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MEETING THE MANEUVERABILITY REQUIREMENTS OF MILITARY HELICOPTERS

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Summary:

The mission success and even the survival of the helicopter in a conflict environment depends upon its ability to escape the numerous threats present. To this end extreme nap of the earth flight is used in order to utilize the cover afforded by trees, buildings and general terrain features. This extreme N.O.E. flight requirement places heavy demands upon the maneuverability and controllability of the helicopter because of operation in close proximity to ground and obstacles.

An examination of the maneuvering requirements of N.O.E. flight was conducted in order to provide a base for the selection of helicopter design parameters to meet them. The examination was based upon flight experience with the BO - 105 helicopter under simulated tactical conditions and calculations with the Dynamic Flight Simulation Program. The results show the importance of a judicious selection of rotor dynamic parameters for safety of flight and control response optimization in N.O.E. operations by helicopters.

1. Introduction

The greatly increased range and effectiveness of modern land based and airborne anti-aircraft detection- and weapons-systems has forced the development of new operational tactics to counter this threat. In the case of helicopter operations extreme nap of the earth (NOE) flight with its rigorous demands upon maneuverability and control response is part of the new doctrine. NOE-flight allows the helicopter to utilize the cover afforded by trees, buildings and general terrain features thus reducing the probability of detection and avoiding contact with the opponent's air defense systems.

The demand for extreme NOE-flight means essentially a movement in the horizontal plane. The vertical excursions are held to a minimum in number, altitude and time duration to avoid detection. This means the dominant maneuvers are turns and fast pull-ups and push-overs in various combinations with their ensuant controllability and maneuverability requirements.

The limits of performance in NOE-flight are directly influenced by the harmony between the pilot's subjective opinions and the actual characterisitics of the aircraft. Unlike the flight at altitude, NOE-flight at reasonably high speeds in close proximity to ground and obstacles is only possible if the pilot is confident of the aircraft's safety and controllability at all extremes of the necessary maneuvering envelope,including uncoordinated maneuvers. Furthermore the limitation of pilot vision through terrain masking confronts the pilot with the sudden appearance of obstacles in the flight path, thus extremely short control reaction times are absolutely essential for safe NOE-operations. The pilot may even desire a slight degree of instability for sudden maneuvers,if he can stop or reverse the maneuver in as short a time as he can initiate it. The short reaction time in pilot's subjective judgement means a comparison with the pilot's reaction time, whereby from experience a direct correspondence of displacement rate to control displacement is deemed most desirable.

In meeting the maneuvering requirements of military helicopters the designer must be constantly aware of the interplay between the aircraft characteristics and the requirements of the human pilot to assure best possible mission performance capability. Since the maneuvering capability and the control response characteristics of geometrically equivalent rotors can be different dependant upon the rotor's dynamic properties, an understanding of their influence is essential. In this study the basic BO - 105 helicopter was used as the test vehicle and only the rotor dynamics were parametrically varied to evaluate their effect upon the aircraft's performance in N.O.E. maneuvers.

2. Control Requirements for Trim

The basic control angle requirements for trimming out the effects of forward speed on the rotor are independent of rotor type. This means the control angle displacement at the rotor over the airspeed is the same for the different rotors built today. In addition to this necessary trim requirement there are the specifications for maneuvering control margins which again are independent of rotor type. The result is shown in Figure 1, i.e. for any helicopter the basic control angle requirement consists of speed trim and control margin with the magnitude essentially independent of rotor type.

There are furthermore the well-known specifications for control power and damping, Figure 2, which place a requirement upon the control moment produced by a unit displacement of the cockpit control as a function of the damping moment available. This means that this requirement is a function of rotor dynamics as is indicated by the $\overline{\omega}_{\beta}$ curve in Figure 2. Since the damping is fixed by rotor characteristics the only variation possible is in control power per unit control displacement. However here too are the limits through the maximum and minimum roll rates and antropotechnical considerations.

The result is that helicopters with different rotor systems have approximately the same ratio between stick motion and control angle at the rotor. This holds true for both the pitch and the roll axis, thus the investigation was conducted at a constant ratio of control angle at rotor to cyclic stick displacement.

3. Types of Control Response

The motion of the cyclic stick produces changes in control angles at the rotor, thus changing the moments on the rotor and inducing the aircraft to maneuver. The relation between the motion of the cyclic stick and the resulting motion of the helicopter is extremely important, because it forms the pilot's opinion of the aircraft's handling qualities.

The theoretical response type limits are the accelaration response and the rate response, Figure 3. This means that the stick motion corresponds exactly to the shape of the acceleration curve for the former and the displacement rate curve for the latter. These limits are theoretical because the acceleration response presupposes zero damping and the rate response an infinite acceleration, both impossible in reality.

Numerous theoretical, flight simulator and flight test investigations have been conducted to determine the most desirable type of control response from the pilot's standpoint. The investigations showed that rate response is most desirable from the pilot's point of view. Evidence of this are the numerous mechanical and electronic devices installed into helicopters aimed at producing this type of response.

The characteristic parameter of the response type is, τ, the time constant, Figure 4. The time constant is the time interval required for the angular rate to reach 63% of its final magnitude. The pure acceleration response has zero damping and thus a τ value of ∞, the rate response has very high damping and infinitely high control moments with $\tau = 0$. In practice this means the lower the time constant τ, the closer the response to the ideally desired rate control.

