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NUMERICAL SIMULATION OF STEADY AND UNSTEADY VISCOUS FLOW IN TURBOMACHINERY USING PRESSURE BASED ALGORITHM

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The objective of this research is to simulate steady and unsteady viscous flows, including rotor/stator interaction and tip clearance effects in turbomachinery.

The numerical formulation for steady flow developed here includes an efficient grid generation scheme, particularly suited to computational grids for the analysis of turbulent turbomachinery flows and tip clearance flows, and a semi-implicit, pressure-based computational fluid dynamics scheme that directly includes artificial dissipation, and is applicable to both viscous and inviscid flows. The values of these artificial dissipation is optimized to achieve accuracy and convergency in the solution. The numerical model is used to investigate the structure of tip clearance flows in a turbine nozzle. The structure of leakage flow is captured accurately, including blade-to-blade variation of all three velocity components, pitch and yaw angles, losses and blade static pressures in the tip clearance region. The simulation also includes evaluation of such quantities of leakage mass flow, vortex strength, losses, dominant leakage flow regions and the spanwise extent affected by the leakage flow. It is demonstrated, through optimization of grid size and artificial dissipation, that the tip clearance flow field can be captured accurately.

The above numerical formulation was modified to incorporate time accurate solutions. An inner loop iteration scheme is used at each time step to account for the non-linear effects. The computation of unsteady flow through a flat plate cascade subjected to a transverse gust revels that the choice of grid spacing and the amount of artificial dissipation is critical for accurate prediction of unsteady phenomena. The rotor-stator interaction problem is simulated by starting the computation upstream of the stator, and the upstream rotor wake is specified from the experimental data. The results show that the stator potential effects have appreciable influence on the upstream rotor wake. The predicted unsteady wake profiles are compared with the available experimental data and the agreement is good. the numerical results are interpreted to draw conclusions on the unsteady wake transport mechanism in the blade passage.

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OUTLINE

- OBJECTIVE
- INTRODUCTION
- NUMERICAL METHOD AND TURBULENCE MODEL
- VALIDATION OF 3D STEADY AND 2D UNSTEADY FLOW
- 3D STEADY FLOW IN THE END WALL AND TIP CLEARANCE REGION OF A TURBINE
- 2D UNSTEADY VISCOUS FLOW OVER AN AIRFOIL
- 2D UNSTEADY VISCOUS FLOW IN A TURBOMACHINERY BLADEROW DUE TO UPSTREAM ROTOR WAKE
- CONCLUSIONS

OBJECTIVE

- To develop efficient, accurate codes and turbulence models for the prediction of steady and unsteady flow field in turbomachinery, including rotor/stator interaction, noise prediction, and tip clearance effects

NUMERICAL METHOD

- Incompressible flow equations

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\left\{\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) + \rho\,\overline{u_i' u_j'}\right]\right\}$$

- 3D steady flow
  - A SIMPLE type relaxation algorithm is used in steady state flow computation
  - The pressure field is coupled (smooth) by the 4th order dissipation scheme
  - Validate for inviscid flow computation

NUMERICAL METHOD (CONTD.)

- 2D unsteady flow
  - A predictor-corrector time-marching algorithm (one predictor step and two corrector steps, Ho and Lakshminarayana (1991), Issa (1985))
  - An iteration scheme has been incorporated to enhance the coupling between the momentum and turbulence equations
- A control volume approach and a non-staggered grid system are used in the numerical solution of the equations
- A two-equation low Reynolds number turbulence model is implemented to account for turbulence effects at high Reynolds number

NUMERICAL METHOD (CONTD.)

- Discretization procedure
  - Backward differencing for temporal discretization
  - Convection and diffusive term is discretized by: (1). upwind scheme (2) 2nd order + 4th order artificial dissipation (Basson and Lakshminarayana, 1992)
  - Cross derivative terms treated explicitly
  - Source terms treated explicitly

- Role of pressure
  - Pressure affects the velocity field through the momentum equations
  - Pressure is coupled with velocity field indirectly through the continuity equation
  - Substitute the discretized momentum equations into the continuity equation for derivation of pressure equation to ensure consistency

VALIDATION/TEST CASES

- **Unsteady flow through a flat plate cascade**
  - **Reduced frequency ($\omega C/2U$) = 0.5, 1.0, 2.5, 5.0, 7.5, and 15.0**
  - **Incidence = 0 and 5 degrees.**
  - **Pitch/Chord (S/C) = 1.0, Stagger angle = 0°**
  - **Reynolds No. = 3.4×10^5 and 1.0×10^6, Gust Strength (V_g/U) = 0.02.**
  - **Good agreement (both amplitude and phase) with Whitehead's analysis**

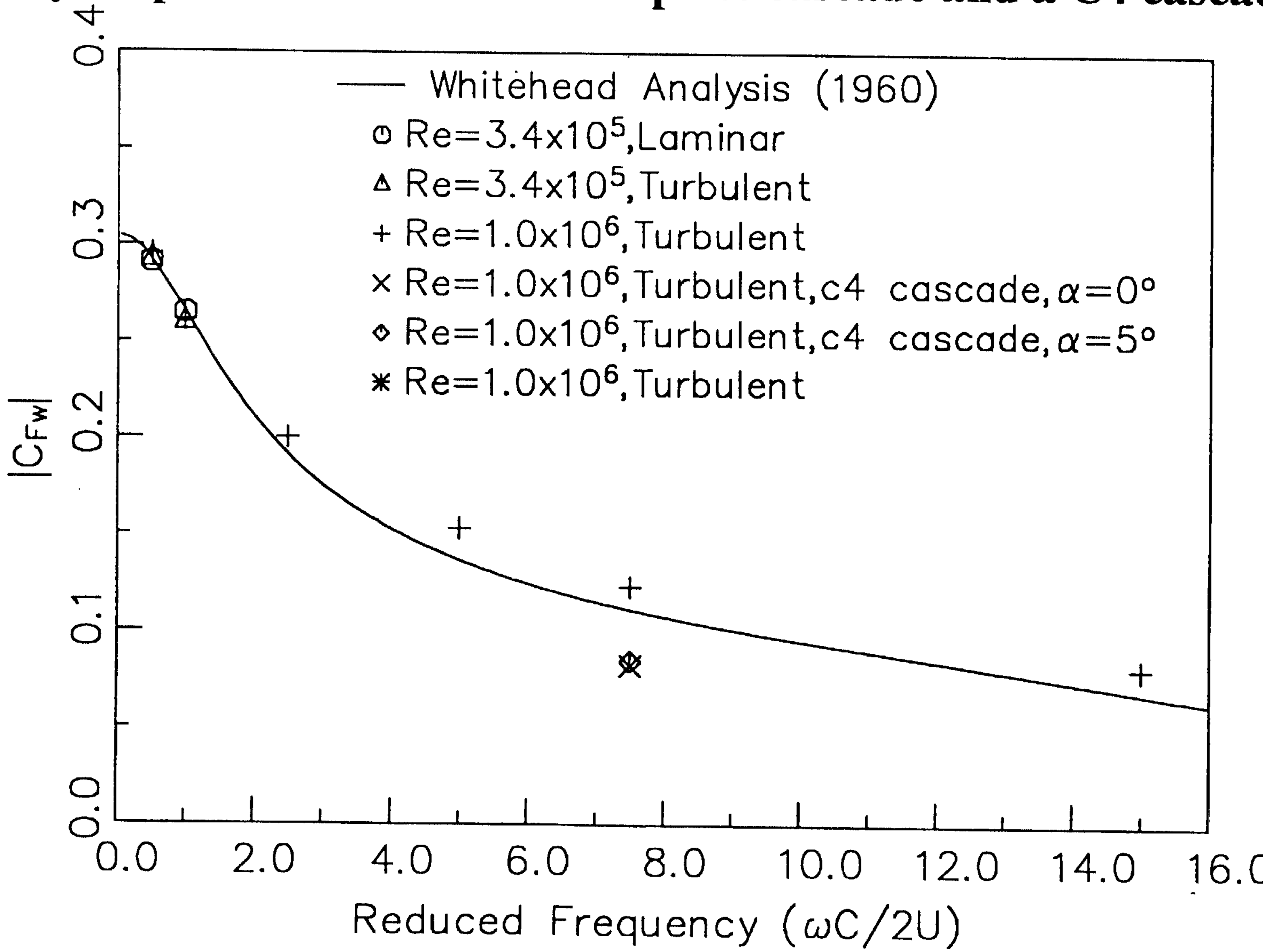
- **Unsteady flow through a C4 cascade**
  - **Reduced frequency ($\omega C/2U$) = 1.0, 5.0, 7.5, and 15.0**
  - **Incidence = 0 and 5 degrees.**
  - **Pitch/Chord (S/C) = 1.0, Stagger angle = 0°**
  - **Reynolds No. = 3.4×10^5 and 1.0×10^6, Gust Strength (V_g/U) = 0.02 and 0.15.**
  - **Practical blade geometry reduces the unsteady response of the blade compared to the flat plate cascade**

VALIDATION/TEST CASES (CONTD.)

- **Unsteady flow through a compressor cascade (Satyanarayana, 1976)**
  - Reduced frequency ($\omega C/2U$) = 0.042
  - Pitch/Chord (S/C) = 0.707, Stagger angle = 45°
  - Reynolds No. = 1.6×10^5, Gust Strength (V_g/U) = 0.082
  - Good agreement between measured and predicted steady and unsteady pressure and wakes.
- **Unsteady flow through a compressor cascade (Stauter et al., 1990)**
  - Reduced frequency ($\omega C/2U$) = 8.48
  - Pitch/Chord (S/C) = 0.964, Stagger angle = 34.2°
  - Reynolds No. = 2.5×10^5, Gust Strength (V_g/U) = 0.25
  - Good agreement between measured and predicted steady and unsteady pressure and wakes.
- **Unsteady flow over an airfoil**
- **Tip clearance flow through a turbine cascade**

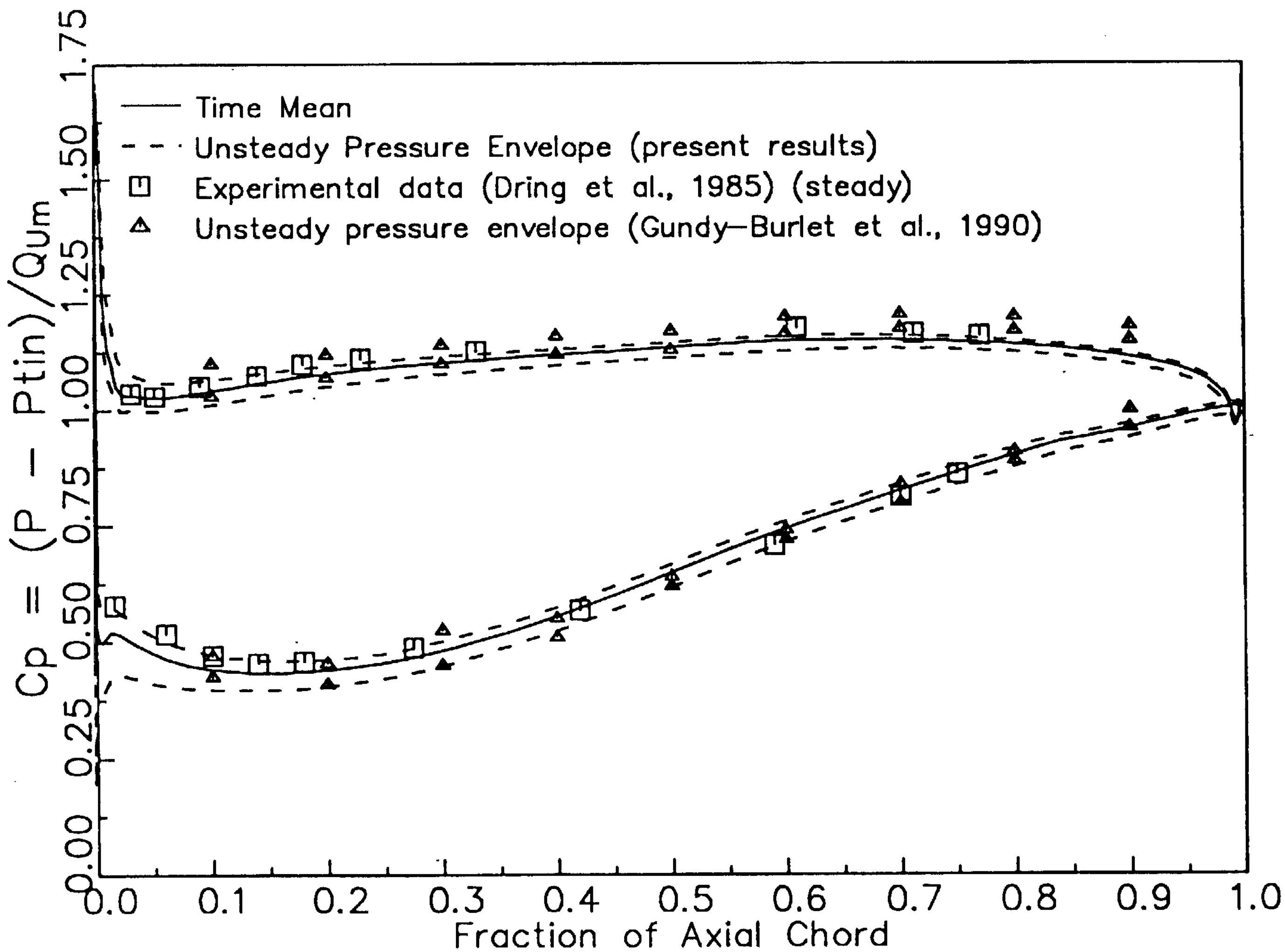
VALIDATION/TEST CASES (CONTD.)

