THE EFFECT OF ROTOR DISC CLEARANCE ON THE LIFT PERFORMANCE OF CONTRA-ROTATING ROTOR BLADES

Ziad Bin Abdul Awal[1], Mohd. Shariff bin Ammoo[2], Nur Syafiqah binti Jamaluddin[3]

[1] *Graduate Researcher, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia*
[2] *Senior Lecturer, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia*
[3] *Ex-UG Student, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia*

Abstract

Contra-rotating rotor blade is a system that can deliver poised torque condition for any rotorcraft without the manifestation of tail rotor contrivance. This system not only aids to sustain the stability of the aircraft, but also surges the aircraft's overall efficiency discrete to the conventional single rotor system. Contra-rotation system is capable of operating in reduced size and henceforth is effusively researched and applied to the unmanned micro aerial vehicle (MAV) technology. This study intended to reconnoiter the effect of varying the axial spacing between the forward rotor and the aft rotor of an archetypal contra-rotating rotor blade system. The quantitative data has espoused that the variation of axial spacing between the forward and aft rotor affected the total efficiency of the contra-rotating rotor blade system. Furthermore, at larger spacing, the effects were more substantial contributing adversely to the overall efficiency of the system.

Key Words: *Contra-rotating system, Rotor disc clearance, Micro aerial vehicle (MAV), Total efficiency.*

* * *

1. INTRODUCTION

The aerodynamics of the helicopter rotor is considered to be one of the most invigorating and disquieting hindrance faced by the aerodynamicists around the world [1]. Consecutively, contra-rotating propellers and rotor blade system is progressively on the interest in aeronautical engineering world due to its inimitable and superior performance characteristics. Though it has been the subject of concern for researchers all over the world for over a century, the attention is ever so high at the present age due to its startling compatibility with unmanned micro aerial vehicles (MAVs). Initial investigation has proven that the contra-rotating system does not only helps to sustain the stability of the aircraft, but also upturns the total efficiency of the aircraft propulsion system. According to Carlton [2], the development of contra-rotating propeller system have started long before and efficaciously caught the attention of worldwide researchers. The analysis of Whitehead Torpedo by Grenhill [3] in 1988 was the first theoretical method to support contra-rotating propeller development. However, the first major study was made by Rota [4] who carried out a comparative test with contra-rotating propeller on a steam launch. Later, he further developed his preceding study [5] by comparing and contrasting his experimental results to the propulsion experiments conducted by Luke [6]. In 1955, Lerb introduced a theoretical solution for the problem regarding the system [7]. A year later, researchers Manen and Sentic [8] produced a method on vortex supported by empirical factors derived from open water experiment. Lerb's theory inspired Morgan [9] who developed a step by step design method for contra-rotating system. The application of lifting surface theory on the contra-rotating propeller was also considered by Murray [10] in 1967. In 1970, Gusteren [11] developed a method for designing contra-rotating system and demonstrated that the interaction upshot of two propellers can be determined with the aid of momentum theory. Tsakonas, et al. [12] further developed the lifting surface theory for the contra-rotating propeller problem in 1983, by applying linearized unsteady surface theory to propeller system in both uniform and non-uniform wake fields.

1.1 Counter & Contra-Rotating System

Counter & contra-rotating system works differently but often causes perplexity as both terms are used erroneously. The difference between the two can be understood from the explanation of Bloom [13]. The elucidation designates that, counter-rotation is a configuration of rotor blades that are attached to two individual shafts which drives them in different direction respectively. Each rotor blade has its own set of mechanical control to vary the pitch angle of the blade. **Fig-1** displays the configuration of a counter rotating system.

