80N22348

PROPELLER DYNAMIC AND AEROELASTIC EFFECTS*

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SUMMARY

Various aspects of propeller blade dynamics are considered including those factors which are exciting the blades and the dynamic response of the blades to the excitations. Methods for treating this dynamic system are described and problems discussed which may arise with advanced turboprop designs employing thin, swept blades.

INTRODUCTION

A propeller on a shaft driven by an engine attached to an airframe represents a dynamic system. This system responds to excitations from the power plant as well as to unsteady aerodynamic forces on the blades. These unsteady forces result from the non-uniform inflow into the propeller as produced by an angle of attack or by interference from the fuselage, wing and nacelles. They can also be caused by aeroelastic phenomena such as classical or stall flutter.

The propeller-engine-airframe combination, as a continuous system, has an infinite number of degrees of freedom and hence, an infinite number of normal modes. Generally, a disturbance will excite all of the modes, but it is only a few of the lowest modes which are of importance.

For purposes of determining propeller blade vibrations one can treat the propeller as an isolated dynamic system excited by the unsteady torque at the hub from the engine and by the unsteady airloads distributed along the blade surfaces. The dynamic response of the propeller to these excitations determines the vibratory blade stress levels, a knowledge of which is essential to assuring an acceptable fatigue life of the blades. Noise and fuselage vibration levels are also dependent to some degree on the propeller dynamics.

This presentation will discuss briefly methods of calculating the dynamic behavior of a propeller and will present some results obtained to date on a NASA research grant to The Pennsylvania State University. This

*supported under NASA Grants NSG-1308 and NSG-3304

grant involves not only the dynamics of the propeller but the unsteady aerodynamics as well; in particular, the interference with the fuselage, wing and nacelles.

The area of propeller blade dynamics promises to become even more important in the future with increasing application of fuel-efficient turboprop installations designed to cruise at high Mach numbers. These propellers, employing innovations such as composite materials, thin blades and sweep, will present challenges in their design and analysis which are not found with current all-metal blades. The environment for a propeller can be more severe than for the compressor of a turbofan engine. As shown in figure 1, at an angle of attack, the inlet duct serves to redirect the inflow into the compressor blades; whereas, the propeller blades experience an unsteady flow because of the angle of attack of the propeller's axis. More specifically, the section angle of attack at a given radius varies approximately sinusoidally with the azimuth angle with an amplitude proportional to the propeller angle of attack and the square of the advance ratio.

The brief discussion to follow of propeller dynamics is perhaps best summarized by reference to figure 2. In treating propeller dynamics, one is concerned with those factors which are exciting the system and with the response of the system to the excitation. These excitations may not depend on the dynamic response of the propeller or they may as in the case of stall flutter. An accurate calculation of the unsteady forces and propeller dynamic response is essential to assuring an adequate fatigue life for the propeller. Such calculations promise to become more challenging in the future as propellers are operated at high cruise Mach numbers. The introduction of new materials and the departure from today's conventional planform and airfoil shapes may also give rise to new problems associated with propeller dynamics.

UNSTEADY FORCES

In addition to the effect of angle of attack, non-uniformities in the inflow to a propeller result from velocities induced by the presence of the fuselage, wing and/or nacelles. These can cause both the magnitude and direction of the velocity vector in the plane of the propeller to vary with position (ref. 1). A computer code has been developed to predict this non-uniform velocity field. As shown in figure 3, the wing is replaced by a single horseshoe vortex having a span equal to that for a trailing rolled-up vortex sheet for an elliptic spanwise loading distribution. The fuselage and nacelles are panelled with sources being placed on each panel. The strengths of these sources are adjusted to assure that the velocity normal to the surface vanishes. This boundary condition can be relaxed to allow for cooling airflow through inlets.

Figure 4 presents the calculated variation of axial velocity for a typical single-engine light airplane as a function of azimuth position for 30% and 75% radial stations. The inboard section of the propeller is seen to experience a significant variation in the inflow equal to approximately 60% of the advance velocity as the propeller rotates. Also of interest is the result shown on this figure that one need not model the complete fuselage in order to obtain an accurate description of the propeller inflow. In this case, the cowling, closed at the rear by a simple faired shape, results in a predicted inflow which is close to that obtained with the complete fuselage. These curves are not symmetrical about a value of 180° because the propeller is yawed relative to the fuselage.

