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Acoustic transmission through a 3D rotating fan using Computational AeroAcoustics

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Abstract

In the context of the evaluation and reduction of fan noise in modern turbofan engines, the possibility to compute the acoustic transmission through a rotor-stator system, accounting for the rotation of the rotor, is evaluated. The objective is the development of a numerical method to simulate the propagation of acoustic waves in a global fixed region which includes a partial moving zone, with equations solved in a fixed reference frame. In order to insure a high order resolution these CAA developments and computations were performed using Onera's CAA solver *sAbrinA-V0*. Firstly, a full or partial 2D moving zone was employed as a reference test case. It was insured that the moving grid acts only as a resolution support and does not affect the propagation of the waves by its rotation. Monopole and planar sources were considered. In order to connect the two (fixed and rotating) zones, spline cubic interpolation functions were employed in the ghost cells rows. Secondly, a cross-shaped rigid obstacle with zero thickness walls was embedded in the moving grid and the interaction between this obstacle and a fixed monopole was computed. Note that, despite the CAA solver can handle any non-homogeneous mean flow, this case was addressed accounting for a medium at rest. The field of application of the method is restricted to non-viscous interactions between boundary layer and acoustics, so the considered mean flows have to respect this condition. Finally, a 3D test case is presented, based on a simplified rotor with four twisted blades with zero thickness in a perfect annular duct. The acoustic interaction of this rotating blades with an helicoidal modal source injected upstream the rotor within a medium at rest was evaluated. Recent developments in *sAbrinA-v0* on improved inlet/outlet acoustic boundary conditions and conclusions of gust-fixed airfoil interactions will allow a proper evaluation of CAA simulations of moving surfaces.

Abbreviations

BC	–	Boundary Condition
BPF	–	Blade Passing Frequency
CAA	–	Computational AeroAcoustics
CFD	–	Computational Fluid Dynamics
NACRE	–	New Aircraft Concept Research in Europe
M	–	Mach number
FWH	–	Ffowcs-Williams and Hawkings
Λ	–	Integral length scale

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I. Introduction - Objectives

After decades of investigations for reducing the noise emitted by aero-engines, having given rise to modern turbofans with high-bypass ratio, further improvements are still expected on the accuracy of the numerical prediction and characterization of the main noise sources. For current CAA methods aiming to simulate in-duct acoustic propagation, the fan noise sources are modeled as a modal distribution injected in front of (upstream) or past (downstream) the rotor-stator stage. With the recent improvement of the CFD capabilities, the generation of dominant deterministic sources due to the wake interactions between the rotor blades the stator vanes can be directly assessed by the numerical computations¹. The downstream propagation of sound from sources located on the stator (fluctuating loads) may be correctly predicted using modal approach and semi-analytical solutions or numerical solvers. In the upstream direction a complex scattering problem overcomes, since the traveling waves meets the rotating blades of the rotor, which generate a screen effect. A part of the acoustical energy is transmitted across the rotor and added to the rotor self-noise contribution, whereas the reflected part is sent back to the downstream direction and can give rise to standing waves associated to trapped modes. The same phenomena may be considered also for the noise generated within the combustion chamber and propagated across the successive stages of turbine blades.

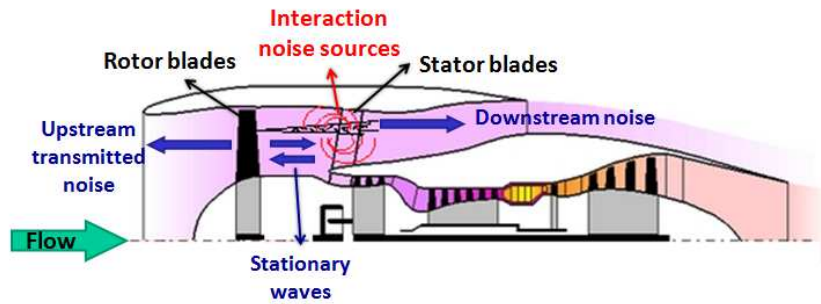


Figure 1: Left : Schematic view of the interaction rotor-stator fan noise sources

In order to evaluate the transmission and reflection coefficients, different models were developed, starting from two-dimensional infinitely thin cascades^{2,3} and extending to more sophisticated configurations such as annular cascades in the presence of mean flow gradients^{4,5,6}. In the same way, different methodologies to study the static waves trapped between the stator and the rotor have been developed by Topol⁷, Hanson^{8,9} and Meyer¹⁰, adding a new degree of complexity to their problems. For example Hanson⁸'s model takes also into account the transmission and the reflection at inlet and exhaust interfaces.

