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Design and Structural Analysis of Propeller Blade for High Altitude Search and Rescue Unmanned Aerial Vehicle

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Abstract

The commercially available UAV are designed for sea level altitude range thus they are not good enough for high altitude search and rescue flight. The objective of this research is to design thrust optimized blade for altitude range of 3000 - 5000 m with density of air 0.90912 - 0.7364 kg/m^3 respectively and perform structural analysis.

Aluminum alloy 1060 being light weight is chosen for blade design. The blade element theory based design and analysis code was developed and user friendly aerodynamic inputs were used to obtain the desired outputs.The blade 2 designed for altitude range of 3000-5000m faced the centrifugal stress of 2.7 MPa where as the bending stress faced by same blade was 3.8 MPa. Thus, the total stress faced by the blade was 6.0 MPa which was at 70% of the blade span.This stress is within limit of yeild strength of Aluminum alloy, 28 Mpa. The FEM based solver (ANSYS) was used for validation. The results of centrifugal stress was 3.11 MPa and combined stress was 9.35 MPa, both stress were observed at the 70% of blade span. The modal analysis shows the first natural frequency occurs at around 12000 RPM. Thus the blade is safe for operating between 0-5000 RPM in altitude range 3000-5000m from sea level.

Keywords

UAV, Propeller, High altitude, Thrust, Bending Stress, Centrifugal Stress

1. Introduction

Many commercially available propeller blades for unmanned aerial vehicles (UAVs) are not good enough for high altitude search and rescue flight because they are designed for sea level altitude. Commercial propeller aircraft have variable pitch propellers with complex mechanism which are suited for wide range of altitude. From the point of manufacturing complexity and cost per propeller it is better to design specific propeller blades for specific mission of UAVs than to design propeller for wide range of applications. The Above Sea Level (ASL) altitude for normal flying condition has been assumed to be in the range of 3000 to 5000m. This range has been chosen because search and rescue operation needed in Nepal are mostly in this regions. So the objective of this research is to design thrust optimized blade for altitude of range 3000 - 5000 m with density of air varying 0.90912-0.7364 kg/m^3 respectively. Due to this huge reduction in the density of the air,total thrust provided by the aircraft reduces at high altitude. After completion, this research work will help to improve propulsive efficiency of future SAR UAVs that will assist in rescue missions.

1.1 Propeller Theories

There are various theories which study the performance of propeller. The Momentum theory is the most fundamental theory and oldest among all of the propeller theories[1][2]. The explanation here is taken from Nelson's work[3]. The momentum theory assumes the propeller is a disk that creates a uniform thrust by the means of pressure difference between front and back of propeller. This theory does not take account for compressibility and viscous effects. The thrust force is given by Newtons Second law of motion, with simple modification equation 1 is used here for further calculation.

$$F_t = \frac{A\rho}{2}(V_s^2 - V_0^2) \tag{1}$$

Where, F_t is the Thrust force , A is disk area, ρ is density of air and V_0, V_s are the upstream and downstream velocity. Furthermore, efficiency is defined as the work output divided by the input work. Kinetic energy can be used to describe the input work, and thrust times velocity defines the work output. The propulsive efficiency (equation 2) and thrust force (equation 1) can be combined to get theoretical efficiency (3) in terms of density, free stream velocity, disk area and thrust. It can be seen from equation 3 that increasing thrust propeller produces, slowing free stream velocity or decreasing propeller disk area decreases the efficiency.

$$\eta = \frac{2}{1+\frac{V_s}{V_O}} \tag{2}$$

$$\frac{F_t}{2\rho V_0^2} = \frac{1-\eta}{\eta} \tag{3}$$

Where, η is the theoretical efficiency. A relatively simple method of predicting the performance of a propeller is given by blade element theory. The explanation here is taken from Dommasch and Weick's work [3] [4] [5]. The thrust force produced by rotating propeller is given by equation 4.

$$F_t = \int_0^r \frac{1}{2}\rho V_0^2 bdrBC_L \left(\frac{\cos(\gamma+\phi)}{\sin^2(\phi)\cos(\gamma)}\right) \tag{4}$$

where ρ is air density, r is the radius of blade, b is chord distribution [6] given by equation 5, B is number of blades and C_L is coefficient of lift. The angles γ given by equation 6 is the angle between lift (L) and drag (D) and ϕ is the effective pitch angle between free stream velocity (V_0) and rotational velocity (V_{rot}).

