

Sustainable Design of Turbofan Engine: A Computer-Aided Design and Finite Element Analysis

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Abstract: A compressive design and analysis of a turbofan engine is presented in this paper. The components of jet engine have been analyzed based on mechanical design concept. An attempt has been to select materials based on sustainability and green design considerations. The energy content (e) of the materials has been one of the parameters for material selection. The choice of material has a substantial impact on cost, manufacturing process, and the life cycle efficiency. All components nose cone, fan blade, inlet shaft, including compressor has been solid modeled using Siemens NX 11.0 CAD software. The finite element analysis of every component was performed and found safe. A tolerance analysis was performed before assembly of the turbofan engine. A numerical analysis was completed on blade and inlet geometries to determine a more efficient turbofan engine. Thermal analysis was executed on the cone and suitable corrections were made. Finally, the cost and the total energy were estimated to show how much energy is needed to manufacture a turbofan jet engine.

Key words: Sustainable design, turbofan, life cycle analysis (LCA), Cost calculation, energy calculation, CAD, FE analysis.

1. Introduction

The research presented here explores in detail fundamental steps in designing and life cycle analysis of a turbofan engine. Jet engines are extremely advanced pieces of machinery that take teams of engineers [1] years of research and design to produce. The primary goal is to design some of the key components located at the frontal end of the turbofan engine, these being: the nose cone, fan blade, inlet shaft, shaft bearings and other local components. By using a basic knowledge in mechanical engineering along with data obtained from outside sources the methodology and procedure for designing and life cycle analysis of such complex parts are presented. The parts and components designed are modeled using three-dimensional modeling program CAD software NX 11.0.

To move an airplane through the air, thrust is generated by a propulsion system. Most modern

airliners use turbofan engines because of their high thrust and good fuel efficiency. The incoming air is captured by the engine inlet. Some of the incoming air passes through the fan and continues into the core compressor and then the burner, where it is mixed with fuel and combustion occurs. The hot exhaust passes through the core and fan turbines and then out of the nozzle, as in a basic turbojet. The rest of the incoming air passes through the fan and bypasses, or goes around the engine, just like the air through a propeller. The air that goes through the fan has a velocity that is slightly increased from free stream. So, a turbofan gets some of its thrust from the core and some of its thrust from the fan. The ratio of the air that goes around the engine to the air that goes through the core is called the bypass ratio.

The fan and fan turbine are composed of many blades, like the core compressor and core turbine, and are connected to an additional shaft. As with the core compressor and turbine, some of the fan blades turn with the shaft and some blades remain stationary. The fan shaft passes through the core shaft. This type of arrangement is called a two-spool engine (one "spool"

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for the fan, one "spool" for the core). Some advanced engines have additional spools for even higher efficiency. A turbofan is very fuel efficient engine. In fact, high bypass ratio turbofans are nearly as fuel efficient as turboprops. Because the fan is enclosed by the inlet and is composed of many blades, it can operate efficiently at higher speeds than a simple propeller. Low bypass ratio turbofans are still more fuel efficient than basic turbojets. Therefore, the airplane inlet slows the air down from supersonic speeds. In turbofans, the core refers to the compressor, combustion chamber, turbine and nozzle configuration, this essentially is the makeup of a turbojet engine. An example of a turbofan engine can be seen below in Fig. 1.

The design of turbofan engine follows a modular concept and each of the modules has its own identity. The main engine modules can be summarized as the following:

- Fan
- LPC (low pressure compressor)
- Cone engine module
- LPT (low pressure turbine)
- Accessory gearbox

Generally, it is the core engine module that is subjected to the most adverse conditions in terms of temperature, pressure, and rotational velocity. It is this module that suffers the fastest deterioration of performance. In addition to its main components the engine needs various systems to become operable. These include amongst others an air cooling and sealing system, a lubrication system, a fuel distribution system, an exhaust and thrust reverser system as well as an air inlet and a nozzle [1].

1.1 The Mathematics

The mathematics describing the thrust of a turbofan engine is presented below. The capture area of the fan, required to achieve the desired mass flow rate, needs to be determined. The total mass flow, \dot{m}_t is given by Eq. (1) below.



Fig. 1 Schematic of standard turbofan engine.

$$\dot{m}_i = \dot{m}_{fan} + \dot{m}_{core} \tag{1}$$

where \dot{m}_{fan} is fan exhaust mass flow and \dot{m}_{core} is core mass flow rate. The bypass ratio, R_b , is estimated as:

$$R_b = \frac{\dot{m}_{fan}}{\dot{m}_{core}} \tag{2}$$

The mass flow rate of fan is calculated as;

$$\dot{m}_{fan} = p_{\infty} V_i A_{fan} \tag{3}$$

where p_{∞} is the pressure of the free steam air, V_i is the inlet air velocity, and A_{fan} is the capture area of fan. Turbojet engine noise is predominately jet noise from the high exhaust velocity, therefore turbofan engines are significantly quieter than a pure-jet of the same thrust with jet noise no longer the predominant source. Since the efficiency of propulsion is a function of the relative airspeed of the exhaust to the surrounding air, propellers are most efficient for low speed, pure jets for high speeds, and ducted fans in the middle. Turbofans are thus the most efficient engines in the range of speeds from about 500 to 1,000 km/h (310 to 620 mph), the speed at which most commercial aircrafts operate. Turbofans retain an efficiency edge over pure jets at low supersonic speeds up to roughly Mach 1.6.

The original low-bypass turbofan engines were designed to improve propulsive efficiency by reducing the exhaust velocity to a value closer to that of the aircraft. A high specific thrust/low bypass ratio turbofan normally has a multi-stage fan, developing a relatively high pressure ratio and, thus, yielding a high (mixed or cold) exhaust velocity. The core airflow needs to be large enough to give sufficient core power to drive the fan. Specific thrust (net thrust/intake airflow) is an important parameter for turbofans and jet engines in general. The higher the fan pressure ratio (fan discharge pressure/fan inlet pressure), the higher the jet velocity and the corresponding specific thrust. Obviously, the core of the turbofan must produce sufficient power to drive the fan via the LPT (low pressure turbine). The corresponding bypass ratio is therefore relatively low. If we raise the turbine inlet temperature, the core airflow can be smaller, thus increasing bypass ratio [2].

Although turbine blade (and vane) materials have improved over the years, much of the increase in high pressure turbine inlet temperatures is due to improvements in blade/vane cooling technology. Relatively cool air is bled from the compression system, bypassing the combustion process, and enters the hollow blade or vane. The gas temperature can therefore be even higher than the melting temperature of the blade [3]. After picking up heat from the blade/vane, the cooling air is dumped into the main gas stream. It is desired to achieve the following goals;

• Design and model important components of a working turbofan jet engine;

• Life cycle study of standard turbofan engine;

• Perform a FE (finite element) analysis on its problematic areas (discussed later);

• Test different blade and inlet geometries to see if a more efficient high speed turbofan can be achieved;

• Energy requirement to manufacture a turbofan engine.

2. Design Parameters: Engine Properties and Flight Characteristics

The methodology for design and analysis is presented for a set of data given below. These values are the standards for many commercial jets operating at cruise conditions. A summary of these basic operating conditions is listed as:

Thrust at cruise condition $(Th_{cruise}) = 42,000$ lbs;

Mach number at cruise $(M_{cruise}) = 0.9;$

Cruising altitude (Alt_{ruism}) = 37,000 ft;

Turbofan bypass ratio (R_b) = 9.5;

Maximum angular engine speed $(N_{max}) = 2,550$ rpm

Once a cruise altitude, target thrust and an average bypass ratio is established, the atmospheric conditions could be determined. The atmospheric conditions at a cruise altitude of 37,000 feet are:

Free steam air temperature $T_{\infty} = 390.6$ °*R*

Velocity of sound $V_{sound} = 968.5 \quad ft_s$

Density of the free stream air $\rho_{\infty} = 0.0216 \frac{lbm}{ft^3}$ Pressure of the free steam air $P_{\infty} = 3.13$ psia

2.1 Analysis and Design

2.1.1 Inlet Fan; Sizing the Fan

The fan draws in enormous quantities of air, producing the over 70% of the engines total thrust. Due to the importance of this single part much of the engine is sized around the Inlet Fan's dimensional requirements. The inlet conditions are listed below.