With the aim of modeling the coupled rotor-stator acoustic interaction problem, the objective of the present study is to simulate the acoustic transmission through a 2D or 3D rotating blade row using a CAA code solving Euler equations in perturbation form. To achieve such a computation, several steps are planned and structured as follows:

- I. Firstly, the acoustic propagation across rotating meshes, without and with immersed bodies, is investigated;
- II. Secondly, a new interface boundary condition is implemented, to match the fixed and the moving part of the geometry;
- III. Finally, the numerical method is validated against analytical and/or numerical solutions for generic 3D benchmark cases especially dedicated for the interaction between the velocity fluctuations and rigid surfaces.

The paper is organized as follows:

Chapter II presents an overview of recent numerical computations and experiments related to turbofan noise achieved at Onera in several projects, showing the relevance of the modal description of in-duct noise sources which is generally considered.

Chapter III presents two basic test-cases, firstly the propagation of an elementary source across a rotating mesh and, secondly, the qualitative evaluation of the acoustic transmission/scattering behavior by some rigid bodies immersed in the rotating field. The emphasis is put on the stability of the adopted numerical strategy and, more

particularly, on the ability of transferring perturbation fields through the interface of the domains without creating spurious numerical reflections.

Finally, early 3D results are presented in Chapter IV, based on the case of the interaction of an acoustical mode with an infinitely thin plate and the 3D validation of *sAbrinA-v0* results against analytical solutions for the interaction of a gust with a flat plate.

II. Toward a better understanding of fan noise emission

For several years, ONERA has applied numerical solvers and methodologies to perform aeroacoustics simulations of fan noise propagation and radiation over complex geometries involving strongly inhomogeneous flows [Figure 2]. These numerical computations were useful to highlight complex phenomena such as acoustic refraction through a shear layer and installation effects. Most of them were achieved by using Onera's CAA solver *sAbrinA-v0* which solves, in the time domain, the full (non-linear) Euler equations in conservative and perturbation form, using high-order finite difference and spatial filtering schemes (6th order spatial derivatives and 10th order filters) with a 3rd order (RK3) Runge-Kutta time marching scheme, using structured multi-block meshes¹¹.

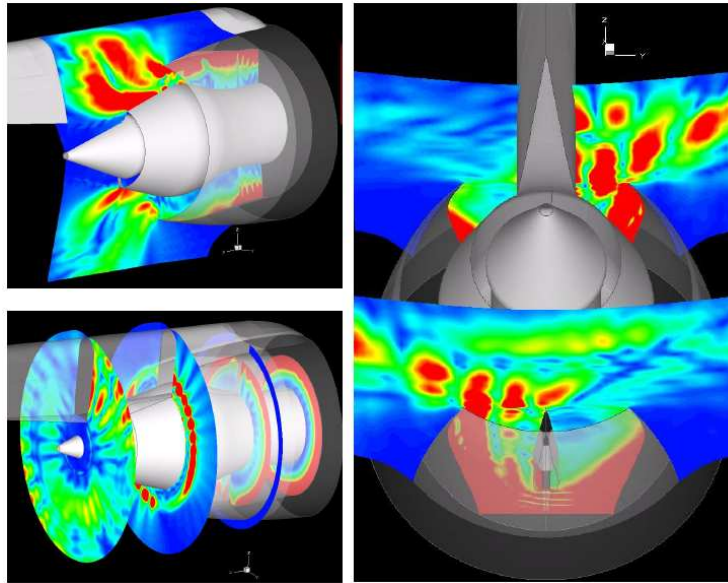


Figure 2: Numerical simulation of fan noise emission in the downward direction for a realistic engine configuration. RMS pressure distribution for a single (13, 1) mode injected in the fan plane in the presence of the inhomogeneous mean flow.

Two different strategies are available in the *sAbrinA-v0* solver for generating Fourier-Bessel (circumferential and radial) acoustic modes, assuming a semi-infinite annular duct and a uniform mean flow in the CFD/CAA matching region. The first one consists in injecting the modes in terms of usual boundary condition (BC) by imposing the downstream analytical solution in fictitious cells at each time step, and taking into account the phase dependency¹². Such BC is not suited to study the screen effects of fixed or rotating blade rows. The second option uses an equivalent-source model from which the modes are entered by means of suited distributed monopoles defined as source terms¹³. The equivalent-source model has the advantage to prevent from managing the outgoing/incoming waves condition in the injection plane, which is not generally possible with usual BCs approaches, and may generate numerical reflections for incoming waves. Later developments¹⁴, have permitted to improve those BCs, following the Tam and Webb¹⁵ method, in order to 1) inject modal and vorticity source waves and 2) evacuate the resulting acoustic and hydrodynamic outgoing waves without spurious reflections. For practical reasons, in the present numerical simulations, only classical BCs were employed.

