Final Report

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Title: Design, simulation and manufacturing of Aircraft Engine and Propeller

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1. Abstract

In this project, we have designed and optimized an aircraft Engine and propeller for commercial lightweight aircrafts like Cessna 172S.The parts were designed and assembled in Catia software and a kinematic simulation is performed in DMU kinematics environment. Several calculations are done to obtain some important parameters both for the engine and the propeller to make sure they meet our design requirements. several simulations are performed in Solidworks flow simulation environment to illustrate the performance and behavior of the propeller in different conditions.

2. Project Description

The project begins with a detailed design phase using CATIA software, where we created and assembled 3D models of the engine and propeller components. The engine design includes critical parts such as pistons, connecting rods, crankshaft, and engine block, all engineered to balance power output with efficiency. For the propeller, we designed the blade geometry and hub assembly to optimize aerodynamic performance and thrust generation.

Once the initial designs were completed, we performed a kinematic simulation in CATIA's DMU kinematics environment to ensure proper movement and alignment of the engine components. This was followed by detailed calculations to determine the engine's power output, using parameters like displacement, bore, stroke, and engine speed. We computed the Indicated Mean Effective Pressure (IMEP) and actual power output to ensure they meet the required performance metrics.

For the propeller, we used SolidWorks Flow Simulation to analyze its performance under different operating conditions. This involved calculating the advance ratio, propeller efficiency, and other key parameters like thrust, coefficient of thrust, and coefficient of power. We assessed whether the engine could produce sufficient power to drive the propeller effectively and iterated on design adjustments to achieve the desired performance.

The project also includes developing a comprehensive manufacturing plan for both the engine and propeller. We selected aluminum alloy for the propeller due to its balance of weight, strength, and cost-effectiveness, and outlined the manufacturing process, including material preparation, forging or casting, machining, heat treatment, balancing, and surface treatment. For the connecting rod, we chose AISI

4340 steel for its high strength and durability, and detailed the steps for forging, heat treatment, and machining.

Overall, this project integrates design, simulation, and manufacturing processes to produce a high-performance engine and propeller system optimized for lightweight commercial aircraft, ensuring efficiency, reliability, and cost-effectiveness.

3. Engineering Calculations

Calculations for the Engine

First, we have to determine the power produced by our Engine by including calculating some parameters like displacement of volume (V_d), Bore (D), Stroke(S), Number of cylinders(N), Engine speed, mean effective pressure (P_m) and mechanical efficiency (η).
The Indicated Mean Effective Pressure (IMEP) for our engine is approximately 185 Kpa and mechanical efficiency is 90%.

$V_d = N \times \frac{\pi}{4} \times D^2 \times S$=4*π/4*0.13^2*0.11=0.0059 m^3

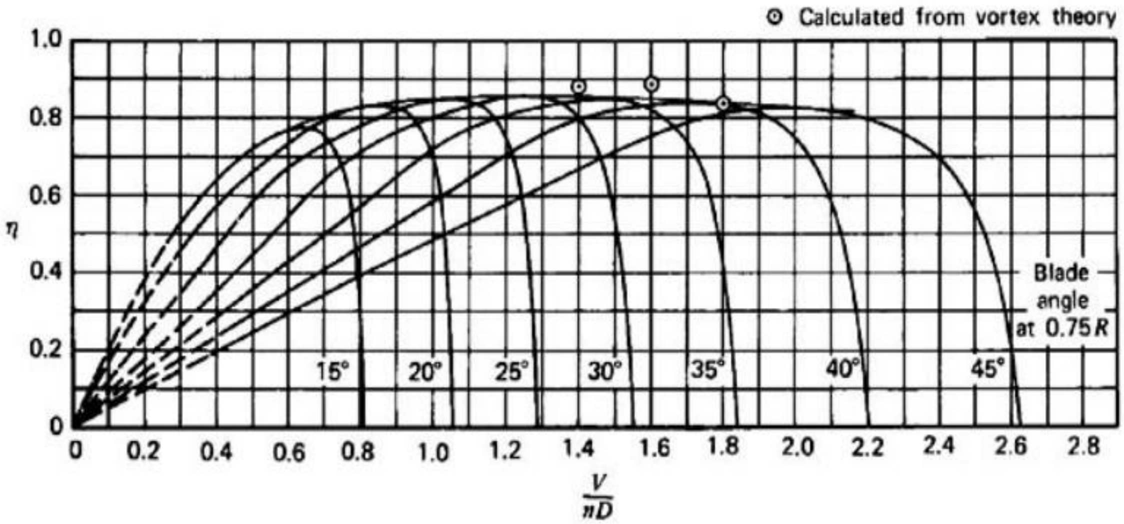
P_m=$\frac{IMEP*60}{2*pi*V_d*RPM}$=$\frac{185000*60}{2*3.14*0.0059*2000}$=149713watt=201Hp

The actual Power (P)=201*0.9=180hp

Calculations for the Propeller

The advance ratio (J) is a dimensionless parameter that describes the relationship between the forward speed of an aircraft and the rotational speed of its propeller, which is obtained by the formula below:
n=2000 rpm=33.3 rps
J=$\frac{V}{n \times D}$=$\frac{76}{33.3*2.07}$=1.1

Now that we have identified the advance ratio, we can determine the propeller efficiency.



