Flight Dynamics of Rotorcraft in Steep High-g Turns

Robert T. N. Chen*
NASA Ames Research Center, Moffett Field, California

An analytical procedure developed to permit a systematic examination of rotorcraft flight dynamics in steep high-g turns is presented. The procedure is used in a numerical investigation of a tilt-rotor aircraft and three single-rotor helicopters that have different types of main rotor systems. The results indicate 1) that strong coupling in longitudinal and lateral-directional motions exists for these rotorcraft in high-g turns; 2) that for single-rotor helicopters, the direction of turn has a significant influence on flight dynamics; and 3) that a stability and control augmentation system that is designed on the basis of standard small-disturbance equations of motion from steady straight and level flight and that otherwise performs satisfactorily in operations near 1g becomes significantly degraded in steep turning flight.

Introduction

MODERN military rotorcraft are being designed with a view toward expanding their roles in tactical missions such as combat rescue, antitank, and air-to-air operations. They are now called upon to perform high-g maneuvers that make frequent excursions to the limits of their maneuvering flight envelopes. When operating in this flight regime, the flying qualities of these aircraft must be satisfactory if the pilots are to have confidence in the full potential of the maneuvering capabilities of rotorcraft. Although a considerable amount of work has been done on stability and control, flying qualities, and flight-test techniques for 1-g flight operations, relatively little has been done in these technology areas for the rotorcraft operating in high-g environments.[1-6] The standard equations of airplane motion for small disturbances from steady symmetrical straight flight[7,8] have been the basis for stability and control analyses, flying-qualities specifications,[9-11] and design analyses of stability and control augmentation systems (SCAS) for rotorcraft. However, for rotorcraft that must frequently perform extreme maneuvers, flying-qualities designs based on small disturbances from steady straight flight may be grossly inadequate. A new analytical framework is needed to permit a systematic examination of the flight dynamics and control characteristics of the basic aircraft and its SCAS to ensure that the overall aircraft-SCAS system will perform satisfactorily, not only in operations near 1-g flight but also in high-g maneuvers.

A fundamental characteristic associated with a rotorcraft in basic maneuvers, such as steep high-g turns, is an increase in control effectiveness and damping, particularly in pitch and roll axes with increasing load factor. The extent of the increase depends, to a large measure, on the type of the main-rotor system used. For a teetering-rotor helicopter, the control in pitch and roll is almost entirely through tilting the thrust vector of the main rotor; therefore, the increase in control effectiveness in these two axes is directly proportional to load factor. At the other extreme, for a hingeless rotor the increase is much less because the direct hub moment, which shares most of the control power, is independent of the thrust level of the rotor system. Further, the interaxis cross coupling, such as pitch, roll, and yaw, that results from collective and pitch-roll coupling which results from aircraft angular rates, also changes with the load factor. The ramifications of these variations in stability and control characteristics in high-g turns on the flying qualities and the design of SCAS for the helicopter need to be investigated.

Asymmetrical rotorcraft, such as single-rotor helicopters, exhibit another phenomenon uncommon to fixed-wing aircraft: inherent sideslip in coordinated (wings level) straight flight[12]. The amount of sideslip depends on side-force characteristics as well as on roll and yaw stability and control characteristics, and it tends to increase as the gross weight of the aircraft increases. Similarly, sideslip is also inherent in a coordinated turn and it tends to increase as the load factor increases. Further, sideslip varies with the turn direction because of the asymmetrical nature of these rotorcraft. The presence of sideslip makes the examination of the static and dynamic characteristics of this class of rotorcraft more difficult than that of fixed-wing aircraft, because the equations governing the equilibrium flight become more complicated and, thus, it is more difficult to compute the trim conditions.

As a basis for understanding these characteristics, a study was conducted to investigate the influence of sideslip on the static characteristics of the helicopter in coordinated steep turns.[13] A set of governing equations was developed, and closed-form solutions were obtained that relate the aircraft attitudes and angular rates to the turn parameters (Earth-referenced turn rate, flight-path angle, and airspeed), angle of attack, and sideslip, thereby decoupling the governing equations and, thus, drastically simplifying the trim computations. In a subsequent study the exact small-disturbance equations of motion about a general steep turning path were developed.[14] These new developments provide an opportunity to establish suitable equilibrium reference flight conditions in coordinated high-g turns and to systematically examine their associated flight dynamic characteristics of this class of aircraft.

This paper presents the results of an analytical study that examines the flight dynamics of rotorcraft in high-g turns. The rotorcraft studied include a tilt-rotor aircraft, which is a representative symmetrical-type rotorcraft, and three single-rotor helicopters: a hingeless-rotor, an articulated-rotor, and a teetering-rotor helicopter. The effects of rotorcraft configuration and turn direction are assessed for a set of selected reference flight conditions, including those near the boundary of the maneuver envelope. The dynamic characteristics of a hingeless-rotor helicopter with SCAS operating in high-g turns are also assessed and the influence of rotor type on the design of SCAS discussed.

Presented as Paper 82-1345 at the AIAA 9th Atmospheric Flight Mechanics Conference, San Diego, Calif., Aug. 9-11, 1982; received Aug. 11, 1982; revision received June 7, 1983.

*Group Leader and Research Scientist. Member AIAA.

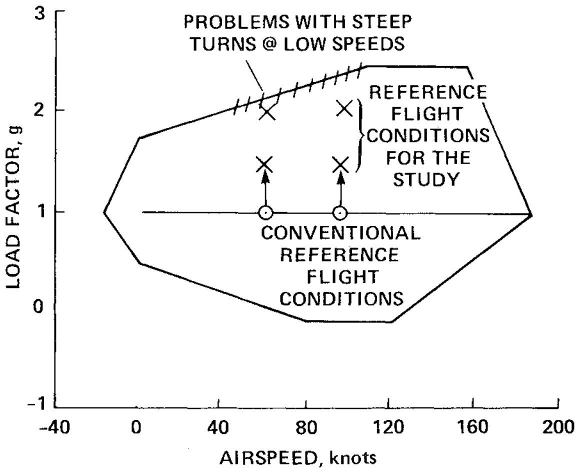

Fig. 1 Choice of reference flight conditions for helicopter flight dynamics study.

Trim Values and Stability and Control Matrices of Rotorcraft in Coordinated Steep Turns

The trim algorithm and the algorithm for computing the stability and control matrices developed in Refs. 13 and 14 for a coordinated steep turn were implemented for a nonlinear, full-flight-envelope simulation model of a current generation military utility helicopter which has an articulated main rotor.[15] These algorithms were also incorporated into a generic nonlinear real-time simulation model[16] which was configured to simulate two single-rotor helicopters, that is, a hingeless-rotor type (representative of a BO-105) and a teetering-rotor type (representative of a UH-1H).[17] For these three helicopters, the study examined two airspeed conditions (60 and 90 knots) for a range of flight-path angles of ± 20 deg and for normal load factors up to $2g$. Figure 1 shows these reference flight conditions on a representative maneuver envelope. Figure 2 shows some sample trim conditions of the simulated hingeless-rotor helicopter. The stability and control matrices, F and G, of the same hingeless-rotor helicopter in coordinated straight-and-level flight, in a 2-g level right turn, and in a 2-g level left turn, all at 60 knots, are shown in Ref. 18.