4. Rotor Dynamic Characteristics, $\bar{\omega}_\beta$

It is a well-known fact that geometrically equivalent rotors with equal mass distributions can posess different control moment capabilities and rate damping characteristics dependant upon the dynamic properties of the rotor. One of the dominant parameters in this respect is the flapping stiffness of the rotor, or as it is also known, the flapping frequency ratio, $\bar{\omega}_\beta$. This ratio is defined as:

$$\bar{\omega}_\beta = \frac{\text{First undamped Rotational Flapping Frequency of Rotor}}{\text{Rotational Frequency of Rotor}} .$$

As seen in Figure 5, it depends upon the mass distribution of the rotor blades and the effective flapping hinge off-set. The $\bar{\omega}_\beta$ values shown in Figure 5 and Table 1 were determined for a constant blade mass distribution. A change in the mass distribution would result in a shift of the rotors $\bar{\omega}_\beta$ value for the same geometric configuration.

Table 1 Characteristics of Rotors considered in the study

a_β	a_β/R	m_{B1}	M_S	I_{B1}	$\bar{\omega}_\beta$
1.2	0.2443	20.045	37.203	92.065	1.2186
0.9	0.1832	21.665	43.460	116.240	1.1561
0.745	0.1517	22.502	46.882	130.23	1.1261
0.6	0.1221	23.205	50.202	144.314	1.0994
0.45	0.0916	24.095	53.755	159.905	1.0730
0.3	0.0611	24.905	57.430	176.580	1.0476
0.15	0.0305	25.715	61.227	194.375	1.0234
0	0	26.525	65.145	213.328	1.0

$m'/2 = 2.7$; $m'/3 = 1.8$; $m' = 5.4$ kg/m; $R = 4.912$ m; $C_\beta = 0$

5. Influence of $\bar{\omega}_\beta$ on Rotor Control Response

As already stated the control response of a rotor is characterized by its time constant, τ. The time constant in turn is a function of the mass distribution, the control moment and the damping moment of the rotor. The last two are a function of $\bar{\omega}_\beta$ as is evidenced in the following Table 2 which shows the derivatives of the control moment, the damping moment and the value of τ for a L.F. = 1.0 condition and constant blade mass distribution.

Table 2. Influence of $\bar{\omega}_\beta$ on Control Power, Damping and Time Constant of a Rotor

$\bar{\omega}_\beta$	$dM_x/d\Theta_c/I_{xx}$ $1/sec^2$ Grad	$dM_x/d\dot{\Phi}\ /I_{xx}$ 1/sec	τ, sec.
1.22	3.48	17.27	0.058
1.16	3.13	14.61	0.068
1.12	2.80	12.65	0.079
1.10	2.41	10.55	0.095
1.07	1.79	8.17	0.122
1.05	1.43	5.70	0.176
1.02	0.89	3.23	0.310
1.0	0.34	0.82	1.225

The profound influence of $\bar{\omega}_\beta$ upon the values of the control moment, damping moment and the time constant τ are evident from the Table. The main reason for this influence is explained in Figure 6 where the effect of $\bar{\omega}_\beta$ upon the control moment is presented. The control moment is in general composed of two parts. One the thrust moment, M_T, due to tilt of the thrust vector, and two the flapping-hinge off-set moment, M_β, due to blade flapping.

The thrust moment is a direct function of thrust magnitude, thus subject to the influence of load factor variations as will be shown later. The flapping-hinge off-set moment is virtually independent of thrust, depending only on a_β, the effective flapping hinge off-set, and thus as shown in Figure 5 directly a function of $\bar{\omega}_\beta$. The larger the value of $\bar{\omega}_\beta$ the smaller the magnitude of τ because of the increase in control moment available due to the increased M_β contribution. Now the effect of changes in $\bar{\omega}_\beta$ upon the helicopters ability to perform the typical N.O.E. maneuvers will be examined.

6. The 90 Degree Change in Direction

As already mentioned the most typical N.O.E. maneuver is probably the sudden change in direction of flight. The requirement to fly between obstacles in close proximity to the ground places very close tolerances upon maneuver execution, and thus the maneuverability and control response requirements of the helicopter. Furthermore since in N.O.E. operations maneuvering flight is the rule and straight and level flight the exception, a reduction of pilot work load and stress during maneuvers to a minimum is of prime importance in the design of helicopters for these operations. Typical time histories of a sudden 90 degree turn are presented in Figures 7 and 8 for the BO - 105 base helicopter with a rotor of flapping frequency ratio, $\bar{\omega}_\beta$, equal to 1.00 and 1.12. It should be noted here that "Quickening" was not used for these maneuvers, because full control travel to the control-stops was used, thus rendering the "quickening" of controls ineffective.

The turn performance of the aircraft is shown in the x-y plane plot of the flight path. From the plot it is seen that the helicopter with the higher $\bar{\omega}_\beta$ value requires about 30% less length distance to complete the turn. This means a 30% safety margin in distance, or a 0.6 second reserve in reaction time. The 0.6 second may seem small, but it is three times the pilot reaction time of 0.2 seconds, thus providing a considerable improvement in pilot confidence.

Another essential difference, and perhaps the most important one, is the control motion and the resulting control response of the aircraft. The aircraft with the flapping soft rotor requires a noticeable amount of control lead inputs as can be seen from the cyclic stick motion and the following response in roll. The stiffer rotor shows a change in the roll rate right with the input, the soft one shows the effect when the lateral stick is almost at the stop.

The advantage due to the ability of the stiff hingeless rotor to produce moments without a change in rotor plane angle relative to the fuselage, and thus at an essentially constant angle of attack, can be seen in the trace of collective stick motion. The soft rotor was given an initial collective pitch input to increase the magnitude of the thrust vector and thus improve roll performance. However, in order to execute the turn a pitching moment is required, as seen in the longitudinal cyclic stick trace. In the flapping soft rotor ($\bar{\omega}_\beta = 1.00$), this produces a change in angle of attack, thus loading up the rotor to the point where collective stick has to be lowered in order not to loose rotor R.P.M. The stiff rotor on the other hand, due to the small angle of attack change due to longitudinal cyclic stick input (it essentially produces only a pitching moment) does not get into any limit conditions and requires simply a gradual increase in collective pitch setting. The maneuvers were not executed at absolutely constant altitude. The softer rotor was even allowed a greater change in altitude which would give it an improvement in the recorded turn performance.