As a result of non-uniform inflow, the aerodynamic loads on a propeller blade can vary significantly with azimuth position. However, the unsteady aerodynamic loads pale by comparison to the unsteady torque of a piston engine. Figure 5 presents some unpublished measurements obtained recently on a four-cylinder, horizontally-opposed engine operating at 1300 rpm. From the figure it is obvious why one should avoid operating an engine continuously at a speed corresponding to a normal propeller mode. The amplitude of the unsteady torque is of the order of 300% of the average value. For turboprop applications, the engine torque is essentially constant so, here, one is more concerned about the unsteady airloads.

BLADE DYNAMICS

The dynamic response of a continuous system to an excitation can be calculated by a solution of the differential equations governing the system or by a lumped-parameter method which approximates the continuous system by discrete masses and springs. Both of these approaches are being tried under the research grant previously mentioned.

Because of the complex propeller geometry and the nature of the exciting forces, a closed-form solution for the equations of propeller blade motion is highly unlikely, if not impossible. Instead, one resorts to classical energy methods to determine the normal modes of the propeller. These normal modes can then be applied to the method of generalized coordinates and forces to obtain the dynamic response. To accomplish the foregoing, one must resort to the use of large computer codes.

A typical propeller for a single, piston-engine, light airplane is shown in figure 6. In this laboratory study, the propeller is clamped in a universal testing machine. An electromagnetic shaker excites the blade at the tip, and a piezoelectric accelerometer measures the blade response at various points on the blade surface. Restrained at the hub by the large mass of the testing machine, the blade responds as if it is cantilevered from the hub with no elastic coupling to the other blade.

Figure 7 illustrates a different test set up for a shaker test. Here, supported on a soft rubber innertube, the propeller responds as a free beam. The electronic equipment is shown in this figure consisting of amplifiers, power supply, frequency generator, oscilloscope and a ubiquitous spectrum analyzer and averager. By sweeping the frequency and noting resonances, one can quickly determine the frequencies of the lower normal modes. A manufacturer will test each propeller model in the manner of this figure to assure that none of the lower modes correspond with exciting frequencies from the engine. Since half of the cylinders of a four-cycle engine fire during each revolution, this impulse frequency in Hertz is given by the product of the rpm and the number of cylinders divided by 120.

Generally, the vibratory motion of a propeller blade will consist of a bending out of its plane of rotation coupled with a bending in the plane and a torsional displacement along the blade. Based on energy methods and the concept of a transmission matrix, a computer code has been developed (ref. 2) which predicts the normal modes for coupled bending-bending or coupled torsion with out-of-plane bending. The modelling of the complete coupling of all three motions has not been accomplished thus far. However, since present propeller blades are very stiff torsionally and in-plane, the lower modes of the coupled bending-bending and bending-torsion models have approximately the same frequencies which are determined principally by the relatively soft out-of-plane bending stiffness. Thus, the lack of a completely coupled numerical model is not too restrictive for the present. However, this may not be the case for future turboprop designs. For this reason a lumped-parameter model is being developed which will allow for complete coupling, sweep and, possibly, anisotropic materials. This model will be discussed briefly later.

The Campbell diagram for the propeller in the previous figures is presented in figure 8. Here, the fundamental exciting frequencies and harmonics for a four-cylinder, horizontally-opposed engine are superimposed on the natural frequencies of the first three normal modes. The predictions are based on the combined bending-bending model for the clamped hub. Observe that the natural frequencies increase with rpm due to centrifugal stiffening. Data points for zero rpm are included in the figure and agree fairly well with the predictions. In cruise, this particular propeller operates at around 2500 rpm. At this rotational speed, the fundamental exciting frequency of the engine and its harmonics do not coincide with any of the natural frequencies of the first three modes. It would not be well to operate this engine-propeller combination continuously at approximately 2200 rpm since the natural frequency of the first mode of the propeller, either clamped or free, coincides with the exciting frequency at this rotational speed.

