Vibration Characteristics of Composite Fan Blades and Comparison with Measured Data

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The vibration characteristics of a composite fan blade for high-tip-speed applications were determined theoretically, and the results compared with measured data. The theoretical results were obtained using a computerized capability consisting of NASTRAN coupled with composite mechanics by way of pre- and postprocessors. The predicted vibration frequencies and mode shapes were in very good agreement with the measured data. Theoretical results showed that different laminate configurations from the same composite system had only small effects on the blade frequency. However, the use of adhesively bonded titanium/beryllium laminar composites may improve considerably the blade vibration characteristics.

I. Introduction

THE application of advanced fiber composites to fan blades is currently under investigation at the NASA-Lewis Research Center. A type of advanced fiber composite suitable for a particular application involving a high-tip-speed fan blade is described in Ref. 1, and the computerized analysis capability for structurally analyzing these blades is described in Ref. 2. The effects of various loading conditions and their relative importance in the high-tip-speed fan blade application were presented in Ref. 3. However, comparisons of predicted results with measured data, the effects of different laminate configurations, and the effects of different composite systems on the tip displacements and vibration frequencies of the composite blade have not been investigated. The results that would be obtained from an investigation of these factors are important in determining the following: 1) accuracy of computerized analysis capability relative to measured data in order to build confidence in the analysis method; 2) selection of ply-lay-up sequences for altering blade structural stiffness relative to tip displacements, vibration frequencies, and vibration mode shapes once the airfoil shape and composite system have been fixed; and 3) selection of composite systems for altering these vibration characteristics but when only the airfoil shape has been fixed.

The objectives of this investigation were to report on comparative results between predicted and measured data for vibration characteristics and to investigate the effects of selected laminate configuration and different composite systems on the blade vibration characteristics and tip displacements.

The computerized analysis method, the blade geometry, the laminate configurations, and the composite systems selected to study improvements in blade vibration characteristics, and a comparison of predicted and measured vibration modes are described herein.

II. Computerized Analysis Capability Description

The computerized analysis capability[2] consists of using NASTRAN in conjunction with composite mechanics embedded in pre- and postprocessors. The pre- and post-processors are especially designed to automate the large amount of information needed to analyze fiber composite compressor blades via NASTRAN. The preprocessors are used to generate three types of information required as input for NASTRAN. Briefly, these types are: 1) finite-element representation, nodal coordinates, nodal thickness, and boundary conditions; 2) nodal pressures and temperatures; and 3) anisotropic material properties generated from input constituent properties, fiber volume ratio, void ration, ply orientation,and ply contours.

The NASTRAN output information, in general, consists of nodal displacements, element force resultants, element stresses and the corresponding principal stresses, and the frequencies for various vibration modes. The overall blade untwist and uncambering can be determined from nodal displacements at the tip. For the analysis of the composite blade, a triangular finite-element representation was used. The element includes bending and membrane responses, centrifugal forces, and anisotropic material properties. This element is identified as CTRIA2 in the NASTRAN library of elements. The finite-element representation consists of 299 nodes and 531 elements.

III. Blade Description, Laminate Configurations, and Composite Systems Investigated

The composite blade has a tip radius of approximately 16.3 in. The root attachment chord is approximately 7.8 in. (Fig. 1). This figure shows the blade as fabricated and trimmed. The blade has a nonlinear twist with an overall twist angle of about 31° from hub to tip. The blade was designed for a tip speed of 2200 fps. The thickness percentages for ply orientations in this blade design were approximately 30% ±40° plies for the blade shell and approximately 70% 0° plies for the core. In addition there were two ±20° plies for transition between the shell and core plies. Near the blade tip, two surface plies (±70°) were used to minimize chordwise deflections. For analysis purposes, the blade root attachment was assumed to be just above the dovetail inserts (Fig. 1). The leading-edge protection device was included in the laminate configuration. Its influence is represented in the element material properties for this region.

The influence of several different laminate configurations on the vibration characteristics of the blade were investigated theoretically for the following symmetric ply sequences from the same composite system: 1) ±40° plies for the shell, ±20° plies for transition, and 0° plies for the core; 2) ±40° plies for the shell and (+10°, 0°, −10°) repeated ply sequence for the core; and 4) (+22.5°, 0°, −22.5°, 0°) repeated ply sequence for the whole blade. The last laminate configuration is usually called interspersed.

