COUPLED, TRANSIENT SIMULATIONS OF THE INTERACTION BETWEEN POWER AND SECONDARY FLOWPATHS IN GAS TURBINES

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OUTLINE

- **Overview and Objectives**
- **Coupling Methodology**
- **Description of Codes, Interface Algorithm**
- **Sample Cases, Results**
- **Summary**

NEED FOR COUPLED ANALYSIS

- Multi-Stage Compressor and Turbine Section Present in Gas Turbines
  - interstage cavities necessary
  - powerstream/mainpath/primary flow: flow above blade platforms
  - secondary flow refers to flow under blade platforms

- Mainpath-Secondary Flow Interact Strongly; can Affect
  - efficiency and power performance
  - component life

- Higher Efficiency and/or Power Requires
  - details of mainpath, secondary flows
  - design, off-design and transient conditions

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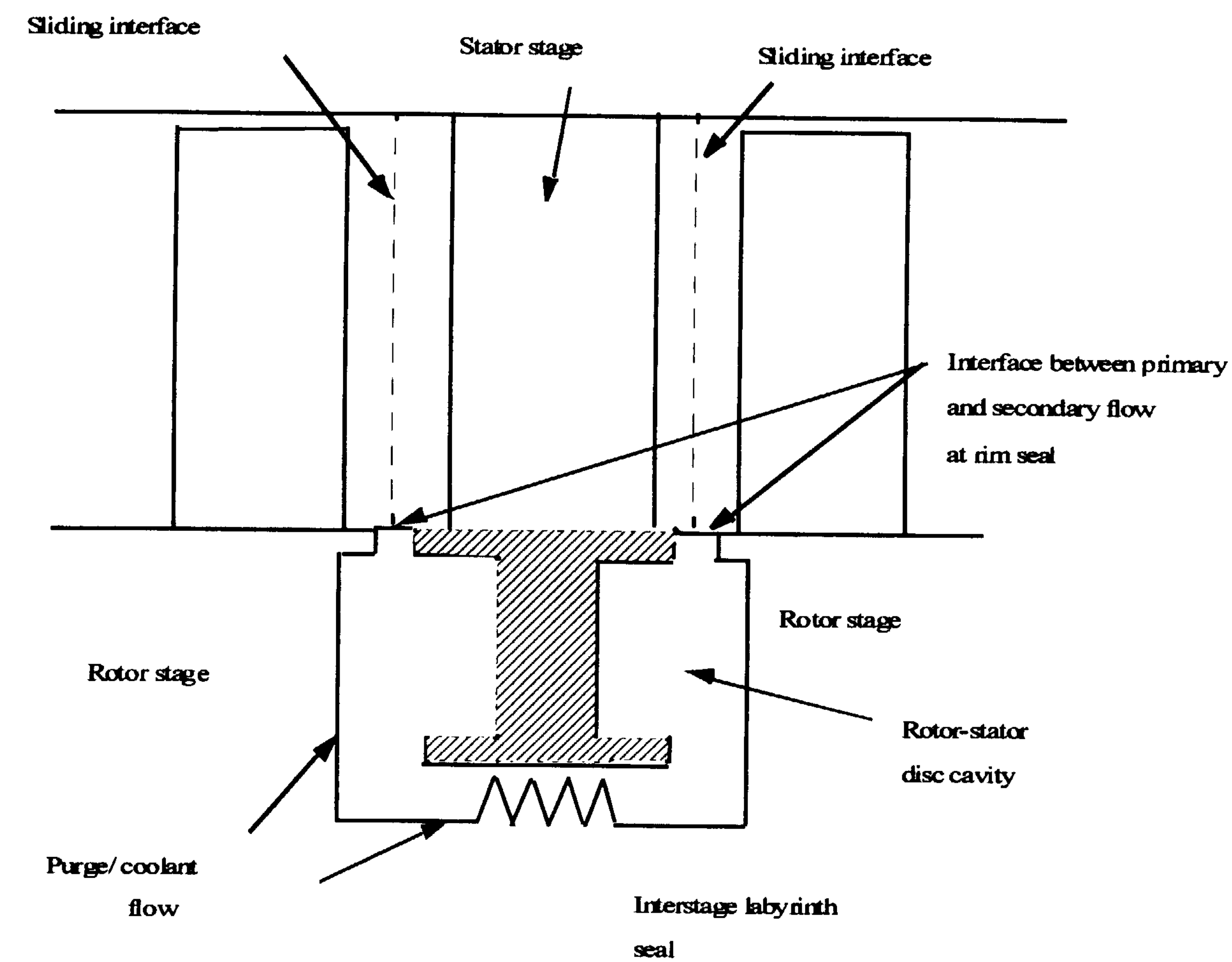
PRIMARY-SECONDARY COUPLING SCHEMATIC



- Rim Seal Details Change in Compressor and Turbine Sections
- Requirements of Leakage/Ingestion/Coolant also Change

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SECONDARY FLOW REQUIREMENT

- Interaction between Primary-Secondary Flow has Different Aspects in Compressor and Turbine Sections

- Compressor Side: Minimize Leakage Flow
  - reduce recirculation, windage losses
  - reduce effects of re-introduction in mainpath
  - affects performance

- Turbine Side: Much More Stringent Requirement
  - mainpath gas ingestion: avoid at all costs
  - coolant flow is a must, but represents efficiency loss
  - optimization of coolant flow requires much more careful attention to transient flow details

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OBJECTIVES OF PRESENT METHODOLOGY

- To Develop a Validated Set of Codes for Coupled, Transient Solutions of Primary and Secondary Flows in Multi-Stage Machines
  - use existing validated codes for different streams: SCISEAL for secondary; MS-TURBO for primary
  - develop interfacing algorithms for coupling the codes
  - graphical user interface for ease of use

- Use of Separate Codes
  - widely different flow physics in primary and secondary flows
  - validated codes available, specifically developed for each flow stream
  - capabilities offered by the combinations

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CURRENT METHODOLOGIES RECAP

- Single Simplified Cavity Flow
  - experiments, analytical, simplified models for cavity flows

- CFD Flow and Heat Transfer
  - 2-D axisymmetric , steady-state
  - complex cavity shapes, heat transfer, some measure of interaction between mainpath-secondary

- 3-D CFD: Analysis
  - steady and unsteady solution in compressor (Allison Group)

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PROPOSED COUPLED CODE METHODOLOGY

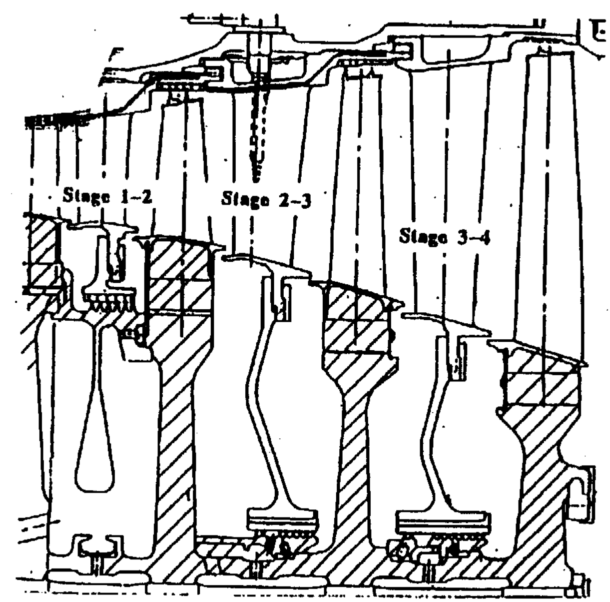
Power Stream

TURBO: density based, finite volume, structured grids, time-accurate, multiple blade rows, high speed flows

Interface

Cavity/Secondary Flow

SCISEAL-U: pressure based, finite volume unstructured, adaptive Cartesian grids, time accurate, conjugate heat transfer, turbulence, low speed flows



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DESCRIPTION OF SCISEAL CODE

Salient Features

- Unstructured Grid Topology with Mixed Elements (quads, prisms, polyhedra), Adaptive Cartesian Grid Capability
- Fully Implicit Pressure-Based, Finite Volume
- Cartesian Velocities, Non-Staggered Arrangement
- Sequential Solution Procedure with SIMPLEC-M for Velocity-Pressure Coupling
- Conjugate Gradient Solvers for Linear Systems
- Flow, Conjugate Heat Transfer, Turbulence
- Links with Grid Adaptor for Solution-Based Adaptation

