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An overset grid method for large eddy simulation of turbomachinery stages

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ABSTRACT

A coupling method based on the overset grid approach has been successfully developed to couple multi-copies of a massively-parallel unstructured compressible LES solver AVBP for turbomachinery applications. As proper LES predictions require minimizing artificial dissipation as well as dispersion of turbulent structures, the numerical treatment of the moving interface between stationary and rotating components has been thoroughly tested on cases involving acoustical wave propagation, vortex propagation through a translating interface and a cylinder wake through a rotating interface. Convergence and stability of the coupled schemes show that a minimum number of overlapping points are required for a given scheme. The current accuracy limitation is locally given by the interpolation scheme at the interface, but with a limited and localized error. For rotor–stator type applications, the moving interface only introduces a spurious weak tone at the rotational frequency provided the latter is correctly sampled. The approach has then been applied to the QinetiQ MT1 high-pressure transonic experimental turbine to illustrate the potential of rotor/stator LES in complex, high Reynolds-number industrial turbomachinery configurations. Both wave propagation and generation are considered. Mean LES statistics agree well with experimental data and bring improvement over previous RANS or URANS results.

1. Introduction

Computational Fluid Dynamics (CFD) has been developed over the past few decades and has been intensively used as a design tool of gas turbines for propulsion or power generation systems. Because of increasing market and environmental constraints that target high efficiency, high power to weight ratio, low noise and high reliability, current and next generation of gas turbine engines will require improved CFD tools. Indeed to contribute efficiently to our understanding and thereby produce better engines, unsteady physical and chemical phenomena that take place in these engines need to be better apprehended. This in the long term will have to be addressed for each sub-component, but also in a fully integrated way: *i.e.* simulating at once the compressor, the combustor and the turbine [1]. In the specific context of CFD, Large Eddy Simulation (LES) [2] is a good candidate and has already been used to simulate the combustor of gas turbines [3,4] and some specific isolated parts of turbomachinery applications [5–13], but few applications are today available in turbomachinery stages [14–17]. In fact, CFD for turbomachinery still remains a challenge because of the high Reynolds and Mach-number

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flows, the importance of several loss mechanisms that greatly impact the operating condition and efficiency of these components as well as mixing effects between hot stream from the combustion chamber and fresh cooling gases, multi-species flows, rotation and technological effects. Current industrial turbomachinery simulations usually involve Reynolds-Averaged Navier–Stokes (RANS) or Unsteady RANS (URANS) equations, which rely on turbulence models [18,19] to predict the mean flow fields in these elements. For the known rotor/stator interactions, URANS is necessary to capture the unsteady deterministic interactions that are present in these configurations [20]. Today the computational cost of RANS or URANS is acceptable for engineering applications and explain their daily use in real applications. However such tools show limits whenever used for testing off-design point computations [14] or even at design conditions when transition to turbulence or secondary flows play major roles. The modeling needed with RANS or URANS limits engineers from further efficiently improving the devices and expensive test benchings of multiple concepts are still mandatory today.

