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MODELLING ASPECTS FOR THE SYNTHESIS AND PERFORMANCE ASSESSMENT OF SOME FUTURE ADVANCED HELICOPTERS

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1.0 Introduction

The pure-rotorcraft point performance and design synthesis models developed in the Advanced Project Office at WHL, have been in regular use in the present form for the last 3 years. These models have been of considerable value in assessing the design and performance implications of any conceptual pure-rotorcraft.

Periodically, interest arises in various types of compound rotorcraft requiring a quick and flexible response to assist in maintaining project momentum. Performance and design synthesis models for compound helicopters have recently been developed with a view to satisfying any future requirement. This paper outlines some of the principles developed for the compound models from the WHL pure-rotorcraft models.

Westlands have been involved in a series of investigations into compound helicopters in collaboration with Rolls Royce both on a private venture basis and supported by the UK MoD. These projects have all shown that some general increase in vehicle performance can be achieved when applying certain fundamental concepts. There is no doubt that extensive analysis in areas such as cost and role are required to determine the validity of such aircraft in the real world. It is also recognised that initially the concept must be technically sound and show considerable benefits over rival vehicles for specific applications. Studies involving the models described are the first steps in judging, on this basis, whether any future exists for these projects.

2.0 General

A compound helicopter is defined as a rotary winged vehicle with supplementary lift and/or propulsion provided by some device(s) other than the rotor. The candidate devices currently catered for within the model are shown in table 1. One of the criticims associated with winged compounds is the reduced hover performance due to wing download. Blown wings offer a reduction in wing area, thus reclaiming some hover performance, whilst retaining the required speed requirements. This family of aircraft have the potential to utilize any excess power in the cruise which may result, for instance, from a demanding engine out requirement. During model development this possibility became of prime interest, consequently compounds with dedicated propulsive power sources are not considered.

The synthesis program is used to define the vehicle characteristics which then allow the point performance model to evaluate the off design performance of the aircraft. Figure 1 illustrates the principle of converging all up mass used in the synthesis model. The components of the dynamic system are matched to the pre-defined point performance requirements whilst payload and fuel considerations are made compatible with the mission. However some basic assumptions have to be made before the synthesis model can be used. As a result second and third iterations are sometimes necessary to converge on an acceptable solution. This mechanism can be shortened by producing carpet plots (figure 2) which use two of the assumed parameters as the independent variables. Aircraft with dual sources of lift and/or propulsion require additional assumptions (eg wing area & section, fan diameter etc) for the synthesis operation. Experience accumulated during various trade-off studies has allowed values for some of these assumed parameters to be accurately targeted thus circumventing the need for a multi-dimensional analysis.

The point performance model is used to determine the principle vehicle characteristics at perceived operating conditions. This model is als useful for estimating the boundaries of the aircraft flight envelope.

The synthesis and point performance models use common routines containing a rotor power model, based on momentum theory, and an aircraft force analysis (figure 3). At this stage of aircraft design many vehicle characteristics are unknown preventing detailed investigation. This, together with with a key software requirement of minimising computer time forced the omission of any pitching moment analysis. However a centre of gravity check does form part of the overall design loop (figure 4).

The compound models contain an optimisation routine to establish the most favourable proportions of rotor lift and/or propulsion. Interfacing the optimiser into the synthesis and performance models probably occupied the largest single slice of development time. Successful optimiser operation will only be possible if the supplied function routine(s) are sufficiently robust. Initially the function routines were littered with previously obscure model scenarios which the optimiser kept finding. This not surprisingly either influenced the solution or caused program crash. This situation was further complicated by two undesirable but legitimate properties of the performance function. Firstly the function routines contain several discontinuities, for example wing stall and intermediate speed gearbox power (figure 13), which though not compromising the optimiser, were consistently hidden from 'view' when analysing the results. Secondly the 'surface' of the function contains areas of relatively flat and well behaved solutions. Conversley there are areas where the surface undulates and thus local minima are common. Whilst the optimiser can easily cope with this situation the value of tolerance required to find the solution is linked to function behaviour and thus optimiser efficiency. A solution lying in a flat area of the function will result in optimiser inefficiency if the tolerance is too tight. If however the solution is in an area of undulation then a wide tolerance may both conceal the local function features and produce a result which permits an accumulative error (eg during a long mission). Thus the final tolerance value represents a carefully chosen compromise.

Currently the performance assessment model will permit optimisation based on any of the four options listed below. The synthesis model however is restricted to the minimum fuel flow option.

1) Minimum fuel flow.
2) Maximum speed.
3) Maximum sustained normal acceleration.
4) Maximum attained normal acceleration.

Future advanced rotorcraft include a range of compound helicopters which are the subject of continuing work at Westlands. Modelling of compound helicopters as defined above has been selected for this paper as we believe it represents an area of considerable potential for rotorcraft into the next century.

3.0 Basic Synthesis Principles

The fundamental processes of the synthesis are shown in figures 1 & 4. Conventional helicopter main rotor sizing is based on the most demanding performance requirement. Usually this results in the size of the main rotor, in terms of blade area, being based on the high speed requirement since thrust capability decreases with forward speed. Some compound helicopters can avoid being speed limited by the rotor in the same way, by using their auxiliary devices. Main rotor sizing for compound vehicles thus becomes an externally defined independent parameter. The concept of 'rotor design speed' (VDES) has been adopted in an attempt to associate the synthesised compound vehicle and its rotor with the more familiar particulars of a conventional helicopter. Rotor design speed has been defined as the speed at which the rotor could, if required, provide all the necessary thrust for vehicle lift. Values for rotor design speed need careful consideration when a winged compound is under investigation. Figure 5 illustrates that problems could exist at intermediate speeds where the total lift generated could be insufficient to support the weight the vehicle. The solution represents an area of design compromise dependent on vehicle application. For a given aircraft mass, increasing blade and/or wing area (and hence their masses) to improve intermediate speed manoeuvrability will inevitably reduce aircraft payload.

The rotor power model is based on the momentum theory with a number of modifications which improve agreement with aircraft flight test results. During the conventional helicopter synthesis development special attention was given to the modelling of power increments due to advancing blade drag rise, retreating blade stall, changes in blade profile drag coefficient as a function of rotor thrust and the variation of fuselage drag due to incidence. The assessment of rotor hub drag is fundamental to the realistic modelling of any high speed rotorcraft since it represents a high proportion of total drag area. Compound vehicles tend to be more vulnerable to performance errors if drag assessment is misjudged (as can be concluded from figure 2). This arises from the higher operating speed than is typical for a comparable conventional helicopter. There is an argument for a reduction in rotor hub drag based on the reduction in blade area implied above. Consequently the compound synthesis has the hub drag

analysis divorced from the rest of the vehicle and is based on the thrust capability of the rotor.

Powerplant modelling falls into two categories depending on the type of engine required. Conventional fixed cycle turboshaft powerplants are scaled from a database containing the characteristics of a number of different engines. This option is used when the auxiliary devices can be powered from an offtake at some point in the transmission train. The concept of an appropriate variable cycle powerplant leaves the transmission layout substantially unchanged from that of a conventional helicopter. This option trades transmission mass for engine mass on a favourable basis but engine complexity is potentially increased. Variable cycle powerplant modelling is still under development since adequate data collapse has proved difficult. Currently each type of variable cycle engine has its own database (derived from a deck) from which interpolation provides the required information.

