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A GENERIC COMPOUND
HELICOPTER MODEL

BY

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A Generic Compound Helicopter Model

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1. Introduction

The desire to significantly expand the flight envelope of rotorcraft, on a cost-effective basis, has led to the reinvestigation of concepts that had been previously discarded. The compound helicopter configuration is one of these concepts, which has been shown to be technically successful in the past, through the development of aircraft such as the Lockheed AH-56A Cheyenne and Fairey Rotodyne, if not financially and politically successful. The compounding of a helicopter originally evolved as a method of increasing the forward velocity potential of the conventional helicopter. However, it also offers the potential for improved manoeuvrability, greater service ceiling, range and productivity. These benefits, through the use of additional propulsion and lift for the aircraft, come at the cost of increasing the level of complexity of the design and with hover penalties though. These are unavoidable due to the interactions between the various aircraft components and the redundancies in the provision of lift and propulsion inherent in the configuration.

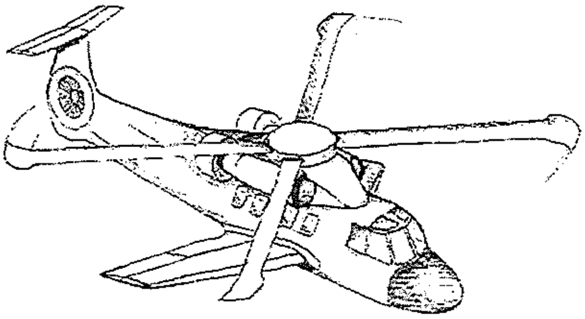

Figure 1: The Compound Helicopter

There is a seemingly endless number of variations in the configuration possible for a compound helicopter, a typical configuration type being shown in figure 1. Part of the designer's difficulty lies in determining which of these choices are worthy of further investigation and, conversely, which should be discarded. While many aspects of the design of such an aircraft seem intuitive, the purpose of this work was to develop a systematic means of eliminating unrealistic configurations and identifying those that hold the most potential for development. The intention was to devise a simple theory that could be implemented with minimal computational complexity, thereby allowing a wide range of configurations to be investigated in a short period of time. Once this had been completed then the configurations that had been selected as having greatest potential could be analysed using a more detailed and intensive simulation. This methodology also has the advantage that it highlights the trends involved with any change made to the configuration, which may be lost in an optimisation routine. The designer will therefore have an understanding of the effect of any modification forced on an aircraft design after the initial configuration has been chosen.

2. Design Issues

Whilst compounding the helicopter offers many advantages, there are many hurdles that must be overcome before the aircraft's full potential will be realised. From an aerodynamics point of view there are the difficulties encountered with the blockage caused by the wing in hovering flight, which reduces the thrust available from the rotor. There is also the detrimental effect that the wing and rotor have on each other's lifting capability when flown in close proximity to one another during forward flight. Whilst the wing is necessary to alleviate the onset of retreating-blade stall on the rotor, it also comes at a weight penalty that restricts the payload of the compound helicopter in comparison to a conventional one. Weight growth, compared with a helicopter, to meet a common mission has been a consistent finding amongst compound helicopter configuration studies and this will call for speed increases to maintain a similar productivity level to the conventional helicopter. The other main addition to the compound helicopter is that of supplementary propulsion, which also adds to the weight difficulties, not to mention the cost of the aircraft. Increased power requirements of the compound helicopter will necessitate that not only does the aircraft outperform the conventional helicopter in terms of speed, but that it also has a productivity advantage to make its cost premium worthwhile.

3. Development of the Generic Model

To meet the need for computational simplicity and enable the analysis of a large selection of configurations to be achieved quickly and efficiently, a closed form solution for the aircraft trim attitude and rotor thrust requirements was devised. The need for a mathematically tractable solution, due to the high level of interdependency between aircraft components, simplifications, such as the use of a point source model, small angle approximations and the neglect of the rotor drag force, had to be made. A series of simultaneous equations were derived which enabled the goal of a closed form solution to be achieved. The inclusion of a wing to the model also brought its own problems with interdependencies that could only be solved by eliminating some of the smaller terms in the simultaneous equations relating to the wing induced drag. This caused difficulties later on with an underestimation of the forward trim tilt of the non and partially thrust compounded aircraft.

As the developed wake of a rotor at high speed begins to approximate that of a circular wing, the interference effects of the rotor on the wing were calculated using a horseshoe vortex representation of the rotor-wake. The reduction in wing incidence that the rotor wake caused was found by performing a standard integration of the vortex-induced downwash across the wing using the Biot-Savart law. The resulting definite integral, relating the incidence change to the wing geometry and rotor thrust, was included in the trim analysis.

