RAPID ASSESSMENT OF SHIP AIR WAKE IMPACT ON HELICOPTER PERFORMANCE

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Abstract

NATO task group AVT-102 is currently looking at “improving safety of air operations at sea by improving the airflow on the flight decks of ships through the use of novel vortex flow control devices” - a task which requires the experimental assessment and optimisation of flow control concepts. However, current techniques are either too costly and time-consuming or too crude. This paper proposes a novel assessment concept based on the use of an unpowered rotor model as a flow sensor. The results of a preliminary experimental feasibility study are presented, demonstrating that there is a simple linear relation between the RPM response of an unpowered rotor to freestream velocity perturbations, and the corresponding thrust response of a powered rotor. The limitations of the feasibility study are discussed and the aims of a follow-on study presented.

Nomenclature

A	rotor disk area
c	blade chord
N	number of blades
R	rotor radius
t_c	thrust coefficient, = $T/\rho\sigma A\Omega^2R^2$
T, Z	rotor thrust
u, w	horizontal and vertical velocity components in rotor axes
V	freestream velocity
α_D	rotor disk incidence angle
ρ	fluid density
μ	tip-speed or advance ratio, = $V\cos\alpha/R\Omega$
σ	rotor solidity, $= Nc/\pi R$
Ω	rotor angular velocity
CFD	Computational Fluid Dynamics
LDA	Laser Doppler Anemometer
LIDAR	LIght Detection And Ranging
PIV	Particle Image Velocimeter

Background

The ability to operate rotary wing aircraft from ships at sea is clearly advantageous for military naval operations; however the risks involved are significant. This is of particular concern during landing manoeuvres, as the ship-helicopter interface is widely considered the most difficult and hazardous phase of a mission, involving high pilot workload and reduced control margins. Such increased workload is due to the complex nature of the flow around ship superstructures, with the problem often compounded by difficult environmental conditions. These circumstances result in helicopter operations being limited to very restricted flight envelopes; these are usually conservative due to the changeable nature of weather conditions during flight trials.

Following on from a NATO RTO conference looking at the fluid dynamics of vehicles operating in the air/sea interface (Ref 1), a task group was set up to look at means of alleviating the impact of adverse air wakes. NATO task group AVT-102 ‘Novel Vortex Devices for Safe Operation at Sea’ began work in April 2002 and is planned to report on its findings in mid-2005. The objective for this group is to “improve safety of air operations at sea by improving the airflow on the flight decks of ships through the use of novel vortex flow control devices”. The group aims to achieve this objective via a three step work programme: firstly, candidate novel vortex flow devices will be assessed experimentally as to the effectiveness at improving the airflow over ship models, followed by CFD modelling of these devices for comparisons with experimental data. Finally, optimisation studies will be done employing both CFD and experimental techniques on selected devices.

Preliminary studies under the aegis of this group have highlighted a general difficulty, which lies in the assessment of the effectiveness of the flow control devices. Fundamentally, it is not immediately obvious what is a desirable as opposed to undesirable effect. For example, a device may decrease turbulence in the wake, but at the cost of reduced local flow velocities and hence reduced collective margin. This is a particular problem for this research programme, where a wide range of devices (with a wide range of fluid dynamic effects) need to be compared and then individually optimised, all within a very limited budget.

Available techniques range from cheap and quick but inadequate (eg single hot-wire traverse along a typical helicopter trajectory) to accurate but expensive and time-consuming (eg powered rotor model testing, Refs 2 and 3). This paper presents an initial feasibility study of an intermediate technique using an unpowered rotor operating in autogyro mode.

This work was undertaken as a final year undergraduate project at the University of Bristol (Ref 4), with all that implies in terms of very limited time and budget, and relative inexperience of the principal investigators. Nevertheless, both the promising results obtained and the high quality of work on the project were felt to warrant broader dissemination.

Existing Assessment Techniques

The problem:

The range of flow structures within ship air wakes can be classified into

(a) discrete vortex flows (eg deck-edge vortices), and

(b) bluff-body type wakes (eg flow in the lee of a frigate hangar)

with the latter generally posing the more significant problems for rotary-wing operations. For wake flows, the impact on flight operations takes two forms:

(i) unsteady airloads due to the wide frequency content of the turbulent separated flow, which impact adversely on handling qualities and pilot workload (Ref 5), and

(ii) quasi-steady changes in airloads due to local, highly three-dimensional, variations in airspeed and flow direction, which impact on both performance (eg collective margin) and control (eg rolling moment).

The impact on workload is probably the most complex to determine, with Reference 5 presenting a novel approach which correlates pilot workload with unsteady loads measured on a model helicopter fuselage; however, for the purposes of an initial experimental assessment of flow control device effectiveness a simple measure of flow unsteadiness using a hot-wire probe or a laser doppler anemometer (LDA) should suffice.