Unsteady response function of a flat plate cascade and a C4 cascade



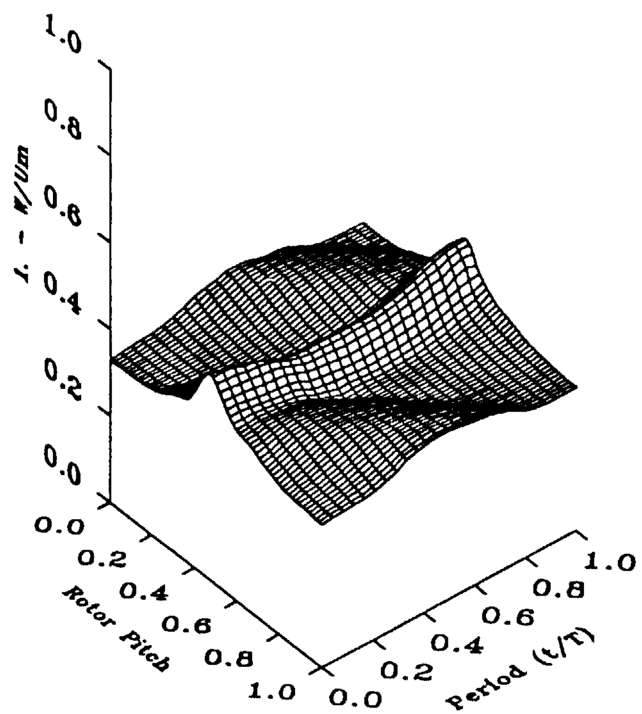
UNSTEADY FLOW IN A TURBOMACHINERY BLADEROW DUE TO UPSTREAM ROTOR WAKE

Time mean static pressure and pressure envelope of a compressor stator.

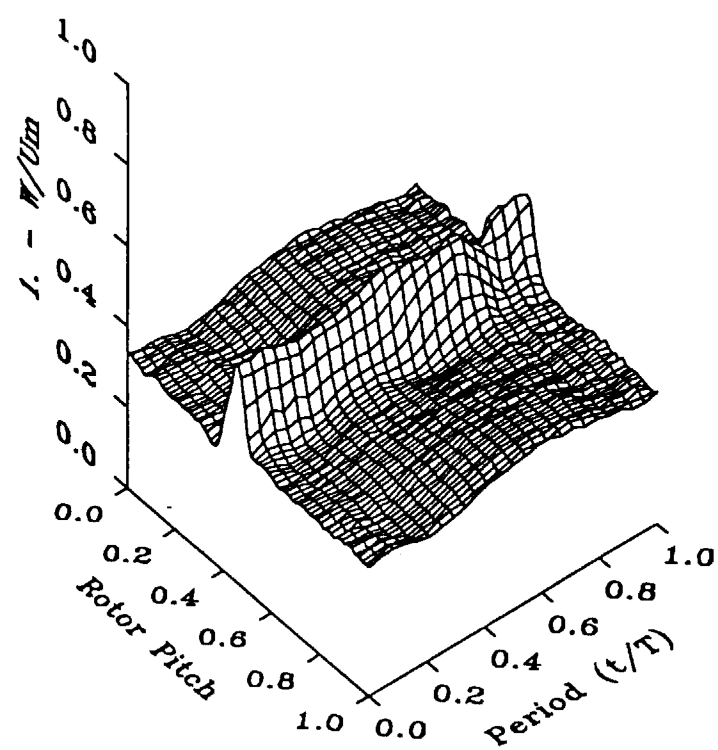


UNSTEADY FLOW IN A TURBOMACHINERY BLADEROW DUE TO UPSTREAM ROTOR WAKE

Time-dependent rotor wake profile at 20% stator axial chord upstream of the stator blade



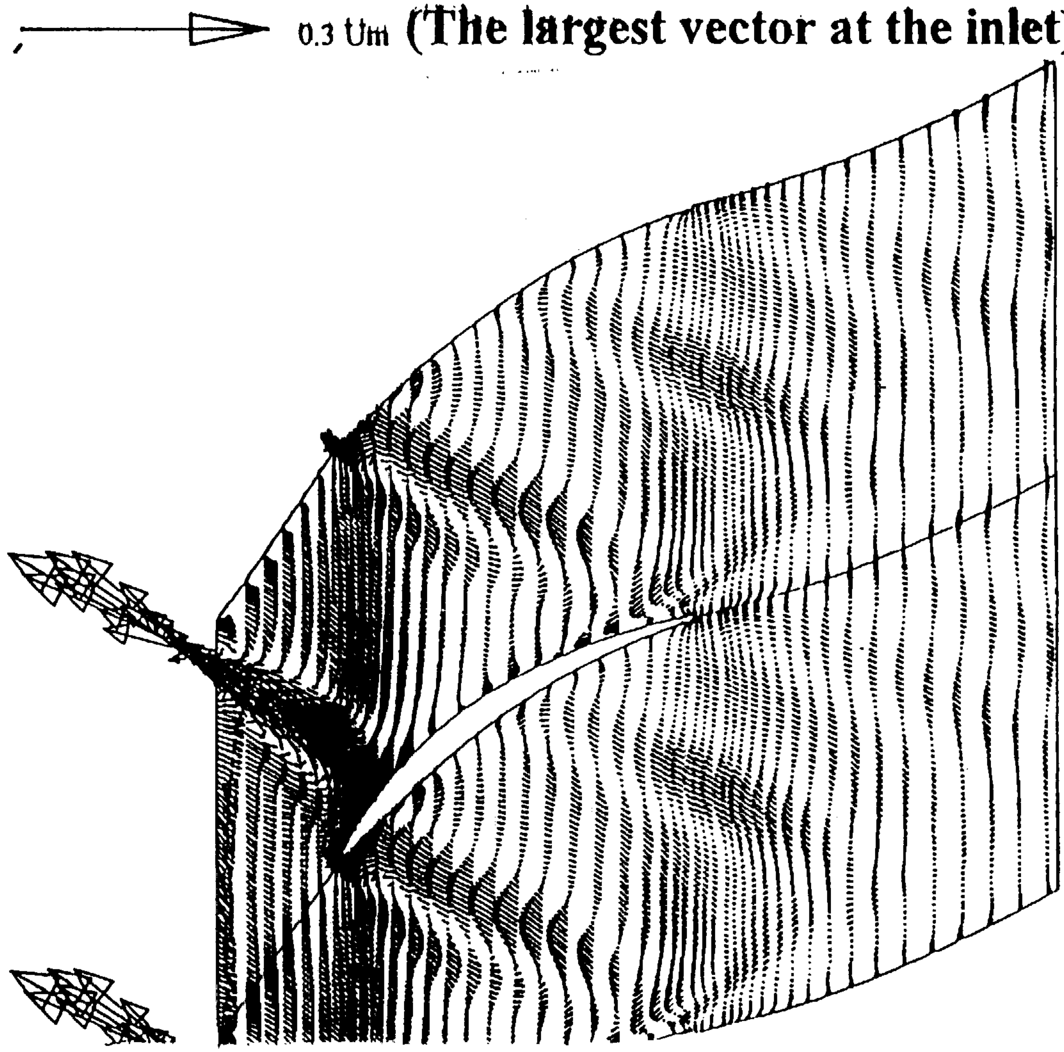
Computation



Experiment (Stauter et al., 1990)

UNSTEADY FLOW THROUGH A COMPRESSOR DUE TO UPSTREAM ROTOR WAKES

The fluctuating velocity (the difference between instantaneous and time-mean velocity) vectors inside a stator (t/T=0.25).

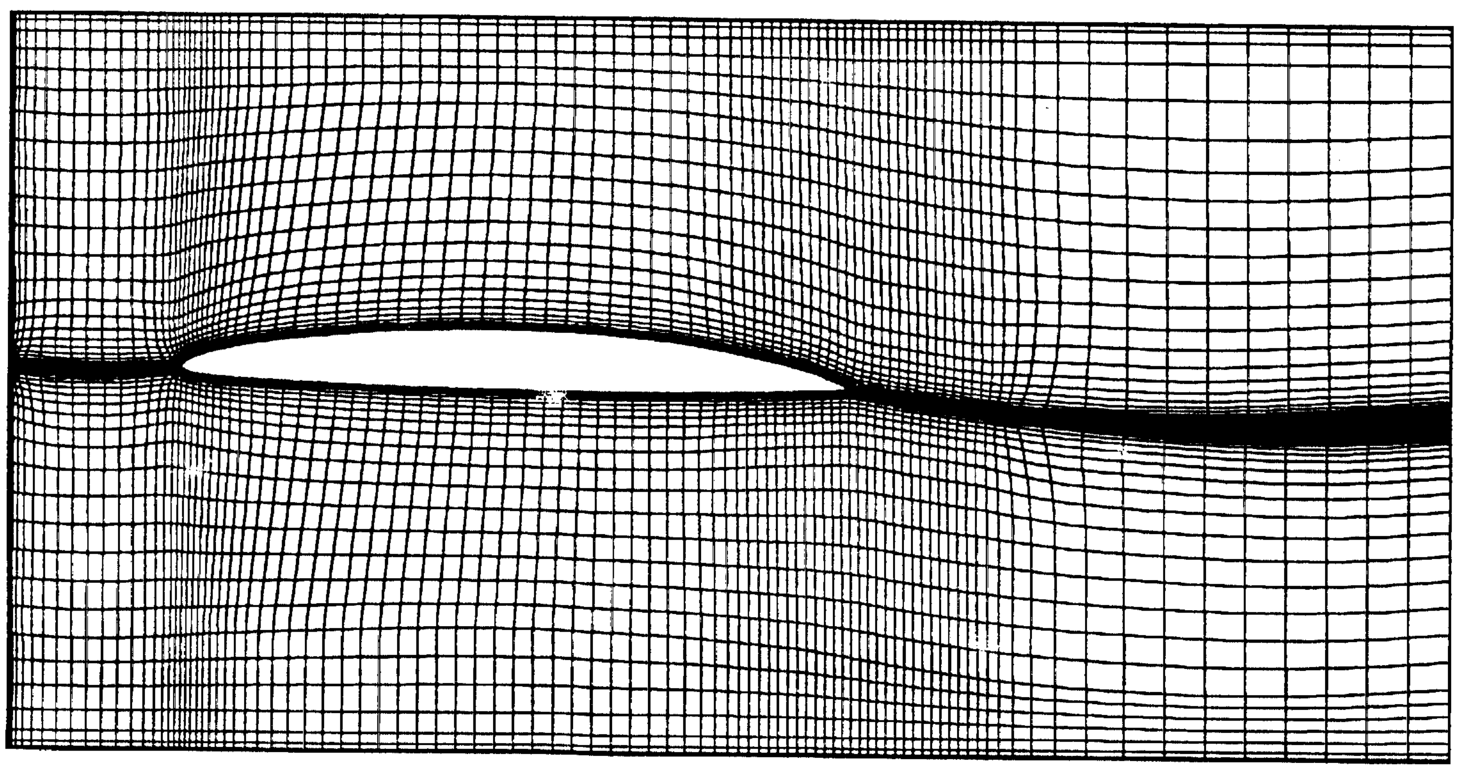


(The largest vector at the inlet)

