NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4342

FLIGHT MEASUREMENTS OF THE VIBRATORY BENDING AND TORSIONAL STRESSES ON A MODIFIED SUPERSONIC PROPELLER FOR FORWARD MACH NUMBERS UP TO 0.95

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SUMMARY

Vibratory stress measurements were obtained in flight on a modified supersonic propeller for forward Mach numbers up to 0.95. The magnitude of the vibratory bending stress was low in relation to the strength of the material throughout the flight range of the airplane. Vibratory bending stress was primarily once-per-revolution stress (1-P), with some 3-P stress evident at Mach numbers above 0.85.

Torsional stresses did not exceed ±1,000 pounds per square inch throughout the flight range. Torsional-stress measurements during ground tests of the propeller indicated no stall flutter when tested in a four-blade configuration. Ground measurements on a three-blade configuration indicated stall flutter had begun to occur at a blade angle of 19.5°.

Results of a propeller feathering operation at a Mach number of 0.95 indicated no excessive stresses. Vibratory bending stress did not exceed ±10,000 pounds per square inch whereas the vibratory torsional stress did not exceed ±1,000 pounds per square inch.

INTRODUCTION

Airplane propellers can be designed to give good efficiencies at high subsonic forward Mach numbers. A propeller designed for these speeds is characterized by the use of thin blade sections at supersonic resultant Mach number in order to attain an optimum advance angle for maximum profile efficiency. This procedure yields a design that is known as a supersonic propeller. A structural and an aerodynamic investigation of such a propeller is reported in references 1 and 2.

In order to study the effects of relaxation of the requirement of optimum advance ratio on the propeller performance, a propeller has been investigated in which the advance ratio is higher than optimum. Such a propeller is referred to as a modified supersonic propeller. The modified supersonic propeller still maintains the use of thin blades which focuses attention on the vibratory-stress characteristics of the propeller.

The vibratory stresses of major importance are the 1-P and stall flutter stresses. The 1-P stress is the stress that occurs once per revolution due to the oscillating aerodynamic load imposed on the propeller as a result of inclination of the thrust axis. (See refs. 3 and 4.) The use of thin blade sections results in a more flexible blade, which in turn lowers the natural bending frequency to a value closer to the operating rotational speed with attendant magnification of the 1-P stress. Since the supersonic as well as the modified propellers have thin flexible blades with low values of torsional frequency, they are more susceptible to stall flutter. (See ref. 5.)

This paper presents flight measurements of the vibratory bending and torsion stresses for a modified supersonic propeller, which are indicative of the 1-P and flutter stresses. Results are presented for level-flight conditions at approximately 25,000 feet and forward Mach numbers up to 0.95. These conditions are representative of the cruise conditions in which such a propeller might be operated.

SYMBOLS

a_n airplane normal acceleration, g units

A local angle of inclination of thrust axis with free-stream, measured at propeller plane, deg

b blade chord, ft

D propeller diameter, ft

h blade thickness, ft

M free-stream Mach number

M_x blade-section Mach number at design forward Mach number of 0.95

q	free-stream dynamic pressure, lb/sq ft
x	radial location, percent radius
β	blade angle, deg
$\beta_{0.7r}$	blade angle measured at 70-percent radial location, deg

EQUIPMENT

The propeller had a diameter of 9.8 feet and was designed for a forward Mach number of 0.95 and an advance ratio of 3.2. The propeller was designed as a four-blade configuration; however, it was always flown as a three-blade installation. One series of ground tests was made with the four-blade configuration of 10-foot diameter. The difference in diameter (0.2 foot) results from the fact that the four-way hub is slightly larger in diameter than the three-way hub. The blades are solid and made of heat-treated SAE 4340 steel. The propeller is predicted by the calculations of reference 6 to be structurally adequate for use in flight under airplane maneuver load factors up to 2.0. The Goodman diagram used for this propeller has terminal points at an ultimate tensile stress of 180,000 pounds per square inch and a working endurance limit of ±56,000 pounds per square inch. (See ref. 6.) The blade is composed of NACA 16-series symmetrical airfoil sections, and the plan form is tapered from a 16.1-inch chord at the spinner surface to an 11.6-inch chord at the tip, while thickness varies from 5.4 percent to 2 percent of the chord. The blade-form curves are shown in figure 1. This propeller is a scaled-up version of the supersonic propeller of reference 1, differing only in pitch distribution.

The propeller has an experimentally determined first natural (nonrotating) bending frequency of 12 cps and a first torsion frequency of 97 cps. It is predicted in reference 6 that the operating speed of the propeller will be far removed from (1-P) resonance and there will be no attendant stress magnification.

The propeller was tested in conjunction with a conical spinner. (See fig. 2.) The spinner has a 17.5-inch base radius and an included nose angle of 41°.

The propeller flight test vehicle is the McDonnell XF-88B airplane which was modified by the addition of a turboprop engine in the nose. (See fig. 3.) General specifications of the airplane can be found in reference 2. The turboprop engine drives the propeller at 1,710 rpm during all normal operating conditions.

INSTRUMENTATION

Determination of Stress

One of the propeller blades was instrumented with three strain-gage bridges (fig. 2) for measuring vibratory bending strain and one bridge for measuring vibratory torsional strain. The bridges were located on the blade center line, with the bending gages at 31.4, 33.1, and 38.2 percent radius and the torsion gage at 73.9 percent radius. The gages were located so as to bracket the positions of maximum vibratory stress calculated in reference 6.

