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PRELIMINARY INVESTIGATION INTO THE ADDITION OF AUXILIARY LONGITUDINAL THRUST ON HELICOPTER AGILITY

Lt P. J. Legge, RN
Royal Aircraft Establishment
Farnborough, UK.

P. W. Fortescue
P. Taylor
University of Southampton
Southampton, UK.

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ABSTRACT

This work is divided into two parts. Firstly, the agility requirements in specific manoeuvres performed by military helicopters are investigated. Secondly, a simple mathematical simulation of the helicopter accelerating and decelerating longitudinally is used to examine the advantages of auxiliary thrust.

For helicopters operating in the Nap-of-Earth environment the longitudinal acceleration and deceleration performance is shown to be uniquely important. Large improvements in agility, measured by a performance function, are obtained by adding auxiliary thrust. The need for the helicopter to change its attitude is drastically reduced, and the pilot workload improved.

The type of flight profile used is also examined, using a non-dimensional Froude number. There was no benefit in a 'maximum effort' flight profile, which consequently further improves the pilot workload.

Auxiliary thrust improved agility performance by increasing the helicopter's ability to change position whilst maintaining precise attitude control.

1 INTRODUCTION

1.1 The concept of agility

For the purposes of this study the word agility is defined as a measure of the ease with which a vehicle (in this case a helicopter) can change its state, for example from forward flight to the hover. It is considered desirable not to constrain the measure of agility to be a measure of time alone, but to allow freedom to include other parameters which might, directly or indirectly, affect agility or handling qualities as well.

Agility is closely allied to the speed, manoeuvrability and handling qualities of the helicopter. Agility demonstration requires clearly defined beginning and end states, and clearly defined constraints in order to apply other parameters to the measure of agility. These other parameters can be loosely collected together in terms of handling qualities, and/or the ease with which the helicopter can be flown: *ie* the extent to which the pilot can adopt carefree manoeuvring within his particular environment. The environment is important because manoeuvres which are relevant to one operator may never be employed by another. This means that any measure of agility for a helicopter must be specified for a particular manoeuvre or sequence of manoeuvres.

Other factors, such as the pilot's workload, his ability to achieve precisely the states required, safety margins and physiological effects may all become constraints within the execution of a manoeuvre, and can, if necessary, be included in the measure of agility. The time taken to execute the change of state remains of paramount importance, however, and the ultimate aim is to reduce this time without prejudice to the other variables involved. As such it is a complex task due to the large number of variables.

1.2 The agility requirement

Agility has become an important helicopter design consideration because the speed and manoeuvrability of the modern helicopter has improved to the point at which other physical and environmental factors have become constraints. The need for the agile helicopter is most significant in NOE flight as practised in the battlefield environment. The battlefield helicopter needs to be agile to avoid detection and missile attack.

The agility of current helicopters is insufficient to allow the use of speeds commensurate with the requirement to maintain operational effectiveness in the battlefield environment. If one wants to avoid detection, it is essential to fly NOE, and one is forced to fly at drastically reduced speed thus reducing payload/range and increasing the time on task.

In addition, where improved agility results in improvements in helicopter handling qualities and controllability, there are benefits in safety and pilot fatigue which are important. The concept of agility recognises the helicopter only as a vehicle changing from one state to another and consequently can be constrained by any parameter which one includes in the analysis. As such, it is a useful way of improving the total operational effectiveness of the helicopter.

There is, therefore, a strong requirement for the study of agility, and for improvement of the capabilities of the agile helicopter, particularly in military applications. It is important, however, to ensure that any study is directed towards the type of manoeuvre considered most important, and most likely to yield significant improvement. This can only be done after consultation with the operators. The need for improvements in agility is at present mostly felt in battlefield helicopters.

Padfield,[1-2], indicates that the possible inclusion of additional lifting surfaces, thrust producing devices and rotor brakes will affect the agility performance. There is an indication that most of the work carried out on agility-related topics is applied to conventional designs and very little has been applied to the design of an agile helicopter with a possibly unconventional configuration. This analytical study can be divided into two parts:

(i) An investigation to determine manoeuvres of importance for military helicopters.

(ii) A computational exercise on selected manoeuvre(s) from (i) to determine the optimum parameters.

2 INTER-SERVICE INVESTIGATION OF AGILITY REQUIREMENTS

The purpose of this investigation was to identify the manoeuvres considered most important by pilots in the British Army, Royal Air Force and Royal Navy. Test pilots from each of the three Services were interviewed and their opinions collated. An analysis of helicopter manoeuvres prepared by D.J. Merkley[3], was used as the basis for the investigation. The following manoeuvres were suggested:

(i) 'Pop-up' (zero forward velocity)

(ii) 'Bob-up'

(iii) Lateral acceleration.

(iv) Lateral acceleration and turn.

(v) Longitudinal acceleration.

(vi) Longitudinal deceleration.

In addition to these, other manoeuvres which were considered particularly relevant to the mission type were discussed. Examples of these are the deck landing and launch of Naval helicopters, and the tactics used to evade a missile attack.

