Flight Handling Qualities of a Large Compound Rotorcraft

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Abstract

Recent years have witnessed a resurgence in the development of a variety of high speed rotorcraft. These include tilt-rotors (Bell/Boeing V-22, Bell-Agusta BA-609), compound rotorcraft (Sikorsky X-2, Piasecki X-49A), and autogyros (Groen Brothers Gyrodyne). The main goal for these vehicles is to exceed the performance of conventional helicopters in terms of flight speed, range and cruising altitude. The evolution of advanced materials, digital fly-by-wire control systems and efficient, lightweight powerplants has made these designs viable; however, these aircraft have also brought significant challenges in terms of complexity. There is a need to address these complexities in design through comprehensive modelling and virtual engineering. Initially taking a historical perspective, this paper will discuss simulation and modelling techniques used to develop a FLIGHTLAB model of the Fairey Rotodyne. Results from the simulation show how the model was capable of demonstrating the flight dynamics throughout the flight envelope including take-off, hover, transition and full autogyro flight. We are entering a new era of rotorcraft designs; their future development will be reliant upon the use of advanced modelling and simulation tools. This paper illustrates the modelling complexities faced and how these tools can predict the flight handling qualities achieved in a 1950's concept, and how the lessons learned might yet have something to offer aircraft designers in the 21st Century.

Nomenclature

α_0	Blade lift curve slope [rad^{-1}]
$C_{l\alpha_t}$	Tail lift curve slope [rad^{-1}]
$C_{l\alpha_t}$	Wing lift curve slope [rad^{-1}]
c	Blade chord [m]
c.g.	Centre of gravity
FGR	FLIGHTLAB Generic Rotorcraft
g	Acceleration due to gravity
HQ	Handling Qualities
ISA	International standard Atmosphere
I_{xx}, I_{yy}	Roll and Pitch moments of inertia
I_β	Blade flapping moment of inertia [kg-m^2]
l_t	Moment arm of tail centre of lift to aircraft c.g. [m]
L_v, L_p, L_r	Rolling moment stability derivatives (i.e. $L_p = \frac{1}{I_{xx}}\frac{\partial L}{\partial p}$)
l_w	Moment arm of wing centre of lift to aircraft c.g. [m]
m	Mass
M_u, M_w, , M_q,	Pitching moment stability derivatives
$M_{\theta_{1s}}$	Pitching moment due to longitudinal cyclic Stability Derivative i.e. $\partial M / \partial\theta_{1s}$
MTE	Mission Task Element
p, q, r	Roll, pitch and yaw rate (deg/s)
PIO	Pilot Induced Oscillation
p_{ss}	Steady state pitch rate per unit control deflection [deg/s.deg]
q_{ss}	Steady state pitch rate per unit control deflection [deg/s.deg]
R	Rotor radius [ft, m]
RPM	Revolutions Per Minute
S_t	Tailplane Area (ft^2)
S_w	Wing Area (ft^2)
S_β	Stiffness number
T_2	Time to double amplitude
u, v, w	Velocity along body X, Y and Z -axes
V	Velocity [m/s]
VTOL	Vertical Take-Off and Landing
Y_v, Y_p, Y_r	Y-force stability derivatives (i.e. $Y_v = \frac{1}{m}\frac{\partial Y}{\partial v}$)
Z_w,	Z-force due to vertical velocity stability derivative (i.e. $Z_w = \frac{1}{m}\frac{\partial Z}{\partial w}$)
α	Angle of attack of blade section
β	Angle of sideslip
γ	Lock number
δ_e	Trim elevator deflection [deg]
ζ_d ω_d	Dutch Roll damping ratio and frequency
θ, ϕ, ψ	Euler attitude angles
θ_{1s} θ_{1c} θ_0	Longitudinal cyclic, Lateral cyclic, Main rotor collective
μ	Advance Ratio ($V/\Omega R$)
ρ	Density of air
ψ	Blade azimuth (0-360°)
Ω	Rotor angular speed [rad.s^{-1}]

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Introduction

2008 is a year of anniversaries for aviation in the United Kingdom: it is 100 years since S. F. Cody made the first powered, manned flight in the UK, 90 years since the formation of the Royal Air Force and 60 years since the first Farnborough Air Show in 1948. At that same air show, the Fairey Aviation Company's FB-1 Gyrodyne was making its first public appearance, having already set a new absolute speed record for a helicopter of 124.3mph (200km/h) (1). The Gyrodyne was the first of a succession of compound rotorcraft prototypes designed and manufactured by Fairey Aviation that culminated in 1957 with the first flight of the Fairey Rotodyne. Keeping with the theme of anniversaries, 50 years ago the Rotodyne Type 'Y' prototype (Fig. 1) was successfully performing its first transitions from hover through forward flight as a helicopter and on to autogyro flight. The Rotodyne represented the ultimate expression of the Gyrodyne concept, merging the technologies of the autogyro, helicopter and the fixed-wing aeroplane. Its design incorporated a number of novel features including a 'torqueless' tipjet-driven main rotor, turboprop powerplants providing compressed air for rotor tipjets as well as longitudinal thrust and yaw control. The Rotodyne was the brainchild of Dr. J.A.J Bennett and Capt. A. Graham Forsyth (1); Bennett had previously worked for the Cierva Autogiro Company thus providing a direct link back to the pioneer of autogyro flight, Juan de la Cierva (he also succeeded Cierva as Technical Director upon his tragic death). It was an ambitious project, aimed at delivering a VTOL airliner/transport in the 40-50 passenger range for the inter-city routes of Europe and North America. Despite the apparent success of the Type Y prototype and tentative expressions of interest for a production version, a combination of technical, financial and political factors served to ultimately doom the project in 1962.

Figure 1 Fairey Rotodyne in Flight

Nevertheless, the 4 years of flying in which the Rotodyne prototype had carried over 1000 passengers in over 120 hours flying in 350 flights(1), had demonstrated the basic feasibility of the compound rotorcraft concept – but what was it like to fly and what can be learnt from its handling qualities?

This question leads us onwards to the central theme of this paper which presents an examination of the Rotodyne and its fundamental concepts using modelling and simulation, or more generally, virtual engineering (2). The objectives of this paper are as follows:

1. To demonstrate the application of modelling and simulation techniques to assess the handling qualities of this novel rotorcraft configuration.
2. To use the results to reflect on the technical challenges faced by the Rotodyne's engineers.
3. To discuss the feasibility of the various aspects of the Rotodyne concept in the context of future compound rotorcraft designs.

Figure 2: Existing and future high speed compound rotorcraft designs

Despite the successes achieved in flight testing, the Rotodyne was a complex design and probably equally complex to fly. Little was written about the handling qualities of the Rotodyne but it had more flying controls than a typical helicopter or aeroplane, with very little automatic stabilisation or management, which would have led to high pilot workload. It is also likely that the aircraft, large, and a compromise between helicopter and aeroplane, possessed unconventional handling behaviour. Today, digital fly-by-wire technology is certainly one technology that could transform designs like the Rotodyne into a practical reality. Indeed, the technologies imbued in the Rotodyne are again returning to the fore and numerous government and industry research programs are exploring various concepts. Examples include the CarterCopter(3), Groen Brothers Gyrodyne(4), Piasecki X-49A ‘Speedhawk’ (5) as well as studies by NASA and Sikorsky(6) (See Figure 2).

It has long been a dream of the aviation industry to achieve V/STOL transportation that could perform comparably with helicopters in the hover but also offer medium range through high cruise speeds and altitudes. The current climate in commercial aviation is also providing an opportunity for such machines. Continually increasing air traffic congestion in European (7) and North American skies is demanding innovative ways to increase airspace and runway capacity and efficiency. One proposal is the introduction of Runway Independent Aircraft (RIA) that could replace small and short haul-aircraft that currently use primary runways (6). This would free up precious runway slots to increase capacity or reduce congestion and the consequent delays. There is also significant military potential, with the US Armed Forces developing requirements for future heavy lift rotorcraft (8) and high speed VTOL armed escorts (9) for the new V-22 Tiltrotor transports. The challenges ahead are significant, nevertheless the technological advances made in digital flight control, advanced materials and powerplant design since the early 1960’s offer a chance to perhaps fulfil the promise that the Rotodyne once symbolized.

The Rotodyne and its operation

Table 1 contains the basic configuration data for the Type Y Rotodyne (Figure 3). A large machine, even by today’s standards with rotor diameter of 90ft, (to put its size into context, today’s largest production helicopter is the Russian Mil-26, which has rotor diameter of 105ft). The reader is directed to Refs (10) and (11) for more detailed design data of the Rotodyne.

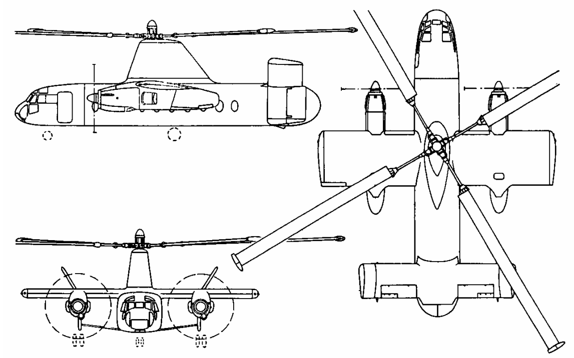


Figure 3 3-view of the Fairey Rotodyne Type-Y prototype

Table 1 Basic Configuration data for the Fairey Rotodyne Type Y

Rotor Diameter	90ft (27.43m)
Fuselage length	58.66ft (17.88m)
Wing span	48.5ft (14.78m)
Weight	33000-39000lb (15000-17727kg)
Power	2 x Napier Eland N.E.L.3 ~2800 SHP each
Propellers	2 x 13ft (3.96m) diameter

The aircraft was designed to operate as a conventional helicopter in takeoff, landing and low speed flight and to transition to autogyro flight once sufficient forward speed had been attained. Control in hover and low speed was achieved through conventional cyclic and collective controls with the rotor being driven by tip jets. The tip jets were supplied with compressed air from auxiliary compressors coupled to the main turboprop engines which was mixed with fuel and ignited. They were governed by the pilot using a typical collective twist grip throttle control. Yaw control was applied by differential blade pitch on the wing-mounted propellers, through pedals. The Rotodyne also featured a full suite of conventional aerodynamic controls, the ailerons and rudders were coupled with the cyclic and pedal controls but the elevators, as far as can be ascertained from the references, were actuated by a separate control inceptor (10). To manage the various rotor inputs, aerodynamic surfaces and propeller/engine systems, a complex mechanical control system was developed. This system also featured a number of interlinks and safeguards to help the pilot maintain rotor and engine systems within operational limits. Of particular note was how the turbine/propeller combination was operated. In the hover, the engines were governed automatically and responded to power demands from the propellers and the auxiliary compressors. In this mode, the pilot had direct control of collective propeller pitch to command thrust as well as the aforementioned differential control for yaw. The propeller collective pitch control was used in conjunction with the rotor controls in the helicopter regime to accelerate to the autogyro transition speed. Once in autogyro flight, the governing was then switched such that the pilot no longer directly controlled collective propeller pitch (differential control was also disabled) and the system became a constant speed propeller governor, where thrust was controlled in a similar manner to a conventional turboprop aircraft via the engine throttles.

