

3D NUMERICAL SIMULATIONS OF ACOUSTIC INSTALLATION EFFECTS ON AFT FAN NOISE FOR TURBOFAN ENGINE

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Abstract

This paper deals with the numerical study of installation effects, a subject which is relevant of the more general purpose of the aircrafts noise prevision and reduction. As an example of installation effects, we study here the potential shielding effect that an empennage airfoil could offer to the reduction of the aft fan noise produced by a coaxial engine. Because the numerical simulations constitute an as powerful as cheap tool of investigation, we use for it a solver developed at ONERA, the *sAbrinA* CFD/CAA platform. In particular, we take benefits from an innovative overlapping method recently implemented in it - a method which allows handling more easily the solid obstacles to be considered. As an illustration of both the methodology and the tool, a full-3D aft fan noise propagation is then computed over an installed (over an airfoil) engine.

1. INTRODUCTION

Acoustic installation effects are a topic of growing interest for aircraft designers. In French national programs and European projects, Airbus leads studies of new aircraft concepts driven by installation effects. Among the most promising concepts, the "Rear Fuselage Nacelle - RFN" [8] configuration based on mounting the engines at the rear fuselage above the empennage (see Fig. 1) takes advantage of a non negligible acoustical shielding effect by the airframe on the fan noise emission.



Figure 1: Artist (left) and schematic (right) views of the RFN concept (with courtesy of Airbus France).

In the context of the numerical simulation of the RFN installation effects, the ONERA's *sAbrinA* FEE (Full Euler's Equation) solver has been used, taken benefits from a two-ways coupling method recently developed in it.

This paper will first resume the main features of the *sAbrinA* solver, a special emphasis being put on the coupling methodology. In a second time, a 3D numerical simulation of the aft fan noise propagation will be presented for an installed (over an airfoil profile) coaxial nozzle, the installation effects provided by the latter being then highlighted and briefly analyzed.

2. FROM THE SIMULATION OF THE AFT FAN NOISE OF ISOLATED COAXIAL ENGINES TOWARD A PREDICTION OF THE RFN INSTALLATION EFFECT

In previous studies [4, 5, 6], the ONERA's CFD/CAA calculation platform - named *sAbrinA* [1, 2, 3] - was used to simulate the downstream fan noise propagation of several (2D or 3D-axi) co-axial engines. In particular, these computations correctly accounted for the refraction effects due to the (strongly) heterogeneous mean flow of the jet. Such a challenge could only be achieved by the help of a CAA solver as *sAbrinA*, a tool based on a classical hybrid process where a preliminary aerodynamic calculation provides a heterogeneous steady mean flow on which an acoustic calculation can then be performed. For this latest computation, the Full Euler's Equations in perturbation are classically solved by the help of high-order finite differences spatial and filter schemes, and a Runge-Kutta *RK3* time scheme. Then, the propagation results can be used as a data entry for any other computation (e. g. a Kirchhoff calculation) providing the far (free) field radiation.

Once this ability to correctly simulate the aft fan noise propagation of an isolated engine was checked, it was decided to make a supplementary step towards the prediction of installation effects characterizing the RFN configuration. The idea was to perform the same kind of simulation, the engine being this time located over an airfoil that could be representative of an airplane empennage wing. In order to reduce the CAA meshing task, it was decided to take benefit from a promising coupling technique - an approach which was recently developed at ONERA [7]. With such a technique (which detail is given below), it becomes possible to mesh several solid bodies in a completely independent way, the single common point between the different grids being the usual minimum 'Points Per Wavelength' criteria. Then, the several body-fitted grids can be sunk in a wider Cartesian background mesh that will make them communicate by transmitting, at each time step and from one to the other, the instantaneous perturbations.

Such a methodology was fully validated in its "one way version", this having been

made for both a 2D industrial case (high lift wing diffraction) [7] and a (more recent) 3D academic case (diffraction by a sphere). A first validation of the "two-ways" version was also provided by an early and simplified simulation of the present "installed exhaust" problem, which was treated in 2D over a medium at rest [13] and (more recently) over its ('take-off') and ('approach') background mean flow. The present work's motivation was thus to go a step further, by treating the same problem, but in 3D. However, due to the complexity of such a CAA simulation, it was decided to attempt it first in a 'medium at rest' case. However, both the *sAbrinA* solver and the two way coupling technique being able to stand for any non-uniform mean flow, this will be extended soon to a real 'in flight' typical engine noise problem.

