TWENTY FIRST EUROPEAN ROTORCRAFT FORUM

Paper No. VII - 6

A STUDY OF GYROPLANE FLIGHT DYNAMICS

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Abstract

The objective of this Paper is to discuss gyroplane stability and controllability. Its aim is to describe the contribution of the results to the development of the new airworthiness design standard BCAR Section T. The literature on gyroplane flight has not hitherto addressed stability and control. This Paper therefore makes a clear contribution to the field, and its novelty is enhanced through the use of the inverse simulation method, and a sophisticated and comprehensive non-linear individual blade/blade element rotorcraft mathematical model.

1. Introduction

A major programme of research funded by the U.K. Civil Aviation Authority into gyroplane airworthiness and flight safety has been underway at the University of Glasgow since November 1993. The aims of the research were to examine gyroplane stability and controllability from a rational and scientific basis; to develop a tool that can be used to support studies into gyroplane stability; and to support the development of a new airworthiness design standard in the UK, BCAR Section T [1]. The programme of work has involved four principal elements:

1. A data gathering exercise, including wind tunnel tests on a typical gyroplane airframe, has been performed to allow generic rotorcraft models to be configured as gyroplanes.

2. Parametric studies were conducted to explore sensitivity of stability and controllability to a variety of design features.

3. Flight tests on a comprehensively instrumented aircraft to allow validation of the models have just been prepared.

4. A parametric study using the validated individual blade model, will allow an assessment of the impact of operational and design parameters on airworthiness and flight safety.

Although the class of aircraft known as gyroplanes (or autogyros) helped to pave the way for the development of the helicopter, they have found no application in contemporary commercial or military aviation. It is in recreational or sport flying that the gyroplane has proved popular. Most if not all designs are however homebuilts, and as a consequence the depth of analysis of the type's flight mechanics is limited by the absence of the mathematical modelling and simulation facilities available to major aerospace organisations. The study of gyroplane flight mechanics is however timely, in the light of the accident rate suffered by the aircraft. For example, in the U.K., there were 6 fatal gyroplane accidents in the period 1989-91, [2]. This, together with the increase in light gyroplane flying in the U.K., has heightened interest in this class of aircraft.

This paper focuses on two engineering model simulations. Firstly, an individual blade/blade element model has been used to examine stability and controls-fixed flight. Inverse simulation has then been used to examine control strategies and flight paths that can influence rotorspeed, since loss of rotorspeed is a common feature in most light gyroplane accidents.

2. Background

The literature on gyroplanes is considerable, Refs. 3-13 for example. However, in a contemporary context, this work is now primarily of historical significance. It provides the basis of the understanding of gyroplane flight, but does not address the issues of stability and control. Examination of the literature shows a logical development of the study of gyroplanes, from the elementary theory of gyroplane flight, to an analysis of aerodynamics and performance and ultimately rotor behaviour, but only for steady flight. Interest then apparently waned and the next logical stage in the study of the gyroplane i.e. stability and control, was not examined. For example, the work of Glauert includes the derivation of simple expressions for rotorspeed as a function of loading and axial velocity, [3]. Wheatley, [9] derived expressions for the flapping angles required for equilibrium flight, presenting results that show how coning, longitudinal and lateral flap angles vary with flight condition. Nowadays, these analyses would be recognisable as classical rotary-wing theory and analogous to that found in helicopter text books. Wheatley even examined higher harmonic components of blade flapping behaviour, [11].

rotors suspended from a teeter hinge. There is no cyclic pitch control, the entire rotor being tilted for/aft and laterally to effect pitch and roll control, respectively. Some configurations, such as the Air & Space 18A, have "conventional" articulated rotor systems, in the case of the 18A, with three blades. Other controls are a conventional rudder and a pusher propeller of fixed pitch.

3. The Simulation of Gyroplanes

The University of Glasgow has had over 15 years experience in rotorcraft flight dynamics. During this time a range of simulations have been developed, and for the current study two of these have been employed. A blade element/individual blade simulation is used to derive the stability characteristics whilst a simplified disc model has been incorporated into the inverse simulation for studies of manoeuvring flight. For both simulations it was necessary to obtain a set of appropriate configurational data. The data used was by necessity representative of the aircraft which was to be flight tested later in the programme, the VPM M16 Tandem Trainer, Figure 1. Much of the data was derived from the manufacturer's documentation, however it was necessary to perform wind tunnel tests to obtain aerodynamic force and moment coefficients.