STALL FLUTTER

In addition to responding to an unsteady inflow or engine torque, a propeller blade can experience the aeroelastic phenomena of stall flutter. This fact is not a new one, but is mentioned in the literature as early as 1941 (ref. 3). Unlike classical flutter which requires a combined bending and torsion motion together with a phase shift between the aerodynamic force and the angle of attack, stall flutter can occur as a pure bending or torsional oscillation. Because of negative damping provided by aerodynamic lift and moment beyond the stall, stall flutter can occur at much lower speeds than would be predicted for classical flutter. Figure 9 clearly illustrates the aerodynamic mechanism which can sustain stall flutter of a pure oscillatory nature (ref. 4). Three hysteresis loops for the moment coefficient are shown for a 0012 airfoil oscillating about mean angles of attack of 0, 12 and 24 degrees. For each loop the reduced frequency equals

.112 and the amplitude of α equals 6 degrees. For $\alpha = 0° \pm 6°$, the airfoil is unstalled so that the closed integral of C_M over α represents work which must be done by the system to sustain the oscillation. For $\alpha = 24° \pm 6°$, the airfoil is completely stalled so that, again, the area within the counter-clockwise closed hysteresis loop represents work which must be done by the system. For $\alpha = 12° \pm 6°$ the situation is different. Here the area enclosed by the clockwise loop minus that enclosed by the counter-clockwise loop is positive as a result of the airfoil operating in and out of the stalled region. This net area represents work being done on the airfoil which represents negative damping; and hence, the possibility of a self-sustaining oscillation.

Some recent unpublished test data obtained at NASA LeRC with a model propeller are shown in figure 10. For a given blade angle, the section angles of attack increase as the advance ratio decreases. Thus, decreasing J, a value is reached below which a portion of the blade is stalled resulting in the inception of stall flutter as noted on the figure.

FUTURE STUDIES

A lumped parameter model of an elastic propeller blade is being developed as an alternate to the blade dynamics program described earlier. The lumped parameter model will allow one to calculate the dynamic response of the propeller to exciting forces and torques without determining the normal modes first. A simplified sketch to illustrate the model for the clamped hub case is shown in figure 11. Here the blade is divided into finite elements. The inboard end of each element is attached by three orthogonal equivalent springs to the adjacent element. The axes of two of these torsional springs lie along the principal axes of the blade sections. Their spring constants can be easily calculated knowing the section modulus of elasticity, moment of inertia and element length. Each element is also allowed to rotate along a locus through the shear centers of the sections. The third equivalent torsional spring in the radial direction at the shear center allows for this torsional motion.

If the mass center and elastic axis are not coincident, an acceleration transverse to the blade produces an inertial moment which tends to twist the blade. Also, the fact that the blade is twisted and tends to bend about the section major axis will produce a coupling between blade bending and torsion.

A program has been developed, based on modified vortex theory, which predicts the time-dependent blade loading given the velocity vector field in the propeller plane (ref. 5). In order to validate this program and to learn more about the details of the flow through a propeller, an experimental flight test program will be conducted to measure the unsteady velocities immediately behind a propeller for different flight conditions. Figure 12 illustrates a three-component, hot-film anemometer mounted on a transversing mechanism which is supported on a truss attached to the firewall. The probe is isolated from fuselage vibration by a soft mounting. The system is designed so that measurements can be taken around the azimuth at varying radial locations and distances downstream of the propeller. The airplane to be used for this experiment is a Piper Cherokee 180 having a fixed-pitch propeller. For these tests the standard rear seat is replaced by a single seat on the left side with an instrument rack on the right side. The right front seat is removed and a battery pack put in its place.

In addition to the flow field measurements, it is planned to measure the unsteady bending moment distribution along the blade. Miniature strain gages will be bonded along the blade and the output transmitted across the hub by means of an FM multiplexing system.

CONCLUDING REMARKS

The subject of propeller blade dynamics promises to become more important in the future. Advanced turboprop designs incorporating thin, swept elastic blades, and operating in a non-uniform inflow environment, will require sophisticated analyses of their aeroelastic behavior. In addition to avoiding resonances at multiples of the propeller rotational speed, the designer may have to be concerned with the possibility of stall flutter.

REFERENCES

1. Jumper, S. J.: Computer Prediction of Three-Dimensional Potential Flow-fields in which Aircraft Propellers Operate. M.S. Thesis, The Pennsylvania State University, February 1980.

2. Martinovic, Z. N.: A Study of the Dynamic Behavior of Propeller Blades. M.S. Thesis, The Pennsylvania State University, March 1979.

3. Bollay, William and Brown, C. D.: Some Experimental Results on Wing Flutter. Jour. Aero. Sci., vol. 8, no. 8, June 1941, pp. 313-318.