The trim analysis did not make any allowance for the impact of compressibility effects on the advancing blades or the influence of retreating blade stall, so practical limits were applied, after solving the trim equations. To account for the compressibility effects a simple restriction of the advancing blade tip to a Mach number below 0.92 was applied. Aircraft that operated with the wing stalled were eliminated immediately, even if the configuration was feasible, as this is inefficient and would require an inappropriate degree of freedom in the design process. The rotor thrust limit caused by retreating-blade stall was determined by forcing the first three terms of the Fourier series for the aircraft's rolling moment to zero. Should a particular configuration be deemed feasible, then the power requirements were found using actuator disc theory, including Stepniewski's factor. For some analyses take-off limitations were applied including an estimation of the wing blockage in hover, derived from the work of Lynn [1], and the ability to hover at 5000ft with one engine inoperable. Further limits were applied to account for the gust response problems that may occur for an unloaded rotor, 10 percent of the aircraft MTOW being the lower limit of the rotor thrust imposed. So that unrealistically low rotor speeds would not appear in the results from the analysis, another limit was applied, to ensure the aircraft retained a minimum of a third of the lateral control travel in hovering flight, so that manoeuvring flight remained possible.

To analyse the productivity of the different configurations, it was necessary to know the relative empty weights of the various aircraft. This was achieved by taking the baseline helicopter to have an empty weight of half the MTOW. To this weight was added the weight of the wing, power plant and transmission using, as a basis, the results of the statistical analyses of Torenbeek [2] and Tischenko, *et al* [3]. The results of the latter study were modified to include the findings of Lastine [4], regarding the weight penalty incurred by a compound helicopter transmission. Once the weights of these components were known, not only could the payload, and hence productivity, of the aircraft be determined, but using this weight break down and the power requirements, the cost was estimated using the results of Harris and Scully's study of the cost of rotorcraft [5]. This was then linked to the productivity as a cost-effectiveness measure, the productivity estimate simply being the payload multiplied by the maximum velocity of the aircraft, in order to maintain the results in a generic format rather than tying them to a specific mission.

The final performance measure included in this paper was that of manoeuvrability. The maximum load factor was determined at the bottom of a symmetrical pull-up manoeuvre, to avoid the need for a new trim solution, for the various configurations. This simply took the maximum lift that could be generated by the rotor and wing and related it to the aircraft's weight. This assumed that the aircraft would be flown in a similar manner to a fixed wing aircraft, and unfortunately, due to the nature of the trim models used, could not account for the change in rotor inflow and the wing and stabiliser offsets from the aerodynamic centre of the aircraft.

4. Configuration Analysis Work

In keeping with the goal of finding generic configuration trends, the analysis was not tied to any specific mission, rather it was used to investigate the general performance parameters of power requirements, velocity capability, manoeuvrability, productivity and cost-effectiveness. The closed form trim model and actuator disc theories are intrinsically limited in the configuration variables that can be examined. Those studied in this work were therefore restricted to the wing span, wing setting angle relative to the fuselage, wing aspect ratio, supplementary thrust ratio to aircraft drag in the direction of flight, wing location, rotor speed and supplementary propulsion efficiency. Secondary variables such as blade number, fuselage drag and additional aircraft geometry are necessary to enable the calculation of the performance parameters. However, the significance of their influence is better investigated with higher fidelity simulations, and much work along these lines has already been completed for the conventional helicopter, so these were felt of lesser import for this study.

To best observe the trends, the analysis was used to produce 3-D surface plots, representing the effect of varying two aircraft parameters on a single performance attribute. This was achieved using Matlab® software, the effect of modifying the remaining primary variables being found by creating a series of plots and cross-referencing between them. While the model can be utilised for any aircraft size and geometry, a 4 ½ tonne aircraft using a 4 bladed rotor and of similar dimensions to the Sikorsky S-76 was used for the analysis contained herein.

5. Model Limitations

In order to achieve the aim of a closed form trim and rotor thrust solution the assumptions made have imposed some limitations on the model. The elimination of some of the smaller wing induced drag terms resulted in a minor underestimation of rotor thrust, but more significantly this created a underestimation of the forward trim tilt of the aircraft when combined with the small angle assumption. This latter effect was most noticeable for the winged helicopters that did not use thrust augmentation. The underestimation was of the order of three degrees for aircraft using extremely large wings. This did not affect the fully thrust compounded aircraft, due to its level fuselage attitude (the rotor disc attitude and fuselage attitude were linked for simplicity), so more confidence can be placed in these results.

