Implicit Large Eddy Simulation of Tip Vortex on an Elliptical Foil

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ABSTRACT
In this study, Implicit Large Eddy Simulation (ILES) in OpenFOAM has been employed to study tip vortex flow on an elliptical foil. This type of foils has similar tip vortex behaviour as a propeller, making it a suitable benchmark for both numerical and experimental investigations of tip vortex flows in cavitating and non-cavitating conditions. The study includes investigation of the impact of streamwise and inplane mesh resolutions in tip vortex roll-up and its transportation. Vortex properties such as trajectory, axial and inplane velocity distributions, and also vortex core pressure distributions are computed for each mesh resolution and compared with available experimental data. Comparisons show that at least 16 cells per vortex diameter in inplane section is required to predict the tip vortex in the near field region. Results of varying foil angle of attack show the capability of the current numerical approach in ranking tip vortex properties. Employed numerical approach is fully capable of capturing the accelerated axial velocity at the vortex core for different operating conditions, and shows very good agreement with the experimental observations.

Keywords
Tip vortex, cavitation inception, implicit LES, numerical simulation, OpenFOAM.

1 INTRODUCTION
Close to the tip of a lifting wing with finite span, a pressure differential exists between the upper and lower surfaces which drives the fluid around the tip from the high pressure side on the lower surface to the low pressure side on the upper surface. This makes the flow highly three-dimensional at the tip region creating a vortex pattern. The vortex then moves downstream and rolls up more and more of the wing wake until its circulation is nominally equal to that of the wing. This typically extends to a few wing spans downstream of the trailing edge. This proves to be a challenging flow field to study because of the presence of turbulence and the large gradients of pressure and velocity in all three directions especially across the vortex core (Arndt and Maines 1994). The evolution of the strength and size of a tip vortex along its path is a complex phenomenon, governed by both viscous diffusion and the capture of vortex lines. Modeling and prediction of the minimum pressure coefficient are difficult, especially in the vicinity of the wing where the tip vortex is far from being axisymmetric (Franc and Michel 2005).

Tip vortex characteristics of a propeller has a direct impact on the propeller tip vortex cavitation inception which is important in defining the boundaries of the cavitation free bucket chart of a propeller. The co-existence of phase change and tip vortex creates a complex flow structure in the tip region of propellers which involves very small scale dynamics both in time and spatial coordinates. Understanding the physics of these flows is important in finding the tip vortex inception speed in order to prevent or control the occurrence of cavitation on propellers (Bensow and Bark 2010, Zhang 2014).

The current study focuses on the numerical prediction of tip vortex flows around an elliptical foil. The vortex structures around the foil resembles the propeller tip vortex behavior while making it possible to be tested in more details both experimentally and numerically. Moreover, the tip vortex at the selected operating conditions is relatively stationary which lowers the computational requirements (Penning 2016).

The main focus of the paper is to find the computational mesh requirement to predict the tip vortex in the near field region. For tip vortex cavitation inception, experiments show that cavitation begins at a short distance downstream of the wing (within one chord length at most), and that the roll-up process is already significantly initiated at such a relatively short distance (Franc and Michel 2005, Berntsen 2001). Therefore, the focus in the current research to predict and transport the tip vortex 1.5 chord length downstream of the foil. In the previous studies (Asnaghi 2015), the tip vortex of the same case and condition is analyzed with a steady approach. In the current study, the analysis is extended to unsteady computations to account for the unsteadiness of the flow in the vortex creation and propagation.

The investigation contains the mesh variation in both streamwise and inplane directions by employing hexahedral dominant cells, generated by StarCCM+. For each mesh resolution, the vortex properties, including the vortex trajectory, vortex axial velocity at the vortex core, velocity distributions at different inplane sections

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downstream of the foil, and the pressure distribution are computed and compared with available experimental data. It is shown that at least 16 computational cells are required for ILES across the vortex diameter in order to be able to predict the tip vortex in the near field region. The streamwise mesh requirement is less, around half of the inplane resolution requirement for the elliptical foil. RANS model cannot predict the tip vortex correctly even by employing the curvature corrections for these resolutions.

