knowledge, the long-term goal of being able to comput the flow around a complete rotorcraft configuration, to the accuracy and confidence needed to predict hover payload and low-speed handling characteristics accurately on a radically new design, is becoming quite realistic. This paper focuses on one of the remaining problems: the presence of a substantial velocity component directed along the axes of the strong vortices in the rotor wake. This is an aspect which is missing from two-dimensional vortex representations, but is of first-order importance to the wake/airframe interaction problem. The measurements presented here suggest that these features may also be of first-order importance to other problems of current interest such as blade-vortex interaction.

The tip vortices shed from the rotor blades convect downstream and downward. These interact with the airframe in hover and low-speed flight, resulting in periodic vortex-induced loads on the airframe. When the vortex impinges on the airframe, it interacts with the boundary layer, causing separation and apparent vorticity redistribution. Since the early eighties, research on this interaction has been steadily progressing. A basic test case has been developed at Georgia Tech using a two-bladed rotor and a hemisphere-cylinder airframe model (Fig.1). To date experimental work at Georgia Tech[1,2] and computational efforts at Ohio State University[3,4] have been able to isolate details of the first order phenomena associated with the interaction at the front part of the airframe

Issues

Recent experimental work on this problem is documented in Ref.2. Fig.1 summarizes the state of knowledge on this problem at the author's organization and elsewhere. The rotor azimuth when the boundary layer interaction on the top of the airframe is initiated has been located to within 6 degrees. What happens to the vortex after that is still a debated question. Lee et al.[4] postulate vorticity redistribution by convection, which reduces the suction peak on top of the airframe within 1 ms. The axial flow in the tip vortex has not been captured for most of the interaction. The results of Kim et al. [1] indicated that the effects of axial velocity were of first-order importance to the interaction. Kim was able to explain high positive pressure coefficients on the ABS of the airframe by the stagnation of the axial velocity, and obtained evidence from flow visualization of such stagnation. The re-formation of a tight vortex core on the RBS was postulated by Conlisk. Further progress requires knowledge of the axial velocity in the core: this is the primary focus of this paper.

There is considerable debate regarding the axial velocity in the vortex core, even about its sign. Early theoretical work by Batchelor[6] postulated a jet-like flow in the core of a wing tip vortex. It is well-known that leading edge vortices over sharp-edged delta wings have strong jet-like cores until vortex breakdown occurs. Magnitudes as high as 3 times the freestream speed have been observed. These are explained, using potential flow concepts, as the velocity induced by the vortex filaments in the vortex sheet rolling up along the edge. The tip vortex of a straight fixed wing, on the other hand, displays little if any axial velocity[7] beyond a few chord lengths. The authors postulated a difference between the axial velocity from a square-edged rotor tip versus a rounded tip. Measurements on rotating wings tell a different story. Shivananda[8] used a split-film anemometer to resolve all three components of velocity in the wake of a single-bladed, square-edged rotor in hover. He found a wake-like core; the axial velocity was directed back along the trajectory of the vortex towards the blade. Thompson et al.[9] studied the same rotor blade wake, and resolved all three components of velocity in the vortex using a laser velocimeter. They were able to achieve high data rates using an off-axis light receiving system, and incense smoke particles which stayed inside the core. They showed not only a wake-like vortex core, but also secondary features inside the core, indicating several layers of vortex sheet roll-up. There is some flow visualization evidence in the literature on propeller wakes which supports this finding. A limited set of measurements made by Liou[10] above the cylinder model used in the present paper, in the core of the tip vortex from the present two-bladed rotor, found only a wake-like direction inside the core. The data were too limited to examine secondary features. Informal communications with developers of computational codes indicate that Euler equation solvers capture a jet-like core axial flow from the rotor blade tip. Recent vortex measurements using a 3-component laser velocimeter at the University of Maryland on a single-bladed rotor in hover[11] found wake-like axial velocity in the core, but the measured velocity profiles appeared to dissipate very rapidly within the first 90 degrees of wake age, the dissipation being attributed to "turbulence" inside the core. Resolution of these observations is needed to form general models for vortex interaction with the airframe On the other hand, it appears that with these resolved, the vortex-airframe interaction can be understood to a surprisingly detailed level.

## PRESENT SCOPE OF WORK

This paper starts by summarizing previous results on the pressures and flow-visualization on the sides of the airframe, where the effects of core axial velocity from the cut vortex filament are expected to be seen. We next describe measurements of the axial velocity in the tip vortex and in the inboard vortex sheet (which is the blade wake), as they interact with the top of a cylindrical airframe. With these measurements in hand, we re-examine the correlation between results from flow visualization near the airframe surface and pressure measurements on the surface during vortex collision with the surface.

## EXPERIMENTAL DETAILS

The experiments were carried out in the John J. Harper low-speed wind-tunnel at the Georgia Institute of Technology. This is a closed-circuit tunnel with freestream turbulence levels of 0.3% in its 2.13m x 2.74m atmospheric test section. Details of the test configuration are given in Fig. 2. The advance ratio for all the experiments was 0.1. Table 1 shows the test parameters.

## PRESSURE MEASUREMENT

The pressure data shown were acquired by superposing high-response condenser microphone data on time-averaged static pressures from a Barocel. The unsteady data sampling was triggered by an optical encoder mounted on the rotor shaft. The data were averaged over 6 deg. rotor azimuth and ensemble averaged over 100 rotor revolutions. The time averages were constructed from static pressure signals using a much longer period.