Figure 4 illustrates the three main rotor states in flight for the Rotodyne. Although the rotor was less sensitive to RPM changes than conventional helicopters the pilot still had to observe overspeed limits but could safely accept variations of up to 16% of the total RPM range of (105-150RPM) (10). For transition to autogyro flight a step-by-step approach was devised that achieved complete conversion in around 30 seconds. The initiation speed for transition was usually 60-80kts and it could be performed in level flight or in a gentle climb. As the aircraft was accelerated using a combination of cyclic and collective propeller pitch, the tip-jet throttles and collective were simultaneously reduced such that they were idling when 110kts and 4° of rotor collective had been reached. The final step was to turn off the tipjets and disengage the clutches – the rotor was now completely free to autorotate. The rotor speed would continue to reduce as the speed increased and the pilot would fix the collective pitch at a constant setting.

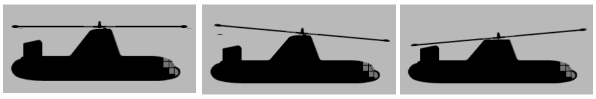


Figure 4 Schematic showing the rotor states in the three main flight regimes of the Rotodyne

The fundamental feature of the Rotodyne was the ability to fly at higher forward speed with the main rotor in autorotation. The key principle of this characteristic is that the rotor is no longer driven by any engines but by the airflow through the rotor disc. This was important as autorotation helped to mitigate two key limitations for the attainment of high speeds in rotorcraft:

- Retreating blade tip stall
- Advancing blade compressibility effect

The retreating blade stall limit is dependent on the rotor advance ratio, μ, and can be increased by reducing the blade mean lift coefficient, increasing the blade tip speed or area or by decreasing the rotor lift or forward thrust(11). In autorotation, the rotor is tilted back (Figure 4) and the task of generating forward thrust is performed by using propellers instead. The rotor is further alleviated from generating thrust by the provision of a fixed-wing, which as speed is increased takes on a greater proportion of the total vehicle lift. As such, the rotor speed and lift coefficient can also be reduced, also delaying the onset of compressibility effects on the advancing blade. By selecting a particular speed and a wing incidence by controlling the elevator, a varying longitudinal cyclic input was necessary for trim, thus presenting the rotor disc at different angles to the oncoming flow. This enabled the control of the trimmed flight rotor flapping to minimise vibration and prolong fatigue life. It also provided the pilot a means to optimise RPM for varying stability or performance needs. A rotor in autorotation also has reduced tip loading, further reducing the high speed tip effects.

Transitioning back from autogyro to helicopter mode was essentially the reverse procedure. This first entailed a reversion to propeller pitch control under constant engine speed governing and a reduction in speed to 110kts. Next the clutches were re-engaged and tipjets re-ignited, sometimes re-ignition was delayed until lower a speed of around 80kts after which the Rotodyne was brought into landing under normal helicopter controls.

Modelling and Simulation

The Rotodyne simulation was constructed in the commercially available modelling software package, FLIGHTLAB (12). Modelling this type of aircraft brought a number of challenges; first, a free unpowered rotor system had to be modelled. A standard FLIGHTLAB rotor model could be used except that only the airframe-bearing connection was complete and the engine-drivetrain-rotor path was left unconnected. The blades themselves were modelled as rigid beams with scaled mass and inertia properties from a known conventional helicopter rotor. The rotor featured a precone of 4.5 degrees and zero twist along the blade. Rotor blade flap and lag dynamics were modelled using a blade element model with 5 aerodynamic segments per blade. A 3-state Peters-He inflow model was chosen but no rotor/wing/propeller interference effects were implemented.

The rotor tip-jets were modelled as simple thrust generators at each blade tip with a simple drag model added at each blade tip to allow for the tipjet nacelles. The maximum thrust applied by the tip-jets was calculated by assuming a maximum tip-jet power of 4000hp (2983kW) (10). With a rotor speed of 16rad/s at takeoff, a maximum thrust of 3.4kN (764lbf) per tip-jet is computed. The propellers were modelled using a blade element approach derived from the FLIGHTLAB rotor models. The constant speed governor and differential pitch control were modelled by including controlled hinges at each blade root to allow blade feathering and positive/negative pitch.

The cyclic and collective controls were implemented in the normal manner and were controlled by the pilot's cyclic and collective sticks when flown in piloted real-time simulation (13). The Rotodyne also required wing, tail and fin surface models and these were implemented using a segmented, 'multi-body dynamics' approach (14).

The aerodynamic data for the airframe featured a number of approximations and estimations. The fuselage data was based on a similar bluff body rotorcraft fuselage but was scaled to the actual dimensions. The wing, tail and fin aerodynamics used data of similar airfoils to that of the actual airfoils used (10).

The inertia properties also required estimation as no published data was available. An 'autoCAD 2000i' model was created that featured all the major airframe components. By matching the mass to that in the published data by adjusting the average density of the solid material, the model was able to give an estimate of the moments of inertia (15).

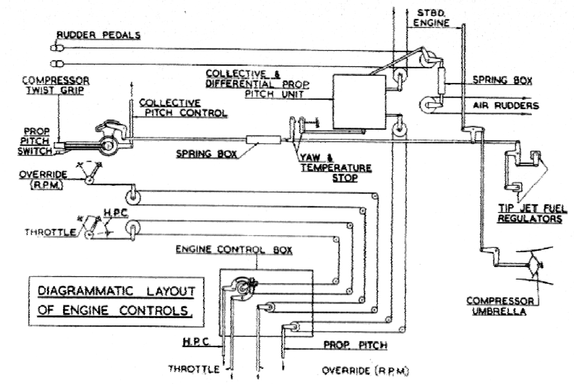


Figure 5 Schematic of the Rotodyne engine and power control system

Perhaps the greatest challenge of all was the modelling and implementation of the control system (see Figure 5). This was not only difficult because of the complexity of the system, but also due to the need to engineer and implementation that could be controlled using the inceptors available in the flight simulator cockpit. The control system was created in FLIGHTLAB's CSGE (Control System Graphical Editor) package. The lateral stick was configured to drive the ailerons as well as lateral cyclic. This was not the same for the elevators where the pilot was able to trim using a separate fore-aft movement of a 4-way trim hat on the centre control column in the cockpit. The longitudinal stick only controlled the longitudinal cyclic of the rotor.

The pedal connection to the aerodynamic rudders was active in all flight conditions. A separate 'Pitch Switch' determined whether the collective and differential pitch propeller controls were active or if they were under constant speed control. When set to 1, control in yaw was achieved by changing the collective pitch angle of propellers differentially. The collective propeller range was -10° to +35°. At -10° collective pitch, a differential pitch of ±4.5° could be commanded via the pedal inputs. This differential blade angle limit reduced with increasing collective propeller pitch until it was zero at a collective propeller pitch of +12°. The collective channel was straightforward with the stick input directly geared to the collective blade angle.

Overall, the model provided a level of fidelity suitable for general stability, flight dynamics and handling qualities analysis. The model could be trimmed to equilibrium at various flight conditions from the hover under tipjet power through to high speed autogyro mode. The paper presents a range of results obtained with the model which include:

- Trim and performance computations.
- Extraction of linear time invariant models and stability parameters.
- Dynamic response and control analyses
- Comparison of parameters against rotorcraft handling qualities criteria.
- An investigation of the application of modern flight control techniques to the Rotodyne configuration

The results presented demonstrate the insight that can be derived from a model of this type as well as highlighting the virtual engineering challenges faced in the design of advanced compound rotorcraft.

Trim and Performance characteristics of the FLIGHTLAB Rotodyne

The first analysis is a study of the trim and performance characteristics. In Helicopter mode, the Rotodyne trim characteristics are very similar to that of a conventional helicopter, increasing forward speed requiring increased forward cyclic. Of course, with no torque to counteract, the aircraft is symmetric in forward flight and the pedals remain centred. Without using any elevator trim or additional propeller thrust, the maximum trimmed forward flight speed was found to be approximately 80kts. The model could maintain hover at maximum tipjet thrust up to an altitude of 4100ft ASL (at the nominal weight). In autogyro flight the model was trimmed at maximum propeller thrust from 0-10000ft ASL. In all, trim solutions for level flight were achieved for 0-70kts in Helicopter mode, 80-110kts for Transition mode and 120-177kts in autogyro flight. The Transition mode trims featured incremental reductions in tipjet and collective with increasing speed. A simple proportional feedback controller for the tipjets was also added to mimic the pilot behaviour in controlling the trim rotor speed. It must also be added that this system was deactivated once the trimming had finished. The trim strategy changed at the 80kts Transition mode condition, as the rotor collective and tipjets were fixed and the trim algorithm adjusted the throttles to vary the propeller thrust to achieve trim, the rotor was free to rotate at whatever speed it converged on. The increments of collective and tipjet were chosen arbitrarily by the author except for the final target of 3.5° and zero tip jet thrust at 110kts autogyro speed that were designed to match the published information in Refs (10,11).

The results in Figure 6 show the relationship of the rotorspeed and flapping with the rotor collective, elevator trim and speed in autorotative flight. The results demonstrate the typical autogyro characteristic of the Rotodyne – rotorspeed decreasing with increasing forward speed. The elevator trim control is also effective at controlling the trim rotorspeed; as the elevator is moved from a positive angle (nose down pitching moment) to a negative one, the rotorspeed reduces. The pitching moment generated by the elevator modifies the cyclic pitch required for equilibrium in pitch and consequently the trim disc tilt to the flow is adjusted. The relationship between collective, elevator and forward speed with longitudinal flapping is shown in Figure 6 (b). It was stated in (10) that the broad aim when flying the Rotodyne was to keep flapping below 5 degrees, which is realistic based upon the results shown.
When the pilot varies the elevator/cyclic controls, they are effectively changing the distribution of the lift between the rotor and the wing, as shown in Figure 7. According to (3), the Rotodyne's autorotating rotor should have provided somewhere in the realm of 65% of the total lift, this compares favourably with the results presented.