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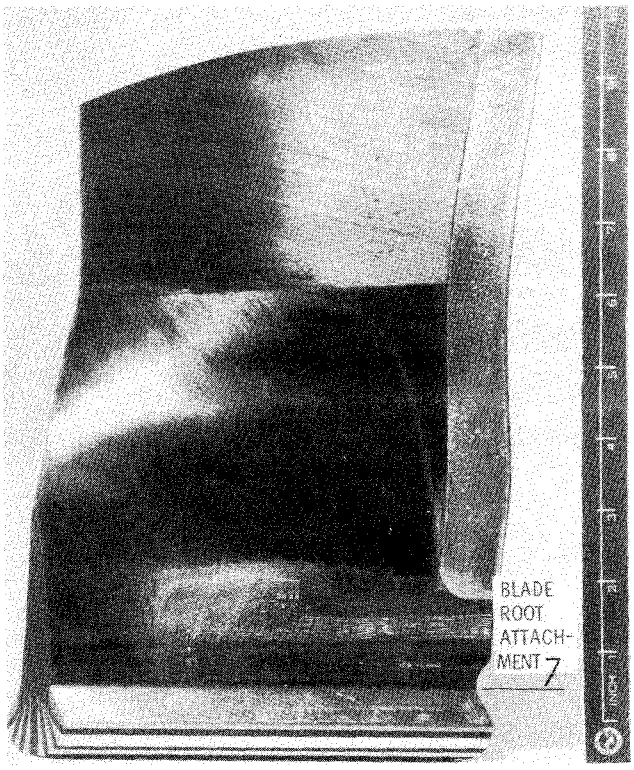


Fig. 1 High-tip-speed composite blade, HTS/K601 (±40°, ±20°, 0°).

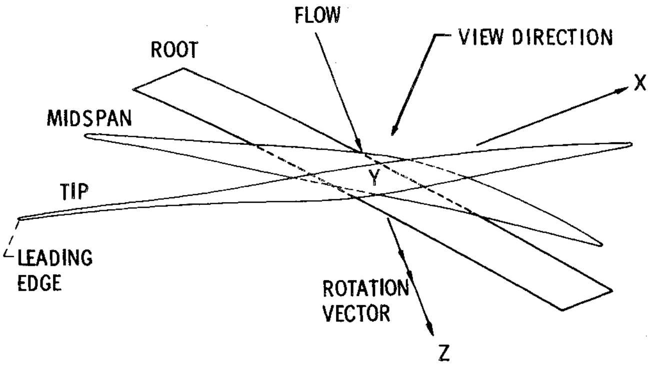


Fig. 2 Blade global coordinates used in NASTRAN and view direction for computer plots.

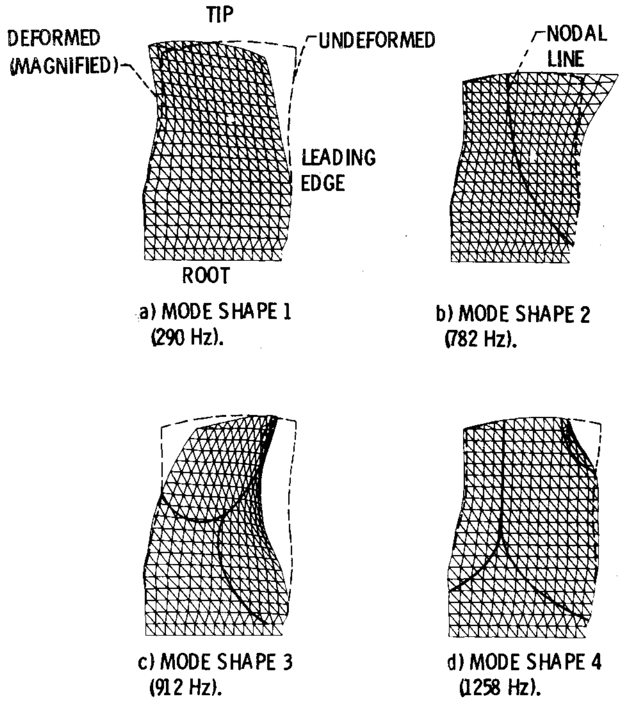


Fig. 3 Predicted vibration mode shapes for high-tip-speed composite blade, HTS/K601 (±40°, ±20°, 0°).

The effects of different composite systems on the vibration characteristics of the blade were investigated theoretically for three different composites: a high-strength-graphite fiber in two polyimide matrices (HTS/K601 and HTS/PMR) both with approximately 0.57 fiber volume ratio, and a titanium/beryllium adhesively bonded laminar composite with about 0.70 beryllium volume ratio. In the titanium/beryllium composite, the titanium lamina were 5 mil thick and the beryllium lamina were 10 mil thick.

