Laboratory of Thermal Turbomachines National Technical University of Athens (LTT/NTUA)

Capabilities, Experience, Achievements, Possibilities

National Technical University of Athens

• The **National Technical University of Athens (NTUA)** is the oldest and most prestigious technological educational institution of Greece.

• NTUA was established in1836, a few years after Greece gained its independence.

• NTUA took its present form in 1917 and was organized into the Higher Schools of Civil Engineers, Mechanical & Electrical Engineers, Chemical Engineers, Surveying Engineers and Architecture.

• Presently, NTUA is divided into nine academic Schools, eight being for the engineering sciences, including architecture, and one for the general sciences.

School of Mechanical Engineering	School of Chemical Engineering
School of Naval Engineering	School of Rural Engineering
School of Electrical & Civil Engineering	School of Mining and Metallurgy Engineering
School of Civil Engineering	School of Architecture
School of Applied Mathematical and Physics Science	

• The **Laboratory of Thermal Turbomachines (*LTT*)** was founded in **1982** by Professor ***K. Papailiou***.

• The laboratory, since its establishment, exhibited extensive and distinguished presence in the fields of gas turbines diagnostics and modeling, in turbo machinery CFD and in experimental studies.

• Today, it hosts two research groups:

- **Diagnostics & Modeling Group**
- **Parallel CFD & Optimization Group**

•Professor ***K. Mathioudakis*** *i*s the Lab Director since **2006.** He also Heads the Diagnostics & Modeling Group.

Educational Activities

➢Undergraduate Classes

1. *Thermal Turbomachines (1D)*
2. *Design of Thermal Turbomachines (2D)*
3. *Gas and Steam Turbine Operation (Design & Off-Design)*
4. *Principles of Jet Propulsion (Design & Off-Design)*
5. *Aircraft Engine Operation (Mission Analysis, Noise etc.)*
6. *Gas Turbine Diagnostics (Aerothermal, Vibrations etc)*

➢Postgraduate

- ➢*Gas Turbines Power Plants*

➢Seminars (Indicative)

- ➢*Power Plant Diagnostics*
- ➢*Vibrations in Turbomachinery*

LTT Activities

➢A computerized Gas Turbine educational suite has been developed (VLab: ***Virtual Laboratory*** *of Gas Turbines for Naval and Aircraft Propulsion*) in support of undergraduate and postgraduate courses,and a variety of tailored made (web)seminars are offered .

➢**Measuring campaigns** for turbomachinery components, micro-turbines **testing** and innovative control methods evaluation are performed. The testing facilities can adapt to a wide variety of requirements and objectives.

➢Research has been performed for over more than 25 years and services are offered in **Engine Health Monitoring and Diagnostics, as well as** the field of **gas turbine performance modelling**, ranging from new aero engine configuration concept analysis to multi-fidelity, multi-physics models, including special interest tipics such as weather hazards analysis (e.g. rain/hail ingestion), environmental impact of air transportation etc.

➢The **Parallel CFD & Optimization** group performs research and offers services in Computational Fluid Dynamics, having developed a suite of in-house tools, a generic optimization platform based on enhanced Evolutionary Algorithms (EASY),Aero/hydrodynamic optimization tools based on adjoint methods and hybrid (gradient-based & stochastic) optimization methods.

➢*The Diagnostics & Modeling Group* is one of the ***leading academic groups*** in the field of gas turbine diagnostics, with several innovative diagnostic methods developed and validated. At the same time Engine Health Monitoring Systems have been developed, built and installed in Power Plants.

International Distinctions

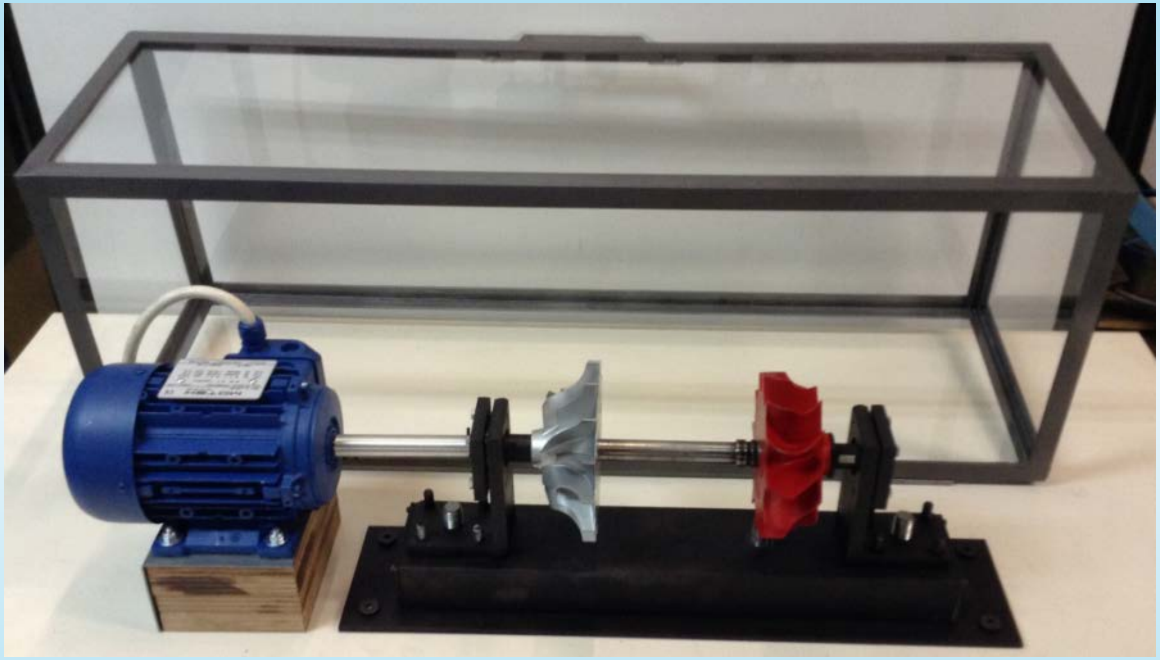
- *Best paper* ***award in Controls and Diagnostics, 1992 ASME International TURBO-EXPO.***
- *The annual Outstanding Service Award of the Controls and Diagnostics Committee of the ASME for 2002, was granted to a member of the group.*
- *Best paper* ***award in Controls and Diagnostics, 2002 ASME International TURBO-EXPO.***
- *Best paper* ***award in Education, 2003 ASME International TURBO-EXPO.***
- *PE Publishing Award for the best paper published in the ImechE Journal of Power and Energy, 2004.*
- *Best paper award in Cycle Innovations, 2012* ***ASME International TURBO-EXPO.***

Services (under contract or / and in collaboration)

- Design and analysis of turbomachinery components
- Testing of turbomachinery components and gas meters
- Development of engine performance models & diagnostic methods
- Design, development and installation of EHM systems
- Development of simulation software tools
- On site measurements and analysis

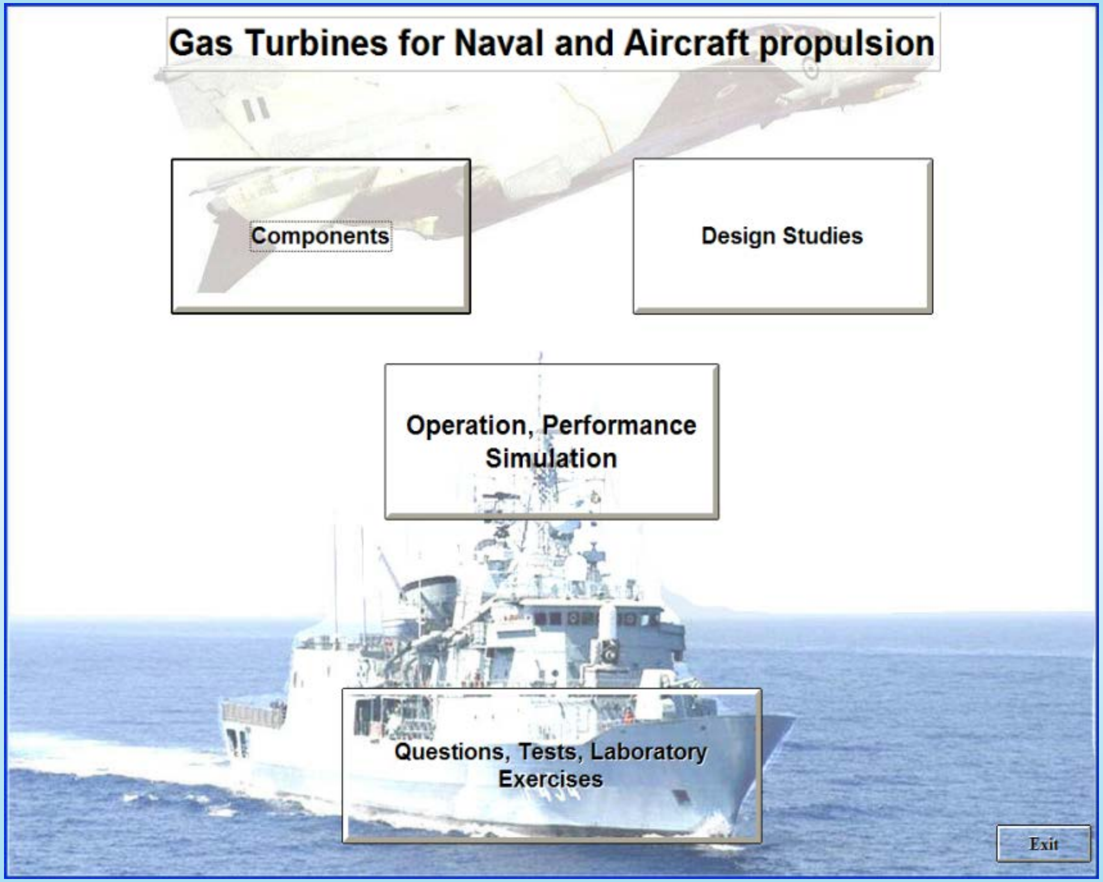
- **Educational Activities**
- **Test Facilities & Measurement Expertise**
- **Engine Modeling**
- **Diagnostic Methods**
- **Parallel CFD & Optimization**

Classes + Experimental Training



Diagnostics Course: Simulator of Mechanical fault in turbomachinery shafts

VIRTUAL LAB for Gas Turbine Education



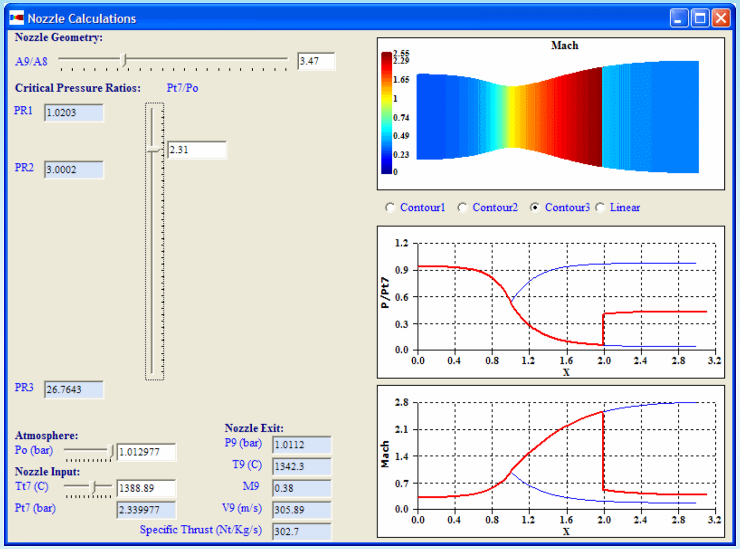
Installed in Hellenic Naval Academy, Hellenic AirForce Academy and LTT/NTUA

VIRTUAL LAB for Gas Turbine Education

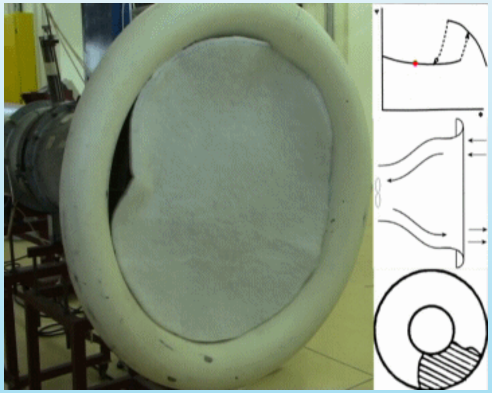
Principles of Gas Turbine components operation

