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COMPARISON OF PROPELLER ANALYSIS METHODS AND EXPERIMENTAL DATA

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Abstract: *An analysis of a propeller of known geometry was carried out using three various methods: vortex theory, vortex theory with lifting line correction (VT+LL) and a 3D panel method. Analysis results were compared with experimental data measured in a wind tunnel that was built for the purpose of propeller testing. The comparison indicates that the VT+LL method offers the best propeller efficiency prediction of the presented methods, although the 3D panel method has been used in a simplified way and will be further improved. The ambition of the work presented is to develop and validate a simple and reliable tool for propeller optimization.*

Keywords: Propeller, Vortex theory, 3D panel method.

1. Introduction

Vast expansion of powerful electrical propulsion units for UAVs and light sport crafts initiated a demand for propellers optimized for the new working conditions. Department of Fluid Mechanics and Thermodynamics of CTU in Prague is subsequently working on the development and validation of tools that can be reliably used for optimization of propellers and for their analysis. Three analysis methods are presented in this paper – vortex theory, vortex theory with lifting-line correction (VT+LL) and a 3D panel method. These methods have been used to analyse a 0.5 m in diameter propeller of known geometry and the results have been compared with experimental data measured in a wind tunnel that was built for the purpose of propeller testing.

2. Experiment

An open return wind tunnel with a 1.2 m circular test section and 150 kW of power was built by the Department in Letnany, Prague. The test section was equipped with custom made aerodynamic scales for torque and thrust measurement as well as devices for the measurement of RPM and power drawn by the electric motor powering the propeller. The tested propeller was designed by the authors using the vortex theory and manufactured based on 3D data in STL format. The geometry of the propeller was known at the entry to its manufacturing process and has been assumed to be made sufficiently geometrically precise without further check. The propeller’s performance was measured for the RPM range of 600-6000 r/min and wind tunnel velocity range of 15-30 m/s. Finite size of the test section was taken in account by corrections according to Brandt (2011). The experimental data contain quite heavy scatter that is believed to be caused mostly by mechanical vibrations of the tested propulsion. Since insufficient resolution of the experiment did not reveal any dependency of the propeller’s performance on Reynolds number and Mach number all further computations were carried out for constant RPM of 6000 r/min.

3. Vortex Theory

The vortex theory was introduced in 1912 by N. Y. Zhukovsky and until today remains a useful tool for the design and analysis of propellers (well covered by Alexandrov (1954)). The vortex theory substitutes

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the propeller impact on the flow by a rigid vortex system that consists of helicoidal vortices blending into cylindrical vortex sheets as it supposes an infinite number of blades. The theory allows to easily compute the induced velocities at the propeller plane for a given circulation distribution. A sufficient propeller description that (along with the operating conditions) defines the vortex structure consists of one dimensional geometrical prescriptions for twist and chord length along blade radius and two dimensional airfoil data. In the approach described in this paper the airfoil data were obtained by M. Drela's Xfoil with a viscous and compressible computational model.

The vortex theory generally best describes propellers with small loading, for which the wake contraction downstream is low and the rigid cylindrial vortex structure gives a sufficient approximation. Another limiting aspect of the vortex theory is that it lacks interference between particular cylindrical vortexes, as if each blade section acted independent on each other, which also means that no tip loss can be taken in account. This fact is very limiting for the optimization of propellers as it does not allow to compute the optimum circulation distribution along radius of the blade. To deal with this issue, the lifting line theory has been combined with the vortex theory. The lifting line theory describes the downwash distribution of a lifting line constructed by a system of horseshoe vortices and has been derived for the description of aircraft wing loading (described by McBain, 2012). Even though its assumptions of the vortex structure do not correspond to those of cylindrical vortices of the vortex theory, it has been proposed by the authors to offer a rough and simple way to overcome some of the issues of the vortex theory. The downwash computed by the lifting line theory is then simply added to axial velocity calculated by the vortex theory. Zero circulation condition has been prescribed at the blade's tip to accomodate for the tip losses.

4. Panel Method

Another useful tool for computing propeller aerodynamic properties is the panel method. The panel method solves Laplace's equation for potential flow. As a boundary condition, zero normal flow through blade surface discretized by panels is prescribed together with free stream velocity.

The implemented algorithm is a low order panel method using constant singularity distribution over each panel. The structured mesh is formed by quadrilateral panels. Potential doublet (dipole) was chosen as a singularity type for each panel. The velocity perturbation formulation of the panel method was selected instead of the more common potential perturbation formulation. This allows for easier velocity field calculations, especially away from the surface, while potential values are not immediately available. The basic concept of the different modifications of panel method is well covered in the book of Katz and Plotkin (2001). As was theoretically proven by Hess (1972), quadrilateral flat panel with constant doublet distribution is equivalent to a vortex ring made of vortex filament segments placed at the panel edges. The constant strength doublet panels are therefore represented by vortex rings, which is an equivalent substitution.