The results from the Royal Navy investigation were somewhat mixed. This was due to the variety of different roles which were carried out - ASW, SAR and Commando. The only role which revealed a useful application for agility study was the Commando role. There was indication that an improved longitudinal performance which made fewer demands on the pilot to change the attitude of the helicopter in pitch would be desirable. This suggests that any agility study should follow change in position criteria rather than change in attitude criteria.

The need to accelerate and decelerate longitudinally without change in aircraft pitch attitude was noted by Army pilots flying Lynx helicopters in an anti-tank role. This is important to prevent the following:

(i) Loss of visual acquisition or radar lock during pitch forward on acceleration.

(ii) Appearance of the aircraft tail rotor, with its attendant noise source, above the line of cover or tree-line during pitch forward on acceleration.

(iii) Loss of visual cues for the pilot during aircraft pitching.

(iv) Danger of a tail-rotor ground strike during the pitch back on aircraft deceleration.

(v) In order to prevent the main rotor entering autorotation on deceleration it may be necessary to allow the helicopter to climb during the nose-up manoeuvre. This is extremely undesirable as, for this type of mission, above tree-top height is too high. The heights above ground level are less than 50 ft at all times.

Army pilots also indicated other possible limitations to further improvements in agility due to fast change of attitude (rather than position). It was considered unlikely that further increases in angular rates would be too much for the pilot, but it was felt that these might make navigation, an essential factor in NOE, almost impossible for the crew. There would be a consequent need for uprating the performance of some avionic equipment. Army helicopters operate under circumstances which are entirely dominated by their local terrain. The agile helicopter is essential to Army operations, and it appears that the biggest room for improvement lies in the longitudinal acceleration and deceleration without excess attitude change. This must imply a change in the basic helicopter configuration.

Royal Air Force pilots flying helicopters in the Battlefield Support role also indicated that there was substantial room for improvement in longitudinal agility performance. The most important point made by these pilots refers one to the definition of agility: 'A measure of the ease with which the helicopter can change its state.'

It is essential that all the relevant parameters are included, not just the time factor. In this case, turning rates are not the dominant factor in the study of agility, but *workload* is. The ability to accelerate and decelerate without pitching the aircraft would drastically reduce the pilot workload. At present the pilot's workload is too high in trying to remain low, at speed, with the aircraft attitude pitched forward or back. The pilot is constrained by his need to avoid tail rotor ground strikes, autorotation entry, or any gain in height. This area holds the greatest room for improvement.

The object of NOE flying is to avoid detection by the use of cover, so the helicopter must be able to move quickly and discretely from one item of cover to the next. Any increase in height will affect detectability. The helicopter should have the following characteristics:

(i) High dash speed.

(ii) Good longitudinal and vertical acceleration/deceleration.

(iii) Small turn radius.

(iv) Good handling qualities and controllability.

(v) Low pilot workload.

Most modern helicopters have greater capability in these areas than did their predecessors. Most can generate sustained normal accelerations of at least +1 g in turns, and some can approach this figure longitudinally. However, these accelerations can only be achieved by making significant lateral or longitudinal attitude changes, and there is always an undesirable requirement to gain height in deceleration. To avoid these effects the pilot becomes unwilling to use his speed capability.

To achieve longitudinal acceleration and deceleration without attitude change, some form of longitudinal or X-force is required. There may be human factors which will impose constraints on the amount of acceleration allowable; this will be greater for specialised attack helicopters. In view of the current state of helicopter agility research and of the results of the investigation carried out in all three British military helicopter operators, it was concluded that the greatest benefit to helicopter agility was likely to be achieved by provision of longitudinal thrust, or X-force.

3 COMPUTATIONAL ANALYSIS

3.1 Theoretical considerations

In studying the application of an X-force to the longitudinal motion of a helicopter, we are interested mainly in a vehicle which accelerates from rest, reaches a cruise speed and then decelerates to a stop. Obviously, the distance, acceleration rates, and the cruise speed are all variables. J.P. Jones[4], deals with the problem by ignoring all movements normal to the flight path and all manoeuvres in roll, pitch and yaw. Consequently the problem reduces to that of a point mass in linear acceleration from rest to a cruise speed - a simple kinematic model where change of position criteria are dominant over change of attitude criteria.

For a given distance to be covered, and for a given combination of acceleration and deceleration rates there is a minimum transition time, which corresponds to the case in which the vehicle spends all of its time in acceleration and deceleration, and none in cruise. This is the so-called 'maximum-effort' situation. This minimum time to cover a distance is a useful parameter as it depends only on the acceleration rates available. The speed achieved in this period is consequential rather than an independent variable. This suggests that, instead of working in completely arbitrary values one should use the minimum time as the standard of time for non-dimensional analysis. A non-dimensional Froude number, F , can be defined which is the ratio:

$$F = \frac{\text{Distance travelled in acceleration/deceleration}}{\text{Total distance travelled}} .$$

In the maximum effort situation F is unity. In addition, the Froude number can be related to the associated times so that:

$$\frac{T}{T_m} = \frac{1 + F^2}{2F} .$$

The time penalty for using a particular mission profile (acceleration, cruise, deceleration) is given by the ratio T/T_m in this equation. Fig 1 shows the variation of this ratio with F . In the range $0.6 < F < 1.0$ this function varies slowly and there is only a 10% time penalty for operating at Froude numbers as low as 0.642.

