twice that of the standard C-130E at an STOL distance of about 700 ft on a typical assault mission. The unit cost of 100 VTOL C-130 airplanes is in excess of two and one half times that of the standard version.

The design theme emerging from these studies is that V/STOL performance for the C-130, which is a function of power, lift, and drag, is readily obtained. The achievement of adequate low-speed flying qualities presents the critical design problem, the solution of which constitutes the major portion of the design and development effort involved.

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Some Problems of Design and Operation of a 250-Knot Compound Helicopter Rotor

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A theoretical computer study revealed that a compound helicopter rotor having a value of blade twist approaching zero can be operated at speeds as high as 300 knots at sea level standard conditions. Excessive vibratory stresses and performance penalties are avoided, provided that proper design variables and operating conditions are selected. Among the most important of these are rotor lift, rotor blade twist, and rotor tip speed. The study also revealed that autorotation of the rotor of the compound helicopter is not possible in sustained forward flight without exceeding the vibratory stress limitation.

Nomenclature

a_1 = first harmonic longitudinal flapping coefficient
b_1 = first harmonic lateral flapping coefficient
D_E = rotor equivalent drag
hp = horsepower
L = lift
$M_{(1.0,90.)}$ = advancing blade tip Mach number
q = dynamic pressure
R = rotor radius
V = forward speed
V_L = local velocity
α_c = control axis angle of attack
$\theta_{0.75R}$ = collective pitch at 0.75 radius
ψ = azimuth position
ω = frequency
Ω = rotor angular velocity
ΩR = rotor tip speed

Introduction

STUDIES have shown the compound helicopter to be capable of achieving a speed of 250 knots or more, while retaining many of the low-speed advantages of the pure helicopter over high disk loading VTOL's. Among the advantages are low downwash velocity, low noise level, good low-speed handling qualities, and inherent safety in the event of total power failure. Several studies[1–6] investigated rotor behavior at high forward speeds but were restricted to aerodynamic considerations only. Earlier studies that considered the rotor's aeroelastic characteristics[7, 8] contained restricting aerodynamic assumptions.

Recently, theoretical techniques have been developed by Sikorsky Aircraft and United Aircraft Research Laboratories to account simultaneously for the aerodynamic and elastic characteristics of a rotor blade, without placing restrictions on tip speed, forward speed, or blade design characteristics. These techniques were used to study some of the design and operation problems of a single-rotor compound helicopter at a forward speed of 250 knots.

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Review of Rotor Aerodynamics

Prior to the discussion of coupled rotor aerodynamics and aeroelasticity, some of the aerodynamic considerations of a rotor will be briefly reviewed. The probable variation of rotor tip speed with forward speed is shown in Fig. 1, in which a limiting advancing tip Mach number of 0.9 has been assumed. It is useful to divide rotary winged machines into the three categories shown on the figure: moderate-performance helicopters, high-performance helicopters, and high-performance compound helicopters. Each type of machine has different rotor problems, which one can understand by looking at the rotor environment in each speed range.

The rotor environment for a typical moderate-performance helicopter is shown in Fig. 2. The forward speed is 100 knots with a tip speed of 400 knots (675 fps) giving an advance ratio (ratio of forward speed to tip speed) of 0.25. The shaded circle is the reversed velocity region where the flow is from trailing edge to leading edge. The dashed line is the distribu-

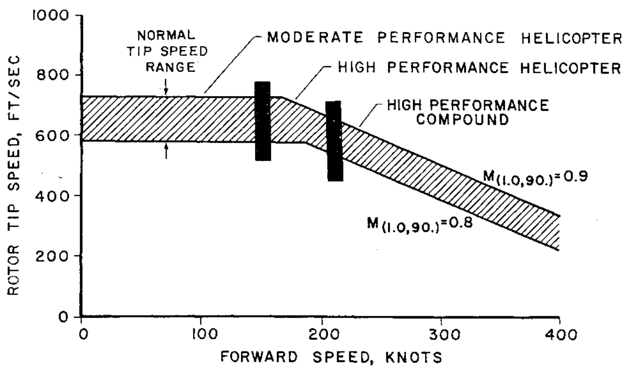

Fig. 1 Projected rotor tip speed range.

tion of dynamic pressure for blade positions of 90° and 270° azimuth (zero azimuth at aircraft tail). It is immediately evident that there is a lopsided dynamic pressure distribution where q at the retreating tip ($\psi = 270°$) is one-third that of the advancing tip ($\psi = 90°$). Since a helicopter rotor, even with an offset flapping hinge, can support only a small rolling moment, the lift on both sides of the disk must be essentially balanced. Therefore, the retreating blade must operate at higher angles of attack than the advancing blade to produce the same lift. If the angle of attack on the retreating blade becomes too high, the blade will stall. Thus, if sufficient power is available, stall will be the limiting factor in rotor operation. In the speed range from 0–150 knots it is relatively easy to design a rotor that will provide the desired combination of lift and propulsive force, and blades can be designed for loadings of around 100 psf.