Inlet velocity: $V_i = 871.65 \frac{ft}{s}$

Inlet temperature: $T_i = 390.6^{\circ}R$

Inlet pressure: $P_i = 3.13 psia$

Inlet mass flow rate: $m_l = 1,378.2 \ lbm/s$

The capture area of the fan, A_{fan} , required to achieve the desired mass flow rate, \dot{m}_{fan} , should be determined. By rearranging Eqs. (1)-(3), shown above, A_{fan} and \dot{m}_{fan} can be calculated using Eq. (4). The fan exhaust mass flow can be calculated from inlet mass flow as below:

$$\dot{m}_{fan} = \dot{m}_l \left[\frac{R_b}{R_b + 1} \right] \tag{4}$$

From the data given above, $\dot{m}_{fan} = 1,246.94 \, lb/s$. Eq. (3) is used to calculate the capture area of fan as:



Fig. 2 Nose cone capture area.

$$A_{fan} = \frac{\dot{m}_{fan}}{\uparrow \rho_{\infty} V}$$
$$A_{fan} = 66.23 ft^{2}$$

This is the capture area necessary to achieve the desired mass flow rate. This area is located between the inlet fan housing and the nose cone, shown in Fig. 2.

2.1.2 Green Material Selection for Least Environmental Impact

Strong, lightweight, corrosion-resistant, thermally steady components are essential to the viability of any aircraft design, and certain materials have been developed to provide these and other desirable traits. Titanium, first created in sufficiently pure form for commercial use during the 1950s, is utilized in the most critical engine components. While it is very difficult to shape, its extreme hardness renders it strong when subjected to intense heat. To improve its malleability titanium is often alloyed with other metals such as nickel and aluminum. All three metals

Table 1	Selection	of cone	material.
I able I	Delection	or cone	materian

are prized by the aerospace industry because of their relatively high strength/weight ratio.

The intake fan at the front of the engine must be extremely strong so that it does not fracture when large birds and other debris are sucked into its blades; it is thus made of a titanium alloy. The intermediate compressor is made from aluminum, while the high-pressure section nearer the intense heat of the combustor is made of nickel and titanium alloys better able to withstand extreme temperatures [4]. The combustion chamber is also made of nickel and titanium alloys, and the turbine blades, which must endure the most intense heat of the engine, consists of nickel-titanium-aluminum alloys. Often, both the combustion chamber and the turbine receive special ceramic coatings that better enable them to resist heat. The inner duct of the exhaust system is crafted from titanium, while the outer exhaust duct is made from composites-synthetic fibers held together with resins. Although fiberglass was used for years, it is now being supplanted by Kevlar, which is even lighter and stronger. The thrust reverser consists of titanium alloy.

The short listed materials for turbofan cone with other parameters are given in Table 1.

We have two constraints-shear stress and deflection-and for material selection, it is recommended that material related to dominant constraint should be selected. We can write as min-max optimization model. An analytical method is presented below. Most of the min-max is supposed to work for continuous

Materials	Density (ρ) (lbm/in ³)	Young's modulus (E), (Mpsi)	Yield strength, (σ_y) , (kpsi)	Embodied energy T(e), (Btu)	$M_1 = \frac{\sigma_y}{e\rho}$	$M_1 = \frac{E}{e\rho}$	Performance index delected
Ti alloys	0.6	16.5	143-750	66.36×10^{3}	$(1.89 - 3.59) \times 10^{-3}$	4.15×10^{-4}	M_1^*
Nickel-based super alloys	2820	28.5-28.8	36.28-98.7	$(15.168 - 17.04) \times 10^3$	2.05×10^{-2} - 8.48 × 10 ⁻³	$(5.93 - 6.73) \times 10^{-3}$	M_1
Magnesium alloys	440	29.5	80	312-346	$(5.25 - 5.83) \times 10^{-4}$	$(1.94 - 2.15) \times 10^{-4}$	M ₂
Aluminum alloys	18.1-25.8	29.5	11.61-65.31	70-75	$6 \times 10^{-3} - 5.15 \times 10^{-2}$	$(1.52 - 2.33) \times 10^{-2}$	M ₂ ^{**} (selected)

Material	(MPa)	E (GPa)	e (MJ/kg)	Density (kg/m ³)	TE1	TE2	TEs
Ti-Alloys	750-1,200	110-120	600-746	4,400-4,800	7.698×10^4	2.418×10^3	7.698×10^4
CFRP	550-1,050	60-150	259-286	1,550	1.204×10^4	339.553	1.204×10^4
Spring steel (low alloy)	400-1,500	460-1,200	32-38	7,800-7,900	6.782×10^{3}	80.236	6.782×10^{3}
Music wire (low carbon steel)	250-395	200-215	29-35	7,800-7,900	1.312×10^4	146.54	1.312×10^4
HD spring (high carbon steel)	400-1,155	200-215	29-35	7,800	1.08×10^4	145.647	1.08×10^4
Valve spring (medium)	305-900	200-216	29-35	7,800	8.58×10^{3}	45.607	8.58×10^3
Stainless steel	170-1,000	189-210	77-85	7,600-8,100	2.23×10^4	378.75	2.23×10^4
Nickel-chromium	365-460	200-230	127-140	8,300-8,500	4.98×10^4	645.408	4.98×10^4
Nickel-based (super alloys)	300-1,900	150-245	135-150	7,750-8,650	2.69×10^{4}	645.408	$2.69 \times 10^{4^*}$ (selected)

 Table 2
 Analytical selection of material under multiple constraints for turbine blades.

function, but in our case TE function is discrete and analytical method would work better. We will use charts generated by CSE between material index M1 and M2 to short list materials useful for fan blades and then use analytical method [5].

The short-listed for blade materials and calculations for TE1 and TE2 are presented below in Table 2. If we rank the material starting with best choice to least choice, they are: Ti-alloys are best for cone & Nickel based super alloy is best for fan blade.

2.1.3 The Manufacturing of Jet Components

Building and assembling the components of a jet engine takes about two years, after a design and testing period that can take up to five years for each model. The research and development phase is so protracted because the engines are so complex: a standard Boeing 747 engine, for example, contains almost 25,000 Pa.

In jet engine manufacture, the various parts are made individually as part of subassemblies; the subassemblies then come together to assemble the whole engine. One such part is the fan blade, situated at the front of the engine. Each fan blade consists of two blade skins produced by shaping molten titanium in a hot press. When removed, each blade skin is welded to a mate, with a hollow cavity in the center. To increase the strength of the final product, this cavity is filled with a titanium honeycomb.

Compressor Disc. The disc, the solid core to which the blades of the compressor are attached, resembles a big, notched wheel. It must be extremely strong and free of even minute imperfections, as these could easily develop into fractures under the tremendous stress of engine operation. For a long time, the most popular way to manufacture the disc entailed machine-cutting a metal blank into a rough approximation of the desired shape, then heating and stamping it to precise specifications (in addition to rendering the metal malleable, heat also helps to fuse hairline cracks). Today, however, a more sophisticated method of producing discs is being used by more and more manufacturers. It is called powder metallurgy; it consists of pouring molten metal onto a rapidly rotating turntable that breaks the metal into millions of microscopic droplets that are flung back up almost immediately. Turbine blades are made by forming wax copies of the blades and then immersing the copies in a ceramic slurry bath. After each copy is heated to harden the ceramic and melt the wax, molten metal is poured into the hollow left by the melted wax due to the table's spinning.

As they leave the table, the droplets' temperature suddenly plummets (by roughly 2,120 degrees Fahrenheit—1,000 degrees Celsius—in half a second), causing them to solidify and form a fine-grained metal powder. The resulting powder is very pure because it solidifies too quickly to pick up contaminants. Turbine blades are made by forming wax copies of the blades and then immersing the copies in a ceramic slurry bath. After each copy is heated to harden the ceramic and melt the wax, molten metal is poured into the hollow left by the melted wax. In the next step, the powder is packed into a forming case and put into a vacuum. Vibrated, the powder sifts down until it is tightly packed at the bottom of the case; the vacuum guarantees that no air pockets develop. The case is then sealed and heated under high pressure.

