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DESIGN, ANALYSIS AND FABRICATION OF A FULLY ARTICULATED HELICOPTER MAIN ROTOR SYSTEM

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ABSTRACT: *This study describes an integrated framework in which the basic elements of Aerospace Engineering (performance, aerodynamics and structure) and functional elements (suspension, visibility and production) are integrated and considered. In this study, a fully functional rotor system has been fabricated that can be used as one of the training resources for Aeronautical students. For making the rotor system, various parts of the system have been designed on Solidworks and complete mechanism has been simulated with ANSYS. System analysis has been done at various RPM's and Angles of Attack (AOA). In terms of merit the right items have been selected and processed to provide them with the right shape. In terms of the design and implementation, various machines such as gas welding, arc welding, CNC milling and radial machinery have been used. Certain parts such as electric motors, linear actuators and loading cells have been used. All the fabricated components and electric motor, actuator, load cells are then assembled. This rotor system can produce less lift due to high dead weight and low power motor and having some safety issues*.

KEYWORDS: rotor mechanism, fabrication, force calculation, simulation, appropriate material design

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INTRODUCTION

Rotor mechanism is the most vital mechanism for any helicopter. Rotor system as a whole helps the helicopter to take off, land and stay still in the air [1]. A helicopter main rotor or rotor system is the multitude of several rotary rotor blades and a control system that propagates the aerodynamic lift force that supports the weight of the helicopter, and the thrust that obviates aerodynamic drag in forward flight [2]. The helicopter rotor is powered by the engine, through the dispatch, to the rotating mast. In this experiment, we have focused on designing and building a fully functional basic rotor system of a helicopter [3-5]. Basically the main objective of this experiment is to find out and understand the functions of a rotor system practically and to motivate the students studying in this field of engineering.

The construction of the rotor system is divided into two parts-designing and fabrication. For designing various parts of the rotor system, we have used Solidworks as the main designing software [6]. Before going into the fabrication process, we have simulated the whole system on ANSYS software to find out its functionality and shortcomings [7].

After a successful simulation, the fabrication process started. For fabrication, we had to choose appropriate materials and process them. Then we had to cut them according to our design to provide them with proper shapes. To fabricate our designed parts, we have used gas welding, arc welding, CNC milling, radial drilling, grinding and lathe machines [8-9]. Apart from the designed parts, we have purchased electric motor, linear actuator and load cells for running the rotor system [10]. After full fabrication, all the fabricated components were assembled with the purchased components. The load cells are mainly used for displaying our experimental forces like lift, thrust and pitch angle.

Apart from the functionality, we have analyzed the mechanism of our rotor system through CFD. One of the main purposes of this experiment is to change the pitch and angle of attack of the blades together and find out the values of lift generated for those conditions respectively [11-12]. We have calculated the theoretical values and collected the practical values and established a comparison between them in this study.

Design analysis and fabrication of a helicopter main rotor system has been investigated in the following articles. Using ice protection system, Flemming et al. [13] investigated the helicopter rotor dynamics. Brown and William [14] studied experiments involving a microwave beam to power and position a helicopter. Scapinello [15], through composite materials applications investigated helicopter rotor used materials. Potter [16] applied an experimental study to identify improving reliability and eliminating maintenance with elastomeric dampers for rotor systems. In another work, Cohen et al. [17] studied a design study of a scale model bearingless helicopter rotor system using composite materials. Mouille [18] performed an experimental study of design philosophy for helicopter rotor heads. Kim et al. [19] investigated modelling of the aerodynamics of coaxial helicopters–from an isolated rotor to a complete aircraft. Fulmer et al [20] studied design of a helicopter hover test stand. Cansdale [21] studied aeroelastic model helicopter rotor. Shin et al. [22] investigated design, manufacturing, and testing of an active twist rotor.

The lift produced by our rotor system was less due to high dead weight and less powerful motor. With better materials and more powerful motor the efficiency of the rotor system and the amount of lift produced by it can be developed significantly.

This manuscript contains the full details about our design, modelling, simulation, final output and comparison between theoretical and practical values of generated lift.

DESIGN AND FABRICATION

Upper swash plate

The upper swash plate connects to the rotor shaft, through special linkages. As the motor engine turns the rotor shaft, it also turns the upper swash plate and the rotor blade system. Furthermore, system provides blade grips, which integrate the blades to a hub.

The structure of upper swash plate is fabricated using mild steel of 124.69mm outer diameter and 88mm inner diameter along with 15mm depth. It required material turning, facing and sanding using lathe machine height. Weight factor has been kept under consideration.

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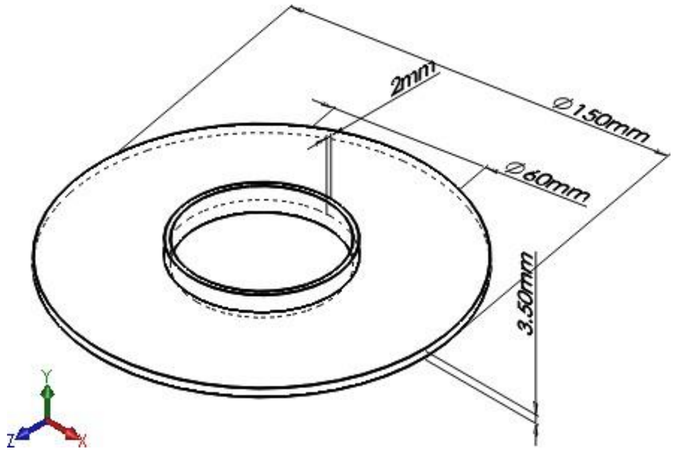

(a)

(b)

(c)

Fig. 1. (a) 3D view of upper swash plate; (b), (c) Fabrication process of upper swash plate.