Moreover, the presence of solid structures as vanes or bifurcation can re-distribute the acoustic energy on several other modes, and thus completely modifying the expected dominant modes. Such effect was observed during the

NACRE experiments [Figure 3] in Onera's CEPRA 19 anechoic open-jet wind tunnel, in which a fan noise simulator based on a TPS (Turbine Power Simulator), in association with an Airbus aircraft model, was used to study acoustic engine installation effect. The nozzle of the TPS was equipped with a circular array of wall pressure transducers, and a large RMS modulation was observed in the azimuthal direction due to the presence of an internal bifurcation. This effect was afterwards confirmed by the CAA computations¹⁶ where an important part of modal content was reconstructed and simulated.

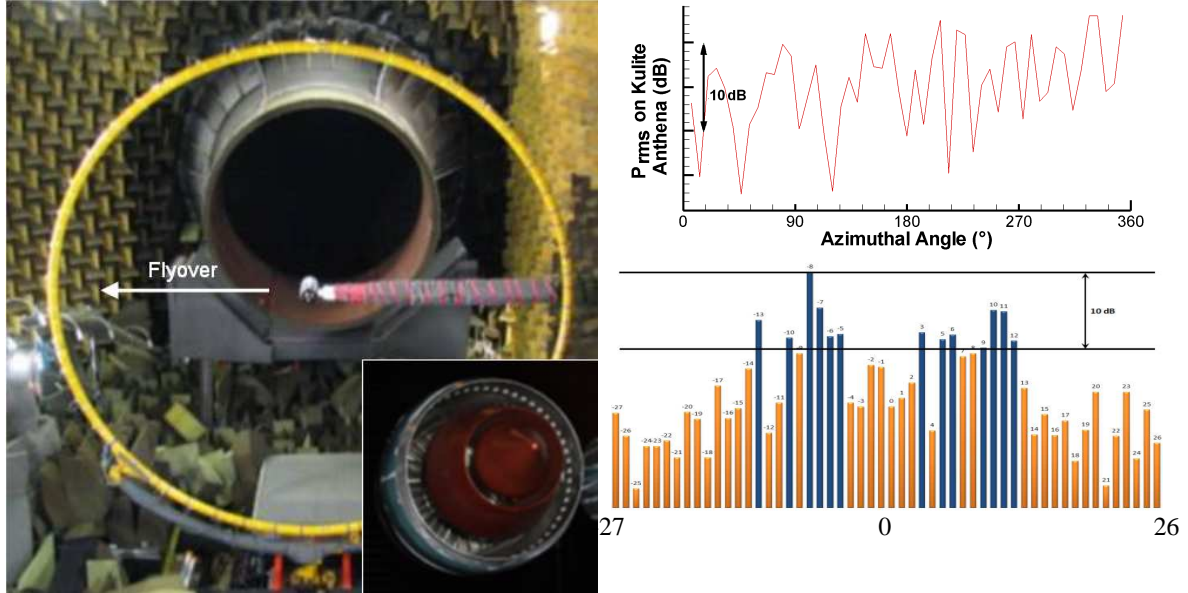


Figure 3: Left : View of the fan noise NACRE experiment in the Onera's CEPRA 19 anechoic open-jet wind-tunnel (in medallion: the Kulite array inside the bypass duct); Right: Kulite array inside the bypass duct : wall pressure fluctuations at the BPF (top : RMS on each Kulite sensor, bottom : azimuthal Fourier transform).

In a similar way the impact of the rotor wake on the stator blades creates an interaction noise at the harmonics of the Rotor Blade Passing frequency. This noise is propagating in the upstream direction and scattering across the fan blades (screen effect) before radiating in the free field through the inlet. Such aerodynamic/acoustic coupling might be simulated either by solving the Euler equations in a rotating reference frame (attached to the rotating blades) and considering a rotating source model or by using a fixed reference system (attached to the stator) and performing the rotation of part of the mesh (sliding block) associated to the rotor. In the present simulations, the second approach has been chosen, which may allow simplifying the resolution of Euler equations in perturbation form in such a way that the Coriolis and the centrifugal forces are directly accounted for. But in this case the convection flow has to be interpolated at each time step as a function of the angular position of the rotor blades. The main practical interest is that, in the fixed parts (upstream and downstream domains), the disturbance field (computed in the fixed reference frame) is directly provided without requiring interpolations.