The interference model assumed that the rotor wake is fully formed and approximates to that of a circular wing. At lower velocities this assumption will begin to break down, hence the configurations with which this model has been analysed have been limited to velocities above 100 knots. Also restricting the analysis were the rudimentary boundaries used for the compressibility and retreating blade stall limits on the rotor, due to the use of actuator disc theory and the closed form trim solution. The former simply constrains the tip speed below a set Mach number and does not take account of the critical drag rise on the power of the aircraft, or the effect that the reduced blade incidences of the unloaded rotor have on the local Mach numbers on the blade. Dynamic stall has been included through a quasi-static estimation, but the effect of the changes in the rate of pitch change with reduced rotor speed could not be included.

6. Maximising the Velocity Potential

The conventional helicopter is limited in velocity by the boundaries of retreating-blade stall and compressibility effects on the advancing blade. The addition of supplementary thrust and a wing to the helicopter allows these boundaries to be manipulated, but also brings a new restriction in the form of the problem of rotor gust-response. Whereas the conventional helicopter power requirements are set by the hover condition, the compound helicopter's power requirements are set at the maximum velocity.

Looking at figure 2 of the maximum velocity capability of a range of configurations, varying the supplementary thrust ratio and the wing area, all of the limits mentioned in the preceding paragraph become apparent. With a reduced rotor speed to show the benefits of compounding, the point representing the conventional helicopter and a large portion of the aircraft utilising only a small amount of thrust compounding, on the left-hand side of the figure, are constricted by retreating-blade stall. The higher plateau, which represents the aircraft attaining the compressibility limit, is notably only reached by aircraft using both thrust and lift compounding, hence overcoming retreating-blade stall. The addition of thrust or lift compounding separately does not benefit the aircraft in speed potential significantly. The third boundary that of rotor gust-response, is denoted by the large drop off in velocity capability of the configurations to the right of the plot, and the chamfer formed in the compressibility plateau is caused by the power limit of 3000-hp imposed on the program. There is a fifth limit that of the supplementary wing stalling, but this was avoided throughout the analysis for the reasons noted in section 3.

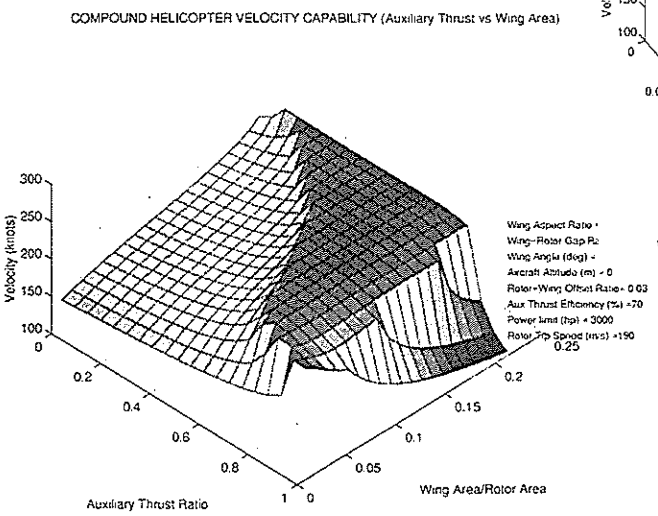

Figure 2: Velocity Capability – Varying Supplementary/Auxiliary Thrust and Wing Area

A point highlighted by this velocity analysis and previous work has been the need to reduce the rotor speed to realise the full velocity advantage of the compound helicopter. Past research has suggested the use of variable speed rotors, but these can create difficulties in avoidance of resonant conditions. The analysis conducted to produce figure 3, however, indicates that the full velocity potential of the compound aircraft could be utilised with a constant reduced rotor speed, while still maintaining a control margin for low speed manoeuvrability. This can be achieved because of the retreating-blade stall avoidance afforded by the wing in forward flight and the excess power a compound helicopter will have in hovering flight. It will however, necessitate the use of high inertia blades, for safety reasons, and assumes that the majority of the compound helicopter's power is available to the rotor during hover. The three main features of this plot are the curved surface representing the intrusion of the gust-response limit on the rotor, the flat slope to the left, being caused by the basic compressibility limit applied. The partially hidden limit towards the peak is that of retreating-blade stall. Of note is the small wing area necessary to achieve the maximum velocity potential of the aircraft.