Assessment of quasi-steady impact on performance and control is more problematic, particularly considering the range of different flow control devices being considered. One class of device aims to reduce/delay/alleviate flow separation (Ref 6), hence reducing the size of the wake region; however, although unsteadiness (workload) and local velocity deficits (performance) may be improved, this could be at the expense of greatly increased downwash angles near the flight deck (performance, control). Another class of device (Ref 7) aims to deflect the flow, aggravating separation and hence increasing the size of the wake region. This may give a more uniform wake flow over the flight deck (control, performance), but at the expense of increased velocity deficit (performance) and flow unsteadiness (workload). Clearly, some means is required to quantify the relative impact of these effects on helicopter performance and control. One approach being looked at by AVT-102 is to characterise the physics of ship air-wakes, and then to identify the impact (adverse or otherwise) of individual flow features on flight operations. However, this technique is unlikely to be sufficiently discriminating to aid in detailed assessment and optimisation, although it will be use in initial selection of candidate flow control devices.

Conventional assessment techniques

Air wake assessment methodologies divide naturally into two categories:

(i) the first (and most complex) looks at the ship and helicopter as a single 'integrated' fluid dynamic configuration.

(ii) the second (and most common) treats the two sequentially, characterising the ship air wake first then determining the helicopter response.

For the former category, the most straightforward technique is full-scale flight trials, with all the attendant cost and time scale difficulties these entail. At the other extreme, it is now becoming possible to undertake numerical CFD analyses of ship/helicopter interactions, although the combination of complex geometries, highly unsteady flows and translating/rotating elements makes this a highly challenging task. Consequently it remains costly, time-consuming and difficult to validate. Although one could now theoretically undertake a full unsteady simulation of a coupled ship/rotor/helicopter fuselage flowfield, this does not to the author's knowledge appear to have yet been done. In practice, the representation of the rotor flow is simplified, for example replacing it by an actuator disk model (Ref 8).

A 'simpler' approach is to physically model the wake/vehicle interaction directly in a wind tunnel using a powered helicopter model (Fig 1a). The model is traversed through the airwake of a ship model and the rotor thrust coefficient variation measured – effectively using the model as a flow measurement probe (Fig 1b). This technique has recently been applied to ship/helicopter interaction studies at NASA Ames (Ref 2) and at NRC in Canada (Ref 3). This is an attractive approach, capable of representing the rotor/wing interactions accurately in a controlled environment. However, for the purpose of rapid assessment and optimisation of ship geometry and flow control devices, it remains too complex, time-consuming and costly.

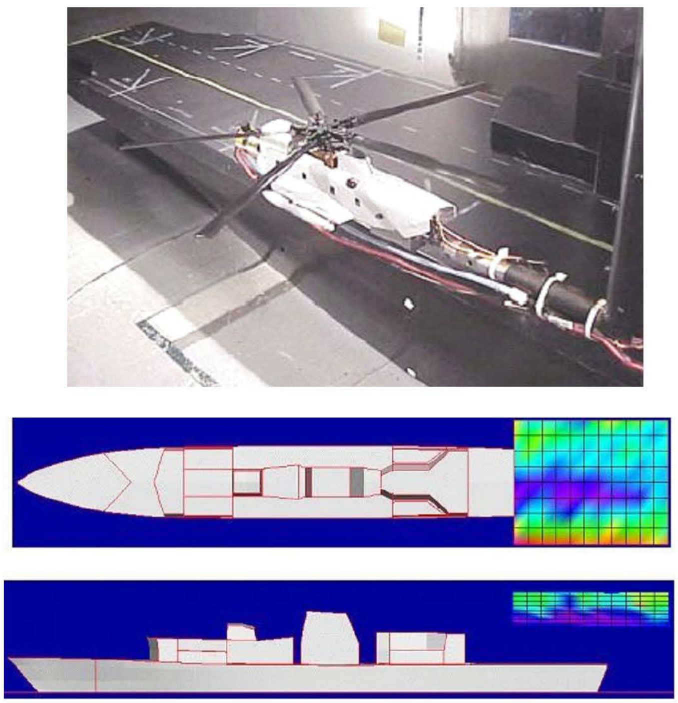


Figure 1: Examples of a powered rotor model (Ref 2), and the effect of an air wake on thrust coefficient (Ref 3)

The latter category of assessment methodologies characterise the air wake on its own, either experimentally or computationally. This prescribed flow is then applied to a helicopter flight dynamics model, from which the impact on performance and control may be determined analytically or from piloted simulation studies. However, the level of wake modelling varies widely.

The air wake aft of a typical ship superstructure is highly three-dimensional and unsteady, with large regions of reverse flow, making it very difficult both to measure and then to represent in a simulation model. Current wind tunnel experiments rely largely on point-measurement techniques, ranging from a single hot-wire probe traversed along a typical flight-path to a full wake traverse using three-component LDA. Full-scale sea trials are usually limited to a small number of point measurements using LIDAR or ultrasonic anemometers.

Given the similar magnitude of rotor diameters and airwake width, the critical missing element in many of these datasets is any spatial correlation across the unsteady wake. Although possibly small in symmetric flows, it may be expected that spatial correlations (eg eddy sizes) will become significant in cross-flow conditions as large vortices are shed from upwind hangar and flight deck edges. Vortex structures tend to be intermittently unsteady (Ref 9) or even bi-stable, so flowfields determined from time-averaged point measurements are potentially rather unrepresentative of the instantaneous flowfields. The time-averaged response of a helicopter (or anemometer) to an unsteady wake flow is therefore not necessarily the same as the steady response to a time-averaged wake flow, or even the unsteady response to a time-averaged flow with local turbulence added [i]. Canadian research reported in Reference 10 indicates that addition of unsteady spatial correlation effects increased the level of the unsteady rotor response.

