FLIGHT FLUTTER TESTING OF ROTARY WING AIRCRAFT

USING A CONTROL SYSTEM OSCILLATION TECHNIQUE

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SUMMARY

This paper describes a flight flutter testing technique in which the rotor controls are oscillated by series actuators to excite the rotor and airframe modes of interest, which are then allowed to decay. The moving block technique (see ref. 1) is then used to determine the damped frequency and damping variation with rotor speed. The method has proved useful for tracking the stability of relatively well damped modes. The results of recently completed flight tests of an experimental soft-in-plane rotor are used to illustrate the technique. This technique will also be used for flight flutter tests of the NASA/Army XV-15 Tilt Rotor Research Aircraft, to investigate its propeller whirl flutter stability characteristics, and this application is also discussed briefly.

INTRODUCTION

A soft-in-plane rotor has recently been built and flight tested by Bell Helicopter Company. This type of rotor system has the potential for ground and air resonance instability. The potential mode of instability, the lead-lag motion of the blades coupled with the fuselage rigid body roll mode, has a frequency of 0.75 per rev (3.55 Hz) in the rotating system. The mode was predicted to be well damped, since sufficient elastomeric lead-lag damping was employed. However, since it was the first rotor of this type developed by Bell Helicopter Company, an extensive ground/air resonance test program was conducted to investigate the ground/air resonance phenomena.

The measurement of the stability characteristics of rotary wing aircraft is complicated by the need to excite modes in a rotating system and by the fact that both the rotor and the airframe are subject to steady state harmonic loading. This loading tends to mask the transient response of any relatively well damped mode. The development of an on-line flight flutter testing technique for helicopters or tilt-rotor aircraft hence becomes a formidable task, both to cause the proper excitation and to reduce the data. A flight flutter testing technique has been developed, as described in this paper, to oscillate the rotor controls by means of the series actuators in a sense and a magnitude prescribed by the user.

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SYMBOLS

$F(\omega)$	Fourier transform of $f(t)$
SCAS	stability and control augmentation system
$X(\omega)$	Fourier transform of a response
$f(t)$	excitation signal
t	time
Ω	rotational speed of rotor
ω	frequency of a mode in a dynamics system
ω_1	frequency of the mode of interest in a dynamics system
ω_ζ	blade lead-lag natural frequency

ROTOR EXCITATION SYSTEM

For a soft-in-plane rotor test program, it is desirable to excite the rotor at a relatively low amplitude and at a prescribed frequency. The system developed to perform the excitation for flight flutter testing of the Bell Model 609 soft-in-plane rotor uses the SCAS actuators, driving them from an HP203A dual signal generator. This rotor exciter can supply either a continuous signal of a single frequency, or a pulse spectrum which can be selected to excite only one natural frequency of several which may be present. A functional diagram of the system is shown in figure 1. The upper portion shows the system which drives the rotor, and the lower part shows the nulling system. This nulling system is an option which allows the user to cancel the steady state one-per-rev and two-per-rev signals before the input spectrum is applied, thus isolating the response to the input signal only. Figure 2 shows a diagram of the rotor exciter. Point A has a pulse output to the computer to indicate when the input has been completed. Point B is the demodulated one-per-rev to the nulling system.

The underlying principle behind the single-mode excitation technique can be explained in terms of a linear system with many degrees of freedom. The Fourier transform of the response vector is obtained by post-multiplying the matrix of the frequency response function by the column of the Fourier transform of the forcing function. (See, for example, ref. 2) The frequency response functions exhibit peaks corresponding to natural frequencies of the system.

The shape of the Fourier transform of the forcing function is governed by the shape of the forcing function in the time domain. For example, the Fourier transform of the forcing function depicted in figure 3a is shown in figure 3b. $F(\omega)$ has a large magnitude corresponding to frequency ω_1, and a rather low magnitude elsewhere. Since the Fourier transform of the response, $X(\omega)$, is obtained as a matrix product of frequency response function and $F(\omega)$, the response motions will be motions predominately at the frequency ω_1. (This, however, does not mean that the mode of interest alone is excited and the other modes are properly suppressed.) Various types of forcing function f(t) can be chosen to produce a desired spectrum $F(\omega)$.

ON-LINE STABILITY ANALYSIS

The Bell experimental Model 609 flex-hinge rotor, a four-bladed, soft-in-plane design, is mounted on a Bell 1501 fuselage. The elastomeric lead-lag hinge offset is 13.2 percent of the rotor radius which is 752 cm (296 in.). The blade first flapping frequency is 5.08 Hz (1.07 per rev). There are two potentially unstable modes for this experimental soft-in-plane rotor system. One, a coupled roll-yaw mode of the fuselage on the landing gear, has a frequency of 2.3 Hz. The other, the blade first lead-lag mode, has a frequency of 3.55 Hz at low strain conditions.

