Optimizing Performance Variables for Small Unmanned Aerial Vehicle Co-Axial Rotor Systems

Jonathon Bell, Mantas Brazinskas and Stephen Prior

Middlesex University, School of Engineering and Information Sciences, Trent Park Campus, Bramley Road, London N14 4YZ, United Kingdom.
Corresponding Author: Jonathon.bell@hotmail.com

Abstract. The aim of this project was to design and build a test-rig that is capable of analyzing small unmanned aerial vehicles (SUAV) co-axial rotor systems. The intention of the test-rig development was to highlight important aeromechanical components and variables that dictate the co-axial units flight performance, with the intention of optimizing the propulsion systems for use on HALO® a co-axial SUAV designed by the Autonomous Systems Lab at Middlesex University. The major contributions of this paper are: an optimum COTS co-axial configuration with regards to motor and propeller variations, a thorough review and validation of co-axial rotor systems inter-rotor spacing which in turn identified an optimum H/D ratio region of between (0.41–0.65).

Keywords: Co-Axial Rotor, SUAV, Aerodynamics, H/D ratio.

1 Introduction

This paper details the background, concept and investigations into co-axial rotor systems used on full-scale helicopters through to Micro Air Vehicles, with the intent to highlight the key aerodynamic and aeromechanical components which contribute to the systems performance in the flight condition of hover.

The contra-rotating co-axial rotor design offers many advantageous attributes over single rotor systems, with the most often cited advantages being the reduction of the overall rotor diameter of the co-axial rotor system, and lack of need for a traditional tail rotor (which has been estimated to consume 5-20% of the total power produced). These areas are accentuated and highlighted when the design and optimisation of co-axial rotor system at the scale of small UAVs, which also requires a greater understanding of the performance variables that affect the co-axial propulsion system at low Reynolds Number (Re) operation, are investigated.

Recent co-axial rotor research relies heavily upon outdated co-axial rotor system studies, theoretical modelling, and computational fluid dynamics. There is very little empirical data and evidence outside the report of Coleman [1], together with research commenced by a select few research and development departments at universities across the world that identify the optimum conditions of co-axial rotor systems, especially at the SUAV scale. Even with the current research and data available it is difficult to predict the performance and optimize a co-axial rotor system for a specific scale due to conflicting reports.

Much of the funding, currently worth an estimated production value of US$ 2.05 billion (2010-19), for the research of SUAVs (which incorporates co-axial rotor systems) is predominantly fuelled by the international military, where the SUAV rotary winged systems are pitched to play increasingly more vital roles in ISTAR (Intelligence, Surveillance, Target Acquisition & Reconnaissance) operations. The project and study of these exotic systems has been closely aligned with the co-axial tri-rotor small UAV, HALO™ which is in development within the Autonomous Systems Laboratory at Middlesex University.

2 Co-Axial Rotor System Aerodynamics

As aerodynamics and aeromechanics have the greatest influence on SUAVs in-flight performance, this section is a summation of the core components that influence the co-axial rotor system in the flight condition of hover, and in turn have influenced the testing variables used during the analysis phase. Although the evaluation of forward flight is of interest, it was deemed too complex with respect to fabricating a controlled environment such a wind tunnel to be able to simulate these conditions and was considered unfeasible within the constrictions of the project time limit.

The Figure of Merit (FM) when applied to a co-axial rotor system is a non-dimensional efficiency metric that provides a basis to conduct a relative comparison of rotor performance. The FM uses the “ideal” power required to hover (calculated using the moment theory) that is in turn equated against the “actual” power required to hover. An equation for the Figure of Merit by Leishman [2] is given as follows:

$$FM = \frac{1.2657 \frac{C_{T_l}{}^{3/2}}{\sqrt{2}} \left[\left(\frac{C_{T_u}}{C_{T_l}} \right)^{3/2} + 1 \right]}{K_{\text{int}} K \frac{C_{T_l}^{3/2}}{\sqrt{2}} \left[\left(\frac{C_{T_u}}{C_{T_l}} \right)^{3/2} + 1 \right] + \frac{\sigma C_{d_o}}{4}} \quad \textbf{(1)}$$

In terms of the measured co-axial systems power, the definition for FM is:

$$FM = \frac{1.2657 \frac{C_{T_l}^{3/2}}{\sqrt{2}} \left[\left(\frac{C_{T_U}}{C_{T_l}} \right)^{3/2} + 1 \right]}{C_{P\,meas}} \quad \textbf{(2)}$$

