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Wing-Rotor Interactions

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The use of a wing to unload the helicopter rotor is discussed for the cases with and without auxiliary propulsion. Data are presented from the flight test of five wing-rotor combinations showing the effects of the wing on the performance, stability and control, structural loads, and maneuver characteristics of the machines. The major problem areas associated with winged helicopter operation, i.e., rotor speed and roll control during autorotation and autorotation entry, are described and defined analytically. Means of minimizing these effects are noted. It is concluded that the use of a wing is advantageous for rotorcraft with a maximum speed above approximately 140 knots. Design considerations and a guide to wing size selection are given.

During flight tests of the Pitcairn Autogiro in the early 1930's,[1,2] it was found that at about 140 mph the rotor speed decreased to a dangerously low value. A restrictive limit was imposed on the machine's diving speed, and flight at higher airspeeds was considered hazardous. The problem was encountered when the wing carried about 30% of the gross weight of the aircraft; this condition was believed to be the cause of the unacceptable decrease in rotor speed.

Although the trend in autogiro design at that time was toward the elimination of the fixed wing, it was believed by NACA that, for larger-size machines especially, a fixed wing would find use to support the landing gear and to increase the the over-all efficiency of the vehicle. Consequently, a flight-test program was undertaken to define the effects of wing lift on the characteristics of that aircraft. The results of these tests, as reported in Ref. 3, show that by lowering the wing incidence the diving speed restriction of the autogiro could be extended from 140 to 180 mph. Also, it was shown that the interference of the wing on the rotor was negligible insofar as thrust and lift coefficients were concerned. Thus, the first flight-test investigation of wing-rotor interactions was concluded.

The possibilities and problems relating to the use of a rotor and wing in combination lay dormant through the 1940's, as the helicopter had come into existence and the use of a wing with these early low-performance machines provided no advantage. In the mid-1950's, wings were again used on several compound helicopters and convertiplanes (e.g., XV-1, XV-3, and Fairey Rotodyne). The reason, of course, was to provide a more efficient high-speed lifting system. A search through available literature shows no major difficulties relating to wing-rotor interactions; however, based on later experience, it is obvious that these machines were not tested sufficiently in autorotation to define their problems.

In the late 1950's, the compound helicopter was again being seriously considered by the U. S. Army and several companies. The helicopter had shown its worth as a low-speed machine and had outgrown most of the early problems that had plagued the industry. There was a definite need to extend the range, productivity, and speed of the helicopter type. This was especially true in view of the status of other V/STOL aircraft projects.

In early 1960, Bell Helicopter Company (BHC) initiated an investigation of wing-rotor interactions, with particular emphasis on the compound helicopter and tilt-rotor configurations. As in the early 1930's, these effects could not be established with certainty because of the lack of related quantitative data. Consequently, Bell set out to define these effects and to establish design guides for the use of a rotor and wing in combination. The work included analytical and model studies and flight tests of five wing-rotor combinations, ultimately encompassing a speed of over 250 mph. Figures 1a–1d illustrate the test vehicles used.

This paper reports the salient results of these investigations with respect to performance, stability and control, rotor oscillatory loads and vibration, maneuvering, and power-off flight. Additionally, over-all design considerations relating to winged rotorcraft are given.

Performance

Bell investigations of wing-rotor combinations have shown that 1) with a wing, significant lifting system efficiency gains can be obtained above a speed of about 120 knots; 2) some amount of rotor unloading is desirable above speeds of 140 to 180 knots (depending on aircraft size); 3) above speeds of 200 to 220 knots, for efficient operation, it is mandatory to unload the rotor and to use auxiliary propulsion; 4) by the proper choice of parameters, a wing will improve a high-speed rotorcraft's hovering performance; and 5) a wing will lower the maximum rate of climb of a high-performance rotorcraft unless provisions are made to reduce wing download during the climb. Furthermore, it has been shown that these effects are calculable using state-of-the-art techniques.

Hovering

In hovering, the rotor flow on the wing creates a download that increases the required hovering power. This effect is