UNSTEADY VISCOUS OVER AN AIRFOIL

- The unsteadiness is generated by two flapping foils oscillating about one chord upstream the tested foil
- Reduced frequency ($\omega C/2U$)=3.76
- Incidence = 1.34 degrees
- Reynolds No. = 3.78×10^6
- Total no of grid points : 27537 (201×137)
- Reference : D. Keenan et. al., MIT

every second grid line is shown

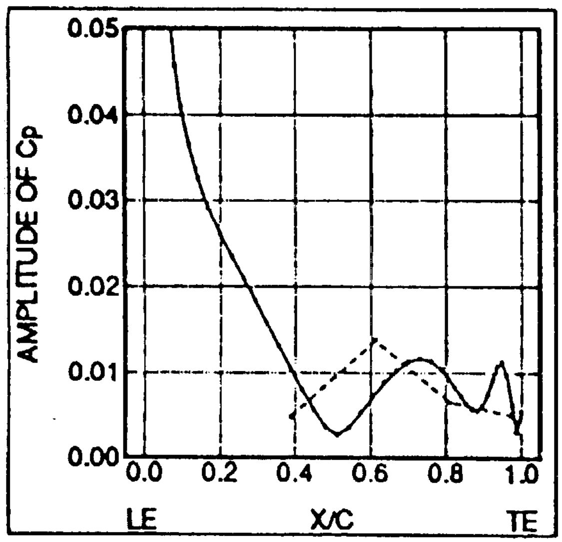


UNSTEADY VISCOUS OVER AN AIRFOIL

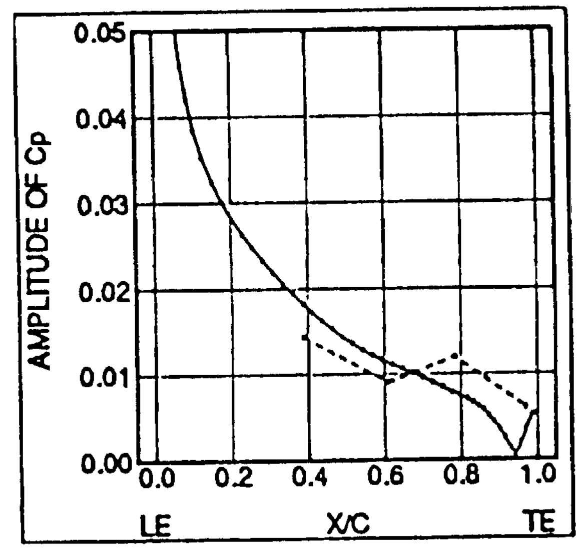
Amplitude of Cp for harmonic n=1

Solid lines = calculations, Dash lines = measurements (Keenan, 1992)

Suction Surface



Pressure Surface



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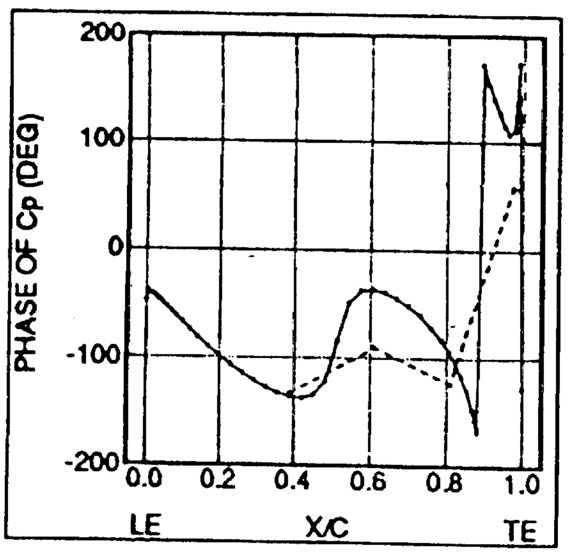
UNSTEADY VISCOUS OVER AN AIRFOIL

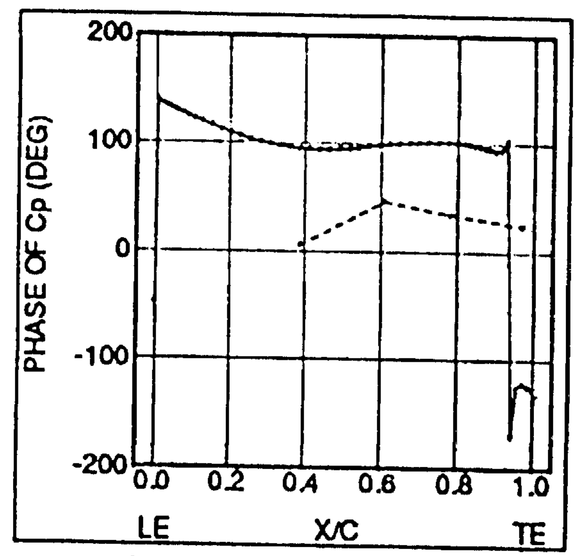
Phase of Cp for harmonic n=1

Solid lines = calculations, Dash lines = measurements (Keenan, 1992)

