Final Project 4: Co-axial Rotor Blades

ME 163: Engineering Aerodynamics
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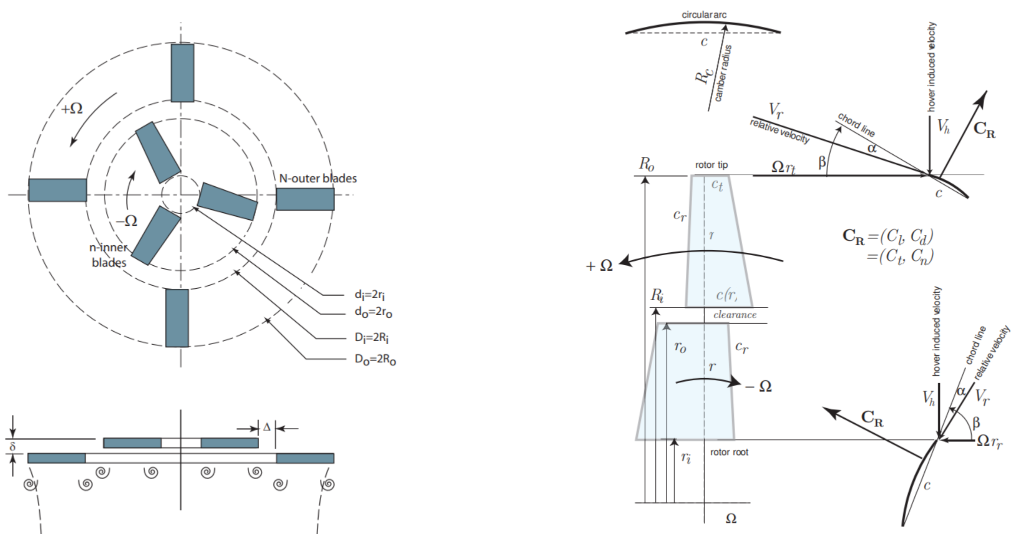
Abstract

The goal of the project was to design the blade profiles for a co-axial rotorcraft in order to meet design parameters. In general, co-axial rotorcraft consist of two blade assemblies, each with their own profiles, that are rotating in opposite directions. Due to this, the net torque induced from the rotors counteracts and becomes zero. This allows for easier flight control and more steady flight, especially at hover. Typically, the two blade assemblies exist on different planes. But in order for simplification of the design problem, both rotor assemblies were restricted to the same plane. After determining rotor dimensions through parameter sweeps, the rotor blades were modelled in SolidWorks using blade section sketches and lofts. From the final design, it was noticed the inner blade assembly needed to produce less thrust than the pouter blade assembly in order for the zero-torque requirement to be met. Also of note, is that the chord length of the inner blades was considerably larger than the blade lengths.

Design Parameters

The rotorcraft and blade dimension parameters are shown in Figure 1a and 1b, respectively. The rotor craft consists of 3 inner blades and 4 outer blades that exist on one plane ($\delta = 0$)



a) b)

Figure 1: (a) Entire Rotor Assembly. (b) Inner and Outer Blades Blade

The parameters outlined below were used as the initial starting point for the rotor blade design. Some of the parameters are given in order to assure that the simplifications used with thin airfoil theory and blade-element theory are satisfied. In defining the parameters, viscous drag and vortex induced drag are ignored. The rotor craft was to perform at MSL conditions making the air density $\rho = 1.225\ \frac{kg}{m^3}$, kinematic viscosity $\nu = 1.467 * 10^{-5}\ \frac{m^2}{s}$, and the speed of sound $a = 340.3\ \frac{m}{s}$.