Lower swash plate

The rotating (upper) swashplate is mounted to the stationary (lower) swashplate by means of a bearing and is allowed to rotate with the main rotor mast. An anti-rotation link prevents the lower swash plate from rotating independently of the blades, which would apply torque to the actuators. The upper swashplate typically has an anti-rotation slider as well to prevent it from rotating. Both swashplates regard as one unit.

The structure of lower swash plate is fabricated using mild steel of 150mm outer diameter and 78mm inner diameter and with a height of 15mm. It required material turning, facing and sanding using lathe machine. Weight factor has been kept under consideration.

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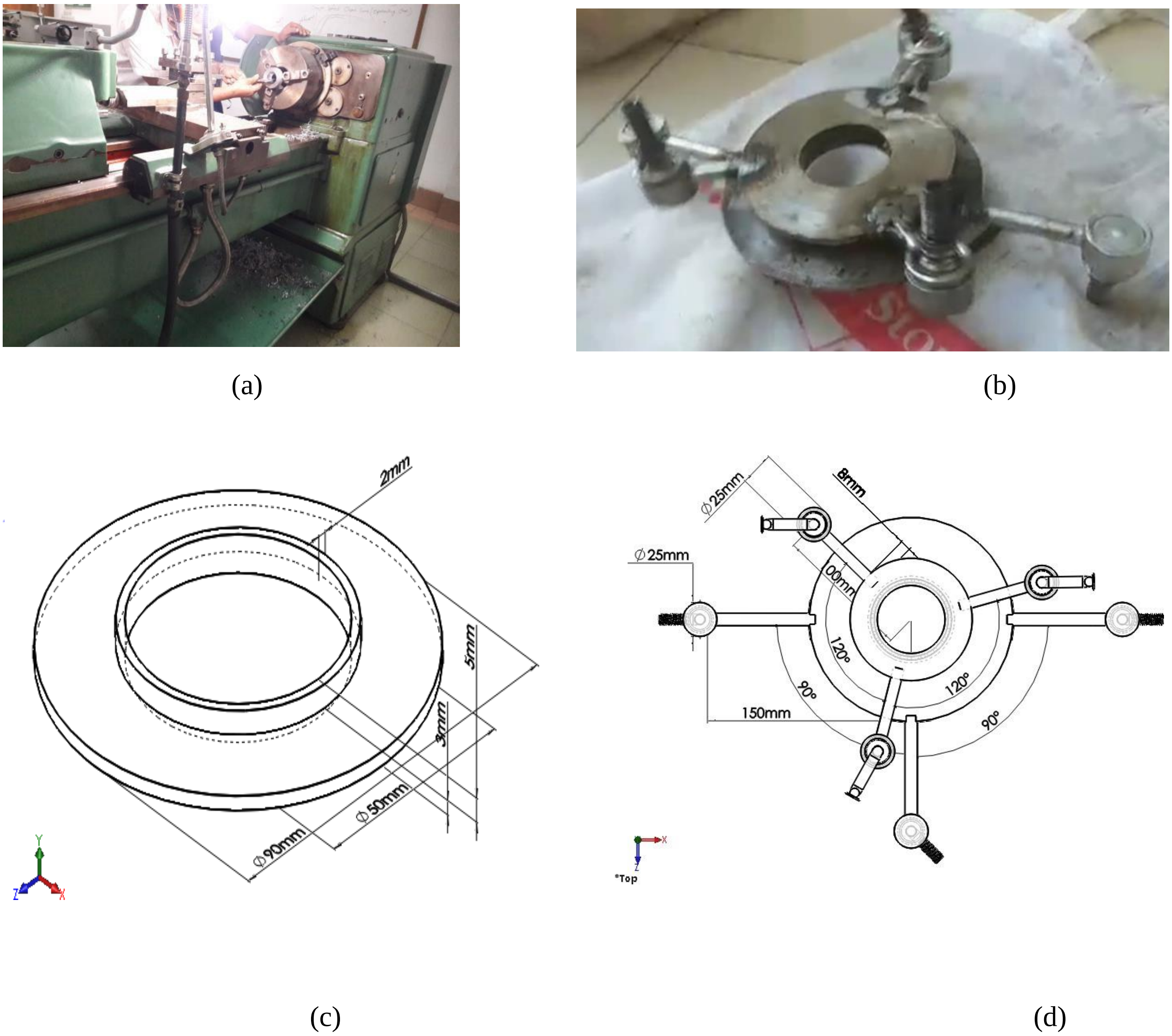

Fig. 2. (a), (b) Fabrication Process of lower Swash Plate; (c) 3D view of lower swash plate, (d) Swash plate assembly (top view).

Shaft

A shaft is regard as revolving machine equipment, usually circular in cross section, which is used to distribute power from one part to another, or from a machine which produces power to a machine which absorbs power. On the other hand, many members, for instance, pulleys and gears are mounted on it.