As forward speed is increased to the high-performance pure helicopter range, the environment of the rotor becomes quite different. At 200 knots (Fig. 3), the dynamic pressure at the advancing tip is almost 10 times that of the retreating blade tip, and allowable blade loading has been reduced to about 40 to 50 psf. Even more serious than the loss of lifting ability of the rotor is its limited propulsive force capability. Studies[1, 2] have pointed out that a rotor's propulsive force capability disappears entirely at high forward speeds. Although the maximum speed for zero propulsive force can be in excess of 200 knots for conventional rotor systems, the practical limit is obviously not that high. The practical limit can be defined as the maximum speed at which the rotor can produce a sufficient propulsive force to overcome fuselage parasite drag simultaneously with the generation of enough lift to provide an economically useful payload. The 200-knot flight

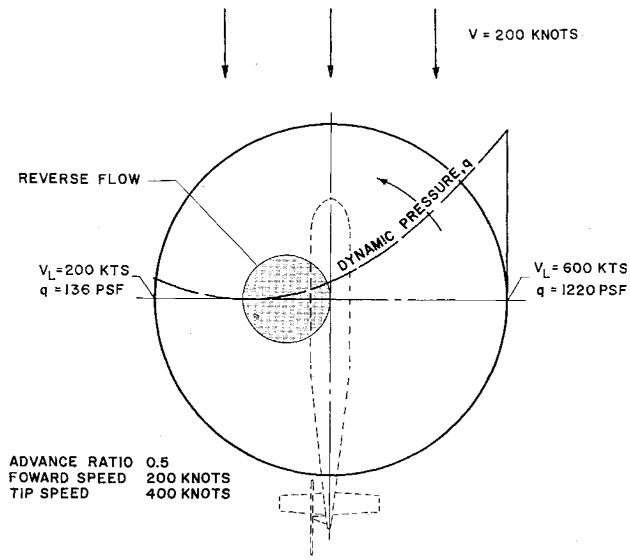

Fig. 3 Rotor environment, V = 200 knots.

condition shown in Fig. 3 is close to the maximum speed that can be expected of a pure helicopter based upon current design concepts.

As forward speed is increased to 300 knots, as in Fig. 4, the tip speed must be reduced to 300 knots in order not to exceed the assumed limiting Mach number of 0.9 on the advancing blade. The result is that the advance ratio is now 1.0, the reverse velocity region at $\psi = 270°$ extends from the center of rotation to the tip, and q at the retreating tip is zero. Under these conditions the rotor lifting ability is greatly restricted, and the rotor can no longer produce any propulsive force. Thus, a wing and propellers are added to produce the required lift and propulsive force. It then becomes advantageous to reduce the tip speed as much as possible to minimize rotor forces. For aerodynamic efficiency, the advancing tip Mach number should be reduced to about 0.8, which will further increase the advance ratio. Some of the difficulties then encountered at high forward speed and the resulting high advance ratios, other than loss of lifting and propulsive force capability, are high blade vibratory stresses, rotor control, flapping response to gusts, and flutter problems in the reverse velocity region. To investigate these problems, theoretical techniques are required which couple the aerodynamic environment and the elastic characteristics of a rotor blade.

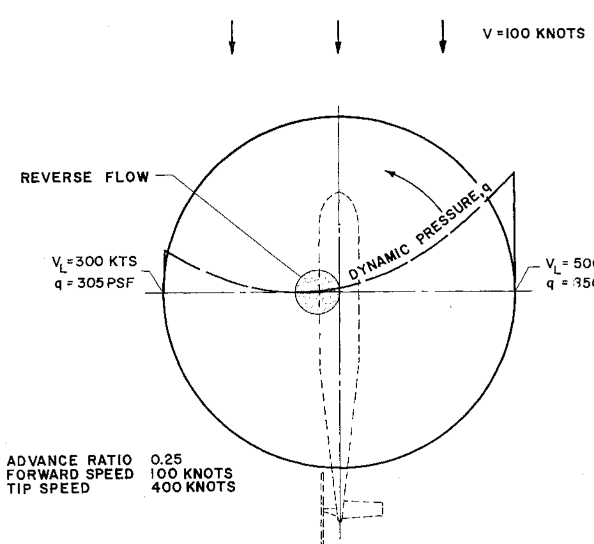

Fig. 2 Rotor environment, V = 100 knots.

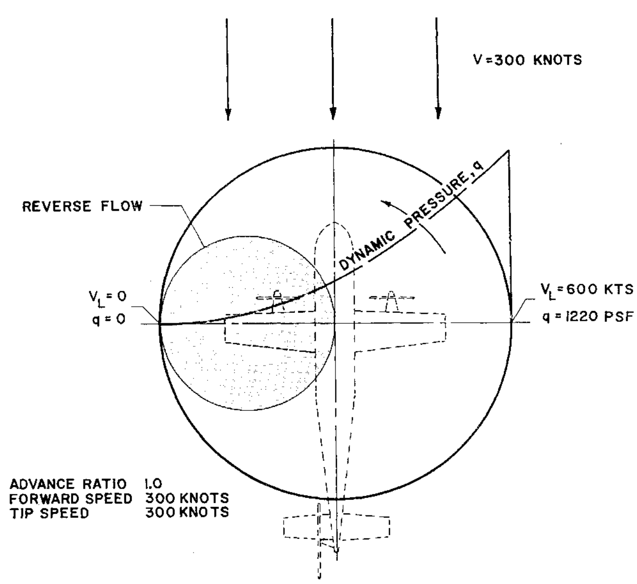

Fig. 4 Rotor environment, V = 300 knots.

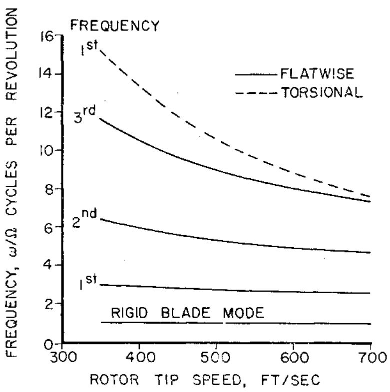

Fig. 5 Blade frequency characteristics.

