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HELICOPTER GUST ALLEVIATION, ATTITUDE STABILIZATION, AND VIBRATION ALLEVIATION USING INDIVIDUAL-BLADE-CONTROL THROUGH A CONVENTIONAL SWASH PLATE

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HELICOPTER GUST ALLEVIATION, ATTITUDE STABILIZATION, AND VIBRATION ALLEVIATION USING INDIVIDUAL-BLADE-CONTROL THROUGH A CONVENTIONAL SWASH PLATE*

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Abstract

A new, advanced type of active control for helicopters and its application to the solution of rotor aerodynamic and aeroelastic problems is described. Each blade is individually controlled in the rotating frame over a wide range of frequencies up to the sixth harmonic of rotor speed.

The concept of Individual-Blade-Control (IBC) embodies the control of individual blade pitch by means of broad-band electrohydraulic actuators attached to the swash plate (in the case of three blades) or individually to each blade, using signals from accelerometers mounted on the blades to supply appropriate control commands to the actuators. Note that the IBC involves not only control of each blade independently, but also a feedback loop for each blade in the rotating frame. In this manner, it becomes possible to alleviate the severe effects of blade-vortex interaction, blade-fuselage interference, atmospheric turbulence, and adverse vehicle dynamics.

The present paper describes the design of a system controlling blade lag, flapping and bending dynamics, and related testing of the system on a model rotor in the wind tunnel. The control inputs considered are blade pitch changes proportional to blade flapping and bending acceleration, velocity, and displacement and lag velocity. It is shown that helicopter gust alleviation, attitude stabilization, vibration alleviation, and air/ground resonance suppression can be achieved using the conventional helicopter swash plate.

Introduction

A truly advanced helicopter rotor must operate in a severe aerodynamic environment with high reliability and low maintenance requirements. This environment includes:

(1) atmospheric turbulence (leading to impaired flying qualities, particularly in the case of hingeless rotor helicopters).

(2) retreating blade stall (leading to large torsional loads in blade structure and control system).

(3) blade vortex interaction in transitional and nap-of-the-earth flight (leading to unacceptable higher harmonic blade bending stresses and helicopter vibration).

(4) blade-fuselage interference (leading to unacceptable higher harmonic blade bending stresses and helicopter vibration).

(5) blade instabilities such as air/ground resonance.

(6) tilt-rotor lag bending during maneuvering flight.

The application of feedback techniques make it possible to alleviate the effects described in items (1) to (6) above, while improving helicopter vibration and handling characteristics to meet desired standards. The concept of Individual-Blade-Control (IBC) embodies the control of broadband electrohydraulic actuators attached to each blade or the swash plate, using signals from sensors mounted on the blades to supply appropriate control commands to the actuators.[1-7] Note that IBC involves not just control of each blade independently, but also a feedback loop for each blade in the rotating frame. In this manner it becomes possible to reduce the severe effects of atmospheric turbulence, retreating blade stall, blade-vortex interaction, blade-fuselage interference, and blade instabilities, while providing improved flying qualities.

It is evident that the IBC system will be most effective if it is comprised of several sub-systems, each controlling a specific mode, e.g., the blade flapping mode, the first blade lag mode, the first blade flatwise bending mode, and the first blade torsion mode. Each sub-system operates in its appropriate frequency band(Fig.1).

The configuration considered in Refs. 1-6 employs an individual actuator and multiple feedback loops to control each blade. These actuators and feedback loops rotate with the blades and, therefore, a conventional swash plate is not required. However, some applications of individual-blade-control can be achieved by placing the actuators in the non-rotating system and controlling the blades through a conventional swash plate as described below and in Ref. 7.

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*U.S. Patent Pending.

Technical Discussion

Reference 3 describes the application of Individual-Blade-Control to helicopter gust alleviation. The feedback blade pitch control was proportional to blade flapping acceleration and displacement, i.e.,

$$\Delta\theta = -K\left(\frac{\ddot{\beta}}{\Omega^2} + \beta\right)$$

A block diagram of the control system is shown in Fig. 2.

