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QUARTERLY TECHNICAL PROGRESS REPORT
ON FUDEMENTAL HYDRODYNAMICS RESEARCH
(ONR - CODE 12)

1 October 1990 Through 31 December 1990

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Prepared by Cognizant ARL Penn State
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PREFACE

Under the sponsorship of The Office of Naval Research (Code 12) AHR Program, The Applied Research Laboratory of Penn State University performs basic research in hydrodynamics and hydrodynamic noise. The hydrodynamics research conducted under this program falls into two basic thrust areas:

- Turbomachinery

  To develop an improved understanding of the fluid mechanics and acoustics associated with low-speed turbomachines and marine propulsors. To employ this knowledge to the development of improved propulsor and turbomachine design methods.

- Drag Reduction

  To develop fundamental understanding of the mechanisms that cause drag on bodies and surfaces and to explore novel methods to reduce drag.

Under each thrust area, one or more projects are conducted under the direction of the principal investigator who initiated the given task. All tasks are designed to provide results that will improve the scientific understanding of various hydrodynamic phenomena associated with the operation of submerged bodies and surfaces.

This report documents the technical progress realized during the last quarter of FY 90 for the projects currently approved under this program.

TURBOMACHINERY Subtask T1

TURBOMACHINE INTERNAL FLOW DEFINITION

(S. A. Abdallah, University of Cincinnati)

BACKGROUND

The internal flow field of a wake adapted turbomachine is dominated by three dimensional and unsteady effects. The three dimensionality of the flow field is demonstrated by the strong secondary flows which have been experimentally measured. The unsteadiness of the flow is due to the interaction of the downstream blade rows with the wakes shed from the upstream blade rows. The development of computational tools to accurately predict these types of flow fields is essential if successful development of high performance turbomachinery is to be achieved.

PROGRESS

1. Fotis Sotiropoulos received the R.T. Davis award from the University of Cincinnati for his research work in Computational Fluid Dynamics under this project. The award consists of a certificate of recognition and a check for $500.00

2. The conversion of our ship hull code to an internal flow code for turbomachinery (stators and rotors) is in progress. Preliminary results were obtained for a Rocketdyne test inducer. This inducer was tested for water. Velocity measurements were obtained at different axial and radial locations as shown in Figure 1. Verification of incompressible codes using the experimental data of this inducer is the subject of a NASA workshop. We will participate in the workshop with our results in May, 1991. The drawbacks of the experimental data are (1) no pressure measurements are available and (2) no velocity profile at the inlet station is available. In our results, we used the experimental data at the first measurement station as the inlet velocity profile. This is a very approximate way to estimate the inlet velocity. However, the computed results show good comparison with the experimental data as shown in Figure (2). The computed results show that the process of converting the ship hull code to a turbomachinery flow solution is proceeding successfully. Further tests are still necessary.