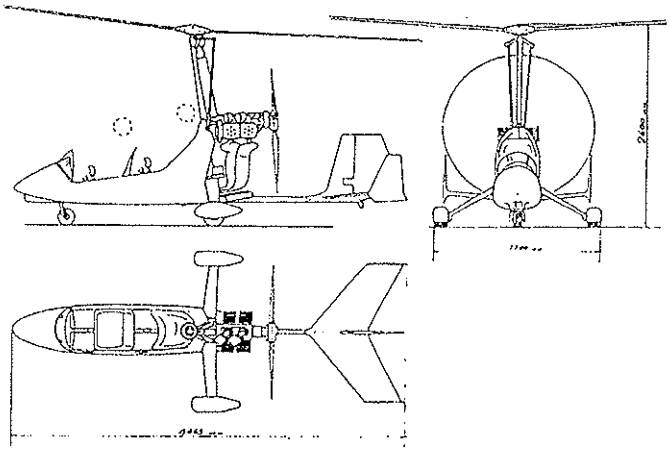


Figure 1 : The VPM M16 Tandem Trainer

3.1 Wind Tunnel Testing

The tests were conducted in the 3m Low Speed Wind Tunnel of the Aeronautical Research and Test Institute (VZLU) of Prague in the Czech Republic. The tunnel is of the Gottigen style, and a 6 component overhead gravitational balance which was used to measure forces and moments. The model was a one-third scale model of a VPM-M14 gyroplane minus rotor but with powered and scaled propeller, Figure 2. A series of configurational tests were carried out including combinations of cowling on/off, horizontal tailplane on/off, fin on/off and power on/off. This allowed the effect of various configurational features to be assessed. The test range was

$$-40^\circ < \alpha < 40^\circ$$

$$-30^\circ < \beta < 30^\circ$$

$$-20^\circ < \delta_r < 20^\circ$$

where δ_r is the rudder deflection, and force and moment coefficients were recorded for all three axes.

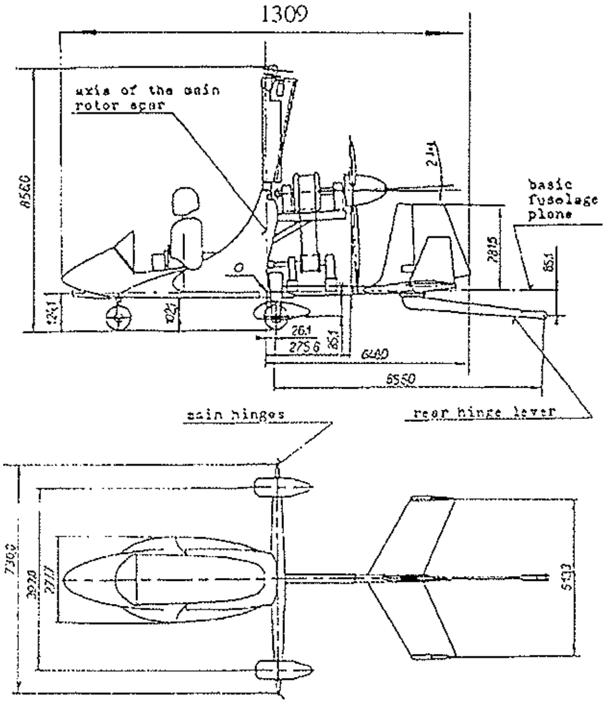


Figure 2 : Wind Tunnel Model of VPM Gyroplane

3.2 The RASCAL Mathematical Model

A description of the mathematical model used in this study, together with the algorithms for trimming and linearising the model, has already been presented in Ref. 14. Key features of the model are given in Table 1.

3.3 The HGS Mathematical Model

Current work on inverse simulation at Glasgow University employs an enhanced model, Helicopter Generic Simulation (HGS), [15] which is accessed by the inverse algorithm, Helinv. The model is nonlinear, and its main features include a multiblade description of main rotor flapping, dynamic inflow, an engine model, and look-up tables for fuselage aerodynamic forces and moments.