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DESCRIPTION OF TURBO CODE

UNCLE_TURBO Applications Group

- Developed for Predominantly Axial Flow Rotating Machines
  - multiple blade row, fans and propellers (ducted and unducted)
  - multistage compressors and turbines (no chemistry yet)
  - rotating/stationary asymmetric configurations with appendages
  - helicopter rotor (hover configuration)
  - complete airframe - propulsor integration

- Developed for Unsteady Flow Analysis
  - uneven blade count, unsteady, nonlinear complex flow
  - combined internal and external flow
  - non-axial inflow conditions
  - inviscid or viscous flows

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CODE COUPLING/INTERFACE ISSUES

- Solution Methodology of the Codes
  - primary variables, flux calculation, turbulence, boundary treatment, internal memory management, ...
- Coupling Level
  - data exchange frequency, data type
- Interface Placement at Rim Seal
- Interpolation Code(s) for Data Transfer from One Code to Other

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CURRENT INTERFACE STRATEGY

- Placement of Interface at Rim Seal

- Coupling Level
  - both codes perform subiterations at each time step
  - data exchange after several subiterations of each code

- Data Type to be Exchanged
  - variables from SCISEAL (ρ,ρu, ...) interpolated to ghost layer in TURBO and used directly
  - TURBO fluxes at interfaces interpolated to SCISEAL interface and used directly
  - fluxes at interfaces matched and maintained

- Timesteps Determined by TURBO based on relative speeds of Rotor and Stator Elements, and Mainpath Grid Size

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COUPLED FLOW SIMULATIONS

Test Cases Computed/In Progress

1. Validation/Checkout Case
   - angular "mainpath" with disc cavity
   - allows single-code (SCISEAL) and coupled runs
   - solutions compared to validate

2. H.P. Rig by UTRC
   - single stator and rotor vane with cavity
   - coupled simulations to be compared with data

3. NASA Low-Speed Air Compressor (LSAC) Facility
   - 3rd rotor + 4th stator + 4th rotor in mainpath
   - associated disc cavity with 1 tooth labyrinth seal

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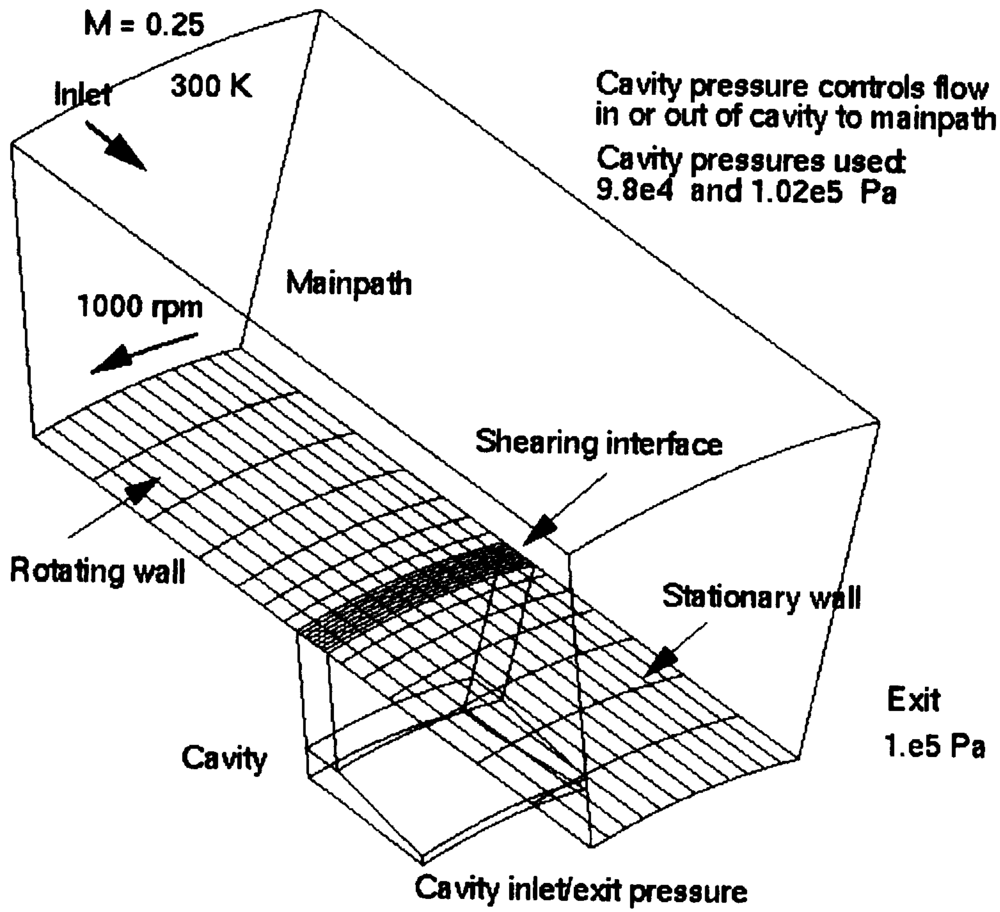
ANNULAR FLOW CASE

- Checkout/Validation Case
- Problem Definition and Boundary Conditions



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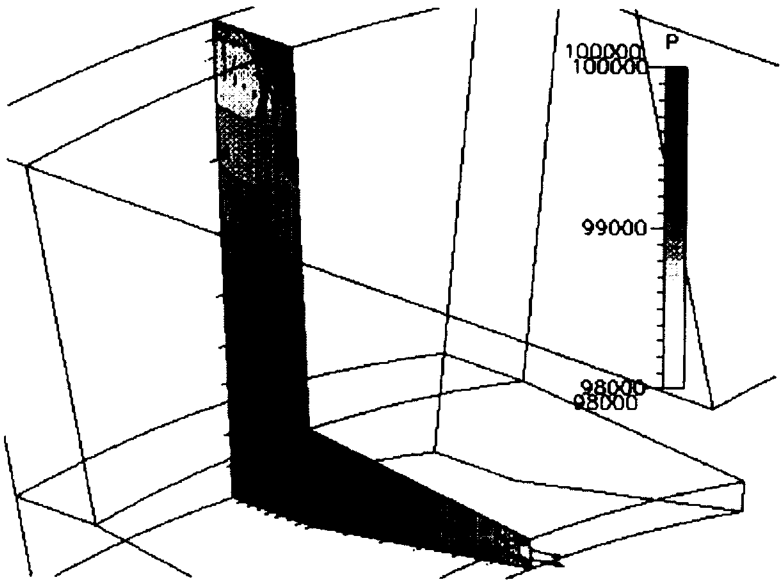
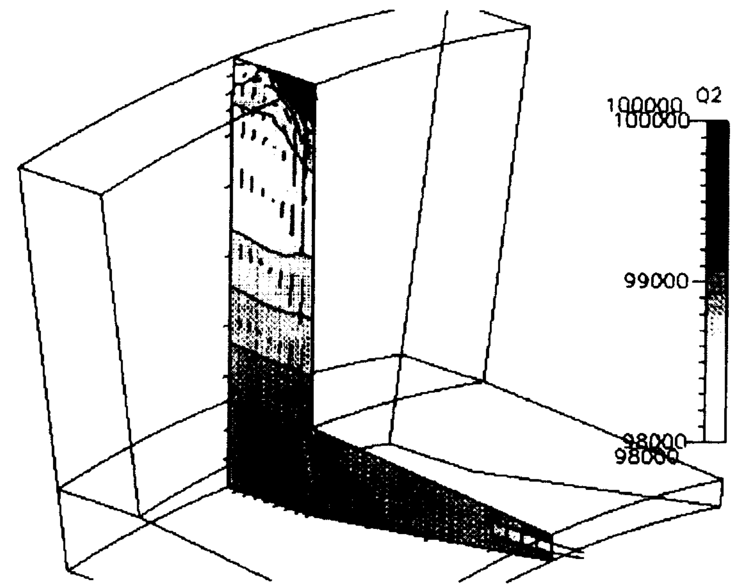
COMPARISON OF RESULTS

