

HELICOPTER GUST RESPONSE CHARACTERISTICS
INCLUDING UNSTEADY AERODYNAMIC STALL EFFECTS

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Abstract

The results of an analytical study to evaluate the general response characteristics of a helicopter subjected to various types of discrete gust encounters are presented. The analysis employed was a nonlinear coupled, multi-blade rotor-fuselage analysis including the effects of blade flexibility and unsteady aerodynamic stall. Only the controls-fixed response of the basic aircraft without any aircraft stability augmentation was considered. A discussion of the basic differences between gust sensitivity of fixed and rotary wing aircraft is presented. The effects of several rotor configuration and aircraft operating parameters on initial gust-induced load factor and blade vibratory stress and pushrod loads are discussed. The results are used to assess the accuracy of the gust alleviation factor given by MIL-S-8698. Finally, a brief assessment of the relative importance of possible assumptions in gust response analyses is made and a brief comparison of gust and maneuver load experiences in Southeast Asia is presented.

The results confirm that current gust alleviation factors are too conservative and that the inclusion of unsteady stall effects result in higher initial load factors than predicted using a steady stall aerodynamic analysis.

Notation

A_g gust alleviation factor; see Equation (1) and (3)
 a two-dimensional lift curve slope of rotor blade section
 b number of blades
 B tip loss factor
 c blade chord, ft
 C_T vertical force coefficient, Thrust/ $\pi \rho \Omega^2 R^4$
 GW gross weight, lbs

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I_a blade mass moment of inertia about flapping hinge, slug - ft²
 R blade radius, ft
 S fixed wing area, ft²
 $t_{3,1}$ partial derivative $\frac{\partial C_T}{\partial \lambda}$
 V forward velocity, knots or ft/sec
 V_{avg} average characteristic velocity for helicopter rotor
 V_g maximum vertical velocity of gust, positive up, ft/sec
 α angle between shaft and relative wind, positive tilted aft, radians
 γ blade lock number, $\rho a c R^4 / I_B$
 Δn incremental rotor load factor; $\frac{MAX THRUST - 1}{GW}$
 Δn_s incremental rotor load factor predicted by linear steady theory for sharp edge gust instantaneously applied to entire lifting device.
 λ inflow ratio, $(V \sin \alpha - v) / \Omega R$
 μ advance ratio, $V \cos \alpha / \Omega R$
 v rotor induced velocity, positive up, ft/sec
 ρ air density, slugs/cubic foot
 σ rotor solidity, $bc / \pi R$
 Ω rotor angular rotational velocity, radians/second
 $\frac{\partial C_L}{\partial \alpha}$ three dimensional lift curve slope for fixed wing

Subscripts

FW denotes fixed wing
 H denotes helicopter

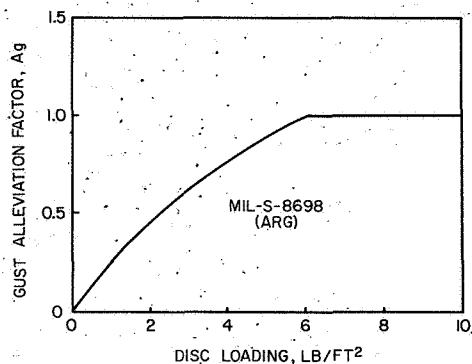


Figure 1. Current Gust Alleviation Factor.

Current procedures for predicting helicopter gust-induced loads involve computing rotor loads by means of a simplified linear theory and modifying these loads by a gust alleviation factor defined in Specification MIL-S-8698 (ARG). The alleviation factor is shown in Figure 1 and is a function of rotor disc loading alone. Further, no alleviation is allowed for disc loadings greater than 6.0 - a value exceeded by many modern helicopters. Attempts to verify the accuracy of this approach through flight test have been complicated by uncertainties regarding the gust profiles. This has led to side-by-side flight tests of fixed and rotary-wing aircraft (Reference 1) in order to build a semi-empirical bridge between the relatively straight forward fixed wing situation and the more complex situation associated with rotary wings. Limited qualitative results on aircraft of comparable gross weight indicated that the helicopter was less gust sensitive than the fixed wing aircraft, but extensive quantitative data from this type of test are, obviously expensive and difficult to obtain. Analytical confirmation of the MIL-S-8698 (ARG) gust alleviation factor has been hampered by the lack of an analysis which can handle both the transient response of the helicopter and the aeroelastic response of the rotor blades, while, simultaneously, providing a reasonably complete modeling of the rotor aerodynamic environment. An improved gust response analysis (described in Reference 2) has indicated that current procedures are too conservative. The primary objectives of this investigation were (1) to develop a similar computerized analysis based on the rotor aeroelastic and unsteady stall aerodynamic techniques developed at Sikorsky Aircraft and the United Aircraft Research Laboratories and (2) to apply the analysis to predict rotor gust alleviation factors for comparison with those given in Specification MIL-S-8698 (ARG) and in Reference 2. The principal contribution of this analysis relative to that of Reference 2 is the inclusion unsteady stall aerodynamics. The resulting computer program was designed to function on the CDC 6600 computer and is catalogued at both the Langley Research Center and the Eustis Directorate.