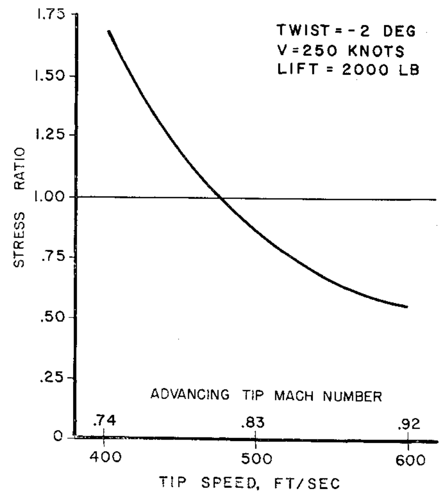

Fig. 7 Blade vibratory stress vs tip speed.

Theoretical Techniques

Two computing techniques using an IBM 7090 have yielded the results presented here. The first method mathematically represents a flexible blade by rigid segments connected by springs and hinges to correspond to the actual mass and stiffness distribution. The calculation proceeds from an arbitrary starting point, and the time history of the blade motion is calculated for a number of revolutions until the blade reaches an equilibrium pattern. Equilibrium is defined as the condition at which the blade segment angular velocities and positions repeat for successive revolutions within a specified small tolerance.

The aerodynamic portion of this calculation includes stall and Mach number effects by using experimental airfoil data, and it contains no small-angle assumptions. Since the angle-of-attack distribution includes the components due to blade bending, the changes in blade loading due to flexibility are automatically included. Aerodynamic damping of the bending vibration is inherent in the calculation, and no additional damping factors are required. An earlier study[9] further describes this method, which considers only flatwise flexibility for a blade of six bending segments and 12 aerodynamic segments. Although this is not the most refined analytical tool for this purpose, the calculations are rapid, inexpensive, and convenient to use. It provides a reliable first approximation for cases where flatwise flexibility is the major contributing factor to blade dynamic behavior.

The second method of calculation[10] couples the refined aerodynamic analysis used in the first technique with flatwise and torsional bending using a normal mode approach. This technique has the capability of using six flatwise and three torsional modes. The normal mode program was used to investigate reverse flow flutter, and all results using the first method were spot checked to insure that flatwise flexibility was the major contributing factor to blade dynamic behavior.

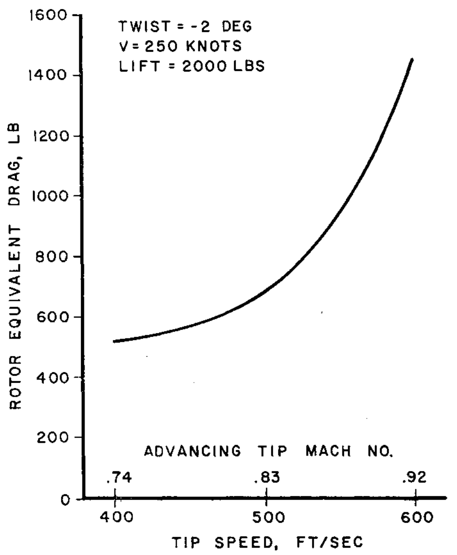

Fig. 6 Rotor equivalent drag vs tip speed.

Results and Discussion

The rotor system used in this analysis was of typical Sikorsky design, fully articulated, with the flapping hinge offset radially from the shaft. This rotor was designed for the 15,000- to 20,000-lb gross weight aircraft and had the following characteristics: radius, 28 ft; chord, 18.25 in.; number of blades, 5; and airfoil section, NACA 0012. The frequency characteristics of this blade are shown in Fig. 5. All calculations were made at sea level standard conditions, and a constant inflow distribution was assumed.

An earlier study[1] suggested a tip speed of 400 fps for good aerodynamic efficiency at 250–300 knots. Figure 6 presents rotor equivalent drag vs tip speed for a twist and rotor lift later to be shown typical for a 250-knot compound helicopter. Rotor equivalent drag is the actual rotor drag (negative when a propulsive force is produced) plus the force equivalent of the rotor shaft horsepower:

$$D \text{ equivalent} = D \text{ rotor} + \frac{550 \text{ hp rotor}}{V \text{ fps}}$$

Rotor equivalent drag represents a true measure of the aerodynamic penalty paid by the aircraft for having a rotor when it is not required to sustain flight. It is apparent from Fig. 6, for the condition specified, that rotor equivalent drag at 600-fps tip speed is three times that at 400-fps tip speed due to the reduced profile losses and compressibility effects at 400 fps. Thus, it must be concluded that the potential performance benefits resulting from a reduced tip speed with a lightly loaded rotor are considerable at 250 knots.

However, only the aerodynamic part of the story is shown in Fig. 6. Figure 7 shows the ratio of blade vibratory stress to an assumed acceptable design stress level (which will hereafter be termed stress ratio). Here it is apparent that the 400-fps tip speed desired for good aerodynamic efficiency results in a blade stress almost 1.75 times the acceptable level. The assumed acceptable stress level was determined from blade life and reliability considerations and, as a rule of thumb, if this level is exceeded by 10%, blade life will be reduced by a factor of 10 for the same reliability level.

Other values of lift and twist were investigated in addition to those presented in Figs. 6 and 7. It was determined that a tip speed of 500 fps represented a good compromise between stress and performance considerations, and this tip speed was used for the remainder of the study.

Figures 8–12 present graphs of the stress ratio, rotor horsepower, and equivalent drag at 250 knots as a function of control-axis angle of attack and rotor lift for twists from $-6°$ to $+2°$ in 2° increments for a fully articulated rotor with no pitch-flap coupling. Stall limits, as defined by the drag torque criterion,[1] are also indicated. A number of important conclusions can be drawn from examination of these figures.

Figure 8 presents the results calculated for a blade of $-6°$ twist and shows the blade vibratory stress level (lower part of figure) to be unacceptably high throughout the angle of attack range at zero rotor lift. For positive rotor lifts the vibratory stress would be still higher. Only in the large negative angle-of-attack range does the vibratory stress approach an acceptable level at which, from the upper curve, it can be seen that the rotor equivalent drag is extremely high. Thus, the $-6°$ twist rotor is not well suited for operation at a flight speed of 250 knots. It should also be noted that the rotor shaft horsepower throughout the unstalled operating range is on the order of 100 to 150 horsepower, and autorotation (zero rotor horsepower) is not possible under these conditions.