From this arises the concept of the 'useful speed', $V_u = 0.6V_m$. This is the highest speed which will be of value in manoeuvres of this kind. For typical acceleration rates the useful speed for a 3 km journey is only about 70 kn. It becomes necessary to travel about 16 km before a speed of 160 kn becomes useful. As shown in Fig 2, there is little to gain by increasing the speed of conventional helicopters over the distances envisaged for the anti-tank role. However, if by some means, as suggested, the acceleration rates are drastically increased then full advantage of this cannot be taken unless the maximum speed rises as well. With 0.3 g available over a distance of 8 km the useful speed becomes 200 kn.

It is essential to monitor the performance of the helicopter model, whereever possible, in terms of Froude number. To achieve maximum Froude number, unity, is a pre-requisite for achieving minimum transition time. The measure of agility will, however, include other parameters apart from transition time, and it is necessary to observe the relationship between Froude number and agility. The time spent in cruise has an effect on pilot workload and his ability to track a target, and fire missiles. It is likely that a measure of agility which includes parameters related to the pilot workload will indicate an optimum Froude number which is less than unity.

3.2 The helicopter model

In order to model mathematically the helicopter in its environment it is essential to make some basic assumptions and simplifications in order to reduce the number of variables involved. It is also possible to choose between two basic types of model.

The first of these is based on simple kinematic principles - the model is reduced to that of any vehicle having attitude, mass, velocity, drag and thrust. Although this is a drastic simplification of the helicopter itself it is possible to use such a model by the use of constraints which restrict its applicability. For example, the helicopter attitude is constrained within certain limits to prevent entry into autorotation at any combination of mass, speed and attitude. The rotor system is constrained to be a constant thrusting device acting at a fixed angle to the helicopter fuselage.

Alternatively the helicopter can be modelled around the traditional flapping and trim equations with all the rotor parameters included. This provides the response of the rotor and of the helicopter to a manoeuvre. The number of variables involved is extremely large, and the problem is quite complex in solution. This type of model is more suitable for an analysis of agility in changing attitude than in changing position. It is extremely well suited to a study of the pitch and roll response of the helicopter and its ability to change attitude state with ease. A simple rectilinear approach is the most appropriate method of studying a helicopter which is accelerating and remaining in level flight.

The following assumptions have been made:

(i) The weight of the aircraft remains constant.

(ii) The amount of thrust available is constant at a pre-determined level. (Reverse thrust is 2/3 forward thrust.)

(iii) The drag of the helicopter was considered to be the normal parasite drag, with values suggested by Refs 5 and 6.

(iv) All accelerations and decelerations over small periods (1 second) were considered linear.

(v) Changes in attitude were considered instantaneous. This is the major reason for rejecting the model based on rotor dynamics. If the positional changes required are achieved without recourse to large changes in attitude then it is reasonable to assume that these changes are instantaneous and that they do not affect the overall transition time. The assumption is valid for the unconventionally configured helicopter with X-force available through auxiliary thrusters. The model is optimistic for conventional helicopters, so the magnitude of any improvement gained from the use of auxiliary thrust will be pessimistic which is considered acceptable.

(vi) Engine response is also considered instantaneous, in view of the relative duration of a typical engine run-up or run-down in comparison with the likely transition time.

(vii) The helicopter attitude would vary between pre-determined limits.

(viii) The helicopter height remains constant. This is achieved by considering the main rotor as a thrusting device which has a vertical component equal to the aircraft weight.

After simplication of the model equations and choice of helicopter size and drag characteristics (Lynx class), five variables remained:

(i) The angle of aircraft pitch forward during acceleration A

(ii) The angle of aircraft pitch back during deceleration A_1

(iii) The speed at which the aircraft enters cruise V_2

(iv) The available thrust, in terms of g , J

(v) The distance to be covered from hover to hover S .

After discussion with pilots of their ideal limits, the angle of nose-down pitch was limited to vary between 0^o and 15^o and the angle of nose-up pitch to vary between 0^o and 10^o. The computer program was used to simulate conventional helicopters at greater angles of pitch than these, but as indicated earlier the results must be considered optimistic.

These five variables were grouped and transition time monitored as follows:

(i) Helicopter configuration - angles of attitude and allowable thrust.

(ii) Helicopter performance - transition time and allowable angles (this to be the second parameter of an agility measurement).

(iii) Helicopter flight profile - to include relative times of acceleration/ deceleration and in cruise, *ie* Froude number.

This means that the problem is reduced from a large number of independent variables to one of three defined characteristics: configuration, agility performance and flight profile.