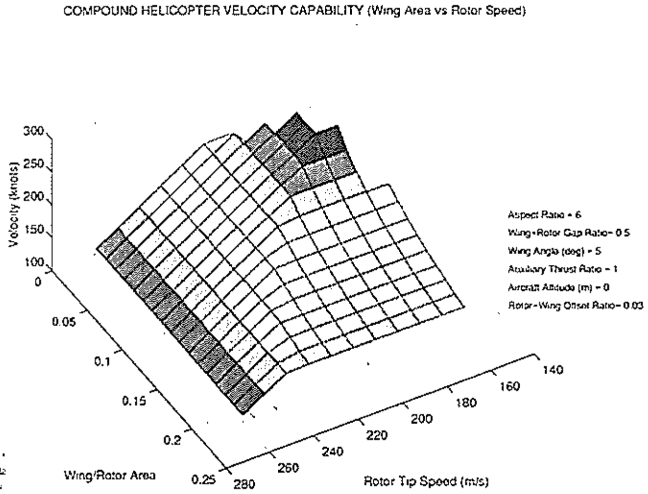

Figure 3: Velocity Capability – Varying Rotor Speed and Wing Area

7. Aircraft Power Requirements

One of the main results highlighted by the analysis was that some aircraft parameters were found to be performance determining, such as the wing angle and wing area, whereas others such as the wing location and wing aspect ratio only had a major influence at extreme locations or aspect ratios. Examining the effect of the wing location in figure 4, it can be seen that when the wing is in close proximity to the rotor the effective wing incidence is greatly reduced, although increasing the rotor-wing gap to a distance of half the rotor radius, the interference effects are reduced to negligible proportions. A major feature of this plot is the significant minimum just below and behind the rotor, which is caused by the use of a single horseshoe vortex to represent the rotor wake. A more uniform interference effect would be expected in real life. Away from this region it does, however, give a reasonable comparison to flight test data, full thrust compounding being used in this particular plot to eliminate the influence of fuselage trim attitude changes.

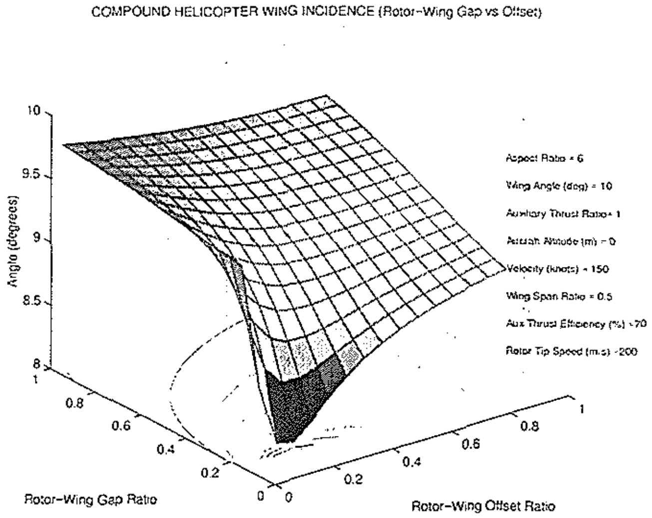

Figure 4: Wing Incidence – Varying Rotor-Wing Gap and Rearward Offset

The wing aspect ratio was also found to be of secondary importance to the design of the aircraft, figure 5; the benefits of an 'optimum' aspect ratio only being of the order of 50-hp. Conventional fixed wing aircraft wisdom states that increased aspect ratio will improve the efficiency of the aircraft, although there are structural and manoeuvre constraints that must be applied. In the case of the compound helicopter there is the added difficulty of the rotor wake. As the wing aspect ratio is increased, not only does it position the tip further into the high-energy hover downwash, but it also incurs greater interference from the 'trailing-vortex' portion of the rotor's wake in high-speed forward flight. For this reason interference effects largely negate the increase in wing efficiency gained by increasing the aspect ratio. As long as the worst inefficiencies are avoided, the aspect ratio should be chosen for other practical reasons such as minimising the hover download and structural requirements.