Comparison of Helicopter and Fixed Wing Gust Response

Before proceeding with a detailed analysis of the helicopter gust response characteristics, it is instructive to compare fixed wing and helicopter characteristics in relatively simple terms. Such a comparison follows.

In analyzing the response of fixed wing aircraft to discrete sharp edge gusts, (eg. Reference 3) the concept of a gust alleviation factor is employed. The gust alleviation factor is simply the ratio of the "actual" incremental load factor produced by the gust to the incremental load factor computed from simple steady-state theory. The "actual" load factor may represent a measurement or may be computed from some more rigorous theory applicable to the unsteady gust encounter situation. Thus, if A_g is defined as the gust alleviation factor, we have

$$A_g = \frac{\Delta n}{\Delta n_s} \quad (1)$$

for fixed wing aircraft we have

$$\frac{(\Delta n)_{FW}}{V_g} = \frac{\frac{1}{2} \rho (V \frac{\partial C_L}{\partial \alpha} A_g)_{FW}}{GW/S} \quad (2)$$

Following the same approach for a helicopter having a rotor as its sole lifting element, we can write:

$$(\Delta n)_H = (\Delta n_s)_H (A_g)_H \quad (3)$$

Using steady, linear rotor theory results from Reference 4, and assuming a sharp edge gust instantaneously applied to the entire rotor, is given by:

$$(\Delta n_s)_H = \frac{\rho b c R \Omega R a}{GW} t_{3,1} V_g \quad (4)$$

$$(\Delta n_s)_H = \frac{\frac{1}{2} \rho (t_{3,1} \Omega R) a V_g}{GW/b c R} \quad (5)$$

$$(\Delta n_s)_H = \frac{\frac{1}{2} \rho (V_{avg}) a V_g}{GW/b c R} \quad (6)$$

Hence, the actual load factor is given by

$$\frac{(\Delta n)_H}{V_g} = \frac{(\Delta n_s)_H}{V_g} (A_g)_H = \frac{\frac{1}{2} \rho (V_{avg} a A_g)_H}{GW/bcR} \quad (7)$$

Equation (7) is of similar form to the corresponding fixed wing equation (Equation 2). Further, by comparing the two equations, it is clear that the characteristic or average velocity for the rotor is given by $t_3, \Omega R$ and that the characteristic area for the rotor is the total blade area. The characteristic velocity V_{avg} , of the rotor is presented in Figure 2. A typical value of V_{avg} is about $0.5 \Omega R$ and the effect of advance ratio (or forward speed) is seen to be small. This contrasts with the fixed wing case where the characteristic velocity is equal to the aircraft's forward velocity.

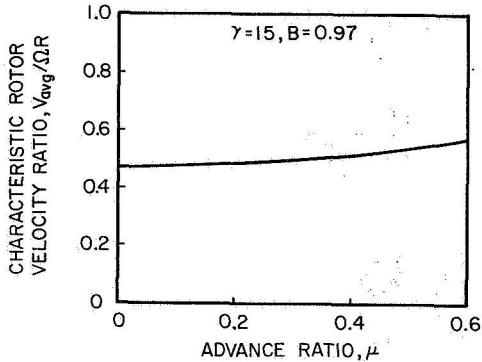


Figure 2. Rotor Characteristic Velocity Ratio.

Now, attempts have been made to measure the gust alleviation factors of helicopters through side-by-side flights with fixed wing aircraft. However, the relative alleviation factors so determined are only meaningful if the Gust Response Parameter for the two aircraft are equal. This equality of Gust Response Parameters is shown in Equation 8:

$$\left(\frac{\frac{1}{2} \rho V_{avg} a}{GW/bcR} \right)_H = \left(\frac{\frac{1}{2} \rho V \frac{\partial C_L}{\partial \alpha}}{GW/S} \right)_{FW} \quad (8)$$

If the relation above is satisfied, Equations (2) and (7) indicate that the following equality also holds:

$$\frac{(\Delta n)_{FW}}{(V_g A_g)_{FW}} = \frac{(\Delta n)_H}{(V_g A_g)_H} \quad (9)$$

Assuming the two aircraft encounter the same gust velocity profile, Equation (9) reduces to

$$\frac{(\Delta n)_H}{(\Delta n)_{FW}} = \frac{(A_g)_H}{(A_g)_{FW}} \quad (10)$$

Thus, the ratio of the gust alleviation factors will be in proportion to the measured load factors

for the two aircraft. If the fixed wing gust alleviation factor is known, $(A_g)_H$ can then be determined.

If Equation (8) is not satisfied, then the gust alleviation factor for the helicopter can be determined from the following relation:

$$\frac{(A_g)_H}{(A_g)_{FW}} = \frac{(\Delta n)_H}{(\Delta n)_{FW}} \left(\frac{\frac{1}{2} \rho V \frac{\partial C_L}{\partial \alpha}}{GW/S} \right)_{FW} \left(\frac{GW/bcR}{\frac{1}{2} \rho V_{avg} a} \right)_H \quad (11)$$

Typical values of the Gust Response Parameters of Equation (8) are presented in Figure 3. The results of Figure 3 indicate that a helicopter having a blade loading of 100 lb/ft^2 and operating at a forward speed of 250 fps will exhibit approximately the same sensitivity to a gust as a fixed wing aircraft having a wing loading of about 60 lb/ft^2 , provided, of course, that the gust alleviation factors for both aircraft are equal. In practice, for this example, the gust alleviation factor for the fixed wing will be significantly higher (meaning higher acceleration) than that for the helicopter.