The NASTRAN element anisotropic stress-strain relationships are represented by the following equation using NASTRAN Users' Manual notation:[4]

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{Bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{Bmatrix} \quad (1)$$

Typical values of these relationships, including density, as predicted by the preprocessor are shown in Table 1. Note that in this table two sets of values are shown: "0" voids and 20% voids. The 20% voids were used in the composites micromechanics of the preprocessor to simulate transply cracks.[2] This is an approximation and is based on visual estimation from photomicrographs of blade cross sections.

IV. Experimental Data

The experimental data used herein in the comparisons of vibration frequencies and mode shapes were obtained by Pratt and Whitney under contract (NAS3-15335) to NASA-Lewis Research Center. These data are for the cantilever frequencies and the corresponding vibration mode shapes. The data were determined using holography for a composite blade made from HTS/K601 with the (±40°, ±20°, 0°) laminate configuration.

Table 1 Representative element properties at radius 10.85 in. predicted by preprocessor for HTS/K601 composite system

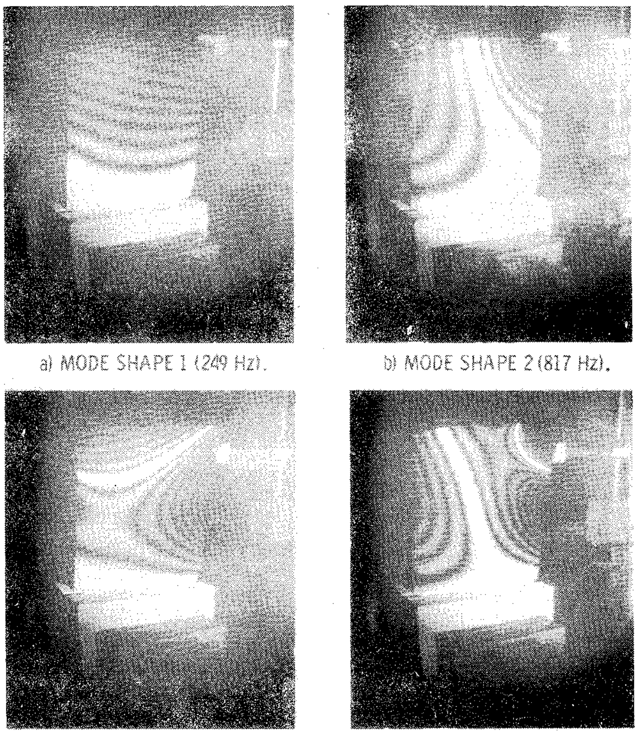
Property (NASTRAN element stress-strain relationships)	Leading edge		Midsection		Trailing edge	
	"0" Voids	20%[a] Voids	"0" Voids	20%[a] Voids	"0" Voids	20%[a] Voids
G_{11}, 10^6 psi	10.7	8.86	11.1	8.62	15.1	11.4
G_{12}, 10^6 psi	5.28	4.34	2.86	2.35	4.36	3.65
G_{13}, 10^6 psi	−0.75	−0.81	0.05	−0.08	−0.28	−0.56
G_{22}, 10^6 psi	6.24	5.26	3.68	3.05	5.47	4.51
G_{23}, 10^6 psi	−0.59	−0.51	−0.03	−0.05	−0.36	−0.34
G_{33}, 10^6 psi	6.09	5.06	3.39	2.81	5.13	4.30
ρ, 10^{-4} lb-sec^2/cm^2	1.45	1.45	1.45	1.45	1.45	1.45

[a] Used in preprocessor to simulate transply cracks due to residual stress.

Table 2 Composite blade vibration frequency comparisons [HTS/K601; (±40°, ±20°, 0°) laminate configuration]

Composite blade boundary condition and properties	Frequency Hz predicted/measured 1	2	3	4
Predicted				
Z-rotation restrained				
"0" voids	327	870	1078	1387
20% voids[a]	290	782	912	1258
Z-rotation free				
"0" voids	261	806	1024	1369
20% voids[a]	240	730	885	1242
Measured	249	817	932	1382

[a] Used in the preprocessor to simulate transply crack due to residual stress.



a) MODE SHAPE 1 (249 Hz). b) MODE SHAPE 2 (817 Hz). c) MODE SHAPE 3 (932 Hz). d) MODE SHAPE 4 (1382 Hz).