Ground Resonance Test

The roll mode stability was monitored by an accelerometer at the top of the mast. The test oscillated the SCAS actuators in a sense equivalent to moving the cyclic stick in a counter-clockwise direction at a frequency near 2.3 Hz. The aerodynamic hub moments and hub shears then excited the fuselage roll mode at its natural frequency. The high damping, the presence of high one-per-rev response, and some unknown noise made the data reduction difficult. Figure 4a shows the roll mode response at 260 rpm when a 7-Hz filter was used. The moving block analysis of this response indicated the modal damping to be at 19.7 percent critical. Figure 4b shows the result of filtering the same raw data through a 3-Hz analog filter. In this case, the moving block technique showed the modal damping to be at 20.8 percent critical. Since the 3-Hz filter brings out the highly damped roll mode more clearly, and since the calculated damping is approximately the same as in the other case, the decay plots of the roll mode in other ground run conditions were all filtered through 3-Hz filters before undergoing the moving block analysis.

The blade lead-lag motion was sensed by a strain gage on the grip damper arm. For the blade lead-lag stability test, the SCAS actuators were cycled as if the cyclic stick were being moved in a counter-clockwise direction at a frequency of one-per-rev minus the blade lead-lag frequency $(\Omega-\omega_\zeta)$. This is equivalent to exciting the lead-lag mode aerodynamically at its natural frequency in the blade rotating system. Figure 5a shows the response of the lead-lag mode to a SCAS input at high collective (immediately before lift-off) and a rotor speed of 280 rpm. The modal damping obtained from the moving block technique was 4.3 percent critical in the rotating system. The data were then passed through a 4-Hz filter with the results shown in figure 5b. The modal damping determined by the moving block analysis was 4.2 percent critical in the rotating system. The filtering process again highlighted the modal decay and did not affect the moving block result.

A summary of damping variations measured at various rotor speeds for the lead-lag mode and fuselage roll mode in the fixed reference system is shown in figure 6. The decrease in damping with increase in blade collective is attributed to the destabilizing Coriolis force and the characteristic of an elastomeric damper, a phenomenon predicted by the ground resonance analysis.

Air Resonance Analysis

The blade lead-lag mode in hover was also excited with the SCAS actuators. Figure 7 shows the lead-lag decay at the design rotor speed of 285 rpm filtered through a 4-Hz filter. The moving block technique determined the modal damping to be 5.4 percent critical.

XV-15 VTOL FLIGHT FLUTTER TEST PLANS

The NASA/Army XV-15 Tilt Rotor Research Aircraft will enter flight testing in September 1976. Bell Helicopter Company, the prime contractor, is building two of these aircraft which will have a design gross weight of 57.8 kN (13000 lb) and a maximum speed of 364 knots. Of primary interest from the standpoint of flutter are the stability of the coupled rotor/airframe system and flutter of the empennage.

Coupled Rotor/Airframe Stability

The XV-15 has a nacelle on each wingtip. Each nacelle houses a T-53 engine and a transmission, and each transmission drives a 25-foot, gimbaled, stiff-in-plane three-bladed rotor. The nacelles are oriented with their shafts vertical for takeoff, landing, and flight in the helicopter mode, and are mechanically tilted 90 degrees for flight in the airplane mode. To prevent aeroelastic instability of the coupled rotor/airframe system, the wing is designed to be very stiff in torsion and in bending (it is 23% thick with spars at 5% and 50% chord, fully monocoque) and the nacelle is attached to the wing at the front and rear spar to make the attachment stiff in pitch and yaw.

The calculated coupled rotor/airframe stability characteristics in the airplane mode of flight indicate that instability occurs first in the wing chordwise bending mode and, at higher speeds, in wing beamwise bending and in torsion These are shown in figure 8. The instability is similar in nature to propeller nacelle whirl flutter, but involves elastic bending of the blade and elastic deflections of the blade pitch control system in addition to the precession of the rotor disc. There is considerable confidence in the predicted stability characteristics, since the coupled rotor/airframe stability analysis has shown excellent agreement with flutter model tests and with tests of a full-scale semi span wing in the NASA Ames 40 x 80 foot wind tunnel (ref. 3).

Empennage Flutter

The XV-15 has an H-tail, a configuration that gives it good high-speed directional stability characteristics. Although flutter was of concern during the design, the empennage was designed to avoid resonance of the empennage modes with rotor excitation frequencies. For good frequency placement, the horizontal stabilizer is very stiff in bending and torsion. The elevator and rudder are powered by irreversible hydraulic actuators (dual for the elevator) with lock and load mechanisms to make them irreversible in the event of a hydraulic system failure. As a result, the empennage has a large flutter margin that has been confirmed by flutter model tests in the 16-foot transonic tunnel at NASA Langley (ref. 4).

Flight Flutter Testing Method

For tests to determine the frequency and damping of the coupled rotor/airframe modes, the research XV-15 will have series actuators in the wing flaperon and rotor blade collective pitch control linkages. The copilot or flight test engineer will control the amplitude and frequency of the actuators, which have limited authority so that a hardover cannot cause excessive stresses or aircraft responses that the pilot cannot easily control. The actuator frequency response is flat to well above the frequency of the highest coupled mode of interest.

