Advanced Simulation Tehnologies and Testing Methodologies Applied in the Design and Development of Aero Gas Turbine Engines

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ADVANCED SIMULATION TECHNOLOGIES AND TESTING METHODOLOGIES APPLIED IN THE DESIGN AND DEVELOPMENT OF AERO GAS TURBINE ENGINES

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Abstract

An overview of Gas Turbine Engine Development, KAVERI, the power plant for the Light Combat Aircraft (Tejas) and a description of the validated numerical tools, aerothermodynamic and mechanical test facilities of the Gas Turbine Research Establishment (GTRE) are presented. The KAVERI engine compressor, combustion system, turbine, analytical tools, blade heat transfer, exhaust system, Integrated Nozzle Actuation System (INAS), Non-intrusive Stress Measurement System (NSMS) and thermal paint tests are described in detail.

Introduction

Gas Turbine Engines combine disciplines from all major engineering sciences in a most interactive, interdependent and optimized way. Due to ever increasing performance levels and higher thrust to weight ratios, the engine components should be designed to perform better and withstand higher temperature levels with longer life. Hence the aerodynamic loadings, materials, cooling techniques, structural components, mechanical systems, combustors, afterburner and nozzles are designed to the limit of our present know-how. To achieve this, sophisticated methods, design tools, state of the art measurement tools in the rigs, thermal painting techniques, component testing and engine developmental testing are required.

Up until the end of the 80's, the design of Gas Turbine Engines was based on an empirical approach, requiring a large number of tests for substantiation. By the end of the 80s, the fast- expanding power of supercomputers enabled the introduction of the computing codes that had been developed into the design process enabling justification to minimize test compliments.

The present paper discusses the state-of-the art CFD, Thermal and Structural tools and sophisticated measurement methodologies adopted by GTRE in the successful design of Kaveri engine comprising of the fan, compressor, combustor, turbine and afterburner.

Three-Dimensional Methods

During the preliminary design phase of an engine, several technological solutions are possible. Hence high-speed tools are essential to indicate the trends, and take the first options before finalizing the engine cycle. Examples include axi-symmetrical throughflow methods for turbines and compressors, and one-d methods for combustor and afterburner.

As soon as the design phase has been launched, the use of 3D-design methods become essential to take into account the complexity of the flow pattern or geometry (3D blade assemblies). This is a standard approach and GTRE has adopted the same in the design and development of Kaveri engine.

Mechanical Engineering

The structural component deflections, growths, stresses and vibratory modes which influence the design are evaluated using 3D Finite Element analysis models simulating the engine operating environment. In-house codes are used for processing FE results and lifing.

Thermal Engineering

While an initial approach using a simplified model makes it possible to determine the gross temperature levels encountered by the various parts, 3D methods are used determine the thermal gradients and further analyze the behavior of the parts during the detailed design.

Validation of Software and High Performance Computing

The commercial software used for analysis of the engine components is shown in Fig.1a-1c. These software and in-house developed preliminary design and analysis

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software are validated through rig and engine level test measurements. These software are loaded on 32 processor IBM P690, 32 processor PACE 32 and 8 noded HP high performance parallel computers along with high end workstations.

Fan and Compressor

Design and Analysis

GTRE has been using the 3D Reynolds Averaged Navier-Stokes CFX code in which the turbulent phenomena are represented as a temporal average by means of sophisticated models (k, ε, ω, etc.), for the aerodynamic analysis. Kaveri engine fan and compressor are optimized using CFX code applied to steady flows. CFX code is capable of solving flow through a series of fixed and rotating blade rows. Various realistic interfacial boundary conditions between these blade rows are implemented in the code. The code is capable of predicting the aerodynamic behavior in multistages as in the three stage fan and the six stage compressor, Fig. 2. The velocity vectors in the compressor [1] are shown in Fig.3a. These results are useful in not only optimizing the profiles but also for adapting the blading to the flow produced by the upstream blading. The modern compressors are subjected to increased aerodynamic loading and the small scale effects such as blade tip radial clearance, leaks through walls etc which are to be predicted . Fig.3b shows the quantification of the influence of tip clearance allowing the fluid escaping from the pressure side to suction side inducing an eddy which reduces the compression efficiency.

Detailed stress analysis has been carried out for the most critical operating condition on the fan, HPC and disks (Fig.4) in order to meet the structural integrity and life requirements using ANSYS Finite Element Software (material and geometric nonlinearity models used). Fig.4c shows the strain gaging carried out during engine tests on aerofoils and validation Campbell diagram generated from measured data. The possible resonances, flutter and related structural dynamics issues have been identified and solved through extensive design iterative studies.

Combustion Chamber and Afterburner

Design and Analysis

State-of-the-art combustor and afterburner systems incorporate high-end technologies for successful performance. Quite a few technological issues have been sorted using the advanced analytical tools (CFD, Thermal and Stress) and testing to achieve the design intent during the development of successful combustor and afterburner systems.

Combustor

Figure 5 shows the 3-D CAD model of the combustor that has been developed [2,3]. It comprises of pre diffuser, dump diffuser, flame tube and atomizers, the other important components being swirler, flare / heat shield, etc. 3D RANS Fluent code with chemical kinetics has been used for the for CFD and Conjugate Heat Transfer (CHT) Analysis to arrive at the final design meeting the aerodynamic performance. Some of the components modified during the development are the flare, atomizer, and liner hole configuration. Fig. 6 shows the metal temperatures obtained from the CHT analysis. The CFD and CHT analyses are used in conjunction with a parametric study to produce a design which minimizes the temperature non-uniformities inside the chamber resulting in the intended Radial Pattern Factor (RPF) and Circumferential Pattern Factor (CPF), Fig.7. It may be noted that the analyses includes all the geometric features consisting of cooling holes as the prediction of heat flows is an essential element in the sizing of the walls.

A detailed stress analysis has been carried out for the most critical operating condition in order to meet the structural and life requirements using MSC/NASTRAN [4]. Fig.8 and Fig.9 shows the estimated Von Mises stress distribution for the casing and liner respectively. The operating stresses have been compared with the properties of Inconnel SU-718 material and it has been found that the CCOC meets twice of design pressure condition with wall thickness provided. Using a detailed sub-model of CCOC, the casings life has been estimated to be greater than design target.

Afterburner

Figure 10 shows the layout of the afterburner which has been successfully developed and tested in stand-alone mode at CIAM test facility to estimate its performance in terms of light up, combustion stability, combustion efficiency, total pressure loss and metal temperatures. In these tests, extensive instrumentation has been carried out to characterize the afterburner completely. To arrive at the final geometry, CFD [5,6] has been extensively used in modifying the inlet struts, Fig.11, to deswirl the flow in diffuser, the combination of which has reduced the total pressure loss. The other components that have been modified are the v-gutter, the fuel-injection system and the Pilot ignition System.

The jet pipe liner and jet pipe casing temperatures have been predicted using a validated one- dimensional heat transfer model, which accounts for radiation and convection from hot gas. Empirical correlations have been used for the heat transfer coefficients and adiabatic film temperature estimation. Using this model, liner metal temperature has been predicted for life calculations at various engine-operating conditions.

The buckling strength [7] of the Jet Pipe Liner has been improved by addition of circumferential stiffened rings, pin supports and corrugations and a best configuration, which meets the buckling and weight requirements for the maximum load condition, has been achieved. This has been achieved through an Eigen value-buckling analysis. A Finite element shell model of the baseline configuration as shown in Fig.12 has been generated using MSC/PATRAN. The Liner has been subjected to aerodynamic pressure and thermal loads. As a part of optimization study, various design iterations have been carried out wherein the buckling strength has been chosen as the primary objective function along with weight as the other important design aspect. The structural integrity test for checking the strength of the liner has been carried out on a stand alone afterburner at CIAM, Russia and was proven to be capable of withstanding the flame out condition at the most severe point in the flight envelop.

High and Low Pressure Turbines

Design and Analysis

In a similar way as for the design of fan, turbine design also uses the 3D Reynolds Averaged Navier-Stokes CFX code. Several design modifications were carried out for the High Pressure Turbine Stage to meet the design intent. The mach number distribution is shown in Fig.13.

