Theoretical Design of Coaxial Rotor Micro Air Vehicle

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Abstract: **In recent years, there has been rapid development of autonomous unmanned aircraft equipped with autonomous control devices called unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs). These have become known as "robotic aircraft," and their use has become wide spread. They can be classified according to their application for military or civil use. There has been remarkable development of UAVs and MAVs for military use. However, it can be said that the infinite possibilities of utilizing their outstanding characteristics for civil applications remain hidden.**

In this paper detailed design procedure for designing a micro air vehicle weighing from 20 gram to 500 gram is presented. Using such design procedure for pay load capacity of 10 grams is design. Different parameters like rotor blade length, length of stabilizer bar, length of fuselage, total length of body,

totalpower required is find out. To check feasibility of vehicle in hover condition checking parameters like thrust force, lift force, centrifugal force are find out.

Keywords: Micro air vehicle, coaxial rotor, small weight.

I. INTRODUCTION

A. Introduction to Aerodynamics

Aerodynamics deals with the motion of air and with the forces acting on objects moving through air. The same principles of aerodynamics apply to both rotary-wing and fixed-wing aircraft. Four forces that affect an aircraft at all times are weight, lift, thrust, and drag: Terms are define as Weight is the force exerted on an aircraft by gravity Lift is produced by air passing over the wing of an airplane or over the rotor blades of a helicopter. Thrust is the force that moves an aircraft through the air. Drag is the force of resistance by the air to the passage of an aircraft through it.

B. Introduction to UAV & MAVs

Unmanned Air Vehicle (UAV) is remotely piloted or self-piloted aircraft that can carry cameras, sensors, communications equipment or other payloads. Micro Aerial Vehicles (MAVs) are a subset of Unmanned Air Vehicles (UAVs) characterized by their relatively small size.MAV is a small and ultra-lightweight air vehicle systems with a maximum wingspan length of 15 cm and a weight less than 100 grams. MAVs are ideal for tasks that larger, where more expensive vehicles may not be able to perform.

C. Introduction to coaxial micro air vehicle

Definition: A coaxial micro air vehicle consists of a pair of rotors turning in opposite directions. The rotors are mounted on a mast with the same axis of rotation. The two rotors are placed one above the other. It is an extremely compact structure that can be used for MAVs. It occupies a very small footprint on the ground and is the best option when size and mass are constraints. It offers more thrust and lift than any other configuration as there are 2 rotors giving lift. In a situation where requires the wingspan to be minimum and the mass being a constraint as well, a coaxial configuration is the best fit.

II. GENERAL DESIGN PROCEDURE

- Relation between take off total power (kW) & gross weight (kg)

  $P_{TO}^{\text{Coaxial UAVr}} \approx 0.0764.W_O^{1.1455}$

- Relation between Rotor Diameter in (m) & gross weight in (kg)

  $D^{\text{Coaxial UAV}} \approx 0.4331.W_O^{0.385}$

- Relation between Tail Rotor Diameter in (m) & gross weight in (kg)

  $D_{TR}^{\text{Coaxial UAV}} \approx 0.0886.W_O^{0.393}$

- Relation between Main Rotor Diameter in (m) & Fuselage length in (m)

  $L_F = 0.824.D^{1.056}$

- Relation between Main Rotor Diameter in (m) & Airframe Overall (Rotor Turning) length in (m)

  $L_{RT} = 1.09.\ D^{1.03}$

- Gross weight includes empty weight -WE & useful load (W_u)

  $W_u = W_{PL} + W_F + W_c$

Where W_{PL} =Payload ,W_F =Weight of fuel, W_c =Weight of crew

$W_E^{\text{Coaxial UAV}} = 0.59.W_o$ (Empty weight)

$W_U^{\text{CoaxialUAV}} = 0.44.W_o$ (Useful Weight)

$W_{PL}^{\text{Coaxial UAV}} = 0.22.W_o$ (Payload Weight)

- Relation between gross weight in(kg) & maximum speed in (km/hr)