A four-component strain-gage bridge was located at each strain measuring station. The four gages were used to attain the desired output sensitivity as well as to cancel gage outputs due to centrifugal forces and minimize the effect of temperature changes. The output of the strain-gage bridges was recorded on a Consolidated oscillograph. The galvanometers used to record bending strain had a response curve that was flat to 100 cps; the response curve of the galvanometer used to record torsion strain was flat to 190 cps. A sample record showing the recorded wave shape is presented in figure 4.

Determination of Aq

The Aq factor, or the local angle of inclination of the thrust axis at the propeller plane (measured relative to the free stream) times the dynamic pressure, was determined during flight tests without a propeller installed, as described in reference 1. Angle determination is considered accurate to $\pm 0.2^{\circ}$.

General Airplane Instrumentation

The source of static and total pressure for the airspeed system was a Kollsman type 651 pitot-static head, mounted 1 tip chord length ahead of the wing tip of the airplane. The impact pressure and static pressure were recorded with a standard NACA airspeed recorder. Measurement of airplane normal acceleration, propeller-root blade angle, and propeller rotational speed was made using standard NACA instrumentation.

TESTS AND PROCEDURE

Strain-gage records were obtained during engine starts at 5,000 feet and during essentially level flight at approximately 25,000 feet. For the engine starts, the recording equipment was turned on while the propeller was feathered and remained on until the propeller was operating at flight idling rotational speed (1,380 rpm). The flight records were obtained during level-flight acceleration to maximum Mach number by increased main-jet power followed by a shallow dive. The power coefficient of the propeller during the tests varied from 0.39 to 0.43, the thrust coefficient varied from 0.12 to 0.09, and the advance ratio ranged up to 3.6.

The stress values were determined from visual inspection of the strain-gage records simply by reading amplitudes throughout the record length whenever there were significant variations in strain.

RESULTS AND DISCUSSION

Vibratory Bending Stress

The variation of vibratory bending stress, excitation factor Aq, and normal acceleration with flight Mach number for a typical flight test at 25,000 feet is presented in figure 5. The variation of normal acceleration is presented to reflect the flight path of the airplane, which is in turn related closely to the variation of Aq, the 1-P excitation factor. The excitation factor Aq, the product of inclination of the propeller and dynamic pressure, corresponds to the flight condition for which stress was measured. The angle A is the inclination of the thrust axis relative to the free stream; therefore, the determination of Aq does not include the effect of differences in induced angle at radial locations along the blade.

The strain records indicate an almost pure 1-P wave shape for Mach numbers up to approximately 0.85. This evidence of 1-P stress is reflected in the variation of vibratory bending stress (fig. 5) in that the stress follows the variation of Aq for this Mach number range. Above $M = 0.85$ the stress does not follow the variation of Aq. This indicates that the vibration is no longer predominantly 1-P because there are other frequencies present. This is borne out by the strain records which are no longer predominantly 1-P but contain other frequencies, especially 3-P.

The ratio of 1-P stress to Aq is predicted in reference 6 to occur at the 31-percent radial location and to increase in value almost linearly from 12 to 14 for the Mach number range from 0.75 to 0.95. The experimental values of stress per Aq for Mach numbers less than 0.85 should agree with that predicted; as the wave shape indicates, the vibration is predominantly 1-P. The results obtained in flight indicate a maximum stress per Aq of 13.7 ± 1.0 for the Mach number range from 0.75 to 0.85 at the 31.4-percent radial location. The value of 13.7 is the mean of all the measurements in this Mach number range while the ±1.0 represents scatter. An investigation was made in an attempt to find the reason for the scatter. The possibility of changes in yaw was considered and found to be negligible. Also, a brief investigation of the effect of pitching velocity was considered and found to have no effect on the scatter. The most likely conjecture is that these changes in acceleration coupled with a possible error in the estimate of the slope of the lift curve are the major contributions to the scatter.

A check on the vibratory bending stresses that the propeller might be subjected to through the normal flight test range of the McDonnell XF-88B airplane can be estimated from reference 1. This reference presents the variation of Aq with Mach number for the range of altitude and maneuver load factors that the airplane is normally operated through. Use of the experimentally determined 1-P stress per Aq of 13.7 indicates the stress. The maximum excitation factor that could be expected with the McDonnell XF-88B airplane in the range of Mach numbers would be 1,300 degree-pounds per square foot at a maneuver load factor of 2.0g at 30,000 feet and a Mach number of 0.75. The resulting 1-P stress would be 17,800 pounds per square inch. Under these conditions the maximum steady stress would not exceed 30,000 pounds per square inch. The bending stresses encountered in this installation are low in relation to the strength of the material based on a Goodman diagram with terminal points at an ultimate tensile strength of 180,000 pounds per square inch and a working endurance limit of ±56,000 pounds per square inch. This combination of steady and vibratory stress would result in a factor of safety of 2.7. The change in inclination of the thrust axis of the test airplane is small; however, other propeller installations such as those found on transports, bombers, and long-range fighters experience considerable change in wing loading with correspondingly large changes in stress.

