Development of Tools and Support for Measurements in the NASA 80x120 Foot Wind Tunnel

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Abstract

This report describes the first study leading to the application of Particle Image Velocimetry to diagnose rotor type flows in the NASA Ames 80x120-foot wind tunnel facility. The necessary steps towards the implementation of PIV to study rotor type flows were first investigated in the Army Rotor Hover Chamber. The model problem consisted of the three-dimensional flow generated by a two-blade rotor at different wake ages.

1 - Introduction

A view of the test set-up is shown in figure 1. The rotor is a two-blade configuration with 7-foot diameter, and the blades are formed from NACA0012 profiles. The rotation speed of the rotor is set at 900 rpm. For the velocity measurement, the PIV system is configured in the stereoscopic mode with the cameras satisfying the Scheimpflug focusing condition.

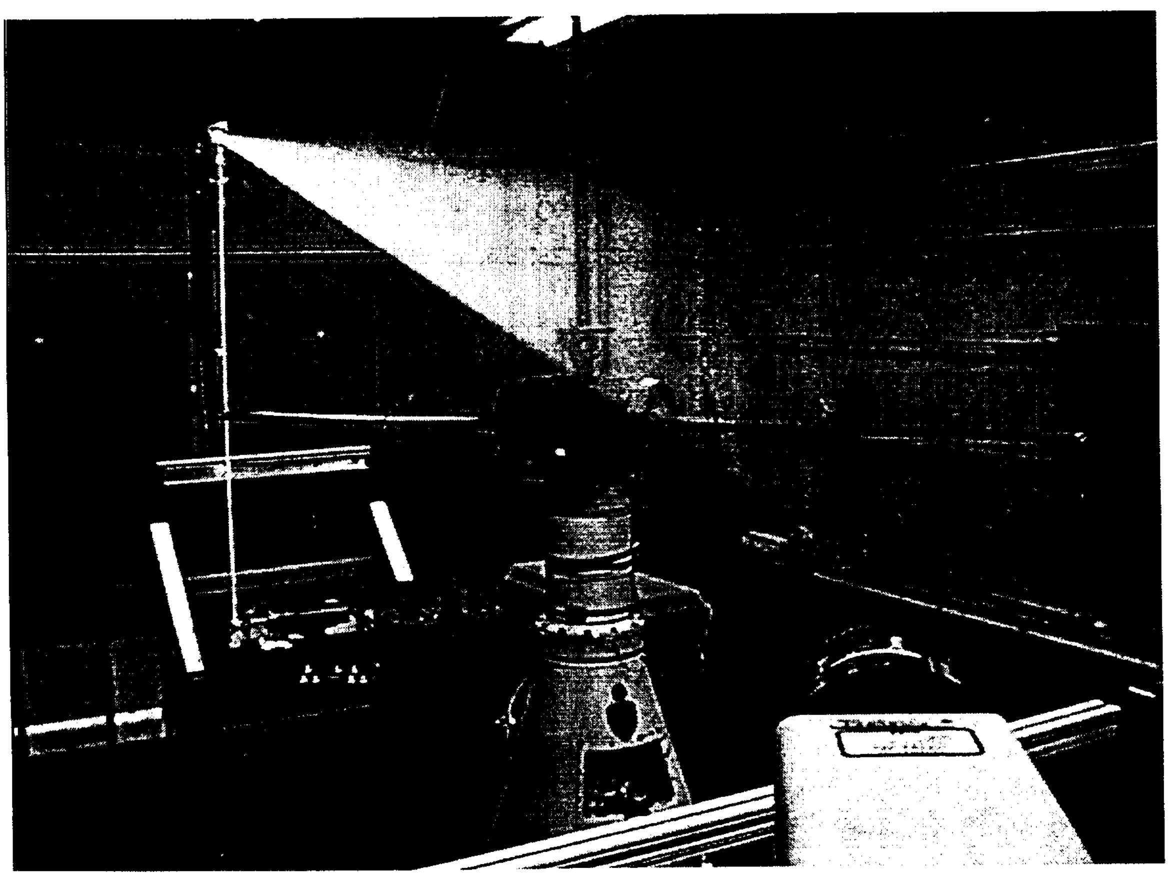

FIGURE 1: VIEW OF THE TEST FACILITY

2 - PARTICLE IMAGE VELOCIMETER

The application of the PIV technique to map the configuration shown in figures 1 is not straightforward. In this configuration the PIV cameras are placed at an angle different from normal incidence to the laser sheet. The focal plane of the camera lens and the object plane are coincident only at a single line. To ensure focus throughout, an imaging condition known as the Scheimpflug condition is realized. This condition states that focus is achieved when all three planes, object, lens and image, intersect at a common line as shown in the schematic in figure 2. In practice the focus condition is achieved by tilting the stock camera lens. In this experiment the lens is 55 mm in focal length, the view angle is tilted about 45^{O} from the normal axis and tilt angle between the image and the lens planes is about 8^{O}.