Results obtained for a $-4°$ twist are shown in Fig. 9 for rotor lifts of zero and 2000 lb. The vibratory stress levels have been substantially reduced from the previous case but are still too high near the angle of attack for best performance, about $+2.5°$ angle of attack. Also, as for the $-6°$ twist blade, rotor shaft power is on the order of a few hundred horsepower throughout the entire unstalled operating range for both lifts; thus, autorotation is again not possible at these conditions.

For a $-2°$ twist, Fig. 10 shows that the vibratory stresses at low lifts are below the assumed limit. Furthermore, the angle for minimum equivalent drag is now below the acceptable stress level, making operation of the rotor at 250 knots both aerodynamically efficient and within limits of vibratory stress.

The minimum equivalent drag for all conditions investigated was on the order of 600 lb, corresponding to an over-all power penalty of about 460 hp. The increased drag for a 4000-lb lift was only about 60 lb greater than for a rotor lift of zero. Therefore, for best performance the rotor should carry positive lift rather than be completely unloaded by the wing. However, at $-2°$ of twist, the vibratory stress at 4000-lb lift is excessive. It should be noted that, although autorotation is possible at 4000 lb of lift at about 9° angle of attack, it is poor from both a vibratory stress and performance standpoint. A good operating condition for this rotor appears to be a low lift (2000 lb) at approximately zero angle of attack with a collective pitch of about zero degrees.

For an untwisted blade (Fig. 11), it is possible to get an extremely low stress at zero lift and zero angle of attack, as would be expected for a 0° twist blade. Otherwise the results are qualitatively similar to the $-2°$ twist.

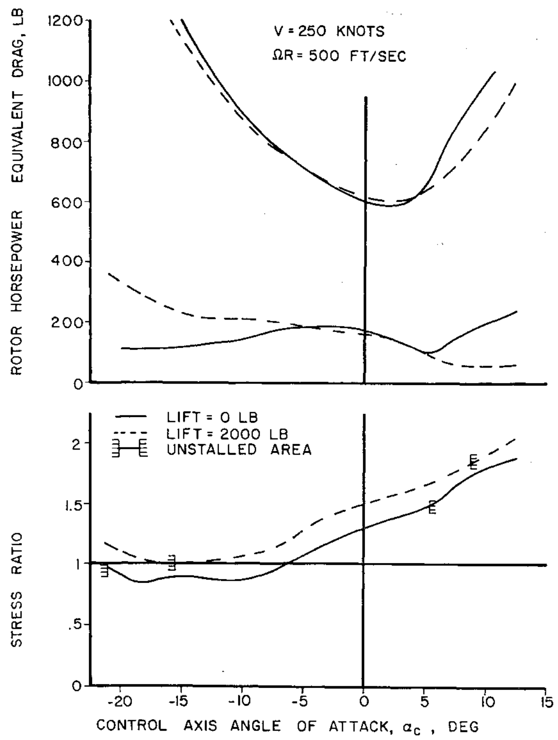

Fig. 9 Characteristics of rotor with $-4°$ twist blades.

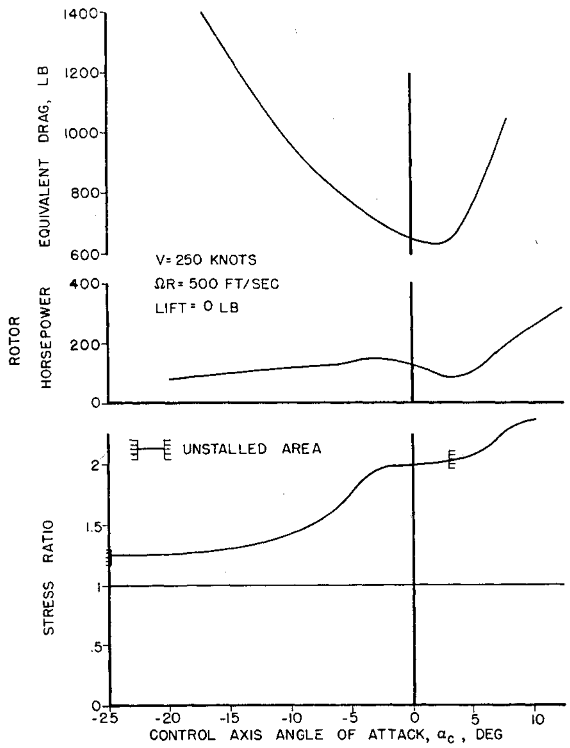

Fig. 8 Characteristics of rotor with $-6°$ twist blades.

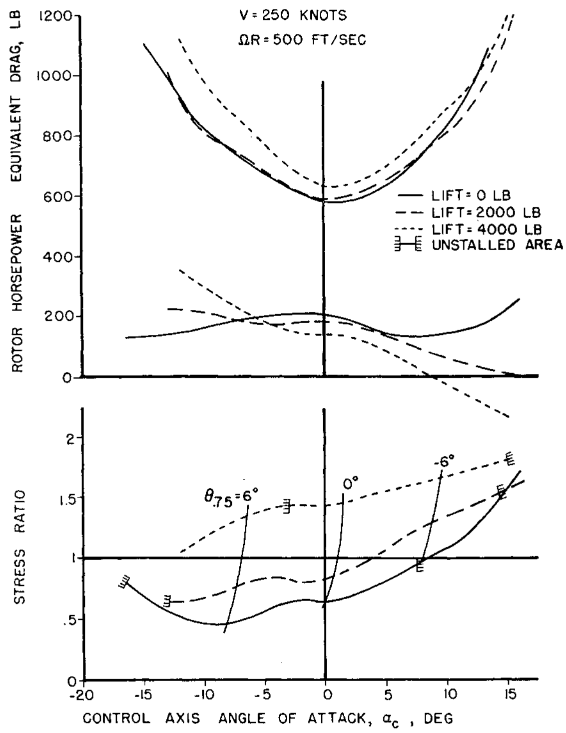

Fig. 10 Characteristics of rotor with $-2°$ twist blades.