Model item	Characteristics
Rotor dynamics (both rotors)	• up to 10 individually-modelled rigid blades • fully-coupled flap, lag and feather motion • blade attachment by offset hinges & springs • lag damper
Rotor loads	• aerodynamic and inertial loads represented by up to 10 elements per blade
Blade aerodynamics	• lookup tables for lift and drag as function of angle-of-attack and Mach number
Wake model	• momentum-derived dynamic wake model • uniform and harmonic components of inflow • rudimentary interaction with tail surfaces • ground effect
Transmission	• coupled rotorspeed and engine dynamics • up to 3 engines • geared or independently-controlled rotor torque
Airframe	• fuselage, tailplane and fin aerodynamics by lookup tables or polynomial functions
Atmosphere	• International Standard Atmosphere • provision for variation of sea-level temperature and pressure

Table 1 RASCAL Mathematical model description

3.4 Inverse Simulation

An inverse simulation is one in which a mathematical representation of a particular manoeuvre is used as an input to a vehicle simulation [16]. The aim is to calculate the control actions required of the simulated vehicle to fly the defined manoeuvre. The advantage of this type of simulation is that it is possible to determine the response of the vehicle in specific forms of manoeuvring flight. In the context of the current work the aim has been to simulate manoeuvres where the vehicle is likely to experience rapid and large changes in rotorspeed for example, in low g conditions. The fact that the gyroplane model has been written in generic form is also significant as this allows parametric studies to be performed.

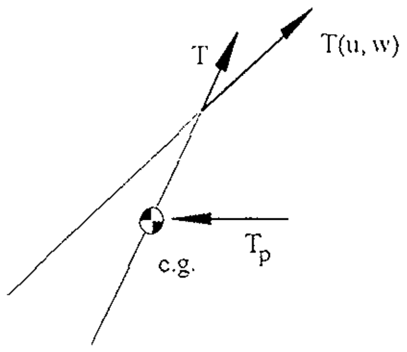
4. Stability of Gyroplanes

The RASCAL model was applied to a parametric study designed to quantify the sensitivity of gyroplane stability to design and operational variables. It was discovered that the gyroplane has rigid-body modes that have the characteristics of a conventional fixed wing aircraft i.e. oscillatory short-period pitch and phugoid modes in the longitudinal degree of freedom, and an oscillatory dutch-roll with aperiodic roll and spiral modes in the lateral/directional degrees of freedom. Centre-of-mass position, mass, airframe configuration (such as absence or presence of a cowling, tailplane and vertical fins), airspeed and rotor blade section were all investigated. However, it was found that stability is largely insensitive to variations in these parameters with the exception of the vertical location of the centre-of-mass in relation to the propeller thrust line, Table 2.

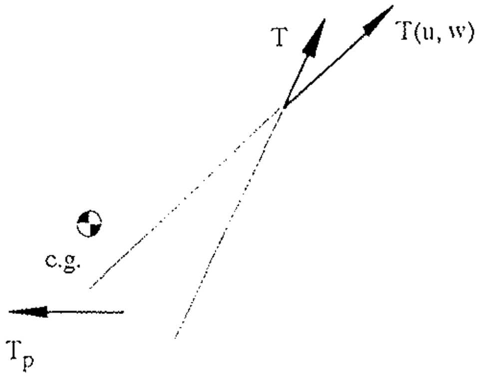
C.G. Relative to Propeller	Time to Half (Double) Amplitude (s)	Period (s)
3in. Above	5.61	29.84
Default	5.07	23.92
3in. Below	(2.04)	12.53

Table 2 Phugoid mode characteristics

It is clear that the phugoid is rendered grossly unstable as the centre-of-mass is placed below the propeller thrust line. Perhaps this type of dynamic behaviour is normally what is to be expected of rotorcraft and the question ought really to address why the phugoid is so stable for the other configurations. The mechanism is unique to the gyroplane - with the propeller thrust line below the centre-of-mass the large nose-up pitch moment can only be balanced by the main rotor thrust line passing aft of the centre-of-mass. If it is sufficiently far behind, then a speed or angle of attack disturbance causing an aft tilt of the rotor will not be destabilising, Figure 3. In fact the stabilising influence is magnified by the fact that the rotor is so lightly loaded, since basic rotor theory shows that this will produce a large thrust change in response to an increase in angle of attack. This latter effect will also tend to augment the destabilising effect of rotor flap-back if the thrust line lies ahead of the c.g. This mechanism is then consistent with the apparent "cliff-edge" in phugoid stability with small changes in vertical c.g. position. There is circumstantial evidence to suggest that handling difficulties are indeed caused by having the propeller thrust line above the c.g., and it is an important safety aspect since there is a trend for owners to fit more powerful engines (and hence larger diameter propellers).