4. Carta, F. O. and Niebanck, C. F.: Prediction of Rotor Instability at High Forward Speeds, Volume III, Stall Flutter. USAAVLABS Tech. Report 68-18C, February 1969.

5. Aljabri, A. S.: Prediction of Propeller Performance and Loading in Uniform and Nonuniform Flowfields. M.S. Thesis, The Pennsylvania State University, November 1978.

PROPELLER TURBOFAN COMPARISON

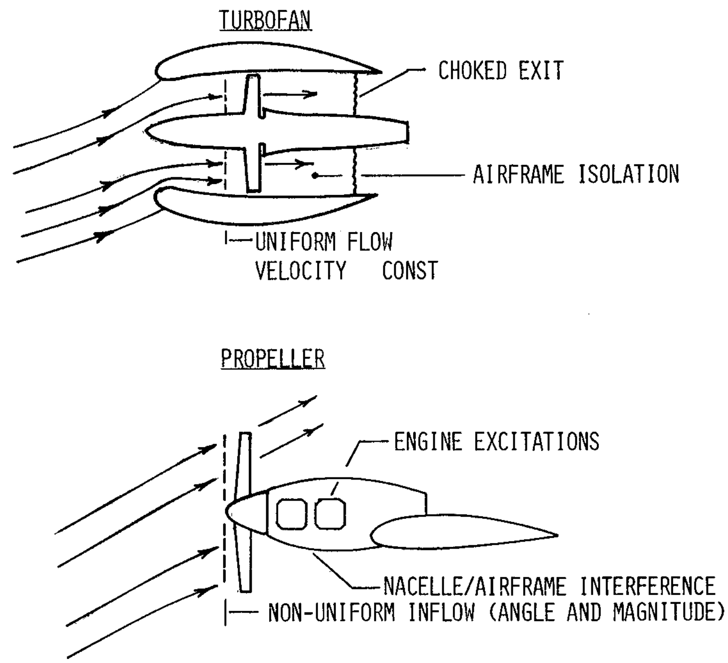


FIGURE 1

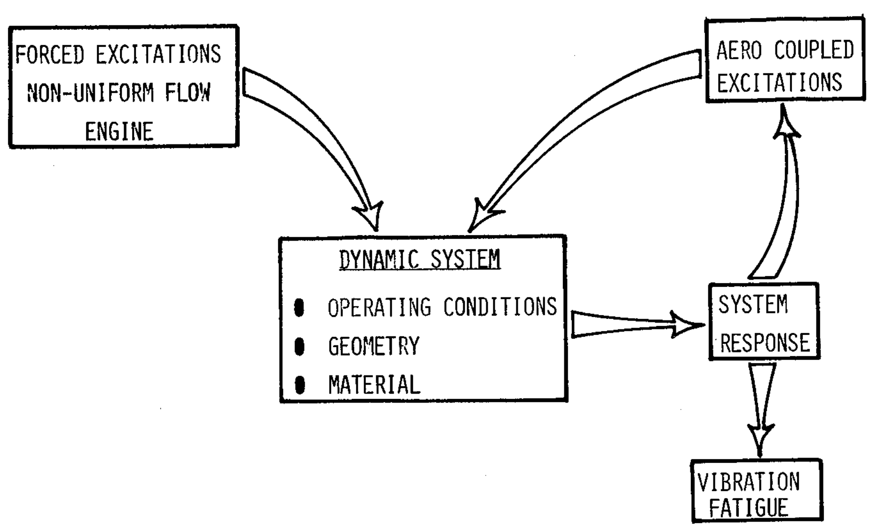
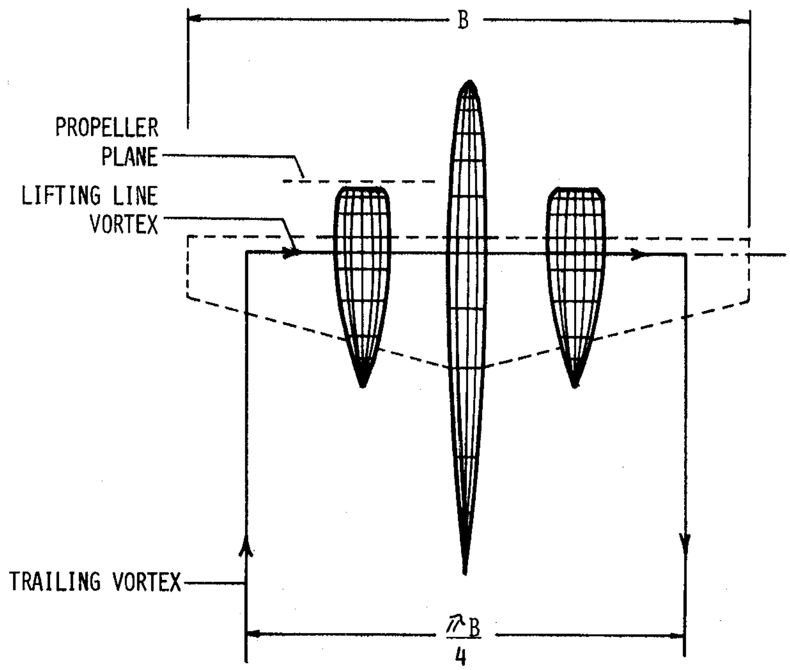