Proper lifting flow is realised using the Kutta condition. The Kutta condition in the form of zero circulation on the blade trailing edge is satisfied by adding wake panels to the trailing edge with such circulation to cancel the trailing edge circulation. The wake panels are of the same type as blade surface panels. For quasi-steady flow (i.e. when the propeller is maintaining constant rotation rate and forward velocity) all the wake panels shed by a pair of trailing edge panels maintain constant circulation. Practical realization of infinite free form wake is not possible, therefore the wake length is chosen as a compromise between precision and computation time.

The shape of the wake is initialized as a regular helical surface, which already gives satisfying results. An original iterative free wake modeling algorithm was implemented to align the wake panels with local velocity field (i.e create force free wake). The wake panel nodes are shifted according to the local velocity to satisfy the force free condition. This results in a slight change in circulation distribution on the blade surface, which together with a different wake panel position changes the induced velocity at each wake panel. The procedure is repeated until the wake is fully or at least reasonably well aligned with the flow.

The structured surface mesh is derived from the same data used for CNC machining of the propeller molds. The data consist of a set of equidistant propeller sections - airfoils. Since the implemented panel method is sensitive to meshing irregularities, especially sudden changes in paneling density and high aspect ratios of panels, it was necessary to interpolate the provided data using splines in order to create proper mesh with arbitrary number of panels. The geometry of one blade is rotated to obtain the second blade so the effects of blade interactions are accounted for.

Convergence and sensitivity studies were performed in order to verify performance of the algorithms. In mesh density sensitivity study the result showed that the value of thrust was reasonably converged for 750 panels, while the value of shaft power (due to induced drag) was showing slight decreasing tendency even with 3400 panels per blade. This is in accordance with expectations that numeric integration of pressure over the surface estimates induced drag poorly. For more accurate results, the velocity field evaluation in the Trefftz plane as described by Katz and Plotkin (2001) would be necessary. Studying the effects of wake length showed that wake extending to at least one diameter distance behind propeller is sufficient and further increase in length has negligible effects on the solution.

The panel method has some advantages over simpler models. The method fully considers the actual blade geometry and provides results even for highly skewed and swept blades. It allows obtaining the velocity information throughout the whole domain, provides pressure distribution on the blade surface and is a great tool for simulating wake effects. Its advantages of simulating multi body interactions are especially useful in multiblade propeller designs. After some modification to accommodate the unsteady case, an off-axis free stream velocity may be defined to simulate aircraft flying in a side slip or a multicopter forward flight. On the other hand the panel method fails in predicting lift around stall conditions and without incorporating coupled viscous boundary layer model it will always underestimate the drag forces.

5. Data Comparison

Both experimental and computed thrust and shaft power were evaluated in dimensionless forms as thrust and power coefficients (c_t and c_p respectively) and plotted against dimensionless velocity (λ) related to the advance ratio:

$$c_t = \frac{T}{\rho n_s^2 D^4} \tag{1}$$

$$c_p = \frac{P}{\rho n_s^3 D^5} \tag{2}$$

$$\lambda = \frac{V_0}{\pi n_s D} = \frac{J}{\pi} \tag{3}$$

Propeller's efficiency is then defined as:

$$\eta = \frac{c_t}{c_p} \lambda \pi \tag{4}$$

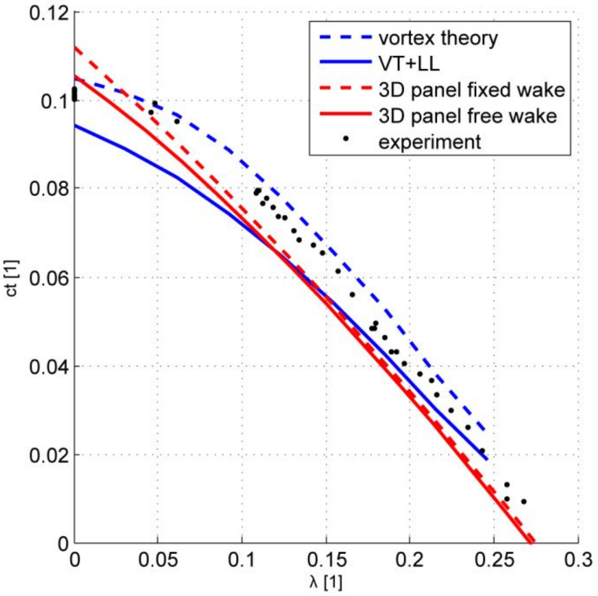

Fig. 1: Comparison of thrust coefficient.