Theory of compressor operation

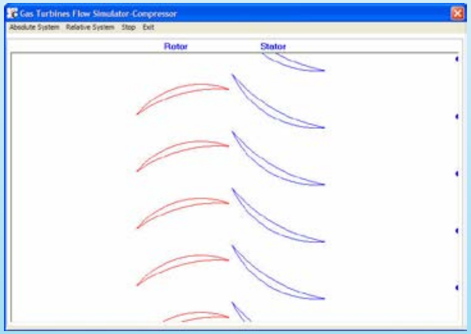
Nozzle Calculator



Rotating Stall physical demonstration

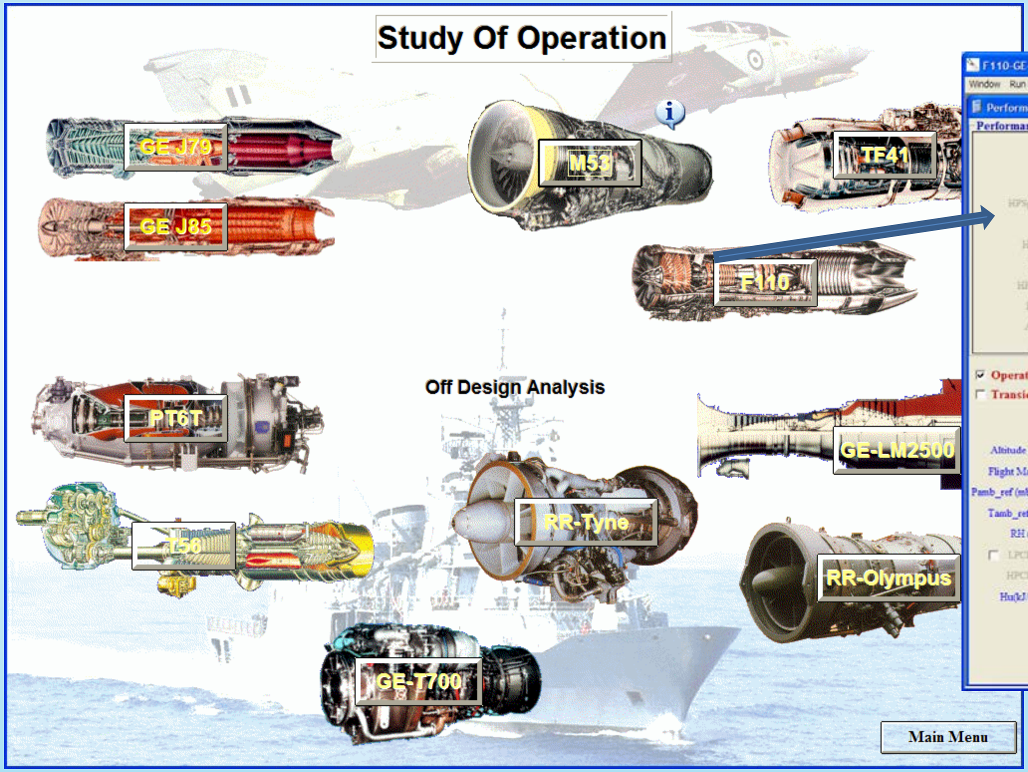


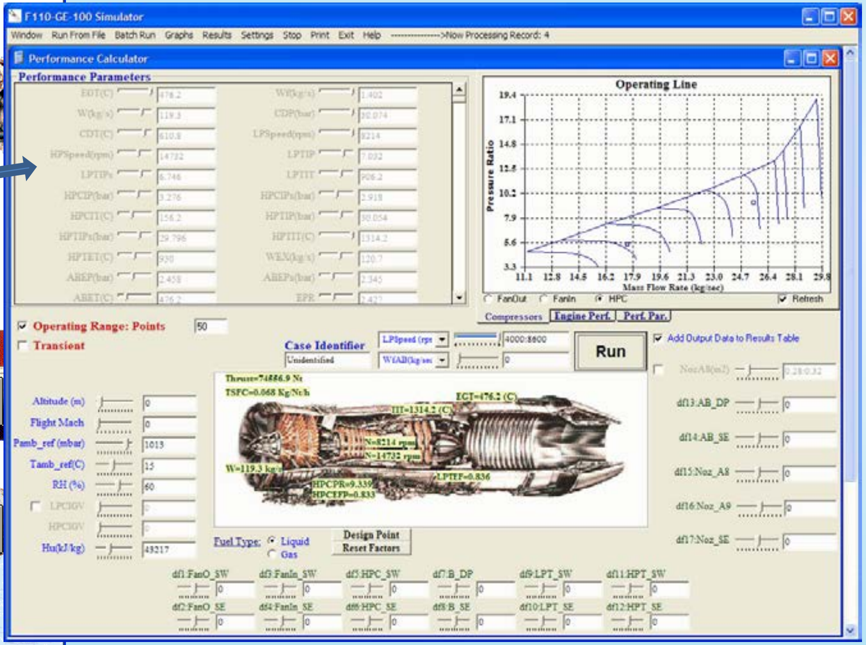
Flow in Compressor Cascades



VIRTUAL LAB for Gas Turbine Education

Jet Engine Performance

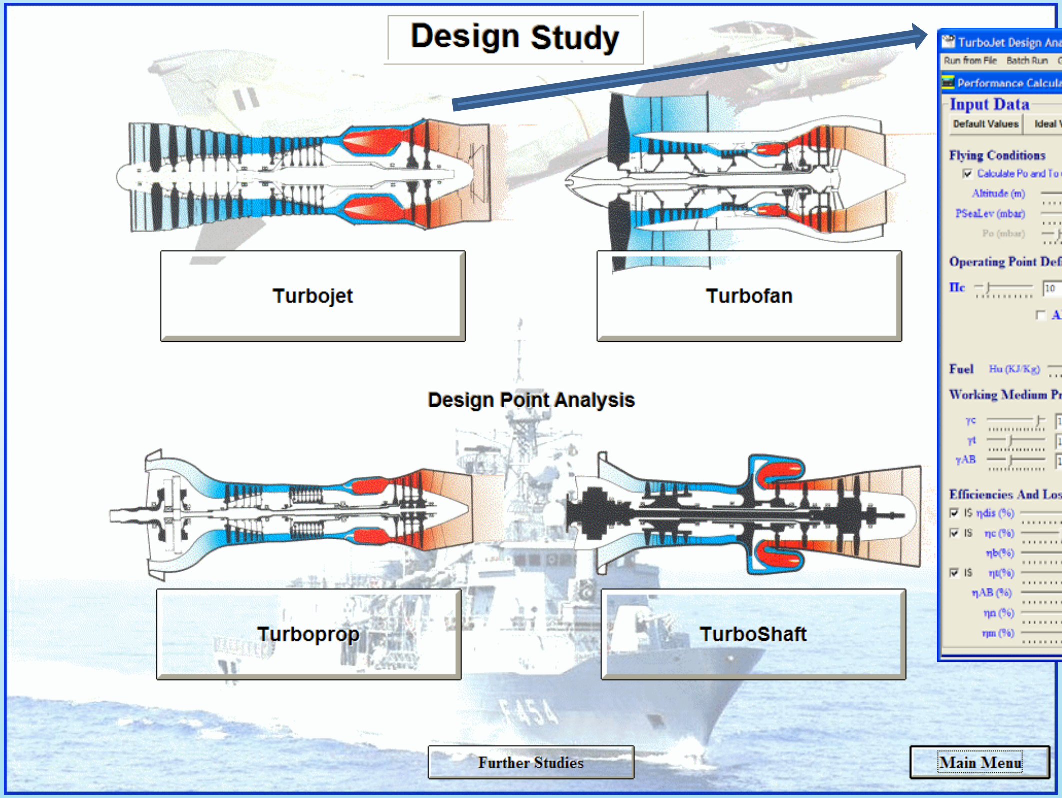


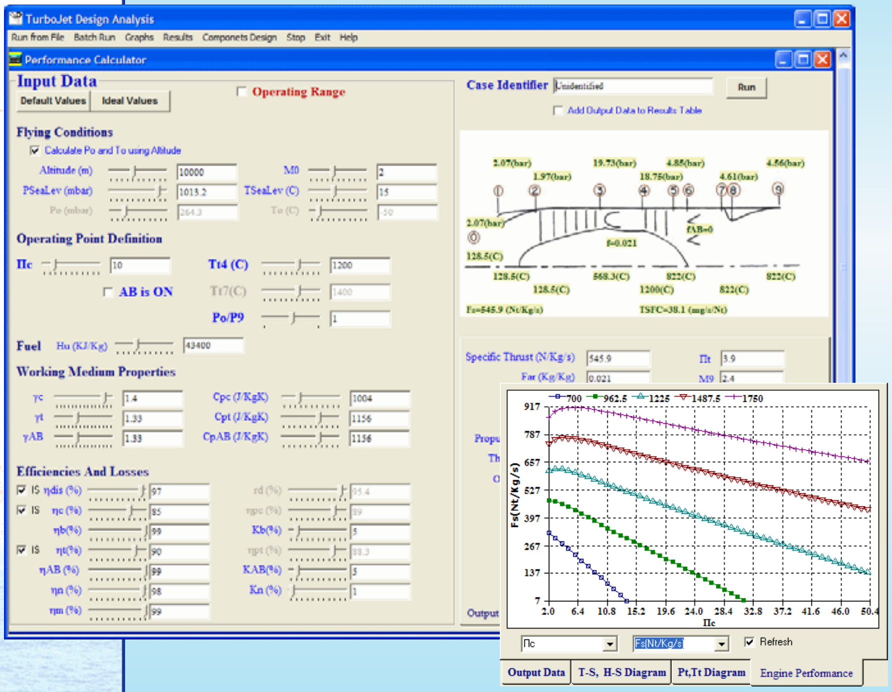


Πρόγραμμα προσομοίωσης λειτουργίας κινητήρα F110

VIRTUAL LAB for Gas Turbine Education

Design Studies

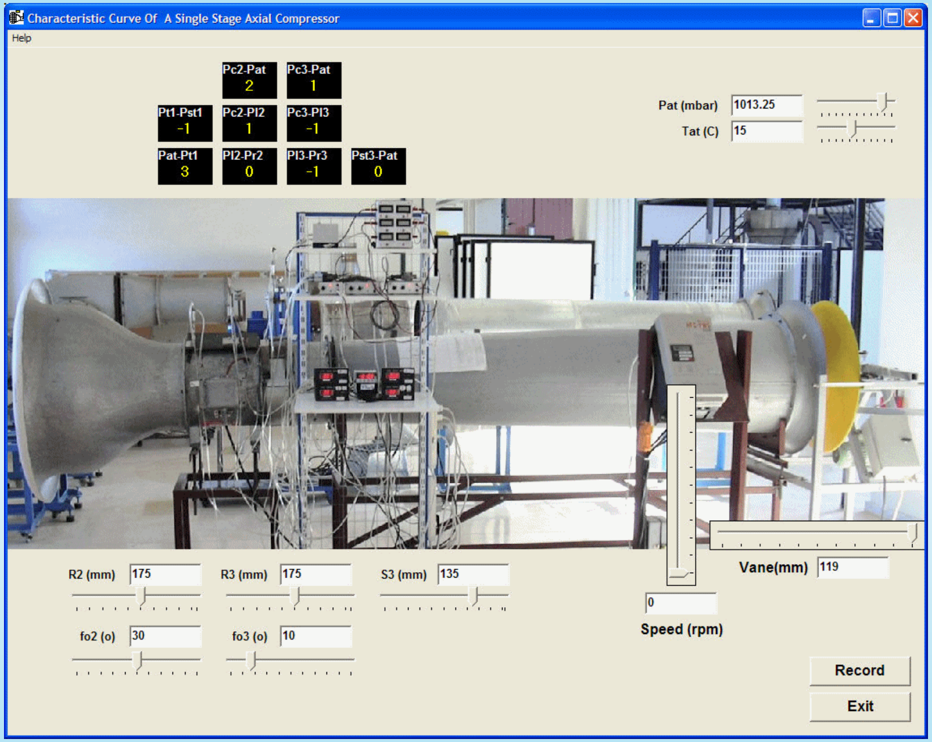




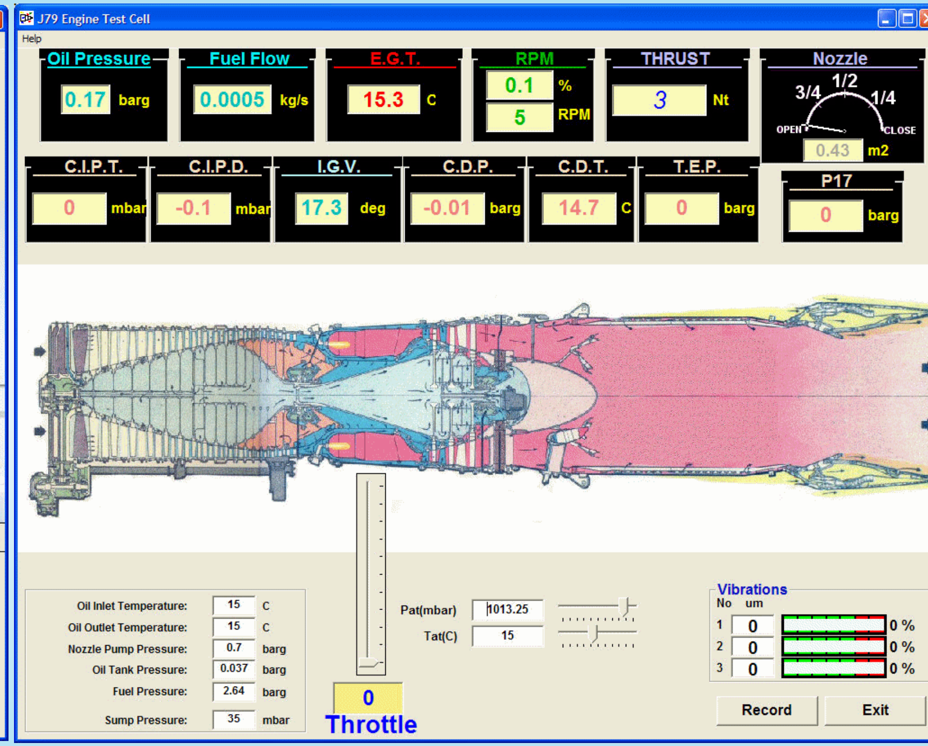
Πρόγραμμα Υπολογισμού Turbojet

VIRTUAL LAB for Gas Turbine Education

Virtual Test Facilities and Lab Exercises



Axial Fan Characteristic Measurement

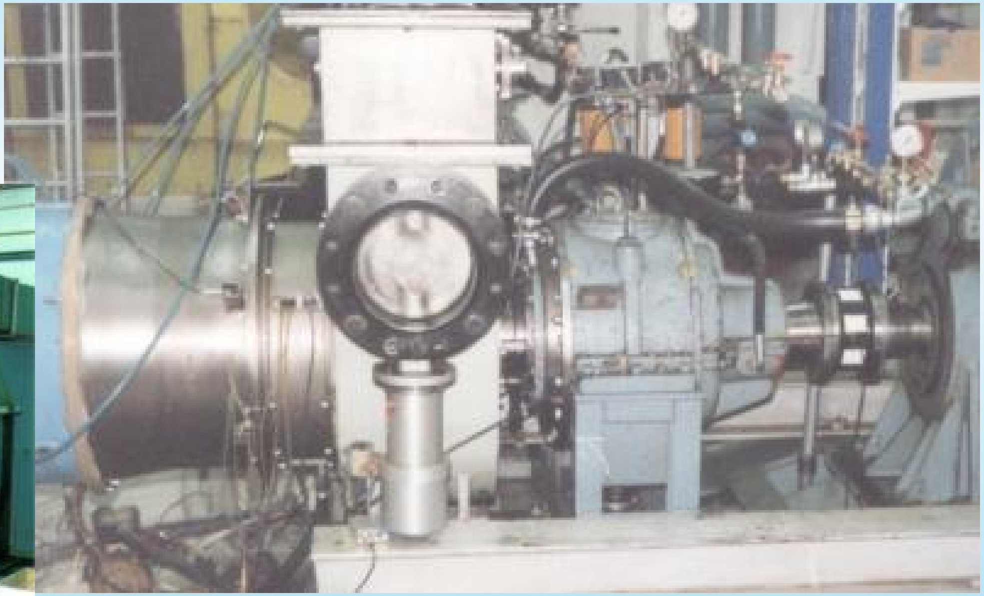


Jet engine Cell Testing

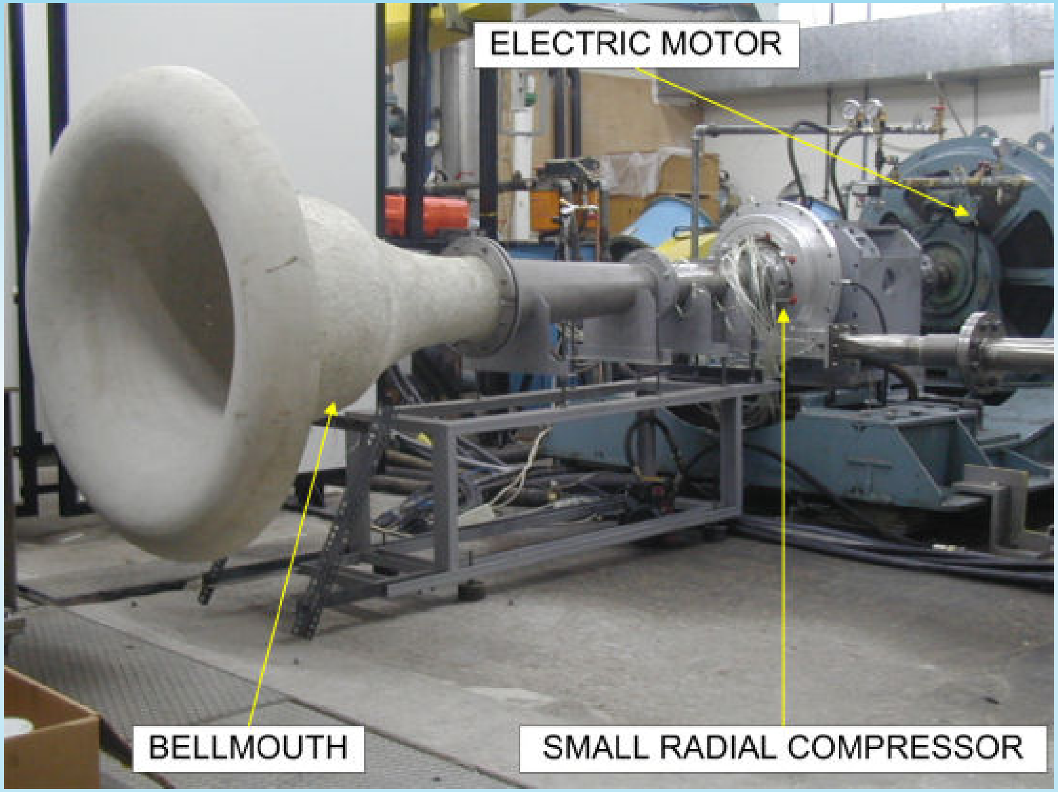
- Educational Activities
- **Test Facilities & Measurement Expertise**
- Engine Modeling
- Diagnostic Methods
- Parallel CFD & Optimization

Compressor Test rig - I

Max. Power: 750kW
Max. Speed: 24,000 and 80,000 RPM
(depending on gear box)
Gearbox 1 Ratio: 8:1
Gearbox 2 Ratio: 26.6:1
DC Motor Speed: 3,000 RPM

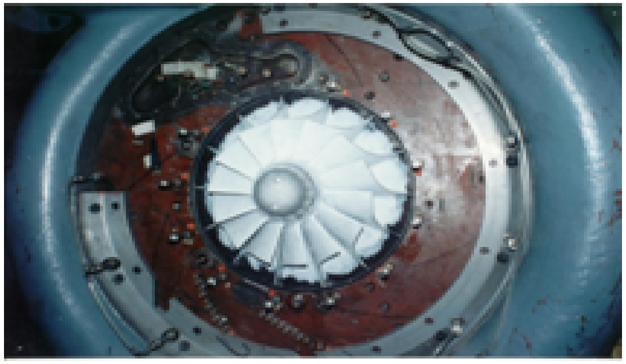


Compressor Test rig - II

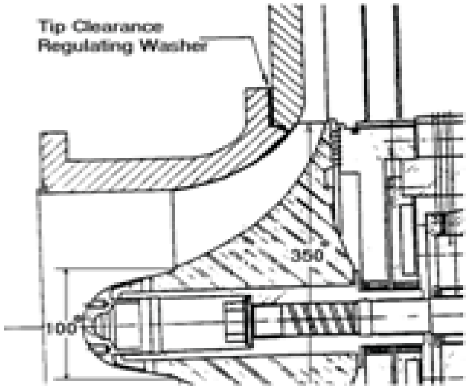


Experimental Investigation of Radial Compressor Faults

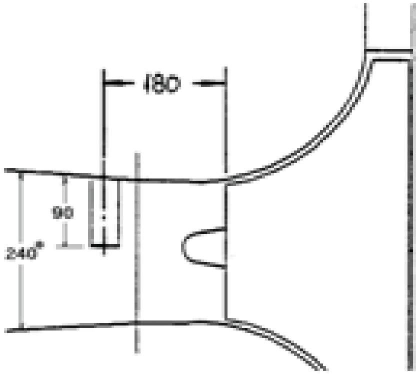
Impeller Fouling



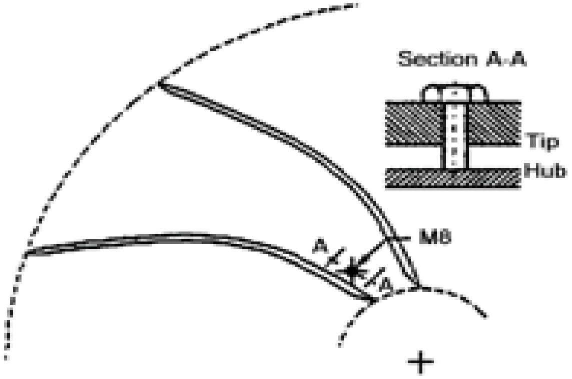
Tip Clearance Increase



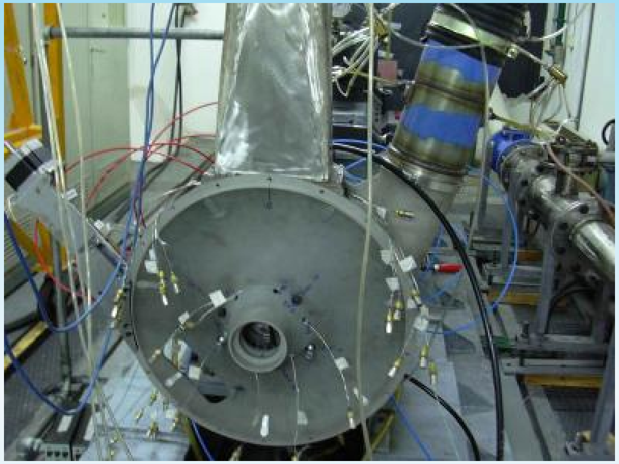
Inlet Distortion

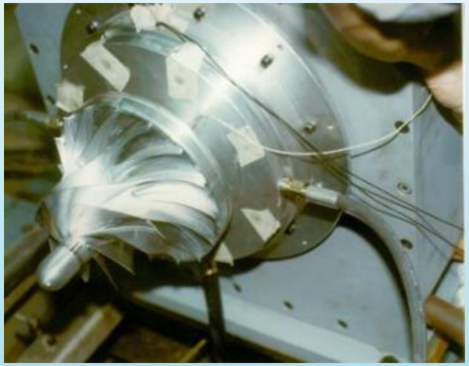


Diffuser Distortion

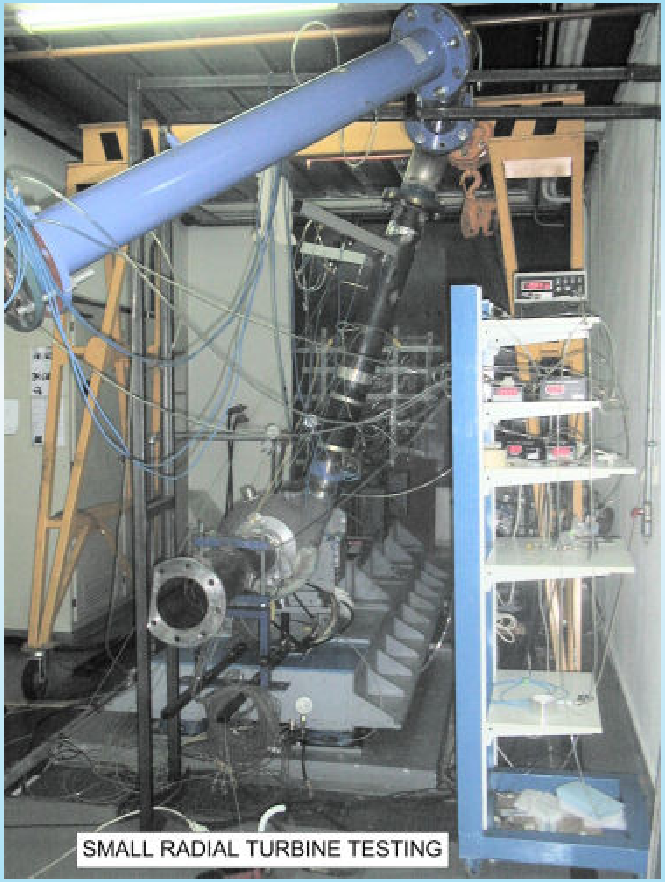


Compressor-Turbine Test Rig

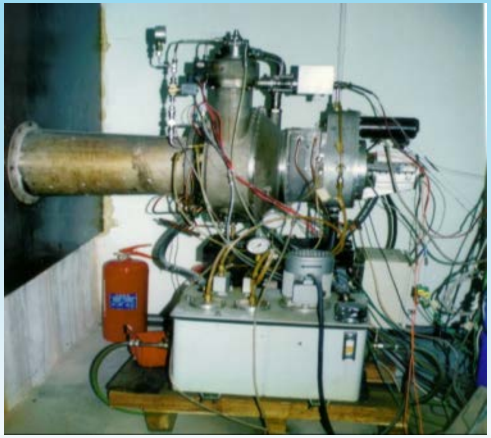




(Small) Gas Turbine Engine and Component testing

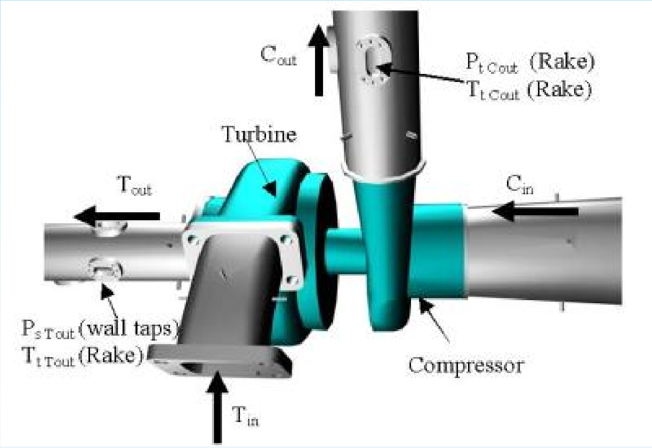


Small Tuebine test



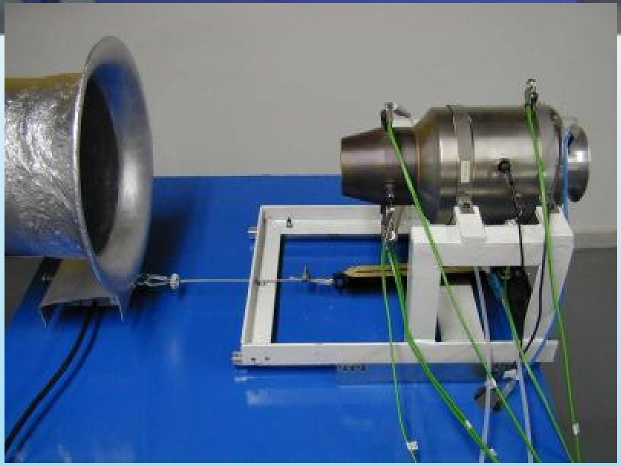
Small Gas turbine Test (50kW)

