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Some Issues Relating to Design and Development of an All-Composite Aero Gas Turbine Engine Rotor

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ABSTRACT

The paper addresses some of the issues involved in the development of an all-composite aero gas turbine engine rotor with a view to reducing the total engine weight and increasing the thrust-weight ratio beyond 20:1. It identifies the materials to be used for different components, i.e. shafts, discs and blades in the high and low temperature regions. The various problems anticipated in its development are discussed and solutions recommended, wherever possible.

1. INTRODUCTION

Over the past few decades, composites are being used extensively in diverse applications. The development of advanced high strength composites has led to their widespread use in aerospace applications. In this paper, we concentrate on the application of suitable composites in the most critical part of an aeroengine, i.e. the rotor, which is subjected to severe mechanical and thermal loading.

The present-day aeroengine rotors are predominantly metallic. It is the author's view, an 'all-composite shaft-disc-blade assembled or integral aeroengine rotor' is a distinct possibility, but it may take another 20-30 years for its full development and implementation in an aeroengine. This, however, would be possible through replacement of important constituents, viz., shafts, discs and blades of the rotor system, by composites in stages. As a first step, it will be essential to perform a complete analysis and develop a design of an aeroengine rotor (Fig. 1) based on all relevant aspects like rotordynamic behaviour, mechanical strength, fatigue and fracture, thermal effects, etc. A composite aeroengine rotor is expected to be much lighter than its metallic counterpart. A lighter rotor would naturally have smaller static and dynamic loads, requiring lighter support systems, i.e. bearing housing, etc. Thus, a considerable reduction in the overall weight of the aero gas turbine engine could be effected.

2. LITERATURE SURVEY ON COMPOSITE ROTORS

Designers now realise that nickel-base and titanium alloy systems used predominantly in present-day aeroengine rotors have reached the limits of their development. Further improvement in their characteristics will result only in marginal improvement in the performance of gas turbines. Aeroengines of the future are expected to have a thrust-weight ratio of 20:1 and much higher efficiency, which may require a turbine entry temperature (TET) of 2500 °K. Consequently, designers have felt the need to explore new materials, particularly the composites. Some of the future composite materials identified[1] for high

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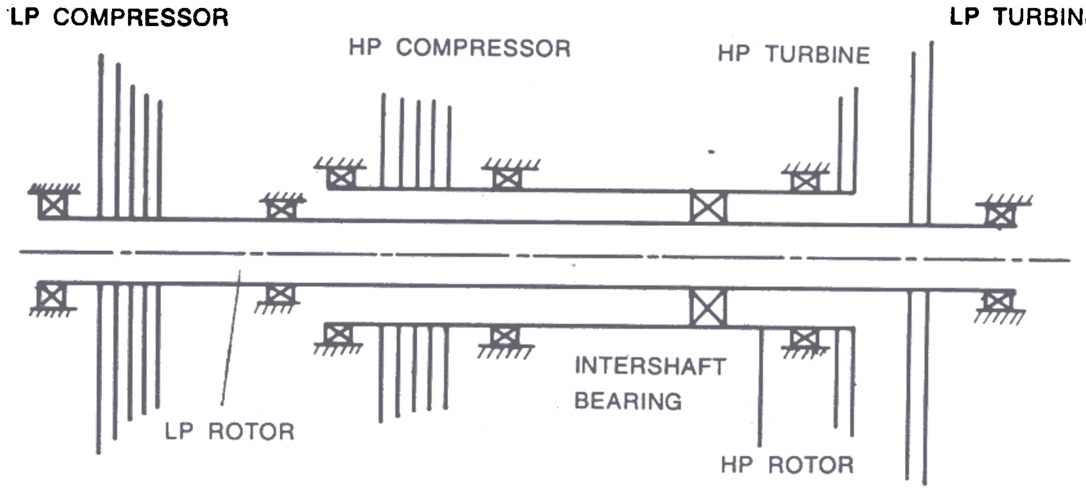

Figure 1. Schematic of a two-spool aeroengine rotor

temperature applications are glass and ceramic matrix composites and carbon-carbon composites. A study at Rolls-Royce[1] predicts the use of composites in aeroengine up to about 50 per cent by the year 2010.