The capability of the numerical analysis to rank different operating conditions is also tested by analyzing the foil at three different angle of attacks, AOA. It is shown that the numerical approach is capable of predicting the trend of variation in tip vortex properties making it an appropriate tool in a propeller design process.

2 GOVERNING EQUATIONS

2.1 Conservation of Mass and Momentum

As the current study concern vortex flows, the governing equation includes the incompressible conservation of mass and momentum equations,

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \frac{\partial (\rho \mathbf{u} \mathbf{u})}{\partial x_i} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mathbf{\tau}_{ij} - B_{ij} \right),
\]

Here, \( B_{ij} = \rho \left( \eta_{ij} - \frac{\partial u_i}{\partial x_j} \right) \) is the subgrid stress tensor and \( \mathbf{\tau}_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) \) is the shear stress. In ILES, implicit LES, modelling, no explicit function is applied for B; instead the numerical dissipation is considered enough to mimic the action of B (Arndt and Fureby 2007, Bensow and Liefvendahl 2008, Fureby 2007).

Cavitation inception of a vortex is a complicated phenomenon as it involves a vortex with a low pressure region in the core, and also nuclei to expand in that vortex core. The pressure gradient of a vortex forces nuclei to move towards the center of the vortex. When such a nucleus reaches a critical pressure it will rapidly expand, but it will also take an elongated shape. But the generated cavity also moves with the flow and is thus moved away quickly. As a result, cavitation inception of a tip vortex begins with flashes of cavitation and is very difficult to discern (Arndt et. al 1991).

The dependency of the cavitation inception of vortices on the fluid nuclei content is strong. This is mainly due to the fact that vortex occurs in the fluid bulk, not exactly on the surface. For cases like the sheet or bubble cavitation that happens on the surface, the surface generates additional nuclei or disturbance in the pressure which expedites the cavitation inception and reduces the dependency to the bulk fluid nuclei content. But vortex cavitation depends fully on nuclei in the bulk flow and it is observed that lack of nuclei will delay the inception pressure to far below the vapor pressure (Shen 2001, and March 2009).

From visual observations such a delay can be recognized, because with a lack of nuclei the radius of the cavitating core at inception will be very large. Similar as with bubble cavitation the few nuclei which reach the critical pressure and expand suddenly, will reach a larger size. With an abundance of nuclei, the inception radius will be smaller and inception will occur less randomly. Note that for steady vortex cavitation such an abundance of nuclei can cause a collection of gas in the core.

The precise structure of a cavitating tip vortex at inception is still unclear, and the inception conditions remain a topic for research. Experiments are difficult because it is not possible to directly measure the pressure in the tip region due to its sensitivity to disturbances, while the region of minimum pressure is very small. It is expected that CFD can give more insights in the parameters controlling tip vortex inception.

One criteria for prediction of cavitation inception in CFD is to consider minimum pressure. Until now, however, the correlation of the experimental inception pressure with the calculated minimum pressure in a tip vortex is still bad, even in steady conditions and on simple forms like foils (Berntsen 2001, Schot 2014). Different parameters can cause this discrepancy, where one is the nuclei content in the experiment and the way its treated in numerical simulations. This, however, requires further investigations before reliable predictions of tip vortex inception can be made. Even though, the numerical methods can be used to provide further details in order to evaluate different designs, making it possible to compare cavitation inception trends on different propellers designs. Here, we have employed a cavitation index,\[
\sigma = \frac{p-p_{sat}}{\rho u_f^2},
\]
to plot pressure. Negative values of this cavitation index represents regions where cavitation inception is expected.

3 ELLIPTICAL FOIL

3.1 Description

The geometry of the tested foil is an elliptical planform having the NACA 662 – 145 as cross section having mean line equal to a = 0.8, see Figure 1. Having NACA 6 series section introduces a low adverse pressure gradient over the foil and therefore longer laminar boundary layer.