4 MEASUREMENT OF AGILITY PERFORMANCE

4.1 Choice of variables and function

The need to actually measure a quantity which can be called helicopter agility performance is paramount. It is likely that any measurement will be relevant only to a particular type of manoeuvre, but it may be possible to apply weighting factors to manoeuvres in order to arrive at an all round figure for a particular helicopter. If this is possible, then it will be possible to compare similar helicopters in terms of agility performance.

The first element of an agility measurement is certain to be the transition time to complete a change of state. As agility is defined as the ease with which a helicopter can change its state, other parameters need to be included in the measurement.

The major question is "Which parameters, and how are they to be measured?". The pilot's workload is one which is very relevant but extremely difficult to measure. Because the study is directed towards the longitudinal motion of the helicopter, and the effect of adding auxiliary thrust, it was felt that by far the most important parameter was the aircraft attitude. It is easy to measure, directly related to workload, and the performance equation can be kept relatively simple. This means that the problem of validation is kept within manageable limits.

This measurement of agility performance is relevant only to the helicopter performing this type of accelerating manoeuvre. It has no relevance in a banked turn or with high yaw rates, and should never be used out of context. The parameters used to develop the measurement are the transition time for the manoeuvre, the angle of aircraft pitch, and the time for which that pitch is maintained.

The performance function is to involve three variables:

(i) transition time T

(ii) angle of forward pitch A

(iii) angle of aft pitch A_1 .

It is likely therefore, that with three variables, two weighting functions would be required. These are K_4 and K_5 , operating on A and A_1 with the resultant performance measure P , having units of seconds. The performance function, in general terms, was considered to be:

$$P = T + K_4 \text{ (function of A)} + K_5 \text{ (function of } A_1) \; .$$

A reduction in P represents an improvement in agility performance. A reasonable function, from experience in optimisation procedures, might be

$$P = T + K_4 \left(f_n A^2\right) + K_5 \left(f_n (A_1)^2\right) \; .$$

However we are not interested solely in the maximum angle of pitch, but also in the amount of time spent at that angle. It is necessary to integrate with respect to time, and the performance equation finally becomes:

$$P = T + K_4 \int_{\text{accel}} A^2 dt + K_5 \int_{\text{decel}} (A_1)^2 dt \; .$$

The terms A^2 and $(A_1)^2$ could be replaced by terms in $(A)^n$ and $(A_1)^n$. These terms at present penalize more heavily large diversities in attitude. This is extremely desirable. It is possible that a more powerful function such as A^4 would penalize large angles too heavily. This can only really be determined by trial and error and by validation, but contemporary control work uses A^2 .

4.2 Validation

This function has no basis in actual experience unless it can be validated by use of a suitable example. The example is used to show that the function can give realistic measurement of the agility performance, and to indicate the most reasonable values for the constants K_4 and K_5 . In carrying out this validation exercise it is essential to use a conventional helicopter configuration. In addition, it is necessary to adopt a mission profile which is familiar to the helicopter user, as it is he who will look to the validation exercise to be convinced of the validity of the performance function. If results can be obtained with familiar data which corresponds to familiar experience there is reasonable justification for the theory.

In order to do this a large range of values of K_4 and K_5 were used, and distances of 500 and 1500 m. A conventionally configured (*ie* no auxiliary thrust) helicopter was used, and the attitude angles were varied independently between 0^o and 60^o (forward) and 0^o and 30^o (aft). The values of the performance function were then plotted against attitude angle. The cases of acceleration and deceleration were treated separately.

In the analysis of these curves, Figs 3 and 4, one is looking for the value of the constant which produces an optimum, or minimum, at the angle which the pilots consider is the optimum for the conventional helicopter. In addition it is necessary for the optimum to be well defined, but with a reasonable angular range, say, of about 10^o. The comparison is based on judgement, of course, and it is an attempt to match another quantity based on judgement. In the result, however, there are good grounds for accepting the figures produced as they perform well in indicating the preferred attitude range for flying a conventional helicopter. The best curves are achieved with the values:

$$K_4 = 0.050$$
$$K_5 = 0.100 \ .$$

The variation of distance in this validation exercise had no effect. For the acceleration case the curves produced by $K_4 = 0.05$ gave good results up to forward pitch angles of 30^o, followed by increasing penalties. In the deceleration case the breakaway attitude angle was 20^o. This was considered to be reasonable and in accordance with current experience. On completion of the validation exercise the performance function can be used for non-conventionally configured helicopters for examining their agility performance. In particular the following comparisons can be made:

(i) Configuration vs agility performance .

(ii) Flight profile vs agility performance .

5 RESULTS

5.1 Configuration

Combinations of differing thrust limits, forward and rearward attitude angle limits were used to examine the effect of changing configuration on the agility performance. The amount of available thrust was varied up to 0.5 g as shown in Fig 5. It is the use of aircraft attitude in addition to the available thrust which is of significance, Figs 6, 7, 8. The amount of pitch necessary to produce the optimum agility was never greater than 10^o of forward pitch and 5^o of aft pitch except with very low thrust levels. For all practical applications of auxiliary thrust to the helicopter these figures can be taken as the relevant maximum limits. They are of significance for several reasons.