The three important constituents of an assembled rotor are shafts, turbine/compressor discs and blades. Studies on composite shafts started in 1970's[2-4] with two viable materials, viz., boron/epoxy and carbon/epoxy. In earlier applications, the shafts mostly operated in the subcritical range. However, recent studies have shown that maximum reduction in the weight of the rotor system can be achieved by its supercritical operation, for example, 60 per cent in case of a helicoper tail drive rotor[5]. The present trend in research is, therefore, towards such aspects as elaborate optimisation procedures[5-7], cost sensitivity analyses, possibility of supercritical operations and related rotor dynamic aspects[5-10] like estimation of critical speeds, unbalance response and balancing.

Studies on tapered composite shafts[6] have shown that while meeting the torsional strength requirements, it was possible to obtain configurations which resulted in an increase of 20-30 per cent in natural frequencies and reduction of 50-60 per cent in maximum dynamical stresses. Rotordynamic experiments on composite shafts[8,10] have revealed several interesting phenomena like increased sensitivity to unbalance near the critical speed and presence of dominant nonsynchronous components at some particular speeds. Modal testing on the two nonrotating tubular composite shafts ($\pm 45^\circ$ and $\pm 60^\circ$) has been performed[11] and damping ratios in flexural as well as shell modes have been obtained. Keeping in view the importance of shell modes in thin walled structures, damped free vibrations in shell modes of a tubular shaft have been studied in detail[12]. Possibly, in the first study[13] of its kind, the propagation of delamination in rotating fibre reinforced carbon/epoxy shaft has been studied experimentally and material constants C and n for carbon/epoxy shaft have been evaluated. Equivalent modulus beam theory (EMBT)[6,14] appears quite adequate for dynamic analysis of composite shafts. Improved theories[9,15] derived from shell theories and layerwise approach[15], however, give more accurate results, particularly the stress fields. In summary, the feasibility of using composite drive shafts is well established. Methodologies for its analysis and design have been fairly well developed. However, their application in rotors is not so widespread as yet, because of high cost, higher level of uncertainty in material properties and lack of experience in use of composites. All these factors deter designers to use composites.

Published literature on the design of nonmetallic compressor/turbine discs and shafting for gas turbines appears to be nonexistent. Though, it has been suggested[1] that in future gas turbines, compressor may be either a glass or metal matrix and the turbine is likely to be of ceramic. Blades are the most critical component, since the TET depends on the capacity of HP stage turbine blades to withstand high temperature. Design and use of ceramic turbine blades on experimental, and, to a limited extent, on commercial basis have been reported in literature.

3. DESIGN OF NONMETALLIC ENGINE ROTOR

Important steps in the development are

3.1 Material Selection

In gas turbine application, special consideration has to be given to the components exposed to high temperature on turbine side. The variation in temperature of gas along the length of the aeroengine can be obtained from thermodynamic cycle. The transient and steady state temperature distributions in structural components will depend upon several factors like radiation effects, heat transfer characteristics, type of blade cooling, etc. The materials suggested below are essentially based on a qualitative assesement of temperature effects on new composite materials. Fibre reinforced composites in epoxy or glass matrix appear to be ideal materials for the shaft on the compressor end because of their high specific strength and modulus up to 250 °C and 400 °C, respectively. For the shaft on the turbine end, glass ceramic, ceramic or metal matrix composites will be required. The LP stage compressor discs may be of carbon fibre reinforced plastics (FRPs), while others can be of glass matrix or metal matrix composites. Turbine discs have to be of carbon-carbon, ceramic or metal matrix composite. Compressor blades of LP stages can be of carbon FRP, while compressor blades of HP stages may be of glass matrix or metal matrix composites. Turbine blades have to be necessarily of ceramic.