## FLOW VISUALIZATION

Flow visualization was done by expanding a collimated and video-synchronized pulsed Cu-Vapor laser beam into a sheet. A two-camera setup is used for the experiments. This setup has shown the capability to resolve time-scales down to 0.1 millisecond. Two identical intensified video cameras are focussed on the same area and the shutter of one is delayed by a predetermined time interval. This simulates a high-speed camera by providing two flow images separated by a very small time interval..

## VELOCITY MEASUREMENTS

The streamwise and vertical components of velocity were measured above the airframe using a 5-watt Argon-ion laser with the beams being projected from outside the test section. Light was collected in the backscatter mode. The lateral component of velocity, which is essentially along the axial direction of the tip vortex above the airframe, was measured using a fiber optic probe within the airframe. The measurement region for the present set of experiments is shown in Fig. 2. In the present set of experiments, we were unable to obtain a satisfactory signal-to-noise ratio with a 12.5mm diameter quartz window installed flush with the airframe surface. The window had to be removed for the measurements: this precluded any attempt to interpret data closer than 12.5mm to the surface. For this reason, measurements were not made in the boundary layer during the final stage of collision, where the tip vortex core is within 12.5mm of the surface.

With the fiber optic probe, the solid angle of light collection was substantially higher even in the backscatter mode than it was in the earlier configuration where the collection optics were placed outside the test section. This made it possible to re-examine the feasibility of core velocity measurements. Data at several locations were checked for repeatability. In most of the measuring grid shown, the data rate was high enough (several hundred points per second) to enable collection of 100,000 individual points per measuring location, in order to sort out the ensemble-averaged periodic velocity with a resolution of 1 degree of azimuth. In the collision region, the data rates fell below a hundred points per second, and the number of points was reduced to 30,000 for some runs and 25,000 for others.

Table 1. Test Conditions, Dimensions and Uncertainties

| | |
|---|---|
| Freestream Velocity | 5 m/s. ± 0.25% |
| Rotor rpm | 1050 ± 1 or 2100 ± 1 |
| Rotor collective pitch | 10 deg. |
| Rotor diameter | 0.9144 m. |
| Tip path inclination from horizontal | pitchdown: 4.06 deg. left side down 2.02 deg. |
| Vortex strength | 1 $m^2/s$ ± 10% |
| Cylinder diameter | 0.137 m |
| Rotor tip height above cylinder | 0.137 m |
| Boundary layer Reynolds number | 80,000 ± 10% at x = 0.236 m |

## RESULTS

Figure 3 shows the azimuth-resolved lateral velocity component at $Zb/R = 0.0605$ and $Xb/R = 0.352$. The number of data values counted in each 1-degree azimuth interval is also plotted on the figure. The vortex core passage is centered at about 200 degrees. In this azimuth interval, only a few particles are counted, but a consistent variation of lateral velocity is obtained. The lateral velocity reaches a peak of about 8 m/s. Secondary "blips" are observed: these occur repeatably, so that they must be attributed to real flow features. Immediately outside the "core", there is two sharp reversals of the gradient of the lateral velocity on both sides. The paucity of particles counted in the core must raise concerns about the accuracy of the velocity measured with those particles which do remain in the core. However, the results appear consistent, after several repetitions. Further measurements with particles of smaller diameter are needed before these questions can be fully resolved.

### Correlation Between Pressure and Axial Velocity

Figure 4 shows the correlation between instantaneous pressure and lateral velocity measurements across the tip vortex at four selected rotor azimuth values. The rotor azimuth values are chosen to match the vortex age: hence the values above 180 degrees. At $\Psi = 204$ deg., the vortex is at $Zb/R = 0.0385$, still well above the airframe surface. The suction pressure coefficient on the surface only reaches -0.5. The magnitude of lateral velocity reaches 12 m/s in the core of the tip vortex: this exceeds the peak of tangential velocity (approximately 10m/s) measured around this vortex previously. The lateral component is directed along the vortex core at the top of the cylinder, and the sense of this velocity is wake-like for positive values. The late al velocity is quite low elsewhere. Twelve degrees of rotor azimuth later, the vortex is roughly 12.6 mm above the surface. At $\Psi$ = 228 deg., the pressure coefficient reaches almost -8, and then returns to -4 within the next twelve degrees. The measured peak value of axial velocity fluctuates, but is still of the order of 9 m/s at $\Psi$ = 228 deg.

Secondary Features in the Core

In Fig.4, we do not observe the secondary features in and around the core which were observed in Fig. 3. On re-examination we conclude that the features in Fig. 3 constitute very thin regions. Given the approximate convection speed of the tip vortex, and our azimuth resolution of 1 degree, the thickness of these regions is estimated at about 1. 25mm. We postulate these to correspond to the roll-up of discrete layers of vorticity into the tip vortex. The data in Fig. 4, on the other hand, were assembled from data taken at different stations along the X-direction at the same rotor azimuth. The spacing between successive measurement locations was 2.54mm, simply too large to capture the secondary features. It should be noted that the age of the vortex at this station is more than 180 degrees.

The secondary features in the core velocity profile were reported first by Thompson et al [9]. in the wake of a single-bladed rotor in hover. Their results are reproduced in Fig. 5. They concluded after examination of their velocity data that the secondary features were regular, consistent, and repeatable, and their excursions were greatly in excess of the uncertainty in their velocity measurements. Their results required a data acquisition standard of 100,000 points per component, a wake structure and trajectories whose periodicity had been carefully confirmed, and an azimuth resolution of 0.5 degrees.