Generating wake models with unsteady spatial correlations numerically requires a state-of-the-art CFD code, since unsteady separated flows over complex 3-D geometries with reattachment remain a major challenge. Introducing small, possibly quite intricate, flow control devices further increases the difficulty. Experimentally, determination of unsteady spatial correlations conventionally requires simultaneous measurements at several points in the flow, increasing the instrumentation complexity, the time required for wind tunnel testing, and the amount of data post-processing. The recent development of Particle Image Velocimetry (PIV) does however offer the potential to directly measure instantaneous flow structures, although 3-D PIV remains a difficult and time-consuming experimental technique.

A Possible Alternative Technique

For the purposes of assessing the impact of a particular ship air wake (with or without flow control devices) on helicopter performance and control we

[i] This may seem an obvious point, but it is one that appears to be widely misunderstood when it comes to validation of CFD predictions of ship air wakes.

are primarily interested in the changes in thrust and rolling moment. Acknowledging that for preliminary assessment purposes computational methods, comprehensive flow surveys and full scale flight trials are impracticable, the powered rotor technique described above appears to provide the best (experimental) approach. However, it still remains a complex, costly and time-consuming approach. Further, it can be considered to be providing both too much and too little information – absolute levels of thrust etc are not necessarily of direct relevance, while for full representation of the helicopter/wake interaction it would be necessary to vary the rotor cyclic and collective settings, and the rotor disk inclination.

Alternatively, we can regard the powered rotor model as a flow sensor that integrates the unsteady thee-dimensional flowfield over a particular region of interest. The likely response of such a sensor to (for example) variations in flow velocity and downwash angle (or horizontal and vertical velocity components u and w) is suggested by the typical (non-dimensional) longitudinal rotor thrust derivatives z_u and z_w presented in Figure 2 from Reference 11.

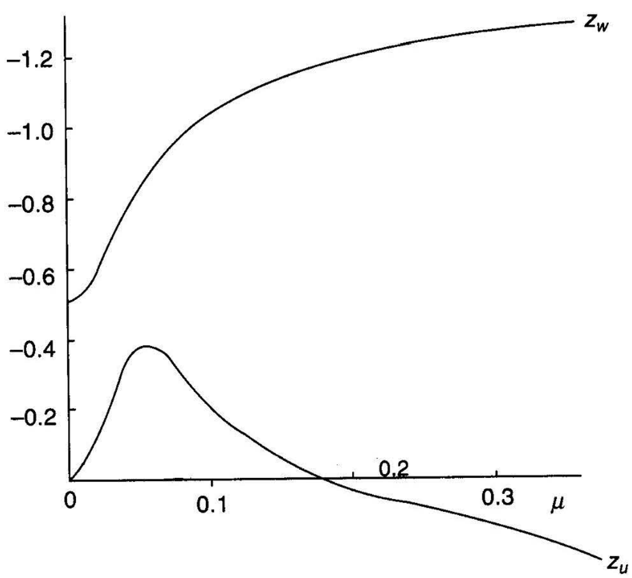


Figure 2: Typical variation of rotor thrust derivatives with advance ratio (Ref 11)

Noting that in Reference 11 thrust Z is positive downwards, horizontal velocity perturbation u is positive aft and vertical velocity perturbation w is positive upwards, it can be seen that at the low advance ratios typical of recovery to a ship (ie where z_u and z_w are both negative) the increased downwash velocity and reduced horizontal velocity seen in a hangar wake will both tend to reduce thrust, with the downwash effect of a significantly greater magnitude.

A possible alternative sensor concept would be to use a flat disk-wing sting-mounted in a similar manner. However, this would still require a force balance, and would not respond correctly at high incidence (≡ low advance ratio) where the lift curve slope of a low-aspect-ratio wing changes sign. Further, the wake from the disk would be very different from that of a rotor, leading to large differences in the interaction with the ship air wake.

A proposal for a rather simpler technique was put forward to the UK MoD in 2003 (Ref 12), namely to use an unpowered rotor operating in autogyro mode as a flow sensor. The basic hypothesis underlying this concept was that the rotor RPM would respond to variations in onset flow angle and velocity in a similar manner to the thrust of a powered rotor. Mechanically, this would be much simpler to manufacture, while instrumentation could be limited to a tachometer (possibly an optical device). Two immediate questions were raised:

(i) the effects of the interaction of powered rotor inflow and downwash on the airwake are not accounted for, and

(ii) is the blade RPM an equivalent performance metric to the thrust coefficient?