(a) Propeller Thrust Line Passing Through C.G



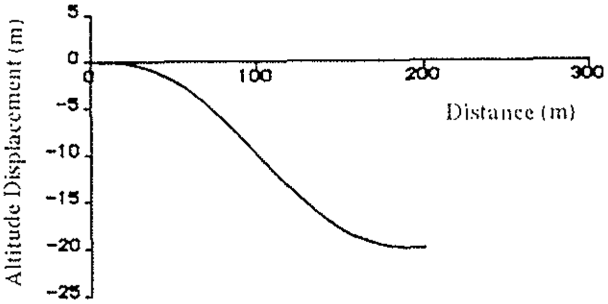
(b) Propeller Thrust Line Passing Below C.G.

Figure 3 : Schematic of Main Rotor Trust Line Relative to C.G. in Undisturbed and Disturbed Flight

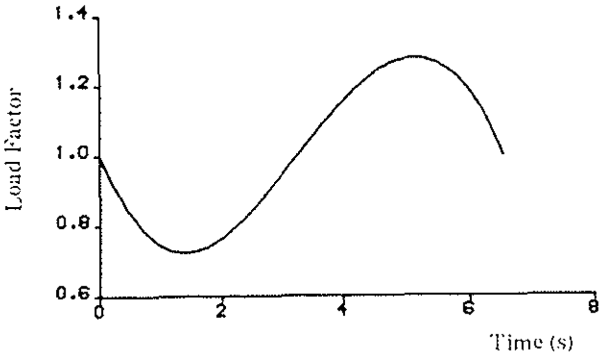
5. Inverse Simulation of Manoeuvring Gyroplane

Inverse simulation has the ability to predict the state and control time histories that result from a subject vehicle flying a specified manoeuvre. An existing rotorcraft inverse simulation, Helinv, has been modified to include a generic gyroplane model which allows the control and state histories of typical gyroplane configurations flying representative manoeuvres to be established. For example, a common problem encountered during the manoeuvring of gyroplanes is the rapid and sudden loss of rotorspeed. Inverse simulation is an ideal tool to identify the flight conditions where this is likely to occur and to quantify what rotorspeed loss can be expected. Further, inverse simulation can be used to identify possible control strategies which might allow the manoeuvre to be flown whilst avoiding potentially catastrophic rotorspeed losses.

An example of such a manoeuvre is the "push-over/pull-up" shown in Figure 4. The altitude profile for the case where a height loss of 20m is experienced over a distance of 200m is shown in Figure 4(a), whilst the resulting load factor profile when this trajectory is flown at a constant velocity of 60 knots is shown in Figure 4(b). This information can be used to "drive" the inverse simulation, and with an appropriate set of configurational data it is possible to obtain a complete picture of the vehicle's dynamic characteristics during the manoeuvre. Results for a VPM M14/16 are shown in Figure 5 for the case where the manoeuvre is flown at a constant velocity of 60 knots and for the case where speed is allowed to increase from 60 knots at the entry of the manoeuvre to 75 knots at the exit. From the plots it is clear that in both cases there is a large and rapid decay in rotorspeed (approximately 20%) during the push-over phase. It is also clear that this decay is slightly lower for the constant velocity manoeuvre with the added benefit of smaller stick and rudder displacements (albeit with more attention required on the throttle). These results would indicate that the manoeuvre is best performed at constant speed to maintain rotorspeed and minimise pilot workload.



(a) Flight Path



(b) Load Factor Profile

Figure 4 : Push-over/Pull-up Manoeuvre

As previously mentioned the generic formulation of the mathematical model allows the influence of various configurational parameters to be assessed. Two such studies are now presented.