A hollow cylinder shaft is brought of 330mm length and with a diameter of 18mm. The material used is mild steel, and again weight factor has been kept under consideration

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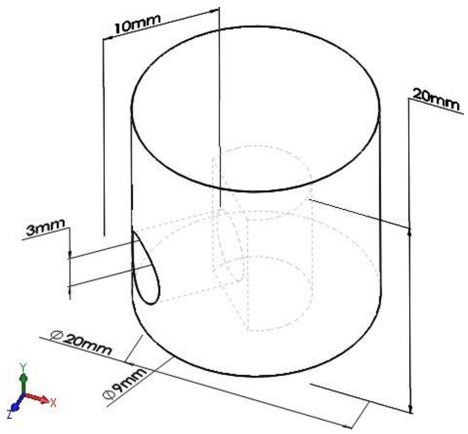
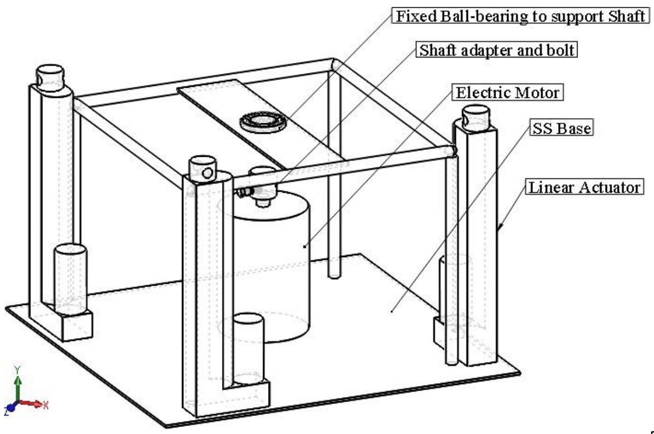


(a) (b)

Fig. 3. (a) 3D view of Shaft, (b) Fabrication Process of Shaft.

Motor base

An electric motor is known as electrical machine that regulates electrical energy into mechanical energy. Most electric motors work through the combination between the motor's magnetic field and electric current in a wire winding to produce force in the form of shaft-rotation. Electric motors can be employed by direct current (DC) sources, for instance, from batteries, motor vehicles or rectifiers, or by alternating current (AC) sources, such as a power grid, inverters or electrical generators. An electric generator is mechanically congruent to an electric motor, but works in the opposite direction, converting mechanical energy into electrical energy. Motor Bases



are fabricated of mild steel which offers a base of motor. The structure of motor base is fabricated using available. Mild steel of length 250mm width 180mm and height 3mm. It required material cutting, fitting and welding. Weight factor has been kept under consideration.

(a) (b)

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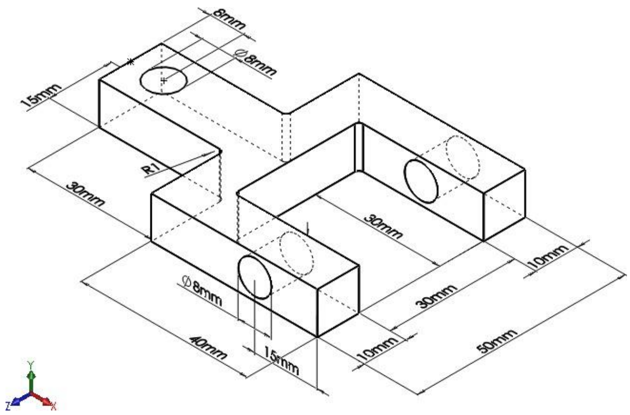
Fig. 4. (a) 3D view of motor base, (b) Fabrication Process of motor base.

Articular joint

The structure of articular joints is fabricated using available mild steel. It required material cutting, drilling. It is fabricated in CNC machine. Weight factor has been kept under consideration.

(a)



(b)

Fig. 5. (a) Fabrication process of Articular Joint, (b) 3D view of Articular Joint.

Rotor blade

The structure of fuselage is fabricated using mild steel and wood. It required material cutting, fitting, riveting and welding. Blade ribs are given proper airfoil shape while spars are made of steel of I-section. The whole structure is covered with aluminum sheet with the use of rivet gun. Also, the weight factor has been kept under consideration.