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Figure 1a

CFD CODE VERIFICATION INDUCER
DATA PLANES AND GEOMETRY DEFINITION

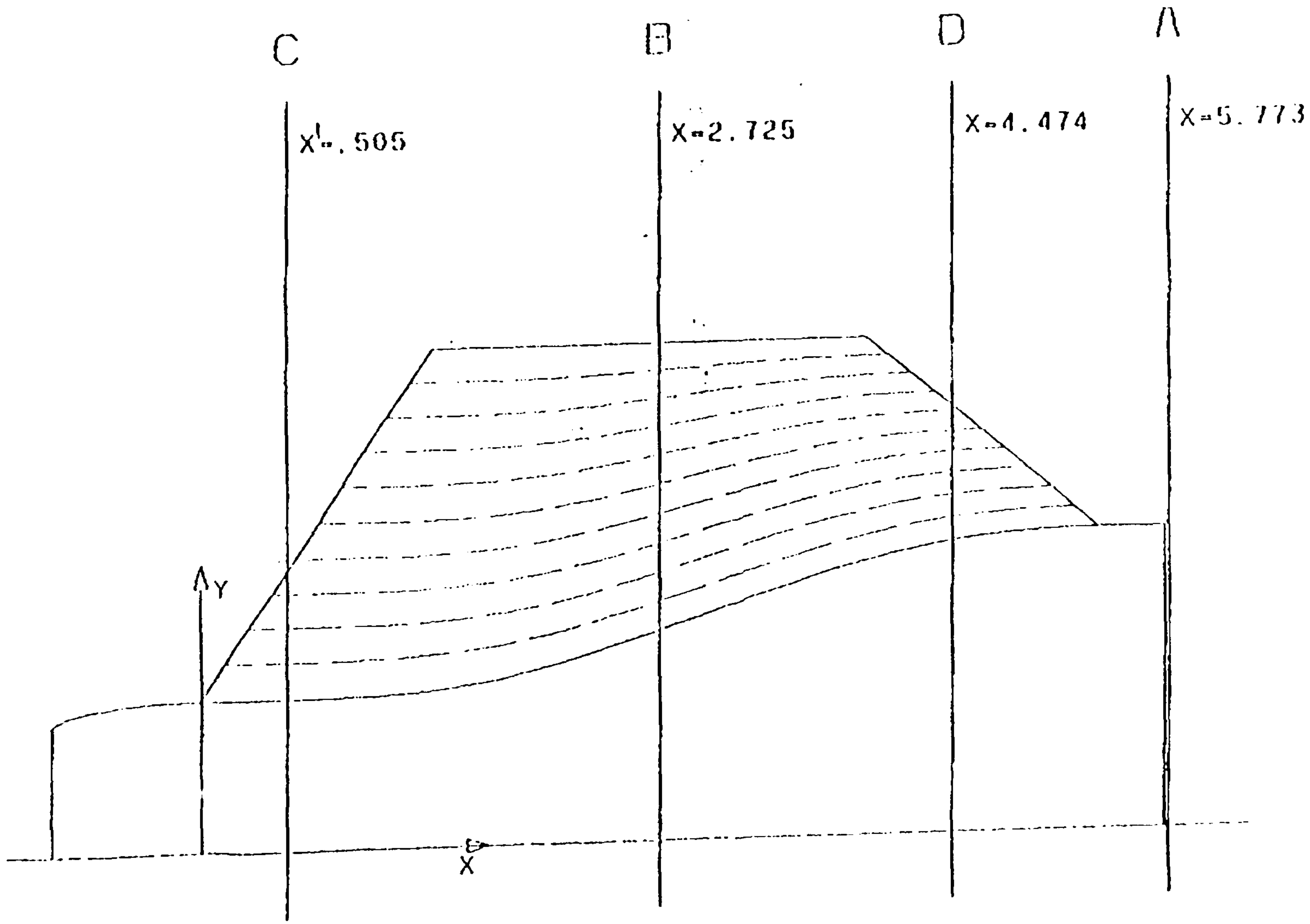
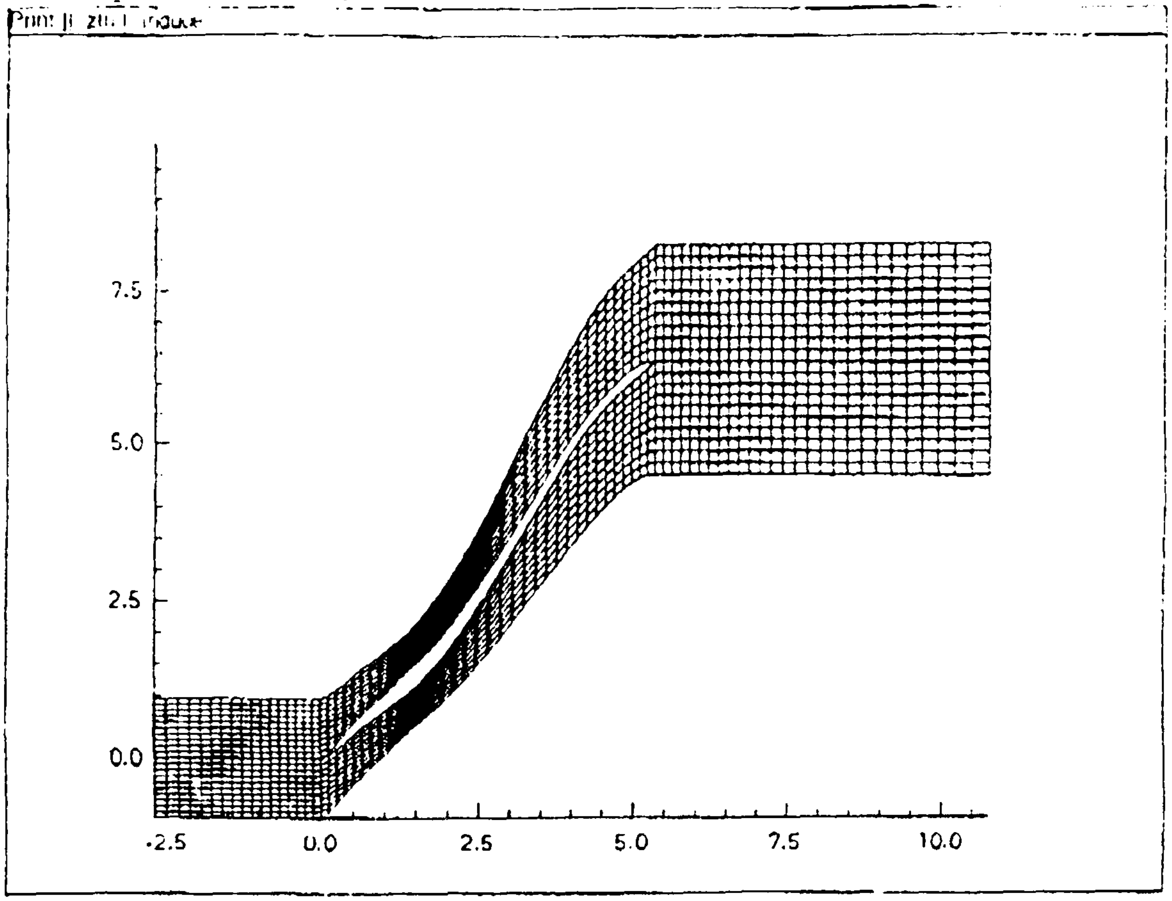