3. A TWO-WAY COUPLING, USING A DOUBLE OVERLAPPING METHOD

Several "overlapping" (or "overset") methods especially dedicated to CAA were recently proposed [9, 10, 11]. One can remind that all these methods are simply a "high(er) order" extension of the classical Chimera methods initially developed for CFD purposes. In the same manner, the present overlapping method is based on a CFD Chimera method initially developed by Steger et al. [12] – a method consisting in a Cartesian / curvilinear meshes coupling.



Figure 2: The 'two-way coupling' method. Left side: the body-fitted curvilinear grid (grey disk), the Cartesian overlapping mesh (white square), and the two areas of data transfer (red and green rings). Right side: the sticker local transformation of the curvilinear system of coordinates into a Cartesian 'reference domain' one.

Let us consider a body fitted curvilinear grid overlapped by a Cartesian mesh, as it is shown on the left side of the Figure 2; two coupling areas (here, in red and green) can be defined so that a double data transfer (from one grid to the other, and vice-versa) is performed at each step of the temporal integration process. More clearly, each one of the two coupling areas will be dedicated to a particular sense (from the curvilinear mesh toward the Cartesian one - in red, or from the Cartesian grid toward the curvilinear one - in green) in the data transfer, the latter consisting in an interpolation process. One can note that the distance between the two areas must be sufficient enough so that no interpolating point is interpolated at the same time. Practically, this minimum distance is driven by the half-width of the stencils characterizing the derivation and filtering operators.

Concerning the high-order interpolation process itself, it is commonly admitted that the Lagrange polynomials are the ones which offer the best quality / price ratio, since they present both a good accuracy and a light CPU time consumption. All the results presented below were conducted with Lagrange polynomials of 6^{th} order. One can underline the fact that, if the "Cartesian \Rightarrow curvilinear interpolation" coefficients can be easily obtained, the identification of the "curvilinear \Rightarrow Cartesian interpolation" ones is not straightforward at all. A way to turn out this problem is to stick up the curvilinear system of coordinates into an intermediate

Cartesian one (referred to as 'reference domain', see the right side of the Fig. 2). This is made with the help of some local sticker transformations, each one being evaluated through the numerical inversion of a linear system (see [7] for details).

Practically, the calculation of the "Cartesian \Rightarrow curvilinear" and "curvilinear \Rightarrow Cartesian" interpolation sets to be applied is conducted as a post-processing of the grids loading, preliminary to any simulation. Finally, regarding the single Cartesian grid, it has to be noticed that the 'near-field' region comprised within the "curvilinear \Rightarrow Cartesian interpolation" area (in grey, on the Fig. 2) has no physical sense. But, thanks to the curvilinear \Rightarrow Cartesian data transfer which acts as a forcing, these unphysical perturbations field remains confined in the 'near-field' region, and do not pollute the 'far-field' one. On the same way, regarding this time the single body-fitted curvilinear grid, all the spurious waves that could be generated by its peripheral boundaries will remain confined far away from the obstacle, their propagation being cancelled by the Cartesian \Rightarrow curvilinear retroaction (green area).

4. A NUMERICAL SIMULATION AS AN ILLUSTRATION OF THE METHODOLOGY AND TOOL

4.1 Test Case Description

We consider here a coaxial engine of realistic shapes and dimensions (in the following, R indicates the outer radius of the secondary exhaust). We propose to highlight the potential acoustic shielding that could be offered by an airfoil located under the engine, all that with respect to a particular aft fan noise component. The latter, to be emitted at the upstream of the secondary exhaust, is the mode (2, 2) characterized by a reduced frequency of kR = 11.84 - which corresponds to 1/2 BPF (Blade Passing Frequency) for the engine at full thrust (take-off). One can notice that both this aft fan noise specification and the exhaust \leftrightarrow airfoil relative position were prescribed by the airframer (Airbus France), this being made accordingly to preliminary studies of the industrial requirements and needs.