It should perhaps also be noted that the stiffer rotor reaches a higher value of normal load factor, which together with the better roll performance produce shorter turn radius and better turn performance. This difference in load factor attained, as will be shown later, is influenced by the markedly larger blade flapping motion of the flapping soft rotor which is evidenced by the envelope of flapping motion in Figure 7.

In typical helicopter fashion both aircraft loose speed through the maneuver, whereby the stiffer rotor in this case shows the larger velocity decrease. In connection with this decrease in airspeed should be mentioned that it precludes the theoretically possible unstable cyclic stick gradient of stiff rotors from becoming reality.

Having discussed the turn performance differences of the two helicopters, let us turn to the reasons behind them.

7. Factors affecting the Maneuvering Performance of Helicopters in N.O.E. Operations

The preceding example once again confirms the numerous results of flight tests, pilot opinion polls and computer investigations which show a marked improvement in maneuverability and controllability of helicopters with increasing values of $\bar{\omega}_\beta$. In order to understand the reasons for this improvement and their application to N.O.E. flight the two typical N.O.E. maneuvers (turns and fast pull-ups and push-overs) were divided into their elements and examined for $\bar{\omega}_\beta$ influences. The main results of this study are summarized in the following paragraphs.

7.1 Influence of Load Factor and $\bar{\omega}_\beta$ on the Time Constant

The reasons for the influence of $\bar{\omega}_\beta$ upon the sensitivity of the time constant τ to load factor were already discussed in the preceeding general discussion. Now actual magnitude of this influence is shown in Figure 9, where the variation of τ with load factor for four values of $\bar{\omega}_\beta$ is presented. The significant point of the plot is the marked increase in magnitude of τ with decreasing load factor for the lower values of $\bar{\omega}_\beta$.

This large increase in the value of τ is caused by an equally large reduction in control moment available, which in turn produces a decrease of stick sensitivity (or control power) of equal magnitude. The pilot of a helicopter flying N.O.E. must constantly change direction to avoid obstacles, which in turn means constant changes in load factor during the flight. These load factor changes however produce changes in the helicopters stick sensitivity due to fluctuation of control moment magnitude, thus demanding from the pilot a constant readjustment to the variable sensitivity. The resulting pilot insecurity is then reflected in a degradation of performance of the pilot/aircraft combination.

It is thus one of the most important considerations in designing helicopters to meet N.O.E. flight requirements to select the rotor dynamic characteristics so that crisp,constant control response under all possible flight conditions is ensured. This will reduce pilot work load and stress, allowing him to devote more attention to the mission at hand and in this way improve mission performance.

7.2 Influence of $\bar{\omega}_\beta$ on Maximum Attainable Load Factor

The rotor flapping stiffness, $\bar{\omega}_\beta$, has a pronounced influence upon the maximum attainable load factor of a rotor, Figure 10. The figure shows a plot of the retreating blade angle of attack, α_{270} as a function of load factor for several values of $\bar{\omega}_\beta$. It can be seen that any chosen value of retreating blade angle is reached at a higher load factor for higher values of $\bar{\omega}_\beta$, i.e. for stiffer rotors. This, of course, means that the onset of retreating blade stall, and thus a degradation in rotor performance is pushed out to higher values of load factor.

The reason for this difference in performance is, as already mentioned, blade flapping angle, Figure 11. The flapping soft rotor has in forward flight higher longitudinal flapping angles than a rotor of higher flapping stiffness, at a given load factor condition. These angles mean that at the 90 degree and 270 degree position the blade flapping velocity has a maximum value, thus producing an increment in blade angle of attack. Since for positive rotor angles of attack the flapping is "up" at $\psi = 180^o$, the blade flaps down on the retreating side and up on the advancing side. This motion produces a decrease in advancing blade angle of attack and an increase in retreating blade angle of attack,thus advancing the stall onset and compromising rotor performance.

7.3 Effect of $\bar{\omega}_\beta$ on Turn Performance

A linearized, decoupled analysis of turn performance parameters was conducted in order to determine the main influence factors. The analysis was conducted under the assumption of constant airspeed and altitude, which is permissible if as in this case only qualitative results are desired.

The analysis showed that if roll performance alone is considered, Figure 12, the difference in x-distance between the flapwise softer and the flapwise stiffer rotor is only 10%. However, the superposition of the $\bar{\omega}_\beta$-Load Factor relationship over the roll performance, Figure 13, shows a difference of 30% between the two. This coincides with the results of the dynamic simulation calculation shown in Figure 7.

These results emphasize the already stated importance of selecting an optimum value of $\bar{\omega}_\beta$ for the desired mission performance. Higher maneuverability requirements require higher values of rotor flapping stiffness within the constraints of relevant design and mission considerations.

7.4 Dependance of Control Response upon $\bar{\omega}_\beta$

Another important point considered in this part of the analysis was the control response of the helicopter, Figure 14. The object of the maneuver was to reach a prescribed roll angle and to stabilize the aircraft at this angle. Such maneuvers are necessary in N.O.E. flight where the flight path must be picked out between obstacles and overshoots can not be tolerated. Zero time constant control inputs were used in order to compare the resulting control response type to the desired rate type control.