Figure 3 and 4 show the effect of increasing open-loop gain K upon the IBC gust alleviation system performance. Note the experimental reduction in gust-induced flapping response in accordance with the theoretical closed-loop gain 1/(1+K).

The Lock number of the model blade was 3.0. For a full size rotor, the increase in damping due to the increase in Lock number results in the flapping at excitation frequency becoming the dominant response. Also, with increased blade damping it becomes possible to use higher feedback gain for the same stability level, and as a consequence the IBC system performance improves with increasing Lock number.

Following the successful alleviation of gust disturbances using the IBC system, Ref. 7 showed the theoretical stabilization of blade flapping response for other low-frequency disturbances, e.g., helicopter pitch and roll attitude.

Reference 5 describes the application of Individual-Blade-Control to blade lag damping augmentation. The feedback blade pitch control was proportional to blade lag velocity, i.e.,

$$\Delta\theta = -K\frac{\dot{\zeta}}{\Omega}$$

A block diagram of the control system is shown in Fig. 5, and Fig. 6 shows the augmentation of blade lag damping, as evidenced by the reduction in slope of response phase angle at resonance.

Reference 6 describes the application of Individual-Blade-Control to helicopter vibration alleviation. The feedback blade pitch control was proportional to blade bending acceleration, velocity, and displacement, i.e.,

$$\Delta\theta = -K\left(\frac{\ddot{g}}{\Omega^2} + \frac{\dot{g}}{\Omega} + g\right)$$

Block diagrams of the control system are shown in Figs. 7 and 8, and Fig. 9 shows some preliminary experimental results for K=3.

IBC Through a Conventional Swash Plate

Several important dynamic phenomena of the helicopter rotor occur at harmonics of rotor rotational speed:

(1) Gust-induced flapping, both quasi-steady and at 1P

(2) Motion-induced flapping, both quasi-steady and at 1P

(3) Airload-induced vibration at NP and (N±1)P

(4) Rotor fuselage air/ground resonance at 1P

Previous investigations have shown that individual-blade-control (IBC) can alleviate items (1) to (3) above (Ref. 7). Reference 5 demonstrated that blade lag damping can be augmented using IBC to suppress item (4).

It is now shown that IBC can be implemented through a conventional swash plate to alleviate items (1) to (4) for four-bladed rotors:

The control requirement for the mth individual blade is

$$\theta_m = -K_A\frac{\ddot{\beta}_m}{\Omega^2} - K_R\frac{\dot{\beta}_m}{\Omega} - K_P\beta_m - k_A\frac{\ddot{g}_m}{\Omega^2} - k_R\frac{\dot{g}_m}{\Omega} - k_P g_m - \frac{K\dot{\zeta}_m}{\Omega}$$

The corresponding control requirement for the swash plate is

$$\theta = \theta_o + \theta_{1_c}\cos\psi + \theta_{1_s}\sin\psi + \theta_2$$

Using the mathematics of Ref. 8, P. 351, the control algorithms are

$$\theta_o = \frac{1}{N}\sum_{m=1}^{N}\theta_m = \frac{1}{4}(\theta_1 + \theta_2 + \theta_3 + \theta_4) \text{ for } N = 4$$

$$\theta_{1_c} = \frac{2}{N}\sum_{m=1}^{N}\theta_m\cos\psi_m = \frac{1}{2}(\theta_1\cos\psi_1 + \theta_2\sin\psi_1 - \theta_3\cos\psi_1 - \theta_4\sin\psi_1)$$

$$\theta_{1_s} = \frac{2}{N}\sum_{m=1}^{N}\theta_m\sin\psi_m = \frac{1}{2}(\theta_1\sin\psi_1 - \theta_2\cos\psi_1 - \theta_3\sin\psi_1 + \theta_4\cos\psi_1)$$

θ_2 = 0 except for IBC at 2P, 6P, 10P --- (Ref. 8, P. 348)

The physical significance of the above equations is that IBC of a four-bladed rotor having a conventional swash plate is possible for those IBC functions involving the zeroth (quasi-steady), first, third, fourth, and fifth harmonics of rotor speed, e.g., gust alleviation, attitude stabilization, vibration alleviation, and air/ground resonance suppression, since no differential collective θ_2 is required for these harmonics.