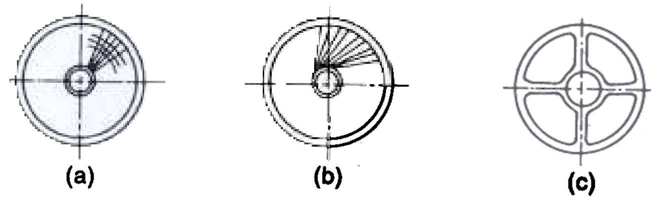

Figure 2. Composite discs

3.2 Structural Integrity

The basic idea to be adopted in the design of various components is to have, as far as possible, uniform stress, which should automatically lead to an optimum weight because of nonisotropic nature of composites and possibility of matching their directional properties/strength with the direction of loads. The second important factor would be to design light flexible components with adequate material and other type of passive damping, so that the components could be made to operate satisfactorily above several natural modes, specially because composites offer a higher inherent damping compared to metals. Structural integrity of the component is to be ensured by comparing the stress developed with the allowable values and application of suitable failure criteria. With proper use of high strength fibres, it should be possible to design thin walled shafts and discs. The fact that the composite material offers several additional parameters under the designer's control, like properties of the matrix and the fibre, proportion of matrix and fibre (volume fraction), fibre angle, number of layers and stacking sequence, etc. would enable much better optimisation of designs, leading to considerable reduction in their weight (compared to metallic components).

Some preliminary ideas about a typical composite disc are depicted in Fig. 2. Figure 2(a) shows fibres aligned in radial and circumferential directions, which will carry radial and hoop stress, respectively. Several layers of each in a symmetrical sequence will be required. In Fig. 2(b), a single layer of sufficient thickness may be adequate. It will be easier to fabricate the disc shown in Fig. 2(b). Figure 2(c) shows a design with

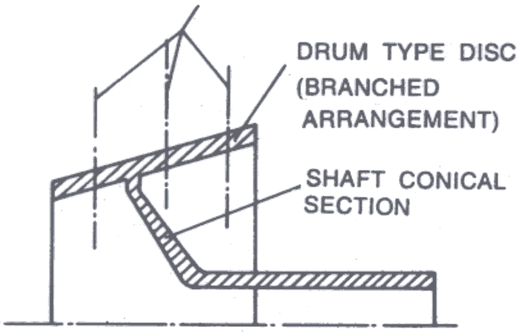

Figure 3. Schematic of branched arrangement and shaft conical section.

ribs made of high strength fibres. For shafts, proper placement of rotor critical speeds and limiting shaft deflections within the clearance limits will have to be ensured. Also, conical section of the shaft and forward and backward swept branch arrangements (Fig. 3) used commonly for LP compressor stages will be more amenable to the added design parameters of composites. The concept of uniform stress used in metallic discs has to be extended to composite discs. The steady state centrifugal loading, thermal loading and dynamic stresses due to disc bending vibrations are to be taken into account. Adequate passive damping in selected modes, falling in the range of excitation frequencies is to be designed into the disc. As for the blades, the free-standing-blade approach will not be valid, since the discs are expected to be flexible. Hence, 'bladed-disc' approach is to be used, i.e., blades and disc will have to be designed together. The control of mistuning in composite bladed-disc in comparison to metallic bladed-disc and its effect on forced vibration response would require careful analysis.

3.3 Fabrication

Preliminary considerations lead to filament winding for shafts and drum type discs and use of prepregs for components of complex shape. For metal and ceramic matrix composite components, the fabrication procedure will have to be identified specifically after the material selection is finalised and design completed. New methods may have to be developed for some components like discs with fibre orientation shown in Fig. 2 and blades of complex shape with special features like cooling passages, etc.

4. OTHER ISSUES

The other important issues in the dynamic design of a composite aeroengine rotor are

4.1 Rotor Configuration

Because of a higher E/ρ value of composites compared to metals, larger bearing spans without actually lowering the rotor critical speeds are possible. Therefore, a detailed rotordynamic analysis will have to be first carried out to see if a basic change in bearing configuration of the aeroengine rotor would be necessary to simplify the design. For example, it may be possible to reduce the number of bearing supports or to do away with an intershaft bearing and/or some or all the squeeze film dampers which will be a major simplification in an aeroengine rotor. Another interesting feature is the possibility of operations at very high rotor speeds (30-40 krpm), which would altogether alter the aerothermodynamics of the aeroengine, leading to basic configurational changes as well as requirement of special rolling element bearings for ultra high speeds.

