MBDYN, DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY AT POLITECNICO DI MILANO

Final Report, GSoC

Kuldeep Singh
Mentors: Louis Gagnon & Prof: Giuseppe Quaranta

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1 CYCLOCOPTER ROTOR MODEL IMPROVEMENT

Cyclocopter rotor has cycloidal blade system in which multiple rotor blades rotate on cylindrical plane. Cyclocopter rotor has the unique ability to change direction of the thrust almost instantly. That is why Cyclocopter vehicle has vertical takeoff and landing capability with excellent thrust characteristics.

1.1 AIM

The main focus is to solve the airflow over the cyclocopter rotor. Multiple methods, using which we can solve the flow over the cyclocopter rotor, but each has its own pros and cons. Finally, the double multiple stream-tube method was chosen to solve the flow, the reason for which has been explained below.

ANALYTICAL METHOD This method is very light from the computational point of view but it does not consider the interaction of the blades. Which means the flow of one blade is affected by the other blades but this effect has not been considered in this model.

CFD ETC. Here we are manage to capture the blade interaction but these method are computationally heavy and time consuming. So one can not use such methods in the design stage.

DOUBLE MULTIPLE STREAMTUBE (DMST) METHOD This method has both the advantage that it captures blades interaction as well as, it is very light from the computational point of view. In this method the rotor is divided into two parts upstream half and the downstream half (that is why the word **Double**). And the incoming flow is divided into multiple stream-tubes. Now, two theories (Momentum and Blade element theory) are used, to find the induced velocity for both, upstream and downstream half. Here the induced velocity from the upstream half is added to the incoming flow of downstream half and **this is how the interaction between the rotor blades** is happening.

2 SOLVER

2.1 LIST OF MAIN INPUTS FROM THE USER SIDE

- Number of blades (nBlade)
- Chord length
- Drum Radius
- Air properties (Mainly density(ρ)...)
- Blade span
- Omega (Rotation Speed)
- Pitch angle information (here the blade pitching angle should be known at every angular position (ψ))
- K_{emp} - This is an empirical constant. Which takes care of the 3D losses, non-uniformity of the flow and other effects into the consideration and as article (C.Y. YUN 2006) suggests that we can take $K_{emp} = 1.15$
- DeltaT Or it would be better if we directly define the number of stream-tubes in the free-stream flow
- For Lift and drag coefficient information of an airfoil (c81 file)
- Other - Input related to the position, orientation etc. of the rotor blade and axis, which are usually given in the every **mbdyn** simulation

2.2 IMPLEMENTATION OF THE DMST MODEL IN THE MBDYN

Right now all the above mentioned inputs are well written in a input file(**CROP.mbd**). Already there exists a code to read this input file. Writing the output in proper conventional format is also available in mbdyn.
The **major task** is to find the **inflow** at each angular location in the upstream and downstream half of the rotor. For this pseudo code based on the articles [1], [2] and [3] of the DMST model has been given below.

2.3 PSEUDO CODE

- Form $\psi = 0$ to 180° (Upstream half of the rotor), if there are total **n** stream-tubes, then there would be **n** discrete angular positions, where the equation 2.1 needs to be solved to calculate λ (we will take positive real root of the equation). The equation 2.1 came by combining the thrust from Blade element theory and Momentum theory. In equation 2.1, except λ everything is known,

$$4\ K_{emp}\ \lambda^2 = \sigma(1+\lambda^2) * (C_l cos(\phi) - C_d sin(\phi)) \tag{2.1}$$

  - Here, λ is nothing but ratio of induced velocity and rotor speed.
  - $\phi = tan^{-1}(\lambda)$
  - $\sigma = nBlade * chord\ /\ 2\pi R$, where nBlade, chord, Drum radius (R) is known from user input
  - Pitching angle (θ), is known at every angular location (ψ) by mbdyn, this information is also given through input file
  - C_l and C_d are taken from the c81 file
  - $K_{emp} = 1.15$
  - The above equation will always have only one positive real root

- After finding at each discrete location, the resultant local flow velocity can be calculated like this
  - $U_P = \lambda$ R * Omega ; Normal component to the blade element
  - U_T = R * Omega ; Tangential component to the blade element

- Once the flow velocity is known, lift (dL), drag(dD) and thrust(dT) can be calculated at each discrete elemental location. For that matter force and moment in any reference frame can be calculated, by applying the appropriate rotation. Here

$$dL = \frac{\rho({U_T}^2 + {U_P}^2) * c * C_l * nBlabe * d\psi}{4 * \pi}$$

  similarly

$$dD = \frac{\rho({U_T}^2 + {U_P}^2) * c * C_d * nBlabe * d\psi}{4 * \pi}$$

  and finally

$$dT = dLcos(\phi) - dDsin(\phi)$$

- Similarly, we need to find the induced velocity vector for the Downstream half (180° < ψ <360°) of the rotor

- Here the induced velocity from the upper half will also be added in the incoming flow, which we have calculate already. And this is how the rotor blades are interacting with each other.

