Recent Developments in Structural Design Aspects of Aircraft Engines

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PROLOGUE

The first Indian Institute of Technology was set up in independent India in Kharagpur, a major industrial center in the country in early 1950's under UNESCO cooperation. Professor Kraus from Germany built the department of Mechanical Engineering in initial years and in 1956, Professor Bindu Madhav Belgaumkar was appointed as the first Head from India. The department made rapid strides under his leadership and brought the Institute to a world class in a short period of time. He retired in 1970. It is a great honor for me to deliver this lecture in his memory, being the longest student associated with him ever since 1960 during his active career in IIT and subsequently till 1989 when he departed from this temporary abode of planet earth. Many of us, his students and his colleagues admire him and remember him even today; I would like to state few of those reasons given below, from which we can set our academic and industrial engineering goals.

- Professor Belgaumkar graduated from Banaras Hindu University, a premier Institute of Engineering in pre-independent India – while being a student, he answered the call from leaders of independence movement, particularly Mahatma Gandhi – it was told that he took nearly six years to complete his studies; despite being a brilliant student and that he went to jail during his student days. From then, no-one recalls seeing him in any dress other than white home spun khadi.

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- Despite entering later half of forties, he went to France to do advanced research in Electrical Analogies for Vibration Problems in early 1950's from Victoria Jubilee Training Institute in Bombay and published research papers – this has earned him the coveted Headship of Mechanical Engineering in Kharagpur.
- Professor Belgaumkar built the department meticulously, in an era of very little engineering base in the country, set up some of the most advanced laboratories of world class, particularly in Vibrations, Tribology and Mechanisms and in several other areas, Experimental Stress Analysis, Material Testing, Hydraulic Machines and in the areas of thermal engineering, production technology, industrial engineering …
- While many Heads of the departments take shelter under the administrative responsibilities, he led the teaching programs by always taking at least 15+ hours of teaching, tutorials and laboratory classes.
- Professor Belgaumkar even in his 50's, has been very bold to study and introduce new courses in curriculum, e.g., Vibration and Shock Isolation, Random Vibrations and Noise, Nonlinear Vibrations … and trained students to the world class who can easily compete with the best universities in the advanced world.
- He loved to teach undergraduate classes and encourage students to do free thinking rather than mugging, through special examinations, quiz tests, surprise tests, discussions, seminars – he never left any stone unturned and exhausted all avenues in imparting the training to students. One has to see his board work, how clean it is and how large he would draw his diagrams and explanations on the board.
- Professor Belgaumkar trained young teachers many of them trained through him became responsible to develop the state of art laboratories in other IITs that followed from Kharagpur and occupied key positions in India and abroad.
- In an era, when it is not clearly known what is involved in Masters and Doctoral programs, despite himself being none, he guided several Masters theses and then boldly initiated doctoral programs – I was the first one to receive the doctoral degree under his care in Design Engineering in the country.
- He has always believed that travel and visit to other higher educational institutions is a must for anyone to grow in their career and be able to impart education to others; I was one of the several students who went through this routine – personally he saw me go to one of the best institutions in England and made sure that I will submit for a D Sc degree – this he did even after his retirement, that is how he bonded himself with his students.
- Professor Belgaumkar looked apparently harsh and always demanding very high standards in work – but all of us who were associated with him knew he was the softest at heart, all his outward appearance was only towards keeping us on feet and ready to do more work and pushed us to limits and cutting edge technologies.
- If there was one person in IIT Kharagpur who is punctual, it has to be Professor Belgaumkar, we can set our watches to be 7.00 AM when, we used to say, he steams in to the cycle stand with his bike.
- He realized the importance of scientific bodies and nurtured them well, e.g., Indian Society of Theoretical and Applied Mechanics; he spotted out world bodies, e.g., International Federation of Theory of Machines and Mechanisms and brought India into its map and in fact thanks to him, I was the signatory for the constitution of IFToMM at its inaugural meeting in Poland – he said you sign this document and grow this

organization in India, instead of doing it himself. That is how he loved his students and richly rewarded them with whatever was in his capacity. Today's AMM has its roots to IFToMM.