The first is a fundamental limitation of the proposed technique; however, current airwake flow survey techniques also do not capture this effect. The second question was initially answered by looking at the performance characteristics of autogyros. The limited theoretical work on autogyro performance (eg Ref 13) is rather empirical, gives answers that are very dependent on assumptions made on parasite drag levels, and does not predict performance well at low advance ratios. The corresponding experimental data (eg Refs 14 and 15) used a test procedure where incidence and blade setting were held fixed, and tunnel speed varied to achieve a given rotor RPM. The performance curves given in these reports therefore relate to fixed RPMs, at the higher end of the operational range. Reference 16 notes that the rotor torque derivatives Q_u and Q_w identified in flight tests of a VPM M16 autogyro are both positive, with the upwash derivative Q_w being about 5 times larger than the axial velocity derivative, suggesting that the RPM variation with u and w should be similar to the helicopter derivatives shown in Figure 2, at least at low advance ratio. It should be noted that the velocity components u and w in Reference 16 relate to the aircraft body axes, as do those in Figure 2. In the latter case, Reference 11 then makes the assumption that the rotor disk incidence α_D is small in order to calculate the derivatives shown in Figure 2.

In the absence of sufficient theoretical or experimental data to confirm the hypothesis, it was decided to undertake a basic experimental feasibility study. The first part of this study involved the back-to-back wind tunnel testing of a powered and an unpowered rotor over a wide range of freestream velocity and disk incidence in order to compare their sensitivity to velocity perturbations directly. This was followed by a comparison of the two techniques in a simulated wake flow, although this was curtailed by time limitations and some technical difficulties.

Experimental Details

Testing was carried out in the low-speed open-jet wind tunnel at the University of Bristol. This is a conventional tunnel typical of many University laboratories, with an open working section of 1.1m diameter, and a speed range of 3-40ms^{-1}. Recent installation of a number of tabs on the nozzle rim has reduced turbulence levels to approximately 1% on the centreline, a reasonable value for a small open-jet tunnel of this type. Freestream velocities were monitored using a Testo 440 anemometer positioned in the centre of the nozzle.

In order to directly compare autogyro and powered rotor characteristics a rig was built which could operate in both modes (Figure 3). This was based on a much-modified Kyosho R/C helicopter model, with a cropped two-blade rotor of diameter 0.602m, blade chord of 0.042m and a 12% thick symmetrical aerofoil section. The original collective adjustment mechanism was replaced by a simple locking clamp.

After some experimentation a pitch setting of 2.7° was used to ensure reliable autorotation. In powered mode, a Schumacher Formula 17 electric motor was used to drive the rotor through a 63:16 reduction gear. Motor speed was controlled manually. In order to ensure that the rotor operated as an autogyro rather than in a windmilling mode a toothed belt was used to pre-spin the rotor before running the tunnel up to speed (Figure 4b). One unwelcome consequence of the use of an off-the-shelf rotor assembly for this rig was a high level of friction, leading to difficulties in achieving auto-rotation at low disk incidence angles.

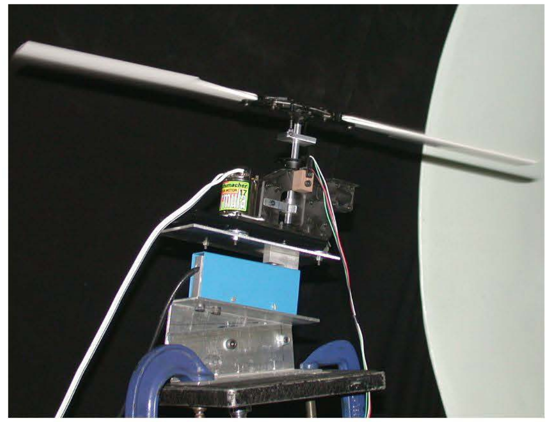


Figure 3: Basic rig set-up

The rig was then mounted on a tripod in the open jet, allowing shaft inclination to be varied over a range of 50° using a combination of an internal hinge and the tripod head. Shaft angle was measured using a digital inclinometer with a precision of ~0.1°. Shaft rotational speed was measured using an optical tachometer picking up on a rotating disk mounted on the shaft. Due to problems with positioning, only six holes could be drilled in the disk, giving readings accurate only to the nearest 10RPM (checked using a stroboscope). The basic rig was mounted on a 2kg load cell (Figure 3), enabling rotor thrust to be measured directly.

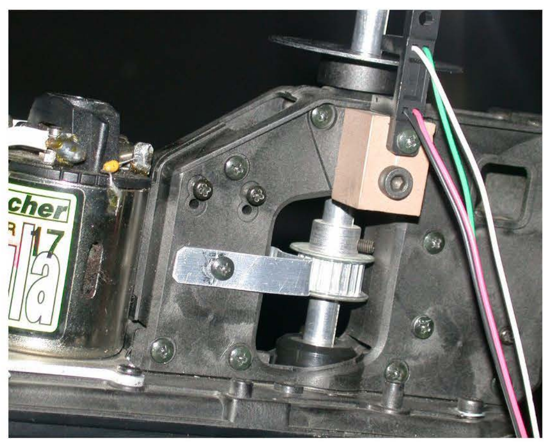


Figure 4: Rotor hub arrangement and autogyro starting mechanism

Given that a typical ship airwake generates downwash in the region of interest, it was necessary to simulate this in the comparison. The rig was set so that the disk was geometrically at a positive incidence, but the direction of rotation was such that the thrust in powered mode was directed downwards. Increasing incidence would therefore correspond to an increasing downwash through the disk, and hence a loss of thrust. In retrospect it would have been better to have used a negative incidence setting, thus avoiding interference from the body wake at high angles.