In general, the 0P, 1P, NP, and (N±1)P harmonics of an N-bladed rotor can be controlled through a conventional swash plate. A typical application for N=4 and 3P excitation is shown in Fig. 10.

The summations of individual blade sensor signals required to obtain the swash plate collective and cyclic pitch components provide a filtering action such that only the desired harmonics 0P, 1P, 3P, 4P, and 5P remain after summation, i.e., no specific harmonic analysis is required. In addition, automatic smoothing of random noise in the signals is achieved.

Since all sensing is done in the blades, no transfer matrices from non-rotating to rotating system are required; therefore no updating of these matrices is required, and no non-linearity problems result from the linearization required to obtain the transfer matrices (see Ref. 9). Also, blade state measurements allow tighter vehicle control since rotor control can lead fuselage response: this lead provides more effective gust alleviation and permits higher control authority without inducing rotor instabilities than would be possible without rotor state feedback (see Ref. 10).

The following equipment is required to implement IBC for gust alleviation and attitude stabilization of an N-bladed helicopter rotor:

(1) one flatwise accelerometer per blade.

(2) one blade root angle transducer per blade.

(3) a means of transmitting signals from rotating to non-rotating system.

(4) swash plate actuator bandwidths up to disturbance frequency.

The following equipment is required to implement IBC for vibration alleviation of an N-bladed helicopter rotor:

(1) three flatwise accelerometers per blade.

(2) one blade root angle transducer per blade.

(3) a means of transmitting signals from rotating to non-rotating system.

(4) swash plate actuator bandwidths up to (N+1)P.

The following equipment is required to implement IBC for air/ground resonance suppression or tilt-rotor maneuvering load alleviation of an N-bladed helicopter rotor:

(1) two lagwise accelerometers per blade.

(2) a means of transmitting signals from rotating to non-rotating system.

(3) swash plate actuator bandwidths up to disturbance frequency.

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FIG. 1 PRINCIPLES OF MODAL CONTROL

Consider the modal equation of motion

$$m\ddot{x} + c\dot{x} + kx = F(t) + \Delta F \qquad (1)$$

where the modal control force ΔF is

$$\Delta F = -K_A m\ddot{x} - K_R c\dot{x} - K_P kx \qquad (2)$$

Then substituting (2) into (1)

$$(1+K_A)m\ddot{x} + (1+K_R)c\dot{x} + (1+K_P)x = F(t)$$

For the case $K_A = K_R = K_P = K$

$$m\ddot{x} + c\dot{x} + kx = \frac{1}{1+K} F(t)$$

and the modal response is attenuated by the factor $\frac{1}{1+K}$

while the modal damping and natural frequency are unchanged.