Some important characteristics associated with the trim conditions are worth noting.

1) In general, in a coordinated turn the sideslip angle β increases with increasing load factor, though somewhat differently in left and right turns (see Fig. 2). The flight-path angle γ and the airspeed also have significant influence on the sideslip. The sideslip tends to increase as the flight-path angle increases, and it decreases as the airspeed increases.

2) The magnitude of the trim pitch attitude θ of the aircraft also increases as the load factor increases. In coordinated right turns, θ tends to increase in the nose-up sense; in coordinated left turns, however, the trim pitch attitude becomes increasingly nose down as the load factor increases.

The stability and control derivatives change substantially as the normal load factor increases from a straight-and-level flight to a 2-g level turn. These changes are due to aerodynamics, kinematics, and inertia. For example, because of aerodynamic effects of the rotor system, the control sensitivity and damping, notably in pitch and roll axes, increase as the load factor increases (for the hingeless rotor helicopter, $M_{\delta_e} = 1.022$ rad/s^2/in., $Mq = -3.993$ s^{-1}, $L'_{\delta_a} = 2.366$ rad/s^2/in., and $L'_p = -9.576$ s^{-1} at 1-g straight-and-level flight to $M_{\delta_e} = 1.173$, $Mq = -4.528$, $L'_{\delta_a} = 2.742$, and $L'_p = -11.168$ at 2-g level right turn). Kinematic effects as reflected in the increase in sideslip (as described earlier) constitute a factor in changing the matrix F. The effects of the turn direction on some elements of the stability matrix F are evident (see Ref. 18) by comparing those for the right and left turns. These effects include, for example, kinematic and inertia contributions owing to the asymmetry in roll attitude Φ, yaw rate r, and the rate of turn $\dot{\Psi}$.

For the purposes of comparative study, the trim algorithm and the computational algorithm for the stability and control matrices were also implemented on a nonlinear full-flight-envelope real-time simulation model for a tilt-rotor aircraft.[19] The study examined three specific configurations: an airplane mode at 240 knots; a conversion mode with the mast angle of 45 deg at 120 knots; and a helicopter mode at 60 knots. Because of the symmetrical nature of the aircraft, it exhibits negligible sideslip.

Flight Dynamics of Rotorcraft in Steep Turns

The discussions in this section are divided into two categories of rotorcraft: symmetrical rotorcraft, as exemplified by a tilt-rotor aircraft, and asymmetrical rotorcraft, typical of the single-rotor helicopters.

Symmetrical Rotorcraft: Tilt Rotor

The specific configuration of the tilt-rotor aircraft dictates, to a large extent, its flight-dynamic characteristics in high-g turns. Figure 3 shows the effect of normal load factor and flight-path angle on the eigenvalues of the tilt-rotor aircraft in coordinated right turns in the conversion mode at 120 knots. In coordinated 1-g flight (straight flight with wings level), there is little or no coupling between the longitudinal and lateral-directional motions as a result of the symmetrical nature of the aircraft. In a high-g coordinated turn, however, substantial coupling develops because of the kinematic, inertial, and aerodynamic effects. As a result, the modal characteristics undergo significant changes as the load factor (or the turn rate) increases. The short period and phugoid modes show an increase in natural frequency and a decrease in damping ratio (Fig. 3). Their mode shapes (eigenvectors) also change. Substantial lateral-directional motions now contaminate the phugoid mode, and a significant contribution to airspeed perturbations is now evident in the short-period mode. However, the excitation of lateral-directional motions in the short period remains insignificant. For the lateral-directional modes, the spiral is stabilized. Although the change in eigenvalues of the Dutch roll and the roll modes is slight, their mode shapes undergo significant changes; considerable contamination of longitudinal motion in these modes is evident, as indicated for the Dutch-roll mode, shown in Fig. 4. Note that the units are in knots, degrees, and seconds. For example, the change in pitch attitude is larger than that of roll attitude in the Dutch-roll mode at a 2-g turn.

The dynamic characteristics of high-g turns in an airplane mode at 240 knots of this rotorcraft were found to be similar, to a large measure, to the 120-knot configuration. The helicopter-mode configuration at 60 knots, however, proved to be the most complex situation of the three configurations studied. As is evident from Figs. 5 and 6, both the eigenvalues and eigenvectors (particularly the latter) undergo considerable changes as load factor increases. In a steep turn at 60 knots ($\gamma = -20$ deg, $n_T = 1.5$) in the helicopter mode, the contamination of the longitudinal motion in the Dutch-roll mode (see Fig. 6a) is even more dramatic than that in the conversion mode at 120 knots, as previously described (see Fig. 4). The change in pitch attitude is more than twice as large as that in roll attitude, and the changes in airspeed and angle of attack are substantial. Further, the change in roll attitude now lags more than 90 deg behind the change in sideslip instead of leading it, as in the 1-g flight case (which, also, is normally the case for fixed-wing aircraft in 1-g flight).[7] The contamination of the lateral-directional motion in the longitudinal short-period mode (see Fig. 6b) in the steep turn is also much more severe than that in the conversion mode at 120 knots (discussed previously).

The severe coupling in the longitudinal and lateral-directional motions in steep turns, as revealed by the mode

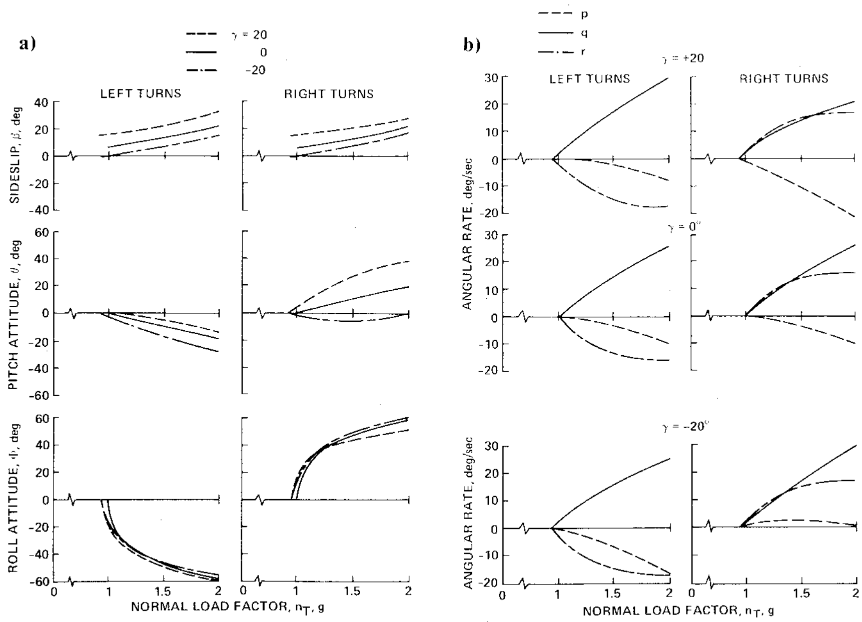

Fig. 2 Hingeless-rotor helicopter in coordinated turns at 60 knots: a) trim pitch and roll attitudes and inherent sideslip and b) trim angular rates.

