Optimizing a Coaxial Propulsion System to a Quadcopter

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ABSTRACT

This article discusses the study of coaxial propulsion systems in UAVs (Unmanned Aerial Vehicles). A coaxial propulsion system is characterized by two propellers being positioned one above the other. In a coaxial propulsion system there is an interference between the flows of the two propellers resulting in a total thrust that is lower than the case where the two propellers are isolated. This propulsion system is normally used because it presents a good thrust to volume ratio since the two engines are near and the total output thrust is higher than in a single engine. The Glauert's theory, also called momentum theory, was used to predict the behavior of coaxial propulsion systems. This theory is a one-dimensional approximation and it was validated against thrust and power measurements for a coaxial system, with good agreement. This approximation compares the efficiency of the coaxial system with the efficiency of two separated propellers, giving therefore an estimation of power losses due to the interference of flows in coaxial systems. Four parameters were chosen to optimize the coaxial propulsion system of a quadcopter: power distribution between the two propellers, rotational direction of the propellers, distance between the two propellers and, lastly, diameter and pitch of the propellers. Several experimentations were realized showing that the efficiency of a coaxial propulsion system is actually independent of the power distribution, rotational direction and distance between the propellers. The pitch and diameter of the propellers are the main influence parameters of a coaxial propulsion system: the efficiency of the propulsion system decreases for lower pitches on the upper or lower propellers, higher pitch on the higher propeller or lower diameter on the lower propeller. Additionally, the efficiency is increased for a higher pitch on the lower propeller and lower diameter, also on the lower propeller. Finally, the efficiency was unchanged for a higher or lower diameter of the upper propeller.

KEYWORDS: Coaxial propulsion system, UAV, Quadcopter, Glauert's theory, Parameter sensitivity.

1. Introduction

In the last ten years there was a growth in the development of UAVs, more precisely in the technological and mechanical areas. The UAVs are usually used for civilian or military operations. In the civilian operations the main applications are related to fire control, search and rescue operations, precision agriculture, maintenance of structures, media cover and inspection of critical areas [1]. In the military operations the main applications are related to ground control, attack, border surveillance and crowd control, being the last two applications mainly used by police forces [2]. The most important component of a UAV is the propulsion system since it is responsible for approximately 90% of the power consumption [3]. Therefore, the propulsion system of a UAV must be efficient and appropriate to the mass of the vehicle in order to obtain a long flight time. Additionally, the propulsion system must attend to the volume of the UAV and, consequently, it must provide an adequate ratio between the thrust and the occupied volume. In order to attend to these needs, it was estimated that coaxial propulsion systems could present a good efficiency maintaining a high ratio between the thrust and the occupied volume.

A coaxial propulsion system is composed of two engines and two propellers disposed one above the other and aligned in relation to their axis of rotation. Normally the distance between the two propellers is approximately equal to the radius of the propellers. The concept of a coaxial propulsion system is not a recent discovery. It is assumed that approximately 35 prototypes of coaxial propulsions systems were built before 1945 but not all showed promising result on the flight tests [5, 6]. After 1945 several prototypes were built and approved in the flight tests such as the prototypes of Hiller, Bendix, Gyrodyne and Kamov [4]. Focusing on UAVs, only recently it was thought to equip this vehicles with coaxial propulsion systems. When a coaxial system is designed for an helicopter it attends to the fact that the upper and lower propellers must rotate in opposite directions in order to guaranty that the momentum created by the propellers on the UAV is equal to zero. This means that there is no need for a tail rotor to stabilize the helicopter. However, in quadcopters (UAV with four arms equally spaced around the center body) there is no tail and, therefore, the need of the propellers to rotate in opposite directions is suppressed. In order to optimize a coaxial propulsion system for a quadcopter several experiments were conducted.

2. Glauert's Theory

The behavior of a coaxial propulsion system can be predicted by several theories. The Glauert's theory is a simple method to predict the behavior of a coaxial system without requiring complex calculations [7]. It is also called the one-dimensional momentum theory and it provides a good approximation according to Colin P. Coleman which conducted several experiments and concluded that the predictions made by the Glauert's theory presented an error of approximately 5% [8]. The momentum theory applies the laws of conservation of mass, momentum and energy to the coaxial propulsion system. It is important to notice that this theory doesn't account for viscid losses or compressibility of fluids. It is possible to study different flight modes but it was chosen only to study the hover mode since it is the main mode used in quadcopters. The vector velocity study of the air flow created by a single hovering propeller is presented in Figure 1.