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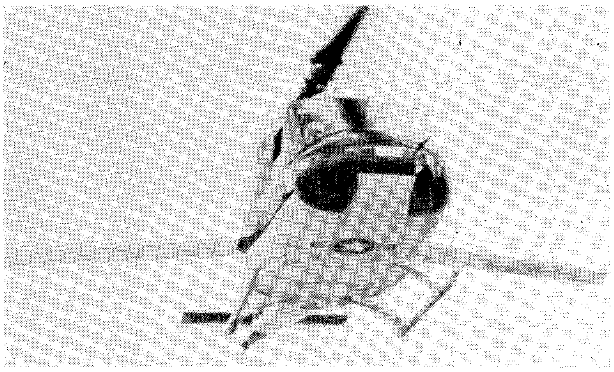
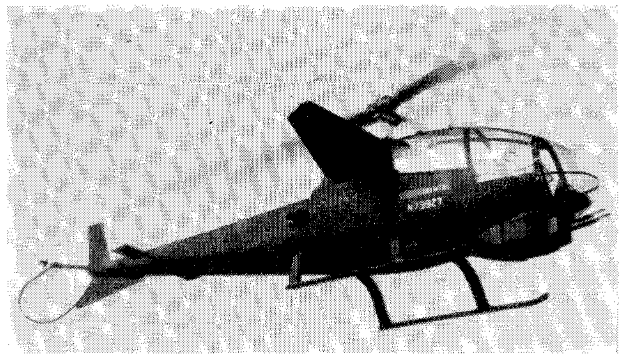
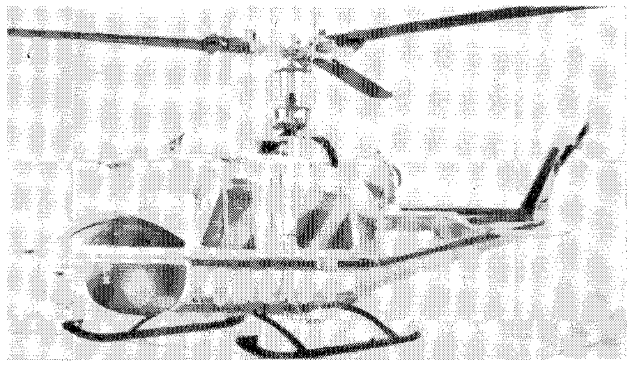


a) **High-performance helicopter with wing**

b) **BHC model 548 (Wing Ding)**



c) **BHC model 207 (Scout)**



d) **BHC model 204B with stub wing and experimental rotor**

Fig. 1 Test vehicles.

shown by Fig. 2, where the ratio of the induced power with and without download is plotted as a function of vertical drag area (f_v)/disk area. The relationship shown is based on simple momentum theory for out-of-ground effect. More refined treatments of hovering download are given in Refs. 4 and 5.

The hovering download effect of the wing on the U. S. Army-Bell High-Performance Helicopter (HPH, Fig. 1a) is shown on Fig. 2. The data point is estimated from flight-test measurements. In ground effect (skid height approximately 3 ft), the power difference due to wing download is negligible.

It is seen that the power increase due to wing download is quite small for the HPH. This is not the general case. Recent BHC design studies have shown that download losses become excessive for single-rotor machines that use the high disk loadings and wing areas typical of current stopped/stowed rotor configurations.

A wing can also be used indirectly to improve hovering performance. With the rotor unloaded at high speed, the blade stall threshold is extended, and this allows reduced rotor solidity and/or tip speed for increased hovering efficiency. For a typical rotor, unloading 30% can increase the stall threshold about 40 knots. If the higher speed is required and full advantage is taken of the wing, a hovering power savings of about 20% can be realized.

Forward Flight

Bell model tests conducted in 1960 confirmed the earlier NACA results[3] that in forward flight a wing has little effect on the rotor as far as lift and thrust coefficients are concerned. As expected, it was found that it is necessary to include the downwash from the rotor in the determination of the angle of attack and induced drag of the wing. With the proper allowance for this effect, combined rotor-wing performance is easily calculated.

Figure 3 shows the calculated wing angle of attack as a function of velocity for a typical winged helicopter. The effect of rotor downwash is quite obvious in the lower-speed range.

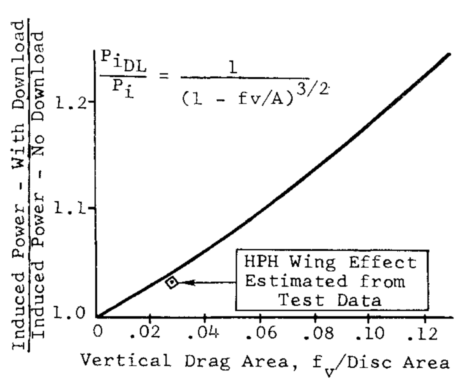


Fig. 2 Download effect on out-of-ground effect hovering power.