It should be noted that in an HP turbine, the temperature of the airflow is several hundred degrees higher than the melting point of the material. Therefore the major effort focus is on areas such as cooling technologies and thermal barrier coatings. Turbo/Fine of Numeca has been used for CHT analysis of the stage. The temperature distribution on the pressure and suction surfaces is shown in Fig.14.

To improve the efficiency of the LPT [8], the geometry has been modified and the design intent could be achieved using CFD, Fig.15 to Fig.17.

Detailed stress analysis has been carried out for the most critical operating condition on the LPT and disks (Fig.18) in order to meet the structural integrity and life requirements using ANSYS Finite Element Software (material and geometric nonlinearity models used).

LPT Damper Design Modification

As a part of improvement to design LPT damper design modification has been carried out using non-linear transient analysis and design modification has been implemented. The design modification is evaluated in state-of-the art dynamic spin rig and implemented in the engine. Fig.18c shows the results of damper evaluation test.

Full Engine CFD Simulation

Although CFD can provide essential information to aid the physical understanding of complicated flow fields, it is generally the requirement to design/modify geometry that drives the application of CFD. When applied to an individual component, the physical understanding gained from CFD is often able to guide design improvements to that component. However, engine is generally characterised by the interaction of a number of components, such as multistage turbomachinery; the intake and the fan rotor; the combustor and the upstream diffuser, and, so on. A truly optimal design/analysis can only be achieved by accounting for all the component interactions. GTRE, in collaboration with CIAM [9] analysed the whole engine ie., inlet of fan to the exit of CD nozzle, using the Euler equations with losses mimicking the viscous flows. The analysis of the whole engine, Fig.19, has shown that the mass flow and hence the thrust improves by opening the HPT nozzle throat. This was carried out on the engine resulting in higher thrust.

Rotor Dynamic Analysis Using Samsef Software

Kaveri Engine Integrated 3D Rotor Structure is modelled using Shell and Volume elements. Coupling between rotor and structure is simulated using FOU3, MEAN and BEARing elements. Campbell Diagram is generated for both LP and HP synchronous critical speeds. Intersection of 1X line with forward synchronous whirl lines are taken as critical speeds. Horizontal lines in Campbell diagram represent axial or torsional modes. Mode shape corresponding to each critical speed is generated (Fig.20). Strain and kinetic energy distribution in the system is generated corresponding to each critical speed. The energy distribution determines the type of the mode, its excitability and structural damping participation.

Health and Life Monitoring of Engine Components

Typically rotor and stator parts of a Aero Gas Turbine Engines experience fluctuating load intensities due to the continuous changes of speed, pressures and temperature levels as demanded by the flight spectrum which in turn leads to fatigue damage of the components. The service life of the components is dictated by the damage contributions of this fatigue loading. In order to ensure that the components that are in service have not exhausted the equivalent declared safe life, it is essential to monitor the damages incurred in these components. An algorithm has been developed by GTRE to relate the engine parameters to the stresses in the components, corresponding to each point in the engine operation profile. The algorithms have innate capability to decompose the major stress cycles into micro cycles and further calculate the cumulative damage of each component. This program analyses the engine performance data after every engine run and keeps updating the data on life consumption and residual life of various components. With this customised life monitoring practice, GTRE is able to keep constant track of the cumulative damage fraction of the critical components such as fan rotor, compressor rotor, low and high pressure turbines (Fig. 21a).

Non-intrusive Stress Measurement System

As a blade health monitoring tool NSMS has been in extensive use in GTRE. This technique uses the time of arrival of blade data from rotating and vibrating blade to characterize the blade dynamic behavior. Fan, Compressor and Turbine stages of KAVERI engine have been instrumented for NSMS. Indigenous processing module is developed for data reduction and this customization has helped immensely enhancing the capability of the present system.

As a tool NSMS has provided valuable inputs for defect investigation of LPT rotor blade. The problem of resonance in the rotor blade was identified and design change was carried out to mitigate the problem. The effect of Combustor pattern factor induced excitations and its influence on blade vibration is also studied using NSMS. Fig. 21b shows the blade amplitudes as measured during acceleration and deceleration of resonance phenomena. NSMS is also used a tool for identifying a cracked blade during engine run.

Integrated Nozzle Actuation System (INAS)

The Integrated Nozzle Actuation System [10,11] is comprised of an engine driven, servo controlled, variable displacement, pressure compensating piston pump capable of positioning four nozzle actuators in response to an aircraft command. The control system consists of an outer control loop driving an inner closed loop pump displacement controller. The pump flow is applied to the actuators to generate a load slew rate and the position of the load is fed back to close the position loop.

The servo pump hanger angle is driven by an electro-hydraulic servo valve that is sourced from a pressure regulated, filtered, and temperature controlled makeup pump supply. The makeup pump also supplies differential flow for the actuators, servo pump case cooling flow, and makes up all internal leakage flow. A spring loaded, accumulator type reservoir maintains the required makeup pump inlet head to ensure complete filling under all environmental conditions, Fig.22. A servo pump inlet selector shuttle valve is used to differentiate and maintain the inlet side of the servo pump at a pressure required for complete filling and cavitation prevention.

An isolation module is located between the servo pump and the actuators to lock the actuators in a fixed position when commanded. The command energizes a pilot solenoid that closes an isolation valve dead-heading the rod or retract side of the actuators. Thermal relief is provided for the dead-headed actuators. Cooling flow is supplied from the make-up pump through the actuator head and rod gland. The cooling flow is routed back to the charge pump through the isolation module via a flow orifice and then sent to the engine heat exchanger.

Thermal Paint Test

High metal temperatures tend to cause hot spots in turbine blades, nozzle guide vanes and combustors and hence temperature mapping assumes considerable significance [12] in component design. Full-field metal temperature (FMT) data can delineate hot spots, validate heat transfer analysis and facilitate selection of internal cooling arrangements for blades and vanes. Thermal painting techniques involves spraying a thin layer of paints on component surface and these thin layers do not disturb aerodynamic or heat flow paths. Thermal paints are organic chemicals blended with special additives and they undergo irreversible colour change as a function of surface temperature. Change in thermal paint colour manifests in form of bands called the isotherms or constant temperature lines. With painstaking efforts, GTRE developed comprehensive thermal paint test procedures covering the entire gamut of paint calibration, surface preparation, thermal paint application, testing with painted engine modules, data deduction and heat transfer analysis. These thermal paint test procedures, after the necessary proof-of-concept tests on rig components, were subsequently employed by GTRE for capturing the temperature data from high pressure compressor, combustor (Fig.23), turbine rotor, internally cooled turbine blades, nozzle guide vanes, turbine casing and CD nozzle.

Outer skin temperatures corresponding to mean section of turbine rotor blade [13] are evaluated through heat transfer analysis and compared with thermal paint test results (Fig.24). Close agreement between the test and analytical results demonstrates the accuracy of thermal paint data.

Test Facilities

In order develop advanced Aero Gas Turbine Engine, it is essential to build up test facilities. The gas turbine components could be tested under simulated engine conditions to validate the design concepts. These are the facilities for testing the engine components like compressor, combustor, turbine, afterburner etc and facilities for the full scale tests. Fig.25a and Fig.25b show the test facilities in GTRE.

Kaveri Engine

With the aid of all advanced tools, GTRE has successfully designed the Kaveri engine, Fig.26, and achieved the design goals.

Conclusions

The know-how acquired by GTRE over the last 25 years with tests and numerical modeling of the gas turbine components is presented. With the sophisticated CFD, thermal and structural tools along with the rig and engine test bed measurements, GTRE is able to design, and develop the advanced Gas Turbine Engine.

