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by C. C. Chamis
Lewis Research Center
Cleveland, Ohio 44135

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Cleveland, Ohio 44135

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ABSTRACT

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 reasonable 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 for 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 for 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.
3. Selection of composite systems for altering the vibration characteristics described in (2) above but when only the airfoil shape has been fixed.

The objectives of this investigation were:

1. To report on comparative results between predicted and measured data for vibration characteristics.
2. To investigate the effects of selected laminate configuration and different composite systems on the blade vibration characteristics and tip displacements.

The blade geometry, the computerized analysis method, 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. BLADE DESCRIPTION

The composite blade for which comparison results between theory and experiment are presented was made from HTS graphite fibers in K601 polyimide matrix (HTS/K601). The blade tip radius was approximately 16.3 inches. The rotor inlet aerodynamic hub-tip ratio was about 0.5. The root attachment chord was approximately 7.8 inches (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 pressure ratio of 2.8 and a tip speed of 2200 ft/sec. The thickness percentages for ply orientations in this blade design were approximately 30 percent $\pm 40^\circ$ plies for the blade shell and approximately 70 percent 0° plies for the core. In addition there were two $\pm 20^\circ$ plies for transition between the shell and core plies. Near the blade tip, two surface plies ($\pm 70^\circ$) were used to minimize chordwise deflections.

III. COMPUTERIZED ANALYSIS CAPABILITY DESCRIPTION

The computerized analysis capability (Ref. 2) consists of using NASTRAN in conjunction with composite mechanics embedded in pre- and postprocessors. The pre- and postprocessors 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.
3. Anisotropic material properties generated from input constituent properties, fiber volume ratio, void ratio, 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 logic of this computer capability is illustrated schematically in the flow chart (Fig. 2). 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. A schematic of the finite element representation is shown in Fig. 3. The finite element representation consists of 299 nodes and 531 elements.

IV. LAMINATE CONFIGURATIONS AND COMPOSITE SYSTEMS INVESTIGATED

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°, 0°) repeated ply sequence for the core; (3) ±30° plies for the shell and (+10°, 0°, -10°, 0°) 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.

The effects of different composite systems on the vibration characteristics of the blade were investigated theoretically for three different composites: a high-modulus-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 mils thick and the beryllium lamina were 10 mils thick.

V. 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.

VI. RESULTS AND DISCUSSION

The predicted, magnified, deformed shape due to blade steady state loads (aerodynamic pressure and temperature, and centrifugal forces) is shown in Fig. 4. The blade analyzed was made from HTS/K601 (±40°, ±20°, 0°) composite. As can be seen in Fig. 4 there is significant relative blade overall deformation, in particular, at the leading edge tip. The blade chordwise deformation results, primarily, from the untwisting and uncambering of the blade.

Predicted and measured data for the first four frequencies of the blade are summarized in table I. The data are for a composite blade made from HTS/K601 (±40°, ±20°, 0°) laminate configuration. The predicted data were determined by modifying the ply properties to account for transply cracks (Ref. 2). These cracks were present in the blade as a result of high transverse lamination residual stresses. The cracks were eliminated subsequently by changing the polyimide resin.

As can be observed in table I predicted results are in reasonable agreement with the measured data except for the first mode. However, it is known that the first frequency may be affected by the end fixity conditions assumed for the end support. In the NASTRAN model, used herein, the boundary conditions applied to the blade root consisted of fixing the three translations in nodes 1 to 15, Fig. 3. For better correlation the support needs also to be modeled in the analysis.

The predicted mode shapes (computer plots) for the first four frequencies are shown in Fig. 5. The corresponding holograms are shown in Fig. 6. As can be seen by comparing corresponding mode shapes in Figs. 5 and 6, the predicted mode shapes are in remarkably good agreement with the holograms.

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 computerized analysis capability used herein predicts vibration frequencies and mode shapes of composite blades which are in reasonable agreement with measured data, and (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.

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 II. The results in this table are for a blade from the HTS/PMR composite and with four different laminate configurations. As can be observed from the results in table II, only the laminate configuration (+22.5°, 0°, -22.5°, 0°) (interspersed) reduced the first three vibration frequencies by more than 5 percent 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 II 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) on the blade frequencies are summarized in table III. The important observation from the results in table III is that the blade vibration frequencies are substantially increased (about 50 percent) 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. 7. 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 while the titanium/beryllium composite system has the least deflection.

VII. 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 postprocessors predicted vibration frequencies and mode shapes which were in reasonable 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 percent for the first three modes). The presence of voids and partial delaminations, however, have significant effects.

3. 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.