Operating Conditions

- Total Thrust $T = 50\ N$
- Rotor tip Mach number $^{R_0\Omega}/_{a} < 0.5$
- Chord Reynold Number $R_{ec} = \frac{c(r)r\Omega}{v} < 200{,}000$
- Constant induced hover velocity $V_h = \sqrt{T/2\rho A}$

Fixed Parameters

- No net torque.
- Circular arc sections, $R_0 = 2R_c$.
- Local angle of attack $\alpha(\mathrm{r}) = \arcsin[c(r)/2R_c]$.
- Same rotation speed ± Ω for both the inner and the outer blades.
- Outer blades N = 4, and inner blades n = 3.
- The total thrust T (force along the axis of the rotors), is uniformly distributed.
- $^{d_i}/_{D_0} = 0.25$.
- δ = 0.
- $\Delta = \mathrm{D_i} - d_0 = 0.05D_0$.
- The overall rotor solidity $\sigma = \frac{(\mathrm{NA_{bo}+nA_{bi}})}{\mathrm{A}} \leq 0.1$

Design Process

In order to start the design process, I needed to choose some initial parameters such as the outer radius of the rotorcraft, R_0, and the thrust ratio between the inner and outer blades, T_i/T_0. From there I could do sweeps between specified ranges for the rotation speed, Ω, and outer radius of the inner blades, r_0 in order to optimize the rotorcraft.

With the rotorcraft being used in the atmosphere of the earth, and only needed to produce 50 N or about 11 lbs., the rotorcraft appeared liked it would need to be a Group 1 UAS which typically has dimensions between 0.5 and 2 meters. Since I wanted the vehicle to have the least intrusion possible, and the least amount of power required to operate the vehicle, I chose the outer radius R_0 to be 0.25 meters so the diameter was 0.5 meters. This is because the motor power is linearly proportional to the Torque required to turn the blades, and since torque is linearly proportional to the radius of the vehicle, the smallest radius would give the smallest power required.

For the inner and outer thrust ratio, intuition said that the inner blades would need to produce more thrust due to having a smaller radial position compared with the outer blade. So, I started at an arbitrary ratio of $T_i/T_0 = 1.5$ to give the inner blades a larger thrust requirement but by not a significant amount. While simulating however, it was determined the ratio needed to be $T_i/T_0 = 0.75$ in order to produce a net torque as close to zero as possible.

With these two parameters chosen, I was then able to determine the rest of the parameters needed to define the blades in terms of R_0, T_i/T_0, r_0, and Ω. The range of values I chose to sweep through for omega was [470,680] rad/s or about [4500,6500] rpm, which is the typical rpm capabilities of most motors commercially available, and 680 rad/s is the max rotation speed allowed before going above the rotor tip Mach number criterion for the outer radius I chose. For the outer radius of the inner blades r_0, I chose to sweep through [0.08, 0.10] m after some trial and error to get net torque values near zero. The resultant fixed parameters were then plotted against the given criterion already specified as shown in Figure 2.