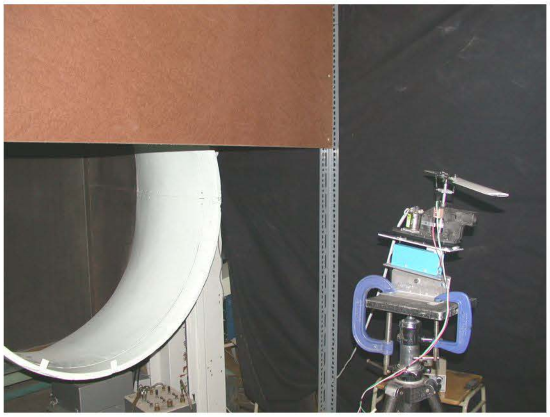


Figure 5: Moveable blockage arrangement

The simple rig described above could not readily be moved in the flow, so interactions with a bluff-body wake were simulated using a moveable blockage across the tunnel nozzle (Figure 5). Unfortunately, the flow around the blockage was such that it generated an upwash around the rotor rather than the required downwash, taking the flow outside the envelope for which the technique had been validated.

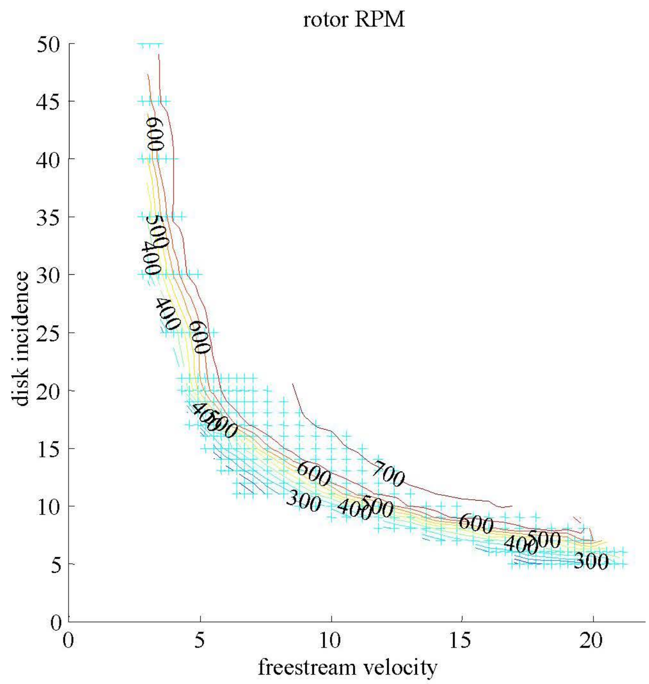
Back-to-Back Comparison

For simplicity, powered and unpowered tests were conducted with the same blade pitch setting of 2.7°, which gave the most consistent autorotation performance. In unpowered mode, maximum rotor speed was ~700RPM, a limit imposed by the onset of excessive vibration. Powered tests were run at a constant speed of 1500RPM, giving a maximum thrust coefficient t_c of ~0.03. This is rather low (Ref 11 suggests a range between 0.06 and 0.1), but was constrained by the low pitch setting and excessive vibration at higher speeds.

Autogyro mode

Testing in autogyro mode was undertaken at fixed rotor incidences, from 5 to 21° in 1° increments, and then from 25 to 50° in increments of 5°. The speed range was determined by the autorotation envelope, from 2.8 up to a maximum of 21ms^{-1}. Observed rotor speeds ranged from 70 to 730RPM, corresponding to tip-speed ratios from 0.1 to 4.

Figure 6a shows contours of constant rotor RPM for the basic V-α_D test matrix (with + denoting the achieved data-points). The rotor speed behaves much as one might expect, increasing with both disk incidence and freestream velocity. The crude nature of the experimental rig is reflected in the relatively high disk incidence required to sustain autorotation. At the high-speed end, an incidence of ~9° is needed to achieve maximum RPM (at a tip-speed ratio of ~0.9). The corresponding disk incidence for the large autogyro rotor tested in Reference 14 was ~1°, indicating that with an improved mechanical arrangement the lower limit of the autorotation envelope shown in Figure 6a could be greatly reduced. In this experiment the upper RPM limit was set by the onset of excessive vibration; however, Figure 6 suggests that the RPM had already reached its aerodynamic limit at this point. This limit could be increased by reducing blade profile drag (ie by increasing test Reynolds Number, or improving the aerofoil section).