The results show as expected the close conformance of the stiffer rotor to rate control. The significant point however is the time required to stop the roll rate and stabilize at the desired angle. Aided by the high value of damping and control power the flapping stiff rotor can stop the roll rate as fast as the stick can be moved. The flapping soft rotor requires a definite time interval of holding the stick against the opposite stop to cancel out an acquired roll rate. Even though the times involved are short,in comparison to the pilot response time they make the difference between "crisp" or "spongy" response, which in turn reflects upon the N.O.E. maneuvering capability of the helicopter. The ability to stop practically instantaneously a given roll with a high flapping stiffness rotor allows the pilot to use full control travel for maneuver initiation, thus producing a marked improvement in effective maneuverability through flight safety and increased pilot confidence.

7.5 Effect of $\bar{\omega}_\beta$ upon the Minimum Attainable Load Factor

The minimum, or negative load factor limit has a large influence upon the helicopters exposure time in overflying obstacles and thus the degree of detectability and vulnerability. The current breed of military helicopters such as UTTAS and AAH have a requirement for -0,5g capability in their specifications, however in actual N.O.E. operations even this limit is exceeded with helicopters which have no operational or manueverability restrictions at this point.

In general there are two limits for the minimum attainable load factor in a helicopter. One is the aerodynamic thrust limit of the rotor, similar to the maximum positive load factor. The second, and actually the practical limit, is the reduction and reversal of available control moments with diminishing load factor, Figure 15.

Figure 15 shows the available control moment and damping as a function of $\bar{\omega}_\beta$ for three values of load factor. It is seen that at each value of $\bar{\omega}_\beta$ a reduction in load factor is followed by a decrease in available control moment and damping. The difference in controllability comes from the fact that at higher values of $\bar{\omega}_\beta$ this reduction in control moment comprises perhaps 10% of the total moment available and at low values it takes away the whole control moment, or even reverses its sense relative to control input. The effect of this limitation in controllability with decreasing $\bar{\omega}_\beta$ values is a deterioration in vulnerability and safety of flight unless the N.O.E. speed envelope is significantly reduced.

7.6 Variation of Exposure Time and Exposure Altitude with the Minimum Attainable Load Factor Limit

As already mentioned the N.O.E. operations are forced upon the military helicopters because of the range and accuracy of modern AA-Weapons. Every time that the helicopter leaves the cover of terrain he may be exposed to hostile action, Figure 16. The higher and longer he flies over the cover, i.e. the higher the exposure time and altitude, the greater the likelihood of detection and destruction.

Figure 17 presents a plot of exposure time and exposure altitude for various values of minimum load factor limit in overflying a 25 meter obstacle. It was assumed that the pull-up was started as close as possible to the obstacle in order to simulate a hard maneuver. The plot shows that for positive limit values of "g" the exposure time is over 5 seconds at heights which go up to 50 meters over the 25 foot cover assumed, which means over-ground altitudes of 75 meters. The exposure times of over 5 seconds are uncomfortably close to the reaction times of currently known AA-Weapons systems with appropriate influence upon the vulnerability of the helicopter.

The plot shows the drastic reduction possible in the exposure time and altitude envelope with the widening of the maneuvering envelope to negative values of minimum limit loadfactor. This expansion,as seen in Figure 15,can be effected by proper selection of rotor dynamic parameters.

An interesting point is the small reduction in the exposure time and exposure hight possible with a small reduction in flight speed. To obtain significant improvements in the exposure time/exposure altitude envelope (at constant L.F.-limit) quite large reductions in speed are necessary. Thus again showing the advantage of using a stiffer rotor with a lower value of minimum load factor limit, especially in view of the fact that load factors lower than -0,5 are not unusual in today's N.O.E. operations.

7.7 The Compound Maneuver

Up to now the two N.O.E. maneuvers, the turn and the quick-pull-up and push-over were considered separately. However in actual operations the maneuvers are often combined as shown for example in Figure 18. This means that upon overflying an obstacle the pilot realizes that he has to change his direction of flight.

This requires maneuvering capability at the apex of the pull-up where the fuselage attitude allows the pilot to oversee the terrain in front of him. The ability to maneuver at reduced values of load factor, as shown in Figure 15, is strongly dependant upon the stiffness of the rotor selected. Figure 19 is a plot of time required to reach a given roll angle for three values of $\bar{\omega}_\beta$ at a load factor of -0,5g. The time for the rotor with $\bar{\omega}_\beta = 1.00$ is not shown, ~~because~~ for this low value of g it is off the plot.

The figure shows a marked difference between a rotor with an $\bar{\omega}_\beta$ value of 1.05 and 1.12. The increase however becomes very small, even in comparison with the pilot reaction time, if $\bar{\omega}_\beta$ is further increased. Thus for combined maneuvers which require control moments at a reduced value of "g" the benefit obtained through an increase in rotor flapping stiffness approaches asimptotically a set limit value. Of course the differences between the roll time required would increase with a further reduction of load factor below -0.5g.

8. Conclusions

Some of the most severe demands upon exact controllability and maneuverability in helicopters are the result of extreme N.O.E. flight requirements, be it in transitioning from one point to another or in actual combat action. To meet these maneuvering requirements the designer is faced next to the choice of rotor aerodynamic and geometric parameters, with the selection of the dynamic characteristics of the rotor. This last selection can be critical because of its strong influence upon the helicopters control and maneuvering characteristics. Following points should be considered in making this selection:

- An increase in the rotor flapping frequency ratio, $\bar{\omega}_\beta$, increases the available control moment and damping, thus increasing the controllability and maneuverability.

- Rotors with higher flapping frequency ratios can produce control moments essentially independant of rotor angle of attack or load factor.

- This independance of load factor and the smaller flapping angles characteristic to rotors of higher flapping frequency ratios provide an expansion in the helicopters attainable load factor envelope both in the positive and the negative direction.

- The time constant, τ, of a rotor is in inverse proportion to the rotor's flapping frequency ratio. Thus the larger $\bar{\omega}_\beta$ the smaller τ, and the closer the response to the desirable "rate control", which in turn reduces the requirement for any kind of CASAS devices in maneuvering flight.