Turbocharger Testing



Test Facilities

Small Turbojet Test Cell



Low-Speed Section

- Test stand for industrial small blowers (DIN 24163 standards)
- Linear cascade tunnel for testing linear compressor or turbine blades and perform detailed study of the flow field
- A contra- rotating compressor (2 stages) test rig
- Gas Meters Calibration Unit

➢Low-Speed Section

➢**Test stand for industrial small blowers (DIN 24163 standards)**

➢**Gas Meters Calibration Unit**

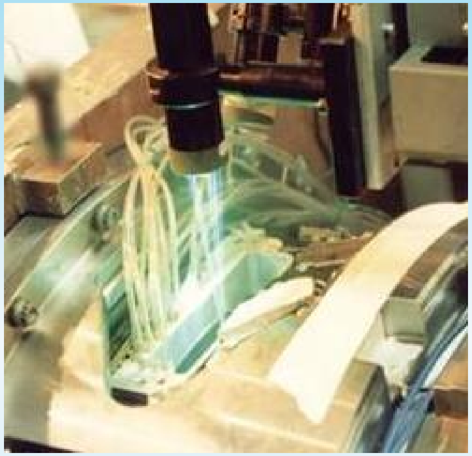
Test stand for industrial small blowers (DIN 24163 standards)

Gas Meters Calibration Unit

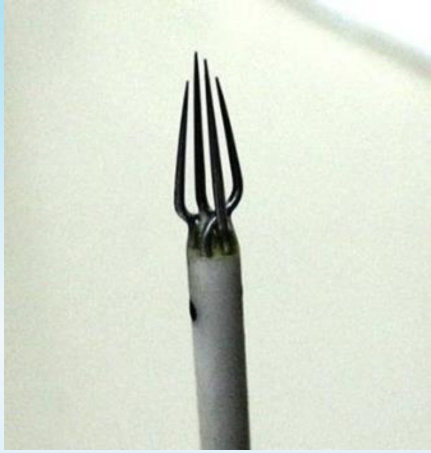
Wide Range of Instrumentation and Measuring Know-how

Pressure Probes and Rakes

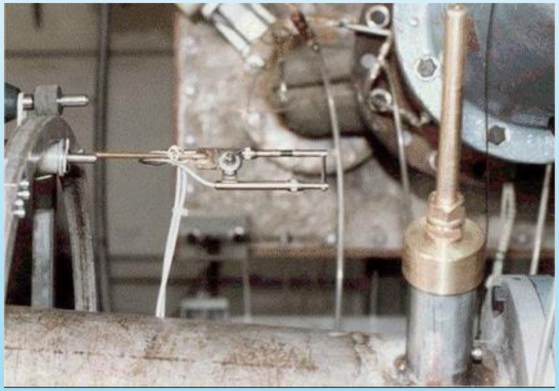
3-D LDV



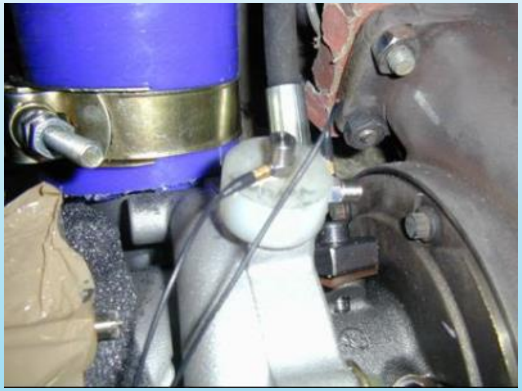
Hot Wires



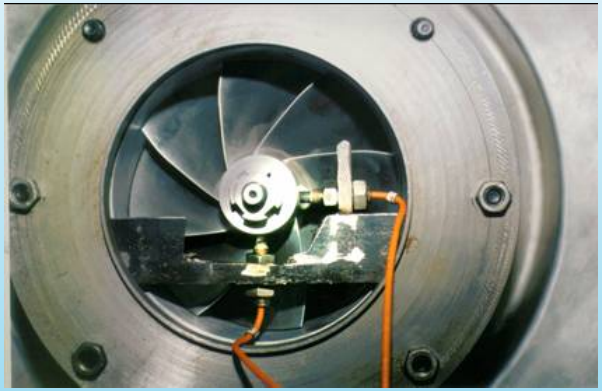
Acoustic Measurements



Vibration Measurements



Mechanical Proximity



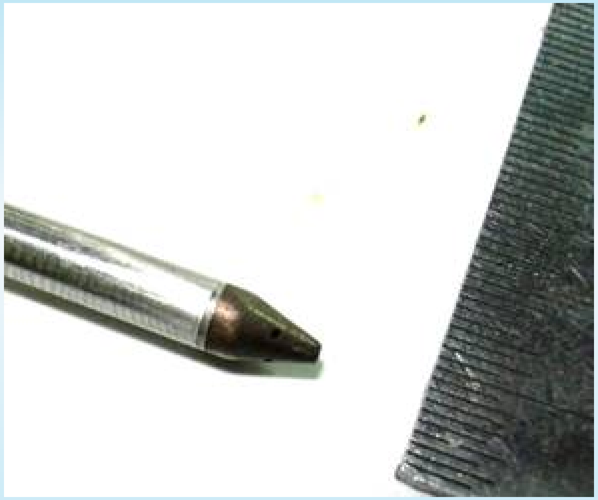
Pressure Probes For Turbomachinery Flows (I)

Subsonic 3-hole

Transonic 5-Hole

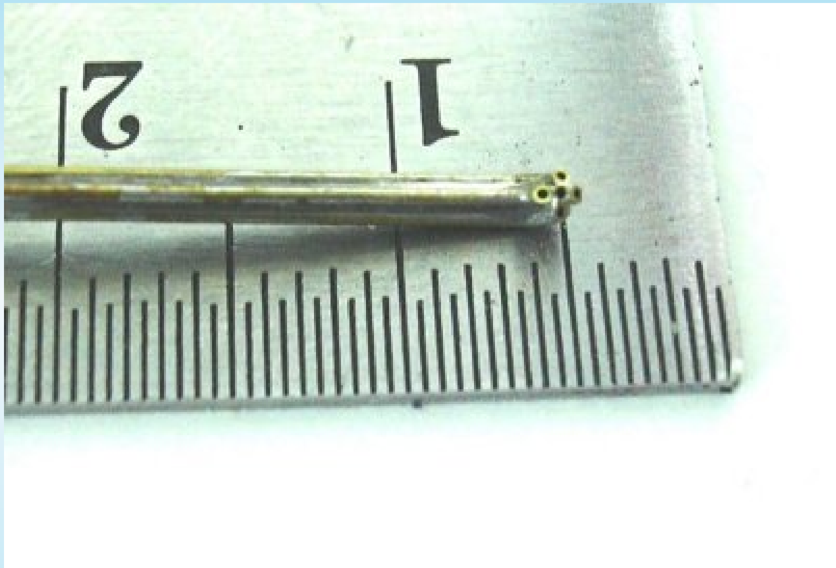
3 Hole + TC

Pressure Probes (II): Special Applications



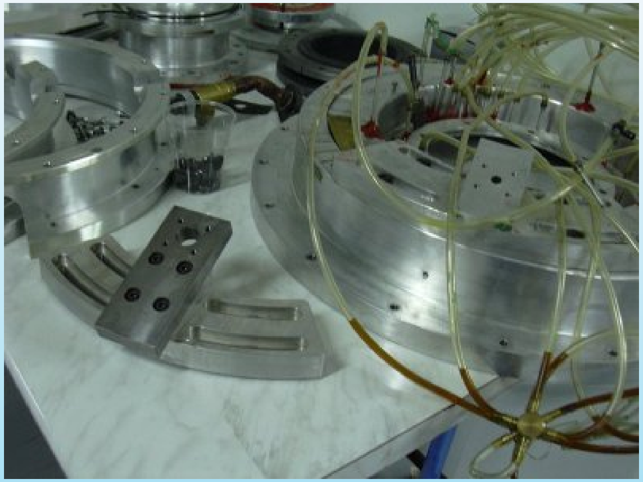
Long Nose probe for measurements with access restrictions, reduced interference

Probes (III) Custom Made Miniature Probes



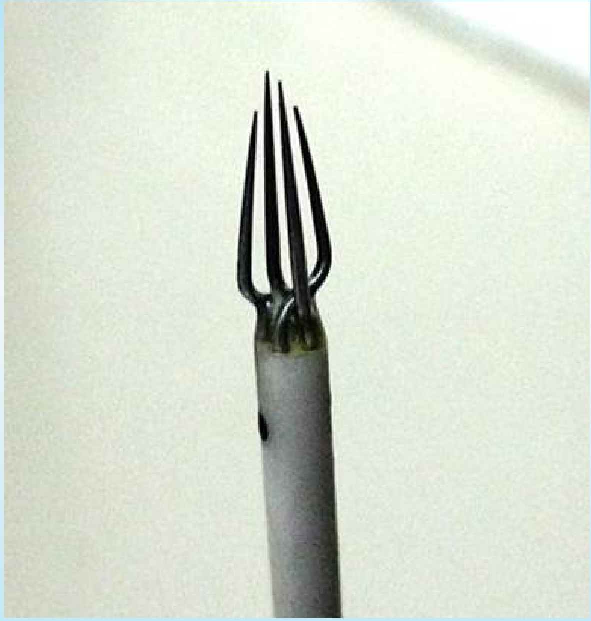
Miniature 5-Hole Probe

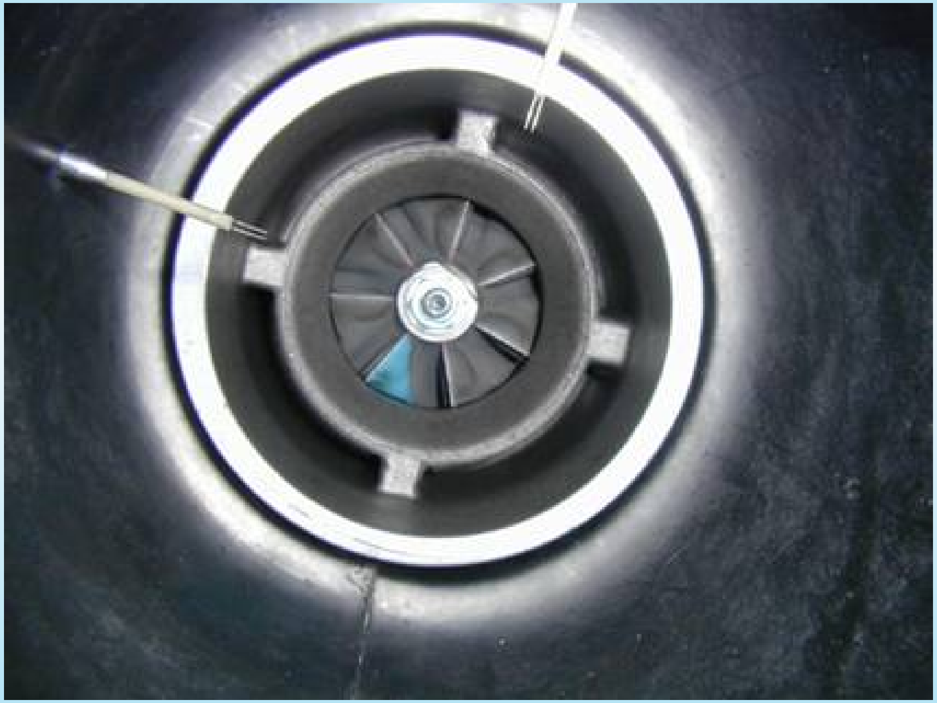
for measurement in radial compressor passages



Fast Response and Turbulence Measurements

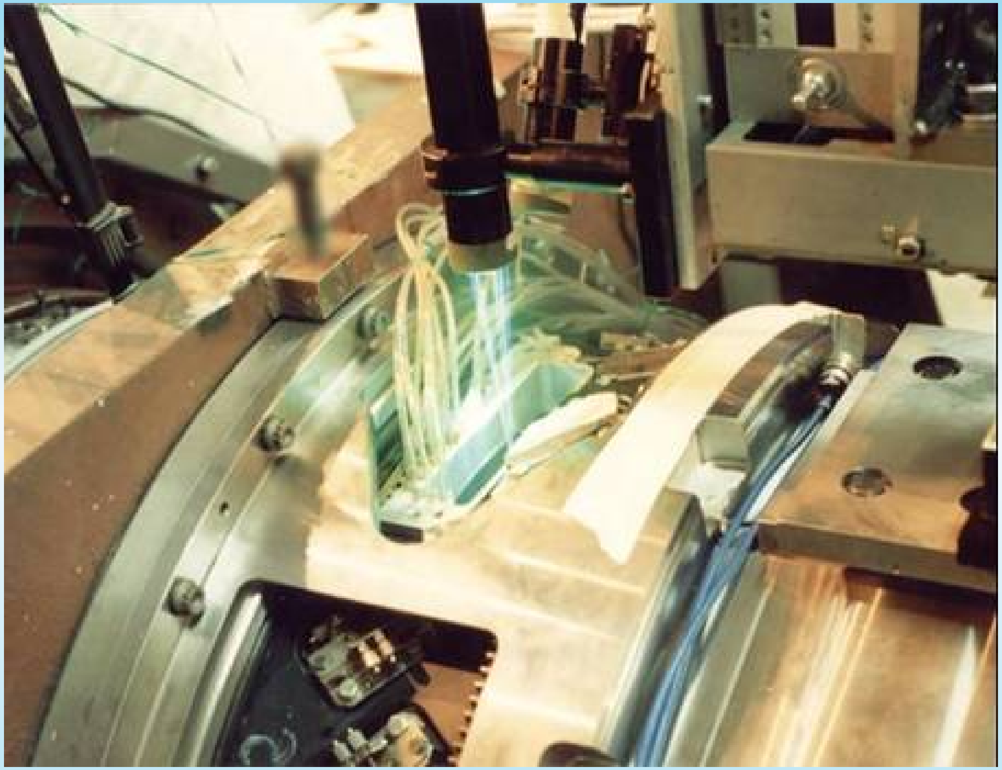
Crossed Hot wire probe





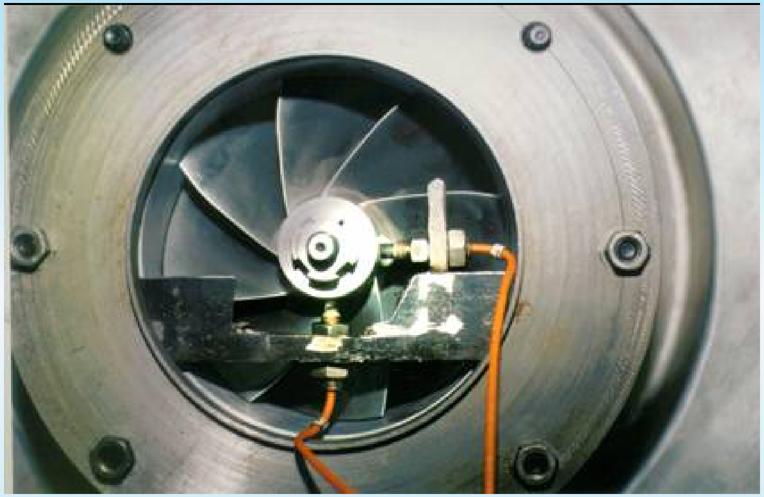
Hot wires for Turbocharger Surge Studies

LDV for Non Intrusive Velocity Measurements



Fiber-optic 3-D Laser system measuring on an Annular Cascade

Mechanical Behavior of Turbomachinery Components
Vibration measurements



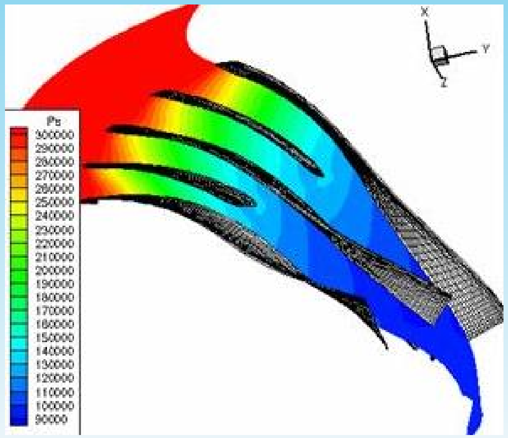
Shaft orbit measurement for compressor commissioning

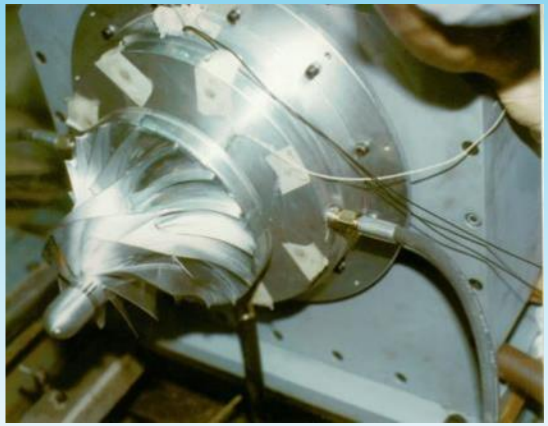
Accelerometers on turbocharger casing

Accelerometers on cartridge for monitoring

- Educational Activities
- Test Facilities & Measurement Expertise
- **Engine Modeling**
- Diagnostic Methods
- Parallel CFD & Optimization

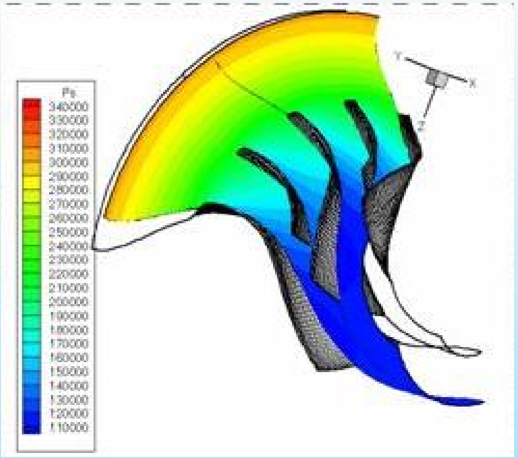
Turbomachnery Analysis, Design, Optimization