Figure 1b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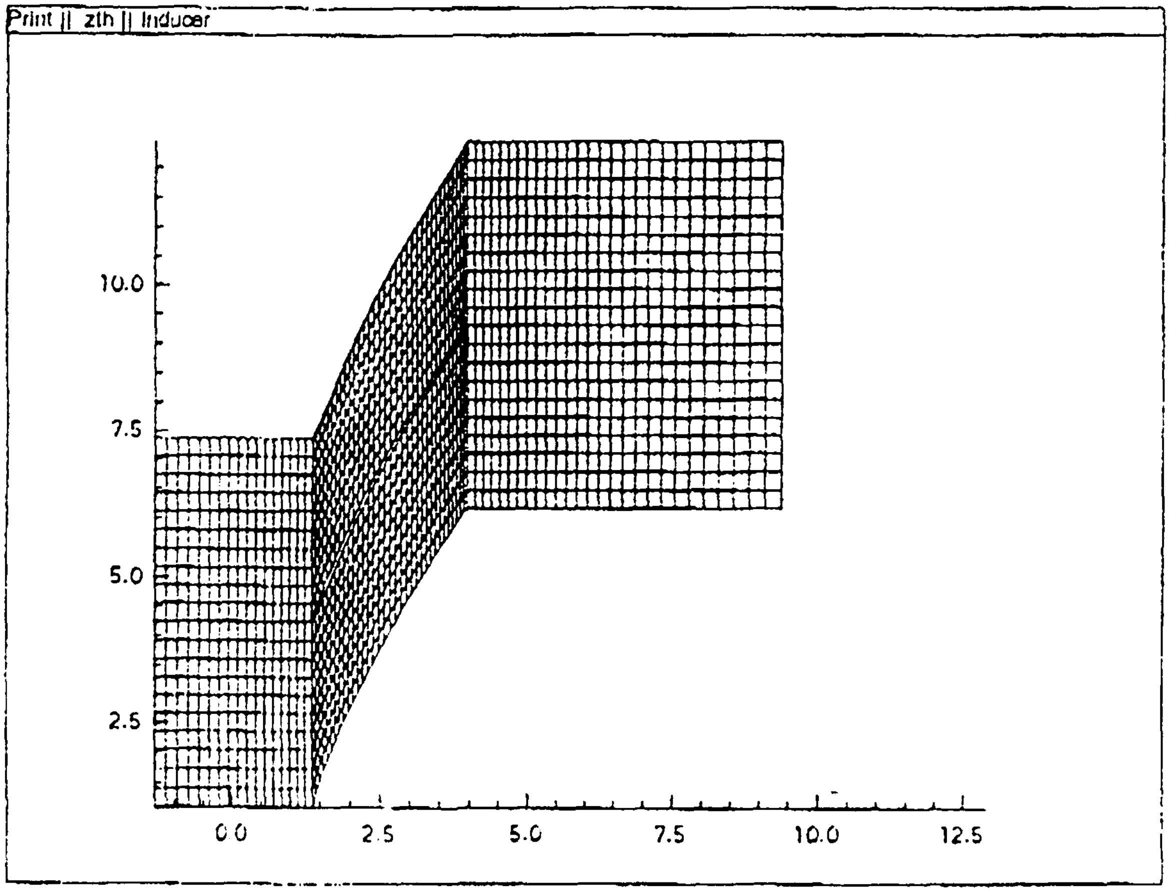
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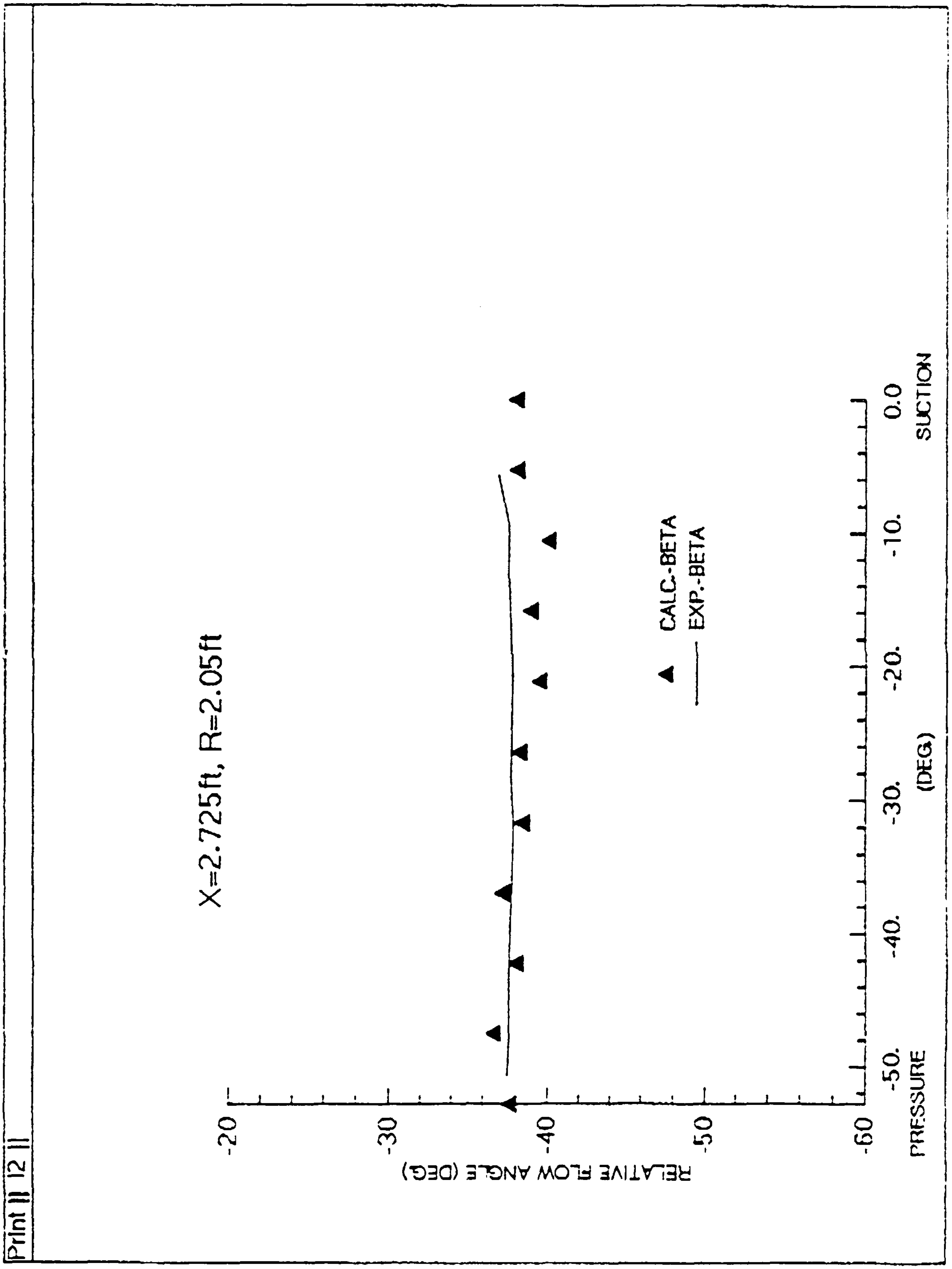
Figure 1c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-40
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PRESSURE
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(DEG)
-20.
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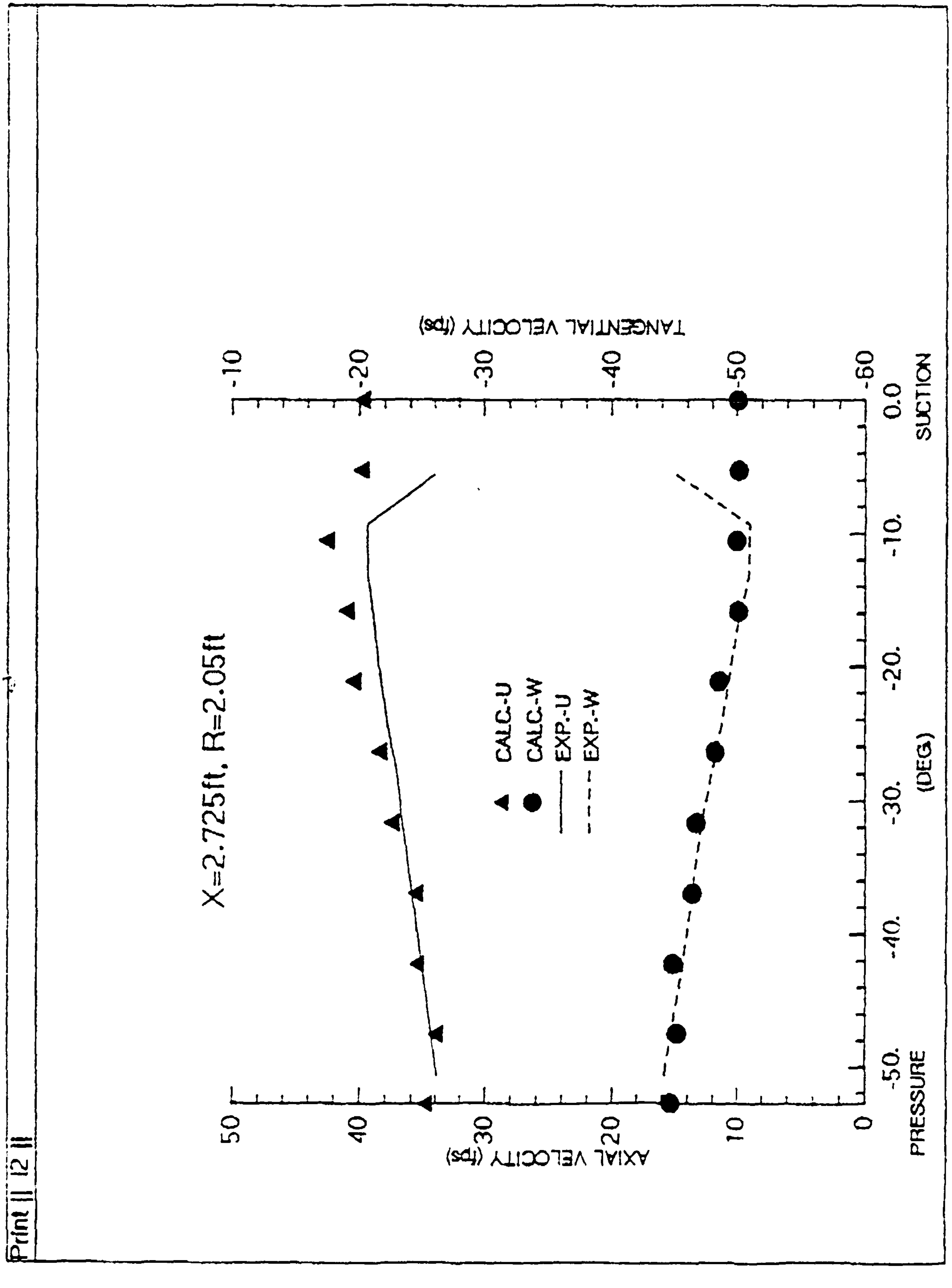
SUCTION