The process of design synthesis requires 'rubber' engines which although of fixed characteristics can be scaled in size. A mechanism to scale the engines to a series of performance requirements has bee developed. The engine size factor (ESF) is determined by comparing the power required for each requirement to the power available from the datum powerplant under the same conditions.

$$\text{ESF} = \frac{\text{Engine power required to meet performance requirement.}}{\text{Engine power available from datum powerplant.}}$$

Each requirement yields a value of engine size factor which is then useful for comparing the power aspects of requirements under different conditions. The engine size factor adopted for the remainder of the synthesis cycle is simply the largest value of ESF generated by an individual requirement. This represents the most demanding requirement in terms of power.

The method of mass estimation has been developed following a well established pattern. The vehicle is broken down into its basic components which are individually assessed. A statistical weights data base has been assembled covering a wide range of rotorcraft sizes and applications with which to monitor the model output. This method of mass analysis has demonstrated considerable versatility for compound synthesis since the options for mass implications based on new technology, techniques in construction or the use of advanced materials have been installed with ease. Project aircraft can thus be assessed on a basis of performance against technical risk.

Figure 4 illustrates the manual synthesis process which is used in conjunction with the computer model. The external iteration is necessary in order to identify solutions for any assumed parameters. The adopted procedure is to run the model for a range of values of speed and drag area thus generating a matrix of aircraft which are then plotted in a similar way to figure 2. This procedure allows the characteristic trends of the assumed parameters to be assessed, an important asset since at this stage of the design process interpretation of trends is often as significant as the solution. The carpet plot shown in figure 2 illustrates just such a trend namely the critical nature of drag area for high speed rotorcraft. A likely aircraft is selected and drawn (figure 6), so that an estimate of drag area can be obtained. This value pin-points the solution on the carpet plot enabling further runs to close the cycle and identify the solutions particular characteristics. A vehicle centre of gravity check is then performed to ensure a legitimate solution has been achieved.

The design synthesis model uses an optimisation process which calculates the minimum fuel flow for a specified flight condition. This is achieved by identifying the independent variables, which depend on configuration, and repeatedly supplying differing values of these variables to the performance function. The optimiser receives the appropriate values of fuel flow from the performance function and converges on the minimum fuel flow by controlling the values of the independent variables. If the requested flight condition lies outside perscribed limits the function adds penalties to the fuel flow in proportion to the magnitude of limit penetration thereby making the condition unattractive. Figure 7 illustrates several of the many parameters which have to be checked to verify a valid flight condition.

4.0 Lifting Devices

4.1 General

Previous investigations of various auxiliary lifting devices indicated further, more detailed analysis to be necessary to confirm areas of potential gain. The synthesis and performance assessment models now available provide the means for several of the more promising options to be pursued.

Initial construction of the synthesis model concentrated on the conventional mechanically flapped wing, as the least complex option. This device represents a known area of technology and since vehicle layout is substantially similar to a conventional helicopter no significant configurational problems were encountered. This contrasts with the other two lifting devices considered where the possibility of fundamental changes in powerplant design exist.

There are a number of modelling implications associated with the addition of a wing to a rotorcraft which need addressing. Any form of device will generate interference effects, and thus losses, with any other body placed within its flowfield. The effects of wing-rotor and wing-fuselage interference have been accounted for by using an analysis developed from that described in reference 1, whilst wing download considerations based on momentum theory have been developed within Westlands. The model also includes wing spoilers which would be frequently used when the vehicle is executing a descending and decelerating manoeuvre, for example when on an approach.

4.2 Wing Data Handling

One of the ultimate aims of the modelling package is to be able to select any of several wing sections and compare the performance with other sections. Consequently the wing module has been designed to facilitate the handling of wing data input from a library of wing section characteristics. This library contains the data on a number of sections any one of which can be invoked for either the synthesis or performance assessment models. Each file within this database conforms to a standard format, depending on type, but all contain section data such as lift and drag characteristics, thickness/chord and flap/chord ratios etc. Other wing parameters, area and aspect ratio being among the most significant, are all required to be defined prior to modelling. During vehicle definition experience and judgement are required to assign values to these parameters if lengthy parametric analysis is to be avoided.

4.3 Blowing Options

The augmentor and circulation control wings each require a supply of air blown through to the trailing edge as illustrated in figures 8 & 9. The first solution addressed for these wings was a compressor driven directly from the main gearbox. This option like the mechanically flapped wing, only requires a conventional turboshaft engine and thus represents an area where modelling confidence is high. The remaining option of bleeding air from the powerplant in large varying quantities requires fundamental research into engine design. This particular area has been investigated by Rolls Royce, however some powerplant considerations are discussed in Section 5.

4.4 The Mechanically Flapped Wing

This option represents the simplest solution considered for the provision of auxiliary lift and thus modelling confidence is high. It therefore provides a good datum from which to compare the results of both the more sophisticated lifting options and the original pure helicopter. Matching of the required vehicle lift and drag forces is achieved by varying the main rotor thrust vector and wing life (vi the wing flap angle) as illustrated in figure 3. A variable incidence mechanically flapped wing has been included within the model, though this is usually used to identify the best wing setting angle for the fixed incidence wing.

4.5 The Circulation Control Wing

This option has the merit of demonstrating the differences in overall performance compared with the augmentor wing. Blowing considerations being similar allow many modelling aspects to have some commonality. The blowing provides an increased lift capability over the mechanically flapped wing therefore permitting a combination of increased lift (manoeuvrability) at low speed and a reduction in wing area required in the cruise over the conventional wing. The principle of circulation control wings is well known but a wide range of specific data is difficult to acquire. Thus total wing optimisation is currently not possible, however significant information about the application of circulation control wings has been uncovered by undertaking wing parameter trade-off studies. This wing has no flaps as illustrated in figure 8, so vertical and horizontal balance is achieved by varying the main rotor thrust vector and varying the wing lift by controlling the blowing. The required blowing mass flows are considerably lower than the augmentor option allowing less demanding design constraints. The lower blowing mass flow rates and pressures are significant to powerplant design since the possibility exists of bleeding air upstream of the mixer (see Section 5.4) without adversely compromising the cycle.

4.6 The Augmentor Wing

One of the earliest ideas for powered lift relates to blowing over a plain flap using the minimum of air so that the flow just remains attached. The augmentor wing concept goes one stage further, as illustrated in figure 9. This represents an attempt to maximise wing lift whilst providing the possibility of some auxiliary propulsion. Air ducted through the flap system permits local supercirculation and thus the generation of large lift forces. C_L max now becomes speed dependent (reference 2) and therefore a wider stall margin can be achieved. Thrust augmentation from secondary flow has been shown to more than offset losses incurred. A wide range of adequate data for this wing is also difficult to acquire, thus work is again limited to parametric trade-off studies.

The modelling of the augmentor wing is based on the interpolation of C_L-alpha characteristics for a range of blowing coefficients and flap angles. Drag assessment is performed using a traditional conventional wing method with extra terms for vortex drag and thrust augmentation.