Fig. 4 Holographs of vibration mode shapes. High-tip-speed composite blade, HTS/K601 (±40°, ±20°, 0°).

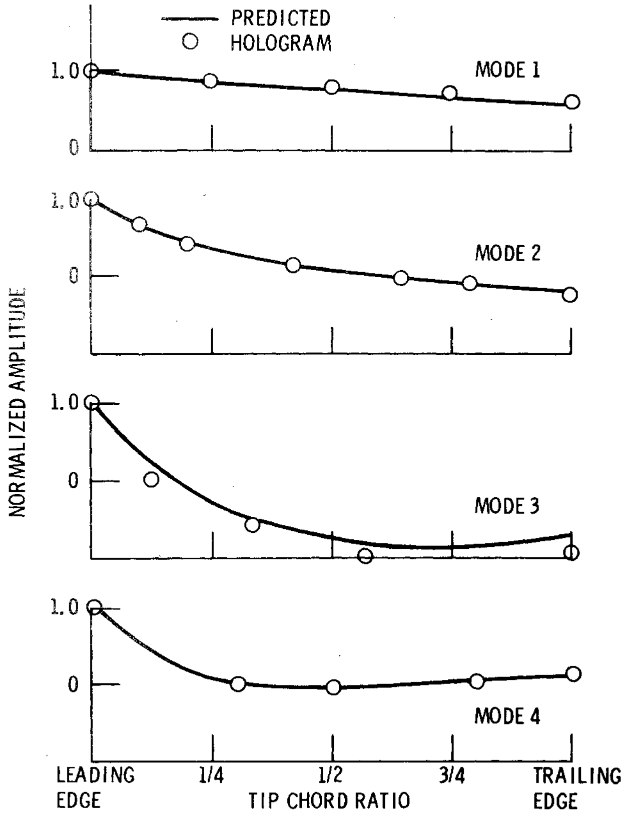


Fig. 5 Comparison of predicted and hologram-normalized amplitudes across the chord at the blade tip.

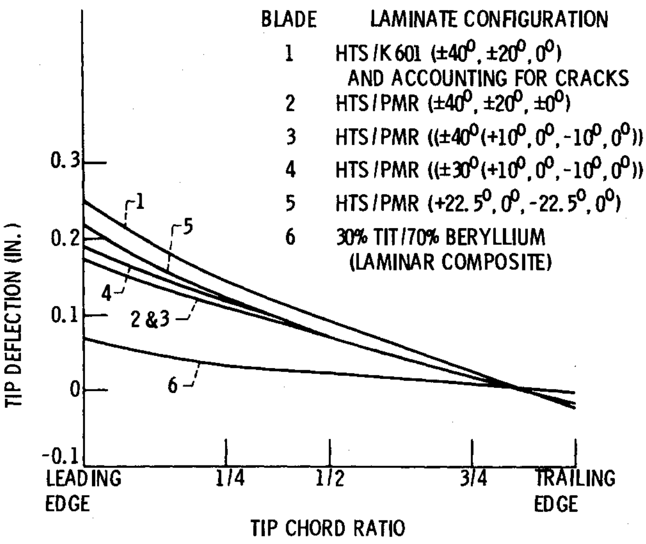


Fig. 6 Comparisons of tip deflections of high-tip-speed composite blade with different laminate configurations.

V. Results and Discussion

Predicted and measured data for the first four frequencies of the blade are summarized in Table 2. The data are for a composite blade made from HTS/K601 (±40°, ±20°, 0°) laminate configuration.

Four sets of predicted results are shown. These are for *Z*-rotation restrained with "0" and with 20% voids, and *Z*-rotation fixed with "0" and with 20% voids. The blade global coordinates used in NASTRAN are shown in Fig. 2. The view direction in Fig. 2 refers to the computer plots to be described later.

As can be seen in Table 2, the measured data are in good agreement with predicted results for the *Z*-rotation "free" case. As can also be seen in Table 2, the first frequence is more sensitive to both the *Z*-rotation condition and voids than the other frequencies. The *Z*-rotation condition effect is well known and was anticipated. The condition of 20% voids reduces all the frequencies by approximately 10%.

NASTRAN computer plots of the predicted mode shapes for the first four frequencies are shown in Fig. 3 for the *Z*-rotation restrained case and 20% voids. The view direction relative to the global axes in the NASTRAN model is shown in Fig. 2. The corresponding holograms are shown in Fig. 4. As can be observed by comparing corresponding mode shapes in Figs. 3 and 4, the predicted mode shapes are in remarkably good qualitative agreement with the holograms.