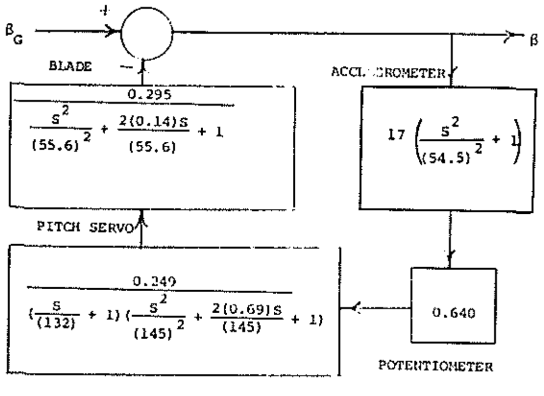


FIG. 2 GUST ALLEVIATION SYSTEM MATHEMATICAL BLOCK DIAGRAM

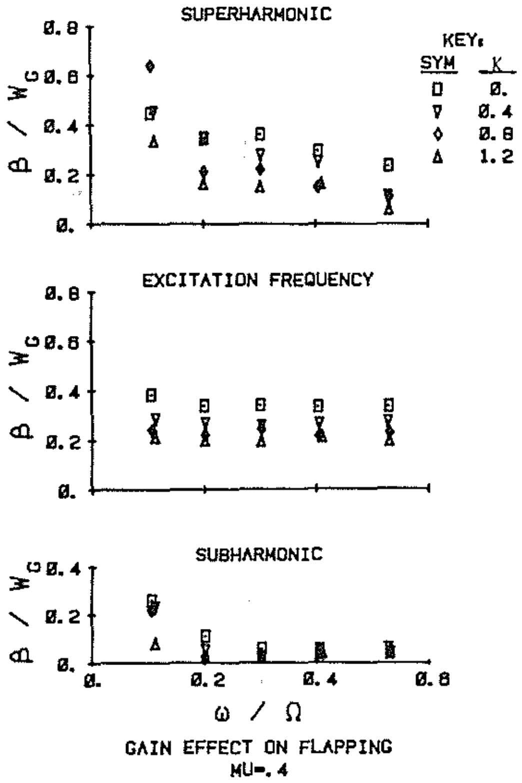


FIG. 3 Effect of Feedback Gain on Flap Angle Response to Gust ($\mu = 0.4$)

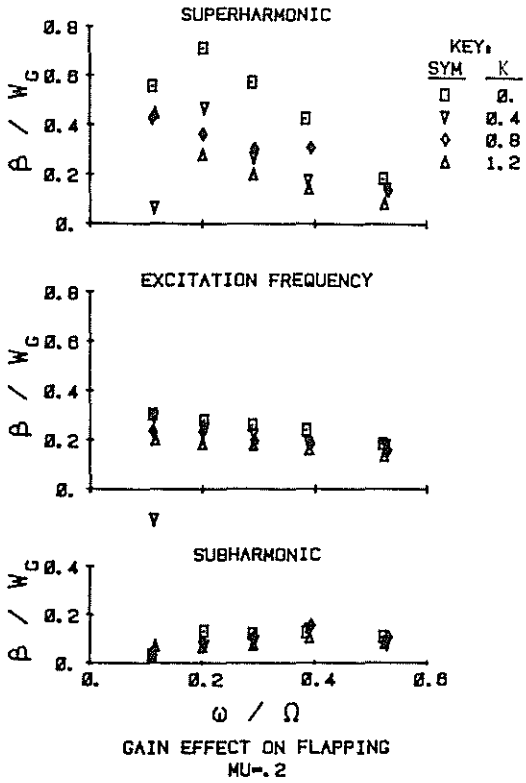
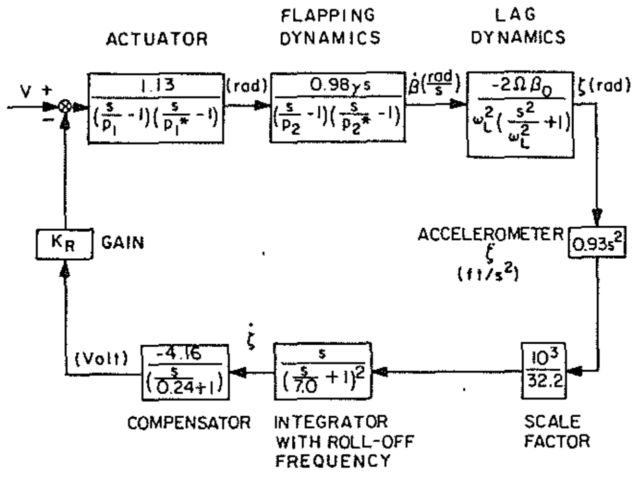