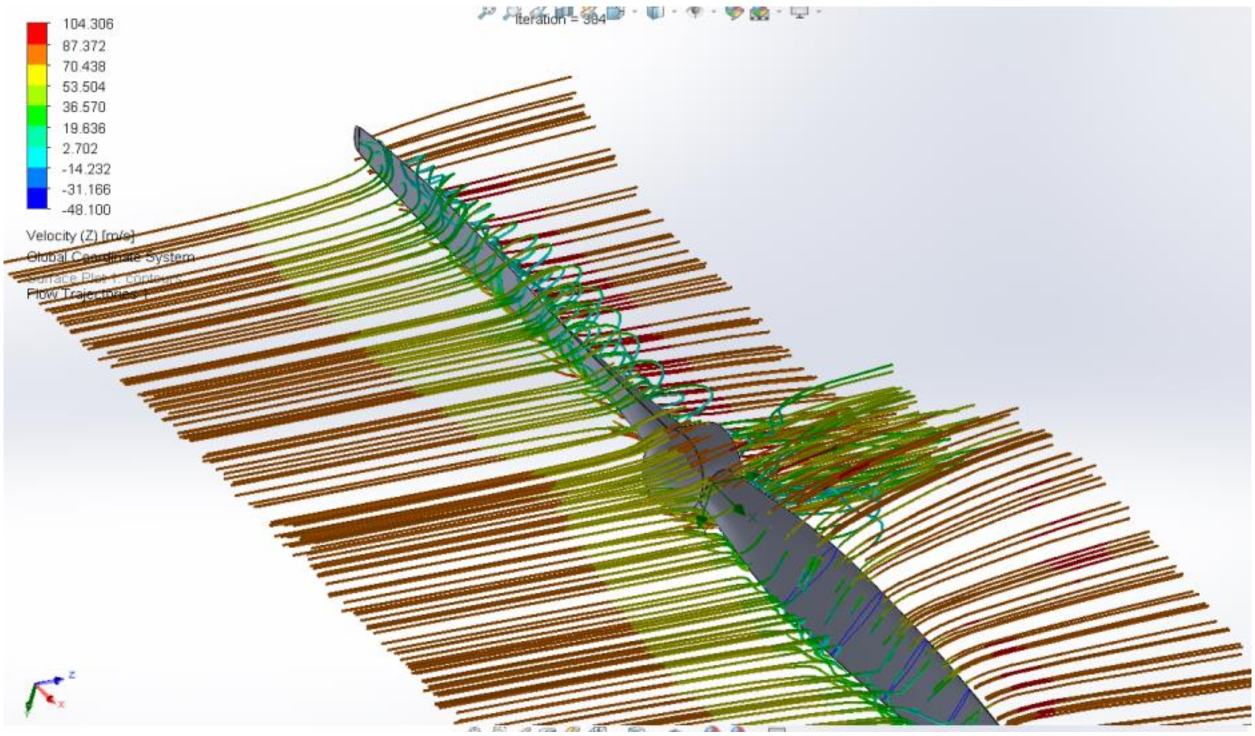
So, the propeller efficiency (η) is 85%.

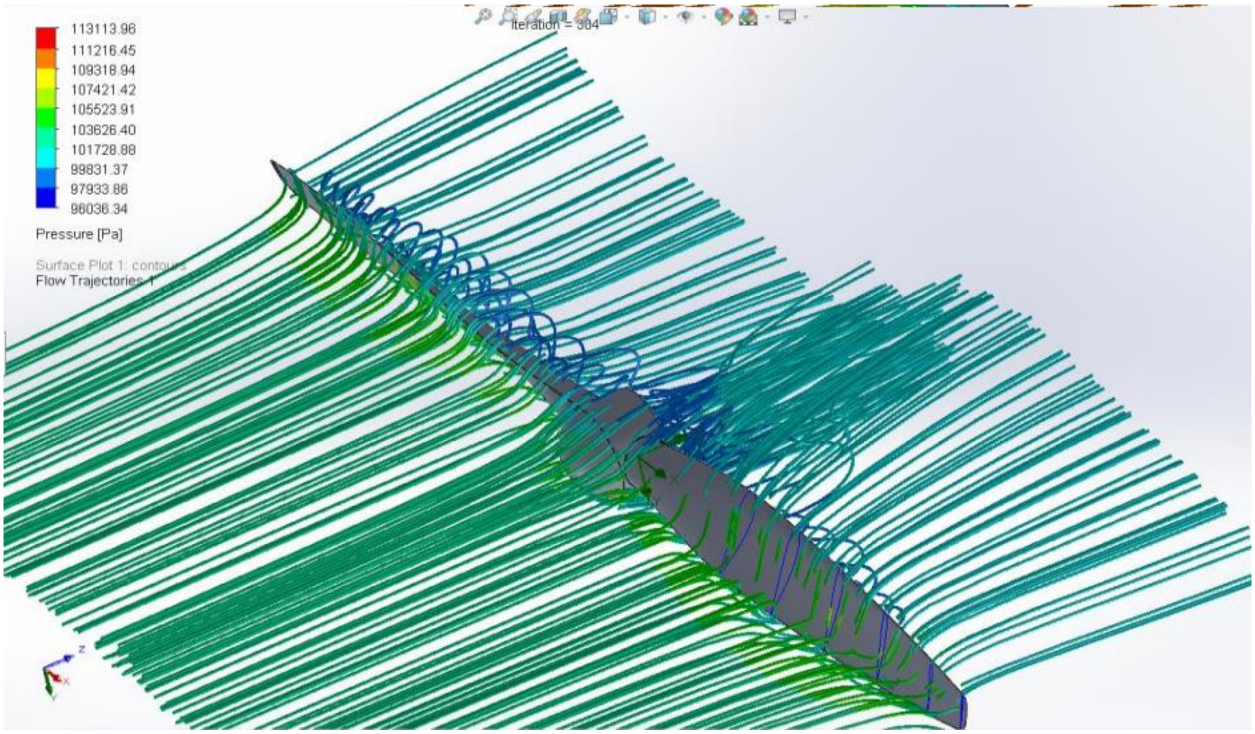
Other parameters like Thrust produced by the propeller, coefficient of thrust and coefficient of power are calculated further by the flow simulation below.