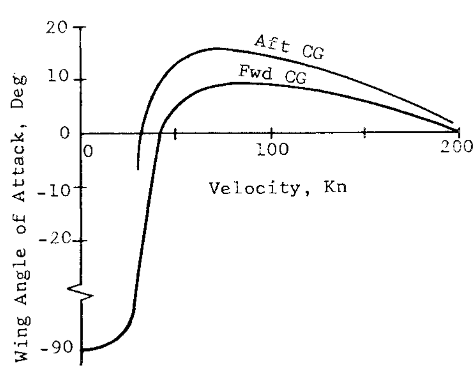


Fig. 3 Wing angle of attack vs velocity for typical winged helicopter.

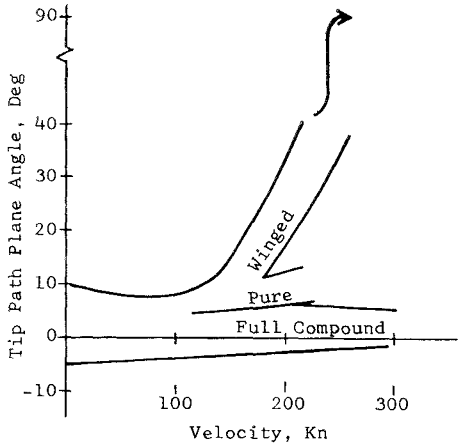


Fig. 4 Tip path plane requirements for pure, winged, and full compound helicopters.

Although a wing does not affect the rotor directly, it does have a major impact on the design of the rotor and aircraft because of its influence on the tip path plane and control angles requirements. As the speed of a pure helicopter is increased, the rotor tip path plane has to be tilted to provide the propulsive force. The required tip path plane and control angles are greatly increased for a winged helicopter as the rotor is unloaded by the wing. This can become the major factor limiting the speed of a high-powered winged helicopter. This effect is illustrated by Fig. 4, where the required tip path plane angles are shown as a function of velocity for a pure, winged, and full compound helicopter. For the winged helicopter illustrated, the tip path plane angle becomes excessive at about 175 knots.

With respect to rotor design, negative blade twist is desirable for the pure and winged helicopters because of the inflow down through the rotor disk. For the full compound, near zero blade twist is required for optimum performance.

The power reduction at high speed due to a wing is small except for high gross weight conditions where, without unloading, the rotor is partially stalled. This was demonstrated by flights with the HPH and Wing Ding (Figs. 1a and 1b). The addition of the wing to the HPH resulted in an increase in the "rotor's" L/D by approximately 10% at 120 knots and 20% at 150 knots. With the wing, approximately the same maximum speed as that of the basic machine was obtained but at a 20% higher gross weight. Similarly, the Wing Ding was flown at about the same speed as the basic ship but at about 25% higher gross weight.

Figure 5, taken from Ref. 6, shows the effect of the 64-ft^2 wing of the HPH with and without auxiliary propulsion. For the weight noted, without auxiliary propulsion, the power savings resulting from the wing is about 100 hp at 140 knots; with jet engines producing about 1535 lb forward thrust, the power saving is 200 hp at ~175 knots. Above 160 knots as a full compound, the rotor was unloaded about 70%. In that speed range with the auxiliary propulsion (only), the rotor was unloaded about 15% because of the lift produced by the jet nacelles and pylons. Below about 90 knots, the wing degraded the performance of the aircraft slightly.

Climb

The final comment with respect to performance is that the rate of climb of a rotorcraft can be reduced by a wing. This was especially true for the HPH with auxiliary propulsion. As a full compound, the HPH has a maximum rate of climb of nearly 3000 ft/min. During high-power climb, downloads were measured on the wing which represented a loss of over 200 hp. From the standpoint of reducing download during high-power climb, as well as obtaining optimum wing-incidence during cruise flight, an efficient wing lift control would be desirable.

Stability and Control (Power-On)

With the Wing Ding, the principal effects of the wing on stability and control were the decrease in low-speed roll control power due to the added inertia of the wing, the reduction in effectiveness of the horizontal elevator due to wing downwash, and the reduction in pitch control power with speed as the wing lift increased. Roll control power was augmented by lateral cyclic-aileron coupling; therefore, in the higher-speed range, roll characteristics were comparable to the basic ship. This machine was found to be unacceptable from the standpoint of low-speed gust sensitivity. Also, control through transition was marginal because of negative wing stall effects.

The primary effects of the wing on the HPH were the improved roll stability due to wing damping, the decreased roll response due to the wing damping and the reduced rotor control power associated with high wing lift, and the decreased rotor pitch damping and control power associated with high inflow and wing lift. Rotor downwash traversing the wing during transition was noticeable but was not particularly objectionable. Rearward and sideward flights and low-speed maneuvers were executed with no difficulty. Throughout the speed envelope, the machine's gust sensitivity was found to be increased, making it more comparable to a light airplane in this regard.