Cavity Flow with Ingestion in Cavity



single code
SCISEAL



coupled codes
SCISEAL-TURBO

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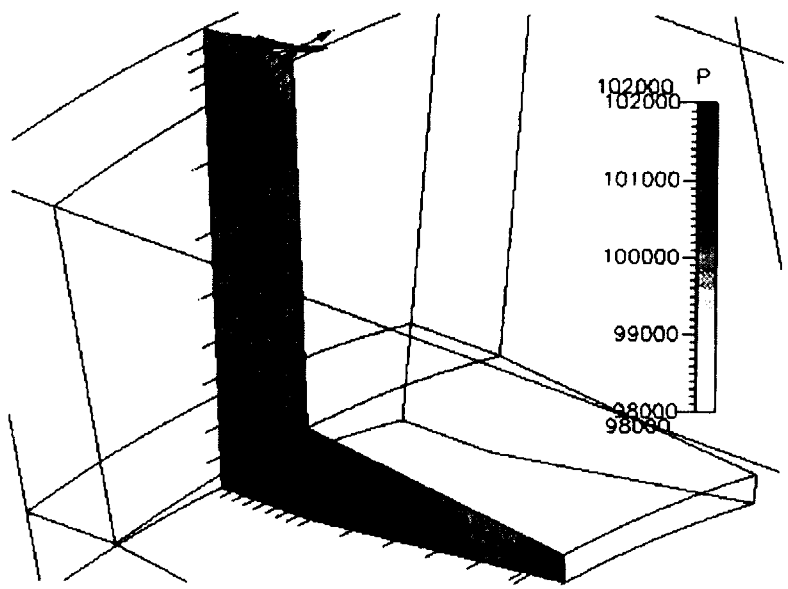
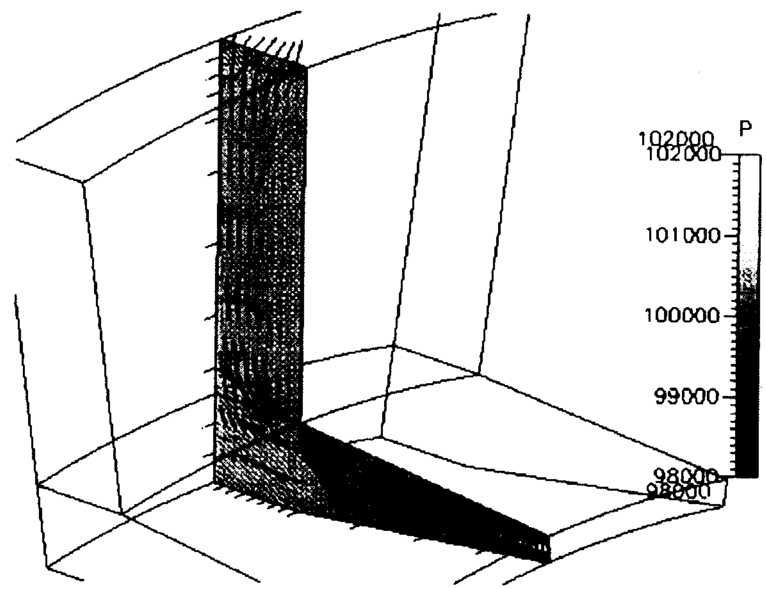
COMPARISON OF RESULTS

- Cavity Flow with Flow Out of Cavity
- Flow Rates from Coupled Runs Match to Within 10% of the Values for Single-Code Runs (outflow velocities differ due to graphical post-processing)



single code



coupled codes

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H.P. RIG UTRC

- Single Stator and Rotor Stage;
  High-Work Design

- 48:58 Blade Numbers, Changed to 48:60;
  Allows a 30° Sector for Flow Calculations

- 4 Blades in Stator, 5 Blades in Rotor
  - 49x12x15 grid in each stator blade passage
  - 36x12x12 grid in each rotor blade passage
    (total ~ 61K cells)

- Cavity + Rim Seal: 16 domain multi-block grid
  - all flow areas modeled exactly
  - 33000 cell grid

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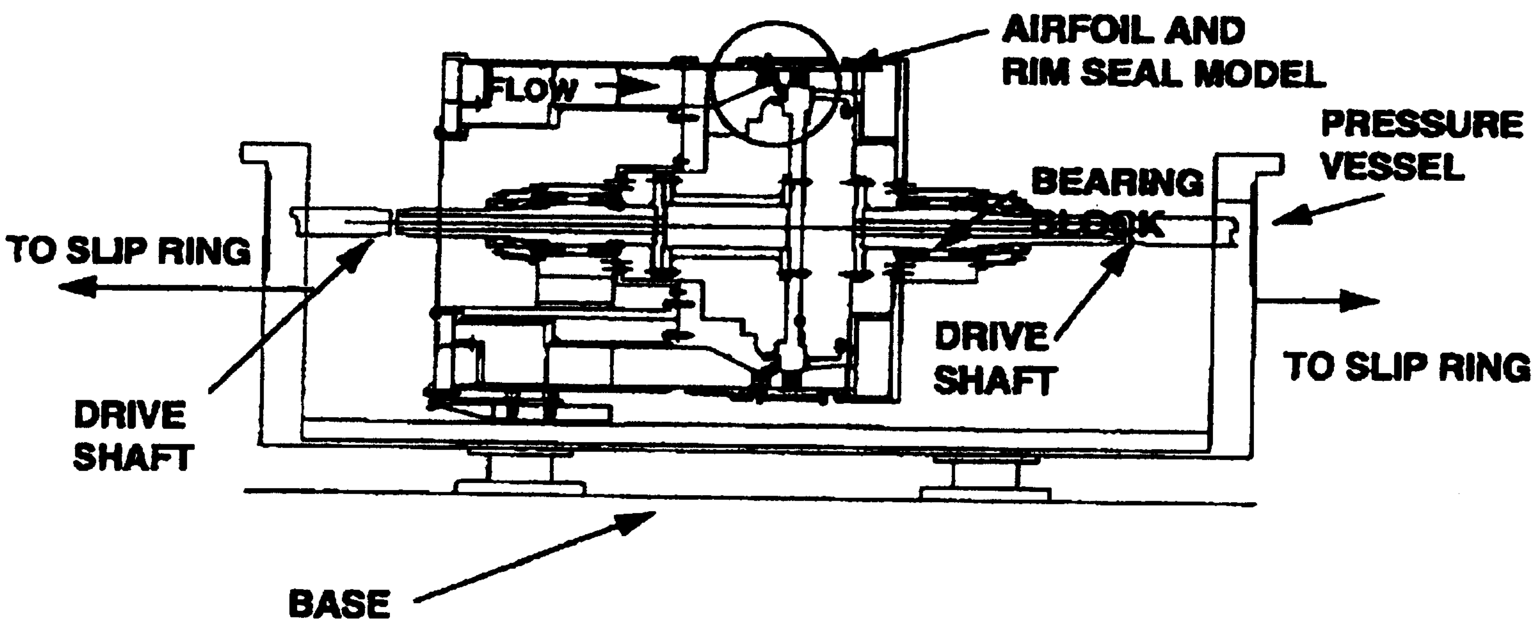
SCHEMATIC OF THE H.P. TURBINE RIG

CROSS-SECTION OF RIM SEAL INGESTION RIG



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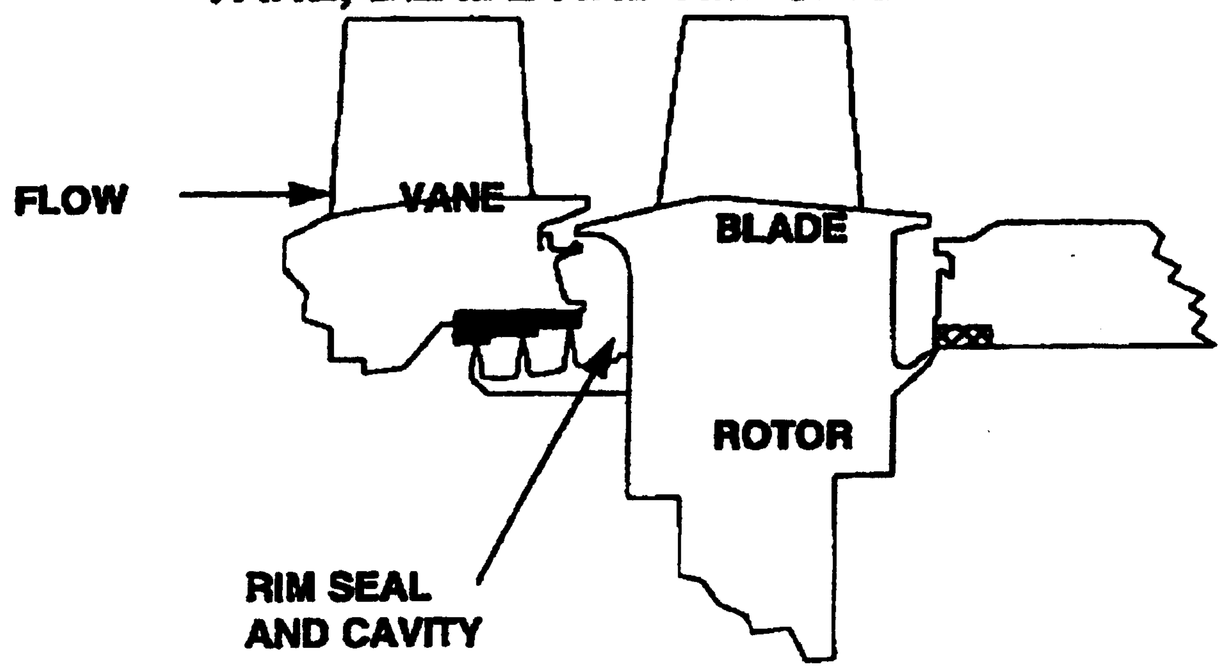
DETAILS OF THE FLOWFIELD IN H.P. RIG

