rotor aircraft could be resized based on noise rather than performance.

Attainment of specific acoustical requirements was not a constraint in the initial design of these aircraft. Figure 8 clearly serves to show that we cannot continue to design aircraft without giving consideration of, and perhaps, concession to noise level reduction, and still expect to put on the market a product which would meet with public acceptance.

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Helicopter Gust Response at High Forward Speed

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An analytical study was made of the response of helicopters and compound helicopters to discrete gusts. A sophisticated mathematical model was developed. The effects of the gust's shape, gradual penetration, nonsteady aerodynamic rotor flow, and aeroelastic blade behavior were investigated. The responses of a wide variety of configurations were determined, and many parameters, such as forward speed and rotor loading, were varied. The results indicate that the added considerations of sine-squared gust profile, nonsteady aerodynamics, and gradual penetration have a primary effect on the gust loads. The results have been synthesized into a simple empirical expression that offers a convenient method for designers to determine the gust response of contemporary high-speed pure, winged, and compound helicopters. The existing helicopter gust requirements were found to be inadequate.

Nomenclature

c = const
C_T = rotor-thrust coefficient
g = gravitational constant
H = ramp length, ft
K_g = gust-alleviation factor
K_{gw} = wing-gust coefficient
L_w = wing lift, lb
R = rotor radius, ft
S = rotor area, ft
T_{hover} = rotor thrust in hover, lb
V_g = gust velocity, fps
W = gross weight, lb
Δn = gust load, g
ΔT = rotor thrust increase, lb
$\Delta\lambda$ = inflow ratio increase
μ = advance ratio
μ_g = mass ratio
ρ = air density, slug/ft^3
σ = rotor solidity ratio

Introduction

ROTARY-wing aircraft experience milder reactions to gusts than do most fixed-wing aircraft. One of the earliest reports on this subject is a paper by Focke,[1] in which pilot reactions in a helicopter with side-by-side rotors are compared with those in a fixed-wing airplane. A similar test was conducted later by NACA,[2] with instrumentation to measure normal forces in the aircraft flying through turbulent air.

The relatively mild behavior noted in rotary-wing aircraft is not substantiated by simple theoretical considerations. It has been customary to determine the normal rotor forces due to sharp-edged gusts by using charts such as those developed by NACA.[3] Since this method does not take into account rotor limits at high advance ratios, as discussed by Livingston and Murphy[4] and by Ham and Young,[5] it yields very conservative results.

The requirements of MIL-S-8698(ASG)[6] permit the use of an alleviation factor that is a function of rotor-disk loading. For disk loadings greater than 6 psf, however, this factor is unity. Drees and McGuigan[7] investigated the effect of sine-squared gusts, with the gust velocity experienced by the aircraft assumed to be equal to the gust velocity at the center of the rotor. Gust alleviation factors of about 0.6 were found for the sine-squared gust shapes.

The rapid development of helicopters with higher forward speeds and higher disk loadings, and the addition of wings and auxiliary propulsion in the case of compound helicopters, have made the present methods of determining gust response inadequate. At high speeds and for disk loadings greater than 6 psf, the computed load factors are too high. When, in addition, gusts are superimposed on maneuver loads (as has occasionally been required in certain design studies) an unrealistic design situation is created.

Approach and Scope of the Study

The objective of the study was to investigate the effect of discrete gusts on a great variety of rotary-wing aircraft. The study included pure single-rotor helicopters with tail rotors, tandem and side-by-side helicopters, and compound

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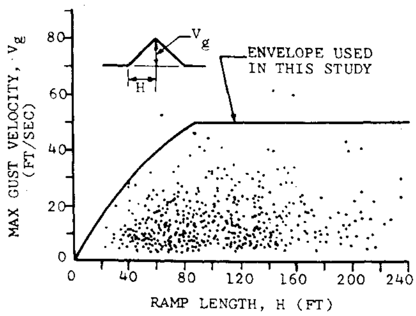

Fig. 1 Envelope of gusts based on flight tests with fixed-wing aircraft.

configurations. No attempt was made to include the effects of random gusts in the analysis. The original approach was to establish a gust-alleviation factor by comparing the results of a simple analysis for sudden gusts with the results of an analysis that models the gust and the aircraft in as much detail as is possible with the present generation of computers.