Vibratory Torsional Stress

The propeller was predicted by the calculations of reference 6 to be free of flutter throughout the operational range of the airplane. This prediction was borne out by the flight test program. Torsional stress data were obtained from the strain measurement at the 73.9-percent radial location. The measurement of torsional stress did not exceed ±1,000 pounds per square inch throughout the flight range.

The results of vibratory torsional stress measurements during ground tests for a three-blade and four-blade configuration are presented in figure 6. The three-blade propeller was partly stalled and had begun to flutter at a blade angle of 19.5° as evidenced by the rapid stress rise and from examination of the recorded wave shape. The record showed the characteristic rapid rise in stress at a frequency of 100 cps compared with the calculated natural torsional frequency of 100 cps in reference 6. The four-blade configuration, which was tested on the ground only, absorbed maximum power (2,500 horsepower) without any evidence of flutter. The blade angle was not advanced beyond 19.6° as the engine reached its maximum allowable temperature at this setting. Since the propeller was designed for a four-blade installation, although flown with only three blades, the design is considered flutter-free for all operating conditions.

Engine-Start Condition

A time history of the vibratory bending stress, blade angle, and rotational speed during an air start of the engine is presented in figure 7. The start occurred at an altitude of 5,000 feet at an airspeed of 250 miles per hour. The start resulted in a maximum vibratory stress of ±6,000 pounds per square inch. This stress occurs during the time the propeller is windmilling and accelerating the engine to starting speed. The rotational speed is approximately 200 rpm and the blade angle has just reached its starting angle of 62°. The peak stress level appears to be a result of four-per-revolution (4-P) resonance in the first mode. The wave shape of the stress record indicates a strong 4-P component on top of the basic 1-P component. The 4-P component appears and the overall stress builds up rapidly to a peak and decreases equally fast as the 4-P component disappears. The leveling off of the rotational speed and stress occurs while the engine control system is firing the engine. The rapid rise in rotational speed after 30 seconds indicates that the engine has started, and the rotational speed rises until flight idling rotational speed is attained (1,380 rpm). The momentary decrease in stress during this time is due to the airplane trim change, and corresponding change in 1-P excitation, that occurs during an air start. The torsion stress does not exceed ±1,000 pounds per square inch during the start.

Propeller Feathering Operation

A time history of the propeller feathering operation at $M = 0.95$ showing vibratory bending stress, blade angle, and rotational speed is presented in figure 8. The feathering occurred because of a control malfunction during a rapid pushover into a steep dive. The results of the feathering operation indicated no excessive stresses. The vibratory bending stress did not exceed ±10,000 pounds per square inch whereas the vibratory torsional stress did not exceed ±1,000 pounds per square inch.

The bending stress decreases slightly at the beginning of the operation due to a decrease in 1-P excitation. The rapid rise in stress beginning after 1 second is a result of the increase in blade angle which results in increased incremental angle of attack as the blade traverses around the disk as well as an increase in angle of inclination of the thrust axis shown by an increased normal acceleration. The drop in stress after 3 seconds while the blade angle is still increasing is due to the low propeller rotational speed at this time. Apparently, at rotational speeds lower than 900 rpm, the excitation is reduced sufficiently that the stress level drops rapidly.

CONCLUDING REMARKS

Results are presented of vibratory stress measurements obtained in flight on a modified supersonic propeller for forward Mach numbers up to 0.95.

The magnitude of the vibratory bending stress was low in relation to the strength of the material throughout the flight range of the airplane. Vibratory bending stress was primarily once-per-revolution stress (1-P), with some 3-P stress evident at Mach numbers above 0.85. Torsional stresses did not exceed ±1,000 pounds per square inch.

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Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 28, 1958.

REFERENCES

1. O'Bryan, Thomas C.: Flight Measurements of the Vibratory Bending and Torsion Stress on a Supersonic-Type Propeller for Flight Mach Numbers Up to 0.95. NACA RM L56D20a, 1956.

2. Hammack, Jerome B., Kurbjun, Max C., and O'Bryan, Thomas C.: Flight Investigation of a Supersonic Propeller on a Propeller Research Vehicle at Mach Numbers Up to 1.01. NACA RM L57E20, 1957.

3. Gray, W. H., Hallissy, J. M., Jr., and Heath, A. R., Jr.: A Wind-Tunnel Investigation of the Effects of Thrust-Axis Inclination on Propeller First-Order Vibration. NACA Rep. 1205, 1954. (Supersedes NACA RM L50D13.)

4. Rogallo, Vernon L., Roberts, John C., and Oldaker, Merritt R.: Vibratory Stresses in Propellers Operating in the Flow Field of a Wing-Nacelle-Fuselage Combination. NACA TN 2308, 1951.

5. Baker, John E.: The Effects of Various Parameters, Including Mach Number, on Propeller-Blade Flutter With Emphasis on Stall Flutter. NACA TN 3357, 1955. (Supersedes NACA RM L50L12b.)

6. LaMont, C. W.: Structural Analysis of the 150010 Supersonic Blade Design. Rep. No. C-2484, Curtiss-Wright Corp., Propeller Div. (Caldwell, N. J.), Jan. 4, 1954.