FIG. 4 Effect of Feedback Gain on Flap Response to Gust ($\mu = 0.2$)



$P_1 = -300(1+j)$

$P_2 = -12.1 + 82.57j$

$\omega_L = 28.74$ rd/s

FIG. 5 Block Diagram of the System with Compensator

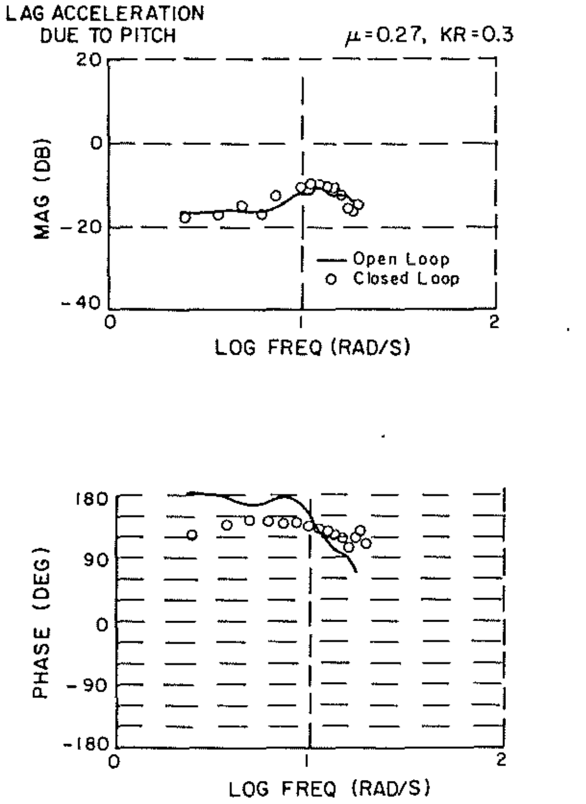


FIG. 6 Experimental Results, $\mu = 0.27$, $\Omega = 37.7$ rad/s. Pitch θ to Accelerometer Difference Signal $1/2\,(R-e)\,\ddot{\zeta}$

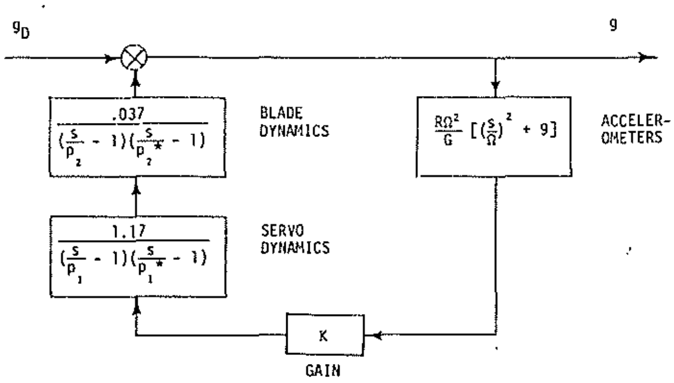


FIG. 7 Inner Loop Block Diagram Yielding H(s) (Vibration System)

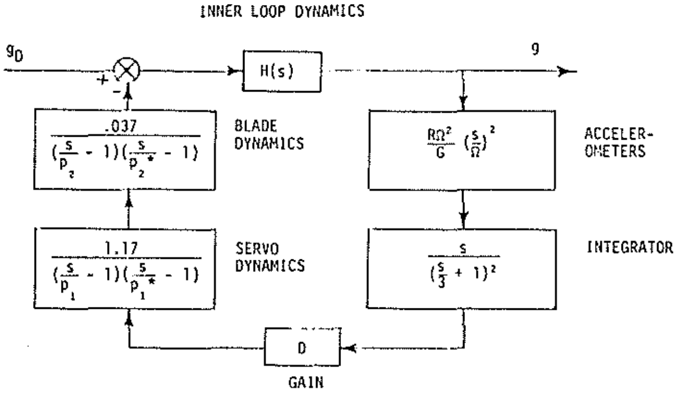


FIG. 8 Outer Loop Block Diagram (Vibration System)