Frequency and damping of each mode of interest will be determined from the decay of that mode. The test procedure will be to select either the flaperon or collective actuator and tune its excitation frequency to the modal frequency, then turn off (the actuators automatically center) and record the decay. This procedure was used in the full-scale test in the 40 x 80 foot wind tunnel, and gave good results. The decays will be monitored and analyzed on the ground for flight safety during flight envelope expansion.

The excitation system will also be used to generate transfer functions by slow-sweeping excitation frequency. These transfer functions will be used for an additional check on the validity of the coupled rotor/airframe stability analysis.

Tests to evaluate the empennage flutter characteristics will excite the empennage modes with doublet inputs to the elevator and rudders. These will be generated through the series SCAS actuators.

CONCLUDING REMARKS

1. For an elastomeric damper such as the one used on the Model 609 blade lead-lag hinge, the characteristics of the material depend on its strain. Since the lead-lag displacement (hence strain) varies with flight conditions, the lead-lag frequency varies throughout the flight test. It was learned from this study that, in the moving block analysis, a good estimate of the assumed frequency of computation could help the convergence.

2. The dynamic and aerodynamic environment of a rotor change as the flight condition changes; hence the steady state one-per-rev and two-per-rev harmonic loads also vary. Therefore it is suggested that the nulling system be retuned whenever the flight condition changes. However this option was not used during the Model 609 test because the rotor synchro was not operational.

3. Because of the limitations on SCAS authority for the Model 609 testing, the signal-to-noise ratio for the modes of interest was relatively low. Therefore, a number of different analog filters were used to clean up the data. Low-pass filters from 3 Hz to 12 Hz, however, made no appreciable difference in damping calculations.

4. The single-mode excitation technique, using the SCAS actuators, produces excellent stability data since the input signal is well under the user's control. Depending on the input magnitude phasing and limitations of the SCAS authority, any mode in a rotary wing aircraft can be excited by the oscillation of the rotor controls in a prescribed manner. But whether the initial condition (mode shape) of the aeroelastic mode of interest is excited properly remains to be seen. The moving block analysis in most cases can be used in conjunction with the single-mode excitation technique to assess the stability information from ground run or flight test with real time computation. This testing and data reduction package is useful for on-line flight flutter testing of rotary wing aircraft.

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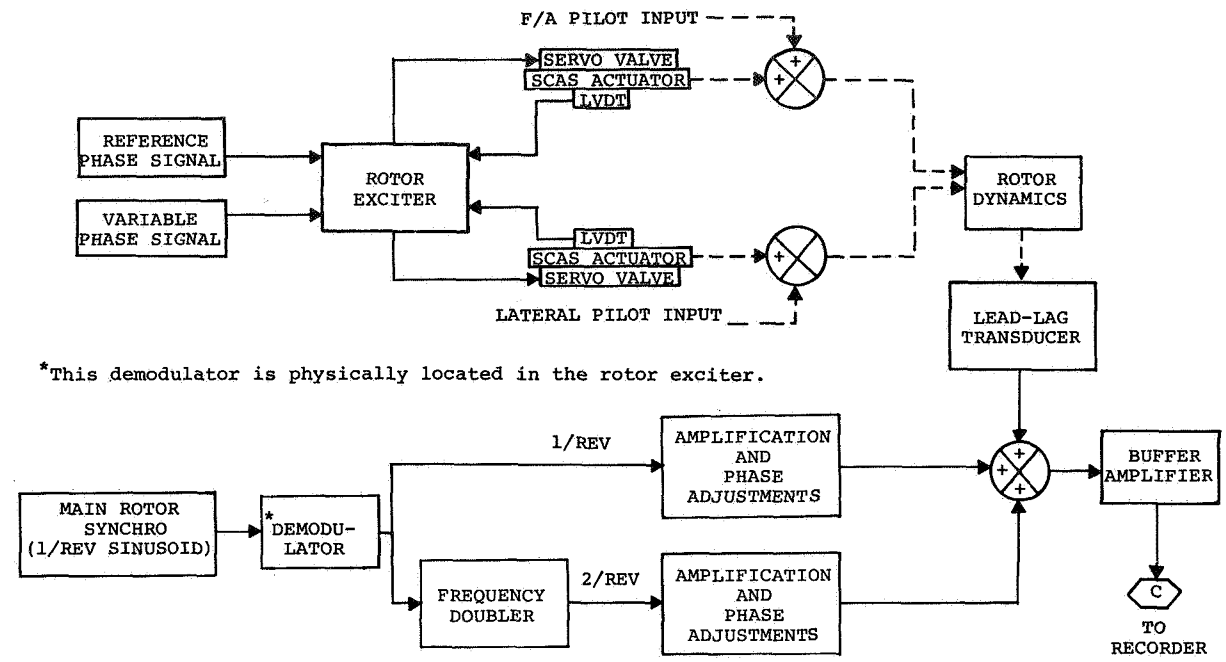


Figure 1. Functional block diagram of rotor excitation system.