2.1.4 Design of the Inlet Fan

To determine the actual dimensions of the inlet fan A_{fan} is modified. The calculated A_{fan} is the area of an annulus, since the engine's nose cone is located at the center of the inlet fan, indicated in Fig. 1. Since the nose cone only redirects air and does not draw any in, this area is not accounted for in the calculated 66.23 ft². To account for the nose cones area, as well as obtain radii for both the inlet fan blades and the nose cone, a ratio needs to be established. For a typical turbofan engine, this ratio was found to be 3.54. Knowing this, the two radii are calculated by Eq. (5). where, $A_{annulus}$ is equivalent to A_{fan} , A_2 is the total area of the inlet fan and A_1 is the area of the nose cone. By substituting the basic equation for a circle's area into Eq. (5), where;

$$A_{annulus} = A_2 - A_1 \tag{5}$$

$$R_1 = \frac{R_2}{3.54}$$
(6)

Eq. (5) can be expanded into Eq. (6), shown below.

$$R_2 = 12 \sqrt{\frac{A_{annulus}}{0.92\pi}}$$
, $R_2 = 57.443$ in and $R_1 = 16.227$ in
 $R_3 = R_2 - R_1 = 41.216$ in

The nose cone is the forward most section of a turbofan jet engine. Its primary purpose is to help slow down the flow of air before it enters the engine. It also allows for air to be redirected into the blades of the turbofan and its profile shape is designed such that it minimizes air resistance and temperature gains from aerodynamic heating. The nose cone is in fact hollow in many cases and houses many rotating components used to transmit power, change the pitch of the propeller, and so forth.

First, the general dimensions of the nose cone had to be established. These dimensions are: the radius of the nose cones base (R_l) , the overall length (L_{total}) , the radius at any given point x (y_x) where x varies from zero, at the nose cones base, to x, at its tip. These dimensions can be seen below, in Fig. 4, for a general parabolic shape profile.

After analyzing the data presented in Fig. 5 the $x^{1/2}$ power series was chosen as the initial profile shape. This choice was based on the criteria of the extent of testing data available and the performance ratings in the transonic range, specifically between 0.8 and 1.2. The $x^{1/2}$ power series profile was chosen since it provided testing data at seven different Mach numbers and operated at the highest performance rating at Mach 0.9, 1.1 and 1.4. This series is generally characterized by its blunt tip and the fact that its base is not tangent to the body tube. Due to this, the base is usually smoothed out to rid the profile of this discontinuity.



Fig. 3 Typical parabolic nose cone.



Fig. 4 Up-close view of inside the nose cone.



Fig. 5 Fan blade drawing.

2.1.5 Dimensioning the Nose Cone

Once it was established that the $x^{1/2}$ power series would serve as the general nose cone profile shape determining the specific dimensions could be considered. Eq. (7), shown below, is the governing equation for the shape and dimensions of the nose cone with the variable n defining the final shape [6].

2.1.6 Material Considerations of the Nose Cone

For the nose cone design two primary materials were being considered, Aluminum (Al) and Titanium (Ti). The reason for these specific two is because each material is extremely light when compared to heavier ones such as steel, which are readily available, have high melting points and can handle significant stress. By nature, Ti is far more expensive than Al since it offers a higher melting point, lighter weight and far exceeds the strength. The main reason Al was still considered is because for a part like the nose cone, which experiences small temperature differentials and relatively low applied forces, Al generally handles these requirements.

$$y_x = R_1 \left(\frac{x}{L_{total}}\right)^n, 0 \le n \le 1$$
(7)

2.1.7 Analysis and Design of the Nose Cone

Nose cone is designed so that it minimizes air resistance and temperature gains from aerodynamic heating. The primary reason for this is due to the addition of thermal loads and distributed forces that occur across its surface. The primary load that the nose cone is subjected to is the resultant of the aerodynamic drag.

The drag force (F_D) is quite substantial due to the large frontal area and high speed air passing over it. The drag force on the nose cone is calculated as:

$$F_D = \frac{1}{2} \rho_\infty V_i^2 A_r C_D \tag{8}$$

where C_D is the nose cone's drag coefficient and A_r is the reference area, V = 800 ft/s; and $C_D = 0.38$. The reference area, A_{ref} , is calculated below.

$$A_{ref} = \pi R_{base}^2$$
(9)
$$A_{ref} = 5745 f t^2$$

The values for ρ_{∞} and V_i pre-defined in the flight characteristics section F_D is found out as below.

$F_D = 556.703 \, lbf$

The nose cone is in fact almost entirely hollow and the minimum allowable thickness will be chosen to reduce the overall weight and cost of the engine. For this design, a thickness of 0.5 inches is chosen and will act as a starting value and it would be further refined during the force analysis.

2.1.8 Thermal Analysis of the Nose Cone

Due to the high-speed air traveling over the nose cone a temperature rise will inevitably occur, this is due to frictional forces, and is known as aerodynamic heating. At subsonic speeds these temperature gains are generally minimal but for thoroughness a thermal analysis was still deemed necessary.

The thermal load will be caused by the temperature difference the surface outer surface area will undergo. The mechanism of heat transfer is convection and conduction since the outer surface is exposed to a fluid and the inner area of the nose cone is a solid. Heat will also transfer out the nose cone and to nearby parts depending on the temperature gradient [4].

First the temperature difference between the free stream air (T_{∞}) and the nose cone's surface (T_s) was analyzed. Since the nose cone is being analyzed at cruise conditions it is assumed that its initial surface and body temperature are uniform at T_{∞} . Due to the reduction in speed of the airflow at the nose cones surface the temperature rises as the kinetic energy is produced to internal. This increase in temperature at the surface, recognized as the stagnation point, is known as the stagnation temperature (T_o) and is dependent on the air properties and speed. It is calculated as:

$$T_o = T_\infty (1 + M^2)$$

 $T_o = 453.82 \,^{\circ}R$
(9)

 T_o had a 63.27 °R difference from T_s and due to this there is heat transfer from the stagnated air to the surface of the nose cone by means of convection. This rate of heat transfer across the surface, known as the flux (Q"), was found using Eq. (10), seen below.

$$Q'' = h^2 (T_{1,s} - T_{1,\infty}) \tag{10}$$

The above equation is modified as:

$$Q'' = h^2 (T_{1,\infty} - T_{1,o}) \tag{10a}$$

To determine the heat flux, the average convection coefficient (\bar{h}) needed to be determined. This can be done by calculating the average Nusslet Number (\overline{Nu}) along with the Prandtl Number (Pr) for air and the equivalent length (L_c) [2]. These values were calculated below.

$$L_c = \frac{V}{A_s} \tag{11}$$

V = volume of a cone, A_s = surface area.

Assuming; $V = 1.806 ft^3$; $A_s = 2.103 ft^2$; Pr = 0.72.

 $L_c = 0.859 ft$ and then \overline{Re} is calculated as

$$\overline{Re} = \frac{\rho_{\infty} V_i L_c}{\mu}$$

$$Re = 4.85 \times 10^7$$
(12)

$$\overline{Nu} = 0.332 \overline{Re}^{\frac{1}{2}} P r^{\frac{1}{3}}$$
(13)

$$Nu = 2071.714$$
$$\bar{h} = \frac{\overline{Nu}k_f}{L_c}$$
$$\bar{h} = 6.725 \frac{lb}{ft \cdot s \cdot {}^\circ R}$$
(14)

So, by using Eq. (10a);

$$Q'' = -425.459 \ \frac{lb}{ft \cdot s}$$

The negative sign simply denotes the direction of the heat transfer. This can be altered by simply changing the sign and thus the direction, so $Q'' = 425.459 \frac{lb}{ft \cdot s}$ is in the direction towards the nose cone. In addition to heat entering the nose cone through convection heat is also leaving the system by conduction. The rate at which this heat is lost is entirely proportional to the temperature difference as well as the thermal conductivity (k) of the nose cone material. The thermal conductivity of aluminum (k_{AL}) was found to be:

$$k_{Al} = 29.625 \frac{lb}{s}$$

°R

2.1.9 Fan Blade

With the basic geometry of the inlet fan the actual size of the fan blades can be found. This was done by first knowing the desired length of the blades. Since the maximum length, the blades can be predetermined to be 41.22 inches, due to geometric restraints, indicated in Fig. 3, this will be used as the maximum allowable length. To calculate the necessary length needed to achieve the desired cruise conditions a basic power analysis needs to be performed on the turbofan engine and the fan blade in specific. The torque of the engine needed to be calculated below.

