INVESTIGATION OF A VORTEX-BASED THREE-DIMENSIONAL CORRECTION FOR UNSTEADY EFFECTS IN THE ACTUATOR LINE METHOD

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ABSTRACT

1. Introduction

The Actuator Line Method (ALM) is a numerical approach used in computational fluid dynamics to represent lifting surfaces by distributing actuator points along a blade span. Aerodynamic forces are computed using blade-element theory and tabulated airfoil data based on the local angle of attack. This method allows coarser grids, greatly reducing the costs of numerical simulations and it has found widespread use in aerodynamic simulations of wind turbines [8].

With the economic considerations of wind power generation, blades of wind turbines are gradually becoming longer and more flexible, and ALM has been increasingly used for studying aeroelastic effects in wind turbines [9]. Although the aeroelastic effects are directly dependent upon the non-stationary aerodynamics, only recently have unsteady effects been studied and implemented in ALM, but still limited to two-dimensional analysis [2].

In the ALM, the forces are projected onto the CFD grid through a Gaussian kernel with characteristic length scale ε. This smearing process alters the velocity induced by the shed vorticity, which in turn alters the blade loadings.[6] To address this, a correction of unsteady effects was recently proposed for the 2D ALM [1], based on the linearized vorticity equation. Based on the same principles of [1], this study proposes a correction that is applicable to the three-dimensional unsteady ALM simulations. The correction intends to reduce the mesh dependency and improve the accuracy of ALM simulations in unsteady conditions. In the final version of the paper, the results of the correction will be compared with theoretical and Doublet Lattice Method [4] results.

2. Methodology

The correction method is based on the linearized vorticity equation. The indicial response of a three-dimensional ALM segment generates a smeared vortex ring [1]. Therefore, the wake of an unsteady ALM simulation forms a vortex wake with a spanwise shed vorticity, as shown in Figure 1(b). The velocity induced by each smeared vortex segment can be computed through the equations provided by [5], which were originally developed to correct for the effects of the streamwise vorticity (shown in Figure 1(a)).

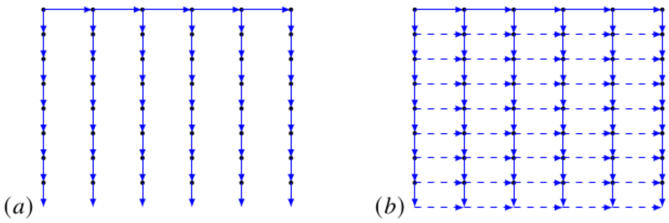

Figure 1: Vortex sheet without (a) and with (b) shed vorticity in spanwise direction

The general concept of the correction is based on the observations of [1,2] that a value of $\varepsilon/c=0.4$ has good agreement with Theodorsen's and Wagner's theory in 2D. $\varepsilon/c=0.4$, however, requires a finer grid than most ALM simulations, because the value of ε is related to grid spacing [5]. Therefore, the proposed correction has the objective of reproducing the results from a finer smearing parameter ε_c in a simulation with a larger numerical ε_0. The proposed approach, similar to methods for trailing edge correction, involves subtracting the erroneous velocity induced by the large computational kernel and adding the velocity induced by a vortex that mimics the effect of an optimal kernel.

Under a linear approximation, the sampled actuator-line velocity u_y^s is given by the superposition of the induced velocity u_y^v and the quasi-steady velocity u_y^{QS} :

$$u_{y,\varepsilon_0}^s=u_y^{QS}+u_{y,\varepsilon_0}^v$$

Using the vortex sheet modeled by a free-wake vortex model, the induced velocity of the numerical simulation with the original Gaussian u_{y,ε_0}^v can be modeled. Using the same principles of the vortex-based smearing correction [5], the corrected velocity is

$$u_{y,\varepsilon_c}=u_y^{QS}+u_{y,\varepsilon_c}^v=u_{y,\varepsilon_0}^s-u_{y,\varepsilon_0}^v+u_{y,\varepsilon_c}^v$$

The methodology was implemented in the open-source spectral-element CFD solver Nek5000 and applied to a rectangular wing in harmonic plunging motion to assess its performance in a 3D unsteady context. Alongside the proposed correction, the vortex-based smearing correction for the streamwise vortices was used and more details about the method and the code can be found in [5].