FIGURE 2



SIMPLIFIED WING-FUSELAGE-NACELLE NUMERICAL MODEL

FIGURE 3

PREDICTED AXIAL VELOCITY RATIO AT PROPELLER

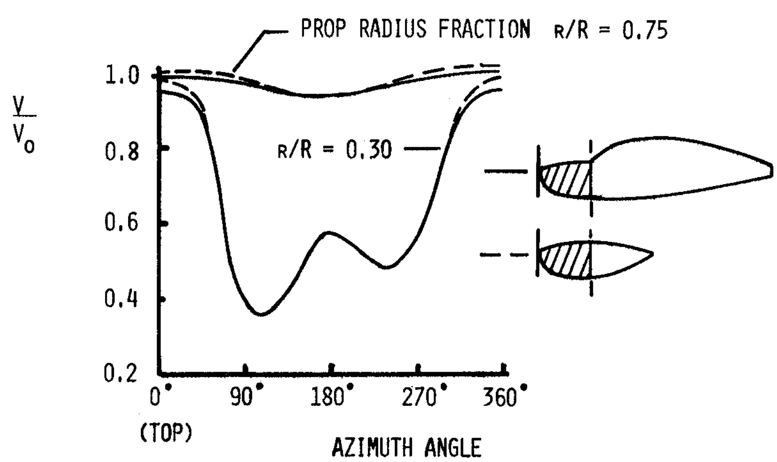


FIGURE 4

VARIATION OF TORQUE WITH
PROP SHAFT ROTATION

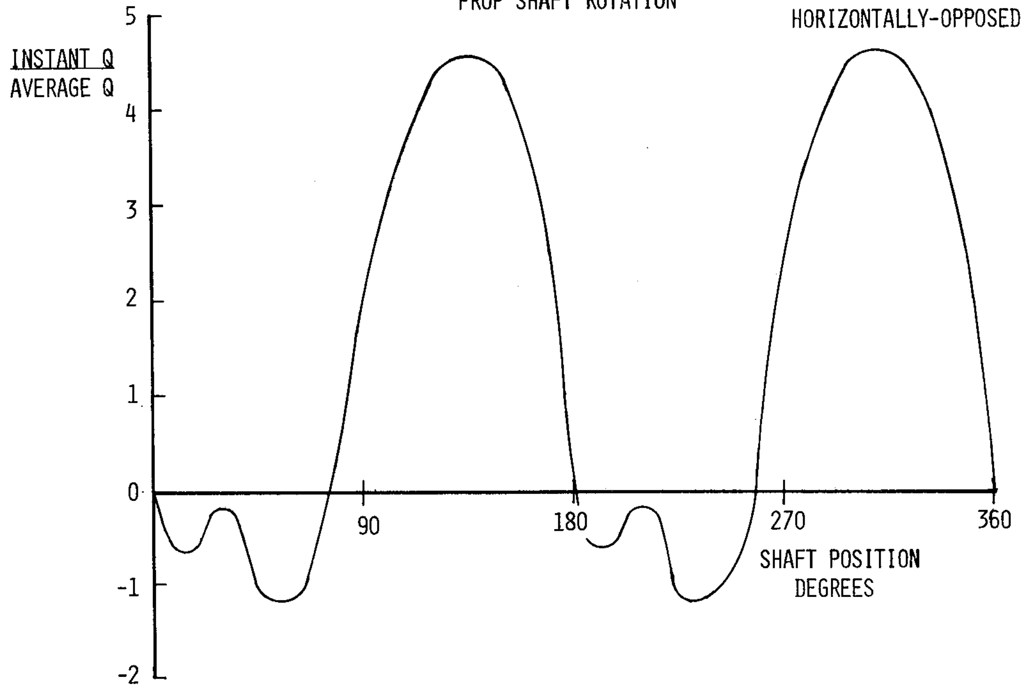


FIGURE 5

PROPELLER NATURAL FREQUENCY TEST
HUB CLAMPED

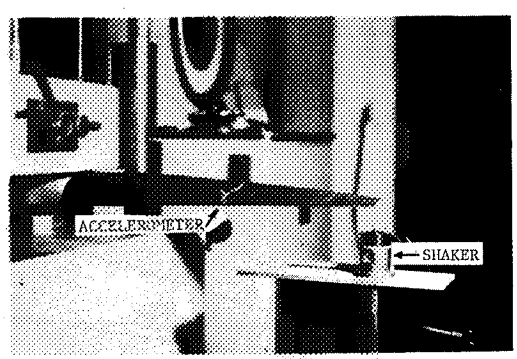


