# Development of a Test-Rig for Exploring Optimal Conditions of Small Unmanned Aerial Vehicle Co-Axial Rotor Systems

**J.C. Bell; M. Brazinskas; S. D. Prior; C. Barlow; M. A. Erbil; M. Karamanoglu**

*Department of Product Design and Engineering, School of Engineering and Information Sciences, Middlesex University, Trent Park Campus, Bramley Road, London, N14 4YZ, UK*

*Email: Jonathon_C_Bell@yahoo.co.uk*

## *Abstract*

*Due to the recent increase in development and use of co-axial rotor system at the scale of small UAVs a greater understanding of the performance variables that affect the co-axial propulsion system at low Reynolds number operation has become increasingly apparent when optimizing such systems.*

*This paper focuses on and details the development and fabrication of a small UAV co-axial rotor system test-rig, and investigations into the optimal inter-rotor spacing range between contra-rotating rotors.*

*An integrated test-rig has been specifically designed for the testing and analysis of commercial off-the-shelf (COTS) propellers and out-runner motors which are predominantly used in SUAV propulsion systems. The test-rig incorporates linear motion, yaw, force and other performance measurements, to help validate the identified core co-axial rotor system performance attributes. The co-axial test-rig was used to investigate co-axial rotor systems inter-rotor spacing which identified an optimum H/D ratio region of (0.41 – 0.65).*

***Keywords:*** *Co-Axial, UAV, Contra-Rotating, Aerodynamics Test-Rig.*

## Introduction

A co-axial rotor system is defined as a pair of contra-rotating rotors mounted directly one above another on concentric shafts. Co-axial rotor systems are primarily linked with helicopter designs used for vertical takeoff and landing aircraft (VTOL). The earliest recorded co-axial helicopter was designed by helicopter pioneer Louis Breguet, the system was also arguably the first successful helicopter design of flight [1].

The co-axial rotor system is not only associated to rotary-winged aircraft, there are successful commercial and military fixed wing systems which use the benefits of the co-axial rotor system, namely the ability to combine the theoretical power of two propellers into the equivalent diameter of a singular propeller. A successful example of the contra-rotating propeller concept is the Tupolev Tu-95. The aircraft uses four contra-rotating turboprop propeller units and has been in production since 1956 see (figure 1).

**Figure 1 - Tu-142M Bear F [2].**

Together with fixed-wing co-axial rotor systems the Russian military are the world's biggest advocates and users of co-axial rotor system helicopters, namely the Ka-52 'Alligator' attack helicopter produced by Russias largest aircraft manufacturing company KAMOV Design Bureau. KAMOV are renowned for their work on rotary-winged co-axial rotor system, and have produced over 38 helicopter systems (the majority co-axial). Considering these facts there is very little documentation available concerning the aeromechanics and setups of their co-axial rotor systems.

**Figure 2 - Ka-52 "Alligator" [3].**

To understand the paper and further develop the benefits of the co-axial rotor system used for propulsion on an unmanned aerial vehicle (UAV) a basic understanding of the advantages and disadvantages of the rotor system needs to be discussed.

As discussed by Coleman [4] and Syal [5] the single main advantage of the co-axial rotor system is the lack of a tail rotor. The tail rotor of a singular rotor system consumes up to an estimated 5-10% and at times 20% of the total power supplied by the engines [6]. It is used by the system to counteract the yaw effect of the main rotor, for a co-axial rotor system the yaw cancelation derives from the contra-rotating rotors.

Further validation and investigations into the advantages and disadvantages are given below with examples discussed that are deemed most applicable to the SUAV co-axial unit development [7]:

**Co-Axial Advantages:**

- No drive train losses due to tail rotor absence.
- No possibility of tail rotor strike; a major cause of helicopter crashes.
- Shorter fuselage, small helicopter. The advantages of a smaller propulsion system to SUAVs are obviously an area of great interest.
- Directional stability through cancellation of main rotor gear torque moment (Yaw torque reaction).
- Compact size through use of concentric shafts.
- Increased pressure differential over rotor system; increased thrust, higher efficiency for increase in thrust, which translates into a reduction in rotor diameter for a given thrust.