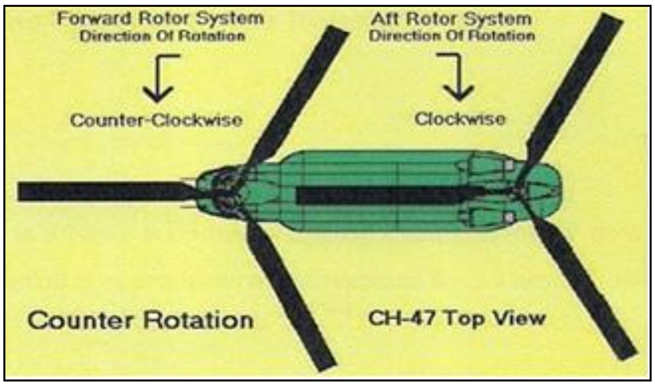

Fig-1: Counter rotating propeller [13].

On the contrary to counter rotating configuration, contra-rotation has a set of propellers or rotor blades that are mounted one in front or top of another on the same axis as shown in **Fig-2**. Generally, a single source driving mechanism is common for this type of co-axial configuration; however the direction of rotation is separated by a gearbox to drive both systems in opposite direction respectively.

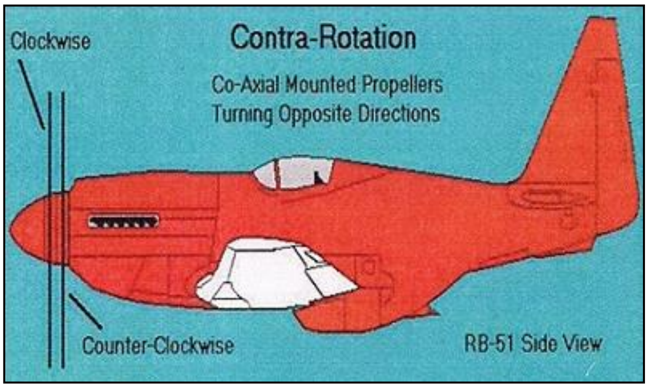

Fig-2: Contra-rotating propeller [13].

1.2 Advance Ratio, J

The ratio between the distance the propeller moves forward in one revolution and the diameter of the propeller is known as advance ratio. Mathematically, advance ratio can be expressed using the following equation.

$$J = \frac{V}{n \times D}.$$

1.3 Rotor Axial Spacing

Rotor spacing is the axial spacing between the rotors in the system. In this investigation, the axial spacing is defined in accordance to the diameter of the rotor blade. The length of rotor spacing used here are D/8, D/4, D/2 and 3D/4 where D is the diameter of the rotor blade. Experiment results obtained through the variation of axial spacing have been used for comprehensive comparison with the research of Saito, et al. [14].

1.4 Coefficient of Thrust, C_T

Coefficient of thrust is an essential parameter to measure the total efficiency of the propeller. Generally, it is a function of propeller design in terms of Reynolds number, moment at tip and advance ratio, [15]. Mathematically, coefficient of thrust is expressed as follows;

$$C_T = \frac{T}{\rho n^2 D^4}$$

1.5 Coefficient of Power, C_P

Another substantial parameter for total efficiency measurement is the coefficient of power. Apart from that, it is also used to ascertain the power output that drives the propeller or rotor blade. The mathematical expression of the power coefficient is as follows;

$$C_P = \frac{P}{\rho n^3 D^5}$$

1.6 Total Efficiency, η_T

The total efficiency of a contra-rotating system can be calculated by dividing the product of thrust coefficient and advance ratio to the power coefficient [14]. The mathematical expression is given by the following equation.

$$\eta_T = \frac{J \times C_T}{C_P}$$

2. METHODOLOGY

2.1 Conceptual Design

The initial schematic overview of the axial spacing between the contra-rotating rotor blades is illustrated in **Fig-3**. The testing rig designed for fabrication is presented in **Fig-4**.