Suction Surface



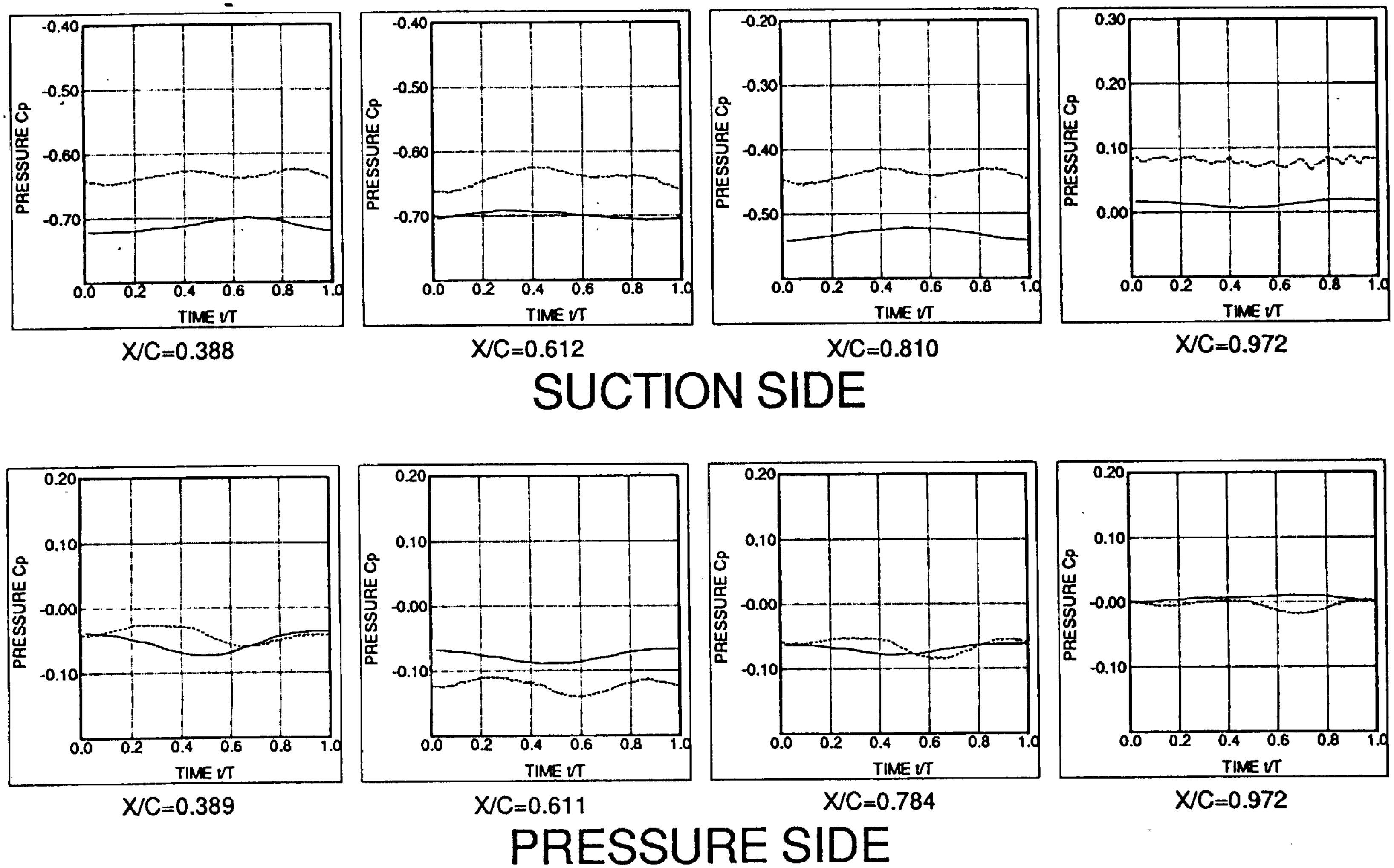
Pressure Surface



TIME HISTORY OF Cp

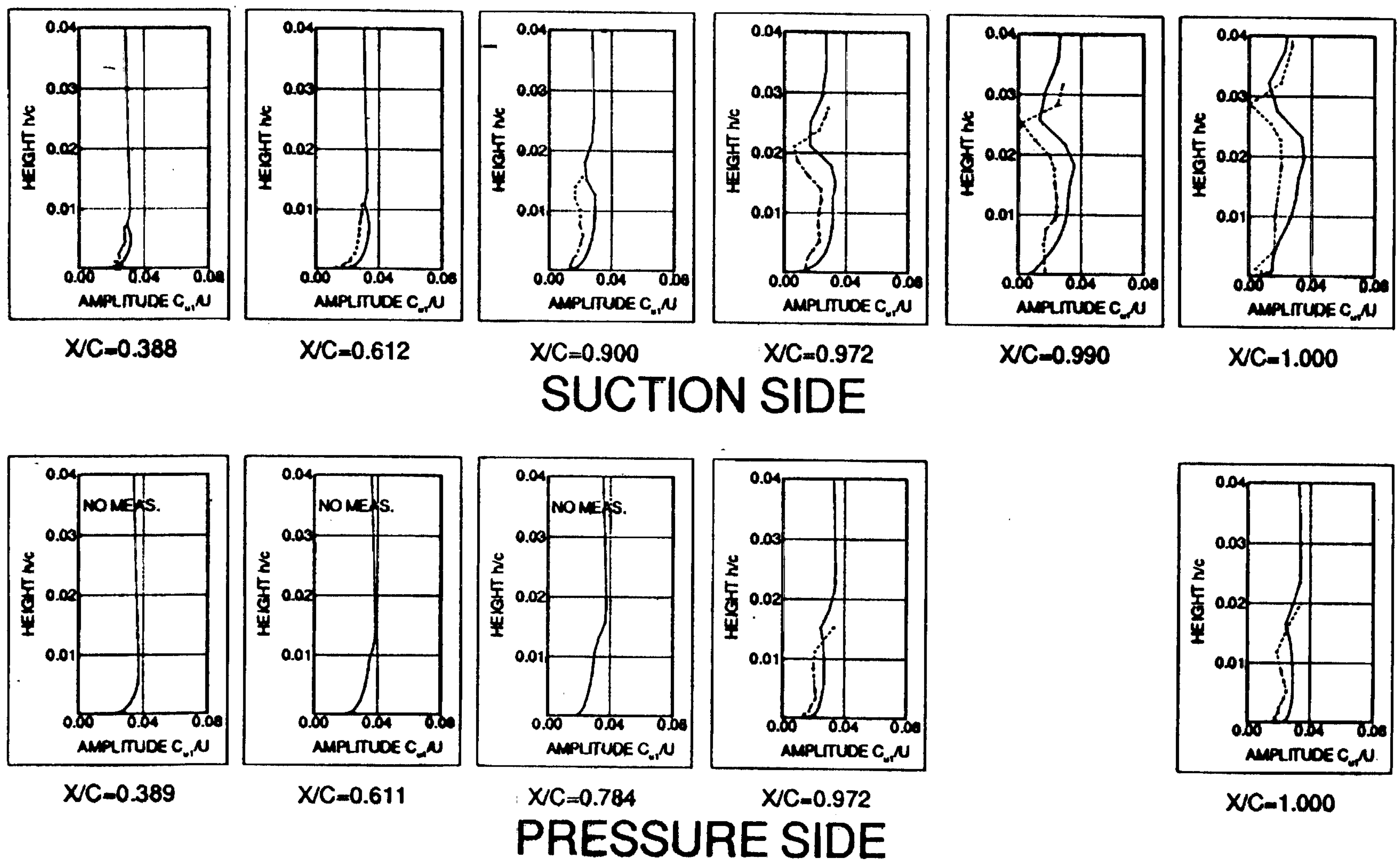
LAKSHMINARAYANA AND HO

Solid lines = calculations   Dashed lines = measurements

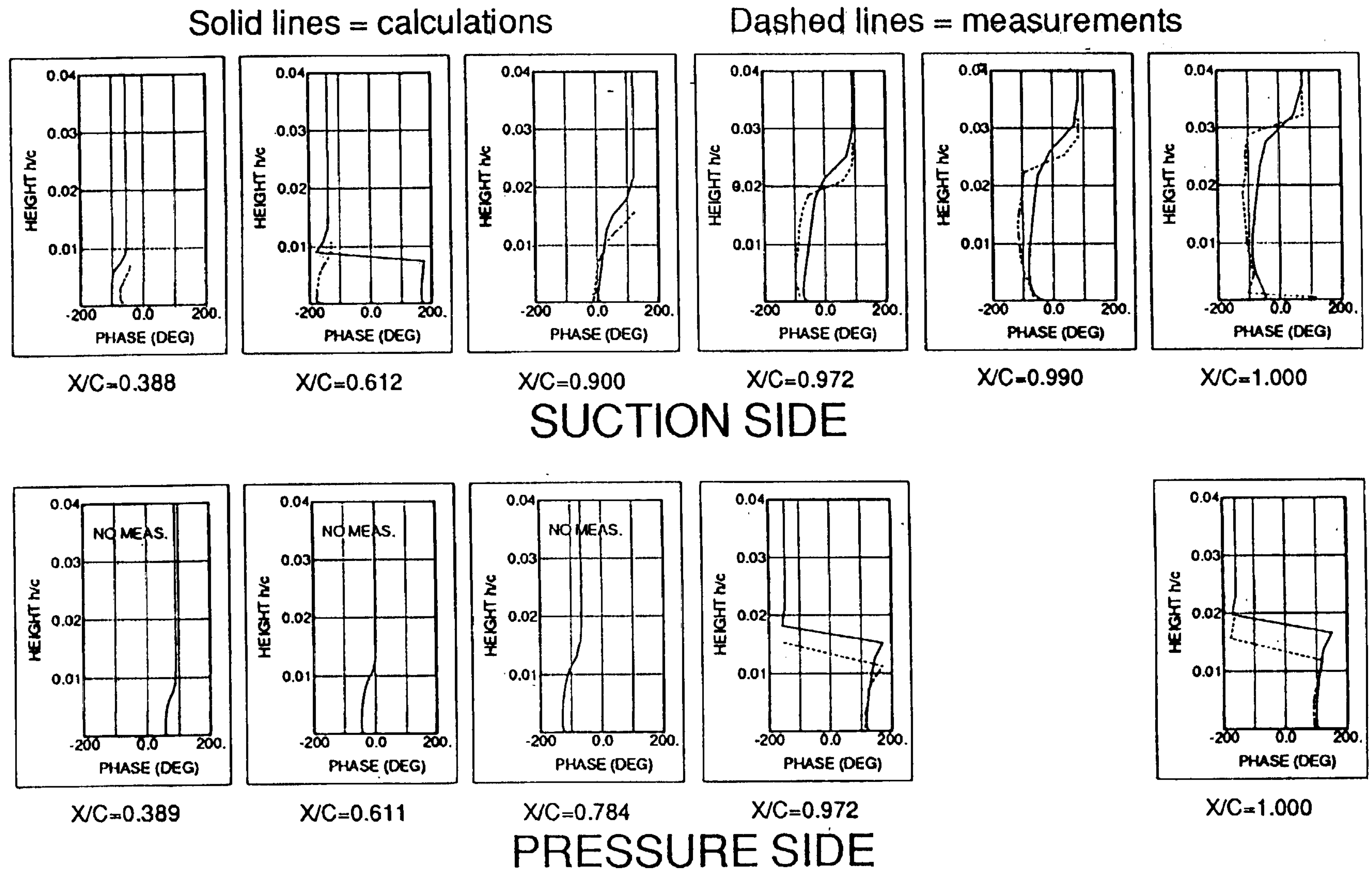


AMPLITUDE OF VELOCITY FOR HARMONIC n=1

Solid lines = calculations   Dashed lines = measurements



PHASE OF VELOCITY FOR HARMONIC n=1



TIP CLEARANCE MODELLING

3D STEADY FLOW IN THE TIP CLEARANCE REGION FLOW OF A TURBINE

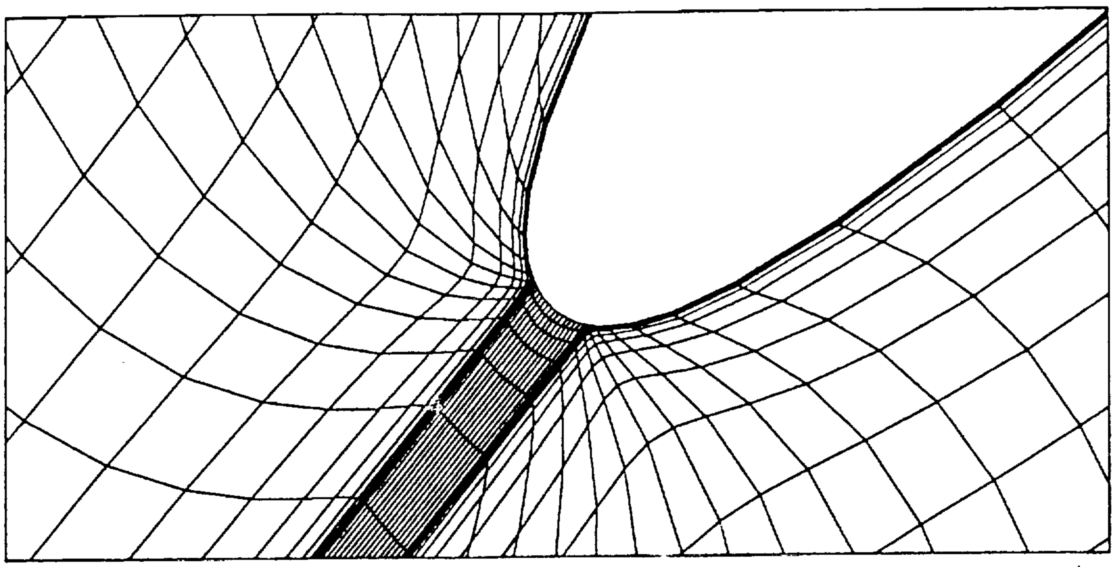
- **Turbine Cascade experimental data : Bindon (1986, 1987, 1990)**
  - **$C = 0.186$ m**
  - **$S/C = 0.7$**
  - **$\tau/C = 2.5$ %**
  - **$Re = 4.7 \times 10^5$**
  - **$\alpha_1 = 0°$, $\alpha_2 = 68°$**
  - **Grid : 81 x 57 x 57,   with 41 x 21 x 15 in the tip gap**

3D STEADY FLOW IN THE TIP CLEARANCE REGION FLOW OF A TURBINE

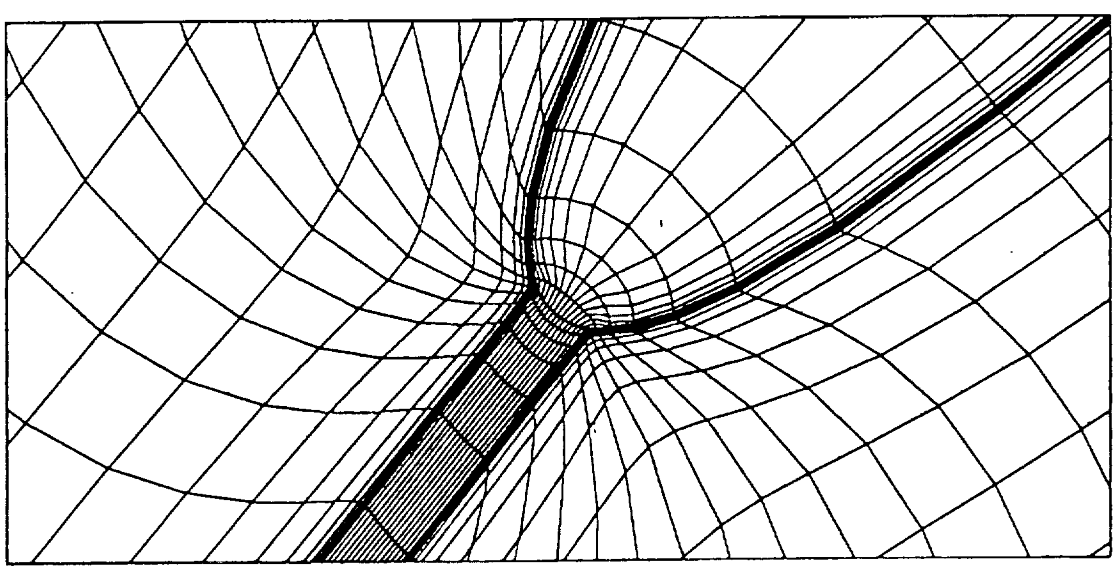
- Grid Methodology
  - Combined algebraic and elliptic approach.
  - Interior generated by elliptic generator- solved iteratively by Minimum residual method, while updating source terms and coefficients after each iteration.
  - Apply elliptic smoothing to interface to remove discontinuities, but the grid spacing normal to surface is altered. Restore grid spacing normal to surface.
  - Imbedded H grid topology; Three smaller H grids imbedded into large grid; No discontinuities in grid at blade tip; actual tip geometry mapped into computation domain; good tip gap resolution