- The "rate type" response produced by higher values of flapping frequency ratio reduces the time and space requirements in N.O.E. maneuvers providing increased safety margins to the pilot and reducing exposure time and vulnerability in service.

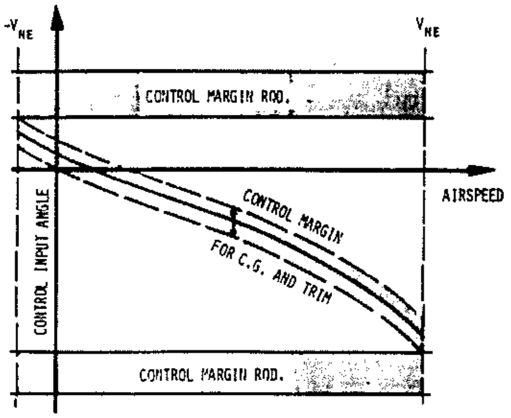

Figure 1: Control Angle Requirements for Trim and Control

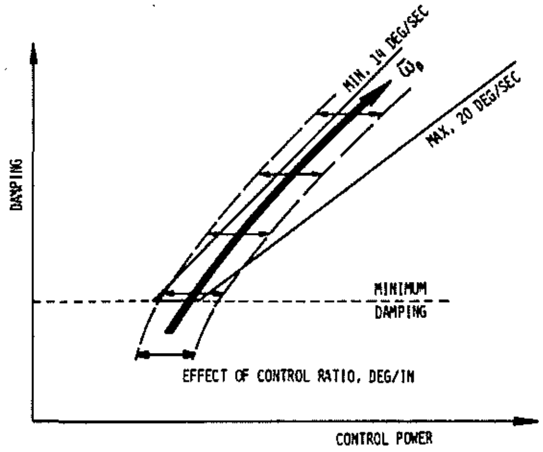

Figure 2: Response Requirements per unit displacement of control.

