On the use of moving grid interface for fan noise computation

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Introduction

Accurate noise simulations of fans are very important issues as various kinds of fans are widely used in aircraft, cars and air conditioning systems. It is known that the noise radiated by low-speed fans is of tonal and broadband character, and both contributions are equally important in most configurations[1]. This paper seeks to perform numerical broadband sound simulations of a ducted industrial fan, whose inlet geometry is simplified to an axisymmetric cylindrical duct with axial uniformity. The simulation is carried out based on DLR CAA solver PIANO, which is based on structured, curvilinear multi-block grids.

It is well known that generating a good 3-D structured mesh for complex geometries such as fans is one of the most time-consuming steps, not to mention making the additional effort to advance the mesh in time to fit the time varying fan geometry. Inspired by the fact that rotating reference frame is successful applied for fan flow simulation in CFD filed[2], we present a new concept for fan noise simulation: The whole computation domain is separated into two parts. In the region near the rotating fan blade, a set of newly formulated governing acoustic equations in the rotating reference frame are used. In the region far away from the fan blade, a common' governing acoustic equations in a fixed reference frame are used. The remaining problem then is to couple the two system. In this paper a moving grid interface is used where two regions are connected.

Moving Grid Interface

For a moving grid interface problem, two general approaches exist from the view point of a grid. One is to use a re-meshing or deforming grid which is caused by nodes movement, the other is to use a overlapping grid[3], where a fixed Cartesian grid is the background mesh and the moving interface is represented as an immersed boundary mesh conforming to the moving interface. Emphasis in this paper has been put on the second approach, but a general curvilinear grid is considered instead of Cartesian grid.

Because the numerical scheme in PIANO[4] is based on a high order finite difference method, as sketched in figure 1, each interface point such as node Q needs three points such as nodes $P1, P2, P3$ and $M1, M2, M3$ on both sides, so that at the interface the additional three columns points of block B extend to the attached grid block A and lead to an overlap region. The implementation technique is challenged with two problems, i.e, (1) identifying the block the ghost points belong to and searching suitable donor neighbor nodes for the interpolation; (2) calculating the high-order interpolation coefficients. In the following we will explain our procedure in more detail:

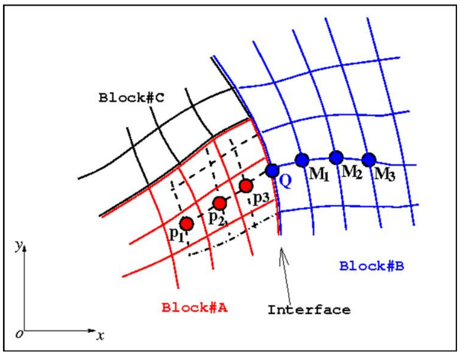

Figure 1: Sketch of moving grid interface

Step 1: Because the boundary of a block can be described by a polygon, in a first step of the algorithm we pick up boundary points of one block and connected them to a closed multi edge polygon. In a second step starting from one ghost point we make a horizontal ray and let the ray propagate to the right. If a node lies inside this polygon, there is an odd number of intersection. If a node is outside the polygon, there is an even number intersection. By this way we can decide whether the point lies inside the block. With the same algorithm we also can locate 4 donor neighbor nodes, which defining four segments of one polygon surrounding the investigated ghost point.

Step 2: The issue on choosing an appropriate interpolation scheme for aeroacoustic applications has already been investigated in several studies. The conclusion of the studies are: numerical accurate interpolation is mandatory for a successful CAA algorithm. In the current paper a 2D Hermite interpolation scheme, which is fourth order accurate, is studied. Because the 2D Hermite interpolation scheme is based on a Cartesian mesh, before directly use the interpolation scheme we transform the curvilinear grid in physical domain to Cartesian grid in computation domain. We obtain then a set of non-linear equations for grid to grid transformation. This non-linear equations are solved by Newton-Raphson method.

Governing Acoustic Equations

Based on Euler Equations in the rotating reference frame and fixed reference frame, we splitted primitive variables into steady mean-flow quantity (denoted by subscript 0) and fluctuations quantity (denoted by superprime). Table 1 exposes the linearized results which are used in the two regions correspondly. In the region near the rotating fan blades the rotating system governing acoustic equations are applied. In the region far away from the fan blade, the fixed system governing acoustic equations are applied. Here the ϱ, p, and $\boldsymbol{u}$ denote the density, pressure and local velocity. Compared with the fixed system governing equations, the mass and energy equations in the rotating system preserve the same form, while the momentum equation has one additional term $2\Omega \times \boldsymbol{u}'$, which comprises the influence of rotation.