FIGURE 6

PROPELLER NATURAL FREQUENCY TEST
FREELY-SUPPORTED

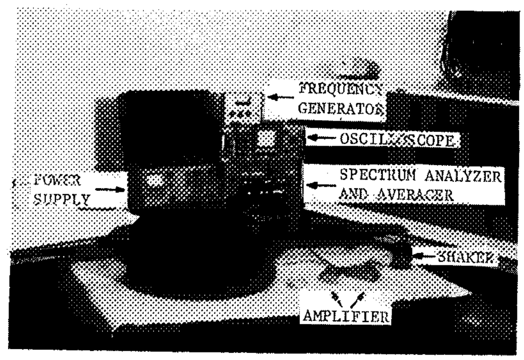


FIGURE 7

CAMPBELL DIAGRAM
ENGINE EXCITATIONS AND PROP NATURAL FREQUENCIES

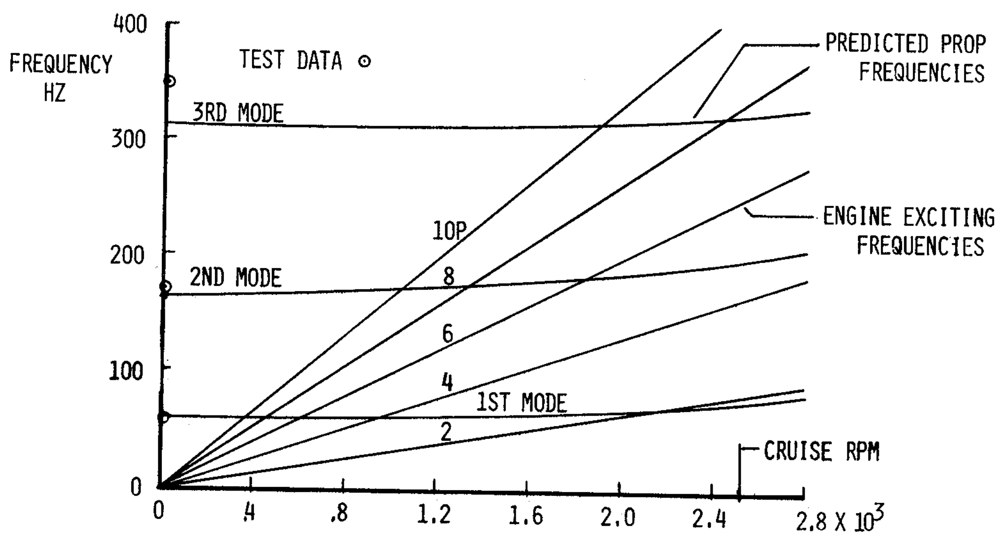


FIGURE 8

EFFECT OF MEAN INCIDENCE ANGLE
ON MOMENT HYSTERESIS LOOPS

(NACA 0012 AIRFOIL OSCILLATED ± 6°)