The disk loading was varied from 4 to 10 psf and the rotor-thrust coefficient C_T/σ from 0.02 to 0.10. Rigid, semirigid, and articulated rotors were evaluated. Variations were made in Lock number, number of blades, and blade dynamics. The speed range varied with configuration: pure helicopters were studied at speeds up to 225 knots, and compound helicopters, up to 350 knots.

Mathematical Models of the Gust and the Aircraft

The mathematical models of the discrete gusts included sudden, sharp-edged, ramp, rooftop, and sine-squared shapes. In the case of the sudden gust, it was assumed that the gust instantaneously engulfs the entire aircraft. The sharp-edged gust is felt first by the front of the rotor disk; the tail rotor is the last part of the aircraft to enter the gust.

The rooftop and sine-squared gust functions are defined by the peak gust velocity and the ramp length. The ramp length and gust velocity were established from the measured gust response of fixed-wing aircraft.[8,9] Figure 1 shows that most gusts are within an envelope that reaches a maximum of about 50 fps for ramp lengths in excess of 90 ft. For shorter ramp lengths, the maximum gust velocity is less.

The mathematical representation allows the detailed analysis of any basic configuration with two rotors. Wings, tail planes, and auxiliary propellers and jets are included. The number of blades per rotor can be varied from two to four; the rotor configuration may be articulated, semirigid or rigid. Blade flexibility, with full aeroelastic feedback, is optional.[10,11]

The aircraft was first trimmed to a predetermined flight condition. It then entered the maneuver, which for this study was flying into the gust. The gust velocity on each part of the aircraft was determined at each time step and was included in the angle-of-attack calculations for rotor blades, fuselage, and wing and tail surfaces.

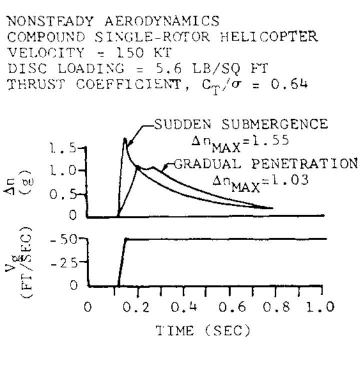

Fig. 2 Comparison of responses to sudden and sharp-edged gusts.

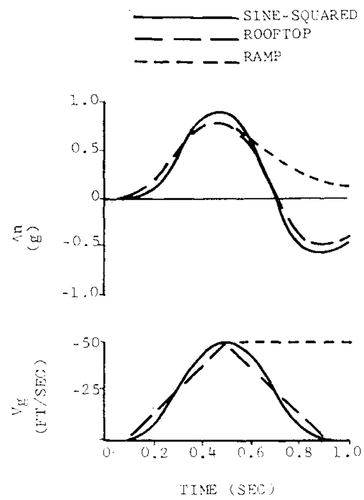

Fig. 3 Response to gradual penetration of shaped gust.

Physical Considerations

Before discussing how the various aircraft configurations respond to gusts, the effects of the new elements that have been added to the mathematical models of the gust and of the aircraft should be considered. The basis for comparison is the hypothetical case of a sudden gust applied instantaneously to the entire aircraft.