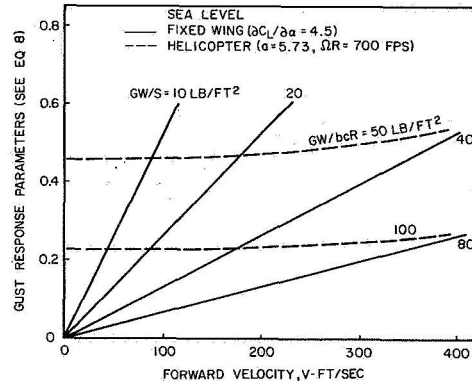


Figure 3. Fixed Wing and Helicopter Gust Response Parameters.

Factors Influencing Helicopter Gust Response

The computation of gust induced loads for helicopters is a difficult analytical task because the rotary wing lifting system is a complex aeroelastic mechanism operating in complicated aerodynamic environment. Principal factors which can be expected to influence the gust response of a helicopter are described briefly below.

- a. Rotor blade response - Helicopter rotors differ from fixed wings in that the blades (wings) of the rotor are relatively flexible and, in many cases, are articulated relative to the fuselage. The blades, therefore, are much more responsive to gust loads than is the aircraft as a whole and react in such a way as to reduce or isolate (at least temporarily) the fuselage from the impact of the gust. Thus, while the blades are responding to the gust, the fuselage has time to build up vertical velocity which, in turn, reduces the effective velocity seen by the rotor. A simple example illustrating

the magnitude of the various forces contributing to the fuselage acceleration is shown in Figure 4 for a sharp edge gust applied instantaneously to a rotor having nonelastic flapping blades and operating in hover. In this extreme case, because of the overshoot of the blade flapping response, the peak acceleration experienced by the body is about the same as it would have been had the blades been completely rigid (i.e. equal to the acceleration given by the gust term alone). As seen in Figure 4, the forces associated with the blade dynamic response are large; hence any factor influencing the blade is potentially important.

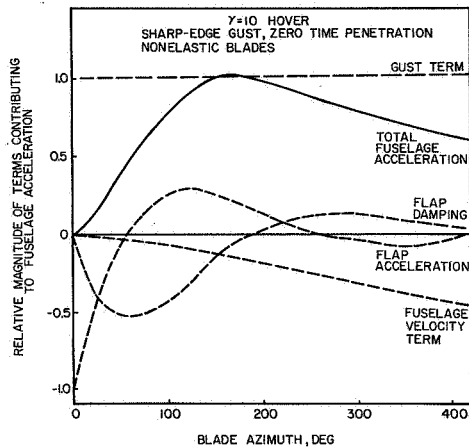


Figure 4. Comparison of Terms Contributing to Fuselage Acceleration.

- b. Fixed wing response - If the helicopter is fitted with fixed wings (compound configuration), additional gust loads are, of course, generated. These can be treated using available fixed-wing techniques and are not of primary concern in this study.
- c. Rotor Aerodynamic Modeling - The ability of a rotor to generate load factor during a gust encounter will depend on the proximity of the blade trim angle of attack distribution to stall. A rotor operating on the verge of stall prior to a gust encounter can be expected to generate less additional lift due to the gust than can a rotor initially operating further away from stall. The modeling of stall aerodynamics is important; therefore, the impact of unsteady aerodynamics on rotor stall was investigated in this study.
- d. Gust Characteristics - Gust profile and amplitude are, of course, potentially important factors. In addition, the speed of the helicopter as it penetrates a given gust front can be expected to be significant. Figure 4 indicated the fuselage acceleration for a gust applied instantaneously to the entire disc. With a finite-time penetration of the gust front, the contribution of each blade to the fuselage loading will not be identical (as in Figure 4) but rather will

be phased so that the peak loads for each blade occur at different times (see Figure 5). As a result, finite-time penetration of the gust reduces the peak fuselage accelerations produced by a given gust profile.

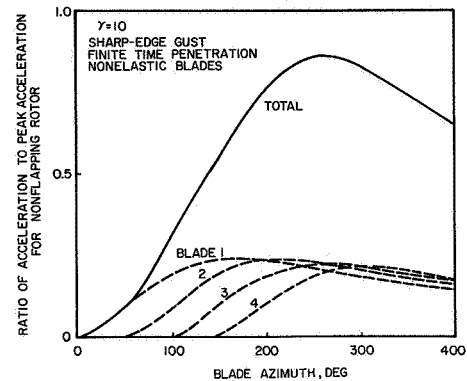


Figure 5. Finite-Time Penetration Causes Peak Blade Forces to be out of Phase.

- e. Control system inputs - The ultimate effect of gust on the helicopter must be influenced by any reaction of the pilot or stability augmentation system to the initial loads produced by the gust. It is possible (but unlikely with a properly designed system) that the largest loads produced by the gust will not be the initial loads but, rather, those associated with the longer term response of the coupled system represented by the aircraft, pilot, and stability augmentation system (See Schematic in Figure 6). These longer term effects depend on the specific design characteristics of the aircraft system and no attempt was made to model them in the present study. Hence, the gust-induced loads considered are the initial loads caused by the gust for a controls-fixed rotor operating condition.