In pitch, the large horizontal elevator of the HPH coupled to the cyclic longitudinal control provided excellent pitch control and damping. Elevator damping and control effectiveness increased with speed, which more than made up for the deficiences in rotor control and damping. Pitch control and stability characteristics of future winged helicopters will be satisfactory if the wing is mounted somewhat aft of the aircraft's center of gravity to avoid large unfavorable pitching moment changes with power and if a large controllable horizontal surface is used which is located well behind and above the wing.

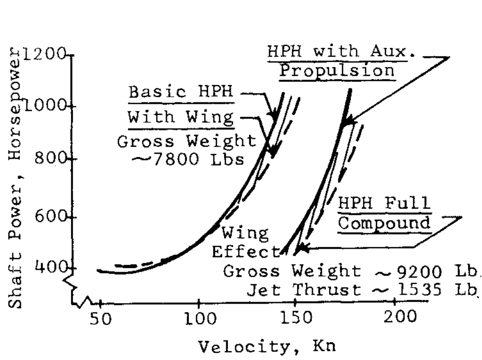


Fig. 5 Wing effect on high-speed performance.

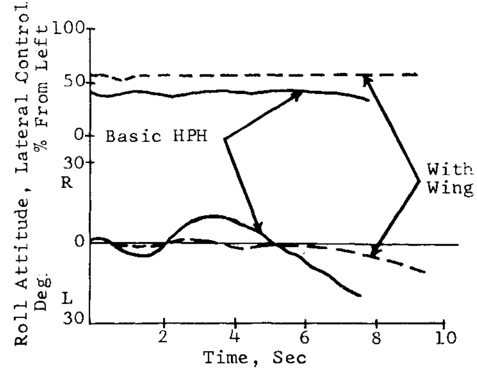


Fig. 6 Roll stability: HPH with and without wing.

During the early flights with the winged HPH, it was found that the reduction in roll sensitivity (resulting from increased inertia of the wing and lower rotor thrust) was excessive. Because of the reduced roll control power and wing damping, roll response also decreased to a marginally acceptable value. These effects had been anticipated, and the machine's control system was modified to provide differential wing incidence coupling with lateral cyclic control. Subsequent flight tests showed that this feature is quite desirable. At 160 knots, the ± 1.5 deg/wing panel for full left-right cyclic control increased the roll response by over 75% and the sensitivity about 60%. The response of the winged HPH at that speed was still lower than desired; however, the coupling value used was near the optimum for a 200-knot compound helicopter because of the increase in effectiveness of wing differential incidence at the higher speeds.

In general, the roll stability of the winged HPH was good even without the Bell gyro stabilizer. Fig. 6 illustrates the effect of the wing on the roll characteristics of the HPH at a speed of about 138 knots. The pilot was asked to make a small control input and then return the controls to neutral and hold. With the wing, this is seen to be possible, although a slow divergence to the left was encountered. Without the wing, the maneuver could not be executed because of a resulting divergent short-period oscillation.

Structural Loads and Vibrations

Qualitatively, the effect of the wings for the machines tested was to improve the ride from the standpoint of pilot comfort level. Quantitatively, the wing effects on structural loads and vibration level are given by Fig. 7 for the basic and winged HPH. It is seen that in all cases the wing is beneficial. The reduction in rotor chord oscillatory loads is especially significant. These favorable effects result from the reduced retreating blade stall and the lower advancing blade compressibility losses associated with unloaded rotor operation.

The same effects of the wing were indicated generally during the higher-speed tests with auxiliary propulsion. In the high-speed range, however, it is possible to mismatch the rotor-wing lift and the rotor-auxiliary propulsion thrust so that high rotor loads result.

Maneuvering

The wing on the HPH and even the small one on the model 207 Scout (Fig. 1c) improved the high-speed maneuver characteristics of those machines from the pilot's standpoint. With the full-compound HPH, the maneuver characteristics were investigated thoroughly, demonstrating about a 2-*g* envelope to near 200 knots. This work is reported in Ref. 7.

During the maximum load factor maneuvers of the HPH, it was found that rotor lift increased about 300% and the wing (airframe) lift 20%. This contribution of the wing is significant, however, since in level flight it carried about 70% of the gross weight of the machine. Increased longitudinal control-elevator coupling would be desirable to provide more wing lift during a maneuver; however, this approach conflicts with forward flight controllability requirements.