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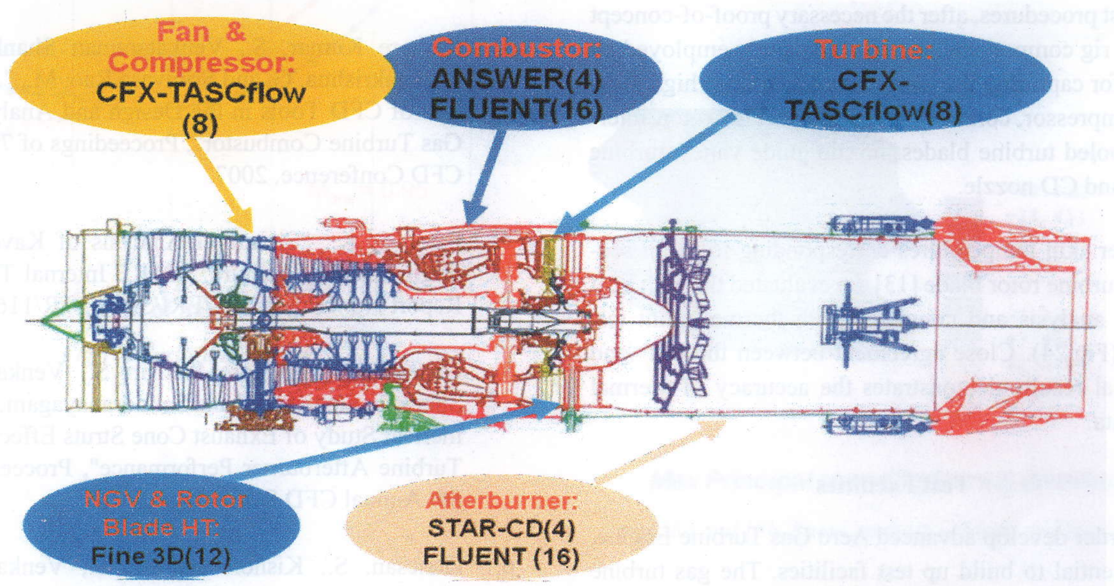


Fig.1a CFD software used for different components of Kaveri Engine (Number in brackets shows the parallel node licences)

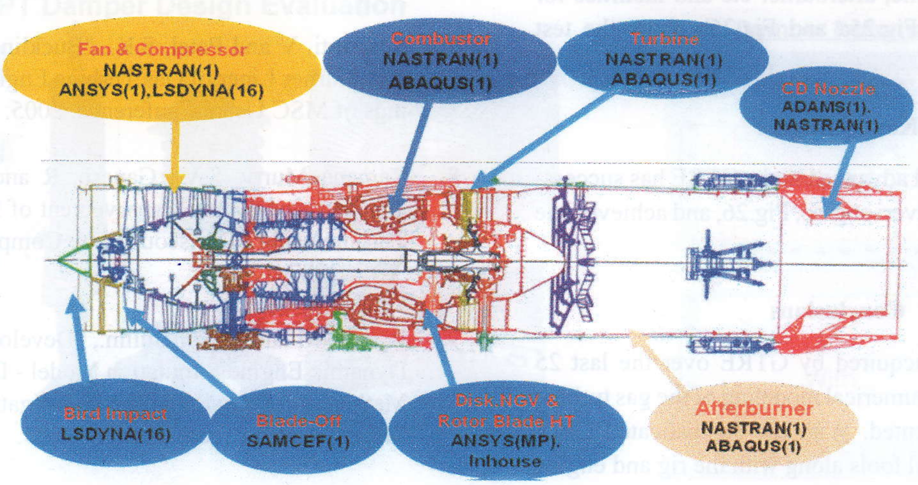


Fig.1b Structures software used for different components of Kaveri Engine (Number in brackets shows the parallel node licences)

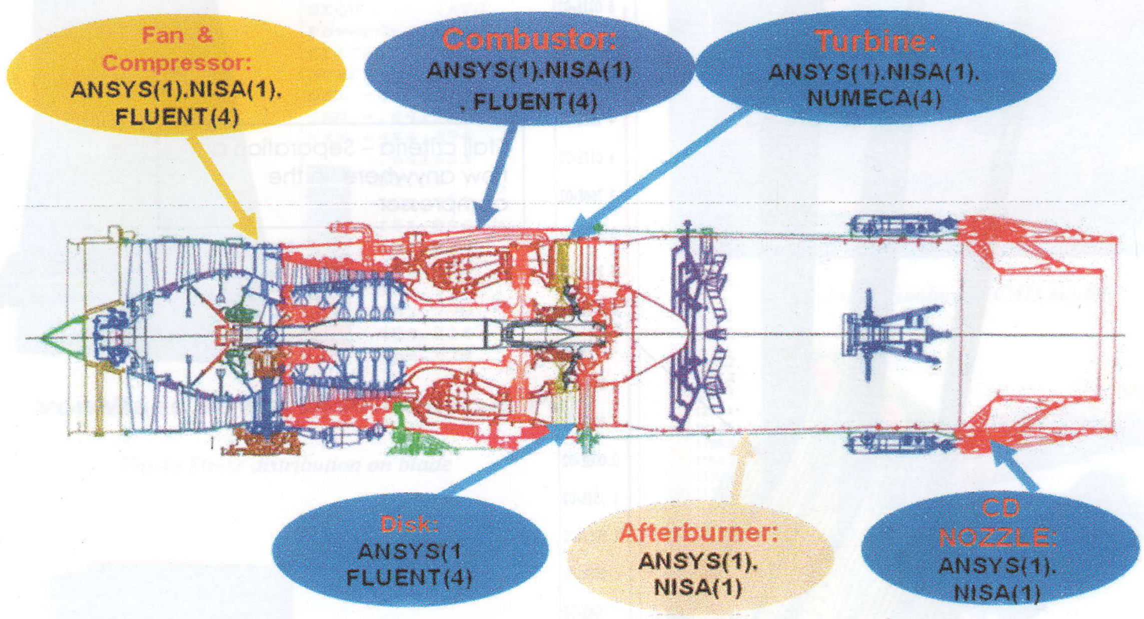


Fig.1c Thermal software used for different components of Kaveri Engine (Number in brackets shows the parallel node licences)