- I can go on and on; his contributions in those formative years of India are immense and not measurable. That's why we remember him on every AMM conference and I am honored this year to speak to this august body in his memory.

Professor Belgaumkar is a great visionary and he knew we have to bring mechanical engineering design to the core problems of the country, internal combustion engines, turbo machinery, power plants, etc. One of the areas he was obsessed with is Turbine Blade Vibration and its importance in all rotating machinery design. When I was young, I felt I was his victim and like an arranged marriage, I had to carry out his wishes on Blade vibration, when all that was known is Rayleigh's method for the fundamental bending mode. Now I know I am probably the luckiest person to have this match and immensely satisfied myself in developing something that became useful to the country at large. It is befitting to talk of this subject to day while remembering him and that's how I have chosen this topic.

1. INTRODUCTION

Charles Parsons' steam turbine of 1884 was hailed as "Vibration Free" engine when the world is getting accustomed to the limitations of reciprocating steam engines and the resulting vibration problems. The steam turbine made rapid strides with a phenomenal expansion: (1900's - 2 MW, 1920 - 50 MW, 1950 - 100 MW, 1970 - 1000 MW, 1980 - 1500 MW). Very soon, steam turbine blades and then the gas turbine, compressor and turbine blades, developed into some of the most worrisome vibration problems, which continue to be most challenging in the modern day turbomachine designs, limiting their life.

Frank Whittle tested the first aircraft jet engine W.2.B in March 1942, in his own words, *Frequency of turbine blade failures was becoming the latest technological barrier to overcome* – since then aircraft engines have seen major developments, the barriers have become more pronounced with light weight, high thrust military applications.

Professor Belgaumkar followed these developments closely at the end of II world war and the very first opportunity he had to get some work done on Blade Vibrations was through Professor K Laxminarayana, his student then, who performed vibration tests on compressor blade for his Master's thesis in IIT Kharagpur.

He then pursued further in this line of work and found me to be the slave for a doctoral program. He drove me subsequently further even after his retirement to continue working on blade vibrations. While most of the work to me initially was theoretical and experimental in nature, practical applications in this field came subsequently, QEII steam turbine blades, GTX engine blade programs and Narora steam turbine failure and recently Kaveri engine design. I will briefly narrate in this paper what is all involved in the compressor structural design of an aircraft engine, thanks to Professor Belgaumkar who had the vision of developing this subject matter more than four decades ago.

2. GENERAL CONSIDERATIONS IN MODERN AIRCRAFT ENGINES

A modern light weight and high thrust aircraft engine exhibited in Aero India 2003 Air Show in Bangalore is shown in Fig. 1 below.

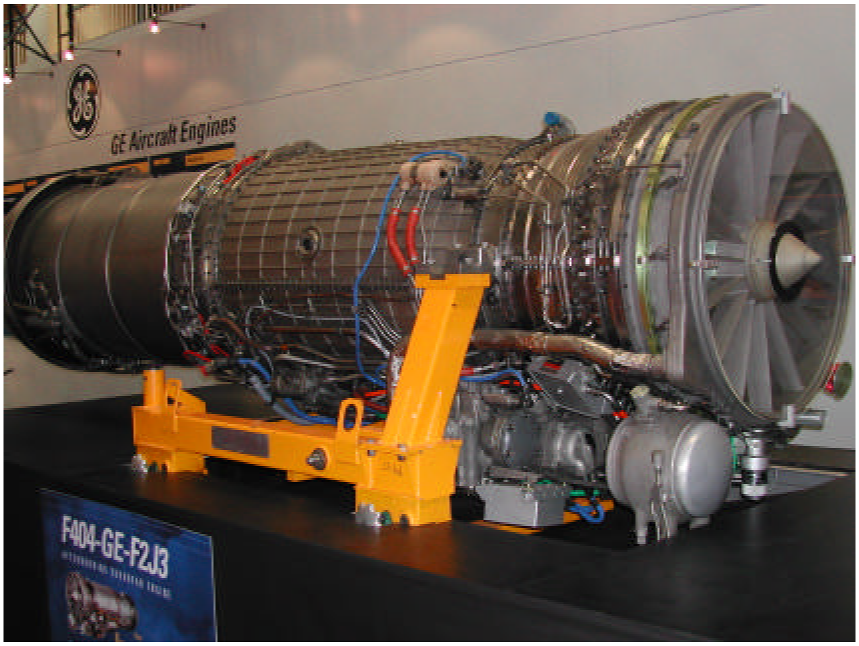

Fig. 1 A Light Weight High Thrust Air Craft Engine

Fig. 2 below shows a typical cross-section of a modern aircraft engine.