Table 1: Governing acoustic equations in two systems

	Rotating system
Mass	$\frac{\partial \rho'}{\partial t} + \boldsymbol{u}' \cdot \nabla \rho_0 + \boldsymbol{u}_0 \cdot \nabla \rho' + \rho' \nabla \boldsymbol{u}_0 + \rho_0 \nabla \boldsymbol{u}' = 0$
Momentum	$\frac{\partial \boldsymbol{u}'}{\partial t} + \boldsymbol{u}_0 \nabla \boldsymbol{u}' + \boldsymbol{u}' \nabla \boldsymbol{u}_0 + 2\Omega \times \boldsymbol{u}' = -\frac{1}{\rho_0^2}(\rho' \nabla p_0 - \rho_0 \nabla p')$
Energy	$\frac{\partial p'}{\partial t} + \boldsymbol{u}' \cdot \nabla p_0 + \boldsymbol{u}_0 \cdot \nabla p' + \gamma p' \nabla \boldsymbol{u}_0 + \gamma p_0 \nabla \boldsymbol{u}' = 0$
	Fix system
Mass	$\frac{\partial \rho'}{\partial t} + \boldsymbol{u}' \cdot \nabla \rho_0 + \boldsymbol{u}_0 \cdot \nabla \rho' + \rho' \nabla \boldsymbol{u}_0 + \rho_0 \nabla \boldsymbol{u}' = 0$
Momentum	$\frac{\partial \boldsymbol{u}'}{\partial t} + \boldsymbol{u}_0 \nabla \boldsymbol{u}' + \boldsymbol{u}' \nabla \boldsymbol{u}_0 = -\frac{1}{\rho_0^2}(\rho' \nabla p_0 - \rho_0 \nabla p')$
Energy	$\frac{\partial p'}{\partial t} + \boldsymbol{u}' \cdot \nabla p_0 + \boldsymbol{u}_0 \cdot \nabla p' + \gamma p' \nabla \boldsymbol{u}_0 + \gamma p_0 \nabla \boldsymbol{u}' = 0$

Computation Results

Figure 2 and figure 3 show the computation results of two test cases, which are selected to verify the implementation and are plotted in time series. In the first test case, a simple 2 blocks Cartesian mesh is used and the right block moves upwards relative to the fixed left block. The constant mean-flow direction is from left to right. In the second test case a curvilinear mesh is used. The outer blocks are steadily rotated in anti-clock wise around the grid center, while the inner blocks keep fixed. There is no mean flow in the second test case. An acoustic pressure pulse of Gaussian shape as initial condition is set in both test cases, and is put inside the fixed grid and rotating grid correspondingly. The obtained results show the expected outcome. One can see that the pressure pulse evolves into an annular pressure signal with increasing radius as time increased. Meanwhile the maximum amplitude of the signal decreases. The center of the ring moves in the direction of the mean flow convection and a part of the annular signal passes through the interface where moving block and fixed block are connected. One observes that waves have no serious deformation between blocks.

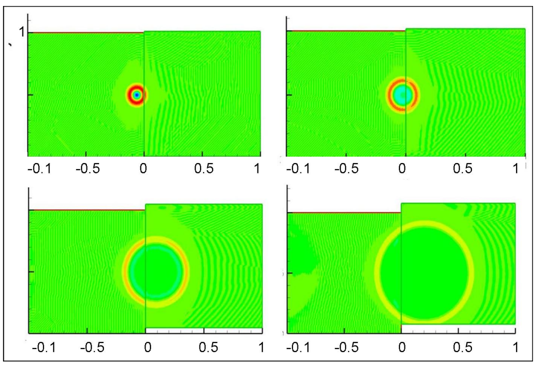

Figure 2: Acoustic pressure pulse in translation movement grid

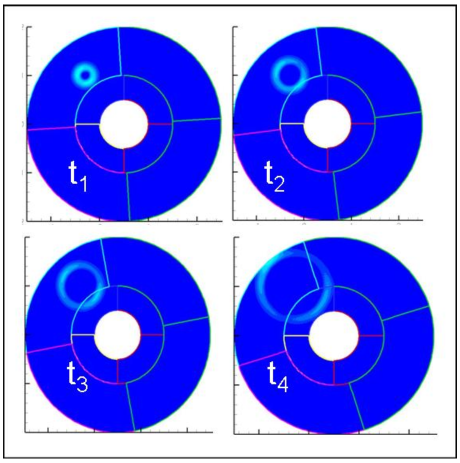

Figure 3: Acoustic pressure pulse in rotating movement grid

Conclusion

A set of acoustic governing equations in rotating reference frame are derived, and a moving grid interface is implemented to DLR's acoustic solver PIANO, so that PIANO is avaliable for simulating broadband fan noise in future. Based on Hermite interpolation, the moving grid interface is developed in accordance with the high resolution numerics finite difference scheme. The implementation was verified on simple test cases and the results showed that the moving grid interface did not introduce significant distortion of the acoustic signal.

Acknowlegement

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