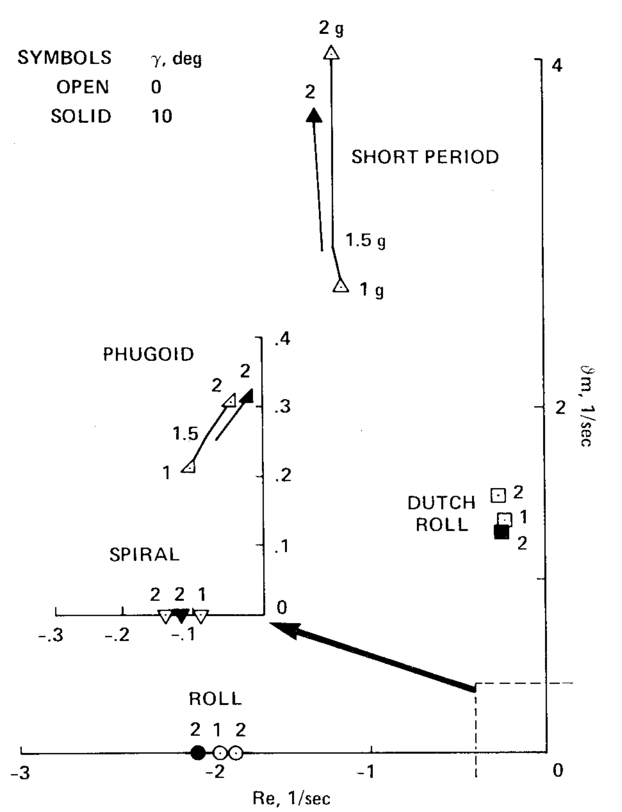

Fig. 3 Effect of normal load factor on eigenvalues of the tilt-rotor aircraft: conversion mode, 120 knots.

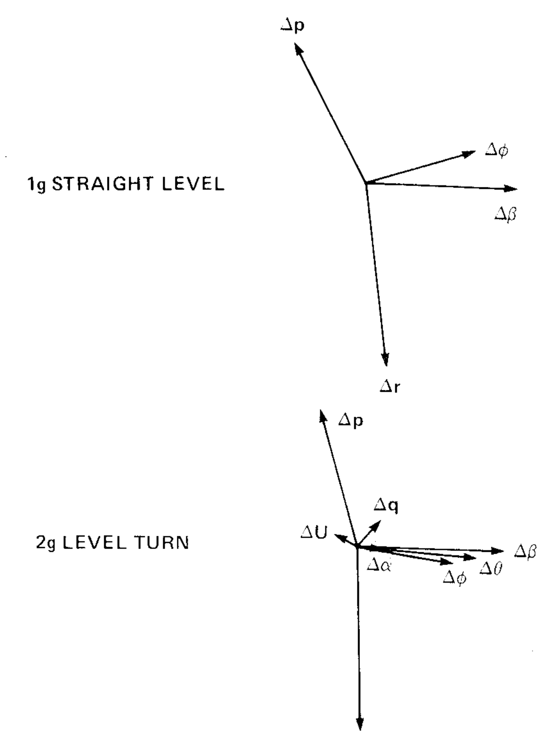

Fig. 4 Effect of normal load factor on Dutch-roll mode shape: tilt-rotor aircraft, conversion mode, 120 knots.

shapes, has also been confirmed by examining the transient response of the flight variables to cockpit control perturbations and by assessing the differences between the eigenvalues of the coupled and the uncoupled longitudinal and lateral-directional motions. It is evident that even for a symmetrical rotorcraft, the flying-qualities design analyses based on small perturbations from straight flight, as traditionally used, are inadequate for predicting flight dynamics in high-*g* maneuvers.

Asymmetrical Rotorcraft: Single-Rotor Helicopters

For the purpose of this paper the discussions that follow will focus primarily on a hingeless-rotor helicopter. Only brief comments on the effect of rotor type are given here.

For a single-rotor helicopter, coupling between the longitudinal and lateral-directional motions generally exists even in coordinated 1-*g* flight because of the presence of sideslip and the aerodynamic and inertial effects inherent with this class of aircraft. The coupling becomes more severe in coordinated turns at a higher load factor, not unlike the symmetrical rotorcraft described earlier. Table 1 summarizes the eigenvalues of the hingeless-rotor helicopter in coordinated right and left turns at 60 and 90 knots over a range of normal load factors. As is evident from the comparison of coupled and uncoupled longitudinal and lateral-directional eigenvalues, significant differences exist between 2-g left and right turns. The differences in 1-g flight are comparatively small, indicating that the coupling in the longitudinal motion and the lateral-directional motion are relatively benign in comparison with that of a higher load factor.

The effects of load factor and the direction of turn vary with each individual dynamic mode; they are discussed next.

Lateral-Directional Modes: Dutch Roll (Lateral Oscillation)

Both the frequency and damping ratio of the Dutch-roll mode are relatively insensitive to the variation in load factor and the direction of turn (as noted in Table 1), and, also, to flight-path angle. However, the eigenvector of the Dutch-roll mode (or mode shape) changes rather dramatically with load factor. Some changes with respect to the turn direction are also evident, as shown in Fig. 7. In 1-g flight, the contamination from the longitudinal motion is relatively small. This is not the case at a higher load factor: a dramatic increase in the excursion of pitch attitude per degree change in sideslip

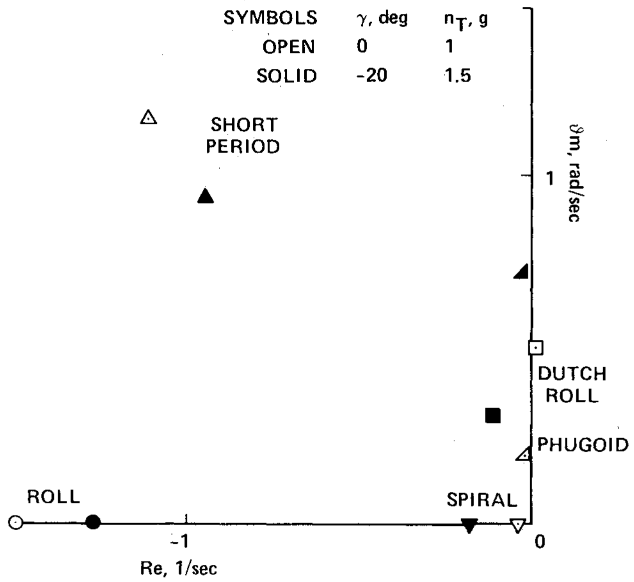

Fig. 5 Effect of normal load factor and flight-path angle on eigenvalues of the tilt-rotor aircraft, helicopter mode, 60 knots, right turn.

