COMPUTATIONAL FLUID DYNAMICS PROGRAM
AT NASA AMES RESEARCH CENTER

Terry L. Holst
Chief, Applied Computational Fluids Branch
NASA Ames Research Center, Moffett Field, California

ABSTRACT

The Computational Fluid Dynamics (CFD) Program at NASA Ames Research Center is reviewed and discussed. The presentation is broken into several sections as follows: First, the technical elements of the CFD Program are generally listed and briefly discussed. These elements include algorithm research, research and pilot code development, scientific visualization, advanced surface representation, volume grid generation, and numerical optimization. Next, the discipline of CFD is briefly discussed and related to other areas of research at NASA Ames including Experimental Fluid Dynamics, Computer Science Research, Computational Chemistry, and Numerical Aerodynamic Simulation. These areas combine with CFD to form a larger area of research, which might collectively be called computational technology. The ultimate goal of computational technology research at NASA Ames is to increase the physical understanding of the world in which we live, solve problems of national importance, and increase the technical capabilities of the aerospace community.

Next, the major programs at NASA Ames that either use CFD technology or perform research in CFD are listed and discussed. Briefly, this list includes turbulent/transition physics and modeling, high-speed real gas flows, interdisciplinary research, turbomachinery demonstration computations, complete aircraft aerodynamics, rotorcraft applications, powered lift flows, high alpha flows, multiple body aerodynamics, and incompressible flow applications. Some of the individual problems actively being worked in each of these areas is listed to help define the breadth or extent of CFD involvement in each of these major programs.

State-of-the-art examples of various CFD applications are presented to highlight most of these areas. The main emphasis of this portion of the presentation is on examples which will not otherwise be treated at this conference by the individual presentations. Thus, a good survey of CFD applications research at NASA Ames can be obtained by looking at this presentation in conjunction with the individual NASA Ames presentations made at this conference.

Finally, this overview is concluded with a list of principal current limitations and expected future directions. Some of the future directions include algorithm research, turbulence/transition research, multidisciplinary research, graphics and workstation research and applications which will address more realistic simulations in the engineering world.
COMPUTATIONAL FLUID DYNAMICS
TECHNICAL ELEMENTS

ALGORITHM IMPROVEMENTS

ADVANCED SURFACE REPRESENTATION AND GRID GENERATION (EXPERT SYSTEMS)

RESEARCH CODES FOR INTEGRATING EMERGING TECHNOLOGIES

NUMERICAL OPTIMIZATION (DESIGN CONCEPTS)

PILOT CODES FOR DEMONSTRATING NEW CAPABILITIES

ADVANCED PARALLEL ALGORITHMS

SCIENTIFIC VISUALIZATION
COMPUTATIONAL TECHNOLOGIES
THRUSTS

COMPUTATIONAL FLUID DYNAMICS
- TURBULENCE/TRANSITION MODELS
- CODE VALIDATION DATA

COMPUTATIONAL CHEMISTRY
- CHEMISTRY MODELS
- SURFACE PHYSICS MODELS

EXPERIMENTAL FLUID DYNAMICS

NUMERICAL AERODYNAMIC SIMULATION
- PATHFINDING FOR ADVANCED COMPUTATIONAL SYSTEMS
- LEADING-EDGE COMPUTATIONAL CAPABILITY FOR AEROSPACE COMMUNITY

COMPUTATIONAL TECHNOLOGIES
- INCREASED UNDERSTANDING OF GOVERNING PHYSICS
- SOLUTION OF PROBLEMS OF NATIONAL IMPORTANCE
- INCREASED TECHNICAL CAPABILITY OF AEROSPACE COMMUNITY

COMPUTER SCIENCE RESEARCH
- ADVANCED ARCHITECTURES
- NETWORKING
- GRAPHICS/WORKSTATIONS
MAJOR PROGRAMS USING CFD
NASA Ames Research Center

TURBULENT/TRANSITION PHYSICS AND PHYSICAL MODELING

HIGH-SPEED REAL GAS FLOWS
- THERMO- AND CHEMICAL-NONEQUILIBRIUM
- RADIATION
- COMBUSTION
- RAREFIED FLOW EFFECTS

INTERDISCIPLINARY RESEARCH
- CFD + COMPUTATIONAL ELECTROMAGNETICS
- CFD + COMPUTATIONAL STRUCTURAL MECHANICS
- CFD + ACTIVE CONTROLS
- CFD + HEAT CONDUCTION