Figure 6 examines the magnitudes of the lateral velocity component in the wake of the rotor. The figure shows the lateral component at several points along a horizontal line at Zb/R = 0.022, all measured in the 1-degrees rotor azimuth interval beginning at 24 degrees. The lateral velocity is seen to reverse in a small region. The reasons for this are unknown, but correspond to the suction region observed by Kim [1] adjacent to the strong stagnation region towards the advancing blade side of the top of the airframe.

Lateral Velocity in the Blade Wake

Figure 7 examines data similar to that of Fig. 6, at a rotor azimuth of 24 degrees, along the horizontal line at Zb/R = 0.088. This shows a high value of lateral velocity along a broad region. This corresponds to the "inboard vortex sheet", which is a region of spanwise shear on either side of the viscous wake of the blade. The high positive lateral velocity here is further evidence that this velocity stems from the viscous effects on the blade.

Persistence of Suction on the Retreating Blade Side

Figure 8 shows the surface pressure trace at $\Psi$ = 240 degrees, along a horizontal line, at the 255-degree cylinder azimuth, which is 15-degrees below the horizontal diameter of the cylinder, under the RBS. The pressure trace shows a high level of suction persisting even so late in the interaction. Note that this pressure profile differs from those shown in Fig. 4: this is not the typical velocity profile associated with vortex swirl. Instead, it is reminescent of a surface with a ground vortex rising from it.

## CONCLUDING REMARKS

This paper shows the very substantial effects of the lateral velocity in the wake, and in particular the axial velocity in the core of the tip vortex, on the rotor/airframe interaction problem. The magnitude of the core axial velocity is even greater than the peak swirl, even at a vortex age of well over 180 degrees. The axial velocity inside the core is wake-like, with a bell-like profile. Outside this region, there are secondary features including regions of jet-like flow: these are postulated to be due to velocity induced by the vortex sheets rolling up into the vortex.

There is a substantial level of lateral velocity inside the blade wake, which is usually considered to be a vortex sheet.

Persistent suction on the RBS, even below the horizontal diameter of the airframe, indicates strong suction due to the re-formation of the vortex on the RBS. A stagnation region due to a jet-like impingement by axial velocity in the core has been measured before on the ABS. Thus it is seen that the axial velocity in the vortex is substantial, and has first-order effects on the wake/cylinder interaction.

## ACKNOWLEDGEMENTS

This work is performed under a subcontract from the Ohio State University Foundation under Army Research Office Grant No. DAAH 04-93-G-0048. The Technical Monitor is Dr. Tom Doligalski. The assistance of Robert Funk is gratefully acknowledged.

## REFERENCES

1. Kim, J.M., and Komerath, N.M., "Summary of the Interaction of a Rotor Wake with a Cylinder", AIAA Journal, Vol. 33, No. 3, March 1995, p. 470-478.

2. Mahalingam, R., Peterson, K.G., Funk, R., Komerath, N.M., and Conlisk, A.T., " Recent Experiments on Vortex Colllisions with a Cylinder", AIAA 95-2236, June 1995.

3. Affes, H., and Conlisk, A.T., "A Simplified Model for the Interaction of a Rotor Tip Vortex With an Airframe", AIAA 92-0320, Jan. 1992.

4. Lee, J., Xiao, Z., Burggraf, O.R., Conlisk, A.T., and Komerath, N.M., "An Inviscid Analysis of Vortex-Surface Collisions", AIAA 95-2237, June 1995

5. Affes, H., Xiao, Z., Conlisk, A.T., Kim, J.M., and Komerath, N.M., "The Three-Dimensional Boundary Layer Flow Due to a Rotor Tip Vortex", AIAA 93-3081, June 1993.

6. Batchelor, G.K., "Axial Flow in trailing vortices", Journal of Fluid Mechanics, 20:645-58, 1964.

7. McAllister, K.W., Takahashi, R.K., "NACA 0012 Wing Pressure and Trailing Vortex Measurements". NASA TP 3151, November 1991.

8. Shivananda, T.P., "Pressure Measurements Near the Tip of a Hovering Model Rotor Blade and a Preliminary Investigation of the Flow in the Wake". PhD Thesis, Georgia Institute of Technology, School of Aerospace Engineering, December 1977.

9. Thompson, T.L., Komerath, N.M., Gray, R.B., "Visualization and Measurement of the Tip Vortex Core of a Rotor Blade in Hover". Journal of Aircraft, Vol. 25, December 1988, p. 1113-1121.

10. Liou, S.G., Komerath, N.M., McMahon, H.M., "Measurement of the Interaction Between a Rotor Tip Vortex and a Cylinder". AIAA Journal, Vol. 28, No. 6, p. 975-981, June 1990.

11. Leishman, J.G., Baker, A., Coyne, A., "Measurements of Rotor Tip Vortices Using Three-Component Laser Doppler Velocimetry". Proceedings of the AHS Aeromechanics Specialist Conference, CT, October 1995.