VIII. REFERENCES

1. Hanson, M. P. and Chamis, C. C.: Graphite-Polyimide Composites for Applications to Aircraft Engines. NASA TN D-7698, 1974.

2. Chamis, C. C. and Lynch, J. E.: High-Tip Speed Fiber Composite Compressor Blades: Vibration and Strength Analysis. NASA TM X-71589, 1974.

3. Chamis, C. C. and Minich, M. D.: Structural Response of a Fiber Composite Compressor Fan Blade Airfoil. NASA TM X-71623, 1975.

TABLE I. - COMPOSITE BLADE VIBRATION FREQUENCY COMPARISONS (HTS/K601; (±40°, ±20°, 0°) LAMINATE CONFIGURATION)

COMPOSITE BLADE	FREQUENCY CPS PREDICTED/MEASURED			
	1	2	3	4
PREDICTED	290	782	912	1258
MEASURED	249	817	932	1382

TABLE II. - 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 III. - COMPARISONS 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 MILL FOR TITANIUM, 10 MILL FOR BERYLLIUM.

NOTE: COMPOSITE DENSITY, (LB/IN.^{3}): HTS/K601 ≈ 0.050
HTS/PMR ≈ 0.055
TIT./BER. ≈ 0.085

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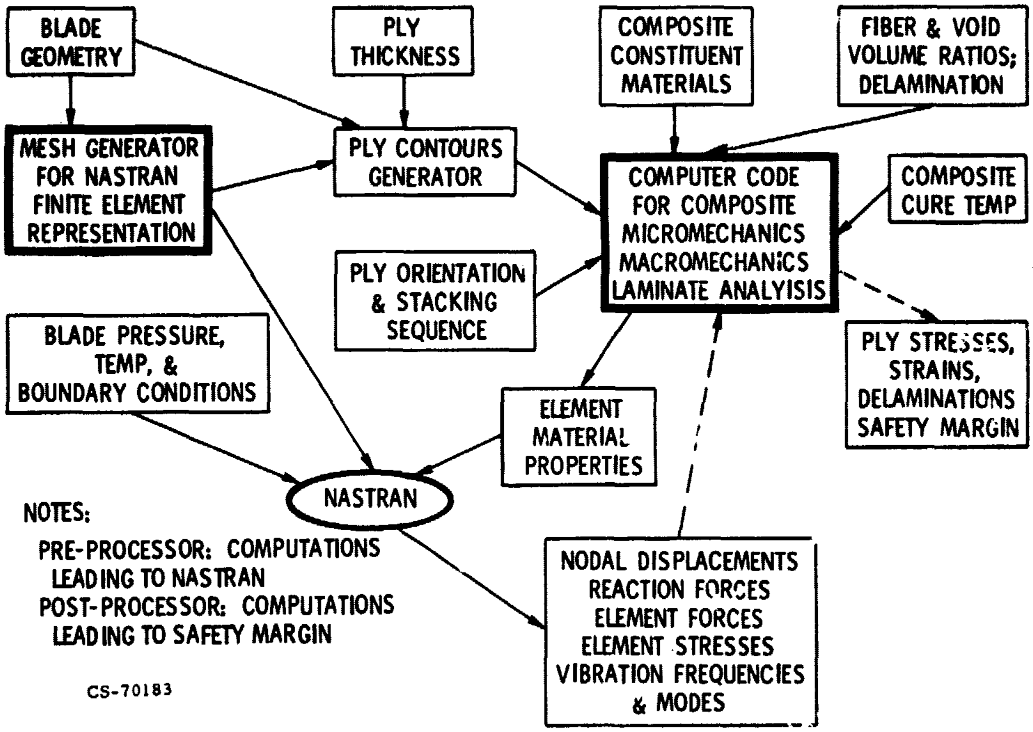

Figure 2. - Analysis of fiber composite blade using NASTRAN.

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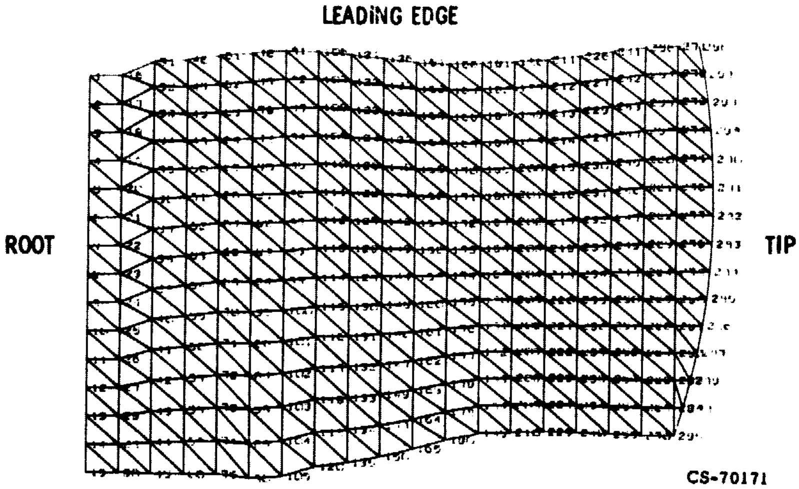

Figure 3. - NASTRAN finite element representation for fiber composite blade.

