Computational Technique For Weight Reduction Of Aero- Engine Rotor

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Introduction

Stress and failure analysis of Aero-Engine components, especially rotating parts such as blades, discs, shaft of compressor or turbine play a very vital role in the performance of gas turbine engines, as they constitute nearly 30 per cent of overall engine weight. Reduction of disc weight would not only increase the over-all engine thrust-to-weight ratio, but would also have an impact on the weight of the associated supporting structures like shafts, bearings etc. High rotational speed and thermal gradients, across the disc bore and rim, force the bladed disc to operate at high stress levels. There is extensive coverage in literature on the assessment of peak stresses at the dovetail / fir-tree roots and flange bolt-holes [2]. Usage of new materials including those with dual-grain structure, assessment of over-speed and burst-speed margins, usage of advanced finite element methods and experimental validation have been covered in detail in the available literature (1,2,3, & 4). *
This paper however gives an overview of the critical rotating structures of compressor spool which were optimized using a general purpose linear optimization program and also highlights additional unique features, specific to the requirements of aero-engines, which were incorporated into the program. The components, which were analyzed and optimized and discussed in this paper with reference to enhancement of the versatility of optimization program, are
High Pressure Compressor Rotor (HPC) It has been possible to measure the versatility and use existing linear software quite successfully not only in the area of weight reduction but also in designing feasible components and structures, starting from designs that initially violated critical design constraints

Analysis Model

Figure.1 indicates the base-line independent disc models of a typical aero engine compressor discs with shape variables to be optimized for weight with necessary design constraints. It represents last three stages and has conventional circumferential dovetail root configuration. Using the base line model, having axi-symmetric boundary conditions imposed on the disc, with objectives to minimize the peak stresses, carried out shape optimization. Shape variables were used as design variables and optimization was carried out at 16000 rpm with elastic properties. The base line geometry consisted of approximately 20,000 grids and 9,000 elements. It was, as expected, subjected to blade centrifugal loads, thermal loads and disc centrifugal loads.Case1: In case of significant displacement, typically for fan stages [1], a non linear analysis is required. The non linearity is due to the significant deformation of the structure that modifies the stiffness matrix and the force field. In such a case, at each iteration of the computation, the deformation is determined and the associated stiffness matrix and forces are updated [3]. The convergence is obtained when the evolution of deformations is small between two steps. At the end of the process, the deformation is identified as well as the structure updated stiffness matrix.Case2: In case of small displacements, only two iterations are generally performed [4]. The deformation is computed and two additive stiffness terms are identified. A [Ks] Term, due to the structure deformation than modifies its stiffness. A [Kr] term due to the force field evolution (spin softening). The stiffness matrix is updated ([K1] = [K] + [Kr] + [Ks]) and the problem is solved again but with the basic force field and without geometry update (which are already accounted for in the updated stiffness matrix). It can be seen that one single static analysis does not give an accurate results. The rotation effects are requiring at least two successive linear analyses .or one non linear analysis (for fan for instance).

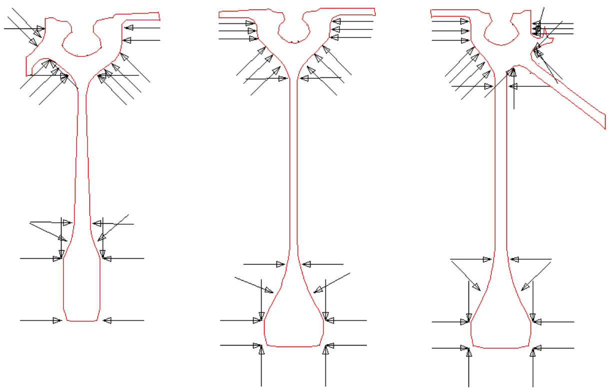

Figure 1: Shape Variables for Stages IV, V & VI of Compressor

Evaluation of Burst-Speed & Over-Speed Margins

A sector of Engine rotor and the grid model with hoop stress distribution are shown in Fig 2. Evaluations of burst-speed margins involve calculation of area weighted mean hoop stress and radial stress(awmhs) in each element and average it over the entire continuum. The program provides easy "hooks" to interface external FORTRAN (C, C++) programs. A simple FORTRAN program was written to calculate the burst speed margins based on hoop as well as radial stresses in the rotor. The radial growth variation with over speed limits is shown in Fig 3.