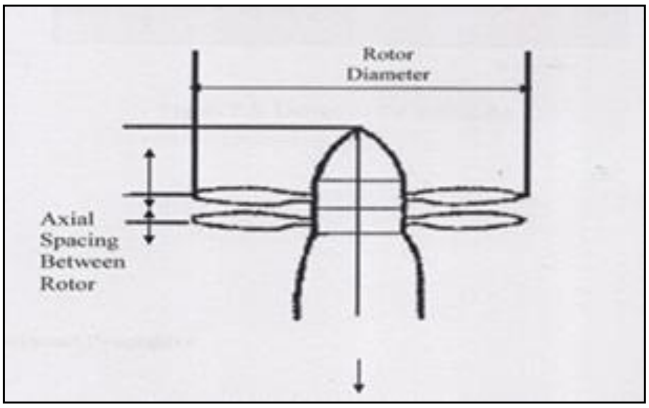

Fig-3: Contra-rotating model propeller (schematic diagram).

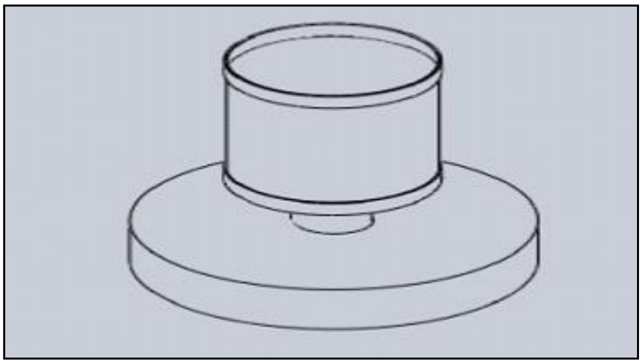

Fig-4: Design of the testing rig.

2.2 Experimental Procedures

The outcome of this study were largely dependent on two types of experimental slants; the qualitative approach and the quantitative approach. Inclusive minutiae have been discussed further in the text.

2.2.1 Qualitative Approach

One of the most apt technique to study the air flow characteristic around the rotor blade is through the smoke flow visualization test. Using the smoke tunnel, this method enables to visualize the direction of the airflow impending to a surface [16]. It also assists in comprehending the behavior of the airflow. **Fig-5** shows the diagram of smoke tunnel.

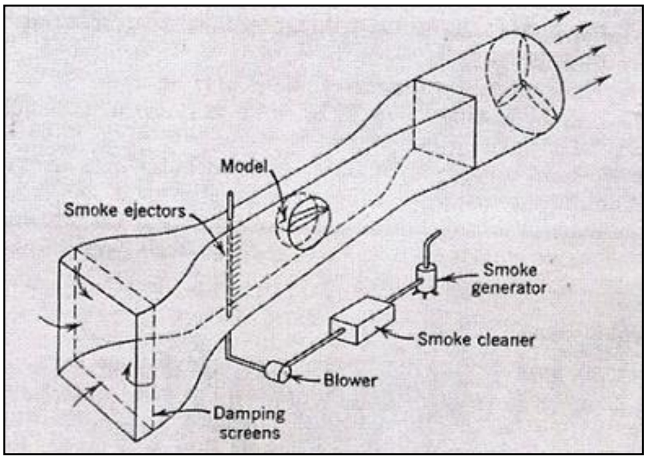

Fig-5: Smoke tunnel schematic diagram [16].

2.2.2 Quantitative Approach

Contra-rotating model along with the test rig were utilized to quantify the value of airspeed and aerodynamic thrust force acting on the system. Subsequently, the performance of the model was evaluated in terms of its efficiency. There were two measurements involved here; quantification of airspeed and quantification of thrust force.

a) Air Speed Quantification

This experiment has been conducted by wavering the axial spacing value and the throttle was set at different fixed values based on the division of the throttle level on the radio transmitter.

b) Thrust Force Quantification

Based on the concept of vertical take-off and landing (VTOL) aircraft, the thrust forces acting on respective axial spacing configuration has been measured using a digital weighing scale. It is considered that in a steady flight condition, the forces acting on the system are stable as well. **Fig-6** shows the apparatus set up for the thrust force quantification process. Assuming a straight and level upward flight, the thrust force acting upward must be equal to the summation of weight and drag acting downwards. However, in this research, the effects of drag were disused since the main concern was regarding the variation of axial spacing. Therefore, mathematically, the summation of vertical forces can be expressed as $\sum F_y = T - W = 0$. The reading of the scale was taken as the gross mass of the system configuration. Here, the total mass acting is the summation of gross mass and the present mass.