At the maximum load factor obtained during the maneuvers, the weight of the vehicle was nearly equally divided between the rotor and airframe. Figure 8 shows the lift distribution during a 185-knot cyclic turn maneuver. Lift contributions of the auxiliary jet engines, rotor, and airframe are shown, and their sum is compared to the center-of-gravity accelerometer flight data. Rotor lift is based on flight-measured blade beam bending moments; airframe lift is based on measured wing moments correlated with the results of small-scale wind-tunnel tests.

During the maneuver tests, it was confirmed that at very high speed a rotor cannot develop high thrust without en-

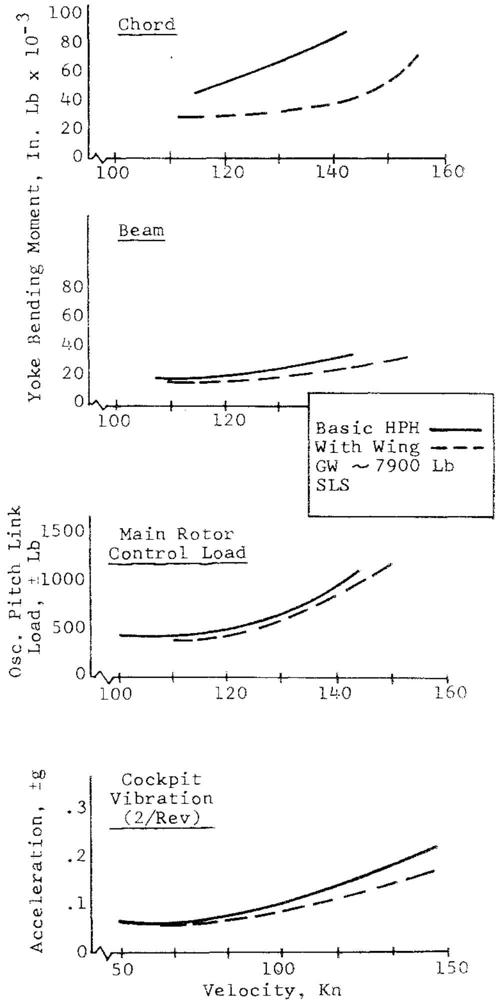


Fig. 7 Effect of wing on structural loads and vibration.

countering damaging oscillatory moments and producing high vibrations. Consequently, compound helicopters should be designed such that, during a maneuver, only a small increment in load factor is demanded of the rotor. Even more stringent, some means must be provided to restrict the rotor lift and the related high structural loads and vibrations that the rotor can develop while maneuvering.

A high-speed compound helicopter must be provided with a sufficiently large wing so that the required normal load factor can be obtained with very little contribution from the rotor. Additionally, some device such as a rotor collective

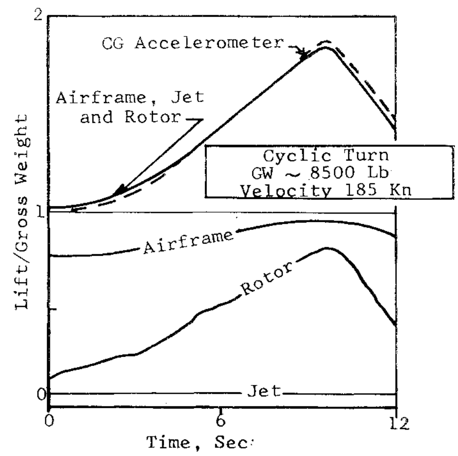


Fig. 8 Lift distribution during HPH maneuver.

pitch bob-weight, pitch-cone coupling, or a collective or cyclic control rotor speed governor should be used to provide the required rotor protection. These devices essentially increase the apparent lift curve slope of the wing in relation to that of the rotor by operating directly on the rotor. Another approach to changing the relative lift slopes is to provide a means of increasing the wing lift during a maneuver (e.g., flaps or incidence adjustment).

A "rigid" rotor is beneficial for maneuvering, as it provides strong control power throughout a wide range of rotor thrust conditions. The "rigid" rotor is less forgiving than the flapping type, however, and very severe structural loads can be encountered if no special precautions are taken to limit its thrust.

Power-Off Characteristics

During powered flight, wing-rotor interactions have been shown to be generally favorable and simple to define and optimize analytically. It is with the rotor power off, during autorotation and autorotation entry, that wing-rotor interactions can cause serious problems. The NACA work with the Pitcairn Autogiro is an example. The following paragraphs describe these unfavorable wing-rotor interactions, show their relation to various rotorcraft parameters, and discuss means of eliminating them.

Problems

Two basic problems were encountered with the winged HPH and the Wing Ding: rotor speed and roll control. These problems had been anticipated; however, their severity had not been appreciated fully. The roll and rotor speed control problems occurred both separately and together, in steady-state autorotation and during autorotation entry. As an autorotation entry was made with a normal wing setting, the rotor speed decayed, control became sluggish, and, as the rate of sink built up, severe roll disturbances from the wing required full lateral control correction.

