Optimization of Tri-Rotor Propeller for Maximum Lift Efficiency

Merve Sali
Department of Industrial Engineering
Alma Mater Studiorum University of Bologna
Viale Risorgimento, 2 – 40136, Bologna, Italy
merve.sali2@unibo.it

Abstract

This paper presents the simulation of a tri-rotor contra-rotating propeller for the thrust and lift efficiency during vertical take-off. In fact, the second rotor worked in the opposite direction in respect to the first and the third rotors. Our multi-rotor system includes three rotors with two blades for each rotor. For this study, NACA 0012 untwisted and symmetric airfoil was chosen. The airflow analysis experimented with CFD (Computational Fluid Dynamics) simulation. Therefore, the optimization of the tri-rotor propeller was performed with different pitch combinations to achieve adequate lift efficiency with sufficient overall thrust value. Critical angle of attack for the chosen airfoil gave the boundary conditions for the pitch of rotors. The results of simulations showed us the most efficient combinations for three rotors work better with increasing pitch angle from top to bottom.

Keywords
Multi-rotor propeller, VTOL, Thrust force, Hover lift efficiency, Optimization

1. Introduction
Tilt rotors aircraft like the V22 and the V280 have some problems in terms of efficiency in the various configurations (Zhou et al., 2020), (Boling et al., 2020). In vertical mode, they need the large rotors of helicopters to achieve high lift to power ratios. On the other side, disk-loading depends on rotor tip speed (Milluzzo & Leishman, 2010). Tip speed affects noise which is critical in civil and military applications (Sternfield H., 1980), (George, 1978). A tip speed over 0.7 Mach is the limit from Vietnam War era papers (Dittmar et al., 1978), (Hanson & Fink, 1979). Finally, disk-loading and the tip-speed affect the auto-rotation capability. On the contrary, low disk loads affect efficiency in horizontal, airplane-like operations, making the propeller drag so high that decreases the propeller efficiency (Biggers & Linden, 1985), (Fredericks et al., 2013). On the other hand, the purchase and maintenance costs of a convertiplane are justifiable only if they outmatch any helicopter in terms of speed, range and safety (Piancastelli et al., 2017). A natural compromise would have been to allow rotor over speed in Vertical and STOL operations, which last a few minutes and are very critical in terms of lift requirements (Piancastelli et al., 2015). This can be achieved by asking the engine designers and manufacturers the capability to allow the power turbine to over speed, adopting a variable cycle turboshaft. On the other side, variable cycle turboshafts are highly required for V/STOL aircraft where vertical flight requires 200% - 400% more power than airplane mode (Ferguson, 2015),(Schneider & Wilkerson, 1990), (Antcliff et al., 2019). Other design mantras are also to be investigated. Having two counter-rotating rotors like the V22 and V280 requires a connecting shaft between the two engines for emergency single-engine operations (de Voogt & St. Amour, 2021). This torque shaft lives a difficult life in the very flexible structure of the wing at the higher speed possible to contain the enormous transmission weight, cost and maintenance requirement. Theoretically, you can go to hybrid by adopting electric motors and a power generator with a battery (Fredericks et al., 2013). Practically, since motor weight grows much more than linearly with power output you would need many power packs. Even if the multiple power pack solution increases safety, it would affect in a very negative way reliability and maintenance costs (Rancourt, 2016). The overall structural weight will also be increased. Adding propellers to your airplane may also add speed to the air flowing on wings and control surfaces. Unfortunately, the air from the propellers is affected by a swirl that depends on power settings and vehicle flying conditions (W., 2021). This is the reason why many modern designs with very efficient laminar wings prefer a push configuration for the propeller (Streit et al., 2011), (Xu et al., 2018). A very big mantra especially for "western bloc" designers have also been the contra-rotating propeller solution. After WWII, for reasons unknown to the Authors, "western bloc designers" have abandoned the contra-rotating

propellers. The reasons for these can be reliability and noise. However, contra-rotating propellers like the Tupolev Tu-95 and most of the Kamov helicopters are common in the “Eastern bloc”.

The advantages of this solution are a wider efficiency range. This means better efficiency in hover and horizontal flight (Zdunich et al., 2007). This is due to the lower frontal disk area and the drag. Finally better performance at different vertical speeds, due to the absence of the settling with power region and better autorotation performance with lower vertical speed (Taamallah, 2010). Contra-rotating propellers are therefore very interesting for tilt-rotor aircraft. At the price of more noise and a little more complicated variable pitch mechanism, the advantages are far more important than in a helicopter or an airplane. Following this path, this paper investigates whether it is convenient or feasible to use three rotors propellers. This solution would be theoretically even more convenient than the contra-rotating propeller with high lift and high-speed efficiency. This design solution is better than the two rotor solutions theoretically.