TURBOMACHINERY DEMONSTRATION COMPUTATIONS
- 3D TURBINE ROTOR-STATOR
- MULTI-STAGE COMPRESSOR ROTOR-STATOR

COMPLETE AIRCRAFT AERODYNAMICS
- NASP
- F-16 (TNS, TRANAIR)
MAJOR PROGRAMS USING CFD (CONTINUED)
NASA Ames Research Center

ROTORCRAFT APPLICATIONS
- AEROACOUSTICS
- ROTOR/FUSELAGE INTERACTION
- HELICOPTER/TILTROTOR PERFORMANCE PREDICTIONS
- DYNAMIC STALL COMPUTATIONS

POWERED LIFT
- STOVL AIRCRAFT (HARRIER, E-7)
- UPPER SURFACE BLOWING APPLICATIONS
- JET FREESTREAM MIXING
- THRUST AUGMENTOR EJECTORS
- STOVL DELTA WING IN GROUND EFFECT

HIGH ALPHA
- HARV APPLICATIONS (F-18)
- OGIIVE CYLINDER COMPUTATIONS
- UNSTEADY FLOWS
MAJOR PROGRAMS USING CFD (CONCLUDED)
NASA Ames Research Center

MULTIPLE BODY AERODYNAMICS
• SPACE SHUTTLE (LAUNCH CONFIGURATION)
• SRB/ET-ORBITER SEPARATION
• AIRCRAFT STORE SEPARATION
• SPACE SHUTTLE C/SPACE SHUTTLE II

INCOMPRESSIBLE NAVIER-STOKES
• SSME APPLICATIONS
• HYDRODYNAMICS
• HIGH LIFT CONFIGURATIONS
• ARTIFICIAL HEART BLOOD FLOW SIMULATION
ADVANCED SIMULATION AND ANALYSIS PROJECT (ASAP)

VAN DALSEM, VOGEL, LUH, SORENSON, ATWOOD

OBJECTIVE
- REDUCE THE "CLOCK TIME" REQUIRED TO OBTAIN THE SURFACE DEFINITION AND GRID ABOUT A COMPLEX CONFIGURATION BY AT LEAST AN ORDER OF MAGNITUDE

APPROACH
- DEVELOP AN INTEGRATED, INTERACTIVE SURFACE DEFINITION AND GRID GENERATION CAPABILITY TAILORED TO THE CFD ENVIRONMENT

FUTURE DIRECTIONS
- EXPLORE APPLICATION OF AI TO ENHANCE NONEXPERT USER PERFORMANCE
- INVESTIGATE:
  - GRID QUALITY MEASURES
  - SOLUTION-ADAPTIVE TECHNIQUES
  - NEW GRID GENERATION APPROACHES (STRUCTURED AND UNSTRUCTURED)

PAYOFF
- A POWERFUL, EASY-TO-USE TOOL THAT SIGNIFICANTLY REDUCES THE TURNAROUND TIME FOR CURRENT AND FUTURE CFD ANALYSES
ADVANCED SIMULATION AND ANALYSIS PROJECT (ASAP)

VOGEL, LUH, SORENSON, ATWOOD

F-18 FOREBODY GRID BY 3DGRAPE: SELECTED AXIS-NORMAL SURFACES

SURFACE GRID FOR GENERIC HYPersonic AIRPLANE

2D ZONING COMPARISON: HUMAN EXPERT vs EXPERT SYSTEM (EZGRID)
OBJECTIVES

- Develop capability to analyze complex geometries very quickly
  — Includes leading-edge separation, jet plumes, and unsteady effects (time stepping)

APPROACH

- Low-order panel method with time-stepped wakes

FUTURE DIRECTIONS

- Couple with boundary layer code to include viscous effects
- Use for design and analysis of wind tunnel models and to determine wind tunnel wall interference

PAYOFF

- Efficient, reliable tool for use in low speed applications
PANEL METHOD APPLICATIONS
ASHBY, IGUCHI, BROWN

80- BY 120-FOOT WIND TUNNEL INLET

VELOCITY VARIATION ACROSS INLET

E-7 STOVL MODEL

CHORDWISE PRESSURE DISTRIBUTION
ON E-7 WING PMARC COMPUTATION;
2y/b = 0.6, \( \alpha = 8^\circ \)
TWO-DIMENSIONAL COMPUTATIONS OF MULTI-STAGE COMPRESSOR FLOWS