Effect of Gradual Penetration

As far as we knew, the gradual penetration of a rotorcraft into a gust had never been thoroughly analyzed. It was found that including this effect made a marked difference in the calculated responses of rotary-wing aircraft to gusts. Figure 2 shows, for a typical case, the effect of gradually penetrating a sharp-edged gust, in comparison with the sudden submergence of the entire aircraft in a gust of the same strength. Steady-state aerodynamics and infinitely stiff blades were considered, for an AH-1G Huey-Cobra flying at 150 knots into a 50 fps vertical gust. For the effect of gradual penetration, the gust-alleviation factor, $\Delta n_{\text{grad pen}}/\Delta n_{\text{sudden}}$, was found to be 0.66. The penetration provides for a gradual buildup of rotor lift, during which the aircraft is permitted to accelerate in the direction of the gust. By the time that the entire rotor disk is submerged, the aircraft is moving with the gust to some degree, and the apparent gust velocity experienced by the aircraft is reduced a corresponding amount. Simultaneously, however, the aircraft pitches upward because the front of the aircraft reacts first to the gust. This movement tends to increase the gust load and to oppose the alleviation due to heaving.

Effect of Gust Shapes

As the next step in our study, the combination of gradual penetration with gradual (rather than sudden) gusts was investigated. Figure 3 shows the results for ramp, rooftop, and sine-squared gust shapes.

The response in each of these cases is much smoother than it is with a sudden gust (Fig. 2). The gust-alleviation factors are 0.52 for the ramp and rooftop cases, and 0.57 for the sine-squared case. Clearly, combining the effects of gradual penetration and gradual buildup of the gust hardly changes the magnitude of the effects considered individually. Neither does the type of gust (all with ramp lengths of 90 ft) make much difference, although the sine-squared shape is the safest for establishing design rules.

The effect of ramp length, for the sine-squared gust, was investigated for the envelope of gust velocities and ramp lengths shown in Fig. 1. Figure 4 shows some of the results. The maximum gust-load factor Δn occurs when the ramp length is 90 ft and the gust velocity is 50 fps. The maxima

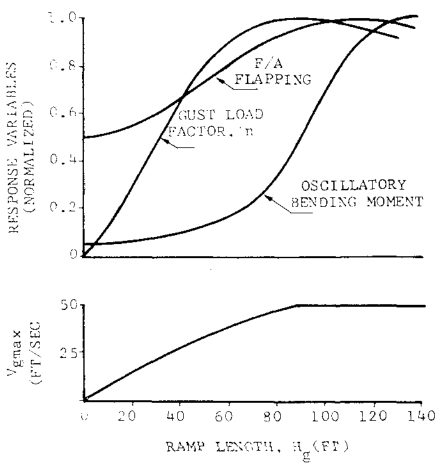

Fig. 4 Effect of gust magnitude and ramp length on rotorcraft response.

of flapping, fuselage pitching velocity, and oscillatory rotor loads, however, occur at ramp lengths between 100 and 120 ft. For future studies, it may be advisable to select a ramp length of 100 ft to reflect the over-all design requirements, although the maximum gust load is slightly reduced. The remainder of the results presented are for a ramp length of 90 ft.

Effect of Nonsteady Aerodynamics

A simplified approach[12] was used to account for nonsteady-aerodynamic effects. It involves a method of computing the rotor-induced velocity due to a time-variant wake pattern that forms after a sudden change in collective pitch. Figure 5 illustrates this effect and shows, as a function of the distance traveled, the inflow at $0.75R$ for four azimuth positions, and the resulting lift function for an infinite number of blades. The Wagner lift function,[13] as derived for gust effects on fixed wings, is included as a multiplication factor to obtain the lift function for a finite number of blades. The lift function for three blades is also shown in Fig. 5. Rotor thrust rises almost to its final value within a travel of about 0.25 rotor diameter. No thrust overshoot is found for advance ratios of about 0.1 and higher. Note that the inflow at the front of the rotor disk reaches its final value earlier than it does at the aft sector of the disk.

The effect of the nonsteady rotor-thrust function on the gust response of the aircraft depends on the rate at which the rotor thrust changes. In the case of a sudden gust, the alleviation factor for nonsteady aerodynamics alone is 0.87, but when the aircraft gradually penetrates either a sharp-edged or a ramp gust, the addition of nonsteady aerodynamics does not change the gust-alleviation factor significantly. This conclusion is important because the consideration of nonsteady aerodynamics complicates the analysis considerably. Costly computer time may be saved by ignoring this relatively minor effect.