EMBEDDED H-GRID TOPOLOGY

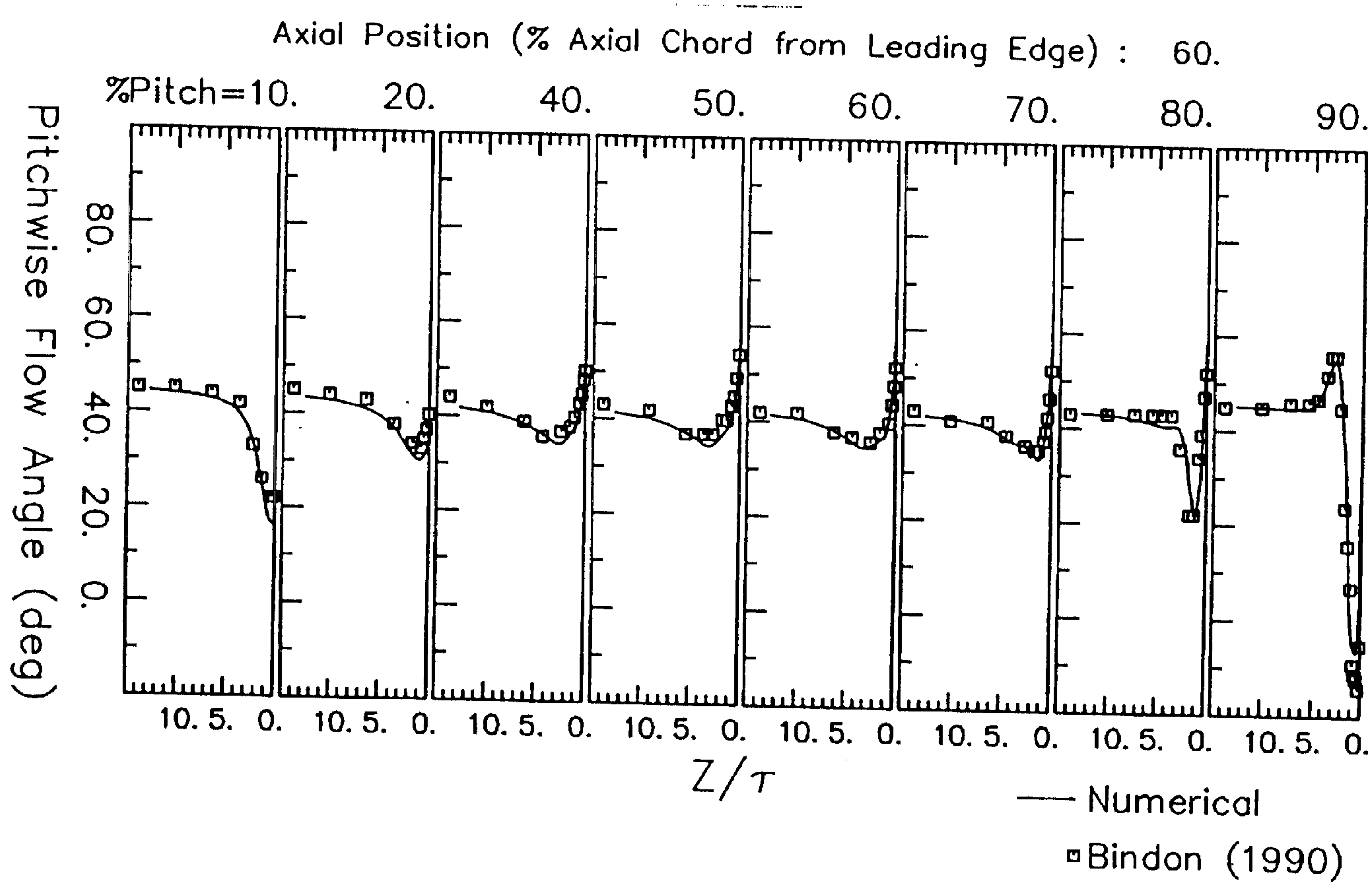
Grid Below Tip Gap



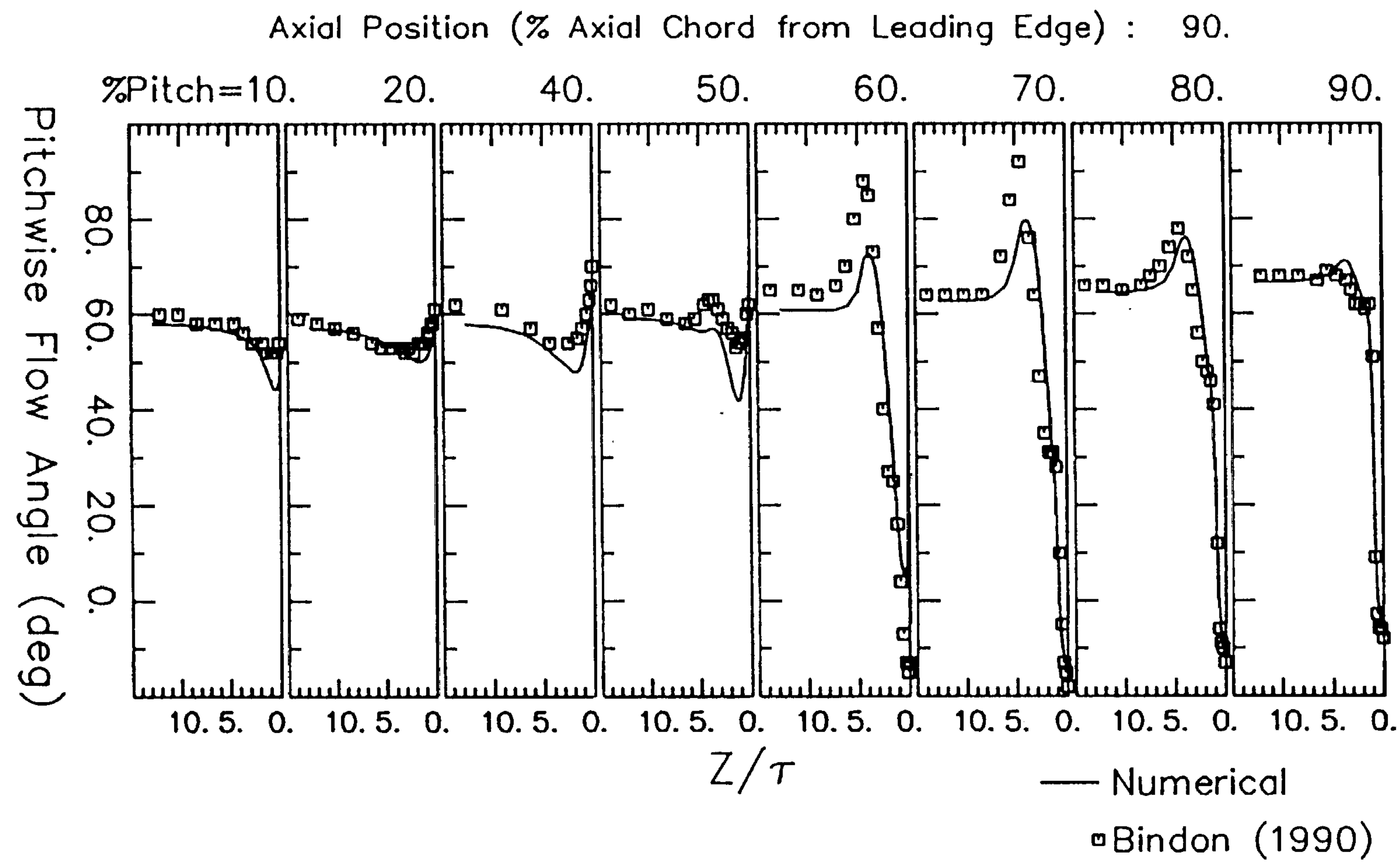
Grid Inside Gap



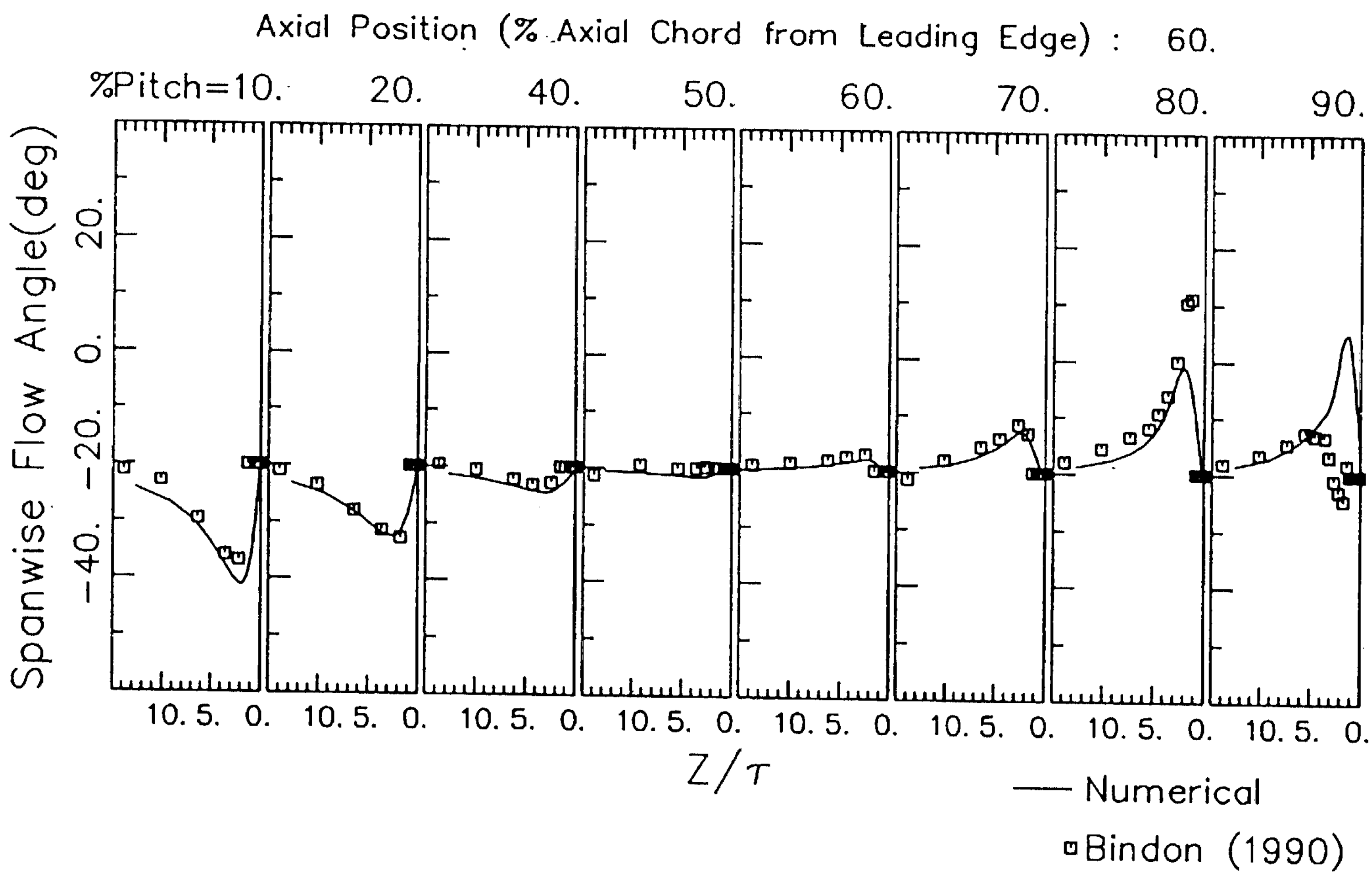
COMPARISON OF MEASURED AND PREDICTED PITCHWISE FLOW ANGLES



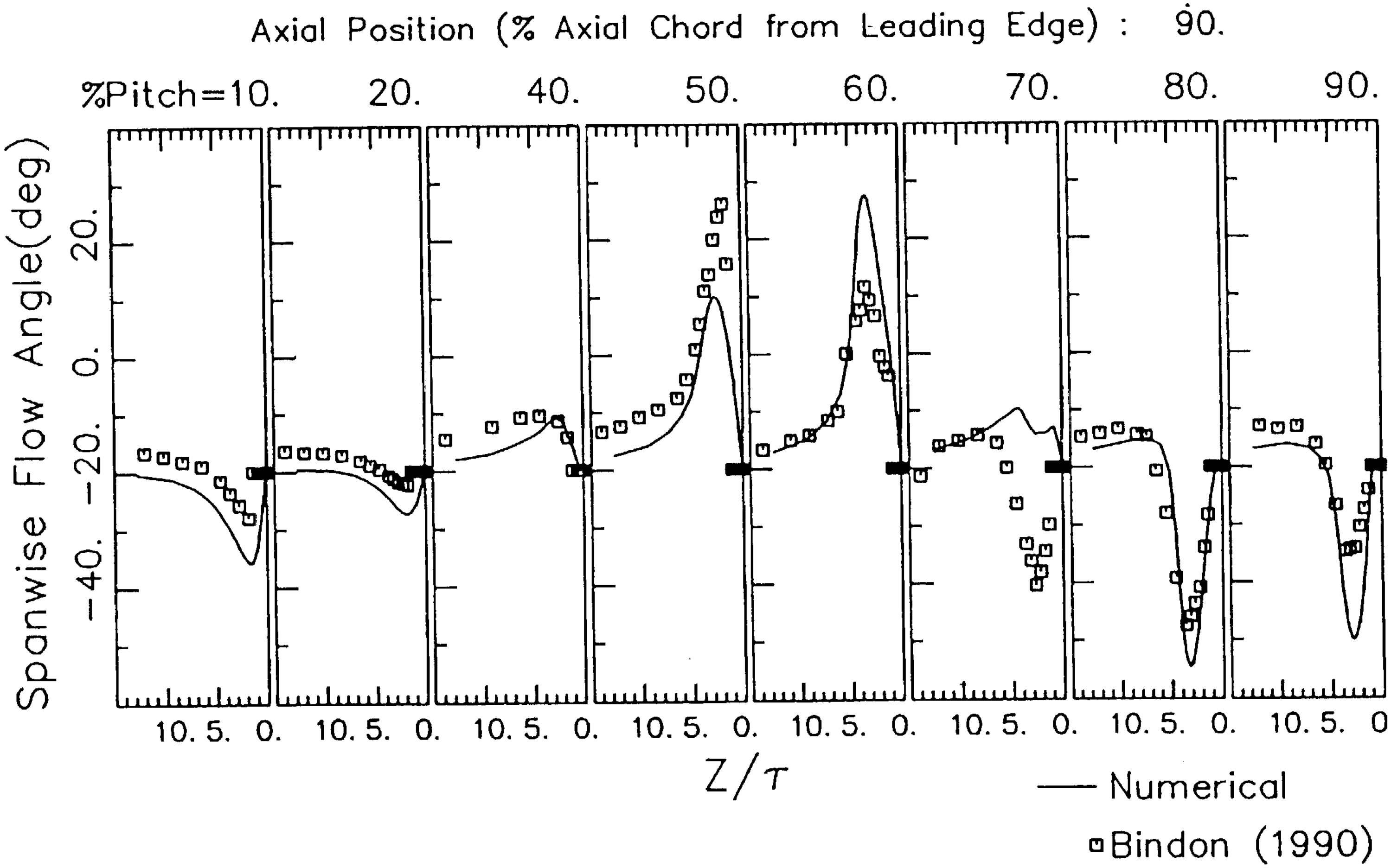
COMPARISON OF MEASURED AND PREDICTED PITCHWISE FLOW ANGLES