Figure 2a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AXIAL VELOCITY (fps)
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PRESSURE
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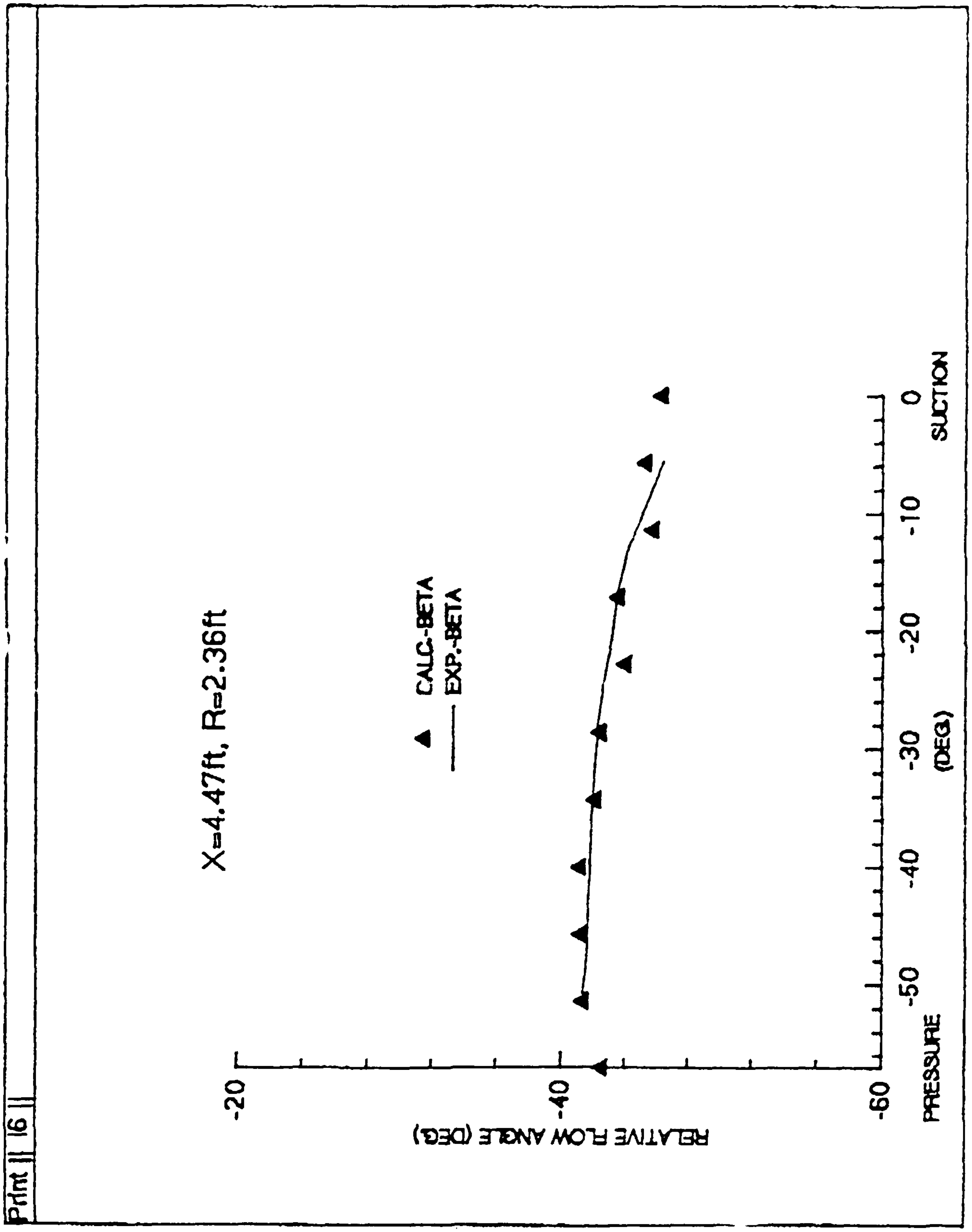
SUCTION