1.1 Objectives
The main purpose of this research is to understand the take-off performance of the three-rotor propeller in connection with adjusting the angle of attack values for each propeller using the CFD simulation technique.

2. Literature Review
There are several research papers for the coaxial rotor propeller. (De Giorgi et al., 2017) studied the numerical investigation of the contra-rotating propeller and worked on improving the performance for larger pitch angles. (Ramasamy, 2013) compared hover performance for single, coaxial, tandem and tilt-rotor design. Consequently, it results that coaxial rotors perform better than the single rotor. Also, the first propeller always affects the second propeller performance even with a large distance between these two rotors. (Barbely et al., 2016) worked on the flow field characteristic of the coaxial rotor to understand the correlation between two propellers. In this research, the pressure on the rotors has been represented with Ro-tUNS unsteady calculations. It is seen that the second propeller was exposed to more pressure.

Moreover, some research showed that one of the major advantages of coaxial propeller design is to increase the efficiency of large-size aircraft by decreasing the swirl produced by downstream of the propeller (Strack et al., 1981). As mentioned before, contra-rotating propellers are used on multi-rotor UAVs which creates more thrust while decreasing the propeller area (Geldenhuys, 2015). On the other hand, besides these advantages contra-rotating propeller has some drawbacks such as the noise (Hanson & McColgan, 1985). Some studies showed that it is higher in contra-rotating propellers than the conventional single propeller (McKay et al., 2021) (Wang & Huang, 2018). Also, despite advantages such as increasing the manoeuvrability and simplifying the control system of multi-rotor propulsion, it is seen that this system does not have the same efficiency as the fixed-wing vehicle. Thus, this fewer efficiency causes a limitation on the range and durability of the multi-rotor UAVs. (Serrano et al., 2019).

3. Methods
3.1. Assignment of Values for Propeller Design
In this study, the aim is to indicate the thrust performance of three rotor propellers at a specified condition. Thus, the preeminent step is the propeller design. Some of the important factors such as design parameters, propeller diameter, propeller rotational speed, and the number of blades must be considered during the designing process. These parameters need to be defined for the perfect flight performance for different flight conditions (Yuan et al., 2020).

Starting the propeller design is possible by clarifying its performance regarding the disk loading and efficiency values. In Figure 1, it can be seen the disc loading and lift efficiency values for some types of aircraft (Maisel et al., 2000).

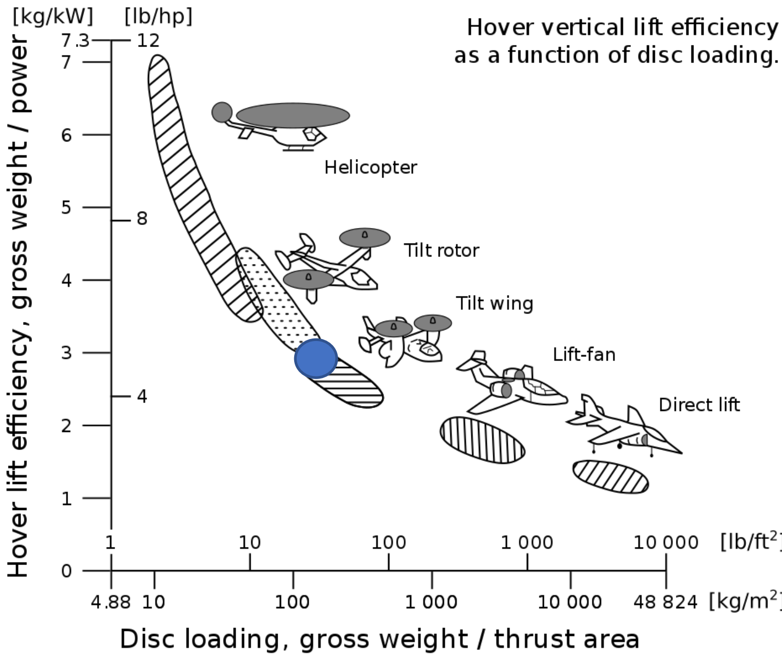

Figure 1. Disc loading – Hover lift Efficiency graph (Maisel et al., 2000)