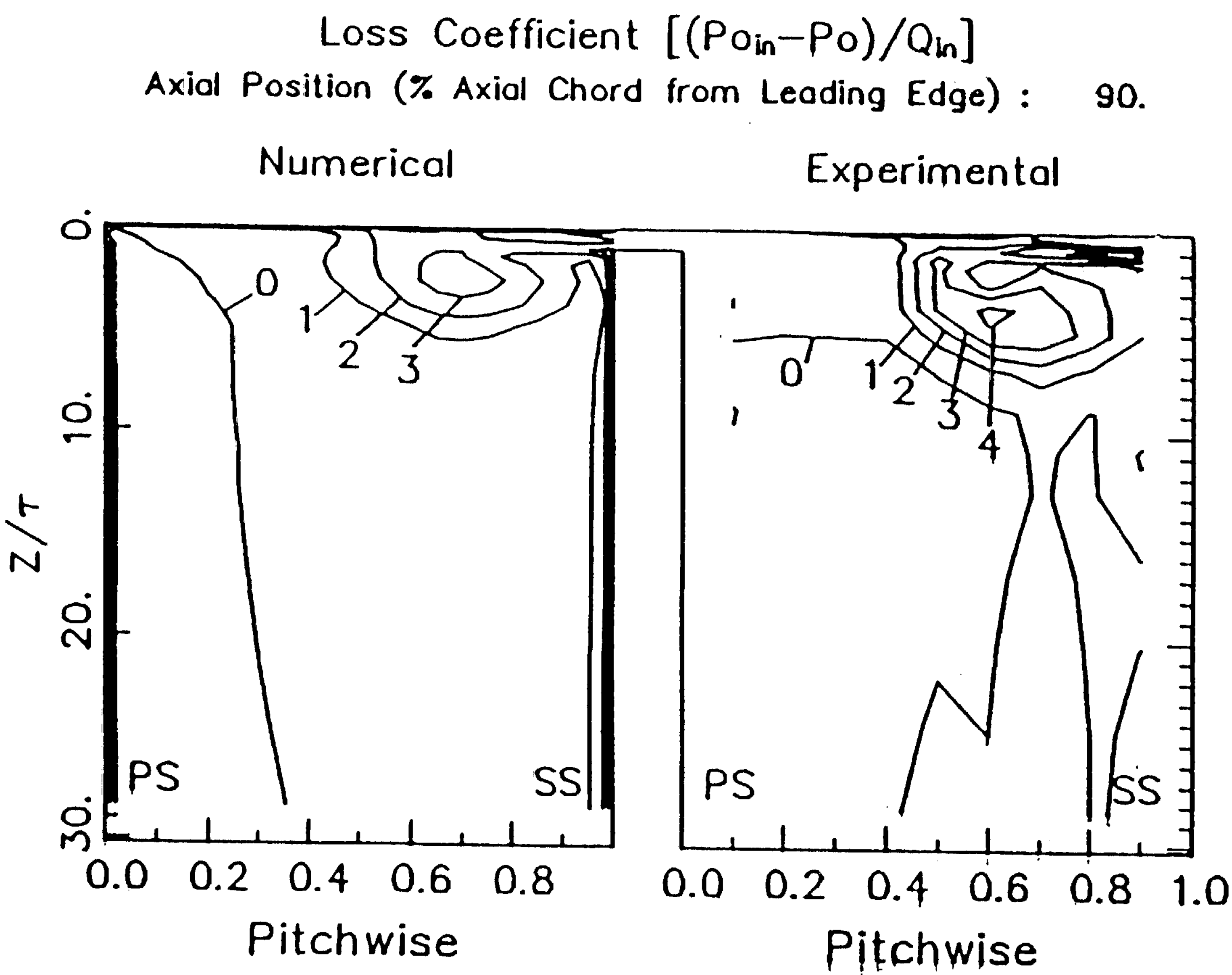
COMPARISON OF MEASURED AND COMPUTED SPANWISE FLOW ANGLES (POSITIVE ANGLE WHEN FLOW DIRECTED TOWARDS ENDWALL)



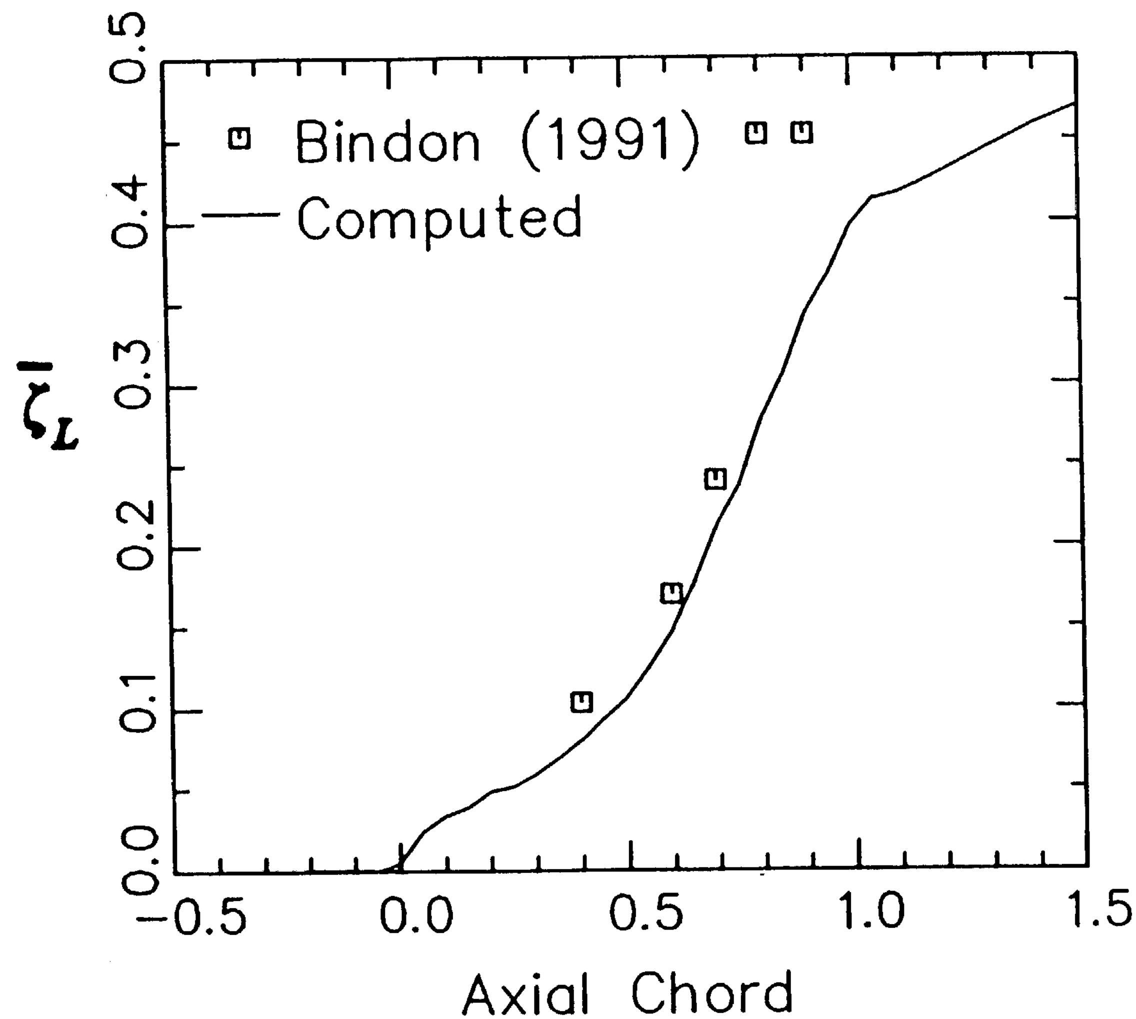
COMPARISON OF MEASURED AND COMPUTED SPANWISE FLOW ANGLES (POSITIVE ANGLE WHEN FLOW DIRECTED TOWARDS ENDWALL)