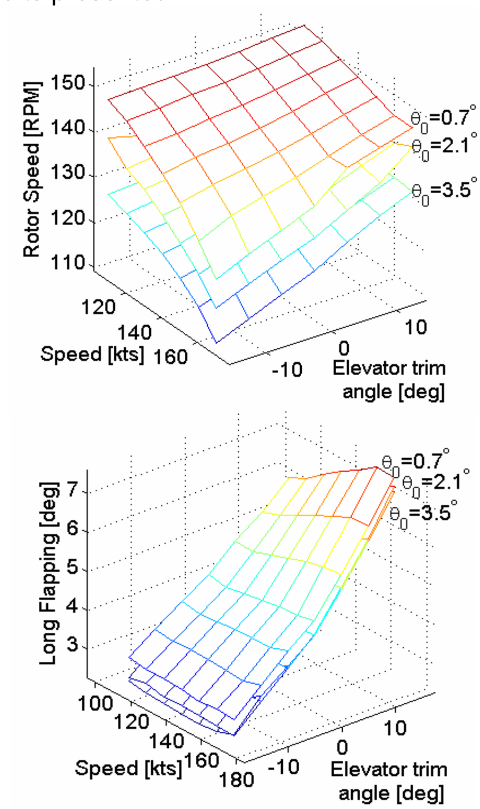
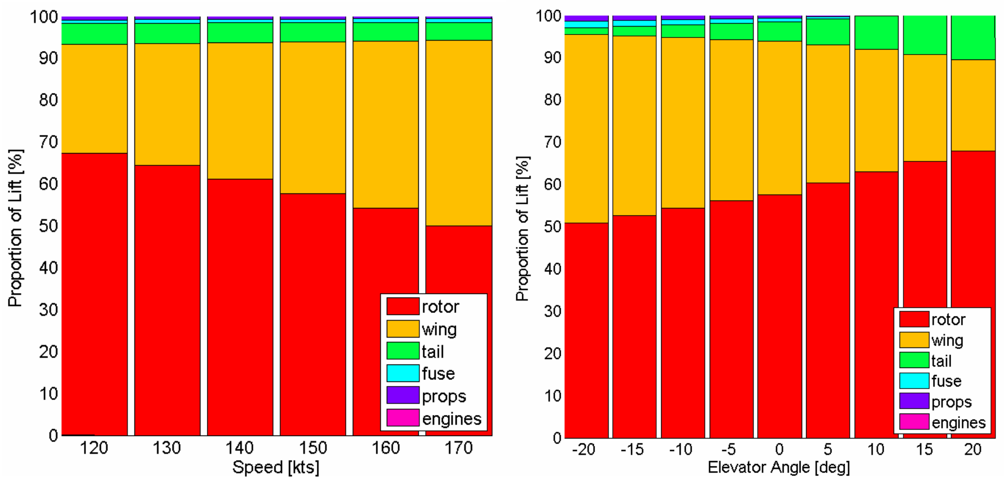
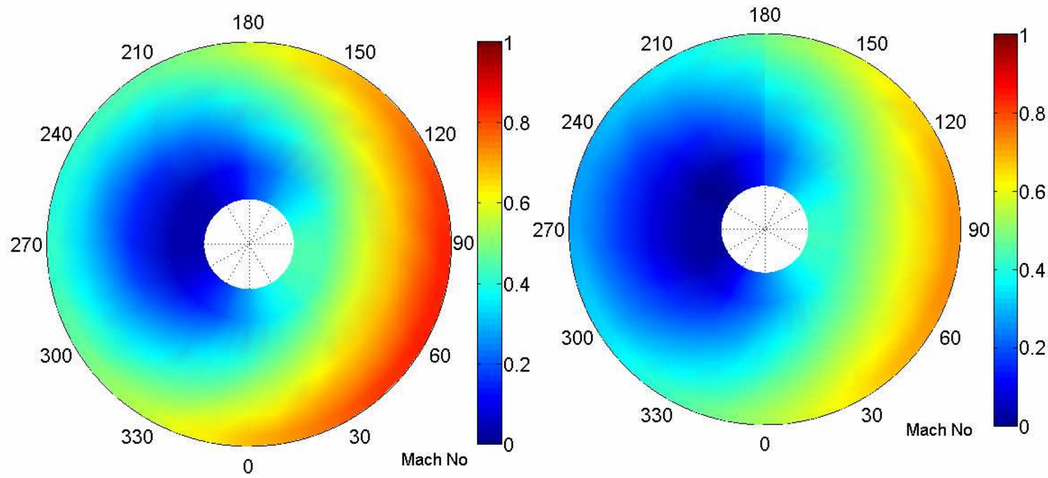


Figure 6 Relationship between Rotor speed and Longitudinal flapping with Elevator Trim, Rotor Collective and Airspeed in Autogyro Flight with Elevator Trim and Airspeed in Autogyro Flight



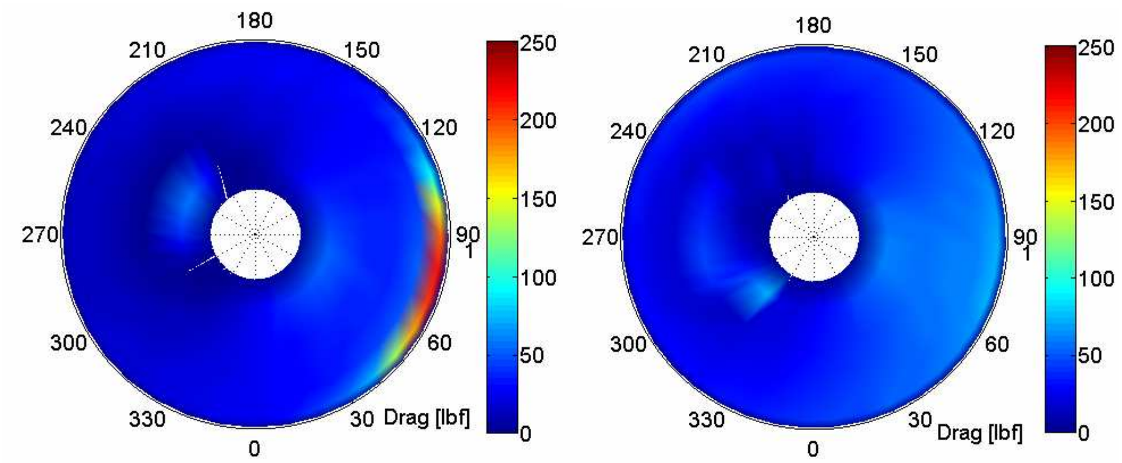
(a) (b)

Figure 7 Distribution of lift from various components of the Rotodyne for (a) varying speed at 0deg Elevator trim and (b) elevator trim positions at



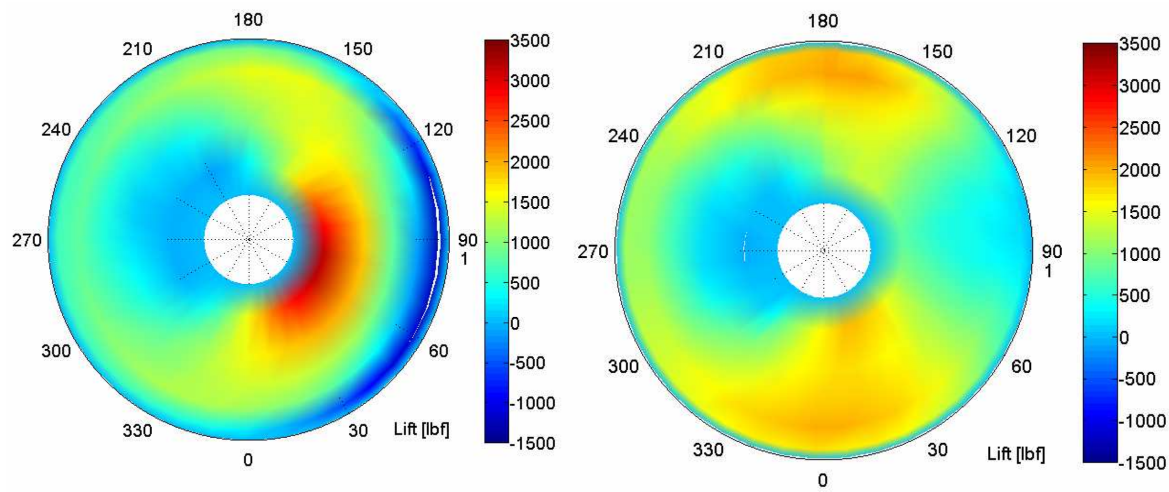
FGR ROTODYNE

Figure 8 Comparison between a FLIGHTLAB Generic Rotorcraft (FGR) and Rotodyne of Mach Number over the Rotor Disc. V=150kts



FGR ROTODYNE

Figure 9 Comparison of Drag over the rotor disc between a FLIGHTLAB Generic Rotorcraft (FGR) and Rotodyne V=150kts



FGR **ROTODYNE**

Figure 10 Comparison of Lift over the rotor disc between a FLIGHTLAB Generic Rotorcraft (FGR) and Rotodyne V=150kts

In Figure 8 it is clear that by slowing the rotor, the Rotodyne's advancing blade Mach number is significantly reduced (up to 0.15-0.2) compared to the FLIGHTLAB Generic Rotorcraft (FGR). This is especially significant considering that both aircraft have equivalent tip speeds at hover. When the lift force distribution is considered in Fig 9, the Rotodyne lift is more evenly distributed along the blade. It is also evident that the advancing blade (ψ=90°) is contributing very little lift, thus further alleviating the compressibility effects such as high drag. This is visible in Figure 9 where the FGR experiences peak drag loads on the advancing blade tip as well as some higher drag at the retreating blade root, whereas for the Rotodyne the advancing blade drag is not noticeably higher than the rest of the disc.

Flight Handling Qualities of the FLIGHTLAB Rotodyne

Ref (16) describes how the complete manoeuvre envelope of an aircraft can be expressed in terms of the frequency and amplitude of the dynamic response. As such, the motions can be divided into 4 main regions to form the constituent parts of the so-called 'Dynamo Construct':

- Low Frequency and Low Amplitude – Stability Mode Analysis
- High Frequency and Low Amplitude – Bandwidth
- Low to Medium Frequency and Medium Amplitude – Quickness
- Low Frequency and High Amplitude – Control Power

This framework is the basis for the mission oriented ADS-33E-PRF (17) handling qualities Dynamic Response Criteria (DRC). Figure 11 illustrates the 4 groups of the DRC, two relating to agility (Control Power and Quickness) and two relating to stability (Stability mode analysis and Bandwidth). The criteria in ADS-33E-PRF are theoretically related for classical rate or attitude response types, so that, for example, attitude quickness tends to control power at large amplitude and to bandwidth at small amplitudes; the character of the higher frequency modes determines the closed-loop stability and the degree of precision achievable in tracking tasks.

The mission orientation of the handling qualities requirements in ref (17) is partly defined by the nature of the mission task elements (MTEs) to be flown. Target acquisition and tracking' phases are typified by combat scenarios while 'all other MTEs' are more relevant to cargo/utility aircraft roles and are used here to show levels of divided attention HQs (divided attention HQs are shown for the Rotodyne due to the multiple inceptors and systems the pilot must oversee in addition to the basic flying task).

The following results will consider the dynamic response criteria in conjunction with non-linear responses and derivative analysis of the Rotodyne model. The discussion is split into two sections. First the open loop stability (small amplitude – low frequency) is discussed then the remaining criteria are considered in the 'response to controls' section.