4. Flow simulation

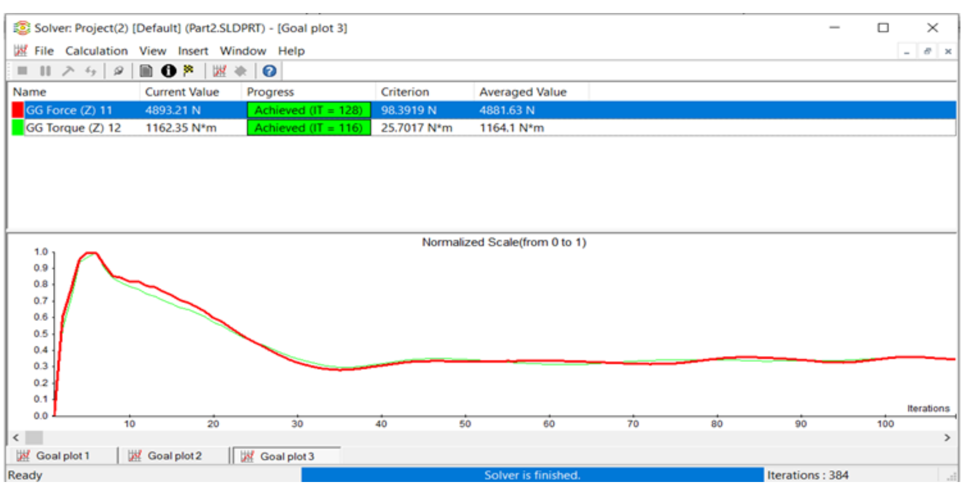
In this part we're going to do a flow simulation of our propeller using SolidWorks software to realize the pressure and flow velocity distribution along the propeller. The aircraft speed is considered to be 76m/s in the z direction.

As we can see in the image below, the downstream flow velocity has increased to almost 90m/s due to the suction effect and thrust generated by the propeller. There is also some wake in the upper section of the left side of propeller and lower section of the right side of the propeller since the blade in these sections oppose to the direction of the air, which is why there is significant wake and vortices behind the hub.

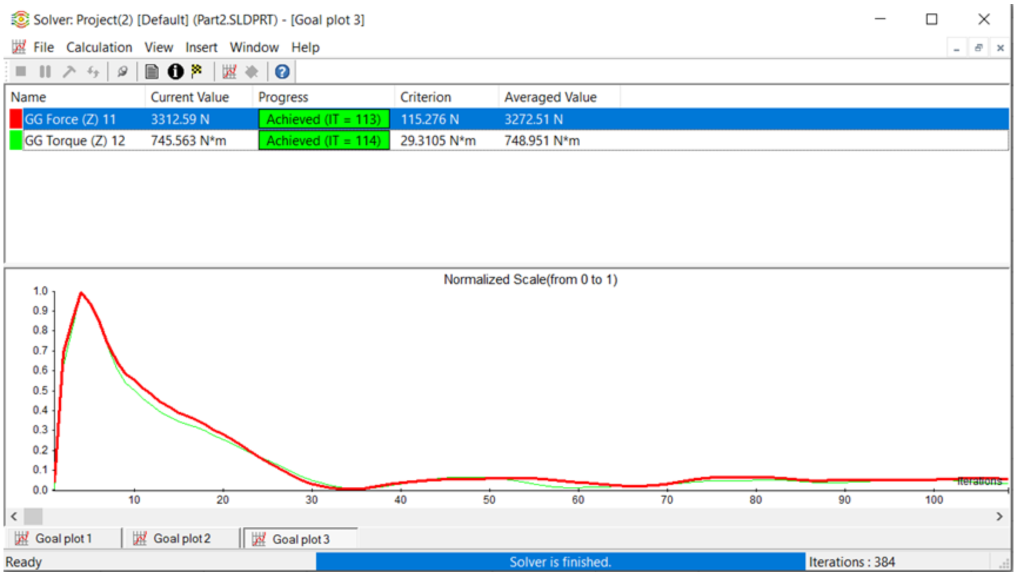




Now we have to calculate whether the motor is able to provide such thrust for the propeller. The higher the angular velocity of the propeller, the higher thrust we get. but we have to see if the engine is able to produce such power for the propeller. The power of the engine is 180 hp so Power(p)=180*746=134280 watt. As we can see if the propeller rotates with 2000 rpm (210 rad/s), the Fz value (thrust) is 4881 N, and the Torque is T=1164.1 N.M.so the power required is equal to P=T.ω/η=1164.1*210/0.85=287601 N which is above the engine capacity. (η is the propeller efficiency and was calculated to be 0.85) and is not acceptable.



Now we assume the angular velocity of the propeller is 1500 rpm (157 rad/s) .So if the propeller rotates with 1500 rpm, the torque produced by the propeller is 748.951 N.M according to results below, which means the power required P=T.ω/η=748.951*157/0.85=131263 N
Which is lower than maximum power produced by engine (134280 N) and is acceptable.



Coefficient of thrust Calculation

Now that we have obtained the exact values of thrust produced by the propeller,We can can calculate the coefficient of thrust. Coefficient of thrust (C_t) represents the normalized thrust produced by the propeller. It relates the actual thrust force generated by the propeller to the air density, the rotational speed of the propeller, and the propeller's size (diameter).

$$F\_thrust = C_t \times \rho \times n^2 \times D^4$$

$$C_t = \frac{4881.6}{1.225 \times 33.33\text{^}2 \times 2.07^4.} = 0.19$$

Coefficient of Power Calculation

The coefficient of power (C_p) represents the normalized power absorbed by the propeller. It relates the power required by the propeller to overcome aerodynamic drag and generate thrust, to the air density, the rotational speed, and the propeller's size.