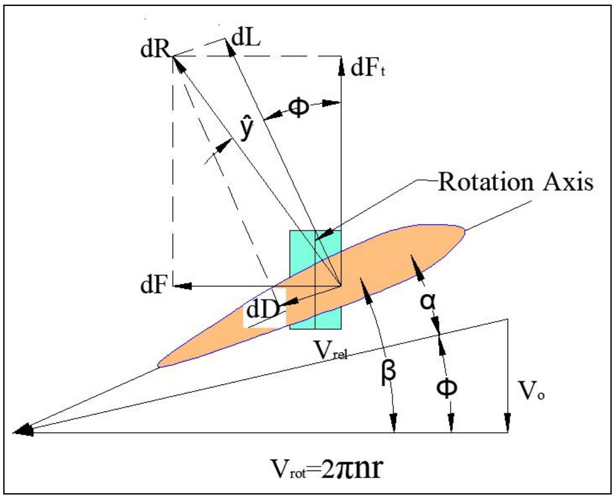

Figure 1: Geometrical parameters of blade

$$b = (0.084241 - 0.85789r + 4.7176r^2 - 9.6224r^3 + 8.5004r^4 - 2.7959r^5)2r \tag{5}$$

$$\tan\gamma = D/L = C_D/C_L \tag{6}$$

The efficiency in term of thrust force and torque is given by equation 7.

$$\eta = \frac{F_t V_0}{2\pi nQ} \tag{7}$$

Where, torque is given as $dQ = rdF$ .The simple blade element theory agrees with momentum theory that efficiency can be increased with increase in the free stream velocity. The simple blade element theory also adds that pitch angles also plays important role in efficiency, with increase in pitch angle theoretical efficiency also increases. The theory chosen here is simple blade element theory for its computational tasks being sufficient for high altitude propeller designing [6]. The third theory is vortex theory which is less often used due to the mathematical complexity used for calculation.This theory differs from momentum theory in terms that it takes into the account of 3D flow field effects on the propeller performance.This is done by calculation of losses due to vortex generation from the induced velocity created by the propeller as lift is created. This loss is similar to induced loss generated by an aircraft wing during flight [7] [8].

1.2 Factors effecting thrust generation

We can see from the equation 4 that increasing the radius of blade can increase the thrust produced. This enables an efficient high aspect ratio blade shape to be maintained but increases the tip velocity which is of critical importance as it may cause drag at high speed. Similarly, the other way to increase thrust is by increasing the solidity of propeller keeping the diameter unchanged. But this would also increase the aspect ratio which results in less efficient propeller blade. Thus, the above-mentioned problem can be addressed by adding more blade. A propeller with three blades can produce more thrust than two blades. The three bladed propellers generate 30% higher thrust [7] but that would increase weight of UAV and upon crash the replacement will cause the cost to be amplified. Thus only two number has been chosen here for design consideration.

Blade angle (β) depends on rotational velocity V_{rot}(=2πnr,where n is revolutions per second), increasing the rotational velocity increases the value of V_{rel} . Thus, overall geometry of blade depends on rotational velocity.

We can see from figure 1 that blade angle depends upon Angle of attack (α) and effective pitch angle (ϕ). The effective pitch angle depends upon the rotational velocity and air velocity. Since air velocity cannot be changed , the rotational velocity can be of great importance here for the thrust generation, with increasing rotational velocity the thrust can be increased but higher rotational velocity will cause increased drag and develop more stress at the motor.

1.3 Basic Design Methodology

The blade element theory is a useful basic methodology for propeller design and analysis. It is most common and still widely used due to its simplicity [9] [10]. There are many free software that uses blade element theory for propeller design and analysis. For example JBLADE [11] or JavaProp [12] are easily available online. However they cannot be modified and doesn't meet all the requirement of user. Consequently, a blade element theory based design and analysis code was independently developed and utilized for High Altitude SAR propellers. This code allowed the easy modifications of details and use of any airfoil by supplying customized aerodynamic data. Operating conditions such as forward flight velocity, rotational velocity (V_{rot}) and air density at design point are essential input parameters. The output results were thrust and efficiency. The designed blade has been further structurally analyzed and results are presented here.

