Design and Analysis of Turbomachinery for Space Applications

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Overview

- Motivation
- Corsair
- Numerical experiments
  - Two-stage supersonic turbine
  - Partial-admission supersonic turbine
  - Centrifugal pump/diffuser stage
  - SSME fuel feed line/inducer
- Future directions

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Motivation

- Incorporate CFD into all aspects of turbomachinery design and analysis
  - Incorporate optimization techniques
  - Reduce design cycle time
- Characterize the unsteady and time-averaged flow fields:
  - Provide unsteady loads for structural/thermal analyses

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CORSAIR

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Corsair - I

- Corsair – 3D CFD code for analysis of turbomachinery components
  - 14 years of development
  - Doug Sondak (Boston University) co-author
- Wildcat is the 2D version of Corsair
- Available free from NASA

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Corsair - II

- Time-dependent equations of motion
  - Full Navier-Stokes, thin-layer Navier-Stokes or Euler
  - Variable fluid properties (Cp, gamma) as a function of P, T
- Third-order spatial discretization of inviscid fluxes
  - Roe
- Second-order spatial discretization of viscous fluxes
  - Standard central differences
- Second-order temporal accuracy

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Corsair - III

- Multi-block O-H grid topology
  - O-grids around airfoils and in tip clearance regions
  - H-grids for remainder of flow field and nozzles
  - Well-suited for parallel simulations
- Grid Motion
  - Arbitrary translation/rotation
  - Blade vibration

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Corsair - IV

- Turbulence models
  - Highly-modified Baldwin-Lomax model
  - Two-equation models (2D only)
- Transition models
  - Abu-Ghannam and Shaw
  - Mayle
  - Roberts

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Corsair - V

- Boundary conditions
  - Steady and unsteady inlet and exit
  - Specified wall temperature or heat flux
  - Film cooling/mass injection
  - Symmetry, part-span shrouds
  - Actuator disk
  - Component linking (cavities, etc.)

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Corsair - VI

- Parallel simulations
  - MPI used for coarse-grain decomposition
    - decomposition by blade row or passage
    - decomposition by O- and H-grids
    - decomposition by component
    - user specified decomposition
  - OpenMP used for fine-grain decomposition

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Corsair - VII

- Miscellaneous capabilities
  - Internal error checking
  - Conjugate heat transfer capability
  - Provides unsteady pressure files for stress analysis
  - Comprehensive design page
  - Will run on Unix, Linux or Windows NT platforms

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Design and Analysis of A Two-Stage Supersonic Turbine

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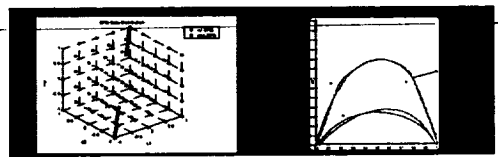
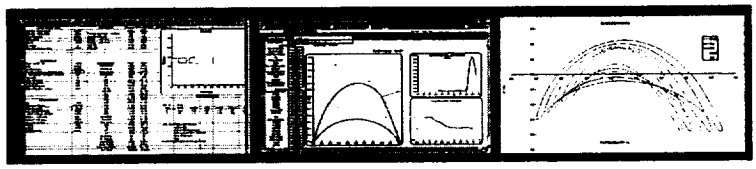
Design Process

Level 3
Design
Optimization



Level 2
CFD
Analysis

Level 1
1D Analysis
&
Design



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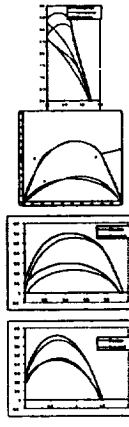
Two-Stage Supersonic Turbine

Baseline CFD Analysis

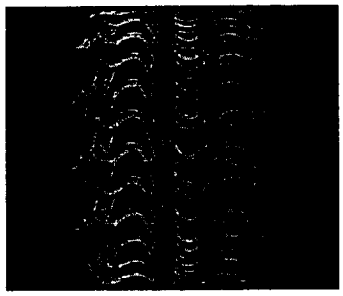


1st Vane

1st Blade

2nd Vane

2nd Blade



Optimized CFD Analysis

Optimized Blade Rows

Current improvement in turbine efficiency is 11 points. This could be traded for approximately 230° R in turbine inlet temperature or ~2.25 seconds of Isp, or a combination of the two.

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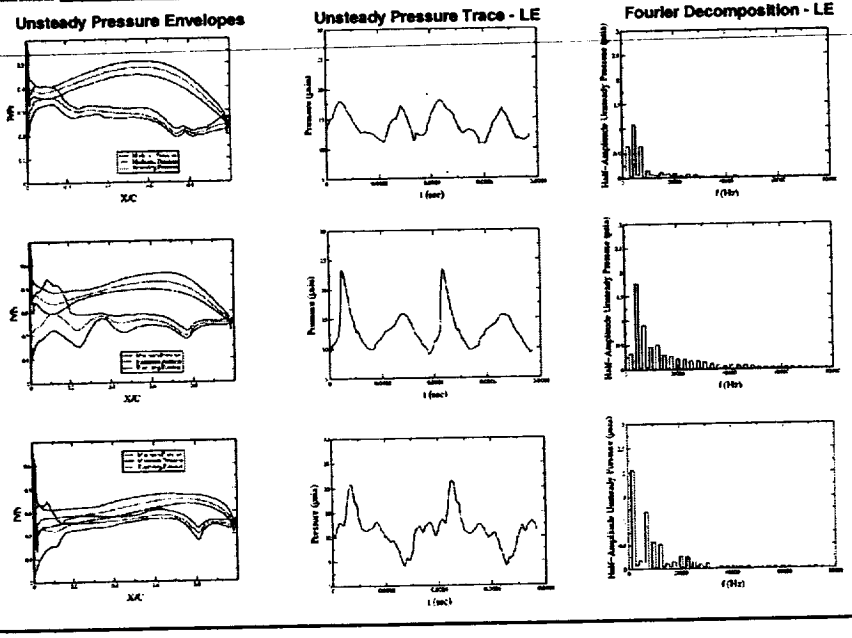
Two-Stage Supersonic Turbine