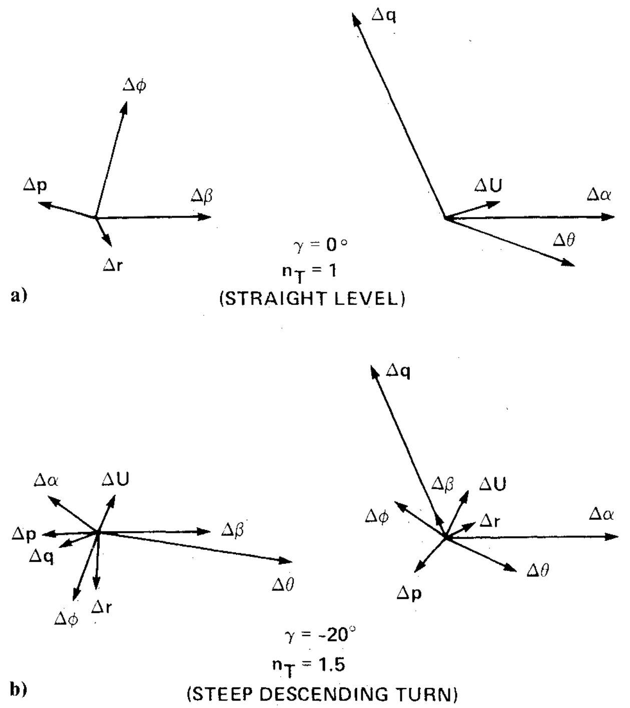

Fig. 6 Influence of steep turn on a) the Dutch-roll mode shape and b) short-period mode shape: tilt-rotor aircraft, helicopter mode, 60 knots.

Table 1 Eigenvalues of the hingeless-rotor helicopter

		Normal load factor, n_T (g)			
	Straight flight	Right turn 1.5	Right turn 2	Left turn 1.5	Left turn 2
		$V=60$ knots, $\gamma=0$ deg, coupled			
Coupled	−4.53	−4.96	−5.28	−4.78	−5.09
	−0.76	−0.56	(0.55; 0.68)	−0.58	−0.20
	(0.44; −0.15)[a]	(0.71; −0.21)	(0.92; −0.16)	(0.79; 0.02)	(1.02; 0.02)
	−9.90	−10.60	−11.51	−10.85	−11.76
	−0.03	−0.33	(2.04; 0.22)	0.13	−0.12
	(2.05; 0.22)	(2.04; 0.22)		(2.06; 0.21)	(2.07; 0.21)
		$V=60$ knots, $\gamma=0$ deg, uncoupled longitudinal			
Uncoupled longitudinal	−4.72		−5.29		−5.34
	−0.82		−0.44		−0.52
	(0.40; −0.12)		(0.58; 0.23)		(0.57; 0.19)
		$V=60$ knots, $\gamma=0$ deg, uncoupled lateral-directional			
Lateral-Directional	−9.61		−11.24		−11.07
	−0.04		0.001		−0.06
	(2.05; 0.22)		(1.98; 0.22)		(2.00; 0.21)
		$V=90$ knots, $\gamma=0$ deg, coupled			
Coupled	−5.46	−5.88	−6.27	−5.81	−6.20
	−0.49	(0.34; 0.92)	(0.44; 0.67)	−0.41	−0.31
	(0.54; −0.52)	(0.68; −0.55)	(0.80; −0.51)	(0.73; −0.31)	(0.89; −0.26)
	−9.87	−10.64	−11.46	−10.80	−11.61
	−0.04	(2.69; 0.21)	(2.69; 0.20)	0.18	0.21
	(2.71; 0.20)			(2.69; 0.20)	(2.69; 0.20)

[a] $(\omega_n; \zeta)$.

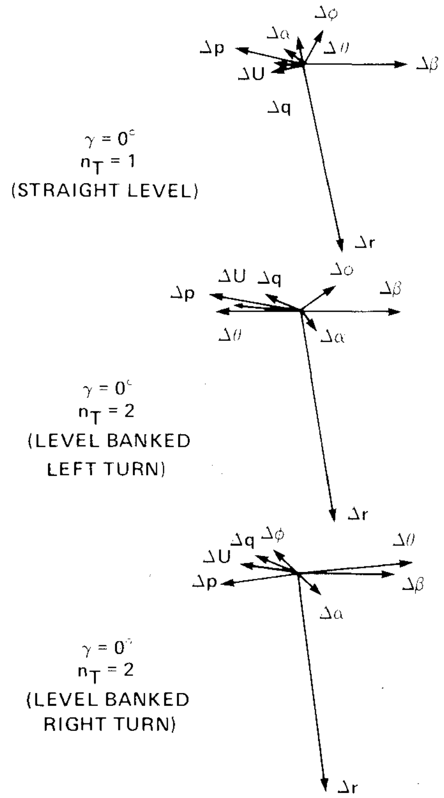

Fig. 7 Influence of load factor on the Dutch-roll mode shape: hingeless-rotor helicopter, 60 knots.

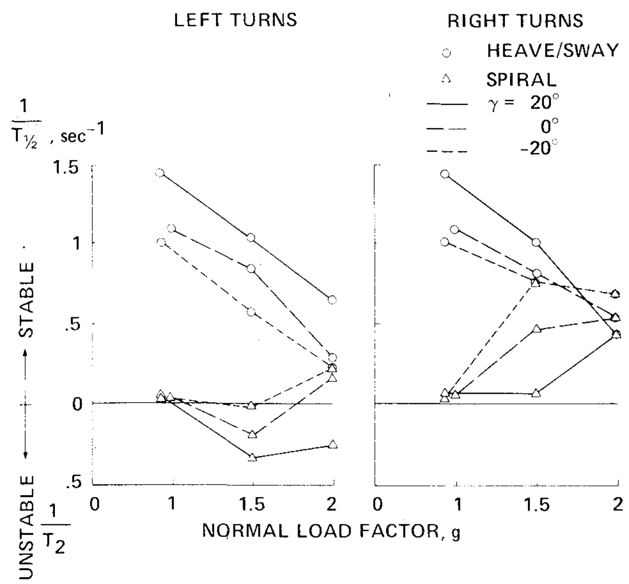

Fig. 8 Effect of turn direction on spiral and heave modes: hingeless-rotor helicopter, 60 knots.

is evident in both right and left turns at 2*g*. It is also important to note that the roll-to-sideslip ratio, $|\phi/\beta|_d$, which is an important flying-qualities parameter, is substantially smaller for a right turn than for a left turn. The phase relationship $\measuredangle \phi/\beta|_d$ is also markedly different: 137 deg for the right turn and 37 deg for the left turn (68 deg for the 1-*g* flight). These characteristics indicate that the direction of turn has potentially significant ramifications for the handling characteristics of this class of rotorcraft.