III. Simplified methodology applied to 2D configurations

One big issue is represented by the propagation of the acoustical waves through a rotating mesh. The mesh has to act only as a support for the moving objects and should not have any impact on the acoustical wave crossing it. Since the computational domain involves resolved acoustic waves fixed to the grid, any movement of the later acts as a convection effect. The acoustical field has to be modified at each time step in order to take into account the grid movement with a "fictive" added flow in the opposite direction with the respect to the movement vector. In such a way the grid "glides" underneath the pressure waves.

To evaluate this aspect, the acoustic propagation of monopole and planar sources has been simulated over a 2D field as presented in Figure 4. The propagating field is considered at rest ($M = 0$). Two cases were investigated:

- In the first one, the complete configuration is rotating around the 0z axis with a constant angular velocity ω_1 .

- In the second one, only the middle part of the grid is rotating, the exterior region being kept fixed. Results for an exterior moving region, in an opposite/same direction, with a different ω_2 angular velocity, $\omega_2 \neq \omega_1$, was also evaluated. The results were identical and will not be presented here.

The pulsating frequency was chosen to correctly compute the acoustical field until the middle of the fixed (outer) region. Outside this region, a high radial grid stretching coefficient strongly dissipates the acoustical waves.

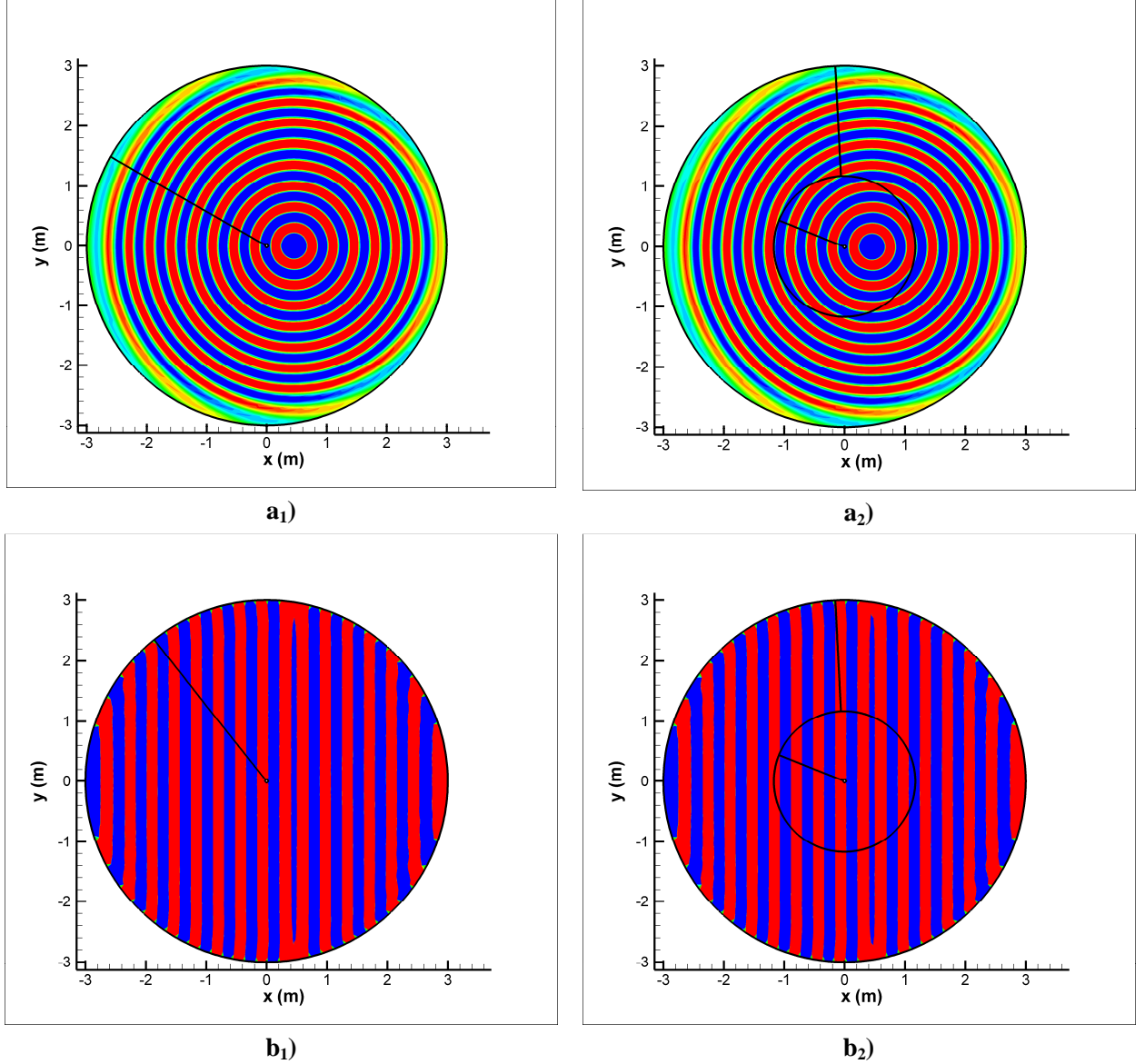


Figure 4: Top : Numerical simulation of monopole propagation over a fully (a_1) or partially (inner zone) rotating mesh (a_2); Bottom : Numerical simulation of a planar wave ($k_y = 0$.) propagation over a fully (b_1) or partially (inner zone) rotating mesh (b_2)

The numerical computations presented in Figure 4 were obtained by solving the Euler equations in perturbation form with Onera's CAA solver *sAbrinA-v0* within the same considerations as the ones presented at the beginning of the second chapter. An important supplementary issue is represented by the communication between the rotating inner and the fixed outer regions at each time step (Figure 4, a_2 and b_2). For sake of simplicity, cubical spline functions were used for the interpolations between the physical region (source zone) and the ghost cells of the

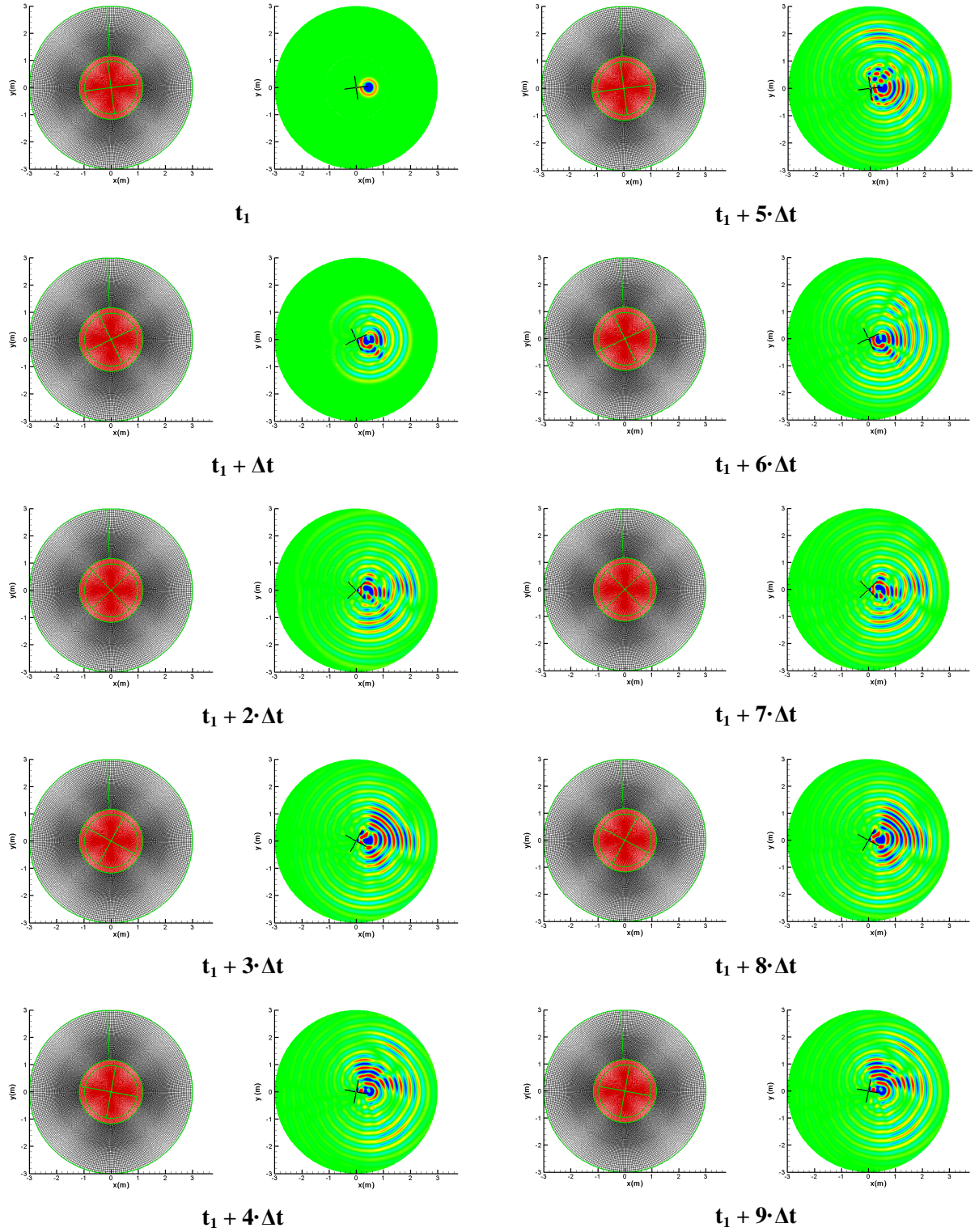


Figure 5: Interaction between a fixed monopole propagation and an infinitely thin rotating cross (black lines). Instantaneous pressure fields and meshes positions at successive time steps.