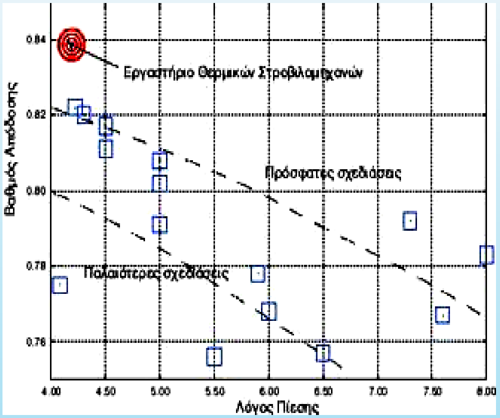


Test Designed Componets

(impeller designed at LTT)



Flow Field Computations for Design

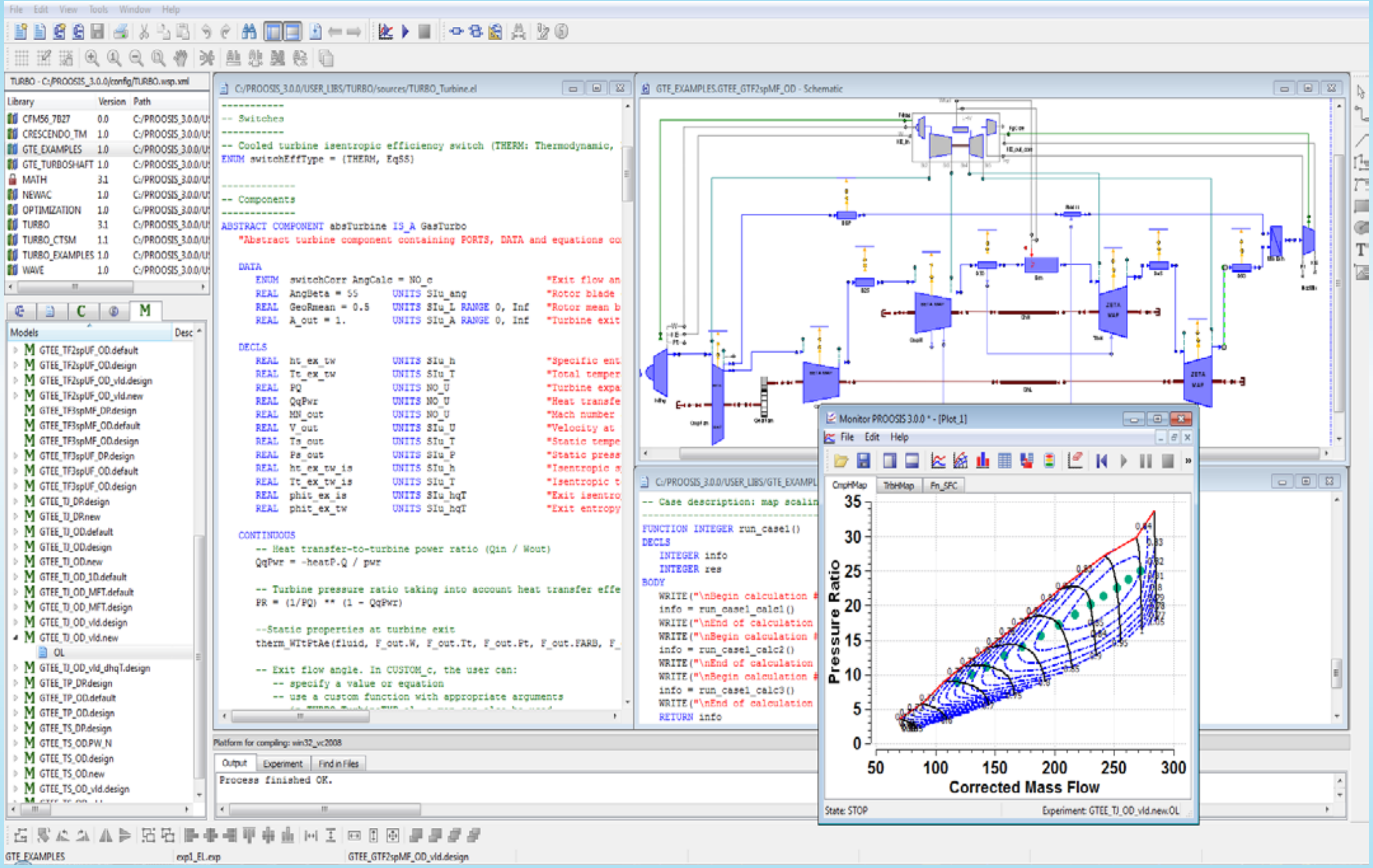


Design optimization achievement

PROOSIS

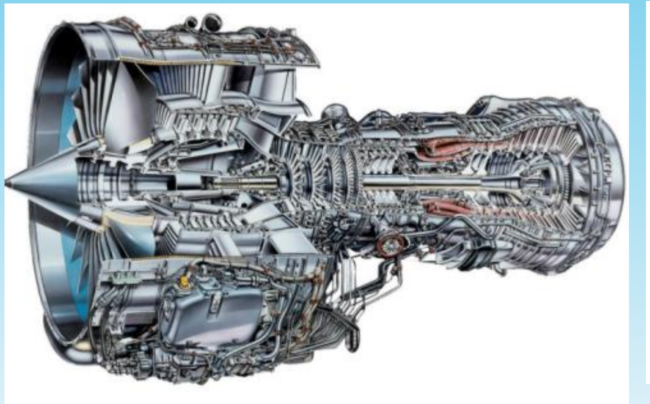
PROOSIS (PRopulsion Object-Oriented Simulation Software)

- Object-Oriented
- Steady State
- Transient
- Mixed-Fidelity
- Multi-Disciplinary
- Distributed
- Multi-point Design
- Off-Design
- Test Analysis
- Diagnostics
- Sensitivity
- Optimisation
- Deck Generation

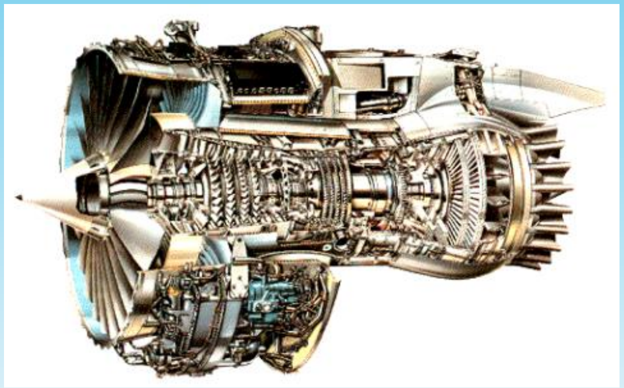


Civil Aero-Engine Models

GE CF6-80C2



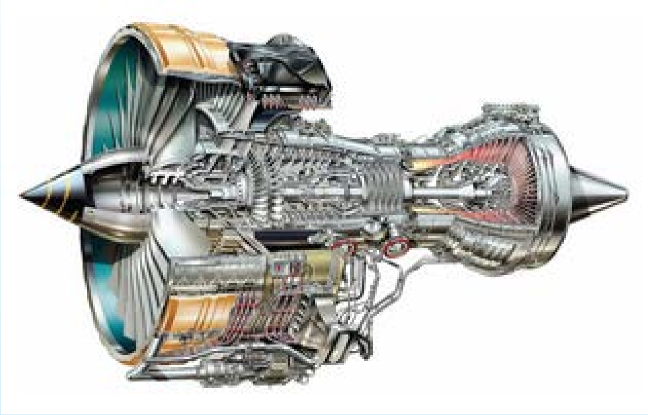
IAE-V2500-A1



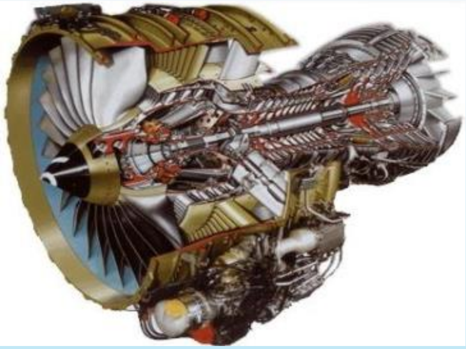
Rolls-Royce RB211-524G

Turbomeca
Makila-1A1

GE CF34-8C1



Rolls-Royce TRENT-772B

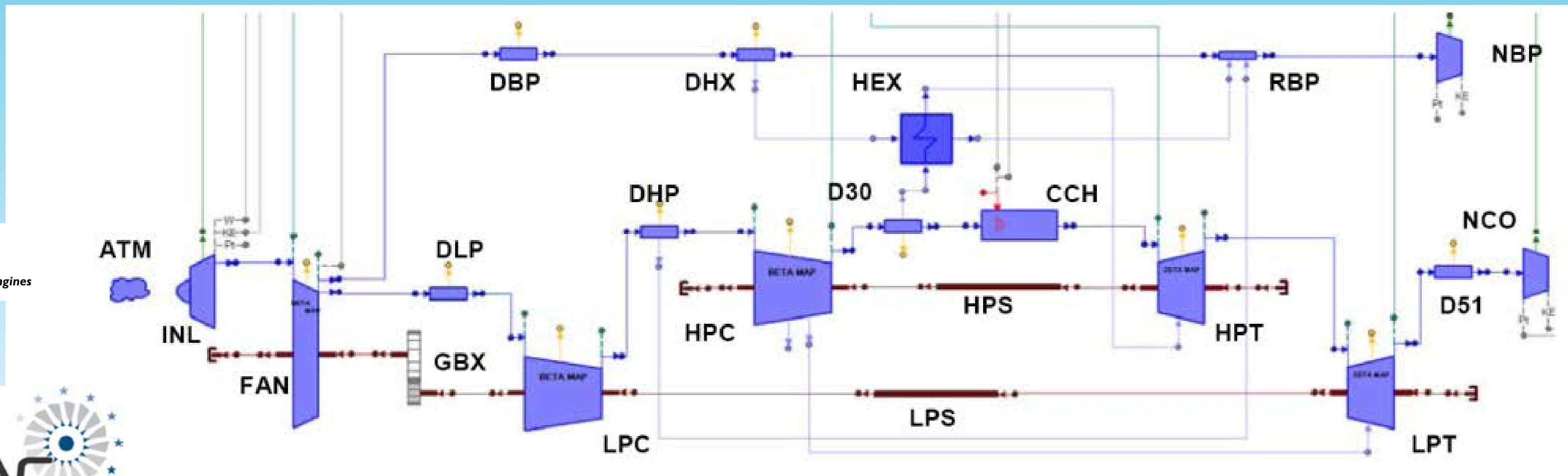


CFMI CFM56-7B27

Variety of Aero-Engine Configurations

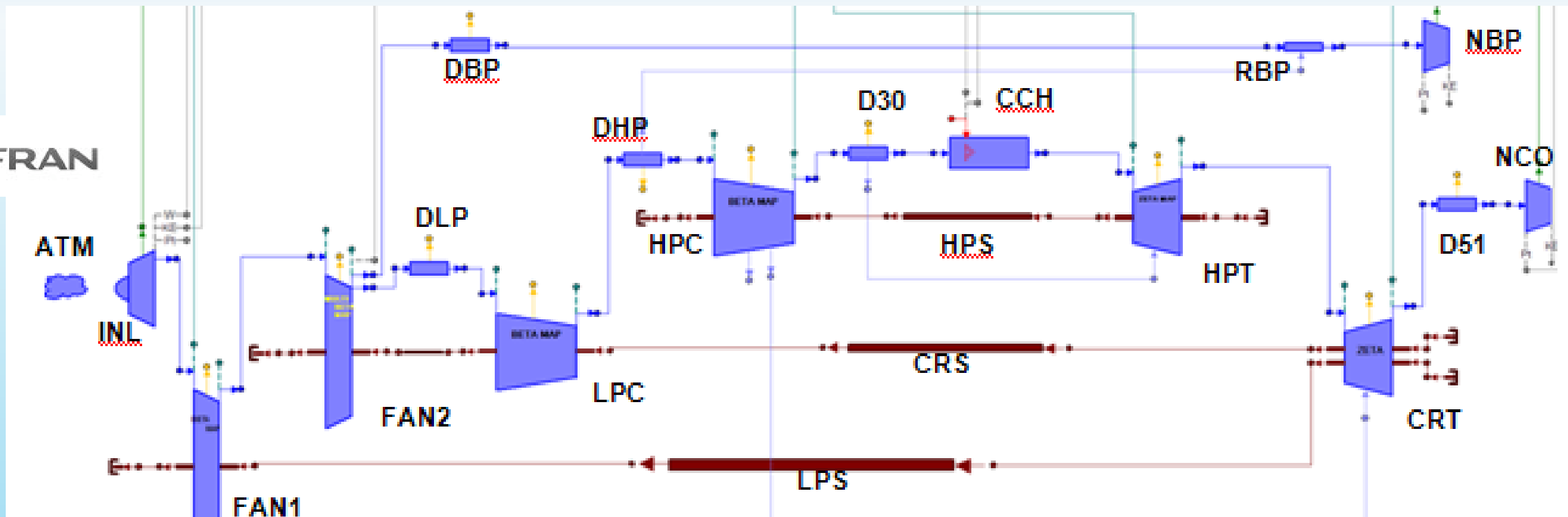
MTU Aero Engines

NEWAC new aero engine core concepts



Geared Turbofan with Active Core

SAFRAN Snecma



Contra-Rotating Turbofan

Industrial Engine Models

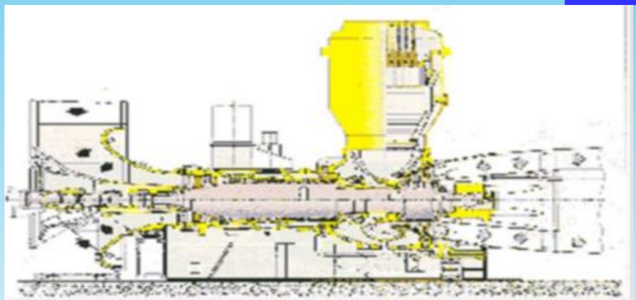


ABB GT8

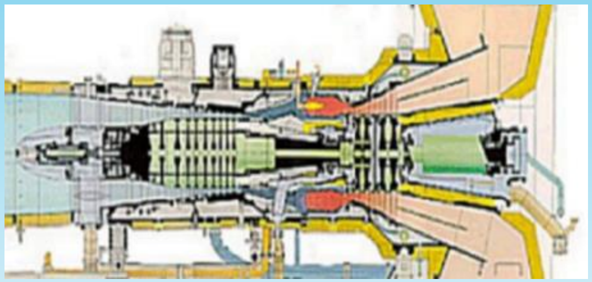
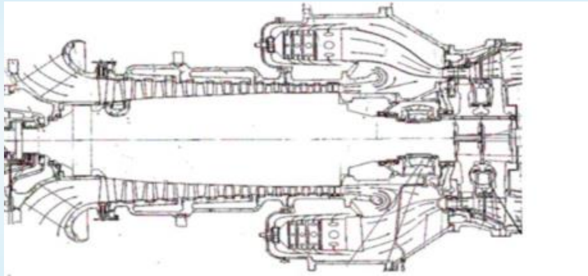