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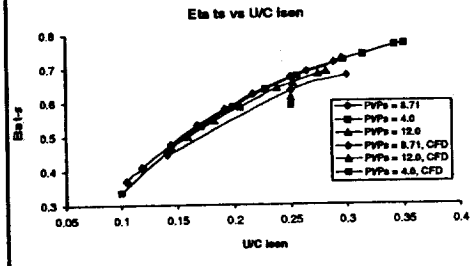
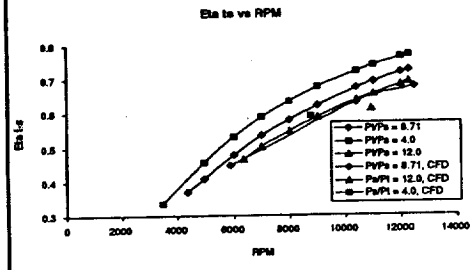
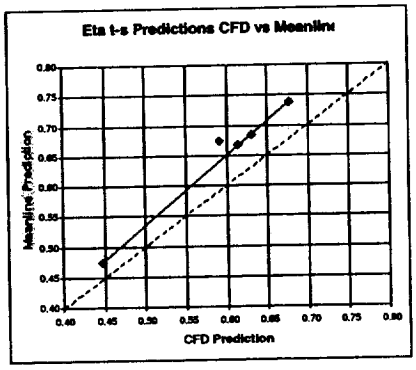
Comparisons with Meanline







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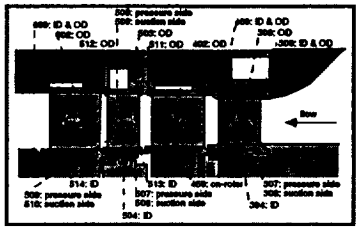
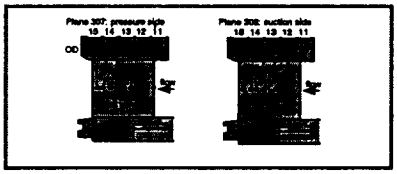
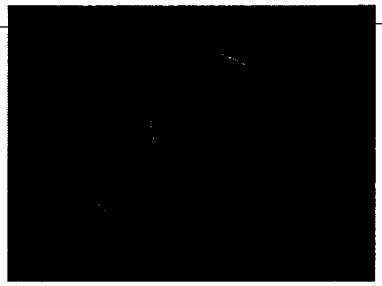
Experimental Apparatus

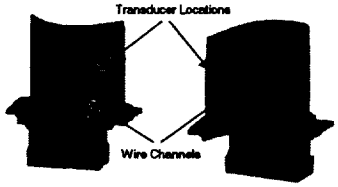
Type	Total Number
Steady-state pressure	71
Temperature	7
Fluctuating pressures:	
1st stage blade	30
Casing	6
Accelerometers	4
Speed	2







TPO Turbine 1st Stage Blades with Instrumentation Pockets Cut into the Surfaces



TPO Turbine 1st Stage Blade Models - Blades 1 and 2 of 6

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Flow in a Partial-Admission Supersonic Turbine

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Simplex Partial-Admission Turbine

- **Simplex supersonic turbine**
  - –Straight centerline nozzles (6 nozzles/95 rotors)
- **Full-Admission simulation**
  - –1 nozzle and 8 rotors modeled, 1.3 million grid points
- **Partial-Admission simulation**
  - –6 nozzles and 95 rotors modeled, 7.1 million grid points
  - –1+ revolutions
- **Flow conditions**
  - –M_1=0.25, Pt_1=801 psia, Tt_1=799 R, Pt_1/P_3=15
  - –Operating fluid is GOX in engine, N_2 in rig experiments
- **Computational resources**
  - –17-38 MPI processes on 450 MHz SGI O2000 processors
  - –1-3 OpenMP threads
  - –$3x10^{-6}$ sec/grid point/iteration using 38 MPI process, 1 OpenMP thread

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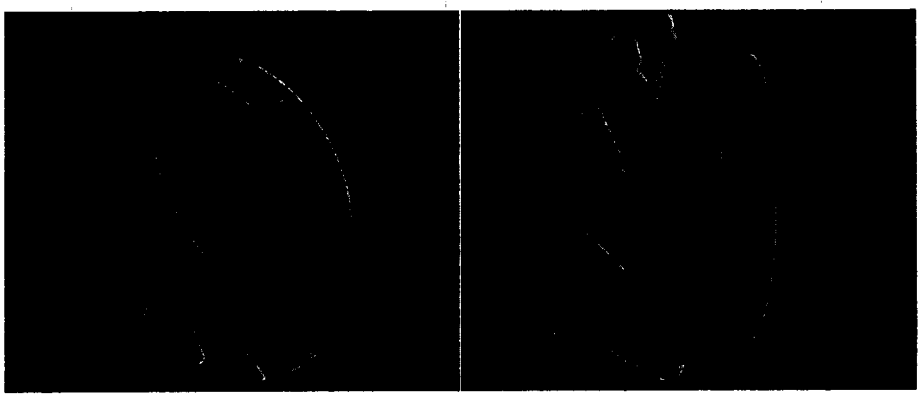
Simplex Partial-Admission Turbine



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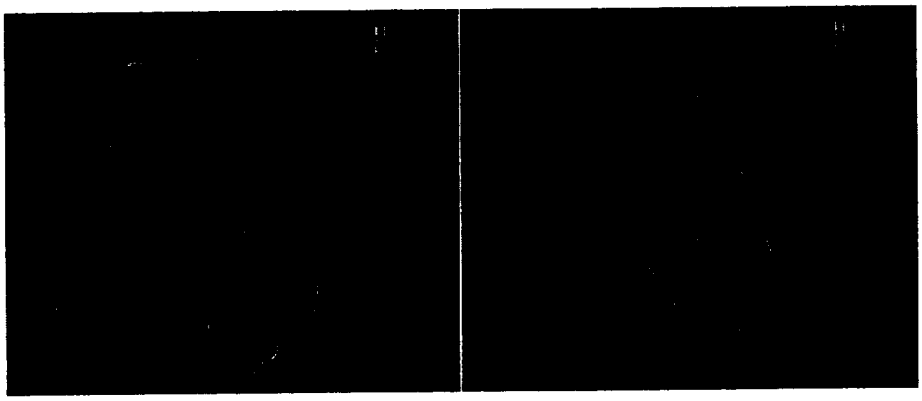
Instantaneous Mach Number