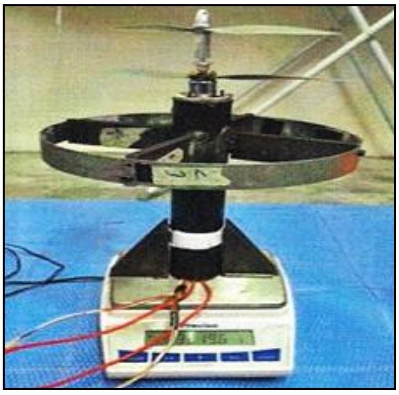

Fig-6: Apparatus set up for the experiment.

3. RESULTS AND DISCUSSION

3.1 Effect of Axial Spacing Variation on the Air Speed

The airspeed, in this study, is the air that flows at the bottom of the testing rig, which represents the speed of air flowing through both forward and aft rotor blades. **Table-1** is the tabulation of the airspeed measurement at different axial spacing and throttle speed. Based on the data form **Table-1**, the graph of air speed versus throttle level was plotted in **Fig-7**. The airspeed demonstrated a linear increment as the throttle level increased, and as the axial spacing between the rotors increased, the airspeed reduced marginally. However, for a shorter spacing, the airspeed reductions were significant, as compared to larger spacing where the change of the airspeed was trivial and trifling. This phenomenon occurs because of the large spacing as the rear rotor is located outside the vortex area of the front rotor where the airspeed unlikely to change.

Table-1: The airspeed measurement

Throttle Level	**Axial Spacing = D/8**				**Axial Spacing = D/4**			
	Stream Air Speed (m/s)				Stream Air Speed (m/s)			
	a	b	c	Average	a	b	c	Average
1	11.65	11.46	10.71	11.27	10.18	10.19	10.22	10.19
2	13.38	13.74	13.73	13.61	12.34	12.59	12.28	12.40
3	15.43	15.31	15.45	15.39	14.16	14.25	14.44	14.28
Throttle Level	**Axial Spacing = D/2**				**Axial Spacing = 3D/4**			
	Stream Air Speed (m/s)				Stream Air Speed (m/s)			
	a	b	c	Average	a	b	c	Average
1	9.26	9.11	8.99	9.12	8.99	9.01	9.04	9.013
2	11.06	11.25	11.05	11.12	11.1	11.09	11.12	11.10
3	13.36	13.22	13.06	13.21	13.12	13.2	13.15	13.15

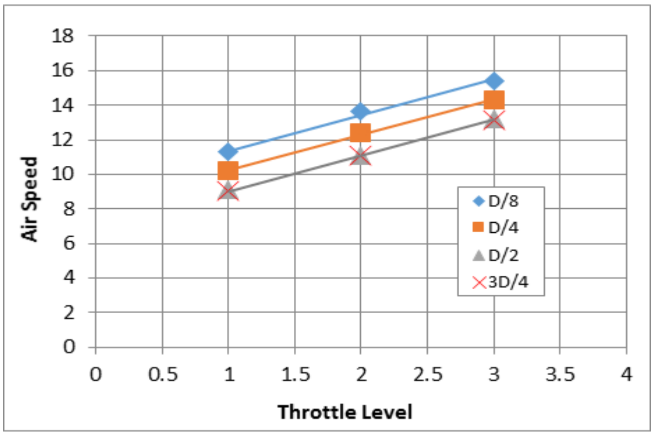

Fig-7: Graph of Air Speed vs. Throttle level.

3.2 Effect of Varying Axial Spacing on Thrust

The flight was presumed to be in a sturdy vertical condition during the whole testing procedure. Fundamentally, for an aircraft that flies straight upward, the upward thrust force is equal to the summation of downward weight and drag force. For simplification, an assumption was made, which is to consider the flight condition being ideal and therefore the aerodynamic drag becomes zero. This was an imperative assumption as it ignores the effect of drag on the total performance and focuses only on the varying effect of the axial spacing between rotors. From the experiment, the reading of the digital weighing scale was used to determine the weight when subjected to different throttle levels during the respective axial spacing mode. **Table-2** summarizes the result of weight measurement for different axial spacing.