  $V_{max}^{\text{CoaxialUAV}} = 78.5.W_o^{0.137}$

- Relation between rate of climb in (m/min) & gross weight in(kg)

  $V_c^{\text{Coaxial UAV}} = 99.5.W_o^{0.268}$

- The lift force is calculated as

  $F_L = 0.5 \times CL \times \rho \times Vmax^2 \times A$

  Total lift force is calculated as

  $F_{L(t)} = F_L \times 2$

- The area A is the area of the total rotor disk is given by

  $A = \pi R^2$

C_L is assumed to be 1.6, a typical lift coefficient value. Density of air is taken as 1.29 kg/m^3

- Total lift force of helicopter body is
  $F_L(t) = FL \times 2$
- Drag force is given by
  $F_D = 0.5 \times C_D \times \rho \times Vmax^2 \times A$
- The centrifugal force is given by:
  $F_C = M_b \Omega^2 R$
  Where M_b = Mass of blade
  Ω = actual speed of rotor blade

A. Design of spur gear:

Let
x = distance between the centers of two shaft
N_1 = speed of the driver
T_1 = number of teeth on driver
d_1=pitch circle diameter of driver
N_2, T_2, d_2 = corresponding values for the driven or follower and
p_c =circular pitch

We know that the distance between the centers of two shafts

$$x = \frac{d_1+d_2}{2}$$

And speed ratio or velocity ratio

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} = \frac{T_2}{T_1}$$

From above equations calculate values of d_1& d_2 or T_1& T_2& circular pitch p_c.

B. Design of shaft:

M= bending moment in N-mm
T= torsional moment in N-mm
d = diameter of solid shaft in mm
d_o = outside diameter of hollow shaft
d_i = inside diameter of hollow shaft
L = length of shaft in mm
n = speed of shaft in rpm.

The torque transmitted by the shaft in N-mm

$$T = \frac{9.55\ x 10^6\ (P)}{n}$$

The maximum torsional shear stress due to torsional loading

$$\tau = \frac{16\,T}{\pi d^3} \text{for solid shaft}$$

The maximum torsional shear stress due to torsional loading

$$\tau = \frac{16\,T}{\pi d^3}\left(\frac{1}{1-k^4}\right) \text{ ----------for hollow shaft}$$

III. DESIGN CALCULATIONS:

A. Calculations taking 40 grams gross weight

- Gross weight includes empty weight – (W_E)& useful load (W_u)
- $W_E^{\text{Coaxial MAV}}$ = 0.59.(0.04) = 0.0235 kg = 23.5 g
- $W_U = W_{PL} + W_F + W_c$
  = 8.8 + 0.003 + 7.797
  = 16.5 g

Since($W_{PL}^{\text{Coaxial MAV}}$ = 0.22.(0.04) = 0.0088 kg = 8.8 g)
Also it is calculated as

- $W_U^{\text{Coaxial MAV}}$ = 0.44.(0.04) = 0.0166 kg = 16.5 g
- Gross weight = $W_E + W_U$ = 23.5 +16.5 = 40.0g
- $P_{TO}^{\text{Coaxial UAV}} = 0.0764.(0.04)^{1.1455}$ =1.19 W
- $D^{\text{Coaxial UAV}} = 0.4331.(0.04)^{0.385}$ = 0.125 m =12.5 cm
- $D_{TR}^{\text{Coaxial UAV}} = 0.0886.\ (0.04)^{0.393}$ = 0.025 m = 2.5 cm
- $L_F = 0.824.(0.125)^{1.056}$ = 0.0916 m = 9.1 cm
- $L_{RT} = 1.09.\ (0.125)^{1.03}$ = 0.128 m = 12.8 cm
- $V_{max}^{\text{Coaxial UAV}} = 78.5.(0.04)^{0.137}$ = 50.507 km/hr = 14.02 m/sec
- $V_c^{\text{Coaxial UAV}} = 99.5.(0.04)^{0.268}$ = 0.699 m/sec
- $F_L = 0.5 \times 1.6 \times 1.29 \times (50.507)^2 \times 0.0625$ = 164.536 kN = 0.1645 N
  Total Lift Force is 0.329 N
- $F_D = 0.5 \times 0.5 \times 1.29 \times (50.507)^2 \times 0.0625$ = 51.417 kN = 0.05141 N
- $F_C = M_b \Omega^2 R = 1.150 \times 10^{-3} \times (390.11)^2 \times 0.0625$ = 10.938 kN = 0.010938 N