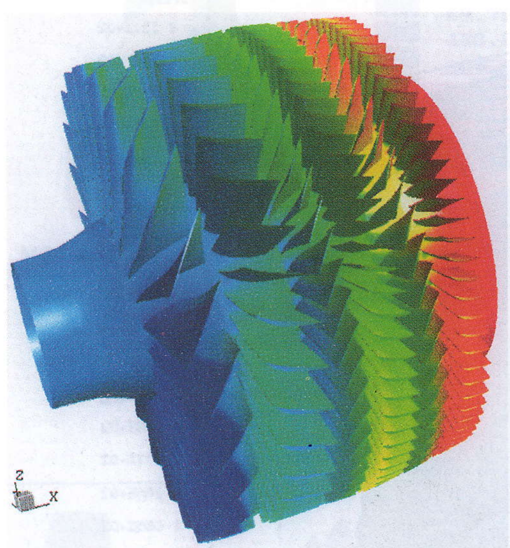


Fig.2a Three stage transonic low pressure

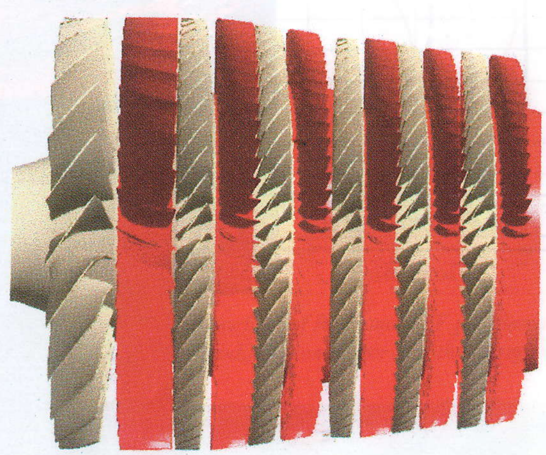


Fig.2b Six stage transonic high pressure compressor

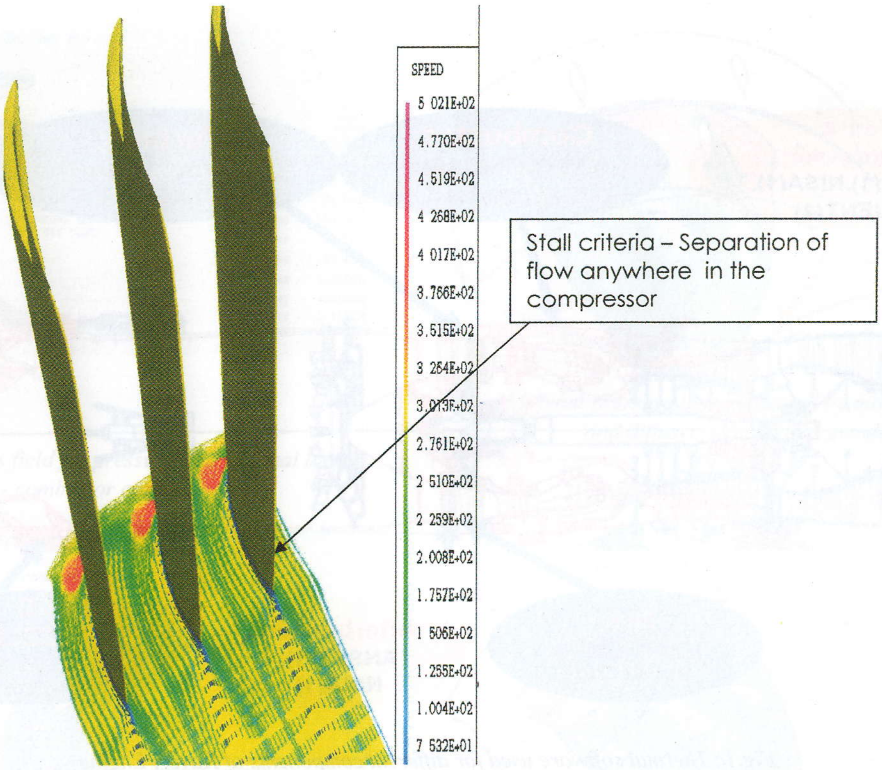


Fig.3a Separation of flow in the compressor

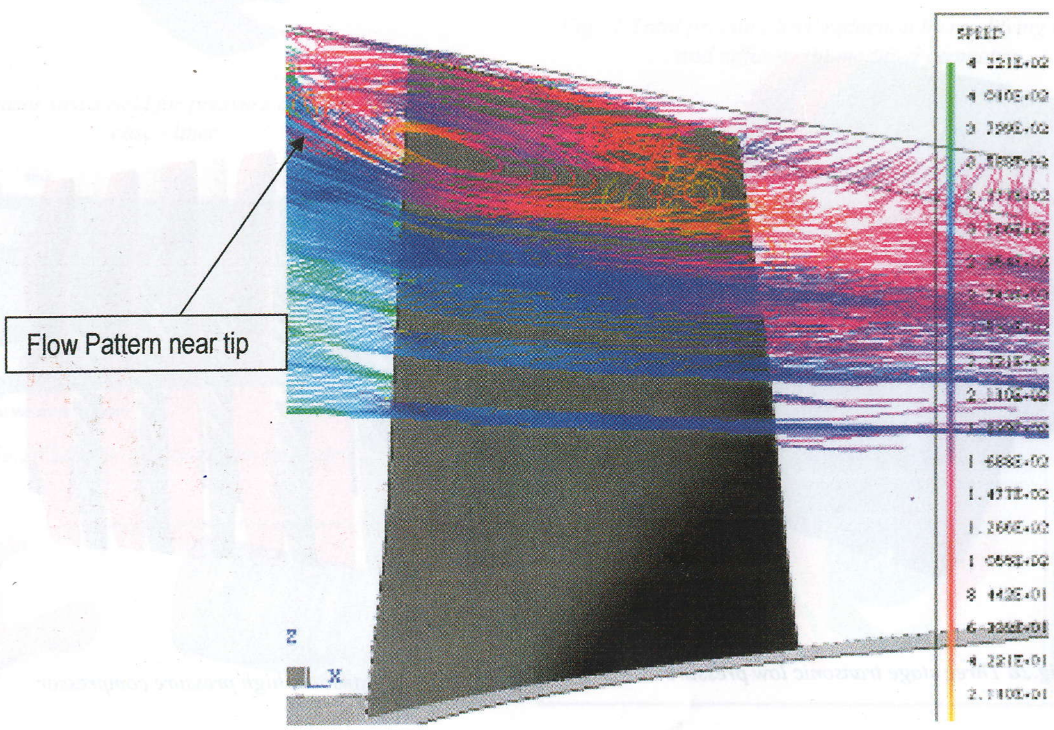


Fig.3b Flow pattern near the tip with radial clearance

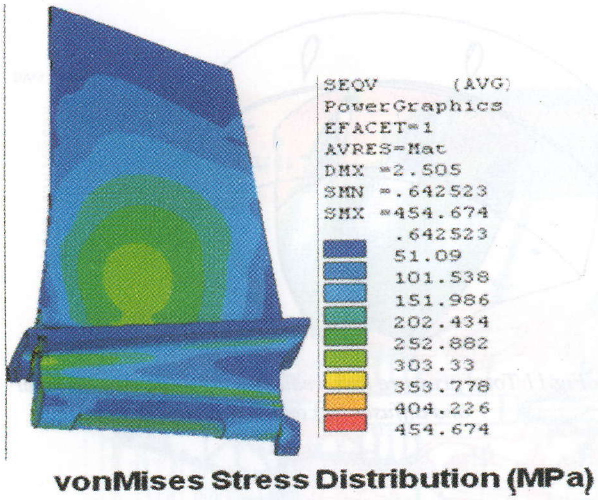


Fig.4a Stress distribution on blade

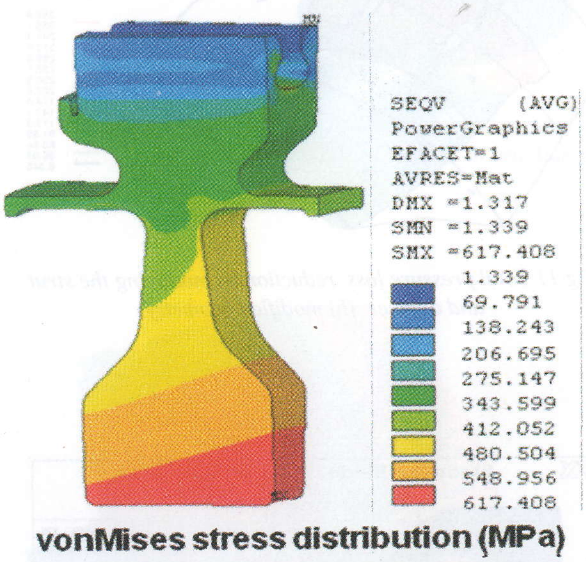


Fig.4b Stress distribution on HPC disk

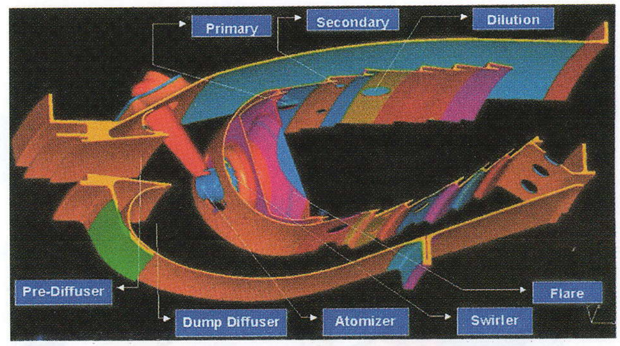


Fig.5 Combustor CAD model

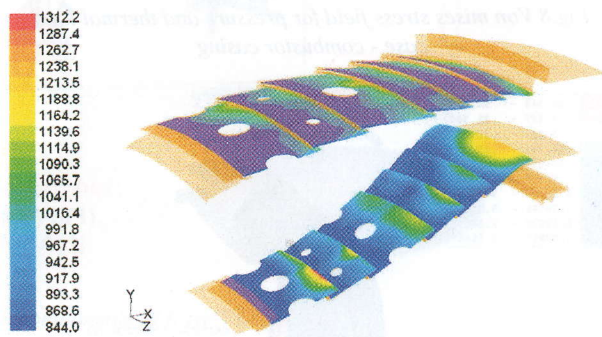


Fig.6 Liner metal temperature contours obtained through a CHT analysis

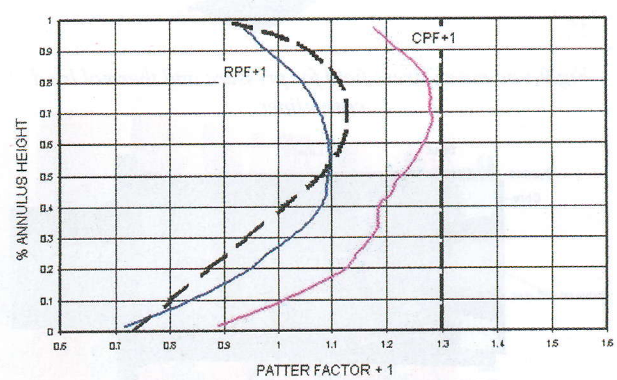


Fig.7 Comparison of RFP and CPF profiles obtained for the modified combustor and the design intent