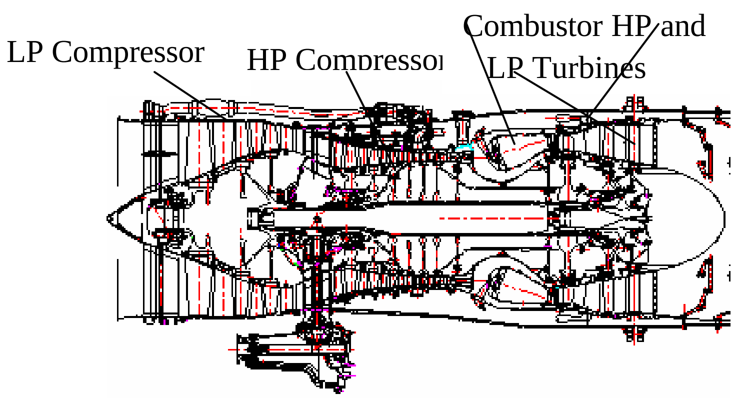

Fig. 2 Typical Aircraft Engine Cross-section

It primarily consists of a compressor, a combustor, a turbine and afterburner. The compressor takes in atmospheric air and compresses to a high pressure, which then enters a combustor where aviation kerosene is burnt to produce high energy gas at a high pressure and temperature. The turbine extracts the energy from these gases, drives the compressor and the exhaust gas gives the required propulsive thrust. The after burner is used to augment the thrust from the turbine exhaust hot gases at a very high velocity. To achieve high performance light weight engines, the compressor and turbine are split into two parts, one a low pressure component, running at a relatively lower speed and the other a high pressure component running at relatively higher speed. To conserve space and weight, the high pressure rotor is mounted on the low pressure rotor, giving what is known as a two-spool engine configuration shown in Fig. 2. The LP compressor and turbine are mounted on one inner spool and the HP turbine and compressor are mounted on the hollow outer spool. A state-of-art engine such as the one shown above is a highly complex piece of machinery requiring interdisciplinary approach in its design. The technologies involved primarily are:

- Aerodynamics
- Combustion
- Heat transfer
- Structural Analysis and Dynamics
- Rotor Dynamics
- Material Science
- Manufacturing technologies

2.1 Aerodynamics

Aerodynamics plays a significant role in fixing the airfoil shapes of the compressor as well as the turbine to obtain optimum performance. In advanced aircraft engines, axial flow compressors are preferred as against centrifugal compressors to achieve the desired compression ratio, so that a required amount of air containing oxygen is taken into the combustion chamber. Several stages are required for obtaining the desired compression ratio; they consist of rotors and stators to guide the flow path. There should not be any tip clearances to avoid pressure losses, and also make sure there is no rubbing. While the air is compressed in the compressor, the combustion gases expand in the turbine section giving away its heat energy. The turbine airfoils are to be suitably designed to achieve maximum work take off in each stage and aerodynamics plays a significant role here.

While designing the airfoils, we should ensure to avoid certain very harmful effects that may occur; they are aerodynamic instabilities – stall, surge and flutter. They place severe restrictions on the design of advanced engines.

Aerodynamics also plays an important role in fixing the unsteady forces that act on neighboring stages, which are responsible for severe vibrations and fatigue failures of blades. Besides the steady gas loads the non-steady periodic forces are to be determined to interact with the forced vibration analysis and stress evaluations under resonant conditions.

