

Assignment 5 Propeller analysis with BEM model

Requirements

- Personal or group task: personal

Introduction

Propeller propulsion systems are known to be very fuel-efficient compared to jet or 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 designs are regarded as the next step towards more energy-efficient 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.

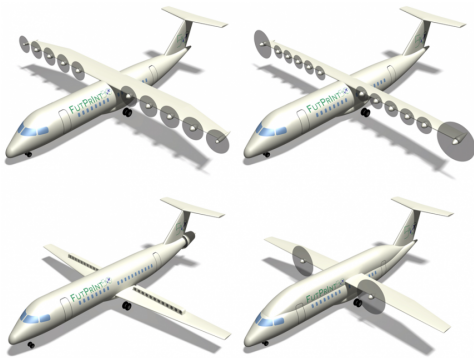


Fig. 1 Examples of propeller-driven aircraft designs. Left: FutPrint50 project concept, DLR. Right: Distributed propeller concept by Airbus.

Tasks

Part 1 The solver

Familiarize yourself with the so-called “Blade Element Method” (BEM) (see for example [1,2,3,4,7]). 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 a good understanding of the methodology perform the following tasks:

1. In the box below add 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. Clearly indicate the velocity components in axial and tangential direction including the contributions induced by the propeller helical vortex system. Again, add your signature and date to this drawing.

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2. Add 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)

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3. Explain the shape of the above velocity distributions based on the loading and associated vortex field produced by the propeller.

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4. 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 hand-drawn sketch to support your reasoning.

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5. 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).

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6. Explain in your own words what is meant by:
- a. the “Prandtl Tip Loss Factor” (add equation)

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- 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

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

- c. Propeller advance ratio, J , and explain why this parameter is indicative for the blade section angle of attack.

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7. 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 consider 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 from scratch

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.
2. Model this propeller in your code and provide a figure that shows the selected propeller planform. Also provide a table with radial chord and twist distribution in the box below.

3. Compare the predicted performance characteristics (thrust, torque, power and propulsive efficiency versus the advance ratio) 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).

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4. Discuss the reasons for possible differences between the reference data and your own results.

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5. Make small geometrical changes to your propeller and discuss its effect in case of a **fixed thrust setting**. Show/discuss/explain the effect on propeller efficiency due to a change in:

- a. the number of blades

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b. the propeller radius

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Propeller-Wing interaction effects significantly influence the aerodynamic, structural and acoustic characteristics of installed propeller and the airframe. In the box below provide a hand-drawn sketch of a typical tractor propeller + wing design showing the spanwise lift distribution for: a) an inboard-up rotation, b) an outboard-up rotation and c) the prop-off case.

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Discuss the form of the 3 loadings based on the contribution of the axial velocity and the tangential velocity induced by the propeller.

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Finally, also discuss what the effect of the propeller inclination angle (w.r.t. the wing) will be on the azimuthal distribution of the propeller loading and the wing loading. Feel free to add one or more figures in the 2nd box below.

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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) <https://www.aerodynamics4students.com/propulsion/blade-element-propeller-theory.php>
- 5) <https://mh-aerotools.de/airfoils/javaprop.htm>
- 6) UIUC propeller data Site: <https://m-selig.ae.illinois.edu/props/propDB.html>
- 7) AE4130-22 part 7, lecture #14, Propeller Propulsion Aerodynamics

Appendix A Example of a simple BEM Matlab Implementation

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 length 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
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```

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(phi));
    %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),

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        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]);

```