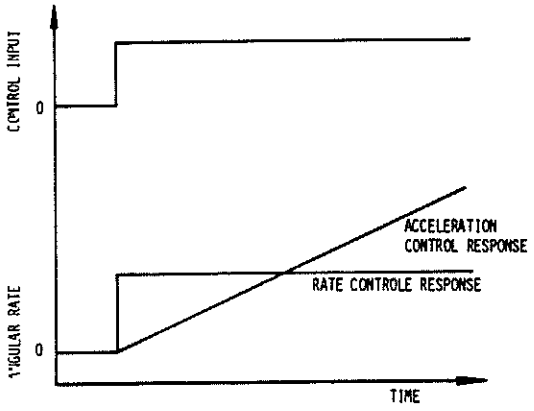

Figure 3: Control Response Types

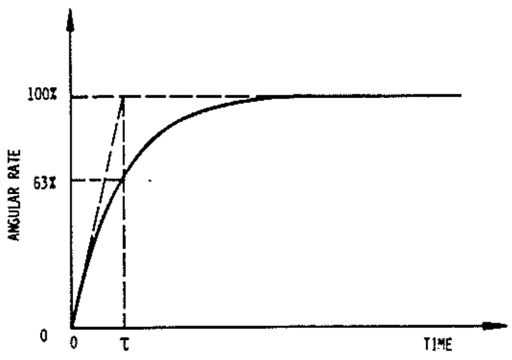

Figure 4: The Time Constant, τ

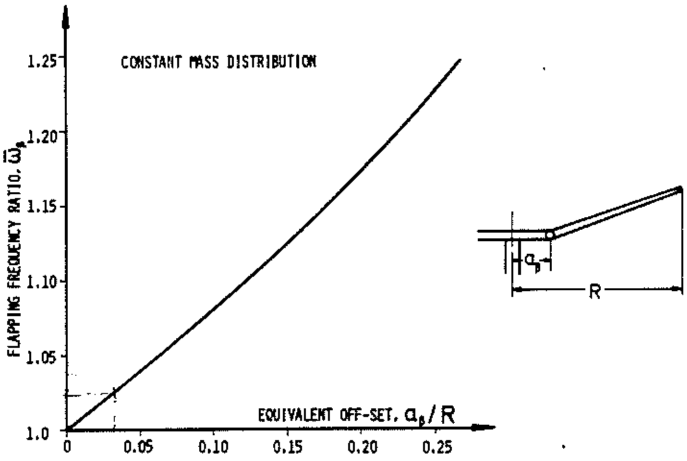

Figure 5: Flapping Frequency Ratio, $\overline{\omega}_\beta$

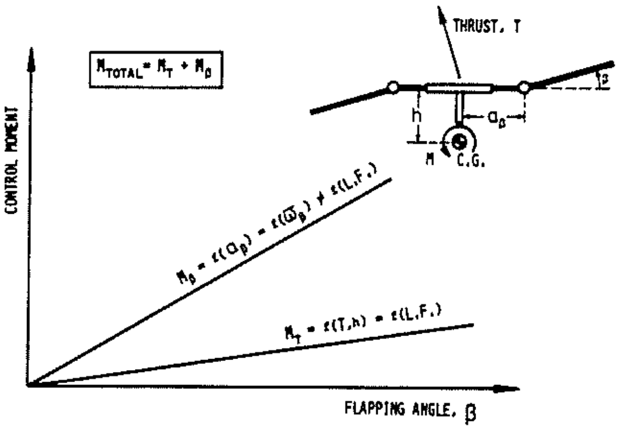

Figure 6: The Control Moment

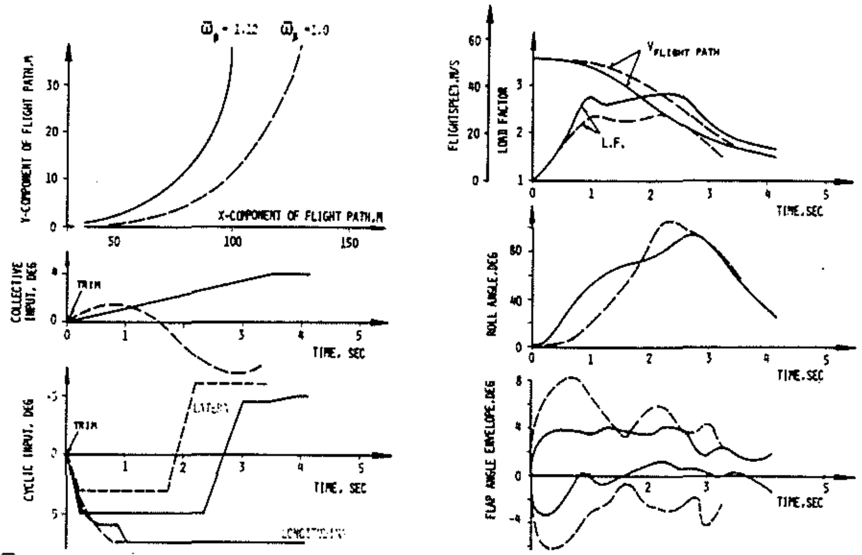

Figure 7: 90 Degree Turn

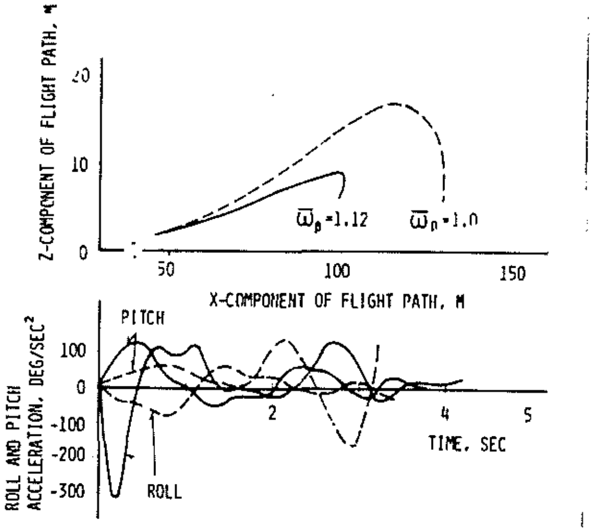

Figure 8: 90 Degree Turn

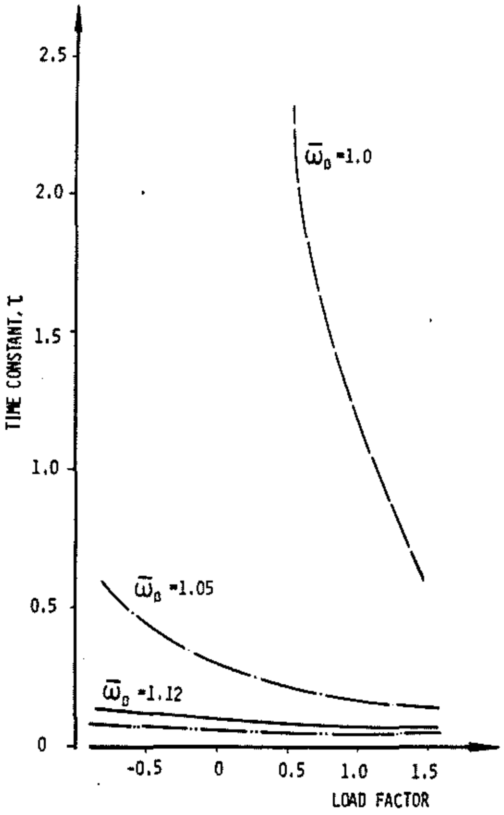

Figure 9: Effect of L.F. and $\bar{\omega}_\beta$ on the Time Constant

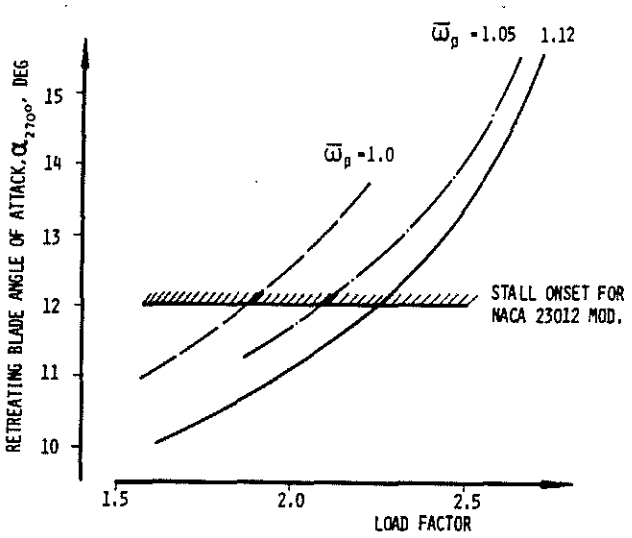

Figure 10: Influence of $\bar{\omega}_\beta$ on Limit Load Factor

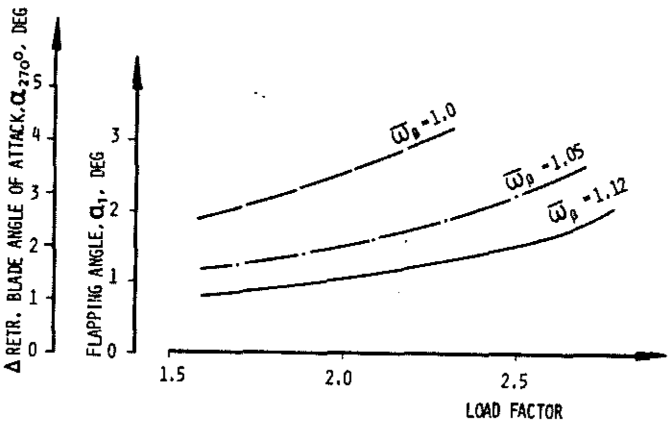

Figure 11: Influence of $\bar{\omega}_\beta$, L.F and α_1 on Retreating Blade Angle of Attack, α_{270°