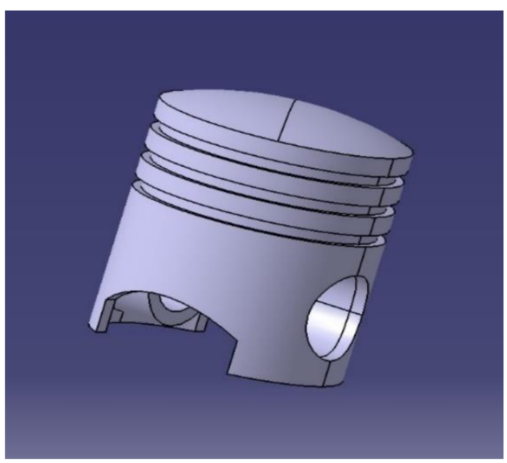
$$C_p = \frac{P * \eta}{\rho \times n^3 \times D^5} = \frac{180 \times 745.7 \times 0.85}{1.225 \times 33.33^3 \times 2.07^5} = 0.0938$$

5. Assembly parts and their performance

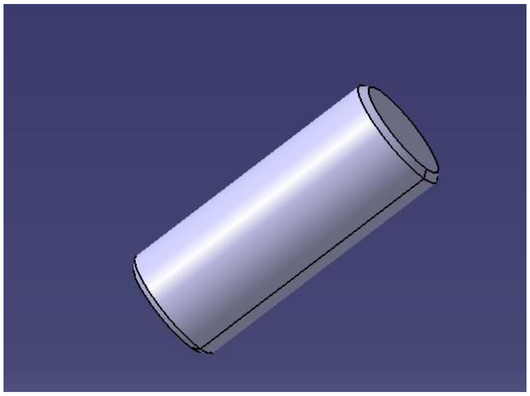
Part name	Quantity	Number
Piston	4	1
Piston pin	4	2
Connecting rod	4	3
Connecting rod cap	4	4
crank shaft	1	5
Engine Block	1	6
Engine Flange	1	7
spacer	1	8
Rear spinner Bulkhead	1	9
Hub	2	10
Propeller Blade	1	11
Nose Cone	1	12

In this part, I'm going to present the parts that I designed for aircraft Engine and propeller blade using Catia Software and provide the final assembly of my design.

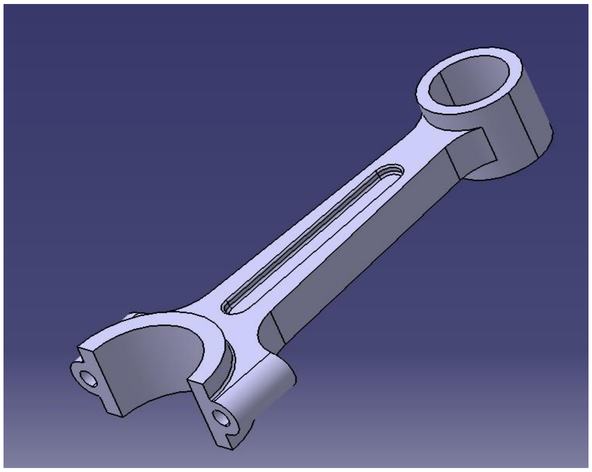
Piston: The piston moves up and down inside the cylinder, driven by the combustion of the fuel-air mixture. It transfers the force from combustion to the crankshaft.



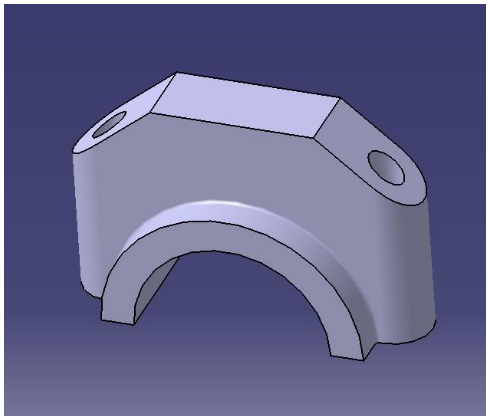
Piston Pin (Wrist Pin/Gudgeon Pin): Connects the piston to the connecting rod, allowing the piston to pivot as it moves up and down within the cylinder.



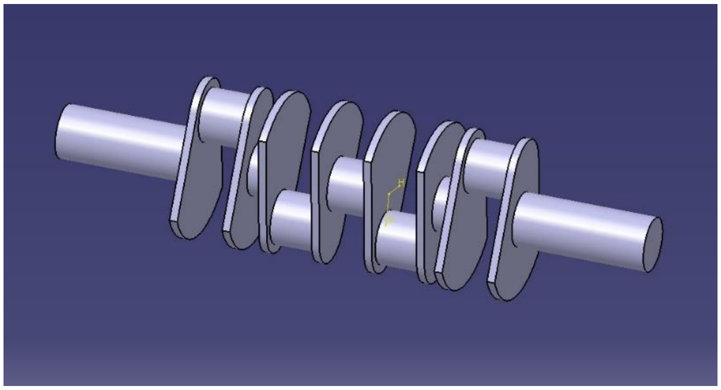
Connecting Rod: The connecting rod links the piston to the crankshaft. It transmits the piston’s motion to the crankshaft, converting the piston's linear motion into rotational motion.