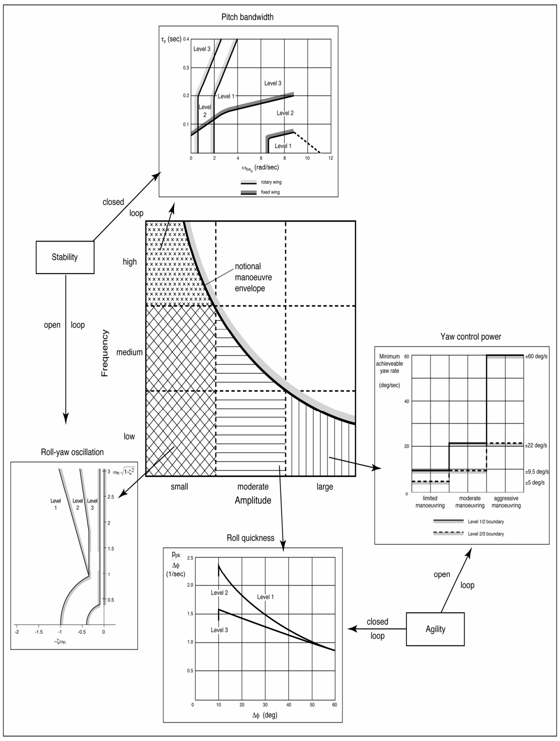


Figure 11 Dynamic Response Criteria (16)

Stability (Small Amplitude – Low Frequency Response) Analysis

The primary method of assessing the stability was by the extraction of linear state-space models from the nonlinear model. This powerful technique enables the estimation of stability and control derivatives of the model in a way that by virtue of their simplicity, permit greater insight into the cause and effects of the dynamic behaviour.

Figure 12 shows the principal parameters that describe the longitudinal stability of the Rotodyne model. Part (a) contains the longitudinal stability derivatives decoupled from the lateral dynamics across a range of speeds from hover to maximum autogyro speed .The static stability is reflected by the derivative M_w, a weakly negative value denoting that the Rotodyne was marginally stable in pitch. Z_w, the heave damping parameter, exhibits a behaviour which is somewhat a mix of the classical fixed-wing and helicopter. For a fixed-wing aircraft, the negative increase of Z_w is linearly proportional to the forward speed, while for a helicopter it tends to plateau to a constant value at high speeds (16) - the Rotodyne's Z_w curve is somewhere between them. Z_w is important in reflecting the initial onset of the response to a disturbance such as vertical gust. The damping in pitch is given by M_q, which for most of the speed range is fairly constant. Figure 12(b) also presents the classic 'Thumb Print plot' (18). This chart was an early attempt at relating measures of a fixed-wing aircraft's short period stability to its likely pitch handling qualities. The results for the Rotodyne have been plotted against these boundaries and are quite some distance into the 'unacceptable' region. The natural frequency ω_n is low while the damping ratio is one in the hover, becoming less damped as speed increases. This combination, although stable, would manifest itself to the pilot as a sluggish and imprecise response to control inputs, possibly leading to PIO tendencies in high gain tasks due to the very low short period mode frequency

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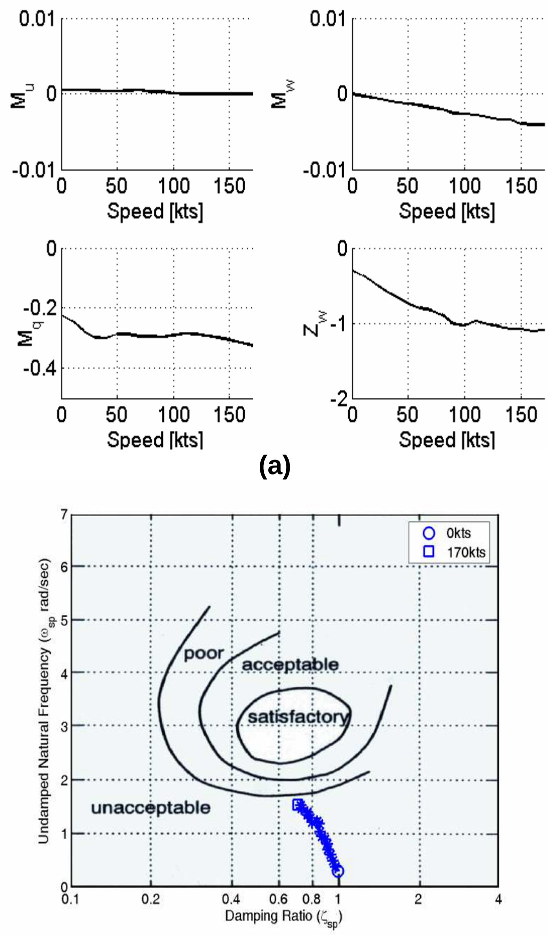

Figure 12 Longitudinal stability parameters for the Rotodyne: (a) Stability Derivatives (b) Short-Period thumb print plot

It is interesting to contrast this assessment with how the dynamic modes compare to the low-speed criteria for pitch axis in the rotorcraft ADS-33E handling qualities criteria (17). Figure 13(a) shows the loci of the longitudinal eigenvalues from 0-170kts compared against the handling quality level boundaries. A classical pair of Short period and Phugoid modes is evident – the Short Period begins as a pair of subsidence modes that combine to form one oscillatory mode which increases in frequency and damping with speed. The Phugoid mode, although unstable, becomes close to the Level 2/1 HQ boundary as speed increases.

The low and high speed Lateral-Directional modes are presented in Figure 14(a) and (b) respectively. The ADS-33 stability criteria for divided attention flight are again used for comparison but instead the lateral eigenvalues are plotted. Two of the three key classic lateral-directional modes are visible on the low speed figure, namely the Dutch Roll and Spiral modes, while the third mode, the roll subsidence, is beyond the left hand x-axis limit in (a) but can be seen in (b). The Dutch roll mode is a coupled roll-sideslip-yaw oscillation that is often described as nuisance mode. As such, it can 'interfere' with the pilot's ability to maintain a trim in gusty conditions and coordinated turns and can cause uncomfortable ride quality for passengers (19). From Figure 14(a), the Dutch Roll mode is within the Level 2 for all speeds.

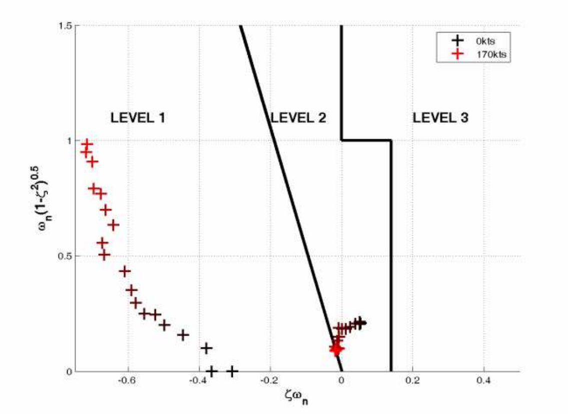

Figure 13 Root Locus of Longitudinal eigenvalues with speed compared to the ADS-33E Hover and Low speed (Pitch) stability criteria for divided attention

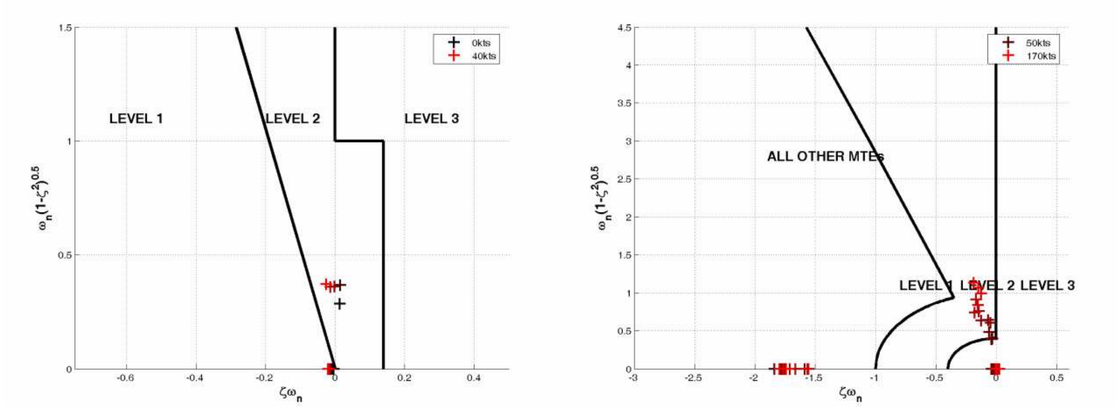

Figure 14 Lateral eigenvalues with speed compared to ADS-33E (a) Hover and Low speed stability criteria and (b) Lateral-Directional stability criteria in forward flight (All Other MTE's)

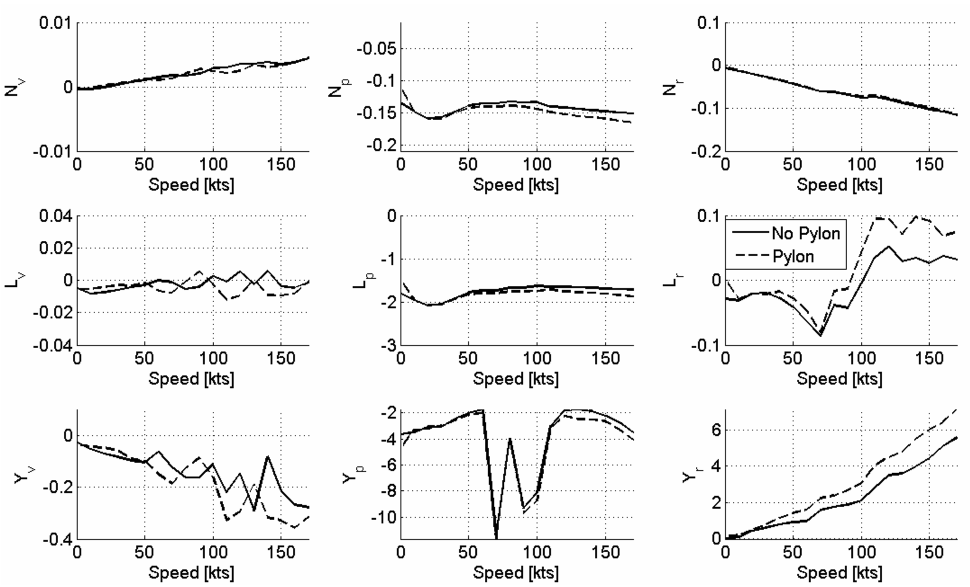

Figure 15 Lateral Stability Derivatives for FLIGHTLAB Rotodyne

For the Rotodyne, the Dutch Roll mode has a low to moderate frequency across the speed range but is weakly damped. A useful approximation to this mode is provided by (16) and is presented below. The damping is given by:

$$2\zeta_d \omega_d = -\frac{\left(N_r + Y_v + \sigma_d\left[\frac{L_r}{V} - \frac{L_v}{L_p}\right]\right)}{\left(1 - \frac{\sigma_d L_r}{L_p V}\right)} \quad (1)$$

And the frequency by:

$$\omega_d{}^2 = \frac{\left(VN_v + \sigma_d L_v\right)}{\left(1 - \frac{\sigma_d L_r}{L_p V}\right)} \quad (2)$$

Where:

$$\sigma_d = \frac{g - N_p V}{L_p} \quad (3)$$

The principal influencing derivatives for this mode are N_p and L_v which couple the rolling and sideslip-yaw motions. As shown in Figure 15, both of these derivatives are negative and relatively large compared to the other lateral derivatives. The more negative N_p is, the greater destabilising effect it has on the Dutch Roll oscillation, as it tends to superimpose a roll motion into the mode such that $N_p p$ adds negative damping (16).