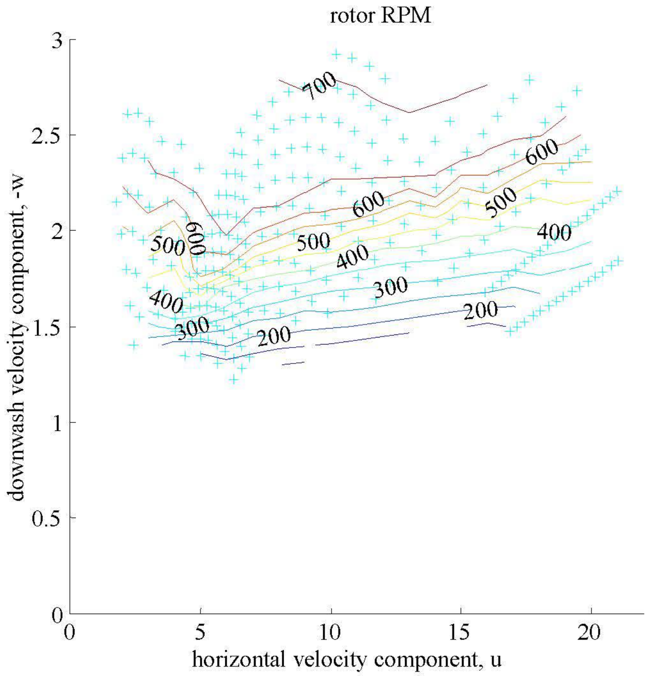


Figure 6: Basic autogyro mode results, showing RPM as a function of freestream velocity and direction

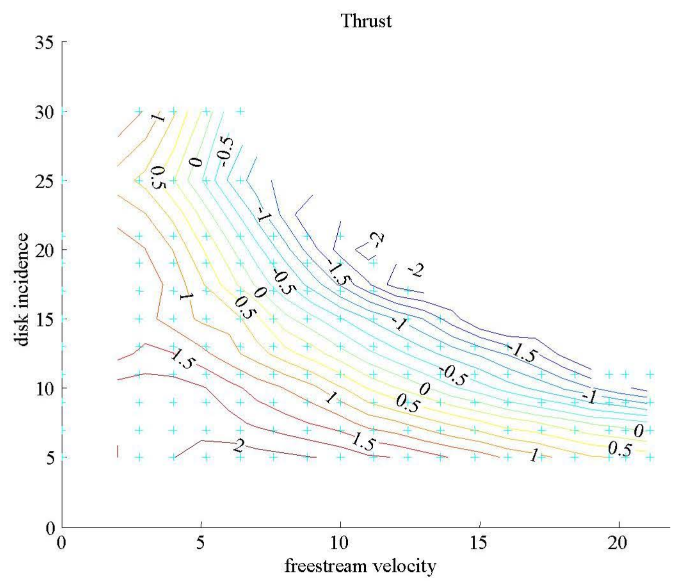
Figure 6b shows the same data plotted in terms of horizontal and vertical components of the freestream velocity relative to the rotor disk. This form of presentation shows the effect of velocity perturbations more clearly. Note that the rotor disk is inverted, so that w corresponds to a downwash velocity. An increase in vertical velocity component always increases rotor RPM; however the effect of horizontal u component depends on the initial value. At high u, positive velocity perturbations reduce RPM (as the effective incidence reduces), but the opposite effect occurs at low u. A similar sign change with speed can be seen in the helicopter thrust derivative z_u shown in Figure 2. Figure 6b also shows that the rotor RPM is most sensitive to variations in downwash (again similar to the helicopter behaviour shown in Figure 2), with maximum and minimum RPM corresponding roughly to downwash velocities of 2.8 and 1.3ms^{-1} respectively. A reduction in minimum incidence for autorotation to the levels seen in Ref 14 and 15 would extend the autorotation envelope down below 0.5ms^{-1}.

Powered rotor mode

Testing in powered mode was undertaken at a constant 1500RPM, at fixed rotor incidences from 0 to 20° in 2° increments, and also at 25° and 30°. For each incidence the freestream velocity was increased from a minimum of 2.8s^{-1} in 1.2ms^{-1} steps. Maximum velocity at each incidence was limited by loss of control of the motor RPM (!).

Figure 7a shows contours of constant rotor thrust for the basic V-α_D test matrix (with + denoting the achieved data-points). The direction of rotation is such that the rotor is effectively operating inverted, so that thrust decreases (from a positive static value) with increasing disk incidence and freestream velocity. Observed thrusts ranged from +2N at low forward speed, to a minimum of –2N at the point where speed control was lost.

Figure 7b shows the same data plotted in terms of horizontal and vertical components of the freestream velocity relative to the rotor disk. Note again that the rotor disk is inverted, so that w corresponds to a downwash velocity. An increase in downwash velocity always reduces rotor thrust; however once again the effect of horizontal u component depends on the initial value. At high u, positive velocity perturbations increase thrust but the opposite effect occurs at low u.