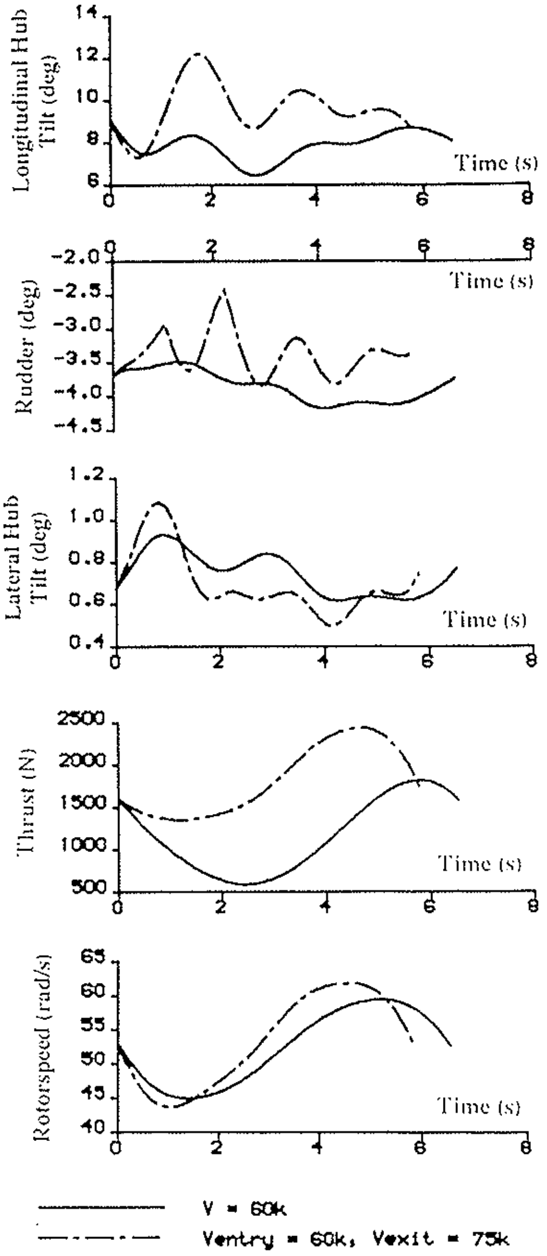


Figure 5 : Inverse Simulation Results for a Push-over/Pull-up Manoeuvre

5.1 The Effect of Tailplane on Manoeuvre Response

Figure 6 shows the inverse simulation results for the push-over/pull-up manoeuvre for the baseline VPM configuration with and without a tailplane. As the whole manoeuvre is performed at 75 knots, and with VPM possessing a relatively large tailplane it is no surprise that the plots for both longitudinal hub tilt and pitch attitude are quite different for the two cases. In performing the push-over phase of this manoeuvre the tailplane produces a restoring nose-up pitching moment. When the tailplane is removed, and the initial pitch down motion (due to the initial forward stick input) is arrested this beneficial moment is not present and a large aft stick motion is required to avoid the nose dropping too low. In fact the nose down attitude achieved is 50% greater without the tailplane, and occurs earlier in the manoeuvre. The larger longitudinal stick motions required to complete this manoeuvre are clearly visible.