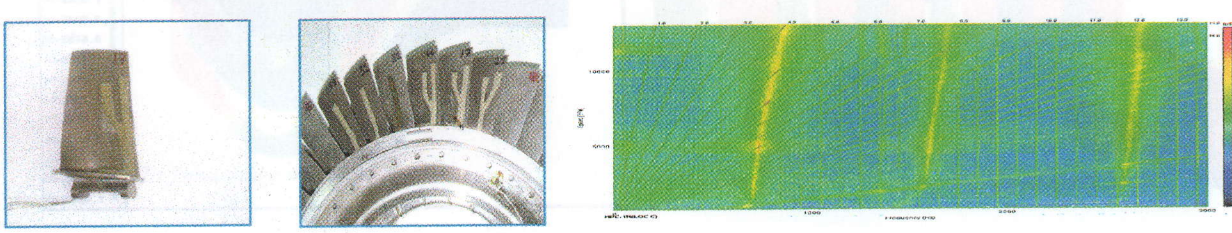


Fig.4c HPC-IR - single blade and blades in assembled condition and campbell diagram

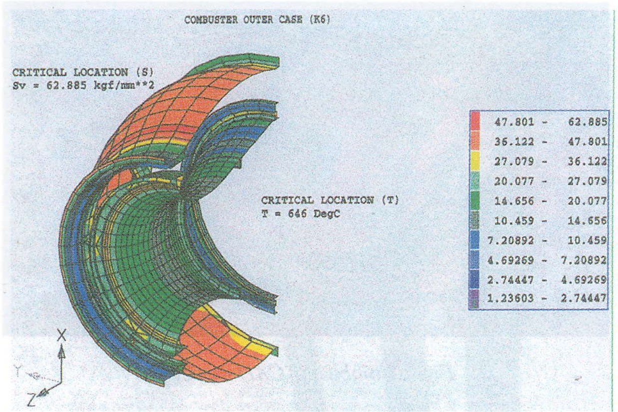


Fig.8 Von mises stress field for pressure and thermal load case - combustor casing

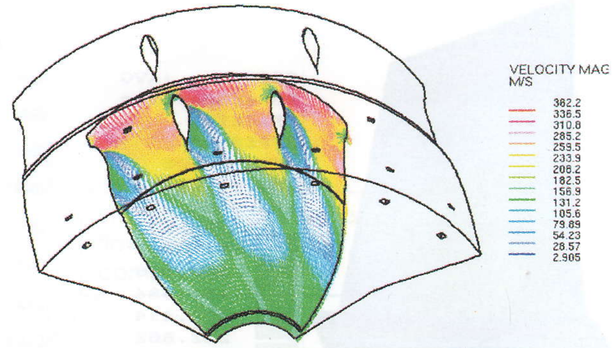


Fig.11 Total pressure loss reduction by modifying the strut and diffuser (a) original geometry

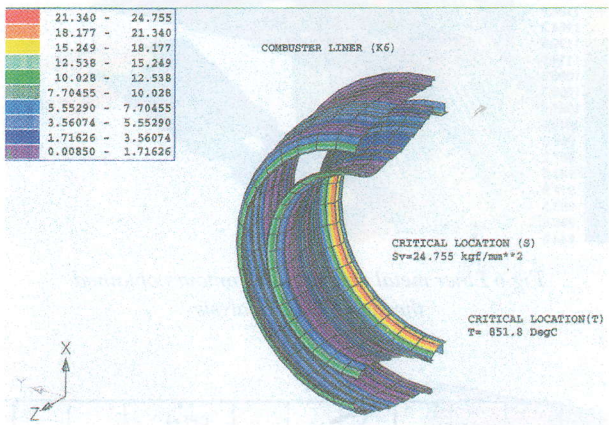


Fig.9 Von mises stress field for pressure and thermal load case - liner

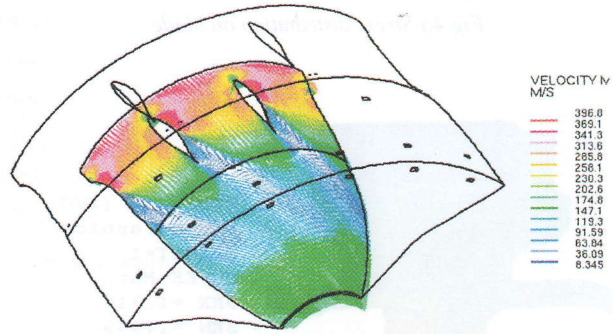


Fig.11 Total pressure loss reduction by modifying the strut and diffuser (b) modified geometry

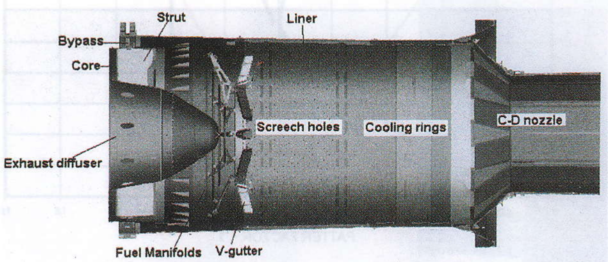
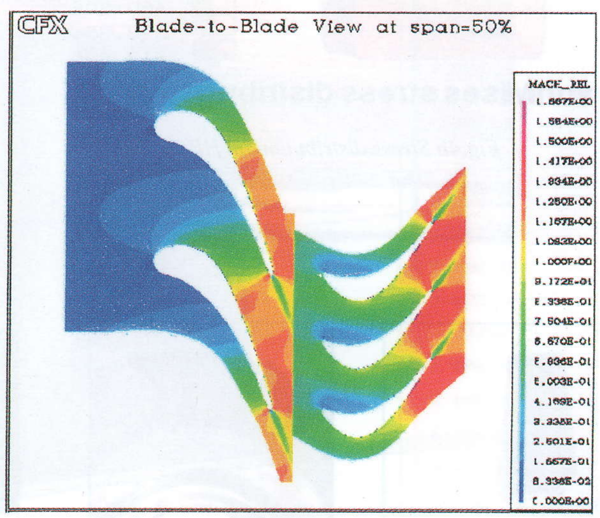