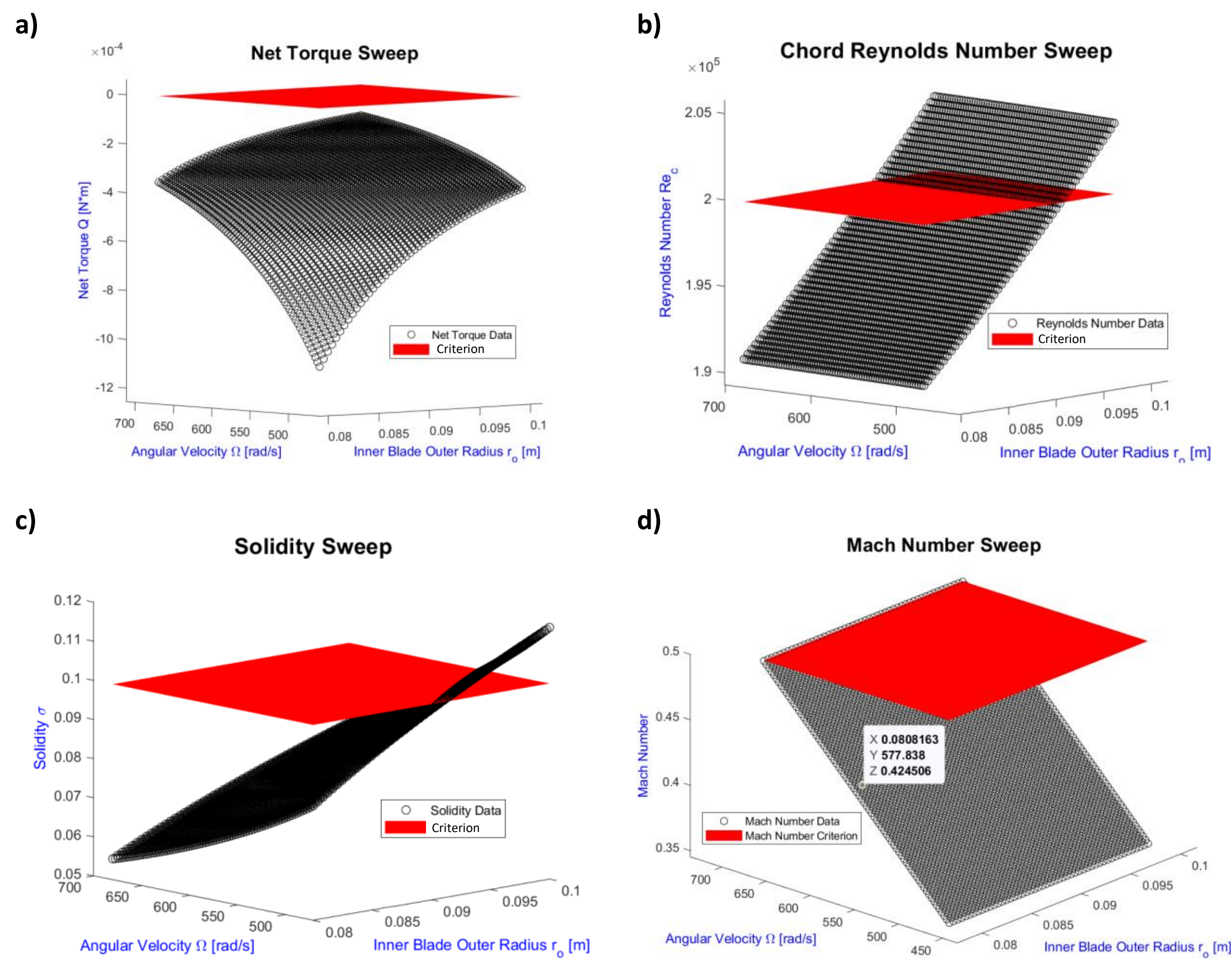


Figure2 2: (a) Net Torque, (b) Chord Reynolds Number, (c) Solidity, (d) Rotor Tip Mach Number

Results

From analyzing the net torque figure, it is seen that we want the max rotation speed, and the largest inner blade outer radius possible to decrease the net torque as close to zero as possible. But the Chord Reynolds number criterion prevents this. Taking both of these into account, it was determined that the best Ω and r_0 values would be 680 rad/s and .094 meters, respectively. Using these parameters, the summary of the dimensions is given below:

- $R_o = 0.25$ m
- $r_0 = 0.094\ m$
- $R_i = 0.1065\ m$
- $r_i = .0625$ m
- $\Omega = 680$ rad/s
- $\sigma = 0.0734$
- $T_i = 21.43\ N$
- $T_0 = 28.57\ N$
- Rotor Tip M = 0.4996
- Net Q = $-1.1615 * 10^{-4}\ N * m$
- Net Motor Torque = $Q_m = 0.2144\ N * m$
- Motor Power = $Q_m * \Omega$ = 145.8 Watts

The blade profiles parameters including c(r), α(r), β(r), $C_t(r), and\ C_n(r)$ are shown in Figure 3. The isometric, top, and right images of the inner and outer blades ar4e shown in Figure 4.