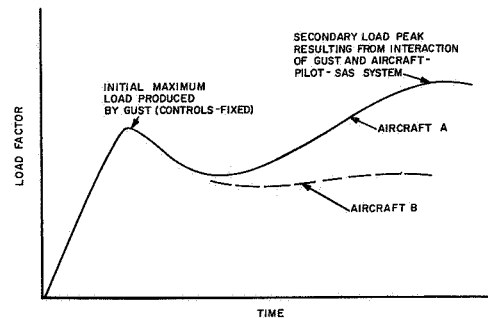


Figure 6. Schematic of Possible Load Factor Time Histories.

Brief Description of the Analysis

Complete documentation of the equations used in the analysis is given in Reference 5, while procedures for running the associated computer program may be found in Reference 6. Both of these references can be obtained from the Eustis Directorate of USAAMRDL.

Briefly, the analysis is essentially a digital flight simulator that can be used to determine the fully coupled rotor - airframe response of a helicopter in free flight. This is accomplished by the numerical integration of the blade - airframe equations of motion on a digital computer. The principal technical assumptions and features of the analysis are listed below.

1. The blade elastic response is determined using a modal approach based on the equations defined in References 7 and 8. The number of modes used consisted of three flatwise, two chordwise and one torsion for each blade.
2. The aerodynamic modeling of the blade includes unsteady aerodynamic effects based on the equations and tabulations defined in Reference 8 which assume that the lift and moment coefficients can be expressed as functions of instantaneous angle of attack and its first two time derivatives. Steady-state drag was used, however, because of a lack of data on unsteady drag in stall.
3. Rotor inflow is assumed constant for this study although provision for time-varying induces velocities is available. The constant value is determined from classical momentum theory and was invariant with either position on the disc or with time. In view of the short times required for peak loads to be achieved, this assumption is considered reasonable.
4. The response of each individual blade is considered.
5. The fuselage is a rigid (nonelastic) body having six degrees of freedom. Provisions for fixed wings are included. The aerodynamic forces on the wings are computed using simple, finite-span wing theory, neglecting stall and unsteady effects.
6. Fuselage aerodynamic forces and moments are determined using steady-state nonlinear, empirical data.
7. The gust is assumed to be both two dimensional (i.e. does not vary along the lateral axis of the rotor) and deterministic in nature. Although three dimensional and random gust effects may prove important, their inclusion was beyond the scope of this study.

Simple Linear Gust Theory

As stated earlier, it was desired to cast the results obtained in this investigation in terms of correction factors (gust alleviation factors) that could be applied to results obtained from a simple specification eventually evolved.

The simple theory used is that defined in Reference 4, in which blade stall and compressibility effects are neglected. In addition, it is assumed here that the gust is sharp-edged and is instantaneously applied to the entire rotor. The increment in rotor load factor produced by the gust is then given by Equation (5). Using the relation,

$$GW = \rho \pi R^2 (\Omega R)^2 \left(\frac{c_T}{\sigma}\right) \sigma \quad (12)$$

the incremental rotor load factor given by simple theory is

$$(\Delta n_s)_H = \frac{a}{2} t_{3,1} \left(\frac{1}{c_T/\sigma}\right) \frac{V_g}{\Omega R} \quad (13)$$

The ratio of the $(\Delta n)_H$ computed by the more complete analysis described herein to the value given by Equation (13) represents a gust alleviation factor which can be used to correct the load factors results given by Equation (13). Thus:

$$(A_g)_H = \frac{(\Delta n)_H}{(\Delta n_s)_H} \quad (14)$$

Values of A_g presented in this paper are based on a rotor blade lift curve slope, a , of 5.73. Hopefully, if A_g shows reasonably consistent trends, it can be used with some confidence to rapidly predict rotor load factors for combinations of parameters other than those considered in this study.

Scope of Study

Gust load factors, blade bending moments, vibratory hub loads, and rotor control loads were calculated for a range of values for rotor thrust coefficient-solidity ratio, blade Lock number, advance ratio, and blade flatwise and torsional stiffness. The effect of adding a wing was also investigated. The responses associated with three types of vertical gusts were investigated: sine-squared, ramp, and sharp-edged. The sine-squared gust and the ramp gust reached a maximum value of fifty feet per second at a penetration distance of ninety feet. The gust profiles are displayed in Figure 7. Three types of rotor systems were evaluated: articulated, nonarticulated (hingeless), and gimbaled. Emphasis in this paper is placed on the results for the reference articulated rotor. The reader is referred to Reference 10 for details of the other configurations studied. The articulated rotor properties can be found in Table I, together with the natural frequencies of the blades. As indicated, the number of modes used

consisted of three flatwise, two chordwise, and one torsional modes.