Fig.10 Layout of afterburner geometry



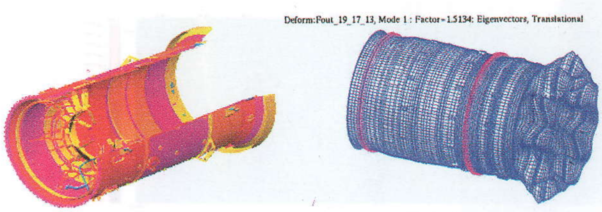


Fig.12 Buckling analysis of jet pipe liner

Fig.13 Mach number distribution at mean section

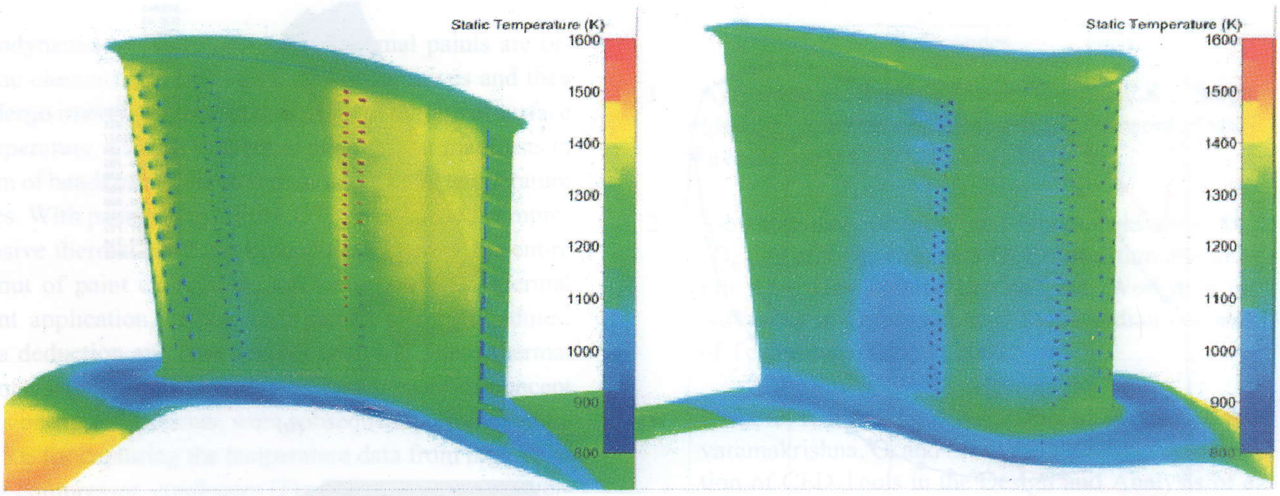


Fig.14 Temperature distribution on the nozzle guide vane on the pressure and suction surfaces

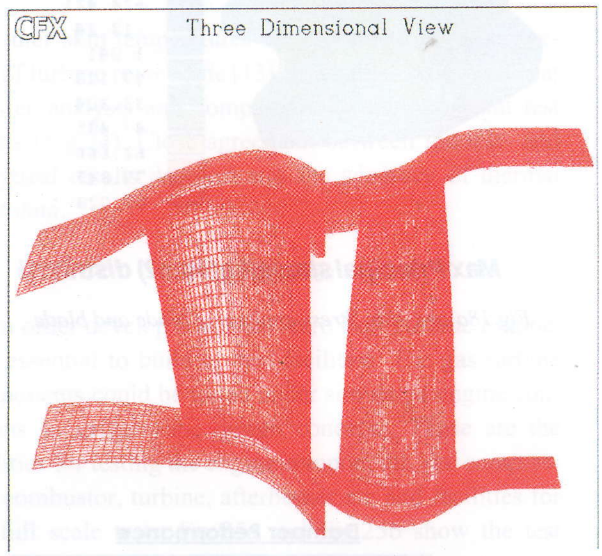


Fig.15 Three D computational grid

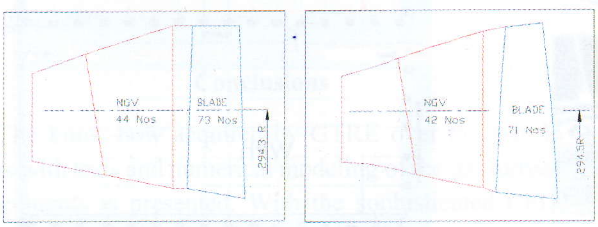


Fig.16 Original and modified flow paths

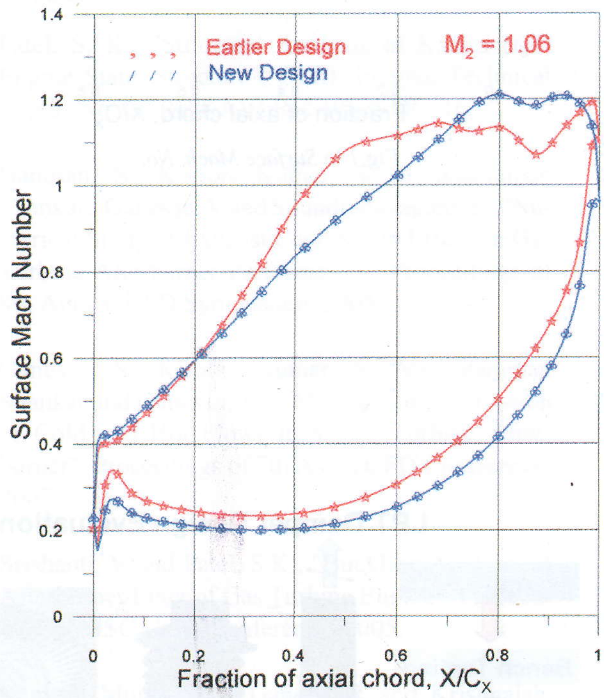


Fig.17a Surface Mach No. vane rotor

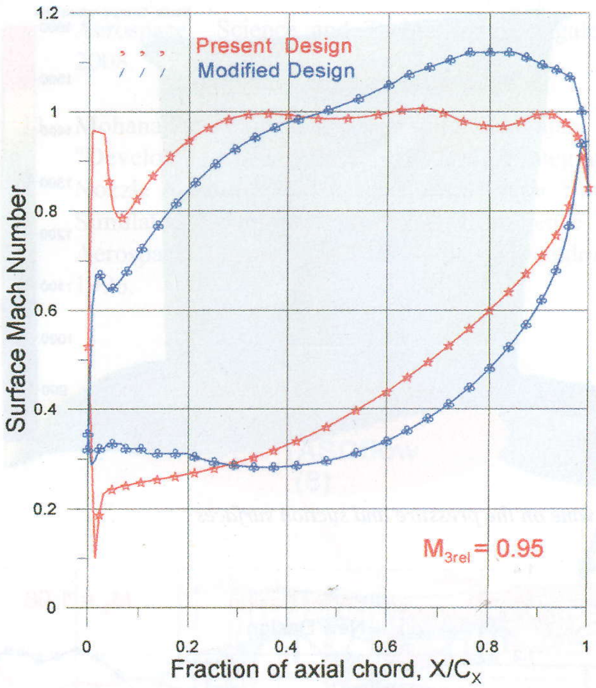
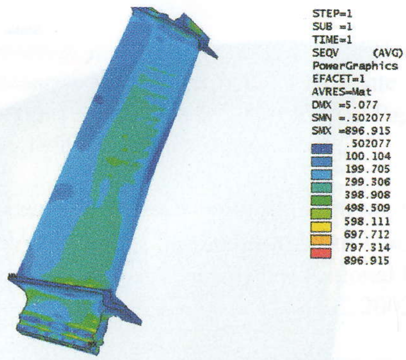


Fig.17b Surface Mach. No.



(a)