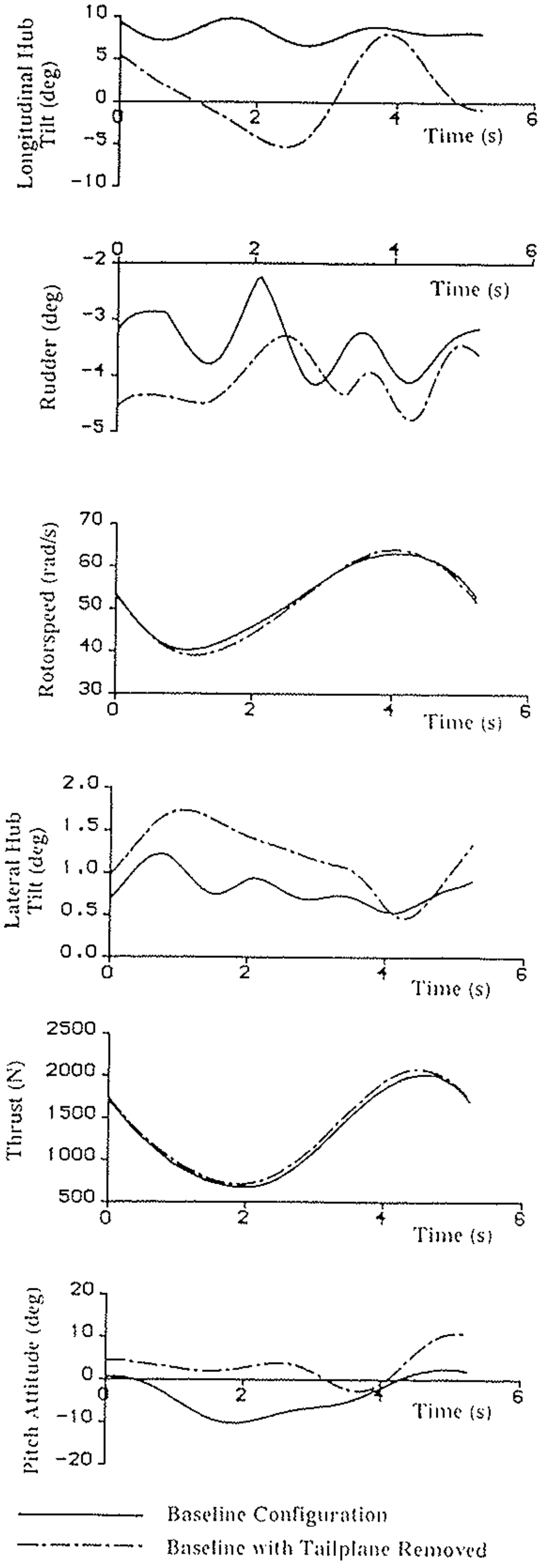


Figure 6 : Inverse Simulation Results for Push-over/Pull-up Manoeuvre - Effect of Tailplane

5.2 The Effect of Vertical C.G. Location on Manoeuvre Response

Results from previous simulations have indicated that the vertical location of the thrustline of the propeller with respect to the centre of gravity is a significant factor in determining the stability of a gyroplane. This can be investigated using inverse simulation by calculating control inputs and responses for the same manoeuvre flown with the thrustline in different vertical positions. The results are shown in Figure 7 where the range of thrustline locations is from 20cm above the C.G. (similar to the current baseline value) through the C.G. itself, then to 20cm below it. This of course is an unrealistic range of possible values for one configuration, however it will highlight the effect this parameter can have. The main effect is that for thrustline locations low on the aircraft the nose-up pitching moment produced for a given thrust is greater. This can be easily observed from the plot of longitudinal thrust tilt which shows larger displacements required as the thrustline location is lowered. The pulse of longitudinal stick occurring from 1 to 3 seconds is the most significant portion of this response as it is this which reverses the pitching motion from down in the push-over to upwards in the pull-up phase (as indicated on the pitch attitude and rate time histories). It should be noted that there are secondary effects such as the pitching moment due to the propeller thrust changing sense from nose down with the thrustline above the C.G. to nose up when the thrustline is below the C.G.