$$T = \frac{5252 \, HP}{N} \tag{15}$$

where: T is the engines torque in ft/lb, HP is the engines horsepower and N is the speed of the engine in revolutions per minute. The horse power of the engine is calculated from thrust below.

$$HP = \frac{T_h \cdot V}{550} \tag{16}$$

From the engine properties, the horsepower can be calculated by knowing the thrust at cruise conditions and assuming the speed of the aircraft to be the speed of the air at the given altitude and Mach number. From Eq. (16),

$$HP = 66562.3 hp$$
 (17)

If the shaft transmits its power at an efficiency of 97%; the shaft horsepower, $[SHP]_g$, can be found using Eq. (18).

$$[SHP]_g = 0.97 \cdot HP$$

$$[SHP]_g = 64565 hp$$
 (18)

2.2 Shaft, Bearing, and Gearbox

Once the torque and $[SHP]_g$ is calculated, three more values are necessary to determine the speed and power of the fan blade, these being: the number of bearings between the gearbox output and the propeller, N_g , the gearbox reduction ratio, G_r and the power loss due to the bearings, P_b . For this analysis [*PLB*] and G_r will be based on average propeller values and are assumed to be 3.70 and 6.00% respectively. To determine N_g , the number of objects that are fixed to the shaft needs to be accounted for. An up-close view of the inlet assembly, shown in Fig. 8, reveals that there is a total of five objects that are fixed to the shaft and thus can be treated as bearings.

With these values known the shaft horsepower at the propeller, $[SHP]_p$, the propellers rotation speed, N_p , and the propellers torque, T_p , can be found using Eqs. (19) and (21), shown below.

$$[SHP]_{p} = [SHP]_{g} \cdot \left(\frac{100 - [PL]_{b}}{100}\right)$$
(19)
$$[SHP]_{p} = 64527 \ hp$$

$$N_p = \frac{N_{max}}{G_r} \tag{20}$$

$$N_p = 689 \, rpm$$

$$T_p = \frac{5252 \cdot [SHP]_p}{N_p} \tag{21}$$

$$T_n = 491807 \, ft - lb$$

This concludes the basic power analysis of the engine and fan blade, with the previous values the necessary diameter for the fan blade, D_b , is found below.

$$D_b = \frac{632.7 \cdot [SHP]_p^{0.2}}{689 \, rpm}$$
(22)
$$D_b = 114.871 \, in$$

The following design parameter are now defined:

• The fan diameter is less than the maximum allowable diameter of 114.88 inches so the fan blade will satisfy the geometric requirements.

• Knowing the nose cone's diameter is 32.45 inches the mean-width ratio blade ratio is thus 0.2825, meaning that 28.25% of the props disc area is blades.

• In real life applications propellers are generally created such that each inch of the blade diameter is equivalent to 2.5 inches of pitch. Therefore, the prop pitch of this fan blade is 287.175 inches.

The thickness of blade is estimated to be 0.5 in. The fan blade the width of each blade, w_b , is determined below [3].

$$w_b = \frac{\pi \cdot C_b}{b_\# + c \cdot b_\#}$$
(23)
$$w_b = 15\,786\,in$$

With the maximum width and the length of the blade known the fan blade can now be modeled.

2.2.1 Force Analysis of a Fan Blade

To accurately analyze the lift and drag force a propeller blade which experiences the pressure distribution across the frontal surface needs to be defined. An actual blade for a propeller is designed to have low drag and high lift, since this is always made from a streamlined shape and of a high strength material due to its extremely thin thickness at the base. To overestimate the drag force on the blade the following properties will be used:

• A drag coefficient of 0.30 will be used for the blade;

• A rectangular reference area will be used corresponding to the blades maximum height and width.

Using Eqs. (11) and (10) for the reference area and drag force, respectively, the total drag force on the blade was calculated to be:

$$A_{ref} = h \cdot w$$
$$A_{ref} = 906.67 \ in^2 \approx 6.30 f t^2$$
The drag force, $F_D = \frac{1}{2} \rho_{\infty} V_i^2 A_r C_D$

$F_D = 481.99 \, lbf$

This value for drag force is far larger than what the blade will experience during operation.

2.2.2 Blade Rotor

Geometry of the Rotor: The blade rotor is a component of the propeller, it is the center ring that is usually fixed to the shaft and which the blades are mounted to. The rotor is hollow and contains numerous rotating components that are directly mounted to the shaft which runs through the center. The blade rotor houses many parts that are connected to the shaft and exist in series with other components located in the nose cone and other areas of the engine. For the blade rotor, there are four primary dimensions of interest, these being: the length, l, the thickness, t_r , the initial radius, R_i , and the final radius, R_f . With these values a solid model could be produced and the geometric restraints for the inner components can be established.

First the initial radius is to be determined. As it can be seen in Fig. 6, the initial radius of the blade rotor is directly related to the radius of the nose cone's base. The difference between the two radii is the product of two dimensions, the thickness of the nose cone, t_n , and the thickness of the blade plate, t_b . An up-close view of these dimensions as well as the nose cone and blade rotors radii as in Fig. 6.



Fig. 6 Blade rotor drawing.

For analysis, the following assumptions are made:

$$t_r = 1.12 \text{ in}, \ t_{rc} = 0.77 \text{ in}, \ t_b = 0.25 \text{ in},$$

$$\delta_{rb} = 0.024 \text{ in}$$

where δ_{rb} corresponds to the appropriate clearance between the blade plate and the blade rotor. These assumptions will be evaluated in each of their respective FE analyses. If it is found that an individual part will fail due to its loading its thickness will be increased and the dimensions of the surrounding components will be changed accordingly. With initial dimensions defined r_i can be determined using Eq. (24) and the corresponding inner radius can be found using Eq. (25).

$$R_i = R_{base} - t_n - t_b$$

$$R_i = 15.575 in$$
(24)

$$r_{i} = R_{base} - t_{n} - t_{b} - t_{rc}$$

$$r_{i} = 14.807 in$$
(25)

This dimension governs the angle at which the blade plate operates at and using a scaled drawing was determined to be, on average, between 20°-25°. For this analysis, θ is assumed to be 21.6°, knowing this and the width of the fan blade *L* and *R*_f can be calculated using Eqs. (26) and (28), the corresponding outer radius can also be calculated using Eq. (27).

$$L = w_b \cdot \cos\theta$$

$$L = 14.427 in$$
(26)

$$r_f = r_i + [w_b \cdot \sin \theta]$$

$$r_f = 20398 in$$
(27)

$$R_f = r_f + t_r \tag{28}$$

$$R_f = 21.1438 in$$
 (23)

The drawing of the blade rotor and blade plate can be seen in Fig. 6. As it can be seen from Fig. 6 the blade rotor and the blade plate have extremely similar geometries. For the design of the blade plate the section was segmented into pieces, the first being the piece of the left of the bend, circled in Fig. 7 and the second piece pertains to the right-hand side. The piece to the right of the bend has relatively simple geometry, since the thickness of the plate is known to be 0.50 inches and the slope is to be equivalent of the



Fig. 7 Solid model of individual fan blade, 4 views.

blade rotor the outer and inner radii can be established simply by altering Eqs. (24)-(28). These new equations along with results of the blade plate calculations can be seen below as Eqs. (24a)-(28a), which correspond to the outer and inner initial radius, the length of the blade and the inner and outer final radius, respectively. It should be noted that the subscript b in the previously mentioned equations denotes that these dimensions are now for the blade plate.

$$R_{ib} = R_{base} - t_n$$

$$R_{ib} = 15.837 in$$
(24a)

$$r_{ib} = R_{base} - t_n - t_b - \delta_{rb}$$

$$r_{ib} = 15.563 in$$
 (25a)

$$L_b = L_i = 14.427 in$$
 (26a)

$$r_{fb} = r_{ib} + [w_b \cdot \sin \theta] + \delta_{rb}$$

$$r_{fb} = 21.398 in$$
(27a)

$$R_{fb} = r_{fb} + t_r$$

$$R_{fb} = 21.898 in$$
(28a)

The Hollow Section. The Hollow Section, as the name implies, is a circular gap within the rotor, this area is where the primary shaft is located which the entire blade pitch control is fixated to. At this point in the analysis the height of the hollow section, $R_{\rm H}$, is

unknown since the shaft diameter has yet to be determined. When the shaft's dimensions are calculated R_H can be found using Eq. (29), shown below.

$$R_H = D_s + \delta_{br}$$

$$R_H = 10.15 in$$
(29)

where: D_s is the diameter of the shaft and δ_{br} is the clearance between the shaft and the blade rotor. From here we will move to the uppermost section, the electronics shaft.