VANE, BLADE AND RIM SEAL MODEL



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H.P. RIG

- Main Path Condition
  - Upstream pressure: 155 kPa (22.4 psia)
  - Temp = 302.6K (544.6R)
  - $\dot{m}$ = 5.766 Kg/s, axial flow

- Downstream Pressure = 122.7 kpa (17.8 psia)
  - 3600 rpm

- Cavity Inlet Conditions (2 Considered)

1. Total pressure = 150.35 kPa (0.97 P_{upstr}), T = 302.6K
2. Total pressure = 124 kPa (0.80 P_{upstr}), T = 302.6K

Case 1 shows Egress from Cavity
Case 2 Nearly Zero Flow Across Rimseal

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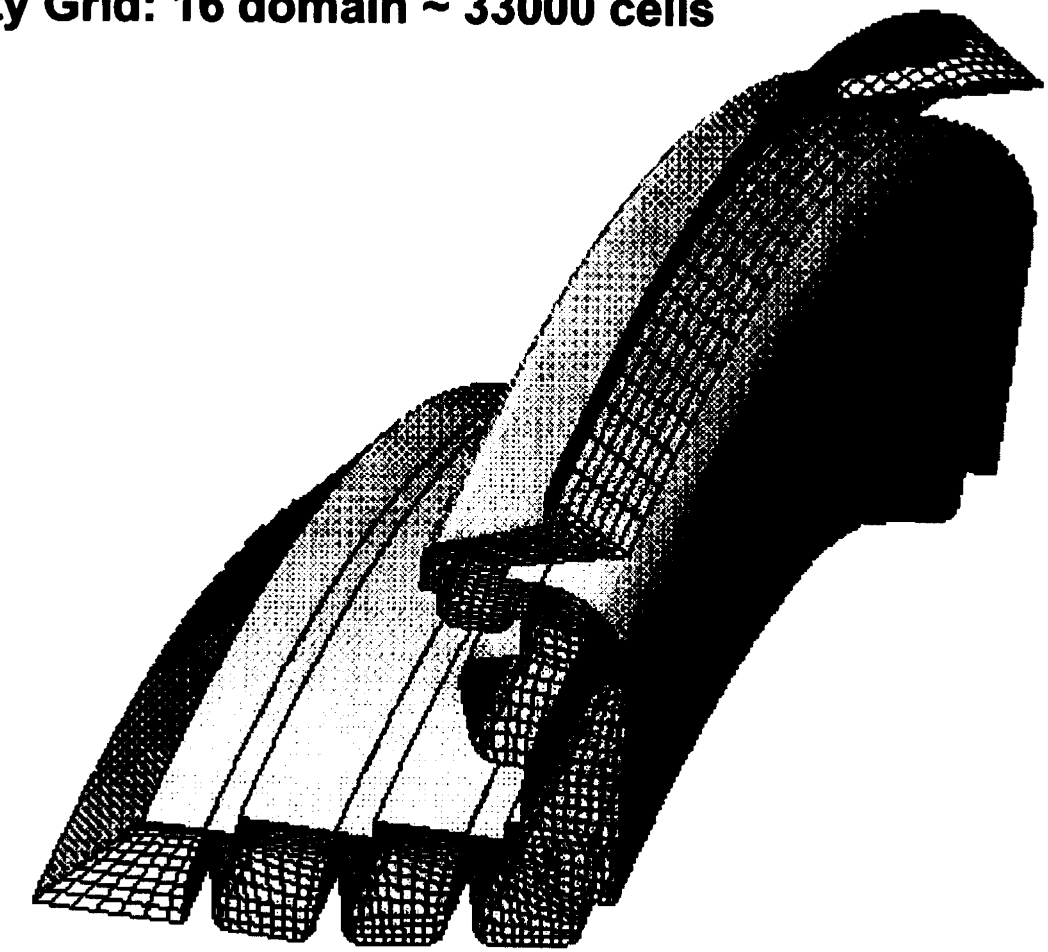
H.P. RIG

- Cavity Grid: 16 domain ~ 33000 cells



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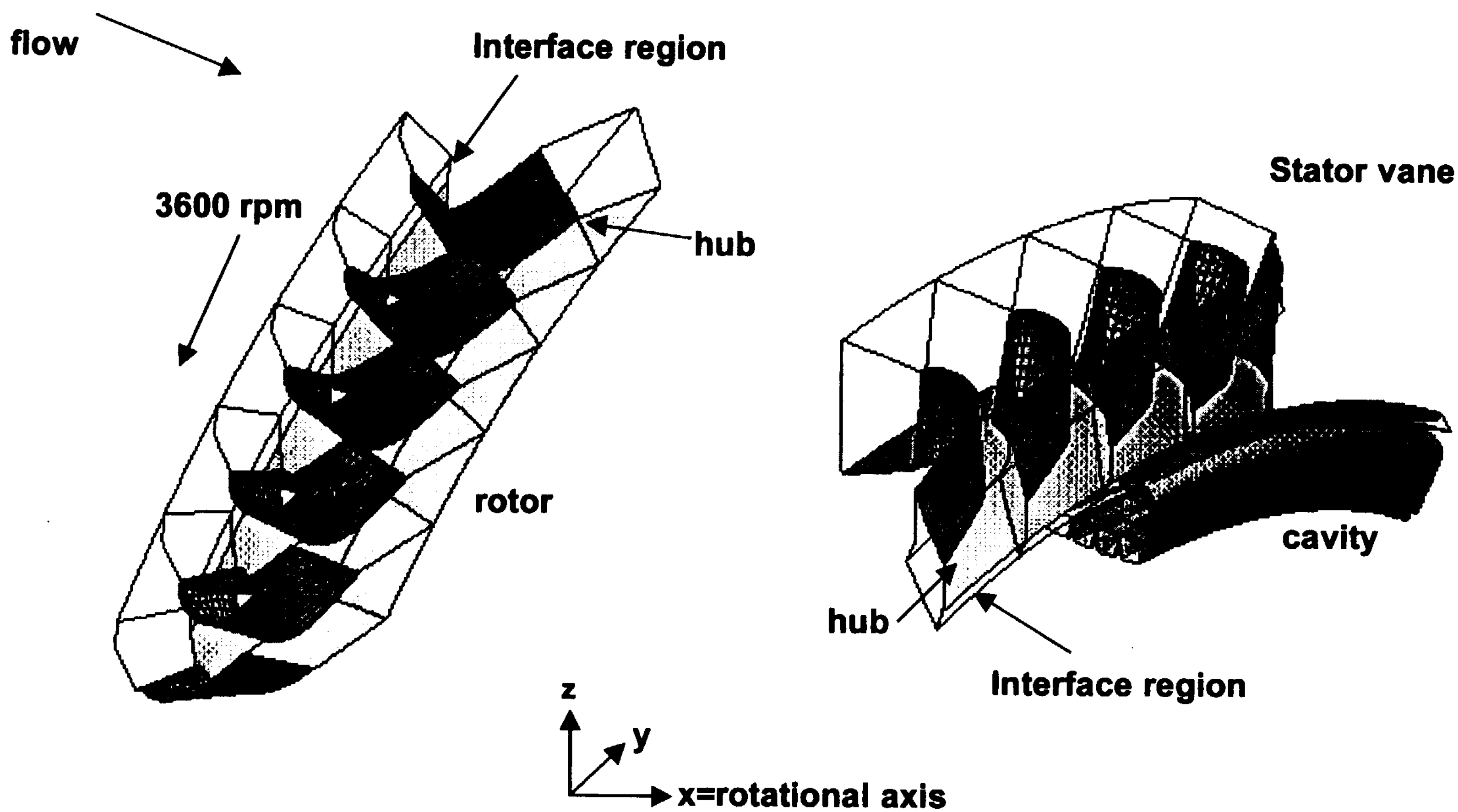
H.P. RIG