Table-2: Weight measurement calculation

Throttle Level	**Mass (g) (Scale reading – weigh of support)**				**Weight (N)**
Axial Spacing : D/8					
	a	b	c	Average	
1	1974.33	1975.83	1975.03	1975.06	19.375
2	1735.33	1728.23	1732.23	1731.93	16.990
3	1538.63	1538.23	1538.23	1538.23	15.090
Axial Spacing : D/4					
	a	b	c	Average	
1	1986.03	1990.03	1984.06	1984.06	19.464
2	1830.53	1849.03	1840.70	1840.70	18.057
3	1496.83	1499.23	1499.93	1499.93	14.714
Axial Spacing : D/2					
	a	b	c	Average	
1	1879.53	1875.33	1877.00	1877.00	18.413
2	1848.13	1843.23	1844.23	1844.23	16.732
3	1818.03	1818.93	1819.76	1819.76	14.077
Axial Spacing : 3D/4					
	a	b	c	Average	
1	1824.23	1822.33	1824.66	1824.66	17.900
2	1564.83	1575.43	1570.50	1570.50	15.407
3	1357.93	1398.6	1369.9	1369.96	13.439

Here, the thrust produced was measured from the mass of the system times by the gravitational speed. **Fig-8** reveals the effect of different axial spacing to the thrust produced. The figure demonstrates a trend line that shows a distinct characteristic behavior such that, as the throttle level increased, the thrust produced decreased. Propulsive power of a vertical flying aircraft is equal to the product of thrust and the speed. Mathematically, P = T x V, with the assumption that the power is constant, it makes the thrust to be inversely proportional to the speed. This explains the phenomenon of the reduction of thrust as the throttle level increased, since the increment of throttle level also contributes to the decrement of the thrust.

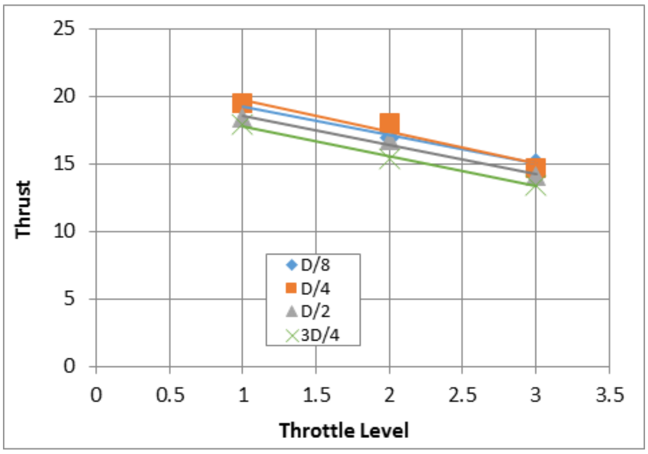

Fig-8: Graph of Thrust vs. Throttle level.

3.3 The Effect of Varying Axial Spacing on the Total Efficiency

It is understood that total efficiency is directly proportional to the advance ratio and thrust coefficient, but inversely to the power coefficient. Subsequently, the advance ratio is defined as the ratio of true airspeed to the product of rotor speed and the diameter of the rotor. The calculations of advance ratio are shown in **Table-3**. Mathematically, advance ratio can be expressed using the following equation;

$$J = \frac{V_\infty}{nD}$$

Table-3: Calculation of advance ratio

Stream Air Speed, V (m/s)	**Speed of Rotor, n (rps)**	**Rotor Diameter, D (m)**	$J = \frac{V_\infty}{nD}$
Axial Spacing : D/8			
11.273	217.751	0.252	0.206
13.617	220.714	0.252	0.245
15.397	222.964	0.252	0.274
Axial Spacing : D/4			
10.197	216.390	0.252	0.187
12.403	219.179	0.252	0.225
14.283	221.556	0.252	0.256
Axial Spacing : D/2			
9.120	215.029	0.252	0.168
11.120	217.557	0.252	0.203
13.213	220.203	0.252	0.238
Axial Spacing : 3D/40			
9.013	214.894	0.252	0.167
11.103	217.536	0.252	0.203
13.157	220.132	0.252	0.237