Figure 2b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-20
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SUCTION
(DEG)
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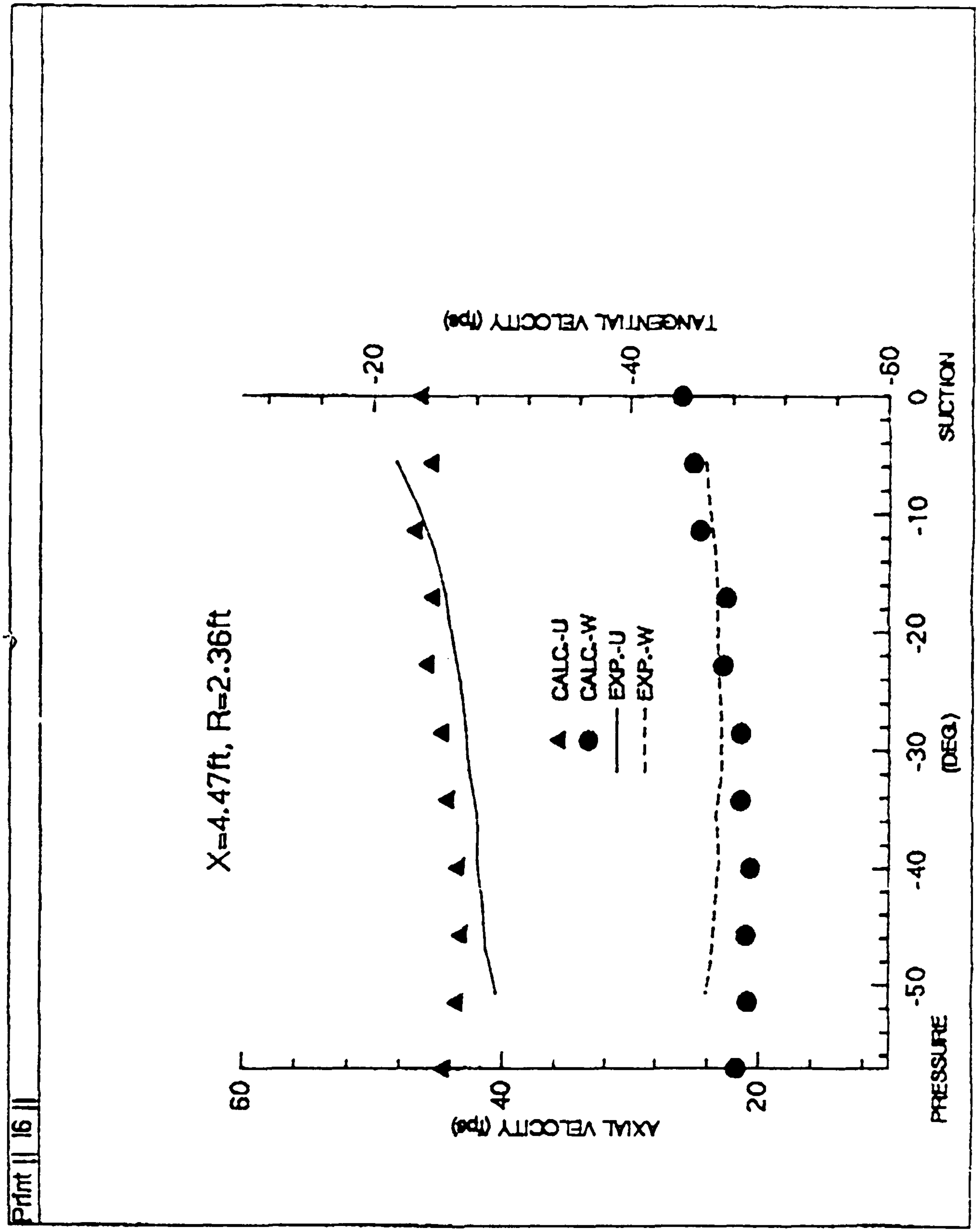
Figure 2c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AXIAL VELOCITY (fps)
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SUCTION
PRESSURE
Print || 16 ||