For a positive twist of +2° (Fig. 12), it is possible to autorotate the rotor at either 2000-or 4000-lb lift with a vibratory stress slightly in excess of the assumed limit. However, as shown in this figure, a performance penalty would be paid at 250 knots relative to operation with some power to the rotor, and of course the hovering and low-speed performance is severely compromised by a positive twist. Presumably, with greater positive twist, it would be possible to autorotate at 250 knots without exceeding the stress limit at the cost of still greater low-speed performance penalties. It appears that a compound helicopter design requiring a rotor autorotating at high speeds will have to pay a severe low-speed performance penalty, unless blade construction techniques other than those used in this paper can eliminate the problem of excessive vibratory stresses.

From this analysis, it appears that a twist of about −2° would represent an acceptable design value for 250-knot operation for this rotor system. A negative twist is desirable for hovering and low-speed performance, and −2° represents about the highest value that can be used without incurring stress or performance difficulties at the high-speed condition.

Additional significant parameters are presented for a blade with −2° twist in Figs. 13–15 for rotor lifts of 0, 2000, and 4000 lb, respectively. These parameters are the harmonics of vertical shear force at the blade root, and the longitudinal

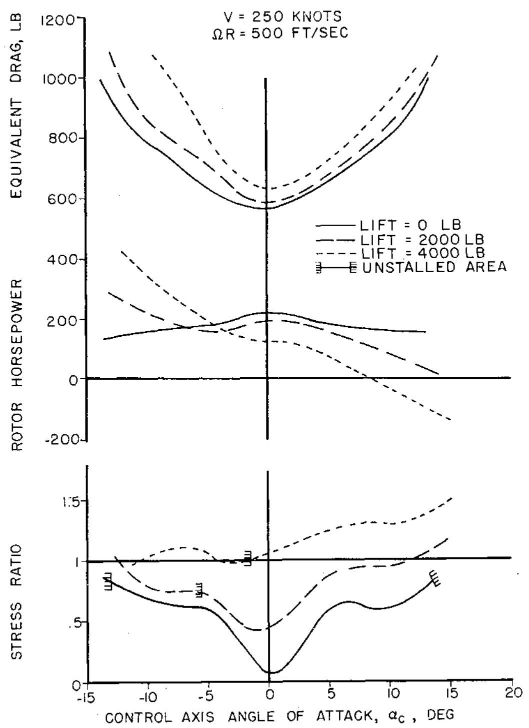

Fig. 11 Characteristics of rotor with 0° twist blades.

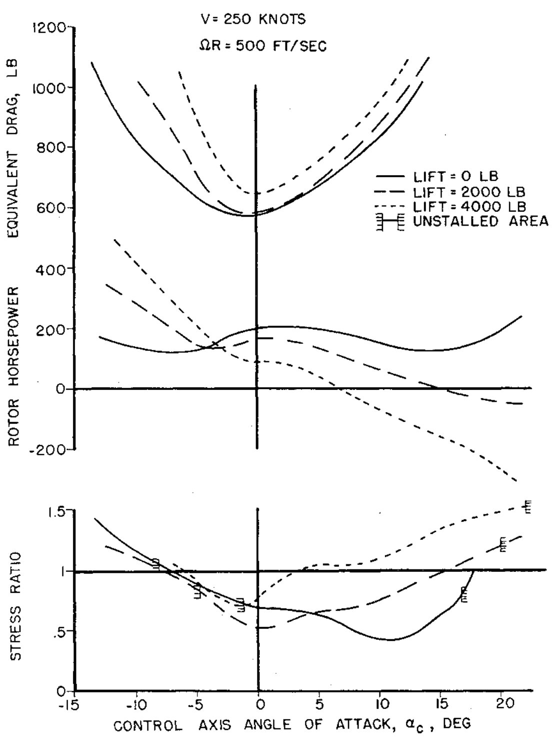

Fig. 12 Characteristics of rotor with 2° twist blades.

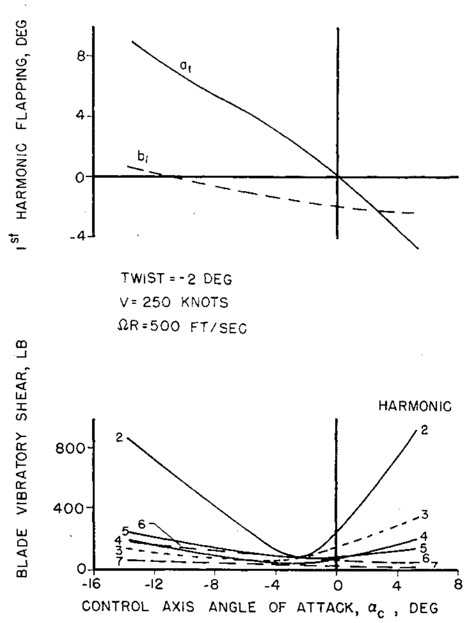

Fig. 13 Flapping and vibratory shears for zero lift.