3. Preliminary Results

First, simulations without correction were performed with $\varepsilon_0=2c$ and $\varepsilon_0=c$ for a wing with an aspect ratio of 10 under plunging motion with reduced frequency k=1. The results of a simulation with $\varepsilon_0=2c$ and with correction for $\varepsilon_c=1c$ were compared to the results of the uncorrected simulations, in Figure 2. The circulation amplitude and phase responses are nearly identical, confirming the correction's ability to reproduce the results of smaller smearing parameters.

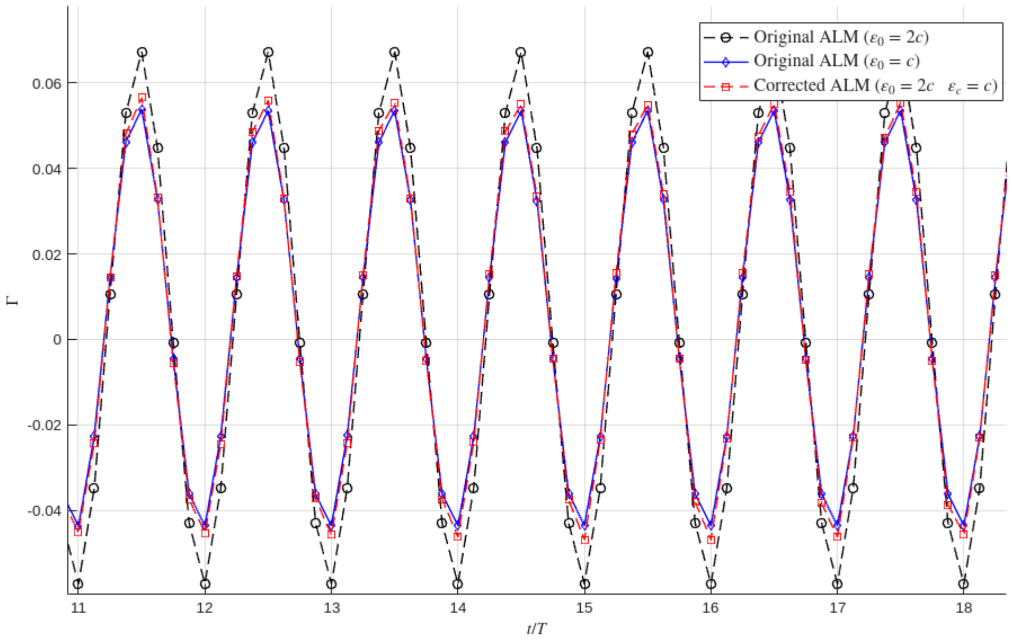

Figure 2: Time-dependent circulation at the wing root (AR=10, k=1).

Then, a rectangular wing under plunging with an aspect ratio of 6 and a reduced frequency of $k=1/3$ was simulated with $\varepsilon_0=2c$, for different values of ε_c. The results at the root are compared to the theoretical results of [7] in Table 1. In order to compare to the theoretical results, the non-circulatory terms (which are not calculated by ALM) were added, using Theodorsen's formula. An excellent agreement with the reference value was found by applying the correction to 0.4c, which is the value that showed the best results in 2D applications [2].

ε_c	2.0 c (uncorrected)	1.0 c	0.4 c	Reference[7]
$\frac{\bar{L}}{2\rho U^2 b_0 \bar{h}/b_0}$	-0.2545+0.8461i	-0.1737+0.7673i	-0.0515+0.6805i	-0.020+0.681i

Table 1: Complex normalized lift values at the root for rectangular wing with AR=6.

4. Preliminary Conclusions and Next Steps

The results demonstrate that the proposed correction reproduces the results of an ALM simulation with a smaller smearing parameter, reducing the sensitivity of the unsteady ALM to the mesh resolution. For the wing with AR=6 with correction to $\varepsilon_c=0.4c$, the method showed a great agreement at the wing root, when added to the non-circulatory term, which indicates that the method is promising.

In the final paper, we plan to extend the parametric studies and analysis, investigating if the method is adequate for correcting the non-stationary effects in general cases and compare the results to the Doublet Lattice Method for further validation.

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