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COMPUTATIONS OF THREE-DIMENSIONAL STEADY AND UNSTEADY VISCOUS INCOMPRESSIBLE FLOWS

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The INS3D family of computational fluid dynamics computer codes is presented. These codes are used to as tools in developing and assessing algorithms for solving the incompressible Navier-Stokes equations for steady-state and unsteady flow problems. This work involves applying the codes to real-world problems involving complex three-dimensional geometries. The algorithms utilized include the method of pseudocompressibility and a fractional step method. Several approaches are used with the method of pseudocompressibility including both central and upwind differencing, several types of artificial dissipation schemes, approximate factorization, and an implicit line-relaxation scheme. These codes have been validated using a wide range of problems including flow over a backward-facing step, driven cavity flow, flow through various type of ducts, and steady and unsteady flow over a circular cylinder. Many diverse flow applications have been solved using these codes including parts of the Space Shuttle Main Engine, problems in naval hydrodynamics, low-speed aerodynamics, and biomedical fluid flows. The presentation details several of these including the flow through a Space Shuttle Main Engine inducer, vortex shedding behind a circular cylinder, and flow through an artificial heart.

OUTLINE

- ⊙ Objective and Approach

- ⊙ Summary of Flow Codes
  - INS3D Family of codes
  - CENS3D

- ⊙ Applications and Results
  - Space Shuttle Main Engine (SSME) components
  - Artificial Heart Flow

- ⊙ Summary and Future Work

- ⊙ Movie
  - Circular cylinder vortex shedding
  - Artificial heart flow

OBJECTIVE AND APPROACH

⊙ **Objective**

- To develop CFD capability for simulating steady and unsteady viscous incompressible flows (Incompressible **N**avier-**S**tokes)

⊙ **Approach**

- Develop and assess algorithms, and implement in codes
- Develop / implement physical models for engineering analysis (turbulence, cavitation, porous medium, etc.)
- Apply the codes to real-world problems

SUMMARY OF INS3D

⊙ **Governing equations**

- Incompressible Navier-Stokes equations in generalized 3-D coordinates for steady-state solutions
- Pseudocompressibility approach

⊙ **Numerical scheme**

- Finite difference, central differencing plus artificial dissipation
- Approximate Factorization
- Single or multiple zones

⊙ **Turbulence Models**

- Algebraic models
- $k - \epsilon$ model

⊙ **Applications**

- Numerous SSME related simulations

⊙ **Status**

- Distributed to numerous users across the nation
- Available through COSMIC

EXTENSIONS TO INS3D

- ⊙ INS3D family of research codes used to study various approaches to solving the INS equations in generalized 3-D coordinates

Pseudocompressibility Approach

- ⊙ INS3D-UP (Steady-State and Time-accurate calculations)
  - Upwind flux-difference splitting of uniformly high order
  - Line-relaxation implicit scheme
  - Characteristic boundary conditions

- ⊙ INS3D-LU (Steady-State and Rotating reference frame)
  - Finite-volume method
  - Spectral radius or flux-difference split based dissipation
  - LU-SGS Implicit Scheme
  - Non-reflecting boundary conditions
  - Completely vectorized

EXTENSIONS TO INS3D, continued

Fractional Step Approach

⊙ INS3D-FS (Time-accurate problems)

- Finite-volume method on a staggered mesh
- Accurate treatment of geometry
  ⇒ Exact discrete mass conservation
- Two-step fractional step method :
  Solve momentum equations in time (AF scheme)
  Correct for pressure and velocity (Poisson equation)

SUMMARY OF CENS3D CODE

⊙ Governing Equations

- Compressible Euler and Navier-Stokes equations and species transport equations in generalized 3-D coordinates

⊙ Numerical Methods

- Fully-coupled and implicit thermal-chemical nonequilibrium finite-rate-chemistry
- Finite volume / flux-limited TVD, optional high-order flux difference split upwind scheme
- LU-SGS implicit scheme

⊙ Applications

- SSME preburner, main combustor and nozzle

⊙ Status

- Research code

VALIDATION CASES

- ⊙ INS3D
  - Internal flow : Channel, Backward-facing step, Rectangular duct, Turn-around duct
  - External flow : Circular cylinder (steady-state), Ogive cylinder
  - Juncture flow : Cylinder-plate, Wing-plate, Cavity
- ⊙ INS3D-UP
  - Internal flow : Driven cavity, Backward-facing step, Square duct with a 90° bend
  - External flow : Oscillating plate, Circular cylinder (steady and vortex-shedding flows)
- ⊙ INS3D-FS
  - Internal flow : Driven cavity
  - External flow : Impulsively started circular cylinder, vortex shedding from a circular cylinder