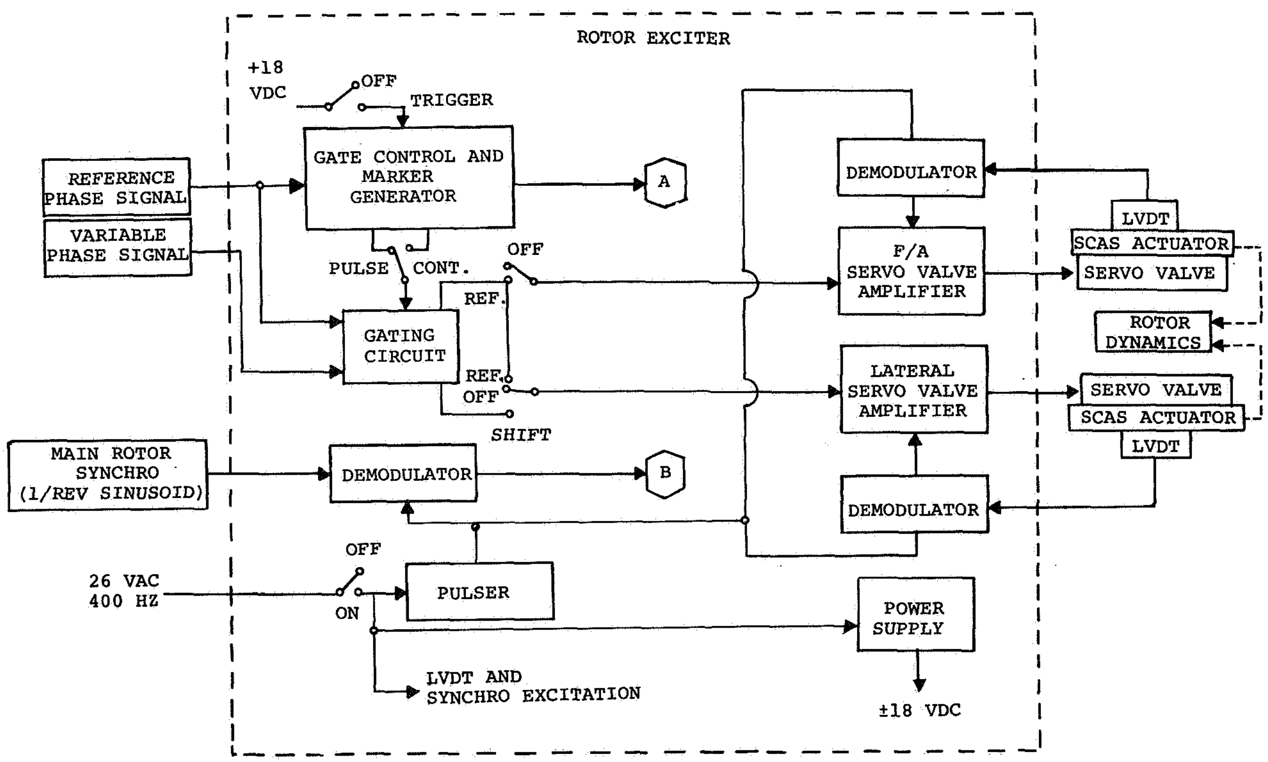
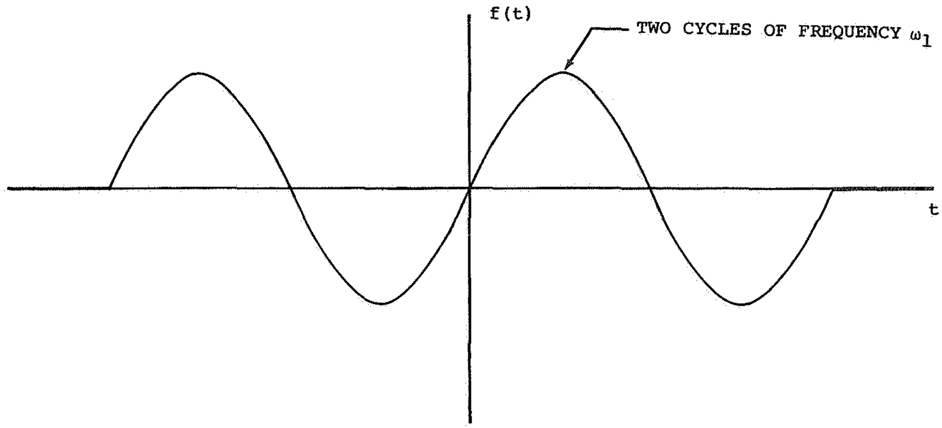
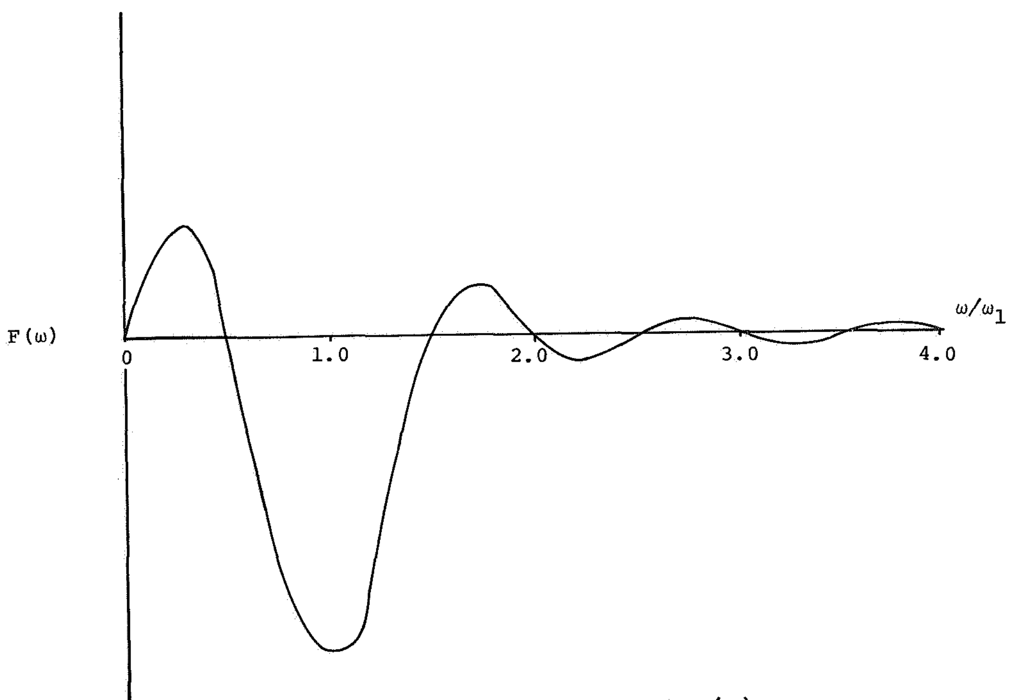