FULL ADMISSION

PARTIAL ADMISSION

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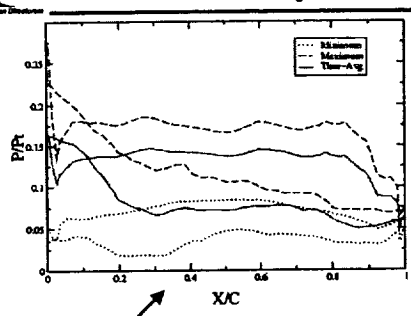
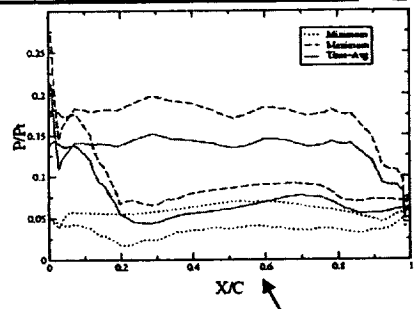
Unsteady Pressure Envelopes

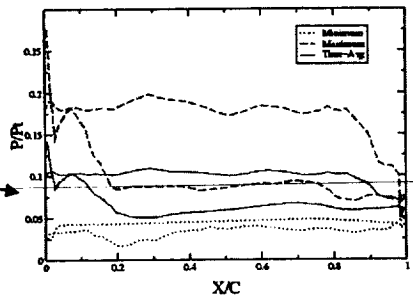




Full Admission

Partial Admission In Jets

Partial Admission In and Out of Jets



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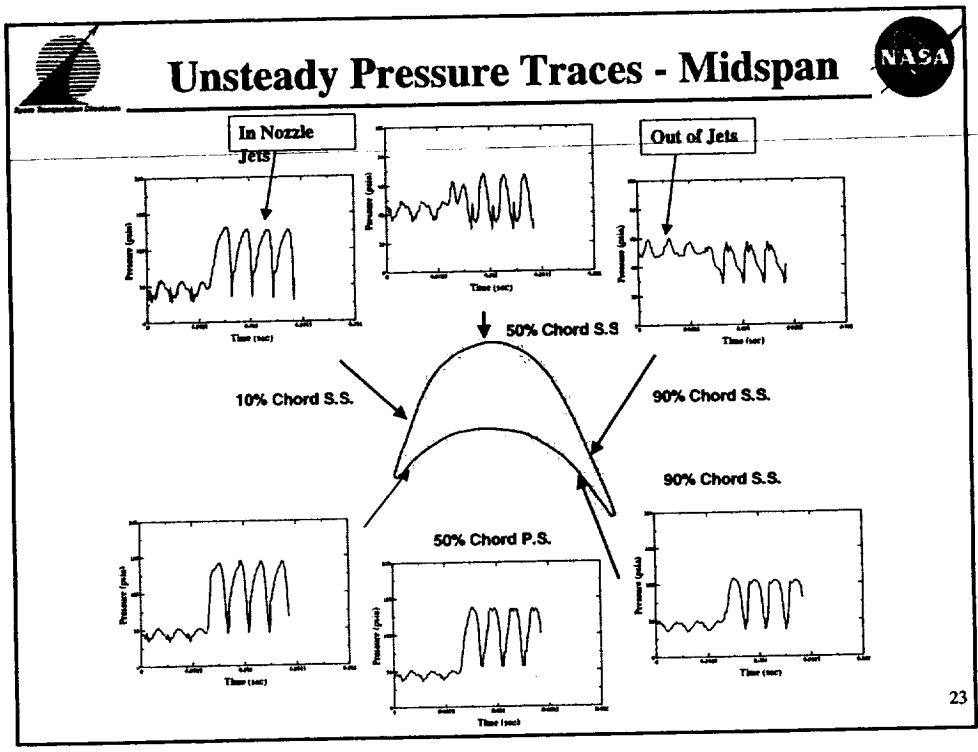
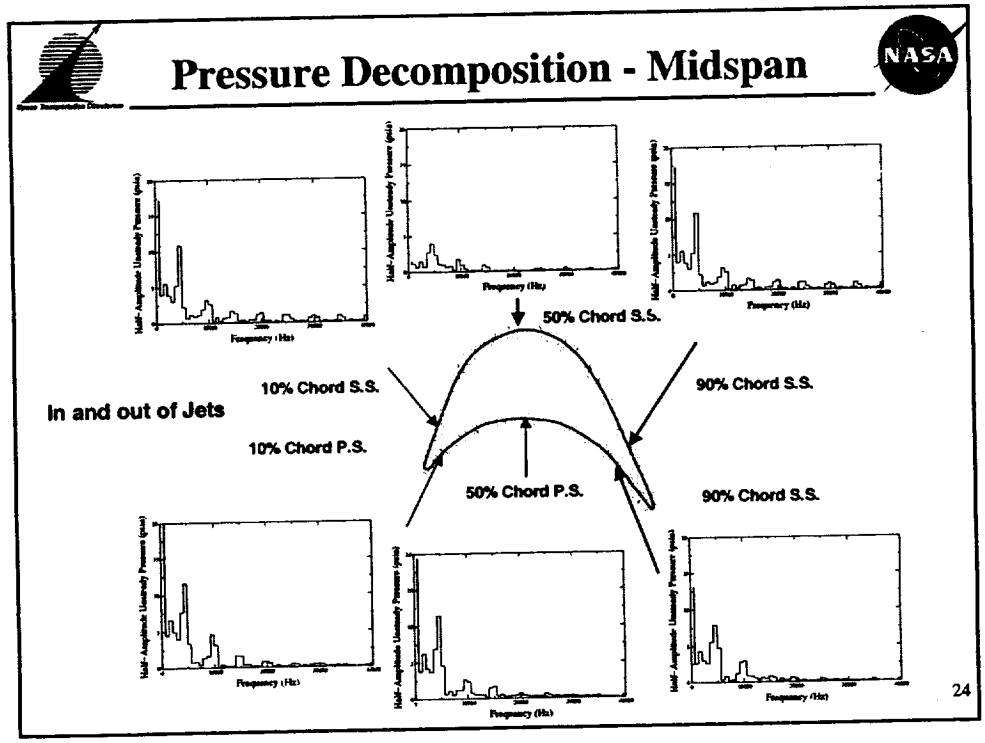
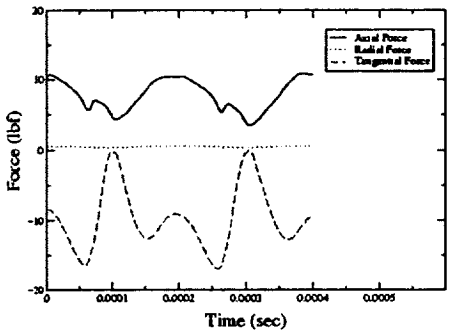