Lateral-Directional Modes: Roll

The time constant of the roll mode decreases with load factor, with left turns decreasing slightly more than right turns. This is the result of an increase in roll damping with the load factor. The shape of this mode is essentially unchanged and the contamination from the longitudinal motion is very slight.

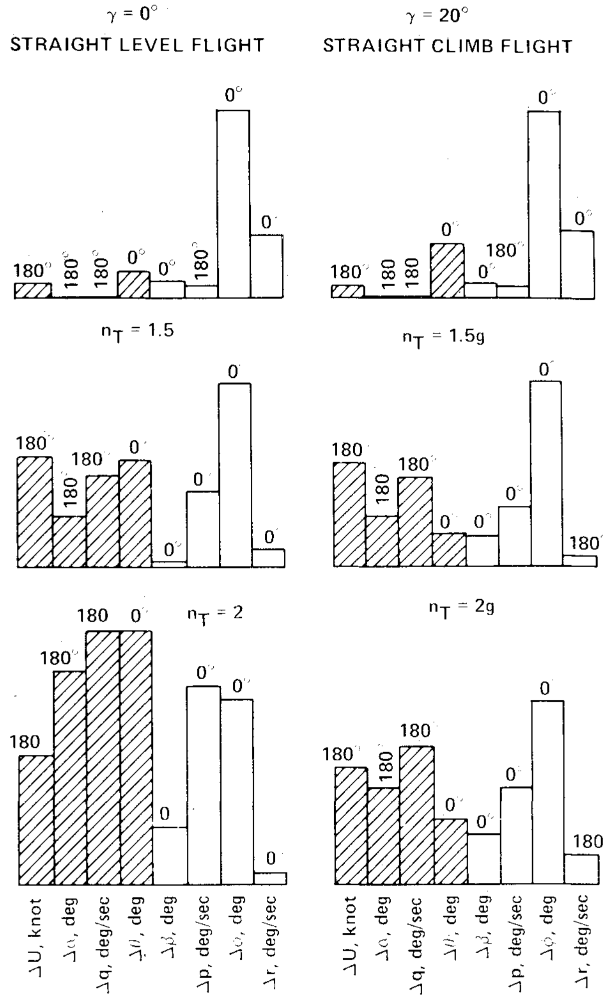

Fig. 9 Influence of load factor and flight path on the spiral mode shape: hingeless-rotor helicopter, 60 knots, left turns.

Lateral-Directional Mode: Spiral

Both the eigenvalue and the eigenvector of the spiral mode change dramatically with load factor, flight-path angle, and the direction of turn. An important characteristic was found with respect to the influence of the turn direction on the stability of the spiral mode: for right turns, spiral mode is stabilized as the load factor increases; for left turns, it is destabilized, initially, as the load factor increases. The destabilization is particularly pronounced in climbing left turns (see Fig. 8), in which the time to double amplitude of the spiral mode can be as small as 3 s at $n_T = 1.5$ with $\gamma = 20$ deg. Also, as the load factor increases further, the spiral mode becomes merged with the longitudinal heave mode (to be described later) to form a stable oscillatory mode. The destabilizing effect in left turn delays this merging of the heave and spiral modes to a higher load factor, as shown in Fig. 8.

There is a dramatic increase in the contamination of the longitudinal motion in the spiral mode as the load factor increases (Fig. 9). The influence of the flight-path is also shown in the figure. With reference to the same roll-attitude perturbation, the contamination of the pitch-attitude motion in the sprial mode is more pronounced in a level left turn than in a climbing left turn. Although the spiral mode is stable in a 2-*g* level left turn (see Fig. 8), the contamination of the

Table 2 Eigenvalues of the hingeless-rotor helicopter with SCAS having both feedback and feed-forward gain matrices (coupled)

	Normal load factor, n_T (g)				
	Straight flight	Right turn		Left turn	
	1.0	1.5	2	1.5	2
	$V=60$ knots, $\gamma=0$ deg, coupled				
Coupled	−4.88	−5.56	−6.01	−5.29	−5.75
	−0.49	−0.30	(0.52; 0.80)	−0.46	(0.30; 0.75)
	(0.71; 0.63)[a]	(0.87; 0.11)	(1.03; 0.04)	(1.01; 0.50)	(1.22; 0.36)
	−10.71	−11.46	−12.44	−11.73	−12.70
	−0.27	−0.66	(2.21; 0.78)	−0.07	(2.00; 0.76)
	(2.04; 0.74)	(2.18; 0.76)		(1.98; 0.75)	
	$V=90$ knots, $\gamma=0$ deg, coupled				
Coupled	−5.98	−6.62	−7.13	−6.52	−7.07
	−0.44	−0.60	(0.46; 0.94)	−0.29	(0.14;0.94)
	(0.81; 0.24)	(0.85; −0.07)	(0.95; −0.14)	(0.91; 0.22)	(1.02; 0.14)
	−10.70	−11.53	−12.43	−11.71	−12.60
	−0.23	−0.27	(2.68; 0.70)	−0.09	(2.78; 0.66)
	(2.70; 0.67)	(2.72; 0.69)		(2.71; 0.67)	

[a] $(\omega_n; \zeta)$.

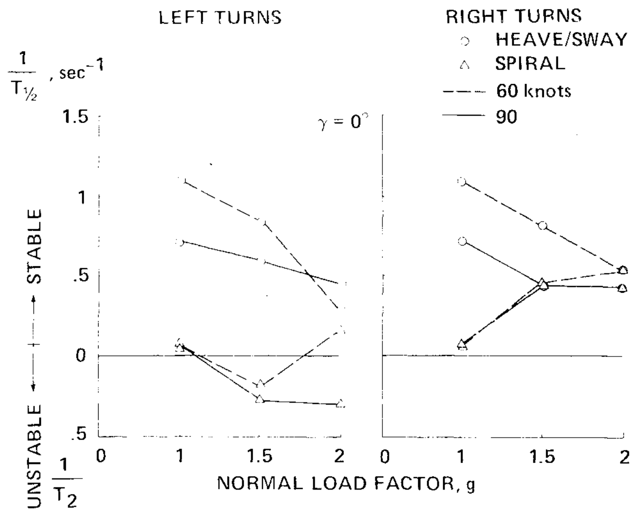

Fig. 10 Effect of speed on spiral and heave modes: hingeless-rotor helicopter, coordinated right and left turns.

longitudinal motion, in general, is much larger than its counterpart in a climbing left turn, at normal load factor of 2.