GUNDY-BURLET, RAI

OBJECTIVE
- DEVELOP CAPABILITY TO CALCULATE UNSTEADY VISCOUS FLOWS WITHIN MULTI-STAGE TURBOMACHINES

CURRENT APPROACH
- SOLVE THE TWO-DIMENSIONAL NAVIER-STOKES EQUATIONS USING A ZONAL METHOD TO SIMULATE ROTOR-STATOR INTERACTION

FUTURE DIRECTIONS
- EXTEND TO THREE-DIMENSIONS

PAYOFF
- BETTER UNDERSTANDING OF UNSTEADY FLUID DYNAMICS IN TURBOMACHINES
- INCREASED RELIABILITY AND EFFICIENCY OF TURBOMACHINES

INSTANTANEOUS TEMPERATURE CONTOURS
\[ M_{\infty} = 0.07, \ Re = 100,000/\text{in.} \]
TIME-AVERAGED PRESSURES IN THE SECOND STAGE OF A 2.5 STAGE COMPRESSOR
GUNDY-BURLET, RAI

\[ M_\infty = 0.07, \text{ Re } = 100,000/\text{in.} \]

GRID 1 2 3 4 5 6 7 8 9 10 11 12

ROTOR RESULTS

STATOR RESULTS

\[ C_p \]

NUMERICAL
- SUCTION SURFACE
- PRESSURE SURFACE

EXPERIMENTAL
EFFECT OF TANGENTIAL LEADING EDGE
BLLOWING ON VORTICAL FLOW

YEH, TAVELLA, ROBERTS

OBJECTIVE
- TO INVESTIGATE THE ABILITY OF TANGENTIAL LEADING EDGE BLLOWING TO CONTROL VORTICAL FLOW AT HIGH ALPHA

APPROACH
- UTILIZE DELTA WING GEOMETRY
- SOLVE THIN-LAYER NAVIER-STOKES EQUATIONS USING MULTIPLE-ZONE GRID APPROACH TO ACCOMODATE JET-SLOT GEOMETRY
- UTILIZE ALGEBRAIC TURBULENCE MODEL FOR SURFACE BL AND WALL JET

FUTURE DIRECTIONS
- EXTEND TO FULL AIRCRAFT CONFIGURATIONS
- INVESTIGATE BLLOWING CONTROL CONCEPTS

PAYOFF
- INCREASED UNDERSTANDING OF VORTICAL FLOW PHYSICS
- NEW TOOL FOR STUDYING BLLOWING CONTROL CONCEPTS

COMPUTED “OIL FLOW” ON DELTA WING SURFACE
$M_\infty = 0.3, \, Re = 1.3 \times 10^6, \alpha = 40^\circ$

BLOWING

NO BLOWING
EFFECT OF TANGENTIAL LEADING EDGE BLOWING ON VORTICAL FLOW

YEH, TAVELLA, ROBERTS

\(M_\infty = 0.3, \alpha = 40^\circ, Re = 1.3 \times 10^6, X/C = 0.36\)

NORMALIZED TOTAL PRESSURE CONTOURS

SURFACE PRESSURE DISTRIBUTION

○ EXPERIMENT
--- CALCULATED
EULER VALIDATION/PRESSURE INTEGRATION
MELTON, ROBERTSON, MOYER

OBJECTIVES
• CFD VALIDATION FOR FLO57 EULER CODE
• ENHANCE WIND TUNNEL PRESSURE INTEGRATION FOR PREDICTING FORCES AND MOMENTS

APPROACH
• FLO57 FINITE VOLUME 3D EULER CODE
• COMPUTE DISCRETIZATION ERROR BY COMPARING CFD FORCE AND MOMENT INTEGRATION WITH CFD PRESSURES INTERPOLATED AND INTEGRATED AT MODEL TAP LOCATIONS

FUTURE DIRECTIONS
• INVESTIGATE NEW METHODS FOR INTEGRATING CFD AND EXPERIMENTAL RESULTS

PAYOFF
• VALIDATION OF FLO 57 FOR DELTA CONFIGURATIONS
• REDUCE INSTRUMENTATION CONSTRAINTS ON COMPLEX WIND TUNNEL MODELS
• INCREASE ACCURACY OF FORCE AND MOMENT PREDICTIONS FROM WIND TUNNEL PRESSURE INTEGRATIONS
EULER VALIDATION/PRESSURE INTEGRATION