One inconvenience of off-axis imaging is that to obtain the accurate velocity field the camera view must be first freed from perspective effects. The basis for this correction is established by considering the principal planes and coordinate systems involved in the off-axis imaging arrangement as illustrated in figure 2.

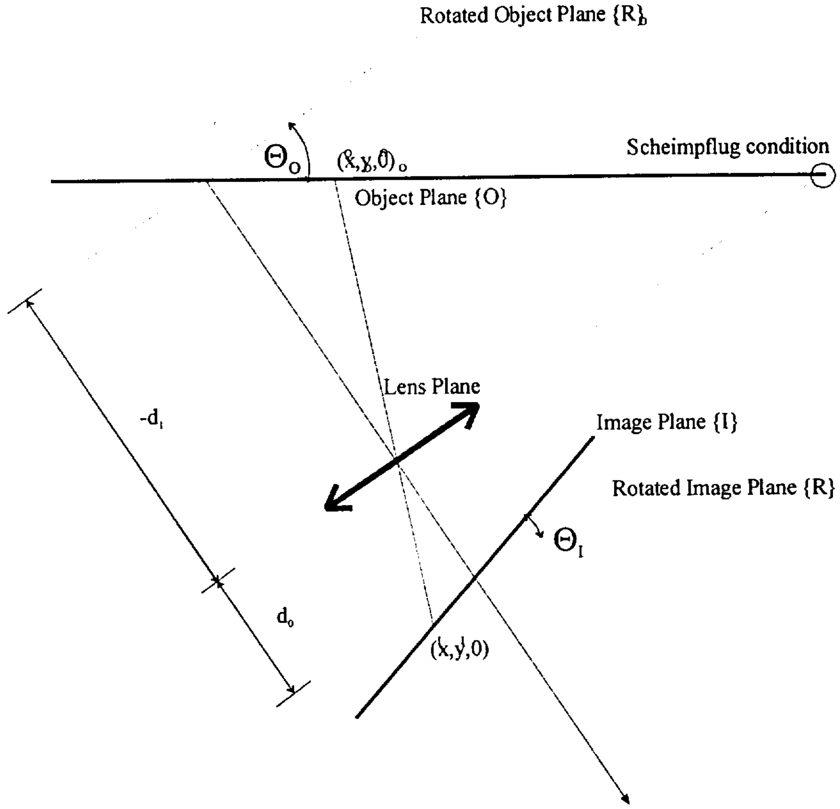

FIGURE 2: IMAGING WITH THE SCHEIMPFLUG CONDITION

In this figure, the reference frame attached to the Object Plane is denoted as *{O}*. The camera lens view angle is θ_O; this angle is measured between the normal to the object plane and the optical axis of the lens. The principal plane of the lens and its axis form a reference plane *{L}*. The image plane rotated by θ_I constitutes another important reference frame *{I}*, the image reference frame. The angle of rotation, θ_I, is determined from the condition required for sharp focus, called the Scheimpflug condition, which states that the Image, Object and Lens planes must intersect at a common line. As per figure 2 this condition is observed when the following relationship exists between the tangents of the camera lens view angle and the tilt angle of the image plane:

$$tg\theta_O = \frac{d_1}{d_0} \cdot tg\theta_I \qquad (1)$$

Where $\boldsymbol{d_0}$ and $\boldsymbol{d_I}$ are the distances from the image plane and the object plane to the principal plane of the lens, respectively, measured along the optical axis.