4.2 Rotordynamics

This has a direct bearing on strength and structural integrity of the rotor system. Important considerations will be the estimation of critical speeds, steady state response, transient response during rotor acceleration/deceleration, possibility of unstable operations and cross-excitation in multispool rotors. Disc gyroscopics and rotary inertia effects, as well as bearing nonlinearities, are expected to play a more dominant role, if the rotors have to operate at ultra high speeds. Rotordynamic analysis has to include detailed stress analysis of rotor components due to steady loads, dynamic loads, transient manoeuvre loads, thermal effects and internal stresses developed due to assembly.

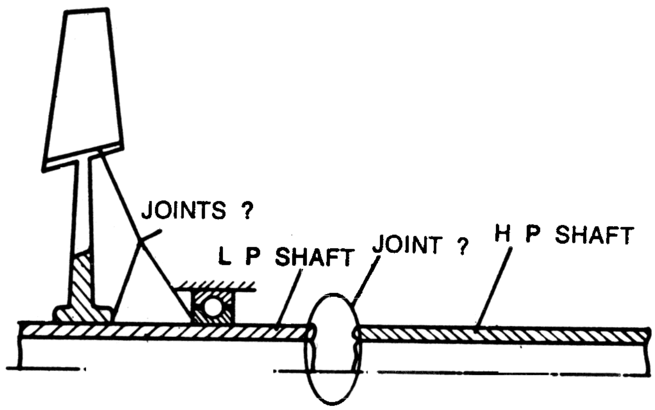

Figure 4. Difficulties in joining of components and mounting of rotors.

4.3 Degradation of Material Properties

The assessment of creep behaviour and degradation of the material properties of various composite materials, particularly those subjected to high temperature, is important.

4.4 Joining of Composite Members

Joining of composite members (Fig. 4), for example, shafts in low and high temperature regions, blade and disc, disc and shaft, is envisaged to be a serious problem in the development of composite rotors. Similarly, special arrangements are needed to support composite rotors on rolling element bearings with metallic races mounted on the composite surfaces. It would be necessary to carry out in-depth investigations to tackle these problems and obtain feasible solutions.

5. DYNAMIC RESPONSE & STRESS ANALYSIS

Rotordynamic analysis could be based on classical as well as higher order shear deformation laminate theories using the layerwise approach. Ritz method can be used for estimating rotor critical speeds, unbalance response, transient response, unstable operation and stress analysis. The simplified Ritz analysis has to be supplemented by finite element modelling (FEM) for accurate prediction of stress in sections involving sharp changes, conical sections and branched arrangements. FEM has to be invariably used for complicated structural parts like the discs, twisted aerofoil section blades and various joints. Figure 5 shows the scheme to evaluate stresses in shaft section.