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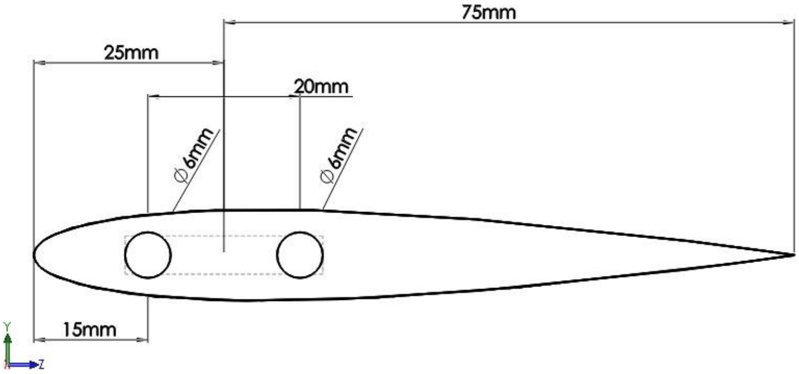
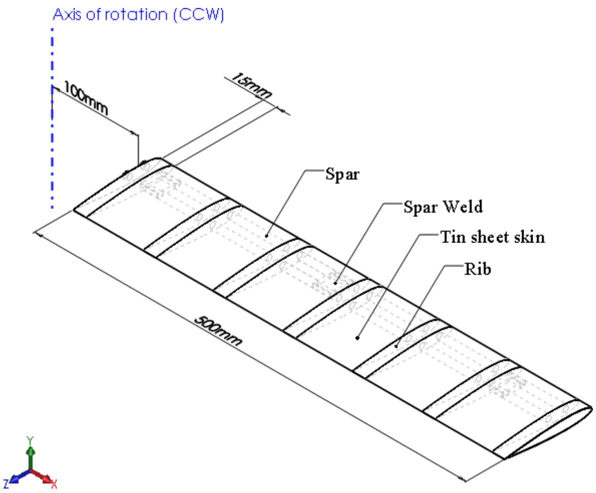
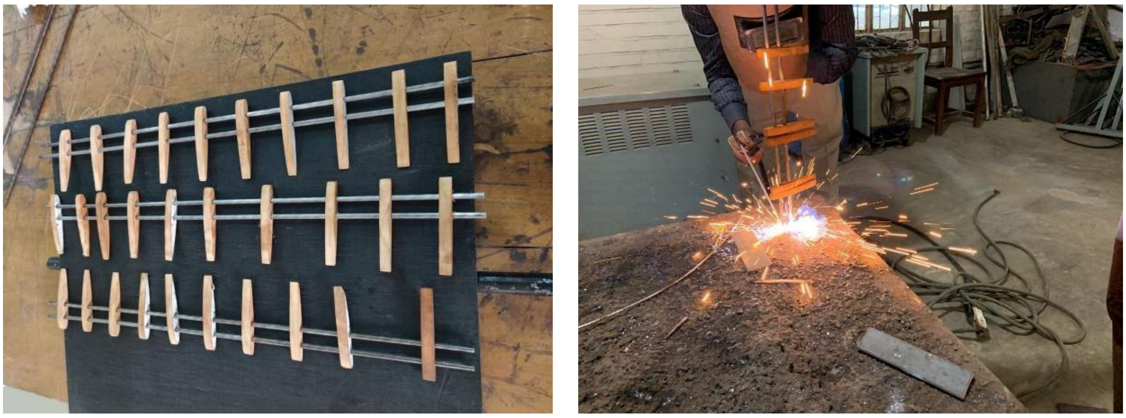


(a)



(b)



(c)

Fig. 6. (a) Front view of blade, (b) 3D view of blade, (c) Fabrication Process of blade.

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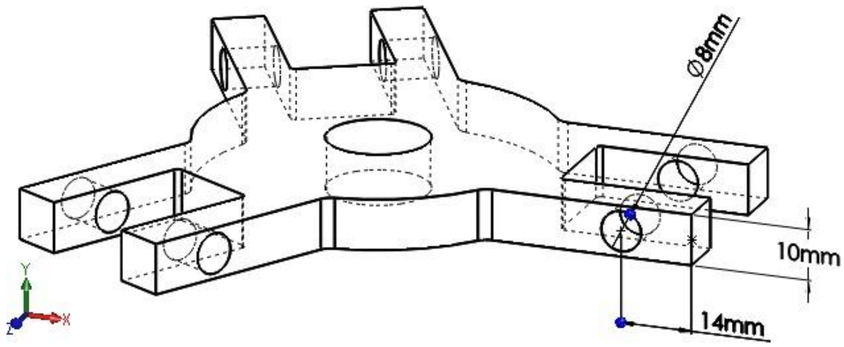
Rotor hub

The structure of rotor hub is fabricated using mild steel of 70mm diameter and 3 pairs of 35mm tooth length and with a height of 17mm. It required material cutting, drilling and is fabricated in CNC machine and drilled using drilling machine. Weight factor has been kept under consideration.



(a)

(b)

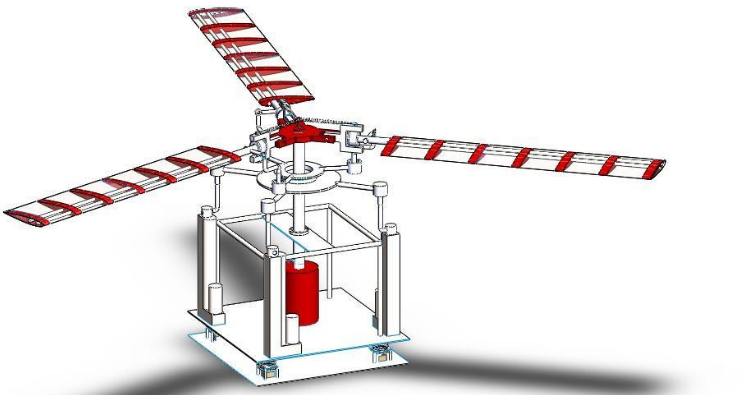
Fig. 7. (a) 3D view of Rotor hub, (b) Fabrication process of Rotor hub.