(i) They allow full use of likely radar 'locked-on' tolerances.

(ii) They allow the pilot to maintain visual cues at all times.

(iii) The use of 10^o forward pitch and 5^o aft pitch reduces the requirement for auxiliary thrust by 0.1 g, without significant reduction in agility performance.

(iv) Obviously, the more thrust which is available the better, but the study shows that with the configuration 30 10 05 (0.3 g thrust, 10^{o} forward, 5^{o} aft) the agility performance is significantly better than for the conventional helicopter.

For the configuration 00 30 15 (no thrust, 30^{o} forward, 15^{o} aft), the optimum conventional configuration, the agility performance was measured at 49 over 500 m . The configuration 30 10 05 produces a measurement of 27 over the same distance. It is important to note that further increases of auxiliary thrust, say to a configuration of 50 10 05 improve the agility only to a value of 23. The law of diminishing returns applies to this case, and 0.3 g was found to be adequate.

(v) These runs were carried out with a maximum cruise speed of 150 kn. Very few mission profiles, only those with high acceleration rates, reached the cruise state. The effect is a slight reduction in attitude angles for the optimum case.

(vi) The 5^{o} limit in nose-up pitching is useful in that it keeps the helicopter away from autorotative entry at all speeds under consideration. For this reason it is thought that the provision of reverse thrust is a particularly essential requirement for the agile helicopter.

Operational effectiveness are the key words in this analysis. The intention is not merely to reduce the time of transition from A to B. It is to produce a vehicle which is better able to carry out its operational mission. This implies that there are a large number of factors to be taken into account. The fact that this type of vehicle can outperform while remaining practically horizontal is of significant importance. It is easier to fly and will be more effective in the visual or radar assisted tracking of targets. It can fire missiles and maintain control over them throughout its phases of acceleration and deceleration. The pilot's workload is reduced, and his ability to concentrate on the tactical situation is increased. The helicopter is more operationally effective.

5.2 Mission profiles

Mission profiles were varied by using different values of distance along with different values of cruise velocity. For each distance the cruise velocity was increased until a Froude number of 100% was achieved. For distances of 250 m to 2000 m this produced a range of values of agaility performance with a range of Froude numbers between 10% and 100%, shown in Fig 9.

There is no advantage in operating at Froude numbers greater than 75%. For most applications, Froude numbers of the range 60%-90% are ideal - there is usually a deterioration of agility performance as the Froude number approaches 100%.

There are other significant advantages in not operating at $F = 100\%$, the 'maximum effort' situation:

(i) The pilot has more time to assess the distance available for deceleration, and knows his cruise speed accurately before commencing deceleration.

(ii) There is less requirement for an accurately determined point at which to change from acceleration to deceleration.

(iii) The pilot's workload is reduced as a result of these factors and the helicopter is easier to fly.

(iv) There is a reduced requirement for absolutely accurate flying, reducing the level of skill required and increasing the likely operational effectiveness.

6 IMPLICATIONS ON FUTURE HELICOPTER DESIGN

The requirement to add an X-force to the conventional helicopter leads to some form of vehicle using either a tilting rotor, or auxiliary thrust. Tilt rotor and tilt wing solutions imply larger vehicles which will be inherently more difficult to fly in the NOE environment. Because of this the auxiliary thrust solution seems the more likely, despite possible weight problems. Twin ducted fans or a single rear propeller are possible solutions, as is the use of additional powerplant. All these solutions imply extra cost, complexity and weight.

The best method for controlling the available longitudinal thrust would also need careful study. Simple schemes could include a straightforward thrust control mounted on the collective lever, or more advanced control configured vehicle techniques could be employed. These would be of particular benefit in reducing the pilot's workload. Optimization of any solution is a problem for simulation. This presents the problem, ultimately, of simulating realistically the longitudinal acceleration.

It is likely that future helicopters will need auxiliary thrust if their maximum speeds are to be increased. This study shows that there are significant gains to be made in agility if this thrust can be available to accelerate and decelerate the helicopter.

This will, for the first time, give the helicopter pilot the freedom to operate without needing to use large nose-up and nose-down attitudes in the NOE environment. Acceleration performance not dissimilar from fixed-wing aircraft should be achievable, with the added advantage that the helicopter has always possessed direct-lift control.

There are problems in the production of the high speeds. It is essential to realise that full benefits from improvements in agility will not be gained if maximum cruise speeds are not allowed to rise as well. With higher acceleration rates achievable through auxiliary thrust, the useful speed over typical NOE distances will rise towards 200 kn. 300 kn is a target to aim for which will ensure good agility with high acceleration.

There are several types of rotorcraft which are, at present being developed to improve maximum speeds. One of these, the Advancing Blade Concept helicopter (ABC), would appear to be particularly relevant to the agility performance case, as well as to the improved speed case. The ABC is an excellent vehicle for the addition of thrust in some form, either using turbofans or ducted propulsors. With the addition of reverse thrust, the agility performance of this helicopter can be improved to match its improved speed capability. A small, fast, agile helicopter of ABC design, with additional, reversible thrust would be an ideal vehicle for the anti-tank role.

