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Conservative and accurate method for turbomachinery stage interfaces

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Résumé :

Une méthode d'ordre élevé et conservative pour le traitement des conditions des interfaces inter-étage dans les turbomachines est développée en utilisant des reconstructions k -exactes de la solution dans le plan $r - \theta$. Les résultats obtenus pour la configuration d' étage de turbine à haute pression BRITE démontrent l'intérêt de l'approche proposée par rapport aux méthodes standard d'ordre faible.

Abstract

A high-order and conservative method is developed for the numerical treatment of turbomachinery stage interface conditions in patched grids, using k -exact solution reconstructions in the $r - \theta$ plane. Results obtained for the BRITE high-pressure stage demonstrate the interest of the proposed approach against standard low-order methods.

High-order, patched interface condition, conservative interpolation

1 Introduction

Turbomachinery configurations are dominated by the relative motion of fixed and mobile wheels. The resulting flow field is highly unsteady, and the understanding and control of rotor/stator interactions is of paramount importance for aerodynamic, aeroelastic and aeroacoustic design. For this purpose, advanced simulation tools like Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) are being applied to turbomachinery configurations in order to improve the description of the unsteady flow field (see, e.g. [1, 2]). For this type of advanced modeling, the use of high-order numerical schemes is mandatory, to ensure low levels of numerical errors despite the relatively coarse and distorted grids typically available for industrial configurations (see, e.g. [3, 4]). To achieve a truly high-order overall accuracy, boundary conditions need to

be also high order. Rotor/stator boundary stage interface condition in use in an industrial code like *elsA* [5, 6] ensure conservation of mass, momentum and energy across the interface, but are only first-order accurate. This filters the signals exchanged between the rotor and the stator blocks, destroying small unsteady structures and over-damping the larger ones.

Preliminary investigations of possible treatments for patched grid interfaces [7] showed that high-order and conservative solutions can be obtained combining high-order interpolations along the interface with a consistent high-order finite volume method for the discretization of the inner cells. In the present work, we focus on second and third order finite volume methods involving k -exact reconstructions of the solution over mesh cells by means of a successive correction technique [8]. The k -exact reconstruction is used for generating high-order approximation of the fluxes both inside the domain and at the interface, so that it is intrinsically conservative. For turbomachinery stage conditions, the reconstruction is generated in cylindrical coordinates, and specifically in the $r - \theta$ plane, to avoid geometrical conservation problems due to the discrete representation of the geometry at the stage interface. The proposed methodology was implemented in the structured solver *elsA* and validated for some well-documented test cases, including the BRITE HP turbine stage.

2 Conservative patched grid method

The first step of the proposed patched grid algorithm is the computation of connectivity between the stator and rotor blocks. This is done by means of a polyclipping algorithm [9]. For turbomachinery stage interfaces, orphan points, i.e. points that not within the discrete approximation of the stage interface in the neighboring grid (see Figure 3) can be present, since the number of grid points used to discretize stator and rotor row in the azimuthal direction can be different. If not taken into account, this effects leads to geometrical conservation losses.

In order to avoid orphan points and subsequent errors on the flux integrals, we propose to operate a change of the reference frame from the Cartesian coordinates (x, y, z) , where x in the rotation axis, to the cylindrical coordinates (x, r, θ) , where $r = \sqrt{y^2 + z^2}$ and $\theta = \text{atan}(z/y)$. In the transformed plane, the rotor/stator interface is a parallelogram and no orphan points can be generated due to the discrete representation of the interface. This ensures a geometrically conservative polyclipping algorithm.

Once the connectivity has been determined, the second or third order k -exact method [8] is used to reconstruct the solution at the interface. For simplicity, in this paper we restrict our attention to the second-order method. For a second-order polynomial reconstruction of the solution in the inner cells, gradients of the primitive flow variables are approximated from the solution available from the first neighbours of each cell (see Figure 1). At patched grid interface, the least-square system is changed to take into account all first neighbours of the current and opposite blocks (see Figure 2).

The reconstructed solution is finally used to compute the integrated fluxes along each

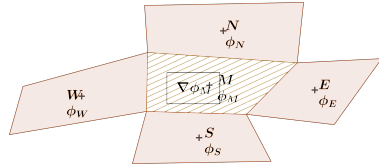


Figure 1: Rank one stencil for first order gradient reconstruction on a inner cell.

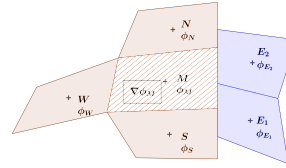


Figure 2: Rank one stencil for first order gradient on a patched interface cell.