3.2 Experimental Tests

In the experimental tests (Arndt et. al 1991, Arndt and Keller 1992, Arndt and Maines 1994, Pennings et. al 2015, Pennings 2016), cavitation inception is studied on a series of elliptical planform hydrofoils, such as the one used here. It is observed that the cavitation inception and its growth in the tip region strongly depends on the size and number of nuclei in the free stream and also on the strength of the

Figure 1. NACA 662 – 145 section (Schot 2014)
vortex. Further, in most of the tested conditions the lowest pressure region of the tip vortex appears in a region very close to the tip where the vortex is not completely rolled up. It is also noted that for this type of foil, an excess axial velocity exists in the vortex core which increases with AOA, angle of attack; the axial velocity at the vortex core can go up to 2.4 times of the free stream velocity value. It is highlighted that the presence of bubbles in the flow and them being trapped into the vortex does not significantly affect the vortex trajectory. The vortex is asymmetric, indicating the velocity measurements made with a single traverse through the vortex can be misleading. It has been suggested to use particle image velocimetry (PIV) for further study and analysis. Observation indicates that the cavitation inception occurs both inside and outside the vortex core. Nuclei, which cavitate just outside the core, quickly spiral into the vortex axis. Moreover, it is noted that in strong water, where the amount of the nuclei is limited, larger bubbles are created when inception occurs. Then considering the inception pressure provides more consistent cavitation data than considering the saturation pressure. In weak water, it is found that the cavitation inception pressure was often greater than the saturation pressure. Moreover, significant level of tension can be tolerated before inception occurs in the strong water.

Following the suggestion by Arndt et al. (1991) to use PIV for tip vortex analysis, Pennings et al. (2015) conducted Stereoscopic PIV measurements on the Arndt’s foil in non-cavitating and cavitating conditions. They employed correlation averaging in PIV images post processing in order to minimize the interrogation area size.

In the current study, the experimental study conducted in the test tunnel of the Laboratory for Ship Hydrodynamics at Delft University of Technology is selected for comparison with the numerical results (Pennings 2016).

3.3 Computational Domain
The computational domain has the same dimensions and geometry as the cavitation tunnel at TU Delft. In Figure 2, the computational domain and related boundary conditions are presented.

Figure 2. Computational domain of the elliptical

In the computational domain, the inlet is placed approximately five chord lengths in front of the foil, and the outlet is placed ten chord lengths behind the foil. The foil is positioned in the middle of the channel width where the distance to each side is equal to 150 mm. The chord length of the foil at the root is equal to 125.6 mm, and the coordinate system is located at the center of the chord at the root. The trailing edge has been cut off with a thickness of 0.3 mm, and the total area of the foil from the 3D CAD model is 0.01465 m² which is used as the reference area to compute non-dimensional parameters, e.g. lift coefficient.

The resolution study is conducted for the foil having geometrical AOA of 9 degrees. Two other AOAs, 7 and 5 degrees, are tested for ranking the operating conditions.

3.4 Computational Mesh Description
One of the most challenging parts of numerical analysis of tip vortex flows is to provide appropriate mesh resolution at the vortex core region. As one of the main tasks of the research was to find the spatial resolution requirement for numerical analysis of tip vortex flows, applying hexahedral cells at the tip vortex region became advantageous. To address this, Star-CCM+ of CD-Adapco is used to generate the mesh.

At the first step, a coarse mesh is employed to simulate the tip vortex in order to find the approximate trajectory vortex path. The trajectory location is then used in StarCCM+ to define refinement zones. Two cylindrical regions are considered around the trajectory path to specify the mesh resolution, having 10 and 60 mm diameter, respectively, corresponding to approximately 10 and 60 times the vortex core diameter. These cylindrical regions extend two chord length downstream of the foil. In Figures 3 and 4, general distribution of the cells in the streamwise and inplane directions are presented.

Figure 3. Streamwise mesh distribution, P1S1

Figure 4. Inplane mesh distribution, P1S1

Five different resolutions are created for 9 degrees of AOA. The surface resolutions and prismatic layers (y⁺=1) of these meshes are the same, and the only difference between them is the resolution of the inner refinement cylinder, Figure 4. In Table 1, specifications of these computational meshes are presented. It is reported that the tip vortex core for the selected operating condition has a diameter equal to 1 mm. Therefore, the sizes and dimensions in Table 1 are selected.
accordingly. The inplane cell size, and the vortex diameter are described by \( h \) and \( d \), respectively.