respective connecting zone (target zone). To insure the continuity of the interpolations at the beginning and the end of the target zone, the source zone was virtually increased with twice its ghost cells number in the azimuthal direction. It should be mentioned that, for the problems detailed here, the interpolations were performed only in this azimuthal direction. It can be observed that this treatment was sufficient to insure continuity at interface. However, one well known problem of spline interpolations is represented by the large required allocated time and memory to perform the mathematical operations. The application of recent work at Onera¹⁷ on optimized interpolation processes for aeroacoustic problems will allow improving the performances of the present results and therefore the spline interpolation issue will not be discussed in detail here.

In Figure 4 the results obtained for the monopole and planar wave sources are shown at an identical relative propagating time t/T where T represents the acoustical wave pulsation period. It may be observed that the results are respectively identical and the propagation is not affected by the rotating zones. The discrepancies on the outer boundary are due to the stretched grids. Comparisons with reference solutions of propagation over a complete fixed domain were performed and the results were in perfect agreement.

Once this step achieved, an idealized rotating object was embedded in the central rotating field. We consider that the solid body acts only as diffraction surface for the acoustical waves. In order to insure a zero pressure gradient to the moving object, a first assumption is that we don't take into account the viscous effects near it. A second assumption is that at each time step the propagation is performed as for a fixed medium, which may imply that the solid moving body speed may not exceed the celerity of the propagating wave.

In Figure 5 are represented, at different time steps, instantaneous pressure fields of a spatially fixed monopole source impacting a cross-shaped object with infinitely thin walls. This cross-shaped object was designed by using a part (black lines) of the azimuthal boundaries of the inner rotating domains (red grids). The complete 2π temporal rotating process was divided in 16 blocks with a Δt size. The simulation time step was specially chosen to be able to discretise, simultaneously, with a precise number of iterations, the acoustical harmonic propagation and the rotating angular speed ($625 \text{ it.}/T$ and $50000 \text{ it.}/T_{\text{rot}}$, respectively). The instantaneous fields are shown starting for an arbitrary recording time t_1 . Since the considered rotating speed was sufficiently small comparing to the sound speed, the RMS convergence was obtained very rapidly as it may be observed comparing the $t_1+4\cdot\Delta t$ and $t_1+9\cdot\Delta t$ results. As expected the acoustics is periodical with the respect to the number of the cross blades in such a way that no differences were observed between the second blade passing period RMS integration and the successive next ones.

IV. Toward the evaluation of the interaction of acoustical sources with 3D in movement fan blades

Since the main purpose of this paper is to investigate the interaction of an acoustical wave created at the leading edge of the stator with the rotor blades, the upper methodology has to be applied to a 3D domain. Some early results are presented in Figure 6 for an idealized fan obtained by rotating the annular grid with 10 degrees on a limited part of it extension and by splitting it in 6 zones. In the upper side of this figure, only rigid boundaries of those zones are represented, the fan blades being colored in red, and representing the azimuthally boundaries of the inner 4 zones. Those zones were the only ones being in rotation.

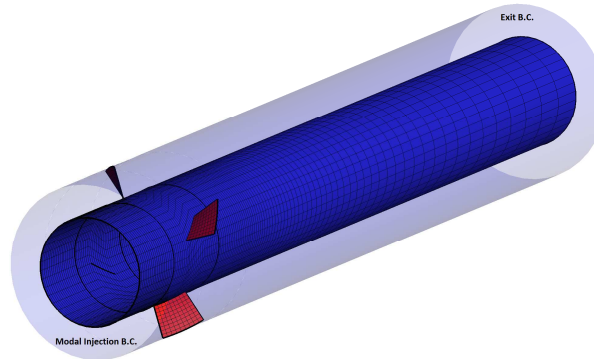


Figure 6: Idealized fan grid used to characterize the acoustical transmission across 4 fan blades of a guided modal wave

Despite an imperfect retro-propagating waves interaction with the injection plane, to reduce the global mesh size and computation time a classical modal injection upstream boundary condition (acoustical modal waves BC) was considered in the upward direction of the annular zone at rest. Shortly, this BC will be modified in the Tam and Webb¹⁵ way to allow the acoustical or vortical waves injection and complete absorption for the upwind traveling ones. In the downstream direction, a second zone at rest was created firstly well resolved to evaluate the acoustical transmission and secondly stretched to evacuate the acoustical waves. Between the two fixed zones and the rotating one, cubic spline interpolations were employed in the ghost cells in the same way as for the 2D cases and only in the azimuthal direction.