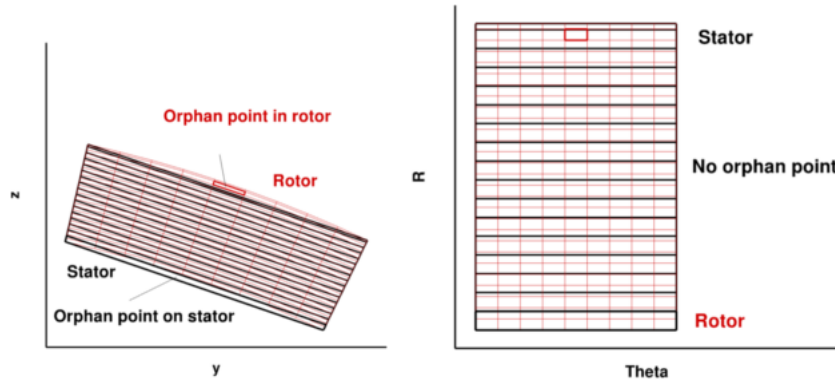


Figure 3: Example of orphan point

intersected face on both sides of the interface.

The last step consists in using the fluxes computed in (x, r, θ) to obtain the fluxes in the (x, y, z) frame by the formula :

$$\iint f(x, y) dx dy = \iint f(r, \theta) r dr d\theta \quad (1)$$

3 Numerical results

3.1 Advection of a hot-spot through a patched interface

The proposed methodology is first validated on a simple test case, roughly representative of a turbine wake crossing a rotor/stator interface. A hot-spot, i.e. a Gaussian temperature profile, is injected in the computational domain and convected along a patched grid composed of two blocks, representative of a stator and a rotor block. Initially, both rows are fixed (i.e stator) and we just observe the mass flow rates computed on right and left side of the patched grid boundary. The meshes are designed in such

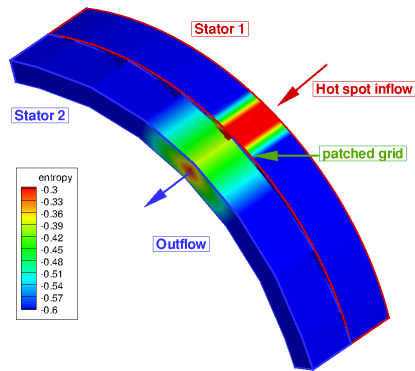


Figure 4: *Hot-Spot configuration and steady entropy field*

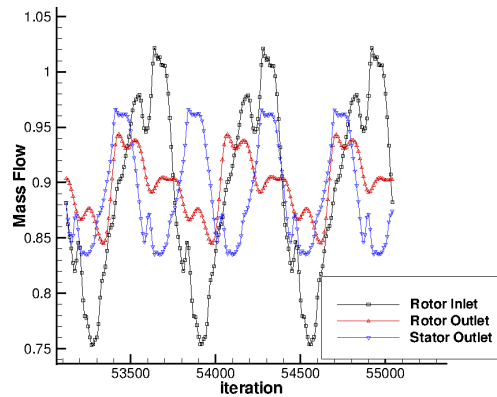


Figure 5: *Hot-Spot - Mass flow on both sides of the patched grid interface for the two proposed approaches*

a way to have orphan points and a significant discretisation effect (Figure 3). The first stator is composed by $26 \times 9 \times 51$ cells and the second is composed by $26 \times 65 \times 57$ cells. A steady state is achieved and entropy field is represented on Figure 4)

Two methods are compared: the first one uses polyclipping algorithm in the (r, θ) plane to avoid orphan points but the flux integration process was realized in (x, y, z) frame, and the second computes the flux in (r, θ) frame and uses formula (1) to obtain the fluxes in the (x, y, z) frame.

Two considerations are in order for this test case: firstly, the (r, θ) preconditionner ensures that no orphan points are present in the polyclipping algorithm. Secondly, the integration on (r, θ) frame is mandatory to ensure a fully conservative solution. This has an impact on the computed operation point of the turbomachinery stage (see Figure 5): in fact, the computation of fluxes in the (r, θ) frame ensures at each time step and at convergence exact conservation of the mass flow through the patched grid interface. The computation without flux integration in (r, θ) leads to a 0.8% loss in the mass flow.

