THE EFFECT OF BLADE FLAPPING ON THE DYNAMIC STABILITY OF A TILTING-ROTOR CONVERTIPLANE

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INTRODUCTION

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The Bell XV-3 convertiplane has been extensively tested over the past several years. An investigation was conducted in the Ames 40- by 80-foot tunnel to study the effectiveness of a number of modifications to correct the wing-pylon oscillation which was evident on the initial flights of the airplane. This investigation, reported in reference 1, showed that the airplane could be flown through transition and gear-shifted to low prop-rotor rotational speed in airplane flight without serious airplane or rotor stability problems. A limited flight evaluation was performed by the Air Force Flight Test Center and is reported in reference 2. The flight evaluation explored the flight characteristics of the airplane from near hover to about 155 knots. Since the completion of the Air Force tests, the airplane has been flight-tested by the National Aeronautics and Space Administration at the Ames Research Center to explore further some of the problem areas noted in previous tests and to study general handling-qualities requirements for V/STOL aircraft. Much of the recent flight testing of the XV-3 has centered around the cruise configuration of the airplane in order to study the effect of the large flapping rotors on the handling qualities at cruising speed and above. This paper will deal with what is considered to be the one of the basic problems of the tilt-rotor concept in cruise when flapping prop-rotors are used for propellers. This problem can be divided into four separate but related problem areas:

(1) The high blade-flapping amplitude with steady-state angles of attack and sideslip

(2) The increase in flapping due to maneuvering

(3) The prop-rotor normal force associated with pitching and yawing angular velocities of the airplane

(4) The airframe vibration which accompanies airplane angular velocities

DISCUSSION

The low-disk-loading flapping rotors of the XV-3 (see fig. 1) are of the semirigid, teetering or seesaw, type construction and are driven by a 450-horsepower reciprocating engine in the fuselage. A gear shift is incorporated which permits the operation of the prop-rotors at either of two prop-rotor rotational speeds while maintaining maximum engine rotational speed. Blade flapping is designed into the rotor system to relieve the unbalanced moments across the rotor disk and to provide a means of controlling the aircraft longitudinally and directionally in hover and low-speed flight. The flapping rotor also provides damping about all axes at low airspeed and in hover. When the prop-rotor is converted into a propeller, the control provisions of the rotor are washed out and the blade-flapping function is to relieve the blade stresses that occur once per revolution.

The variations of the steady-state blade flapping angle with airspeed for the two prop-rotor rotational speeds used in this investigation are shown in figure 2. These data are for the masts tilted forward (cruise configuration). The airspeed range of the airplane in this configuration was from 100 to 140 knots. The low prop-rotor rotational speed gives the highest values of flapping and is the one of particular interest since this speed is used in airplane flight to attain the highest possible propeller efficiency. As airspeed is increased, the steady-state flapping decreases for both prop-rotor rotational speeds. Thus, it would appear that flapping should become less of a problem as speed is increased; however, any type of maneuver will introduce additional flapping. The flapping due to maneuvering in pitch at 130 knots airspeed is presented in figures 3 and 4 where the change in blade flapping due to angle of attack and due to pitch angular velocity are presented. The change in blade flapping angle due to angle of attack alone (fig. 3) is relatively small, but the blade flapping due to pitch angular velocity (fig. 4) can be quite large. A pitch angular velocity of only -0.2 radian per second results in a change in blade flapping angle of over 4°. In dynamic maneuvers, the change in blade flapping angle due to angle of attack and pitch angular velocity can add to give even higher blade flapping angles. The XV-3 is provided with a maximum available blade flapping angle of $11\frac{1}{2}^{\circ}$ which should prove adequate for any normal maneuver. It can be seen in figure 4 that the change in blade flapping angles is positive when the pitching angular velocity is negative; because of inertial effects, the prop-rotor disk is lagging the angular motion.

In evaluation flights of the airplane at high airspeeds, pilots have reported a condition in which the airplane oscillated about all axes simultaneously. An analysis of the time histories taken during this maneuver has shown that it consisted of longitudinal and lateral-directional oscillations that were very lightly damped. The damping ratio and period for the two oscillations over the speed range that could be covered with this airplane are presented in figure 5. These data are for the low prop-rotor rotational speed. The longitudinal and lateral-directional oscillations are not directly coupled. They are at different frequencies and oscillations can be performed in either mode without exciting the other, but with such low damping it is easy to excite both modes at the same time. These damping ratios are much lower than are considered acceptable by any of the criteria for airplanes in cruise. Damping ratios of 0.34 for the longitudinal mode and 0.18 for the lateral-directional mode have been specified as the minimum allowable by military handling-qualities specifications. The damping ratios are not only low but also change appreciably over this relatively small airspeed range, approaching zero at the higher speeds. In examining the reasons for this low damping, the longitudinal mode will be discussed and a discussion of the lateral-directional mode would be similar.