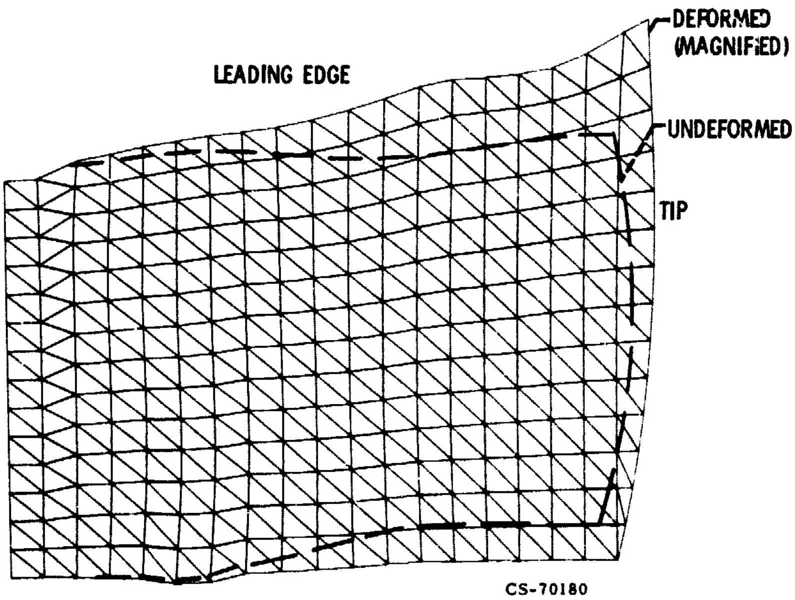

Figure 4. - Composite blade shape at 100% design speed, including centrifugal stiffening effects.

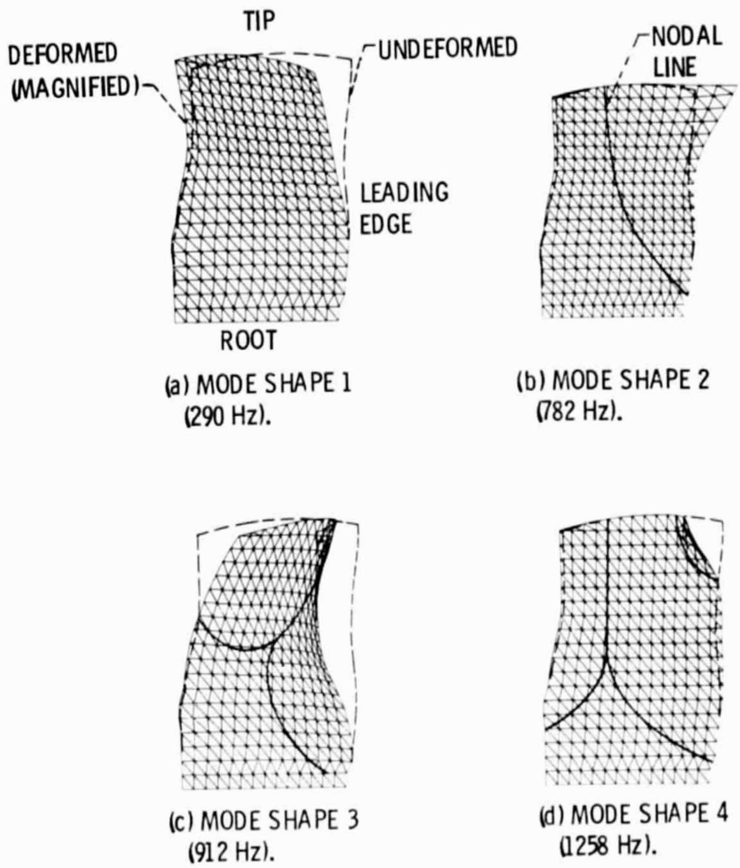

Figure 5. - Predicted vibration mode shapes for high-tip-speed composite blade, HTS/K601, ($\pm 40^0, \pm 20^0, 0^0$).