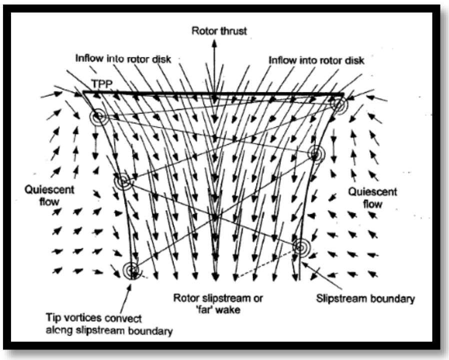

Figure 1: Velocity field in hover mode [7]

From Figure 1 we observe that the velocity of the air that was initially quiescent rises progressively as it is sucked by the propeller. It is important to notice that the velocities just above and under the propeller are equal, but the velocity rises progressively after passing the propeller and finally stabilizes after a certain distance (in the "far" wake). Since the velocity difference on the propeller is equal to zero, this means that the thrust is created by a pressure difference over the propeller. Finally, we can observe that the flow that exits the propeller (the wake) exhibits a limited contraction that is similar to a contracted vein. This form of the flow is called *vena contracta* [3, 4, 7].

The Glauert's theory is based upon the assumption that the propellers can be approximated by an actuating disk with zero thickness, were a pressure difference occurs and a thrust force is applied. When the Glauert's theory is applied to a coaxial propulsion system there are four different cases to account for.

The Glauert's theory provides a relation between the efficiency of the coaxial system and the efficiency of the isolated propellers. This relation is called the induced power factor from interference (κ_{int}), and it is an non-dimensional parameter.

First Case

The first case is when the two propellers share the same plane and are operated at the same thrust, as shown in Figure 2.

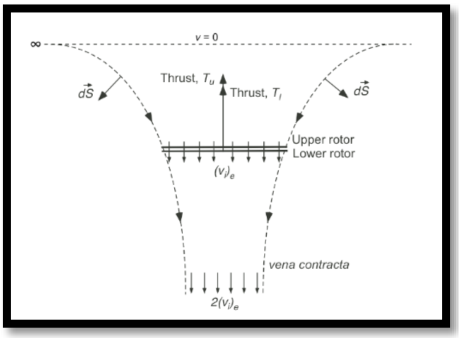

Figure 2: Flow model of a coaxial propulsion system with both propellers sharing the same plane [4]

From the application of the Glauert's theory to the first case we calculated that the induced power factor from interference was equal to $\sqrt{2}$:

$$\kappa_{int} = \frac{(P_i)_{coaxial}}{(P_i)_{isolados}} = \sqrt{2} = 1.414$$

Therefore, we conclude that this coaxial system requires approximately 41% more power than two isolated propellers to produce the same thrust.

Second Case

The second case is when the two propellers share the same plane and are operated at the same power. From the application of the Glauert's theory we concluded that the second case is identical to the first case.

Third Case

The third case is when the lower propeller is in the "far" wake of the upper propeller and both are operated at the same thrust, as shown in Figure 3.

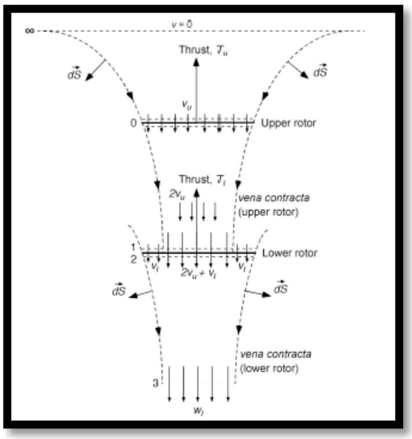

Figure 3: Flow model of a coaxial propulsion system with the lower propeller operating in the *vena contracta* of the upper propeller [4]

From the application of the Glauert's theory to the third case we calculated that the induced power factor from interference was equal to 1.281:

$$\kappa_{int} = \frac{(P_i)_{coaxial}}{(P_i)_{isolados}} = 1.281$$

Therefore, we conclude that this coaxial system requires approximately 28% more power than two isolated propellers to produce the same thrust.

Fourth Case

The fourth case is when the lower propeller is in the "far" wake of the upper propeller and both are operated at the same power. From the application of the Glauert's theory we calculated that the induced power factor from interference was equal to 1.219:

$$\kappa_{int} = \frac{\left(\frac{P}{T}\right)_{coaxial}}{\left(\frac{P}{T}\right)_{isolados}} = \frac{\left(\frac{P}{T}\right)_{Cima} + \left(\frac{P}{T}\right)_{Baixo}}{\left(\frac{P}{T}\right)_{isolados}} = 1.219$$

Therefore, we conclude that this coaxial system requires approximately 22% more power than two isolated propellers to produce the same thrust.