Where:

Ctu + Ctl	=	Rotor Thrust coefficient (Upper, Lower)
Cpmeas	=	Rotor Power coefficient measured
σ	=	Rotor solidity
Cdo	=	Minimum or zero-lift drag coefficient

Rotor flow fields discussed by Leishman and Ananthan [3] are referred to as the *vena contracta* of the upper and lower rotors; it is also referred to as the slipstream of the co-axial rotors. To minimize the interference-induced power factor using the momentum theory the co-axial rotor system is theoretically set in a condition of “the rotors operating at balanced torque, with the lower rotor operating within the *vena contracta* of the upper rotor”[4] as discussed below. Leishman goes on to discuss the ideal flow considerations noting that “one-half of the disk area of the lower rotor must operate in the slipstream velocity induced by the upper rotor” [3]. The flow model of a co-axial rotor system and the vena contracta are detailed in Figure 1.

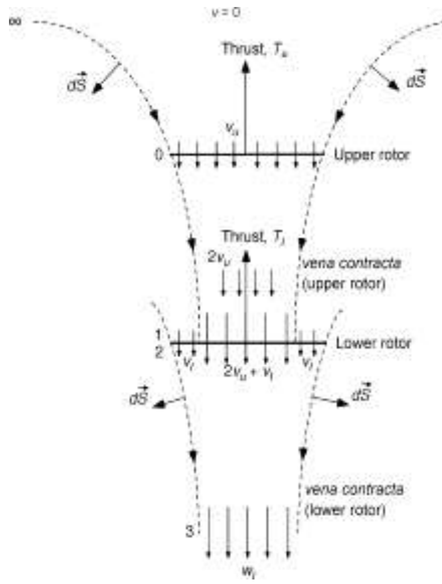

Figure 1 - Flow Model of a Co-Axial Rotor System [4].

The separation distance could therefore have an effect upon the severity of the interference-induced power loses, which would in turn possibly increase the efficiency rating (FM) of the co-axial rotor system.

2.1 Testing Variables

The investigation of the co-axial rotor system primarily revolved around four testing variables, with the aim of this paper focusing on the results on co-axial inter-rotor spacing & system configuration:

- **Inter-rotor spacing** – The separation distance (H) between the co-axial rotor system discs. Inter rotor spacing is one of the fundamental components of the SUAV co-axial system which has been tested due to the associated aerodynamic effects; interference-induced power losses, wake contractions, and rotors *vena contracta*. The H/D ratio is used as a non-dimensional figure to enable comparison of multiple systems across a range of scales.

Figure 2 compares H/D ratios, incorporating full-scale co-axial helicopters to MAVs. The table demonstrates that the SUAV example systems have a significantly higher H/D ratio (average H/D = 0.315), when compared with the average for full-scale systems having an H/D = 0.09.

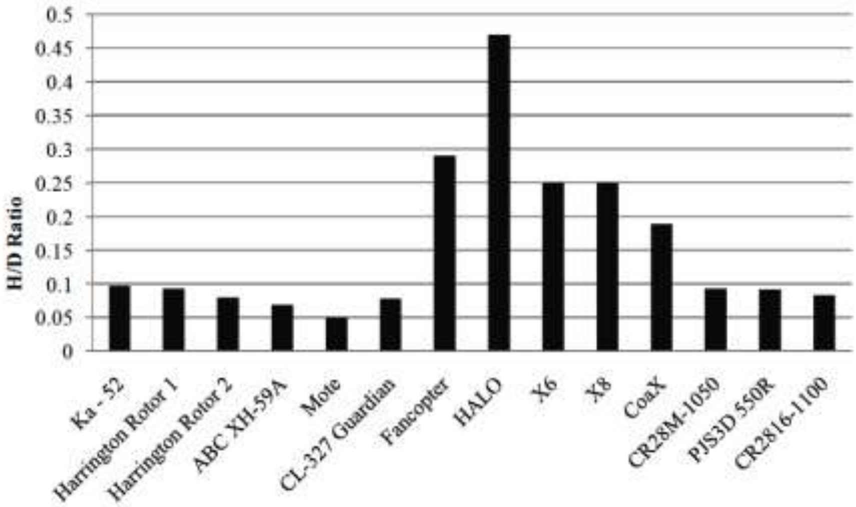

Figure 2 - Inter-rotor Spacing Comparison Chart [5].

- **Propeller Pitch** - The propellers used in the co-axial tests are fixed pitch, but unlike full-scale rotor blades that have an almost uniform pitch throughout the diameter due the design preference of a symmetrical blade section [6]; the test propellers have a varying pitch.