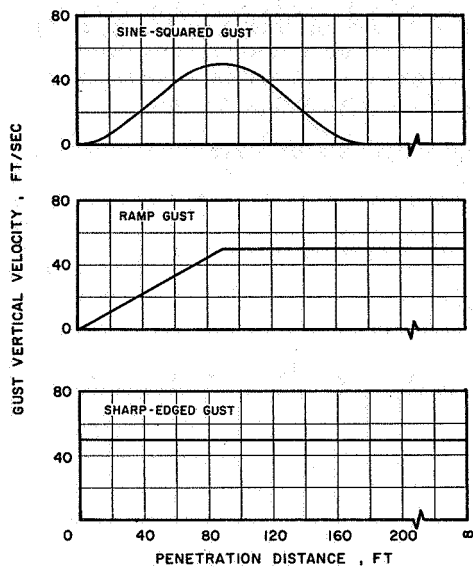


Figure 7. Gust Profiles.

Discussion of Results

Effect of Gust Profile

The effect of gust profile on incremental rotor thrust force for the reference articulated rotor was evaluated by the penetration of three gusts with profiles as shown in Figure 7. The helicopter was assumed to penetrate a stationary gust with a velocity of 350 feet per second. This corresponds to an advance ratio of 0.5.

The time history of the rotor thrust associated with each of the gust profiles is shown in Figure 8. It may be seen from this figure that while the actual gust wave form has little impact on maximum rotor force and consequently on rotor load factor, the particular time histories behave differently, although in an expected manner. Initially, the sine-squared and the ramp gust shapes result in similar peak rotor loads at approximately the same time. The sharp-edge gust induces a greater peak load with a faster build up. As the penetration distance increases, the loads produced by the sharp-edge gust and the ramp gust tend to merge since their respective velocities are both 50 fps while the value of the sine-squared gust velocity has dropped back towards zero.

Analysis of the computed results forming the basis for Figure 8 indicates that at the time the maximum rotor vertical force and load factor is reached, the helicopter fuselage has had time to develop only a modest amount of vertical velocity. The vertical velocities at the peak load points of the helicopter associated with the sine-squared and sharp-edged gusts are 6fps, and 3 fps, 3 fps, respectively. These compare to the 50 fps gust velocity, indicating that little gust alleviation

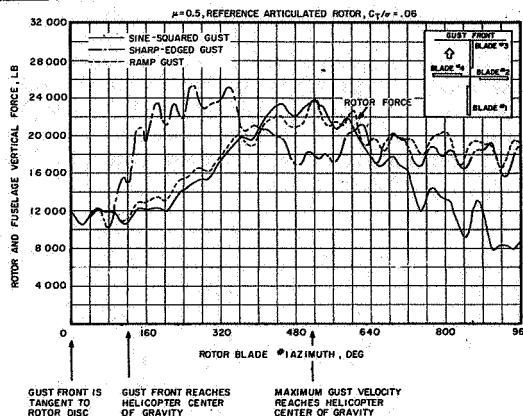


Figure 8. Rotor Force Time Histories.

is being produced by fuselage motion for the condition analyzed.

The three types of gust profiles evaluated did not produce greatly different peak rotor loads. While the sharp-edge gust does produce the largest loads, it is probably the least realistic of the three profiles. Since other studies, such as Reference 2, have used a sine-squared gust, the remainder of the results presented are based on this profile.

Effect of Rotor and Flight Condition Variables

The variation of gust alleviation factor, (as computed from Equation 14), with initial rotor loading is shown in Figure 9 for the three types

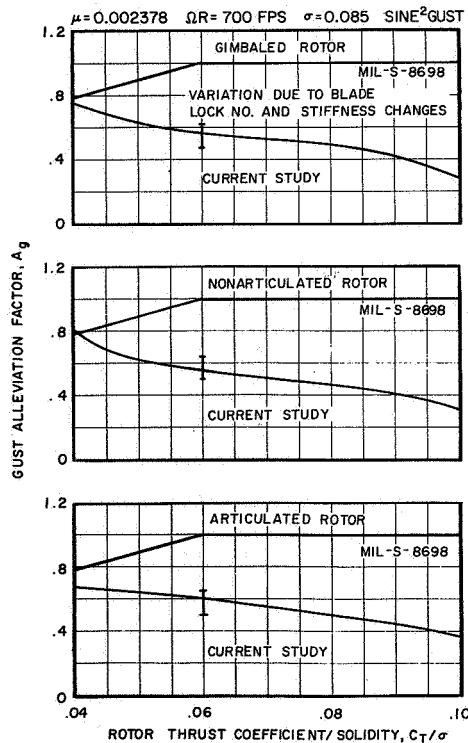


Figure 9. Gust Alleviation Factors for Different Rotors.

types of rotors analyzed. Rotor loading in this figure has been expressed both in terms of rotor thrust coefficient solidity ratio and rotor disc loading. It should be remembered that disc loading is not a unique function of C_T/σ but rather depends on the value of density, tip speed and solidity of the rotor. Values for these quantities are noted on the figure.

The results of Figure 9 indicate that increasing C_T/σ leads to a large reduction of gust alleviation factor. This is similar to the trend noted in Reference 2 and is believed to be related to the loss in average additional lift capability at the higher C_T/σ due to the occurrence of stall. The influence of rotor configuration is seen to be of rather secondary importance. Rotor configuration would be expected to influence fuselage motion through the transmittal of differing rotor pitching moments to the airframe, depending on the degree of rotor articulation. The relative insensitivity of the results to configuration is believed to be due to the short time in which the initial, controls-fixed load factor is generated. As a result, the fuselage response to the differing moments is not large and the load factor tends to be dominated by the rotor blade dynamic response, which is roughly the same for all rotors. This result is also similar to that observed in Reference 2.

