Development of JT8D Turbofan Engine Composite Fan Blades

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A test of a full set of 30 first-stage, composite fan blades in a Pratt & Whitney JT8D turbofan engine has demonstrated that advanced composite materials are very attractive for application to gas turbine engines. Borsic-fiber-reinforced aluminum composite is particularly attractive because of its high modulus, high strength, and low density. This paper presents the blade design considerations and fabrication development techniques using this new material and discusses component and engine testing. Advanced analytical techniques to determine the stresses and dynamic characteristics of blades made of anisotropic materials were required. An extensive fabrication development was conducted before structurally sound composite blades were made. Consequent improvements in blade design resulted in a direct weight reduction of 40% as well as indirect weight savings and improvements in performance.

I. Introduction

USUALLY it is difficult to foresee the full advantages to aircraft design and performance which will result from new and improved materials properties. The advantages of increased stiffness, higher temperature capability, or lighter weight can be seen right away. The development of advanced composites, however, may well trigger a new generation of powerplants that would not have been possible with conventional materials. Their high strength-to-density ratios reduce the weights of structures. This benefit is multiplied for rotating parts, where the lower mass is translated into lower centrifugal loads and stresses. A pound saved in a fan blade eventually saves 5–8 lb as lighter supporting structures become feasible and lead, in turn, to lighter pylons, wings, and fuselage. Additionally, their stiffness-to-density ratios are more than three times those of steel, aluminum, or titanium. For components that are deflection-limited or vibration-limited, a new realm of design papers. A prime example again is the fan blade. In the JT8D turbofan engine, the increased material stiffness permitted the removal of part-span shrouds (see Fig. 1) without violating flutter criteria. The benefit here is engine performance as component efficiency increases.

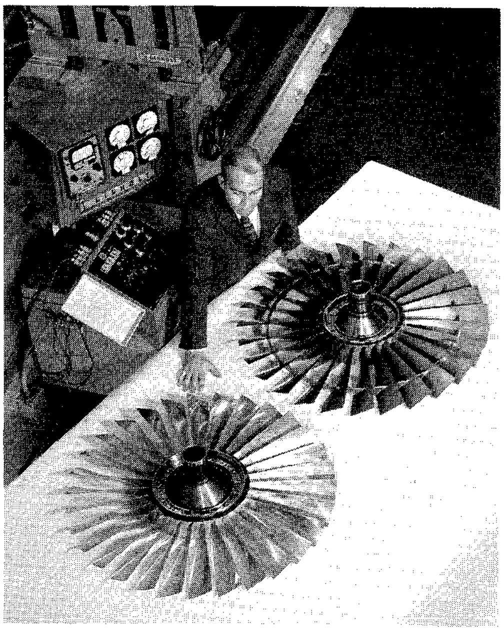

Fig. 1 JT8D Borsic-aluminum (foreground) and titanium fan stages; note absence of midspan shrouds on the former.

The progress and development of the advanced composites for gas turbine engines has been rapid under the stimulus of the Air Force Materials and Propulsion Laboratories. Over the past five years, boron filaments have progressed from a laboratory curiosity to a commercially available material. In view of this potential, a number of programs have been undertaken to develop the technologies required to translate these materials into engine hardware.[1–7] The development of a metal matrix system and its associated fabrication techniques has been accomplished to the extent that successful components have been developed, fabricated, and tested.

Pratt & Whitney Aircraft successfully operated their JT8D turbofan engine with the first-stage fan equipped entirely with boron-aluminum composite blades. The 40-in. metal matrix composite fan is the largest rotating engine component that has been run in an engine. Each blade weighs 15½ oz, or 40% less than the 26-oz titanium blades used in the engine that powers Boeing's 727 and 737, McDonnell-Douglas's DC-9, and Sud Aviation's Super Caravelle. The test run lasted 2 hr and included thrust levels equal to the JT8D takeoff rating. After the test, the blades were in excellent condition. The test was part of the Company's program of demonstrating the feasibility of using metal matrix composites in military and commercial jet engines; however, actual use of the new blades is not comtemplated at this time.

The most conspicuous feature of the JT8D Borsic-aluminum fan blade is the absence of midspan shrouds (see Fig. 1). The shrouds are necessary for titanium blades of the JT8D to stiffen the blades and prevent flutter. The composite blades do not require shrouds because of their increased stiffness-to-mass ratio. In addition to the advantage of having no shrouds, the composite blades have the advantage of being 40% lighter than titanium blades.