Final assembly

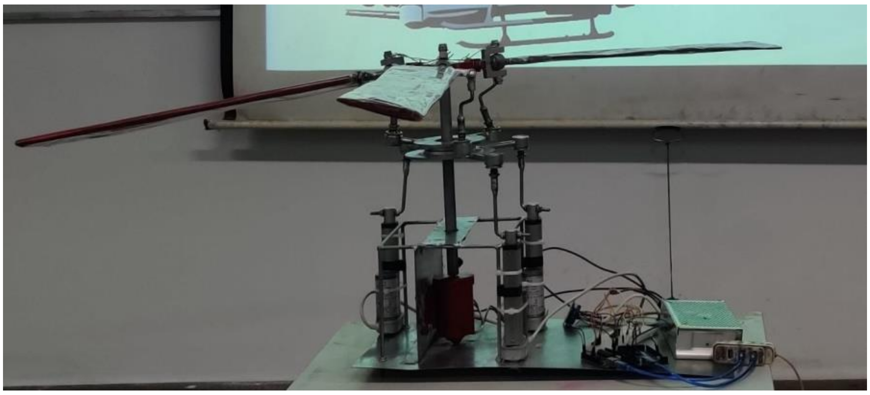
After accomplishing final assembly of all rotor components, the systems are inspected. Assuring safety and airworthy condition, the rotor was set for the following functions-

- To change pitch and angle of attack of blades together.
- To use it for demonstrating basic movements of the rotor blades.
- Forces generated due to various movement of the rotor blades are calculated.

- To measure the lift generated for different rpms and angle of attacks (AOA).



(a)



(b)

Fig. 8. (a) 3D view of Final assembly, (b) Fabrication process of Final assembly.

Detail design
Blade Data

$\mu = 0.4$

$R = 10.11$ m

$c = 0.463$ m

$m = 12.045$ kg/m CT /$\sigma = 0.069$

rotor disk angle of attack $\alpha s = 13^0$

Airfoil section (NACA 0012) characteristics:

$$\text{for } \alpha_0 = 0^\circ$$

$$C_L = \left\{ \begin{array}{c} 6.25 \\ \text{for } |\alpha| < \alpha_{\text{stall}} = 13^\circ \\ 1.1 \sin 2(\alpha - \alpha_0) \\ \text{for } |\alpha| < \alpha_{\text{stall}} = 13^\circ \end{array} \right\}$$

$$C_D = \left\{ \begin{array}{c} 0.006 + 0.005 C_L^2 \\ \text{for } |\alpha| < \alpha_{\text{stall}} = 13^\circ \\ 1.135 - 1.05 \cos 2(\alpha - \alpha_0) \\ \text{forl } \alpha \; |< \alpha_{\text{stall}} = 13^\circ \end{array} \right\}$$

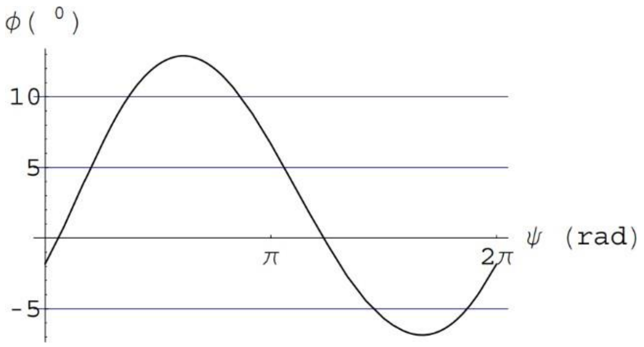


Fig. 9.1. Flapping response.

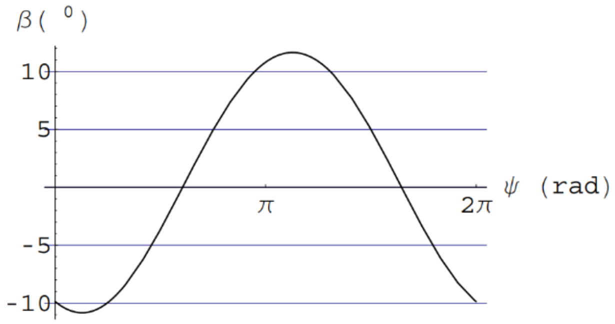


Fig. 9.2. Induced inflow angle of attack.

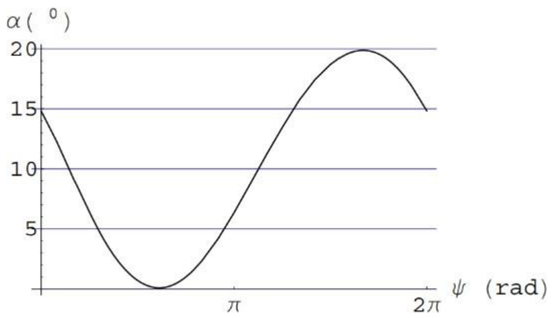


Fig. 10.1. Total effective angle of attack.

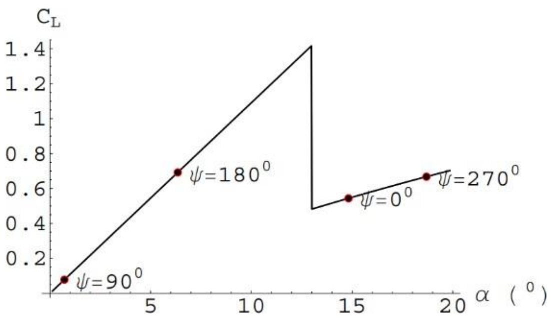


Fig. 10.2. Lift coefficient.

We can conclude (from Fig.17-20) that for an identical flow model and collective pitch θ_0 input the tiny the tiny holds sensible. There forager it's shown that the tiny flap angle formulation will result in inaccurate predictions within the flap response. Then the validity of the tiny elicited flow angle of attack assumption is investigated in varied flight regimes and it's seen that in several traditional modes of chopper flight the idea are often created however in bound superior operations it's not correct. Therefore, it's higher to assume that the flap angle β and flow angle φ area unit massive angles in chopper dynamics.