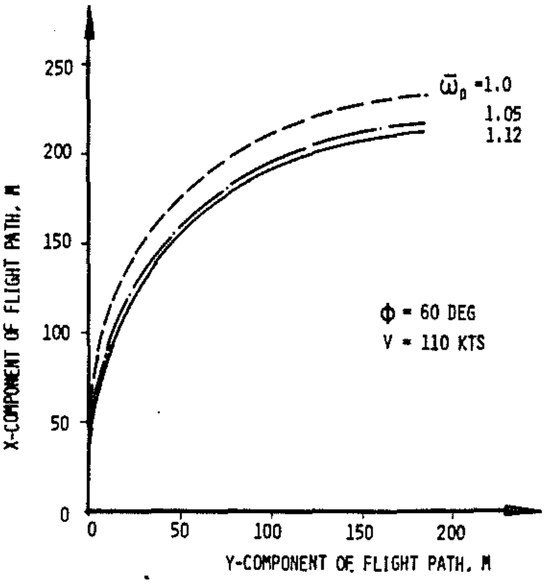

Figure 12: Decoupled 90°- Turn Performance

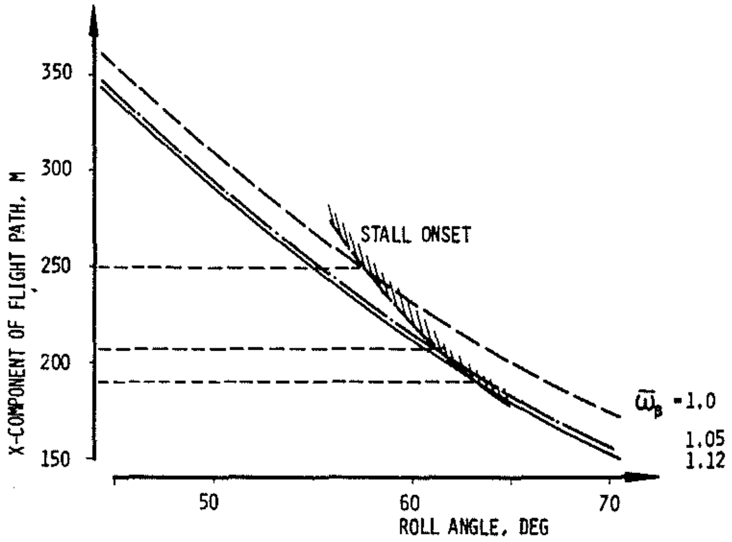

Figure 13: Effect of $\bar{\omega}_\beta$ and Stall on x-Distance for 90° Turn

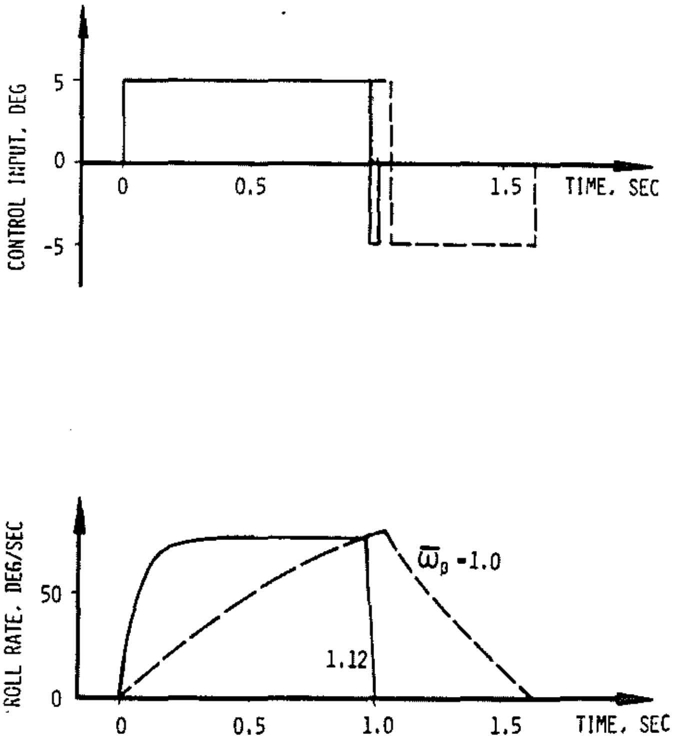

Figure 14: Effect of $\bar{\omega}_\beta$ upon Roll Response

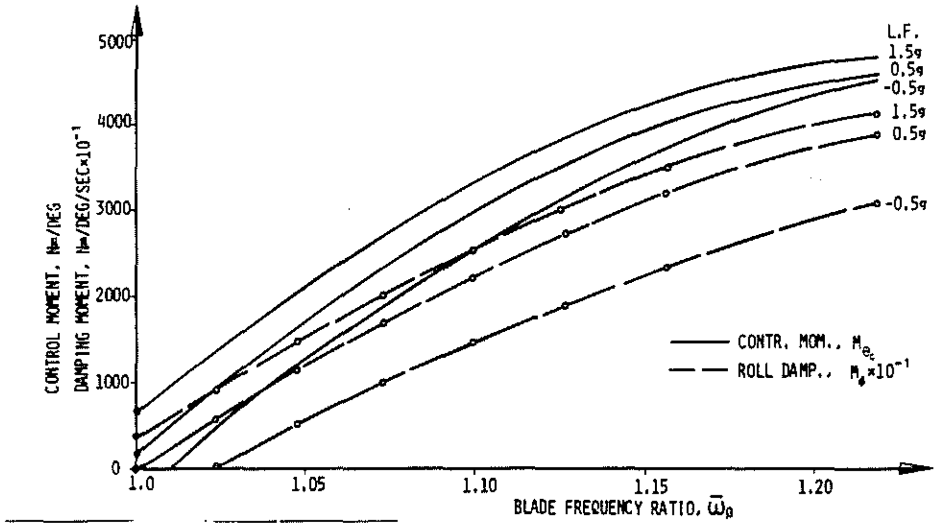