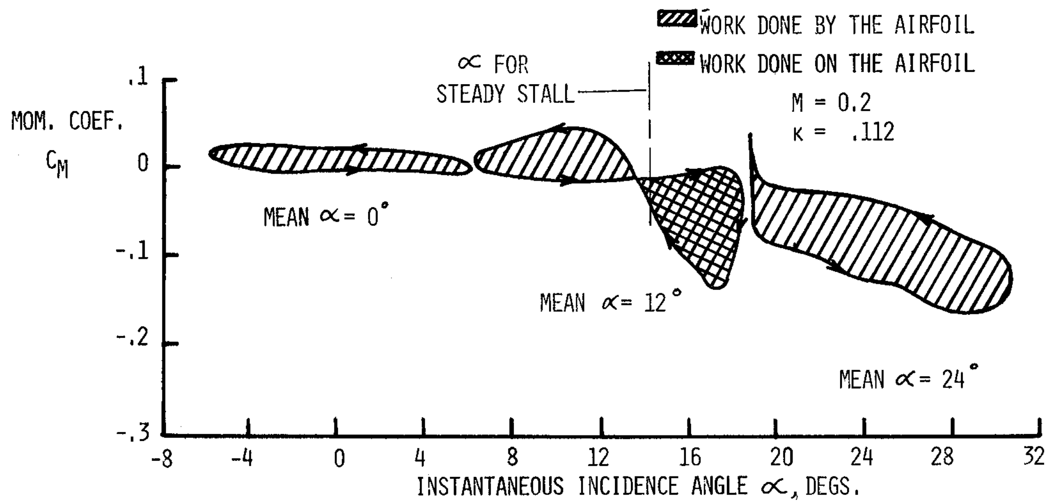


FIGURE 9

TYPICAL STALL FLUTTER CHARACTERISTICS

M = 0.1, 3 BLADES

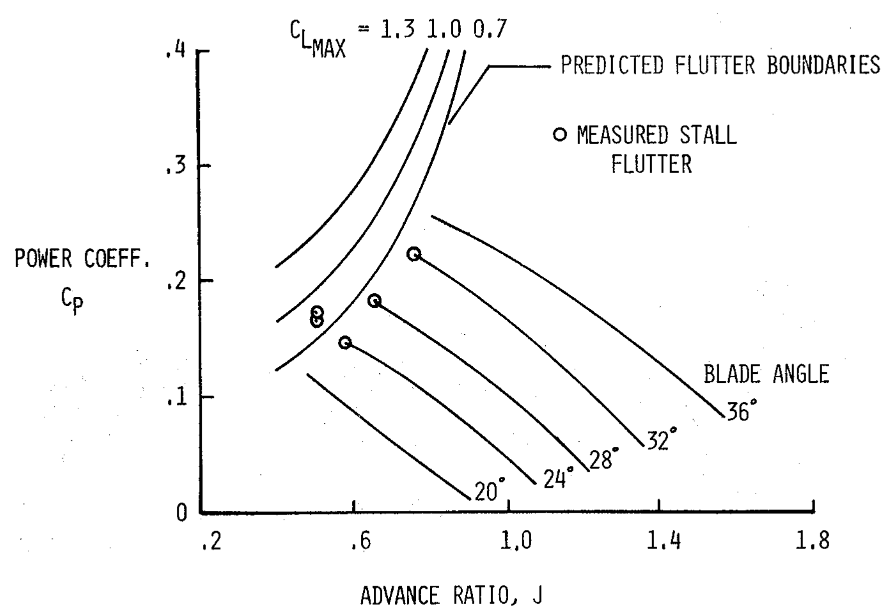


FIGURE 10

LUMPED PARAMETER DYNAMIC MODEL

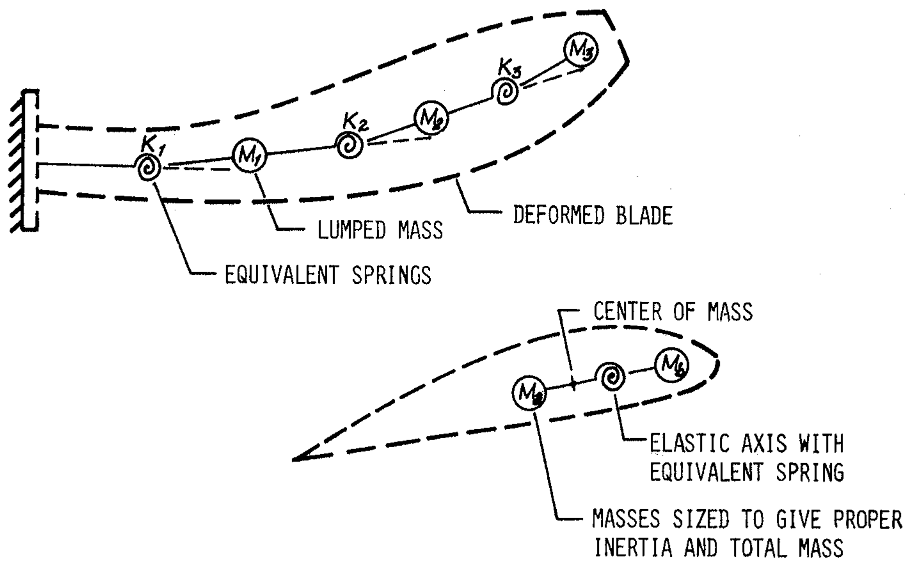


FIGURE 11. TORSION MODEL

FLIGHT TEST APPARATUS FOR IN FLIGHT DETERMINATION OF 3 COMPONENT VELOCITY MEASUREMENT

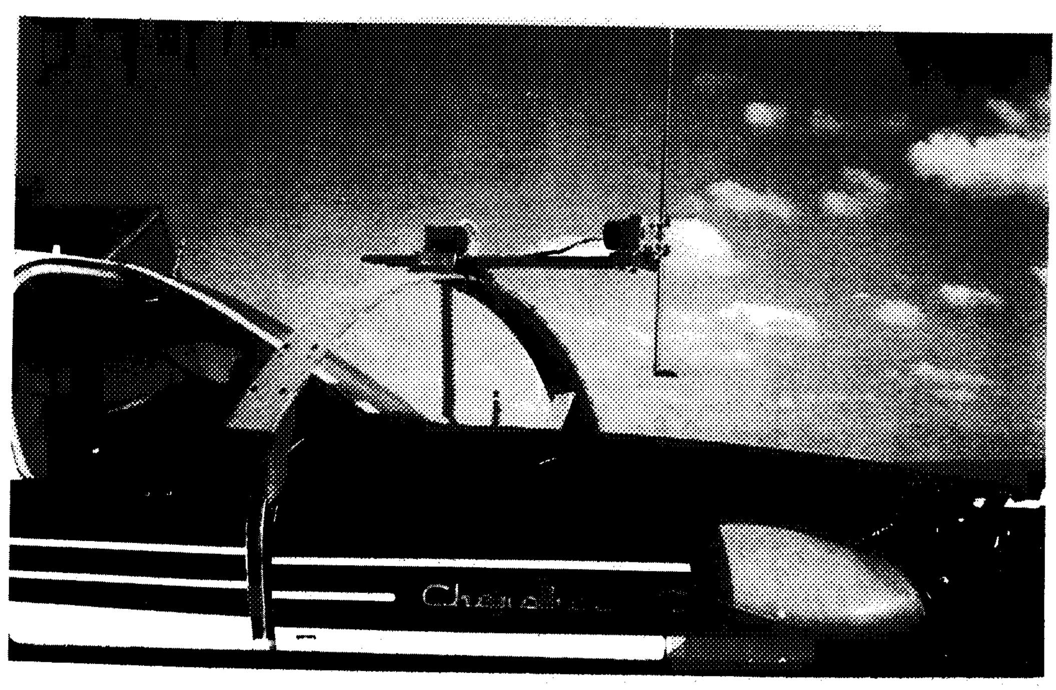


FIGURE 12.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CP-2126		

4. Title and Subtitle	5. Report Date
General Aviation Propulsion	March 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No. E-310
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Conference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A two-day conference was held at the NASA Lewis Research Center on November 28 and 29, 1979, to provide leaders from government, industry, and universities with the latest results of NASA programs in general aviation propulsion. Twenty-two papers were presented on topics including the NASA Quiet, Clean, General Aviation Turbofan (QCGAT) program and the NASA General Aviation Turbine Engine (GATE) program. This publication contains all the papers presented at the conference.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
General aviation aircraft; Nacelles; Engines; Aircraft noise; Turbine engines; Piston engines; Turboprop engine; Rotary engines; Diesel engines; Propellers; Pollution; Exhaust emissions	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	437	A20

* For sale by the National Technical Information Service, Springfield, Virginia 22161

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980 -657-145/5223