**Co-Axial Disadvantages:**

- Complexity of linkages required to operate pitching control. This disadvantage is predominantly linked to full scale aircraft, due to the developments discussed further in the paper this is not wholly applicable to SUAV co-axial rotor systems.
- Inter-rotor wash interference. Reduced efficiency of the lower rotor due to the upper rotor swirling the air in the opposite direction of the lower rotor which requires the lower rotor to run at higher speed to produce the same lift as the upper rotor.
- Importance of flow interaction, requirement for rotor spacing. To ensure sufficiently clean flow for the lower disc, the spacing must be wide enough to allow as little interaction of the swirl of the upper rotor to impinge on the retreating component of the lower disc.

## Co-Axial UAVs

From the recent developments of miniaturised propulsion technology, advancements in UAV control systems, and most prominently as the benefits of using a co-axial rotor configuration are being explored; co-axial systems are fast becoming the competitive choice of propulsion in the commercial and military UAV sectors.

Developers of commercial and military Micro Air Vehicles (MAVs) and Small UAVs (SUAV) have taken the co-axial rotor system concept and produced simplified control systems to exploit the advantages of the co-axial rotor system, namely the systems stability, compactness and flight control characteristics.

The focus of this paper is the optimization of SUAV co-axial rotor system propulsion unit. In effect these systems share a great deal of aerodynamic properties with the propulsion units developed by Skybotix and EPFL at the MAV scale. The major determinant of differentiation between the two systems is the SUAV simplifications of the UAVs coordinate control system i.e. the SUAV co-axial propulsion system replaces the mechanical control linkages for fixed-pitch propellers which are controlled by the flight control system of the aircraft to determine Yaw, pitch, and roll.

Aircraft that employ the “fixed-pitch” co-axial units are predominantly configured in either a tri or quad rotor configuration. SUAVs such as Dragonfly Innovations X6 & X8 (H/D = 0.25-0.26), the Autonomous Systems Lab’s (Middlesex University) HALO (H/D = 0.47), and AirRobots’ AR150 (H/D = 0.37) & AR90 are the prominent co-axial systems at the SUAV scale.

## Co-Axial Rotor System Aerodynamics

The Aerodynamic influences on the propulsion system of a SUAV are the largest defining factor of the aircrafts in-flight performance, this section is a summation of the areas which are of key concern to this paper and various theoretical models.

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) which is in turn equated against the "actual" power required to hover. Figure of Merit by Leishman [8] is given as follows:

$$FM = \frac{Ideal\ power\ required\ to\ hover}{Actual\ power\ required\ to\ hover} \quad (1)$$

Where*:*

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

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

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

Rotor flow fields discussed by Leishman and Ananthan [9] are referred to as the *vena contractors* 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"[8] as discussed in Section 3.4.1. 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" [9]. The flow model of a co-axial rotor system and the vena contracta are detailed in Figure 3.

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 (figure of merit) of the co-axial rotor system.

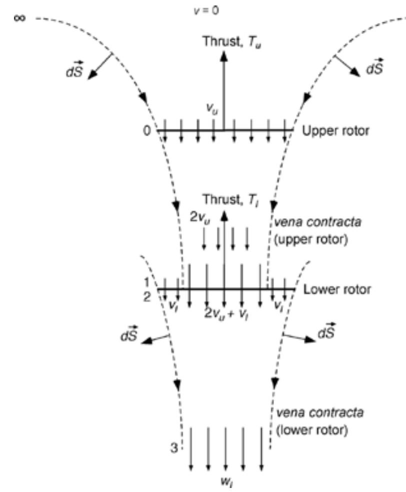


**Figure 3 - Model of a Co-Axial Rotor System [8].**

Taylor [10] discusses the contraction of the rotors wake, giving the ideal wake contraction ratio is 0.707. He also mentions that a rotor wake contracts within 0.25 of the radius of the rotors blade. Vortex wakes are also described in detail by [11] where he presents an overview of the vorticial flows of rotary-wing aircraft.