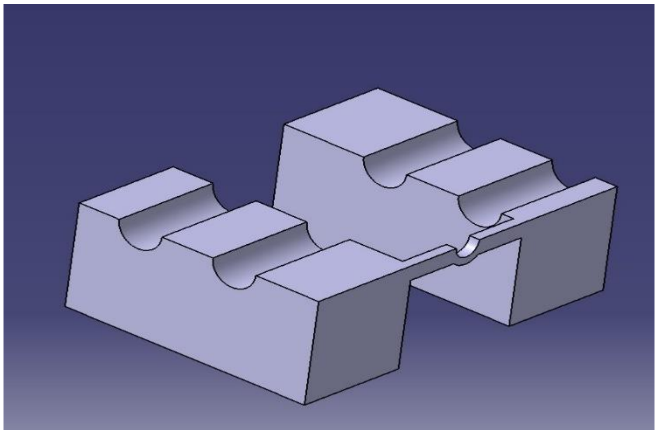
Connecting Rod Cap: Attached to the connecting rod, this cap secures the piston pin in place and helps maintain proper alignment between the connecting rod and piston.



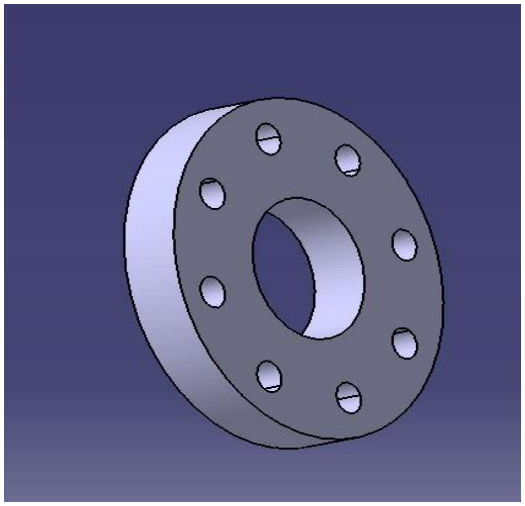
Crankshaft: Converts the linear motion of the pistons into rotational motion, which drives the propeller.



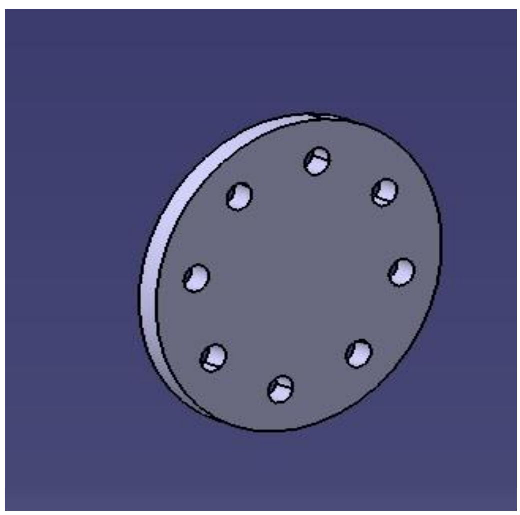
Engine Block: The main structure of the engine that houses the cylinders, crankshaft, and other key components. It provides support and alignment for these components.



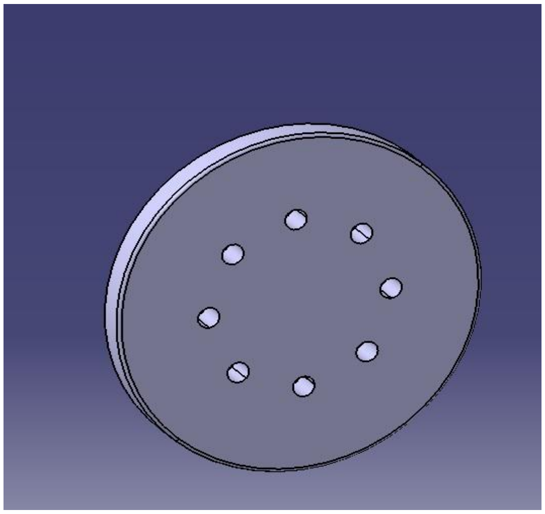
Engine Flange: The part of the engine where it attaches to the aircraft or other components. It provides a mounting point and helps with alignment.



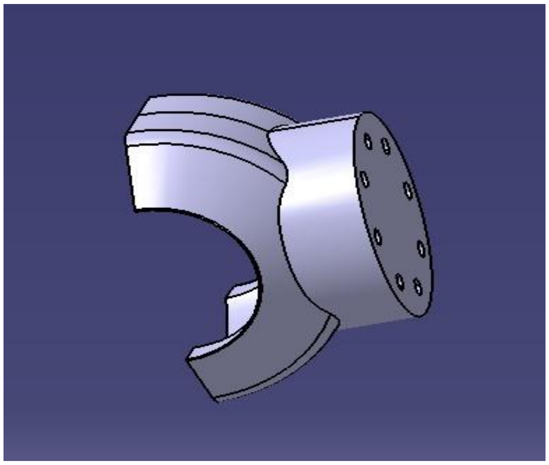
Spacer: Maintains correct spacing between engine components, such as between the engine and the propeller or between different engine parts. It ensures proper alignment and function.