According to Saito et al. [14], this system has a potential higher efficiency compared to a single rotating propeller. By referring to **Fig-9**, it can be understood that the configuration of contra-rotating propeller has a significant improvement in terms of efficiency, compared to single rotor propeller system. The efficiency of the aft rotor is much higher than front rotor, this is due to the absorption of swirl energy by the front rotor. Data from **Table-3** was used to calculate the total efficiency which has been tabulated in **Table**-4. Using this data, the graph of total efficiency versus advance ratio has been plotted in **Fig-10**. This graph showed similar pattern compared to the results obtained from Saito et al. [14], especially, when the axial spacing was D/4.

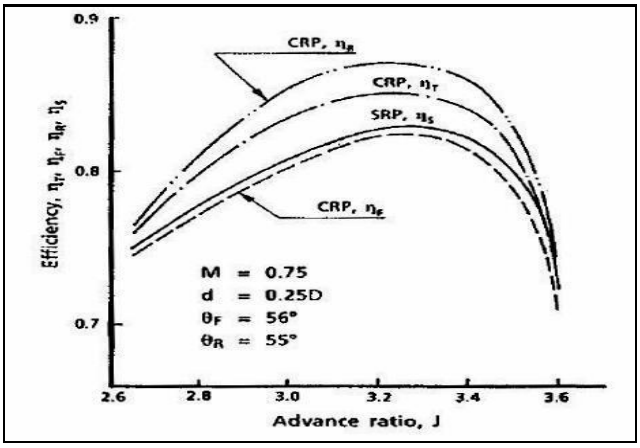

Fig -9: Comparison of efficiency between single rotating propeller and contra-rotating propeller, [14].

Table-4: Total efficiency calculation

Throttle Level	CT	C_P	J	$\eta_T = \frac{JC_T}{C_P}$
Axial Spacing : D/8				
1	0.083	0.019	0.206	0.887323
2	0.070	0.019	0.245	0.939881
3	0.062	0.018	0.274	0.943884
Axial Spacing : D/4				
1	0.084	0.020	0.187	0.80626
2	0.076	0.019	0.225	0.909852
3	0.061	0.018	0.256	0.853789
Axial Spacing : D/2				
1	0.081	0.020	0.168	0.682213
2	0.078	0.019	0.203	0.817298
3	0.075	0.019	0.238	0.858268
Axial Spacing : 3D/4				
1	0.079	0.020	0.167	0.655433
2	0.066	0.019	0.203	0.694626
3	0.056	0.018	0.237	0.718337

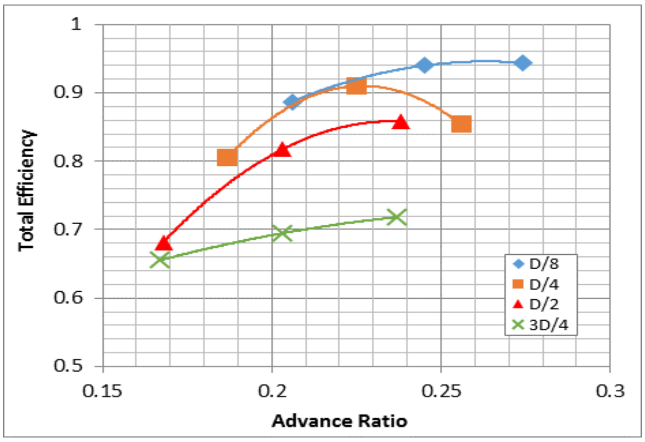

Fig-10: Graph of Total Efficiency versus Advance Ratio.