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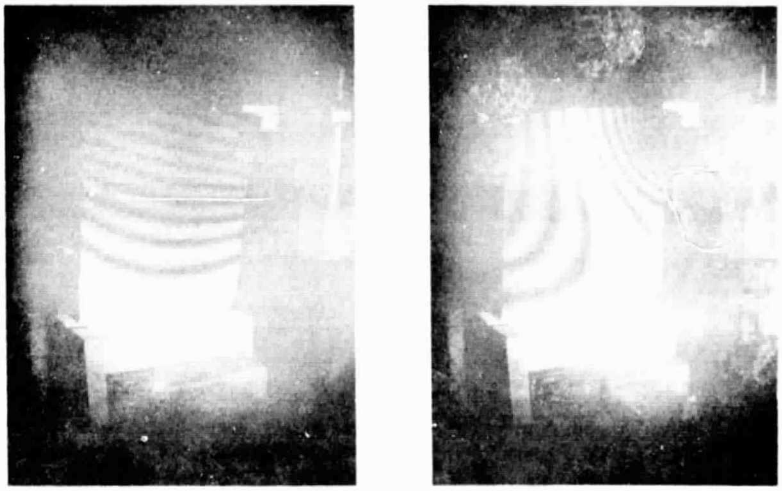
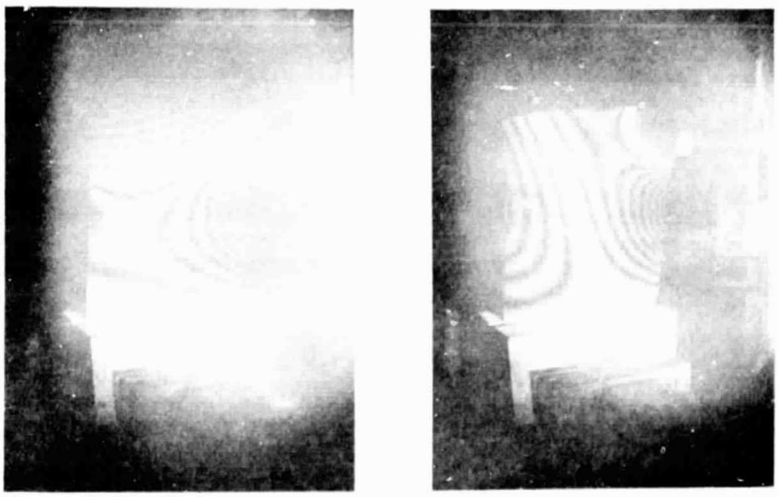


(a) MODE SHAPE 1 (249 Hz). (b) MODE SHAPE 2 (817 Hz).



(c) MODE SHAPE 3 (932 Hz). (d) MODE SHAPE 4 (1382 Hz).

Figure 6. - Holographs of vibration mode shapes. High-tip-speed composite blade, HTS/K601 (±40, ±20, 0).

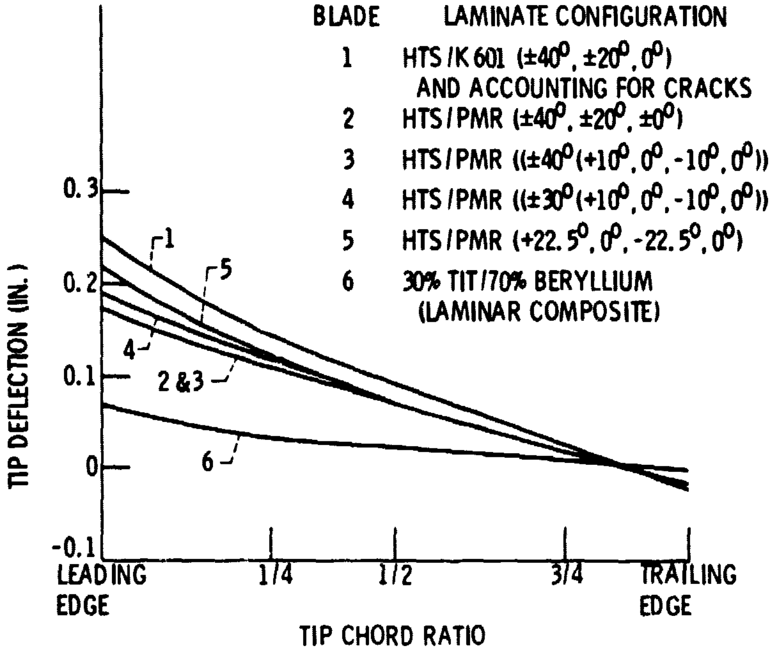


Figure 7. - Comparisons of tip deflections of high-tip-speed composite blade with different laminate configurations.