5.0 Propulsion Devices

Engine considerations are fundamental to the philosophy of vehicle modelling, thus various powerplant aspects and their consequent reflection in the methodology are discussed below.

5.1 The Variable Cycle Engine

Research into this area of compound helicopter engine design has been undertaken by Rolls Royce who have advised on the brief discussion of some powerplant aspects within this paper.

The augmentor and circulation control wing options are designed to operate with a supply of blowing air. One source of supply suggested earlier is via a compressor driven directly off the main gearbox. This concept suffers from the fundamental aircraft design problem of weight and space, thus providing a possible opening for an alternative solution suggested by a variable cycle engine.

The overall powerplant design may be broken down conceptually into essential elements as shown in figure 10. The core or gas generator produces energy which may be divided to develop core thrust and shaft power. For some compound helicopter variants this energy is divided into blowing power, helicopter rotor power and propulsion power.

The rotor power requirement is determined by the design of the rotor and local operating conditions whilst the rotor power available is that generated by the power turbine less the blowing power, propulsion power and transmission losses. For a variable cycle powerplant as jet thrust is increased, the possible range of blowing and shaft powers is reduced.

Cycle thermal efficiency is determined by the core engine with the basic cycle parameters being overall pressure ratio and turbine entry temperature. There is a complex relationship between these parameters, the component efficiencies, the practicality of smal size and whether the design emphasis is on specific power output or thermal efficiency. Detailed core optimisation is a subject in its own right but since the synthesis of a whole vehicle is required a multitude of powerplant assumptions are necessary. These assumptions have been based on, where appropriate, the characteristics of the next generation of engines being studied by Rolls Royce.

5.2 The Variable Nozzle

The world speed record Lynx powered by Rolls Royce Gem engines used fixed nozzles reduced to a third of the datum size, therefore to an extent this concept has been flight demonstrated. The engines were not fully instrumented, so a detailed analysis cannot be carried out but a shift in engine mass flow and turbine entry temperature is apparent. In this particular case the design operating conditions were largely recovered by the injection of water/methanol.

The area of the primary nozzle determines how much energy is converted to core propulsion thrust and how much is available t produce shaft power via expansion through a turbine. The extremes ar a turboshaft with expansion to near ambient pressure through a large nozzle and a turbojet with expansion through a small area nozzle producing high thrust but no shaft power (ie all the available energy appears as thrust). A variable core nozzle where the proportion of thrust to shaft power may be varied by controlling power turbine expansion is of considerable significance for compound helicopter applications.

5.3 The Zero Stage Fan

Several methods of supplying air sufficient to satisfy the required performance of both augmentor and circulation control wings are possible if changes in engine design are considered. Figure 10 illustrates the separate components required from a change in engine design, however new powerplant designs are based on integrating the blowing supply as part of the basic engine. One concept is the addition of a large diameter zero stage fan which essentially provides the same function as that on a modern bypass turbojet. The bypass air which is supplied by the outer section of the fan is ducted to the wing thus providing constant blowing. The inner section of the fan forms part of the basic core cycle since it supercharges the high pressure compressor and contributes to the cycle pressure ratio.

The gross thrust, which is a factor in wing blowing coefficient, is a function of pressure ratio, mass flow, bypass ratio, and blowing system augmentation ratio. In the direction of flight net thrust is a further function of wing flap angle and any thrust recovery. The bypass air delivered by the outer fan to the augmentor wing therefore produces lift and thrust as a function of the wing characteristics. In the circulation control case, zero recovery is assumed and no thrust is generated.

This concept, as illustrated in figure 11, is limited by the fixed blowing power and the practical range of variation in core nozzle area, together with power turbine flexibility and its effect on re-matching of other components. This characteristic may possibly be improved by variable blower geometry or perhaps by using a declutchable system, at the expense of complexity.

5.4 Mixed Flow Powerplants

There are many variations on mixed flow powerplants which need investigation to reveal the best compromise. A mixed flow powerplant is shown in figure 12 where bypass flow supplied from a zero stage fan is mixed with the core flow upstream of the power turbine. When the variable nozzle is opened at low speed, blowing pressure is reduced allowing more shaft power to be developed than with the unmixed design. The many design constraints necessary to achieve effective operation of this type of powerplant, such as the matching of bypass and core pressures at mixer entry, may influence the practicality of this design. Rolls Royce have supplied data based on this concept which has enabled the aircraft synthesis model to compare vehicle characteristics.

5.5 The Variable Pitch Fan

The aim of a variable cycle engine is to emulate the 'power bandwidth' from low rotor power at cruise to the high rotor power at the take-off and low speed within the physical restriction of a specific design. The variable pitch fan has a large power bandwidth by virtue of changing the blade angle, limited only by installation constraints and fine pitch parasitic losses. This device has been considered in some detail by both Rolls Royce as an integral part of the powerplant (figure 10) and by Westlands as a separate propulsion device driven via a dedicated gearbox. This second alternative allows a conventional turboshaft engine to be employed if the aircraft configuration does not require blowing (eg for the mechanically flapped wing). A variable pitch fan also gives potential for reverse thrust which may be of significance for an agile combat vehicle. Like the variable core nozzle the fan option readily allows transfer between power and thrust, however it is anticipated that the fan will prove to be the more efficient propulsion device. For the purposes of modelling, the fan is assumed to be of single stage design operating at pressure ratios between 1.01 (fine pitch) to about 1.3 in the cruise.

6.0 Results and Observations

From the outset it was recognised that as speed increases the rotors capability, and therefore its contribution to vehicle lift and propulsion decreases thus requiring an increasing proportion from the auxiliary devices to maintain level flight. Even where there is a range of permissible rotor lift and propulsion proportions (figure 7) a similar characteristic is apparent due to deteriorating rotor efficiency with speed. The model quickly showed that design point performance requirements needed to be inserted at intermediate speeds in order to define peak rotor transmission loads. Figure 13 illustrates a typical set of results obtained from the point performance model when rotor disc angle and rotor power are each plotted against speed. Clearly design point requirements must be included at speeds corresponding to the peak rotor contribution in order to size any rotor dedicated components. Point requirements are also needed at speeds of around 50 m/s (100 knots) in order to check that total lift can be maintained throughout the speed range. Values for wing area and rotor design speed can be chosen such that the possibility exists that higher vehicle speeds can only be reached by diving. This can be concluded from figure 5 where total vehicle lift is plotted throughout the speed range.

The impact of various combinations of parameters on overall aircraf design may be investigated as suggested earlier. Figure 14 shows th results of just such a study looking at the influence of wing area and rotor design speed on aircraft all up mass for a lift and thrust compound similar to the vehicle illustrated in figure 6. These trends are typical of the results obtained so far for any appropriate combination of compound vehicle, though clearly the design point performance and mission requirements influence the rate of exchange between wing area, VDES and vehicle mass.

Comparisons between the various types of vehicle described are at an early stage and detailed results presented here would be premature. Data is required for a range of aerofoil sections and a range of blowing coefficients before confirmation of any advantage of particular solutions.