According to this model the relationship between the coordinate positions of image points to their corresponding object points is found and given by:

$$\begin{aligned} {}^O x &= \frac{-{}^I(x - x_{CL}) \cdot \left(\cos\theta_I / \cos\theta_O \right) \cdot d_1}{d_0 - {}^I(x - x_{CL})\sin\theta_I \left(1 + \frac{d_1}{d_0} \right)} \\ {}^O y &= \frac{-{}^I(y - y_{CL}) \cdot d_1}{d_0 - {}^I(x - x_{CL})\sin\theta_I \left(1 + \frac{d_1}{d_0} \right)} \end{aligned} \qquad (2)$$

In equations (2) the superscript O and I denote the position of a point in the object and image plane respectively. Implicit into the relationship there is six parameters that are experimentally found by means of a calibration procedure. These parameters are d_0: the distance between the principal plane of the lens and the image sensor, d_I: the distance between the principal plane of the lens and the object plane, θ_O, θ_I, and (x_{CL}, y_{CL}): the coordinates of the optical axis at the sensor plane.

This calibration procedure ensures that the view from the camera is free from perspective effects and it provides the necessary correspondence between the coordinate positions in the object and image plane. An important underlying assumption is that the displacements are assumed to be limited to the object plane, i.e. three-dimensional effects are not considered. When the displacement field is three-dimensional a second camera view is required for the accurate in-plane displacement reconstruction. Additionally, the out-of-plane component of the displacement may also be accurately determined. This is the basis for the stereo-PIV system.