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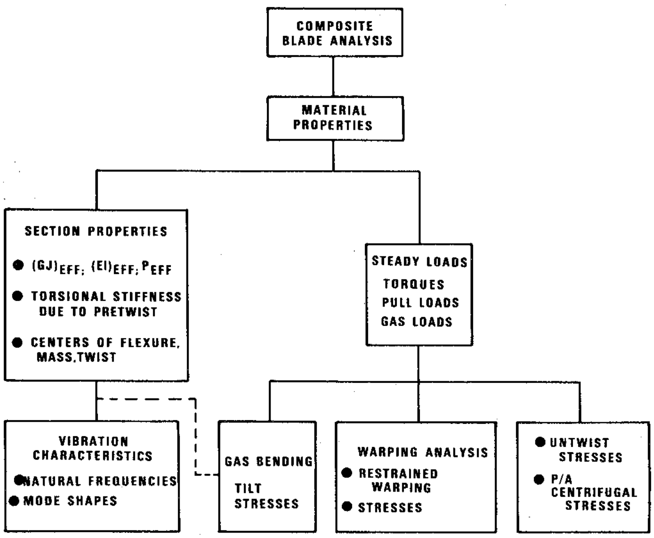

Fig. 2 Composite blade analytical techniques.

II. Analytical Techniques and Results

Advanced analytical techniques were developed and computerized (Fig. 2) to design fan blades fabricated from inhomogeneous and anisotropic composite materials. Broadly speaking, these techniques can be divided into those required to determine the vibration characteristics and those required to determine the stress state in the fan blade. It is first necessary to determine the macroscopic elastic constants of the composite layup, which may consist of plies at different fiber orientation angles. Several investigators[8–12] have devoted extensive efforts to determining the properties of composite materials. Pratt & Whitney has drawn on the techniques developed by these investigators where applicable and, in combination with original analytical and experimental work, developed computer programs for predicting the properties of laminated composite materials. The calculation of these elastic constants is based on the elastic properties of the constituents and is calibrated by specimen tests. After having calculated the elastic constants, the effective section properties of the airfoil at various radial locations are determined. These properties include the effective mass, St. Venant's torsional rigidity, torsional rigidity due to the blade pretwist, flexural rigidity, and centers of mass, flexure, and twist. These properties are then used to determine the natural frequencies and the mode shapes of the blade.

In order to determine the steady stresses in the blade, the steady loads (centrifugal pull load and the torque) are first determined. The centrifugal pull load is dependent upon the spanwise mass distribution of the blade, whereas the torque load is dependent upon the spanwise and chordwise mass distribution and the pretwist of the fan blade.

The interlaminar shear stress, which is of insignificant importance in designing fan blades with metals, is of great importance in composite fan blades because of the relatively low values of interlaminar shear strength of composite materials. The composite consists of alternate layers of 6061 aluminum with imbedded Borsic fibers and 1100 aluminum as shown in Fig. 3. It is evident from Fig. 3 that the interlaminar shear strength of the composite is limited by the low shear strength of the 1100 aluminum. The in-plane shear strength of the composite is higher than the interlaminar shear strength because the alternate layers of 1100 aluminum and of 6061 aluminum with imbedded fibers act in parallel. The interlaminar shear stress occurs in the root of the blade because of the centrifugal pull and bending loads and in the airfoil because of the torsional and bending loads. The torque on the airfoil results in two significantly different shear stresses occurring in two different locations. The maximum in plane

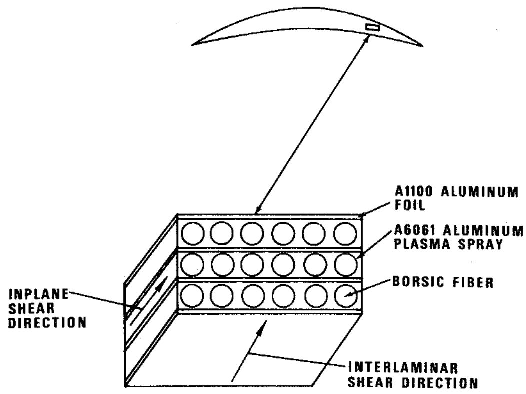

Fig. 3 JT8D first-stage fan blade analytical model.

shear stress (the shear stress in the plane of the plies) occurs on the concave side of the blade at about midchord location. The maximum interlaminar shear stress (the shear stress between plies) occurs near the leading and trailing edges and is lower in magnitude than the maximum in plane shear stress.