3.2 VKI BRITE 2,5D URANS

The BRITE HP turbine stage was experimentally tested in the compression tube facility CT3 of the Von Karman Institute [10] at high vane exit Mach number (pressure ratio 5.11). This case is computed in order to demonstrate the feasibility of the proposed approach for a realistic turbomachinery stage. The computational domain and grid used are described in Figure (6) and Table (1). The use of chorochronic periodic boundary conditions [11] analysis allows simulating just one blade per row. The flow is modelled through the RANS equations completed by the Spalart-Allmaras transport-equation model. We use second order patched grid method in (r, θ) frame to compute

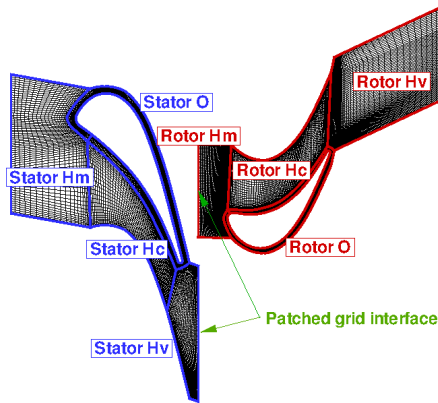


Figure 6: VKI BRITE - View of grid and multiblock decomposition

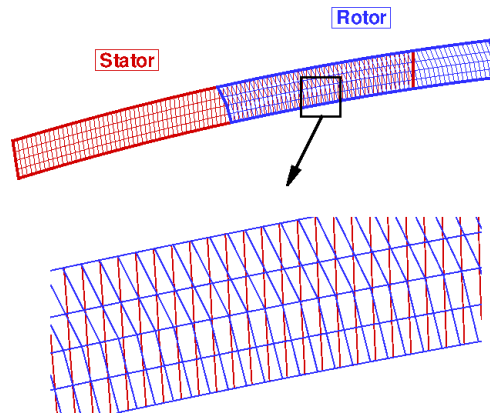


Figure 7: VKI BRITE - Close view of patched grid interface

Block	Stator grid resolution	Rotor grid resolution
O	209x33x5	213x31x5
Hm	21x67x5	47x61x5
Hv	25x91x5	47x77x5
Hc	57x31x5	79x41x5

Table 1: VKI BRITE - Detailed mesh size

rotor/stator interface (See Figure (7)).

Mass flow on Figure 9 show the flow unsteadyness and rotor/stator interactions. Figure 8 provides a snapshot of the instantaneous entropy field, characterized by vortex shedding behind the trailing edge of the stator. Thanks to the accuracy of the proposed treatment, the vortices are well conserved through the patched grid interface.

4 Conclusions

A patched grid methodology dedicated to turbomachinery is presented. The discretisation effect plays an important role for stage computation and the proposed approach allows an accurate and conservative simulation of stage interactions. High fidelity turbomachinery stage numerical simulations are planned in the near future to demonstrate the interest of the proposed approach for more complex configurations.

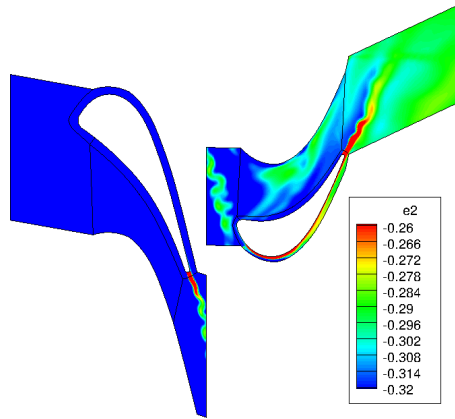


Figure 8: VKI BRITE: instantaneous entropy field

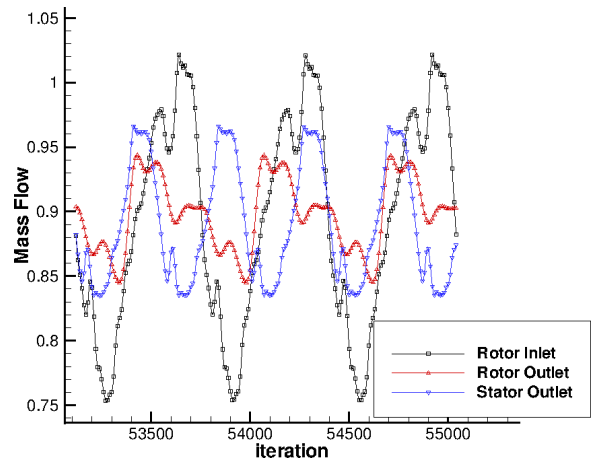


Figure 9: VKI BRITE: time evolution of the mass flows at stator outlet, rotor inlet and rotor outlet

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