Analyzing the four cases above we conclude that a coaxial system is more efficient when the lower propeller is in the "far" wake of the upper propeller and both are operated at the same power.

3. Experimental Tests

Several experimental tests were conducted in order to conclude the influence of different parameters on the efficiency of the coaxial system. A test rig was built to perform these experimental tests. Before performing any test we had to decide if the two propellers were to be tested in a tractor or pusher configuration. A tractor propeller is characterized for pulling the UAV, the rotor axis is in tension. Contrarily, a pusher propeller is characterized for pushing the UAV, the rotor axis is in compression. Based on the Glauert's theory we predicted that the most efficient coaxial system is the one were the lower propeller operates in the "far" wake of the upper propeller (at a distance approximately equal to the radius of the diameter). Therefore, in order to minimize the space occupied by the propulsion system, the experimental tests were conducted with an upper propeller in tractor configuration and with a lower propeller in pusher configuration, as shown in Figure 4.

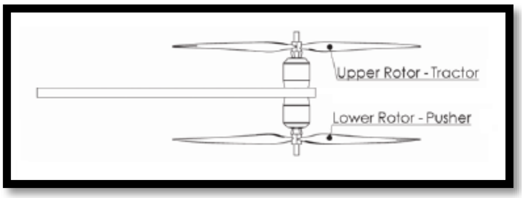

Figure 4: Engines' Configuration - Upper Tractor and Lower Pusher [3]

The electric motor used in the experimental tests was the brushless Axi 2826/12. This motor has a maximum efficiency of 84% and the maximum efficiency range is between 15 and 25A. Additionally, the propellers tested were of the Slow Flyer class. This class was chosen because these propellers are designed for motors with small rotational speeds like the Axi 2826/12 (65000Rpm divided by the diameter of the propeller, in inches). Finally, the thrusts of coaxial systems are to be compared with the thrust obtained from a single motor with a 14x4.7 Slow Flyer propeller (diameter of 14inches and pitch of 4.7inches), since it is the optimized propulsion system of a four motor quadcopter [1]. Therefore, the difference of weight between the propulsion systems must be taken into account. In the results of the experimental tests the thrust shown is the useful thrust, which is equal to the real thrust minus the difference of weight between the coaxial system and the propulsion system composed of a single motor and a 14x4.7 propeller. Additionally, a quadcopter has four propulsion systems, therefore, the total useful thrust will be used, which is equal to four times the useful thrust of a coaxial system.

The parameters chosen to be tested and optimized were: power distribution between the two propellers, rotational direction of the propellers (same direction or opposite directions), distance between the two propellers, diameter and pitch of the propellers.

Power Distribution

Several experimental tests were conducted in order to observe the influence of the power distribution on the efficiency of a coaxial system. Five power distributions were tested: 75%/25%, 60%/40%, 50%/50%, 40%/60% and 25%/75%, where the first percentage is related to the power of the upper mtor and the second percentage to the power of the lower motor. Additionally, these tests were conducted with 14x4.7 propellers.

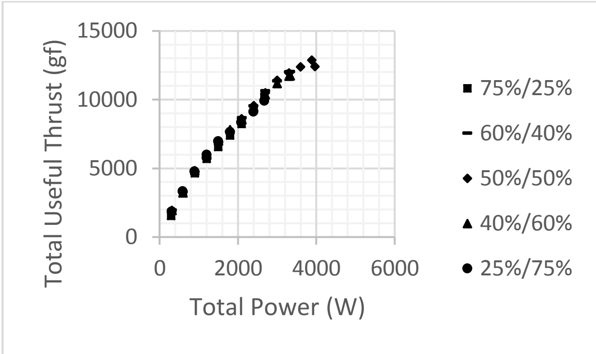

Figure 5: Coaxial propulsion system with two 14x4.7 propellers and same rotational directions

Observing Figure 5 we conclude that the power distribution is a parameter that has little influence in the efficiency of a coaxial system. However, each motor has a power limit, therefore, the distribution of 50%/50% is the one that provides higher total power and higher useful thrust since the power limit of both motors is reached at the same time. The following experimental tests were conducted with a power distribution of 50%/50%.

Rotational Direction

In this experimental test both same and opposite rotational directions were studied.