A quantitative comparison of the mode shapes is shown in Fig. 5, in which the normalized *Z* component (Fig. 4) of the amplitude is plotted along the chord at the tip of the blade. As can be observed from the plots in Fig. 5, the quantitative agreement between predicted amplitude and hologram amplitudes is very good.

The important observations from the above discussion are: 1) the physical characteristics of composite blades can be suitably represented in finite-element models; 2) the com-

Table 3 Summary of the first six modes of the high-tip-speed composite blade (HTS/PMR) consisting of various laminate configurations

BLADE	LAMINATE CONFIGURATION	FREQUENCY, Hz					
		MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6
REFERENCE	(±40°, ±20°, 0°)	400	960	1418	1658	2427	2836
VARIATION 1	(±40°, (+10°, 0°, −10°, 0°))	399	964	1416	1668	2425	2848
VARIATION 2	(±30°, (+10°, 0°, −10°, 0°))	385	919	1385	1551	2245	2664
VARIATION 3	(+22.5°, 0°, −22.5°, 0°)	355	846	1275	1337	1912	2397

Table 4 Comparison of frequencies of the high-tip-speed composite blade for three composite systems

MODE	FREQUENCIES (Hz) FOR COMPOSITE		
	HTS/K601 (±40°, ±20°, 0°)	HTS/PMR (±40°, ±20°, 0°)	[a]TIT./BERYLLIUM (30%/70%)
1	361	400	662
2	939	960	1608
3	1178	1418	2108
4	1485	1658	2333
5	----	2427	3253

[a] Lamina thickness: 5 mil, titanium; 10 mil, beryllium.
Note: Composite density (lb/in.^{3}): HTS/K601 ≈ 0.050; HTS/PMR ≈ 0.055; TIT/BER ≈ 0.085.

puterized analysis capability used herein predicts vibration frequencies and mode shapes of composite blades in good agreement with measured data; 3) the mode shapes are not easily distinguishable (due to coupling effects) as first bending, first torsion, etc., as is customary in blade vibration analysis; and 4) unconstrained Z rotation reduced the first frequency by about 21%, the second by 7%, the third by 3%, and the fourth by 1%.

The results of varying the laminate configuration (but keeping the composite system and airfoil geometry the same) on the blade vibration frequencies are summarized in Table 3. The results in this table are for a blade from the HTS/PMR composite and with four different laminate configurations, with "0" voids and "0"-Z rotation. As can be observed from the results in Table 3, only the laminate configuration (+22.5°, 0°, −22.5°, 0°) (interspersed) reduced the first three vibration frequencies by more than 5% when compared with the (±40°, ±20°, 0°) configuration. It should be noticed, however, that the decrease is greater for the higher modes.

Another point to be observed from the results in Table 3 is that the effect of the core plies is negligible on all six vibration frequencies of the blade with laminate configurations ±40° plies. This is so because of 1) the predominant contribution of the ±40° plies to the blade torsional stiffness and 2) the significant contribution of the torsional stiffness to the vibration frequencies of the blade.

The results of using three different composite systems (same airfoil geometry, "0" voids and "0" Z-rotation) on the blade frequencies are summarized in Table 4. The important observation from the results in Table 4 is that the blade vibration frequencies are substantially increased (about 50% when titanium/beryllium composite is used.

The effects of varying the laminate configuration and composite system on the blade tip deflection under the steady-state loads previously mentioned are shown graphically in Fig. 6. As can be seen in this figure, the variations in the laminate configuration of the same composite system have only a small effect on the tip deflections, whereas the titanium/beryllium composite system has the least deflection.

VI. Conclusions

The results of this investigation lead to the following conclusions:

1) The computerized capability consisting of NASTRAN coupled with composite mechanics via pre- and post-processors predicted vibration frequencies and mode shapes that were in good agreement with measured data. This suggests that this type of capability appears to be adequate for determining the vibration characteristics of composite blades.

2) Variations in the laminate configurations from the same composite system generally had relatively small effects on both tip deflections and vibration modes (less than 5% for the first three modes). The presence of voids and Z-rotation fixity, however, have significant effects.

3) The Z-rotation effect is greater on the first frequence than on the higher ones (about 21% versus 7% maximum).

4) Of the composites investigated, the 30% titanium/70% beryllium adhesively bonded laminar composite gave the least blade tip deflection and the highest vibration frequencies. These characteristics are attractive enough to warrant further work on fabrication and other experimental evaluations of this type of composite blade.

References

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