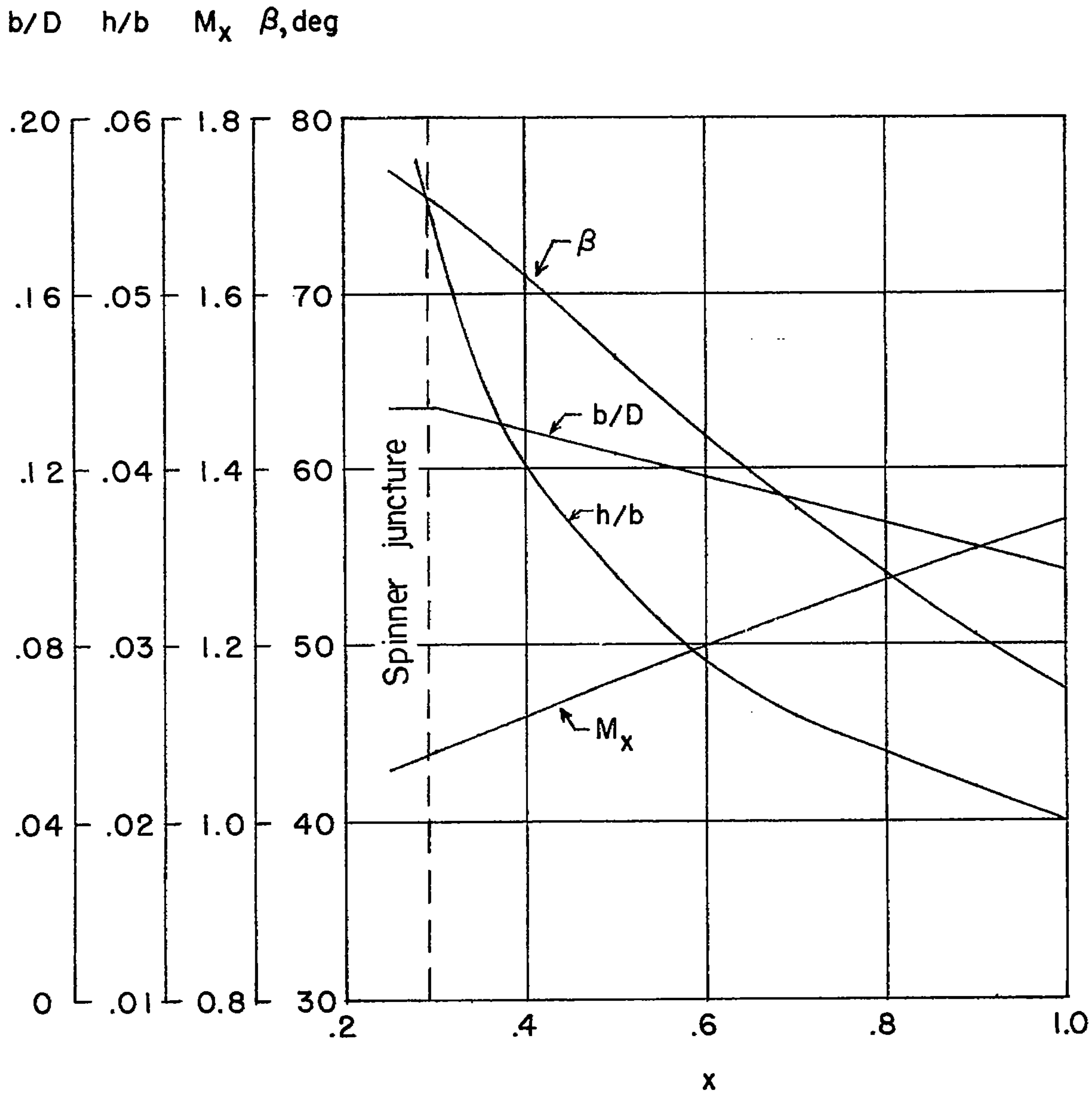

Figure 1.- Blade-form curves for 9.8-foot modified supersonic propeller.