Unsteady Pressure Traces - Midspan
In Nozzle Jets
Out of Jets
50% Chord S.S
10% Chord S.S.
90% Chord S.S.
90% Chord S.S.
50% Chord P.S.
23


Pressure Decomposition - Midspan
50% Chord S.S.
In and out of Jets
10% Chord S.S.
10% Chord P.S.
90% Chord S.S.
50% Chord P.S.
90% Chord S.S.
24

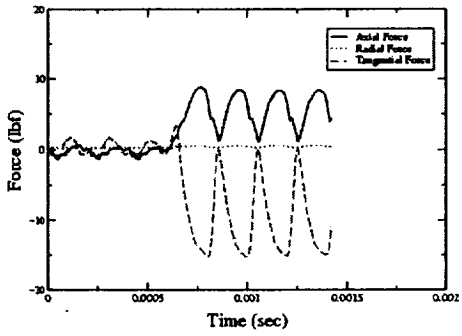
Unsteady Integrated Forces

η=0.633



FULL ADMISSION

η=0.504



PARTIAL ADMISSION

Experimental value from rig - η=0.605 -- two of three probes in flowing region

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Flow in a Centrifugal Pump Stage

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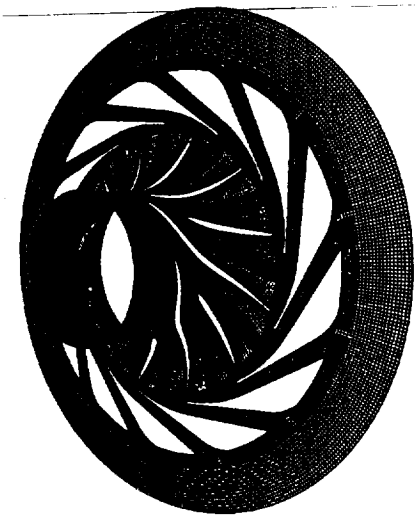
Grid for Centrifugal Stage



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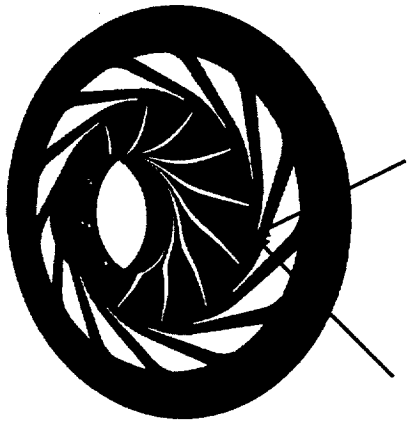
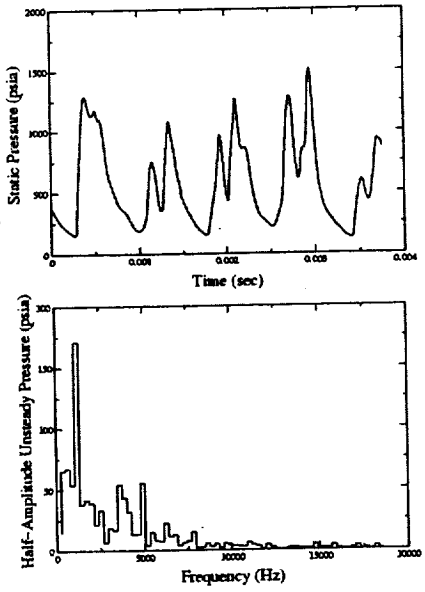
Unsteady Pressure w/o Splitters





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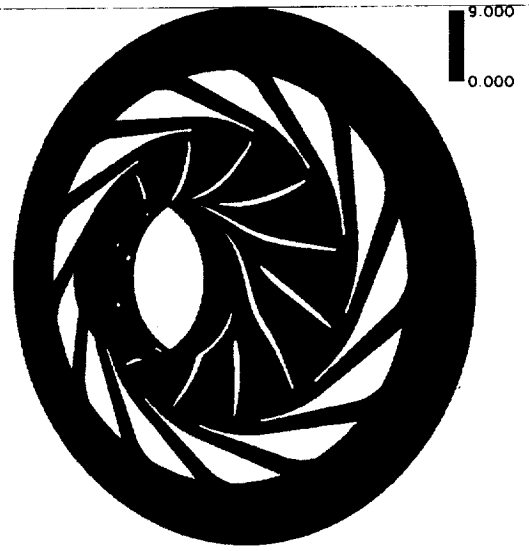
Unsteady Pressure w/ Splitters