SUMMARY OF APPLICATIONS

⊙ Space Shuttle Main Engine (SSME)
(NASA/MSFC, Rocketdyne)

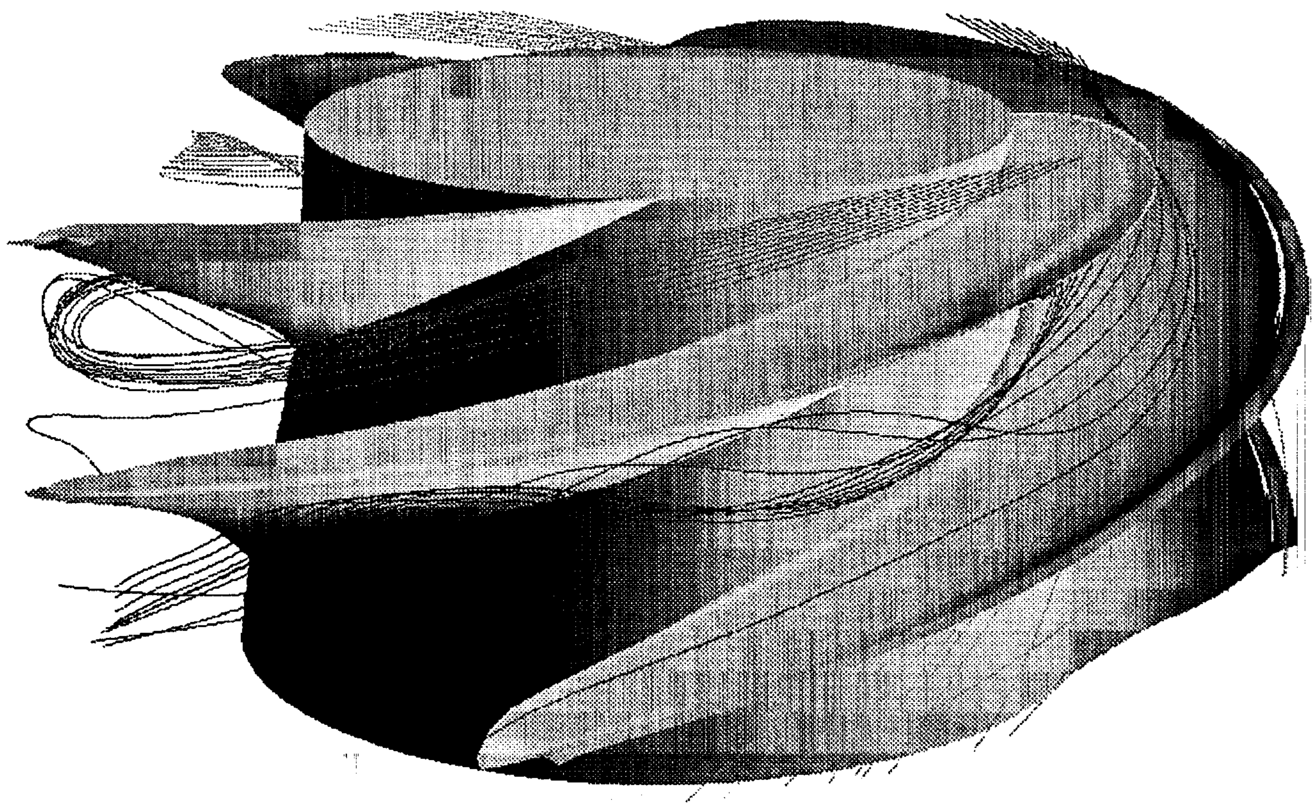
- Hot Gas Manifold, Main Injector
- Bearing
- Impeller/Inducer
- Preburner

⊙ Artificial Heart / Biofluid Mechanics
(NASA Tech Utilization, Penn State Univ and Stanford Univ)

