Experimental investigation of vortex core properties of a finite span wing and an isolated rotor model

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Abstract. This work outlines results of an experimental investigation of vortex core properties of a finite span wing and a helicopter rotor model operating at hover mode. Experimental data was obtained using Stereo-PIV in T1-K wind tunnel at KNRTU-KAI named after A.N. Tupolev. An empirically derived formula is proposed, allowing to estimate the dependence of the vortex core size from the threshold $Q$-value. The wing tip vortices were measured for different angles of attack. The tip vortices from the rotor blades were measured at two collective pitch angles. The results indicate that the obtained empirical equation can be used to estimate the impact of the lowest threshold $Q$-value selection on the size of the vortex core, which facilitates a more objective approach compared to known methods, when used to eliminate non-essential vortical regions.

1. Introduction

Vortex core properties are often analyzed to study their influence on the performance of fixed-wing aircraft and rotorcraft. In recent decades, many vortex core identification methods were proposed, including Eulerian and Lagrangian methods [1]. In this work, data is analyzed using $Q$-criterion because it is representative among other local vortex identification methods [2], which are based on the local analysis of the velocity field and commonly used by other researchers. $Q$-criterion defines a vortex core as a connected region where the Euclidian norm of vorticity tensor is larger than the rate of strain tensor.

Highly rotational flows (for example, in the vicinity of a helicopter’s main rotor) are usually hard to visualize due to the presence of insignificant vortical structures, which satisfy the formal definition of a vortex, but are not related to the vortices. To eliminate such regions, a non-zero cut-off threshold value is usually used, which is significantly lower than the maximum $\overline{Q}$-value ( $\overline{Q} \geq 1$). For example, $\overline{Q} = \left( \frac{b^2}{V^2} \right) Q = 0.002$ was used by Jimenez-Garcia and Barakos [3]. In this work, the influence of the cut-off $\overline{Q}$-value selection on the vortex core size is investigated experimentally for a finite span wing and a helicopter rotor model. The obtained empirical equation allows estimating more accurately appropriate threshold $Q$-value selection when analyzing various wake structures.
2. Experimental setup

The study of tip vortices is based on two experimental studies: a finite span wing (figure 1) and an isolated helicopter rotor model (figure 2). The experiments were conducted in an open-jet, closed circuit T-1K wind tunnel at Kazan National Research Technical University (KNRTU-KAI). The wind tunnel has a jet core diameter of 1.9 meters and the free-stream turbulence intensity of the flow of 0.3%. The nozzle diameter of the T-1K wind tunnel is 2.25 m.

For both experimental cases, Stereo PIV was used to obtain the velocity fields. The flow was illuminated using Nd-YAG Litron 425-10 laser. The exposure time was set to 6 ns, with the acquisition frequency of 8Hz. FlowSense EO cameras with 2048×2048 pixels resolution were used. Two cameras had an offset angle of 10° between each other as shown in figures 1 and 2. Olive oil particles were used as tracer particles, which have low inertial tracking errors, which is an important requirement for flows with vortical structures [4]. The olive oil particles were suspended using 10F03 liquid seeding generator. Adaptive PIV algorithm was used for determining the velocity fields for each experimental condition.

The rectangular wing (figure 1) had an aspect ratio of 7.8 and the chord length \( c = 187 \) mm. The wing had a cross section of a modified Göttingen 387 aerofoil, which had a flat lower surface compared to the original aerofoil. The wind speed was set to \( V_\infty = 28 \) m/s, which corresponded to a Reynolds number of \( \text{Re} = 350000 \). The measurements were performed at \( \alpha = 0^\circ, 6^\circ, 12^\circ \) and \( 18^\circ \) angles of attack, and at different distances downstream of the trailing edge of the wing: \( 1.61 \leq \bar{X} \leq 4.23 \). Here \( \bar{X} = X / c \), where \( X \) is the downstream distance from the trailing edge of the wing to the measurement plane; \( c \) is the wing chord. The experimental setup of the wing is shown in figure 1. The data for each experimental condition (\( \bar{X} \) and \( \alpha \)) was analyzed based on 30 PIV velocity fields, which were then statistically averaged.

The rotor model consisted of four blades with rounded tips and no twist, which were attached to an articulated hub with three hinges. The rotor had a radius of \( R = 0.82 \) m and blades had a constant chord length of 65 mm along the radius. The experimental setup of the rotor model is shown in figure 2. The Reynolds number at \( 0.75R \) of the rotor with respect to the blade chord length, corresponded to \( \text{Re} = 2.57 \times 10^7 \), and the blade tip Mach number was \( M = 0.23 \). Experimental data from PIV measurements was analyzed at two collective pitch angles \( \delta = 8^\circ \) and \( \delta = 10^\circ \) for the hover mode. 30 velocity fields were used for each collective pitch angle to analyze tip vortices. Each velocity field contained 3 to 4 tip vortices.
3. Results

Vortex cores can be identified using $Q$-criterion as connected regions satisfying $\overline{Q} \geq 0$ condition. However, setting the lowest threshold value $\overline{Q}_{\text{thresh}} = 0$ is usually not sufficient when applied to experimental data, because of the prevalence of physically insignificant regions with low vorticity, which are not related to the vortices. In order to eliminate those regions, $\overline{Q}_{\text{thresh}} > 0$ condition is applied. This in turn leads to the decrease of the vortex core size along with increased values of $\overline{Q}_{\text{thresh}}$. This is exacerbated when it comes to highly three dimensional flows.