Figure 2. Diagram of rotor exciter.

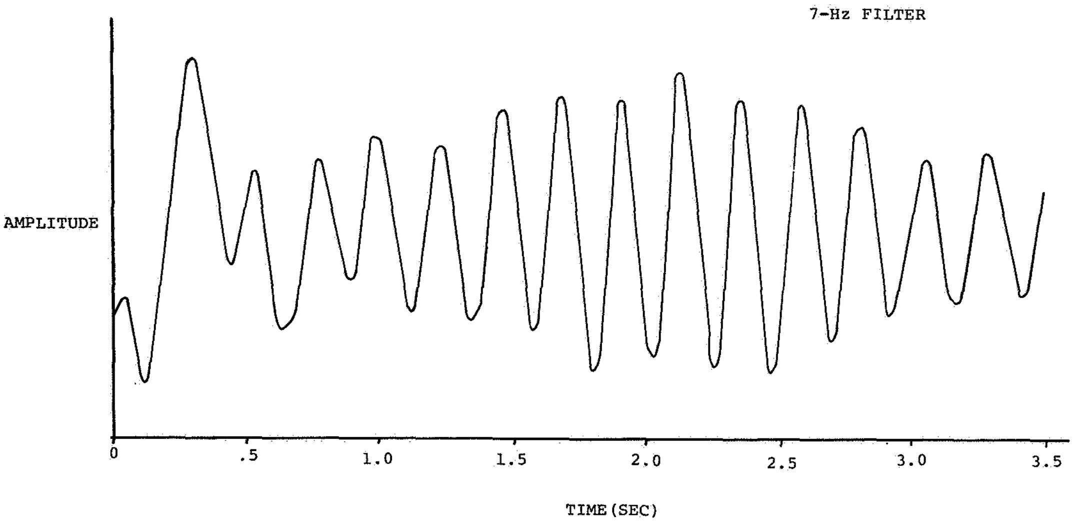


(a) Plot of f(t).

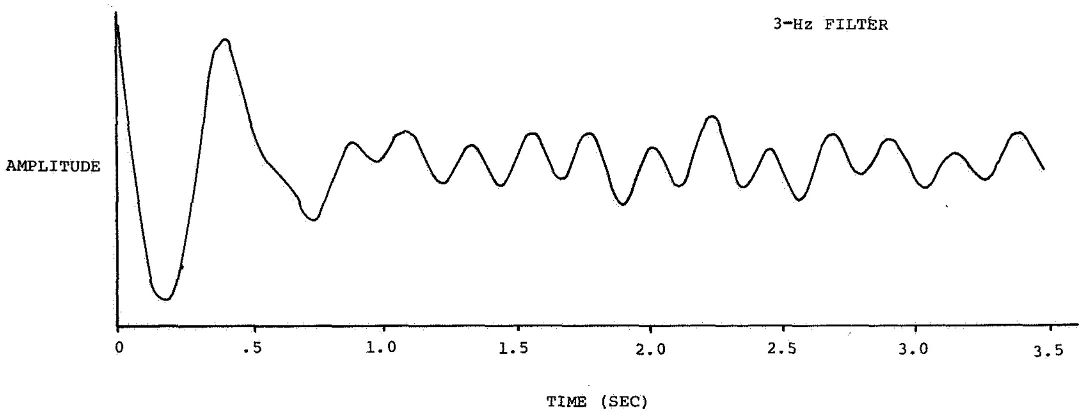


(b) Fourier transform of f(t).