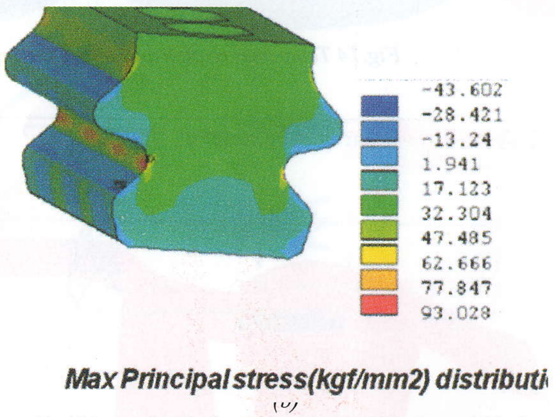


Fig.18a and 18b Stress analysis of blade and blade

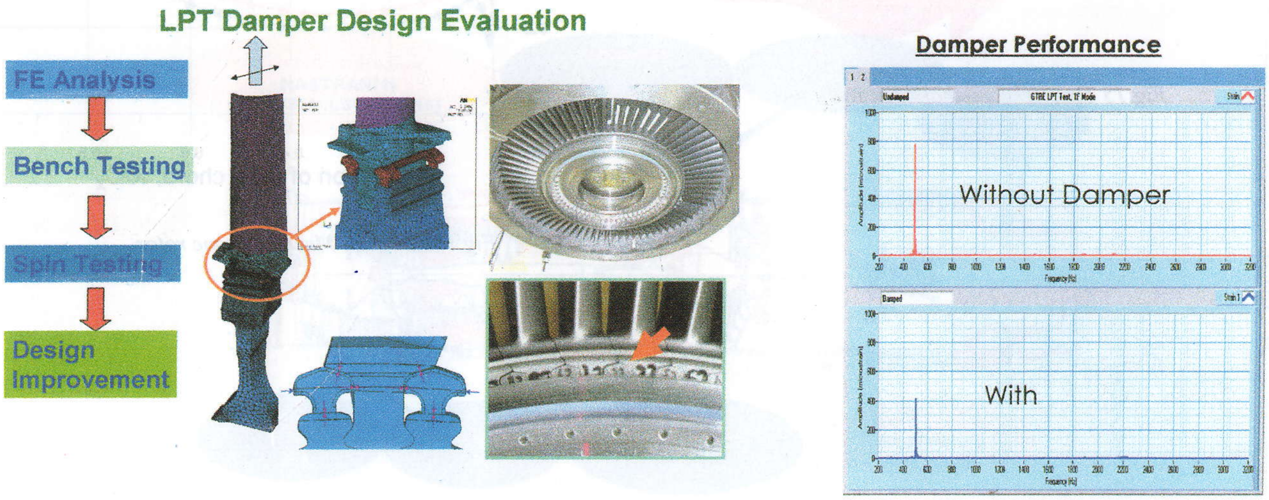


Fig.18c LPT damper performance evaluation

Fig.19 Total temperature distribution

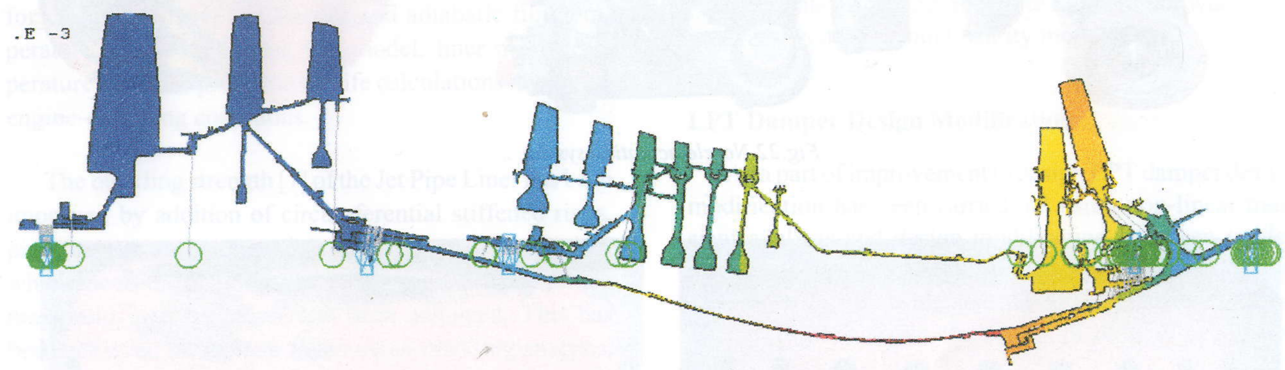


Fig.20 Mode shape corresponding to each critical speed is generated

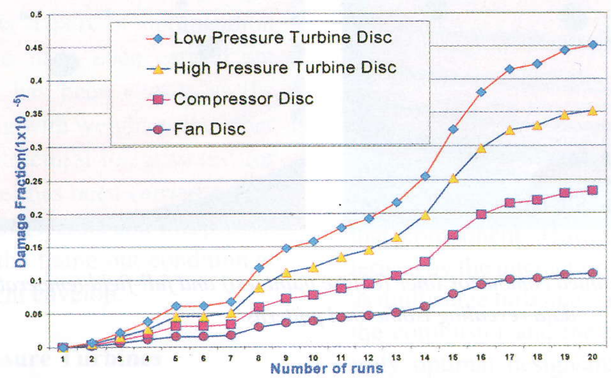


Fig.21a Fatigue life monitoring of Kaveri Engine components through engine computer

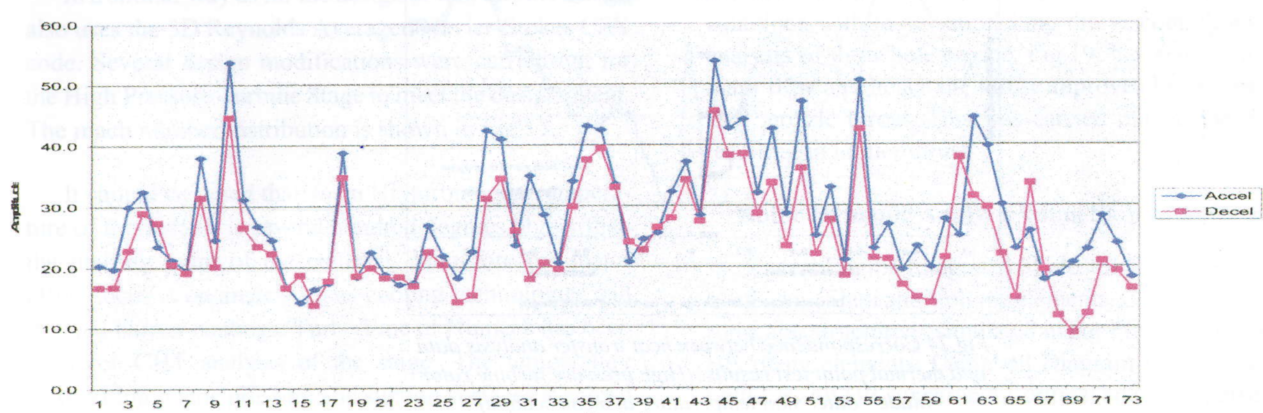


Fig.21b Vibratory amplitudes measured during engine run using NSMS

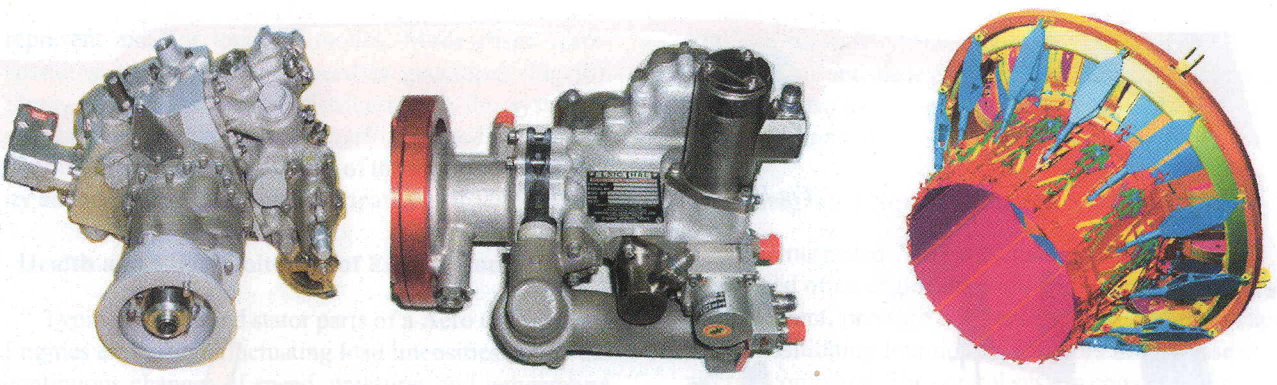


Fig.22 Nozzle actuation system

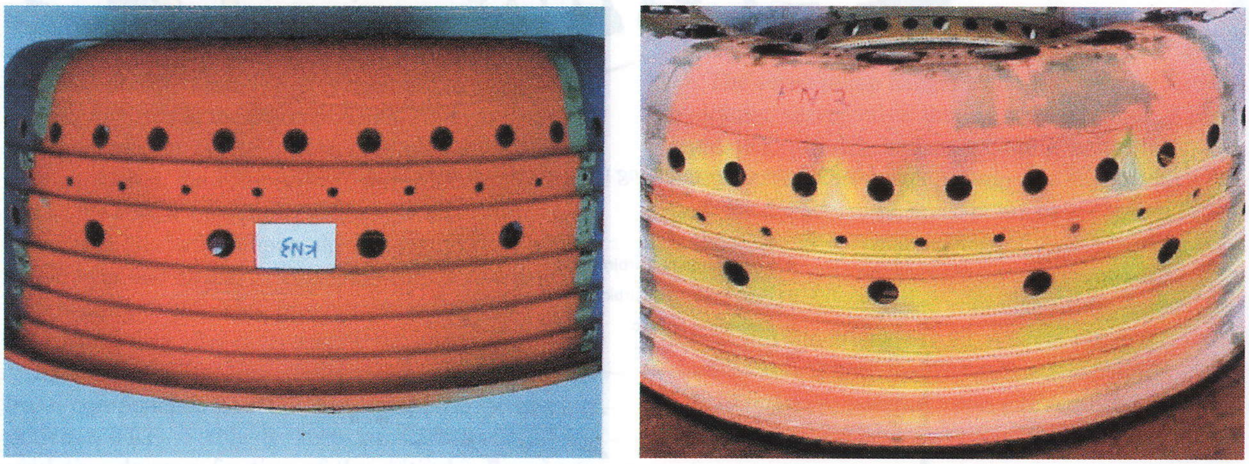


Fig.23 Thermal painted combustor liner (before paint test) and full-field temperature data revealing isothermal patterns