With the rapid development of High Performance Computing (HPC) [21], recent efforts have been made on the prediction of the complex turbulent flows around isolated parts with high-fidelity fully unsteady LES (see review by Tucker [22]). Although much more computationally intensive than RANS, LES can alleviate the modeling efforts by explicitly resolving the temporal and spatial evolutions of the large flow structures while filtering out the smaller ones [23,24]. Preliminary demonstrations show that LES can resolve flows with transitions, separations [5,6,13] and thereby improve heat transfer predictions on structured or unstructured meshes [8,10,12]. Tip-clearance flow predictions [7] have also been addressed successfully with LES. McMullan and Page [14] have demonstrated that LES can predict surface pressure on the Monterey cascade with a sufficiently refined mesh. Algorithmic developments complemented by high performance massively parallel machines allow today to have LES solvers capable of handling 21 billions unstructured tetrahedral cells with a very reasonable speed-up [25] making use of up to one million cores at once [26,27]. Following the analysis of Tucker [28], this capability seems to be approaching LES requirements of most gas turbines in aircraft applications. The application to real machines is currently being investigated and three configurations of compressor stages [14,16,17] and one transonic turbine stage [15,29] have already been reported: a scaled last stage of the Cranfield BBR compressor with a Reynolds number based on the stator midspan chord of $Re = 180{,}000$, the Cambridge axial compressor ($Re = 350{,}000$), the CME2 axial compressor ($Re = 500{,}000$) and the MT1 axial turbine ($Re = 2{,}600{,}000$). Even in these first LES predictions of compressor or turbine stages, numerical challenges are still present. First, the high computational costs relate to the complexity of these flows with high Reynolds numbers $Re \sim O(10^{5-7})$, which impose large grids. Secondly, the modeling difficulty comes from an adequate resolution or modeling of the wall flow physics since it may have a dramatic impact on the main blade-channel flow and vice-versa. Thirdly, current LES codes require high spatial and temporal accuracy [30] that may not survive at the rotating interfaces to yield adequate and relevant unsteady predictions of component interactions. Indeed the numerical treatment of a rotating interface will impact the overall discretization-scheme quality and properties. Typically, resolved vortical, acoustic and entropy waves should travel with the flow and therefore cross the interface without being significantly altered by the numerical treatment to preserve the LES nature of the solver in this region.[1]

The last point is crucial for turbomachinery stage simulations and is rarely discussed or validated in reported LES [29]. In an attempt to provide validation of the interface treatment for LES of turbomachinery, a coupling interface based on overset grids is presently proposed and studied with specific emphasis on the resulting scheme properties. The overset grid method has been proposed and developed for instance by Volkov [31], Magnus and Yoshihara [32], Starius [33], Atta and Vadyak [34], Benek et. al. [35,36], Berger [37], Henshaw and Chesshire [38,39]. It has recently been studied and applied for Computational AeroAcoustics (CAA) [40–42], coupling CFD/CAA [43], conjugate heat transfer problems [44], moving body applications [45–49] or to handle complex geometries [8,50] with very high accuracy [51,52]. It has also been used in RANS of external and turbomachinery flows where it is commonly known as the Chimera method [35] and reported as providing an equivalent accuracy as the sliding mesh method [53]. In the specific RANS context where fields are smooth and independent of time, conservation is sufficient for the rotor/stator interface since the turbulence is fully modeled or described by some extra conservation equations towards the steady state solution of the problem. Numerical requirements of RANS are hence limited to the interpolation scheme at the interface meshes that needs to be conservative, which is usually obtained by taking first-order area-based interpolation within the sliding mesh [54]. For LES, most of the flow structures are resolved so flow fields are time dependent and contain a large range of wave lengths covering all the scales from the geometry up to the finest local grid resolution. To preserve the quality of such simulations all this information should be transferred through the interface with as less influence as possible to maintain flow coherence, evolution as well as the numerical properties of the scheme. The primary objective is thus to avoid dissipating or dispersing the signal within the original context of the numerical scheme used away from this boundary. To meet such requirements, the overset grid method is of interest as increasing its accuracy is straightforward for structured meshes [8,40,41,43,51,52,55–58], though it may lead to some complexity in the generation of these overlapping regions [59]. Overset unstructured meshes have also been developed in the past decade [60–64] and are recently being considered for a high-order interface treatment [42,65].

In the following, the overlapping moving interface is implemented based on a domain decomposition approach [66] with an unstructured compressible high-performance parallel LES solver. The resulting strategy is hereafter called MISCOG for Multi Instance Solver Coupled through Overlapping Grids. The details of the coupling and associated numerical features are

[1] Conventional LES numerical schemes should be high order and centered to minimize dispersion and dissipation. Note that such schemes are by nature highly oscillatory and therefore become unstable and strongly modified by inadequate numerical treatment at the interface.