a) Area weighted mean hoop stress (AWMHS) in disc

$$\frac{\Sigma a^i_e \ * \ \sigma^i_{hoop}}{\Sigma a^i_e} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where a^i_e = Element areas for i=1, 2… n

σ^i_{hoop} = Element Hoop stress, N/mm^2

b) Burst speed margin based on hoop stress is:

$$\text{Sqrt (UTS / awmhs)} > 1.25\ldots\ldots\ldots\ldots \quad (2)$$

c) Over-speed margin based on hoop stress is:

$$\text{Sqrt (0.2 \% proof stress / awmhs)} > 1.18\ldots\ldots \quad (3)$$

d) Area weighted mean radial stress (awmrs) in disc

$$= \frac{\Sigma a^i_e \ * \ \sigma^i_{radial}}{\Sigma a^i_e} \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where a^i_e = Element areas for i=1, 2… n

σ^i_{radial} = Element Radial stress, N/mm^2

e) Burst speed margin based on radial stress is:

$$\text{Sqrt (UTS / awmrs)} > 1.25\ldots\ldots\ldots\ldots \quad (5)$$

f) Over speed margin based on radial stress is:

$$\text{Sqrt (0.2 \% proof stress / awmhs)} > 1 .18\ldots\ldots\ldots \quad (6)$$

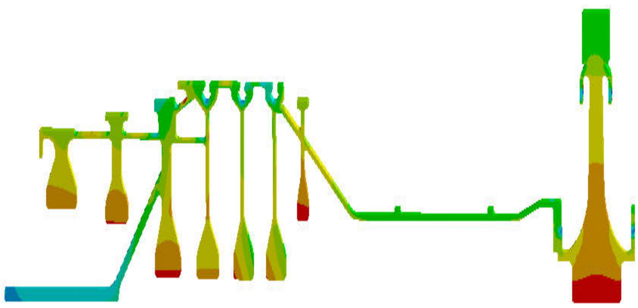

Fig 2 Hoop Stress Distribution in Engine Rotor

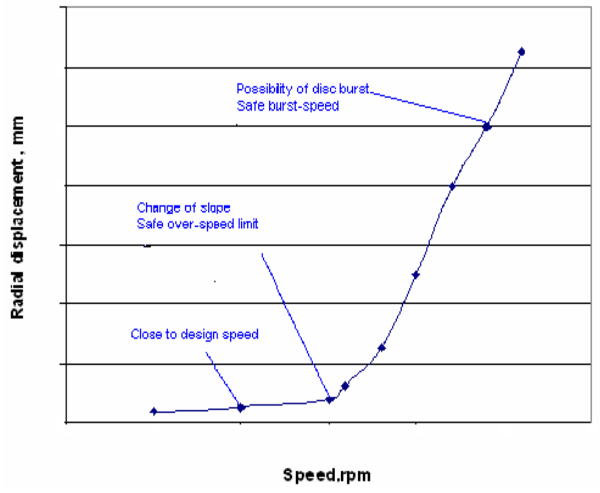

Fig 3 Radial Growth and Burst-Speed Limit

Conclusions

1. The optimization that was carried out converged in 30 design cycles.
2. The final weight was reduced by 10 per cent. Simultaneously and most importantly, all the constraints were satisfied and a feasible design obtained.
3. Based on highest local plastic strain, at the appropriate temperature, indicates a lower range of burst speed.
4. General purpose linear optimization software can be used to handle optimization problem with multiple design constraints effectively reducing the experimental cost.

References

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