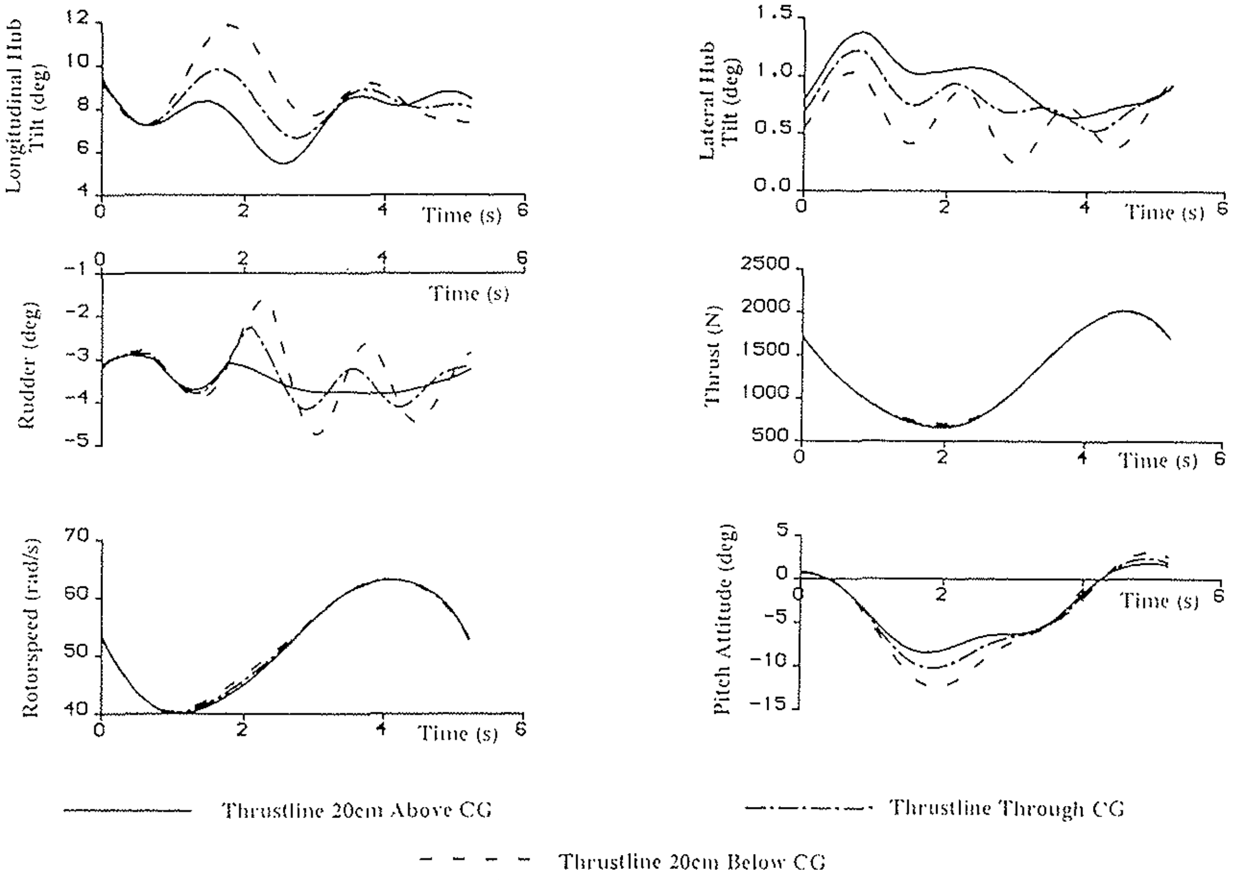


Figure 7 : Inverse Simulation Results for Push-over/Pull-up Manoeuvre - Effect of Thrustline Position

6. Flight Testing

The purpose of the flight test programme is to provide data suitable for model validation. The nature of the validation has determined the instrumentation requirements and experiment design. Specifically, it is desired to validate the rigid-body response of the aircraft across a frequency range of significance to the pilot. Accordingly, the test instrumentation consists of a digital recording system operating at 10 Hz, measuring rotorspeed, pilot control positions, airframe translational accelerations and angular velocities, roll and pitch attitudes and airspeed, angle of attack and sideslip from a 1 m long, nose-mounted air data probe. The experiments encompass steady and transient manoeuvres between 25 and 75 mph including steady heading sideslips as well as steady balanced flight, doublet and frequency sweep inputs on all controls.

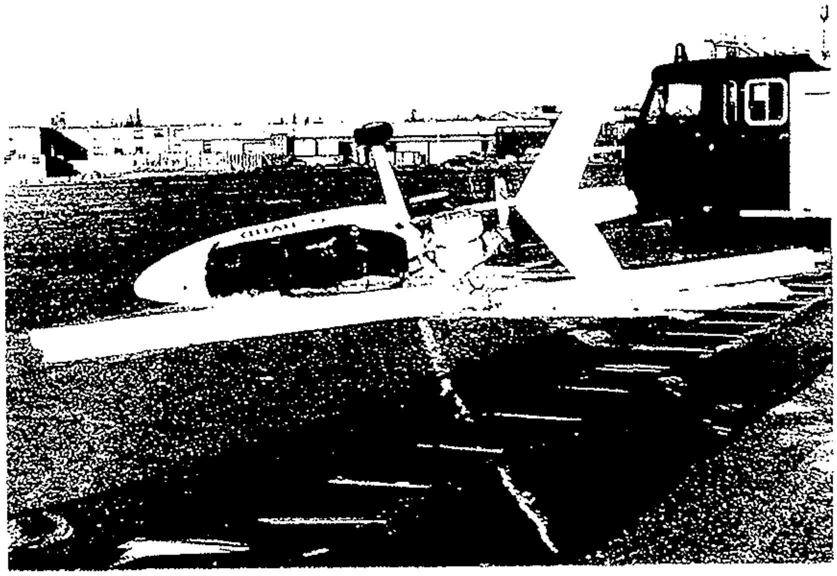


Figure 8 : VPM M16 Gyroplane, G-BVRD, at Cranfield, 12 January 1995
(Photo courtesy of Cranfield University)