- After adding the induced velocity from upstream half of the rotor to the inflow of downstream half of the rotor and then by applying the blade element theory and Momentum theory, we will get this equation.

$$4\ (\lambda - \zeta\ tan(\psi))\sqrt{(}\lambda^2 + \zeta^2) = \sigma\ \left((1 + \zeta^2 + \lambda^2) + (C_l\ cos(\phi) - C_d\ sin(\phi))\right) \tag{2.2}$$

  - Here except λ everything is known, because
  - ζ = (w cos(ψ))/ (omega R) and w = 2 *U_P / sin(ψ) and U_P is taken from the upstream half, which we have already solved
  - σ is constant, same as defined above
  - After getting all the λ's at each discrete location , we can easily calculate the net velocity vector, like this
  - U_T = omega * R + w cos(ψ)
  - U_P = w sin(ψ) + u_d ; u_d = λ * omega * R - w sin(ψ)
- Once the velocity is known we can find force and moment vector in any frame of reference,
- Sum of all these incremental force and moment vector would give us the net force and net moment vector

3 Implementation of DMST inside mbdyn

Important point (Suggested by Louis) The above procedure can be made simpler and we can avoid solving the above two equations because Blade element theory has already been implemented in the mbdyn so we can use it to find the thrust (dT), further this thrust can be used to find the induced velocity by using the momentum theory. And by adding this induced velocity back to the inflow, new thrust can be found and iteratively induced velocity and thrust can be found.

Calculating u_u Here induced velocity for the upstream half can be calculated, using momentum theory, for a given upstream half thrust(dT_u) as follow

$$v_u = \left(\frac{dT_u * sin^2\psi}{2 * \rho * R * d\psi}\right)^{0.5} \tag{3.1}$$

Here

$$dT_u = \frac{T_{blade} * N_b * d\psi}{2 * \pi}$$

So we can write the equation 3.1 as

$$v_u = \left(\frac{T_{blade} * N_b sin^2\psi}{4 * \pi * \rho * R}\right)^{0.5} \tag{3.2}$$

T_{blade} is the blade force at azimuth location ψ, which is known by mbdyn for all the blades at each time step.

CALCULATING u_d Similarly, induced velocity for the downstream half can be calculated by solving this equation:

$$v_d{}^2 * (w^2 + 2 * v_d * w * sin(\psi) + v_d{}^2) = \frac{dT_d}{2 * \rho * R * d\psi}; \quad where \ \ w = \frac{2 * v_u}{sin(\psi)} \tag{3.3}$$

Here

$$dT_d = \frac{T_{blade} * N_b * d\psi}{2 * \pi}$$

So we can write the equation 3.3 as

$$v_d{}^2 * (w^2 + 2 * v_d * w * sin(\psi) + v_d{}^2) = \frac{T_{blade} * N_b}{4 * \pi * \rho * R}; \quad where \ \ w = \frac{2 * v_u}{sin(\psi)} \tag{3.4}$$

To solve the equation 3.3 two different methods were used. One is **bisection** method and second is **analytical** method.

COMPARISON OF BISECTION AND ANALYTICAL METHOD Analytical method gives more accurate answer compare to bisection method. Accuracy of bisection method depends upon the tolerance also and if the tolerance is very low then bisection method takes more time or computation(compare to analytical method) to find the roots. So for **more accurate and faster** results it is always **better to use analytical** method. Figure 3.2 and 3.1 show the comparison between analytical and bisection method for two different tolerances.

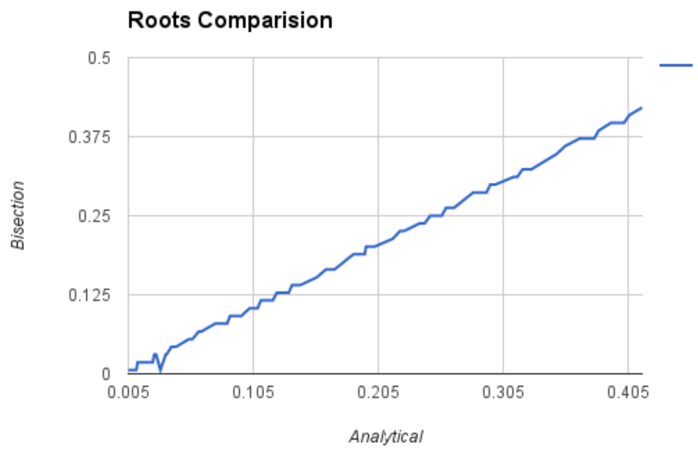

Figure 3.1: Comparison for tolerance = 1e-2

HOW TO DECIDE UPSTREAM AND DOWNSTREAM HALF These two half are decided based on the net rotor force vector($\vec{F}$). If the angel between the net force ($\vec{F}$) and blade position is in range (-$\frac{\pi}{2}$, $\frac{\pi}{2}$) then blade is assumed to be in upper half otherwise blade is in lower half. For example **blade 1** in the figure 3.3 is in lower half and **blade 2** is in upper half.