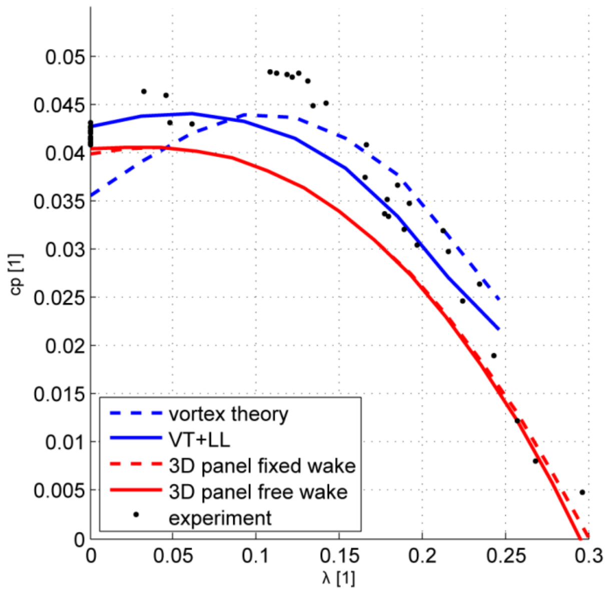

Fig. 2: Comparison of power coefficient.

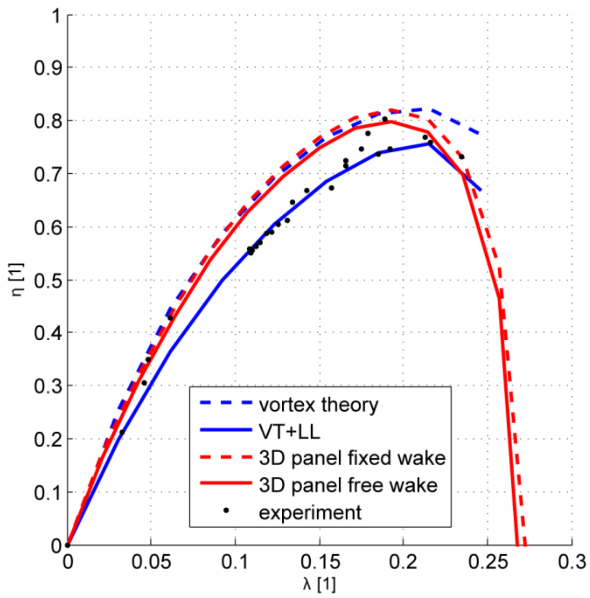

Fig. 3: Comparison of efficiency.

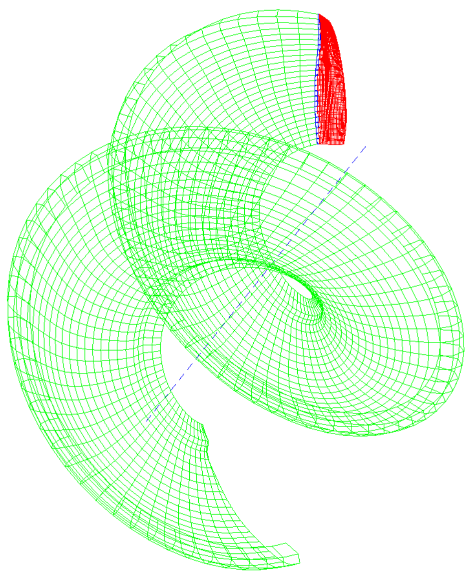

Fig. 4: 3D panel method – blade and free wake.

6. Conclusion

Three methods for propeller analysis were implemented and used to compute the performance of a propeller with a known geometry. An experiment has been carried out to provide experimental data for comparison. The thrust of the propeller was sufficiently predicted by all three methods. Even though the experimental data for shaft power are quite scattered it is clear that the vortex theory gives too optimistic results near static operation. VT+LL method gives very similar results for power as the 3D panel method, the curves are only offset from each other. The authors believe that the reason is the inviscid flow treatment of the 3D panel method. The propeller efficiency is best predicted by the VT+LL method. The Department of Fluid Mechanics and Thermodynamics will put additional effort to implement more sophisticated methods for analysis and optimization of propellers. The experimental facility is planned to be equipped with new measurement devices in the near future to allow for more reliable validation of computational models.

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