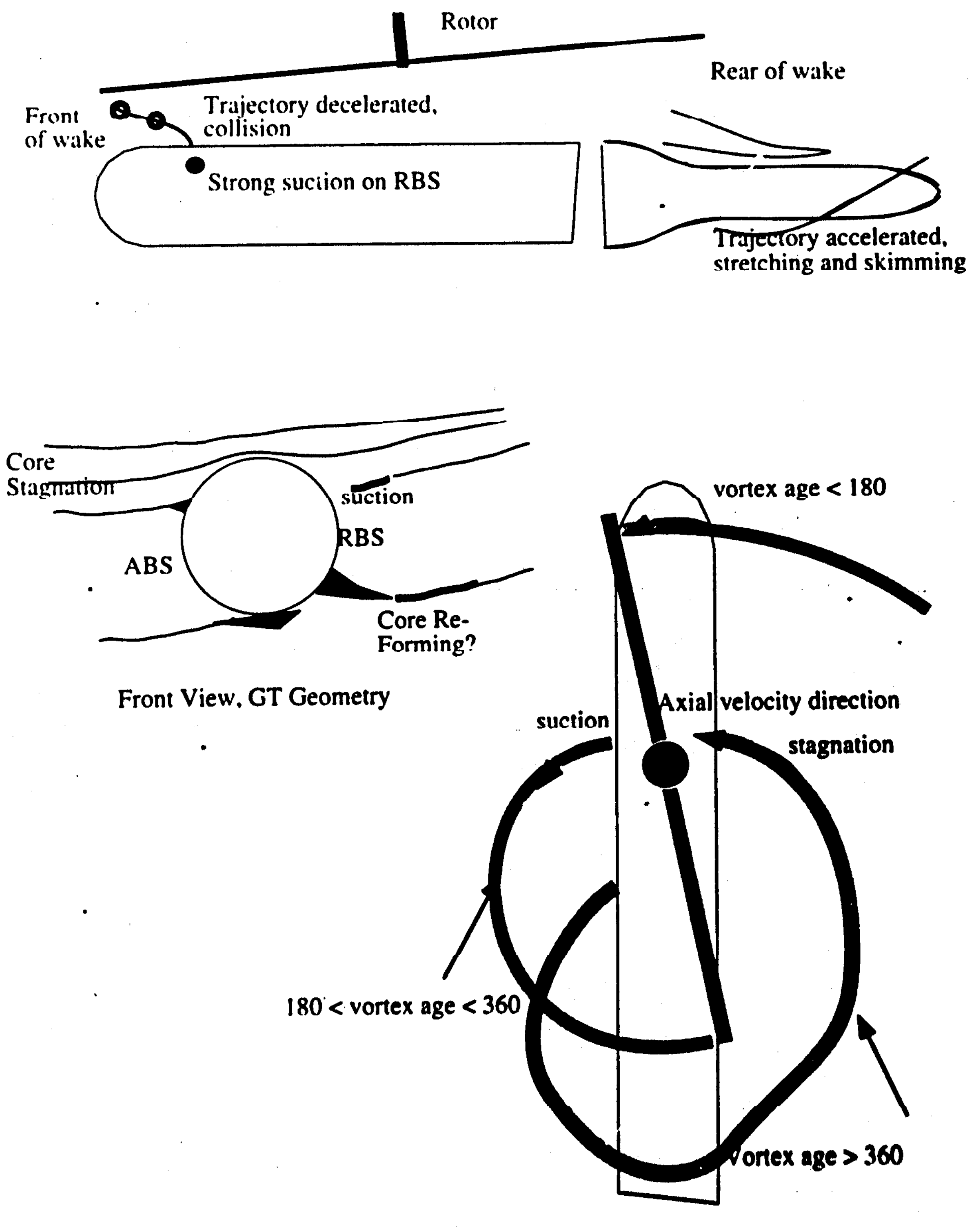


**Fig.1. Summary of the state of knowledge on the interaction process**

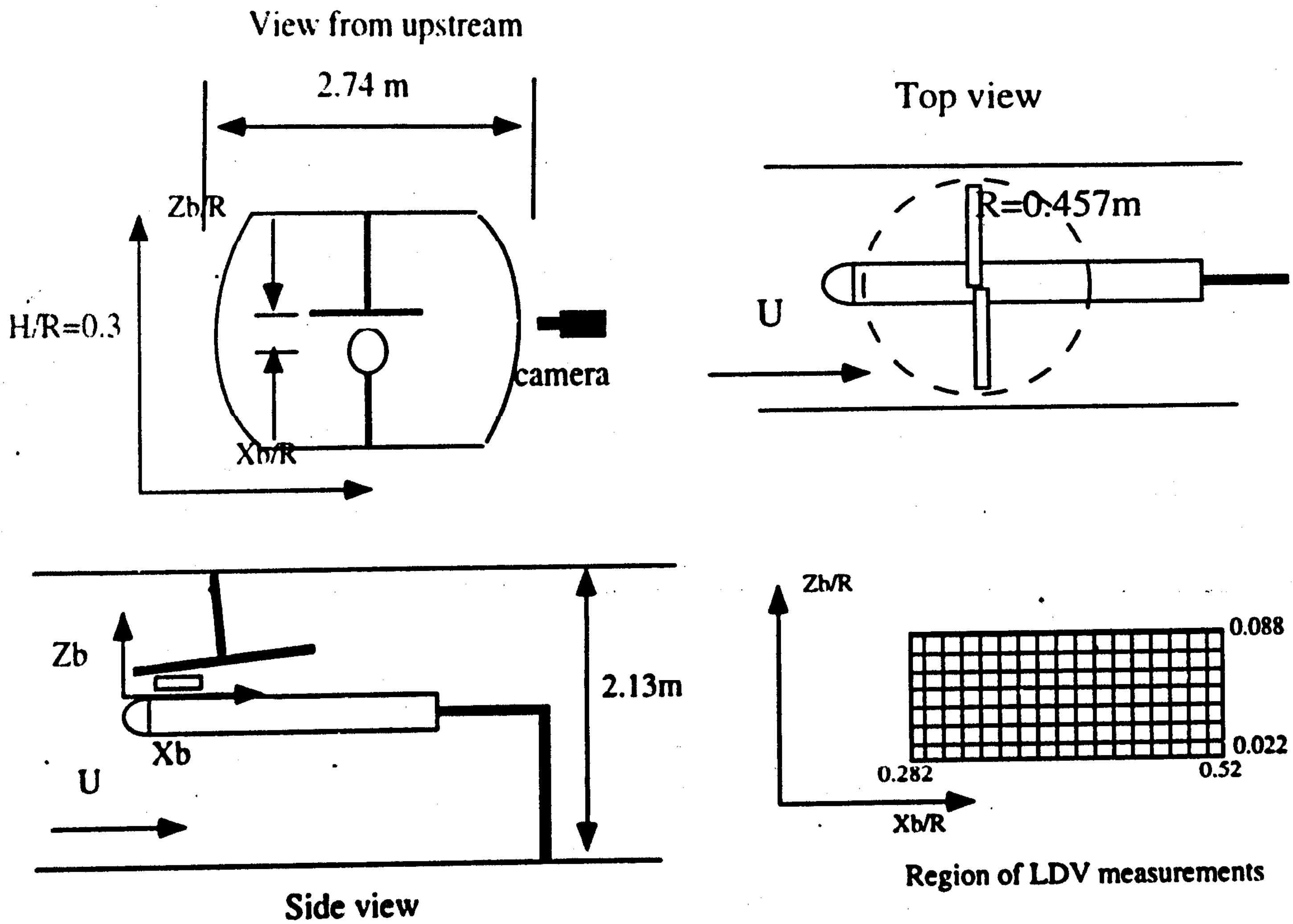