- **Relative Locations of Flow Domains at a Specified Time Instant**



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H.P. RIG SIMULATIONS

- 2D Axisymmetric (No Blades in the Main Path, Steady-State) and 3D Coupled, Transient Runs Simulated

- Rim Seal has Net Flow Entering the Mainpath (for Case 1)
  - 2-D: 0.276×10^{-3} Kg/s per 30° sector
  - 3-D: $0.25\text{-}0.26 \times 10^{-3}$ Kg/s per 30° sector

- Results for Case 1:
  - taken after about 600 steps
  - vector plots: in cavity at different cross-section, 2-D results, mainpath
  - static pressure: in cavity, at hub in mainpath

- Results for Case 2:
  - cavity velocity and pressure fields at similar locations

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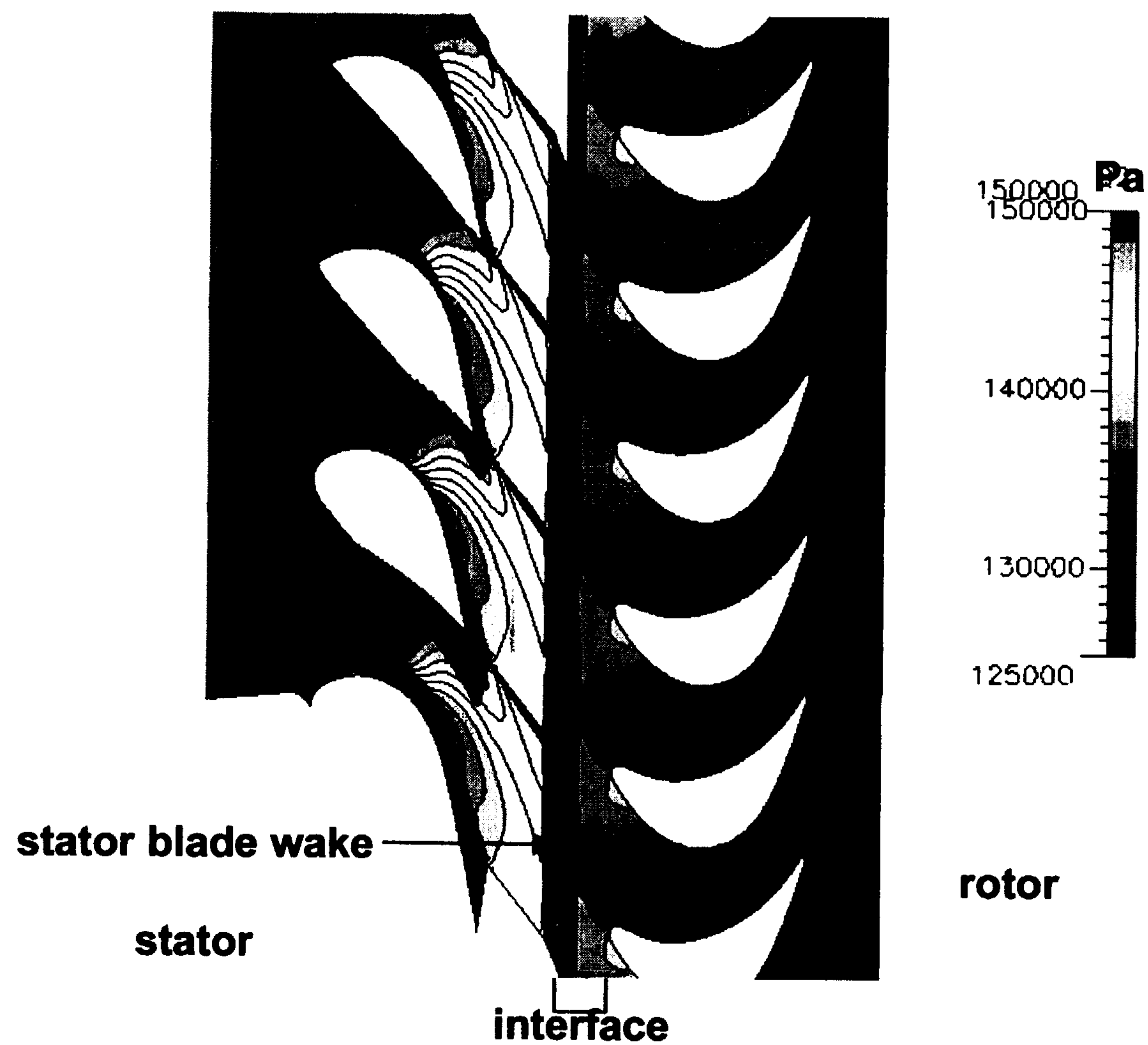
MAINPATH SOLUTIONS

Static Pressure Field at Hub



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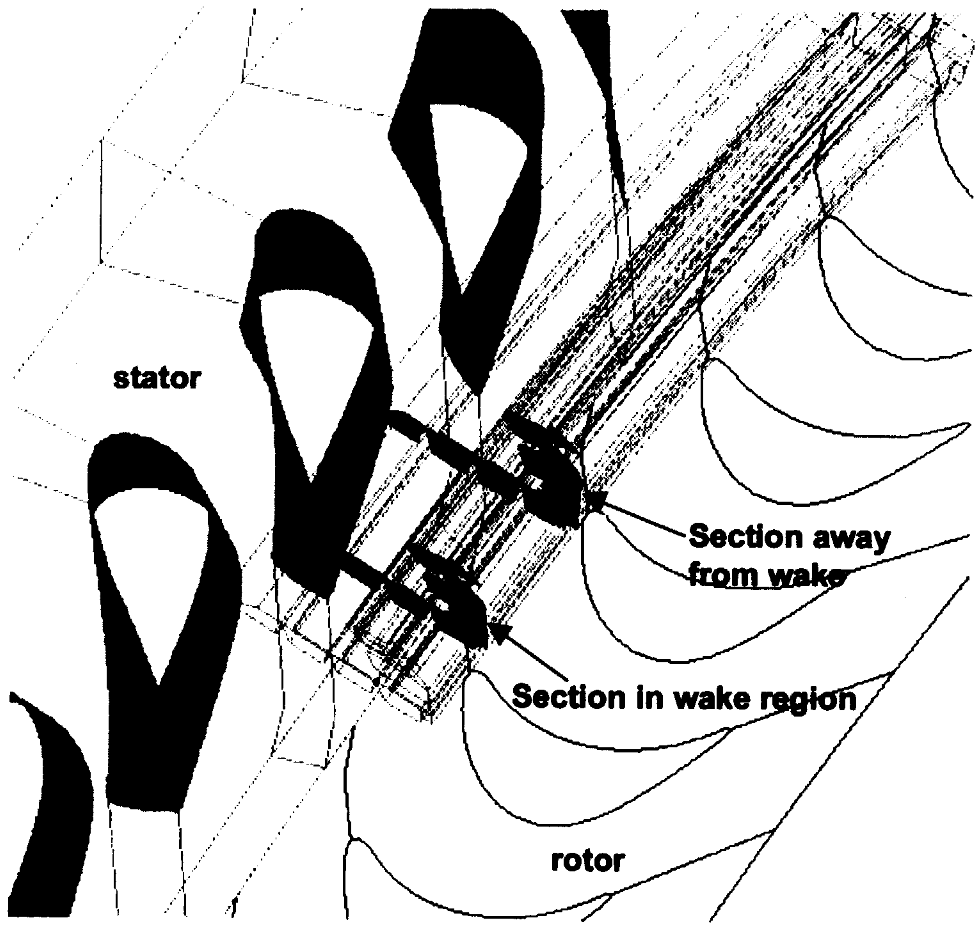
CAVITY FLOW