The test programme was due to start in January 1995, but was delayed due to the loss of the original test aircraft on its acceptance flight, Fig. 8. This was attributed to retreating blade stall on the take-off run, the aircraft having obtained too high a ground speed and insufficient rotorspeed. It pitched up violently and rolled rapidly left before impact with the ground on its left side. It is ironic that a programme designed to investigate gyroplane airworthiness and flight safety should itself come to grief. Further, it is salutary to consider that the accident occurred with a very experienced test pilot who had conducted an in-depth handling test programme on the VPM M16. During this earlier work, Ref. 17, measurements of rotorspeed and phugoid damping and frequency were made, Table 3. The good correlation in rotorspeed is most encouraging in view of the fact that the rotor is in autorotation, and not governed like a helicopter's. Likewise, the prediction of phugoid characteristics indicates good modelling of behaviour in view of the sensitivity of this mode to a wide variety of highly interactional effects.

	Time to Half Amplitude (s)	Period (s)	Rotorspeed (rpm)
Model	5.07	23.92	420
Flight	5	13	370

Table 3 Some Comparisons of Individual Blade Model Predictions with Flight

7. Implications for BCAR Section T

The dynamic stability requirements of BCAR Section T are expressed in terms of short-period and long-period damping and period. While tests to identify these characteristics, and their measurement, are common practice for test pilots, they constitute a mode of operation of the aircraft that other pilots will be unfamiliar with. In addition, no guidance is given as to how non-compliance may be addressed. In fact non-compliance may not imply an unsafe aircraft. Non-compliance may not be possible because oscillations may not be easily identified.

Under these circumstances, it may be appropriate to introduce to BCAR Section T Advisory or interpretative material to direct the builder to construct a configuration that will *tend* to posses positive longitudinal stability. The present studies indicate that placing the c.g. above the propeller thrust line is the only means of doing so. If incorporated, this direction will impact on that part of Section T dealing with weight and balance which currently makes no provision for determination of c.g. position, only a line along which the c.g. lies.

8. Discussion

This Paper has summarised the salient results from a substantial programme of research. In terms of longitudinal stability, there is no evidence to indicate a substantive contributory factor to the accident rate with this class of aircraft. It may be the case that other aspects of operation such as training and experience are predominating.

However, the phugoid-type oscillation does in theory couple with the rotorspeed degree of freedom, and this may be the added dimension to gyroplane stability and control that produces a degree of piloting difficulty. Table 4 shows the longitudinal body states and rotorspeed eigenvectors for the unstable oscillation given in Table 2. It is clear that the oscillation possesses a substantial rotorspeed element. Low-"g" manoeuvres are also known to reduce rotorspeed, but the results given in Figure 4 & 5 earlier indicate that for a bob-down type of profile, the substantial loss in rotorspeed (20% per 1/4 "g") is recovered during completion of the manoeuvre. Of course, the piloting strategy following a push-over input may not be to fly this type of manoeuvre, and the actual strategy may result in catastrophic loss of rotorspeed. However, the evidence from these simulations is that the fundamental flight dynamics of gyroplanes is relatively benign and within the scope of normal piloting ability.

state	$\left\|e_{ph}\right\|$
u	0.75
w	0.12
q	0.02
θ	0.04
Ω	0.59

Table 4 Unstable phugoid oscillation modal characteristics

9. Conclusions

The original aims of the research have been fulfilled. The work is entirely novel and original in content, and therefore makes an important contribution to the field. Gyroplane stability and controllability is in principle governed by the same theory as that for helicopters, certainly in relation to rotor behaviour. Simulations have shown that the dynamic stability of the gyroplane is largely unaffected by configurational changes other than the position of the propeller thrustline relative to the centre of gravity. Hence, as a specific class of aircraft provision of propulsive thrust results in configurations that can be stabilising or destabilising. Advisory material, which is simpler for owners to demonstrate compliance with, has been proposed for BCAR Section T that will tend to ensure positive longitudinal stability.

Acknowledgements

This work is supported by the UK Civil Aviation Authority under Contract 7D/S/1125 "Aerodynamics of Gyroplanes". The Technical Authority is Mr David Howson.

The authors would also like to acknowledge the technical assistance of Mr. Phil Barlow (the UK importer of VPM aircraft) and VPM for their co-operation.

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