Figure 3. Forcing function f(t).

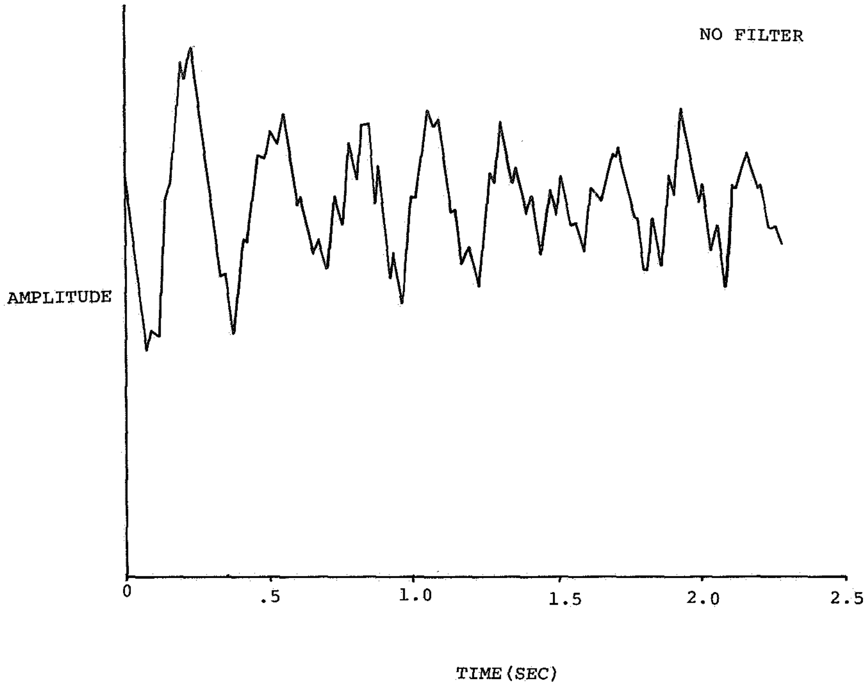


(a) With 7-Hz filter.

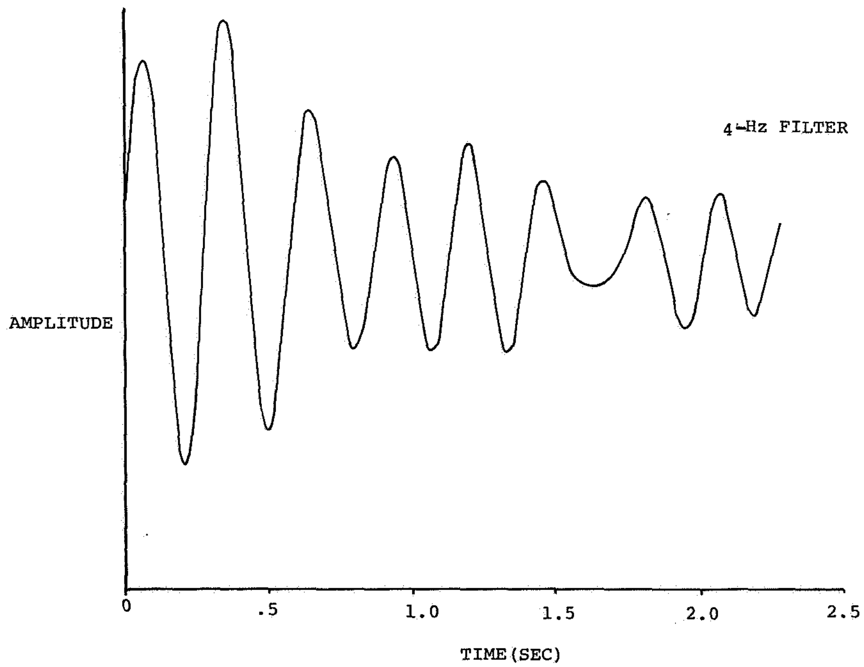


(b) With 3-Hz filter.

Figure 4. Fuselage roll mode decay in ground run. Ω = 260 rpm; low collective.