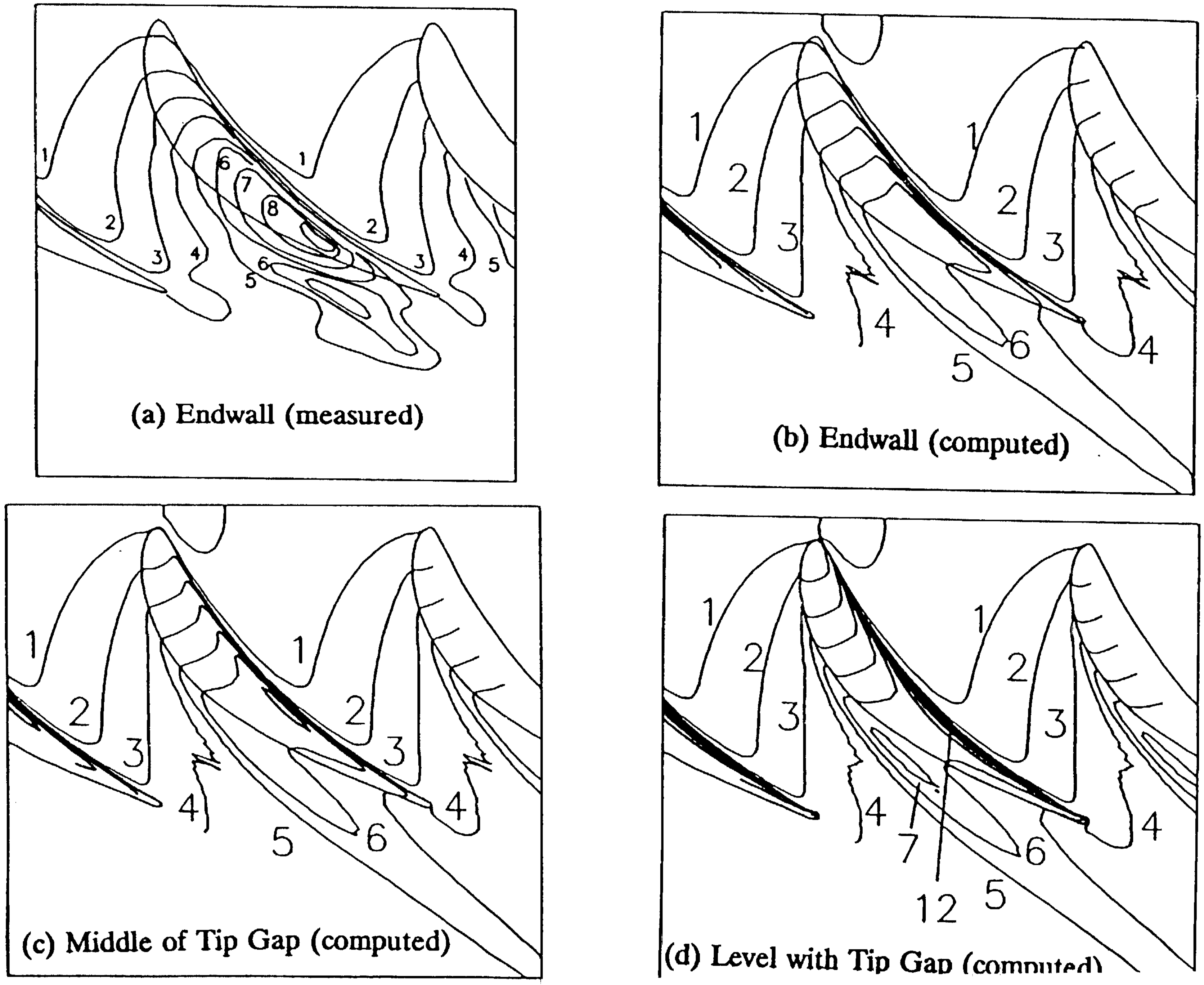
CONTOURS OF LOSS COEFFICIENT (ζ_L) PREDICTED AND MEASURED



AXIAL DEVELOPMENT OF MASS AVERAGED LOSS COEFFICIENT ($\bar{\zeta}_L$)



CONTOURS OF PRESSURE COEFFICIENT (c_p)



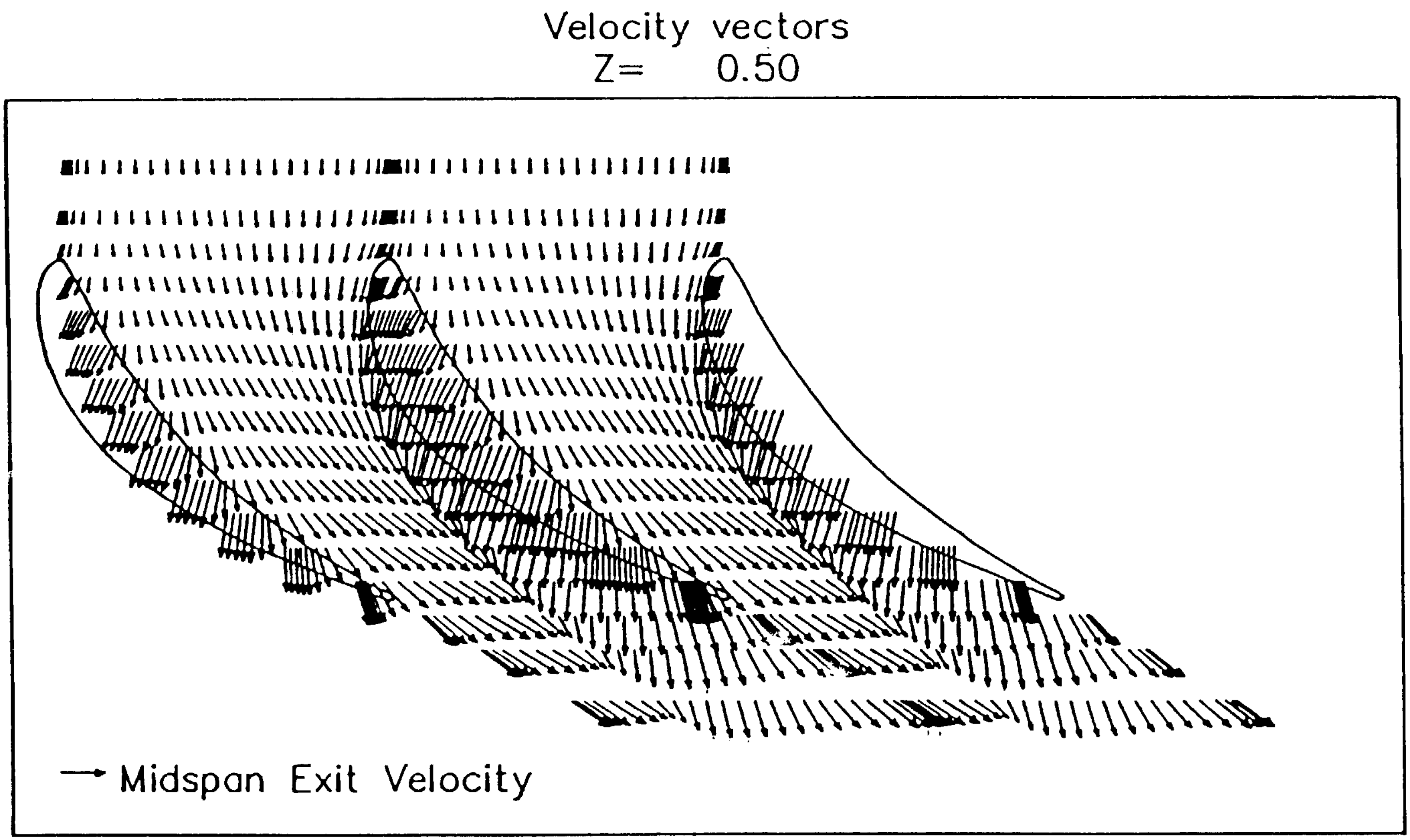
(a) Endwall (measured)

(b) Endwall (computed)

(c) Middle of Tip Gap (computed)

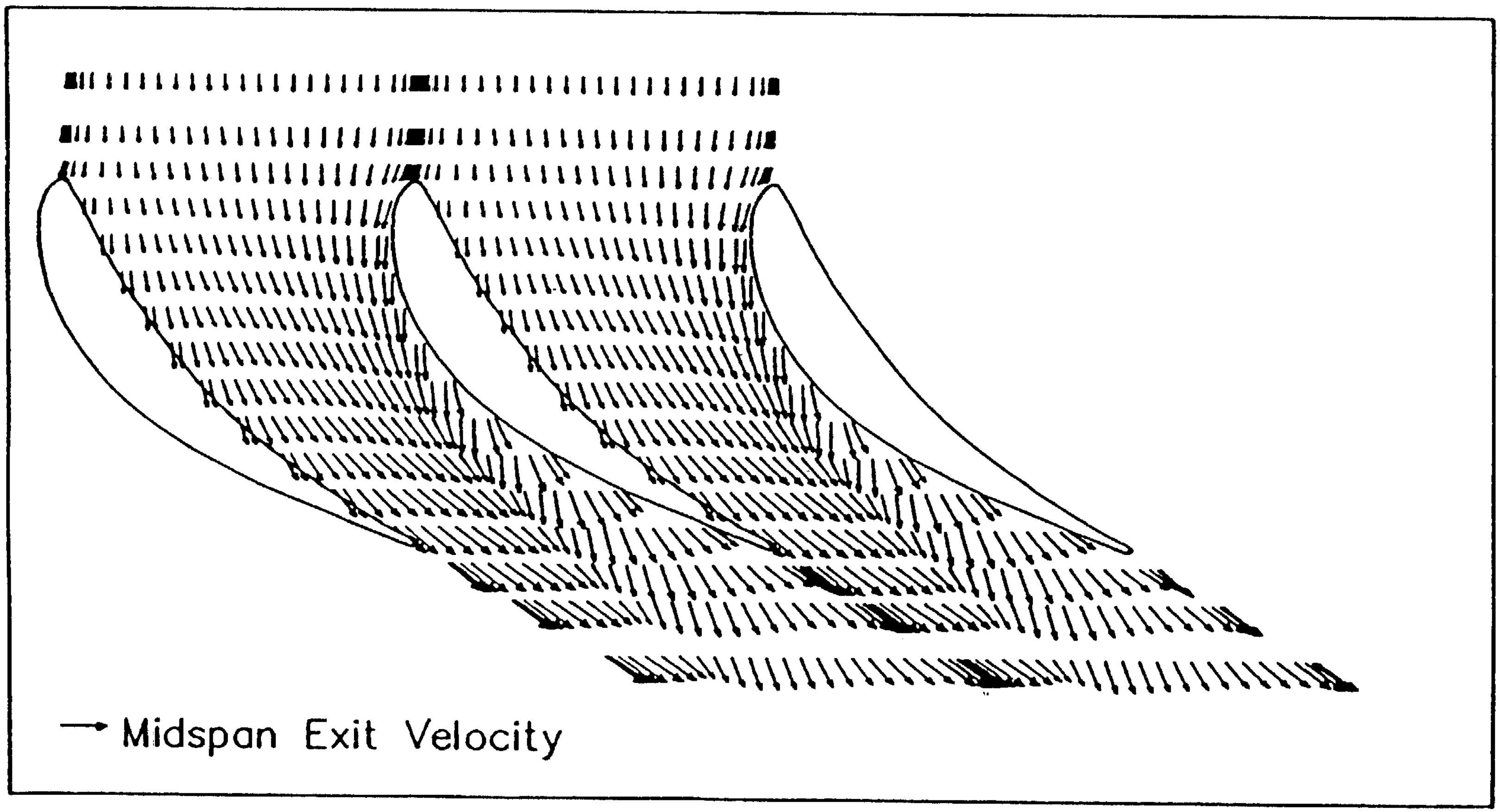
(d) Level with Tip Gap (computed)