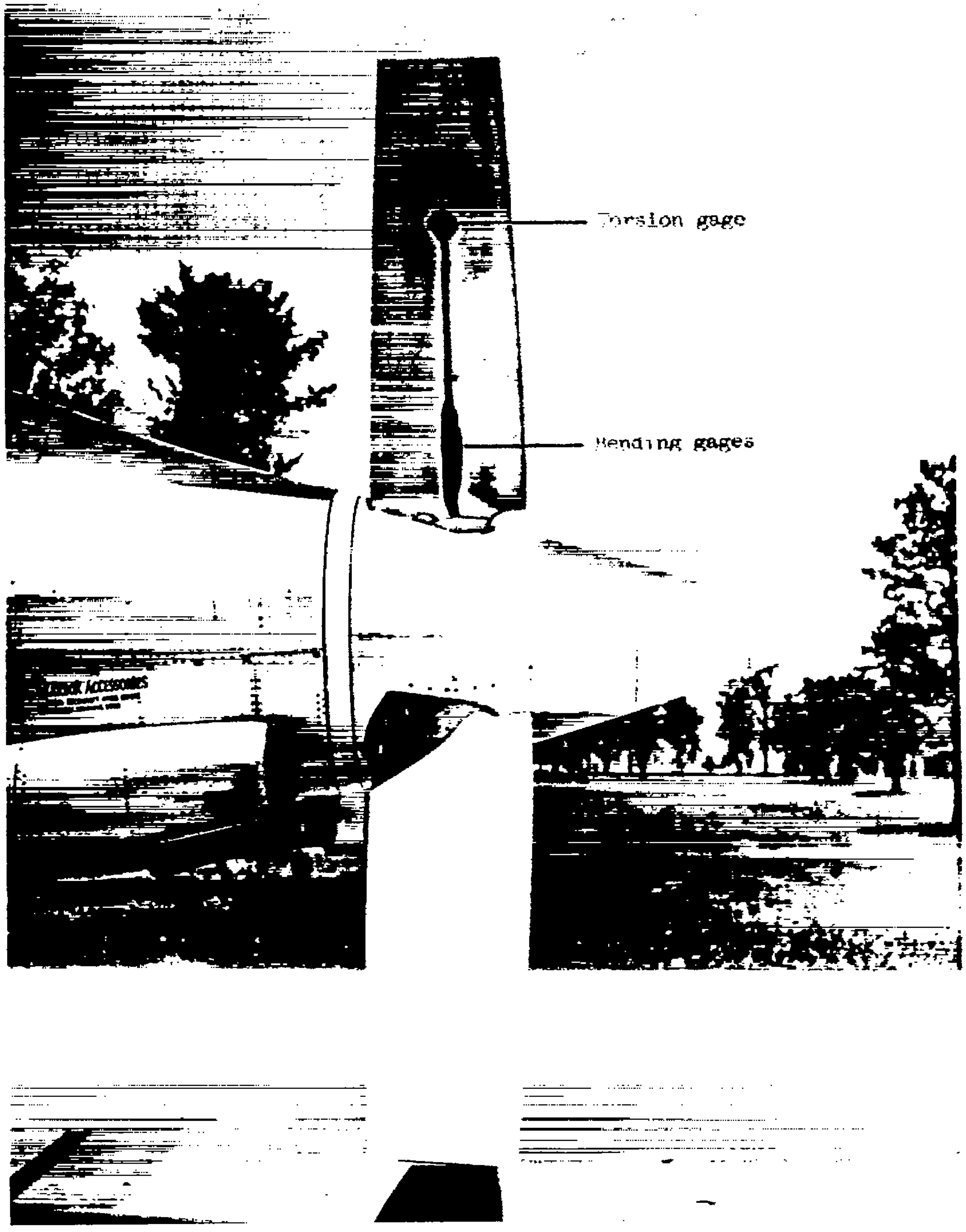

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Figure 2.- Photograph of modified supersonic propeller and conical spinner installed on test airplane.