Airfoil selection

"NACA-0012" was selected as cross section of the blade because of its smooth curve of CL vs alpha and high stall angle and optimum thickness.

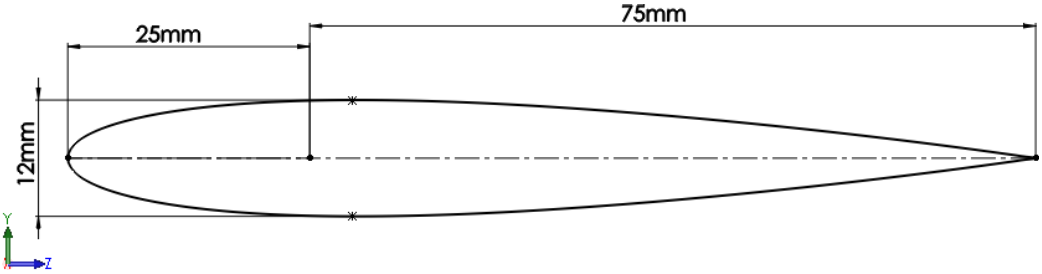
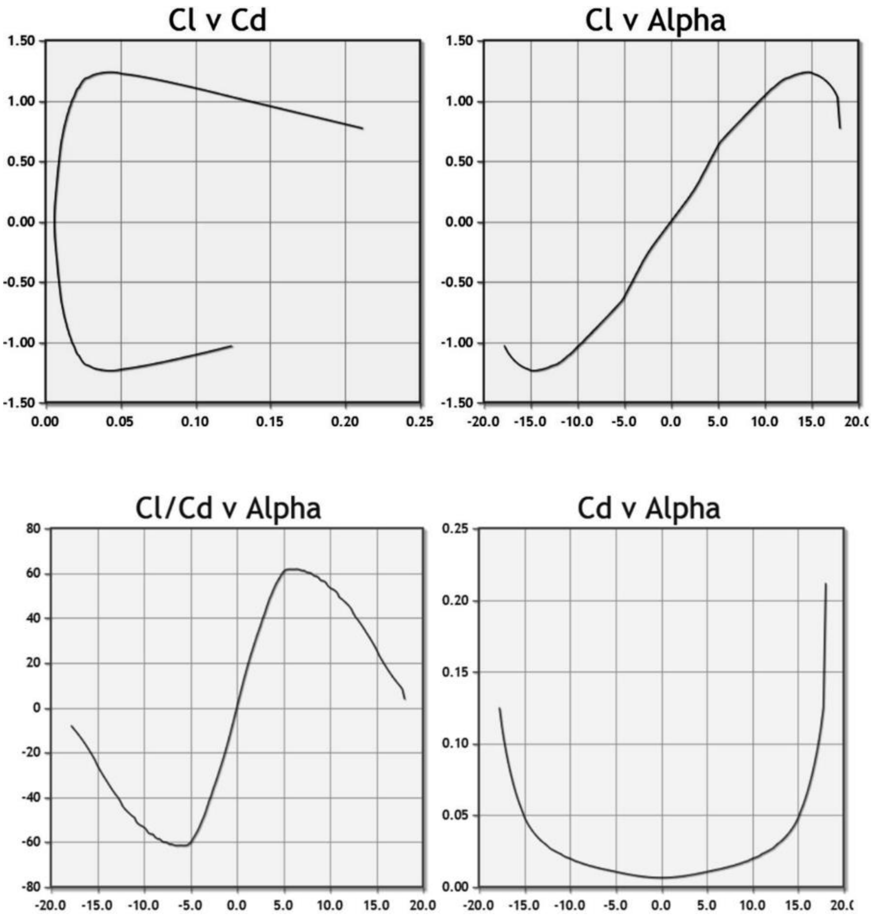


Fig. 11.1. Airfoil NACA-0012.

Chord length: 100mm = 0.1m

Aerodynamic Chord: 25% of chord = 25mm

Max Cl/Cd: 61.7 at α=6.5° with Reynolds no. 500,000, Stall angle: 15° (approx.)



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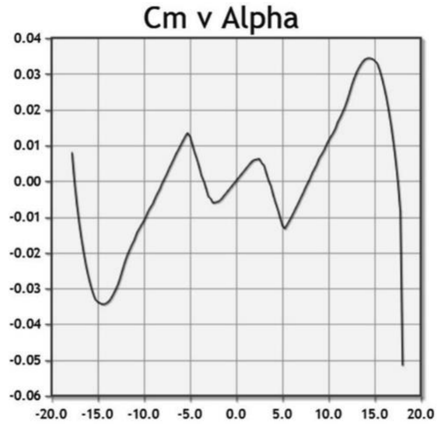

Fig. 11.2. Charts of aerodynamic properties of NACA-0012 at Reynolds no. 500,000.

Blade sizing

The very first step of our design is to determine the dimension of the rotor blade of the rotor mechanism. This part is done by following various design approach of RC helicopter blades.