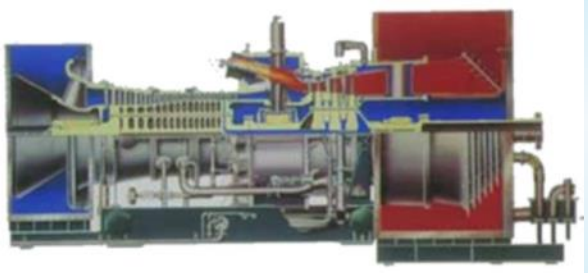
ABB GT-10

ABB GT-13E2

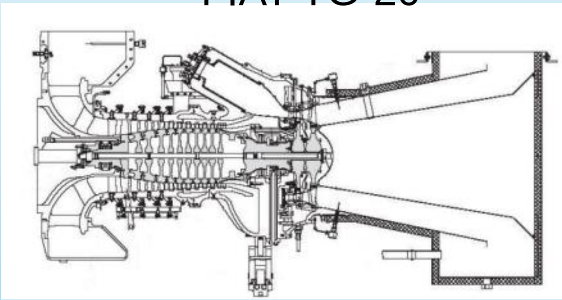
FIAT TG-20



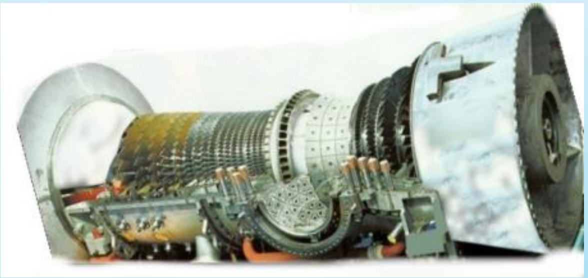
GEC EM610



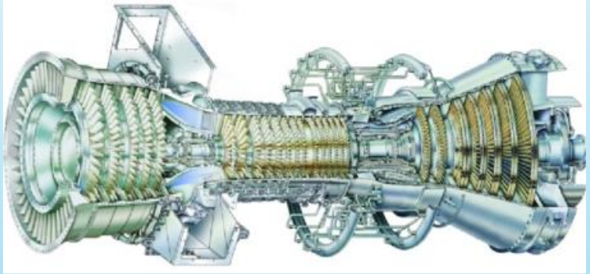
GE PG9171E



Siemens SGT-300

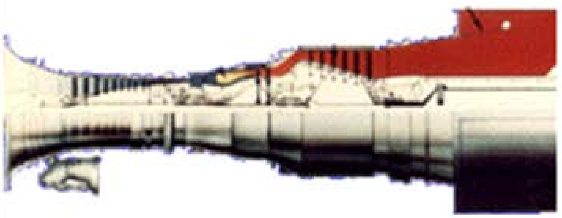


Siemens V64.3

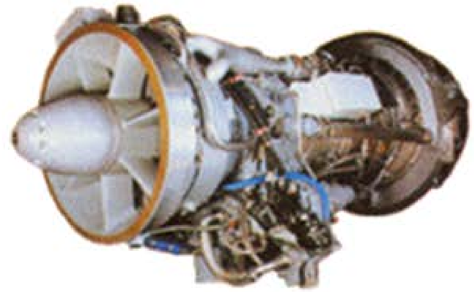


GE LM6000

Marine Engine Models



GE LM2500-30



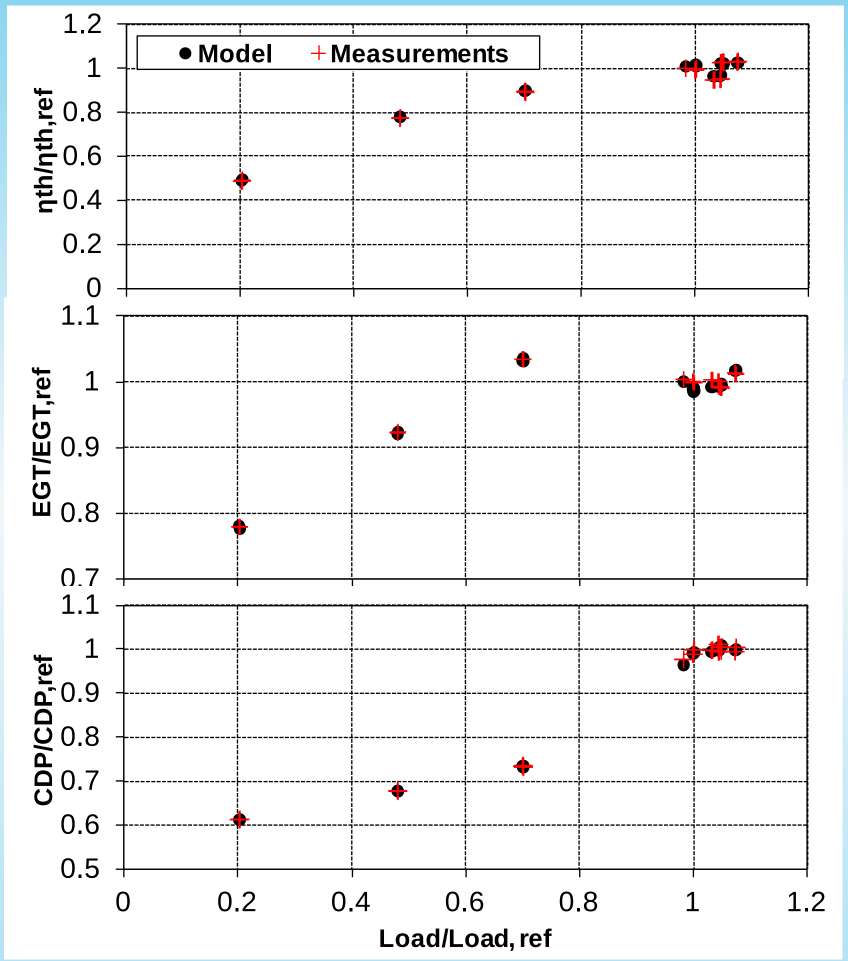
Rolls-Royce Tyne

Rolls-Royce Olympus

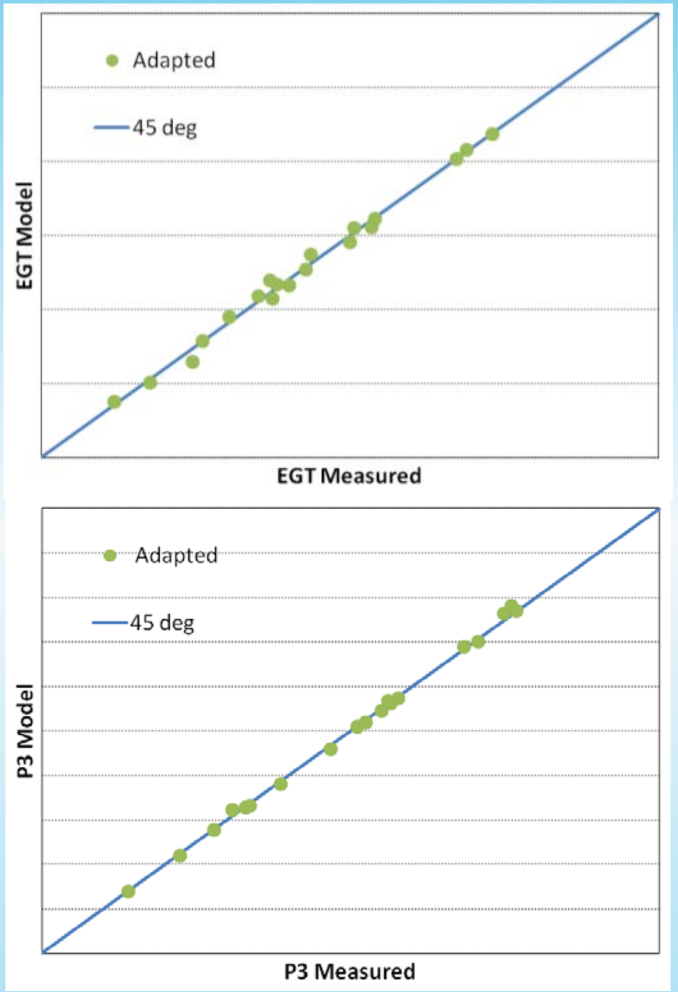
Rolls-Royce MT-30

Rolls-Royce WR-21

Models Adapted to Engine Specific Data



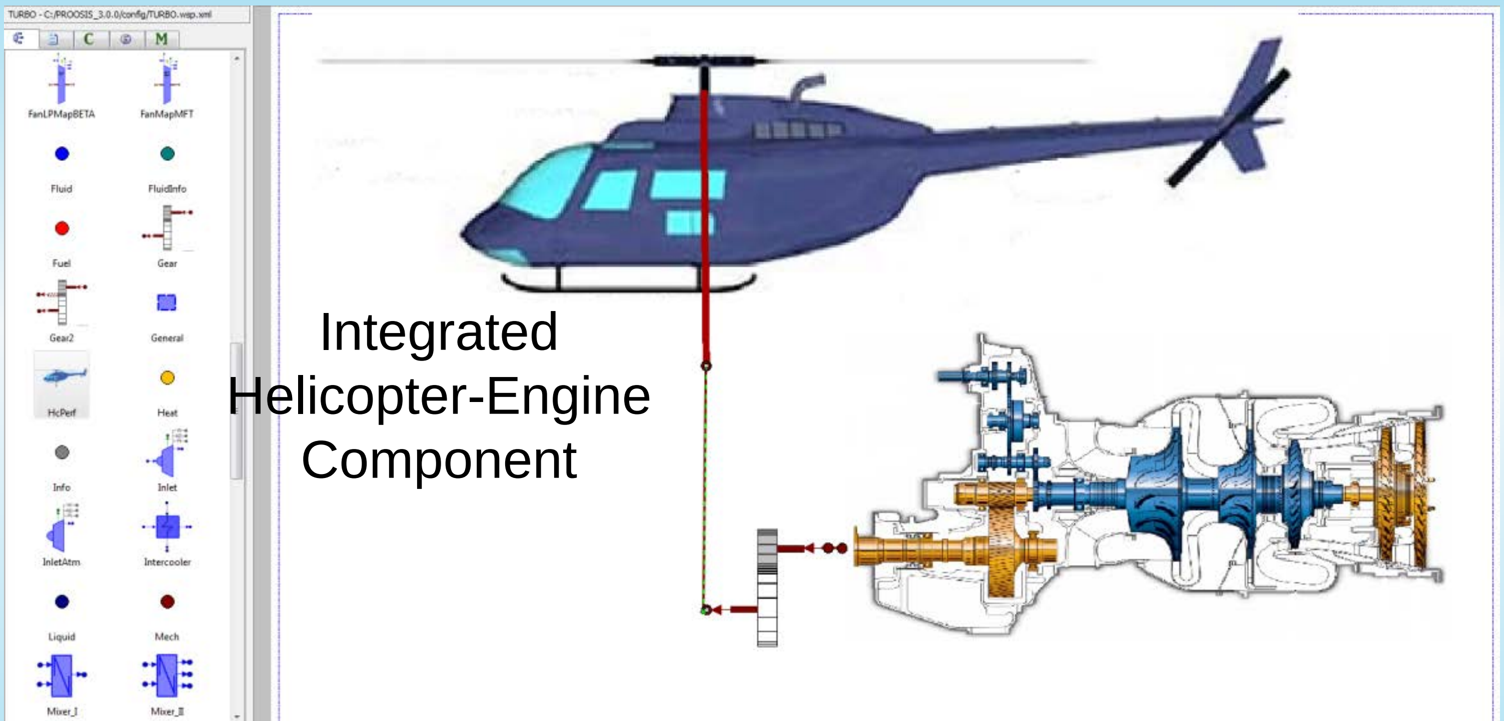
Adapted Industrial GT



Adapted Civil Aero-Engine

Variety of Engine Configurations

Helicopter-Turboshaft Engine Integrated Model

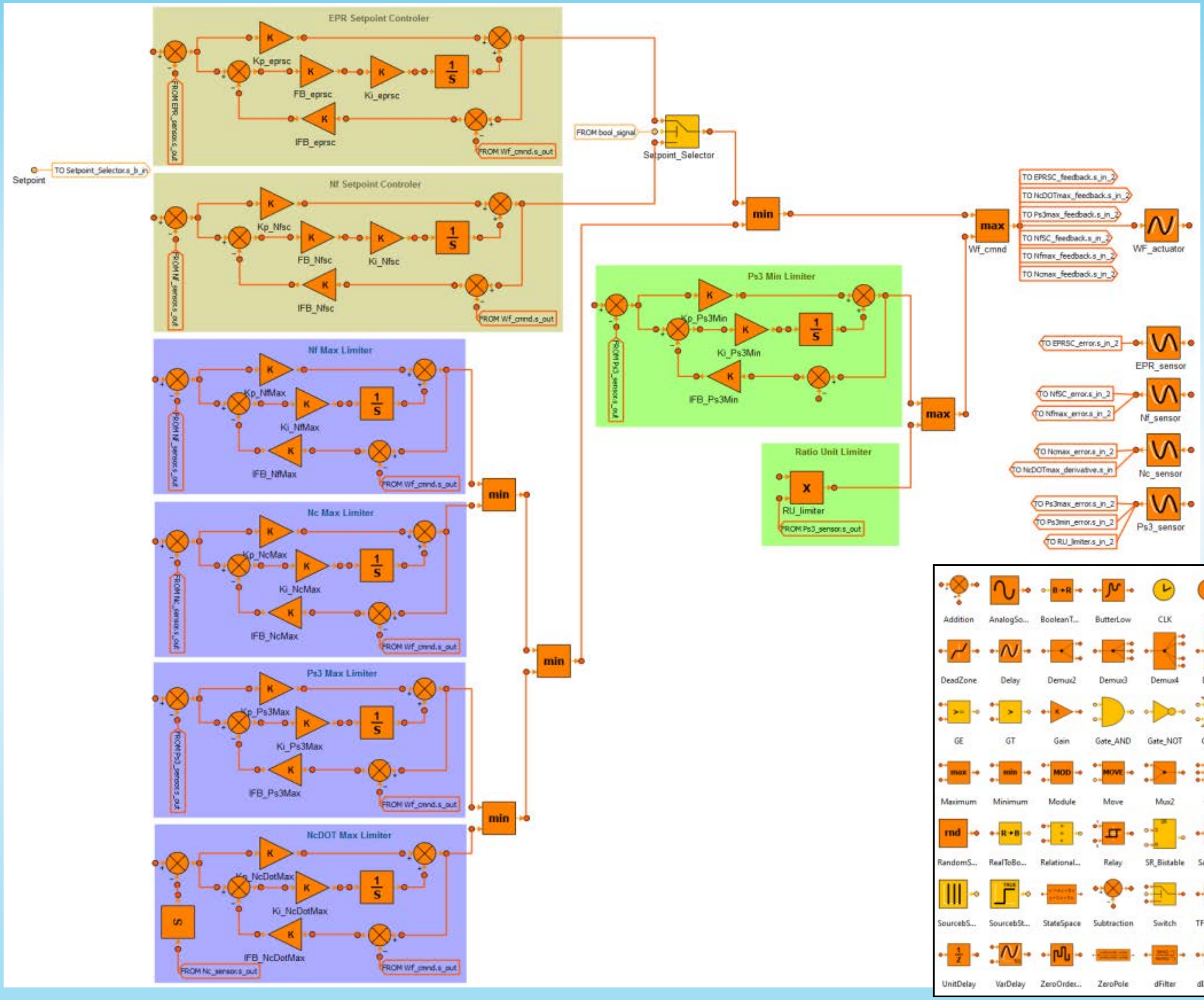


CRESCENDO
SAFRAN Turbomeca
EUROCOPTER

LTT-NTUA Software Tools Sampler

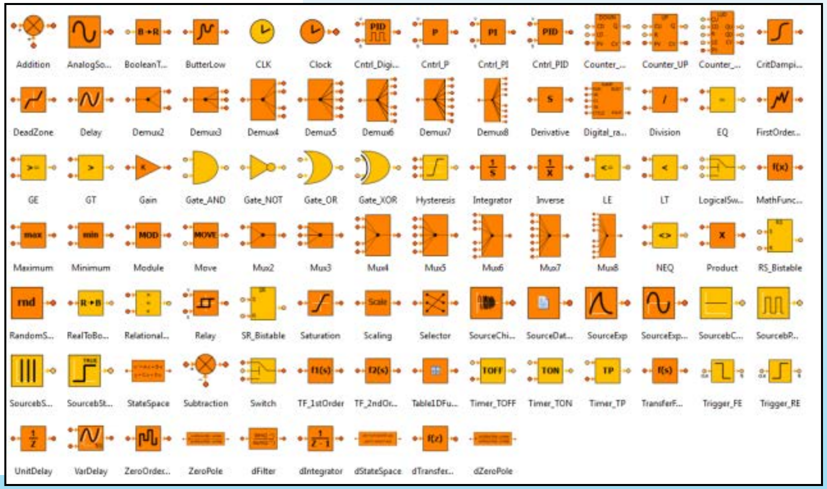
Follow-on Presentation

Control System Modelling

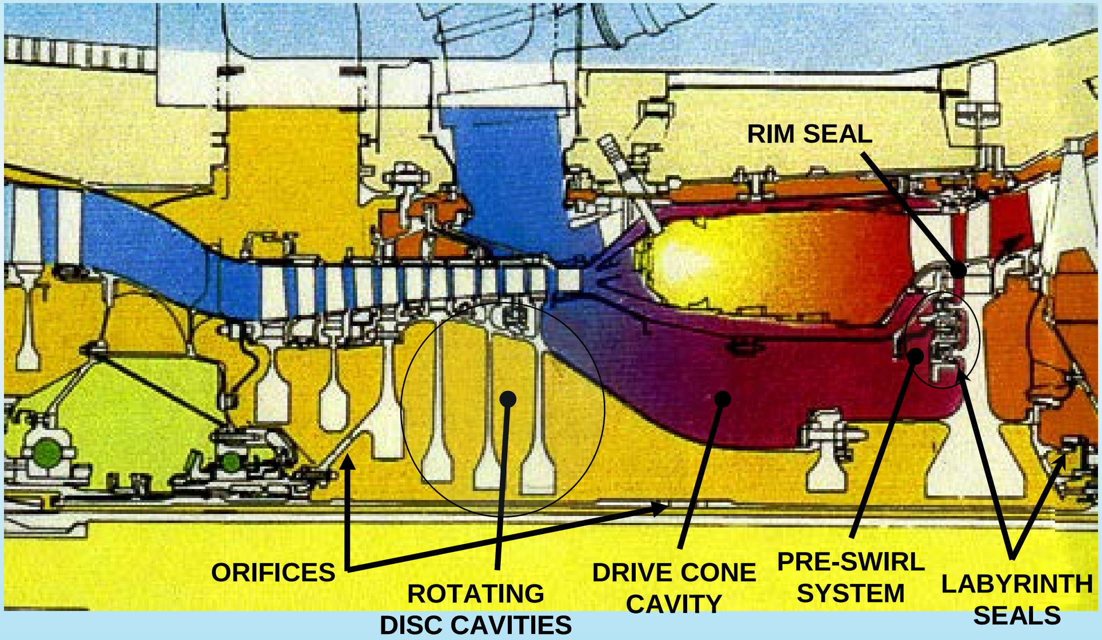


Sensors & Actuators
Volume Dynamics
Tip Clearance Effects

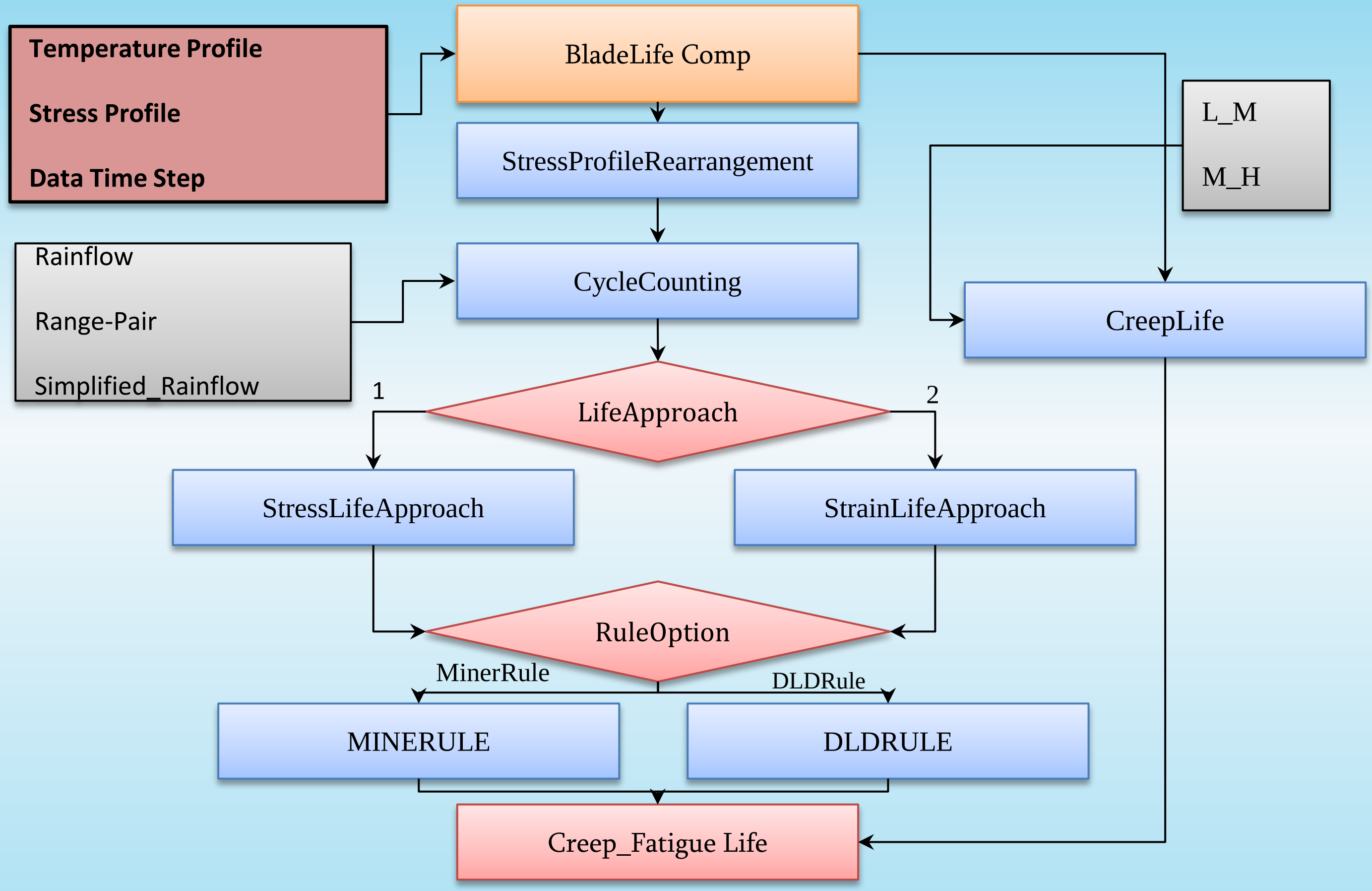
PROOSIS
CONTROL LIBRARY



Secondary Air System (SAS) modelling

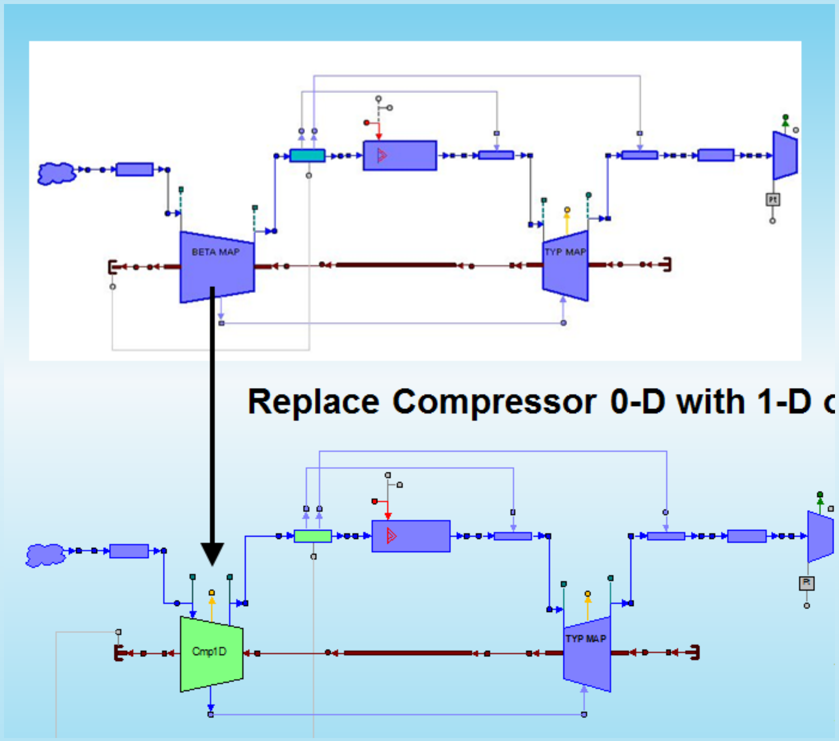


Blade Lifing Computations

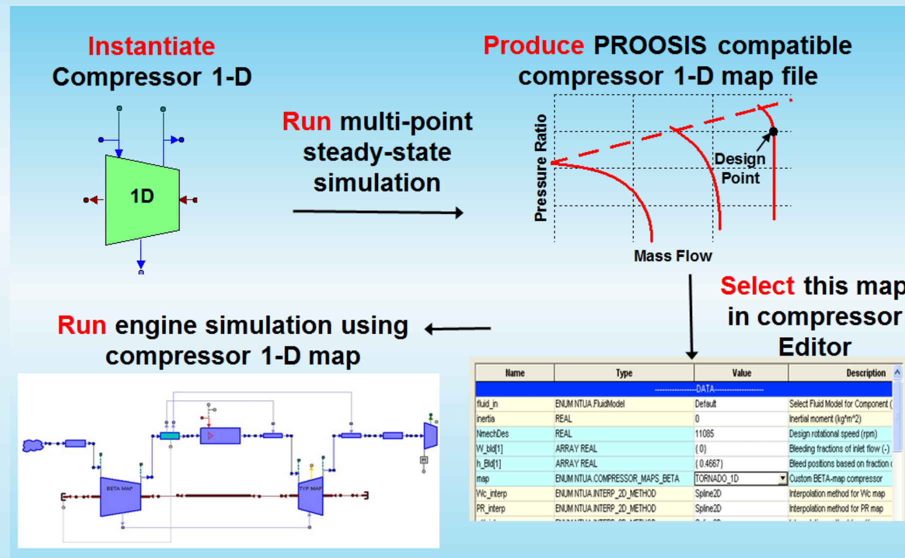


Component Zooming: Coupled and De-coupled Approaches

Coupled



De-coupled



Alexiou, A., Baalbergen, E. H., Kogenhop, O., Mathioudakis K. and Arendsen, P., 2007. Advanced Capabilities For Gas Turbine Engine Performance Simulations. ASME Turbo Expo 2007, Paper Number GT-2007-27086.

Commercial Aircraft's Mission Analysis Computational Model

- Covers all segments of a modern commercial aircraft typical flight: taxi, take off, climb, cruise, descent and approach
- It analyses the trajectory of the aircraft using basic Flight Mechanics longitudinal equations of equilibrium between the applied forces
- It allows the analysis of a variety of possible missions within the limits of safety and traffic regulations
- It delivers the overall mission results: aircraft trajectory, engine performance along the mission, burned fuel and flight duration