1.4 Boundary Conditions and Assumptions

Velocity inlet and pressure outlet are used as the boundary conditions. The atmospheric pressure of 4000m is used as environment pressure. i.e 61400 Pa. The cruising speed of the aircraft is regarded as the velocity of the inlet i.e 10m/s. The surfaces of the propeller are set as wall boundary. The blade has been assumed fixed pitch type. Blade span radius (r=0.15) for 4000m altitude is assumed to be suitable for most of the existing UAV. The free stream air velocity is assumed to be average normal day air velocity.The material chosen was Aluminum for being light weight. The coefficient of lift was taken from experimental value of NASA [13] at the Reynolds number of 30,000. It has been assumed that the Reynolds number holds true for 34,000 as well.

2. Mathematical Modeling

The geometry of blade was first designed using the customized code in Matlab and modeled it in 3D based software, Autocad. The density of three different altitude was chosen such as at sea level, at an altitude of 4000m and at altitude of 8000m. The number of blade was chosen to be only two. The rotational velocity of propeller blade is chosen to have maximum limit of 5000 RPM, this is because the blade will have larger radius and with this geometry, higher RPM will cause blade root to experience more centrifugal force which may results in failure. It can be seen in figure 2 that the increasing rotational speed will increase thrust generation as well.

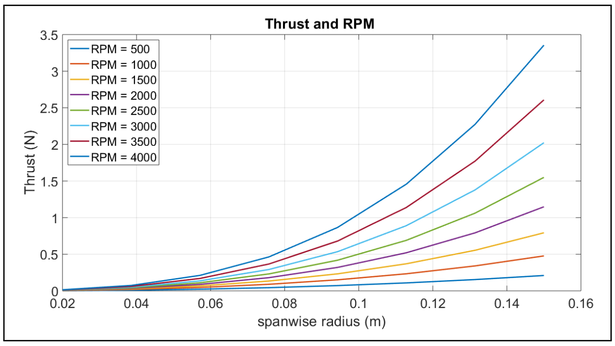

Figure 2: Figure showing thrust distribution for Blade 2 at various RPM

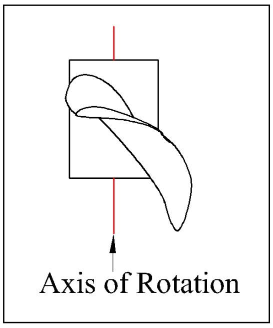

Figure 3: Variation of twist angle in blade designed for altitude 3000-5000m

2.1 Geometric Modeling

High lift low Re airfoil S1223 was used because it makes use of concave pressure recovery with afterward loading [14]. The blade generated the thrust of 3.35 N with radius of 0.15 m for an altitude of 4000m i.e. air density 0.8194 kg/m^3. Keeping all the parameters constant, for the same thrust generation the radius of blade necessary at sea level (air density 1.225 Kg/m^3) was 0.134 m. Similarly, for the same thrust generation at an altitude of 8000m (air density 0.5258 kg/m^3) the radius of blade necessary was 0.167m. Figure 4 shows the same geometry of blade for the same thrust output. The blade thickness increases towards the root which helps to withstand the centrifugal and bending stresses of the blade. The factors effecting the thrust output has been considered before designing the blade.

The twist angle variation for blade designed to operate at altitude 3000-5000m can be seen in figure 3. The chord distribution is given by equation 5 and it can be seen from figure 4 that the root side of the blade is thicker. This is due to fact that the internal loads in a propeller blade increases from the tip to the root, being maximum at the root. In order to keep the blade from breaking off due to the high loads at the root, it has to be thicker there to reduce the stresses induced by the higher loads.

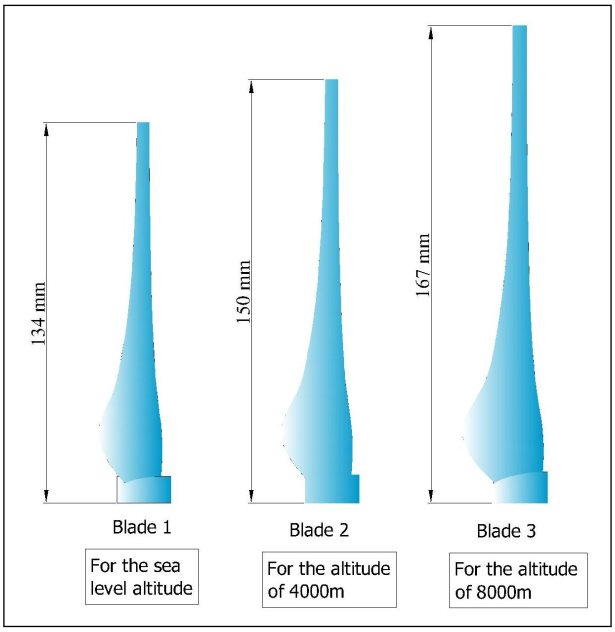

Figure 4: Three different blades for same thrust output (3.35 N)