- **Locations of Cavity Cross-Sections**



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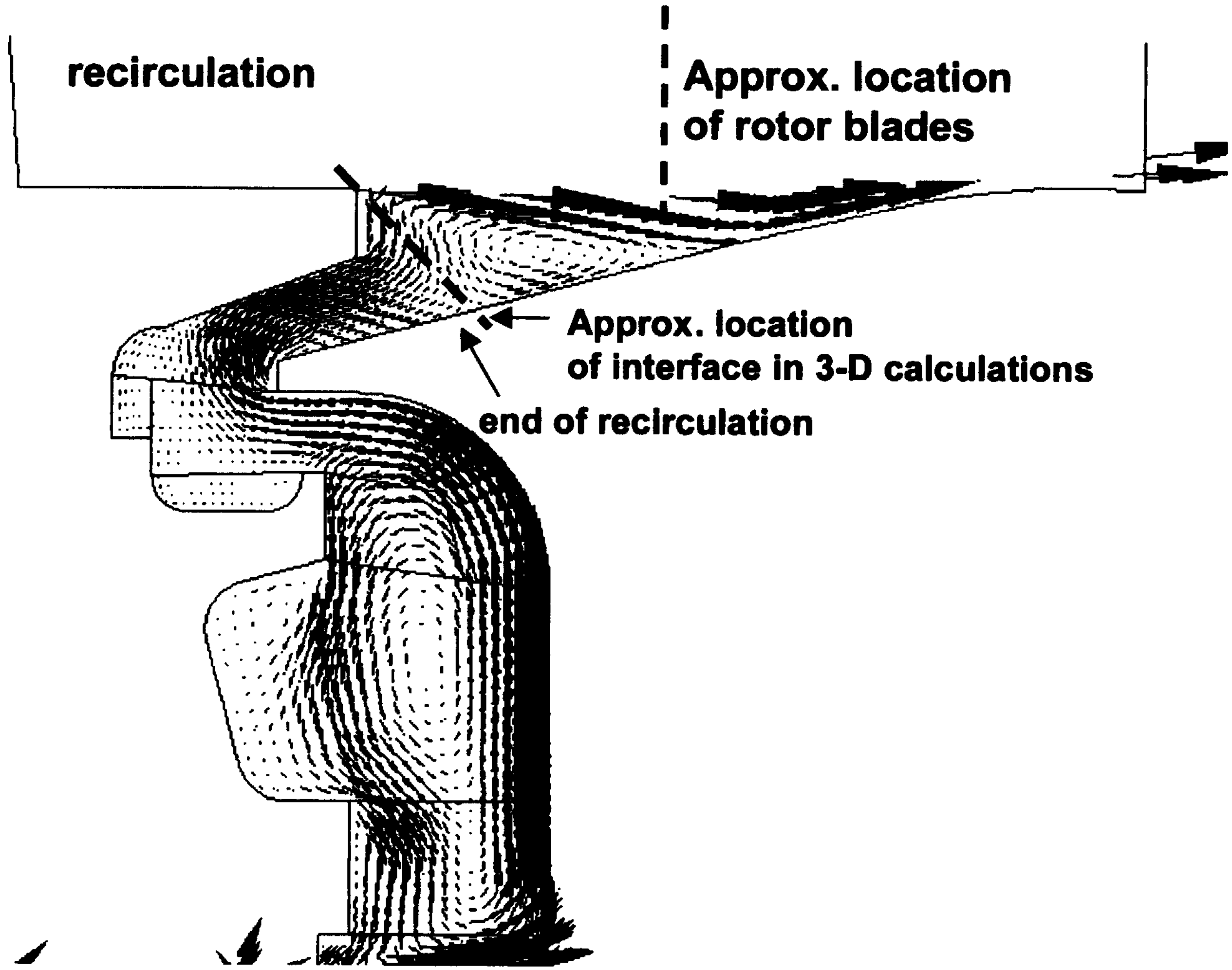
CAVITY VELOCITIES

2-D Axisymmetric, Steady-State Field, Case 1



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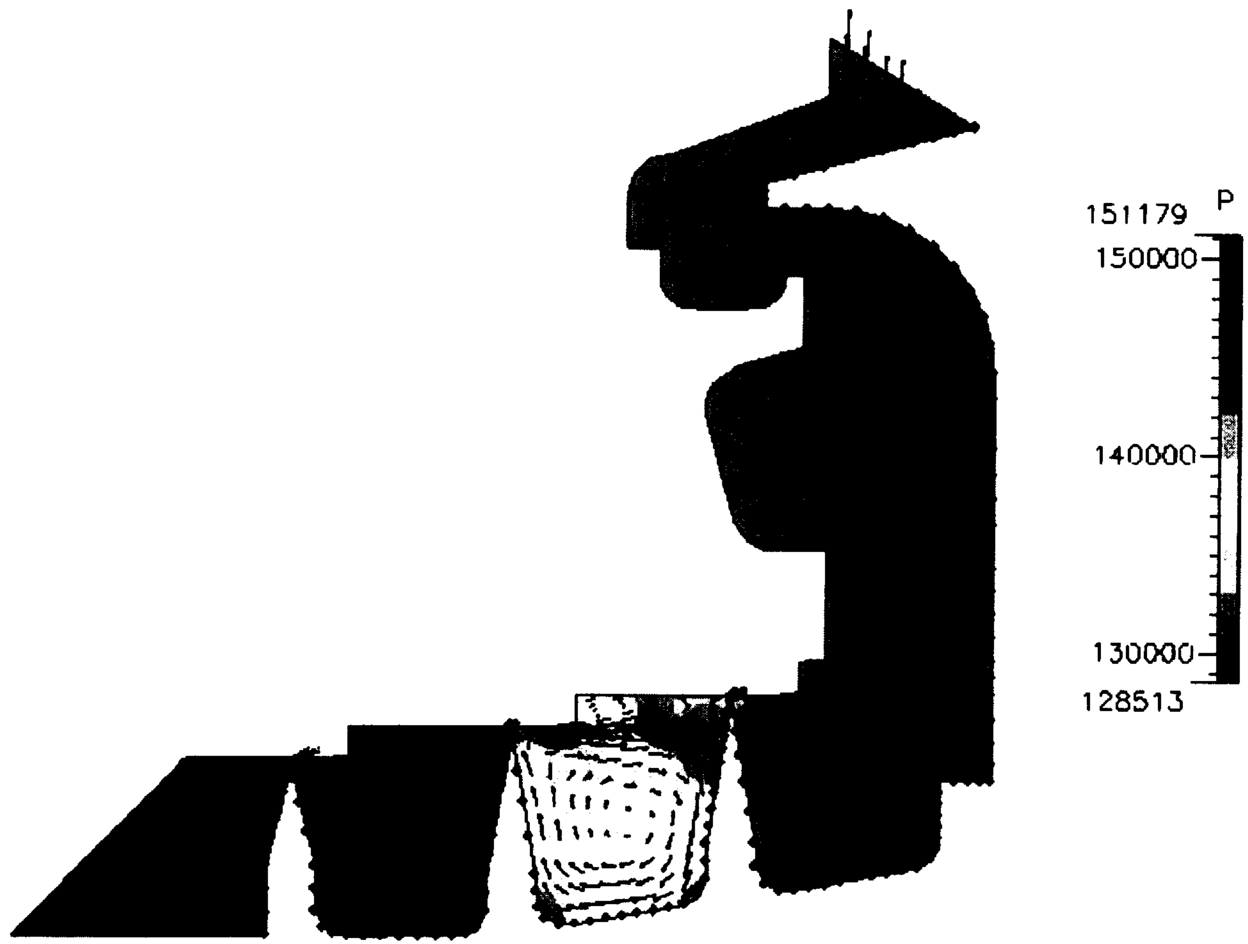
VECTOR PLOTS IN CAVITY