Computations have shown that, if the prop-rotor contribution to damping were ignored, the airplane would have a higher damping ratio than was measured. The computed damping ratio and the measured values for the two prop-rotor rotational speeds tested are shown in figure 6. Since there is a large difference between computed and measured values of damping and also a significant difference between damping with high and low prop-rotor rotational speeds, a negative damping moment produced by the prop-rotors is indicated. This negative damping was also evident in the wing-tip pylon-position data obtained during the flight tests, which indicated that when the airplane had a nose-up pitching motion there was an "up" force on the prop-rotor hub proportional to the rate of pitch. The instrumentation was not sufficient to measure accurately the magnitude of this force. Due to the low tail volume of the XV-3, the force on the prop-rotor hub had a large effect on the dynamic stability of the airplane.

It was predicted in reference 3 that convertiplanes which use flapping prop-rotors would have this problem. Being consistent with helicopter theory, a flapping rotor is essentially a gyroscope and requires a couple across the rotor disk 90° out of phase with the angular motion of the airplane to make it precess and follow its shaft. (See ref. 3.) When airplane pitching motion is introduced, the prop-rotor disk lags the airplane angular motion until sufficient flapping is present to produce the necessary couple aerodynamically by increasing lift on one side of the disk and decreasing lift on the opposite side; thus, the increase in flapping due to airplane angular velocity. The change in aerodynamic force on a blade due to flapping can be resolved into two forces, one perpendicular and one parallel to the prop-rotor disk. These forces are shown schematically in figure 7. This sketch indicates that when the airplane is pitching down the components of the forces due to flapping are forward and down on the inboard side, and rearward and down on the outboard side of the prop-rotor disk. For a constant prop-rotor rotational speed, Ω, the magnitude of the precessing force changes little with airplane flight conditions, but the in-plane force depends on blade angle. At low advance ratios, the blade angles are small; therefore, the in-plane force is small. However, at the high advance ratios, when blade angles are large, this force becomes sufficiently large to affect the dynamic stability of the airplane. It can be seen that the in-plane force is in the direction of the motion and produces a negative damping moment when the prop-rotors are in front of the center of gravity. The method in reference 3 of calculating these forces and moments was developed for helicopters in hover and low-speed flight and will require expansion to analyze damping moments due to flapping prop-rotors at high advance ratios.

The vibration which accompanies large pitch rates is also traceable to the in-plane force on the prop-rotor and shows up as an oscillatory force with a frequency of 2 cycles per rotor revolution. This vibration in the pilot's opinion was large enough to be a limiting factor on the maximum angular rates attainable. Since the in-plane forces and, therefore, the vibration are associated with flapping, the amplitude of the vibration is maximum when the blade flapping angle is maximum. The use of three or more blades on future prop-rotors should alleviate this type of vibration.

While the XV-3 convertiplane is the first VTOL aircraft to be plagued with these blade-flapping problems, they have been encountered in the past on a prototype STOL fighter equipped with flapping propellers mounted on the wing tips. These problems are largely attributable to the compromise required to maintain good hovering efficiency as well as high propeller efficiency in cruise which dictates the use of flapping prop-rotors at high blade angles in cruising and high-speed flight regardless of the disk loading. Solutions to these problems can be approached in several ways on future VTOL airplanes. Higher dynamic stability can be provided in the design of the airplane itself. To illustrate, lengthening the tail about 5 feet would increase the damping ratio of the XV-3 to 0.5 at 140 knots. Another solution would be to place the prop-rotors behind the center of gravity where the in-plane forces would provide positive damping. This would probably result in a pusher configuration. Alternatively, the magnitude of the in-plane forces on the prop-rotor hub could be reduced by supplementing the aerodynamic precessing couple by the use of offset flapping hinges, blade-flapping restraint springs, or other methods. However, there is little information available on the behavior of a prop-rotor at high advance ratios, and additional research is required to determine the optimum method of reducing the in-plane forces associated with this blade flapping and still maintain the desirable features of the light-weight prop-rotor system.

CONCLUDING REMARKS

At high advance ratios the prop-rotor blade flapping due to airplane angular velocity generates a force on the prop-rotor hub in a direction which reduces the dynamic stability of the airplane. This is a problem area that will be common to all prop-rotor configurations with flapping blades, and there is a need for additional research into the problems of flapping prop-rotors at high airplane flight speeds.