A simulation study carried out at RAE Bedford[2], indicated that there were no piloting problems incurred by the addition of an X-force control. Pilots liked the ease with which they could change the aircraft's position and speed by the use of a simple twist-grip control on the collective lever. Workload was definitely reduced, and the aircraft was easier to fly.

Provision of the X-thrust by using turbofan powerplant would be the simplest policy to adopt, but there are penalties to pay in terms of weight and complexity, with resulting cost and reliability problems. This can be offset, to some extent, if the additional engine or engines are easily removable. They can then be considered as aircraft role equipment, and can be fitted to the helicopter only when a mission requiring high speed and/or high agility is to be flown. When low speed, or load-lifting missions are required, the engines could be removed with a resultant improvement in payload. These engines would need to be entirely self-contained, having only fuel and control connections to the aircraft. Without the need for flight safety checks (given an emergency shut-down system), the engines could be removed or fitted in the time available for a role change. The task would be similar to that of loading torpedoes. The resulting multi-role helicopter with high speed and high agility capability would be very attractive.

Important points to monitor in such a design would be the engine response times and the effect on the mission payload of the auxiliary propulsion units. In the NOE environment, at least, the benefits would outweigh the disadvantages.

7 CONCLUSIONS

(1) The study has shown a need for improvement in longitudinal agility in military helicopters. There are large benefits to be gained by improving the helicopter's performance in a hover to hover transition.

(2) Agility is defined as the ease with which the vehicle changes state. A performance function has been developed which gives a measure of agility derived from transition time and aircraft attitude. This type of function could be developed to include other parameters, but it is considered essential to retain the contribution of transition time.

(3) Addition of auxiliary thrust (at 0.3 g) produces a 30% improvement in agility. Attitude can be allowed to vary between 10° nose-up and 5° nose-down without degrading the agility performance. This allows radar and visual tracking of targets and removes the danger of tail-rotor ground strikes.

(4) There is no benefit in attempting a maximum-effort flight profile. A Froude number of about 65% produces satisfactory agility. This is much easier for the pilot to fly. Agility is very closely related to pilot workload.

(5) Over long distances the required 'useful speed' with improved agility may require an increase in helicopter maximum cruise speeds. Auxiliary thrust will be required to achieve these speeds as well as to improve the agility performance.

(6) Developments in the agility of conventional helicopters have been achieved by improving the helicopter's ability to change its attitude. Improvements in agility with helicopters with auxiliary thrust are achieved by improving the helicopter's ability to change position whilst maintaining precise attitude control.

LIST OF SYMBOLS

F	Froude number
T	*transition time*
T_m	transition time (maximum effort)
V_u	useful speed
V_m	maximum speed
A	forward pitch angle
A_1	aft pitch angle
V_2	cruise speed
J	*available forward thrust (in g)*
J_1	available reverse thrust (in g)
S	distance
K_4	performance function constant (acceleration)
K_5	performance function constant (deceleration)
P_a	agility performance (acceleration)
P_d	agility performance (deceleration)
P	agility *performance*

LIST OF REFERENCES

1. G.D. Padfield, B.N. Tomlinson — Piloted simulation studies of helicopter agility. Fifth European Rotorcraft and Powered Lift Aircraft Forum (1979)

2. G.D. Padfield, B.N. Tomlinson, P.M. Wells — Simulation studies of helicopter agility and other topics. RAE Technical Memorandum ST 927 (1978)

3. D.J. Merkley — An analytical investigation of increased HP on helicopter agility in NOE environment. USAAMRDL, Fort Eustis (1975)