- Rim Seal in Slow Moving Mainpath (Blade Wake), Case 1



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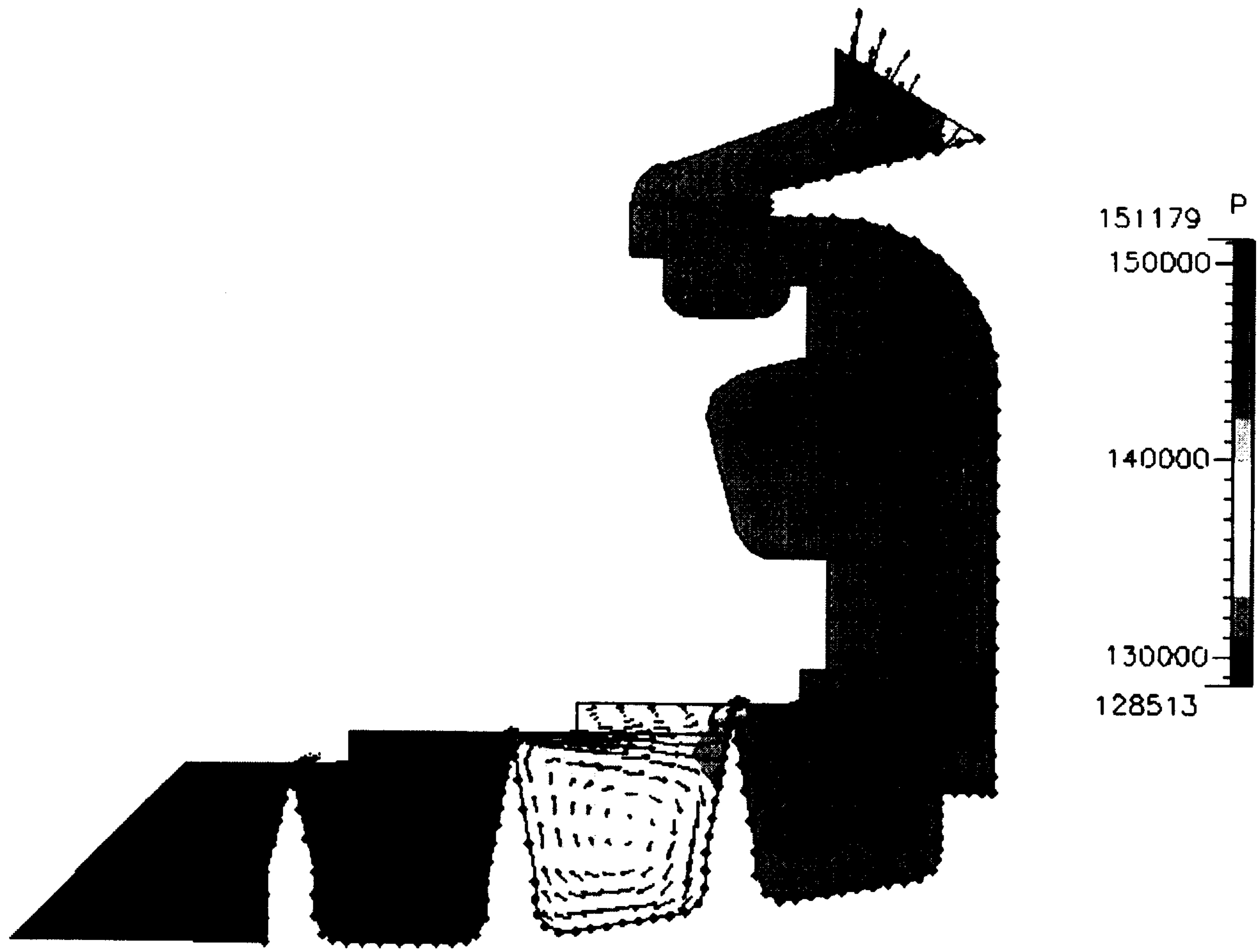
VECTOR PLOTS IN CAVITY

- 3-D, Coupled Solutions, Case 1
- Rim Seal in Fast Moving Mainpath Flow Area



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LSAC RIG

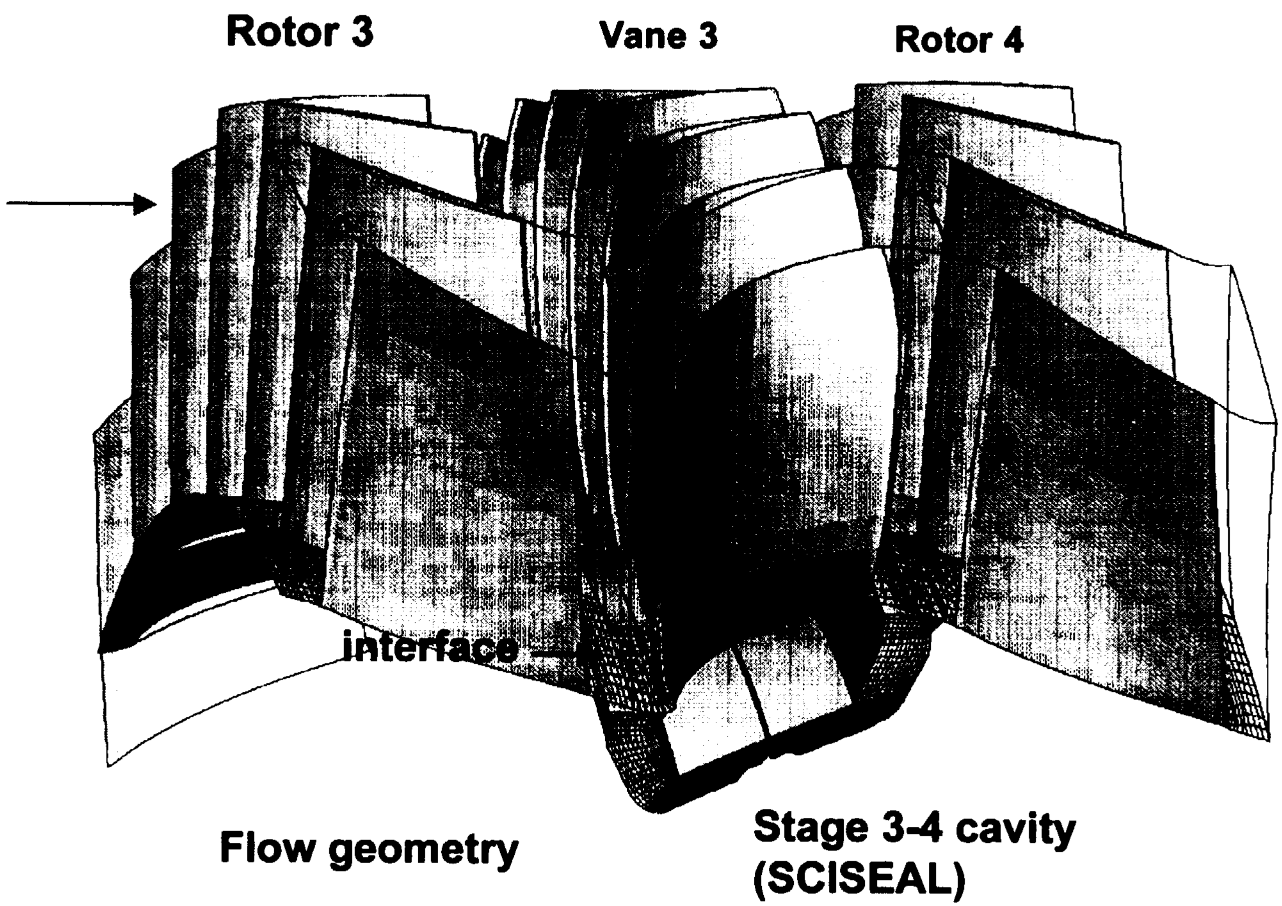
- Low Speed Compressor Facility in NASA LeRC

- Simulation Involve 3rd and 4th Rotor Stages + Stator 3 and Associated Cavity
  - experimental data available for comparison (Wellborn and Okiishi, 1996)

- Validation Case for Coupled Codes

LSAC FLOW DOMAIN

- 2 blade rows + 1 vane (stage 3, 4 blade rows, stage 3 vane) + interstage cavity



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LSAC RIG

- 3 Blade Passages for Rotor 3 and 4, 4 Passages in Stator
  - pi sector with 360/13 degrees
- Grid Sizes: 130K cells in Mainpath, ~ 28K in Cavity
- Mainpath Boundary Conditions:
  - specified profiles of Po, To,flow angles at inlet
  - pressure ratio (static) of 1.02 across 2 stages
  - rotor speed = 958 rpm
- Cavity Boundary Conditions
  - appropriate stationary and rotating walls
  - rimseal conditions are part of the solution