- It can be used to asses the effects of engine degradation and to optimize the flight profile

Commercial Aircraft's Mission Analysis Computational Model

Mission Performance Analysis

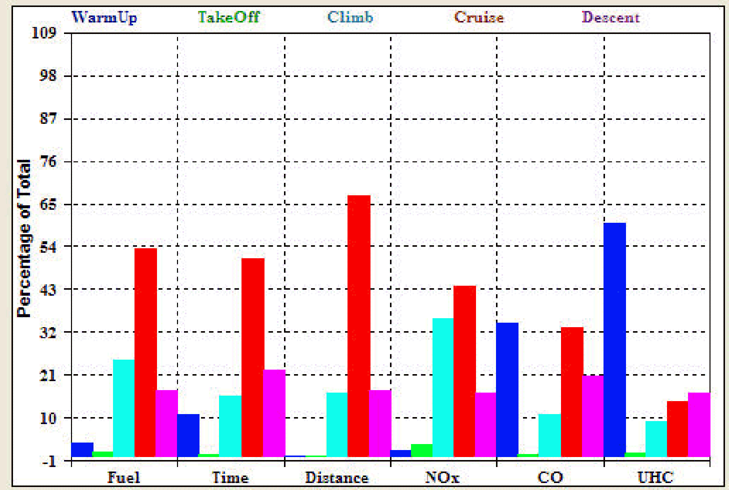
Mission Parameters

Parameter	Value	Unit
Total Flight Range	1000	[km]
Cruise Flight Level	9.144	[km]
Cruise Speed	0.78	[Mach]
Cruise Decel.	0.05	[Mach]
Passengers	120	[-]
Fuel Loaded	7	[tons]
Take-Off TIT	1272	[C]
Theta Initial	7.5	[deg]
Climb Coefficient	1.2	[-]
SDR corrector	1	[km]

Overloaded

RESET

Select Aircraft: Boeing 737-400



Latest Mission Results | Totalized Mission Results | Mission Details

Operating Range

Run Mission

Case Identifier: Unidentified

Optimize Mission

Approximate Model

Reset Mission Results Graph Cases

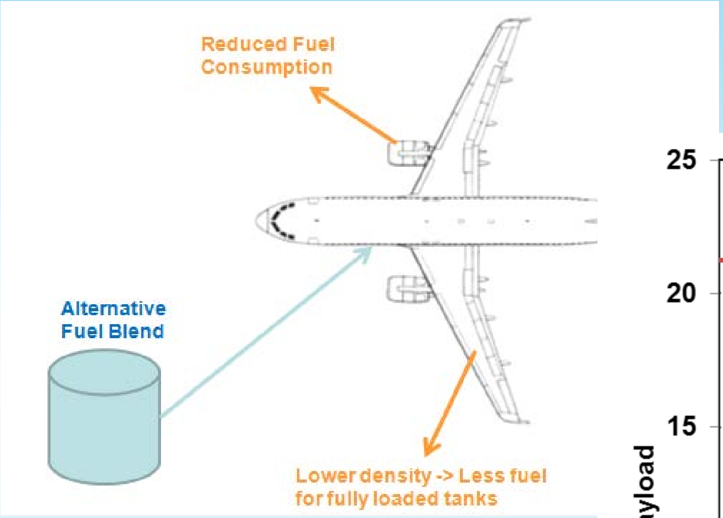
Mission RESULTS

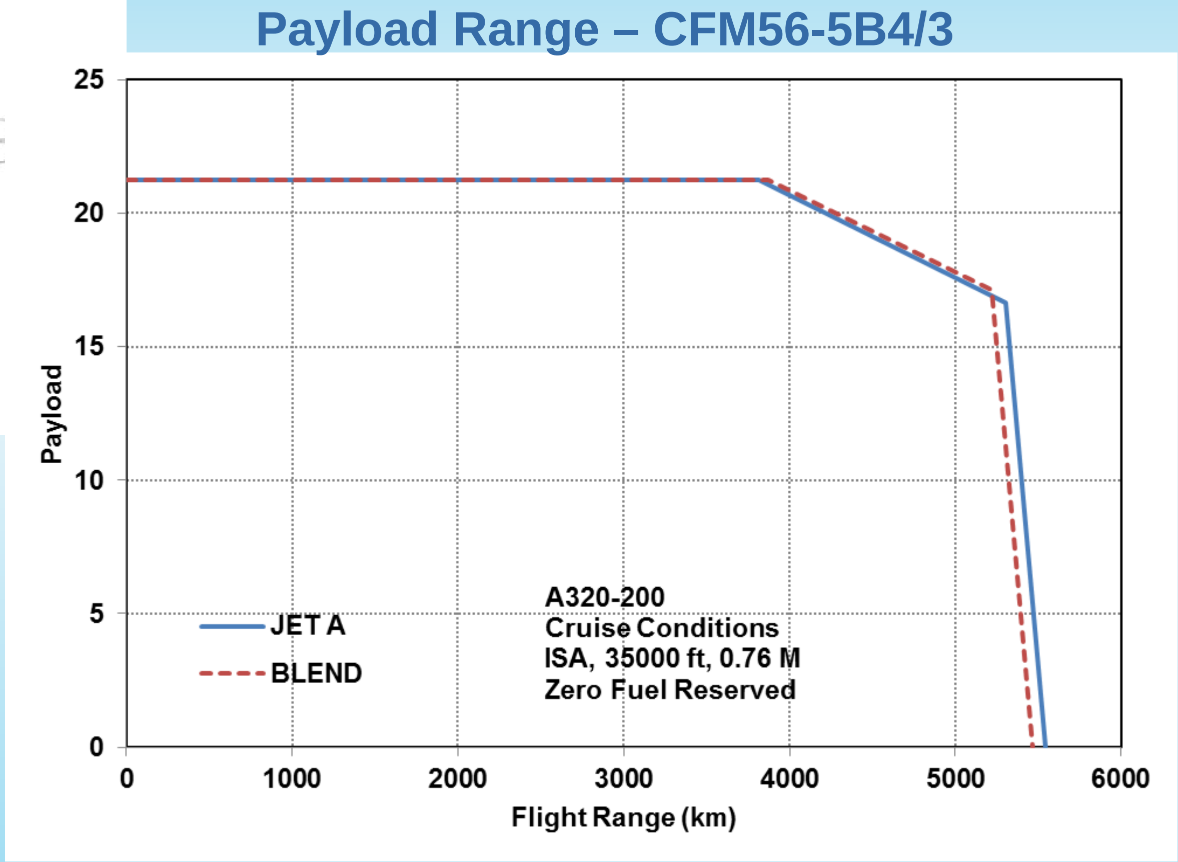
values[%]

Segment	Performance: Fuel Burned	Performance: Duration	Performance: Length	Pollutant Emissions: NOx	Pollutant Emissions: CO	Pollutant Emissions: UHC
WarmUp/Taxi	163.3 [kg]	10 [min]	0 [km]	0.622 [kg]	3.914 [kg]	0.2017 [kg]
Take-Off	59.8 [kg]	25.8 [sec]	1126.1 [m]	1.338 [kg]	0.054 [kg]	0.0025 [kg]
Climb	1165.6 [kg]	14.5 [min]	161.9 [km]	15.135 [kg]	1.245 [kg]	0.0301 [kg]
Cruise	2518.1 [kg]	47.3 [min]	671.2 [km]	18.719 [kg]	3.794 [kg]	0.047 [kg]
Descent	810.8 [kg]	20.5 [min]	169.6 [km]	6.944 [kg]	2.362 [kg]	0.0544 [kg]
TOTAL	4717.7 [kg]	92.7 [min]	1002.7 [km]	42.758 [kg]	11.369 [kg]	0.3358 [kg]
CHANGE	0 [kg]	0 [min]	0 [km]	0 [kg]	0 [kg]	0 [kg]

TakeOffWeight[tn]: 52.4 LandingWeight[tn]: 47.682 TFR error[km]: 2.7 CaseNr: 1 Cost Function: 1

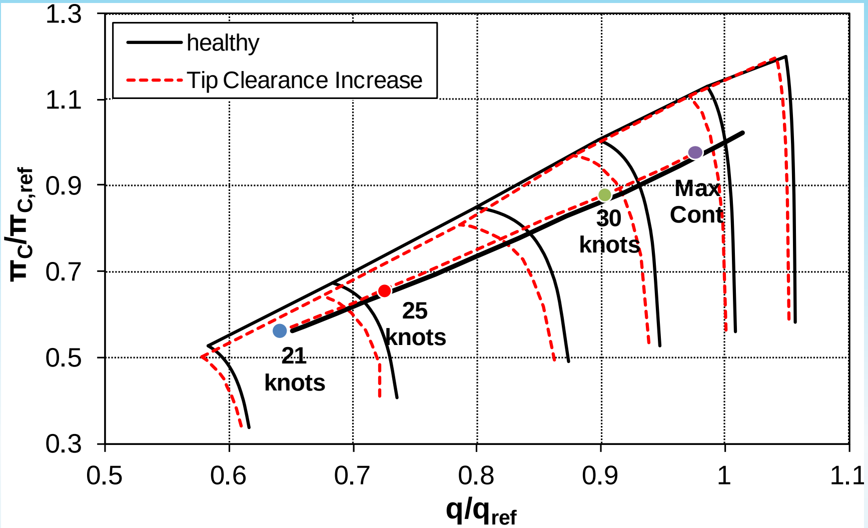
Alternative Fuels in Aircraft Propulsion

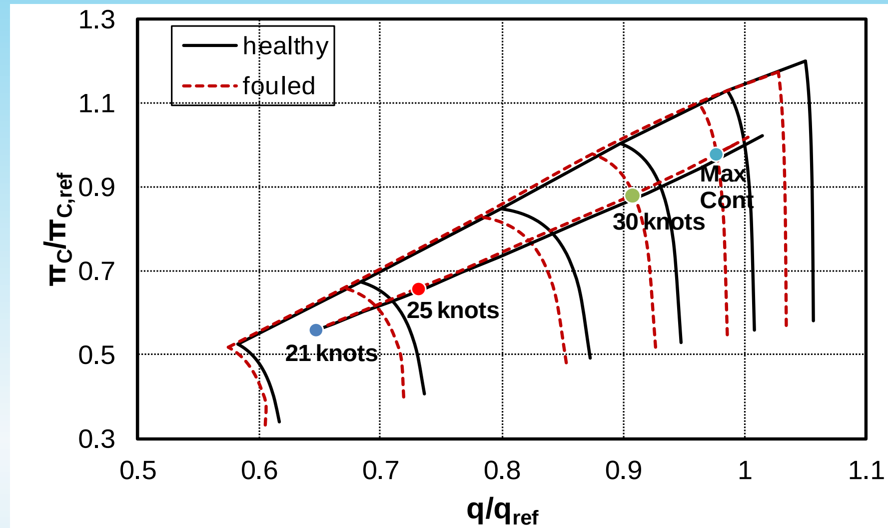


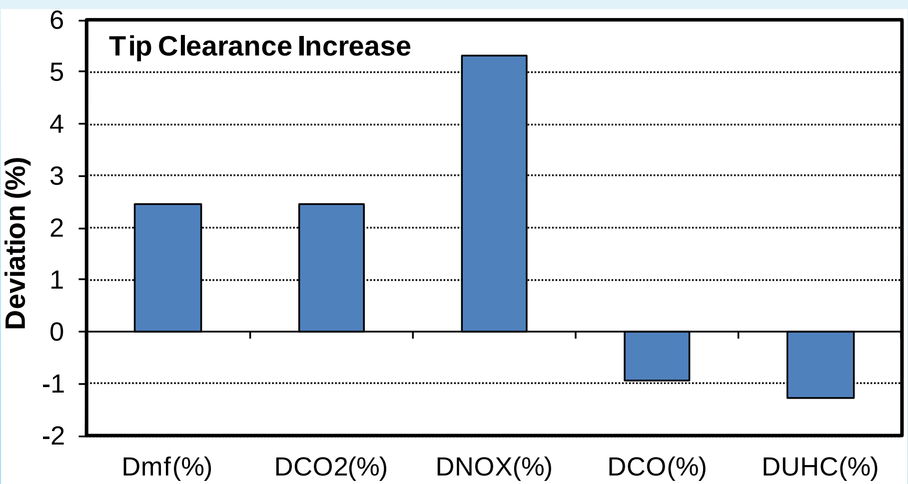


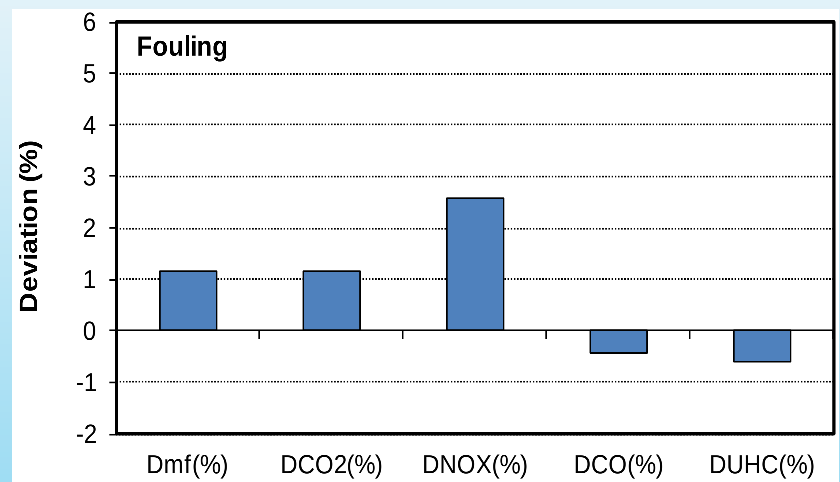
Quantification and Analysis of Compressor Faults on Marine Gas Turbines and Vessel’s Mission

Quantification and Analysis of Compressor Faults on Marine Gas Turbines and Vessel's Mission