Results so far obtained from the synthesis model have been presented in the form shown in figure 2. This carpet plot clearly shows the reduction in vehicle drag area which must be made in order to obtain certain mass and speed targets. The trends exhibited by these parameters are also evident emphasising the significance of their relationship. Model results have also consistently demonstrated an increase in speed performance over the conventional helicopter, however this is fundamentally linked to the point performance and mission requirements. One aspect of the initial studies which has been consistent is the realisation that if cost can be related to mass as has been historically assumed then the importance, in turn, of reducing vehicle drag becomes paramount for the indicated increase in speed performance to be exploited.

7.0 Conclusions

1. The capability to perform parameter trade-off studies has considerably enhanced the understanding of various compound helicopter concepts.

2. Results have demonstrated the extreme importance of vehicle drag reduction for 'high' speed rotorcraft.

3. The models allow complete feasibility and optimisation studies to be performed on families of advanced rotary-wing concepts.

8.0 Acknowledgements

The author wishes to acknowledge the help and advice provided by Rolls Royce plc in the preparation of this paper.

9.0 References

1 W F Durand, Aerodynamic Theory. California Institute Of Technology.

2 D C Whittley, Some Aspects of Propulsion for the Augmentor wing Concept.

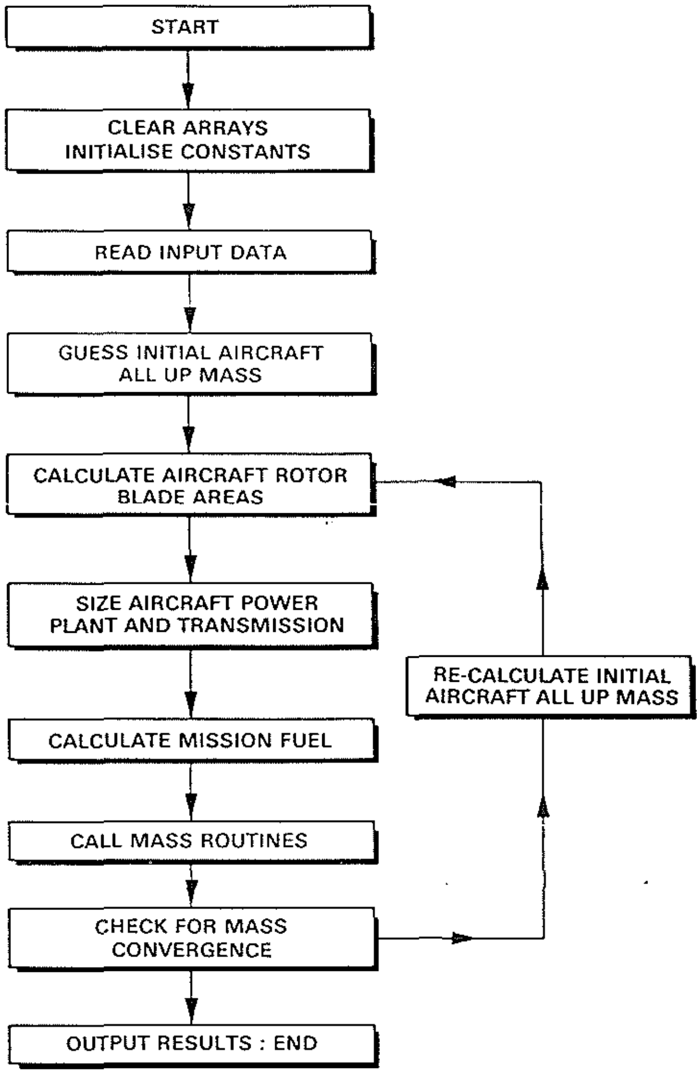

Figure 1
DESIGN SYNTHESIS COMPUTER MODEL FLOW CHART

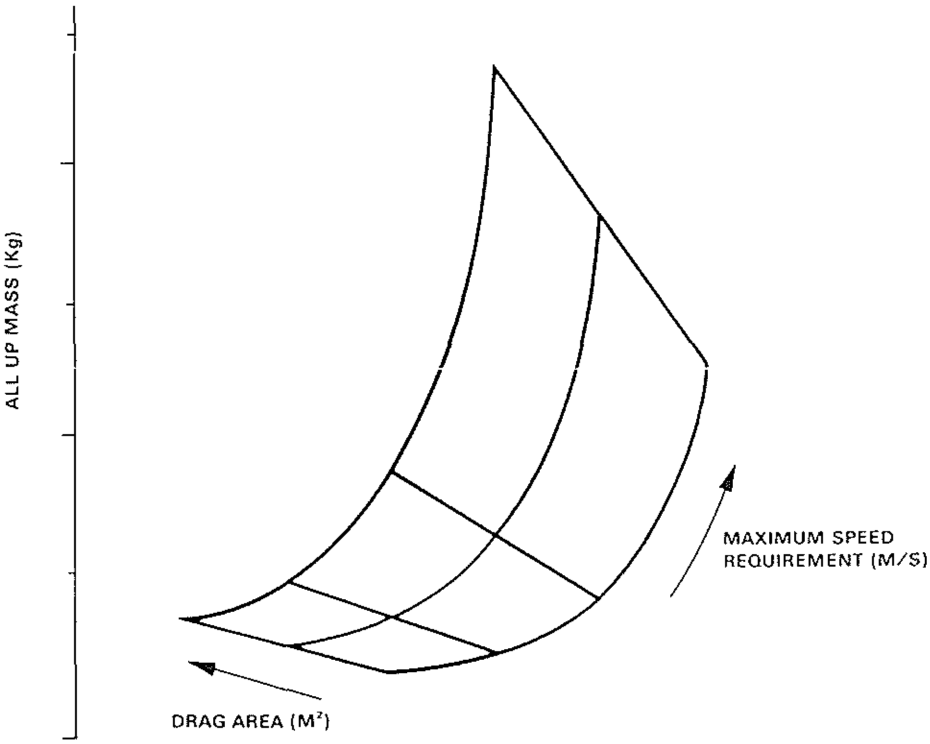

Figure 2
TYPICAL SYNTHESIS RESULTS SHOWING THE INFLUENCE OF
SPEED & DRAG AREA ON ALL UP MASS

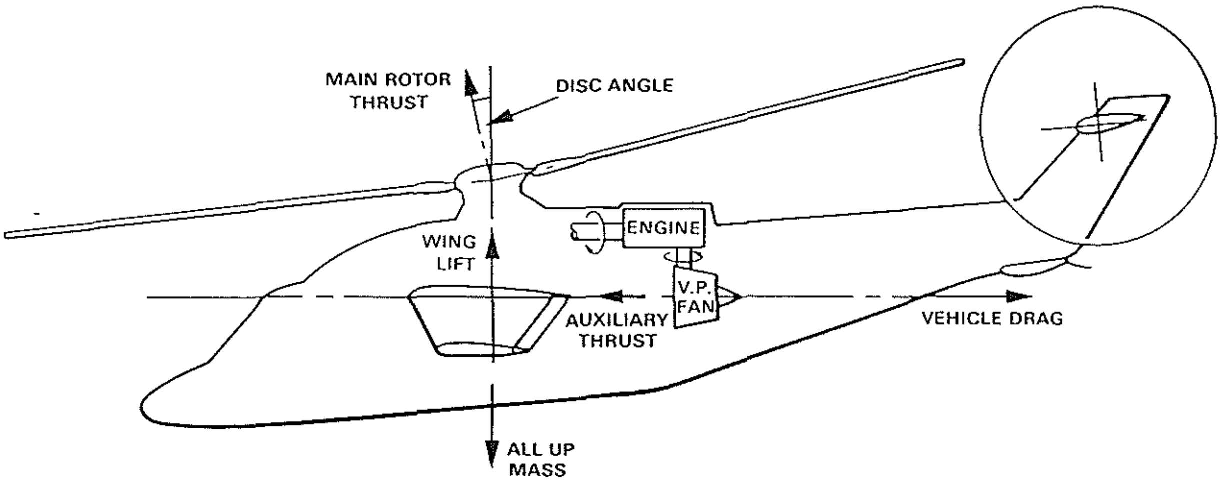

Figure 3
FORCE ANALYSIS FOR A LIFT AND THRUST COMPOUNDED HELICOPTER

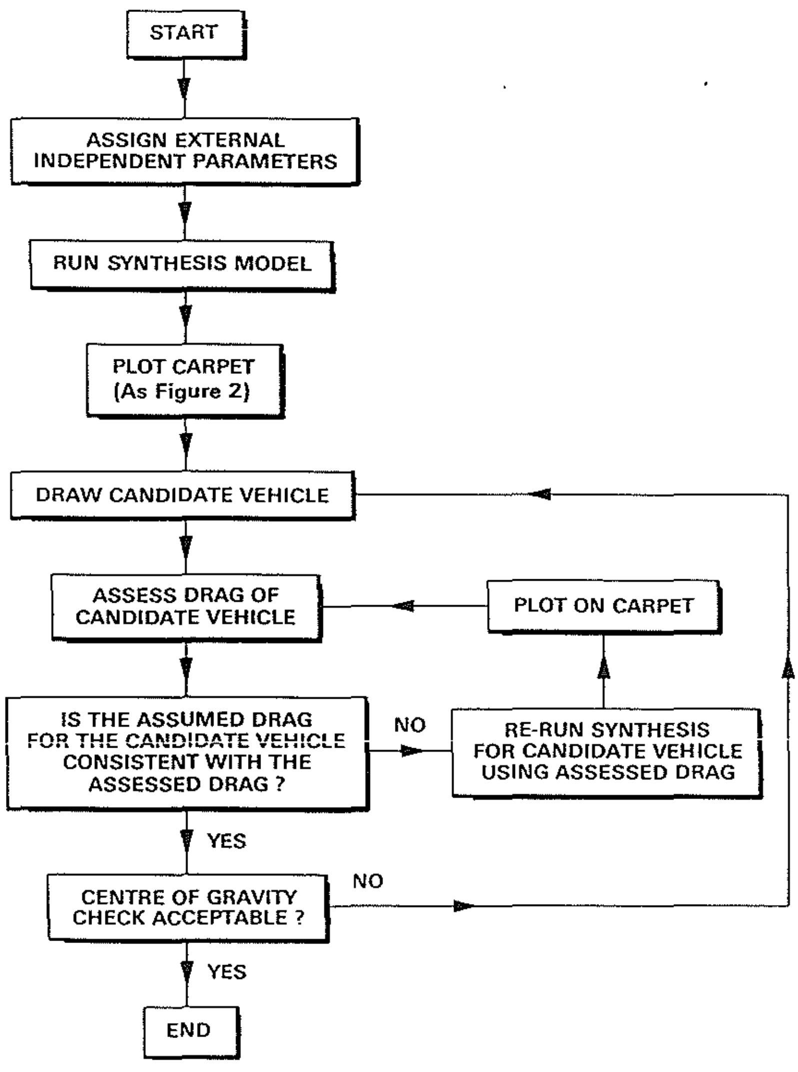

Figure 4
DESIGN SYNTHESIS ITERATION FLOW CHART

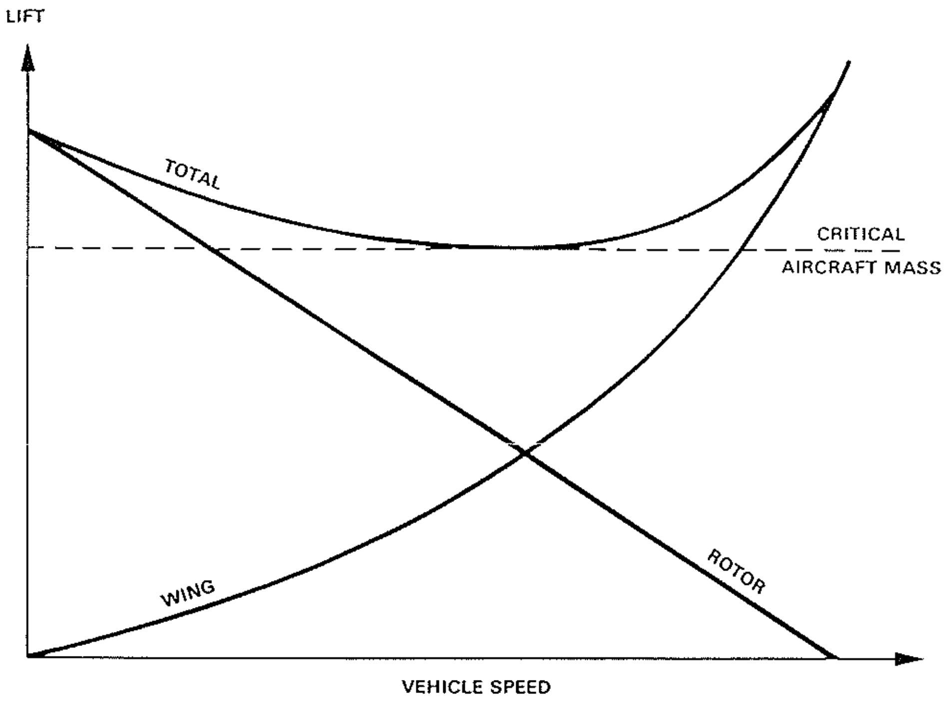

Figure 5
RELATIONSHIP BETWEEN VEHICLE SPEED AND TOTAL LIFT

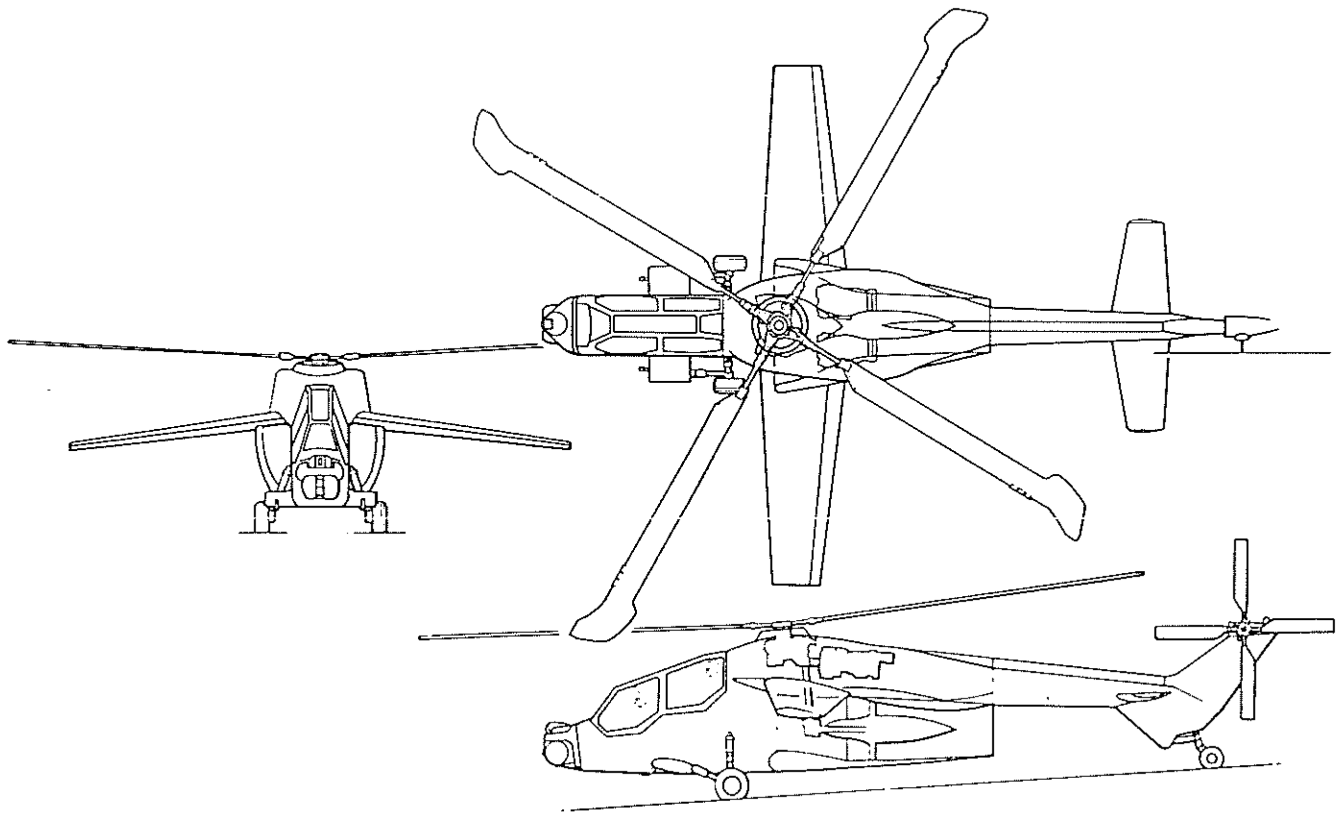