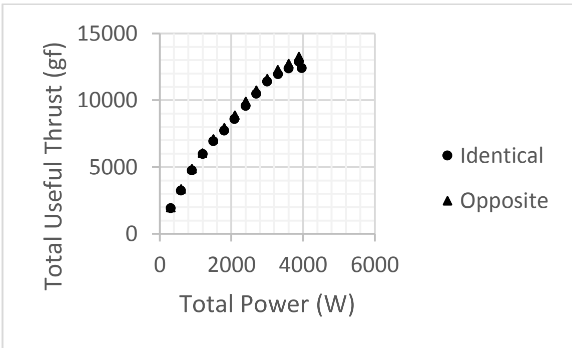

Figure 6: Coaxial propulsion system with two 14x4.7 propellers

Observing Figure 6 we conclude that the rotational direction is a parameter that has little influence in the efficiency of a coaxial system. However, to choose which rotational directions will be used on the following experimental tests, a temperature test was conducted.

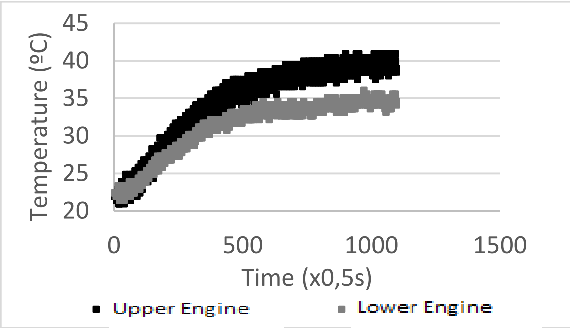

Figure 7: Engines' temperatures in a coaxial system operated at 375W with opposite rotational directions and 22ºC ambient temperature

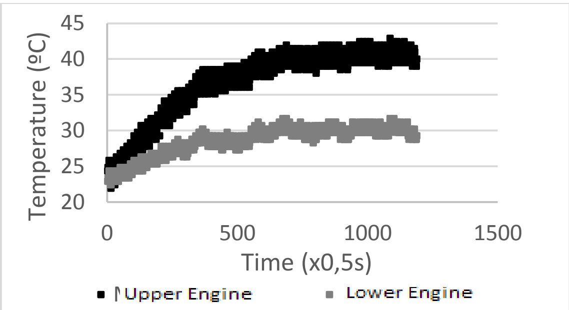

Figure 8: Engines' temperatures in a coaxial system operated at 375W with same rotational directions and 22ºC ambient temperature

Observing Figures 7 and we conclude that the best configuration is when both propellers rotate in the same direction because the efficiency and the temperature of the upper engine are the same but the temperature of the lower engine is 5ºC lower. The following experimental tests were conducted with the same rotational direction on both propellers.

<u>Distance between propellers</u>

Three experimental tests were conducted in order to observe the influence of the distance between the two propellers on the efficiency of a coaxial system. The minimum distance between the two propellers is of 148mm. Introducing aluminum spacers of 15mm we were able to study distances between propellers of 163mm and 178mm.

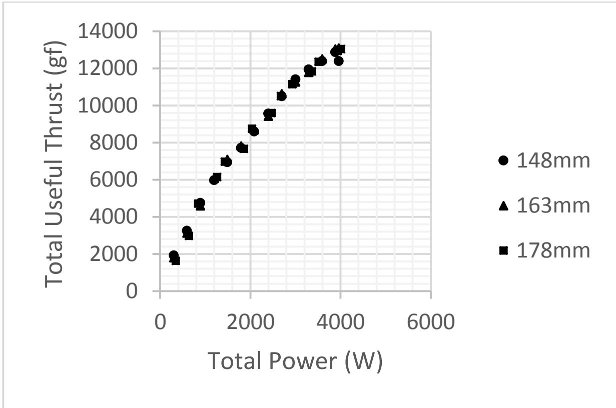

Figure 9: Thrust in relation to the distance between propellers - Coaxial system with two 14x4.7 propellers

From Figure 9 we conclude that the distance between the two propellers is a parameter that has little influence in the efficiency of a coaxial system. However, the distance of 148mm was chosen as the optimized one because there is no need to use spacers to obtain this distance between propellers The following experimental tests were conducted with a distance of 148mm between propellers.

<u>Propeller's Pitch</u>

Several experimental tests were conducted in order to observe the influence of the pitch of the propellers on the efficiency of a coaxial system. The propellers 12x3.8, 12x4.7 and 12x6.0 (the first number refers to the diameter and the second to the pitch, both in inches) were used to perform these experimental tests. The study of the influence of the pitch of the propellers on the efficiency of coaxial system was divided into two parts.

<u>Part I</u>

The first part of this study is related with the variation of the upper propeller's pitch. Pitches of 3.8inches and 6.0inches are being compared with a pitch of 4.7inches.