**Fig.2a. Experimental Configuration**

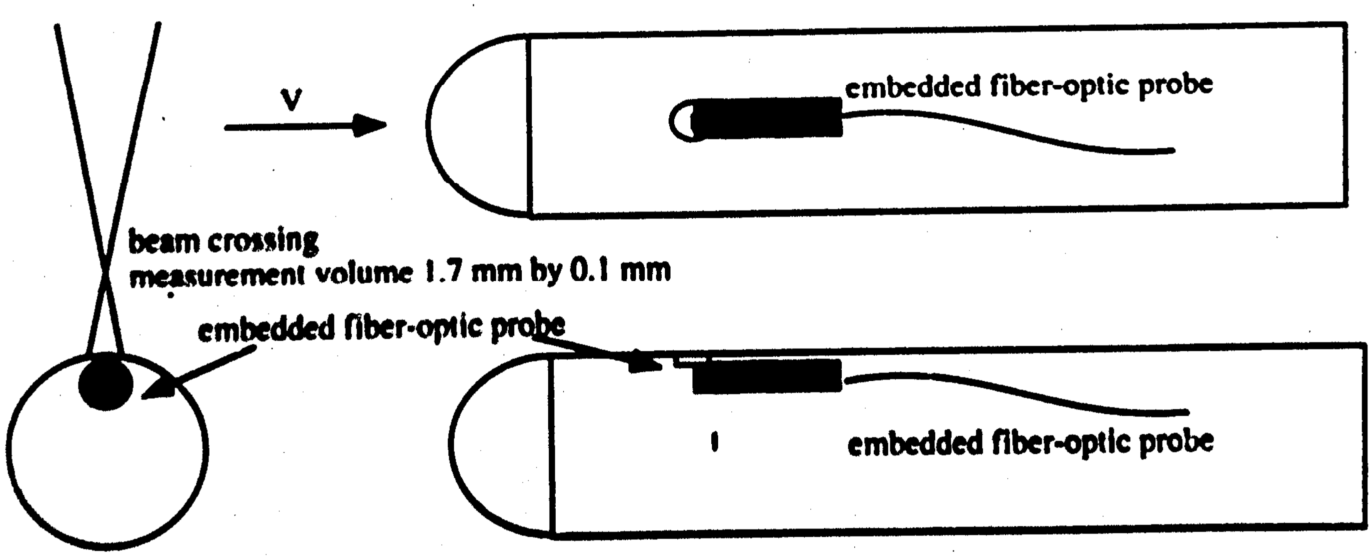


**Fig. 2b. Positioning of probe for laser velocimetry**

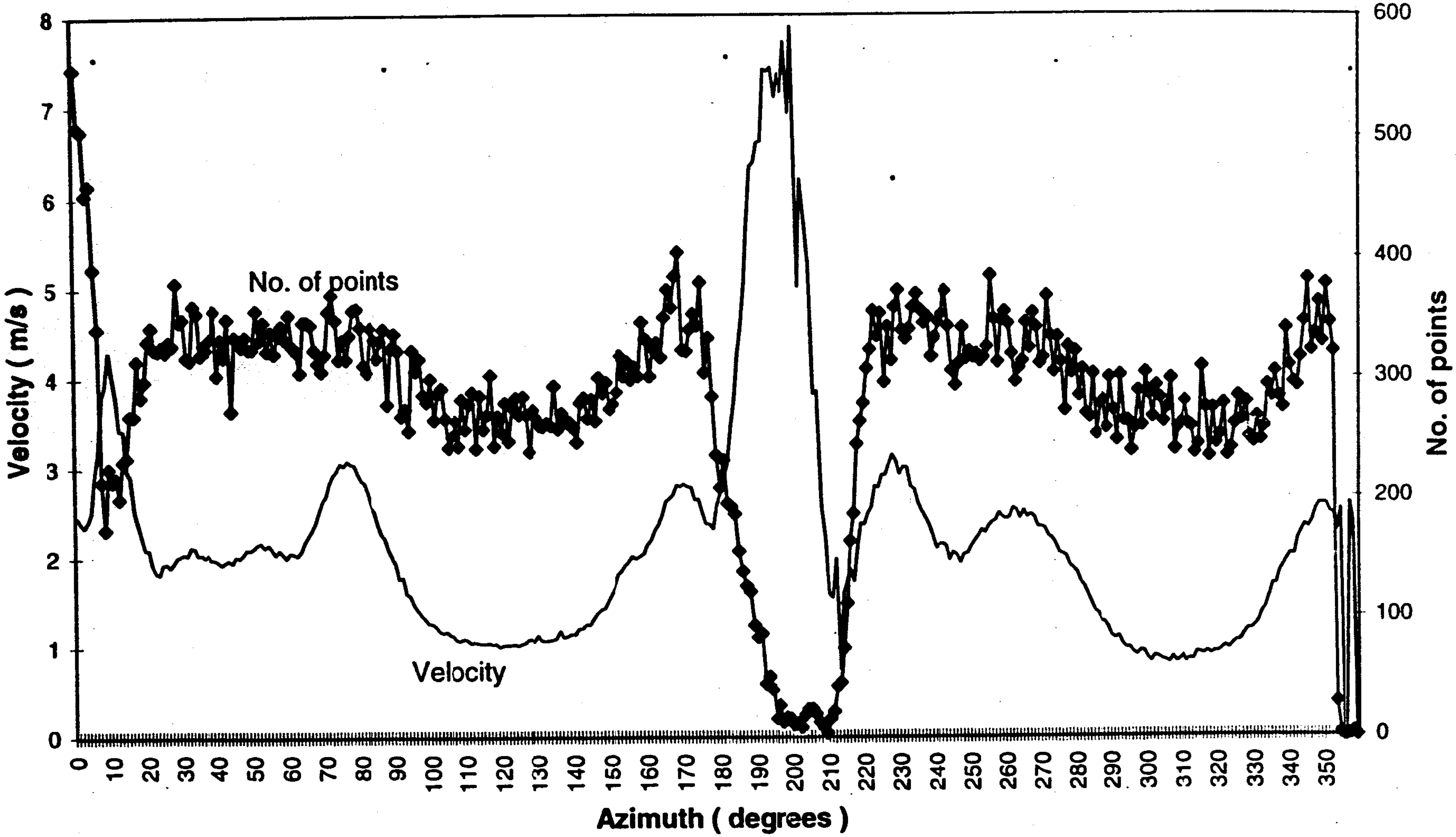