Figure 6
GENERAL ARRANGEMENT OF CANDIDATE VEHICLE

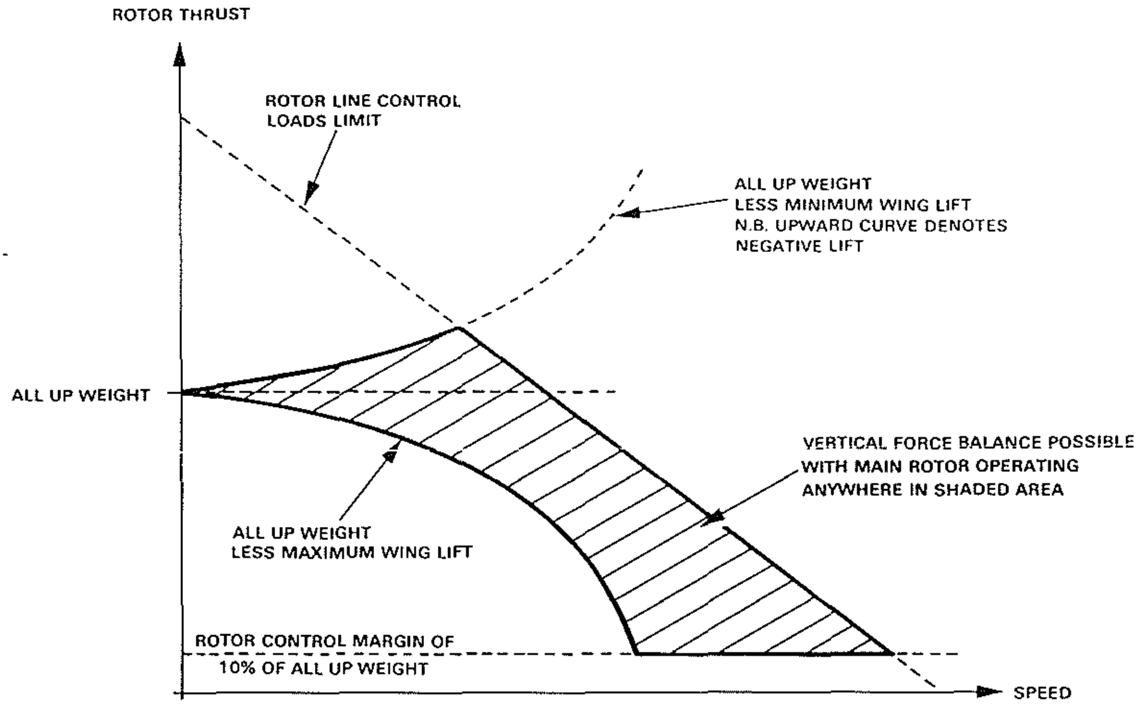

Figure 7
ILLUSTRATION OF ENVELOPE OF PERMITTED OPTIMISER SOLUTIONS

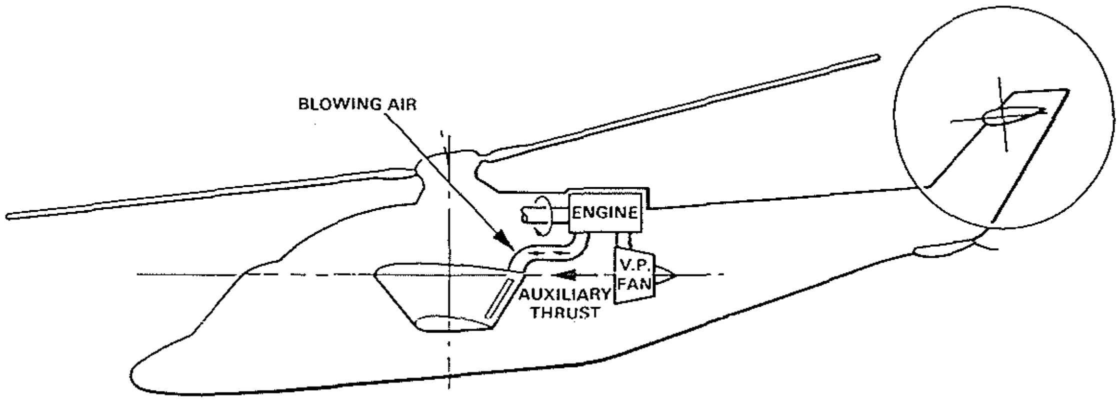

Figure 8
THE CIRCULATION CONTROL WING OPTION

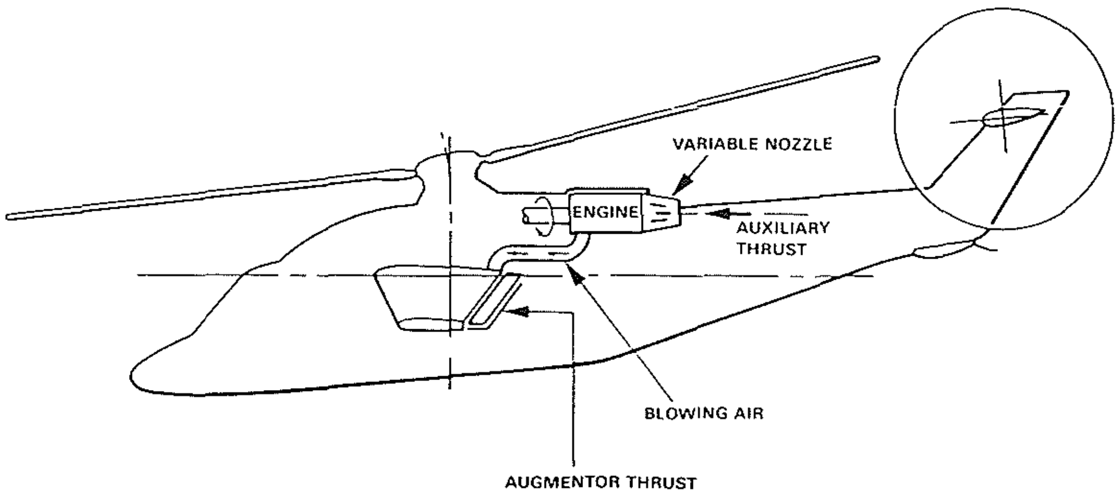

Figure 9
THE AUGMENTOR WING OPTION

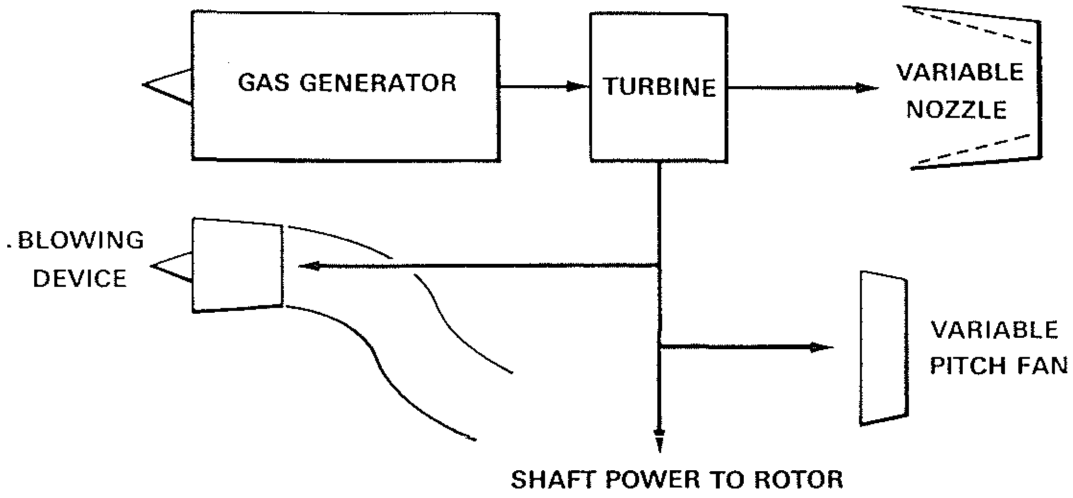

Figure 10
THE ESSENTIAL ELEMENTS OF A VARIABLE CYCLE ENGINE

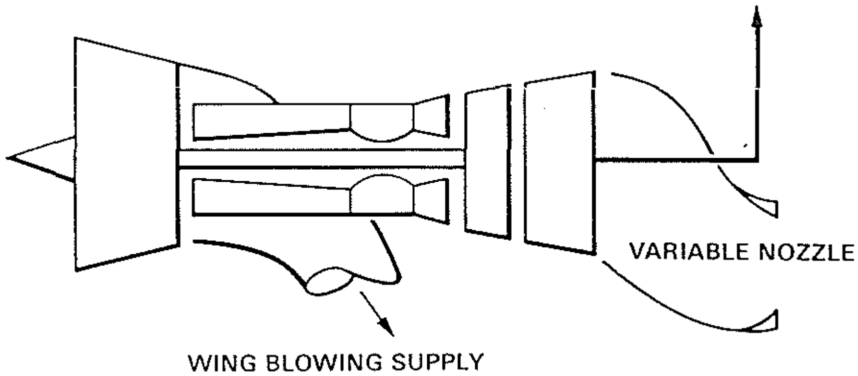

Figure 11
THE ZERO STAGE FAN VARIABLE CYCLE POWER PLANT

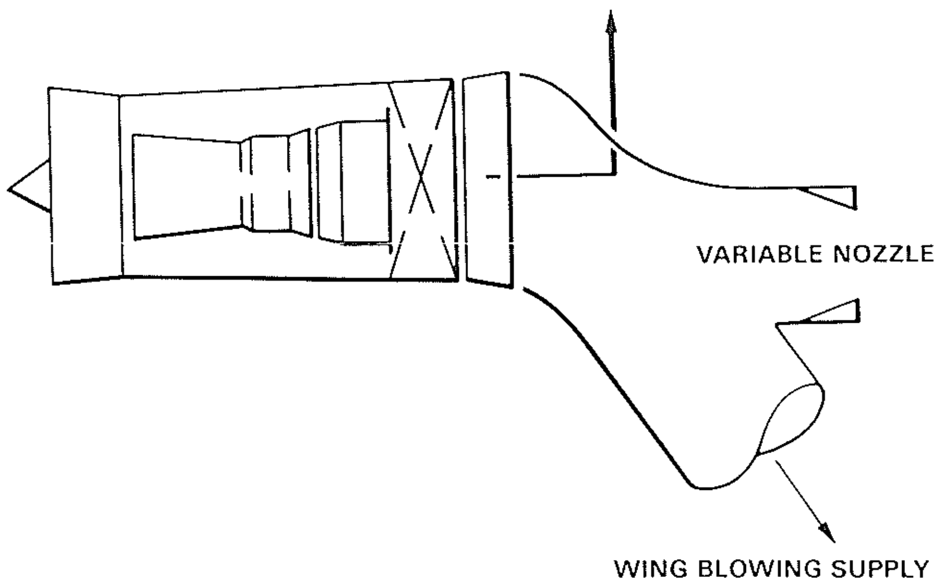

Figure 12
A MIXED FLOW VARIABLE CYCLE POWER PLANT

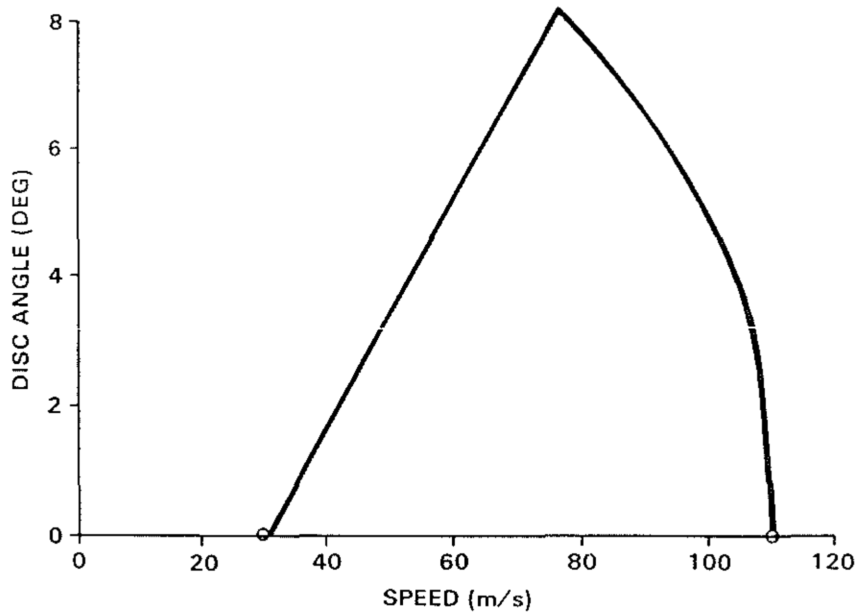

Figure 13A