MELTON, ROBERTSON, MOYER

M = 0.8 DRAG POLAR

UPPER SURFACE Cp's

M = 0.8  $\alpha = 9.0^\circ$  $C_L = 0.45$

EXPERIMENTAL DATA

CFD-FLO57

EXPRESS BALANCE DATA
EXPERIMENTAL PRESSURE INTEGRATION
$\diamond$ EXP PRESSURE INTEGRATION CORRECTED FOR DISCRETIZATION ERROR
$\triangle$ FINAL EXP PRESSURE INTEGRATION CORRECTED FOR DISCRET ERROR AND SKIN FRICTION

SKIN FRICTION CORRECTION
DISCRETIZATION CORRECTION
SPACE SHUTTLE LAUNCH CONFIGURATION

STEGER, RIZK, OBAYASHI, MARTIN, CHIU, BUNING

OBJECTIVE

- DEVELOP CAPABILITY TO COMPUTE FLOW OVER INTEGRATED SPACE SHUTTLE IN ASCENT

APPROACH

- SOLVE 3D REYNOLDS-AVERAGED NAVIER-STOKES EQUATIONS
- USE CHIMERA GRID APPROACH

FUTURE DIRECTIONS

- IMPROVE PLUME SIMULATION CAPABILITY AND CODE EFFICIENCY
- VALIDATE UNSTEADY MODE AND STUDY FAST SEPARATION SIMULATIONS

PAYOFF

- PREDICTIVE TOOL FOR UNDERSTANDING AND REFINING AERODYNAMIC PERFORMANCE OF MULTIPLE BODY VEHICLES
SPACE SHUTTLE ASCENT-MODE RESULTS

$M_\infty = 1.05$, $\alpha = -3^\circ$

SURFACE PRESSURES ON SHUTTLE C

$M_\infty = 0.9$, $\alpha = -3^\circ$

Cp COMPARISONS ALONG ORBITER FUSELAGE DURING ASCENT

COMPUTATION

$M_\infty = 1.05$

$\alpha = -3$

WIND TUNNEL

COMPARISON OF SURFACE PRESSURES
UNSTEADY MULTIPLE BODY AERODYNAMICS

OBJECTIVE
- To develop a general capability for time-accurate simulation of 3-D multiple body viscous flows given arbitrary grid combinations, body shapes, and relative motion between grid systems

CURRENT APPROACH
- Unsteady chimera composite grid techniques
- Implicit time-accurate solver for the thin-layer Navier-Stokes equations

FUTURE DIRECTIONS
- Develop trajectory prediction routines
- Improve efficiency and accuracy of basic algorithms
- Code validation studies

PAYOFF
- A validated computational tool for analyzing complex aerodynamic problems involving multiple bodies in relative motion
TIME-ACCURATE SIMULATION OF THE SPACE SHUTTLE SRB SEPARATION SEQUENCE

PRESSURE CONTOURS
\[ M_\infty = 4.5 \]
\[ \alpha = +2^\circ \]
\[ R_e = 6.95 \times 10^6 \]

ASSUMPTIONS:
- SIMPLIFIED GEOMETRY
- NO PLUMES
- PRESCRIBED SRB TRAJECTORY

DISCRETIZATION
GRIDS:
ET 73X39X45
SRB 53X37X21
ORB 74X77X33

TIME-STEP = 1.36 \times 10^{-3} \text{ sec}
500 STEPS THROUGH BSM BURN
BOOSTER SEPARATION MOTOR (BSM)
BURN-TIME = 0.68 \text{ sec}

(MEAKIN, SUHS)
AIRCRAFT STORE SEPARATION
MEAKIN, SUHS
FREESTREAM CONDITIONS: \( M_\infty = 1.05 \), \( \alpha = +2^\circ \), \( Re = 2.4 \times 10^6 \)