A design analytical investigation was made to determine whether there was a need for cross-ply composite reinforcements to increase the torsional rigidity of the airfoil, resulting in higher torsional flutter parameters and lower angles of untwist during operation. The analysis indicated that the unidirectional Borsic/aluminum composite with about 50% fiber volume fraction had a shear modulus of 8.1×10^6 psi (Fig. 4). This was subsequently verified by specimen tests. The design analysis of the airfoil using this shear modulus showed that the torsional frequency and the angle of untwist criteria would be satisfied. The use of cross plies would have introduced additional fabrication difficulties. It should be pointed out that, in the case of Borsic-aluminum composite for high-temperature application and polymer matrix composites at all temperatures, the story would be quite different. The low shear modulus of unidirectional composites under these conditions would make a cross-ply design unavoidable.

III. Fabrication Development

The Borsic/aluminum tape for the blades was developed by United Aircraft Research Laboratories and is manufactured and sold by United Aircraft's Hamilton Standard Division for military and commercial applications. The tape, which is available in a variety of widths and lengths, is composed of a monolayer of parallel Borsic fibers interspersed with plasma-sprayed aluminum and backed by aluminum foil. The 4-mil fibers, coated with silicon carbide, have an average tensile

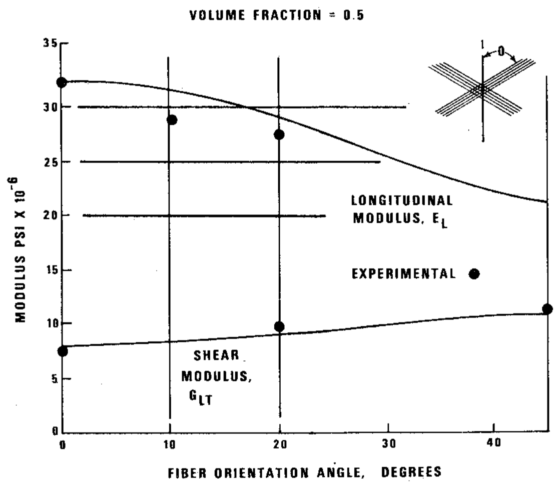

Fig. 4 Borsic-aluminum composite moduli vs fiber orientation angle; volume fraction = 0.5.

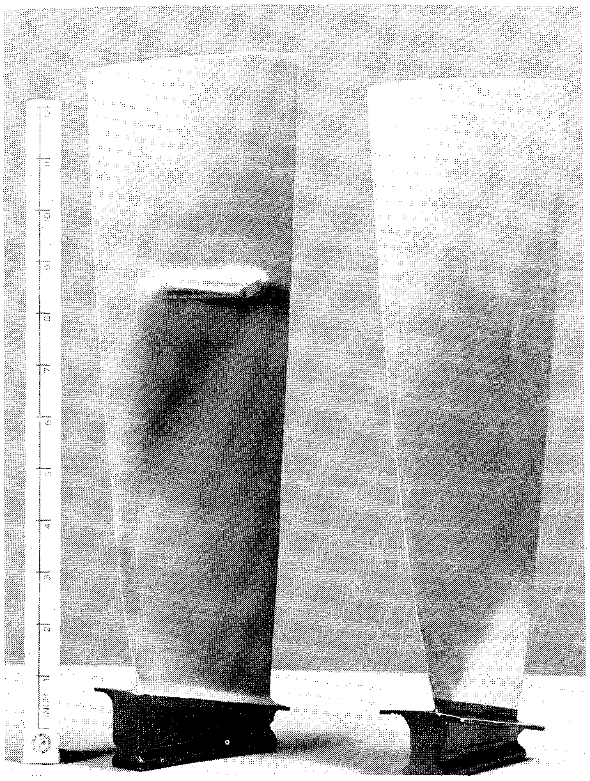

Fig. 5 JT8D first-stage fan blades, titanium alloy and Borsic-aluminum.

strength above 400,000 psi. Approximately 50% of the tape's total weight is made up of Borsic filament. The filament is spaced at 175 fibers/in. of tape width.