3.2. Power Supply:

The power is supplied for the model from a 3.7 V 150mAh Li ion battery. This battery is very useful as it provides a high power with a small size, which is shown in Fig.2.10. Due to its small size it perfectly fits into the requirements of a micro helicopter. The battery is rechargeable up to 1000 times. The battery is directly connected to a microcontroller and it gives power to the system through the programmed microcontroller. The specifications of the battery are:

- Weight: 3.0 g
- Dimensions: 4mm×17mm×19mm
- Nominal voltage: 3.7 V
- Charging voltage: 4.2 V
- Typical capacity: 150 mAh

C. Electric Motors:

- The electric motors used in the model are of 2 types:
  2 no of Main motors.
  1 no Tail motor.
- The two main motors are mounted on a set up . The motors have a KV rating of 1600. They act on a voltage of 3.7 V from the LiPo battery, which gives them a nominal speed of
  $N_n = V \times KV = 3.7 \times 1600 = 5920$ rpm.
- But due to the internal losses due to back EMF of the motor, it is assumed it offers a speed approximately 80% of its nominal value. Hence, actual speed of motor:
  $Na = \eta \times V \times KV = 0.8 \times 3.7 \times 1600 = 4736$ rpm.
- Now, due to the gear system, there is a speed reduction for the shafts and consequently for the rotor blades. Hence, the actual speed of the blades is: $\Omega = \eta \times V \times KV/G$
  $\Omega = 0.8 \times 3.7 \times 1600/12 = 390$ rpm
- The motors are brushless DC motors (BLDC), which weigh 3.6 g and are used because of their superior efficiency and more lasting period in comparison to brushed motors.

D. Design Calculations for Spur Gear:

x = 1.8 cm =18 mm, N_1 = 4736 rpm, T_1 = 7 no, d_1= 2 mm, p_c = circular pitch

We know that the distance between the centers of two shafts

$$18 = \frac{2+d_2}{2} \text{i.e} d_2=34 \text{ mm}$$

And speed ratio or velocity ratio is

$$\frac{4736}{N_2} = \frac{34}{2} = \frac{T_2}{7}$$

i.e. $N_2=\frac{4736 x 2}{34}$

N_2= 278.58 rpm

& T_2 = 119

E. Design Calculations for Shaft:

Consider maximum torsional shear stress for shaft material as 55 N/mm^2

The torque transmitted by the shaft in

$$T = \frac{9.55 x 10^6 \ (1.19)}{4736}$$

$$= 2399 \text{ N-mm}$$

The maximum torsional shear stress due to torsional loading

$$\tau = \frac{16 T}{\pi d^3}$$

$$55 = \frac{16 x 2399}{3.14 x d^3}$$

d = 6 mm

The maximum torsional shear stress due to torsional loading

$$\tau = \frac{16 T}{\pi d^3}\left(\frac{1}{1-k^4}\right)$$

$$55 = \frac{16 x 2399}{\pi (6)^3}\left(\frac{1}{1-k^4}\right)$$

K = 0.41

Since k = ratio of inside to outside diameter

$$\frac{d_i}{d_o} = 0.41$$

$$d_o = 6 / 0.41$$

$$d_o = 14.63 \text{ mm}$$

IV. CONCLUSION

Speed of the rotor is obtained as 390 rpm and at that speed of the rotor, the lift generated is found to be 0.329 N. along with this some lift will be generated by tail rotor also so combine lift force is found to be greater than the weight of the helicopter, which is found to be 0.392 N. Thus, the lift force generated is calculated to be greater than the weight of the helicopter, which is the necessary condition for take-off.

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