Dimensional Pressure in psia = Non-Dimensional Pressure x 105



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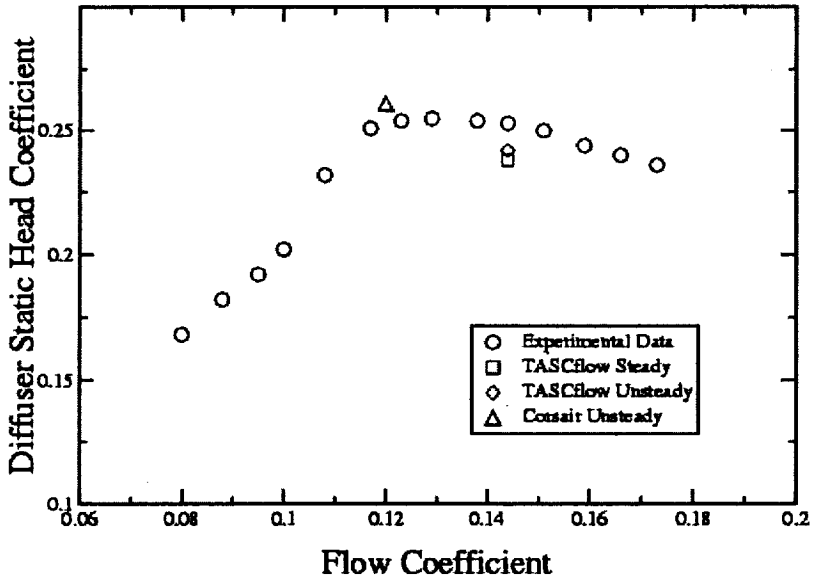
Static Head Coefficient



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SSME Flow Liner/Inducer Simulations

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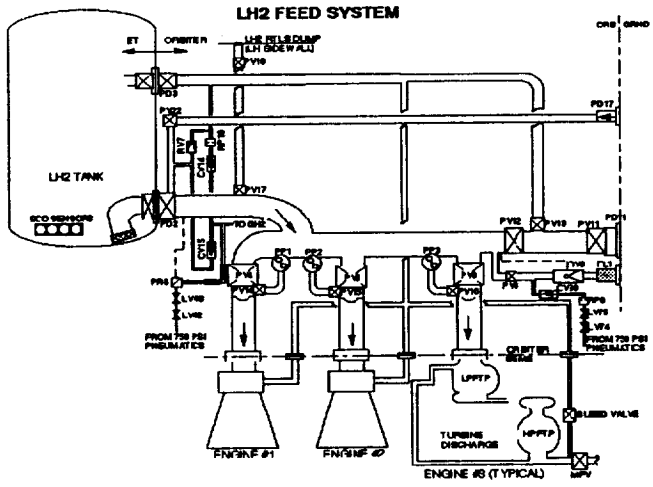
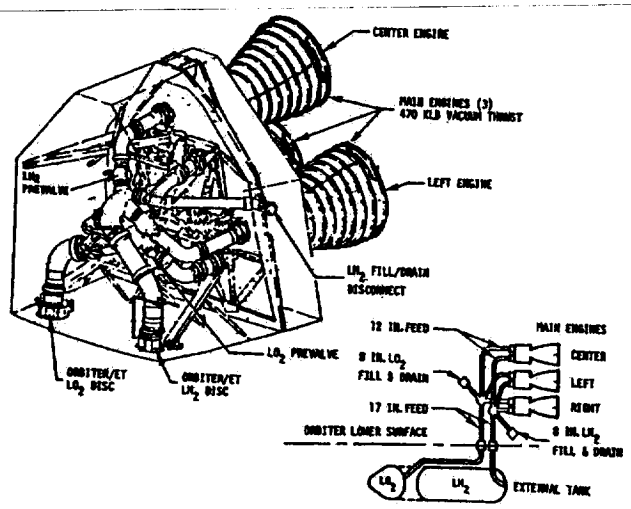
SSME LH2 Feed System



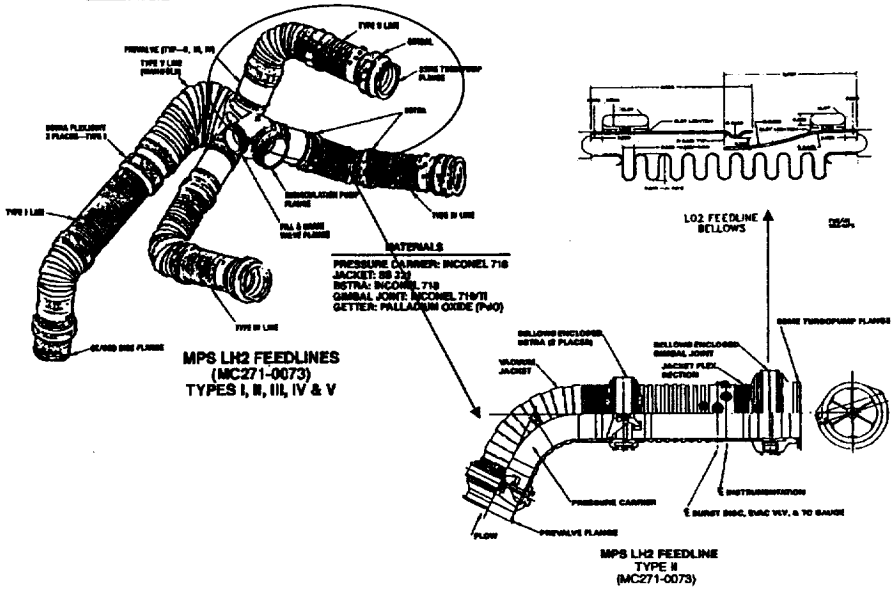
32

SSME LH2 Feed System



33

SSME LH2 Feed System



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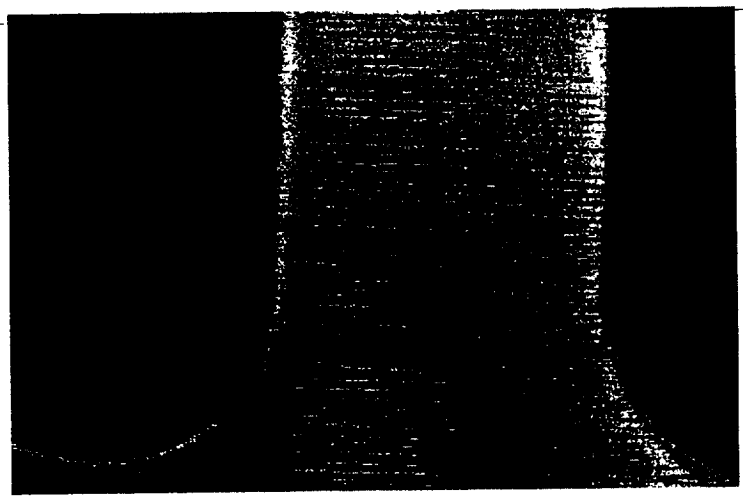
LH2 Flow Liner Slots