The point identified with the blue area shows our targeted value on propeller design. It shows that the tilt-rotor & tilt-wing area for the new design is acceptable. Taking into account this area, the disc loading value range was defined which the limitation for our new design is. It is explained from the formula below that disc loading is related to the ratio between the gross weight (which is the load that the propeller has to compensate) and the thrust area (disc area).

$$\text{Disc loading (DL)} = \frac{\text{Gross weight x Gravity x Safety Factor}}{\text{Thrust area}}$$

In this case, to understand the take-off performance we identified a maximum take-off weight. Also, the disc loading value was defined regarding the tilt rotor& tilt-wing values. With the given information it is easy to calculate the diameter of each rotor. These determined values can be seen in Table 1. One of the major advantages of the three rotor propellers emerged here. Taking the three-rotor into consideration made their diameter was much smaller than the single propeller for the same design concept.

Table 1. Initial Conditions of Tri-Rotor Propeller

	Three Rotor Propeller
Max Take-off Weight	350 kg
Disk Loading	223.727
Diameter of Propeller	2,628 m
Number of Rotor	3
Number of Blades	2

To prevent any complexity, a common symmetric, untwisted airfoil was preferred to use. Because filtering the complexity of airfoil in this design would give us more transparent solutions about the three-rotor correlation. Therefore, NACA 0012 airfoil is preferred (Figure 2). Also, its untwisted, symmetric geometry and was a part of many studies (Sogukpinar, 2018), (Srinivasa Rao et al., 2018), (Haider et al., 2017) in this area made it a perfect choice for the blades.

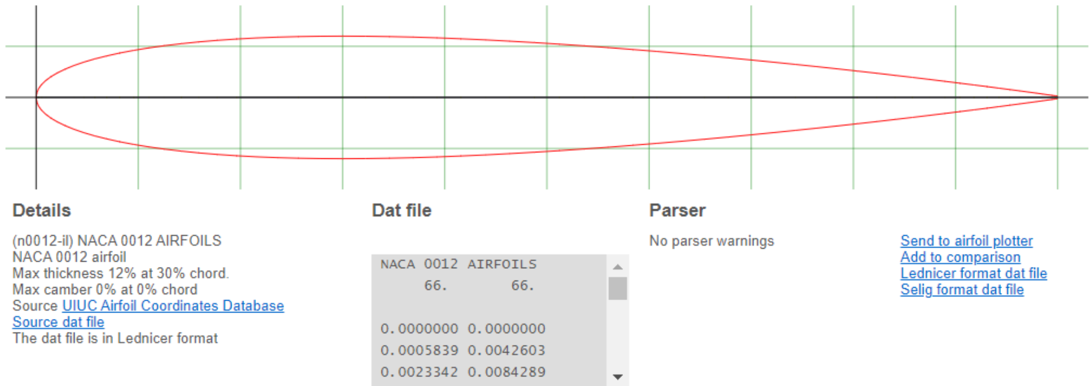

Figure 2. NACA0012 Airfoil

3.1. Propeller Design

The final shape of the tri-rotor design was completed by using these identified values all above. Additionally, rotors were assembled vertically to each other. According to the blade design, the top rotor rotates in the clockwise direction while the second rotor rotates anticlockwise direction. Finally, the lowest rotor rotates clockwise direction, shown in Figure 3.

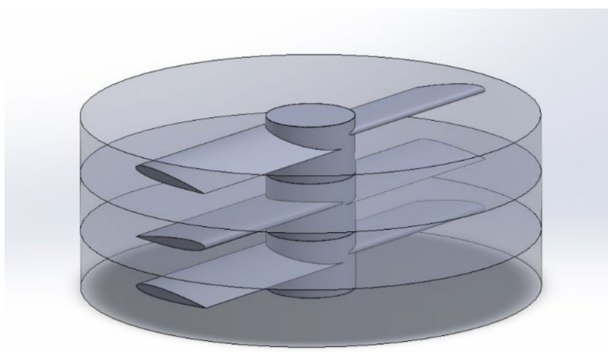

Figure 3. Final design of Tri-rotor propeller

4. Data Collection

4.1. Creating the Simulation Environment

Finding the best blade working condition is only possible with a proper simulation. Therefore, a reliable simulation environment was created by taking into account the values of an aircraft in use. Thus, the Ka-17 Kamov helicopter (Figure 4) was taken as a reference model (*ROTORCRAFT.INFO*, n.d.), and given values of this helicopter were the reference values to be reached. A pilot simulation was created to form the simulation parameters for tri-propeller design.