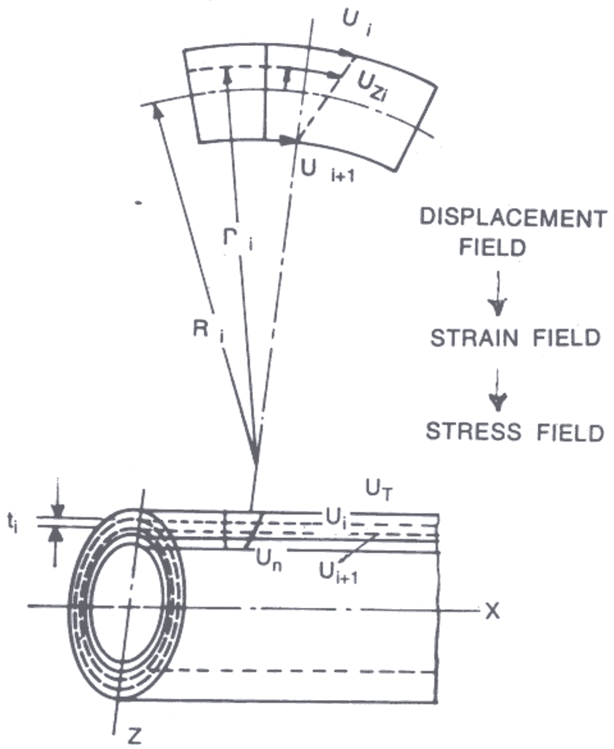

Figure 5. Layerwise approach for stress analysis of shaft

Macromechanical modelling will be necessary for most of the analyses. However, micromechanical modelling may be required in some situations like accounting for different thermal coefficients of expansion for matrix and fibres. While linear analysis is envisaged to be adequate for design, the effect of material and bearing nonlinearities for any significant phenomenon like introduction of instability, sub/super harmonic response or chaotic behaviour, may need to be studied.

6. CONCLUSION

In the author's opinion, a lightweight 'all-composite assembled/integral aero gas turbine engine rotor' with the ultimate objective to reduce the overall engine weight and provide thrust-weight ratio greater than 20:1 will be a major change in aeroengine design and technology. It is envisioned that despite serious difficulties, aeroengines may have all-composite rotors in 20-30 years. It will be timely to start development work in this direction in the country.

REFERENCES

Jeal, R.H. Meeting the high temperature challenge—the nonmetallic aeroengine. *Metals and Materials*, 1988, 539-42.

2. Zinberg, H. & Symonds, M.F. The development of an advanced composite tail rotor drive shaft. 26th Annual National Forum of American Helicopter Society, Washington D.C., 1970.

Worgan, G. & Smith, D. Carbon fibre drive shaft. US Patent 4,089,190, 1978.

4 Yates, D. & Rezin, D. Carbon fibre reinforced composite drive shafts. US Patent 417626, 1979.

5. Hethrington, P.L.; Kraus, R.F. & Darlow, M.S. Demonstration of a supercritical composite helicopter power transmission shaft. *J. Am. Helicopter Soc.*, 1990, **35**, 23-28.

6. Bauchau, O.A. Optimal design of high speed rotating graphite/epoxy shafts. *J. Composite Mater.*, 1983, **17**, 170-81.

Lim, J.W. & Darlow, M.S. Optimal sizing of composite power transmission shafting. *J. Am. Helicopter Soc.*, 1986, **31**(1), 75-83.

8. Zorzi, E.S. & Giordano, J.C. Composite shaft rotor dynamic evaluation. ASME Design Engineering Conference on Mechanical Vibration and Noise. ASME Paper No. 85-DET-114, 1-8.

9. Dos Reis Henrique, L.M.; Goldman, R.B. & Verstrate, P.H. Thin walled laminated composite cylinderical tubes - Part III, critical speed analysis. *ASTM J. Composites Techno. & Res.*, 1987, **9**(2), 58-62.

10. Singh, S.P. & Gupta, K. Rotor dynamic experiments on composite shafts. *ASTM J. Composite Techno. & Res.*, 1996, **18**, 256-64.

Singh, S.P. & Gupta, K. Modal testing of tubular composite shafts. Proceeding of the International Modal Analysis Conference., Florida, 1993. 733-39.

12. Singh, S.P. & Gupta, K. Damped free vibration of layered composite cylindrical shell. *J. Sound and Vibrations*, 1993, **167**(3), 1-19.

13. Chandramouli, G.; Gupta, K. & Pandey, R.K. Delamination propagation in rotating carbon/epoxy composite shaft. *Engng. Fract. Mechan.*, 1994, **49**, 121-32.

14. Singh, S.P. & Gupta, K. Free deamped flexual vibration analysis of composite cylindrical tubes using beam and shell theories. *J. Sound and Vibration*, 1993, **167**(3), 20-39.

15. Singh, S.P. & Gupta, K. Dynamic analysis of composite rotors. *Int. J. Rot. Mach.*, 1996, **3**(3), 189-98.

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