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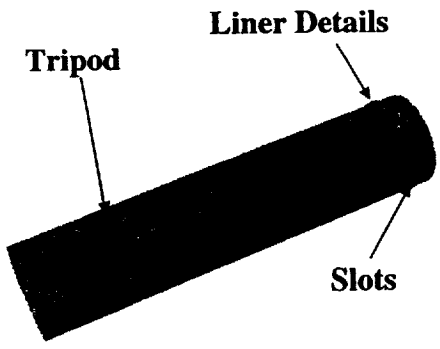
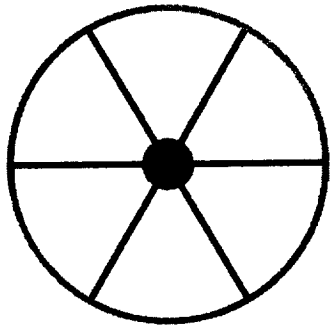
Feedline and BSTRA





View from Upstream

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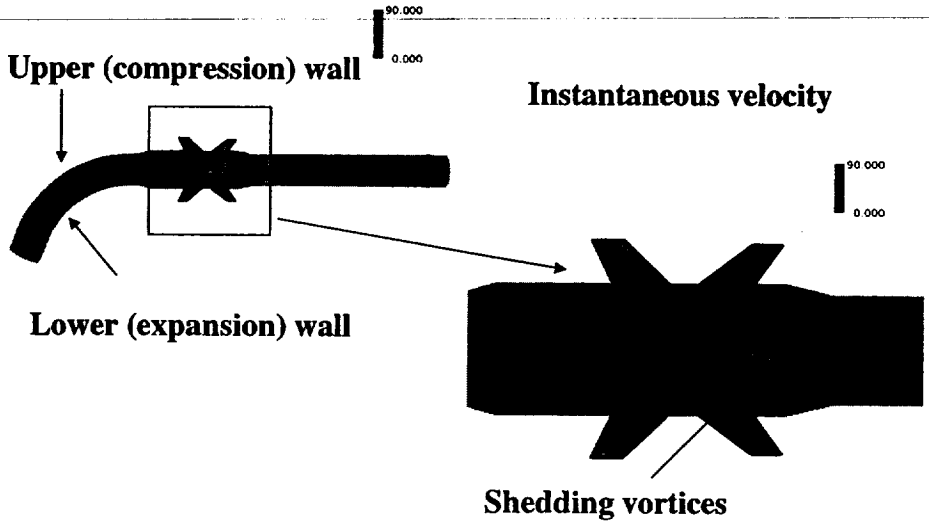
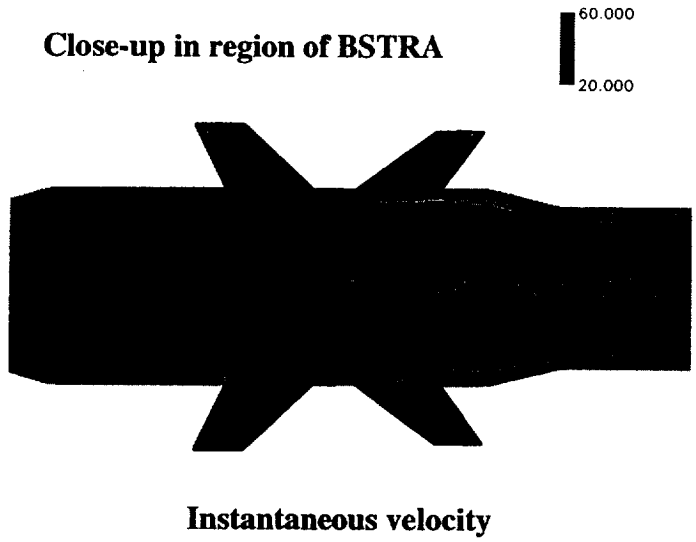
Feedline and BSTRA



37

Feedline and BSTRA



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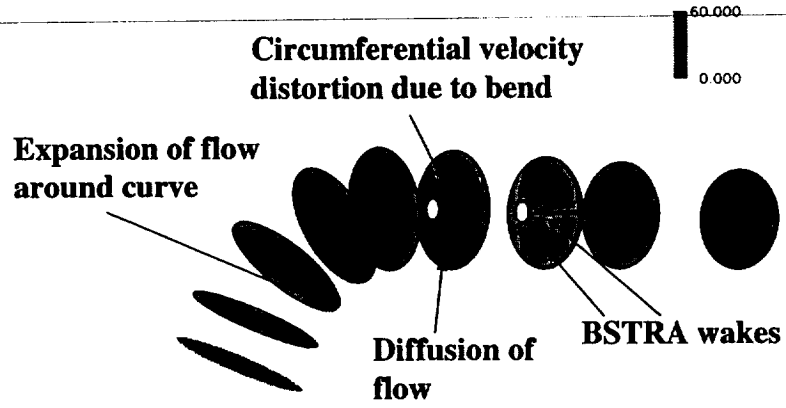
Feedline and BSTRA