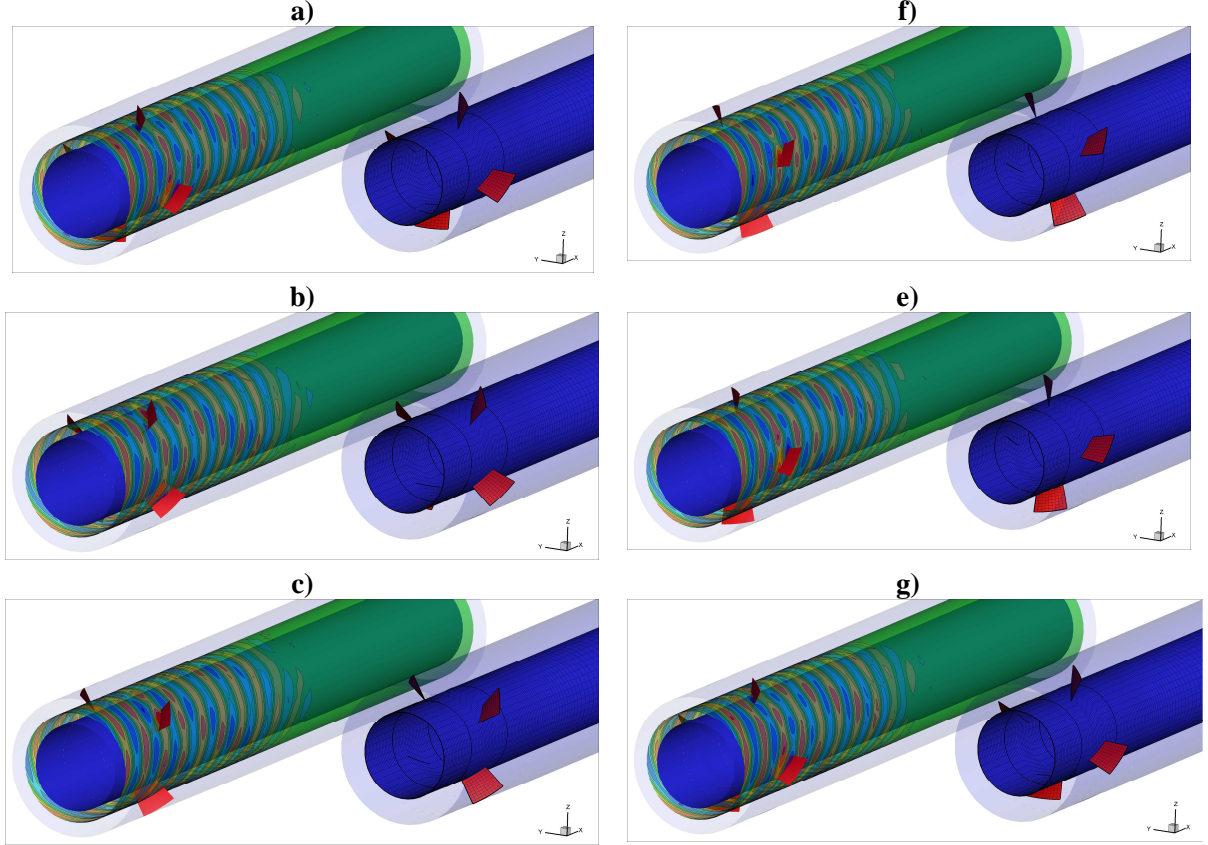


Figure 7: Interaction between an injected modal plane wave and infinitely thin rotating blades (red surfaces). Instantaneous pressure fields and meshes positions at successive time steps

For this case (Figure 7) only one pressure modal wave $(m, n) = (3, 1)$ was considered. We show here only a quarter of the complete 360° rotation obtained after the numerical convergence. As expected the acoustical propagation is largely modified, a part of it being transmitted across the rotating blades the rest propagating in the upstream direction. As expected, a duct mode equal to the number of blades ($m = 4$) is created and may be easily identified on these images. We also observe that in this case, situated at the inferior limit of the problem grid resolution, the azimuthal interpolations, between the fixed and moving regions, using spline functions were sufficient.