The primary assumption of the dimension for the blade is, Disc radius = Blade span = R = 0.5m

Blade Chord = C = 0.1m N = Number of blades

From Blade elementary theory,

Solidity Factor, $\sigma = \frac{\text{Blade Area}}{\text{Disc Area}} = \frac{N \times C}{\pi \times R}$

Now, For 3 Blade, N = 3, Solidity Factor, $\sigma = \frac{3 \times 0.\mathbf{1}}{\pi \times \mathbf{0.5}} = 0.191$

Again, For 2 Blade, N = 2, Solidity Factor, $\sigma = \frac{2 \times 0.\mathbf{1}}{\pi \times \mathbf{0.5}} = 0.127$

Lift curve slope,

$$\mathrm{a} = \frac{\mathrm{a}_0}{1 + \frac{\mathrm{a}_0}{\pi \times \mathrm{e} \times \mathrm{AR}}}$$

Here, a_0= First term in Fourier series = 2 π/ rad E = Oswald Efficiency Factor = 0.9 AR = aspect ratio = R/C = 0.5/0.1 = 5 So, Lift Curve slope,

$$\mathrm{a} = \frac{2\pi/\mathrm{rad}}{1 + \frac{2\pi/\mathrm{rad}}{\pi \times 0.9 \times 5}} = 4.34/\mathrm{rad}$$

Now, Flapping Frequency, $\lambda = \frac{\sigma \times a}{16}\left[\sqrt{\left(\frac{64 \times \theta}{3 \times \sigma \times a} + 1\right)} - 1\right]$; Here, θ = Pitch angle of the blade varies from 0-12^0

Angular velocity for the rotor blade,

$$\omega = \frac{2 \times \pi \times \mathrm{N}}{60}$$

And blade tip velocity,

$$V_{\mathrm{T}} = 0.5 \times \omega$$

coefficient of thrust

$$\mathrm{C_T} = 4\lambda^2$$

Thrust,

$$\mathrm{T} = 0.5 \times \rho \times \mathrm{V_T^2} \times \mathrm{A} \times \mathrm{C_T}$$

Here,

Density of Air, ρ=1.225 kg/m^3 Area = 0.7853981634 m^2

Coefficient of power,

$$C_P = 4\lambda^3$$

Power,

$$P = 0.5 \times \rho \times V_T{}^3 \times A \times C_P$$

Here,

Density of Air, ρ=1.225 kg/m^3

Area = 0.7853981634 m^2

CFD validation

Computational Fluid Dynamics (CFD) may be a powerful tool that is employed extensively in mechanic's applications. It includes machine solutions to the governing Navier-Stokes Equations throughout the flow region. the tactic provides the chance to simulate and analyze complicated issues while not losing the integrity of the matter because of simplified flow models. Vertical begin and landing capabilities area unit essential properties for helicopters or UAVs. Current mathematical models employed in Saab area unit trivial within the sort of propeller disc models and blade component theory.

In this paper, Associate in Nursing analysis in machine fluid dynamics (CFD) is bestowed on a chopper scale model with concentrate on the main-rotor blades. The chopper model's main-rotor blades are encapsulated during a background region and also the flow field is solved exploitation Ansys Fluent. A surface and volume mesh time were generated that contained just about a pair of, 716,385 tetrahedral cells (binary), 476,881 nodes (binary) wherever the Finite Volume methodology (FVM) was chosen as a discretization technique.

Hover and forward cases were examined. Hover flight cases were done by ever-changing all the blades collective pitch angle (θ0). Forward flight cases were done by solely ever-changing the axis of rotation angle of attack (αs) and therefore the collective pitch angle (θ0) at the heavier-than-air craft free stream Mach number of M= zero.185, while not the inclusion of a cyclic pitch motion. Cyclic pitch motion wasn't examined during this analysis.

In conclusion this shows that applying straightforward rotating zone condition with stationary blades to investigate the main-rotor blades victimization CFD will work with a small variation from mathematical results. However, applying overset meshes on blades adding a cyclic pitch motion (θ0, αs area unit present) will with success take away the roll and pitching moment from the results.

CAD modeling

The 3D blade of uniform cross section of Airfoil NACA-0012 was generated using SolidWorks and the domain was created in Ansys Design Modeler. The model includes three blades with zero twist angle and has conjointly a collective and cyclic pitch management, which might be altered mistreatment the intrinsically swash plate. additionally, the model didn't embody a vertical stabilizer and a rotor.

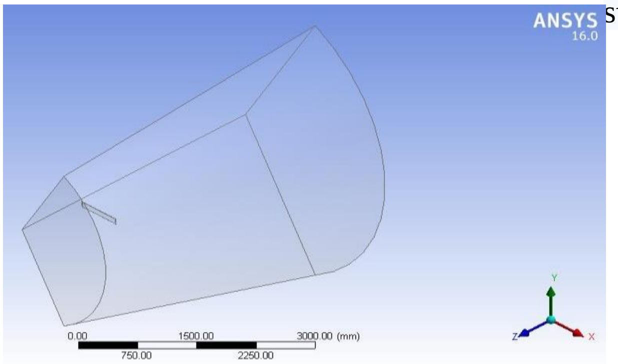

Fig. 12.1. Domain in PBC method.

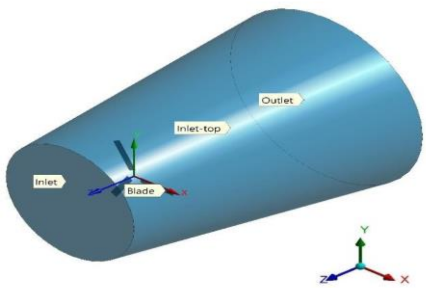

Fig. 12.2. Domain in cylindrical method.