The Electronics Shaft. The electronics shaft is a hollow shell which is located between the primary rotor and the fan blades. The primary purpose of this shaft is to protect the sensitive electrical components that are used in rotating the fan blades. Although there is no information regarding the dimensions for such a piece it is evident that it would be best to minimize the height of such a component to reduce the operating stress.

Before the dimensions of the electronics shaft can be determined its position within the blade rotor must be known. Since the electronics shaft runs wiring and electrical components into the individual fan blades it will be mounted such that the centerlines are aligned. This means that the center of the blade pitch control is exactly at half the length of the blade rotor. At this location, the maximum allowable height, H_{max} , can be calculated using simple geometric relations, shown below, as Eq. (30).

$$H_{max} = L_{es} + L_{sr} + R_{pr} = \frac{r_i + r_f}{2}$$
(30)
$$H_{max} = 18.035 in$$

2.2.3 The Spacing Ring and Primary Rotor

The spacing ring is used to support the electronic shaft at the point where it meets the primary rotor. Its entire purpose is to help dissipate force applied to the electronic shaft and it also prevents any rotation or slip. The primary rotor is the body of the blade pitch control, it is mounted to the primary inlet shaft and both the spacing ring and the electronic shaft are directly mounted to it. Using D_{es} , the remaining thickness and diameters were determined using similar scaling factors used in the previous section, the equations for these factors can be seen below as Eqs. (31)-(33).

$$D_{es} = 0.0625 \cdot w_b \tag{31}$$

$$t_{pr} = 1.8 \cdot t_{es}$$

$$t_{pr} = 1.776 in$$
 (32)

$$D_{sr} = 1.07 \cdot \left(\frac{D_{es} + t_{pr}}{2}\right) \tag{33}$$

 $D_{sr} = 1.478 in$

The radii for the multiple components of the blade pitch control are calculated below. Using equations, A (from before) and B (from before) as well as the scaling factors shown below as Eqs. (34) and (35) the geometry for the blade pitch control can be completely defined. Eq. (30) is used to find R_{pr} .

$$L_{es} = 0.140 \cdot H_{max}$$
$$L_{es} = 2.525 \tag{34}$$

$$L_{sr} = 0.199 \cdot L_{es}$$

$$L_{sr} = 0.501 in$$
(35)

$$R_{pr} = H_{max} - L_{es} - L_{sr}$$

$$R_{pr} = 15.009 in$$
(36)

The drawing of the blade pitch control can be seen in Fig. 13.

3. Primary Inlet Shaft: Sizing the Inlet Shaft

Initial assumptions are listed as:

(1) The turbine shaft is subjected to constant bending and torsion only.

(2) The bending stress is completely reversible and the torsion is steady.

(3) The shaft operates in temperatures between 70 °F-100 °F.

Design parameters are listed below:

Known parameters:

Length of shaft (<i>L</i>)	32.29	inches
Required propeller power (P)	64,527.0	hp
Maximum speed of shaft (N_{max})	2,550	rpm
Midrange beginning moment (M_m)	0	-

Alternating torque (T_a)	0	-
Yield strength (S_y)	111	kpsi
Tensile strength (S_{ut})	156.0	kpsi
Density of steel (ρ_{steel})	0.282	lbf/in ³
Stress-concentration factor (K_f)	2.2	-
Stress-concentration [shear] (K_{fs})	1.8	-
Factor of safety (<i>n</i>)	1.6	-

Failure criterion is to calculate an appropriate diameter for the turbofan's shaft the fatigue resistance of the part will be analyzed. The DE-Gerber criterion has relatively high values up until the materials tensile strength it will the chosen criterion for this design. The De-Gerber equation can be seen below in Eq. (37) and composes of Eqs. (37a) and (37b).

$$d = \left(\frac{8nA}{\pi S_e} \left\{ 1 + \left[1 + \left(\frac{2BS_e}{AS_{ut}}\right)^2\right]^{\frac{1}{2}}\right\} \right)^{\frac{1}{3}}$$
(37)

$$A = \sqrt{4(K_f M_a)^2 + 3(K_{fs} T_a)^2}$$
(37a)

$$B = \sqrt{4(K_f M_m)^2 + 3(K_{fs} T_m)^2}$$
(37b)

In order to calculate the shaft's diameter using the DE-Gerber equation, the following properties need to be defined; endurance limit at the critical location, S_e , the factor of safety, n, the shaft material's tensile strength, $S_{\rm ut}$, the stress concentration factors due to fatigue and shear, $K_{\rm f}$ and $K_{\rm fs}$, respectively, and the alternating and midrange moments and torques, $M_{\rm a}$, $M_{\rm m}$ and $T_{\rm a}$, T_m , respectively.

Material selection: Before any of the previously mentioned properties can be calculated, an initial material, much be chosen for the shaft. Since the shaft being designed will experience relatively high temperatures [assumption 3] the chosen material's melting point must surpass these operation temperatures and the material's strength properties cannot be to adversely affect. Due to these considerations, a carbon steel was chosen to be the initial material, specifically AISI 1060 Q&T at 1,000 °F. The mean mechanical properties of AISI 1060 Q&T and $S_{\rm ut} = 156$ kpsi.

3.1 Determining the Endurance Limit

The first value that will be calculated is the endurance limit at the critical location, S_e . Although this value is generally determined through a lengthy procedure and stress testing, for the preliminary analysis a quicker calculation, using Eq. (38), will be used.

$$S_e = k_a k_b k_c k_d k_e k_f S_e^{\prime} \tag{38}$$

Eq. (38) uses an estimation for the endurance limit, S_e' , as well as six endurance limit modifying factors, $k_a, k_b, k_c, k_d, k_e, k_f$, which are designed to account for the different conditions which affect the failure resistance of the part. The addition of these factors yields a more accurate value for S_e which will indirectly allow a more realistic value for the shaft's diameter to be obtained.

The $S'_e = 78.0$ kpsi is used here. Using Eq. (39), S'_e can be determined by simply knowing S_{ut} for the chosen material. Now that S'_e has been established the endurance limit modifying factors, also known as Marin Factors will be implemented. The modifying factors are estimated as:

$$k_a = a \cdot S_{ut}^b = 0.8723 \tag{39}$$

The size factor, $k_{\rm b}$, is determined as:

$$k_b = 0.732$$

The loading factor, k_c , due to bending consideration, is estimated as:

 $k_c = 1.0$

The temperature factor, k_d , is calculated as:

$$k_d = 1.008$$

The factor k_e is estimated as: 0.0659. Then, S_e value is estimated as below:

$$S_e = 32.814 \ kpsi$$

3.1.1 Stress Concentration Factors

Stress concentration factors account for regions of high stress caused by discontinuities within parts. These discontinuities are known as stress raisers since the stress distributions within the surrounding areas are altered to the point where the elementary stress equations no longer describe the state of stress. The stress concentration factors can be obtained for the appropriate geometry and loading applicable in this design; $K_f = 2.2$, $K_{fs} = 1.8$.

3.1.2 Moment and Torque on the Shaft

To calculate A and B, Eqs. (37a) and (37b), the midrange and alternating torques and moments, M_a , M_m , T_a and T_m must be determined. Since it is already known that the alternating stress is negligible, M_a and T_a are thus equal to zero. Only the midrange moments and torque must be determined, this was done using superposition. Superposition allows for the effects of combined loading to be solved by analyzing each load separately and then summing the resultants. It is hoped that the effect of each load is linearly related to the load that produces it, load does not create a condition that affects the results of another load, and the deformations resulting from any specific load are not large enough to significantly alter the geometric relations between the parts.

Using superposition, the primary loads, F_1 , F_2 , F_3 , F_4 , F_5 and their effect on the shaft and bearings will be analyzed separately. Each load is the resultant of one of the cylindrical parts pushing down on the shaft, and can be calculated using Eq. (40).

$$F_i = \left(\frac{\pi d^2}{4} w_i\right) \rho_{steel} \tag{40}$$

where: w_i is the thickness of the part and d is the corresponding diameter. Using the above equation, the forces from each component on the shaft and their corresponding data could be determined.