According to Saito [14], the rotor spacing showed a diminutive effect on the total efficiency. Similarly, Lesieutre and Sullivan [17] also states that by increasing the axial spacing between propellers has a negligible effect on the efficiency. **Fig-11** and **Fig-12** show the result based on the effects of varying axial spacing between propellers or rotor blades.

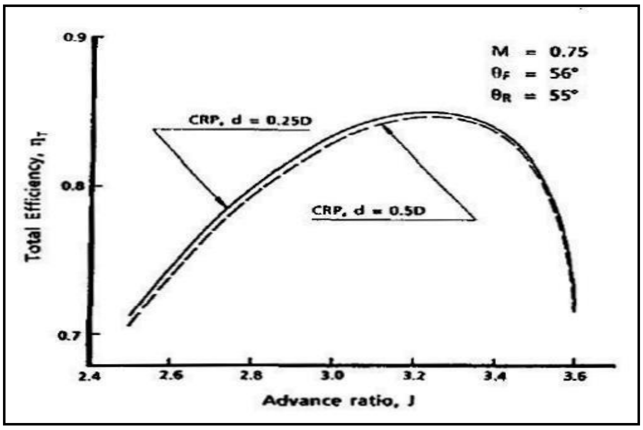

Fig-11: The effect of rotor spacing on the total efficiency to advance ratio, [14].

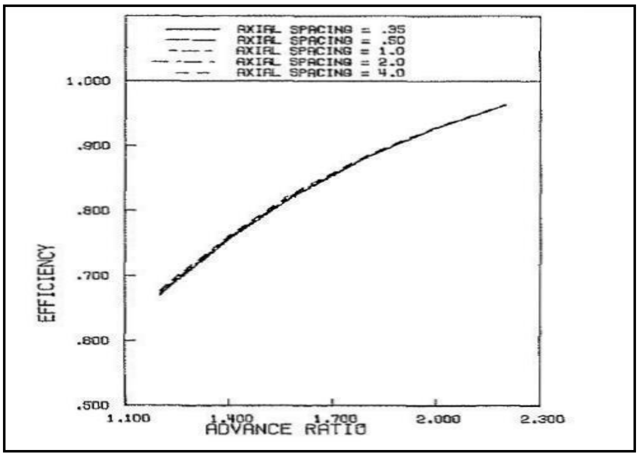

Fig-12: Effect of varying the axial spacing on the efficiency [17].

3.4 The Effect of Varying Axial Spacing to the Air Flow

The airflow between rotors were perceived and analyzed by conducting the smoke test. The smoke flowing through the hub and to the rotors demonstrated a similar trend for all configurations of axial spacing at respective throttle level showing a constant bell-shaped flow. This phenomenon illustrates a typical pattern of air flow from a free stream into the hub obstruction, where the free stream flow curved accordingly to shape of the flow barrier. From the result, it can be seen that, as the speed increases, the width of the bell-shaped smoke region becomes smaller and thinner. Correspondingly, as the axial spacing between the rotors was increased, the width change of the bell-shaped smoke region also showed analogous pattern.

(a) Throttle Level 1

(b) Throttle Level 2

(c) Throttle Level 3

Fig-13: Smoke test result for axial spacing of D/8 at various throttle level.

However, at smaller spacing the air flow from the forward rotor to the aft rotor were more diverged as compared to larger spaced configurations, where the air flow is more converging and focusing to the center. This transpires because, at smaller spacing, the aft rotor is able to recover the swirl loss experienced by the forward rotor as the airflow has not yet dispersed and lost most of its energy.

4. CONCLUSIONS

The objective of this research was to investigate the effects of axial spacing between the rotor blades on the total performance of a contra-rotating rotor blade system. In order to investigate the airflow characteristics of the rotor blade system and the effects of clearance or axial spacing between them, experiments with different spaces between the rotor blades were conducted. Laboratory investigation conducted in this study reveals that the variation of axial spacing between the forward and aft rotor had little effect on the total efficiency of the contra-rotating rotor blade system. However, at larger spacing, the effects were more significant and contributed adversely to the total efficiency of the system. Smoke tests further showed that as the speed increases, the width of the bell-shaped smoke region becomes smaller and thinner for different axial spacing.