The unstable spiral that exists in left turns at some levels of normal load factor and the merging of the spiral mode with the longitudinal heave mode that takes place in steep turns were found in this study to be phenomena common to all the three helicopter rotor types. These phenomena are also present at other airspeeds as shown in Fig. 10.

Longitudinal Modes: Heave

Substantial changes take place in both the eigenvalue and the eigenvector of the heave mode as the load factor increases (see Figs. 8 and 11). The time to half amplitude increases as the load factor increases in both right and left turns. At a higher load factor, this mode begins to merge with the spiral mode, as described earlier. Before the merging, the mode shape undergoes an interesting change, drastically changing the ratio of roll-attitude angle to angle of attack; as a result, it is in line with that of the spiral mode. (At the same time, the spiral mode increases its ratio of angle of attack to roll attitude, and changes their phase relationship in line with that of the heave mode.)

Longitudinal Modes: Pitch

The time constant of the pitch mode decreases with load factor, a result of the increase in pitch damping as the load factor increases. The shape of this mode remains essentially unchanged.

Longitudinal Modes: Phugoid

The undamped natural frequency of the phugoid mode increases with load factor in both directions of turn, as shown in Table 1. The turn direction, however, has a significant influence on the stability and the shape of this mode (Fig. 12). As shown in Table 1, a left turn tends to stabilize the phugoid mode, and a right turn tends to destabilize it. The contamination of the lateral-directional motion in this mode, on the other hand, is somewhat less in right turns than in left turns. With respect to the speed change, the changes in pitch and roll attitudes are more than 90 deg out of phase in right turns, but they are less than 90 deg in phase with the speed change in left turns. In either direction of turn, the ratios of pitch and roll attitude to speed change increase from those in 1-g flight, with the increase being more pronounced in left turns.

Influence of Steep Turns on the SCAS

If the rotorcraft is intended for use in missions that call for extreme maneuvers, the significant changes in its flight-dynamic characteristics with variations in load factor must be considered in the design of the stability and control augmentation system. The traditional approach of using small-disturbance equations of motion from steady straight-and-level flight in the preliminary design of the SCAS can be inadequate.

To demonstrate that this indeed is the case, we now evaluate a sophisticated stability and control augmentation system that has previously been synthesized for the same hingeless-rotor helicopter as investigated in this paper.[20] The control law for the SCAS was synthesized on the basis of linear optimal control theory, which had the familiar form

$$u = -kx + Ju_c \tag{1}$$

where the feedback gain matrix K was a simplification from the full gain matrix obtained from the quadratic synthesis technique.[21] The feed-forward gain (or control cross-feed gain) matrix J was designed, using a least-squares method, to meet the control response requirements.[22] The state equation,

$$\dot{x} = Fx + Gu \tag{2}$$

considered in the design was a set of small-disturbance equations of motion of the hingeless-rotor helicopter from

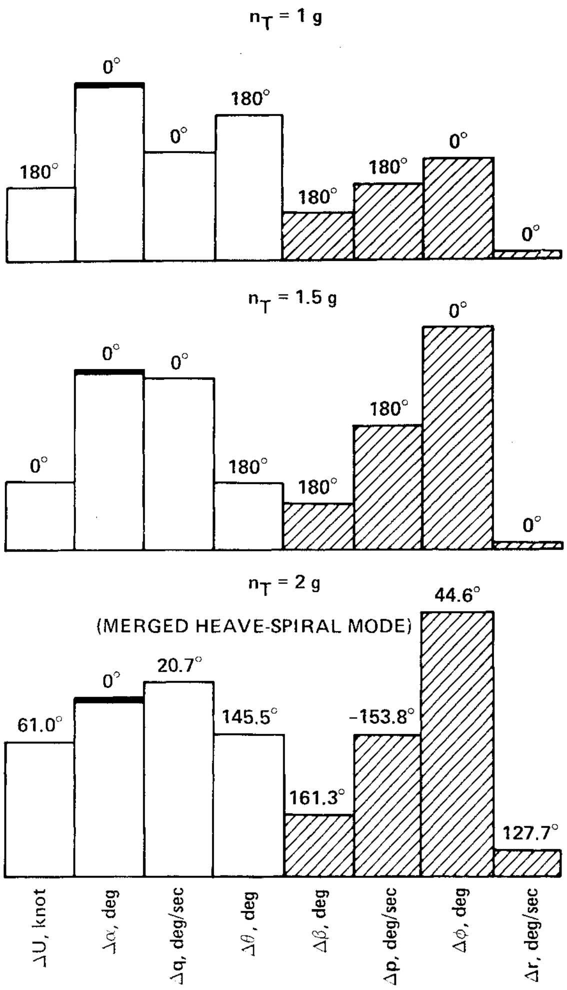

Fig. 11 Influence of load factor on the heave-mode shape: hingeless-rotor helicopter, 60 knots, level right turns.

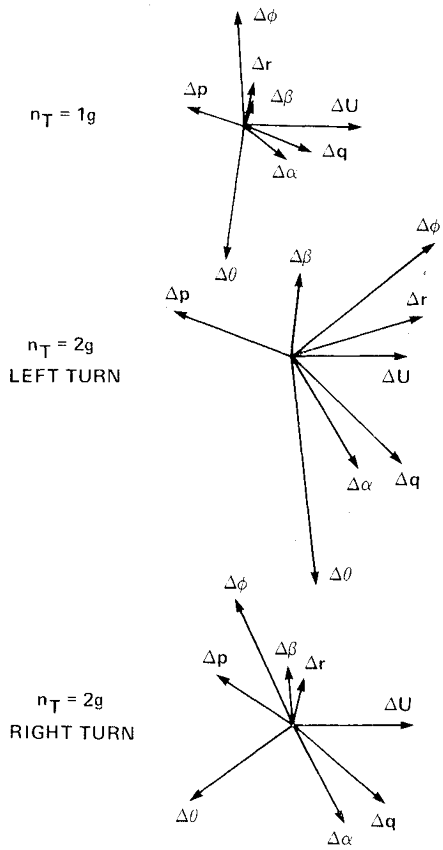

Fig. 12 Influence of load factor on the phugoid mode shape: hingeless-rotor helicopter, 60 knots, level turns.

