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PARALLEL SIMULATION OF LIFTING ROTOR WAKES IN FORWARD FLIGHT

C. B. ALLEN

Abstract. A finite-volume implicit, unsteady, multiblock, multigrid, upwind solver, and structured multiblock grid generator for rotors are presented, and applied to lifting rotors in forward flight. These flows are particularly expensive to compute as the accurate capture of the detailed vortical wake requires fine meshes away from the blades and, hence, a parallel version of the code has been developed allowing the use of very fine meshes. Parallel performance of the code is presented, and grid dependence of the computed blade loads and wake analysed, by considering wake capturing, total blade load and sectional load variation around the azimuth. It is demonstrated that the vortical wake capture is severely influenced by grid density, and even with 32 million points grid convergence is not approached. It is also shown that if blade loads only are of interest the vorticity dissipation is not a severe problem, and coarser meshes can be used. However, if more detail is required, for example blade-vortex interaction or aero-acoustic analysis, it would appear very difficult to capture the wake to any reasonable accuracy.

Key Words. Numerical simulation, forward flight rotors, parallel processing, wake capturing.

Nomenclature

a_∞	Freestream acoustic speed
A	Cell face area
c	Rotor chord
C_L	Blade load coefficient
C_{load}	Blade sectional load coefficient
E	Energy
F_z	Force in z-direction
$\mathbf{F}$	Flux vector
$\overline{\mathbf{F}}^{\pm}$	Upwinded flux vector components
$\mathbf{i}, \mathbf{j}, \mathbf{k}$	Unit vectors in x, y, z directions
k	Cell face index
$\mathbf{q}$	Absolute velocity vector $= [u, v, w]^T$
M_{Tip}	Rotor tip Mach number ($= \Omega R_{Tip}/a_\infty$)
$\mathbf{n}$	Outward unit normal vector
P	Pressure
$\mathbf{r}$	Coordinate vector
$\mathbf{R}$	Residual vector
r	Section radius
R	Rotation matrix
R_{Tip}	Rotor tip radius

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S	Surface cell area
t	Time
T	Implicit time-stepping coefficients
u, v, w	Cartesian velocity components
x, y, z	Cartesian coordinates
$\mathbf{U}$	Conserved vector
V	Cell volume

α	Explicit time-stepping coefficient
μ	Advance ratio ($= V_{FF}/\Omega R_{Tip}$)
ω	Rotation vector
Ω	Rotational frequency
Ψ	Azimuth angle
ρ	Density
Θ_{inc}	Rotor shaft inclination angle

1. Introduction

Forward flight rotor flows are extremely challenging for numerical simulation codes, due to the particularly harsh flow regimes. The flow in the root region is very low speed, and can contain regions of reverse flow on the retreating side, while the flow in the tip region is normally transonic on the advancing side. The flow around each blade is also strongly influenced by the wake from previous blades, and so the capture of this wake is important. However, numerical diffusion/dispersion inherent in all CFD codes severely compromises the resolution of flow vorticity, and so this is a serious problem for rotor flow simulation. Hover simulation requires the capture of several turns of the tip vortices to compute accurate blade loads, resulting in the requirement for fine meshes away from the surface, and a long numerical integration time for this wake to develop. Forward flight simulation also requires accurate capture of the vortical wake but, depending on the advance ratio, fewer turns need to be captured, as the wake is swept downstream. However, not only does the entire domain need to be solved, rather than the single blade for hover, but the wake is now unsteady, and so an unsteady solver must be used, which is not only more expensive than the steady solver used for hover, but can easily result in even higher numerical diffusion of the wake. Hence, it is extremely expensive to simulate these flows.

Other, cheaper methods can be used for rotor simulation, for example it is common to use a wake model based on a vortex element or vortex-lattice method [1, 2]. However, these can also become expensive for fine resolutions, resulting in simplifying assumptions, often related to vortex roll-up, which can lead to incorrect representations. Another cheaper approach is the vorticity transport formulation, see for example [3, 4], which has very low inherent diffusion, and has been proven to preserve and convect vortices over extremely long distances. Simulations with this method have been demonstrated to capture both unsteady hovering wakes, and wake breakdown in forward flight. However, this approach is, as are free wake models, limited to incompressible flow.

Ultimately, for many aspects of rotor design and analysis, a mainstream CFD solution of the entire, compressible, flow field is desirable, and that approach is considered here for forward flight. Of particular interest is the development and capture of the unsteady vortical wake and, hence, a grid dependence study has been performed. To this end, the simulation code has been parallelised to allow the use of very fine meshes.