One of the purposes of the Wing Ding was to obtain quantitative data with respect to these phenomena. Consequently, that machine was designed so that a large variation of basic parameters could be evaluated. Successful autorotation was accomplished with the Wing Ding at normal rotor speed and with a fixed wing incidence only after the maximum lift capability of the wing was reduced to less than 30% of the machine's gross weight.

Autorotation problems were not encountered with the model 207 Scout and the winged 204B (Figs. 1c and 1d). Throughout their flight envelopes, maximum wing lift/gross weight ratio for these machines never exceeded about 0.27.

The HPH had been designed with an adjustable wing incidence feature. It was expected that the pilot would be able to effect autorotation by actuating the wing incidence setting switch. This proved to be inadequate, as the electric actuator speed was too slow. The final solution for the HPH was to couple the wing incidence to the collective control with a hydraulic servo unit so that the wing incidence decreased with down collective.

Explanation and Solution: Roll Control

The roll control problem is readily explained. Upon autorotation entry, the rate of sink builds up, increasing the angle of attack and lift of the wing. For 1-g flight, the rotor lift is necessarily reduced, and, for a flapping rotor with no offset hinge or flapping restraint, the control power is reduced a like amount. As the angle of attack of the wing approaches the stall angle, one wing inevitably stalls first, creating a roll disturbance that is difficult to correct with the reduced control power available. Further disturbances are caused by the wing's wake hitting the rotor; however, it is difficult to establish the magnitude of this effect.

The roll problem was accentuated with the differential wing incidence-lateral cyclic coupling used to provide improved roll response at high speed. With that coupling, normal pilot corrective action would increase the angle of the stalled wing panel and decrease the angle of the unstalled panel, aggravating the situation.

This problem is minimized considerably by use of a "rigid" or offset flapping hinge rotor. Tests of the winged HPH with a four-bladed "rigid" rotor showed this. A word of caution is in order, however, for although the "rigid" or offset hinge rotors produce control moments at low thrust, their control power is reduced considerably, especially at low rotor speed (by as much as 50%). During the emergency conditions that exist when other than practice autorotations are made, large reductions in control power may be unacceptable.

Explanation and Solution: Rotor Speed Decay

The rotor speed decay problem is also simple in its fundamentals; however, as there are many factors involved, the explanation is more lengthy. For this, consider the steady-state autorotation case. If steady-state autorotation is possible and there are no large trim changes between level flight and autorotation, then safe autorotation entry can be effected. The conditions that have to be met during autorotation are 1) moment equilibrium, 2) horizontal force equilibrium, 3) vertical force equilibrium, and 4) energy balance. Additionally, various mechanical and other limits must be considered. These limits are rotor speed, blade stall, minimum collective pitch, longitudinal cyclic displacement from level flight trim, blade flapping, and fuselage attitude.

Energy and Force Balances and Blade Stall Limits

From the energy and force balance considerations, the equilibrium rotor angle of attack may be calculated as a function of forward speed, rotor thrust or wing lift, and rotor speed. The results of such calculations are shown by Fig. 9 for the parameters of the winged HPH at forward speeds of 100, 135, and 170 knots. Superimposed on the plots are the required rotor collective pitch angles (θ_C at $\frac{3}{4}R$) and the blade stall limits.

For the HPH, rotor speed limits are 294 and 339 rpm, and the minimum collective pitch setting results in a three-quarter radius blade pitch of approximately 0°. These limiting values are so noted on the autorotation maps of Fig. 9. For these conditions, it is seen that steady-state autorotation is possible only in the shaded areas of the plot. As speed is increased, the shaded area diminishes, and steady-state autorotation becomes impossible at some high forward speed.

It is possible to improve the situation by lowering the minimum collective pitch setting. This is not considered to be an acceptable solution of itself, although marginal situations may be improved in this manner. If the collective angle is set too low, a pilot can inadvertently overspeed the rotor severely during high-gross-weight (thrust) autorotations. Difficulties have been encountered with existing helicopters in this respect.

Moment Balance and Angle Limits

Thus far, the constraints that have been considered are the force and energy balances and the rotor speed and collective pitch limits. There remains to investigate the moment equilibrium and other constraints required for acceptable autorotation characteristics.

For this, consider steady-state autorotation at 100 knots. The equilibrium rotor speed area from Fig. 9 is shown on Fig. 10 and, additionally, superimposed are curves that represent moment equilibrium for various elevator and wing incidence settings. The principal parameters of the HPH are used; however, to simplify the calculations, the moment balance curves do not represent that machine exactly.