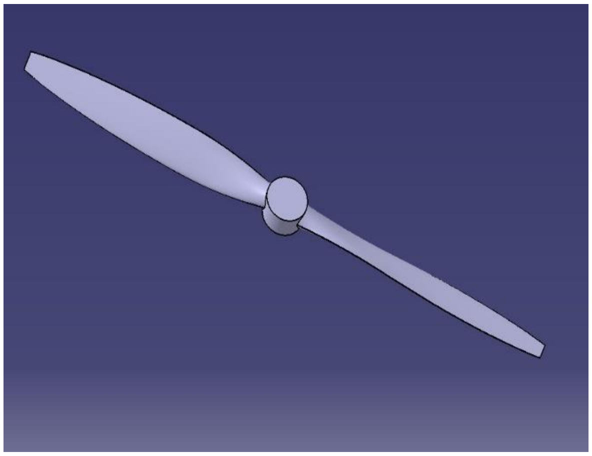
Rear Spinner Bulkhead: Its primary functions are to ensure proper alignment of the propeller, provide structural integrity to the spinner assembly, and handle the aerodynamic loads during operation.



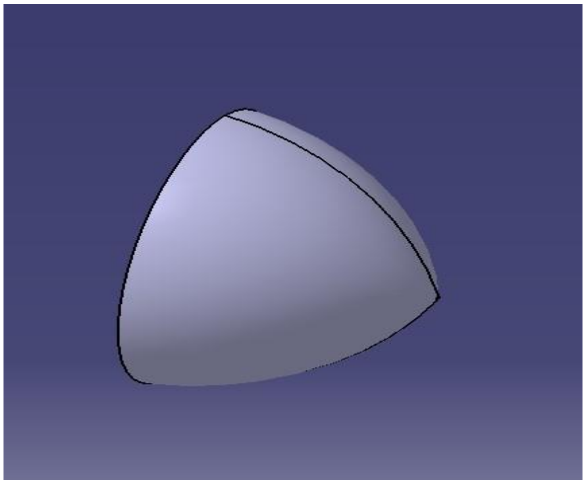
Hub: The central part of the propeller to which the blades are attached. It transmits power from the engine to the propeller blades and provides a mounting point for the blades.



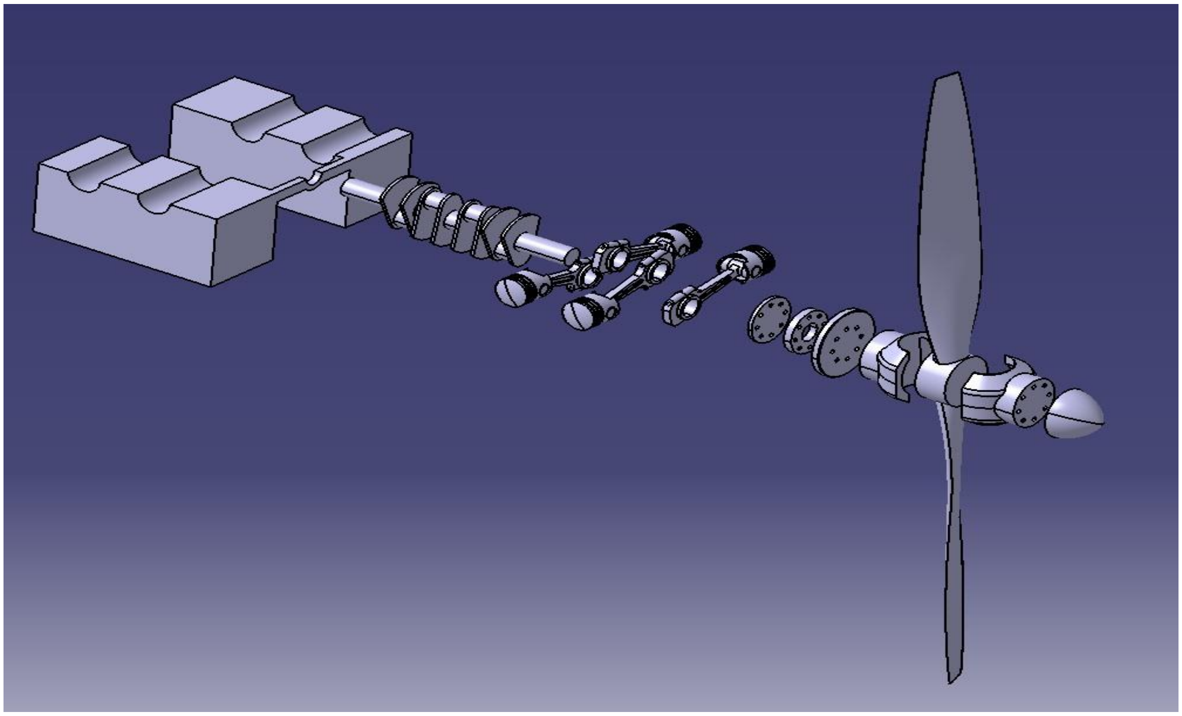
Propeller Blade: The aerodynamic component of the propeller that generates thrust. The shape and angle of the blades influence the efficiency and performance of the propeller.