**Figure 3.** **Periodic azimuth resolved lateral velocity**

$Xb/R = 0.352$, $Zb/R = 0.0605$

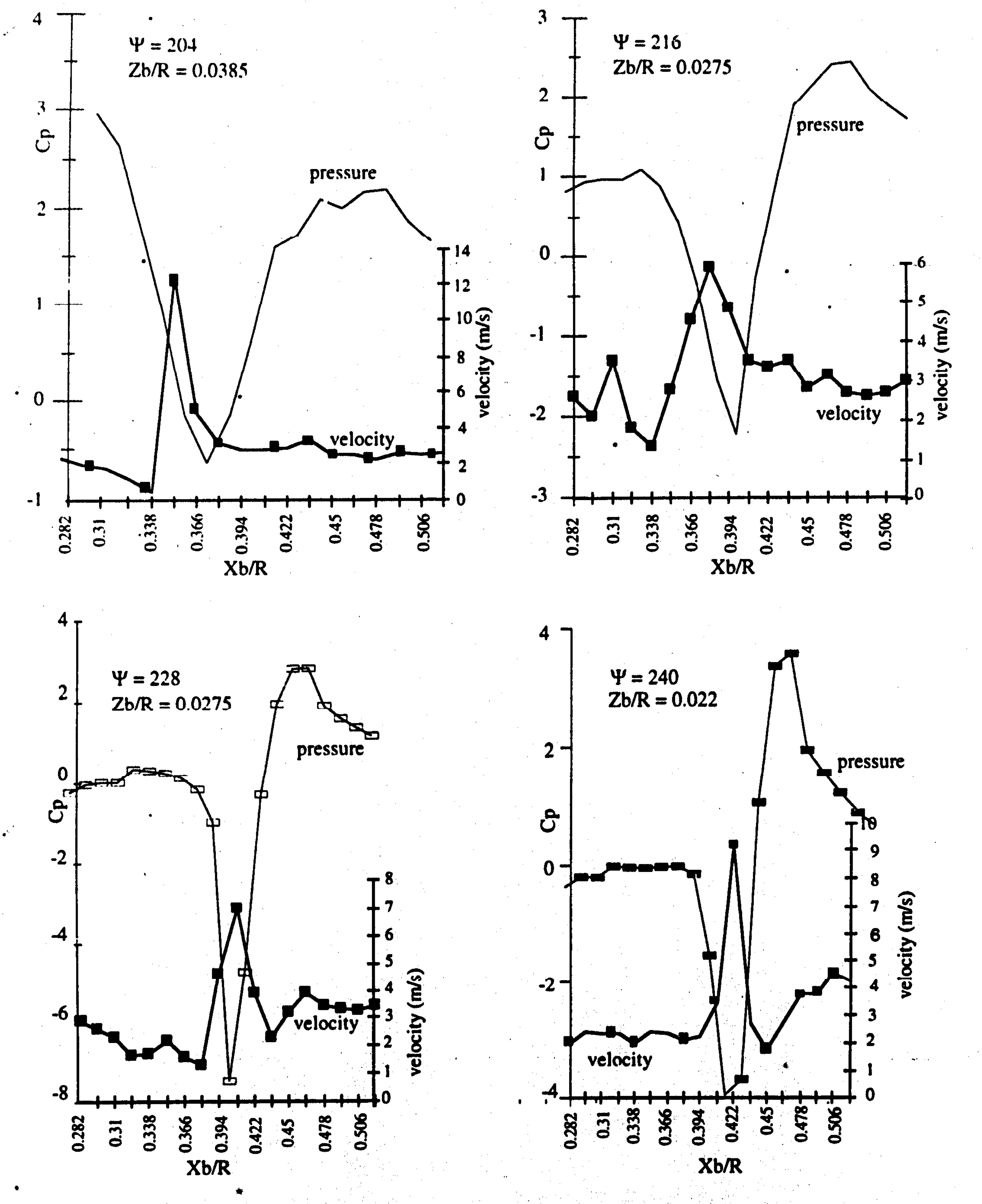


**Fig. 4. Correlation between surface