Assignment 5   Propeller analysis with BEM model

Requirements

- Personal or group task: personal
- Minimum/Maximum number of pages: 8 / 15 (excluding title page and drawings)
- Font size: 10 – 12

Introduction

Propeller propulsion systems are known to be very fuel-efficient compared to jet of turbofan engines provided the operational Mach number is not too high ($M<0.7$). This is the major reason why so-called “open rotor” systems and distributed propeller systems are regarded as the next step towards more efficient, green, aircraft (Fig. 1). In this assignment you will be introduced to the major characteristics of propellers and ways to estimate their performance characteristics. This will be based on an analysis of the single propeller as the so-called counter-rotating open rotor system (CROR) requires a more rigorous solution technique that is felt beyond the scope of this assignment.

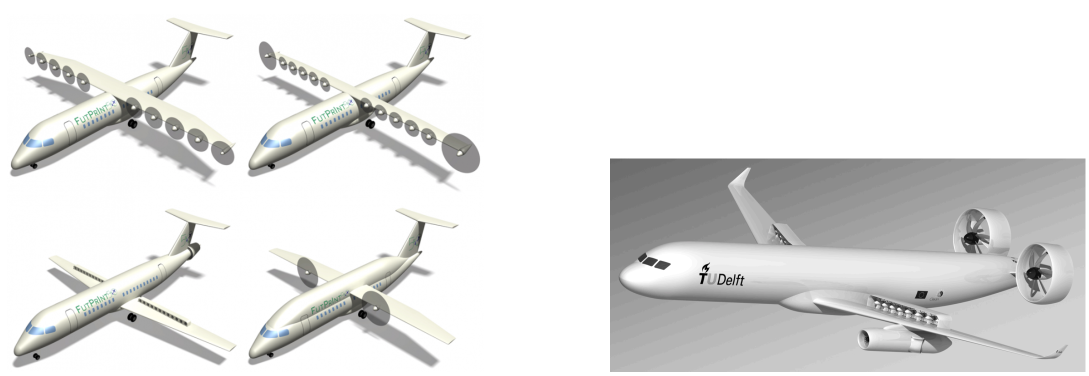

Fig. 1 Examples of propeller-driven aircraft designs. Left: FutPrint50 project concept, DLR. Right: Distributed propeller concept, CS2-project NOVAIR, TU Delft.

Tasks

Part 1 The solver

Familiarize yourself with the so-called “Blade Element Method” (BEM) (see for example [1,2,3,4]). In the preliminary design phase of propellers this is the most popular approach for the estimation of propeller characteristics like: thrust, torque, power and efficiency. To ensure full understanding of the methodology perform the following tasks:

1. Make a clear hand-drawn sketch (i.e. no copy-paste from an existing document) of the so called "velocity diagram" for a propeller blade section at radial position r and explain the various parameters involved. Include in this sketch also the: lift coefficient, drag coefficient, thrust coefficient and torque coefficient as well as the velocity components in axial and tangential direction induced by the propeller helical vortex system. Again, add your signature and date to this drawing.

2. Make a hand-drawn sketch of the typical radial distributions of the axial flow and tangential flow produced by a propeller (so v_a vs. r and v_t vs. r) and shortly explain the trends in these figures.

3. Explain why the axial velocity increase produced by the propeller in the propeller plane is half the value found far downstream in the slipstream. Add a sketch to support your reasoning.

4. As in open literature different definitions are used for the propeller characteristics (for example C_T versus T_c for the thrust coefficient), provide the definitions that you used in this assignment (thrust, torque and power coefficients).

5. Explain in your own words what is meant by:
    a. the "Prandtl Tip Loss Factor"
    b. Radial flow effect for propellers (sometimes called the "Himmelskamp effect"[1]). Add a drawing to explain the effect that is based on the occurrence of the Coriolis force in the boundary layer over the propeller blade
    c. Propeller advance ratio, J, and explain why this parameter is indicative for the blade section angle of attack.
6. Select an appropriate BEM code to perform the calculations in Part 2 of this assignment. For this, select one the following **3 options**:
    1) Use the sample code that is provided in the Appendix (adapt it as you feel needed to take into account a radial flow correction and local blade section lift and drag polar data)
    2) Use an existing code like JavaProp [5] or another well proven solver
    3) Write your own BEM solver

Part 2 Analysis of the propeller

Based on the selection made in part 1 analyze a propeller with the BEM-code and discuss your findings. For this purpose, do the following:

1. Select a propeller geometry from open literature (provide the reference) for which the main characteristics (thrust, torque, power and efficiency versus the advance ratio), as obtained from experiments, are available. In this case ref [6] might be interesting to you.