Effect of Aeroelastic Feedback

The effects of blade bending and torsion and the associated aerodynamic reactions were found by "flying" the computer model through the gust twice: once with rigid blades and once with flexible blades. Figure 6 shows, for example, the rotor loads on a UH-1B helicopter as it gradually penetrates a sharp-edged, 30 fps gust at a speed of 100 knots. Aeroelasticity has little effect on the rotor's thrust, but it has significant effects on the oscillatory blade loads.

The study has shown that the effects are more pronounced if the stiffness of the control system is reduced, but the analytical model may not have been detailed enough to

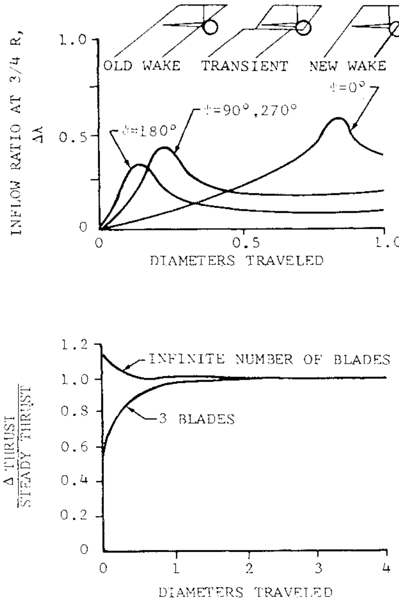

Fig. 5 Effect of a sudden collective pitch change on wake and rotor thrust.

justify a definitive statement. A more comprehensive treatment would include considerations of stall flutter.[14,15] Within the limits of the analysis, however, we found that if the natural frequencies of the rotor are properly separated from the principal rotor harmonics, and if the blades and the control system are torsionally stiff, the effects of aeroelastic feedback on gust response are small. When the blades operate near the natural frequencies, however, the vibratory blade loads are strongly affected.

Configuration Effects

Rotor Loading, Speed, and Lock Number

Table 1 shows the effect of disk loading on the response of a 10,000-lb, single-rotor helicopter with a rotor loading, C_T/σ, of 0.05 for immersion in a 50 fps sudden gust and a sine-squared, 50 fps gust. The flight velocity is 200 knots. The results for the sine-squared gust include the effects of gradual penetration, nonsteady aerodynamics, and aeroelastic feedback.

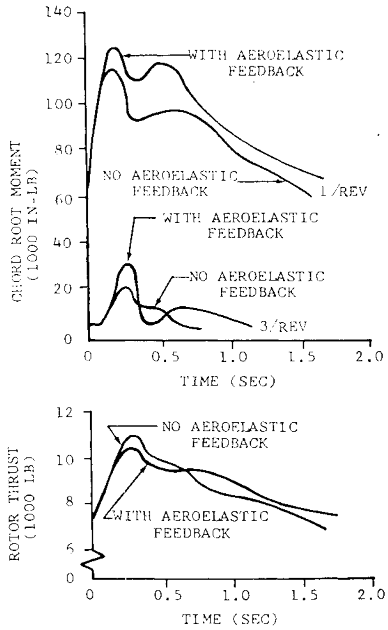

Fig. 6 Calculated time histories of UH-1B rotor loads for a 30-fps sharp-edged vertical gust.

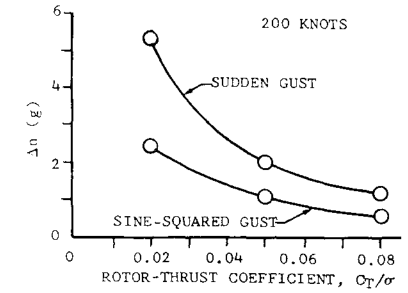

Fig. 7 Effect of rotor-thrust coefficient on the gust load.

Disk loading has only a minor influence on the gust-alleviation factor, which remains about the same for an extreme range of disk loadings. In contrast to the design method required by MIL-S-8698,[6] the gust-alleviation factor should not be eliminated for disk loadings in excess of 6 psf.