The final diameter for the shaft can be determined.

$$d = 9.879 in$$

 $R_{1t} = 217.59 lbf$
 $R_{2t} = 167.49 lb$

To keep standard sizes, the diameter for the shaft is to be rounded to 10.0.

3.2 Tolerance Analysis; Shaft Tolerance

Every mechanical part must account for some degree of tolerance regardless of its application. This tolerance is a measure of variation accumulated during manufacturing and assembly, simply put it is the possible error in the geometry of a part as it moves from the theoretical design to assembly. In the design of aircraft engines tolerances are generally kept extremely low for parts critical to performance and reliability, a typical value is ± 0.0001 inches. For parts that fall outside the scope of these extremely precise tolerances values typically range from $\pm 0.010 \sim \pm$ 0.001 inches. For the tolerance analysis, the parts will be considered in an inward to outward manner, meaning from the innermost parts to the exterior ones.

First the inlet shaft will be considered; it is the centermost part of the turbofan assembly and will therefore govern the tolerances of most surrounding parts. From Eq. (37) and the design parameters the following geometric properties are known for the shaft;

$$d = 9.879 in$$

 $L = 32.290 in$

Lastly the midrange torque must be calculated so that the final diameter can be determined using Eq. (41), where; H is the power in units of horsepower and N_{max};

$$H = \frac{T_m N_{max}}{63025} \tag{41}$$

$$T_m = 10169.36 \ lb \cdot in$$

Factors A and B can be calculated by referring to Eqs. (37a) and (37b).

A = 18,402,166.0

and

$$B = 10,546.06$$

3.2.1 The Final Diameter

To minimize the manufacturing cost the diameter of the shaft was rounded up to 10 in.

The minimum and maximum clearance for the

Table 3 Tolerance data for the shaft assembly.

assemblies can now be calculated. A sample calculation can be seen below and a culmination of the results is displayed in Table 3 where *t* corresponds to the parts tolerance and yellow cells correspond to interference fits.

As it can be seen in Table 3, there are no apparent problems using the diameters and tolerances specified. Tolerances were kept within a reasonable range where most were to the thousandth place and with only one part needing to be extremely precise.

Next the same analysis was performed but in respect to the outer diameters of each piece and the blade rotor, which houses all the mentioned components. Since the diameter of the rotor changes with respect to length the diameter must be specified for each part to keep the analysis accurate. Table 3, is the results of the tolerance analysis on the outer diameters.

 $w_b = 15.786 \pm 0.0001 \text{ in}, \ w_{b,min} = 15.7859 \text{ in}$ $w_{b,max} = 15.7861 \text{ in}, \ c_b = 0.27 \pm 0.0001$ $c_{b,max} = 0.2701, \ c_{b,min} = 0.2699$ $L_b = 47.24 \pm 0.0001 \quad , \quad L_{b,max} = 47.2401$ $L_{b,min} = 47.2399$

4. Solid Modeling: Nose Cone

A step by step method for the solid model is presented below.

(1) First select the *Points* (+) command, afterwards right click to open the general menu and select *options*. This will open the *Points Creation Options* menu. Allows the user to specify the exact x and y coordinates of each point. Each point was input so that a general shape was established.

Part name	Inner, d	t	d_{max}	d_{min}	ϕ_{max}	ϕ_{min}
Inlet shaft	10.00	± 0.0050	10.005	9.995	-	-
Blade mount	10.05	± 0.0050	10.055	10.045	0.0600	0.0400
Block	9.90	± 0.0100	9.910	9.890	-0.0850	-0.1150
Mid-block	9.90	± 0.0100	9.910	9.890	-0.0850	-0.1150
Pitch control	9.99	± 0.0001	9.9901	9.9899	-0.0049	-0.0151
Rear mount	10.01	±0.0050	10.015	10.005	0.0200	0.0000

(2) Then using the *spline* (\backsim) tool each point was selected so that a solid line defining the profile was created.

(3) Since the nose cone is hollow the previous spline had to be mirrored, using the offset (=) tool and a chosen distance of 0.5 inches the reference geometry was created. With the reference geometry established the solid model could now be created. Using the revolve (=) tool the reference geometry was selected and revolved about the *x*-axis indicated. This produced the final solid model.

4.1 Blade Rotor

(1) First a basic profile for a rotor needed to be created. Since the entire length of the rotor was known to be 14.427 inches a line of this length was formed. Now two vertical lines were formed of length 15.575 and 21.438 inches and each was placed at one end of the horizontal line, corresponding to the outer diameters of the front and back of the rotor, respectively.

(2) Next an angled line was formed at the end points of the two vertical lines.

(3) Now the offset tool was used and the angled line was offset 1.12 inches in the downward direction.

(4) Finally, the revolve tool was used, the two angled lines are chosen along with the thin segment of the vertical lines that separate them. These forms the solid model.

The drawing of the blade pitch control can be seen in Fig. 8.

Once the solid model was created holes needed to be drilled from the rotor where the electronics shaft of the blade pitch control part could fit into. Using the center of the blade pitch control as a reference a circle of diameter 1.00 inches was formed.

(5) Using the extrude tool the formed circle was selected, for the length of the extrusion the *threw all* value was selected along with the *Cut* option. This created the necessary whole in the blade rotor.

(6) Lastly the cut hole was selected and the circular

pattern tool was used, the center point and pattern radius correspond to those of the Blade Rotor. A total number of 18 objects were to be created on the patterns circumference in correspondence with the total number of fan blades. The solid model of the blade rotor can be seen in Fig. 7.

4.2 Fan Blade

(1) First a basic profile for a blade needed to be created. This was done by selecting the circle tool and creating two circles off radii 2.00 in. and 0.29 in.

(2) The two circles were then offset by 12.84 in. and joined at both sides using the spline tool. This allowed for the basic blade profile to be established, this profile can be seen in Fig. 7.

(3) Once the basic profile has been created the rectangular pattern tool was selected. Using this tool 6 additional copies of the blade profile were created all of which were equidistant by 6.70 in.

(4) Each profile blade, with exception to the first, was then scaled multiple times by a factor of 1.1 depending on its position. Each blade was scaled by a value of 1.1 by the amount of times equal to the number of blade profiles before it (ex. the 3rd profile was scaled by 1.12 times).

(5) Like step 4, each profile was then rotated by 15° by the amount of times equal to the number of blade profiles before it.

(6) Using the loft tool each profile was then selected; the wireframe result of this can be seen below in Fig. 8.

(7) Lastly, the solid model for the Blade Shell was taken out of from the parts bin. Using the cut tool, the rotor was selected as the cutter part and the solid model for the blade was selected as the part that was to be cut in the respective prompt windows. The purpose of this was to shave off the lower half of the blade and create the appropriate angle where the blade would be mounted to the rotor. The final solid model of an individual fan blade can be seen in Fig. 7.



Fig. 8 Wireframe of the blade pitch control.

4.3 Blade Pitch Control

(1) First the basic profile needed to be created. Using the circle tool, two circles of radii 15.05 and 5.05 were created which represent the inner and outer diameter of the blade pitch control.

(2) Next the two circles were selected and extruded 1.78 inches to form the base cylinder. Then the two corners of the inner cutout were then selected and a fillet of 0.25 in was applied.

(3) Next another was created of diameter 15.55 inches was formed with its center point corresponding to that of the cylinder. This circle is to be used as a guide and is equivalent to the maximum height of the spacing ring.

(4) To create the spacing ring the plane parallel to the previously created cylinder needs to be selected. On this place, another circle was formed of diameter 1.48 with its center point corresponding to that of the cylinder. The circle was then moved 14.0 inches along the z axis, at which point it should sit within the solid cylinder.

(5) Next the circle was selected to be extruded; instead of selecting a distance the option "until location" was chosen. The selected location is the outer circle previously created as a guide. (6) In order to create the electronics shaft the flat upper surface of the spacing ring was chosen and has the place to sketch on. Here a circle was formed of radius 1.00 inches with its center aligned with the midpoint of the spacing ring. The circle was then extruded 2.525 inches.

(7) Next the top of the electronics shaft needed to be trimmed so that it fits properly with the plate the blades would be mounted to. To do this the blade shell part was removed from the bin and the cut tool was implanted again. The blade pitch control was selected as the part to be cut and the Blade Shell was selected as the cutter part.