Figure 15: Effect of $\bar{\omega}_\beta$ and L.F. on Controllability

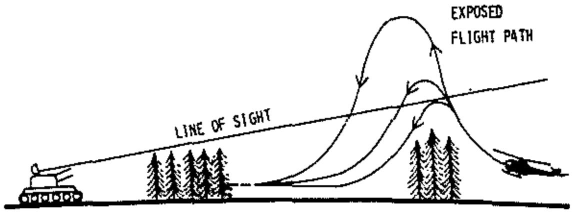

Figure 16: Exposure Time and Altitude

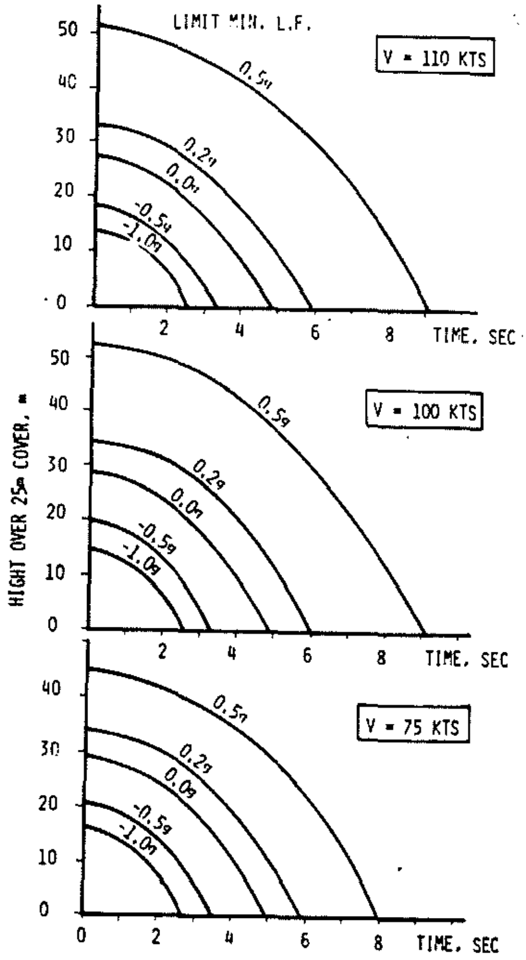

Figure 17: Exposure Envelope

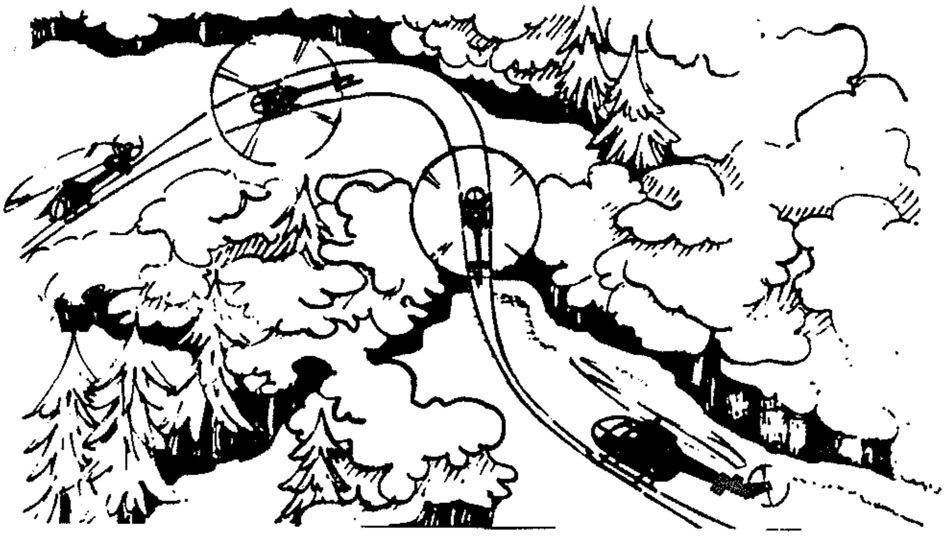

Figure 18: Typical Compound Maneuver

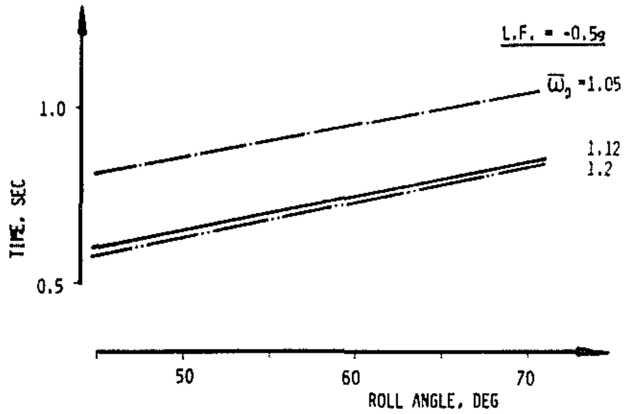

Figure 19: Roll Performance at Reduced Load Factor