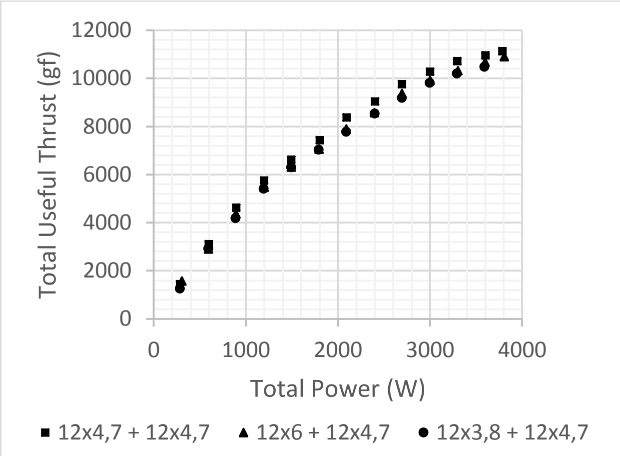

Figure 10: Thrust in relation to the variation of the upper propeller's pitch

Observing Figure 10 we conclude that the pitch of the upper propeller is a parameter that influences the efficiency of a coaxial system: increasing the upper propeller's pitch results in a decrease in efficiency. From the Glauert's theory, which assumes that the lower propeller has no influence in the upper propeller's flow, we could predict that an increase in the upper propeller's pitch would result in an increase in the upper propeller's thrust. Additionally, from the Glauert's theory we could predict that increasing the upper propeller's pitch results in an increase of the velocity on the "far" wake of the upper propeller and, therefore, it results in an increase of the interference between flows. If the interference between flows is increased then the efficiency of the lower propeller decreases. Consequently, an increase in the upper propeller's pitch increases the efficiency of the upper propeller but reduces the efficiency of the lower propeller. Observing Figure 10 we saw that increasing the upper propeller's pitch in 1.3inches (28% of 4.7inches) resulted in an overall decrease of the efficiency of the coaxial system. From this observation we conclude that the increase of efficiency of the upper propeller is lower than the decrease of efficiency of the lower propeller.

In contrast, a decrease in the upper propeller's pitch decreases the efficiency of the upper propeller but increases the efficiency of the lower propeller. Observing the figure above we saw that decreasing the upper propeller's pitch in 0.9inches (19% of 4.7inches) resulted in an overall decrease of the efficiency of the coaxial system. From this observation we conclude that the decrease of efficiency of the upper propeller is higher than the increase of efficiency of the lower propeller.

We can conclude from the statements above that a variation on the upper propeller's pitch results in a decrease of the efficiency of a coaxial system.

Part II

The second part of this study is related with the variation of the lower propeller's pitch. Pitches of 3.8inches and 6.0inches are being compared with a pitch of 4.7inches.

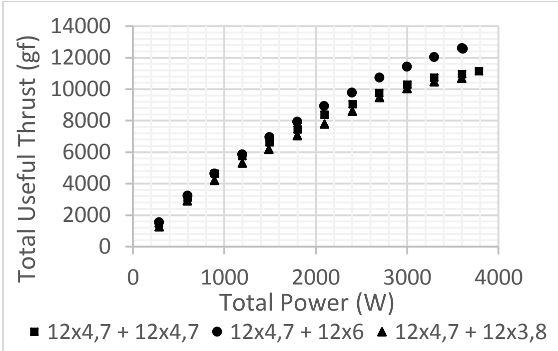

Figure 11: Thrust in relation to the variation of the lower propeller's pitch

From Figure 11 we conclude that the pitch of the lower propeller is a parameter that influences the efficiency of a coaxial system. From the graphic it is possible to conclude that increasing the lower propeller's pitch results in an increase in efficiency. From the Glauert's theory we could predict that the upper propeller's efficiency would be unchanged. Additionally, we could predict that an increase in the lower propeller's pitch would result in an increase in the lower propeller's thrust, as it's been explained earlier. Observing the figure above we saw that increasing the lower propeller's pitch in 1.3inches (28% of 4.7inches) resulted in an overall increase of the efficiency of the coaxial system.

We can conclude from the statements above that a decrease on the lower propeller's pitch results in a decrease of the efficiency of a coaxial system while an increase on the lower propeller's pitch results in an increase of the efficiency of a coaxial system.

Propeller's Diameter

Different experimental tests were conducted in order to observe the influence of the diameter of the upper and lower propellers on the efficiency of a coaxial system. The propellers 12x4.7, 13x4.7 and 124x4.7 were used to perform these experimental tests. The study of the influence of the diameter of the propellers on the efficiency of coaxial system was divided into three parts.

Part I

The first part of this study is related with the variation of the propeller's diameter, maintaining both propellers with the same diameter. Propellers of

12inches and 14inches were used for this experimental test.