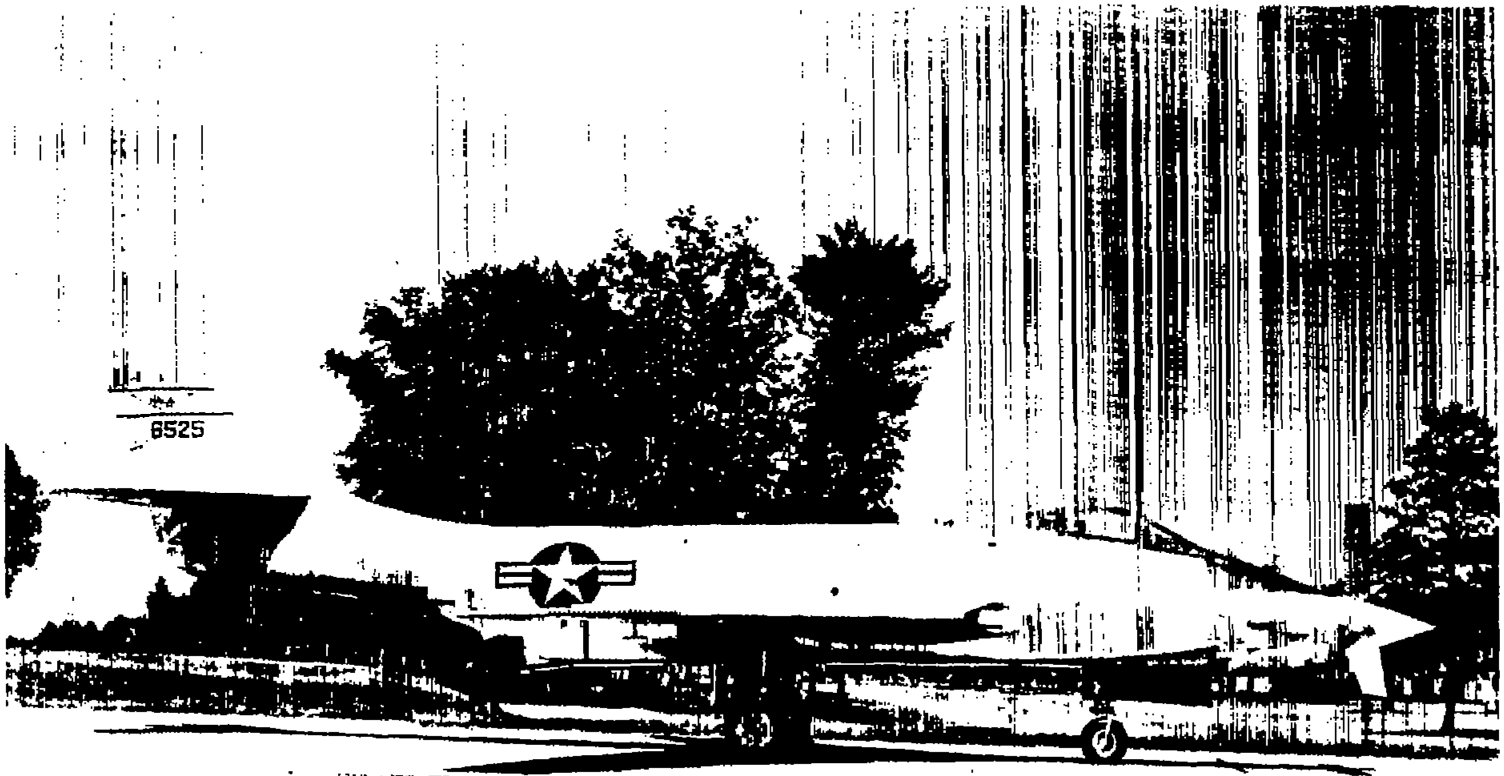

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Figure 3.- Photograph of McDonnell XF-88B airplane showing test propeller installation.

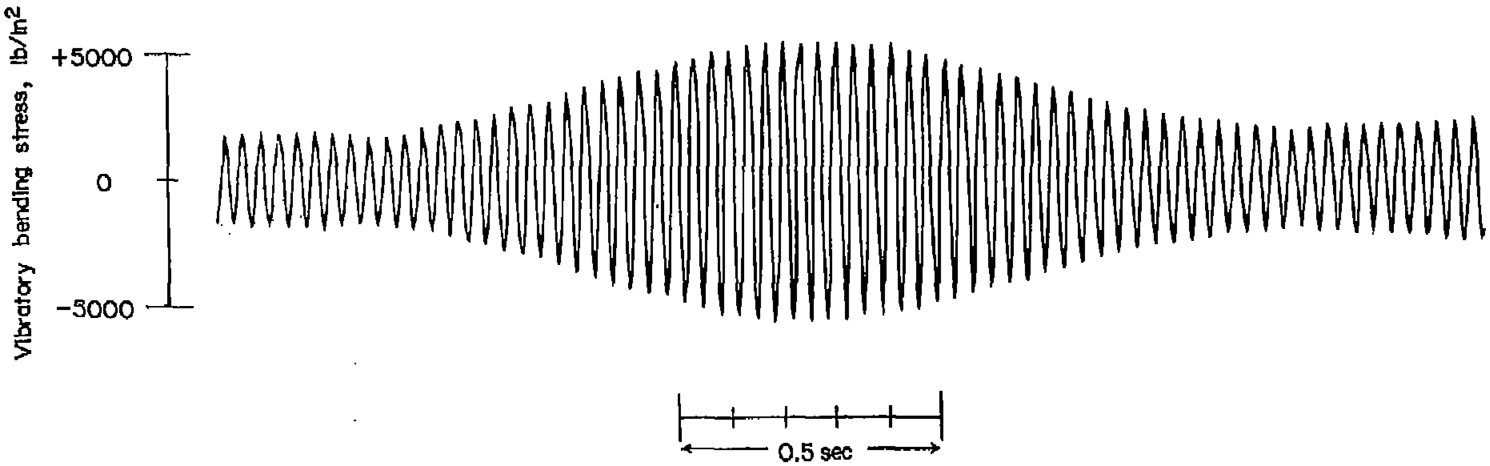

Figure 4.- Typical wave shape of vibratory bending record. M = 0.75.

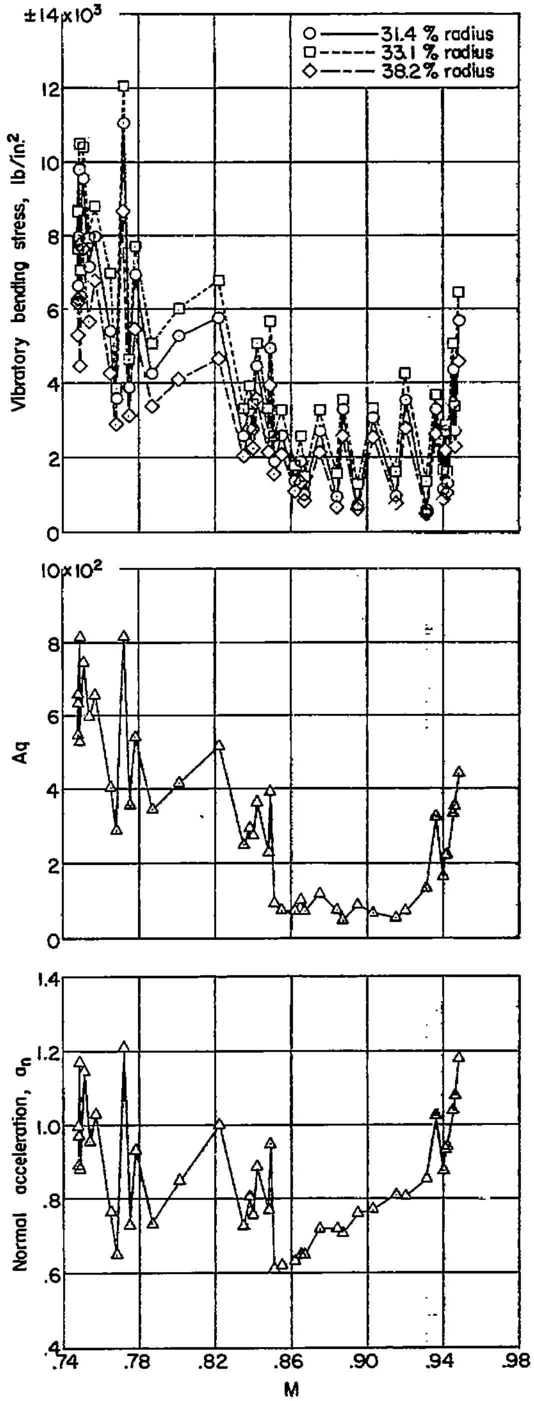

Figure 5.- Variation with Mach number of vibratory bending stress, excitation factor Aq, and normal acceleration for a typical flight run.