The final observations on stability focus on the Spiral Mode. It is usually an aperiodic mode that determines the tendency for an aircraft to diverge or recover to level flight following a roll disturbance. It is largely governed by the numerator which is influenced by the derivative L_r (20), as can be seen in the following approximation:

$$\lambda_s = \frac{g}{L_p}\left(\frac{L_v N_r - N_v L_r}{VN_v + \sigma_s L_v}\right) \quad (4)$$

Where: $\sigma_s = \sigma_d$ (5)

This is because $\left|N_v L_r\right| >> \left|L_v N_r\right|, \left|VN_v\right| >> \left|\sigma_s L_v\right|$. The trend whereby the Spiral mode moves from marginally stable at speeds below 80kts to unstable imitates the trend of the dominant derivative, L_r in Figure 15. An analysis of the effect of the rotor pylon is also included in Figure 15. The streamlined pylon essentially was as a low aspect ratio vertical surface above the centre of gravity but at a location approximately equal to its longitudinal position. The greatest effects are seen in L_r and L_v at high speeds. L_v, often referred to as the dihedral effect, becomes more negative (stabilising) due to the increased sideforce (lift) generated in sideslips acting above the c.g. to produce counteracting rolling moments. Conversely, L_r increases, indicating that the pylon lift due to yaw is acting behind the centre of rotation (c.g.) destabilising the spiral mode.

It is not unusual for fixed or rotary wing aircraft to exhibit a marginally unstable spiral mode and the handling qualities criteria reflect this. For rotorcraft, ADS-33E specifies minima in the time-to-double amplitude, T_2, for the Spiral mode where Level 1 is given for a $T_2 > 20$ seconds. For the Rotodyne, the worst case value is at around 120kts where a T_2 of 27.3 seconds is calculated, which still meets the Level 1 requirements for the Spiral mode.

Response to Controls: Autogyro Mode

The analysis has shown that not unsurprisingly, the Rotodyne possesses a hybrid of fixed-wing and rotary wing stability characteristics. Furthermore, the comparisons with rotorcraft and fixed-wing handling qualities criteria have shown a range of predicted handling qualities from Level 1 to Level 3.

The dynamic response analysis starts with the Rotodyne flying in high speed autogyro flight. It has already been stated that is desirable in this condition to reduce the rotorspeed to reduce drag and delay the onset advancing blade compressibility effects. However, one reported consequence for autogyros is the sensitivity of the control power with the varying rotorspeed (21). Figure 16 demonstrates this effect with a step input in lateral stick at a speed of 150kts at rotor speeds of 145RPM and 120RPM. These different rotor speeds were achieved by trimming with positive or negative elevator angles as described earlier. The results show that the greater steady-state roll rate was achieved at the higher rotor speed. A useful first-order approximation based on the ratio of the control and damping derivatives provides the steady state rate-response per unit control input (16):

$$p_{ss}(\deg/s.\deg) = -\frac{L_{\theta_{1c}}}{L_p} = -\frac{\gamma\Omega}{16} \quad (6)$$

This equation shows that the rate response is effectively proportional to the Lock Number, γ, and the rotorspeed, Ω. However, it must be added that equation 6 is not strictly valid for the Rotodyne in forward flight as L_p would contain significant contributions from the wing, empennage and fuselage. Nevertheless, these can be ignored when comparing the two 150kts conditions as these contributions would remain nearly constant between them. As such, the ratio of the two rotor speeds (145Rpm/121Rpm) is roughly equivalent to the ratio of the roll rates (14°/s / 11.87°/s) thus confirming equation 6.

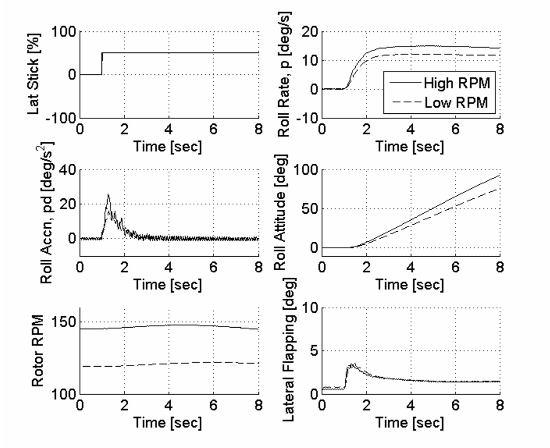

Figure 16 Comparison of roll response to a step in lateral stick input at 150kts at low and high trim rotorspeeds

It has also been shown previously in this paper that in Autogyro mode, the rotorspeed also intrinsically varies with airspeed. This is evident in Figure 17 where the three speeds have different trim rotorspeeds. However, despite the RPM disparity, an interesting result from these responses is that the maximum pitch rate response was almost equal in response to longitudinal stick doublets. This is because the tail and wing play a much larger part than for the roll axis response. To demonstrate this equation 6 is rewritten for the longitudinal axis and it shows that the damping in pitch is important in governing this effect. Equation 7 consists of the breakdown to the contributing basic parameters of the control and damping derivatives in pitch.

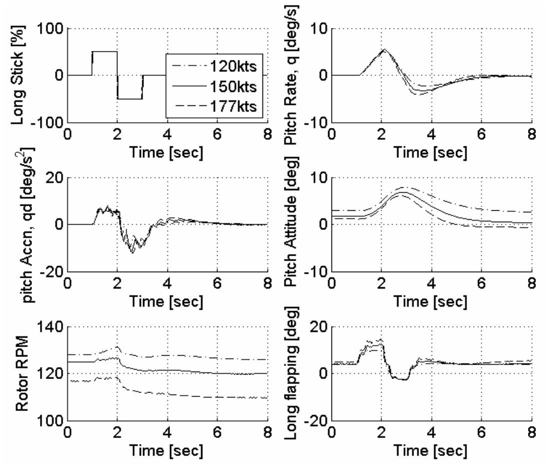

Figure 17 Comparison of responses to a in longitudinal stick doublet input at different trim speeds

The pitch axis is controlled only by the rotor and therefore $M_{\theta_{1s}}$ is independent of the forward speed (if inflow effects are neglected) but the damping has a dependence on the rotor and the forward speed because of the wing and tail contributions. As the forward speed, V, is increased, the wing and tail increase the damping but the reducing rotorspeed acts in the opposite sense. This counterbalance between the two effects can be described by referral to Figure 12 where the pitch damping is fairly constant above 40kts. Using these damping values and the control derivative, $M_{\theta_{1s}}$ in equation 7, the rate sensitivity (the steady-state response per degree of cyclic) is calculated to be almost constant across the speed range (Figure 18) hence explaining the result in Figure 17.

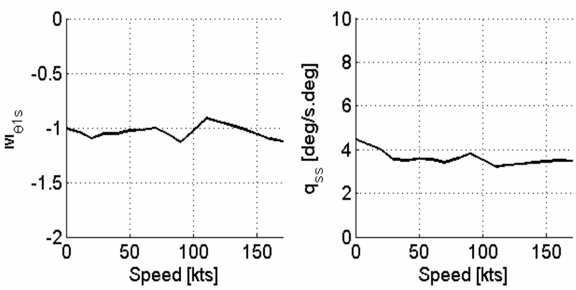

Figure 18 Pitch control derivative and Pitch rate sensitivity parameter with speed

$$q_{ss} = -\frac{M_{\theta_{1s}}}{M_q} = -\frac{-\dfrac{N_b S_\beta \gamma I_\beta \Omega^2}{16 I_{yy}}}{-\dfrac{N_b S_\beta I_\beta \Omega}{I_{yy}} - \dfrac{\rho V S_t C_{L_{\alpha t}} l_t^2}{2} - \dfrac{\rho V S_w C_{L\alpha_w} l_w^2}{2}} \qquad \textbf{(7)}$$

Response to Controls: Helicopter Mode

In the hover, conventional helicopter response characteristics are most prevalent and consideration is given to typical rotorcraft low speed handling qualities issues such as pitch/roll cross couplings and the heave and yaw response. Figure 19 shows the pitch-roll and roll-pitch cross couplings, the roll into pitch coupling, demonstrated by a lateral stick step were minimal as the rotor coupling effect has overcome the large pitch inertia. Conversely, for the pitch to roll coupling the rotor coupling has a much larger effect due to the lower inertia in roll whilst at the same time the primary pitch axis motion is strongly attenuated by the much greater pitch inertia.

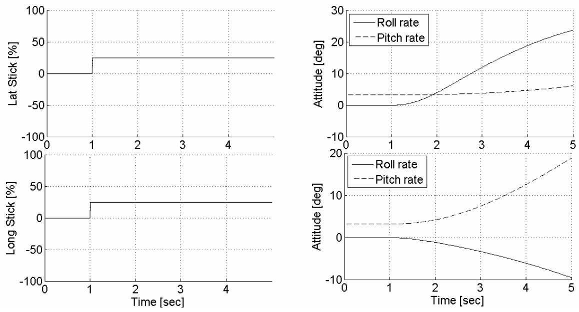

Figure 19 Lateral and Longitudinal stick step inputs in the hover

ADS-33 states: *"Control inputs to achieve a response in one axis shall not result in objectionable responses in one or more of the other axes."* The cross coupling responses are measured within a 4 second period after an abrupt step input in control from the trim. Using the ADS-33 criteria, the roll-pitch coupling is comfortably Level 1 as shown in Figure 20 but in the pitch to roll response they are borderline Level 2/3.

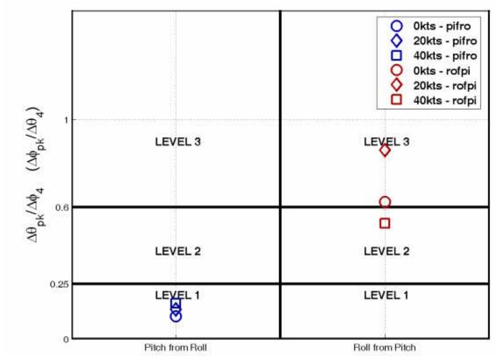

Figure 20 Rotodyne Pitch (roll) to Roll (pitch) Cross Coupling

The yaw control response characteristics are shown by a step input in pedal in the hover (Figure 21). The Rotodyne exhibits an unusual acceleration response type, with the yaw rate linearly increasing with time. The cause for this is the low damping in yaw in hover and a very slow response with a yaw rate of 10deg/s achieved only after ten seconds.