VELOCITY VECTORS AT CONSTANT SPANWISE POSITIONS PROJECTED ON TO A BLADE-TO-BLADE (XY) PLANE



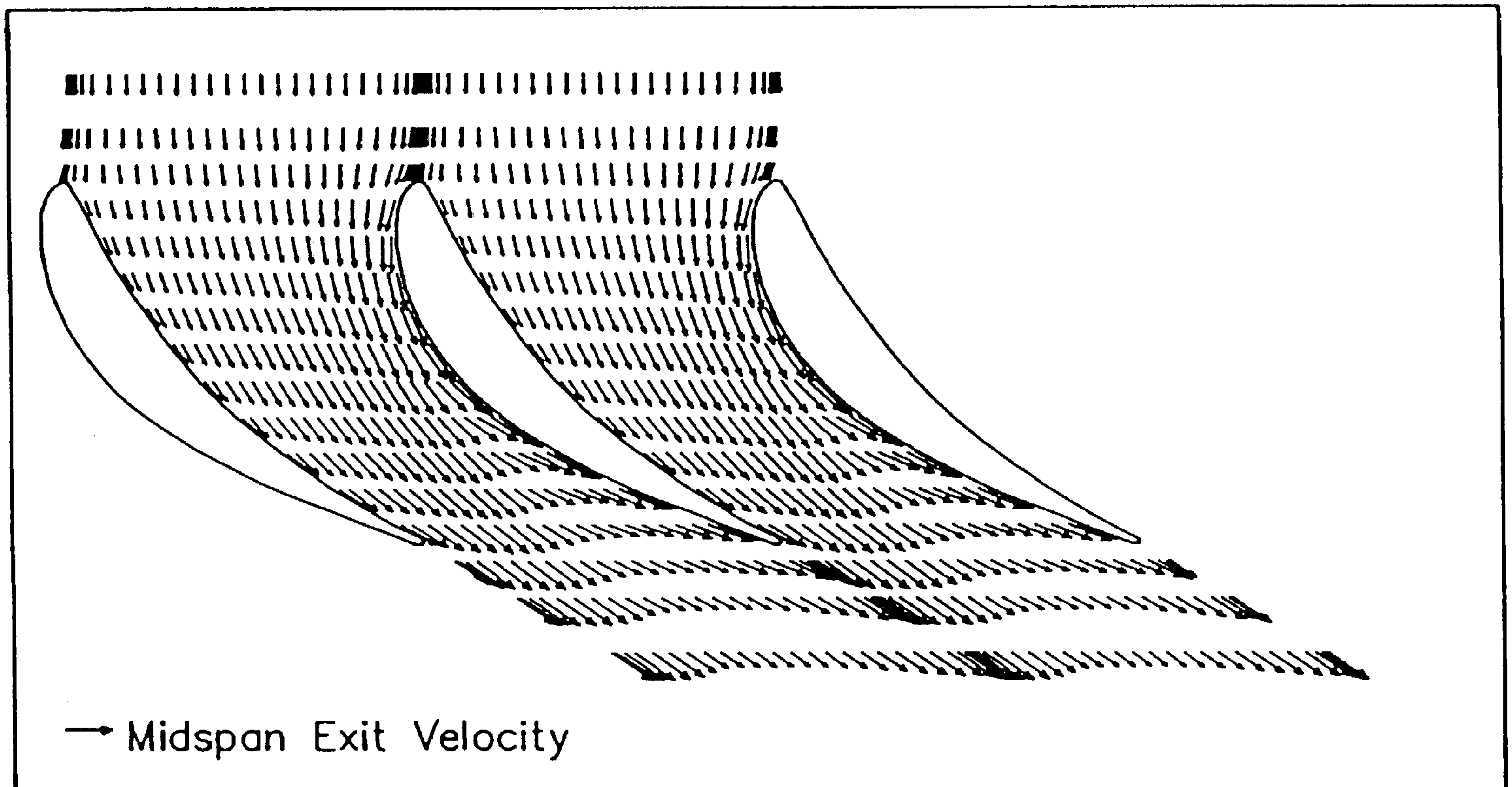
VELOCITY VECTORS AT CONSTANT SPANWISE POSITIONS PROJECTED ON TO A BLADE-TO-BLADE (XY) PLANE

Velocity vectors
Z= 1.10



VELOCITY VECTORS AT CONSTANT SPANWISE POSITIONS PROJECTED ON TO A BLADE-TO-BLADE (XY) PLANE

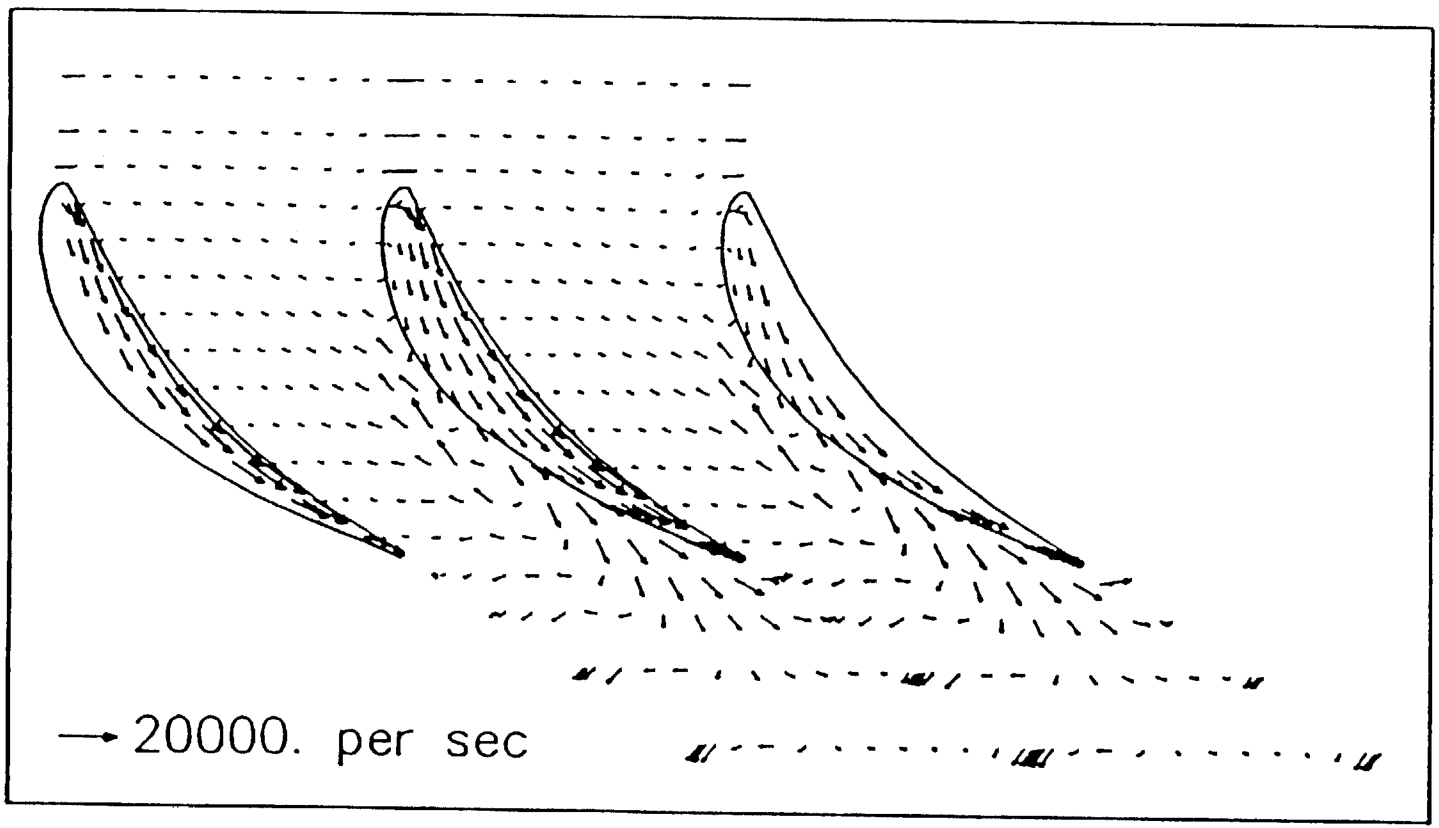
Velocity vectors
Z= 3.00



COMPUTED SECONDARY VORTICITY VECTORS

$$\left[\left(\nabla x \left(\underline{V} - \underline{V}_{midspan} \right) \right) \right]$$

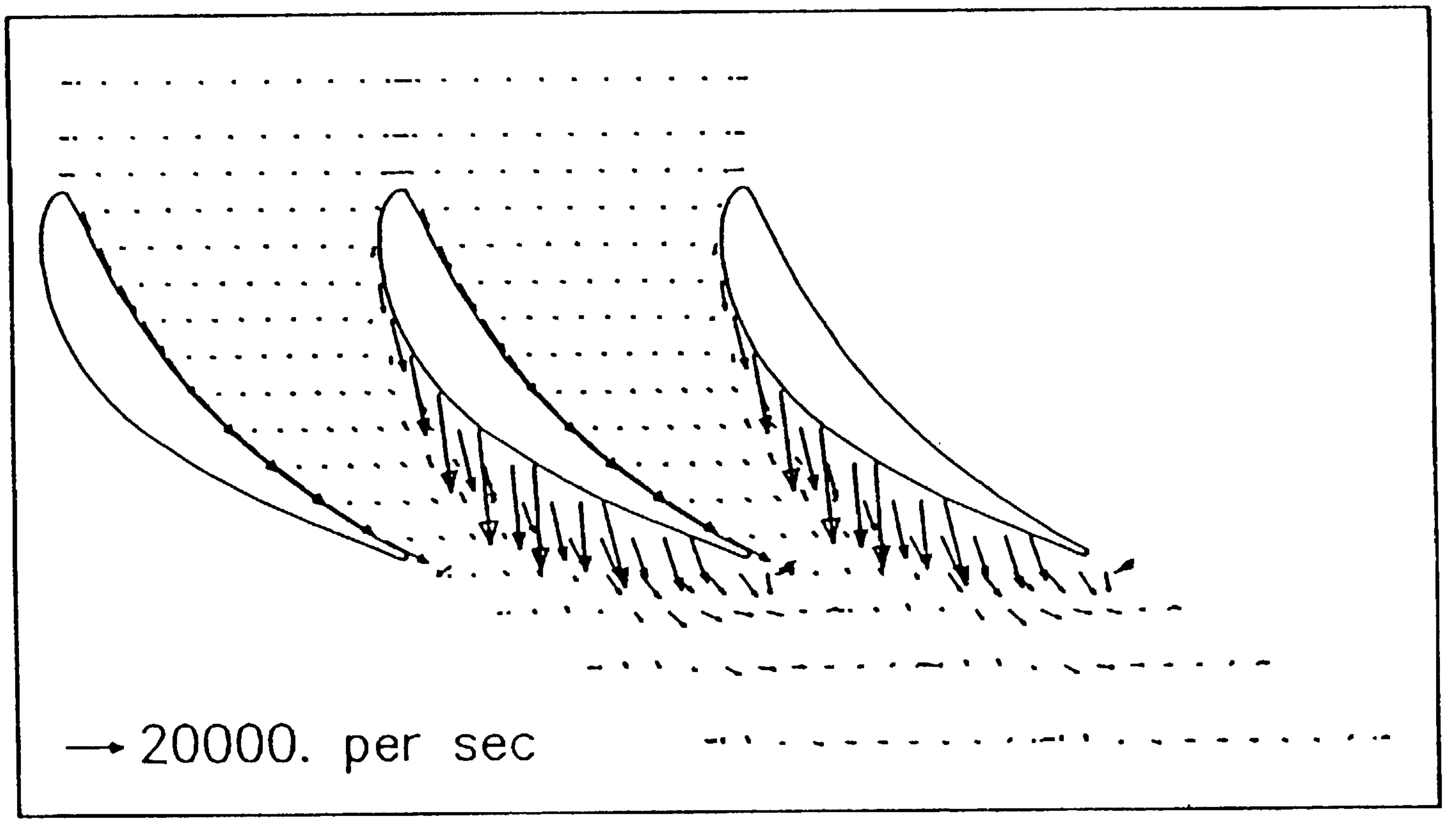
Secondary Vorticity Vectors
Z= 0.50



COMPUTED SECONDARY VORTICITY VECTORS

$$\left[\left(\nabla x \left(\underline{V} - \underline{V}_{midspan} \right) \right) \right]$$

Secondary Vorticity Vectors
Z= 1.00



CONCLUSIONS

- **Geometric series distribution scheme**

  Good control over the boundary points

- **Algebraic-elliptic grid generation scheme**

  Good control over clustering

  Good control over orthogonality

  Enhanced stability of elliptic generation

- **Embedded H-grid**

  Single block discretization for tip clearance cases

  No Modification of blade tip shape required

  Retains H-grid connectivity pattern

- **Effect of artificial dissipation**

  Numerical accuracy vs. convergence rate

  Minimum artificial dissipation should be used

- **Modelling of tip clearance flows**

  Major physical phenomena captured

  Location of leakage vortex, pitchwise and spanwise angles, losses, static pressures predicted accurately

CONCLUSIONS

- **2D unsteady flow computation**
  - **For the rotor-stator interaction simulation case, the decay of rotor wake and the time-mean pressures agree very well with the experimental data. The potential effect of downstream stator on the rotor wake is captured very well.**
  - **The rotor wake decays through out the stator passage. The wake defect becomes insignificant after passing through the stator passage.**
  - **The interaction between the wake and the freestream induces two vortices on either side of rotor wake inside the stator passage. This causes the wake to smear out as it is transported downstream inside the stator passage.**
  - **For the unsteady flow over an airfoil case, the boundary layer velocity profiles and blade pressure agree with the measurements, including the magnitude and phase angle.**