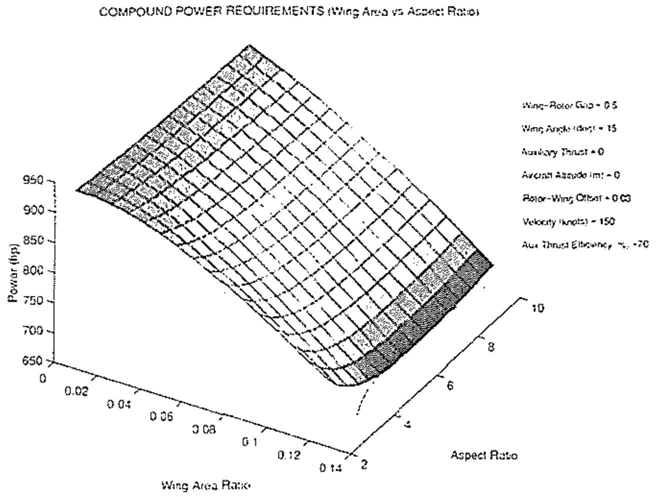

Figure 5: Power Requirements – Varying Wing Aspect Ratio and Area

Of the parameters investigated, the supplementary thrust ratio to drag, the supplementary propulsion efficiency, the wing area and wing angle relative to the fuselage were found to be performance determining. In terms of the power requirements, the addition of supplementary thrust to the aircraft will not be beneficial if the rotor is capable of supplying all of the aircraft's thrust requirements, unless the supplementary propulsion is extremely efficient, due to the increased ram drag it will have in comparison to the rotor. That thrust compounding is power intensive can be seen in figure 6, but it does come with the advantages of increased wing effectiveness and can eliminate the need for changes in fuselage tilt.

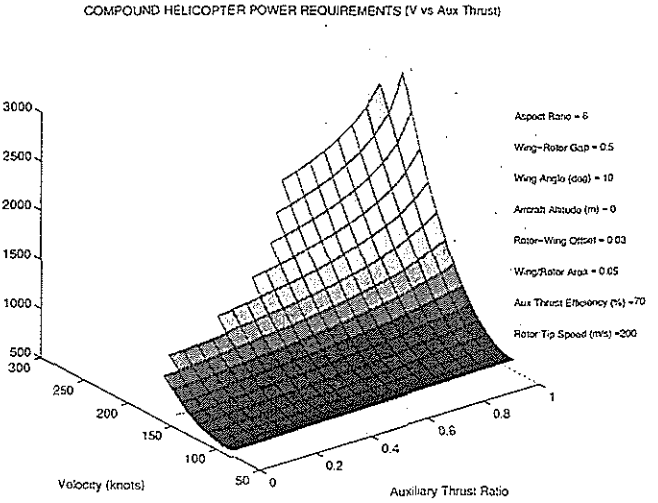

Figure 6: Power Requirements – Varying Velocity and Supplementary Thrust

The addition of the wing is necessary if the limit of retreating-blade stall is to be overcome and greater velocities attained, but it does not necessarily produce reduced power requirements. In figure 7 a small reduction in total aircraft requirements is gained by using a wing of small area and angle, probably due to the reduction in rotor thrust necessary. As more wing area and incidence is added then the greater profile and induced drag incurred by the wing raise the total power requirements, as the supplementary propulsion's higher parasite power outstrips the reductions made in the rotor induced power level. The cut away region at large wing areas and angles represents the limit imposed on the rotor by gust-response considerations.

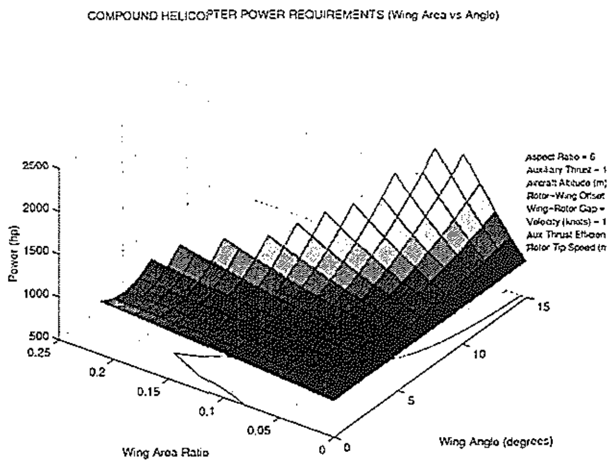

Figure 7: Power Requirements – Varying Wing Area and Aspect Ratio

A further feature of note is the positioning of the trough in the total power requirements, which appears to reduce in wing incidence as the wing area is increased. This suggests that there is an optimum ratio of wing lift to rotor lift, which seems to be reinforced by the similar shapes of figures 8 and 9, of the effect of varying the wing angle and the wing area respectively, against the aircraft velocity. Any distinct mathematical relationship for the rotor to wing lift ratio though will be disguised by interference effects and inefficiencies of the two lifting devices. The viable configurations of both of these plots are bounded on the right hand side by rotor gust response limits and retreating-blade stall limits to the left.