In parallel to this work, PhD studies on gust-airfoil interactions¹⁴, allowed to insure that *sAbrinA-v0* may correctly simulate the acoustical waves created at the impingement of the vortical structures on the rigid surfaces, which may be one of the points of interest of the present paper application. We address here the results obtained for the interaction of a parallel broadband gust (up to 5000 Hz) with an infinitely thin plate of chord $c = 0.15$ m and span $l = 0.45$ m where a uniform mean flow was considered with a convection velocity $U_0 = 60$ m/s. The Von Karman energy spectrum was fitted using a turbulence intensity of 2.5% and an integral length scale of $\Lambda = 6$ mm. For the numerical simulation using *sAbrinA-v0*, only a limited span was considered, $l_{sim} = 10$ mm, the results being

uplicated in this direction, for compacity sake, before the far-field evaluation using FWH integral methods. Detailed presentation of the method, the parameters and the applications on realistic cases can be found in reference 14.

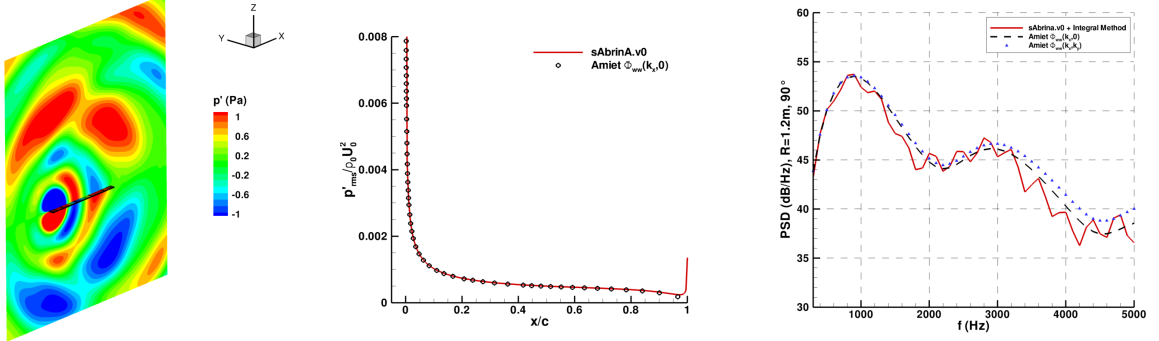


Figure 8: Simulation gust airfoil interaction. Left: snapshot of unsteady pressure field in the mid-span plane. Middle : RMS wall pressure for the 3D flat plate. Right : predicted PSD at 1.2 m above the flat plate

A comparison of RMS wall pressure distribution issued from CAA and from Amiet's response is presented in Figure 8 (middle), showing a perfect agreement. A snapshot of the fluctuating pressure issued from direct CAA computation in the mid-span plane is shown in the left part of the same figure. The RMS pressure levels (Figure 8 – right) for an observer point located in the mid-span plane at 1.2 m above the airfoil were compared between the CAA-FWH numerical computations and Amiet-based solutions and the results are in a very good agreement.

V. Conclusions

The main objective of this paper is to investigate the transmission of acoustic waves through rotating blade rows using a CAA code solving Euler equations in perturbation form. The particularity is that the acoustics is solved everywhere with high order schemes in the fixed global reference frame. In such a way, the acoustical waves propagation has to be corrected at each time step with an opposite “fictive” mean flow component which is opposite to the velocity of the moving grid at the same point. The discretisation grid serves only to the resolution of the waves propagation without being strongly coupled to it. It should be underlined that, outside the moving zones, the pressure levels are directly obtained from the computation. The main restriction of this method is that we have to neglect the viscous boundary layer attached to the walls in order to avoid the solid wall boundary condition modification (or to insure that $dp/dn = 0$ in the fixed global reference frame). Since the methodology involves real moving parts of the grid, some interpolations are required at the interface boundary conditions. For the moment, only the cubical spline functions were used and the results are satisfying. The 2D and 3D test cases described in this paper are only demonstrative for the method and allowed to progressively increase the complexity of the problem, but also highlighting its limitations at the same time.

In the next future, significant progress of the method are expected from parallel research on (i) optimized inlet/outlet boundary conditions for acoustics, (ii) high order multi-purpose interpolations and (iii) gust-airfoil interactions simulations. These expected improvements will allow applying this methodology to realistic 3D cases and to extent its applicability to other industrial problems such as, for example, the evaluation of the combustion noise transmitted through blades in a turbine configuration, or the interaction of the helicopter rotor noise with the upstream tip vortex (blade-vortex interaction).

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