Here,

Blade radius = r = 0.5 m = 500mm, Inlet distance from blade = 2r, Outlet distance from blade = 6r, Inlet radius = 3r.

Outlet radius = 5r, Periodic offset angle = 120°, Rotation is about Z axis

Meshing

It is generally advised to keep the minimum orthogonality greater than 0.15 and maximum skewness lower than 0.95. Having bad cells or elements can lead to incorrect simulation results.

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However, these are general guide rules and depend on the physics solved or where the cells are located.

Table 1. The quality of the mesh.

Method	Mesh metrics	Min	Max	Avg	Standard Deviation
Periodic Boundary Condition	Skewness	7.398e-006	0.9104	0.21911	0.12711
	Orthogonal quality	6.0798e-004	0.99974	0.85324	0.13333
	Aspect ratio	1.1592	5329.	80.541	349.02
	Skewness	1.3236e-004	0.89903	0.22963	0.12203
Cylindrical Domain	Orthogonal quality	0.2231	0.99631	0.86024	8.5651e-002
	Aspect ratio	1.1654	10.809	1.8407	0.46848

DISCUSSIONS

a. Main results: Flight simulations in hover mode
Calculations: Blade length = 500 mm, No of blades=3

Table 2. Flight simulations in hover mode.

θ	θ in Radian	σ	a	Lambda	RPM	Omega	Tip Velocity	Ct
5	0.0872	0.1909	4.349	0.0415	50	5.235	2.617	0.0069

Cp	Thrust	Power	Power in Hp
0.000286963	0.022770386	0.059612732	7.98029E-05

CFD results:

Table 3. Viscous Model: Spalart-Allmaras (1 equation).

θ	RPM		Tip Velocity	Thrust On blade	Thrust on plane below blades (100mm)	Torque
5	50		3.58 m/s	0.0522478 [N]	0.019456 [N]	0.0079284 [N m]

Table 4. Viscous Model: K-omega (2 equations).

θ	RPM	Tip Velocity (In standard frame)	Thrust On blade	Thrust on plane below blades (100mm)	Torque
5	50	3.65 m/s	0.0645128 [N]	0.0248902 [N]	0.00137146 [N m]

Table 5. Viscous Model: K-epsilon (2 equations).

θ	RPM	Tip Velocity (In standard frame)	Thrust On blade	Thrust on plane below blades (100mm)	Torque
5	50	3.16 m/s	0.0535734 [N]	0.020338 [N]	0.0069038 [N m]

In this study, we have a built a fully functional rotor system. Blade length of the rotor is 500 mm and no of blades is 3. There are two portions of our calculation. One is flight simulation in hover mode and the other is CFD results based on 3 viscous models. The values taken from the actual working rotor have been calculated here and a CFD calculation using 3 equations is also taken. For every case θ is 5° which is 0.0872 in Radian and RPM is 50.

In hover mode, C_p is 0.000286963, tip velocity is 2.617 m/s, thrust is 0.022770386 N, power is 0.059612732 and power in HP is 7.98029E-05. These tip velocity, thrust and power are less than the CFD results.

Comparing the CFD results, it has been found that for 1 equation, tip velocity is 3.58 m/s which is less than the tip velocity of K-omega 2 equations and greater than K-epsilon 2 equations. Thrust for 1 equation is 0.0522478 N which is less than both 2 equations result. Torque calculated for 1 equation is 0.0079284 Nm which is greater than both 2 equations result.

For K-omega 2 equations, tip velocity is 3.65 m/s which is greater both 1 equation and K-epsilon 2 equations result. Thrust calculated is 0.0645128 N which is greater than both 1 equation and K-epsilon 2 equations result. Torque calculated is 0.00137146 Nm which is less than both the other cases.

For K-epsilon 2 equations, tip velocity is 3.16 m/s which is less than both 1 equation and K-omega 2 equations result. Thrust calculated is 0.0535734 N which is greater than 1 equation but less than K-omega 2 equations result. Torque calculated is 0.0069038 Nm which is less than 1 equation result but greater than K-omega 2 equations result. There were certain limitations in fabrication of the rotor mechanism.

As finalizing the design and understanding the blade momentum theory took much time, we had to fabricate the rotor mechanism in shortest possible time. Due to shortage of material availability we had to choose the material that was already prepared at the market. Due to lack of proper machinery like 3D printer we had to choose random cutting machine. The rotor blade performance would have been much better if the blade airfoil material was balsa wood instead of furniture wood. Due to lack of funding used motor was purchased for our fabrication. For further development of this project some improvements can be done.

Composite material can be used instead of mild still. Balsa wood can also be used for airfoil. To further increase the lift and overall performance a better motor and better battery can be used. Further development like tail rotor mechanism and other parts of a helicopter can also be built.

CONCLUSIONS

This paper presents designing and fabrication process of a basic helicopter rotor mechanism.

- The process started with understanding the basic helicopter mechanism.
- After understanding the basic theory, we started to learn about different joints and different mechanisms. Like the swash plate mechanism, blade mechanism, articular joint, hub mechanism.
- We also studied about the different machining technique like CNC machining, lathe machining, uses of vice.
- After understanding all those we started to design the whole machine.
- We started to build small parts and after manufacturing all those parts we started to assemble it.
- We studied both practical result and result we found through simulation and compared them in this study.
- This study is basically for understanding the different joints that are used in rotor and the different motion that the helicopter blade used like flapping motion, pitch up or down motion and feathering motion.

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