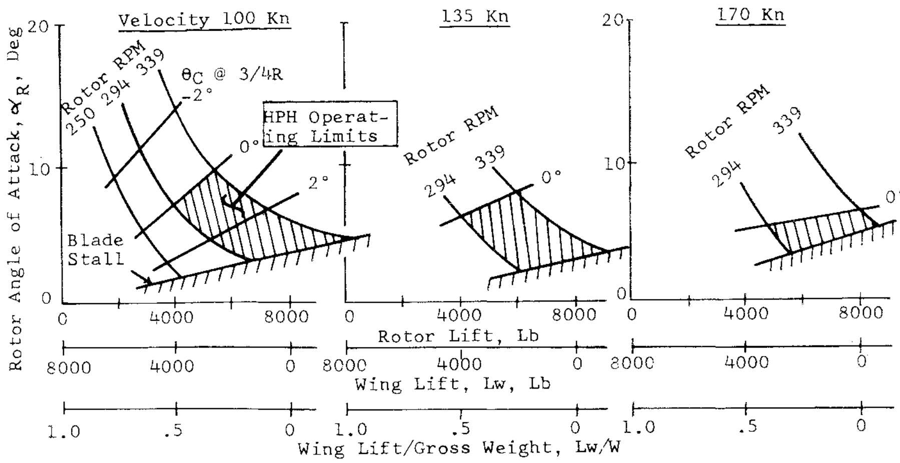


Fig. 9 Autorotation maps for HPH showing equilibrium rpm, stall, and collective pitch limits.

Control, fuselage attitude, and blade flapping angle limits are indicated on the curves. Limiting control angles are based on a ±1.5-in. control displacement from level flight trim; fuselage and flapping angle limits are assumed to be ±8° and ±10°, respectively.

From Fig. 10, it is seen that for a wing incidence setting of +10° (which is near the level flight incidence required to avoid wing download at forward center of gravity at moderate speeds) steady-state autorotation cannot be achieved at an elevator setting of 0° without exceeding the established longitudinal control limit. If a larger control shift from level flight were acceptable or if the level flight trim were changed favorably by adjusting the elevator incidence, autorotation would be possible, but only by exceeding the −8° fuselage attitude and/or the low rotor speed limits.

If, for the same wing setting, the elevator angle is increased 10° to lower the wing lift, it is seen that steady-state autorotation is possible in the lower rotor speed range, but only by exceeding the fuselage and control angle limits.

Similarly, the case for a −10° wing setting shows no autorotation capability at 0° elevator within the operating limits. When the elevator incidence is adjusted to −10° for this wing setting, satisfactory autorotation is seen to be possible throughout the full rotor speed range; however, this is at slightly negative wing lift values.

Thus, it is possible to arrive at a configuration to obtain satisfactory steady-state autorotation. In every case investigated, there have been specific values of elevator size and setting, wing incidence, center-of-gravity location, etc., where satisfactory autorotation is possible. There have been cases, however, where autorotation can be accomplished at one center-of-gravity limit but not at the other.

The approach presented here has been found to be quite useful in evaluating the effects of various parameter changes. For instance, if a propeller geared to the rotor is used, above a speed of about 100 knots, reversed thrust and a driving torque can be generated from the airstream to supply power to the rotor. The propeller can thus be used to minimize the rotor angle-of-attack requirement and also to lower the fuselage (and wing) angle, thereby reducing wing lift.

Increasing the wing area has little effect on the limiting rotor speed curves but has a major influence on the moment equilibrium curves and limiting angles. With a large wing, it is more difficult to arrive at a satisfactory moment balance because small angle changes produce large wing lift increments.

Autorotation Entry

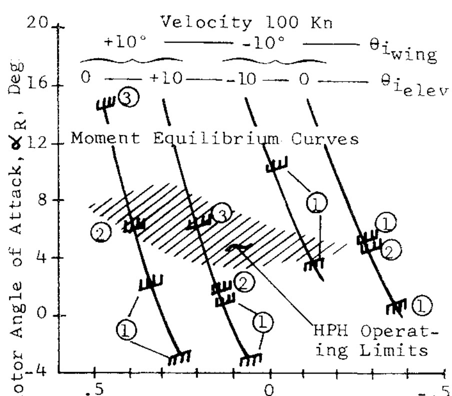
Early in the HPH program, there was concern with respect to the technique to be used during autorotation entry at high speed; with the wing incidence-collective coupling, this did not turn out to be a problem. Above a speed of about 150 knots, there is no need for autorotation in the normal sense of the word. All that is required is to be able to control the attitude of the aircraft while reducing speed so that altitude is maintained, or perhaps increased. The machine decelerates to the lower speed where normal autorotation flight and landings can be made. Attitude control during power failure must be more or less automatic because of the rotor deceleration rates; a pilot will not have time to react, especially for entry conditions with high rotor power. For a practical configuration, the ship/rotor must pitch to the required angle of attack automatically or with a small natural effort by the pilot.