A co-axial rotor parameter that is of significant interest to the optimization of the propulsion system is the spacing between the contra-rotating rotors. As motioned towards in the aforementioned section the interference-induced power loss, wake contractions, and the rotors *vena contracta* could all be associated to the inter-rotor spacing, or separation distance of a co-axial rotor system. In Coleman's paper he continually refers to the H/D ratio of the co-axial rotor systems that are evaluated throughout. The H/D ratio is given as:

$$H/D\ Ratio = \frac{Inter-Rotor\ Spacing}{Propeller\ Diameter} \quad (4)$$

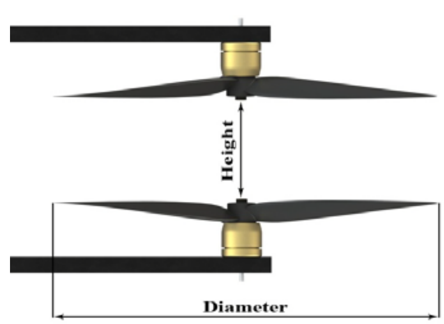


**Figure 4 – Inter-Rotor Separation Distance.**

The vertical separation distance is measured from the centre of the rotors hubs as shown in Figure 4.

Prior to Coleman's [4] review of co-axial rotor systems the separation distance parameter has had relatively little research attention. There have been very few tests and systems which have solely reviewed the co-axial rotors separation distance and noted the performance and efficiency of the system.

At the MAV scale a thorough review and analysis of the co-axial rotor system has been completed by Bohorquez [12] at The University of Maryland (UMD). The investigation of rotor spacing in the co-axial rotor system is given as an H/R ratio (height/rotor radius). It was noted that "rotor spacing has a limited effect on the co-axial rotor performance and is not a critical parameter that has a dramatic effect on performance" [12]. To be able to maximize performance of the co-axial rotor systems at the MAV scale the H/R ratio should be 0.357 or above (this equates to an H/D ratio of 0.714).

The theoretical studies by Syal [5] adversely show that high inter-rotor spacing is beneficial to full-scale co-axial rotor systems performance. Syal remarks that "*higher inter-rotor spacing is desired to reduce the induced losses of the co-axial rotor system in hover. With a higher inter-rotor spacing, a small fraction of the lower rotor lies in the slipstream wake generated by the upper rotor*"; the spacing recommendation is given at 75% of the rotor radius.

## Test-Rig Development

The test rigs priority is to be able to test and measure co-axial rotor systems configuration variables. The components used in the setup for a co-axial rotor system at the small UAV scale (using HALO's components as a datum) has dictate the majority of the test rigs overall design.

The early concepts of the test rig initially were linked to developing a linear actuating system with the priority of the mechanics leaning towards a light weight and simplistic construction

The two out-runner motors acting in a co-axial condition must be kept concentric and aligned at all times during the thrust testing process to negate any adverse non-co-axial conditions. To solve this problem a system that uses a linear actuator to securely control the movement of the load bearing arms, which the motors are to be mounted on was considered. Systems such as screw driven linear actuators manufactured by SKF (ball screws, planetary roller screws), On Drives (lead screws) produce stable "X" axis linear actuators. Due to the required high precision manufacturing and system weight – a simplified and lightweight deviation of this type of platform was designed.

The co-axial rotor system test rig structure is designed specifically to match the dimensions of the linear motion components, which in turn match the required inter-rotor spacing range required (20 mm – 300 mm). The core component of the linear motion assembly is a dual threaded revolving lead-screw.

To establish the optimum lead-screw diameter for the co-axial test rig a logical range of lead-screws diameters were initially considered. One of the predominant requirements of the system was the overall mass of the test rig, and as the lead-screw is one of the only components fabricated out of medium carbon steel the selection of the correct component was crucial.

Using the performance equation (5) for torque to move the lead-screw nuts and traversing platforms whilst at maximum load the following workings out show that:

$$Torque(Nm) = \frac{Load\ (N) x\ Lead\ (mm)}{2000\pi \times Efficiency\ (\%)} \qquad (5)$$

The load is estimated from the maximum thrust of the AXI 2217/20 at 14.8 V with the GWS 1060X3 HD propeller which is 1.1 kg per unit.