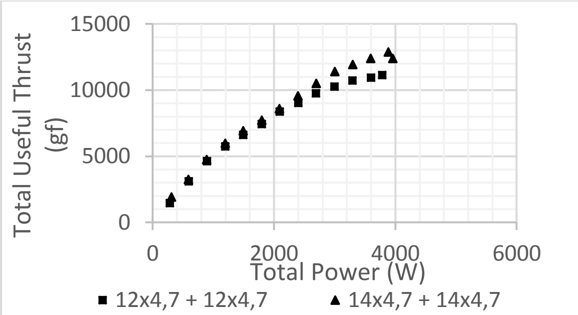

Figure 12: Thrust in relation to the same variation on both propellers' diameters

From Figure 12 we conclude that the diameter of a propeller is a parameter that influences the efficiency of a coaxial system: increasing the diameter of both propellers results in an increase in efficiency. More precisely, we can see that the increase of efficiency is higher for higher power consumptions. From the Glauert's theory, we could predict that an increase in the diameter of both propellers would result in an increase of efficiency.

Part II

The second part of this study is related with the variation of the upper propeller's diameter. The increase and decrease of the upper propeller's diameter will be separately studied.

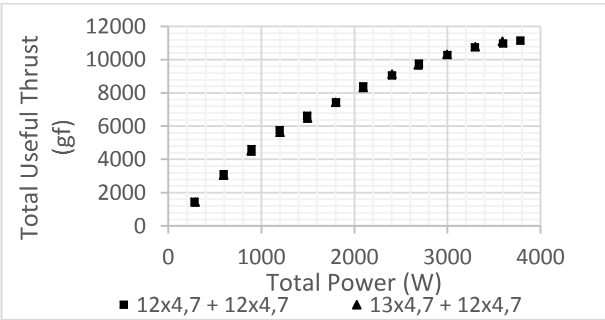

Figure 13: Thrust in relation to the increase of the upper propeller's diameter

Observing Figure 13 we conclude that the increase of the diameter of the upper propeller has little influence in the efficiency of a coaxial system. From the graphic it is possible to conclude that increasing the upper propeller's diameter has no effect on the efficiency of a coaxial system. From the Glauert's theory we could predict that an increase in the upper propeller's diameter would result in an increase in the upper propeller's thrust. Additionally, from the Glauert's theory we could predict that increasing the upper propeller's diameter would results in an increase of the sectional area of the flow on the "far" wake of the upper propeller and, therefore, it results in an increase of the interference between flows. If the interference between flows is increased then the efficiency of the lower propeller decreases. Consequently, an increase in the upper propeller's diameter increases the efficiency of the upper propeller but reduces the efficiency of the lower propeller. Observing the figure above we saw that increasing the upper propeller's diameter in 1inch (8% of 12inches) had no result in the overall efficiency of the coaxial system. From this observation we conclude that the increase of efficiency of the upper propeller is approximately equal to the decrease of efficiency of the lower propeller.

Similar conclusions were drawn when studying the influence of decreasing the upper propeller diameter.

We can conclude from the statements above that a variation on the upper propeller's diameter has almost no influence in the efficiency of a coaxial system.

Part III

The third part of this study is related with the variation of the lower propeller's diameter. The increase and decrease of the lower propeller's diameter will be separately studied.

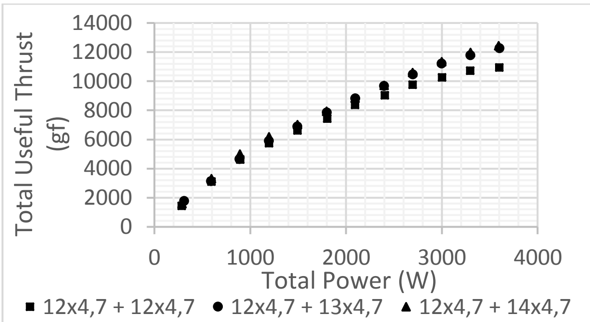

Figure 14: Thrust in relation to the increase of the lower propeller's diameter

Observing Figure 14 we conclude that the increase of diameter of the lower propeller influences the efficiency of a coaxial system. From the Glauert's theory we could predict that the upper propeller's thrust will be unchanged. Additionally, from the Glauert's theory we could predict that increasing the lower propeller's diameter results in an increase of the lower propeller's efficiency. Observing Figure 14 we saw that increasing the lower propeller's diameter in 1inch and 2inches (8% and 17% of 12inches) resulted in an increase of the overall efficiency of the coaxial system.

Having studied the influence of increasing the lower propeller's diameter we now need to study the influence of a decrease.

