

Assignment 5 Propeller analysis

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 (see 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 lecture.

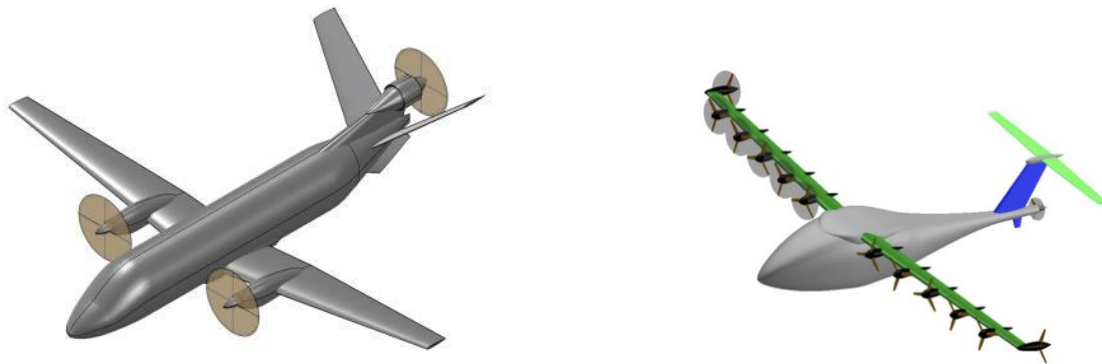


Fig. 1 Examples of propeller application in sustainable aircraft designs. (Left: Y. Fefermann et al., “Hybrid-Electric Motive Power Systems for Commuter Transport Applications”, ICAS-2016-0438, 2016, Right: N.K. Borer et al, Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator, AIAA, 2019)

Tasks

Part1 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 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.
2. Make a 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 as needed.
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 shortly what is meant by:
 - a. the “Prandtl Tip Loss Factor” for propellers
 - 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 options²:
 - 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

Part2 Analysis of a 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 literature (provide the reference) for which the main characteristics (thrust, torque, power and efficiency versus the advance ratio), as obtained from experiments, are available.
2. Model this particular 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.
3. Provide a graph in which, for a particular case (at a moderate thrust level), the axial velocity

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

² In case you choose to write your own solver please add the source code as an addendum to your assignment.

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>

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 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]);

```