Figure 4. Камов: Ka-17

In this simulation, the blade was obtained by using NACA 23014 and NACA 23009 airfoils considering the values given in reference (*ROTORCRAFT.INFO*, n.d.), and the simulation was regulated and performed to reach the specified maximum take-off (MTOW) value.

SOLIDWORKS Flow Simulation was preferred as software to accomplish the simulation. The settings of the Kamov Ka-17 propeller simulation were recorded to be used for tri-rotor design (Figure 5).

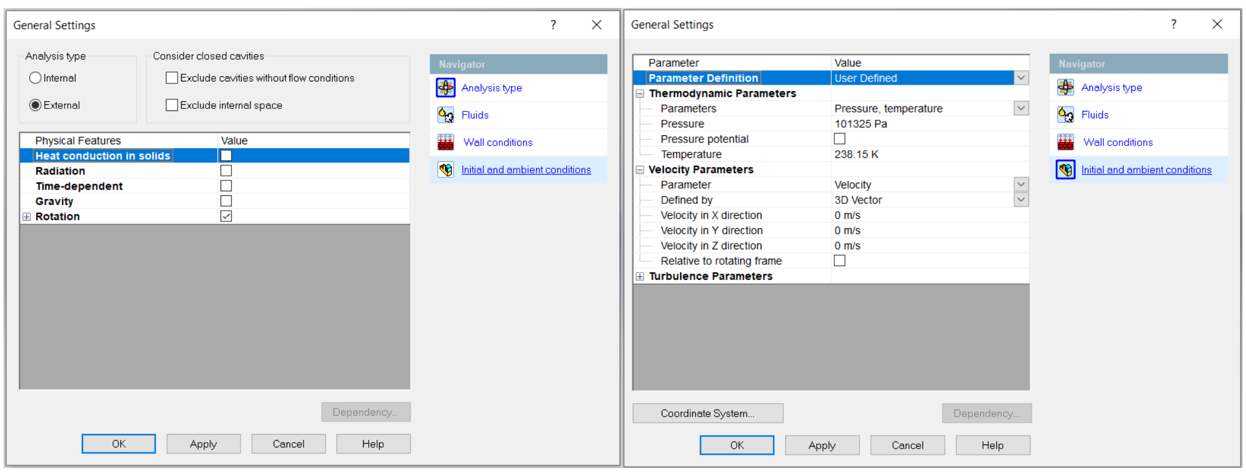

Figure 5. Analysis Type Interface (A) and Initial and Ambient Conditions Interface (B)

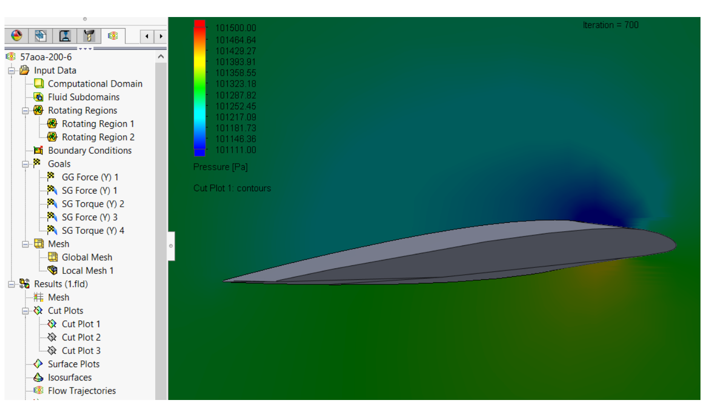

Figure 6. Камов: Ka-17 blade simulation

The simulation was achieved with these settings (Figure 5), and results showed that the lift needed for a sufficient take-off can be approved. Results confirm that defined settings are represented in Figure 6. As you can see from the picture, higher pressure occurred downstream.

But, before performing the simulation it was needed to define the helicopter environment conditions to be able to determine the velocity of blades (Table 2). In this study, Mach number is used under 7.0.

Table 2. ISA Atmosphere Conditions

Altitude	0
Temperature Offset	-50°C
Temperature	238.15 K
Pressure	101325 Pa
Density	1.48219 kg/m^3
Speed of Sound	309.364 m/s

According to these data, Mach number and rotor velocity were calculated. In these conditions, the Mach number is 0.657 and the rotational speed of the rotors is 154.682 rad/s.