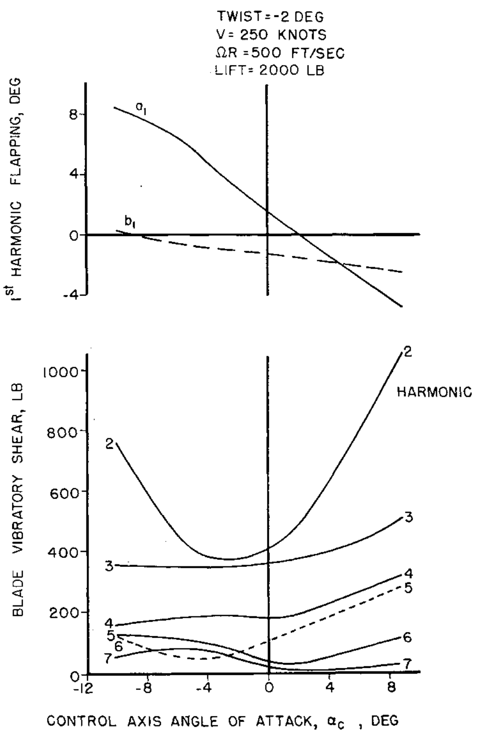

Fig. 14 Flapping and vibratory shears for 2000-lb lift.

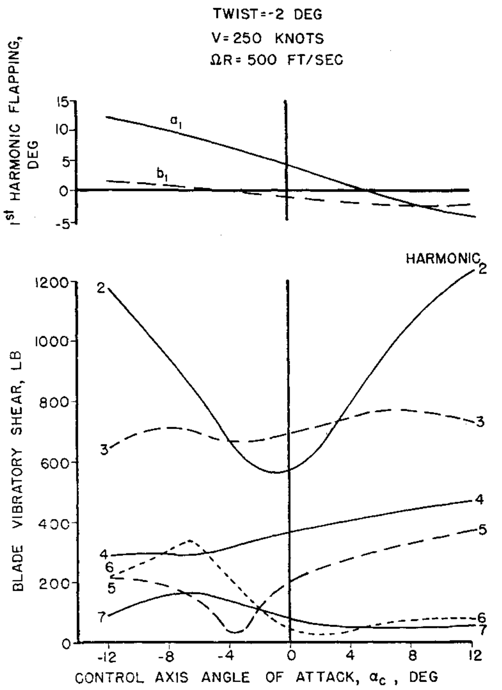

Fig. 15 Flapping and vibratory shears for 4000-lb lift.

and lateral flapping angles, a_1 and b_1, presented as a function of control-axis angle of attack. These data correspond to the data shown in Fig. 10 at the same operating conditions of 250 knots forward speed and a 500 fps tip speed. Harmonics of vibratory root end shear presented include the second through the seventh. First harmonic shear is not included because it is a function of first harmonic flapping with respect to the shaft, which is a function of aircraft trim and not considered in this study. Higher harmonics are relatively insensitive to trim. For the five-bladed rotor assumed, the fourth, fifth, and sixth harmonics are of primary significance.

Examination of Figs. 13–15 indicates that the vertical vibratory shears, which affect the vibration characteristics of the entire aircraft, increase as rotor lift is increased. Minimum vibratory shears for all lifts occur at angles of attack near zero. Thus, a low lift and low angle of attack are indicated for low vibration. For this rotor these values are compatible with the requirements of low vibratory stresses and minimum equivalent drag, as indicated by Fig. 10. As may be seen in Figs. 13–15, these operating conditions also correspond to low flapping relative to the control axis.

Figure 16 presents the tip path plane tilt (sum of control-axis angle of attack and longitudinal flapping angle a_1) corresponding to Figs. 13–15. It can be seen that by having power available (as opposed to an autorotating rotor), the tip path plane orientation can be controlled to either forward or rearward tilts by selection of rotor angle of attack and collective pitch.

Figure 17 shows the variation of stress and rotor performance with forward speeds ranging from 200 to 300 knots. The rotor selected has a blade twist of $-2°$ and is operated at a tip speed of 500 fps and a collective pitch of zero throughout the speed range. Lift is controlled by selection of control axis angle of attack. It may be seen from this chart that with a lift equal to zero this configuration is capable of speeds up to 300 knots without exceeding the assumed stress limit. With a lift of 2000 lb the corresponding speed is 265 knots.

Figure 17 also illustrates that, whereas the blade vibratory stress is quite sensitive to increase in rotor lift, the horsepower and equivalent drag are not greatly affected by lift. Rotor horsepower increases slightly with forward speed for the assumed operating conditions, and rotor equivalent drag increases considerably. This drag increase is due primarily to

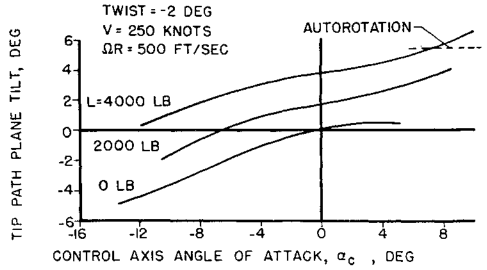

Fig. 16 Tip path plane orientation.

the increase in dynamic pressure which amounts to approximately 300 psf at 300 knots at sea level. The rotor equivalent parasite area D_E/q varies by less than 1 ft^2 between 200 and 300 knots. Even at 300 knots the equivalent parasite area is only 3.5 ft^2 (not including rotor head drag). This is a relatively small fraction of the total parasite drag for this size aircraft.