3.5 Flow Condition and Numerical Setup

The inlet velocity is set equal to 6.8 m/s which corresponds to the Reynolds number of \( 8.5 \times 10^5 \). The outlet pressure is set fixed equivalent to cavitation index 4.2.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Name</th>
<th>Total number of Cells (M)</th>
<th>Cell size (mm)</th>
<th>In-plane (h)</th>
<th>Streamwise</th>
<th>Number of cells in vortex core</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Plane</td>
<td>P1S1</td>
<td>8.3</td>
<td>0.125</td>
<td>0.25</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P2S1</td>
<td>24.4</td>
<td>0.062</td>
<td>0.25</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P3S1</td>
<td>88.3</td>
<td>0.031</td>
<td>0.25</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Streamwise</td>
<td>P2S1</td>
<td>24.4</td>
<td>0.062</td>
<td>0.25</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P2S2</td>
<td>44.3</td>
<td>0.062</td>
<td>0.125</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P2S3</td>
<td>84.9</td>
<td>0.062</td>
<td>0.062</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

4 SOLUTION PROCEDURE

The OpenFOAM package, used in this study for numerical simulation, is an open source code written in C++ to model and simulate fluid dynamics and continuum mechanics. In OpenFOAM, the spatial discretization is performed using a cell centred collocated finite volume (FV) method. A second order implicit time scheme is used for time discretization. The time step is set fixed and small enough to ensure a maximum Courant number to be less than one everywhere in the computational domain for the period of collecting the results. Second order upwinding scheme, linearUpwind, is employed to compute the divergence of Navier-Stokes convection term. The other divergence terms are computed using second order linear schemes. All of the gradients have been corrected for computational cell non-orthogonality effects.

4 RESULTS

4.1 Mesh Resolution

For each mesh resolution, three different vortex properties are computed and compared: vortex trajectory, normalized streamwise velocity (vortex axial velocity), and the cavitation index (Equation (3)). These vortex properties are computed at the center of the vortex core. In order to identify the vortex core center, the minimum pressure criteria is employed, where it is assumed that the minimum pressure occur in the center of the vortex. The streamwise velocity is normalized by the inlet velocity, and the cavitation index is computed according to the inlet velocity, outlet pressure, and the liquid density. The vortex trajectory which represents the location of the vortex core center along the streamwise direction (\( z \) coordinate in the current study) is normalized by the root chord length of the foil.

Figure 5 presents the tip vortex properties at the vortex core for different inplane resolutions. Cavitation index is selected to represent the pressure field, as the negative cavitation index indicates the regions where cavitation can be expected.

The cavitation index curves, Figure 5.a, show that all of the selected inplane resolutions predicts negative pressure at the region close to the tip (\( z/C < 0.2 \)) however the negative pressure predicted by P2S1 and P3S1 is almost twice as the value predicted by P1S1. While the vortex core pressure of P1S1 becomes positive after \( z/C > 0.35 \), the other two resolutions predict negative pressure at the core until the end of the refined zones, \( z/C = 1.6 \). The minimum pressure predicted by P2S1 and P3S1 are almost the same, but the region of this minimum pressure is larger in P3S1. At the end of the refinement region, \( z/C > 1.5 \), all of the resolutions show sudden increase in the pressure. The main reason of this sudden change is an impact of the coarse resolution outside the refined zone into the up-stream region. Comparison of the vortex trajectories, Figure 5.b, shows similar prediction by different inplane resolutions.
Slight difference at the center region, $0.6 < z/C < 1.0$, is considered to be due to the foil wake flow rollup contributions into the tip vortex development.

Figure 6 presents the results of streamwise mesh variations while inplane resolution is kept constant. Results show that the effects of the streamwise resolution on the tip vortex prediction is less than the inplane resolution. This is related to the fact that the flow variations in the inplane section of the tip vortex due to the rotational nature of the vortex is larger than the variations in the streamwise direction.