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2. Deckert, Wallace H., and Ferry, Robert G.: Limited Flight Evaluation of the XV-3 Aircraft. AFFTC-TR-60-4, Air Res. and Dev. Command, U.S. Air Force, May 1960.

3. Amer, Kenneth B.: Theory of Helicopter Damping in Pitch or Roll and a Comparison With Flight Measurements. NACA TN 2136, 1950.

XV-3 CONVERTIPLANE

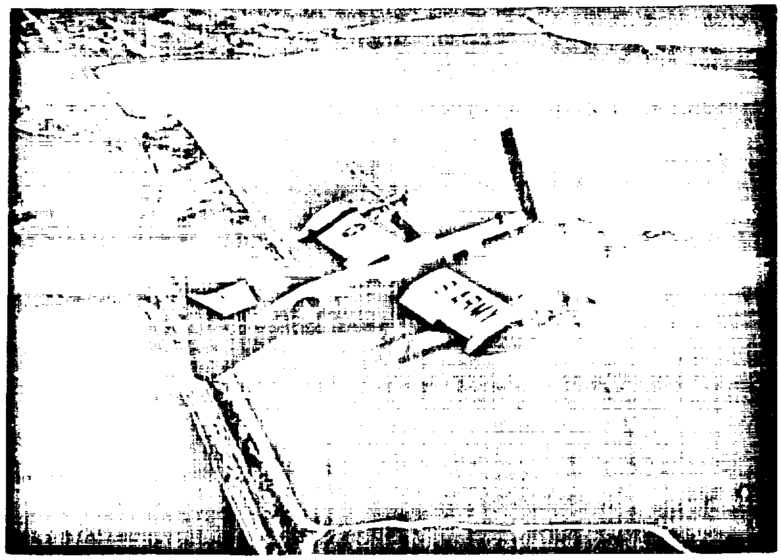

Figure 1

VARIATION OF STEADY-STATE BLADE FLAPPING FOR AIRPLANE CONFIGURATION

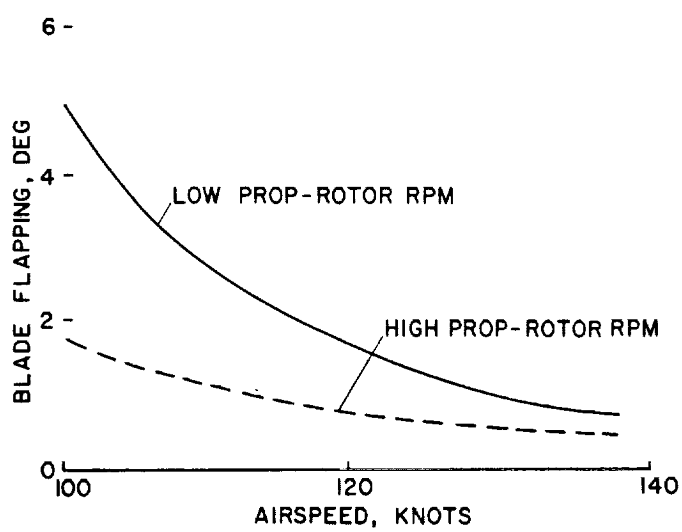

Figure 2

CHANGE IN BLADE FLAPPING WITH