- **Propeller Diameter** (upper and lower) - The diameter of a propeller is one of the most important characteristics in determining the induced power of a rotor system:

$$Pi = \frac{T^{\frac{2}{3}}}{\sqrt{2\rho A}} \tag{3}$$

It has been shown in studies by Leishman that the larger the rotor diameter the lower the disc loading, induced velocities, and a decrease in induced power requirements [2]. Andrews [8] notes that an 8% reduction in upper rotor radius enhances the performance of the lower rotor due to an increase of exposed clean air. This variable will be controlled only using a select ‘family’ of propellers (rotors) to determine the performance attributes related to the decrease of the upper and lower rotors.

- **Co-Axial Rotor Configuration** – The co-axial propulsion unit tested has individual motor units powering the upper and lower rotors. This allows for multiple variations and configurations of the orientation of the motors and propellers to be analysed and the results recorded respectively.

3 Test-Rig Development

Recent developments in the co-axial rotor system for the small-scale UAV sector have resulted from the technological advances in RC propulsion units [7]. One of the earliest recorded co-axial UAV studies was work commenced by Andrews [8] on a Westland Helicopter Ltd developed system called Mote, the system's handling and control qualities are discussed in detail by Faulkner and Simons [9]. It was these studies by Andrews [10] that demonstrated a decrease of 8% to the upper rotor radius enables "the enhanced performance of the lower rotor as proportionately more disc is exposed to clean air". Andrews also discussed the inter-rotor spacing stating that there are no "practical" gains after H/D = 0.05.

More recent test-rigs and co-axial rotor system investigations include the work of the Autonomous Systems Lab (ASL), ETH at Zurich. Bouabdallah has spearheaded the extensive work produced by this team [11]. The significant research systems/platforms developed by the ASL at ETH are CoaX and CoaX 2, both co-axial MAV's. Unlike many co-axial rotor studies the muFly team has designed and built their own co-axial rotor test bed, and recorded the study in detail. A similar system that enables the investigation of MAV co-axial rotor systems is the rig developed by the University of Maryland for the MICOR MAV. Both systems are designed for variable pitch rotor heads.

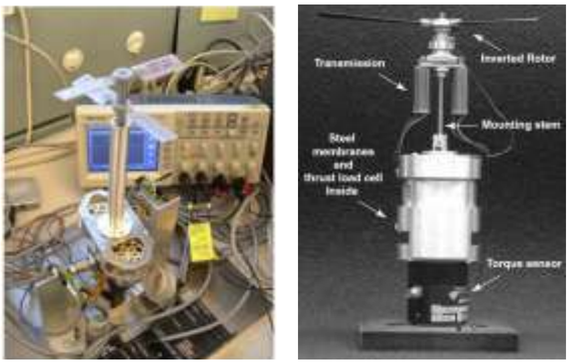

Figure 3 – muFLY [11] & UMD MICOR co-axial rotor system test-rigs [12].

The test-rig's priority was to be able to test and measure various co-axial fixed-pitch rotor system configuration variables. The components used in the setup for a co-axial rotor system (using HALO's components as a datum) have dictated the majority of the test-rigs overall design. The motors used for the co-axial rotor system are the AXI 2217/20 electric Outrunner DC motor, which are inherently stable and give good efficiency ratings of approximately 82%. The propellers used range from dual-bladed, low pitch and slow fly APC 10 inch propellers up to 12 inch Master Airscrew tri-bladed propellers. The range tested encompasses five 'families' of propellers, each with their own performance benefits.

Taking into account the co-axial rotor systems testing variables, and the known datum components set by the HALO configuration, mechanical solutions were developed. Linear motion technology in the form of a motor driven lead-screw was chosen for the inter-rotor spacing control of the co-axial rotor configurations. The desired range of inter-rotor spacing stemmed from using the GWS 1060X3 propeller as a datum measure (10 inch or 254 mm). This permitted the H/D range to be varied within the range (0.08–1.0).

The optimization process of the co-axial rotor system was continually taken place as the testing commenced. To develop a portfolio of test data from the testing components, analyze the efficiency of particular component configurations and testing conditions a data logging and live monitoring tool has been employed. The Hyperion Emeter II is a high performance measurement tool that is able to measure, analyze, and log key performance factors used in electric systems and RC models. The Emeter is supplied with a remote data unit (RDU) which houses a high precision shunt that is capable of accurately handling high currents and voltages, and is able to feed this data back to the Emeter for evaluation purposes.