Figure 2d

TURBULENT SPOT GENERATION BY FREELY SUSPENDED PARTICLES IN A FLAT PLATE LAMINAR BOUNDARY LAYER

(Howard L. Petrie and P. J. Morris)

BACKGROUND

Laminar flow control (LFC) has been an attractive technology for many years but premature transition, induced by particles in the fluid, has prevented its successful hydrodynamic implementation. Although an extensive amount of experimental work and analysis has examined the transition induced by various types of roughness elements and intermittent disturbances such as sparks, basic questions regarding the mechanisms for transition induction by freely suspended particles still remain unanswered. The subject experimental and analytic study of particle induced transition is concerned with these issues.

EXPERIMENTAL PROGRESS

The experimental activities for the last quarter have been concerned with the evaluation and set-up of the test channel and support hardware. A frame to support LDV equipment has been designed and is being built. Also, it is apparent that control of the channel drive motor and therefore the velocity needs some work. A feedback control loop and a finer speed adjustment control are being considered but further evaluation of the problem are needed.

The use of a gravity feed seepage for dye slot injection has been evaluated and the system works acceptably. Bubbles in the dye slot plenum have to be flushed out before uniform dye flow is achieved but this is the only apparent difficulty and this is easily accomplished. Both food coloring and fluorescent dyes have been evaluated.

It is has not yet been determined yet whether or not the honeycomb section is needed in the channel plenum. For the moment, no honeycomb is in the channel although the plenum is designed to accept it. A large piece of honeycomb has been acquired for this purpose and is in-house.

LDV surveys will help to resolve some of these issues and will guide the final configuration of the channel for the experiments. Parts of a HeNe LDV system, located at the channel, is on loan from the Mechanical Engineering Department and is somewhat of an unknown. Digitizing the output of an ARL analog output module with an Aerospace Engineering Department A-to-D board is the present plan for sampling data. Software for data acquisition via this approach needs to be coded. The plan for now is to revise the acquisition routines of an existing code written for LDV computer interfaces at ARL. Additional LDV equipment should be available from ARL in April or May. The ME LDV system and its performance will be evaluated as soon as possible in the next quarter.

Some of the preparations for the fixed particle experiments have been made. These include drilling of particles and preparation of support pieces. The plan now is to place particles on wire at or near the wall. A screen and perforated plate assembly will be placed downstream in the channel to help clean the flow up in return elbow of the channel and to catch particles that may come loose or break free. Plates to set the height of the particles are needed but these are very simple devices. We are still debating about the method for particle release for the freely convecting particle experiments but will commit to a given method for evaluation soon.

PROGRESS OF THE ANALYSIS

A freely suspended particle in a flow is known to affect boundary layer transition. In order to study this effect, we have first predicted the trajectory of such a particle (for various radii, specific gravities and release locations and velocities). The next step is to compute the fluctuations this particle creates to disturb the laminar boundary layer. We propose initially that the disturbance may be considered to be in the form of wave packets. First, we study why and how these wave packets develop, and then set up a computational scheme to simulate them.

DEVELOPMENT OF WAKE PACKETS IN A LAMINAR BOUNDARY LAYER

A wave packet generated by an impulse disturbance causes oscillations in the flow as it spreads out while travelling downstream (Gaster and Grant, 1975). This initial disturbance generates all possible modes and the wake packet forms through selective amplification and interference of the most unstable waves. This phenomenon can be simulated numerically using a linear stability analysis (Gaster, 1975). The wave packet is reproduced computationally linearly by combining spatially unstable modes and summing over all wavenumbers and frequencies.

To study the initial value problem for any general disturbance in a viscous flow, the Orr-Sommerfeld equation must be solved. The eigensolutions to this equation are discrete modes which form a complete system for bounded flows. However, for boundary layer flows with a semi-infinite domain, there is also a viscous continuous spectrum (Gustavsson, 1978). As the Reynolds number increases, one mode approaches the inviscid Rayleigh mode while the higher modes tend towards a neutrally stable inviscid continuum. For three-dimensional disturbances in a piecewise linear boundary layer, the vertical velocity has two parts - one is a dispersive part which comes from Rayleigh equation solution, and the other is a convected part from inviscid continuous spectrum. Also, there is a permanent scar caused by the fact that the streamwise velocity does not vanish at large times. It is advected at the local mean velocity. Most three-dimensional disturbances show a linear increase in energy with time (Landahl, 1980). This behavior is different from that predicted by two-dimensional stability analysis that predicts that transient modes decay.