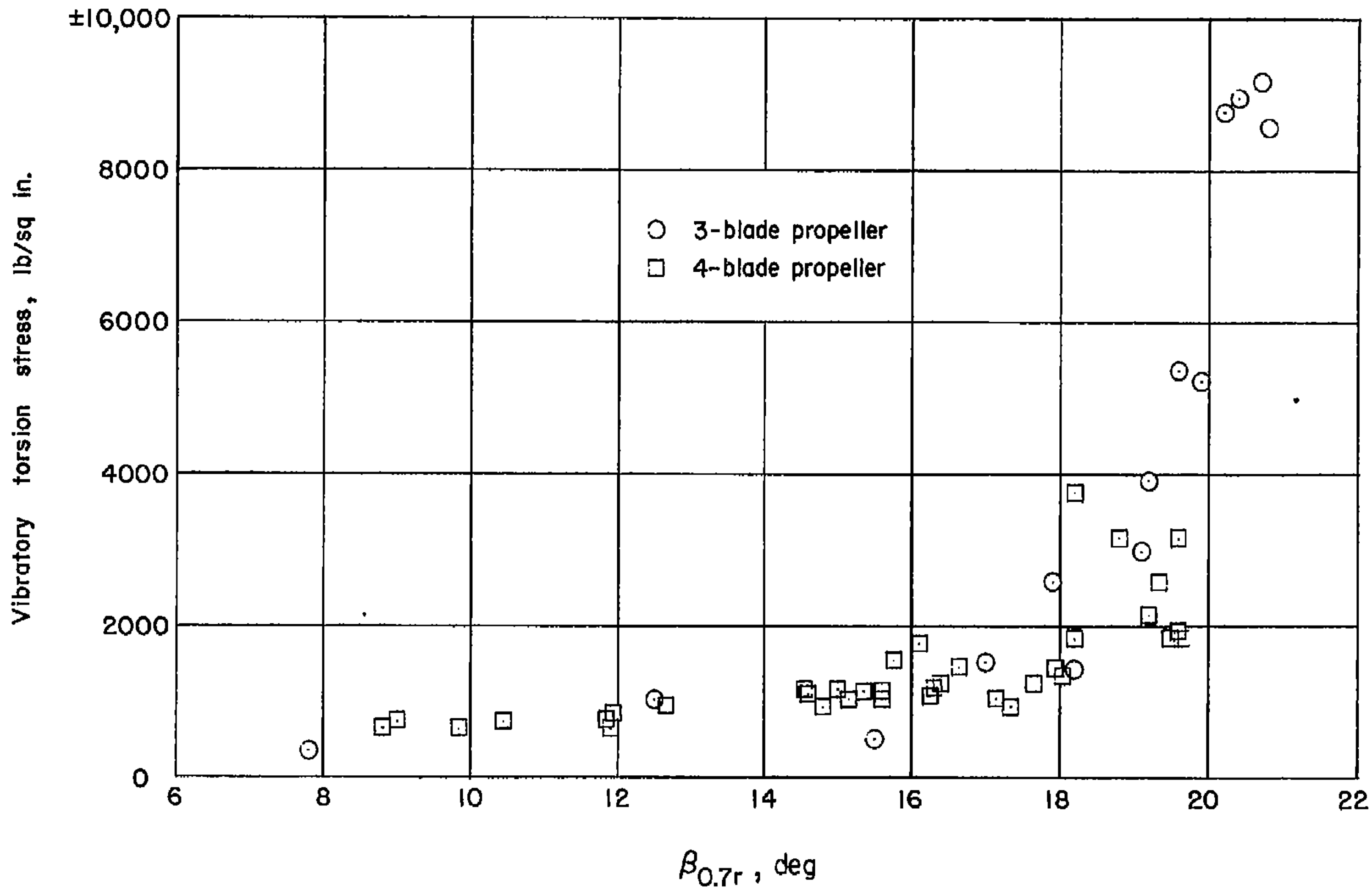

Figure 6.- Torsional stress measurements during static testing of propeller.