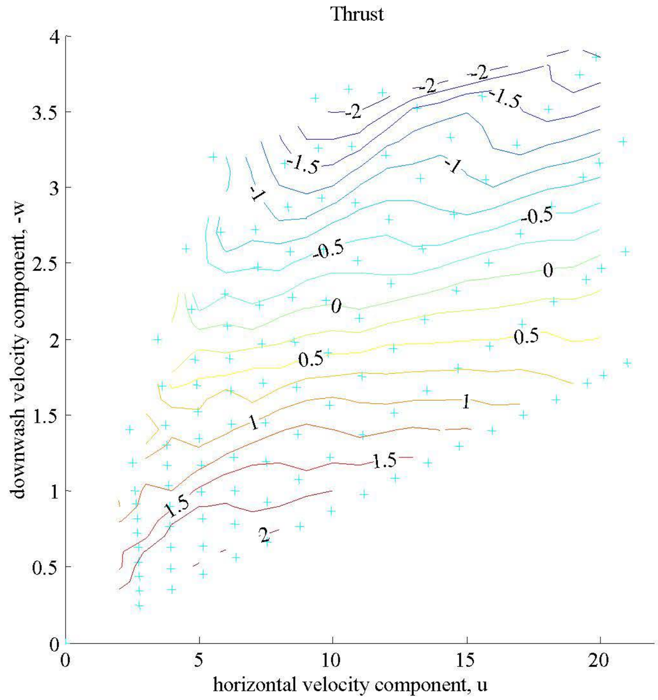


Figure 7: Basic powered mode results, showing thrust as a function of freestream velocity and direction

Unpowered vs powered characteristics

Comparing Figures 6 and 7, it can be seen that the RPM characteristics in unpowered testing are very similar to the thrust characteristics in powered mode. In particular, the appearance of a change in sign in the sensitivity to horizontal velocity perturbations in roughly the same region in Figures 6b and 7b was felt to be very encouraging.

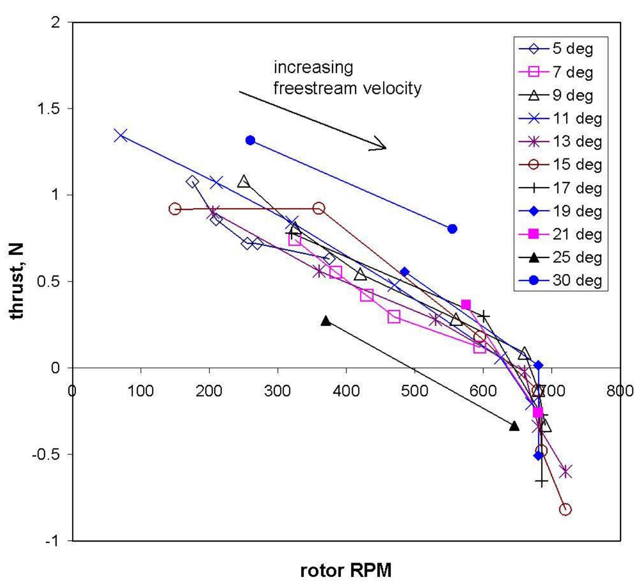


Figure 8: Direct correlation between unpowered rotor RPM and thrust

For a more direct comparison, Figure 8 shows thrust plotted against RPM at the same onset flow conditions. The curves collapse surprisingly well, and a simple linear relationship between the two can be seen. With this rotor orientation, increasing RPM corresponds to reducing thrust. There is some scatter, but given the crudity of the experimental arrangements this is hardly surprising.

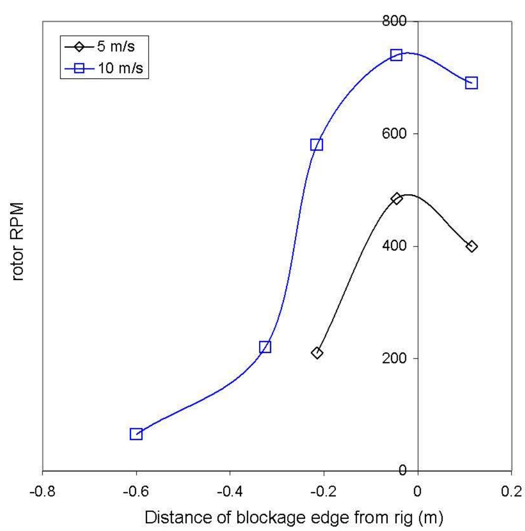
At higher incidences (25° and 30°), there is an offset in the linear relation, which may be due to the interference effect of the wake of the motor housing (Figure 3); nevertheless, the slope remains similar. The linear relationship breaks down when the rotor RPM in unpowered mode reaches its maximum level. A linear extrapolation shows that the minimum observed thrust of –2N would correspond to a nominal autorotation speed of ~1600RPM. The loss of speed control at this point can therefore be seen to be due to the torque absorbed by the rotor falling to zero as autorotation sets in. Onset flow conditions for maximum RPM in autorotation correspond closely to those for zero thrust. Since at this point the powered rotor is running at more than twice the speed of the unpowered rotor, it is not clear at this stage of the investigation whether this is a coincidence or has a more fundamental significance. If so, it implies that only the linear region of the RPM response is of relevance, since a complete loss of rotor thrust is clearly an adverse airwake impact.

In order to compare sensitivity to velocity perturbations, RPM and thrust derivatives were extracted from the gradient of the responses shown in Figures 6b and 7b. However, the error levels in the basic experimental data, coupled with the relatively wide spacing in datapoints meant that the scatter in these derivatives was too large for any reliable quantitative conclusions to be drawn. Qualitatively, they confirmed the results of Figure 8, showing that the sensitivity of both unpowered RPM and thrust to perturbations in u and w are rather similar (although of opposite sign). Overall, the variations in relative magnitude and sign with tip-speed ratio were found to be consistent with those shown in Figure 2 (Ref 11).