2.2 Shear Force and Bending Moment

The shear force and bending moment diagram of blade 2 designed for altitude of 4000m can be seen in Figure 5 and Figure 6. The bending moment is based on resultant thrust loading. Since the thrust force acts upwards, the bending moment acts downwards or anticlockwise. Furthermore, as the radius of blade increases the shear force and bending moment increases as well. All this analysis were limited to the rotational velocity of 5000 RPM. Because this is the maximum speed the blade will receive , as mentioned earlier increasing this speed higher than 5000 RPM will cause the blade root to face more stress. Also the design of blade will be changed for higher RPM which needs further structural analysis.

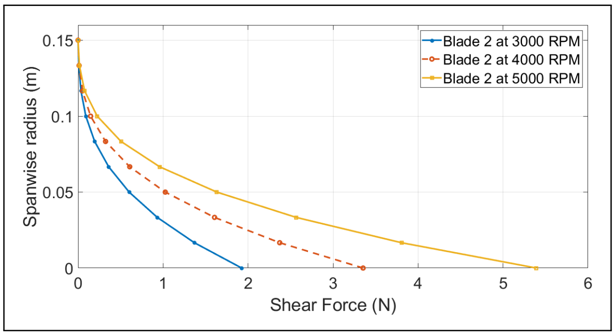

Figure 5: Shear Force distribution for Blade 2 at various RPM

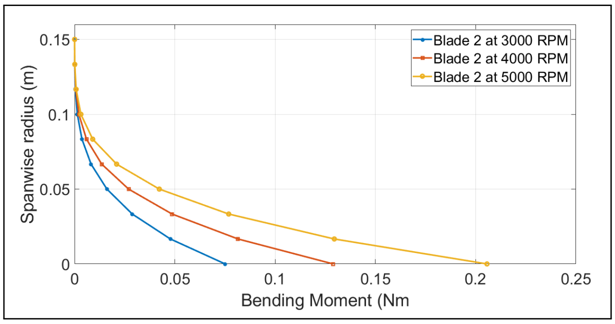

Figure 6: Bending Moment distribution for Blade 2 at various RPM

2.3 Stress Concentration

The load produced by lift force causes the blade to with stand bending stress and the rotational speed causes centrifugal stress. The stress concentration is calculated using equation 8 and can be seen in figures below.

$$\sigma_b = \frac{My}{I}, \quad \sigma_c = \frac{mv^2}{rA} \tag{8}$$

where, σ_b is stress produced due to bending moment, σ_c is the stress produced due to centrifugal force, M is the calculated bending moment, y is the vertical distance away from neutral axis, I is the moment of inertia, m is mass of blade at that section and A is the area of airfoil at that particular section.

The Figure 7 is the bending stress distribution and it can be seen that bending stress is maximum towards 70% of blade span towards root. This is because of the geometry of the blade, as the blade is thicker towards the root. The thicker section at root has more surface area coverage which increases moment of inertia thereby reducing the bending stress. Similarly figure 8 shows the centrifugal stress distribution, here also the stress is maximum towards 70% of blade span towards root. The total stress distribution ,combination of centrifugal and bending can be seen in figure 9. The maximum stress faced by blade is 6.5 Mpa with rotational velocity of blade as 5000 RPM and load of 2.7 N at the root. This stress compared to aluminum yield strength 28 Mpa is in limit and thus blade is safe to operate with rotational velocity range of 0-5000 RPM. For the structural strength purpose the blade root is thick as 7.1 mm where as the tip is thin as 1.5 mm.