ANGLE OF ATTACK AT 130 KNOTS

PITCH RATE=0

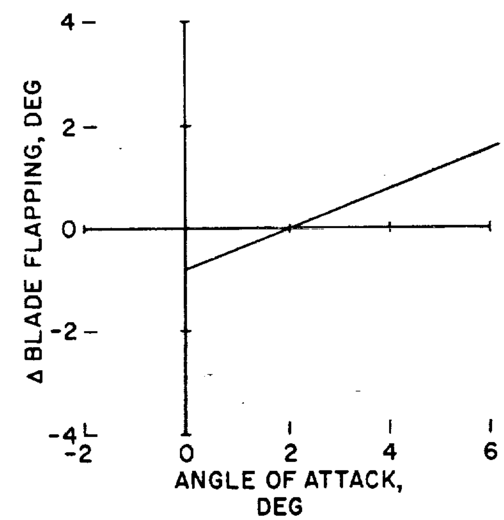

Figure 3

CHANGE IN BLADE FLAPPING WITH
PITCHING ANGULAR VELOCITY AT 130 KNOTS

ANGLE OF ATTACK = 2°

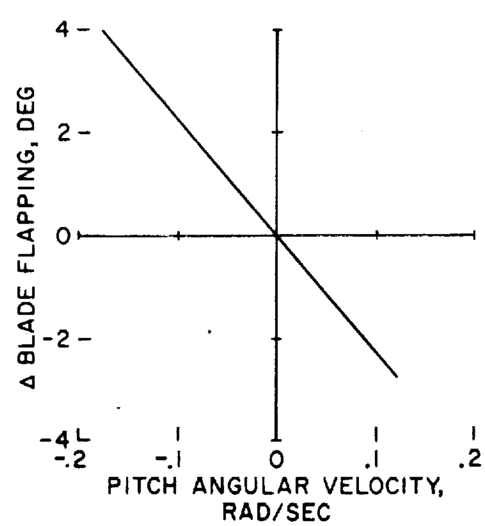

Figure 4

LONGITUDINAL SHORT-PERIOD AND LATERAL-DIRECTIONAL OSCILLATORY CHARACTERISTICS

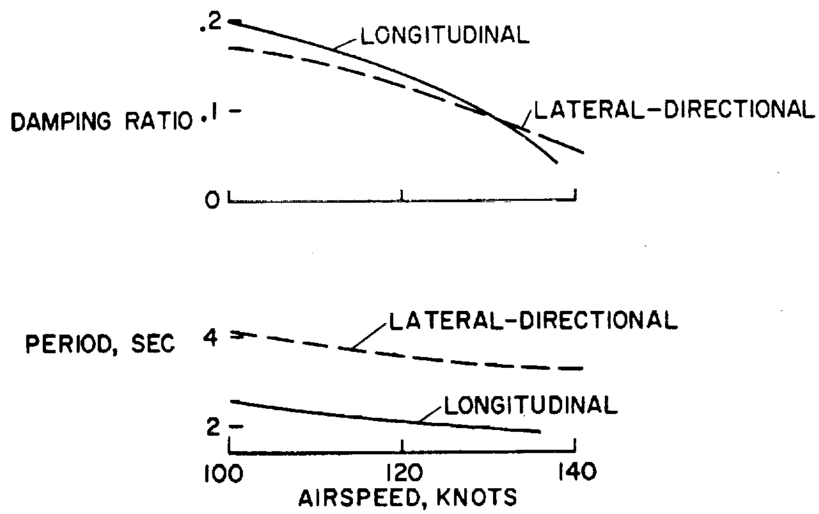

Figure 5

COMPARISON OF LONGITUDINAL SHORT-PERIOD CHARACTERISTICS

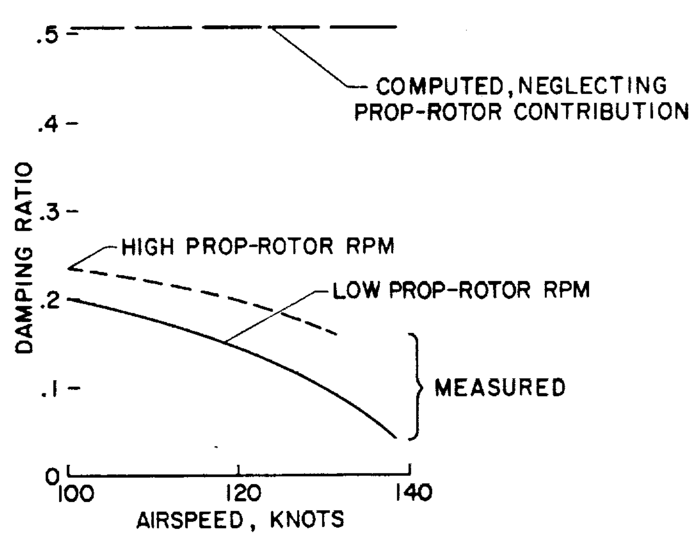

Figure 6

FORCES ON PROP-ROTOR BLADES
DUE TO PITCHING VELOCITY

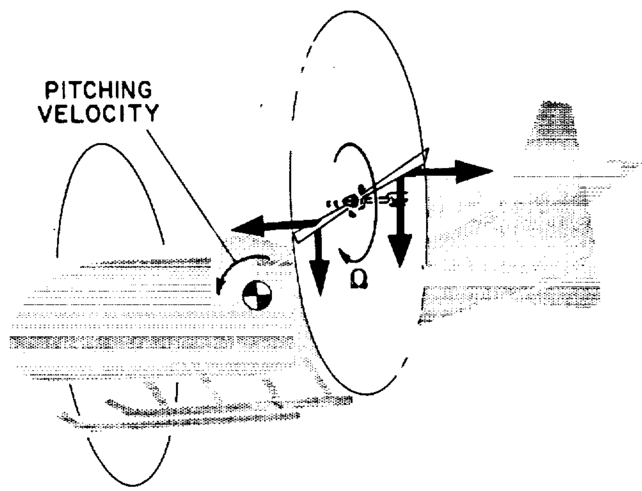

Figure 7