In the compressor stages, the compression of the air raises the temperature and the surrounding engine components get heated. Aerothermodynamics plays an important role in determining these temperature rises that form an input for structural analysis.

In turbine stages, the blades have to be cooled as they face combustion temperatures, particularly the first stage diaphragms and blades. Aero thermal analysis plays a significant role here.

2.2. Combustion

This is the heart of the engine; the compressed air and kerosene should be so mixed to provide the most efficient combustion. The hot gases at high velocity exiting the combustion chamber provide the total energy for the turbine to convert it to mechanical energy as well as provide the propulsion through the thrust of the high velocity jet. The combustion temperatures are very high and the design of the chamber walls poses maximum challenge. The walls must be continuously cooled by mixing with relatively cooler air and the flow path must be smooth to avoid any losses. The design of the chamber poses major challenges from computational fluid dynamics and chemical reactions within the flow.

When the engine starts, there is a sudden rise in temperature with the heat energy released in the combustion process. The heat is then transferred to the entire engine, rotating as well as stationary parts. Thermal expansion takes considerable time and the metal growths and the resulting clearances play havoc with the engine design. The relatively thin casing expands fast while the relatively massive rotors take time to reach steady state conditions – thus the entire engine takes considerable time to reach equilibrium. The thermal stresses are very high during the transient period and the clearances vary continuously between the casing and the rotor blade tips. While no clearances are desirable to contain gases in respective chambers and avoid tip losses, some clearance is essential to prevent any rubbing, which can be catastrophic for the engine. Thus an optimum situation should be arrived at during the startup and shutdown times as well as maneuver timings. This is a challenge in the engine design.

2.3. Heat Transfer

As mentioned in the above sections, heat transfer plays a very predominant role in the design of an advanced aircraft engine. Accurate prediction of temperature rises in the entire engine rotor and stator parts during the transient as well as steady operating conditions is an essential step to ensure a good performance of the engine. Several components such as combustion chamber walls, first stage diaphragms and turbine blades and in some cases the second stage, have to be cooled so that they can sustain the thermal stresses and avoid creep and resulting failures.

Heat may be transferred in three different ways, conduction, convection and radiation. While conduction is relatively simpler, convective heat transfer is more complex requiring the heat transfer coefficients to be properly assessed. In flow paths which are secondary, this is more complex. Computational fluid dynamics plays an important role in determining these heat transfer coefficients. Both conductive and convective coefficients are then used in mechanical analysis to determine the stresses and metal growths, both of which are significant players in the engine design as outlined above. The thermal stresses should be kept controlled to avoid creep and low cycle fatigue and the radial growths should be watched to make the clearances to allowable values for the engine performance and yet avoid any rub.

2.4. Structural Analysis and Dynamics

Ultimately, the engine is designed using structural analysis and dynamics. The engine carries several loads, driving shaft torques, blade loads, thermal loads, centrifugal loads etc., Each component, a blade, a disk, a rotor or casing amongst others all have to withstand steady loads and be within safe limits. Advanced engines, unfortunately operate under limits with optimum minimum weight providing maximum thrust. This translates to the components being subjected to extreme conditions of stress environment. Quite often several of these components, particularly blades and discs are subjected to yield conditions in certain stress raiser locations, e.g., notches, fillets. These components require elastic-plastic analysis and proper assessment of stress conditions. The design has to consider not only operating conditions, but also possible transient loads under maneuvers, over-speeds and some unlikely events such as a bird hit, blade loss, bursting of a disk amongst others. The engine should be capable of safe operation for short durations of such heavy shock loads before the aircraft lands safely.

A major aspect of structural design is to make sure of its integrity. Because of light weight in design and also manufacturability, the casings, disks etc., are joined using bolts at flanges, rabbets. They also separate in some cases chambers of different pressures and ensure no leakage of gas flow from one to another. The design of these joints poses quite a challenge to ensure that the stresses are within acceptable values around the local stress raiser locations such as fillets and at the same time allowing no possible separation under the extremely severe load transfer conditions.

All the structural components must withstand the extreme harsh thermal loads and high temperatures, particularly in the combustion area and the first stage turbine. They should be provided with appropriate cooling to ensure their integrity and sufficient life low cycle fatigue and creep.