It is also evident from Figure 9 that the gust alleviation factors defined in MIL-S-8698 (ARG) are too high (i.e. result in loads which are too high). The conservatism of the current specification is particularly evident at the high thrust coefficient-solidity ratios where rotor stall becomes a factor limiting gust-induced thrust generating capability. On this basis, one would expect the gust alleviation factor for upward gusts to be different from those for downward gusts (i.e. gusts which unload the rotor). While downgusts are not critical from a structural loads viewpoint, they could prove more important from a passenger - comfort point of view.

The results of Figure 9 are for typical reference rotor configurations (see Reference 10 and Table I herein). As part of this study, calculations were made to examine the sensitivity of the computed gust alleviation factors to separate variations in blade Lock Number, bending stiffness and torsional stiffness. Ranges of the parameters considered are noted below:

Lock Number: reference, 0.7 ref. 1.3 ref.

Bending stiffness: reference, 0.5 ref.

Torsional stiffness: reference, 0.5 ref.

The parameter variations listed above were made at an advance ratio of 0.3 and 0.5 for a C_T/σ of 0.06. The range of results is also shown in Figure 9 and as can be seen, the effect of blade Lock number and stiffness is relatively small. Lock number and advance ratio account for most of the small variation shown, with the lower advance

ratios and higher Lock numbers being associated with the lower gust alleviation factors. The relatively small effect of blade stiffness variations is perhaps not surprising inasmuch as the total blade stiffness tends to be dominated by centrifugal stiffening effects. The variations shown for C_T/σ of 0.06 are believed to be representative of those at other C_T/σ values; however, this should be verified.

Articulated rotor load factors predicted using the results of Figure 9 are presented in Figure 10 where they are also compared to the results of Reference 2. Load factors predicted by the current study are seen to be higher than those of Reference 2. This increase appears to be due to the use of unsteady aerodynamics in the current study.

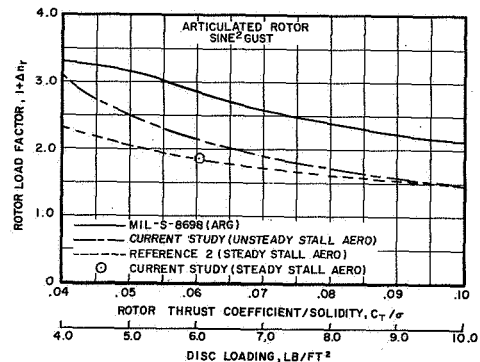


Figure 10. Comparison of Results with Reference 2

Gust-Induced Blade Stresses, Control Loads and Vibration

The effects of a gust encounter on other quantities of interest to the designer such as blade stresses, control loads, and aircraft vibration were briefly examined. In examining these effects, an attempt was made to generalize the results to a limited degree by relating the maximum values produced by the gust to the initial trim values. Results are based on the trim condition of $C_T/\sigma = 0.06$ and an advance ratio of 0.3 are presented in Figure 11. Detailed analysis of the trends shown were beyond the scope of this paper. The reader is referred to Reference 2 for a more detailed discussion.

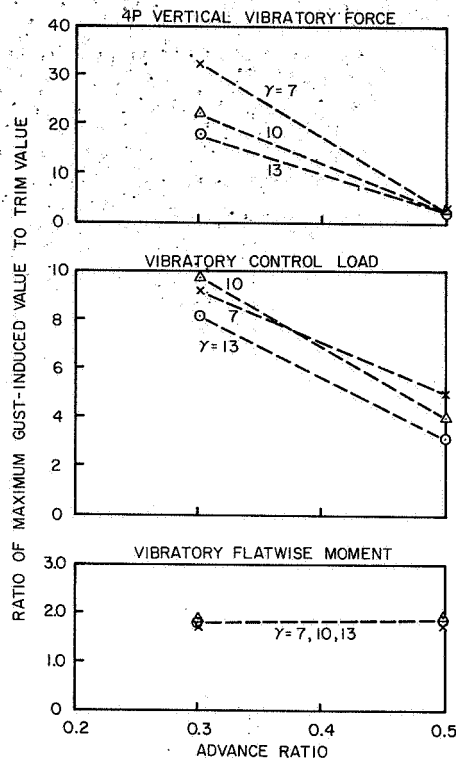


Figure 11. Effect of Gust on Vibration, Control Load and Flatwise Moment, $C_T = 0.06$, 50 fps $SINE^2$ Gust
Sensitivity of Results to Assumptions

As discussed in an earlier section of this report, many factors could potentially influence rotor gust response characteristics. To account for all of these factors leads to a time consuming, complex, digital analysis. In the following paragraphs, the results of a brief examination of the importance of some of these factors are discussed. Only the reference articulated rotor at one operating condition is considered. Any conclusions drawn from these results must, therefore, be considered preliminary and should be substantiated by further investigation. A summary of the results obtained is presented in Figure 12. Shown is the percentage change in the predicted gust alleviation factor resulting from the separate elimination of fuselage motion, blade elastic torsion, finite time penetration, and unsteady stall effects in the analysis. The baseline value corresponds to value for the complete analysis. A positive change in A_g means that the effect eliminated causes an increase in predicted loading. It is evident that the unsteady stall aerodynamic and finite-time gust penetration effects are most important. Excluding unsteady aerodynamics reduces the predicted value of A_g by about 29%. This is because the maximum lift capability of the rotor based on steady aerodynamic stall characteristics is lower than that based on unsteady characteristics (see Reference 9). The reduction is consistent with the observed lower values of predicted load factors obtained in

Reference 2 and previously presented in Figure 10.