WING LOWER SURFACE \( C_p \) DISTRIBUTION
MACH CONTOURS ABOUT STORE

STEADY-STATE

TIME-ACCURATE
STORE-SEPARATION SIMULATION

WING ALONE

WING ALONE

WING AND STORE

WING, PYLON AND STORE

\( t = 0 \) sec

\( t = 0.15 \) sec

\( t = 0.30 \) sec
TURBULENCE MODELING FOR HYPERSONIC FLOWS
COAKLEY, HORSTMANN, KUSSOY, MARVIN

OBJECTIVE
• IMPROVE AND DEVELOP MODELS FOR HYPERSONIC FLOWS

CURRENT APPROACH
• PERFORM COMBINED COMPUTATIONAL AND EXPERIMENTAL STUDIES

FUTURE DIRECTIONS
• IMPROVE COMPUTATIONAL EFFICIENCY
• DEVELOP SECOND ORDER CLOSURE MODELS
• PERFORM EXPERIMENTS USING NEWLY DEVELOPED NON INTRUSIVE INSTRUMENTATION

PAYOFF
• ACCURATE COMPUTATIONS OF HEAT TRANSFER, SKIN FRICTION, AND COMPLEX FLOW STRUCTURES

TEST MODEL GEOMETRIES USED FOR COMPARISONS OF COMPUTATION AND EXPERIMENT

M = 7.2

θ = 7.5°, 15°

64.4 mc

xg = 140-165 cm

20.3 cm

51 cm

2.54 cm
PRESSURE CONTOURS FOR AN IMPINGING SHOCK WAVE FLOW

$M_\infty = 7.2 \quad \theta = 15^\circ$

**BALDWIN-LOMAX MODEL**

NORMIALIZED PRESSURE CONTOURS

$Re = 2.26 \times 10^6$

GRID $80 \times 1 \times 80$

**q-ω MODEL c**

PRESSURE CONTOURS
PRESSURE CONTOURS FOR AN IMPINGING SHOCK WAVE FLOW

$M_{\infty} = 7.2 \cdot \theta = 15^\circ$

COMPUTATION $q-\omega$ MODEL c

EXPERIMENT
HYPERSOONIC APPLICATIONS

OBJECTIVE
- DEVELOP CAPABILITY TO COMPUTE REAL-GAS AEROTHERMODYNAMIC CHARACTERISTICS OF HYPERSOONIC VEHICLES
- USE CAPABILITY TO GUIDE VEHICLE DESIGNS

APPROACH
- SOLVE 3D REYNOLDS-AVERAGED NAVIER-STOKES AND PARABOLIZED NAVIER-STOKES EQUATIONS USING VARIOUS TRANSITION/TURBULENCE MODELS WITH PERFECT GAS, EQUILIBRIUM REAL GAS AND NONEQUILIBRIUM REAL GAS MODELS

FUTURE DIRECTIONS
- IMPROVE TRANSITION/TURBULENCE MODELS, REAL GAS MODELS, AND COMPUTATIONAL EFFICIENCY
- EXTEND APPLICATIONS TO MORE COMPLEX GEOMETRIES

PAYOFF
- PROVIDE DESIGN INFORMATION NOT POSSIBLE TO MEASURE IN GROUND-BASED TEST FACILITIES
- ENABLE DEVELOPMENT OF AEROASSISTED VEHICLES AND AIRBREATHING HYPERSOONIC AIRCRAFT
GENERIC HYPersonic
AEROThermodynamic RESULTS

LAWRENCE

\[ M_\infty = 11.4, \alpha = 0^\circ, Re_L = 29 \times 10^6 \]

SYMMETRY PLANE
PRESSURE CONTOURS

WINDWARD SYMMETRY PLANE PRESSURES

WINDWARD SYMMETRY PLANE HEAT TRANSFER

\[ \text{NORMALIZED PRESSURE} \]

\[ \text{NORMALIZED HEATING RATE} \]

- UPS - SHARP
- UPS - BLUNT
- EXP - SHARP
- EXP - BLUNT

FUSELAGE STATION, in.
HYPersonic exhaust plume/afterbody interaction

Edwards

Nozzle/Afterbody Model

Exhaust gas concentration contours

\[ M_\infty = 6, \quad NPR = 4, \quad \alpha = 0^\circ \]

Generic hypersonic vehicle

Pressure contours

\[ M_\infty = 6, \quad NPR = 100, \quad \alpha = 0^\circ \]

Afterbody pressure comparison between 2nd and 3rd nozzles

\[ M_\infty = 6, \quad NPR = 3, \quad \alpha = 5^\circ \]

\[ \square \quad \text{Experiment} \]

\[ \text{---} \quad \text{Computation} \]

Pressure comparison windward plane of symmetry downstream of nozzle

\[ M_\infty = 1.46, \quad NPR = 6.27, \quad \alpha = 0^\circ \]

\[ \square \quad \text{Experiment} \]

\[ \text{---} \quad \text{Computation} \]
DIRECT PARTICLE SIMULATION OF HYPersonic FLOWS

OBJECTIVE:
• DEVELOP THE CAPABILITIES OF A NEW DISCRETE PARTICLE SIMULATION METHOD FOR RAREFIED HYPersonic FLOWS IN 3D WITH NON-EQUILIBRIUM CHEMISTRY.