[1] Himmelskamp, H.: Profile investigations on a rotating airscrew, Reports and translations, Völkenrode MAP, 1947

2. Model this propeller in your code and compare the performance characteristics with the experimental data (typically for one blade angle setting, β) and provide clear graphs. For this purpose, put the experimental and predicted data in the same graph (use a ruler or graph digitizer tool for this). Discuss the reasons for possible differences between the reference data and your own results.
3. Provide a graph in which, for a particular case (at a moderate thrust level), the axial velocity increase, v_a/V_∞ versus r/R , as found in your calculations, is given. Draw a major conclusion regarding the loading distribution along the span and provide a short explanation.
4. Make small geometrical changes to the particular propeller and discuss its effect. For this, compare two cases: a) a **fixed thrust setting** and b) a **fixed power setting** and show/discuss/explain the effect on propeller efficiency due to a change in:
    a. the number of blades
    b. the propeller radius

References

[1] W.F. Durand, Aerodynamic theory, Vol. 2, 1933

[2] G. van Kuik, The Fluid Dynamic Basis for Actuator Disc and Rotor Theories, ISBN, 978-1-61499-865-5, 2018 (https://doi.org/10.3233/978-1-61499-866-2-i)

[3] M.K. Rwigema, Propeller blade element momentum theory with vortex deflection, ICAS 2010-2.3.3, ICAS conference, Nice, France, 2010

[4] www.aerodynamics.aeromech.usyd.edu.au

[5] http://www.mh-aerotools.de/airfoils/javaprop.htm

[6] UIUC propeller data Site: https://m-selig.ae.illinois.edu/props/propDB.html

Appendix A Example of a simple BEM Matlab Implemenation

Be aware of the fact that in this **sample** code the Prandtl Tip Loss factor (as well as the hub loss factor) is not taken into account. Moreover, lift and drag polars of the blade airfoil sections are provided through a rather simple model. As such this BEM code should not be used as is for this assignment. Merely use it as a basis for your own code in which the above stated issues are addressed.

Reference: www.aerodynamics.aeromech.usyd.edu.au

```
clear all;
%chord legth of blade assumed constant with radius
chord=0.10;
%pitch distance in meters.
pitch=1.0;
%diameter of the propeller
dia=1.6;
%tip radius
R=dia/2.0;
%engine speed in RPM
RPM=2100.;
%thickness to chord ratio for propeller section (constant with
radius)
tonc=0.12*chord;
%standard sea level atmosphere density
rho=1.225;
%RPM --> revs per sec
n=RPM/60.0;
%rps --> rads per sec
omega=n*2.0*pi;
% use 10 blade segments (starting at 10% R (hub) to R)
xs=0.1*R;
xt=R;
rstep=(xt-xs)/10;
r1=[xs:rstep:xt];
%calculate results for a range of velocities from 1 to 60m/s
for V=1:60,
 %initialise sums
 thrust=0.0;
 torque=0.0;
 %loop over each blade element
```

```
 for j=1:size(r1,2),
  rad=r1(j);
  %calculate local blade element setting angle
  theta=atan(pitch/2/pi/rad);
  %calculate solidity
  sigma=2.0*chord/2.0/pi/rad;
  %guess initial values of inflow and swirl factor
  a=0.1;
  b=0.01;
  %set logical variable to control iteration
  finished=false;
  %set iteration count and check flag
  sum=1;
  itercheck=0;
  while (~finished),
    %axial velocity
    V0=V*(1+a);
    %disk plane velocity
    V2=omega*rad*(1-b);
    %flow angle
    phi=atan2(V0,V2);
    %blade angle of attack
    alpha=theta-phi;
    % lift coefficient
    cl=6.2*alpha;
    %drag coefficient
    cd=0.008-0.003*cl+0.01*cl*cl;
    %local velocity at blade
    Vlocal=sqrt(V0*V0+V2*V2);
    %thrust grading
    DtDr=0.5*rho*Vlocal*Vlocal*2.0*chord*(cl*cos(phi)-
cd*sin(phi));
    %torque grading

DqDr=0.5*rho*Vlocal*Vlocal*2.0*chord*rad*(cd*cos(phi)+cl*sin(ph
i));
    %momentum check on inflow and swirl factors
    tem1=DtDr/(4.0*pi*rad*rho*V*V*(1+a));
    tem2=DqDr/(4.0*pi*rad*rad*rad*rho*V*(1+a)*omega);
    %stabilise iteration
    anew=0.5*(a+tem1);
    bnew=0.5*(b+tem2);
    %check for convergence
    if (abs(anew-a)<1.0e-5),
```

```
     if (abs(bnew-b)<1.0e-5),
      finished=true;
     end;
    end;
    a=anew;
    b=bnew;
    %increment iteration count
    sum=sum+1;
    %check to see if iteration stuck
    if (sum>500),
     finished=true;
     itercheck=1;
    end;
  end;
  thrust=thrust+DtDr*rstep;
  torque=torque+DqDr*rstep;
 end;
 t(V)=thrust/(rho*n*n*dia*dia*dia*dia);
 q(V)=torque/(rho*n*n*dia*dia*dia*dia*dia);
 J(V)=V/(n*dia);
 eff(V)=J(V)/2.0/pi*t(V)/q(V);
 icheck(V)=itercheck;
end;
Jmax=max(J);
Tmax=max(t);
plot(J,t,J,q);
title('Thrust and Torque Coefficients')
xlabel('Advance Ratio (J)');
ylabel('Ct, Cq');
legend('Ct','Cq');
axis([0 Jmax 0 1.1*Tmax ]);
pause;
clf;
plot(J,eff);
title('Propeller Efficiency');
xlabel('Advance Ratio (J)');
ylabel('Efficiency');
axis([0 Jmax 0 1 ]);
```