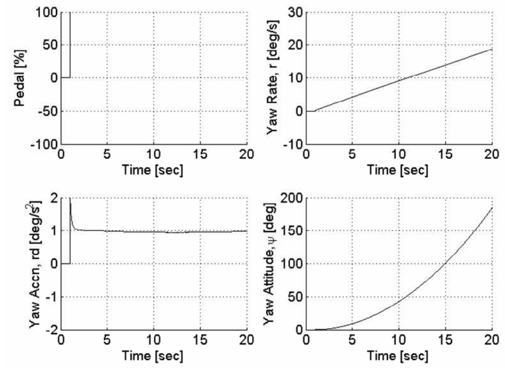

Figure 21 Pedal step input in the hover

The final control response considered is the heave response to collective inputs. Figure 22 shows the comparison of two responses to a step input in collective from the hover. The torque reaction-free tipjet system means that there is very little yaw response to collective inputs, however because the system has no automatic governing the rotorspeed falls rapidly. In controlled flight the pilot would have been able to compensate via the tipjet twist throttles. However, this task would have added pilot workload, especially as there was a time lag in the tipjet thrust response to control (10). Also, the model calculated only a 5% margin of remaining thrust to maintain the desired 156RPM in the hover meaning that higher collective settings would have resulted in lower RPM further complicating the pilot's task in controlling thrust.

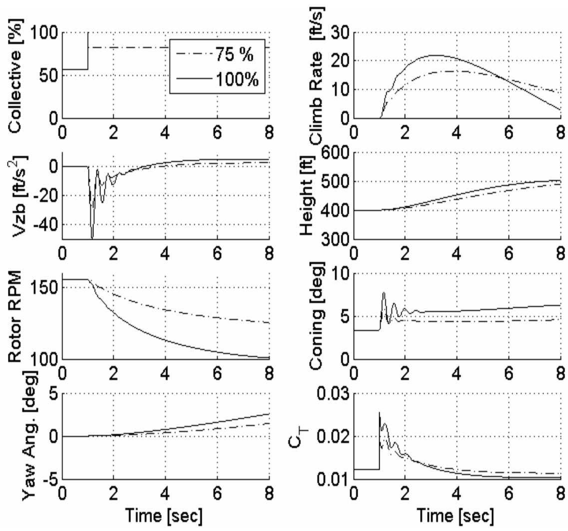

Figure 22 Comparison of vertical response to step inputs of different magnitudes

High Frequency and Low Amplitude – Bandwidth

As discussed previously, the DRC describes how the complete manoeuvre envelope of an aircraft can be expressed in terms of the frequency and amplitude of the dynamic response, Up this point, the analysis in this paper has included the zero frequency trim, the low frequency and amplitude stability and the large amplitude, low frequency control power and cross coupling aspects of the Rotodyne. To complete the handling qualities picture, the remaining two regions of the dynamo construct are presented: Bandwidth and Attitude Quickness.

When trying to precisely track an object, whether a target or when closely controlling flightpath or position, the low amplitude high frequency response is crucial. This is measured via the bandwidth parameter which in ADS-33 is defined as the frequency where the response phase margin is 45 degrees, or the maximum frequency at which pilots can double their gain without threatening the closed-loop stability. Bandwidth is calculated by measuring the attitude response to a frequency sweep input, determining the phase and magnitude over the range of applied frequencies and determining the frequency where the phase margin is 45 degrees. From Figure 23, pitch and roll are seen to be in Level 2 while yaw is marginally within Level 2 in the hover, becoming Level 3 with increasing speed.

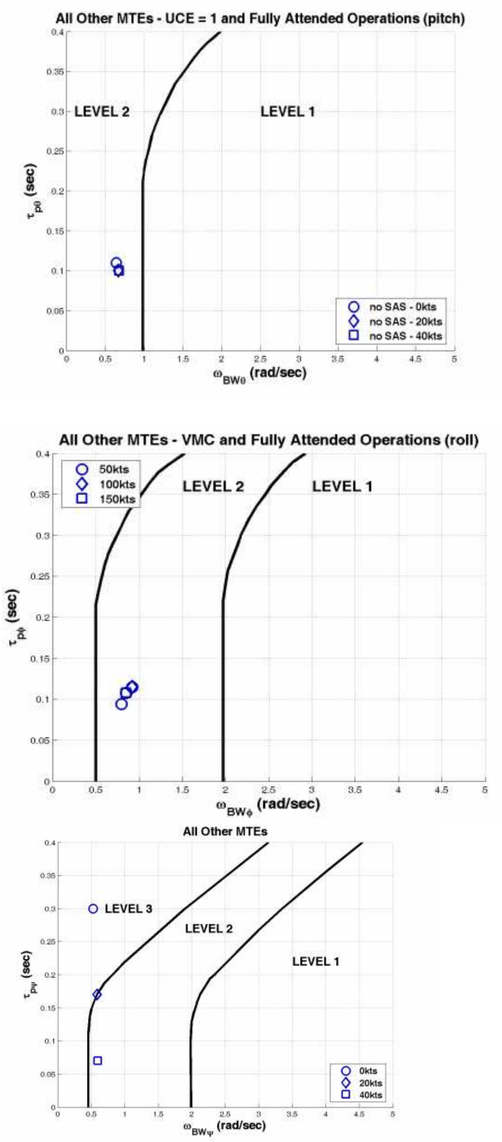

Figure 23 Rotodyne Low speed Bandwidth: pitch roll & yaw axes

Moderate Amplitude – Low/Medium Frequency – Attitude Quickness

Attitude quickness, like bandwidth, is an innovation of ADS-33, providing criteria for agility across large spectrum of manoeuvres from tracking tasks to near maximum manoeuvring. The parameter is calculated as the ratio of the peak rate response to the attitude change achieved, so for the roll axis it would be formed as follows:

$$\text{Roll Attitude quickness} = \frac{p_{pk}}{\Delta\phi} \quad (8)$$

The quickness provides a versatile measure of agility where high quickness can confer the ability for a pilot to make rapid and precise changes in attitude. For the Rotodyne model, quickness results have been computed for a variety of conditions. Figure 24 shows pitch, roll and yaw quickness for low speed manoeuvring where pitch quickness is Level 2 becoming Level 1 as the attitude change increases, while roll quickness is borderline Level 1 and yaw quickness is well within the Level 3 region.

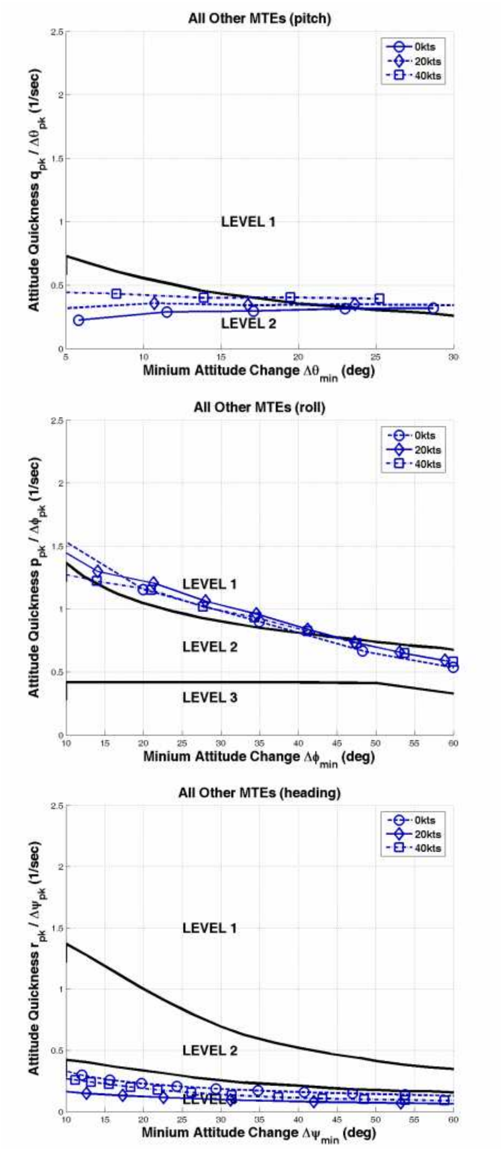

Figure 24 Rotodyne attitude quickness: pitch roll & yaw

As speed increases into the forward flight regime (> 45 knots), roll quickness moves from borderline Level 1/2 at 50kts reducing to Level 2 at 100kts and 150kts. This trend is a consequence of the reduction of roll control power with reducing rotor RPM at high speed.

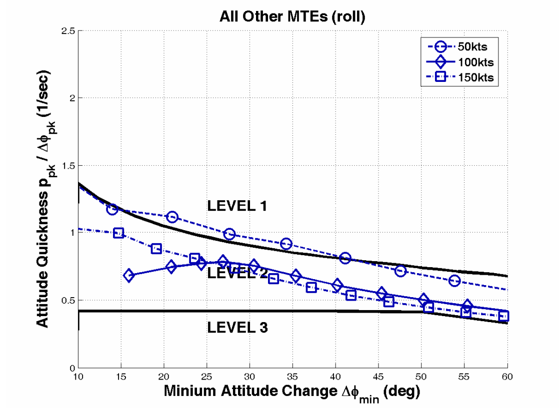

Figure 25 Rotodyne Roll Attitude Quickness: Forward flight (>45 knots)

Controller Assessment

It was recognised early in the development of the helicopter that the use of electronic flight control augmentation would be necessary to achieve good handling qualities (22). The helicopter, in many respects, led the way in the use of electronic automatic stabilisation with the early examples such as a Sikorsky S-58 with so-called Automatic Stabilization Equipment (ASE) specifically designed for helicopters in 1954. This system featured a 4-channel feedback system with series actuators and had accumulated over 30,000 flight hours by 1957, it was also found to improve the response characteristics as well adding stability (22). It is interesting to note that this technology, although new at the time, is entirely within the timeframe of the Rotodyne – was it ever considered for use? Certainly the results presented in this paper indicate that it would have benefited from stability augmentation in the lateral-directional axes and some control quickening, especially in yaw. To investigate this aspect a short study was conducted where modern control system design techniques were applied to the FLIGHTLAB Rotodyne model.

H_∞ Controller Design

This section describes the full-authority H∞ mixed sensitivity ("S/KS") stability, control augmentation system (SCAS) that was designed and implemented on the non-linear FLIGHTLAB Rotodyne model. H∞ control has been applied to rotorcraft for the last 20 years mainly by Postlethwaite, Walker and their co-workers (23) and (24) and shows good potential. A full discussion of H∞ control is beyond the scope of this paper and further details relating to theory and application can be found in (25,26). Essentially H∞ is a control optimisation method that takes a 'worst case' approach to optimisation (27). The method can guarantee stability against certain forms of uncertainty such as uncertainty due to insufficient representative data in the aircraft simulation model, for example when the blade elastic properties are not known. It can also be used to optimise performance, particularly when applied to the two-degree-of-freedom scenario as described here.