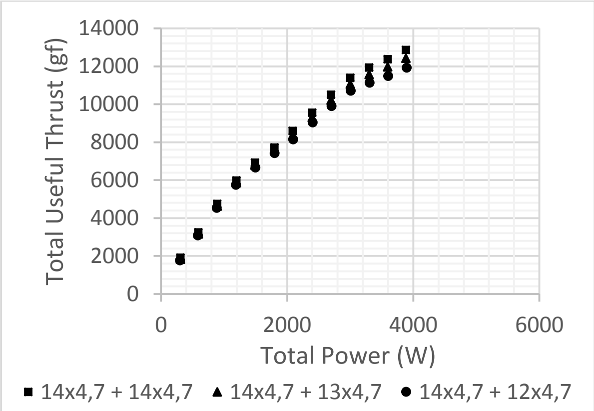

Figure 156: Thrust in relation to the decrease of the lower propeller's diameter

From Figure 15 we conclude that the decrease of diameter of the lower propeller influences the efficiency of a coaxial system. From the Glauert's theory we could predict that the upper propeller's thrust will be unchanged. Additionally, from the Glauert's theory we could predict that decreasing the lower propeller's diameter results in a decrease of the lower propeller's efficiency. Observing the figure above we saw that decreasing the lower propeller's diameter in 1inch and 2inches (7% and 14% of 14inches) resulted in a decrease of the overall efficiency of the coaxial system.

We can conclude from the statements above that a variation on the upper propeller's diameter influences the efficiency of a coaxial system. More precisely, increasing the lower propeller's diameter increases the efficiency of a coaxial system, while decreasing it results in a decrease of efficiency of a coaxial system.

Final optimization of propellers

From the previous results there were three coaxial configurations that showed promising results. These configurations were:

Upper Propeller – 14x4.7 & Lower Propeller – 14x4.7
Upper Propeller – 12x4.7 & Lower Propeller – 14x4.7
Upper Propeller – 12x4.7 & Lower Propeller – 12x6.0

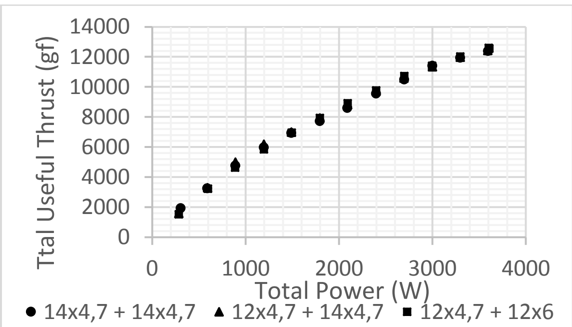

Figure 16: Thrust comparison between the three optimized configurations

Observing Figure 16 we conclude that these three configurations provide the exact same efficiency. Therefore, it was needed to test the response time of these configurations in order to find the optimized one. The response time of the upper and lower propellers was tested. Experimental tests showed that the first and third configurations had the same response time on the upper and lower propellers and, therefore, only the response of one of the propellers was represented in Figure 17.

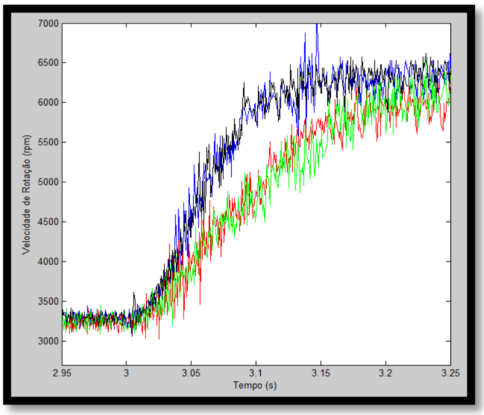

Figure 17: Comparison of the response time of the three optimized configurations - The first configuration is in green, the upper propeller of the second configuration is in blue and the lower is in red, and the third configuration is in black

Observing Figure 17 we conclude that the three coaxial configurations present different response times. It is possible to observe that propellers with the same diameter present approximately the same response time, independently of the pitch of the propeller. Additionally, from the results above it was seen that the response time increases with the increase of the diameter. With this assumption it is obvious that the third configuration would present the lowest response time since it is composed of two 12inches propellers.

We conclude from the statements above that the third configuration (Upper Propeller – 12x4.7 & Lower Propeller – 12x6.0) is the optimized coaxial propulsion system.