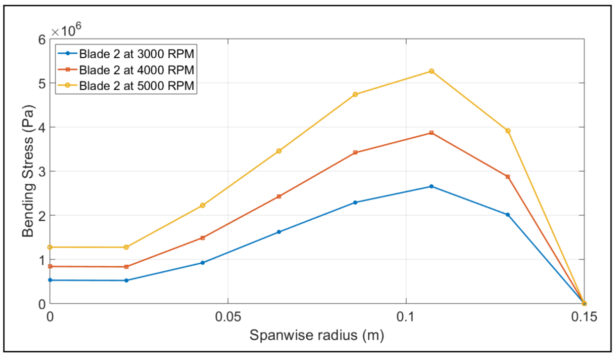

Figure 7: Bending Stress distribution for Blade 2 at various RPM

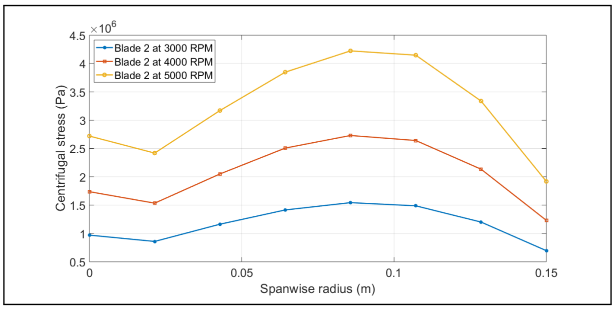

Figure 8: Centrifugal Stress distribution for Blade 2 at various RPM

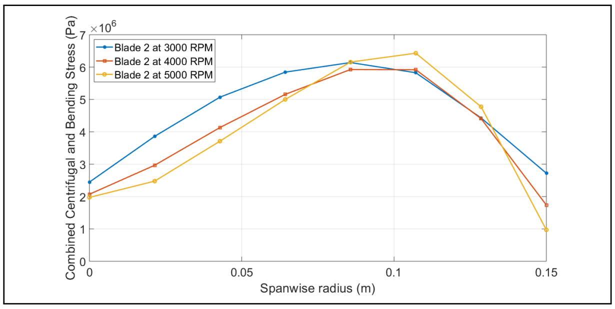

Figure 9: Combined centrifugal and bending stress distribution for Blade 2 at various RPM

3. Results and Discussions

The blade 2 designed for the altitude of 4000m have been analyzed for centrifugal, bending and other stresses. The designed blade was analyzed in FEM based solver, ANSYS static. The results are shown in figures below. Figure 10 shows the maximum centrifugal stress of 3.11 Mpa is developed in the 70% span of blade. The stress developed is due to pure bending caused by rotation of blade at 4000 RPM. Similarly, the combined stress of 9.35 Mpa is also observed at the 70% span of blade. The bending stress is produced by lift force varying from 3.35 N in the tip to 0 N in the root. The blade is proposed to operate under rotational speed of range 0-4000 RPM thus the stress analysis has been limited to 4000 RPM. Furthermore, the yield strength of aluminum is 28 Mpa which is very large than the produced stress. Thus it can be concluded that the blade will operate with out failure with in the rotational speed of 4000 RPM. The fatigue analysis of blade gave infinite life cycles of blade i.e. 10^8 *cycles* shown in figure 12 and figure 13. Although the blade was analyzed at 4000 RPM, it can be operated above the designed RPM (≈5000 RPM) given the factor of safety is high.

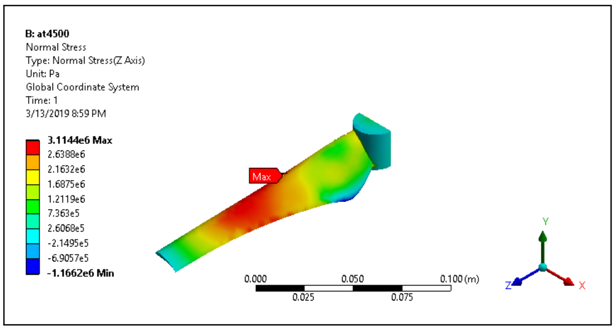

Figure 10: Figure showing centrifugal stress distribution for Blade 2 at 4000 RPM

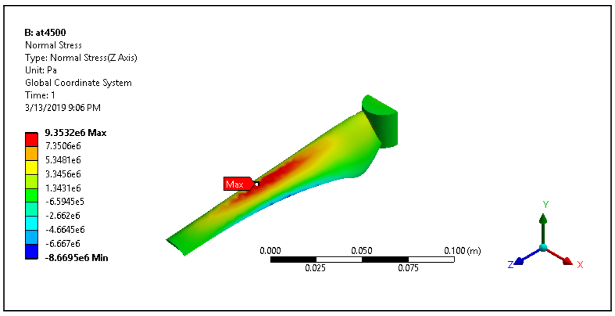

Figure 11: Figure showing centrifugal, bending and other stresses distribution for Blade 2 at 4000 RPM

Figure 14 shows the campbell diagram for blade 2 with propeller rotation speed on x-axis and system frequency in y-axis. The figure shows that first resonance occurs at 12000 RPM, which is safe for the blade because the operating range of blade is 0-4000 RPM and the maximum velocity blade may receive is 5000 RPM.