Design Methodology

The full-authority controller was designed for low speed helicopter flight (0-40kts) to provide an attitude command/attitude hold (ACAH) response type in pitch and roll and rate command (RC) in yaw. The controller was designed to allow the aircraft to operate in a degraded visual environment (DVE) with minimal pilot workload. ADS-33 [17] stipulates that in order to achieve level 1 handling qualities for hover and low speed near earth flight MTEs in a DVE (Useable Cue Environment (UCE), 2), an ACAH response type is required. The controller was designed in a hover condition using a 9-state linearization extracted from the FLIGHTLAB non-linear Rotodyne model. The outputs controlled were roll angle and pitch angle and yaw rate and, in addition, attitude rates were fed back to improve performance. The Stability and Contol Augmentation System (SCAS) structure consisted of separate longitudinal and multi-input lateral-directional controllers. Figure 26 illustrates the basic layout of the longitudinal and lateral-directional controllers:

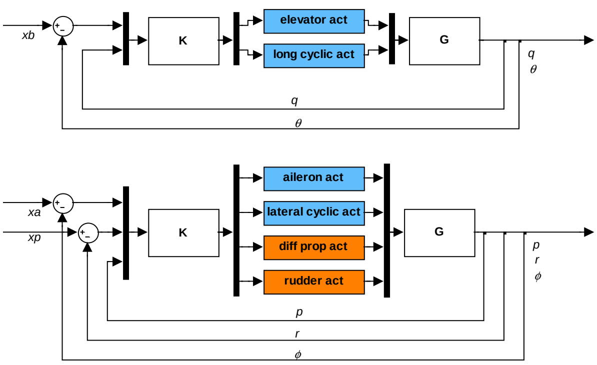

Figure 26: Longitudinal and lateral-directional sub controllers

Where;

K is the H_∞ controller
G is the linear aircraft model
'act' represents the control actuator models
Xa is the pilot lateral stick input
Xb is the pilot longitudinal stick input
Xp is the pilot pedal input

The helicopter rotor and aeroplane controls were geared in a 1:1 ratio in helicopter mode in order to maximise the control power in low speed helicopter mode flight. For example a 100% aft pilot stick input would apply maximum longitudinal cyclic and elevator deflection (11.5 and 20 degrees respectively). The actuator models in figure 28 were based on a first order transfer function:

$$\left(\frac{1}{0.0166s+1}\right)\left(\frac{1}{0.0166s+1}\right) \quad (9)$$

with the rate and saturation limits corresponding to the actuator channel.

Table 2 illustrates the control actuator saturation and rate limits that were modelled:

Table 2: Control actuator saturation and rate limits

Control	Actuator saturation limit (degrees)	Actuator rate limit (degrees/sec)
Elevator, aileron, rudder	+/- 20	+/- 40
Longitudinal cyclic	+/- 12	+/- 24
Lateral cyclic	+/- 7.5	+/- 15
Differential prop pitch (yaw)	+/- 4	+/- 8

Controller Performance and Robustness

Figure 27 shows the linear aircraft response and actuator demands during a 50% step input in the pitch channel about the nominal design point of 0kts. The step input was applied after 1 second and the step duration was 6 seconds; this commanded a pitch attitude of 15 degrees. During the iterative control design process it became apparent that a small amount of actuator saturation was commanded in longitudinal cyclic and elevator in order to achieve ADS-33 Level 1 attitude quickness and bandwidth requirements and this is evident in Figure 27. The figure also illustrates the off axis control inputs in the lateral and directional control channels that were applied by the controller in order to reduce the cross coupling effect from pitch to roll and yaw.

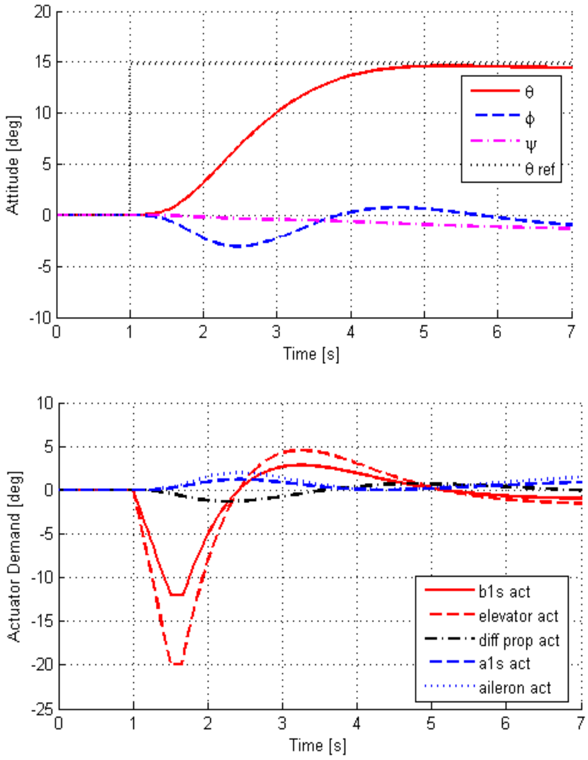

Figure 27: Linear aircraft and actuator response to pitch step input (SCAS on, 0kts, sea-level)

Desktop simulation using linear models is an essential step in the design process of a flight control system, however, it is also important to test the controller using a non-linear flight mechanics model to examine the effects of nonlinearities on performance and to test the controller's robustness. With this in mind, the mixed sensitivity H_∞ controller was implemented on the non-linear FLIGHTLAB model for desktop simulation and testing. Figure 28 shows a comparison of the linear and nonlinear model response and actuator demands for a 15 degree roll step command of duration 6 seconds, again for the nominal controller design condition of 0kts. From the figure it is evident that the linear model is representative of the nonlinear model and that the response time in roll is slow due the large size and inertia properties of the aircraft. The figure also shows that there is a small amount of overshoot present in the non-linear response which was not predicted by the linear model which emphasises the need for non-linear testing.

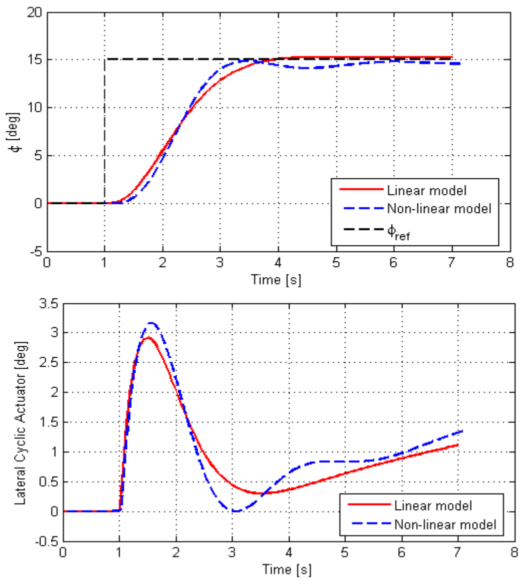

Figure 28: Linear and nonlinear response due to a step input in roll (SCAS on, 0kts, sea-level)

The overall impact that the H_∞ controller has made on the handling qualities of the Rotodyne model are shown in Figure 29. Results are presented for pitch bandwidth and attitude quickness which have both been improved from Level 2 to Level 1.

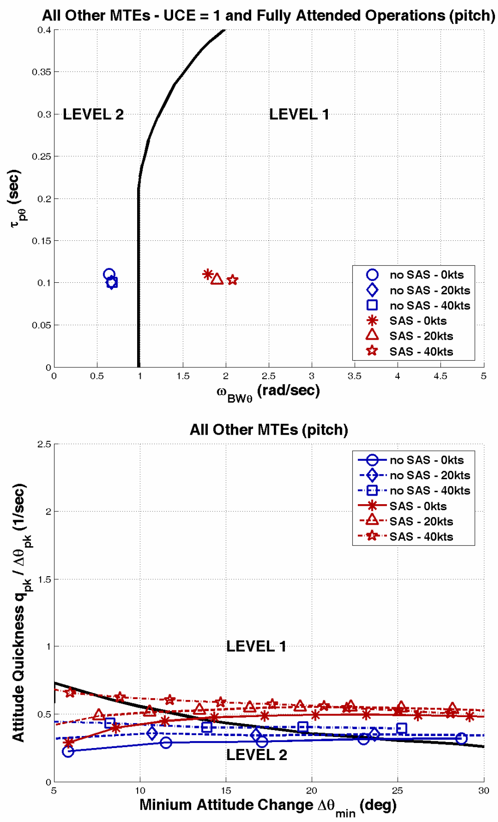

Figure 29 Rotodyne Pitch bandwidth and quickness with controller

The analysis of the bare airframe in this paper has also shown that the yaw control power was inadequate and only Level 3 by the ADS-33 criteria. The lack of yaw control power yaw can be explained by considering the general layout of the aircraft; the inboard location of the propellers on the wing results in a small effective moment arm between the aircraft CG and propeller thrust line. In addition to this, the primary method of control in yaw was differential propeller pitch, which had a maximum pitch range of +/- 4.5 degrees. An investigation was carried out to see what was achievable if the differential actuator pitch range and rate was increased. Figure 6 shows the heading, yaw rate and starboard propeller pitch actuator demands for a yaw rate step demand of 15 degrees/sec applied at 1 second for a total of 21 seconds. The three test cases considered are illustrated in Table 3, which shows the increasing actuator saturation and rate limits. Note that the port propeller pitch actuator demand is the mirror to the starboard demand.

Table 3: Differential propeller pitch actuator saturation and rate limits

Test case	Differential propeller pitch actuator saturation limit [degrees]	Differential propeller pitch actuator rate limit [degrees/second]
1	+/-4	+/-8
2	+/-8	+/-16
3	+/-12	+/-24

Figure 30 shows that the yaw response type with the controller becomes rate command with a large rise time (20 seconds for test case 3). This initially gave an acceleration response type similar to that of the bare airframe. It is evident that as the actuator saturation and rate limits are increased, for the same 15 degrees/sec yaw rate command, the heading quickness of the controller is increased and the time to ψ=180 degrees decreases. The limited success in improving this handing aspect illustrates that more fundamental airframe/system design changes would be required to improving the yaw control characteristics.

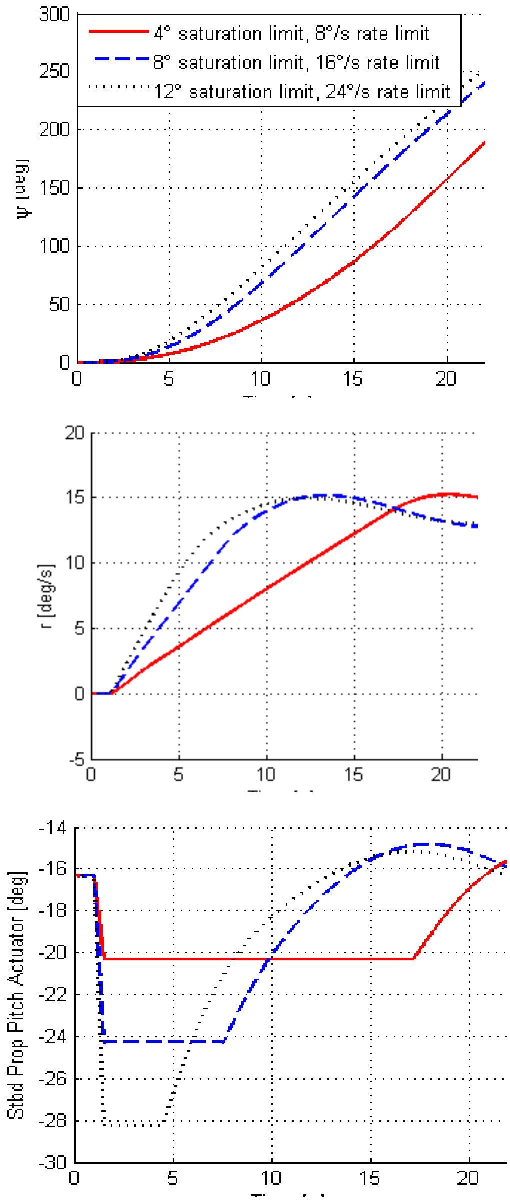

Figure 30: Non-linear response due to step input in yaw (SCAS on, 0kts)

Discussion

Little information survives on what the actual handling qualities of the Rotodyne were like. Refs (10,11) contain some anecdotal reports on problems with low directional stability and also describe how the addition of ailerons was necessary to give satisfactory roll control power at high speed. The initial problems experienced with the directional stability had led to the introduction of upper folding portions of the vertical fins to add stability. To start with, these were angled at 60° dihedral to provide some additional longitudinal stability. However, subsequent flight testing revealed an overly high dihedral effect that was initially attributed to the vertical rotor pylon. Later on, the real cause was identified as the sloping vertical fins, not the pylon. This corroborates the results in this paper where the pylon effect on lateral stability was minimal. Eventually, the fins were set to the vertical and in conjunction with the added ailerons satisfactory rolling characteristics were achieved (11). The effect of the ailerons is illustrated in Figure 31 where the maximum roll rate achievable by model using the cyclic alone decreases once autogyro mode is entered above 100kts. The addition of ailerons stabilises this reduction at a constant level approximately equal to that available in Helicopter mode.