Blade fabrication development was accomplished by using the tools of ply shape and processing parameters, coupled with both destructive and nondestructive inspection (NDI) techniques. The development objectives were to produce a blade having the required strength, stiffness, and airfoil contour. The primary development problems were proper filling of the airfoil die, attainment of required stiffness, selection of processing parameters to insure compaction without melting or fiber damage, diffusion-bonding of the root attachment, and finding effective NDI techniques.

The blade airfoils consists of 70 layers, or plies, of Borsic-aluminum "tape." The tape consists of Borsic fiber (boron coated with SiC) wound on a 1-mil aluminum foil and fixed in place by plasma-sprayed aluminum. The tape is 8-mils-thick as received, and is compacted to a thickness of 5 mils by hot pressing. The matrix alloy used for the JT8D blades was a combination of 1100 (foil) and 6061 (plasma spray). Fiber volume percentage was 50%. Tapes of appropriate shapes were cut to length; the airfoil forming tool was a closed die, and the final layup was developed by trial and error until the die cavity was properly filled and the resulting airfoil had a minimum of uncompacted areas or broken fibers. Because of slight variations in tape thickness, most airfoils had random areas of poor compaction, which were easily corrected by locally adding a layer or two of tape, and repressing.

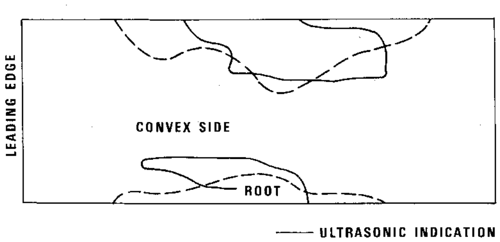

Fig. 6 Nondestructive vs destructive comparison of unbonded areas.

Table 1 Predicted and experimental values of natural frequencies

	Predicted, Hz	Measured, Hz
First bending	137	132
Second bending	450	430
First torsion	740	750

The aluminum alloy dovetail root attachment was separately bonded to the composite airfoil (Fig. 5). 5052 Al alloy blocks were hand-fitted to the airfoil root—one to the concave surface and one to the convex surface. The blocks were then diffusion-bonded to the airfoil in a closed die. The aluminum root blocks were bonded to the airfoil with the same parameters used for the airfoil, except that the time was increased to 3 hr. It proved to be much more difficult to bond aluminum to Borsic-aluminum than to bond the composite to itself, and even more difficult to bond the aluminum root blocks to each other in the areas outside the airfoil (LE and TE). The reason is that the very hard boron fibers tend to break up the ever-present film of aluminum oxide on the surface. This observation is supported by the fact that aluminum will bond better to itself if a layer of Borsic tape is inserted between the parts, and that aluminum will bond better to Borsic-aluminum if the fibers are first exposed. The presence of plasma-sprayed material may also help the process. Both the preceding techniques were used in JT8D blade fabrication.

The pressing cycle consumed one shift (8 hr) and was executed once for every airfoil. The root-bonding cycle took approximately the same amount of time. Conventional root-machining completed the process. The ply layup was all undirectional. This ply layup was selected because the shear modulus of unidirectional Borsic-aluminum composite is sufficiently high over the temperature range of this fan blade to provide sufficient torsional stiffness. Machining of the composite was required to trim the root and the tip to proper length, and to sink into the blade root a slot for a locking device. Electrical discharge machining (EDM) was found to be the best method for shaping the Borsic-aluminum composite. It was very fast and produced an acceptable surface finish, equivalent to 63 rms. Grinding produced a better finish but was very slow. Milling cutters were completely ineffective, even when carbide-tipped tools were used. Therefore, EDM was used for the tip trim operation and the slot; the root bottom surface was ground.

Every blade was subjected to the determination of weight, thickness, density, natural frequency (first and second bending, first torsion), ultrasonic test of root bond, zyglo (root only), 20 $\times$ optical scan, and proof spin test to 9000 rpm.