The pressure distributions predicted by P2S1, P2S2, and P2S3 resolutions show similar trend, even though the pressure predicted by P2S1 is slightly lower than the two other resolutions, Figure 6(a). Contradictory to the inplane resolution variation where increasing the inplane resolution lead to lower pressure at the vortex center, increasing the streamwise resolution leads to slightly higher pressure in the vortex core. Having higher streamwise resolution also leads to prediction of higher axial velocity, Figure 6(c). This means that increasing the streamwise resolution leads to prediction of lower rotational velocity, Figure 7.

Figure 7. Variation of the normalized azimuthal velocity at the vortex core at two sections downstream of the foil for mesh resolutions P2S1 and P2S2. The radius is normalized by $r_v=1.1$ mm and the velocity is normalized by $U_{θ}=6.7$ m/s.

P2S1 resolution, which has coarsest streamwise resolution, shows more rapid decrease of the axial velocity, especially after $0.8 < z/C$. The maximum axial velocity predicted at the center of the vortex by different streamwise resolutions are similar, almost twice the inlet velocity. Similar contribution of coarse resolution outside the refinement region is also observed on the prediction of the pressure and velocity of the tip vortex at $1.5 < z/C$. According to the mesh resolution investigation, P2S2 resolution is considered to be suitable to capture the physics of the vortex at reasonable computational cost.

In Figure 8, the normalized azimuthal velocity at the vortex core region at the section of $z/C = 1.14$ for P2S2 and P1S1 resolutions are plotted and compared with the experimental data. The results related to P2S2 show very good
agreement with the experiment, while P1S1 results show underprediction of the azimuthal velocity.

Figure 8. Variation of the normalized azimuthal velocity at the vortex core at z/C=1.14 downstream of the foil. The radius is normalized by \( r_v = 1.1 \) mm and the velocity is normalized by \( u_\theta = 6.7 \)

In Table 2, numerical prediction of lift coefficient is presented for different resolutions. The results are also compared with the experimental data, Exp.Cl = 0.67, and comparative errors are also included. The comparative error of the lift coefficient for selected resolution, P2S2, is 2.7%.

In Figures 9 and 10 the velocity distributions at three different sections downstream of the foil are presented and compared with the experimental data. The sections are z/C = 0.5, 0.75, 1.14. PIV images are derived by employing sum of correlation (SOC) conditional weighted averaging, see Pennings (2016). The numerical results are time averaged.

Axial velocity distribution shows that the numerical approach can accurately predict the accelerated velocity at the center of the vortex. The vortex roll-up which can be seen in the increase of the axial velocity between z/C =0.5 and z/C =0.75, is slightly under predicted in the numerical simulations. One possible reason for this can be the coarse resolution in the wake region of the foil.

Table 2. Numerical prediction of lift coefficient for different mesh resolutions, experimental value Cl=0.67, AOA=9 deg

<table>
<thead>
<tr>
<th>Case</th>
<th>Cl</th>
<th>Comparative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1S1</td>
<td>0.700</td>
<td>4.4</td>
</tr>
<tr>
<td>P2S1</td>
<td>0.682</td>
<td>1.8</td>
</tr>
<tr>
<td>P3S1</td>
<td>0.684</td>
<td>2.1</td>
</tr>
<tr>
<td>P2S2</td>
<td>0.688</td>
<td>2.7</td>
</tr>
<tr>
<td>P2S3</td>
<td>0.687</td>
<td>2.5</td>
</tr>
</tbody>
</table>

4.2 Ranking Operating Conditions: Variations of Angle of Attacks

In this section results of raking operating conditions are presented. For this purpose, three different AOA are considered: 9, 7, and 5 degrees. For each angle, two different computational resolutions are created, P1S1 which was the coarsest resolution and P2S2 which was cleared as a sufficient resolution for tip vortex analysis of the current case. The flow conditions, i.e. inlet velocity and Reynolds number, are the same.