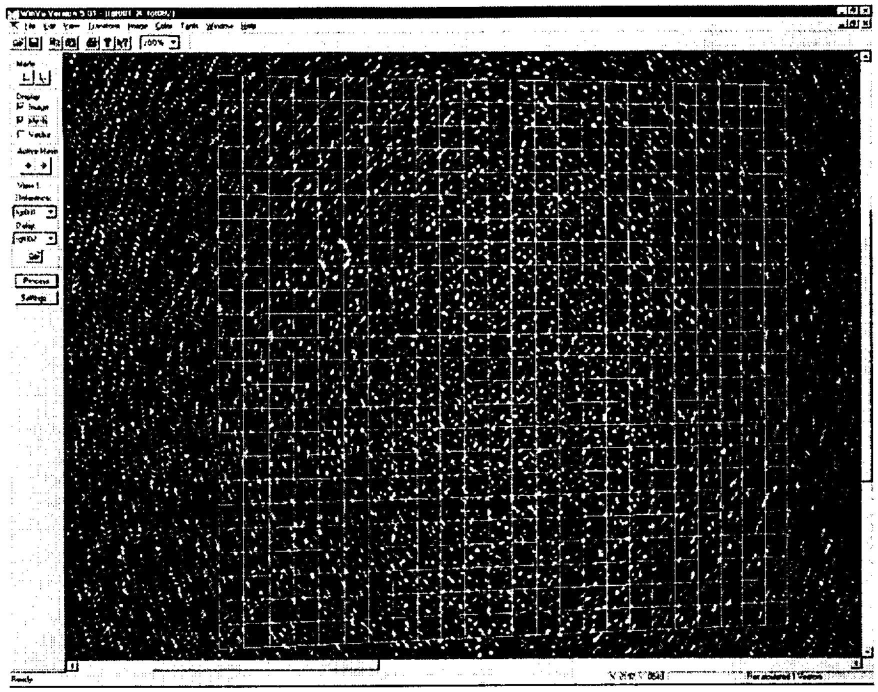

FIGURE 3: IMAGE OF CALIBRATION TARGET

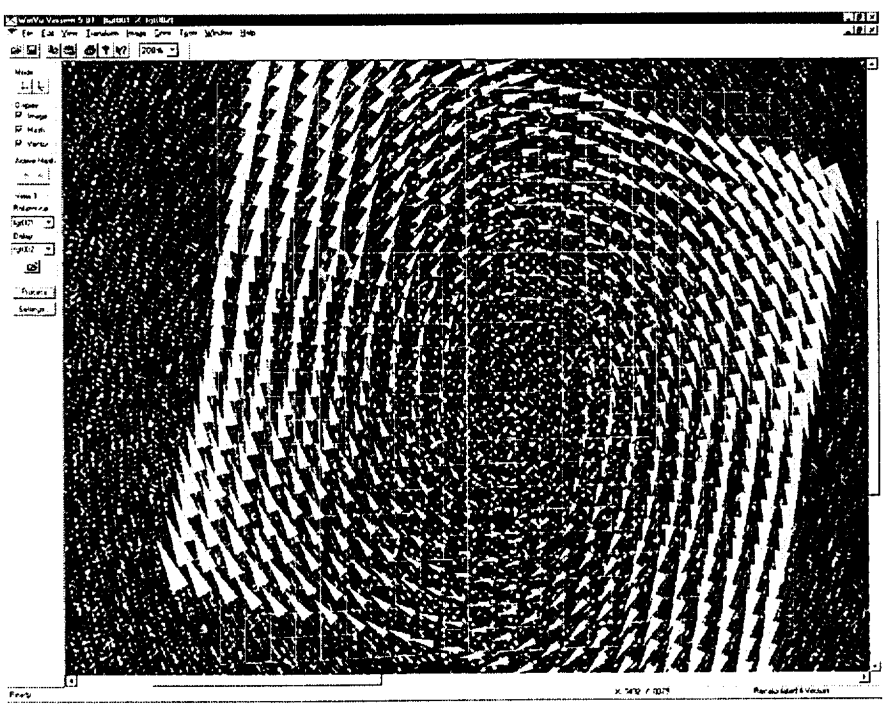

FIGURE 4: IMAGE OF CALIBRATION TARGET

To verify the proposed approach a proof of principle test was carried out, which consisted of measuring the solid body rotation of the calibration target. A composite image of the disk before and after the rotation, as well as the mesh points for the displacement computation mapped to account for the perspective correction, is shown in figure 3.

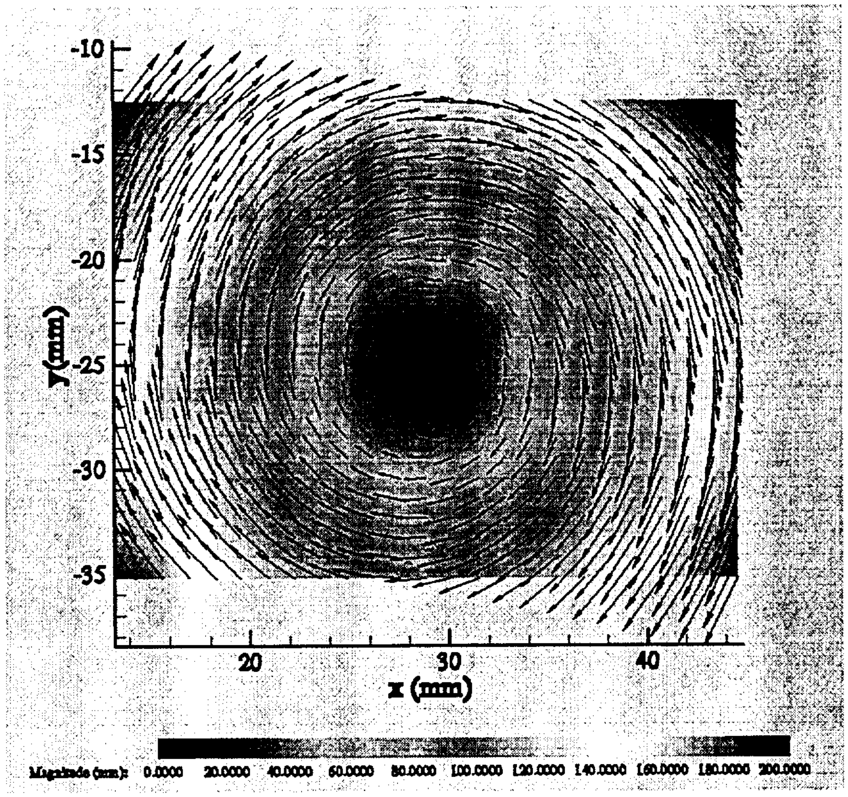

FIGURE 5: SOLID-BODY ROTATION
OBJECT PLANE (CORRECTED)

Upon processing, with the high-resolution correlation algorithm (reference 2), the corresponding displacement field is presented in figure 4. The perspective effect is evident from the figure, which indicates shows an "ellipsoid" field.

Application of the transformation relationships (2) yields the results of figure 5. The figure depicts the vector and the magnitude field of the displacement and clearly demonstrates that an accurate representation of the two-dimensional displacement field is indeed obtained. The range of displacements is 200 microns and maximum difference between the actual versus the measured displacement is less than 2 microns. This test also served as a confirmation of the algorithm's capability to resolve regions with large displacements (velocity) gradients.

3 – TEST RESULTS

The flow images were acquired using an image acquisition/processing system that includes a dual Kodak ES1.0 camera system and a Spectra-Physics dual Nd-Yag, PIV-400, laser system. The camera was operated in the double triggered mode (with the time between image pairs of 30 microseconds) and acquisition rate of 15 image-pairs/second.