Figure 3: Blade Parameters

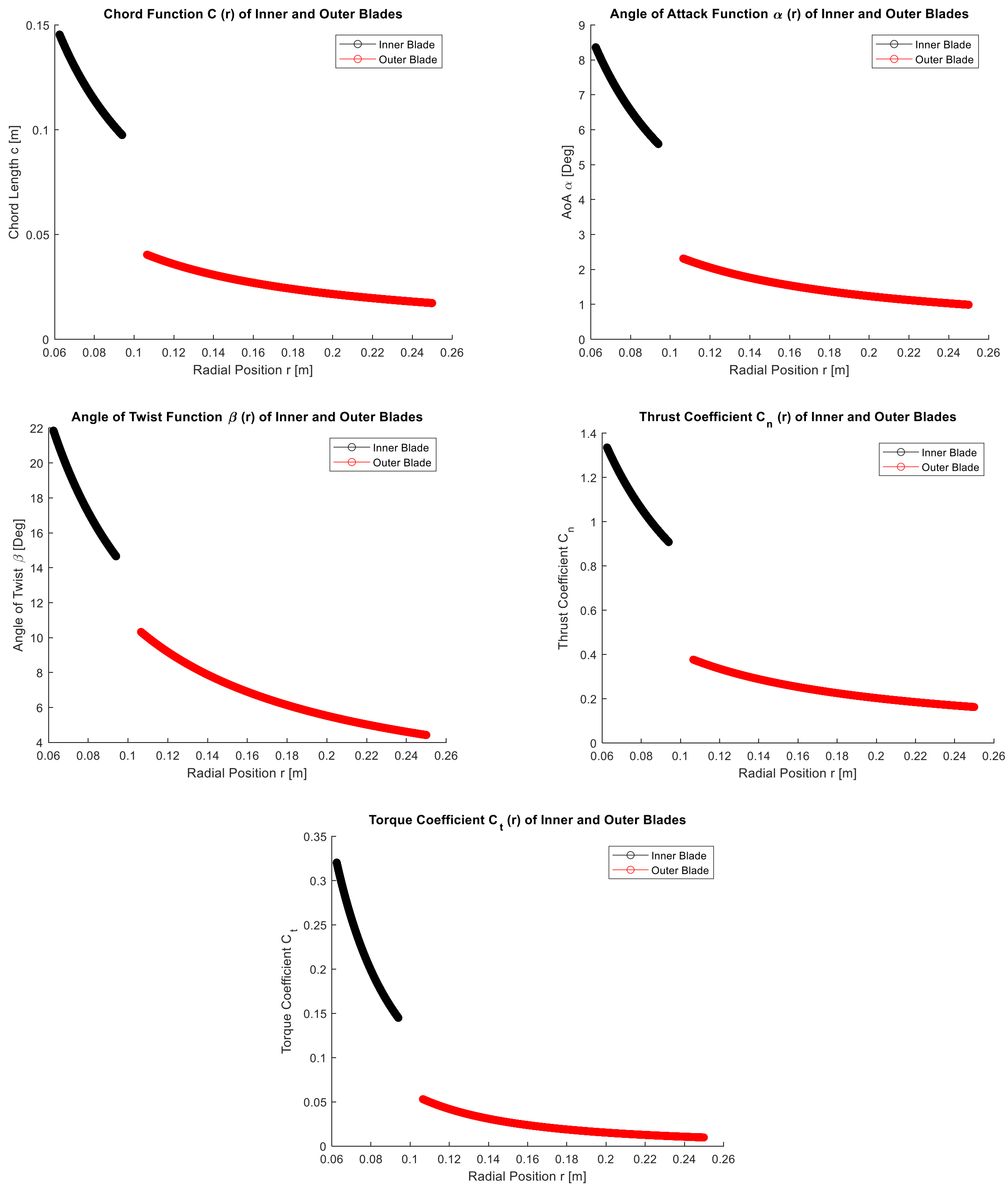


Figure 4: Inner Blade (left), Outer Blade (right)