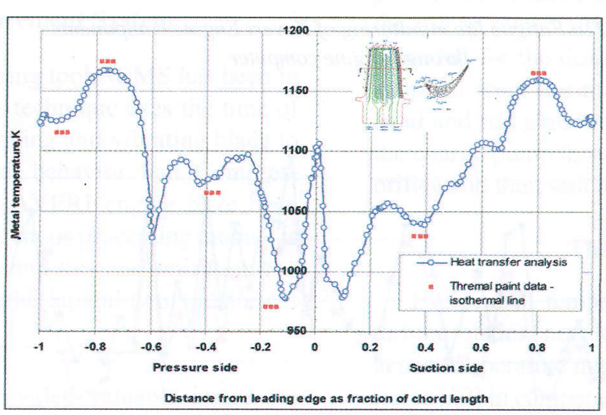


Fig.24 Correspondence between heat transfer analysis data and thermal paint test results. (High pressure turbine rotor blade - outer skin temperature at mean section)

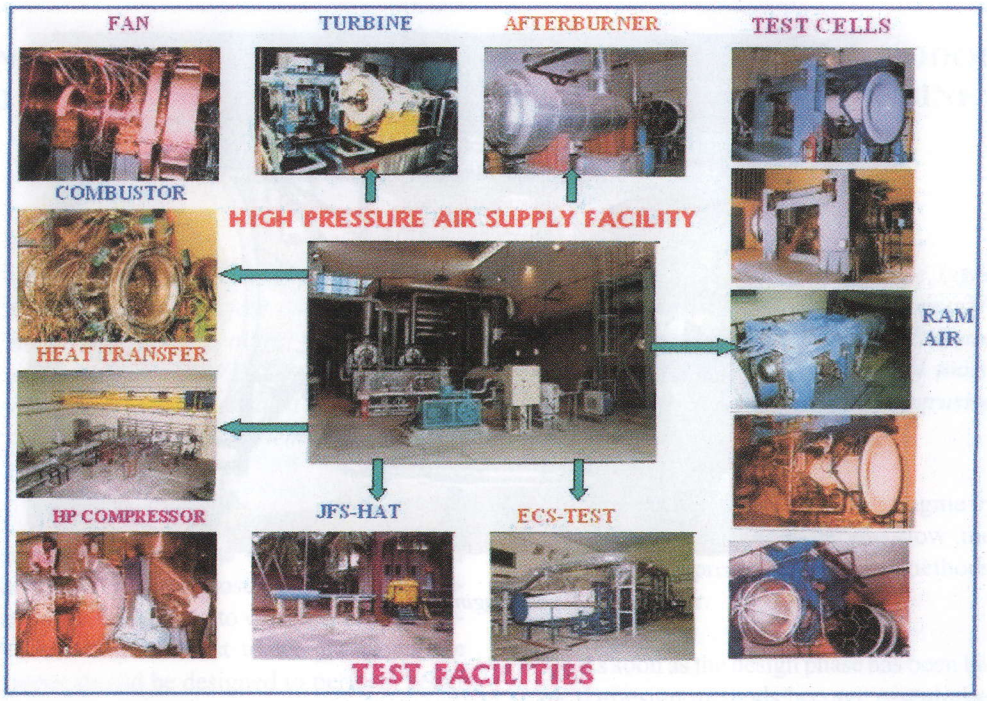


Fig.25a Aerothermodynamic test facilities

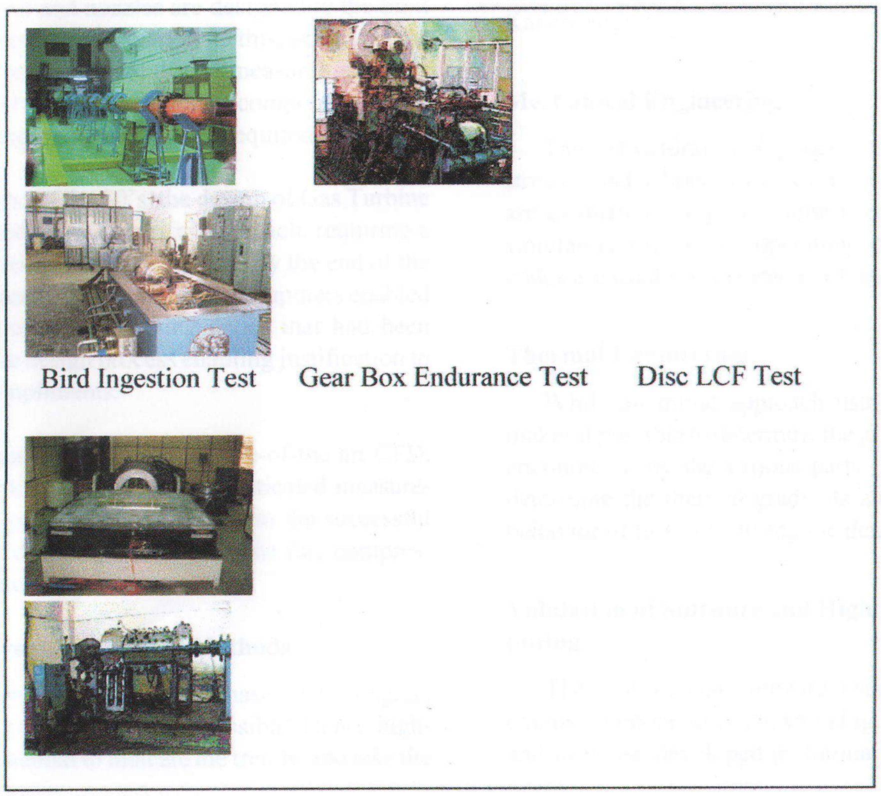


Fig.25b Mechanical integrity and lifting test facilities

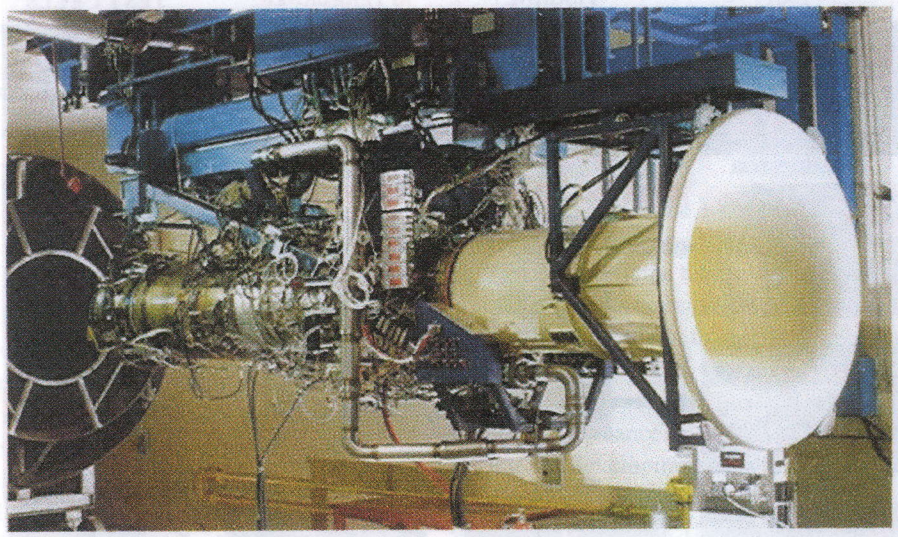


Fig.26 Kaveri Engine on Test Bed