Therefore the required torque to move the lead-screw is:

$$Torque = 0.0376\ Nm\ or\ 3.76\ Ncm \qquad (6)$$

Although this calculation of torque does not take into account variables such as frictional and acceleration torque and the friction resistance of the linear bushings used in the guides, it does however give an estimated value which was enough to select a motor to revolve the sub assembly.

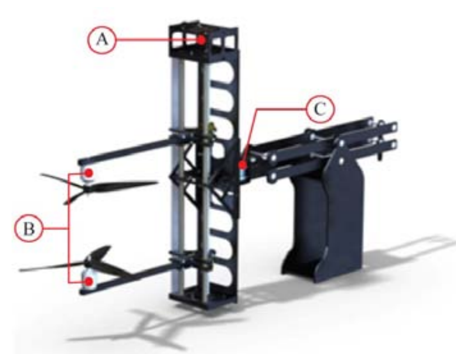


**Figure 5 – Co-Axial Test-Rig in Situ: A) EMG30 motor, B) AXI-2217/20 motors, C) Yaw sensor.**

The co-axial test bench setup is shown in Figure 5. The systems testing variables are manually operated with testing results logged via dual Hyperion 2 data logging tools. Thrust (g) is measured using the existing ASL thrust testing rig which actuates the related co-axial force onto a set of Stanton Digital Scales.

## Results

The calibration of the test rig was the first process to determine the accuracy of the thrust measurement. Two tests were used for varying levels of accuracy:

- Test 1 – The initial test consisted of a spring loaded Newton meter (Salter, measuring up to 10 N) attached to the motor mounting arm of the test rig. Each arm was tested independently up to 9.5 N.

- Test 2 – The second test was used to determine a finer grade of applied force measurement and to stress the system to the upper echelons of its working capacity. The test consisted of dual pulley systems each attached to the co-axial test rigs arms. Once attached the systems arms are incrementally loaded with 0.2 kg masses which are attached the opposing end of the pulleys. Figure 6 depicts the linear trend of the applied force Vs the measured weight, the data measured by the rigs digital scales showed an average incremental error of 1.09%. This margin of error was deemed acceptable for further testing.

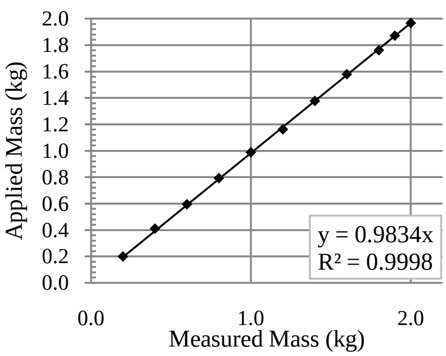


**Figure 6 - Fine Test Rig Calibration Results.**

Continuing the analysis of the test rigs systems level of error the Table contained in has been used and quantified in displays all the systems sensors, instruments and components readings with their individual resolutions. The resolutions of the core components are summarised below:

Using the GWS 1060X3 HD propeller thrust constants and power constants data and applying the noted resolutions the Power In averaged a 4.26% error. The measured thrust and Power Out (errors included into the torque testing process) have average errors of 2.18% and 1.50% respectively. The errors are more prominent at lower speeds (angular velocity), with accuracy increasing respective to speed.

### H/D Ratio Analysis

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™ the propeller and motor combination of primary interest were the GWS 1060X3 HD and the AXI 2217/20.

Figure 7 is a select region of H/D ratios which provided a measurable increase in Thrust at a given Current (A). A range of 12 – 14 Amps was used to plot the variation in Thrust Vs H/D ratio, with H/D ratios of 0.45 and 0.57 showing the least fluctuation and range.

The main observations to be drawn from the H/D testing are summarised below:

- The inter-rotor spacing does have a limited effect upon the total thrust of the co-axial rotor system, with a maximum variation of 4.67% (at 14 Amps, using 0.08 < H/D < 0.41).

- A similar trend in the performance of Power out (W) was seen when plotted against speed (RPM x 1000), with range of H/D ratios of 0.41 – 0.65.