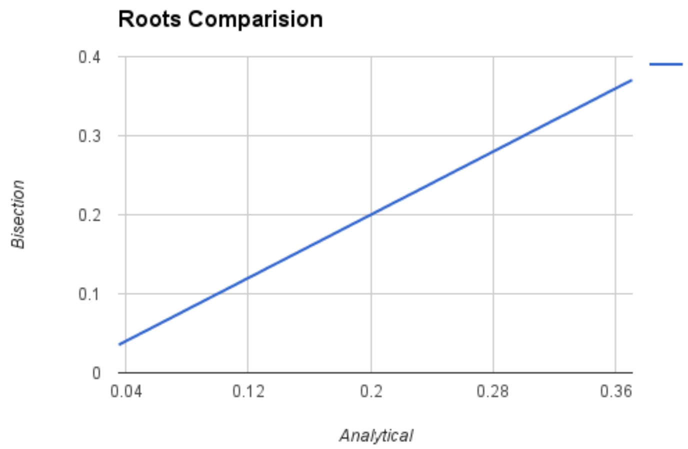

Figure 3.2: Comparison for tolerance = 1e-4

How to find "w" For example if one wants to find the **w** for **Blade 1** which is in lower half. One needs to know the u_u at point **(c, d)**. But at that point of time there **may be or may not be** a blade. So to be on safer side store all the u_u values at each azimuth location and keep updating them. Here **(c, d)** is the mirror image point of blade 1 position (a,b), about the line perpendicular to the net force vector($\vec{F}$). **To find (c, d)** we can assume that vector perpendicular to the F is a line, which is **y = mx** and we know the slope(m) of the line because vector ($\vec{F}$) is known. Here (c, d) is the mirror image of the point (a, b) about this line. Now we can write (c, d) as:

$$c = \frac{(2*(m*b+a))}{(m*m+1)} - a;$$

and

$$d = \frac{(2*m(m*b+a))}{(m*m+1)} - b;$$

and if $\vec{F} = (0, f_1, f_2)$ then vector perpendicular to the F is (0, -f_2, f_1) and $m = atan2(f1, -f2)$ Now (c, d) is known and we have already stored all the updated u_u so based on the **azimuth** location of the (c,d) we can get the u_u. Once u_u is known w can be calculated easily, as given in the equation 3.4.

4 Development in the Code and Conclusion

Work Done Calculation of the inflow **velocity magnitude** for upstream half (u_u) and downstream half(u_d) using Double Multiple Stream Tube Method.

Work To Be Done This velocity magnitude should be divided into proper components. There was little confusion with reference frame(Global and Local).

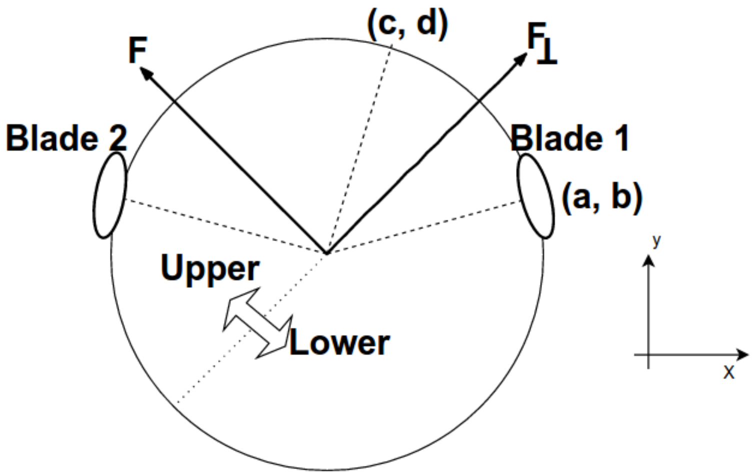

Figure 3.3: Cyclocopter Rotor

- I am guessing that inside the "GetInducedVelocity" function returns the "inflow vector" in global frame. Because I looked inside the class aerodynamicbody and I looked at other models too(1D, 2D etc.))
- But according to the articles induced velocity is added into the local rotor frame. In fact in the two articles [1] and [2] there is a difference of the negative sign.

REFERENCES

[1] Yun, C. Y., Park, I. K., Lee, H. Y., Jung, J. S., Hwang, I. S., & Kim, S. J. (2007).*Design of a New Unmanned Aerial Vehicle Cyclocopter.* Journal of the American Helicopter Society, 52(1), 24. [*http://doi.org/10.4050/JAHS.52.24*].

[2] Gagnon, L., Morandini, M., Quaranta, G., Muscarello, V., & Masarati, P. (2016). *Aerodynamic models for cycloidal rotor analysis.* Aircraft Engineering and Aerospace Technology, 88(2), 215âĂŞ231. [*http://doi.org/10.1108/AEAT-02-2015-0047*]

[3] Lee, C. H., Yong Min, S., Lee, J. W., & Kim, S. J. (2016). *Design, Analysis, and Experimental Investigation of a Cyclocopter with Two Rotors.* Journal of Aircraft, 1âĂŞ11. [*http://doi.org/10.2514/1.C032731*]