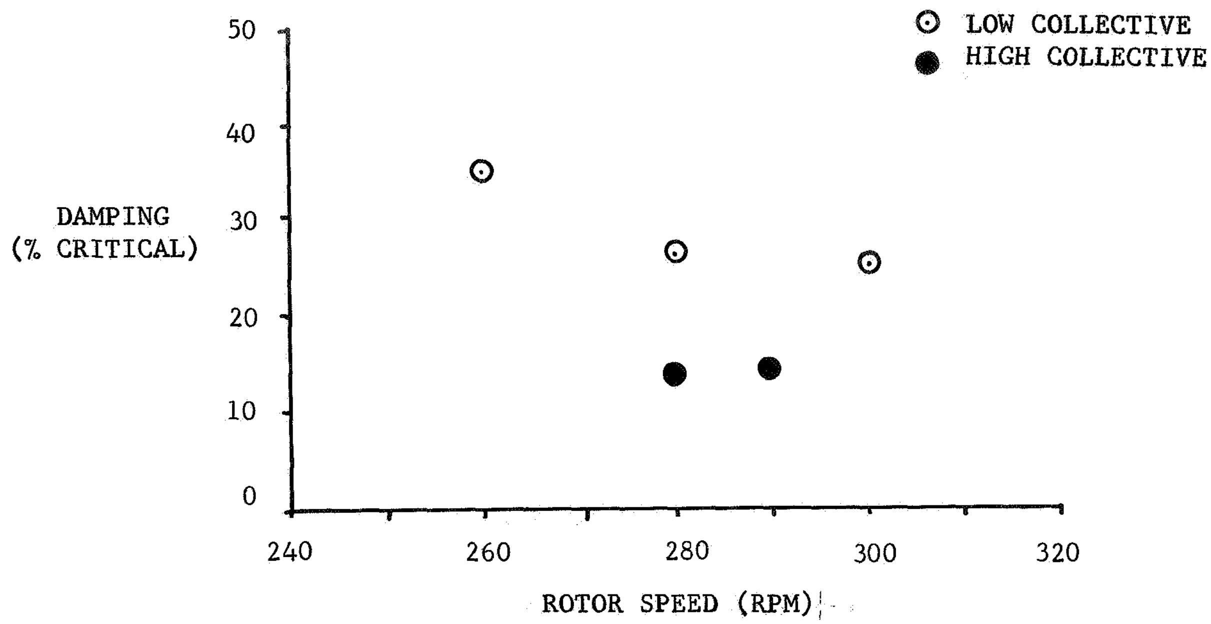


(a) With no filter.

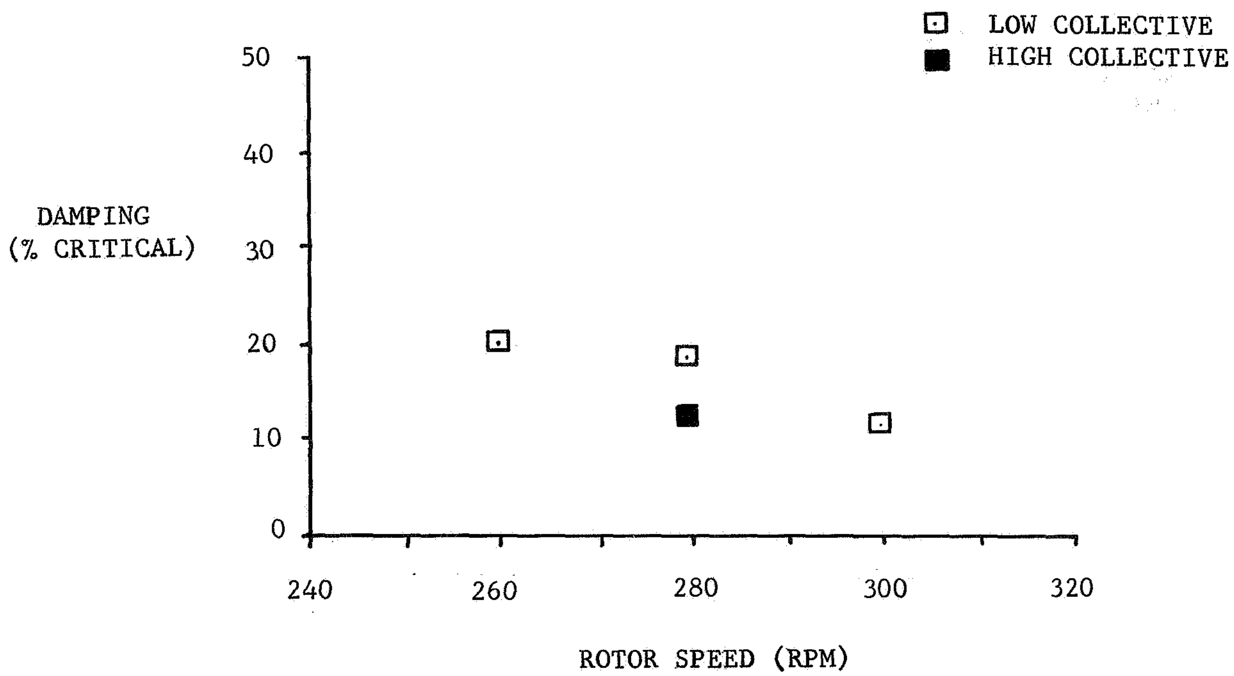


(b) With 4-Hz filter.