Instantaneous velocity

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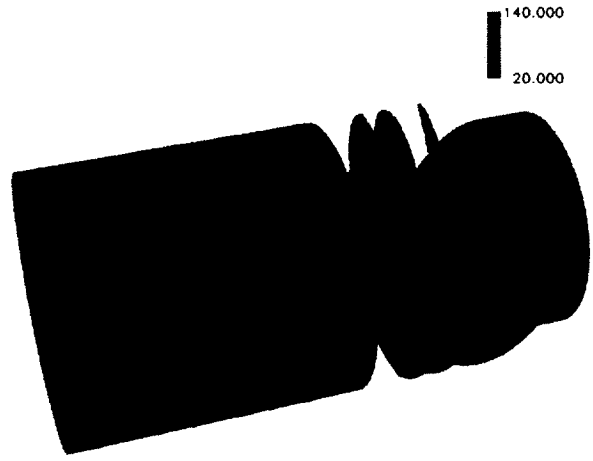
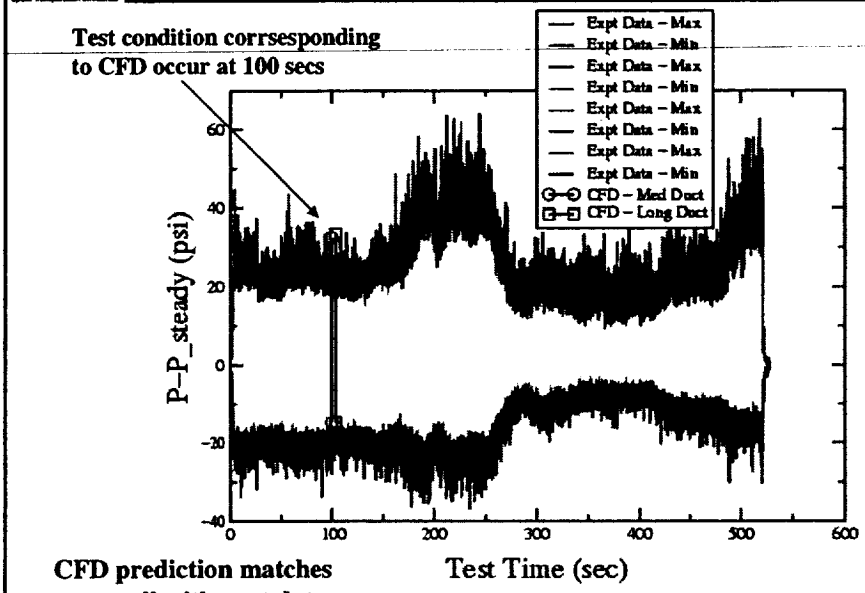
Feedline and Inducer



Instantaneous velocity

40

Feedline and Inducer



CFD prediction matches very well with expt data

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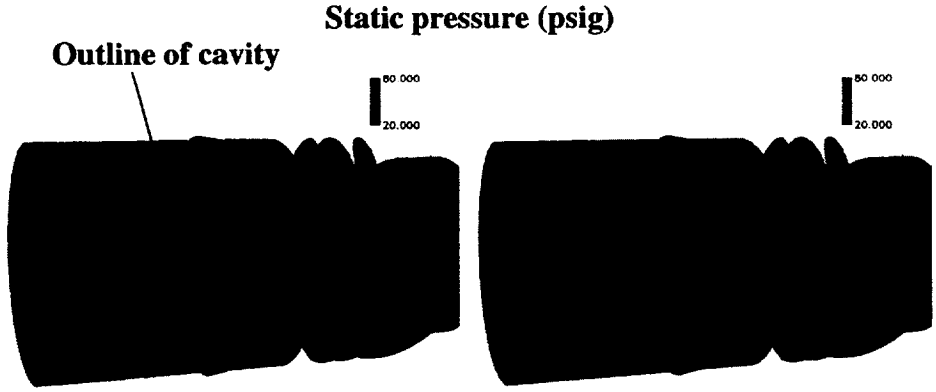
Inducer Simulation w/slots, cavity



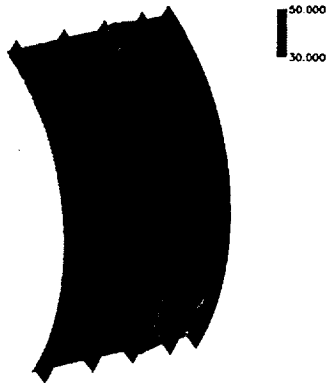
Instantaneous

Time-Averaged (1 revolution)

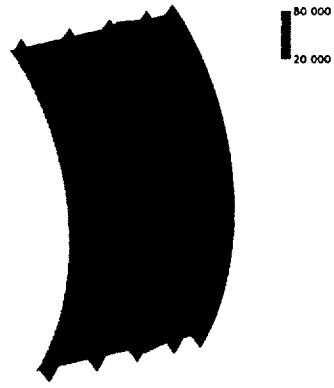
42

Inducer Simulation w/slots, cavity

Static pressure in cavity (psig)



Instantaneous



Time-Averaged
(1 revolution)

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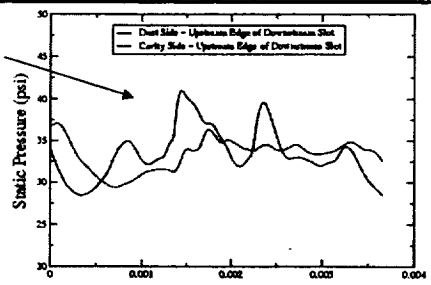
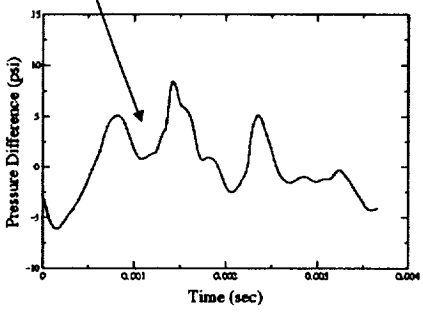
Upstream Edge of Downstream Cavity

Raw traces

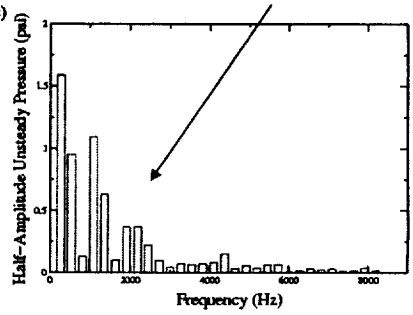


29.9 deg phase difference

Pressure difference



Decomp of
pressure difference



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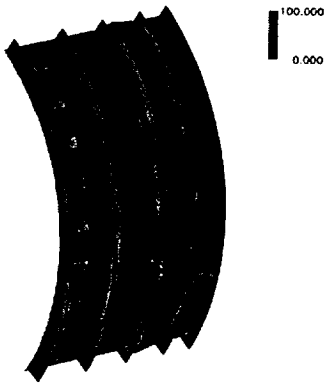
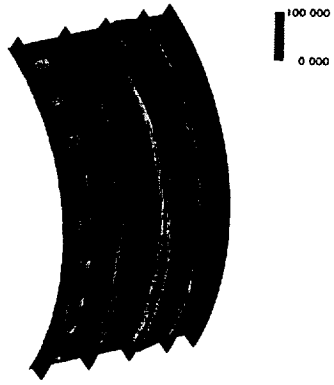
Inducer Simulation w/slots, cavity