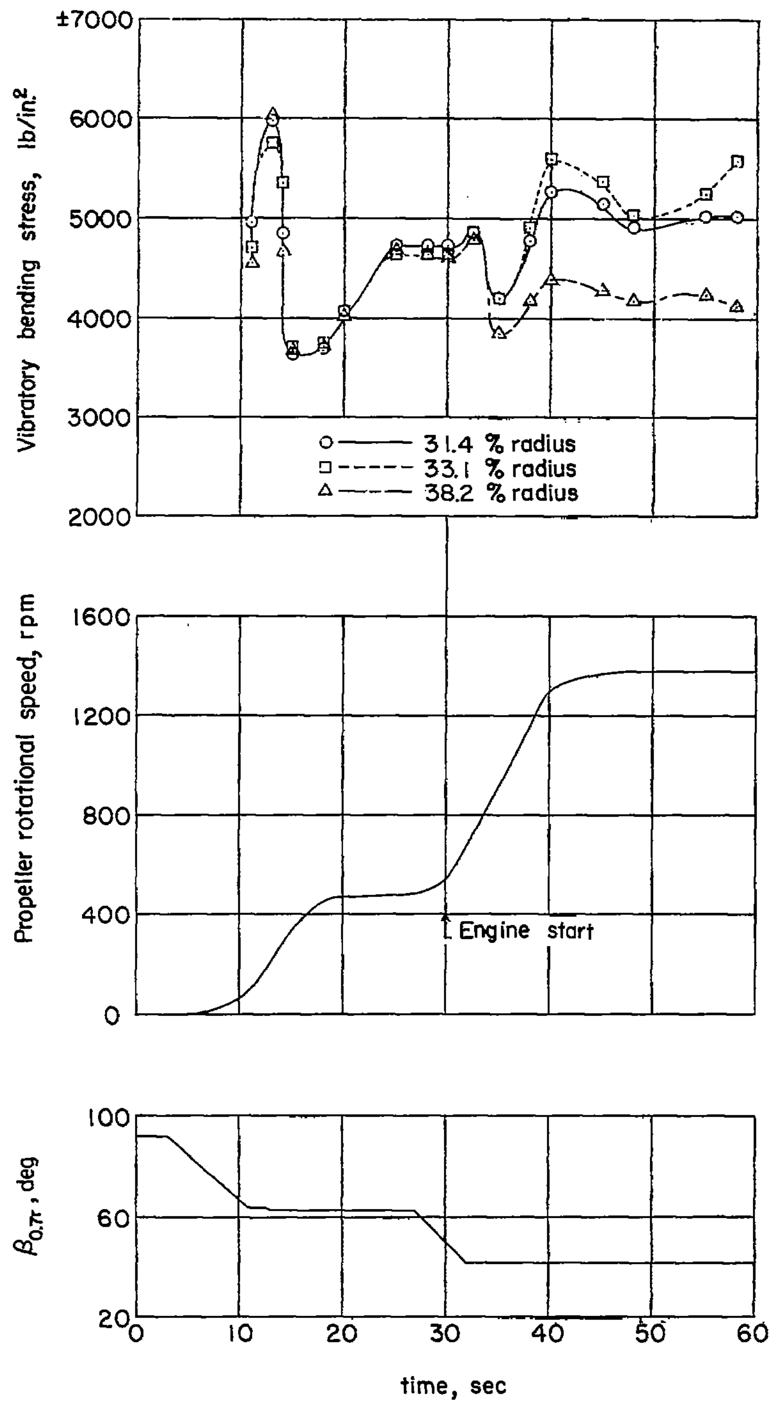

Figure 7.- Time history of vibratory bending stress, rotational speed, and blade angle during air start.

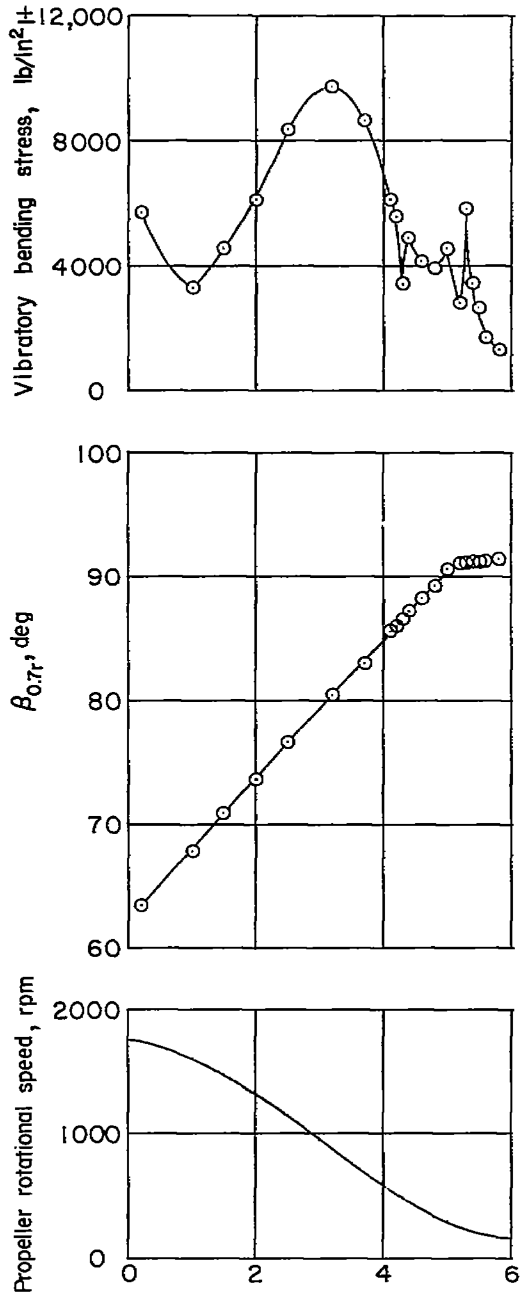

Figure 8.- Time history of propeller feathering at M = 0.95 showing vibratory bending stress at 31.4-percent radial location, blade angle, and propeller rotational speed.