Comparison Coaxial/Single

From the previous experimental tests we concluded that the optimized coaxial propulsion system was obtained with a power distribution of 50%, the same rotational directions on both propellers, a distance of 148mm between the two propellers, a upper propeller with a diameter of 12inches and a pitch of 4.7inches, and a lower propeller with a diameter of 12inches and a pitch of 6.0inches. This coaxial propulsion system was compared to a propulsion system composed of a single engine and a 14x4.7 propeller. The results of this comparison are presented in Figures 18 and 19.

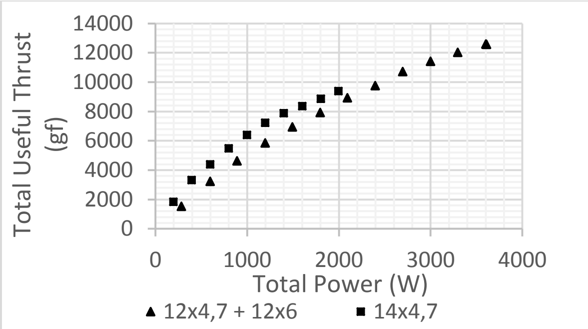

Figure 18: Comparison between the thrust of the optimized coaxial system and the base propulsion system's thrust

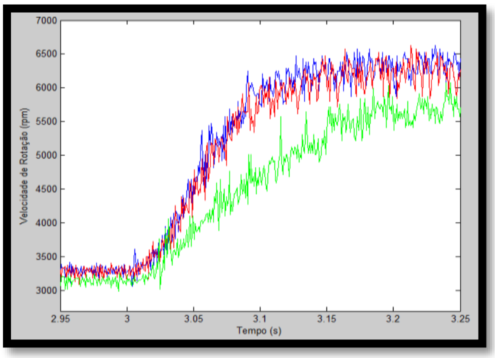

Figure 19: Response time comparison between the optimized coaxial system and the base propulsion system - The base propulsion system is in green, the upper propeller of the coaxial system is in blue and the lower in red

Observing Figure 18 we conclude that the efficiency of the optimized coaxial propulsion system is lower than the efficiency of a single motor with a 14x4.7 propeller. However, the difference between these efficiencies is little and therefore it is possible to affirm that the optimized coaxial propulsion system has a good efficiency. Additionally, from Figure 19 we conclude that the coaxial propulsion system has a response time that is lower than the single 14x4.7 propeller. This result could be predicted from the previous assumption that a 12inches propeller has a lower response time than a 14inches propeller.

We conclude from the statements above that the optimized coaxial propulsion system has an efficiency lower than that of a single 14x4.7 propeller but it presents a lower response time.

4. Conclusions

In the present article, the Glauert's theory was used to predict the behavior of a coaxial propulsion system. We concluded that the optimized coaxial system would present a lower propeller that operates in the "far" wake of the upper propeller.

From the experimental tests we concluded that the power distribution to optimize the behavior of a coaxial propulsion system should be of 50%. Additionally, it was shown that the coaxial propulsion system has the same efficiency whether the propellers rotate in the same or opposite directions but the temperature of the engines was lower when the propellers rotate in the same direction. Regarding the distance between the two propellers, it was proved that this parameter had no influence in the efficiency of a coaxial propulsion system, for the studied distances. Finally, regarding the propellers' diameters and pitches, we concluded that any variation on the upper propeller's pitch resulted in a decrease of the efficiency of a coaxial system. Additionally, a decrease on the lower propeller's pitch results in a decrease of the efficiency of a coaxial system while an increase on the lower propeller's pitch results in an increase of the efficiency of a coaxial system. Regarding the propellers' diameters, we concluded that an increase in the propellers' diameters results in an increase of the efficiency of the coaxial system while a decrease in the propellers' diameters resulted in a decrease of the efficiency of the coaxial system, but maintaining both propellers with the same diameter. Additionally, we concluded a variation on the upper propeller's diameter has almost no influence in the efficiency of a coaxial propulsion system. Contrarily, increasing the lower propeller's diameter proved to increase the efficiency of a coaxial system, while decreasing it resulted in a decrease of efficiency of a coaxial system. Finally, from the statements above we arrived to three optimized configurations of a coaxial propulsion system:

Upper Propeller – 14x4.7 & Lower Propeller – 14x4.7
Upper Propeller – 12x4.7 & Lower Propeller – 14x4.7
Upper Propeller – 12x4.7 & Lower Propeller – 12x6.0

These three configurations presented approximately the same efficiency but the third configuration proved to have the lowest response time and was therefore chosen has the optimized coaxial configuration. This configuration was compared to a single motor with a 14x4.7 propeller and we concluded that the efficiency of the coaxial system was lower than that of the single rotor. However, the response time of the coaxial system proved to be smaller than that of the single rotor.

5. References

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