Velocity magnitude (ft/sec)



Instantaneous

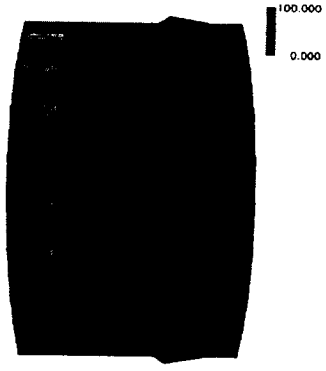


Time-Averaged (1 rev)

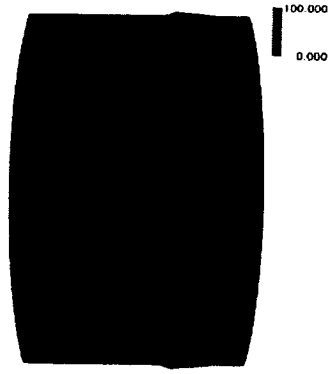
45

Inducer Simulation w/slots, cavity

Time-averaged (over 1 rev) velocity magnitude (ft/sec)



Adjacent Liner



Mid-Cavity

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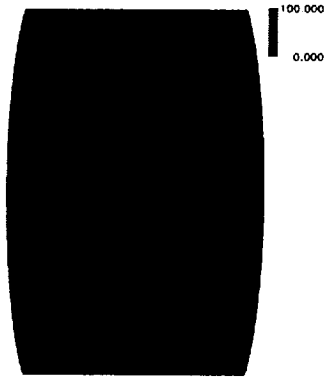
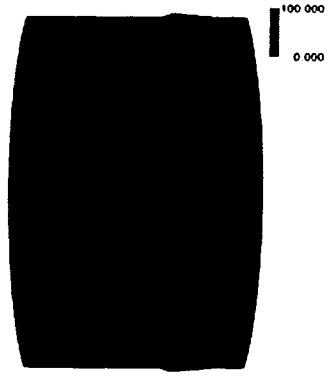
Inducer Simulation w/slots, cavity

Time-averaged velocity magnitude (ft/sec)



Adjacent Bellows



Mid-Cavity

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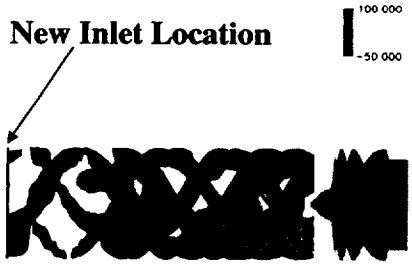
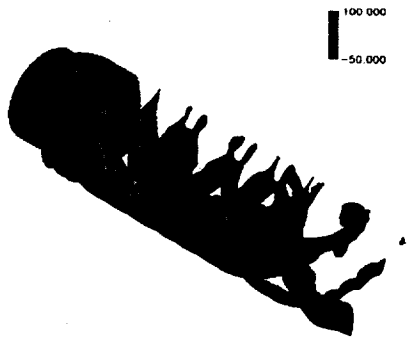
Extent of Inducer Pressure Field

35 psig pressure iso-surface colored by axial velocity

New Inlet Location





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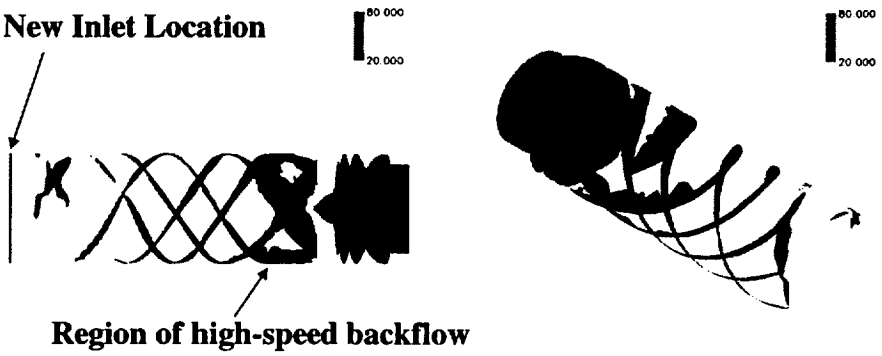
Extent of Inducer Backflow

Axial velocity=-5 ft/sec iso-surface colored by pressure



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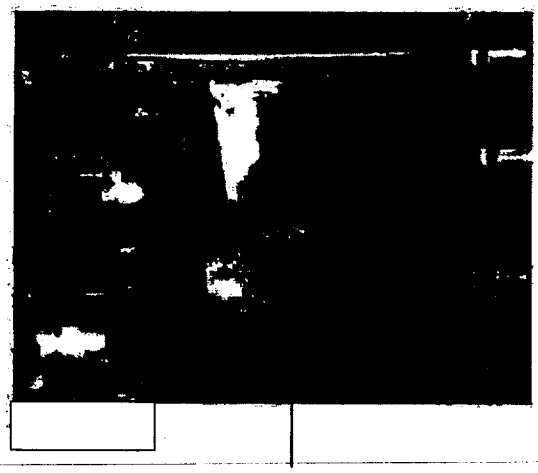
Extent of Inducer Backflow

Extent of backflow varies with inducer design, but in most cases extends one or more duct diameters upstream. The backflow also generates pre-swirl in the flow approaching the inducer.



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Future Directions

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Current Work and Future Plans

- "All-speed" version of Corsair (Phantom)
  - Reformulate equations without perfect gas assumption
  - Primitive variable formulation
  - Tabular fluid properties or compute based on equation of state
  - Sensors to switch between incompressible (pre-conditioning) and compressible physics
  - Dual time stepping to replace Newton iterations for time accuracy
- Two-phase flows
- Cavitation modeling
  - Necessary for accurate pump/inducer design and analysis

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