Finally, it is worth mentioning that finding the most efficient propeller design is possible by implementing a suitable angle of attack on the blades. Because each of the airfoil types has different lift efficiency at a different angle of attack. Critical angles are also important factors affecting the efficiency of the blades. This means that sufficient thrust force can be provided with the maximum angle achieved before the critical angle is reached. Thus, it is very important to understand the features of the airfoil. As seen in Figure 7 below, the airfoil increases its performance until around 8° between 0.6-0.7 Mach number. Thus, in this study angle of attack values were chosen between 0°-8°.

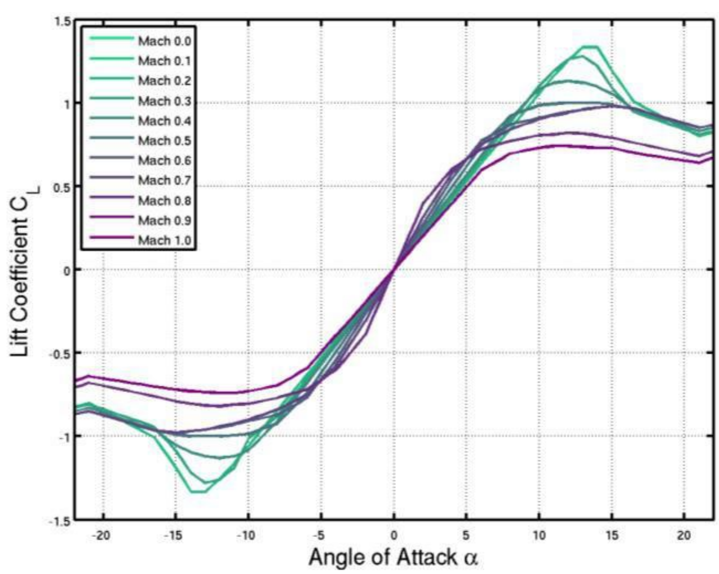

Figure 7. C_L-α graph for NACA 0012

5. Results and Discussion

5.1 Numerical and Flow Results

To understand the rotor behaviours at different angles, we performed several simulations under the same conditions defined in Section 4.1. Results showed that the required thrust for this design can be obtained at high angles. Also, the first rotor has to be designed with min 4° angle of attack. On the other hand, the results showed that the second and third rotor blades can suffer performance loss even at high angles. Therefore, combinations representing key points will be explained in this section.

Case 1

In the first case, it was examined how each propeller would create a lifting force if there were two degrees between the blade angles. Thus, the values of the blade angles are 4°, 6° and 8°, respectively. During the simulation, each propeller showed different thrust force results and the third propeller provided the most lift, while the second propeller contributed less to the overall performance. Total force details during simulation are given in Figure 8. Additionally, thrust force results can be seen in Table 3.

Table 3. Numerical Results of the Combination 1

Thrust Force	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence
Total Force	[N]	3432.581	2846.586	-2537.447	4313.59	100	Yes
Rotor 1	[N]	915.883	876.986	686.858	1056.477	100	Yes
Rotor 2	[N]	368.509	196.824	-1762.08	640.184	100	Yes
Rotor 3	[N]	2230.107	1779.394	-727.676	2818.766	100	Yes