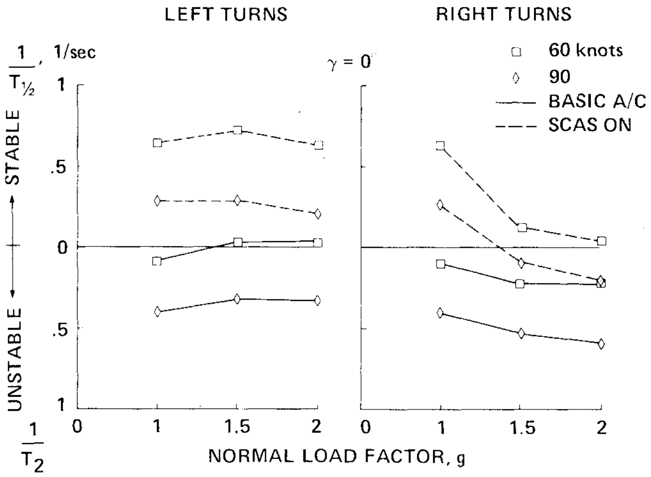

Fig. 13 Effect of turn direction on phugoid mode: hingeless-rotor helicopter, with and without SCAS.

steady straight-and-level flight. Design points considered were hover, 70 knots, and 130 knots. Gains for other airspeeds were obtained using linear interpolation from the three design points.[20]

This SCAS was evaluated in level 1-*g* flight at 60 and 90 knots for purposes of comparison with the previous design, and at 1.5 and 2*g*, both in right and left level turns at these two airspeeds. Table 2 summarizes the eigenvalues obtained for the closed-loop systems. (The corresponding open-loop eigenvalues are given in Table 1.) Comparing the open-loop and closed-loop eigenvalues at 1*g* from Tables 1 and 2, it can be seen that the Dutch-roll mode and the phugoid mode have been satisfactorily stabilized by the SCAS. However, in coordinated steep turns, the phugoid mode becomes significantly destabilized, with instability developed in right turns. In a level, 60-knot right turn at 2 *g*, the phugoid becomes nearly neutrally stable; the phugoid mode becomes unstable in level right turns at 1.5 and 2*g* at 90 knots. Figure 13 shows a comparison of open-loop and closed-loop phugoid modes in terms of the inverse of the time to half amplitude $T_{1/2}$, and the time to double amplitude T_2. Note that the time to double amplitude of the phugoid of the closed-loop system in 2-*g* right turn is about 5.3 s.

The transient responses of the open-loop and closed-loop systems at 60-knot 1-*g* flight, as well as those of the closed-loop system in 1.5- and 2-*g* right turns, to cyclic step inputs are shown in Fig. 14. The nearly neutrally stable phugoid with its frequency at approximately 1 rad/s is clearly discernible in the responses of the closed-loop system in the 2-*g* right turn at 60 knots. The control response characteristics of the closed-loop system in steep right turns at 90 knots are degraded from the 1-*g* flight even more because of the unstable phugoid mode.

We have thus clearly demonstrated that a SCAS designed for a hingeless-rotor helicopter, which otherwise performs satisfactorily in flight near 1*g* can, indeed, become significantly degraded, in both stability and control responses, in steep turns. It is essential, therefore, that the flight dynamics in steep turns, in both turn directions, be considered to ensure that the SCAS will perform satisfactorily not only in operations near 1*g* but also in extreme maneuvers such as in steep high-*g* turns.

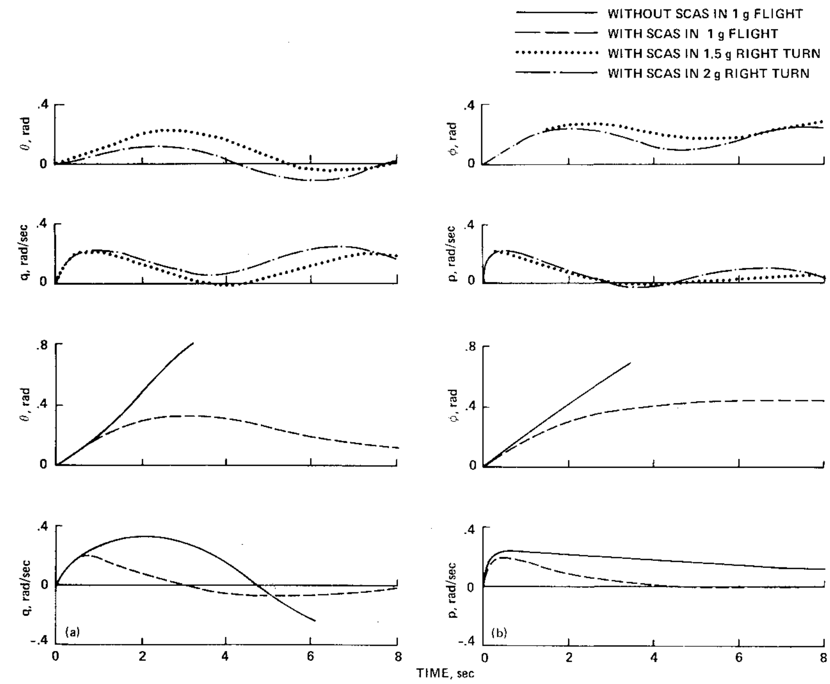

Fig. 14 Responses of the hingeless-rotor helicopter to 1-in. step cyclic stick input: a) longitudinal stick input and b) lateral stick input.

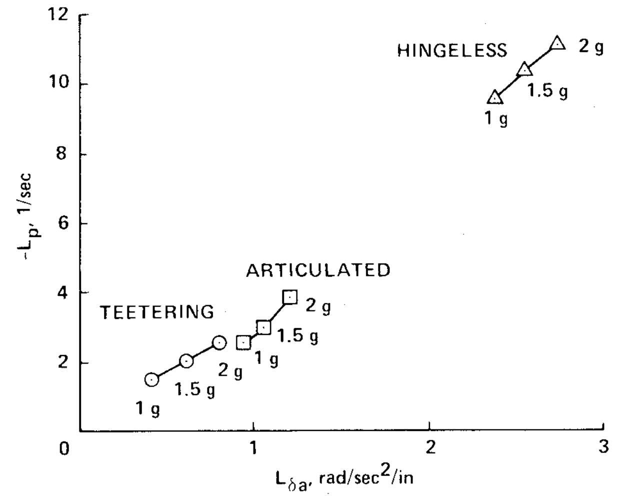

Fig. 15 Effect of load factor on roll sensitivity and damping for three helicopters at 60 knots.