Figure 6 is a composite sum of two frames acquired in quick succession. The condition is 180 degrees wake age. It is noteworthy that the images of the small tracer particles remain in focus across the entire field of view. The most notable feature in the picture is that in addition to providing streakline visualization, as in the case of conventional smoke visualization, the flow streamlines are apparent due to the double exposure. This added feature is essential for the interpretation of the images. Processing of the flow images using the cross-correlation software, yielded the velocity field, as shown in figure 7This finding was consistent for the entire range of experimental conditions tested.

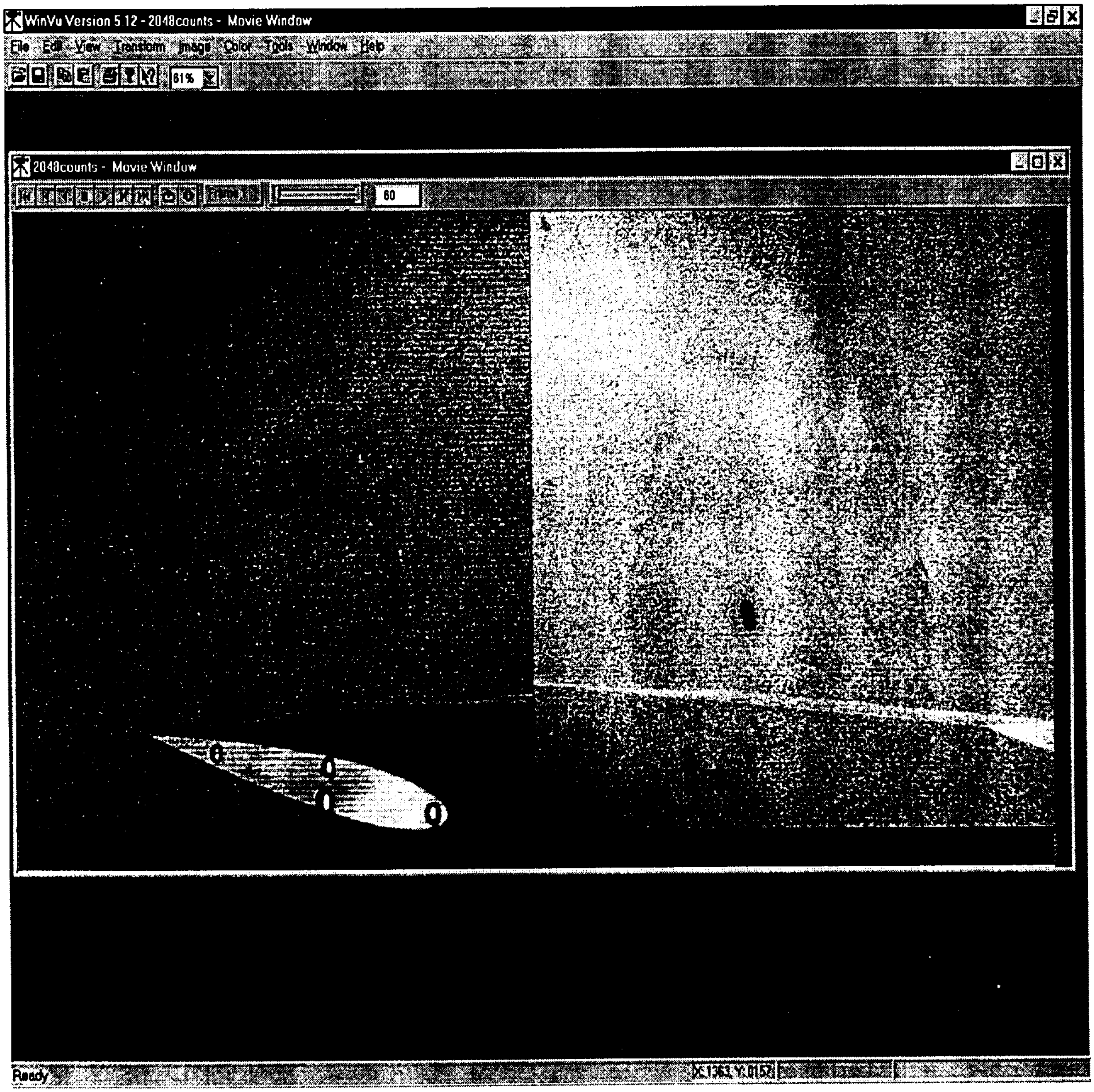

FIGURE 6: STREAKLINE AND STREAMLINE FLOW VISUALIZATION (DOUBLY EXPOSED FRAME)