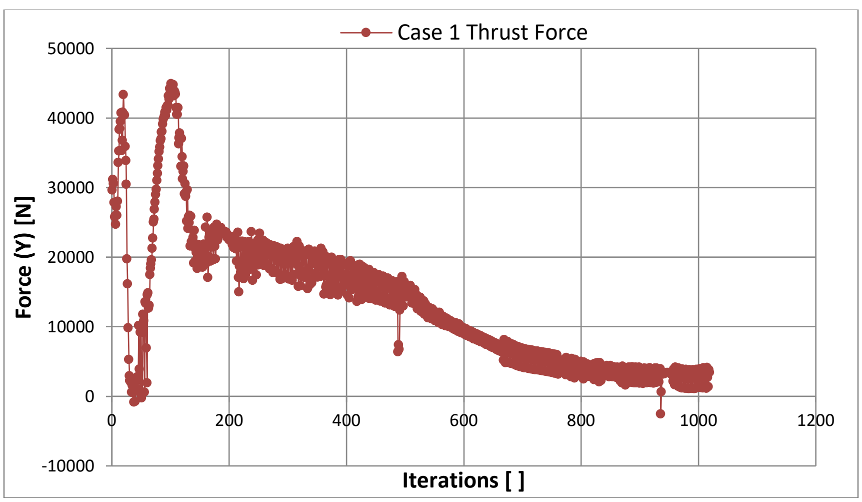

Figure 8. Thrust Force Graph for Combination 1

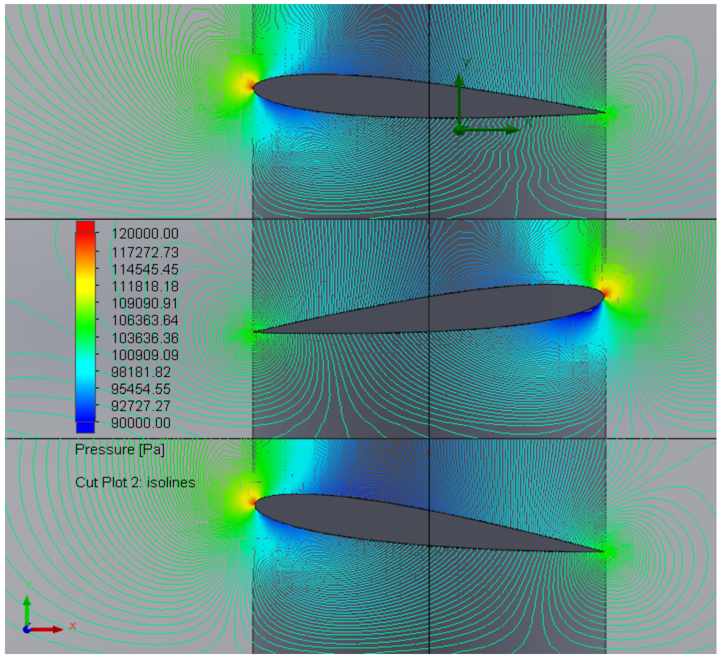

Figure 9. Case 1- Pressure details

As seen from the Figure 9, downstream pressure is higher than upstream pressure for each rotor blade. However, even though the pressure distribution on the first and third blades was similar, the upstream pressure of the second blade was also higher than the others. This high upstream pressure explains why the second rotor blade produces the least lift.

Case 2

In the second case, the highest angle values below the critical attack angle of NACA 0012 airfoil are used. The values of the blade angles are 6°, 7° and 8°, respectively. In this combination, the first and third propellers produced almost the same lifting force, while the second propeller had a slightly negative effect. Still, the design generally produces the desired lifting force. Thrust force values during iterations are shown in Figure 10. Also, numerical results of thrust force can be seen in Table 4.

Table 4. Numerical Results of the Combination 2

Thrust Force	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence
Total Force	[N]	3752.481	3609.514	1811.119	5502.962	100	Yes
Rotor 1	[N]	2222.769	2098.759	1922.042	2332.706	100	Yes
Rotor 2	[N]	-18.355	-92.153	-1145.269	563.9	100	Yes
Rotor 3	[N]	1483.526	1591.855	18.424	2880.707	100	Yes