The effect of rotor-thrust coefficient in hover (C_T/σ) is pronounced, as shown in Fig. 7. C_T/σ is related to the mean blade-lift coefficient and the mean blade angle of attack in hover. The ratio of the angle of attack owing to a given gust and the mean hover angle of attack is large if the latter is small. Hence, low C_T/σ will give high gust loads.

The effect of forward speed was small for the speed range investigated. Figure 8 shows gust response vs forward

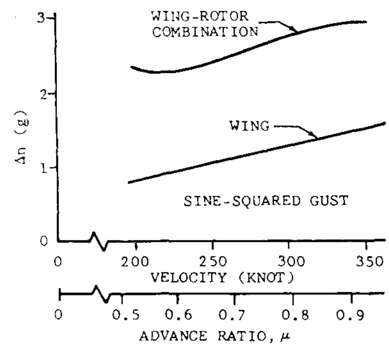

Fig. 8 Effect of forward speed on gust load for compound helicopter.

speed for a compound helicopter with a hovering disk loading of 7 psf and $C_T/\sigma = 0.05$, with a wing area of 10.5% of the rotor disk area. The contributions of the wing alone, and of the wing and rotor in combination, are shown. The advancing-tip Mach number was held constant at $M = 0.9$ by reducing rpm. The small wing on the compound helicopter, not increased rotor thrust, accounts for the slight rise in the gust response; the maximum rotor thrust does not change significantly with forward speed.

For the same compound helicopter, the effects of forward speed on the rotor-flapping and fuselage-pitching velocities during a gust are shown in Figs. 9 and 10 for two values of the advancing-tip Mach number. The maximum flapping velocity increases with speed because the rotor's flapping sensitivity increases with advance ratio. Blade stall and reversed flow reduce this trend, however, at very high advance ratios. The maximum fuselage-pitching velocity is reduced

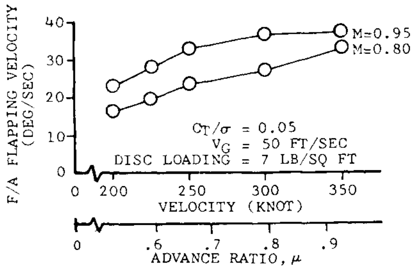

Fig. 9 Maximum flapping velocity vs forward speed for a compound single-rotor helicopter.

Table 1 Effect of disk loading

Disk loading, psf	Δn, sudden, g	Δn, sine-squared, g	Gust-alleviation factor
4	1.91	1.03	0.547
7	1.87	0.97	0.516
10	1.79	0.94	0.531

with increasing forward velocity because the elapsed time to fly through the disturbance is decreased.

Increasing the Lock number results in a higher flapping velocity and a more rapid increase of rotor thrust during the first part of the gust penetration; due to higher translational velocity in the direction of the gust, a lower value of gust load is calculated. The Lock number was varied from 4.43 to 8.31 in the study. The corresponding values of maximum flapping velocity increased from 21° to 26°/sec, and the gust-alleviation factor decreased from 0.69 to 0.54.

Hub Configuration

Rigid hubs and articulated rotors with offset flapping hinges would be expected to produce higher gust factors than semirigid rotors, which provide no moment carryover to the fuselage. Table 2 is an example of the effect of hub-spring stiffness. In this 120-knot case, only the hub-spring stiffness of a four-bladed rigid rotor was varied. The increase in hub stiffness makes the aircraft slightly more gust sensitive.

Gust-alleviation devices such as pitch-cone coupling, pitch-flap coupling, and collective-system bob weights may be used to modify the gust response of any particular rotorcraft configuration.