Finally, it may be appropriate at this point to make brief comments concerning the effect on the design of stability and control augmentation systems of the type of helicopter main rotor. Of the three helicopters examined in this study, the hingeless-rotor helicopter has the least percentage variation in pitch and roll control sensitivities from a 1-*g* flight to a high-*g* turn. Figure 15 shows the effect of load factor in turning flight on the roll-control sensitivity L_{δ_a} and the roll damping L_p for the three types of helicopters at 60 knots. The teetering-rotor helicopter has the largest variation; the roll-control sensitivity (or effectiveness) is varied nearly directly proportional to the load factor. With such a large percentage variation in the loop gain of the teetering-rotor helicopter with its SCAS, along with the strong coupling in longitudinal and lateral-directional motions in high-*g* maneuvers the degradation in stability and control response characteristics of the closed-loop system from 1-*g* flight to a high-*g* turn needs to be examined. In light of the results for the hingeless-rotor helicopter as just discussed, it may be argued that due attention should also be paid to the design of their SCAS's, properly tailored to the load factor, for the teetering- and articulated-rotor helicopters, if these aircraft are intended for use in missions calling for frequent extreme maneuvers.

Concluding Remarks

An analytical procedure has been developed to permit a systematic investigation of rotorcraft flight dynamics in steep high-*g* turns. Numerical examinations of a tilt-rotor aircraft (a symmetrical-type rotorcraft) and three single-rotor helicopters (asymmetrical rotorcraft) with different types of main-rotor systems have been conducted. The results are as follows.

1) Strong coupling exists, particularly at low speeds, in longitudinal and lateral-directional motions in high-*g* turns for both the symmetrical- and asymmetrical-type rotorcraft; flying-qualities and flight-control design analyses based on small disturbances from straight flight are grossly inadequate for prediction of flight dynamics in high-*g* maneuvers.

2) For the single-rotor helicopters examined, the direction of turn has a significant influence on the flight-dynamic characteristics in high-*g* turns. For these helicopters (which have the main rotor turning counterclockwise, viewed from above the rotor), a high-*g* right turn tends to stabilize the spiral mode, and a left turn destabilizes it to develop an unstable spiral mode. On the other hand, a right turn tends to destabilize the longitudinal phugoid mode, and left-turning flight stabilizes the phugoid.

3) A fundamental characteristic associated with the single-rotor helicopter is that the longitudinal heave mode and the spiral mode tend to merge to yield a stable oscillatory mode in high-*g* turns.

An evaluation of a SCAS previously designed expressly for a hingeless-rotor helicopter has also been conducted to examine its performance in high-*g* turns. The results show that the stability and control response characteristics of the aircraft with the SCAS, which otherwise performs satisfactorily in flight near 1*g*, becomes significantly degraded in steep turning flight. It is imperative, therefore, that due attention be paid to the SCAS design, properly accounting for the variations in flight dynamics with load factor, to ensure that the system will perform satisfactorily not only for operations near 1*g* but also in high-*g* maneuvers, if the rotorcraft system is intended for missions requiring frequent excursions to the edges of its maneuvering flight envelope.

References

[1]Wells, D.C. and Wood, T.L., "Maneuverability—Theory and Application," *Journal of the American Helicopter Society,* Vol. 18, Jan. 1973, pp. 10-22.

[2]Livingston, C.L. and Murphy, M.R., "Flying Qualities Considerations in the Design and Development of the Hueycobra," *Journal of the American Helicopter Society,* Vol. 14, Jan. 1969, pp. 49-66.

[3]Keys, C.N., "Rotary-Wing Aerodynamics, Vol. II, Performance Prediction of Helicopters," NASA CR-3083, 1969.

[4]Lewis, R.B. II, "Hueycobra Maneuvering Investigations," *Proceedings of the 26th Annual National Forum of the American Helicopter Society,* Washington, D.C., June 16-18, 1970.

[5]Lewis, R.B. II, Bailes, E., McClellan, R.D., Claxton, J.D., and Buss, M.W., "Engineering Flight Test AH-1G Helicopter (Hueycobra) Maneuvering Limitations," USAASTA-69-11 Final Rept., U.S. Army Aviation Systems Test Activity, Edwards Air Force Base, Calif., March 1971.

[6]Brown, E.L. and Schmidt, P.S., "The Effect of Helicopter Pitching Velocity on Rotor Lift Capability," *Journal of the American Helicopter Society,* Vol. 8, Oct. 1963, pp. 1-6.

[7]Etkin, B., *Dynamics of Atmospheric Flight,* John Wiley & Sons, Inc., New York, 1972.

[8]Seckel, E., *Stability and Control of Airplanes and Helicopters,* Academic Press, New York, 1964.

[9]"General Requirements for Helicopter Flying and Ground Handling Qualities," Specification MIL-H-8501A, Sept. 1961.

[10]"V/STOL Handling, Part I, Criteria and Discussion," NATO AGARD Rept. 577, June 1973.

[11]"Flying Qualities of Piloted V/STOL Aircraft," Specification MIL-F-83300, Dec. 31, 1970.

[12]Winn, A.L. and Kishi, J.S., "Pilot Perceived Jettison Envelope," AD-768171, Final Rept., U.S. Army Aviation Systems Test Activity, Edwards Air Force Base, Calif., June 1973.

[13]Chen, R.T.N. and Jeske, J.A., "Kinematic Properties of the Helicopter in Coordinated Turns," NASA TP-1773, 1981.

[14]Chen, R.T.N., "Kinematic Properties of Rotary-Wing and Fixed-Wing Aircraft in Steady Coordinated High-g Turns," AIAA Paper 81-1855, Aug. 1981.

[15]Howlett, J.J., "UH-60A Black Hawk Engineering Simulation Program, Vol. I, Mathematical Model," NASA CR-166309, Dec. 1981.

[16]Chen, R.T.N., "A Simplified Rotor System Mathematical Model for Piloted Flight Dynamics Simulation," NASA TM-78575, 1979.

[17]Heffley, R.K., Jewell, W.F., Lehman, J.M., and Van Winkle, R.A., "A Compilation and Analysis of Helicopter Handling Qualities Data," Vol. I, NASA CR-3144, 1979.

[18]Chen, R.T.N., "Efficient Algorithms for Computing Trim and Small-Disturbance Equations of Motion of Aircraft in Coordinated and Uncoordinated Steady Steep Turns," NASA TM-84324, Feb. 1983.

[19]Harendra, P.B., Joglekar, M.J., Gaffy, T.M., and Marr, R.L., "V/STOL Tilt Rotor Study, Vol. V, A Mathematical Model for Real Time Flight Simulation of the Bell Model 301 Tilt Rotor Research Aircraft," NASA CR-114614, April 13, 1973.

[20]Miyajima, K., "Analytical Design of a High Performance Stability and Control Augmentation System for a Hingeless Rotor Helicopter," *Journal of the American Helicopter Society,* Vol. 24, July 1979, pp. 29-36.

[21]Bryson, A.E. Jr. and Ho, Y.-C., *Applied Optimal Control,* Balisdell, Waltham, Mass., 1969.

[22]Lebacqz, J.V. and Chen, R.T.N., "Design and Flight Test of a Decoupled Velocity Control System for VTOL Landing Approach," Presented at AIAA Atmospheric Flight Mechanics Conference, Hollywood, Fla., Aug. 1977.