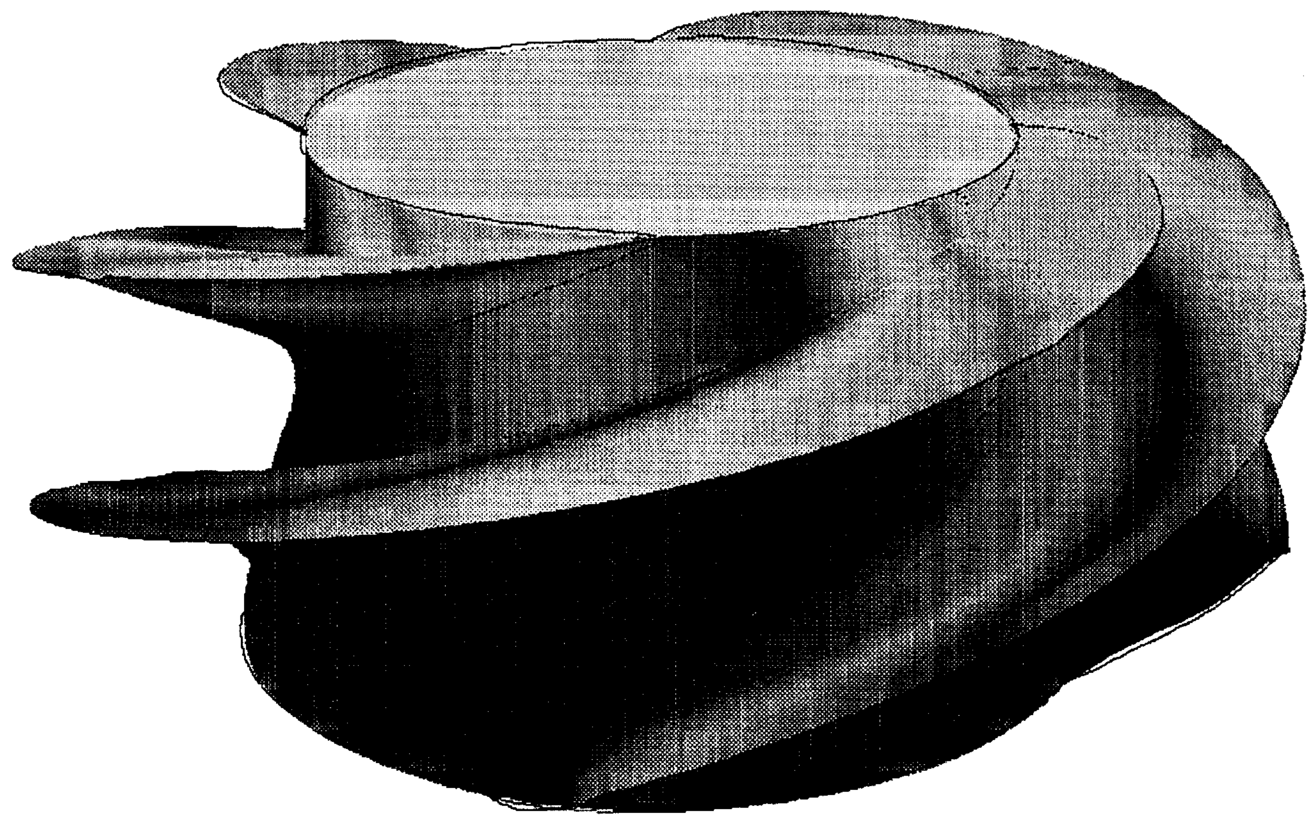
⊙ Low Speed Aerodynamics
- High lift device
- External flow over Automobiles and Trucks

⊙ Naval Hydrodynamics (Submarine)
(DARPA, ONR and David Taylor Research Center)

Particle Traces for SSME Inducer (INS3D–LU)



Surface Pressure for SSME Inducer (INS3D−LU)



FLOW OVER A CIRCULAR CYLINDER AT RE = 105

Computation

Experiment

ARTIFICIAL HEART

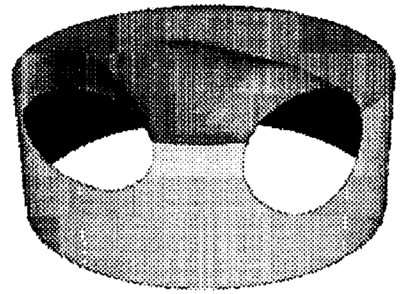
- ⊙ Current artificial devices have problems stemming from fluid dynamic phenomena