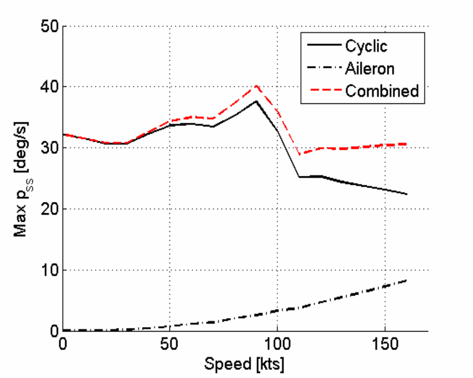

Figure 31 Maximum Roll rate achievable by cyclic, aileron and combined control actions

The Fairey Rotodyne was a truly visionary endeavour and one wonders what it might have led to had it survived the cuts of the early 1960's. Why has there not been a successful follow up, especially as the decades have passed and the enabling technologies of the Rotodyne have become more mature? Certainly, many of the advantages that the Rotodyne once held over helicopters have ebbed away – helicopters have since carried heavier payloads, flown faster and with greater efficiency and less noise. However, this is unfair to the Rotodyne as these accomplishments came later when rotorcraft technology had evolved. It would better to consider what could be achieved by 21st century 'Rotodyne', where a fair comparison is possible with modern designs.

An excellent example of such a study is one by NASA in ref (6) which presents a comprehensive study of three competing future heavy lift rotorcraft designs. Two of the three key designs are shown in Figure 32, the third being a Large Civil Tilt Rotor or LCTR (not shown).

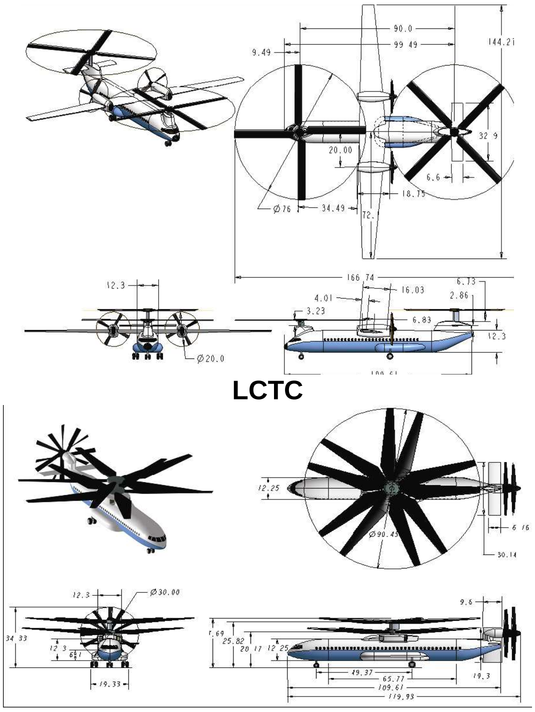

Figure 32 NASA Large Civil Tandem Compound (LCTC) and Large Advancing Blade Concept (LABC)

Both these concepts have clear commonality with the Rotodyne in having large diameter rotors required to operate at high speed complimented by secondary propulsion and lifting/control surfaces. The designs were aimed meeting the following set of notional capabilities for a civil VTOL transport by the year 2020:

- Payload of 120 passengers
- Cruise at M=0.6 (350kts) up to 30,000ft
- Range of 1200 nm

A complete engineering analysis was carried out incorporating vehicle design, performance optimisation, aerodynamics, loads, vibrations and stability, noise, flight control and handling qualities. All these parameters were used to drive cost models that contributed to the final comparisons. The overall conclusion was that the Tiltrotor design offered the best potential to meet the stated goals, with the lowest weight, best cruise efficiency and therefore lowest cost.

This result is supported by another concept competition in Ref (28) which reports the progress of the US Army Aviation Applied Technology Directorate's (AATD) concept design analysis (CDA) contracts for the Joint Heavy Lift (JHL) project. In these studies, a variety of novel rotorcraft concepts including

Tiltrotors and compound helicopters were compared with requirements in payload, range and speed. Again, the Tiltrotors came out on top, with the AATD's speed requirements counting against the slower compound helicopters.

It is still not clear whether there is a future for compound helicopters in light of the advent of the Tiltrotor. Although Tiltrotors were deemed superior in the two studies mentioned above it must be added that the two losing compound rotorcraft in the NASA design study both featured rotor diameters of 90ft – comparable with the already demonstrated Rotodyne. Whereas the winning Tiltrotor design featured a 100ft span wing with two 90ft diameter proprotors at each tip, dwarfing the largest Tiltrotor that has ever existed so far (The V-22: 46ft wingspan, 38ft diameter rotors).

The NASA study in ref (6) also identified the 4 highest risk technologies which, irrespective of the rotorcraft configuration, will be crucial to the development of future heavy lift 'convertiplane' rotorcraft:

- High torque, lightweight drive systems
- High performance, structurally efficient rotor/wing systems
- Low Noise
- 'Super-integrated' vehicle management systems (A system that manages stability, HQ's, loads alleviation, noise through active control)

This final point cannot be emphasised enough, as the challenges presented by these aircraft will require more than just super-integrated control systems but also 'super-integrated' design methodologies. Indeed, the Rotodyne's engineers identified this in the 1950's and to quote ref (11):

"… almost all of these are complex joint engineering problems which feed back elsewhere into the system. The Rotodyne is essentially an aircraft demanding an "integrated" design team and new exchange rates between mechanical and aerodynamic features have had to be learned by the engineers concerned…"

Just as then, the future designs will need truly multi-disciplinary modelling and virtual engineering tools to incorporate the myriad objectives in performance, structures, efficiency, stability, handling qualities, and of course, cost.

Conclusions

The objective of this paper is not to promote particular designs concepts but to bring (back) to life a visionary design that has been forgotten in many respects, but which may still stimulate opportunities for the future. The use of modelling and simulation has been the enabling technology for this work and it would be just as crucial for any future Rotodyne-like design. To summarise the findings of this paper:

- **Trim and Performance analysis:**
  - Model achieved trimmed flight in helicopter, autogyro and transition modes.
  - Model achieved maximum speed of 177kts (very similar to actual aircraft)
  - Demonstrated typical autogyro aeromechanics of interdependence of between Collective, rotorspeed, flapping and forward airspeed.
  - Demonstrated control of rotor/wing lift balance by elevator/cyclic inputs – verified published data that nominal lift rotor lift was ~65% of total at 130-140kts cruise condition.
- **Stability:**
  - Longitudinal:
    - Phugoid mode was stable in all flight conditions: Level 2 HQ's in Hover
    - Short Period was strongly damped in pitch at high forward speeds – considered unacceptable by fixed-wing 'Thumb Print' criteria.
  - Lateral:
    - Rotodyne exhibited poor Dutch Roll mode stability (ADS-33 Level 2/3 HQ's)
    - Good Spiral mode stability (Level 1)
- **Dynamic response to controls:**
  - Autogyro Mode:
    - Demonstrated variation of control power with rotor RPM
    - Ailerons required to maintain constant roll control power across speed range.
    - Large amounts of longitudinal flapping could

be generated by abrupt pitch inputs
- Pitch control power almost constant over entire speed range
- Helicopter Mode:
    - Cross coupling in pitch-roll response (Level 3)
    - Very poor yaw response to pedal inputs (level 3) – exhibited an acceleration response type.
    - Ungoverned rotor would have required high workload to maintain rpm when manoeuvring in heave.

- **Handling qualities criteria :Quickness and Bandwidth**
    - Attitude Quickness:
        - Roll: Level 2 for most flight modes and aggression levels
        - Pitch: mainly Level 2 but Level 1 at high aggression
        - Yaw: Level 3
    - Bandwidth:
        - Roll: Level 2 at low, medium and high speed and Level 2 for all input aggression levels in low speed flight
        - Pitch: Level 2 at all hover and low speed input aggressions
        - Yaw: Level 3 in hover and low speed flight
    - ADS-33 for Heavy lift and non-classical response criteria:
        - The application of the ADS-33 HQ criteria to the Rotodyne model has highlighted issues on the appropriateness HQ's and whether new criteria criteria are required for future vehicles of the scale of the Rotodyne.
        - This has also suggested that new MTE's or existing ones need development for future heavy rotorcraft in both civilian and military roles.
- **H-infinity controller:**
    - Implemented low speed Attitude Command Attitude Hold in roll and pitch axes - improving open loop stability
    - Improved pitch-roll cross coupling and Roll response shaping
    - Improved Pitch Bandwidth and Attitude quickness from Level 2 to Level 1
    - Used realistic actuator limits in multi variable, multi objective problem to achieve HQ improvements.
- **Discussion**:
    - Future designs will need an even more integrated approach than ever before
    - Modelling key to de-risk early using analysis techniques demonstrated in this paper but future design campaigns will need to include hi-fidelity engineering analysis of multiple disciplines simultaneously:
        - Performance
        - Stability and Handling qualities
        - Structural Loads/Vibrations
        - Noise
        - Safety
        - Efficiency (cost)

To conclude, future types of rotorcraft like the Rotodyne concept could still make important contribution in future congested airspaces. It is likely in the author's opinion that future civil and military requirements will demand a mix of Tiltrotors and compound rotorcraft types. However, even 50 years on, many of the concept technologies in the Rotodyne are still immature and will need collaboration across the aerospace community to de-risk.

Acknowledgements

Andrew Stephen who initiated the FLIGHTLAB Rotodyne model through his Final year project is strongly acknowledged for his important contributions. Prof Gareth Padfield from the University of Liverpool is gratefully acknowledged for his contributions and support on this paper. Contributions from the work supported by the EPSRC grant GR/T24159/01 'Optimising Handling Qualities for Future Tilt Rotor Aircraft' are acknowledged. Dr. Mark White and the University of Liverpool are also thanked for the provision of access to software and simulation facilities.

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