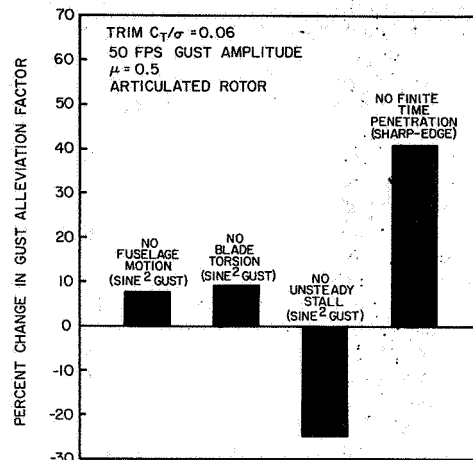


Figure 12. Sensitivity of Gust Alleviation to Analytical Assumptions.

The largest change in predicted gust alleviation factor was produced by the elimination of the finite time penetration of the gust front. As might be expected, when the gust is assumed to affect all blades simultaneously, the blade forces are all in phase and large values of A_g (and hence loading) result.

It should be emphasized that the results presented in Figure 12 were determined for only one reference trim condition. Further work is required to substantiate the generality of the results.

Gust Load Factor Experience in SEA

The earlier portions of this paper have been devoted to analytical techniques appropriate for determining the effects of gust encounters on helicopter response variables. One point which has been made is that rotor blades, because of their flexibility, tend to reduce the impact of the gust on the fuselage. Resulting gust alleviation factors have been found to be low and, hence, one would expect that gust-induced loads on the fuselage could be reduced in importance. Experimental evidence supporting this contention has been acquired by the U. S. Army in SEA. A brief discussion of that data is presented below.

The U. S. Army has been acquiring usage data on its combat operational helicopters in Vietnam since early 1966. Beginning with both the cargo and armored versions of the CH-47A, the CH-54A, AH-1G, and UH-6A helicopters were instrumented to record the history of their actual combat usage.

Since control positions and c.g. accelerations were among the parameters measured and the data were recorded in analog format, occurrences of gust-induced loads were identified and isolated from pilot-induced (maneuver) accelerations by analyzing those particular trace recordings. Gust-induced acceleration peaks, therefore, were identified as those accelerations occurring when both

the cyclic and collective stick traces were steady or, if stick activity was present, the sense of the peaking acceleration had to be in opposition to that expected from the stick control motion.

A total of 1477 hours of flight data were acquired during the measurement programs for the cited aircraft (References 11-13). The conclusive finding in each of these programs was that normal loads attributed to gust encounters were of much lesser magnitude and frequency than maneuver loads. Further, when the total load factor experience was statistically examined for each aircraft, the loads directly attributed to gust encounters were found to be only a small percentage of the total experience. These points are graphically illustrated in Figure 13. The maneuver load scatter band was obtained from References 14 and 15.

It should be pointed out that while gust-induced load factors are smaller than typical maneuver load factors for military aircraft, gust loadings can be an important consideration from a ride comfort standpoint in commercial applications.

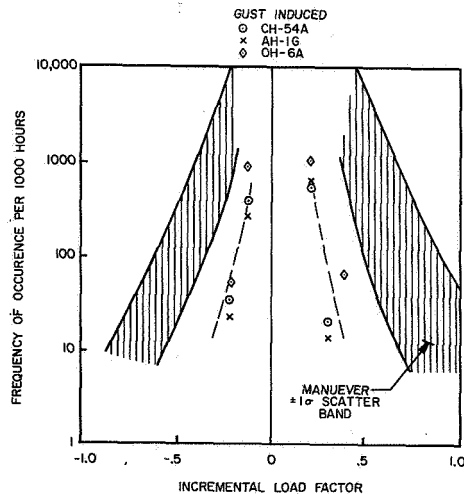


Figure 13. Gust-Induced Loads are Significantly Less than Maneuver Loads.

Conclusions

The following conclusions were reached as a result of this study. It should be noted that Conclusions 1-3 are based on the computation of initial gust-induced load factors for various rotor systems mounted on a single fuselage and operating with the controls fixed throughout the gust encounters.

1. The results of this study generally confirm those of Reference 2, indicating that the current method for computing gust-induced load factors for helicopter rotors (Specification MIL-S-8698 (ARG)) results in realistically high values and should be revised.
2. If the gust amplitude is sufficient to

cause retreating blade angles of attack greater than the two-dimensional, steady-state stall angle, the inclusion of unsteady aerodynamic effects based on the model of Reference 8 results in gust-induced load factors which are higher than those based on a steady aerodynamic model such as that used in Reference 2.