The time-evolution of a small disturbance can be computed using Fourier transform methods. Results show that transient modes do not decay as rapidly as dispersive modes (Henningson, 1988). This method has been extended to the Blasius boundary layer by Breuer and Haritonodis (1990). Both numerical and experimental results indicate the formation of linearly unstable wave packets, and of dominant transients which, for weak initial disturbances, eventually decay due to viscous effects For weak disturbances a linear stability analysis is applicable and this approach is discussed in detail in the next section. For strong disturbances direct numerical simulation is necessary. For these high-amplitude disturbances, the transients do not decay. Non-linear effects lead to the direct breakdown of the disturbance to a turbulent spot, bypassing the wake packet stage.

For low-amplitude initial disturbances in a flat-plate boundary layer at moderate Reynolds numbers, the route to transition is through a wave packet breakdown which occurs over a broad spatial domain (Tso, Chang and Blackwelder, 1990). Since the growing wave packet moves significantly slower than the diminishing transient, hump-like disturbance, there is little interaction between them and only the wave packets are responsible for transition. With strong initial disturbances however, the transition mechanism is through the growth of the transients into a turbulent spot. Initially, we will consider only weak disturbances in modeling the effect of the particles.

NUMERICAL SIMULATION OF WAKE PACKETS

Gaster's theoretical linear model simulates successfully his experimentally-observed wave packet excited by a localized pulse at the wall. While Gaster's simple linear model works well for calculations at a fixed height above the plate, it cannot account for a variation in the vertical direction. A recent method developed by Breuer and Haritonodis (1990) employs a time-marching technique to compute the development of wave packets from small-amplitude disturbances. This approach does capture the dependence of the wake packet on the y-location of the source of the disturbance. This is exactly what is required to study the effect of a particle disturbing a boundary layer as it moves through it. We use Breuer's analysis in the development of our computational scheme, and compare results for the initial disturbance due to a pair of vortices to verify our code. The initial disturbance can then be modified to model the particle moving across the boundary layer.

The equation governing linear, inviscid, small disturbances for the vertical velocity is the Rayleigh equation

$$\left(\frac{\partial}{\partial t} + i\alpha U\right)\left(\frac{\partial^2}{\partial y^2} - k^2\right)\tilde{v} - i\alpha U''\tilde{v} = 0$$

where $k^2 = \alpha^2 + \beta^2$. Here α,β are the streamwise and spanwise wavenumbers respectively. $\tilde{v}$ is the transformed vertical velocity perturbation obtained by taking aFourier transform in x and z of the physical fluctuation quantity

$$\tilde{v}\,(y,t;\alpha,\beta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v\,(x,y,z,t)\,\exp\left[-i\,(ax + \beta z)\right] dx\,dz$$

Under assumption of locally parallel flow, a Blasius profile is used for the basic flow U(y). The velocity fluctuations perpendicular to and along the wavefront, $\tilde{u}_1$ and $\tilde{w}_1$ are related to $\tilde{v}$ by

$$\left(\frac{\partial}{\partial t} + i\alpha U\right)\tilde{u}_1 = \frac{i}{k}\left(\frac{\partial}{\partial t} + i\alpha U\right)\tilde{v}_y$$

$$\left(\frac{\partial}{\partial t} + i\alpha U\right)\tilde{w}_1 = -\frac{\beta}{k}\,U'\tilde{v}$$

The two physical velocity perturbations can be retrieved from these by

$$\tilde{u} = \frac{1}{k}\left(\alpha \tilde{u}_1 + \beta \tilde{w}_1\right)$$

$$\tilde{w} = \frac{1}{k}\left(\beta \tilde{u}_1 - \alpha \tilde{w}_1\right)$$

The Rayleigh equation can be rewritten as a system of two equations

$$\frac{\partial \nabla^2 \tilde{v}}{\partial t} = i\alpha \left(U'' \tilde{v} - U \nabla^2 \tilde{v}\right)$$

$$\nabla^2 \tilde{v} = \left(\frac{\partial^2}{\partial y^2} - -k^2\right) \tilde{v}$$

These equations can be marched forward in time using a Crank-Nicholson scheme and a second-order accurate finite difference for the y-derivative, for which the discretized equations are

$$\nabla^2 \tilde{v}_j^{n+1} - \nabla^2 \tilde{v}_j^n = \frac{i\alpha \Delta t}{2}\left(U_j'' \left(\tilde{v}_j^{n+1} + \tilde{v}_j^n \right) - U_j \left(\nabla^2 \tilde{v}_j^{n+1} + \nabla^2 \tilde{v}_j^n \right)\right)$$

$$\nabla^2 \tilde{v}_j^n = \frac{\tilde{v}_{j+1}^n - 2\tilde{v}_j^n + \tilde{v}_{j-1}^n}{\Delta y^2} - k^2 \tilde{v}_j^n$$

where n refers to the current time-step and j refers to the vertical grid. In vector form, at time-step n, a matrix equation is obtained

$$(I + iR)\, D\tilde{v}^{n+1} = (I - iR)\, D\tilde{v}^n + iS\left(\tilde{v}^{n+1} + \tilde{v}^n\right)$$

where

$$\tilde{v}^n = \left[\tilde{v}_j^n\right]^T \qquad j = 1,2,\ldots,J$$

$$R = \frac{\alpha \Delta t U_j}{2} I$$

$$S = \frac{\alpha \Delta t U_j''}{2} I$$

I is the identity matrix and D is the tridiagonal matrix associated with the Laplacian derivative in the normal direction.