Aircraft Configuration

Single, tandem, and side-by-side rotor configurations were considered, the latter in a tilting-rotor composite aircraft. In the high-speed or fixed-wing mode, the tilting-rotor configuration behaves much like an airplane with high wing loading. Inplane rotor forces increase the gust sensitivity, however, and must be taken into account. As a typical example of the effect of horizontal sine-squared gusts on this type of aircraft, at 350 knots, a 50-fps gust imparted a horizontal acceleration of 0.38 g. This is a moderate response to so severe a gust.

The location of the c.g. and the pitch stability were found to have a rather pronounced effect on the gust response of the tandem-rotor helicopter. The penetration of the front rotor causes the fuselage to pitch upward, so that by the time the aircraft is fully immersed in the gust, its angle of attack is increased. This effect increases the gust load, and is most pronounced for aft c.g. Figure 11 is a time history of the acceleration with a neutral c.g. The dashed curve shows the approximate normal accelerations that would be experienced if only the instantaneous pitch attitude were considered.

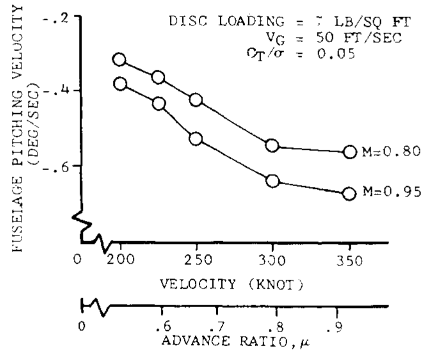

Fig. 10 Maximum pitching velocity vs forward speed for a compound single-rotor helicopter.

Table 2 Effect of hub-spring stiffness

Hub-spring stiffness, in-lb/deg	Δn, sine-squared gust, g	Gust-alleviation factor
1260	1.95	0.756
3675	2.21	0.855

Approximately 0.16 g of the 0.96 g total gust response can be attributed to the pitching of the aircraft.

Finally, compound helicopters are of considerable interest because the rotor and the wing share the lift. In our consideration of wing aerodynamics, we included the effects of nonsteady lift functions, as developed by Küssner[16] and Wagner,[13] to account for the gradual buildup of lift. The heaving caused by the increase in rotor lift reduces the wing's gust coefficient. Because acceleration is normally the highest for low rotor-thrust coefficients (see Fig. 7), the wing's gust coefficient is reduced for low values of C_T/σ. Figure 12 illustrates this effect. For $C_T/\sigma = 0.05$, there is little reduction of the wing gust coefficient K_{gw}, but for 0.02, K_{gw} is reduced from approximately 0.85 to 0.68.

The wing's effect on the rotor becomes apparent when the ratio of computed maximum increase in rotor thrust to hover thrust is plotted against C_T/σ in hover, as in Fig. 13. The wing, by unloading the rotor, increases the margin between the level-flight rotor thrust and the maximum rotor thrust available. At a given value of rotor-thrust coefficient, therefore, the gust loads for winged and compound helicopters are higher than the gust loads for pure helicopters.

Synthesis of Results

The computer program developed for this study is not suitable for daily use by designers of rotary-wing aircraft. Therefore, an important part of the study was the synthesis of results by simple design rules for determining gust loads.

Satisfactory correlation was obtained by introducing an empirical relationship to determine the maximum increase of rotor thrust that results from a 50-fps sine-squared gust. Three main considerations were included: 1) the ratio of the mean blade-angle-of-attack increase caused by the gust to the hovering mean blade angle of attack, which is directly related to the rotor-thrust coefficient ($6C_T/\sigma \approx$ mean blade lift coefficient); 2) the effect of unloading the rotor with a wing; 3) a factor that reflects both the maximum lift capability of the rotor and variations in the rotorcraft's configuration, such as hub type. It was found that the following equation, with empirical coefficients, matches the results of the computer cases with sufficient accuracy for design purposes:

$$\Delta T_{\text{gust}}/T_{\text{hover}} = 0.057/(C_T/\sigma) + 0.85L_w/T_{\text{hover}} - c$$