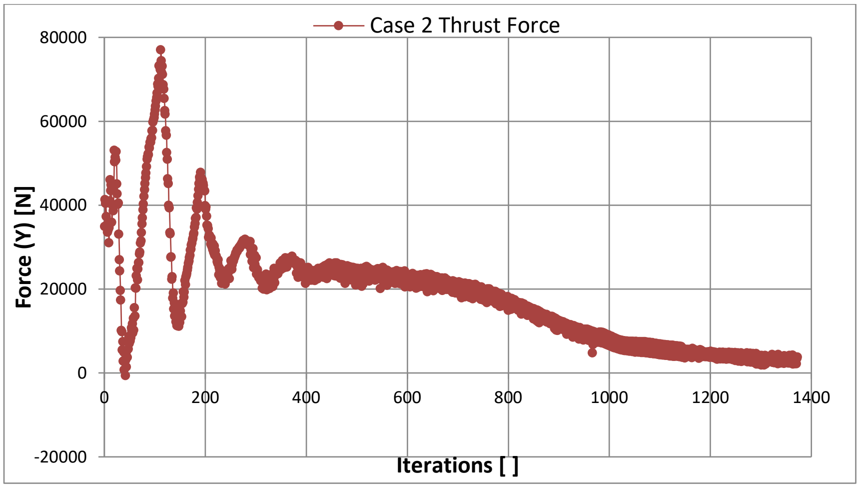

Figure 10. Thrust Force Graph for Combination 2

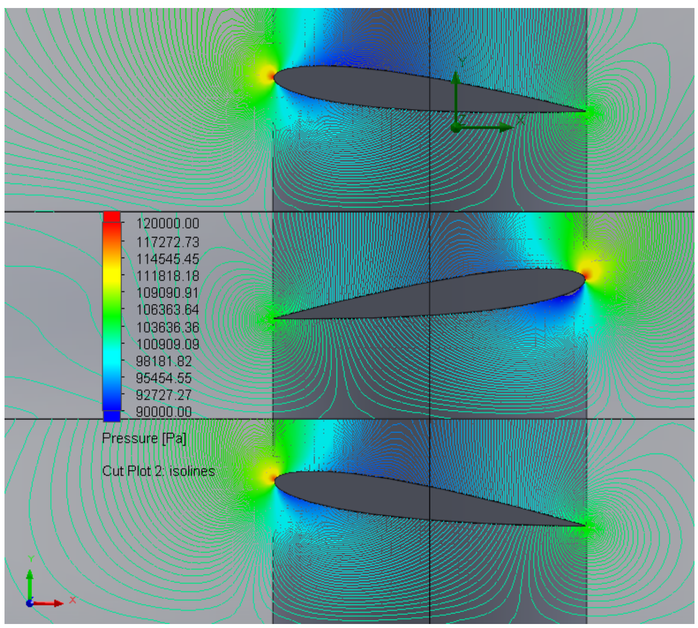

Figure 11. Case 2-Pressure details

Pressure distribution results (Figure 11) are in support of the data in Table 4. The first and third propellers gave sufficient performance to take-off. On the other hand, contrary to the first propeller, the second propeller produced negative results. It barely gave effect on thrust.

Case 3

In the third case, the same angle was given to the second and third propeller to understand better the relation between these two propellers. The values of the blade angles are 4°, 7° and 7°, respectively. In contrast to the first two examples, in combination 3 the third propeller created a considerable amount of negative lift. As a result, sufficient thrust force could not be obtained. Thrust force results can be seen in Table 5 and Figure 12.

Table 5. Numerical Results of the Combination 3

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence
Total Force	[N]	2320.444	3093.692	1147.437	4731.139	100	Yes
Rotor 1	[N]	1634.189	1497.478	1277.703	1658.68	100	Yes
Rotor 2	[N]	1770.866	1386.072	417.129	2380.37	100	Yes
Rotor 3	[N]	-1098.9	201.509	-1275.069	1124.261	100	Yes