COMPOUND HELICOPTER DISC ANGLE AS A FUNCTION OF SPEED

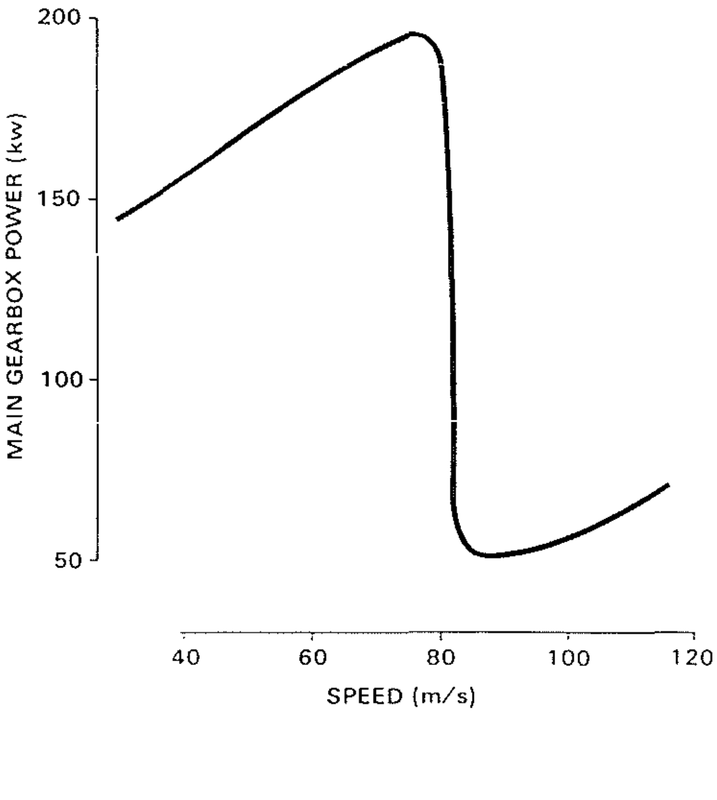

Figure 13B
COMPOUND HELICOPTER GEARBOX POWER AS A FUNCTION OF SPEED

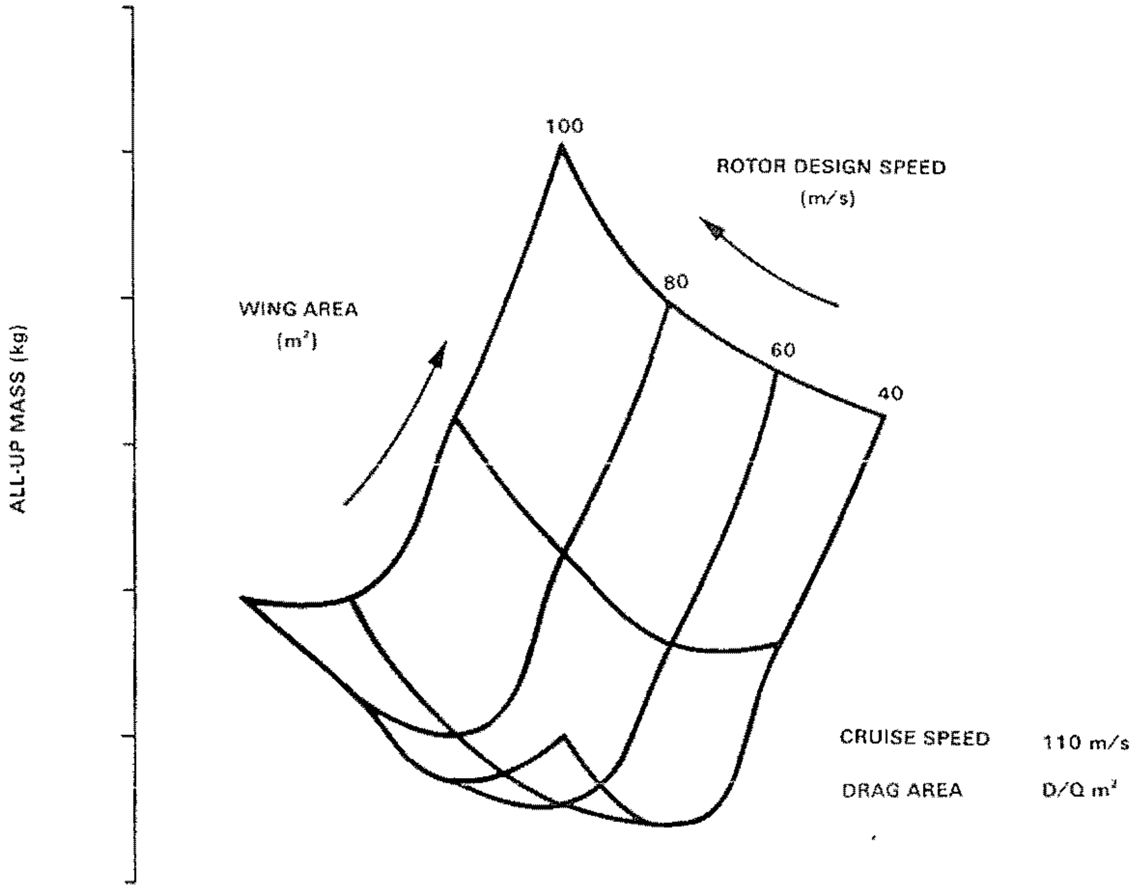

Figure 14
TYPICAL RELATIONSHIP BETWEEN WING AREA, ROTOR DESIGN SPEED AND ALL UP MASS

TABLE 1

COMPOUND HELICOPTER AUXILIARY DEVICES

DEVICE	LIFT OR PROPULSION
Conventional Fixed or Variable incidence wing	Lift
* Circulation Control Wing	Lift
* Augmentor Wing	Lift & Propulsion
Variable Pitch Ducted Fan	Propulsion
Powerplant Jet Thrust using a Variable Nozzle	Propulsion

* These options require a source of blowing which is provided by either a compressor driven from a gearbox or by bleeding air from the powerplant.