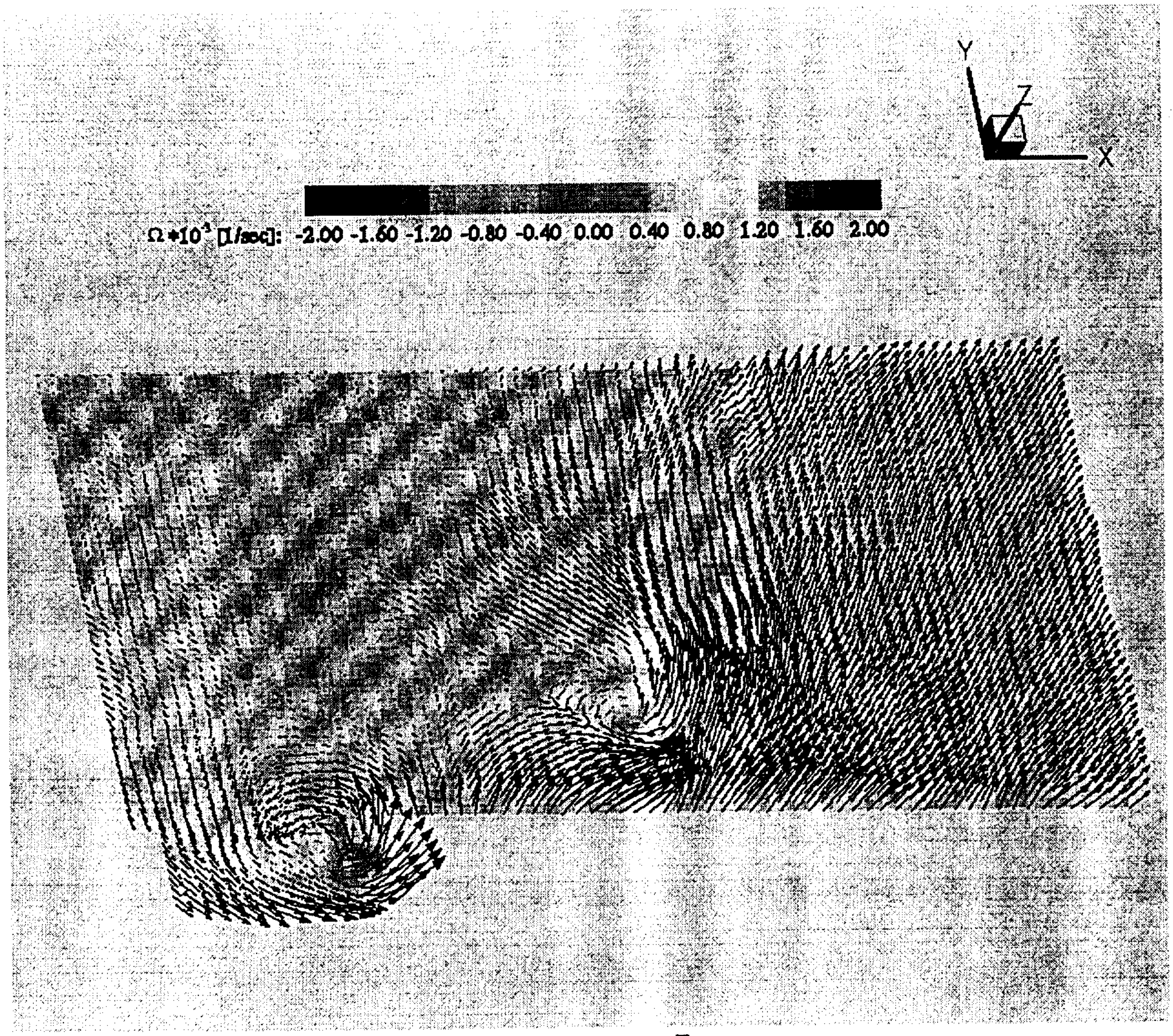

FIGURE 7: VELOCITY FIELD

4 – CONCLUSIONS

In this study the usefulness of the PIV technique as a flow diagnostic tool in large wind tunnel setting is clearly demonstrated. The main features of the technique as it was applied, were the off-axis-imaging mode for 3-D velocity measurement and the high-resolution processing scheme.

REFERENCES

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