The rotor and casing expansions under thermal and centrifugal loads under transient as well as steady state conditions decide the clearances available between them – they have to be carefully assessed to prevent rub as well as contain flow leakages.

A significant part of the design of the rotor system is their supports, viz., the bearings. The rotors transfer their steady loads through these supports to the frame and the engine mount. The deflection path should provide sufficient stiffness so that excessive deflections do not take place. The stiffness provided by these supports should also be sufficient to obtain the desired rotor dynamic characteristics.

The blades, disks, casings, support structure are all flexible elements and have several critical speeds within the operating speed range. They should be accurately assessed and detuned in all the possible speed ranges of the engine. They should be cleared from all per rev excitations as well as nozzle and vane passing excitations. Where they cannot be cleared, proper life estimation is to be made either by using stress based or strain based or fracture mechanics based approaches to guarantee a minimum time between overhauls.

2.6 Rotor Dynamics

The two spool rotor system supported in the bearings and the frame is on the whole, a very low stiffness system and has several critical speeds in the operating range. These critical speeds are to be detuned to ensure engine safety. The general practice is to consider the rotor alone and account for the support stiffness determined separately through a static stiffness analysis. This may be inadequate as the support stiffness and damping are speed dependent and adequate precautions should be taken in determining the overall system critical speeds. Sometimes a lower stiffness of the support may be useful in detuning the system.

The rotor system responds to any unbalance which is always present. The unbalance response at the critical speeds decides the severity and it has to be ensured that the rotor has sufficient life while going through these critical speeds during startup and shutdown periods as well as any maneuvers that affect these critical speeds.

The unbalance response of the system at operating speeds decides the whirling amplitudes, which are the largest at anti-nodal points. At these anti-nodal locations, the clearances will get affected thus making a rub possible. This rub should be avoided. Therefore, while assessing clearances as mentioned above, we should take into account the unbalance response whirl amplitudes. This should be considered under transient conditions at the critical speeds to ensure no rub takes place by considering the radial growths of bladed disks, casings and prevailing temperatures.

The rotor dynamics characteristics can be significantly affected by the nonlinearities in the rolling element bearings, spline joints and their influences may have to be taken into account where necessary. Seals in the rotor system may create instabilities and they should be also properly analyzed to avoid any unstable operating conditions.

Quite often, engine designers resort to squeeze film dampers to fight unbalance response whirl amplitudes at some critical speeds, which may not be avoidable in an optimum configuration. The squeeze film dampers are also nonlinear and a rotor dynamic analysis with these dampers becomes essential to evaluate the rotor dynamic characteristics properly.

Finally an unbalance response calculation at critical speeds and operating speed give the mean and 1x dynamic loads transferred through bearings and the stationary part of the engine should withstand these loads and accordingly designed.

2.7 Material Science

Significant developments in the engine design have taken place because of material science advances, high temperature materials, ceramics, coatings, single-crystal blades amongst others. The higher the temperature of the work medium, higher is the efficiency and efforts are always in this direction to extract as much work as possible in improving the engine performance.

Another recent advance in the modern engine designs is the adoption of composites that are light in weight; these are used in the low temperature zones of the engine, e.g., low pressure compressor.

In the present context, this is not a subject of investigation, it is only necessary to keep in mind these advances in future designs.

2.8 Manufacturing Technologies

Though these are not of direct interest in the design analysis of the present context, it is necessary to keep in mind the importance of manufacturability, assembly and influences of heat treatment and welding.

There are several other things that go with the engine, e.g., gear drives for auxiliaries, piping, pumps etc. and condition monitoring amongst other things. These are not considered here.