4 Analysis and Results

To be able to test the co-axial configuration in the optimal motor and propeller arrangement a series of tests containing various co-axial configurations were analyzed. Eight configurations were used for the optimal motor and propeller configuration for a co-axial propeller system, with only four having contra-rotating rotors. A comparison data set consisting of individual rotors at multiple orientations used in the co-axial configurations gave a datum result for each singular rotor's performance.

The highest performing co-axial configuration, when plotting the measured system Thrust (g) Vs Speed (RPM x 1000), was when the motors are placed on the outside of each mounting arm on the test-rig using an upper – Pusher propeller, and lower – Tractor propeller setup. A similar overall performance measurement was seen when plotting Output Power (W) Vs Speed (RPM x 1000). This data coincides with the finding of Shkarayev [13], where the rotor configuration used on the SUPAERO MAV showed a 20–23% thrust increase when using a pusher configuration when compared to a tractor configuration.

As co-axial rotor systems are compared to their singular counterparts in numerous studies, a study of the individual rotor and motor configurations used in the co-axial testing has also been undertaken. The points of interest and observations are detailed below:

- When comparing the co-axial rotor configurations measured Thrust against the combined two singular rotor systems measured Thrust, the average Thrust output is 23.15% lower.

- The Thrust/Current Ratio of the co-axial rotor system averages a 2.22% decrease per Ampere when compared to the combined singular Rotors.

- Independently the individual tests of each singular rotor comparison gave unexpected and interesting results. Prior to the experimentation phase it was thought that a tractor and pusher propeller operate in an identical fashion, i.e. producing similar Thrust, and Output Power performances (allowing for the inaccuracies of the test-rig, and data logging). Figure 4 depicts the performance variation of the Tractor and Pusher GWS 1060X3 HD propeller in two configurations for each type of propeller. The pusher propeller placed on the upper arm had a thrust increase (at 7,000 RPM) of 7.11% compared to the Tractor Propeller; this trend was also observed on the lower rotor comparison, with the Pusher variant producing 8.29% (at 7,000 RPM) more thrust than its tractor counterpart.

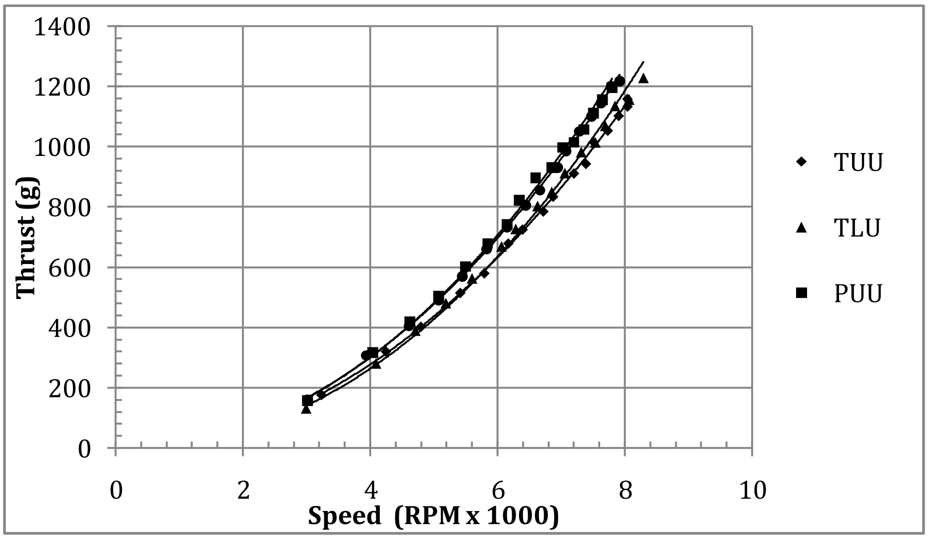

Figure 4 - Individual Motor Configurations - Comparison of Tractor and Pusher Rotors.

Using the optimally determined configuration for the co-axial rotor system, inter rotor spacing tests were commenced with a range from 20 mm to 250 mm ($0.08 < H/D < 1.0$) at 10 mm increments. The system was operated at an unequal torque and thrust balance, with the objective of the testing to establish a co-axial rotor systems static thrust capabilities at a given H/D ratio. As the research is to coincide with the development of the ASLs' HALO™ SUAV the propeller and motor combination of primary focus was the GWS 1060X3 HD and the AXI 2217/20.