pressure on airframe and velocity measurement through vortex core**

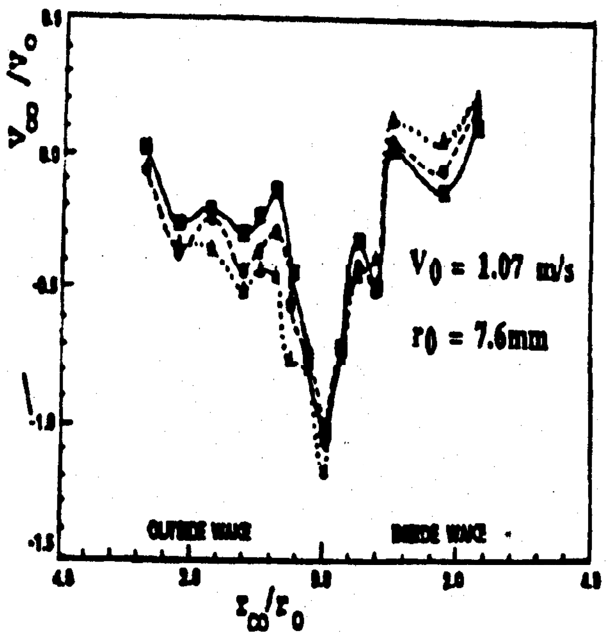


Fig. 5. Core velocities measured by Thompson ( from Ref. 9 )