(8) Lastly the electronics shaft and the spacing ring needed to be patterned around the primary cylinder. This was done using the circular pattern tool. The center of the pattern was chosen as the center of the primary cylinder and the outer radius of the pattern was chosen as the outer radius of the primary cylinder. The number of objects on the circumference of the pattern was chosen to be 18 which corresponds to the number of blades on the propeller. This concluded the modeling phase of the blade pitch control and wireframe and the final model can be seen in Figs. 18 and 19, respectively.

4.4 Primary Inlet Shaft

(1) Unlike most parts, the solid model for the shaft is simple and requires no reference geometry. First, a circle was formed corresponding to the shafts outer diameter, 10.00 in. This circle was then extended 32.35 in. to form the main body of the shaft.

(2) Next the flat rear plane of the shaft was chosen to be drawn on, here a second circle of radius 3.25 inches was formed then extruded 29.35 inches.

(3) Next the front and rear corners of the primary shafts body was chamfered by a value of 1.00 and 0.50 inches respectively.

(4) Lastly a fillet of 0.25 inches was applied to the edge where the primary shaft body and the secondary shaft merge together.

	ĩ		-				
Part name	Outer, d	d _{rotor}	t	d_{max}	d_{min}	ϕ_{max}	φ _{min}
Blade rotor	15.14-20.94	-	± 0.0010	15.141-20.941	15.139-20.939	-	-
Blade mount	12	13.8	± 0.0010	12.001	11.999	1.802	1.798
Block	12	15.4	± 0.0100	12.010	11.990	3.411	3.389
Mid-block	14.5	16.46	± 0.0100	14.510	14.490	1.971	1.949
Pitch control	17.04	17.9	± 0.0001	17.040	17.040	0.861	0.859
Rear mount	11	19.346	± 0.0100	11.185	11.165	8.182	8.160

Table 4 Tolerance analysis of outer diameters for interior parts.

5. Finite Element Analysis

5.1 Nose Cone

Now that the design process has been complete the finite element analysis for each part can begin. For the nose the following assumptions must be considered before the analysis can be underway;

• The nose cone is initially tested at a thickness of 0.50 inch;

• The nose cone is assumed to be forged of aluminum;

• The drag force is a load distributed entirely across the frontal surface and is parallel to the direction of the nose cone;

• The nose cone cannot displace or rotate along its base;

• The only force acting on the nose cone is the calculated drag force of 582 lbf.

The results of the FE analysis can be seen in Figs. 9 and 10.

The nose cone is in no danger of failing due to the loading caused by the drag force. The maximum Von Misses Stress encountered peaked at only a miniscule value of 0.01415 kpsi, far below the ultimate tensile strength of aluminum. For the aluminum alloy the chosen maximum tensile strength ranges from 32-40 kpsi, diving this by the maximum stress from the load yields the factor of safety, seen below in Eq. (42).

$$\eta = \frac{\sigma_{yield}}{\sigma_{max}}$$

$$\eta = \frac{32 \, ksi}{0.01415 \, ksi} = 2261.5$$
(42)

Next the heat transfer of the nose cone was performed using the FE analysis method. For this analysis, the heat transfers from the air to the nose cone using forced convection was considered along with the transfer throughout the nose cone by conduction. Using the temperature restraint on the base the heat flux was applied to the outer surface and the thermal conductivity of the material was gauged. The results of the FE analysis can be seen below in Figs 9-11.

As it can be seen from Figs. 9 and 10 the entire nose cone operates at quite low temperatures. There is some effect on aerodynamic heating but since at that altitude the air is quite cold and the plane is not going nearly fast enough the entire part remains around 0 °F and is clearly in no danger of melting or deforming due to this.

5.2 Fan Blade

The next part that will be analyzed for failure will be the fan blade. Since the drag force calculations are only for an individual fan blade only one blade will therefore be analyzed. This is valid since each blade is symmetric and therefore will experience the same force and possibility of failure. For the fan blade the following assumptions must be considered before the analysis can be underway:

• The fan blade encounters only a loading due to drag therefore the lift forces also acting on the blade are negligible;

• The fan blade is fixed at its lower surface, where all displacement and moments are constant;

• The plate the fan blade is attached to is fixed and therefore all displacement and moments are constant;

• The nose cone is assumed to be made from titanium.







Fig. 10 FE stress analysis of the nose cone, isometric view.



Fig. 11 Thermal analysis of the nose cone, isometric view.

• The forces only act on the frontal surface of the fan blade and act at an angle of 40° in respect to the surface.

Using the previously listed considerations as

parameters the fan blade was tested using a frontal drag force of 500 lbf. The results of the FE analysis can be seen below in Figs. 13-15.

As it can be seen in Figs. 6-8, the stresses in the fan blade are relatively low although the maximum encounter stress is larger than that experienced by the nose cone. Due to the large surface area of the fan blade it acts like a cantilever beam, due to this the maximum force develops at the base of the blade, indicated by the color gradient. Overall the maximum stress that was experienced was 7.143 kpsi. Since the forces on this blade are only estimations this stress is quite considerable and close to the yield of many lighter materials. Due to the high probability that a fan blade will fail at corners and distribute stress poorly in these areas most blades are formed of titanium alloys. Using Eq. (42) the factor of safety for the fan blade is:

$$\eta = \frac{120 \ ksi}{7.143 \ ksi} = 16.8$$

As it can be seen from the results the factor of safety for the fan blade is 16.8. Although this value for a factor of safety is high as it has been mentioned the forces acting on the blade are only estimations.

Comparing these results to that of the nose cone it shows the vast different the geometry makes; the nose cone was subjected to forces only 11.6% higher and the achieved a factor of safety 13,000% higher than that of the fan blade. This shows how sensitive the fan blades are to stress and for this reason titanium has been chosen for the material of the fan blades.



Fig. 12 Cone thermal analysis nose cone, side view.



Fig. 13 FE stress analysis of fan blade, side view.



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Fig. 14 FE analysis of fan blade, frontal view.



Fig. 15 FE analysis of fan blade, isometric view.

5.3 Inlet Shaft

The last part that will undergo a finite element analysis is the primary inlet shaft. Although the geometry of the shafts design is simple the calculations and forces it must undergo are extensive. The shaft is used to transmit work and toque, and has six forces acting on it at different points, the forces due to the weight of the mounted components and the distributed force from its own weight. Before the FE analysis will be performed the following considerations must be considered:

• The shaft is fixed at both of its end surfaces;

• The mounted components apply no force other than their own weight;

• The concentrated forces act only on the upper surface of the shaft;

• The distributed load acts across the entire shafts center axis.

Using the previously mentioned considerations as parameters the FE model for the shaft was produced. The concentrated and distributed loads on the shaft are equivalent to those calculated in Eqs. (4) and (5) and displayed in Table 4. The results of the FE analysis can be seen in Fig. 16.

It is seen in Fig. 16, the resulting stress on the shaft is extremely low, with the maximum stress only peaking around 0.0109 kpsi.

These stresses were seen at the ends of the shaft where they were fixed. It is reasons like this why stress concentration factors are accounted for in the calculations for the shafts diameter since any increase or decrease in diameter at a specific point will cause an area prone to high stress. Due to the low maximum stress, any steel would suffice as far as preventing failure goes. The factor of safety for this part will not be calculated since like the values obtained in the nose cone FE the 8 results would be on the order of thousands.

These calculations were then backed up my performing an FE analysis by hand; this is a complicated procedure which requires numerous



Fig. 16 FE analysis of primary inlet shaft, side view.

equations and time. For simple geometry such as the shaft the FE analysis becomes plausible however for other geometries the task quickly becomes too great for a normal person. The calculations and results of the FE analysis can be seen below on the following pages.

6. Solid Models of the Final Assembly

Now that all the calculations and analysis of each part have been performed the final part was assembled. Below in Figs. 17-20 some images of the final solid model can be seen.

6.1 Final Assembly

Engines are constructed by manually combining the various subassemblies and accessories. An engine is typically built in a vertical position from the aft end forward, on a fixture that will allow the operator to manipulate the engine easily during building up. Assembly begins with bolting the high-pressure turbine (that closest to the combustor) to the low-pressure turbine (that furthest from the combustor). Next, the combustion chamber is fastened to the turbines. One process that is used to build a balanced turbine assembly utilizes a CNC (computer numerically controlled) robot capable of selecting, analyzing, and joining a turbine blade to its hub. This robot can determine the weight of a blade and place it appropriately for a balanced assembly.