Thus far, only steady-state operating conditions have been discussed, and under this condition a $-2°$ twist blade with a conventional flapping hinge operating at a low lift was found acceptable with respect to both aerodynamic and elastic considerations. However, Fig. 18 presents another aspect. Here the response of the rotor to a 30-fps sharp-edge up-gust is shown. The lower portion of the figure shows the blade stress time history, and the upper portion the tip-motion time history for four successive revolutions. The first revolution (0–1) shows the steady-state vibratory stress to be within the acceptable level and the tip motion to be small as expected. At the end of the first revolution the rotor suddenly encounters a 30 fps sharp-edge up-gust. In the second revolution (1–2) the resultant stress increases to over three times the acceptable level and the tip motion to over 9 ft. The tip motion is made up of both blade flapping and elastic deformation of the blade. It should also be noted that the lift has increased by a factor of about 7. After the second revolution the blade vibratory stress, tip deflection, and lift decrease somewhat as shown but, of course, are still far from

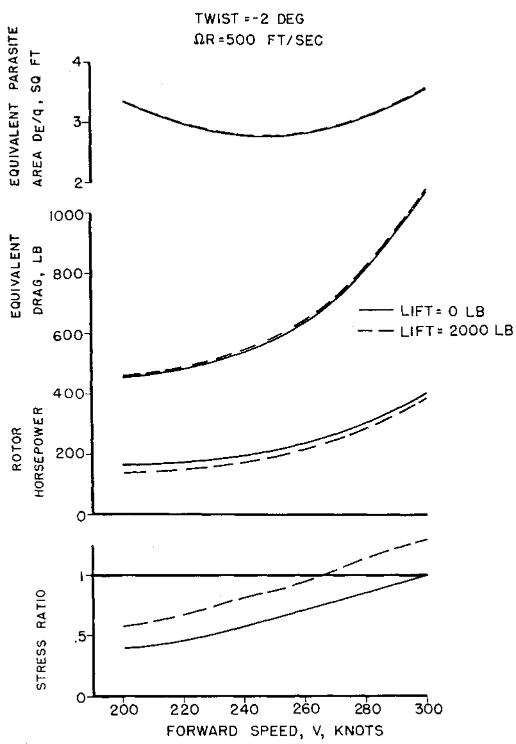

Fig. 17 Effect of forward speed on stress and performance.

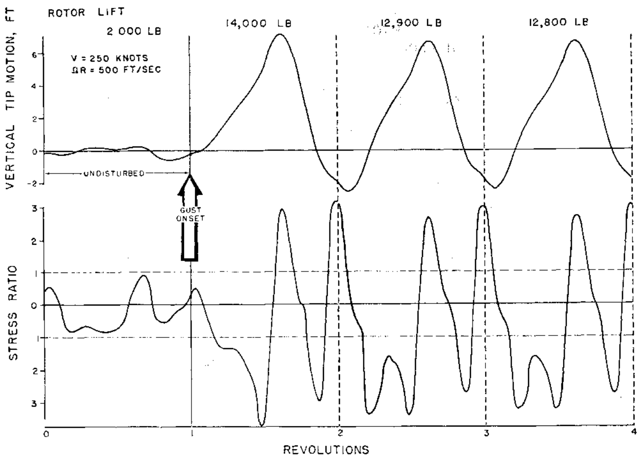

Fig. 18 Response to 30 fps up-gust, zero pitch-flap coupling.

acceptable. These very high stress levels are completely unacceptable, but even if they could be tolerated in a transient condition, both rotor/wing and rotor/fuselage clearance problems would result, and stability and control problems due to the large change in rotor forces could be serious.

One device that has been used to decrease rotor sensitivity to angle-of-attack changes is the "delta-three" hinge to provide pitch-flap coupling. Figure 19 shows the effect of pitch-flap coupling on blade stress for both steady-state and a 30-fps up-gust, as given in the previous figure. The negative pitch-flap coupling ratio signifies that as the blade flaps up, the pitch is reduced by the ratio shown on the figure.

Two important conclusions can be derived from Fig. 19. First, a pitch-flap coupling ratio of about −2 reduces the vibratory stress to an acceptable level for a transient condition when the rotor is subjected to the gust. Second, negative pitch-flap coupling of up to −2.25 has almost no effect on the steady-state stresses.

The response of the rotor to a 30-fps up-gust with a −2 pitch-flap coupling ratio is given in Fig. 20. The stress has been reduced to a tolerable point for a transient condition, and the tip motion has been reduced to about 3 ft which should not create any interference problems. The increment in rotor lift has been reduced to about 3000 lb from 12,000 lb for the previous case with zero pitch-flap coupling.

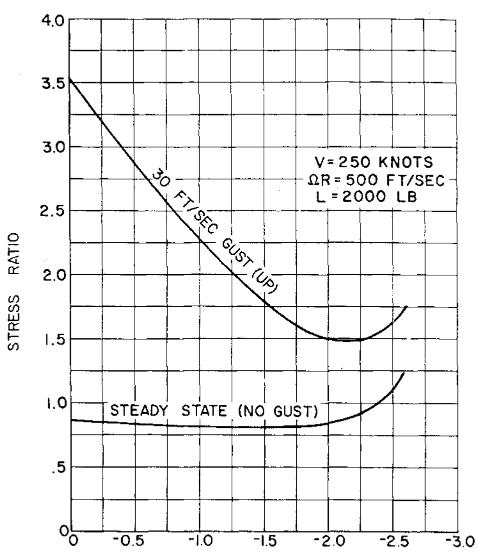

Fig. 19 Effect of pitch-flap coupling on blade response to gust.

The possibilities of either blade flapping instability or torsional divergence with and without pitch-flap coupling were also investigated at a speed of 330 knots, which is 10% in excess of the highest speed of Fig. 17, and 32% in excess of the assumed design cruise speed at 250 knots. The calculation showed that the rotor was stable both in flapping and torsion with and without a delta-three hinge. These conclusions are in agreement with experimental results.[10] Also, the rotor response to a 30-fps sharp-edge up-gust was checked at 330 knots, and a pitch-flap coupling of −2 was again found effective in controlling both stress rise and tip motion. However, as might be expected from the results of Fig. 17, the steady-state stress prior to gust onset exceeded the acceptable level.