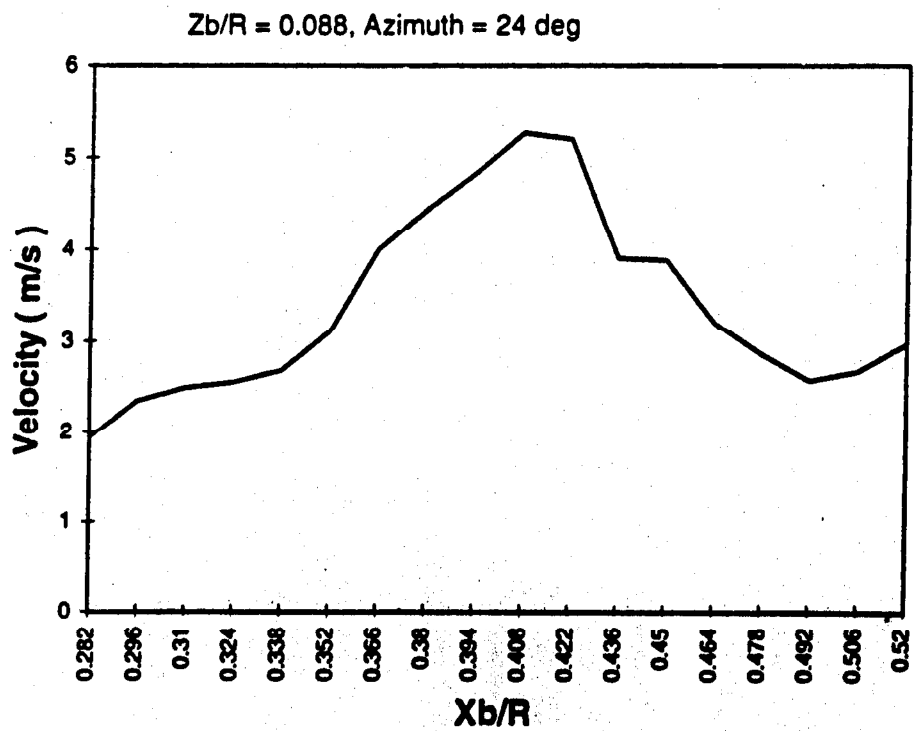


Fig.6. Velocity profile along a horizontal line near the rotor

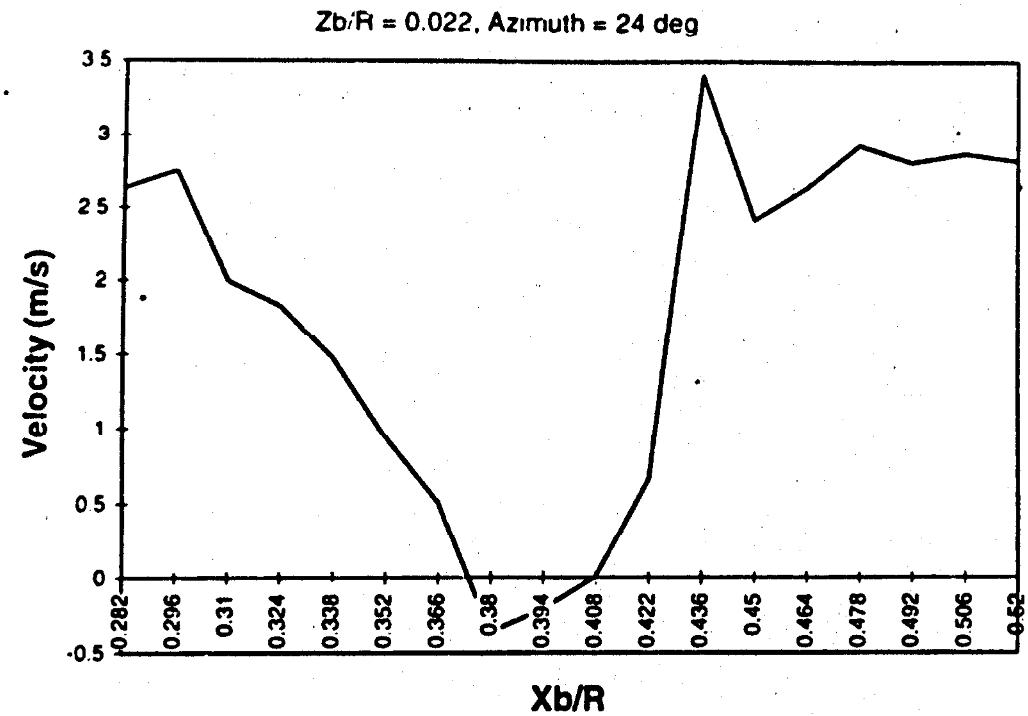


**Fig. 7. Velocity profile along a line near the cylinder surface**

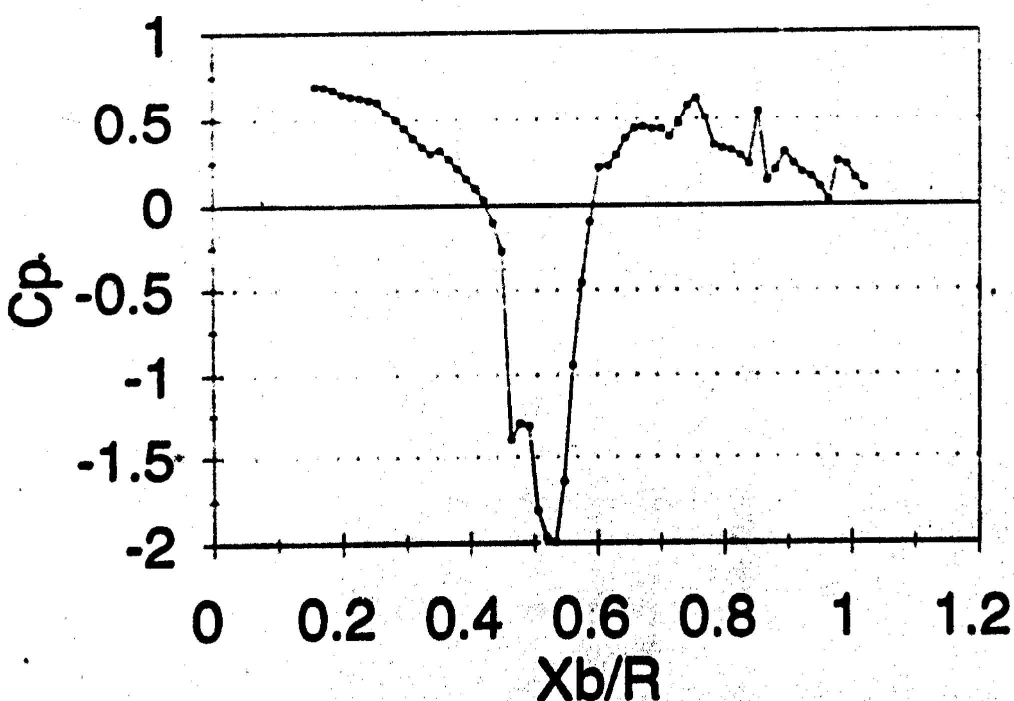


**Fig. 8. Unsteady pressures on the cylinder surface late in the interaction Cylinder azimuth = 255 deg, rotor azimuth = 222 degrees**