  - High shear stress damages the red blood cells and arterial walls
  - Stagnation and secondary flow regions lead to clotting
  - Desire short residence time in artificial environment
  - Large pressure losses cause heart to work harder

- ⊙ Apply CFD technology to analyzing blood flow through artificial hearts and to suggest improved design

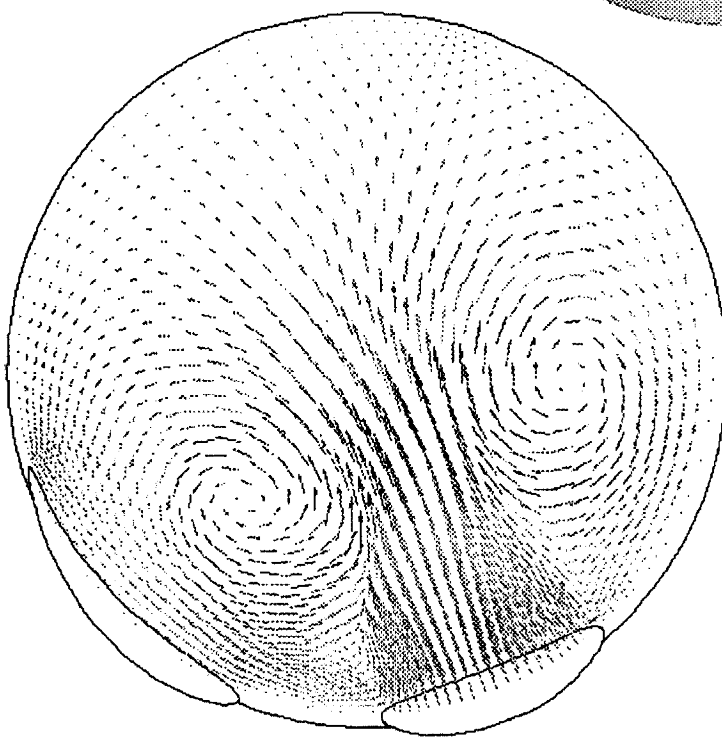
  - Develop moving boundary capability
  - Apply time accurate flow solvers to Penn State Artificial Heart
  - Develop simple non-Newtonian fluid model

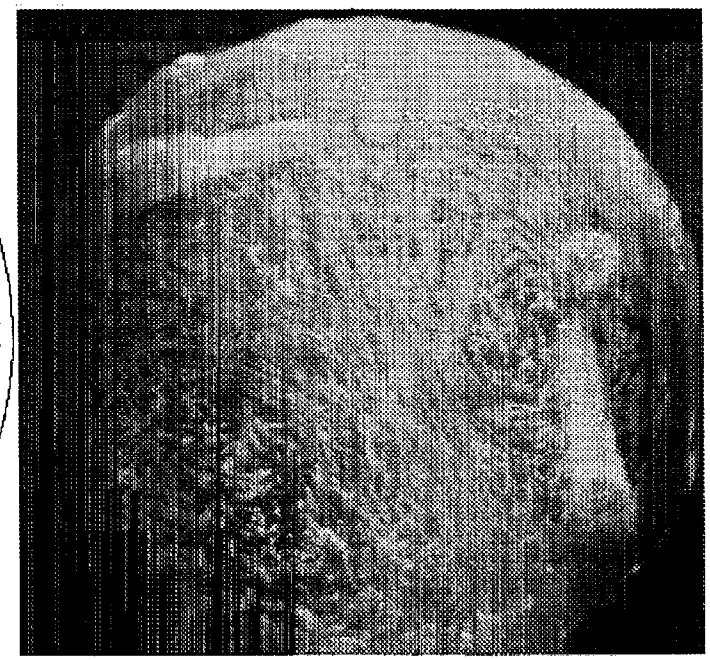
Penn State Artificial Heart – INS3D-UP Code



Computation

Experiment





CONCLUDING REMARKS

- ⊙ Incompressible and low speed flow simulation codes have been developed (INS3D-xx, CENS3D).
- ⊙ Results of computer simulations have made significant impact on analysis and redesign of the SSME power head.
- ⊙ These codes are being extended to analyze other important real world problems.
- ⊙ Future work includes further enhancement of these codes and improvement in physical modeling.