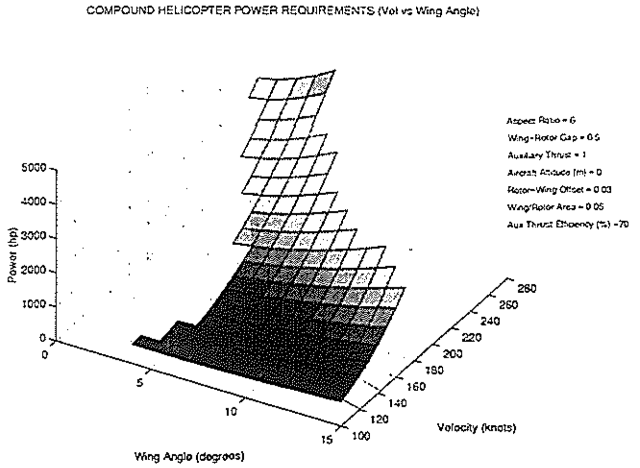

Figure 8: Power Requirements: Varying Wing Angle and Velocity

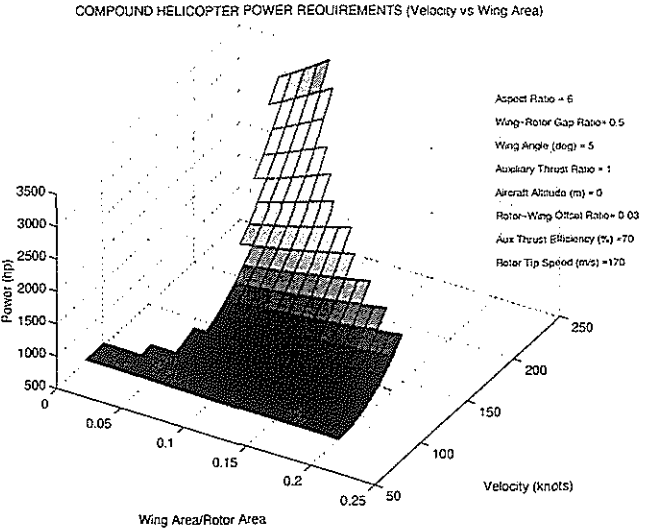

Figure 9: Power Requirements: Varying Wing Area and Velocity

8. Productivity

The productivity of a compound helicopter is potentially degraded in comparison to a conventional helicopter, despite the increase in speed capability, through the addition of the wing, extra transmission and larger power plant(s), as the weight of these items reduce the payload that can be carried. The analysis, used within, simply determines the productivity of the aircraft using the product of the payload and the aircraft's maximum velocity, a fixed upper power limit being imposed. This gives a good generalised indication of the relative productivity of the various configurations, but should be taken with some caution. The reason for this caution is that a configuration with excellent speed capability and poor payload may come across with the same productivity as one with poor speed perfromance and excellent payload, although the usefulness of these two contrasting aircraft will come down to the specific mission to be performed. The generalised productivity analysis does, however, give the designer an idea of the type of configuration, which they should be aiming for.

Figure 10, shows the productivity when varying the supplementary thrust ratio and the wing area. It shows the main features found when analysing the productivity of the various compound helicopter configurations. An interesting outcome was that certain fully thrust compounded configurations, utilising a small wing area to avoid retreating-blade stall, sufficient power and a reduced rotor speed to off-set the compressibility limits on the advancing blade, could exceed the productivity of the conventional helicopter by up to 30 percent. The productivity of the fully thrust compounded aircraft with a small wing area in the figure comfortably surpasses that of the conventional helicopter, which is limited, along with many of the partially thrust compounded aircraft by retreating-blade stall. This was found to be the case even when both aircraft employ an optimum rotor speed, despite the conservative nature of the analysis, which favours the conventional helicopter.