Therefore, the explicit form for the velocity at the (n + 1)th time-step is

$$\tilde{v}^{n+1} = (D + i\,(RD - S))^{-1}\,(D - i\,(RD - S))\,\tilde{v}^{n}$$

Similarly for $\tilde{w}_1$ the matrix equation is

$$(I + iR)\,\tilde{w}_1^{n+1} = (I - iR)\,\tilde{w}_1^{n} - T\,(\tilde{v}^{n+1} + \tilde{v}^{n})$$

where

$$T = \frac{\Delta t \beta U'}{2k}\, I$$

This can also be integrated forward in time using the current values for $\tilde{v}^n$ and $\tilde{v}^{n+1}$. The quantity $\tilde{u}_1$ is obtained simply from

$$\tilde{u}_1 = \frac{i}{k}\,\tilde{v}_y$$

As a test case for our code, we use the initial conditions of Breuer et al. which simulate a localized, impulsive disturbance in the form of two pairs of counter-rotating longitudinal vortices, represented by the stream function

$$\Psi = \bar{x}\bar{z}\bar{y}^2 \exp\left(-\bar{x}^2 - \bar{y}^2 - \bar{z}^2\right)$$

where $\bar{x},\bar{y},\bar{z}$ are the three Cartesian coordinates scaled by appropriate scaling factors

$$\bar{x} = x/l_x; \qquad \bar{y} = y/l_y; \qquad \bar{z} = z/l_z$$

At $t = 0$ the center of the disturbance is located at $x = 0$, $z = 0$.

Since all the matrices are tridiagonal, the system of two matrix equations is readily integrated in time. Furthermore, for fixed α, β and Δt the matrices need to be evaluated and combine only once. Hence time- marching for $\tilde{v}$ at the next time-step reduces to a simple multiplication of a matrix by the vector $\tilde{v}$ at the current time step. This speeds up the computations for each pair of (α, β). 64 modes are used for α and 32 for β. These are sufficient to produce smooth contour plots for various velocity fluctuations. These may be obtained at any desired time t by taking the (inverse) fast Fourier transform of the transformed velocities to convert the fluctuations back to physical space. This is done at each y-location to get complete picture across the boundary layer. The code for this test case is in the final stages of development.

PLANS

The main experimental activities for the next quarter will be to resolve the channel speed controller problems. ARL technicians will be asked to make an evaluation as the Aerospace Engineering Department does not have this kind of technical support. The frame to support the

LDV system will be built and an evaluation of the LDV system performance will be made as soon as possible. The channel and its support pieces should be close to being ready for the fixed particle experiments by the end of the next quarter.

The wave packet development is being computed using linear theory and a computationally efficient time-marching scheme. Computations for weak initial disturbances will be extended to include moving sources, such as particles in a boundary layer. Work is in progress on how to model the particle as an initial disturbance. The models will be based primarily on experimental results available in the literature. For a moving particle, the wave packets generated at each y-location can be computed individually and then superposed linearly to get the entire flow field. Once the formation of incipient turbulent spots is understood, their prevention or control may be attempted.

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Subtask DR2

TURBULENT BOUNDARY LAYER MODIFICATION BY SUCTION

(Howard L. Petrie)

BACKGROUND

Small amounts of wall suction reduced boundary layer turbulence substantially. Data presented to the sponsor and discussed in past annual reports have shown that suction coefficients, C_q, as low as -0.0001 can reduce turbulent boundary layer (TBL) RMS and Reynolds stress levels noticeably. The suction coefficient is the ratio of the velocity induced by suction normal to the surface to the freestream velocity. This has the potential benefits of TBL flow quieting and may also be useful for reducing possible TBL sources of unsteady forces and noise affecting propulsors.

Speculative explanations for the effects of wall suction on TBLs have been given. Suction may counteract the ejection velocity of lifting streaks of low momentum fluid or suction may stabilize the sublayer to delay and prevent bursting at the wall. To date, most research involving suction with turbulent boundary layers (TBLs) has used discrete spanwise slots or a continuously porous surface to apply suction. The emphasis of many of these past efforts has been on heat transfer and skin friction changes with suction. Much of this past work was limited to mean velocity profile measurements or turbulence measurements at relatively high suction rates. Recent flow has visualization and hot-wire work by Antonia, et al. (1988, 1989) has examined the effects of suction on the structure of the TBL in greater detail. The flow visualizations support that suction does stabilize wall streaks such that they oscillate less in the spanwise direction and persist longer prior to lifting.

PROGRESS

A series of experiments were conducted in the 12-inch diameter water tunnel at ARL over a period of 5 weeks. LDV surveys, drag balance measurements and limited surface pressure fluctuation measurements were made. Both a uniform and a tailored suction surface were considered. Data analysis has begun but is not completed. A brief review meeting has held with the sponsor in November 1990.

PLANS

Data analysis will be completed in the next quarter and a draft of a comprehensive memorandum will be written. The project will run out of funds before either of these tasks are accomplished.

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2. Antonia, R. A. and Fulachier, L. "Topology of a Turbulent Boundary Layer With and Without Wall Suction," JFM, V198, 1989, pp. 429-451.

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FIELD	GROUP	SUB-GROUP	turbomachinery, drag reduction, particle trajectories, transition, computational fluids, unsteady 3-D flows, turbulent flow

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Under the sponsorship of The Office of Naval Research (Code 12) AHR Program, The Applied Research Laboratory of Penn State University performs basic research in hydrodynamics and hydrodynamic noise. The hydrodynamics research conducted under this program falls into two basic thrust areas: (1) Turbomachinery - To develop an improved understanding of the fluid mechanics and acoustics associated with low-speed turbomachines and marine propulsors. To employ this knowledge to the development of improved propulsor and turbomachine design methods. (2) Drag Reduction - To develop fundamental understanding of the mechanisms that cause drag on bodies and surfaces and to explore novel methods to reduce drag.

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