Improved Actuator Line Method for Ducted Fan Applications

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Abstract: An Actuator Line Method (ALM) based on integral velocity sampling is developed for application to ducted fans and does not rely on a tip-loss function for finite span effects. In this work, the lifting surface is replaced by momentum source terms in the unsteady Reynolds-averaged Navier-Stokes equations. The source terms are computed at discrete locations along the blade's span before being spread on the mesh using a nonisotropic gaussian kernel allowing the source term distributions to mimic the geometrical attributes of the blade at that location. The determination of the local effective freestream vector, a common difficulty of ALM approaches, is done with an integral velocity sampling that accounts for the blade-local induced velocity. Including the projection function in the computation of the effective freestream vector makes the formulation more general and removes the ambiguity surrounding the sampling of the effective freestream vector. The method is implemented as User Defined Functions in *Ansys Fluent* and uses a fraction of the mesh size rendering this approach a useful tool for optimization processes.

Keywords: Actuator Line Method, Computational Fluid Dynamics, Rotor Replacement Techniques

1 Problem statement

The Actuator Line Method is widely used in the renewable energy and the aeronautics fields as a tool to simulate the effect of a lifting and draging surface on the flow field without having to carry out computationnally intensive blade-resolved simulations. The technique was first introduced by Sørensen and Shen [1] to study wake behavior of wind turbines and was then used, to a lesser extent, in rotorcrafts in the work of Forsythe et al. [2] amongst others. The classical ALM formulation uses discrete velocity sampling where the sampling location coincides with the center of an isotropic gaussian kernel such that this point is not perturbed by the local bound vorticity. This method is restricted to kernels that are symmetrical in space because the center of the force distribution must coincide with the center of the assumed bound vortex. The scope of this work is to extend the integral velocity sampling developped by Spalart as reported in the appendix of Churchfield et al. [3] to an ALM formulation for ducted fans. This formulation directly accounts for the effect of the kernel on the sampled velocity allowing for any kernel integrating to 1 to be used. This improved formulation allows the source terms to act on a volume that mimics the actual geometry of the blade instead of a being constrained within a cylinder centered on the quarter chord.

2 Formulation

Each blade is modeled using N control points that can be equally spaced in the span or concentrated towards the tips to better capture strong gradients. The effective freestream vector at station N_i is computed with Equation (1) which is the result of the integral velocity sampling devised in Churchfield et al. [3] :

$$\vec{U}_{i\infty} = \int\int\int g(x,y,z)\,\vec{U}\;dxdydz \tag{1}$$

where $g(x,y,z)$ is the kernel used to spread the source terms. Equation (1) states that the effective local freestream vector is equal to the integral of the velocity at each actuated cell weighted by the kernel itself. The resulting freestream vector is independent of the kernel choice, but the kernel should be chosen to ressemble the real force distribution of an airfoil as shown in Figure 1. Equation (2) provides a nonisotropic gaussian kernel with the gaussian widths ϵ_c, ϵ_t and ϵ_r reflecting the local airfoil properties.

$$g(x_c,x_t,x_r) = \frac{1}{\epsilon_c\epsilon_t\epsilon_r\pi^{3/2}}\exp\left(-\frac{(x_c-x_{c,0})^2}{\epsilon_c^2} - \frac{(x_t-x_{t,0})^2}{\epsilon_t^2} - \frac{(x_r-x_{r,0})^2}{\epsilon_r^2}\right) \tag{2}$$

where the subscripts c, t and r refer to the coordinate in the chord-wise, thickness-wise and radial (spanwise) direction respectively while the subscript 0 denotes the center of the kernel. When applied to ducted geometries, care must be taken so that $g(x,y,z)$ is not projected outside the fluid domain because of the proximity between the blade tip and the duct.

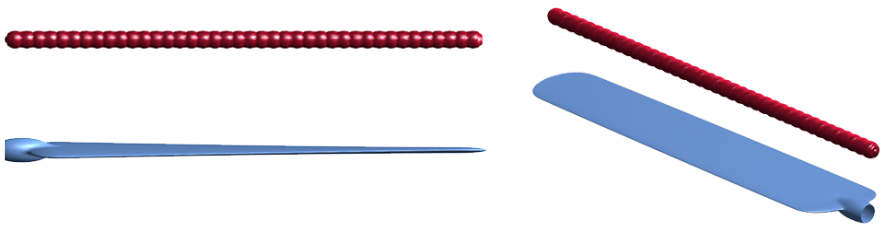

Figure 1: Force projection isocontour ($g = 20$) for the proposed nonisoptropic gaussian kernel projection (blue) and the classical isotropic gaussian kernel (red)

3 Conclusion and Future Work

The present work improved on the classical ALM formulation by using a new way to compute the effective freestream vector making it capable of reliably simulating ducted geometries. Future work will focus on using this ALM formulation in the optimization of a ducted helicopter tail rotor. Validation and optimization results will be discussed in the full paper and presented at the conference.

References

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