Effect of wake simulation

With the basic rig mounted so that the rotor is effectively inverted, a blockage element mounted horizontally across the wind tunnel nozzle (Figure 5) was moved gradually downwards to simulate a helicopter descending into a ship airwake. The rotor disk incidence was set at a constant 7° for both powered and unpowered tests. Wake simulations were run at 5 and $10ms^{-1}$, with higher speeds precluded by the extreme blockage levels. These tests were performed towards the end of the allotted time for this student project, and were consequently rather limited in scope.

Figure 9 shows the effect of blockage position relative to the rig, with –0.6m corresponding to unconstrained flow. The variations in rotor RPM and thrust are reasonably similar, but unlike Figure 8 both show the same direction of change, and apparently a different slope. On further investigation it was realised that the simple blockage element used was in fact generating an upwash rather than a downwash at the rotor rig, so that the vertical velocity component w was of opposite sign to that in the previous 'calibration' tests. Insufficient time remained to modify the experimental arrangement, but some exploratory tests at negative disk incidence angles established that in autogyro mode the rotor would begin to autorotate at an incidence of –13°, indicating some asymmetry in the rotor response to $\pm w$. Direction of autorotation is the same for both positive and negative incidences, hence the change in relative sign.



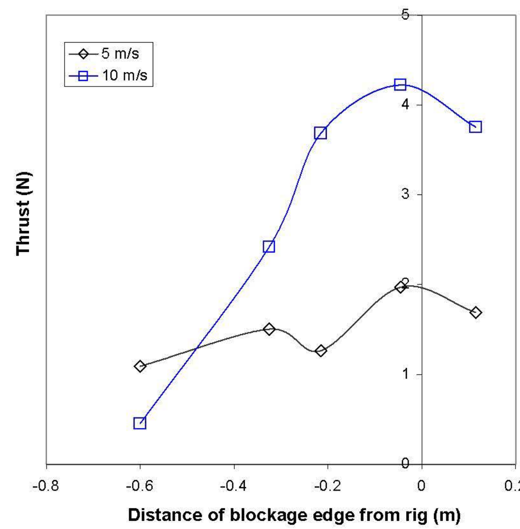


Figure 9: Effect of wake simulation on rotor RPM and thrust

Taking this into account, Figure 9 does indicate (in a rather preliminary fashion) that the RPM response of the unpowered rotor to velocity variations remains similar to the thrust response of a powered rotor even (a) in a highly unsteady wake flow, and (b) well outside the velocity envelope over which the basic concept was investigated

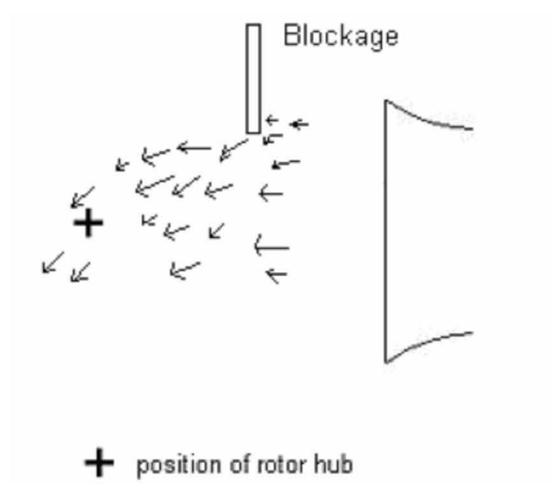


Figure 10: Upwash effect of moveable blockage

Summary

An alternative low-cost experimental technique for the rapid assessment of the impact of ship air wakes on helicopter flight operations has been proposed, using an unpowered rotor as a flow sensor. The technique represents an intermediate level of sophistication, being simpler but less representative than using powered scale rotor models, but more representative (and potentially simpler) than conventional flow surveys.

The concept has been the subject of a preliminary experimental investigation as part of an undergraduate research project, which has demonstrated that there is a direct linear relation between the thrust response of a powered rotor to flow velocity perturbations and the RPM response of an unpowered rotor operating in autogyro mode to the same perturbations. It therefore appears feasible to use an unpowered rotor as a flow sensor when concerned with ship wake/rotorcraft interactions; however much work remains to be done.

A follow-on study will now be undertaken, again as an undergraduate research project at the University of Bristol. One element of this project will be to significantly improve the mechanical arrangement, in order to extend the autorotation envelope, and to improve the data quality (rotor thrust and RPM). The rig orientation will be inverted in order to reduce fuselage/motor housing interactions and the rig structure will be aerodynamically 'cleaned up'. An alternative means of simulating an airwake encounter will be developed. A further element will be a proper analytical study of the concept (building on autogyro experience at Bristol), with the aim of modelling the rotor response and hence clarifying the level of correlation between RPM and thrust. Finally, the basic concept does not provide any indication of airwake impact on control. It may be possible to measure rolling moment in a simple manner, but a more sophisticated approach would be to look at phase-averaged rotor speed variations. With a two-bladed rotor, any cyclic variation in angular acceleration may be correlated with lateral and fore-and-aft variations in flow velocity, and hence with rolling and pitching moment.

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