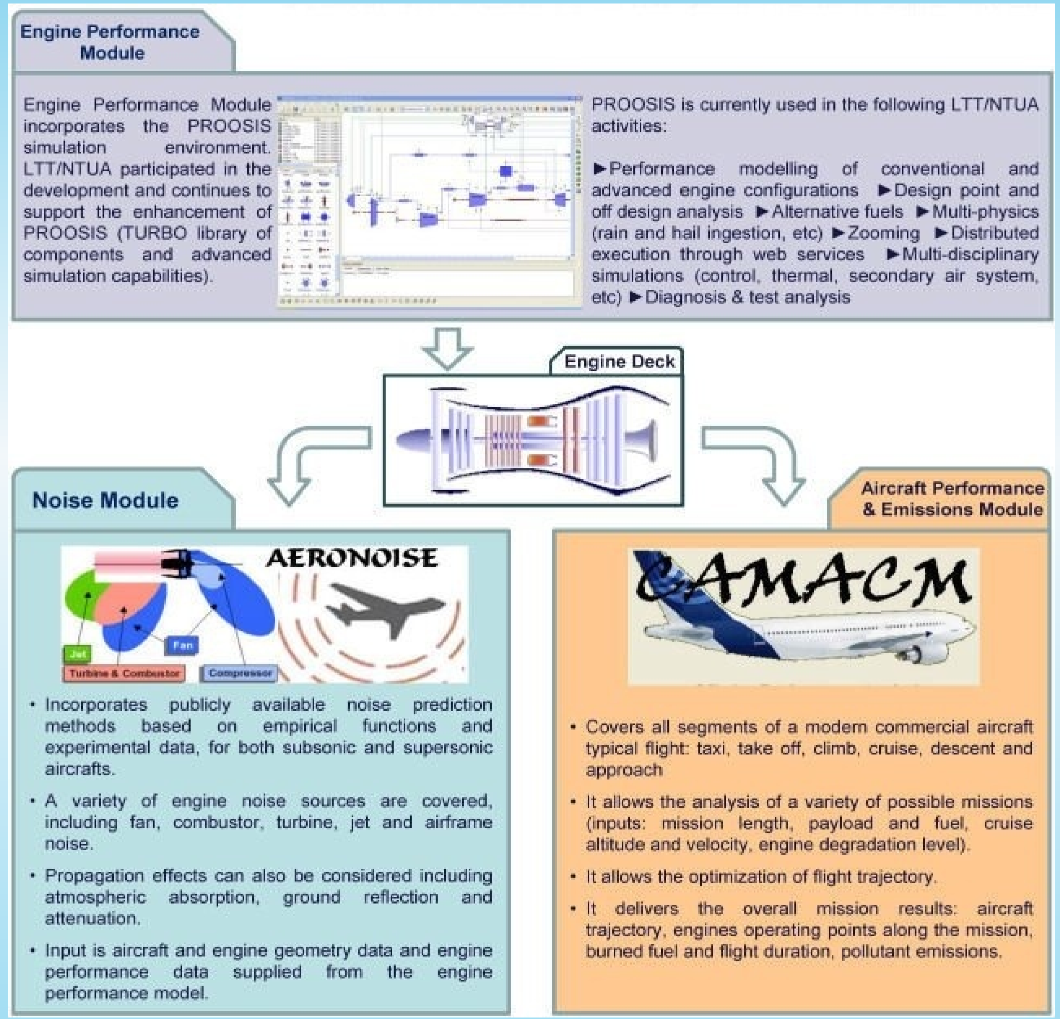






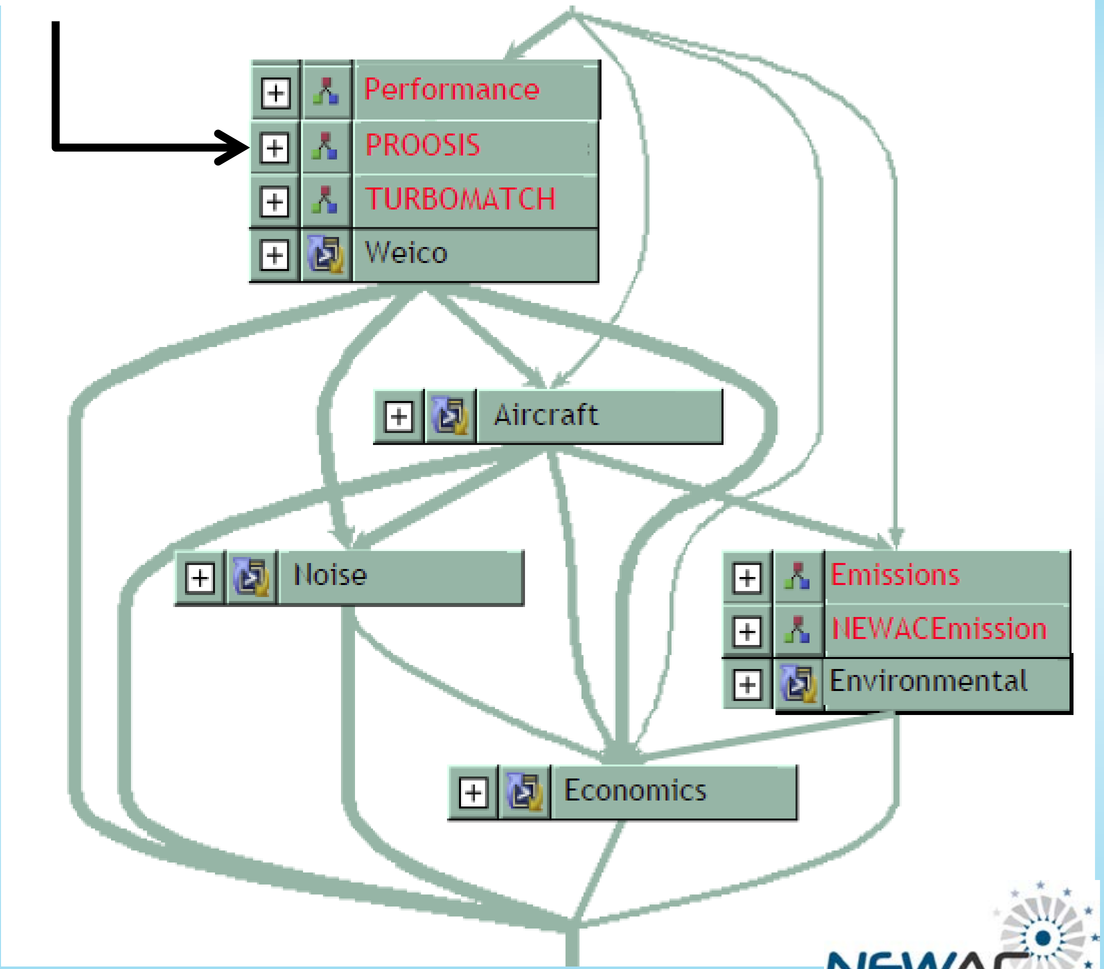


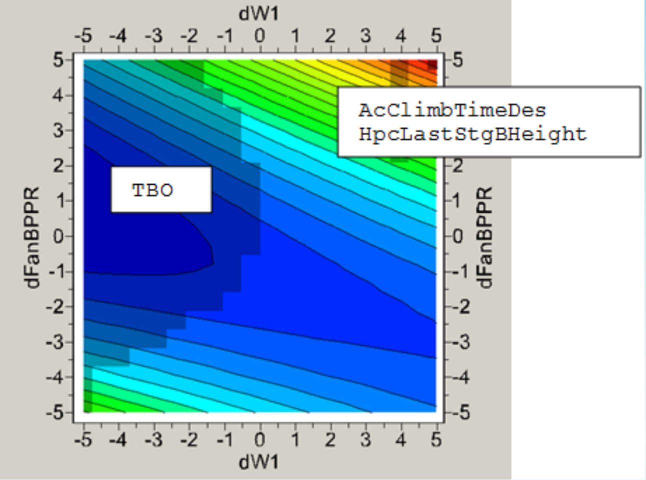
Tools for Noise and Emissions



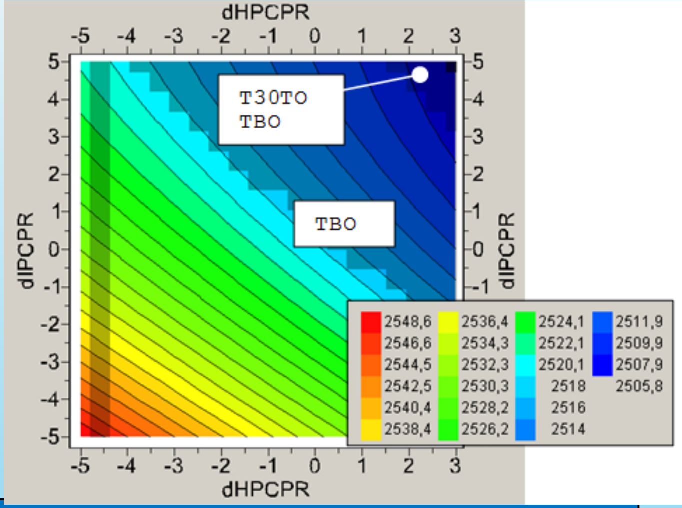
Multi-Disciplinary Design Optimization

PROOSIS executable deck in iSIGHT





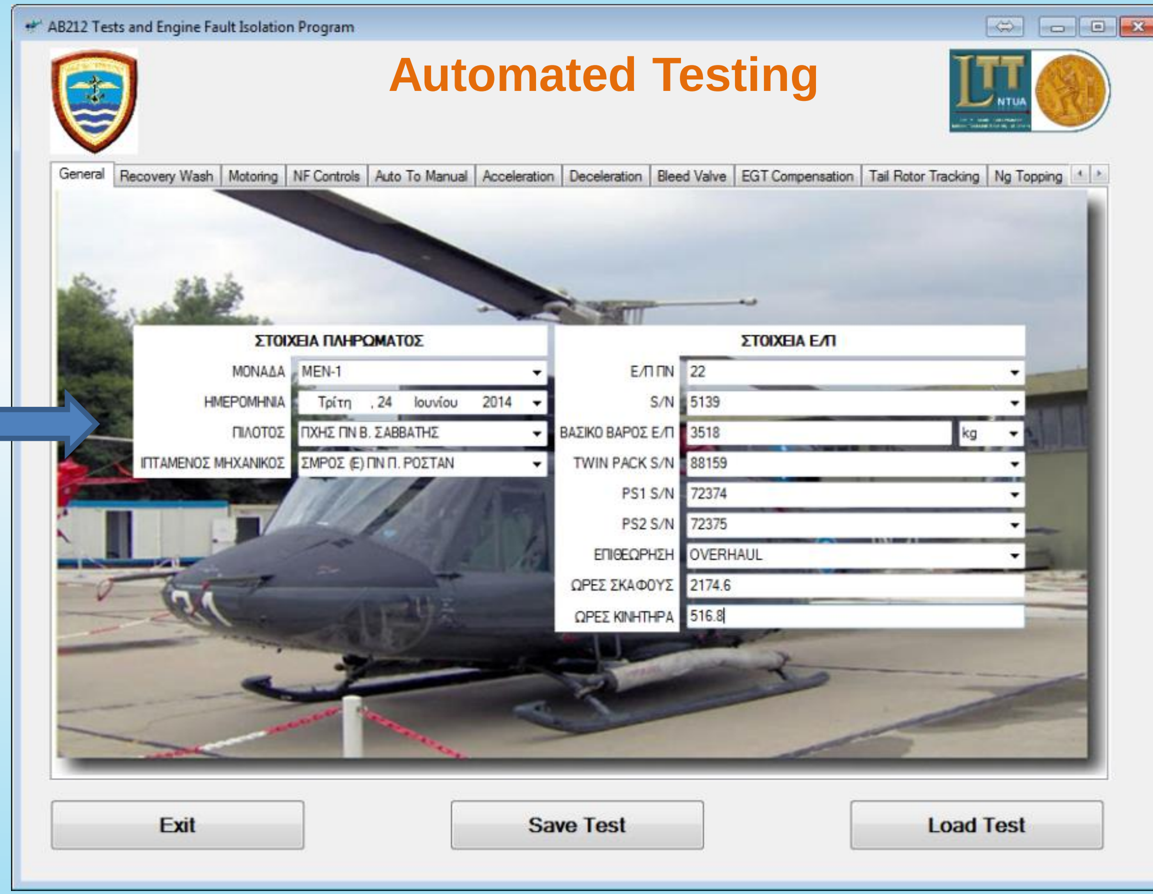
Fuel Burn Contour Plots



Software Package for Helicopter Testing Automation

AB212 Helicopter Flight Tests (I)

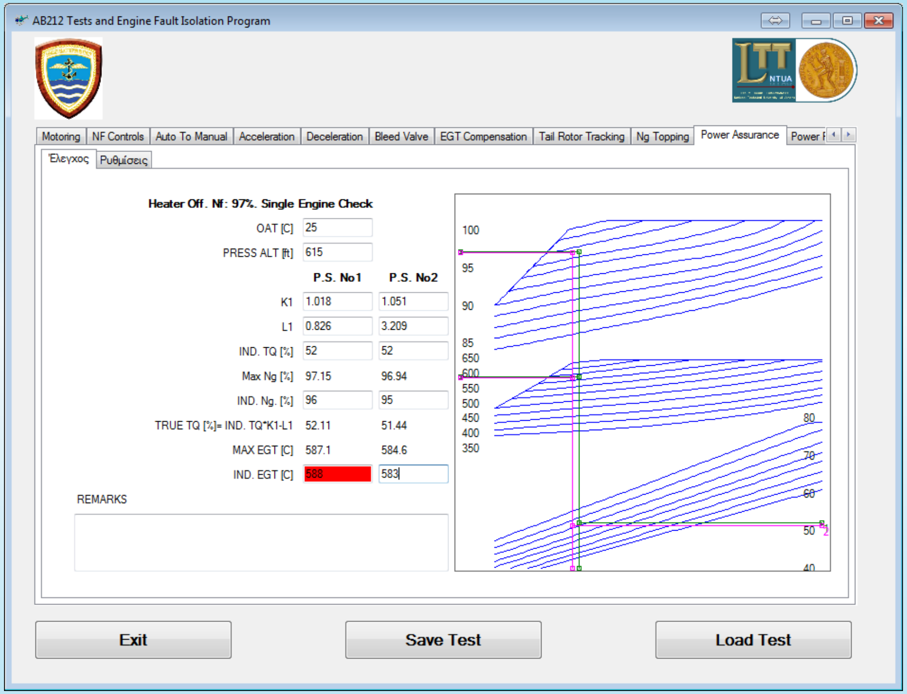
Manual Testig



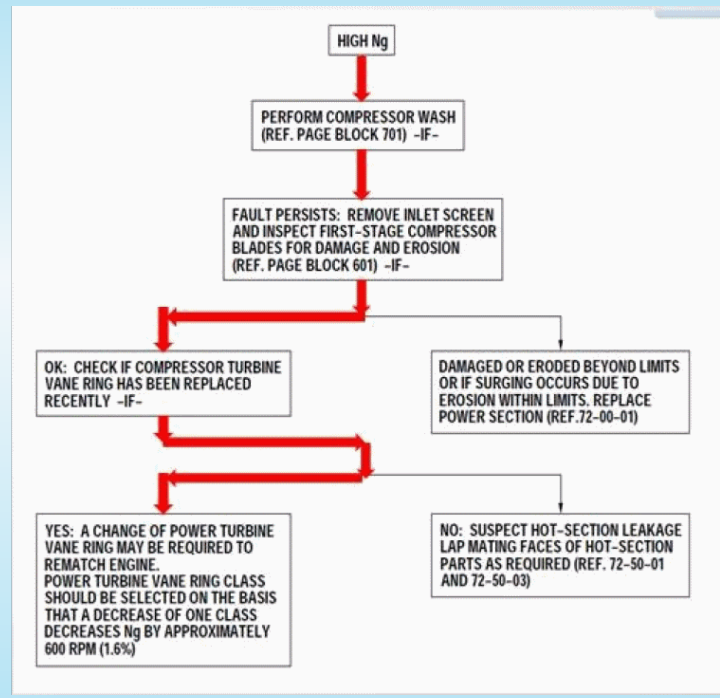
Software Package for Helicopter Testing Automation

AB212 Helicopter Flight Tests (II)

Test parameters calculation – limits check



Fault Tree Diagnosis

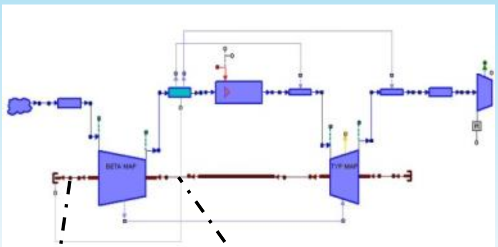


- *Increase test reliabiliy*
- *Simplify tet procedure*
- *Minimize testing time and cost*

Distributed Simulation via Web Services

Client (NLR)

PROOSIS



PROOSIS Web Component

Enables remote use and sharing of User Libraries over the Internet without distributing the code of the libraries

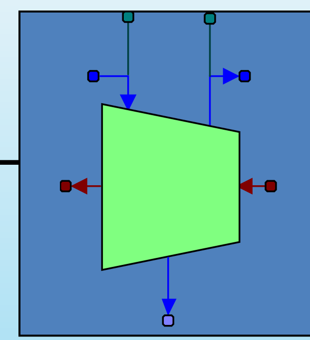
Internet

Server (NTUA)

Application Server

PROOSIS Web Service Operation

Stage-Stacking Function



- Educational Activities
- Test Facilities & Measurement Expertise
- Engine Modeling
- **Diagnostic Methods**
- Parallel CFD & Optimization

LTT/NTUA Diagnostic Methods

- **Original Methods Developed**
  - **Gas Path Analysis (Aerothermodynamics)**
  - **Fast Response Measurements**
- **Technological Background for implementation**
- **Integrated Systems Developed**

Capabilities

- Perform Testing (in Lab, in situ)
  - (Measuring equipment, know-how)
- Constitution of data collection systems
  - (Hardware, Software)
- Test Data Analysis and Interpretation
- Constitution of Supporting software
  - (Data Analysis software, Engine Models)
- Constitution of Integrated Systems

- Educational Activities Test Facilities & Measurement Expertise
- Engine Modeling
- Diagnostic Methods
- **Parallel CFD & Optimization**

NTUA > School Mech. Eng. > Fluids Section > Parallel CFD & Optimization Unit

K. Giannakoglou, Professor NTUA, kgianna@central.ntua.gr

Research Activities:

Development and parallelization (on CPUs and GPUs) of:

1. **in-house Computational Fluid Dynamics (CFD) tools/software,**
2. **a generic optimization platform based on enhanced Evolutionary Algorithms (EASY),**
3. **Aero/hydrodynamic optimization tools based on adjoint methods,**
4. **Hybrid (gradient-based & stochastic) optimization methods.**

Applications in: turbomachines, aircraft/car aerodynamics, etc

Research Group:

Prof. K. Giannakoglou, 4 Post-Docs, 15 PhD students.

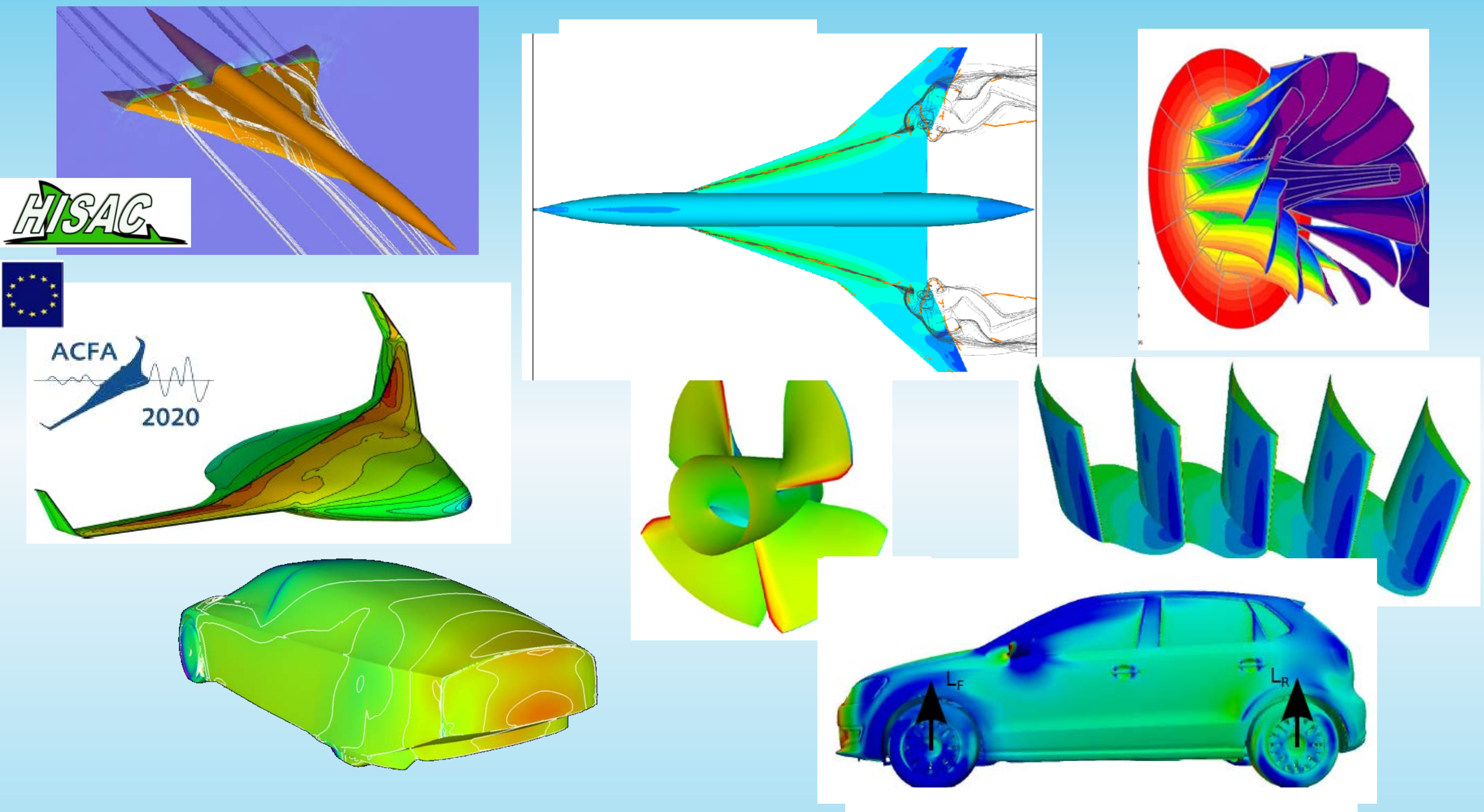
Research Computational Infrastructure:

CPU and GPU cluster with 44 Teraflop computing power in total.