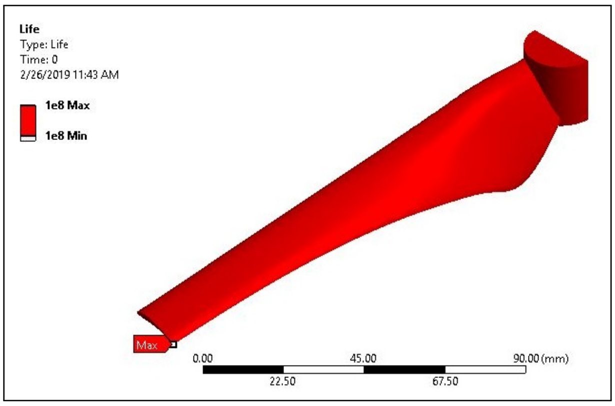

Figure 12: Figure showing the number of cycles of Blade 2 before it fails

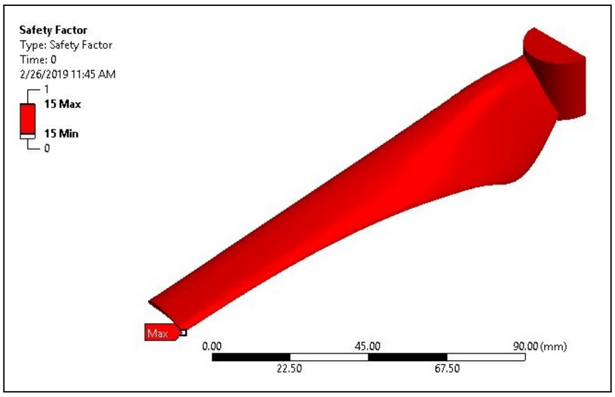

Figure 13: Figure showing factor of safety for Blade 2

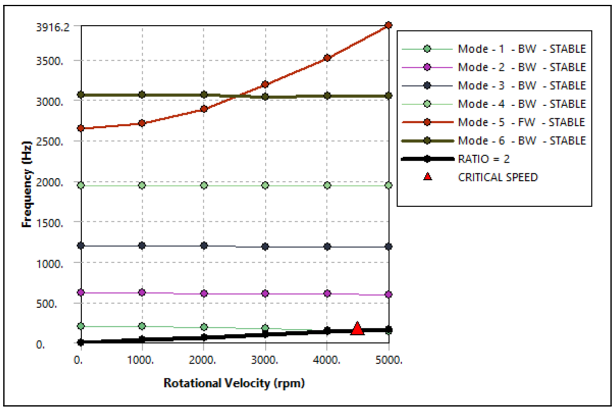

Figure 14: Campbell diagram for blade 2

From the figure 14 it can be seen that the first flexural frequency of the blade occurs at 200 Hz (200 Hz × 60 = 12,000 rpm) operating the blade at 12000 RPM will excite the critical frequency at 4500 RPM which may lead to failure. But this frequency is not faced by the propeller as the maximum rotational speed blade will face is limited to 5000 RPM only which is far below the first natural frequency 12000 RPM. Thus , blade is safe for operation in range of 0-5000 RPM.

The analytical results for stress distribution match the ANSYS result. The centrifugal stress is with in 15% error margin where as combined stress is largely varied. This is because analytically only centrifugal and bending stress was considered as total stress. There are other stress such as torque,aerodynamic twist which solver considers but was not considered while calculating analytically.Thus small variation in result is seen in combined stress analysis.

Recommendations

High altitude SAR propeller has been designed for altitude range of 3000-5000m. Only numerical analysis has been performed for the designed propeller. Thus, future work could be carrying out thrust rating test and vibration test for these altitude specific blades.

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