It is also possible to maneuver the aircraft so as to produce high rotor thrust while decelerating to a lower speed. Although satisfactory for test, such a technique will probably not be acceptable for a production aircraft because of the added restrictions that it imposes on the flight path of the vehicle during emergency conditions.

It was noted earlier that the final configuration of the HPH used wing incidence coupled to the collective control. With this feature, the machine performed satisfactory autorotation entries up to nearly 200 knots and satisfactory steady-state autorotation up to 150 knots.

Design Considerations

A small wing with a low maximum lift capability (Lw/W max < 0.3) will not cause problems, and a fixed wing installation can be used. In the absence of test data, full fuselage carry-



Limits: 1) Control ±1.5 in. from level flight trim
2) Fuselage attitude, ±8°
3) Blade flapping, ±10°

Fig. 10 Autorotation map with all constraints.

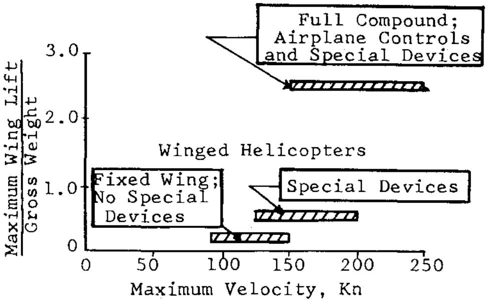


Fig. 11 Guide to wing "size" selection.

through and a $C_{L\max}$ of 1 should be used in defining the Lw/W ratio.

In all cases, the wing airfoil section should have smooth stall characteristics. The wing incidence should be set high to eliminate download at forward center of gravity but sufficiently low so that the wing is not near stall at aft center of gravity and cruise speed.

The angle-of-attack stability of the wing-fuselage-elevator must be positive to avoid nose-up pitching upon autorotation entry. For most designs, this requires a placement of the wing center of pressure slightly aft of the ship's rearward center of gravity. The wing should be located high above the center of gravity from considerations of angle-of-attack stability, lift carry-through, and hovering download. It should also be located forward and low with respect to the elevator to minimize elevator effectiveness losses.

A high-speed helicopter can probably use a wing with an $Lw/W \sim 0.4$ to 0.6 (limited by control) to over-all advantage if the rotor is sized for the wing ($2C_T/\sigma$ of 0.16 to 0.18 at sea level). A lower-speed helicopter that carries external stores will probably use a wing (pylon) with a similar lift capability. For these cases, some form of wing lift or rotor speed control will be necessary for satisfactory autorotation.

A full compound helicopter will have an $Lw/W > 2.0$. For this case, full airplane-type control should be used, and special devices must be provided to reduce the apparent lift curve slope of the rotor relative to that of the wing.

As the lift capability of a wing is increased, the autorotation problems and the complexity and weight associated with the wing installation become greater. For a given design, the decision as to whether to use a wing, or what "size" wing to use, depends on the detail requirements and parameters of the aircraft. In many cases, that decision will depend on whether or not the wing can serve a dual purpose (i.e., external stores support; landing gear or fuel housing).

Figure 11 provides a guide to the choice of wing "size" as a function of speed and configuration. The overlap areas indicate speeds where sound engineering judgment will be required for the final selection of wing "size."

Means of mitigating or correcting the autorotation problems associated with winged helicopters include the use of special devices acting on the rotor or wing. These are a collective or cyclic rotor speed governor, wing incidence or flaps coupled to collective, retractable wing spoilers, and the use of a high elevator-longitudinal cyclic gearing ratio. Additionally, a tilting pylon (rotor shaft), a propeller geared to the rotor, and a "rigid" or offset flapping hinge rotor can be used.

Conclusions

A wing offers important advantages for the helicopter, compound helicopter, and other rotorcraft configurations. With the exception of the autorotation problems discussed herein and the excessive download in hovering for high disk loading machines, there are no major harmful side effects. Proved techniques are available to eliminate the autorotation problems.

For rotorcraft with a maximum speed above $\sim$ 140 knots, a wing should be used. For machines with a lower maximum speed, the improvements due to a wing will be marginal unless it can be made to serve a dual purpose.

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