Funding:

EU Projects (FP6/7: HISAC, ACFA, HYDROACTION, AQUAGEN, AboutFLOW, IODA, SmartAnswer, FORTISSIMO), directly from Industrial outfits (Dassault Aviation, Volkswagen, Andritz Hydro, Toyota Motor Europe, Schlumberger, etc), software developers & vendors (ICON, NUMECA, SOFISTIK, ENGYS etc), Greek companies (Hellenic Aerospace Industry, Public Power Corporation, various SMEs). Income from selling the optimization software EASY.

CFD Simulations

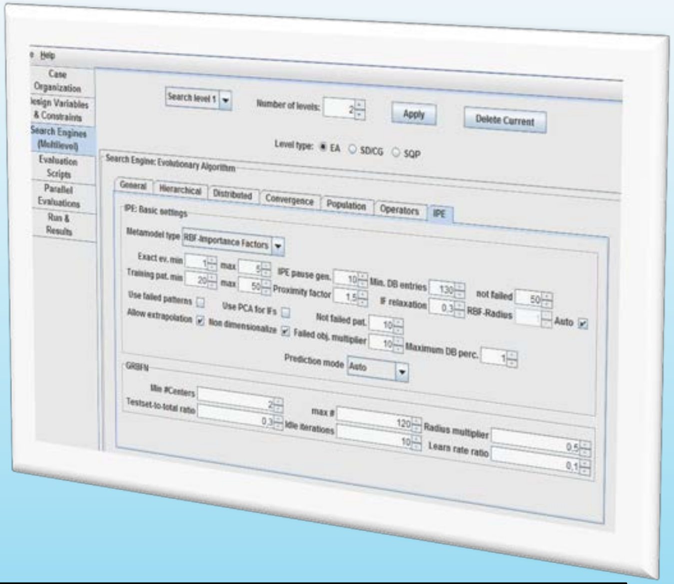


Reynolds-Averaged Navier-Stokes solvers for compressible or incompressible, steady orunsteady flows, based on either the GPU-enabled in-house code and OpenFOAM.

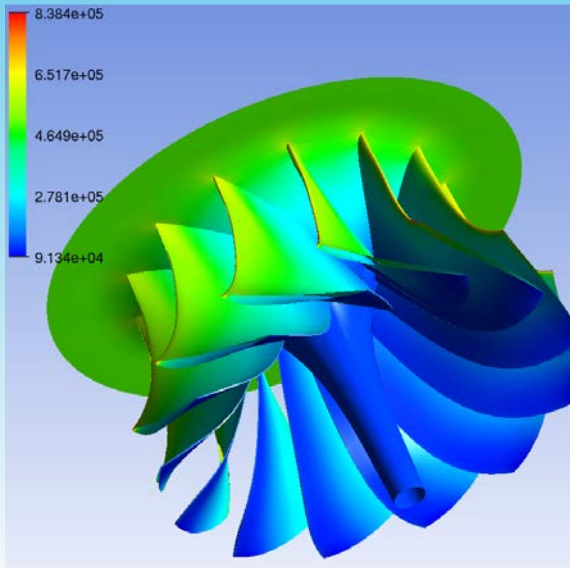
The Evolutionary Algorithms System (EASY)

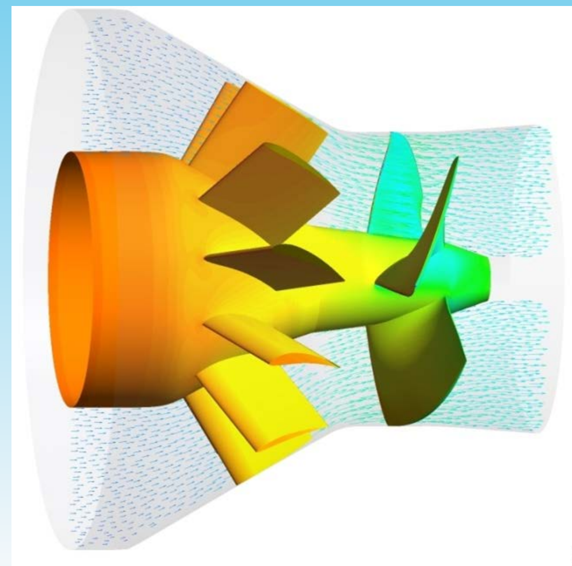
A generic-purpose optimization platform which accommodates any evaluation tool (CFD, CSM, etc) and is particularly suitable <u>for computationally expensive problems</u>, since it offers:

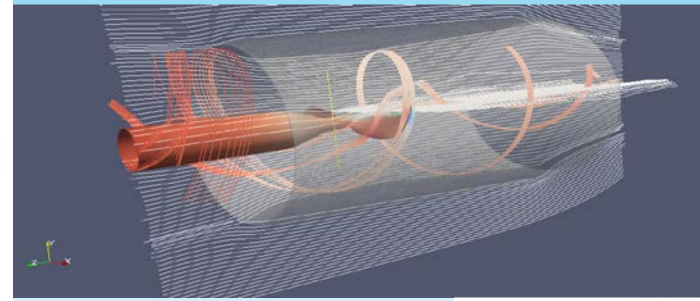
- Distributed EAs.
- Built-in surrogate evaluation models (metamodels – Metamodel Assisted EAs).
- Hierarchical schemes.
- Asynchronous evolution on multiprocessor platforms.
- Principal Component Analysis to enhance EAs and MAEAs
- Cluster & Grid computing.



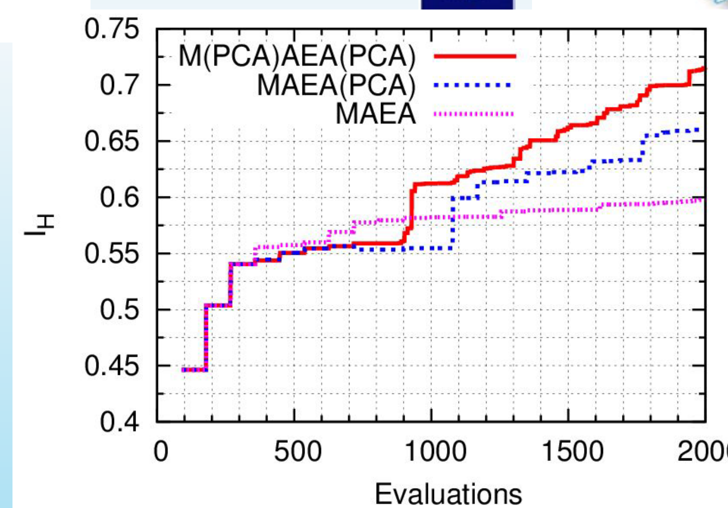
Optimization of hydraulic machines using EASY







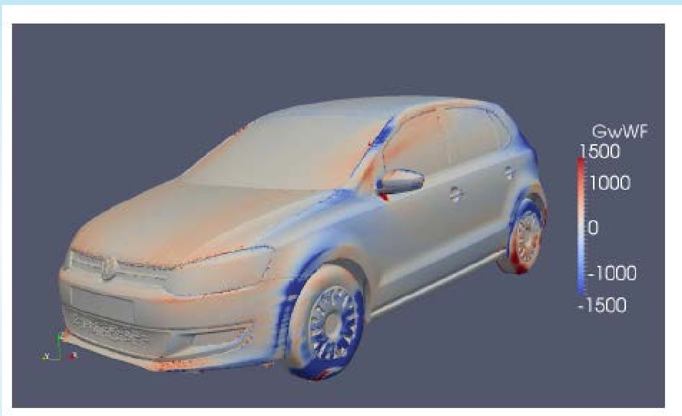
Design of the Francis runner, at 3 operating points with two objectives: (a) exit velocity profiles' quality and (b) uniformity of the blade loading and two constraints (head and cavitation). <u>372 design variables, in total</u> (with such a high number of design variables, standard EAs usually fail to provide a solution with an affordable computational time)



EASY has been purchased (open source) by Andritz Hydro and is currently used for the optimization of Francis, Matrix, Kaplan, Bulp, pump & pump-turbines runners, Pelton distributers and draft tubes coupled with in-house CFD tools.

Development of (Continuous) Adjoint Methods

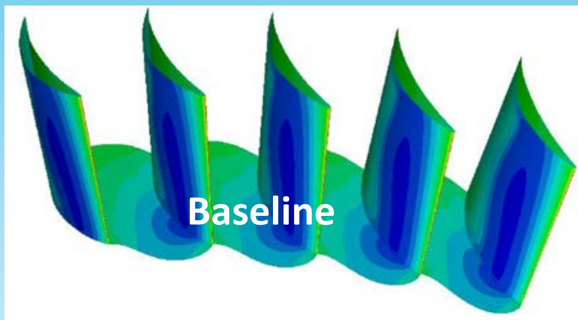
- For shape, flow-control, robust-design and topology optimization problems
- The first continuous adjoint methods to widely-used turbulence models.
- Development on the in-house codes and OpenFOAM.
- Automated s/w, including parameterization and morphing tools.

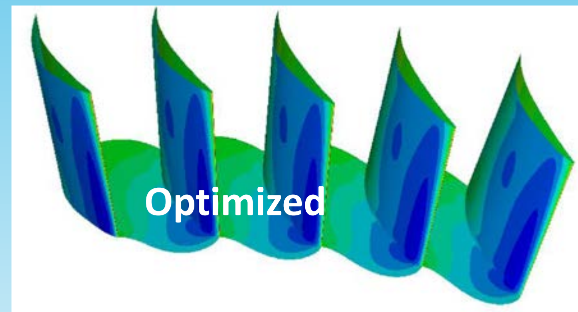


*The **Adjoint Method**, apart from supporting an optimization loop, provides the **Sensitivity Maps** (picture: Sensitivity Map of Lift on the Polo Car). This colored map helps the design to make decisions (blue: pull outwards, red: push inwards) in order to minimize or maximize the objective function.*

__Adjoint-based Sensitivity Map__ on the pressure and suction side of a __Francis turbine__, for the control of the exit swirl profile and cavitation.

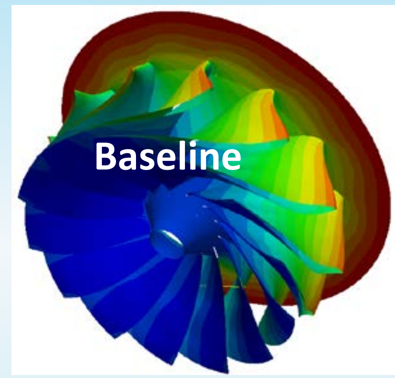
Adjoint-Based Optimization - Applications

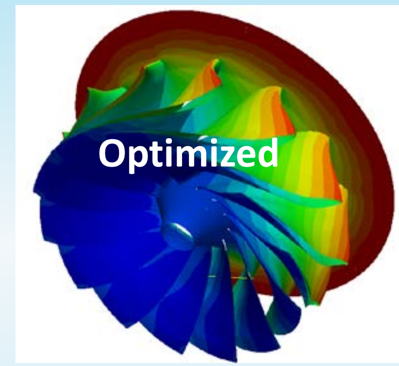


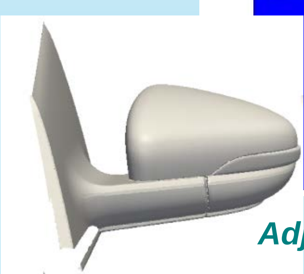


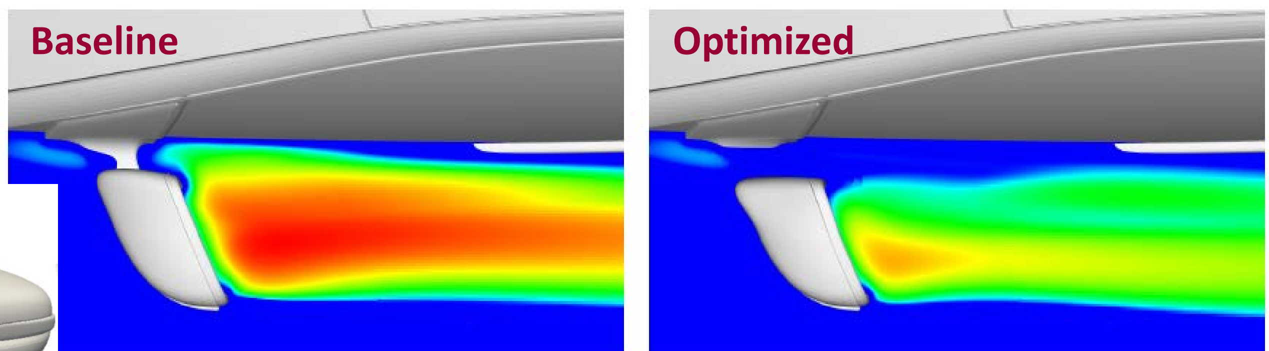
Adjoint-based ***Shape Optimization*** *of a 3D* ***compressor row****, for minimal viscous losses, with geometrical constraints, using the continuous adjoint method.*

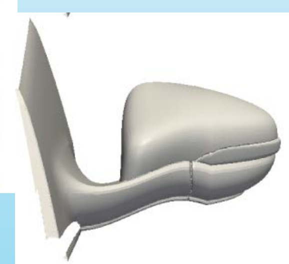
Adjoint-based ***Shape Optimization*** *of a Francis runner to reduce/eliminate cavitation.*





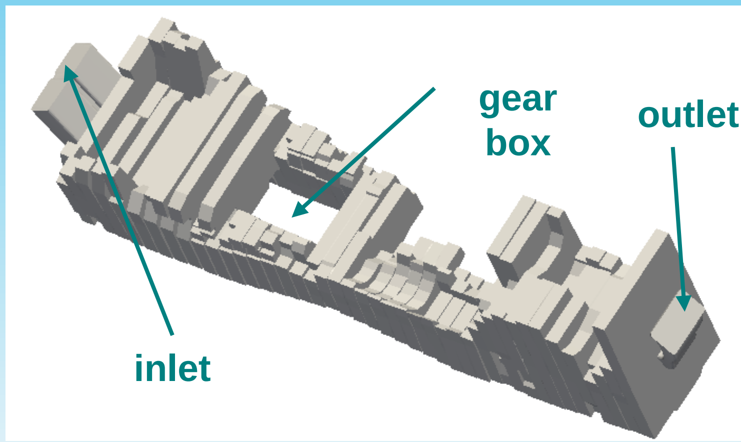


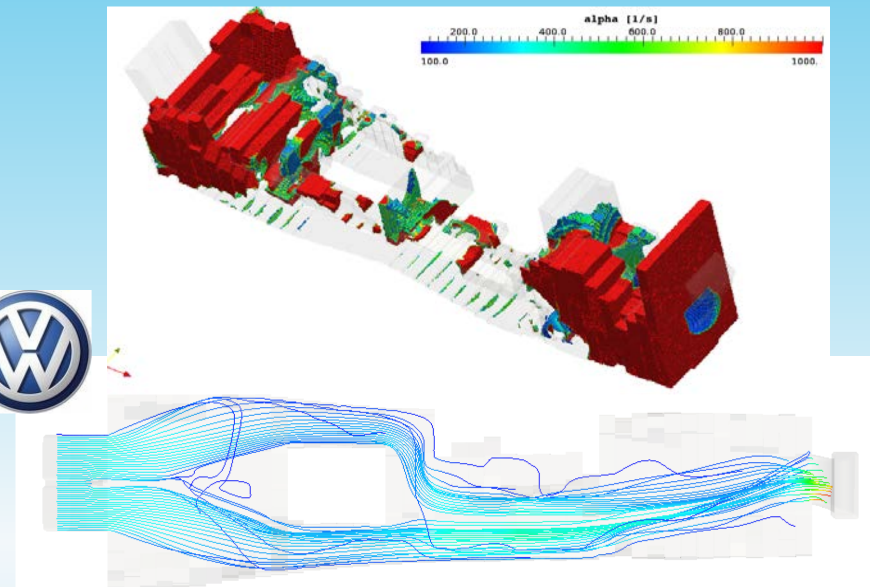




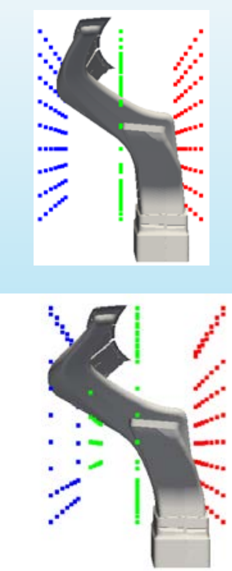
Adjoint-based ***Shape Optimization*** *of the side-mirror of a passenger car in order to reduce the noise perceived by the driver.*

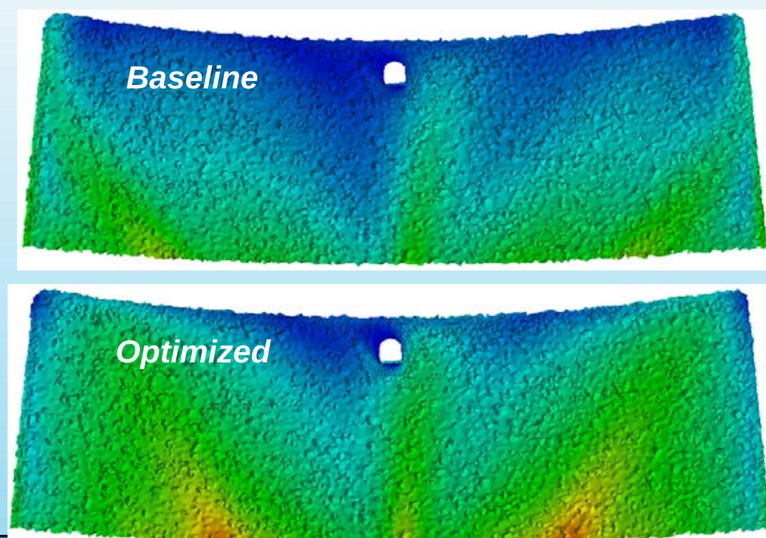
Adjoint-Based Optimization - Applications





***Adjoint-based Topology Optimization** solidified parts of the flow passage in this HVAC duct of a passenger car, for minimum total losses (losses reduced by 45%).*





***The shape optimization** of the defroster nozzle, part of the HVAC unit of a TOYOTA car, led at a new shape with improved defrosting performance. The optimized geometry complies with manufacturing and topological constraints and reduces the time needed for defrosting the windshield by 15% .*

Laboratory of Thermal Turbomachines National Technical University of Athens (LTT/NTUA)

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https://www.ltt.ntua.gr/index.php/en/contact