Once the turbines and combustion chamber have

been assembled, the high and LPCs are attached. The fan and its frame comprise the forward most subassembly, and they are connected next. The main drive shaft connecting the low-pressure turbine to the low-pressure compressor and fan is then installed, thus completing the engine core.

After the final subassembly, the exhaust system, has been attached, the engine is ready to be shipped to the aircraft manufacturer, where the plumbing, wiring, accessories, and aerodynamic shell of the plane will be integrated.



Fig. 17 Inner assembly, 4 views.







Fig. 19 Frontal mount, 4 views.



Fig. 20 Read mount, 4 views.

The overall cost a turbofan engine usually ranges on the order of millions. Due to such advanced technology, extensive testing, low tolerances and the multitude of staff working on such a project estimating a cost can be quite challenging. It is for this reason that most of the cost analysis will come from analyzing material and possibly labor costs.

7. Cost Analysis

The overall cost a turbofan engine usually ranges on the order of millions. Due to such advanced technology, extensive testing, low tolerances and the multitude of staff working on such a project estimating a cost can be quite challenging. It is for this reason that most of the cost analysis will come from analyzing material costs.

Material costs is calculated as:

$$\rho_{Ti} = 0.1620 \frac{lbf}{in^3} , \quad \rho_{Al} = 0.0975 \frac{lbf}{in^3} , \quad \rho_{St} = 0.2820 \frac{lbf}{in^3}$$

The cost of each part was then determined by finding their corresponding volume and multiplying this by the density then cost per pound of material, C. This is represented by Eq. (43).

$$Cost [\$] = V\rho C \tag{43}$$

An example would be the inlet shaft, knowing its outer diameter is 10.00 inches and the length is 32.29 and that the density and cost of AISI 1060 Steel is $0.2820 \frac{lbf}{in^3}$ and \$455 per ton the total

material cost is;

$$Cost [\$] = \left[\frac{\pi d^2}{4}\right] \rho C$$
$$Cost [\$] = \$162.70$$

Table 5, displays the results of the material cost analysis for each part, these values were calculated using Eq. (43).

As it can be seen from Table 5, the largest of the material costs occur from the fan blade. The reason for this is due to the large volume of the fan blades along with the extremely expensive cost of titanium. It should be noted that most areas were scaled up therefore the total cost is a high overestimation of the actual costs. This overestimation will be used to account for unforeseen costs and cover complications that will inevitably occur.

8. Life Cycle Analysis and Energy Estimation of Turbofan Engine

Aircraft systems, due to high cost and the risks associated with their development, are a major use of life cycle analysis (LCA). To ensure competitiveness, engineers must pay more attention to economic feasibility. This is achieved through an LCA approach to engineering design. The system life cycle includes development, production design, operation, maintenance, and disposal. The design process is divided into three major phases: (i) conceptual design, (ii) preliminary design, and (iii) detail design. These artificial categories, along with test and evaluation, make up the four-basic phases of system design. It is essential that design engineers should be sensitive in utilization and the disposal of recycling, reuse, and disposal to landfill.

9. Energy Estimation

An attempt has been made to estimate the total energy required to manufacture the indexing head for a milling operation. The total energy is a composite of embodied energy and the processing energy. The procedure is presented below [7].

9.1 Embodied Energy

A bill of materials is drawn up, listing the mass of each component used in indexing head design and the material of which it is made. Embodied energy is the energy consumed by all the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport, and product delivery.

A list of embodied energies of some representative materials has been provided in Table 6. Similar data for CO_2 emission kg/kg are also available in the literature [5] and are used for estimation CO_2 emission. Multiplying the mass of each component by embodied energy and summing up gives the total embodied energy.

All mass of materials was estimated in lbs. and then converted to kg to facilitate the use embodied energy data available. The total embodied energy is 15,310 MJ. However, it may be useful to upgrade this value as most of the materials energy used may be more than estimated here.

 Table 5
 Processing energy estimation for turbofan engine.

9.2 Processing Energy

This section focuses on primary shaping processes since they are generally the most energy-intensive steps of manufacture of indexing head. The materials and manufacturing processes are presented in Section 5. The process energy and CO_2 per unit mass are retrieved from Ref. [5]. Multiplying the mass of each component by its primary processing energy like milling, turning, drilling, or grinding and summing up gives an estimate of the total processing energy along with CO_2 emission.

The processing and embodied energy per kg is retrieved from Ashby [5]. The processing could also be calculated from the manufacturing power calculated from unit power (P_u) given in most of the manufacturing textbook.

The total energy to manufacture an indexing head for milling operation is about 16,335 MJ and CO_2 released in atmosphere is about 800 kg. All other GHG emission like SO₂, CH₄, N₂O, and H_g can also be estimated. However, here only CO₂ is presented for

Parts	Mass of material (kg)	Processing energy (MJ/kg)	Processing energy
Inlet shaft	400, super alloy steel	4.6	1,840 MJ
Nose cone	8, aluminum	2.9	60 MJ
Blade rotor	687, nickel based super alloy	4.06	2,817 MJ
Blade pitch	60 low carbon CD steel	5	300 MJ
Electronic tube	1, medium carbon steel	4	4 MJ
Spring ring	1, medium carbon steel	4	4 MJ
Fan blade	205 nickel based super alloy	5	1,025 MJ
Total processing energy			6,050 MJ

Table 6	Embodied	enrgy	estimation	for	turbofan	engine.
						~

Parts	Mass of material (kg)	Embodied energy (MJ/kg)	Estimated embodied energy	
Inlet shaft	400 kg super alloy steel	38	15,200 MJ	
Nose cone	8, Al	240	1,928 MJ	
Blade rotor	687, nickel based super alloy	150	103,050 MJ	
Blade pitch	60 low carbon CD steel	35	2,100 MJ	
Electronic tube	1, medium carbon steel	38	38 MJ	
Spring ring	1, medium carbon steel	38	38 MJ	
Fan blade	205, nickel based super alloy	150	30,750 MJ	
Total embodied energy			15,310 MJ	

atmospheric pollution due to manufacture of one indexing head. The total energy spent in manufacture of a turbofan engine is estimated here is 159,154 MJ or close to 600,000 kWhr [7].

10. Conclusion

An attempt has been to present complete design and analysis including FE analysis. The solid modeling of each components of the turbofan has presented based on the designed dimensions using CAD software NX 11.0. the final assembly of the turbofan presented some problems in NX modeling and the software was modified to finally present the assembled 3-D view of the tubofan engine. The assembly problem was mainly related to tolerances and it has to be modified again and again to get the final assembly. The cost analysis has also been presented and it is hoped that this approach will open cost estimation of aircraft engine before it is manufactured. We have also attempted to estimate the total energy including embodied energy and processing For sustainability energy.

considerations the energy estimation should be useful.

References

- [1] Raymer, D. 2006. *Aircraft Design: A Conceptual Approach* (4th ed.). AIAA Education Series.
- [2] Hoburg, W., and Abbeel, P. 2014. "Geometric Programming for Aircraft Design Optimization." Warren Hoburg, Pieter Abbeel. AIAA Journal 52: 2414-26.
- [3] Kirschen, P. G., Burnell, E., and Hoburg, W. 2016. "Signomial Programming Models for Aircraft Design (AIAA 2016-2003)." Presented at the 54th AIAA Aerospace Sciences Meeting, 10.2514/6.2016-2003.
- [4] Anderson, J. D. 2001. *Fundamentals of Aerodynamics* (3rd ed.). McGraw-Hill.
- [5] Ashby, M. F. 2009. *Materials and the Environment: Eco-Informed Material Choice*. Canada: Elsevier Inc.
- [6] Shigley. 2008. Mechanical Engineering Design (eighth ed.), edited by Richard G. Budynas, and J. Keith Nisbett, McGraw Hill.
- [7] Jha, N. K. 2018. "Computer Aided Design and Finite Element Analysis under Sustainability Consideration of Turbofan Engine." Presented at 9th International Conference on Engineering Education for Sustainable Development (EESD 2018), Rowan University, Glassboro, NJ, June 3-6, 2018.