4. J.P. Jones — Accelerated flight. Westland Helicopters RP399 (1971)

5. A.R.S. Bramwell — Helicopter dynamics. Edward Arnold (1976)

6. C.N. Keys — Rotary wing aerodynamics, Vol. II. Performance prediction of helicopters. NASA CR-3083 (1979)

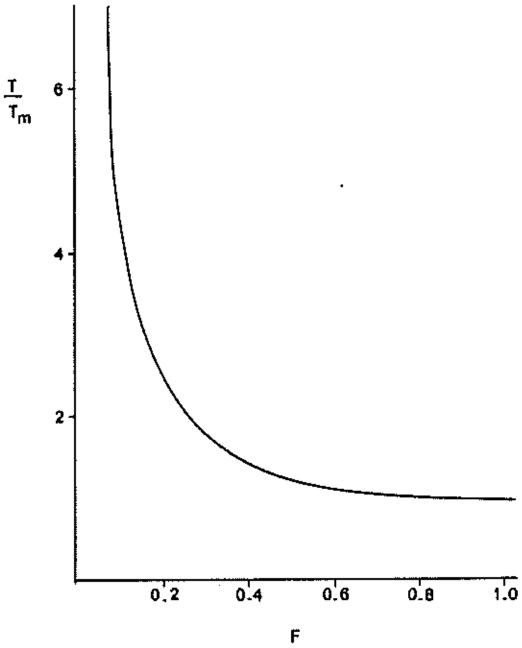

Fig 1 Time penalty as a function of Froude number

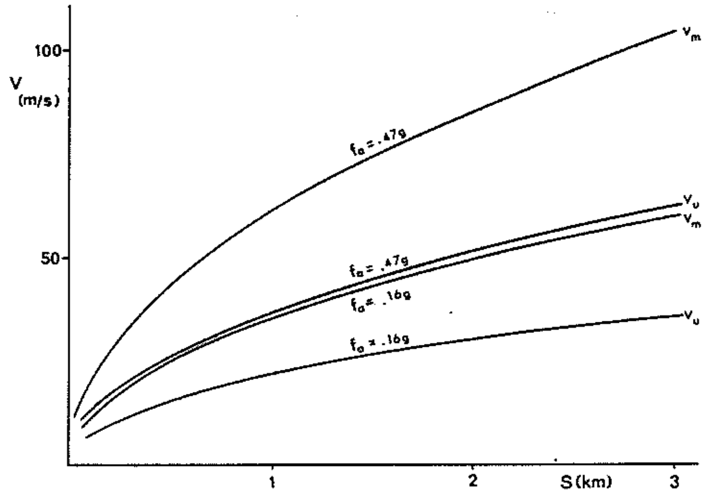

Fig 2 Minimum and useful speeds as a function of distance and acceleration

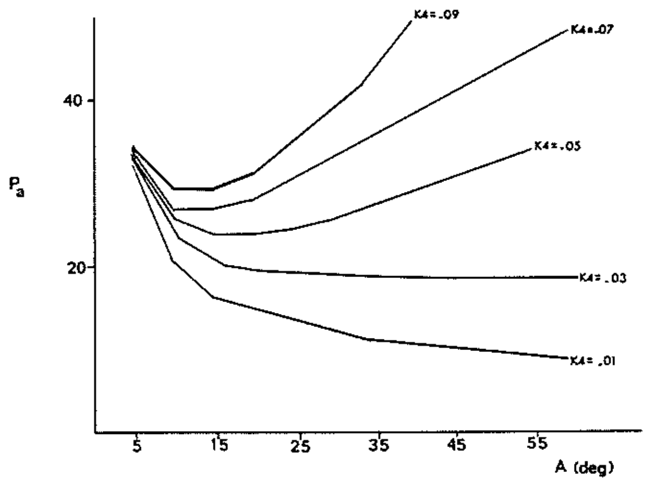

Fig 3 Choice of weighting function K4 (acceleration)