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LSAC RIG

- Solution in Progress
  - very low speeds in mainpath present some difficulty

- Calculated Mainpath Flow Rates Yield Flow Coefficient ϕ of 0.34

- Representative Vector Plots in the Cavity Shown and Compared with Sample Data

- Calculated Leakage Rates ~ 0.045% as against 0.05%, estimated at $\phi = 0.4$

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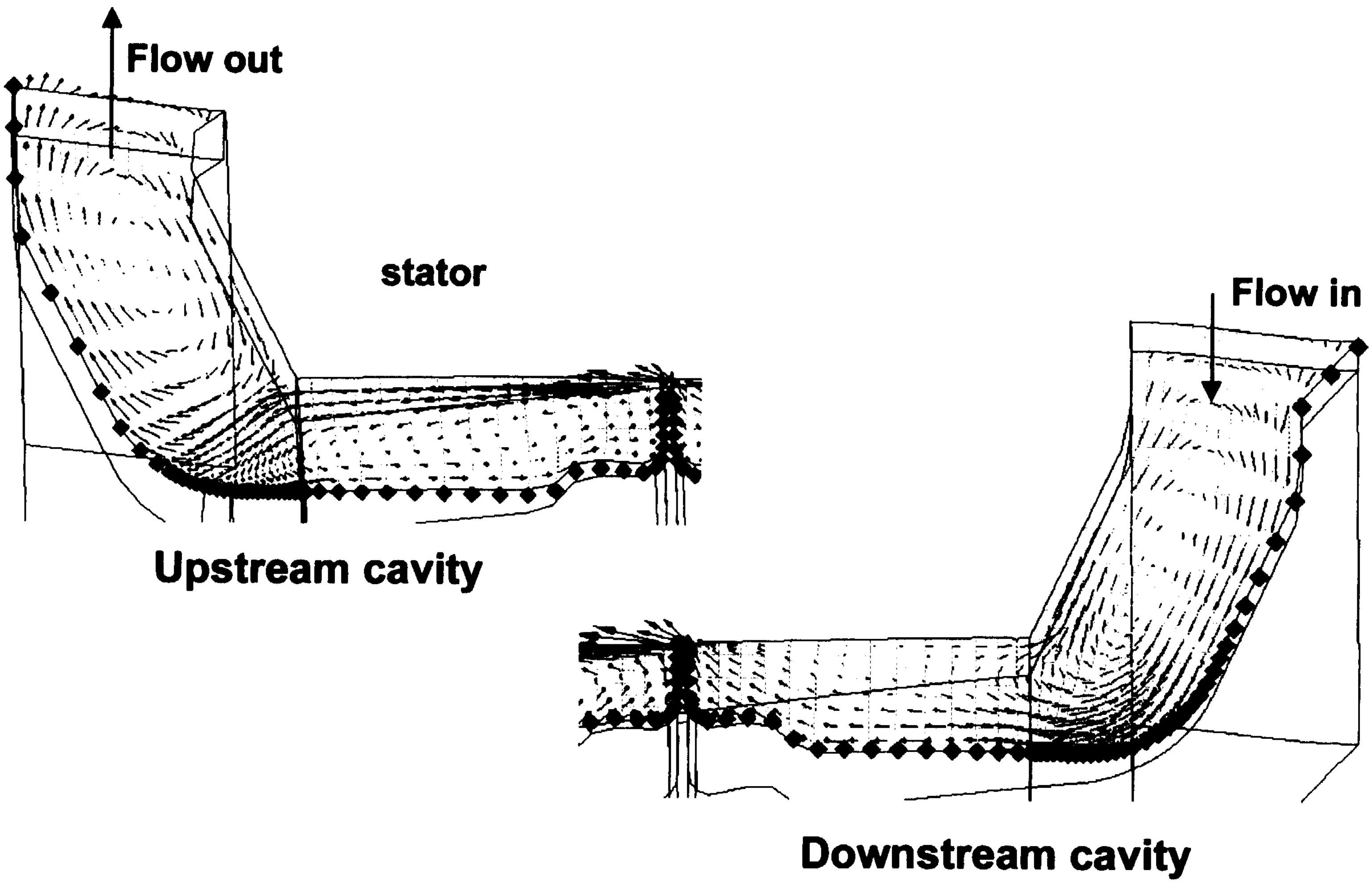
LSAC RIG

Cavity Vector Plots, Plane Under Stator Blade



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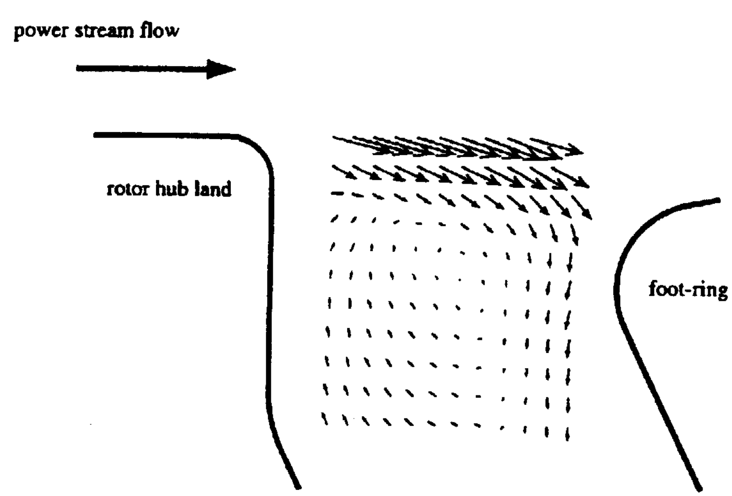
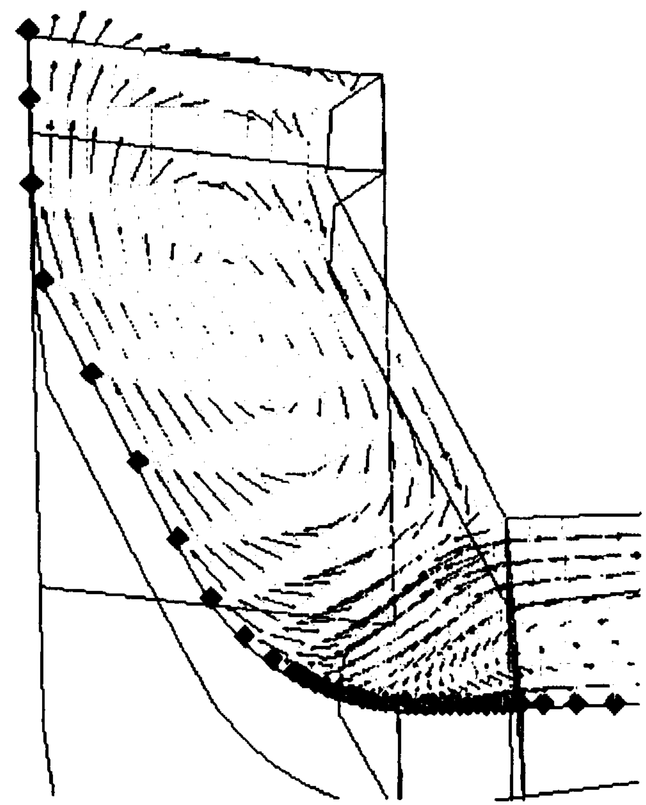
LSAC RIG

Vector Plot in Upstream Rim Seal Under Stator Blade (Qualitative Agreement)



Experiment



Computed

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REMARKS ON SIMULATION PROCEDURE

- Steady State Solution for SCISEAL and Startup Solution for TURBO Without Interfacing as Initial Condition is a Must

- Maximum CFL Numbers in TURBO were Kept about 10-12 for Stability

- Different Number of Subiterations in the Two Codes Needed per Data Exchange
  - allow the solutions to settle after each exchange
  - 25-40 for SCISEAL, 3-5 for TURBO

- Time for Execution was Long as Expected; Testing to see if Higher Stable CFL can be used with Current Number of Subiterations

SUMMARY

- Interaction between Mainpath and Secondary Flow Important; Need Details of Transient, Detailed Flow Information for Performance Prediction and Designs

- Numerical Methodology for Coupled, Transient Simulations Developed
  - validated codes: SCISEAL and MS-TURBO for secondary and primary flows
  - interfacing algorithm to link data at interface

- Validated Using a Checkout Case; by Comparing Coupled Code Solutions with Single-Code (SCISEAL Solutions)

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SUMMARY (CONTINUED)

- Flow in H.P. Rig Simulated at 2 Cavity Inlet Pressures
  - 2-D, steady-state, axisymmetric and 3-D transient, coupled solutions obtained, reasonable agreement of leakage flows
  - variations in rim seal seen at different θ locations
  - ingestion predicted at the lower cavity inlet pressure as seen in experiments

- LSAC Simulations in Progress
  - representative cavity vector plots
  - in qualitative agreement with experiments

- Additional Validation Cases being Sought from WPAFB
  - compressor and/or turbine sections

- Future Plans
  - improve post-processing
  - β-release to NASA, OEM
  - continue validation simulations, H.P. Rig data, LSAC, WPAFB data

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