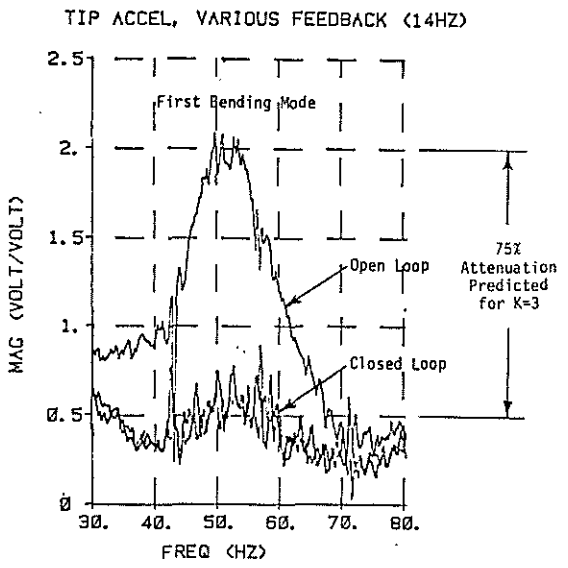


Fig. 9 Open and Closed Loop Tip Accelerometer Response to White Noise Pitch Input in Hover

FIG. 10 TYPICAL APPLICATION OF IBC USING THE CONVENTIONAL SWASH PLATE

CONSIDER A TYPICAL CONTROL REQUIREMENT FOR BLADE 1:

$$\theta_1 = \bar{\theta}_1 \sin 3\psi_1$$

THEN THE CONTROL REQUIREMENTS FOR BLADES 2,3,4 ARE:

$$\theta_2 = \bar{\theta}_1 \sin 3(\psi_1 - 90) = \bar{\theta}_1 \cos 3\psi_1$$

$$\theta_3 = \bar{\theta}_1 \sin 3(\psi_1 - 180) = -\bar{\theta}_1 \sin 3\psi_1$$

$$\theta_4 = \bar{\theta}_1 \sin 3(\psi_1 - 270) = -\bar{\theta}_1 \cos 3\psi_1$$

THE CORRESPONDING CONTROL REQUIREMENTS FOR THE SWASH PLATE ARE:

$$\theta_{1_c} = \frac{1}{2}(\theta_1 \cos\psi_1 + \theta_2 \sin\psi_1 - \theta_3 \cos\psi_1 - \theta_4 \sin\psi_1) = \bar{\theta}_1 \sin 4\psi_1$$

$$\theta_{1_s} = \frac{1}{2}(\theta_1 \sin\psi_1 - \theta_2 \cos\psi_1 - \theta_3 \sin\psi_1 + \theta_4 \cos\psi_1) = -\bar{\theta}_1 \cos 4\psi_1$$

THEN THE RESULTING CONTROL DISPLACEMENT FOR BLADE 1 IS:

$$\theta_1 = \theta_{1_c} \cos\psi_1 + \theta_{1_s} \sin\psi_1$$

$$= \bar{\theta}_1 \sin 4\psi_1 \cos\psi_1 - \bar{\theta}_1 \cos 4\psi_1 \sin\psi_1$$

$$= \frac{1}{2}\bar{\theta}_1(\sin 5\psi_1 + \sin 3\psi_1) - \frac{1}{2}\bar{\theta}_1(\sin 5\psi_1 - \sin 3\psi_1)$$

$$= \bar{\theta}_1 \sin 3\psi_1 \qquad \text{AS REQUIRED.}$$