Currently there is no definitive method of $\overline{Q}_{\text{thresh}}$ value selection. Dubief and Delcayre [5] proposed two possibilities of selecting $\overline{Q}_{\text{thresh}}$ value: (1) the easiest way is the visual comparison of the vortices by selecting different threshold values (which is based on a subjective opinion); (2) $\overline{Q}_{\text{thresh}}$ value can be identified by maximizing time-averaged vorticity fluctuations in turbulent flows. In this work, an empirical equation is proposed, which allows factoring the influence of $\overline{Q}_{\text{thresh}}$ on the vortex itself.

The $\overline{Q}$-value varies within the vortex core in the $0 < \overline{Q} < \overline{Q}_{\text{max}}$ range. $\overline{Q}_{\text{thresh}} = 0$ corresponds to the original vortex core size $S_{\text{max}}$. The increase of $\overline{Q}_{\text{thresh}}$ value leads to a decrease of the core area $S$. $\overline{Q}_{\text{thresh}} = \overline{Q}_{\text{max}}$ condition corresponds to a single point. In this work, results are presented in terms non-dimensionalized values $\overline{Q}/\overline{Q}_{\text{max}}$ and $S/S_{\text{max}}$, where $\overline{Q}_{\text{max}}$ and $S_{\text{max}}$ are a maximum $\overline{Q}$-value and vortex core area at a specified downstream distance $X$ and an angle of attack $\alpha$.

The dependence $S/S_{\text{max}} = f(\overline{Q}/\overline{Q}_{\text{max}})$ for the wing is shown in figure 3. Here, the results are presented for different downstream distances $X$ and angles of attack $\alpha$.

Here, $Q_{\text{max}}$ represents the largest $Q$-value within the vortex core. $S_{\text{max}}$ is the vortex core area when the lowest cut-off $Q$-value is equal to zero. Equation (1) can be used to estimate the impact of the lowest cut-off $Q$-value selection on the reduction of the vortex core area $S/S_{\text{max}}$.

It is evident from figure 3 that the relation $S/S_{\text{max}} = f(\overline{Q}/\overline{Q}_{\text{max}})$ is non-linear. The largest curvature of this relation corresponds to highest angles of attack $\alpha = 12^\circ$ and $\alpha = 18^\circ$ where the tip vortex intensities reach largest values. It should be noted that $\alpha = 18^\circ$ is the critical angle of the wing and hence the $S/S_{\text{max}} = f(\overline{Q}/\overline{Q}_{\text{max}})$ curve can be associated with well-developed separated flow regions. Based on this experimental data, an empirical equation (1) was obtained by averaging $S/S_{\text{max}} = f(\overline{Q}/\overline{Q}_{\text{max}})$ at the distance range $2.14 \leq X \leq 4.23$, for $\alpha = 12^\circ$ and $\alpha = 18^\circ$:

$$
S/S_{\text{max}} = \frac{1-\overline{Q}/\overline{Q}_{\text{max}}}{(1+\overline{Q}/\overline{Q}_{\text{max}})^2}
$$

where $0 \leq S/S_{\text{max}} \leq 1$.

Based on equation (1), the 5% decrease of the vortex core area occurs at $\overline{Q}/\overline{Q}_{\text{max}} = 0.01713$, i.e. $\overline{Q}/\overline{Q}_{\text{max}} \geq 0.01713$ condition ensures that the vortex core size does not decrease by more than 5% from its original size ($S/S_{\text{max}} = 1$). Let us consider a wing tip vortex, obtained at $X = 3.21$ and $\alpha = 18^\circ$, which is shown in figure 4. Here, the lowest cut-off $Q$-value was set to $\overline{Q} = 3.6$. The largest $Q$-value corresponded to $\overline{Q}_{\text{max}} = 311$. By substituting $\overline{Q}/\overline{Q}_{\text{max}} = 0.01158$ into the equation (1), it follows that this cut-off $Q$-value corresponds to the decrease of the vortex core by 3.4% compared to the original core size at $\overline{Q} = 0$. 


The comparison of the obtained equation (1) with the data for the rotor model is presented in figure 5. It can be seen, higher collective pitch angle $\delta = 10^\circ$ better agrees with equation (1) compared to $\delta = 8^\circ$.

Figure 3. The dependence of the dimensionless vortex core area from the dimensionless $Q$ parameter of the wing.
4. Conclusions

Results of PIV-measurements, carried out on a finite span wing and a four-bladed rotor model, are presented. The dependence of the vortex core size from its lowest threshold $\bar{Q}$-value is analyzed for different angles of attack ($0^\circ \leq \alpha \leq 18^\circ$) and at different downstream distances from the trailing edge of the wing ($1.61 \leq \bar{X} \leq 4.23$).

An empirical equation was obtained, which facilitates a more objective approach compared to currently known methods, which can be used to estimate the decrease of the vortex core size for different threshold $\bar{Q}$-values. It is shown that obtained $S / S_{\text{max}} = f\left(\bar{Q} / \bar{Q}_{\text{max}}\right)$ relations are mostly non-linear and can be approximated by a simple algebraic equation at certain distances. It is demonstrated that the obtained equation can be used with sufficient accuracy for various experimental conditions.

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