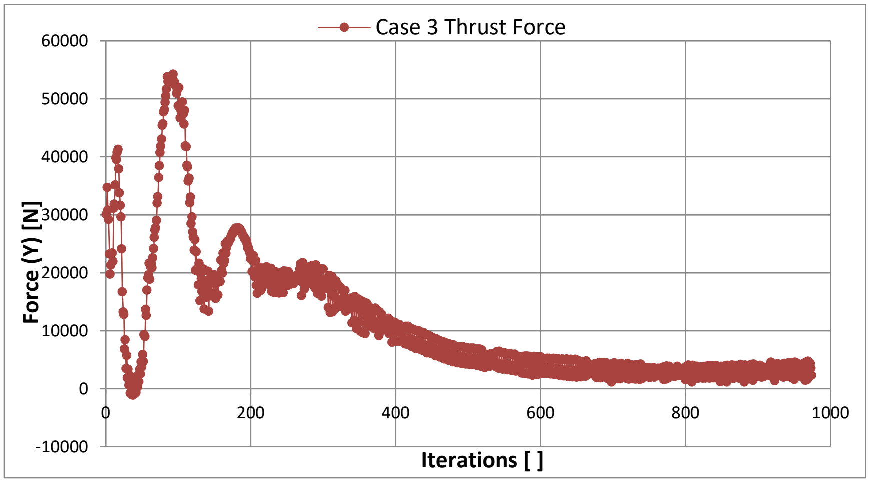

Figure 12. Thrust Force Graph for Combination 3

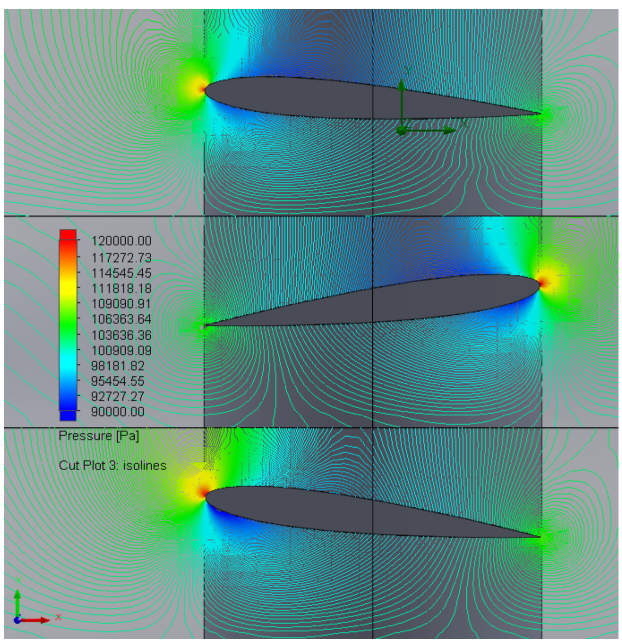

Figure 13. Case 3-Pressure details

Pressure results clarified that the first and second propellers are creating lifting force. But, as seen in Figure 13, the third propeller has overpressure the upstream. Still, the first and second propellers worked in harmony and created positive thrust.

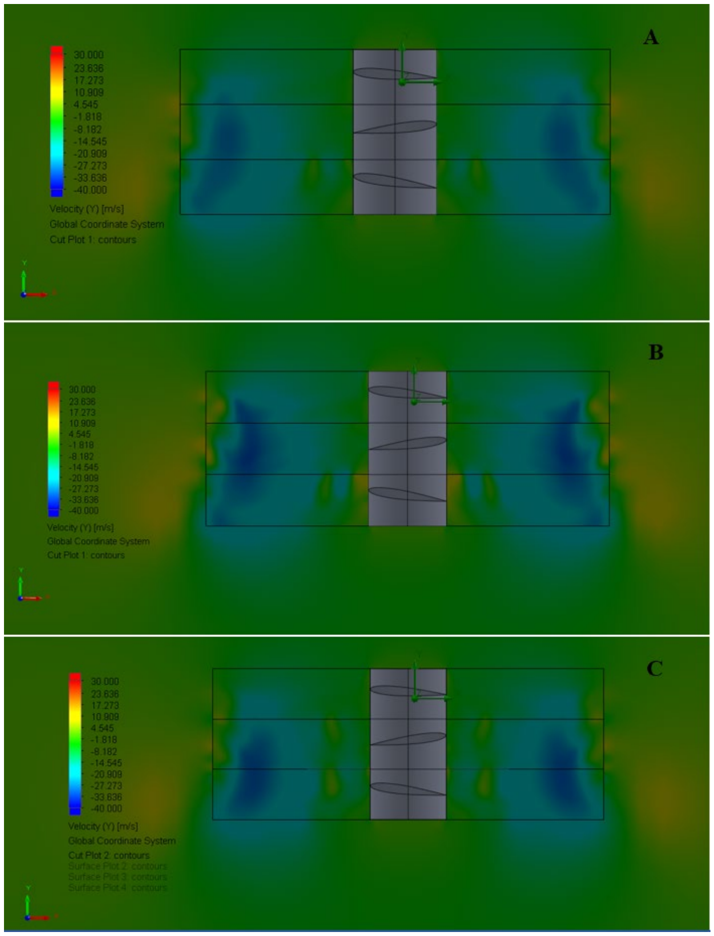

Figure 14. Velocity Flow Results for A) Combination 1, B) Combination 2 and C) Combination 3

As seen from the pictures represents flow velocity, the first rotor always gives positive thrust. However, the second and third propellers can produce variable results in most cases. As seen in Figure 14, among the three different combinations operating under the same conditions, combination 1 produced the highest speed.

6. Conclusion

This paper describes the results obtained from three different combinations that we have analyzed in a simulation environment with proven accuracy. An increase in the pitch angles of the blades from the top to the bottom will increase the operating efficiency of the propeller. On the other hand, the results of a few other configurations indicate that one of the rotors may be either inefficient or subtracting the power and lift. This depends on the combinations of the pitch angles of the three rotors. This fact, in addition to the mechanical complications of three rotors, the variable-pitch hub makes the three rotors propeller critical. In any case, further analyses are required.

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Biography

Merve Sali is a Ph.D. Student of the Department of Industrial Engineering, at Alma Mater Studiorum University of Bologna. Merve is involved in Generative Design and Stylistic Design Engineering studies.