IV. Nondestructive Inspection

Many useful NDI techniques were used in the JT8D blade development, but an effective means of looking at the internal structure of the composite was not found. X-ray revealed edge fiber breakage and tip ply orientation but could not penetrate the thicker sections of the airfoil, probably because of the pressure of tungsten filament cores. Ultrasonic inspection of the airfoil was attempted but was not completely effective. It was used successfully to evaluate the bonded joint between the root blocks and the airfoil. Its effectiveness was enhanced by the flat surfaces of the root blocks; ultrasonic inspection of finished roots was rendered ineffective because of the configuration of the surfaces. Figure 6 demonstrates the good reproduction of a deliberately unbonded root block area by ultrasonic C-span. Dimensions, weights, densities, and natural frequencies of the blades were consistently uniform, once the development cycle was completed. Optical

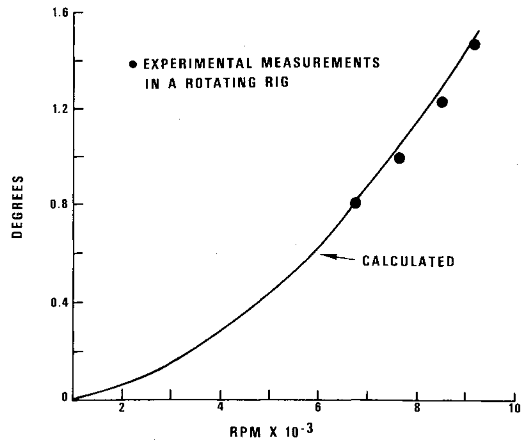

Fig. 7 JT8D first-stage fan blade, Borsic-Al, angle of untwist vs rpm.

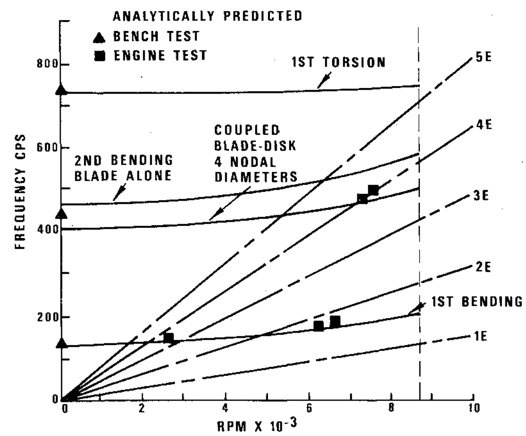

Fig. 8 JT8D first-stage fan blade, B-SIC-Al, frequency vs rpm.

and Zyglo inspection was also used to detect any surface defects.

The ultimate means of NDI was a proof test in the spin pit. Every blade was spun to 9000 rpm (105% of design speed). Detailed inspection of the blades before and after testing revealed any structural weakness not previously detected. Defective root bonds were found on a few of the blades.

V. Evaluation

Bench tests of several blades were carried out to determine the natural frequencies in first and second bending modes and the first torsional mode. Table 1 compares calculated natural frequencies in bending and in torsion modes at zero speed with the measured values.

Several blades were strain-gaged and rotated up to full design speed in an evaucated rotating rig to determine the stresses and angular displacements of the blade as a function of rotational speed. Figure 7 compares analytically predicted angle of untwist with measured values; agreement is good.

Following an exhaustive individual blade tests NDI program, 30 of the blades were selected and installed in a JT8D experimental engine; 9 of them were strain-gaged. The engine was operated for a total time of $\sim$2 hr. The test consisted of four separate runs, two of which were taken up to red-line speed. The test objective was primarily a structural demonstration. However, some airflow measurements were taken, and they indicated an increase in airflow of 1% as compared to an engine with shrouded titanium blades. A thorough examination after the test program showed that the blades were in good condition, with no indications of structural degradation.

Figure 8 compares predicted natural frequencies in first and second bending modes and in first torsional mode with the experimental values. For fan blades of moderate size with a dovetail attachment and no part span shrouds, the first bending resonance by second-order engine excitation is unavoidable, even when advanced composite materials are used. The natural frequency of a fan blade in bending at zero speed is benefitted very much by the high modulus-to-density ratio of advanced composites. However, there is not a corresponding benefit in the natural frequency at full speed. The contribution of centrifugal stiffening effect to the natural frequency in bending at speed is very substantial and in many cases forms the major portion of the natural frequency at speed. This centrifugal stiffening effect is practically independent of the elastic modulus and the density of the material. The elimination of shrouds drops the bending frequency of moderate and large-size fan blades more than is compensated by the high stiffness-to-density ratio of the advanced composites. However, the engine test indicated to noticeable resonance of first bending by 2E, and there was no cracking, splitting, or delamination.

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