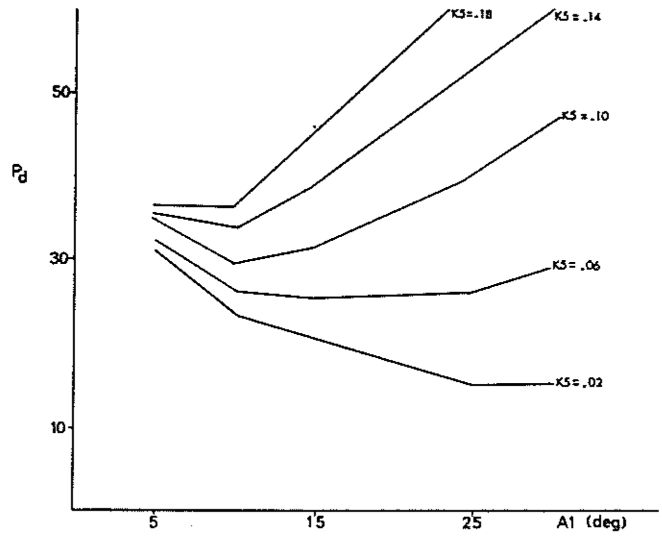

Fig 4 **Choice of weighting function K5 (deceleration)**

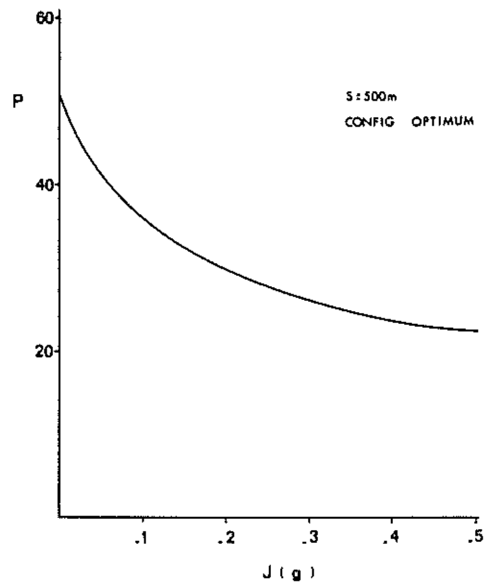

Fig 5 **Agility as a function of thrust (g)**

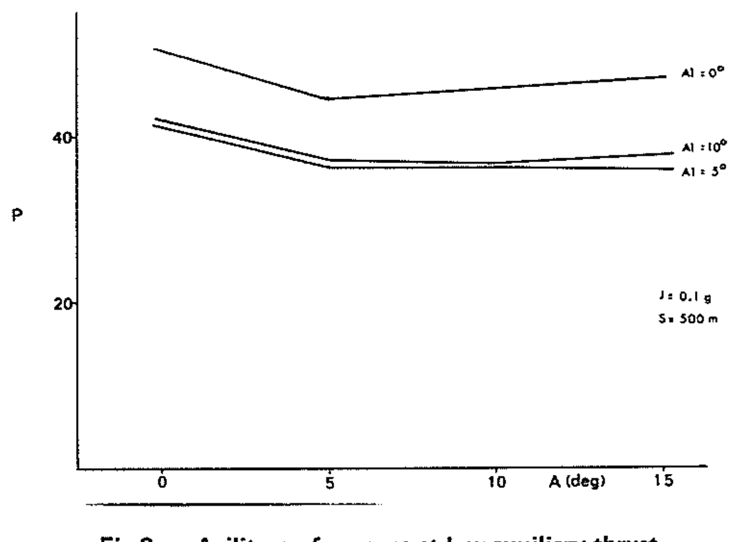

Fig 6 **Agility performance at low auxiliary thrust**

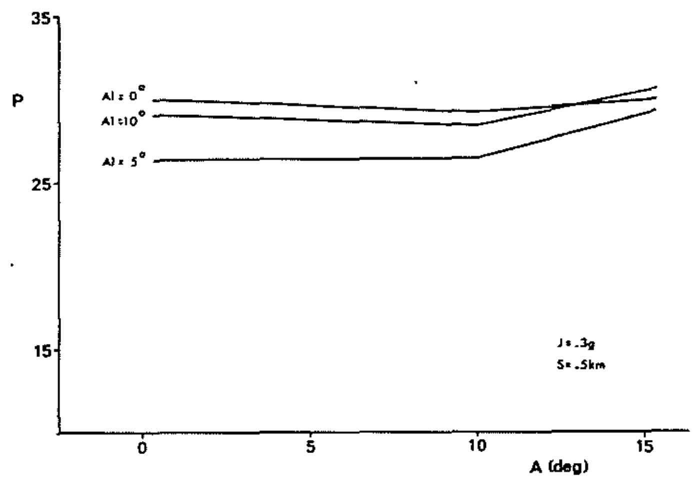

Fig 7 Agility performance at medium auxiliary thrust

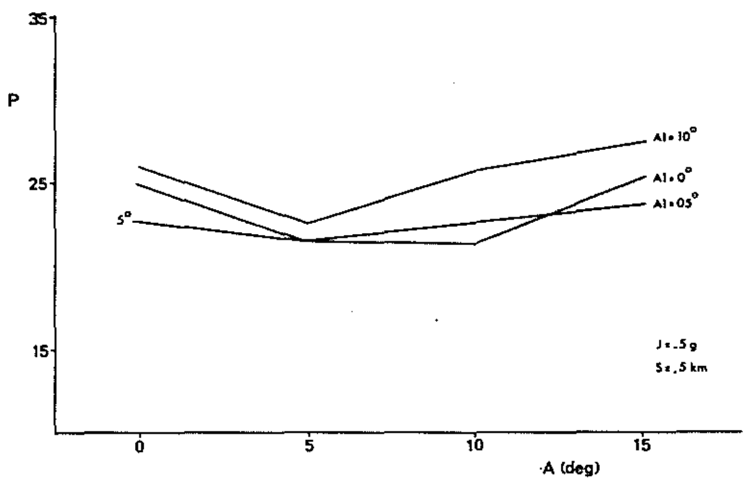

Fig 8 Agility performance at high auxiliary thrust

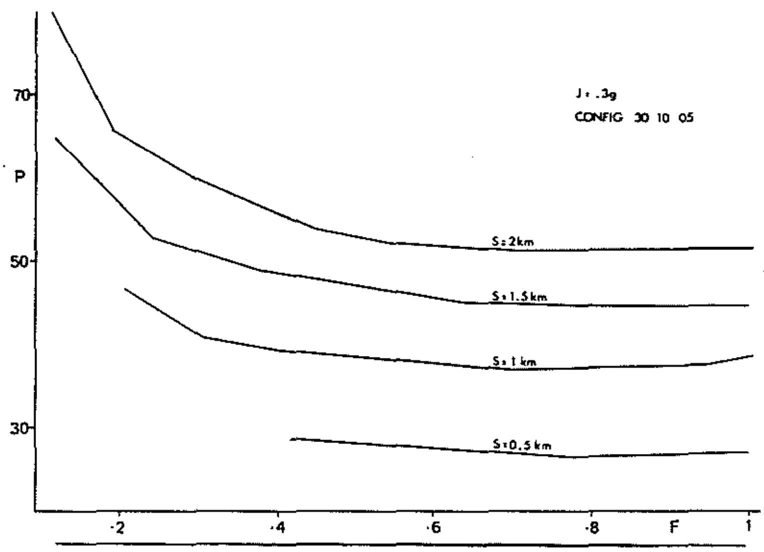

Fig 9 Agility performance as a function of Froude number