Figure 9. Comparison between numerical and experimental normalized axial velocity distributions, P2S2 resolution

In Table 3, numerical prediction of lift coefficients of each AOA are presented and compared with the experimental data. For all of the tested angles, increasing resolution from P1S1 to P2S2 will lead to better prediction of lift force. However, the accuracy of lift prediction decreases by decreasing foil AOA.

Table 3. Numerical prediction of lift coefficient for different angle of attacks for mesh resolutions P1S1 and P2S2

<table>
<thead>
<tr>
<th>Angle of Attack (deg)</th>
<th>Exp. Cl</th>
<th>Mesh Resolution</th>
<th>Num. Cl</th>
<th>Comparative Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.47</td>
<td>P1S1 0.53</td>
<td>P2S2 0.5</td>
<td>6.3</td>
</tr>
<tr>
<td>7</td>
<td>0.58</td>
<td>P1S1 0.63</td>
<td>P2S2 0.61</td>
<td>5.1</td>
</tr>
<tr>
<td>9</td>
<td>0.67</td>
<td>P1S1 0.700</td>
<td>P2S2 0.688</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Figure 11 shows the variation of axial velocity and cavitation index at the vortex core for different AOA for
the two resolutions. The influence of the mesh resolution on the vortex properties has the same trend for all of the AOA.

![Graph](image1)
![Graph](image2)

Figure 11. Variation of vortex core properties, different AOA

Results indicate that for the AOA of 7 degrees, the vortex close to the foil is stronger than the other two AOAs, while at AOA of 9 degrees, the vortex roll-up contributes more to the vortex formation slightly downstream, and as a result the decay of vortex is slower compared with the two other AOAs. This shows that resolutions P1S1 and P2S2 predict different rankings of operating conditions. As P2S2 resolution is proved to provide better prediction of tip vortex characteristics, it can be deduced that in order to be able to rank different operating conditions, P2S2 resolution should be employed.

### 4.3 Cavitation Prediction

In Figure 12, the iso-surfaces of the averaged pressure is plotted for different mesh resolutions. The iso-surfaces represent the region with the pressure below the saturation pressure. For these simulations, the outlet pressure is set to represent conditions with cavitation index equal to 4.2.

From the figure, the contribution of the mesh resolution on the pressure prediction can be easily observed. As it is discussed before, increasing resolution from P2S2 to finer resolution does not change the results very much, and this resolution is considered to be sufficient for this study.

![Graph](image3)

Figure 12. Pressure iso-surfaces (p=psat) for different mesh resolutions, AOA=9 deg

<table>
<thead>
<tr>
<th>P1S1</th>
<th>P2S1</th>
<th>P3S1</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
</tbody>
</table>

(a) Averaged  
(b) Instantaneous

Figure 13. Averaged and instantaneous distributions of pressure iso-surfaces (p=psat), Q=5000 iso-surface, and velocity streamlines for AOA=9 deg, P2S2 resolution

### 5 CONCLUSION

Implicit LES simulations of tip vortex flow over an elliptical foil is performed in this study, using OpenFOAM.
Numerical setup and conditions follow the experimental test conditions recently conducted by Pennings at Delft University of Technology (Pennings 2016). Different spatial resolutions are investigated to see the mesh resolution impact in tip vortex prediction and transportation. It is found that the mesh resolution requirement in the inplane section of the vortex is higher than the streamwise direction, due to having higher flow gradients in the inplane direction. The suggested value for mesh resolution in the inplane section is $h = 1/16d$, and in the streamwise direction is $2h$, where $d$ is the vortex core diameter.

Comparisons of the velocity distributions between numerical results and experimental PIV images show very good agreement. It indicates the capability of the current numerical method employed here can predict the trend of the flow variation on different operating conditions, and therefore is a proper tool to be used for design purposes. Note, however, that a lower resolution than suggested here gives a different ranking between conditions.

Comparison of averaged and instantaneous fields shows the contribution of the small scale flow dynamics into the vortex roll-up from the wake flow. This clears the importance of the wing wake flow simulation accuracy on the tip vortex prediction, and also indicates the necessity of unsteady simulation of the tip vortex.

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7 REFERENCES