3. STRUCTURAL ASPECTS OF LP COMPRESSOR

While basic principles of structural, thermal and flow design aspects are well established and numerical methods developed to deal with these governing equations, the major impediments have always been the ability to model intricate geometries and handle the size of the number of finite elements or cells that one would like to adapt in obtaining the desired accuracy of response results. With the advances in computational facilities, it has now been possible to realistically handle complex situations – linear and nonlinear, elastic and plastic, contact or no contact, subsonic or supersonic, complex convective flows, steady state or transient conditions, instabilities, which hitherto could be studied only by relative simple models. Simultaneously, numerical codes to deal with these complex problems have now become a reality, making the life of a design engineer simple by concentrating on the engine safety aspects rather than developing the necessary tools to solve these problems. I would like to illustrate few case studies where such in-depth analyses are made while dealing with an LP compressor module.

The fan casing which houses the low pressure compressor module, also designated sometimes as fan of the engine, is supported by front frame and middle frame of the engine. The fan has three discs and is mounted on low pressure spool in the middle frame and the front frame bearings. The casing carries all the stator vanes. There is an anti-icing system in the front frame which circulates hot air to prevent formation of ice at high altitudes.

This compressor usually has three stages, the first stage has wide chord twisted long blades and the disc is mounted in the bearings located in the front frame. Discs I and II, Discs II and III are joined together through bolted joints; Disc II is joined to the low pressure spool which is supported in bearings located in the middle frame. Disc III is left overhung. Disc I supporting wide chord blades is made of a bifurcated construction to take the centrifugal, thermal and gas loads under steady and transient conditions and should also withstand the vibratory loads having sufficient life as stipulated by time between replacements and overhauls. All the blades on discs should in the most critical condition be just about to rub, so that the clearances between the blade tips and the casing are minimized to get the optimum compressor performance. Rub should also be prevented during the cross-over of a rotor critical speed when large whirl amplitudes are expected. Finally, net weight should be made minimum, which brings limiting conditions of operation taking all these aspects into account.

Each blade undergoes several modifications in an optimization procedure. On all the discs design changes are to be made to achieve optimum geometry for minimum weight and structural integrity. For the optimum geometry, the peak von Mises stress should be within yield and the radial and axial displacements play an important role in the design as mentioned earlier.

There are several bending, torsional and coupled frequencies that can be critical to the engine. A Campbell diagram gives the critical speeds (the vertical axis represents the natural frequencies – actual values not shown). Per rev, nozzle passing, strut passing and difference frequency excitations are to be considered. Usually, fundamental and second harmonic of these excitations are significant and a decision has to be made to identify which crossings are more important and need to be corrected. This is best done by estimating the life for each of these resonances.

The life of a blade can be estimated by using High Cycle Fatigue theories, Local Stress-Strain approach or Fracture Mechanics theories. The methodology involved is shown in Fig. 3. One of the major problems in life estimation is the damping in the system – fortunately, it is now possible to assess this damping quite accurately by analytical means, thus enabling a good life estimation at the design stage.

The Fan Disc Drum assembly is critical to the structural integrity and optimum performance of the engine within the designated flight envelope. A 2-D axi-symmetric analysis forms the baseline for detailed 3-Dimensional stress analysis at peak stress regions. The assembly includes all the Rotor discs, Drum seals, Sealing rings and Conical shaft.