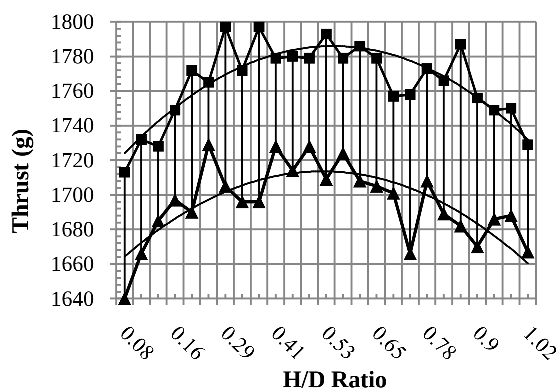


**Figure 7 - Variation of Co-Axial Thrust with Rotor Spacing.**

## Conclusions

This paper has been a challenging and rewarding process. It has brought to light many factors of the co-axial rotor system, and components used in the propulsion systems for SUAVs which previously have had limited documentation. The main contributions of the paper can be summarised as:

- The design and construction of a test rig to enable measurement of individual and co-axial propeller systems.
- Investigation of the performance effect of the H/D ratio on co-axial propeller systems.

One of the main areas of interest and which has had the greatest influence on the co-axial tests rigs 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 = 0.41 – 0.65 is advantageous of the performance of SUAV scale 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 the low Reynolds number.

The foundation of the optimization process for the co-axial rotor systems 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 SUAV co-axial rotor system. The section below discusses improvements and critical appraisal of the current test-rig:

- One of the failings of the testing rig was the lack of system reaction torque sensor. Due to this lack of component it was difficult to measure and interpret the co-axial systems yawing motion.
- Individual rotor thrust is calculated using the thrust constants and factors from the individual rotors performance graph. For future work and developments to the test rig, the design should incorporate individual load cells.

## `References


[1] Hirschberg, M.J. & Daley, D.K. (2000). *US and Russian Helicopter Development in the 20th Century*. American Helicopter Society International.

[2] Kopp, C. (2010). *Tupolev Tu-95 and Tu-142 Bear*. Retrieved 01 August, 2010, available from: http://www.ausairpower.net/research.html

[3] Gennady, M. (2009). *Ka-52 "Alligator" Attack Helicopter*. Retrieved 27 October, 2010, available from: http://origin-www.airliners.net

[4] Coleman, C.P. (1997). *A survey of theoretical and experimental coaxial rotor aerodynamic research*. NASA Technical Paper 3675.

[5] Syal, M. (2008). DRUM: *Contributions to the Aerodynamic Optimization of a Coaxial Rotor System*. (Published Master's Thesis). University of Maryland: USA.

[6] Prior, S.D. (2010). Reviewing and Investigating the Use of Co-axial Rotor Systems in Small UAVs. *International Journal of Micro Air Vehicles*, vol. 2, *no. 2*.

[7] Zed, H. (2001). *Operational considerations for a co-axial, contra-rotating rotor*. Retrieved 02 July, 2010, available from: http://www.helosim.com/coaxialarticle.html

[8] Leishman, J.G. & Syal, M. (2008). Figure of Merit Definition for Coaxial Rotors. *Journal of the American Helicopter Society*, vol. 53, *no. 3*, pp. 290.

[9] Leishman, J.G. & Ananthan, S. (2006). Aerodynamic Optimization of a Coaxial Prop rotor. *Annual Forum Proceedings - American Helicopter Society*, vol. 62, *no. 1*, pp. 64-86.

[10] Taylor, M.K. (1950). *A Balsa-Dust Technique for Air-Flow Visualization and Its Application to Flow Through Model Helicopter Rotors in Static Thrust*. NACA, USA.

[11] McCroskey, W.J. (1995). *Vortex Wakes Of Rotorcraft*. AIAA: USA.

[12] Bohorquez, F. (2007). DRUM: *Rotor Hover Performance and System Design of an Efficient Coaxial Rotary Wing Micro Air Vehicle*. (Published PhD Thesis). University of Maryland, USA.