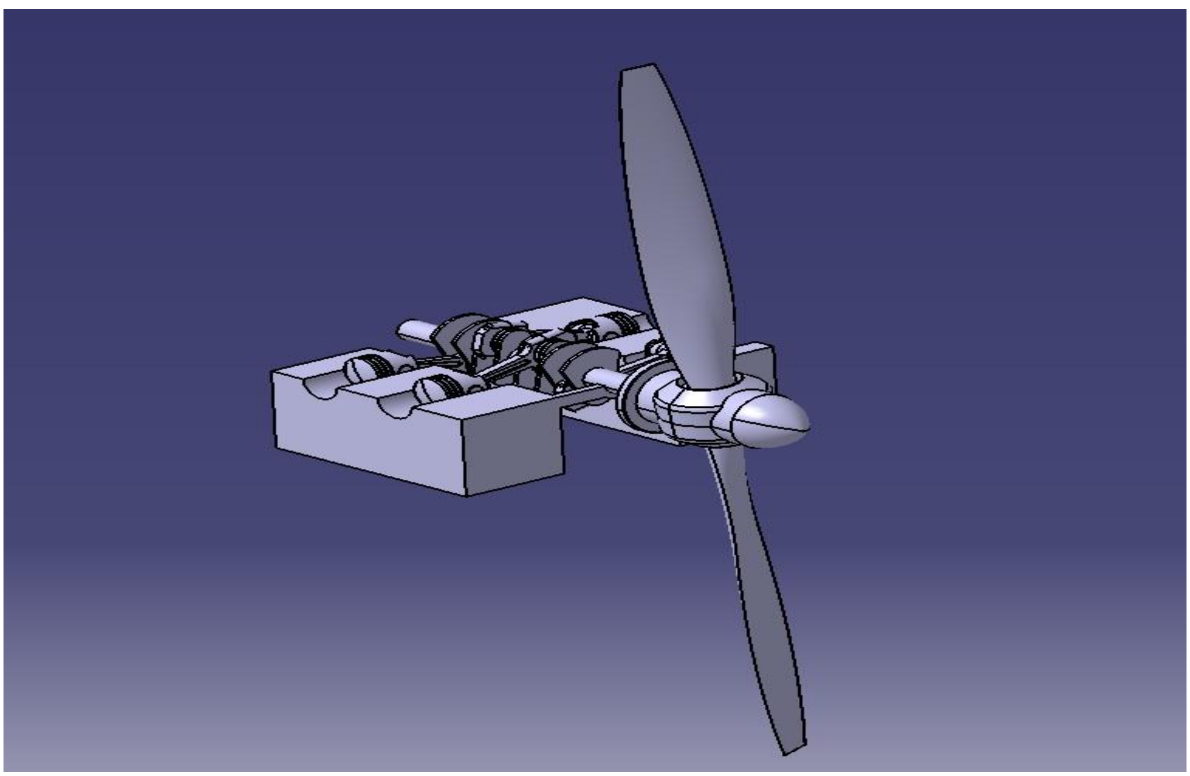


Nose Cone: The streamlined, front part of the engine that reduces aerodynamic drag and helps direct airflow smoothly into the engine. It may house sensors or other components.



Final Assembly





6. Manufacturing Plan

In this part, we're going to express the manufacturing plan both for the propeller and also our connecting rod which is a significant part of our engine.

Manufacturing Plan for the propeller

Propellers are made from various materials, each suited for different applications. Aluminum alloys are lightweight and corrosion-resistant, commonly used in general aviation. Composite materials, including carbon fiber and fiberglass, offer high strength-to-weight ratios and are used in performance and recreational aircraft. Wood propellers, made from laminated hardwoods, are valued for vintage and experimental aircraft. Stainless steel and titanium provide excellent durability and resistance to corrosion but are typically used in specialized applications due to their cost.

Material Selection

For our project, aluminum alloy is generally the best choice. It offers a good balance of weight and strength, which meets the aircraft's performance needs. Aluminum is cost-effective compared to composites or titanium, making it a practical option. It provides good durability and corrosion resistance, suitable for the diverse conditions the aircraft may face. Additionally, aluminum propellers are easier to maintain and repair, which is beneficial for the aircraft's upkeep.

Manufacturing Process

Material Preparation: Aluminum billets or sheets are cut into rough shapes or blanks that approximate the final blade size.

Forging or Casting: The aluminum blanks are formed into the rough shape of the blades through forging (heating and pressing) or casting (pouring molten aluminum into molds).
Machining: The forged or cast blades are precision machined to achieve the final dimensions and surface finish.
Heat Treatment: The aluminum undergoes heat treatment to enhance its strength and durability.
Balancing: The propeller is dynamically balanced to eliminate vibrations and ensure smooth operation.
Surface Treatment: Surface treatments like anodizing or painting are applied for corrosion resistance and aesthetics.
Inspection and Testing: Rigorous inspections and tests are conducted to ensure the propeller meets design specifications and performance standards.

Manufacturing Plan for the Connecting Rod

The objective of this part is to select the appropriate material for a connecting rod where the constraints are to make the product as light and cheap as possible and yet strong enough to carry the peak load without failure in high cycle fatigue. The fracture toughness also needs to be above a certain minimum value. A further requirement is that the connecting rod should not buckle during operation. The material must maintain its properties at high operating temperatures typically in aircraft engines and Corrosion resistance is crucial because aircraft components are exposed to harsh environments. These constraints are used to select an appropriate cross section and material for construction.

Materia Selection

If ‘A’ denotes the area of cross-section of the connecting rod and ‘L’ its length and ‘ρ’ the density of the material of which it is made then the mass ‘m’ is:
m= ρAL (1)
If the applied force on the connecting rod is ‘F’ and the endurance limit of the material as ‘σ’, the fatigue constraint requires that,
F/A<sigma (2)
The mass from equation (1) by eliminating ‘A’ is then given by,
M> $FL\,\frac{\rho}{\sigma}$ (3)
In order that the mass is minimized we need to maximize the material index, ‘M’:
M=$\frac{\sigma}{\rho}$ (4)

Creating a chart with „ σ “ and „ ρ “ as axes and applying an additional constraint that the fracture toughness exceeds 15 MPa identify materials with high values of this index. This is the selection process for direct tension or compression load on the connecting rod. The selection is shown in Figure 1 and uses the Level 2 Materials Universe of CES EduPack software.