This expression takes into account the strong influence of C_T/σ (see Fig. 7) and the rotor unloading due to wing lift, L_w, before the gust affects the aircraft (Fig. 13). Figure 14 shows the correlation between the computer cases and the empirical equation with $c = 0.3$. To reflect the effects of hub construction and other less influential parameters, the use of $c = 0.2$ is recommended for rotors without hub-moment

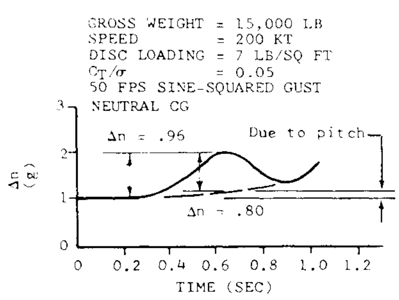

Fig. 11 Time history of tandem helicopter's response.

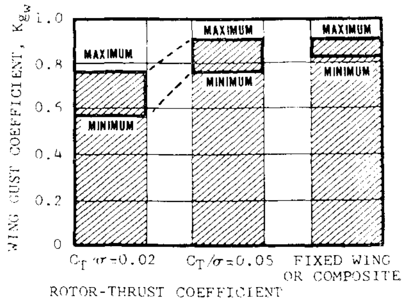

Fig. 12 Effect of rotor-thrust coefficient on wing gust coefficient.

carryover (semirigid) and $c = 0.1$ for articulated and rigid rotors.

An alleviation factor of 0.85 is suggested for the wing-load increase due to gusts. The relationship of K_{gw} and C_T/σ (see Fig. 12) needs to be explored more fully before the reduction of K_{gw} with reduced C_T/σ can be included in a simplified approach.

Attempts to correlate the gust-induced increase in dynamic rotor loads with an empirical expression were unsuccessful because of the wide variation of blade frequencies inherent in the rotor parameters.

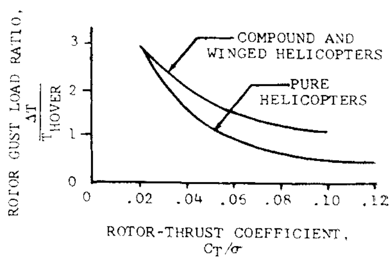

Fig. 13 Rotor gust-load ratio vs C_T/σ.

Conclusions and Recommendations

The present MIL requirements are not adequate for designing rotary-wing VTOL aircraft. An empirical relationship was developed to determine more realistic values for gust responses.

The sophisticated method developed for this study shows that the influences of gradual gust penetration and gust shape on the aircraft's response are quite strong. Aeroelastic blade deformation has a relatively small influence on the gust load for rotors with good blade-resonance characteristics and high torsional frequency. Nonsteady aerodynamics affect the re-

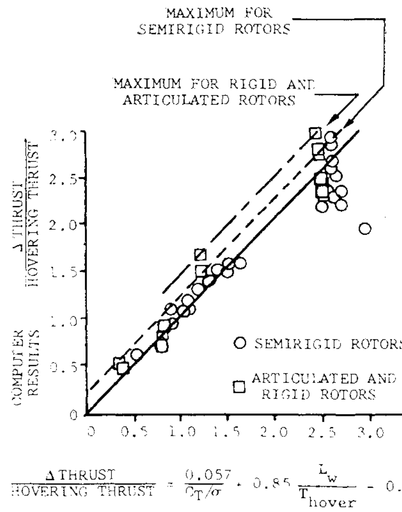

Fig. 14 Correlation of results with simple empirical expression.

sponse to sudden gusts, but become insignificant when gradual penetration is included.

Disk loading, tip speed, forward speed, Lock number, and the number of blades have only small effects on gust loads. The rotor-thrust coefficient, C_T/σ, and the presence or absence of a wing are major factors. The effect of pitching due to penetration tends to increase the gust load, particularly on tandem-rotor helicopters. Rigid rotors and articulated rotors with offset flapping hinges showed a tendency toward higher gust factors.

Future studies of the gust responses of helicopters should include experimental verification of these conclusions, with statistical considerations of random rather than discrete gusts.

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