ACKNOWLEDGEMENT

The authors would like to thank Faculty of Mechanical Engineering of Universiti Teknologi Malaysia for providing the facilities to conduct this research.

REFERENCES

[1]. Awal, Z. B. A. and Ammoo, M. S. b., A Case Study on the Air Flow Characteristics of the Hirobo-FALCON 505 Controllable Helicopter’s Main Rotor Blade, Applied Mechanics and Materials, Trans Tech Publications-Switzerland, Vol. 527, pp. 39-42, 2014.

[2]. Carlton, J. S., Marine Propellers and Propulsion, 2nd edition, pp. 199-200, 2007.

[3]. Greenhill, A. G., A Theory of the Screw Propeller. Trans. RINA, 1988.

[4]. Rota, G., The Propulsion of ships by means of contrary turning screws on a common axis, *Trans*. RINA, 1909.

[5]. Rota, G., Further experiments on contrary turning co-axial screw propeller, *Trans*. RINA, 1912.

[6]. Luke, W. J., Further experiments upon wake and thrust deduction, *Trans*. RINA, 1914.

[7]. Lerbs, H. W., Contra-rotating Optimum Propellers Operating in a Radially Non-Uniform Wake, DTMB Report No. 941, 1955.

[8]. Manen, J. D. and Sentic, A., Contra Rotating Propellers. *ISP*, 3, 1956.

[9]. Morgan, W. B., The design of contra-rotating propellers using Lerbs’ theory, *Trans*. *SNAME*, 1960.

[10]. Murray, M. T., Propeller Design and Analysis by Lifting Surface Theory, ARL, 1967.

[11]. Gunsteren, L. A. Van., Application of momentum theory in counter rotating propeller design, *ISP*, 1970.

[12]. Tsakonas, S., Jacobs, W. R., Liao, P., Prediction of steady and unsteady loads and hydrodynamics forces on contra-rotating propellers, Journal of Ship Research, Vol. 27(3), pp.179-214, 1983.
[13]. Bloom, G. S., Helicopters: How They Work - Counter Rotation Vs Contra Rotation, The Helicopter Page. Website: http://www.helicopterpage.com/html/dol.html
[14]. Saito, S., Kobayashi, H., Nasu, K. and Nakamura, Y., Performance Calculation of Counter Rotation Propeller, 23rd Joint Propulsion Conference, June 1987.
[15]. Spakovsky, Z. S., Greitzer, E. M. and Waitz, I. A., Unified Notes, Thermodynamics and Propulsion, Version 6.2, 2008-2009.
[16]. Pope, A. and Harper J. J., Low-Speed Wind Tunnel Testing, John Wiley and Sons, 1966.
[17]. Lesieutre, D. J. and Sullivan, J. P., The Analysis of Counter-Rotating Propeller Systems, SAE Paper No. 850869, 1985.

BIOGRAPHIES

Dr. Mohd Shariff bin Ammoo – is a Senior Lecturer in Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM). He completed his PhD from Cranfield University, United Kingdom in 2003. With over 25 years of teaching experience, his research area includes - Aircraft Structural Integrity and Supporting Structural Analysis, Helicopter Design, Instrumentation etc.

Ziad Bin Abdul Awal – is an aeronautical engineer. He is currently a postgraduate researcher in the Department of Aeronautics, Automotive and Ocean Engineering under Faculty of Mechanical Engineering at Universiti Teknologi Malaysia (UTM). He completed his Bachelor's Degree in Mechanical-Aeronautics in February 2014 from UTM. His research area includes Computational Fluid Dynamics (CFD), Structural Design Analysis, Aerodynamics, Rocket Propulsion, Unmanned Air Vehicles (UAVs) etc.

Nur Syafiqah binti Jamaluddin- is a former student of Universiti Teknologi Malaysia. She completed her Bachelor's Degree in Mechanical-Aeronautics.