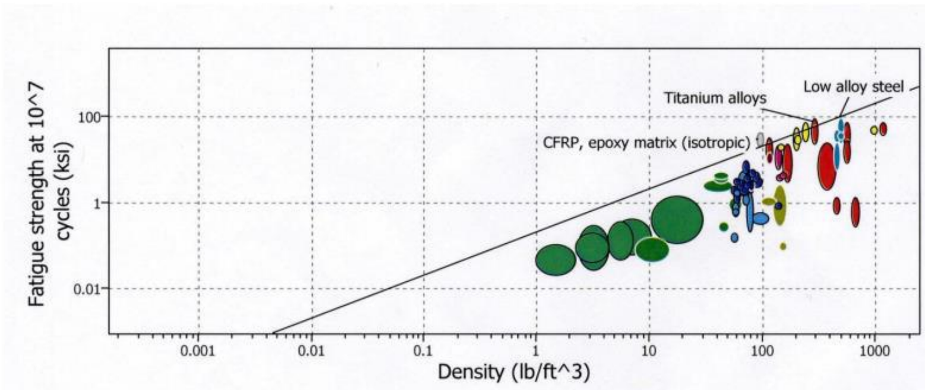


Figure 1: Fatigue Strength vs. Density

From Figure 1 a number of candidate materials emerge. The prominent one is low alloy steel which is extensively used as the connecting rod material for engines running at high rotational speeds. So, several material options are considered, including steel alloys like AISI 4340 and AISI 4140, known for their high tensile strength and fatigue resistance. These alloys are also easily machinable and widely available, though they are heavier compared to alternatives. For our connecting rod however, AISI 4340 is preferred for its higher tensile strength and toughness compared to other materials, and it's more commonly used for high-performance applications like aircraft engines.

Manufacturing Process

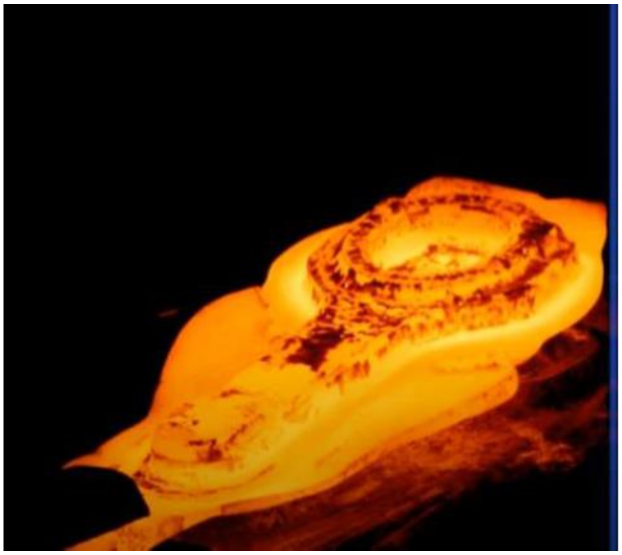
The forged connecting rod process includes several steps: blanking, heating, roll forging, closed die forging, trimming and punching, heat treatment, shot blasting, and correction.

Blanking: In the blanking step, raw material (1.875-inch diameter 4340 alloy steel bar) is cut into specific shapes and sizes, preparing it for the forging process. This ensures the material is ready for subsequent heating and forming.

Heating: The steel billets are heated in a furnace to a temperature range of 1,200 to 1,300°C (2,192 to 2,372°F). This high temperature makes the metal malleable and easier to shape during the forging process.

Roll Forging: The heated billets are passed through rotating rolls with grooved patterns that gradually shape the material into a rough approximation of the connecting rod. This step helps elongate and reduce the cross-section of the billet.

Closed Die Forging: The roughly shaped billet is placed in a closed die, which precisely matches the final dimensions of the connecting rod. Under high pressure, the billet is compressed to take the shape of the die, ensuring detailed features and tight tolerances.

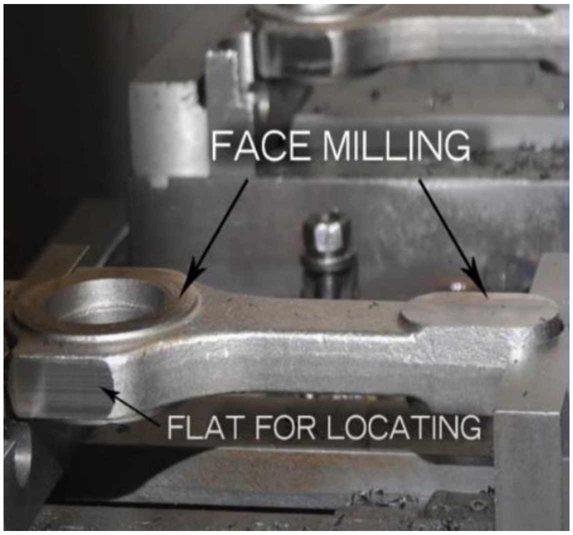


Trimming and Punching: Excess material (flash) that forms around the edges during forging is removed. Trimming is done using trimming dies, and punching creates any necessary holes or cuts for the rod's final design.

Heat Treatment: The forged connecting rod is heated to a high temperature and then rapidly cooled (quenched) to improve its mechanical properties, such as strength and toughness.

Shot Blasting: The connecting rod surface is cleaned using shot blasting to remove any scale or other impurities.

Machining: CNC milling machines remove excess material and achieve the exact dimensions required for the connecting rod. This step ensures the rod meets the design specifications and includes shaping, bore milling, and surface finishing.



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8. Appendix

Displacement Volume	V_d
Mean Effective Pressure	P_m
Actual Power	P
Advance Ratio	J
Propeller Efficiency	η
Coefficient of Thrust	C_t
Coefficient of Power	C_p
Number of Cylinder	N
Thrust Force	F_t
Rotational Speed	n
Air Density	ρ
Stroke	S