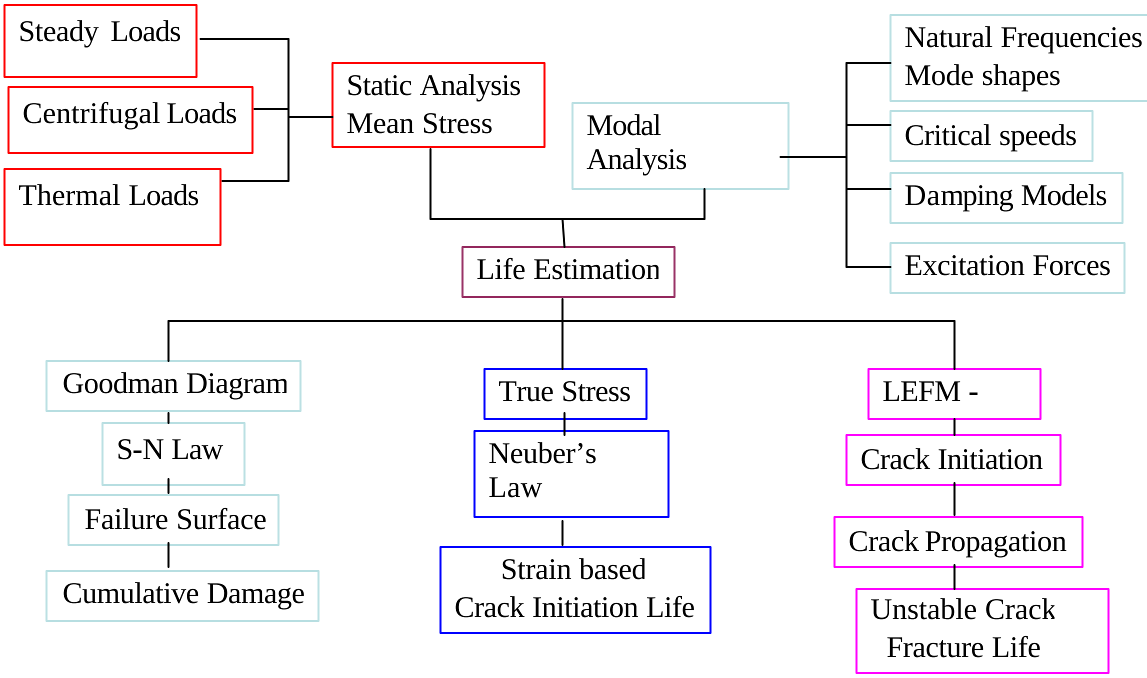

Fig. 3 Life Estimation Methodology

In this analysis, axial gas loads are applied at the respective centers of pressure and the tangential loads are applied at the disc rim. One set of nodes at the bearing location in the 1st stage disc is constrained in the axial direction. Heat Transfer coefficients and bulk temperatures are applied and thermal couplings are applied at all contact regions, Orthotropic Material Properties are used to model discontinuities in hoop direction. Bolt holes are modeled as regions with holes in axi-symmetric structure. Analysis is conducted at the rated speed.

The radial displacements take part in deciding the clearances; the third stage is more vulnerable where the displacement is a maximum. The displacements at sealing rings and drum seal also play an important role. The first stage disc is subjected to maximum stress which decides the geometry to satisfy the structural integrity.

The casing in advanced light aircraft engines is very thin, 1.5 to 2 mm thick and therefore is subjected to severe deformations and stresses. The radial displacement is important in making sure that there is no rub and the steady stresses limit the casing thickness. Considering pressure, thermal and axial loads, the radial displacements are determined. The displacement field of the casing coupled with radial growths of the rotor and other inputs such as rotor unbalance response will decide the cold and hot clearances of the system.

Usually peak stresses occur at the junctions of the blades/struts with the casing; they play an important role, as they become stress raisers for potential crack initiation sites.

It is necessary that the structural integrity of bolted joints between the disc, seal ring and drum assembly in the compressor is properly verified and that the different pressure chambers are properly sealed to prevent compressor losses. The boundary conditions for the axi-symmetric model are also shown.

The contact status is assessed in this assembly through a nonlinear anaysis. The contact pressures can also be obtained so as to ensure the bolted joint integrity.

4. ROTOR DYNAMICS

Rotor Dynamics plays an important role in the engine design. In recent years, considerable advances have taken place from simple beam model analysis. The support characteristics is generally the main issue, from bearings, dampers and also seals play significant role in engine dynamics. The bearings in an engine are supported in flexible structures, the front frame of the fan, the middle frame … The casing itself is 1.5 to 2 mm thick in advanced light engines and they add to considerable flexibility of the system. Therefore, it has become a necessity to be able to couple rotors and stators into a single model. Moreover, it is a complex process to determine the stiffness of the frames supporting the bearings for simulation of the rotor.

Making approximate beam models of the engine spools for the analysis purposes has therefore become obsolete and one uses now solid elements directly in the model. Thus, one can use the same solid model and mesh adopted for structural and thermal analysis. A typical mode shape of an engine is shown in Fig. 4.