APPROACH:
• FLUID IS MODELED AS A LARGE COLLECTION OF DISCRETE PARTICLES THAT INTERACT WITH EACH OTHER THROUGH COLLISIONS.
• SIMPLIFIED PHYSICAL MODELS ARE USED ALLOWING ORDERS OF MAGNITUDE INCREASE IN COMPUTATIONAL EFFICIENCY WHILE ENHANCING STATISTICAL ACCURACY.

FUTURE DIRECTIONS:
• REALISTIC 3D GEOMETRIES WITH MORE GENERAL BOUNDARY CONDITIONS.
• EXTENDED MOLECULAR MODELS TO ACCOUNT FOR ADDITIONAL INTERNAL DEGREES OF FREEDOM, CHEMISTRY AND WALL-PARTICLE INTERACTIONS.

PAYOFF:
• DIRECT PARTICLE SIMULATION IS APPLICABLE AT LOW DENSITIES AND HIGH MACH NUMBERS BEYOND THE REACH OF CONTINUUM METHODS.
• ENABLES PARTICLE SIMULATIONS ON A MUCH LARGER SCALE THAN PREVIOUSLY POSSIBLE.
• PROVIDES NEEDED INSIGHT IN THE DESIGN OF PROPOSED HYPersonic VEHICLES.
PRINCIPAL CURRENT LIMITATIONS

PHYSICAL MODELS/ALGORITHMS
- BOUNDARY LAYER TRANSITION MODELS
- TURBULENCE MODELS FOR SEPARATING AND REATTACHING FLOWS
- TRANSITION/TURBULENCE MODELS FOR REAL GAS FLOWS AND FLOWS WITH COMBUSTION
- REAL GAS FLOW VALIDATION DATA
- FAST, USER FRIENDLY GEOMETRY DEFINITION/GRID GENERATION SOFTWARE
- FAST, ACCURATE ALGORITHMS FOR COMPLETE SIMULATIONS
- SCIENTIFIC VISUALIZATION SOFTWARE

COMPUTER SYSTEMS
- COMPUTATIONAL SPEED
- NETWORK BANDWIDTHS
- HIGH-SPEED LARGE-VOLUME MASS STORAGE
- TOOLS FOR ANALYZING MASSIVE RESULT FILES
FUTURE DIRECTIONS

ALGORITHM RESEARCH
- Improved algorithms for computing real-gas turbulent flows
- New algorithms to exploit advanced multiple processor computer architectures
- New grid-generation concepts for complex configurations, multiple moving bodies and unsteady flows

TURBULENCE RESEARCH
- Improved turbulence models for perfect-gas separating and reattaching flows
- New turbulence models for real-gas flows
- Methods for managing turbulence to reduce drag, improve component performance, minimize heat transfer, and control combustion processes

MULTIDISCIPLINARY RESEARCH
- Numerical methods for solving fully coupled combinations of equations for aerodynamics, gas chemistry, structures, controls, propulsion and electromagnetics
FUTURE DIRECTIONS
(CONCLUDED)

GRAPHICS AND WORKSTATION RESEARCH
- IMPROVED USER EFFICIENCY THROUGH ADVANCES IN GRAPHICS AND WORKSTATION TECHNOLOGY

APPLICATIONS CODES
- AIRCRAFT MANEUVERING NEAR PERFORMANCE BOUNDARIES
- POWERED LIFT AIRCRAFT OPERATING IN AND OUT OF GROUND EFFECT
- HYPersonic VEHICLES INCLUDING INLET, ENGINE AND EXHAUST FLOWS
- ROTORCRAFT IN HOVER, TRANSITION AND FORWARD FLIGHT
- TURBOMACHINERY INCLUDING PUMPS, COMPRESSORS AND TURBINES
- METHODS FOR NUMERICALLY OPTIMIZING DESIGNS
- DESIGNER-FRIENDLY CODES WITH 'EXPERT SYSTEMS' ELEMENTS