Figure 5. Blade lead-lag decay in ground run. Ω = 280 rpm; high collective.



(a) Blade lead-lag damping.



(b) Fuselage roll mode damping.

Figure 6. Damping in fixed system.

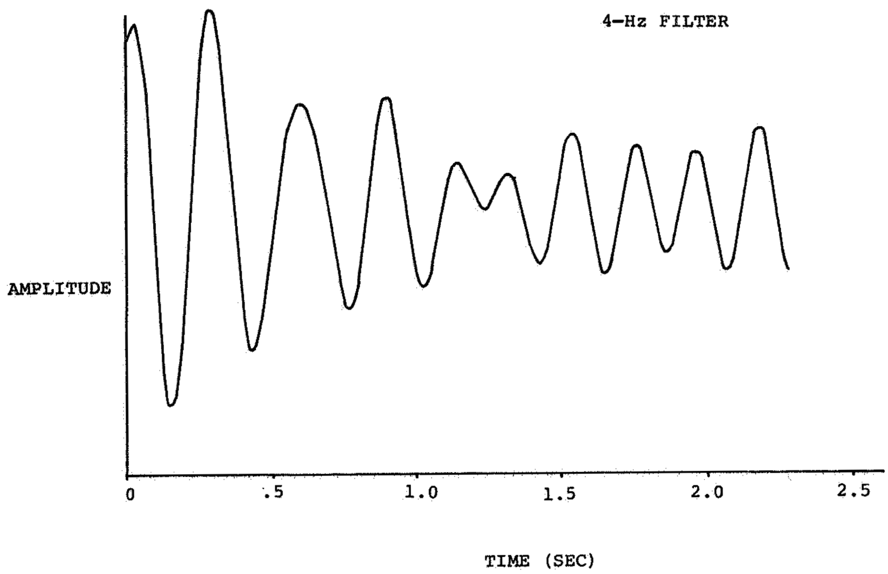


Figure 7. Filtered blade lead-lag decay in hover, Ω = 285 rpm.

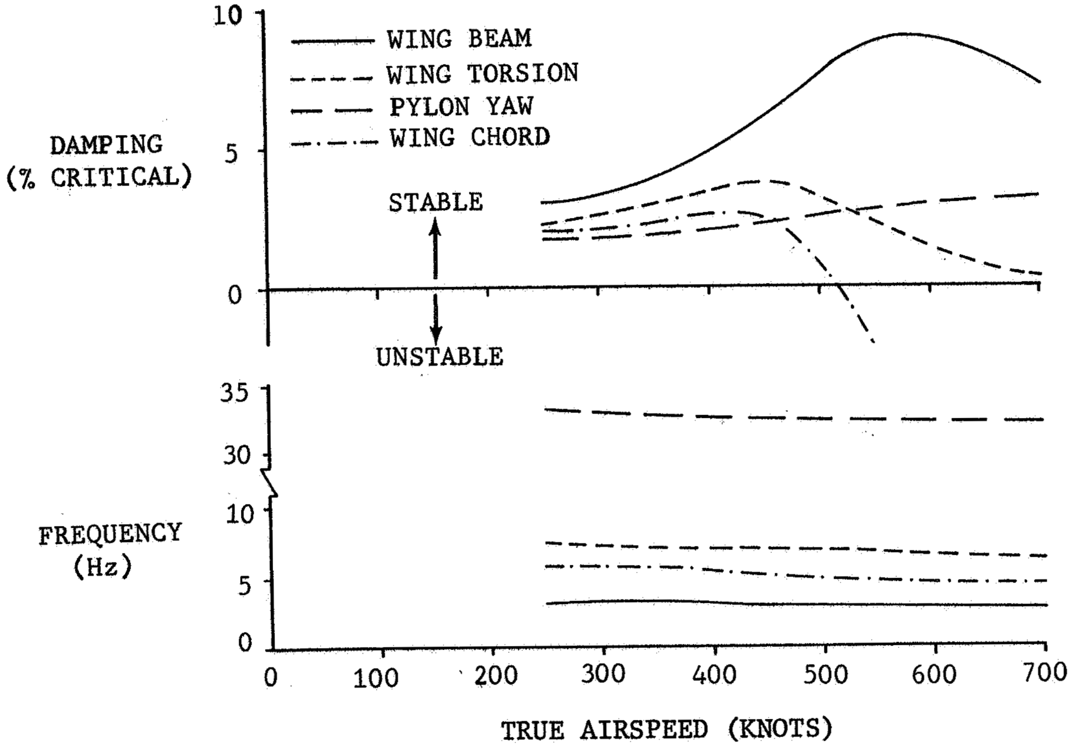


Figure 8. Calculated stability for XV-15 at density altitude 6096 m. (20000 ft).

NASA-Langley, 1976 L-10567