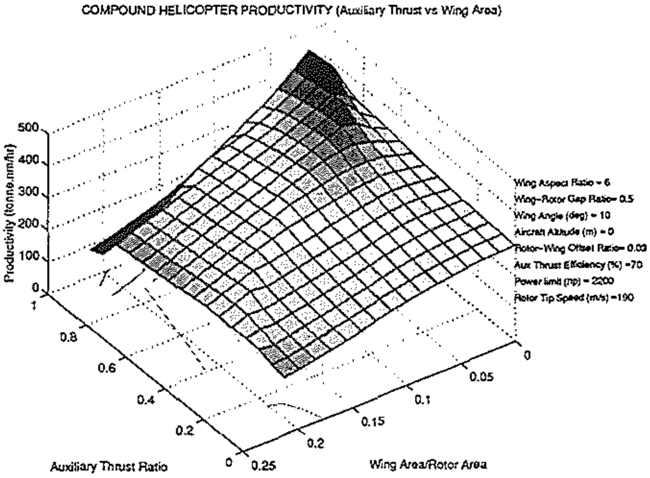

Figure 10: Productivity – Varying Supplementary Thrust Ratio and Wing Area

Figure 10 can be compared with figure 2, portraying the velocity limits, where the same four regions are apparent. Aircraft limited by gust-response, to the left of the plot, have a significant productivity penalty due to the reduction in velocity potential caused by the gust response restrictions combined with payload reductions. The central region of an almost constant upward slope represents the aircraft limited by advancing blade compressibility limits, the upward slope being a result of the payload penalty imposed on the aircraft by the addition of larger wings. The addition of more wing area to the aircraft, after the retreating-blade stall limitations have been overcome, being detrimental to the productivity. A slightly concave portion of the slope is evident just before the peak, which is due to the speed of the aircraft being power limited below that imposed by the rotor limitations. High power levels and/or high supplementary propulsion efficiencies are required to overcome the power limitations of the fully compounded aircraft and obtain its full productivity capability. Beyond the peak and to the right of the Mach limited configurations, the aircraft are constrained by retreating-blade stall. Thrust compounding on its own has a neutral or slight benefit on the productivity of the aircraft due to the slight unloading benefit it allows the rotor for the avoidance of retreating-blade stall. Although when combined with the wing the improved wing effectiveness, and stall alleviation, it brings gives the substantial productivity benefits seen.

9. Cost Effectiveness

While it is important to have a highly productive aircraft, the aircraft's initial cost has to be reasonable, otherwise the customer will not be in a position to purchase it, despite the benefits it provides. Simply the benefits of its productivity have to be affordable. Previous portions of this analysis have shown the fully compounded helicopter to be potentially more productive than the pure helicopter, however the fully compounded aircraft is more power intensive. This latter point is potentially detrimental to the compound helicopter's overall viability, since the power plant is probably the most expensive component of the aircraft.

Using the same geometry and aircraft parameters as for the productivity plot of figure 10, a plot of the initial cost of the aircraft divided by the productivity is given in figure 11. Interestingly a trough forms where a configuration moves from being limited by retreating-blade stall to where it is fully alleviated and compressibility becomes the limiting factor, which corresponds to the ridge in the previous figure between these two limitations. The most cost-effective aircraft on this trough are those that have the smallest wing-area, and therefore the greatest thrust compounding ratios. The addition of wing area, apart from that required to alleviate retreating-blade stall is again shown to be detrimental, partly due to the cost, but mainly due to the reduced productivity outlined in the previous section. Gust-response limits again form a region of poor worth on the right-hand side of the plot.

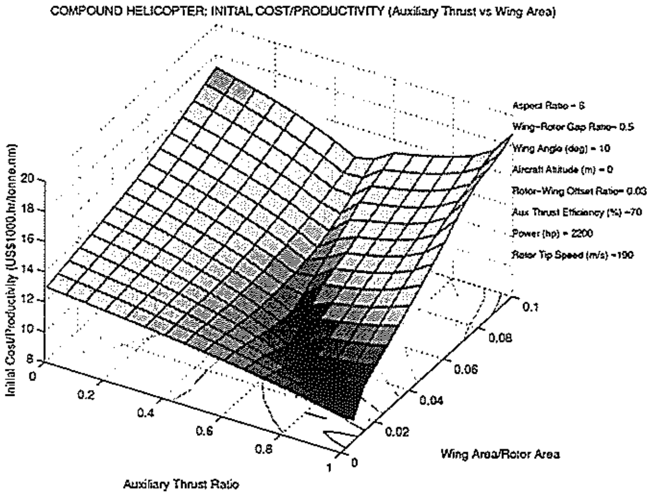

Figure 11: Initial Cost/Productivity

Altering other parameters for this analysis such as the rotor speed can have a significant effect on the cost effectiveness of the aircraft. Increasing the rotor speed improves the velocity capability and hence the productivity of the, previously retreating-blade stall limited, aircraft to the left of the trough, which improves their cost/productivity ratio. Increasing the power limit is advantageous to the productivity of the aircraft to the right of the trough, although the large cost of this additional power exceeds the benefit gained from the increased productivity, unless the supplementary propulsion efficiency is sufficiently high

10. Manoeuvrability

As a conventional helicopter increases in forward velocity, the increase in collective blade incidence required reduces the incidence available to trim and manoeuvre the aircraft before the retreating-blade will stall. This not only places a limit on the velocity of many of the potential compound helicopter and conventional helicopter configurations, but it also restricts the rotor thrust available at any set velocity, hence limiting the manoeuvre loads that can be supported by the aircraft. The addition of a wing, however, endows the aircraft with a second source of lift that incidentally increases in lifting effectiveness with increasing forward velocity, in contrast to the rotor. For this reason the compounded aircraft is expected to have greater manoeuvrability at high speed than the conventional helicopter.