3. Principal parameters influencing gust-induced load factor appear to be nondimensional blade loading, proximity of the rotor trim point to blade stall, and rate of penetration of the rotor into the gust.
4. Gust loadings on military helicopters appear to be significantly lower than those due to maneuvers.

References

1. Crim, Almer D., GUST EXPERIENCE OF HELICOPTER AND AN AIRPLANE IN FORMATION FLIGHT, NACA Technical Note 3354, NACA, 1954.
2. Harvey, K. W., Blankenship, B. L. Drees, J. M., ANALYTICAL STUDY OF HELICOPTER GUST RESPONSE AT HIGH FORWARD SPEEDS. USAAVLABS Technical Report 69-1, September 1969.
3. Bisplingoff, R. L., H. Ashley and R. L. Halfman, AEROELASTICITY, Addison-Wesley Publishing Company, Inc., Cambridge, Mass. 1955.
4. Bailey, F. J., Jr., A SIMPLIFIED THEORETICAL METHOD OF DETERMINING THE CHARACTERISTICS OF A LIFTING ROTOR IN FORWARD FLIGHT. NACA Report No. 716.
5. Bergquist, R. R., Thomas G. C. TECHNICAL MANUAL FOR NORMAL MODES AEROELASTIC COMPUTER PROGRAM, July 1972.
6. Bergquist, R. R., Thomas, G. C. USER'S MANUAL FOR NORMAL MODE BLADE AEROELASTIC COMPUTER PROGRAM, July 1972.
7. Arcidiacono, P. J., PREDICTION OF ROTOR INSTABILITY AT HIGH FORWARD SPEEDS, VOLUME 1. STEADY FLIGHT DIFFERENTIAL EQUATIONS OF MOTION FOR A FLEXIBLE HELICOPTER BLADE WITH CHORDWISE MASS UNBALANCE. USAAVLABS Technical Report 68-18A, February 1969.
8. Arcidiacono, P. J., Carta, F. O., Cassellini, L. M., and Elman, H. L., INVESTIGATION OF HELICOPTER CONTROL LOADS INDUCED BY STALL FLUTTER. USAAVLABS Technical Report 70-2, March 1970.
9. Bellinger, E. D., ANALYTICAL INVESTIGATION OF THE EFFECTS OF UNSTEADY AERODYNAMICS VARIABLE INFLOW AND BLADE FLEXIBILITY ON HELICOPTER ROTOR STALL CHARACTERISTICS. NASA CR-1769.

10. Bergquist, R. R., HELICOPTER GUST RESPONSE INCLUDING UNSTEADY STALL AERODYNAMIC EFFECTS. USAAVLABS Technical Report 72-68, May 1973.
11. Giessler, F. Joseph; Nash, John F.; and Rockafellow, Ronald I., FLIGHT LOADS INVESTIGATION OF AH-1H HELICOPTERS OPERATING IN SOUTHEAST ASIA, Technology, Inc., Dayton, Ohio; USAAVLABS Technical Report 70-51, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, September 1970, AD 878039.
12. Giessler, F. Joseph; Nash John F.; and Rockafellow, Ronald I., FLIGHT LOADS INVESTIGATION OF CH-54A HELICOPTER OPERATING IN SOUTHEAST ASIA, Technology, Inc., Dayton, Ohio; USAAVLABS Technical Report 70-73, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1971, AD 881238.
13. Giessler, F. Joseph; Clay, Larry E.; and Nash, John F., FLIGHT LOADS INVESTIGATION OF OH-6A HELICOPTERS OPERATING IN SOUTHEAST ASIA, Technology, Inc., Dayton, Ohio; USAAMRDL Technical Report 71-60, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, October 1971, AD 7308202.
14. Porterfield, John D., and Maloney, Paul F., EVALUATION OF HELICOPTER FLIGHT SPECTRUM DATA, Kaman Aircraft Division, Kaman Corporation, Bloomfield, Connecticut; USAAVLABS Technical Report 68-68, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, October 1968, AD 680280.
15. Porterfield, John D., Smyth, William A. and Maloney, Paul F., THE CORRELATION AND EVALUATION OF AH-1G, CH-54A, and OH-6A FLIGHT SPECTRA DATA FROM SOUTHEAST ASIA OPERATIONS, Kaman Aircraft Division, Kaman Corporation, Bloomfield, Connecticut; USAAVLABS Technical Report 72-56, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, October 1972, AD 755554.

TABLE I. Reference Articulated Rotor Characteristics

Density Slugs/ft ²	.002378
Tip speed, ft/sec	700.
Radius, ft	25
No. of blades	4.
Blade Chord, ft	1.67
Flap hinge off set ratio	0.04
Twist, deg	-8.0
Young's Modulus, psi	10 ⁷
Mass per unit length at 0.75R slugs/ft	0.18
Lock Number	10.0
Rigid body flatwise frequency	1.03P
First bending flatwise frequency	2.66P
Second bending flatwise frequency	5.06P
Third bending flatwise frequency	8.50P
Rigid body chordwise frequency	0.25P
First bending chordwise frequency	3.68P
Second bending chordwise	10.20P
First bending torsional frequency	5.72P