Since the rotor has been found to be controllable both in steady-state and transient flight conditions at 330 knots, it seems safe to assume that there should be no flapping instability or torsional divergence problems up to a design maximum speed of 300 knots. With a pitch-flap coupling of −2, no serious gust response problems are expected.

However, it must also be realized that pitch-flap coupling will also significantly influence other rotor characteristics. Changes in the linkage ratios between control sticks and rotor head, as well as increased blade feathering motion ranges, would undoubtedly be required to compensate for the reduced lift of the rotor per degree of collective or cyclic pitch which is inherent with pitch-flap coupling. Whether such changes can be achieved satisfactorily has not been considered in this paper.

An earlier study[11] suggested that blade stresses could be reduced at 150 knots for a pure helicopter by the addition of tip weights for blades of moderate twist. If the addition of tip weights could significantly reduce vibratory stresses at 250 knots, as was shown at the lower speed, possibly a greater negative twist than −2° could be used. Increased negative twist would naturally benefit rotor hovering performance. A typical study of the use of tip weights is presented in Fig. 21, which shows that the larger the negative twist, the more effective a given tip weight is at reducing the vibratory stress. For a 0° twist blade, there is virtually no stress reduction with the addition of tip weights. From this figure it can be seen that a −6° twist blade with about a 30-lb tip weight, and a −4° twist blade with about a 15-lb tip weight, would have acceptable vibratory stresses at 250 knots. For the rotor considered, with a thrust between 15,000 and 20,000 lb, each degree of negative twist increases the hovering lift about 100 lb at a constant rotor horsepower. Therefore, a blade of −6° of twist would increase the rotor hovering lift 400 lb over a rotor with −2° of twist. However, 150 lb of weight would have to be added to the blades to reduce the stresses to an acceptable level. Whether there would be any net payload advantage would depend on the magnitude of weight growth of other aircraft components.

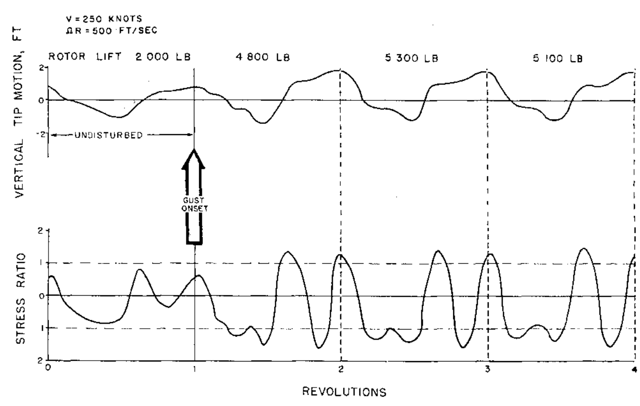

Fig. 20 Response to 30 fps up-gust, pitch-flap coupling −2.0.

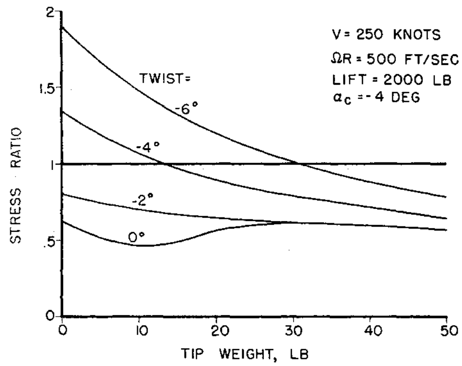

Fig. 21 Effect of tip weight on blade vibratory stress.

An interesting side note to this study is that the first bending mode natural frequency varied from 2.75 cycles per revolution for zero tip weight to 3.2 cycles per revolution with a tip weight of 50 lb. With a 32-lb tip weight, the blade was in a 3/revolution resonance condition, and, as seen in Fig. 21, there was no increase in vibratory stress. In fact, it was found that even the amount of third harmonic vibratory stress did not change significantly through this resonance point. This result was found with both computing techniques. An investigation of this phenomenon is currently under way.

Conclusions

It is possible to operate a conventional helicopter rotor at speeds as high as 300 knots in the compound helicopter regime with satisfactory performance and vibratory blade stresses, provided that blade twist, operating conditions, and control system geometry are carefully selected. This study revealed the following items.

1) Tip speed should be on the order of 500 fps. This is a satisfactory compromise between lower values, which would benefit performance, and higher values, which would benefit vibratory stress.

2) A low value of blade twist is required to achieve satisfactory blade stresses simultaneously with low rotor equivalent drag. A twist of $-2°$ is about the largest allowable negative twist for the rotor considered.

3) A low value of rotor lift is required to avoid excessive vibratory stresses. For the rotor considered in the study, corresponding to a 15,000- to 20,000-lb aircraft, rotor lift should be on the order of 0–2000 lb.

4) Autorotation of the rotor is not possible without exceeding vibratory stress limits. Indications are that a positive twist greater than $+2°$ might allow autorotation without exceeding stress limits, but this would involve serious performance penalties in hovering and low-speed flight, as well as a penalty in high-speed flight. Optimum rotor operating conditions at high speed, from both stress and performance standpoints, correspond to the use of a few hundred horsepower.

5) Control-axis angle of attack should be approximately zero. Tip-path plane angle of attack will also be approximately zero, although moderate forward or rearward rotor tilts can be achieved by moderate variations in pitch and angle-of-attack setting. This capability may be very beneficial in providing adequate clearance between rotor and fuselage tail cone.

6) Blade-root vertical vibratory shear forces are minimized at the same operating conditions that provide satisfactory vibratory stresses.

7) A pitch-flap coupling ratio of about -2 is highly desirable in order to reduce the high vibratory stresses and tip deflections resulting from a gust encounter. However, the influence of this ratio on other rotor characteristics should be evaluated.

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