Fachgruppe: Drehflügler

Out of Ground Effect Blade Tip Vortex Study of a Single Bladed Rotor in Hover

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The wake of a helicopter is strongly influenced by rotor blade tip vortices, which govern the wake's shape and dynamics. These vortices are associated with several adverse effects, including blade–vortex interactions, increased noise, and energy loss. Improving models of blade tip vortices is crucial for more accurate predictions of the flow field around rotorcrafts in order to mitigating these adverse effects. The formation of blade tip vortices can be explained by considering the static pressure difference between the suction side (upper surface) and the pressure side (lower surface) of the 3D airfoil. This pressure difference, along with a span-wise pressure gradient, causes streamlines on the suction side to curve inboard and those on the pressure side to curve outboard. As a result, air flows around the blade tip, since no solid barrier prevents the opposing pressure areas from seeking equilibrium. The blade tip vortex then moves downward from the rotor plane and decays. Along its trajectory the flow field can be visualized using Particle Image Velocimetry (PIV) as illustrated in Fig.1.
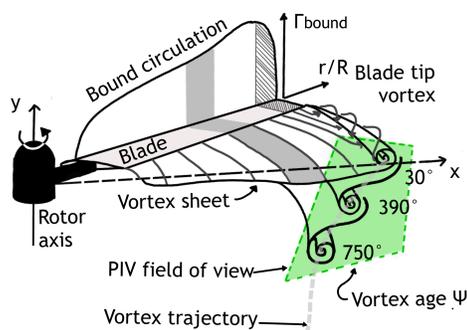

Figure 1: Schematic explaining the formation of a blade tip vortex of a single bladed rotor system and outlining a PIV field of view.
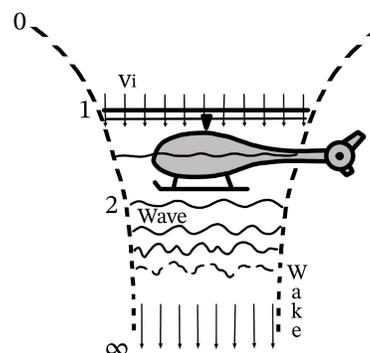
Figure 2: Helicopter diagram illustrating long-wave instabilities and wake contraction over wake age

The following analysis is based on data acquired at the Hover Test Stand (HVG) of the German Aerospace Center (DLR) in Göttingen. Three-component, two-dimensional (3C-2D) PIV measurements were conducted to capture the flow field around a rotor with a radius of 0.76 meters. From this data, vortex characteristics were extracted and systematically analyzed to investigate rotor wake dynamics in hover out of ground effect.

During the analysis of the vortex core radius r_c over varying vortex ages Ψ, the data revealed deviations from expected behavior. While a continuous growth of the vortex core with increasing vortex age was anticipated—consistent with typical vortex diffusion theory—the measurements showed a contraction of the vortex core beginning at approximately 850 degrees of vortex age. This can be seen in Fig.3, where vortex core radius starts to contract between 750-1000 degrees vortex age. This unexpected trend suggests the presence of additional aerodynamic effects influencing vortex development beyond the initially assumed mechanisms.

Wave and wake stretching

A plausible explanation for changes in vortex core size are stretching and contraction of the vortex tube caused by wave and wake stretching, depicted in Fig.2. The change in length of the vortex tube and the vortex core radius have an inverse relationship resulting from the law of conservation of mass.

Wake contraction as described by Landgrebe[1] is one factor that shortens the vortex tube and increases the core radius and directly follows the momentum theory. A second factor causing stretching of the vortex tube are long-wave instabilities, which grow as the vortex ages and moves down the wake. This is based on an idea of Ananthan and Leishman (2004).
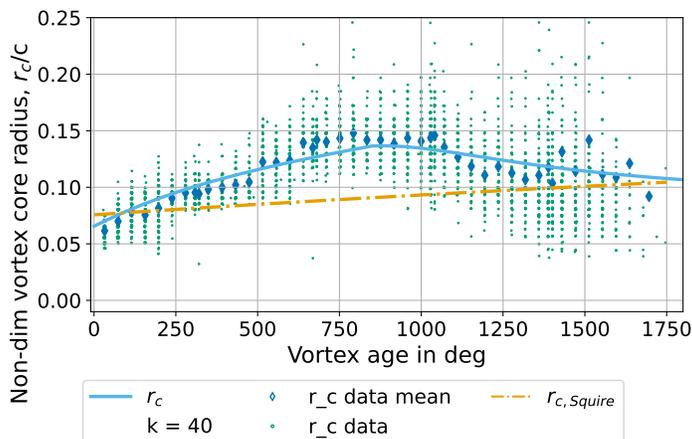

Figure 3: Measured mean vortex core radius with standard deviation over vortex age, and vortex core growth models after Squire's finite-radius version of the Lamb-Oseen model and r_c

Vortex model
The Lamb-Oseen blade tip vortex model, is derived from the 2D Navier-Stokes equations, describes the growth of a laminar vortex through viscous diffusion. Its strong grounding in fundamental physics makes it a suitable basis for the improved vortex model. To include these two factors quantitatively in a blade tip vortex model, the wake contraction and the harmonic long-wave instabilities need to be quantified. The wake contraction can be derived from the vortex trajectory, while the long-wave instability can be quantified through the wave number k and the amplitude a. The amplitude of these disturbances may be estimated from the positional standard deviation of the vortex in the y-direction, the wave number needs to be measured or estimated. Through integration the stretching factor of the long-wave instability can be found to be:

$$L = \int_{\Psi_1}^{\Psi_2} \sqrt{1 + (ak\,\cos(k\Psi))^2} \quad d\Psi. \tag{1}$$

The influence of the wake contraction can be approximated long the wake as the local wake radius contraction C_{WS}^{-1}. Incorporating these into the Lamb-Oseen model $r_{c(\text{Lamb-Oseen})} = \sqrt{4\alpha_L \nu t}$ we get:

$$r_c = \sqrt{r_0^2 + 4\alpha_L \nu t \cdot C_{WS}^{-1} L_{\sin}^{-1}}, \tag{2}$$

with Lamb's constant $\alpha_L = 1.25643$ and the fluid's kinematic viscosity ν and r_0 the initial vortex core radius. For this we estimated the wave number to be 40 and derived the amplitude and wake contraction from the positional data of the vortices. The modified Lamb-Oseen model called r_c is depicted in Fig.3. The curve of r_c captures the overall shape of the measurements well, including the initial rise, and the decline at higher vortex ages. In contrast, Squire's finite-radius version of the Lamb-Oseen model, $r_{c\,\text{Squire}}$ remains nearly flat across all vortex ages and fails to reproduce the observed variation in the data. This demonstrates that the modified Lamb-Oseen model fits the empirical data's shape much more accurately.

Concludingly, the close agreement between the r_c fit and the measured data indicates that models rooted in the Lamb–Oseen formulation can capture the true behaviour of the vortex core radius accurately, using physical modulations. Since the Lamb–Oseen model is strongly grounded in fundamental physical laws, its further investigation and refinement may be well worth pursuing to achieve both improved predictive capability and a solid theoretical basis.

[1]Landgrebe, Anton J. "The wake geometry of a hovering helicopter rotor and its influence on rotor performance." Journal of the American Helicopter society 17.4 (1972): 3-15.