Figure 5 is a select region of H/D ratios that provided a measurable increase in Thrust at a given Current (A). A range of 12–14 A was used to plot the variation in Thrust Vs H/D ratio, with an H/D ratio of approx. 0.5 showing the highest thrust.

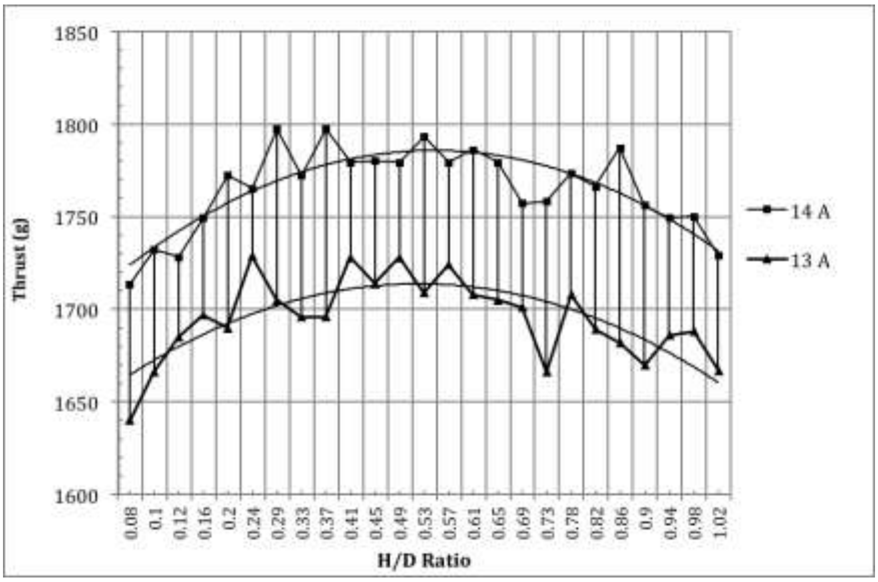

Figure 5 - Variation of Co-Axial Thrust with H/D Ratio.

5 Conclusions and Future Work

There have been multiple areas explored in the process of optimizing a SUAV co-axial rotor system, some of which have had limited research exposure and others which have been detailed thoroughly.

One of the main areas of interest and which has had the greatest influence on the co-axial tests-rig design was the inter-rotor spacing attribute of the co-axial rotor system. The H/D ratio has been prominent in many significant papers, but lacking an empirical value or an optimal dimensionless condition. In this paper the H/D ratio of a SUAV has been explored thoroughly, reviewing the systems performance at incremental stages, the findings from this study have shown that a range of H/D ratio of between (0.41–0.65) is advantageous in the performance of SUAV systems. This finding lends itself to the theory of inter-rotor spacing is a non-dimensionally similar figure, which cannot be applied across a spectrum of systems; this could be attributed to the viscous losses of flight at low Reynolds Numbers (< 50,000).

5.1 Test-Rig Review

The foundation of the optimization process for the co-axial rotor system was the design and development work of the co-axial test-rig. The system was designed to cater for the requirements and variables that were initially deemed to cover all the testing attributes of a Small Unmanned Aerial Vehicle co-axial rotor system.

Although the test-rig was able to cater for the fundamental components of the testing process it did however lack mechanisms and testing apparatus that would have in hindsight allowed for greater and more in-depth analysis of the co-axial rotor system, especially highlighting the individual motor performance within the co-axial unit.

Current research within the Autonomous Systems Laboratory at Middlesex University involves the design and development of the Mark II co-axial test-rig. As briefly mentioned previously the test-rig is being designed to analyse some of the key attributes of the co-axial system that had been overlooked in the original test-rig.

A critical appraisal of the original test-rig and an indication of future improvements are stated below:

- One of the failings of the original test-rig was the lack of a real-time reaction torque sensor. Due to this lack of component it was difficult to measure and interpret the co-axial rotor systems yaw torque balance. As the testing process developed the need for the inclusion of this sensor became apparent.

- Individual rotor thrust is calculated using the thrust constants and factors from the individual rotors static performance graph. For future work and developments to the test-rig, the design should incorporate individual load cells. This key attribute would enable a complete assessment of the operating conditions of the upper and lower rotors independently, and thus provide insight into the induced loses of the co-axial rotor system.

- The future test-rig may incorporate an automated control and recording system such as NI LabView (for data acquisition and test bench control). When employed for further testing this would provide greater accuracy, data analysis and simulation possibilities.

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