Of particular interest in figure 12 is the low manoeuvrability of the conventional helicopter at the relatively high speed and the limited effect that thrust and lift compounding give when applied separately. This plot, of the load factor that can be maintained in a sustained symmetrical pull up manoeuvre, for varied wing area and supplementary thrust, shows only minor manoeuvre benefits for the winged helicopter, as the increased fuselage tilt required when the rotor thrust is reduced limits the effectiveness of the wing. Similarly the addition of supplementary thrust separately provides little additional manoeuvre capability, due to the low level of rotor unloading it enables. It is when these two compounding components are combined, however, that the full manoeuvre benefit of the compound helicopter is shown. The addition of supplementary thrust to the winged helicopter enables it to be 'flown' in a similar manner to a conventional fixed wing aircraft through the manoeuvre maximising the effectiveness of the wing, as can be seen most notably with a full thrust compounding ratio. The addition of the moderately sized wing and auxiliary thrust in figure 12 improves the load factor capability by 2g, but there is a conspicuous area past the peak in this figure that is cut away. This area represents configurations that would be limited by rotor gust response difficulties in level flight, however, this does not preclude the following of the favourable manoeuvre trends to a much greater load factor through the use of a mechanism such as variable incidence wings or flaps to improve the wings lifting ability.

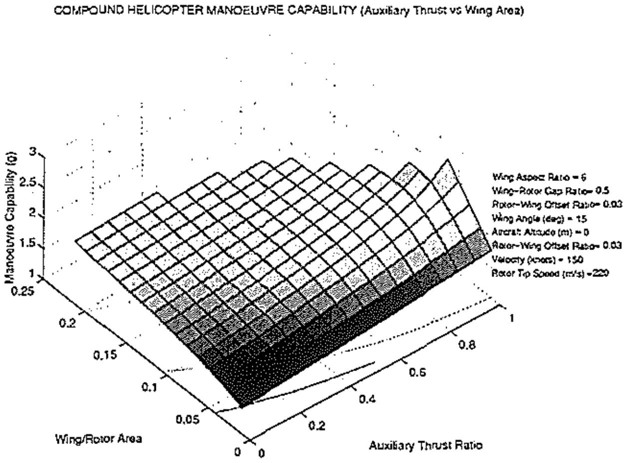

Figure 12: Manoeuvre Capability – Varying Supplementary Thrust and Wing Area

The final points highlighted by the manoeuvre analysis, not shown, are the ability of the fully compounded helicopter, using both thrust and lift augmentation, to maintain its manoeuvrability to high speed, unlike the helicopter. This is mainly as a result of the increase in wing effectiveness as the aircraft velocity increases, supplementing the rotor's decrease in effectiveness. The same effect enables a compound helicopter utilising a reduced rotor speed to have a much superior manoeuvre envelope at high speed compared to the conventional helicopter despite the reduction in rotor thrust available.

11. Conclusions

The results of this closed form analysis show that a computationally inexpensive theory such as this can give a good insight into the problems and trends with designing a complicated aircraft such as the compound helicopter. It does have some drawbacks, however, with inaccuracies in the trim estimation and the rudimentary nature of the boundaries that have to be applied to account for rotor compressibility, dynamic stall effects and gust response.

The trends revealed by the analysis show that there are certain performance driving parameters, such as wing area and the auxiliary thrust ratio, whilst others, such as wing location, only significantly influence the performance at certain extreme conditions. An additional point highlighted by the analysis is that the optimum aircraft configuration will vary somewhat depending on what performance parameter the designer is trying to extend. From a productivity perspective, a wing of small area is beneficial, whereas if manoeuvrability or altitude is the designer's goal, a greater wing area is advantageous. Full thrust compounding on the other hand was important in boosting the velocity capabilities of the aircraft and improving its manoeuvrability, but incurred a large power penalty unless the efficiency of the supplementary propulsion device was high, to negate the disadvantages of its high ram drag.

The analysis highlighted the benefits possible through fully compounding the helicopter of increased velocity, increased productivity and increased manoeuvrability. Apart from the need for a highly efficient supplementary propulsion device, the other main conclusion of this work is that the development of a variable incidence wing or efficient flaps will be needed to fully exploit the compound helicopter's promise. This is necessary to avoid rotor gust response difficulties, minimise the power requirements of the aircraft throughout the speed range and to realise the aircraft's exceptional manoeuvre potential.

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