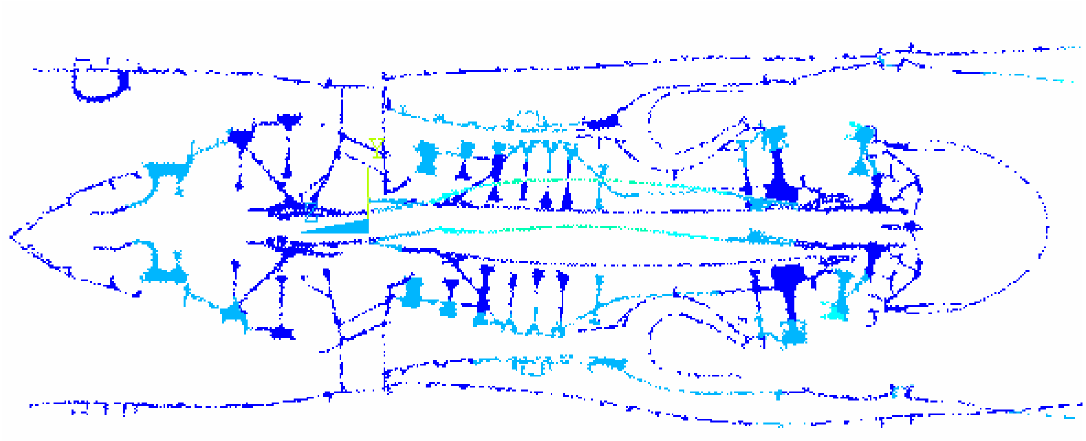

Fig. 4 Mode Shape of a Typical Two Spool Aircraft Engine

The whirl amplitudes at critical speeds will be quite large and the blade tips can rub at these speeds. Taking into account, the transient thermal and steady load growths of the casing and the radial displacements of different stages of the rotor under centrifugal and gas loads and whirling amplitudes at critical speeds, overall clearances required can be fixed.

5. SUDDEN LOADS DUE TO FOREIGN OBJECTS – BIRD HIT

Aircraft engines are commonly subjected to foreign objects hitting the stationary or rotating parts. In some unlikely events, the failure of a blade can cause severe loading on the bearings, a surge in the compressor or flutter of blading can also cause severe damage. The bird hit case is a complex problem, it being a soft body, is modeled in Eulerian space. The strut undergoes severe plastic deformations as shown. When the bird hits directly a rotating bladed disk, the energy is shared amongst different blades and the severity is somewhat less. Here, the case of a bird hit on rotating blades is shown in Fig. 5 below.

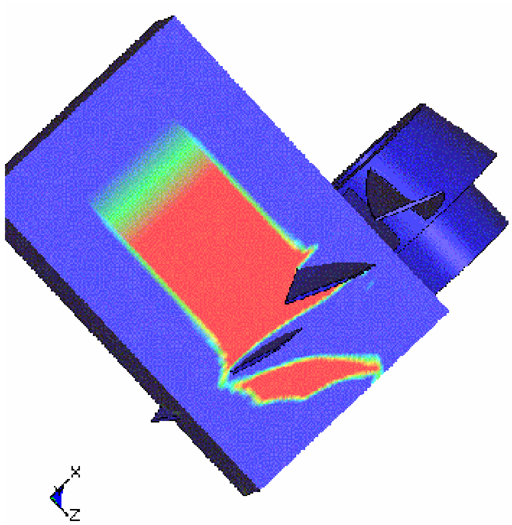

Fig. 5 Bird Strike on A Bladed Disc

6. SUMMARY

In this presentation, Professor B M Belgaumkar was remembered, who shaped the advanced mechanical engineering community in the first Indian Institute of Technology in Independent India; it is due to such visionaries, India today has become capable of addressing several advanced engineering designs. A flavor of what goes in the design of a compressor of an advanced aircraft engine is presented, depicting the state of art of design in the country today. It is sincerely hoped that several young engineers will come forward and take the strengths to further heights meeting the country's needs in future.

7. ACKNOWLEDGMENTS

The author would like to thank several young engineers in QuEST, Bangalore and outside in several organizations who have contributed in one way or other, to the present capabilities discussed here.