4.2 Grids Generation and Computational Set-up

According to what was previously said concerning the double overlapping method, three CAA grids were built for this two obstacles problem:

Two body-fitted curvilinear meshes (surrounding respectively the nozzle and the airfoil) were first derived from CFD grids initially constructed (and used for specific RANS mean flow calculations) by Ai-F and ONERA. Such a re-meshing was conducted with the *ReMesh2D* tool, an ONERA 'in-house' code that allows i) to entirely re-mesh any 2D (structured multi-blocks) CFD grid into a CAA one, ii) to interpolate on the latter the CFD background mean flow, and iii) and to (eventually) extend all this grid & flow material to the third dimension. In the present case, such a re-meshing task led to two meshes of respectively 5 domains / 206 258 nodes (for the nozzle) and 2 domains / 986 055 nodes (for the airfoil, of a 4*R* wingspan extent) – see left side of Figure 3. One can note that these girds were constructed with a concern of a sufficient resolution in term of Points Per *apparent* Wavelength, a criterion which minimum was fixed here to 15 PPW.

Finally, a third mesh was constructed under the same PPW constraint, leading to a 'background Cartesian' mono-domain grid of 9 049 830 nodes. To enhance the exit of the perturbations out of the calculation domain, a stretching was applied to the 8 peripheral rows of points of this background mesh. The two-ways coupling process is sketched on the right

side of the Figure 3, where is shown the principle of the double data transfer between the background Cartesian mesh and each one of the two curvilinear grids.



Figure 3, left side: the two body-fitted curvilinear grids respectively devoted to exhaust (in purple) and to the airfoil (in red), and the limits of the background Cartesian mesh (in blue). Right side: the principle of the two-ways coupling process, sketched by the double data transfer to occur between the each one of the curvilinear grids and the Cartesian one (in blue).

4.4 'Isolated Engine' Calculation

In order to provide an acceptable CFL number (0.9 in this case), the time step was set to a value corresponding to one 140^{th} of the acoustical source period. Once the panel of curvilinear points to be interpolated was correctly prescribed, the calculation was launched, and ran over 15 source periods - a duration corresponding to the necessary time of a well-established stationary state's achievement. On ONERA's NEC-SX8 Super Computer, this 10 243 143 cells / 2100 iterations simulation required 63 470 sec (around 17.5 CPU hour). This indicates an average computational time of 2.95 μ sec / iteration / cell, which a non negligible part (1.3 μ sec) can be attributed to the multiple data exchanges required by the two-ways coupling process.

The Figure 4 displays the instantaneous pressure perturbations field obtained at the end of the simulation; as it can be seen, as they propagate outside the secondary exhaust, the acoustic waves are submitted to successive reflections from both the engine and the airfoil surfaces, a very interesting game of interferences establishing then itself between the two solids. By observing what occurs in the very lower part of the domain (under the profile), it turns out immediately that the airfoil acts as an efficient shield relatively to the sound emitted toward the ground; only a fraction of it succeeds in diffracting and turning out the profile. One can notice the perfect continuity of the wave fronts all over the domain - and more particularly at the curvilinear / Cartesian grids interface (the slight discrepancies of Figure 4's right side is purely graphical) which tends to demonstrate the high quality of the coupling technique. Finally, the 'free field condition' imposed on the peripheral rows of the Cartesian domain seems also to be very efficient, as no reflections appear from it.



Figure 4: Installed engine 3D computation, with a medium at rest: instantaneous perturbed pressure field obtained at the end of the simulation (t = 15T), and shown though both a 3D view (of half the computational domain, left side) and a lateral view (right side)

On that stage, it has to be underlined that all the previous results were strongly driven by the present aft fan noise modal content (and thus directivity pattern), as well as the considered engine/airfoil dimensions and relative locations (and thus shielding/reflecting feature); any other combination of the two latter should lead to different observations - at least in a quantitative way, resulting in another acoustic shielding effect. More important, the heterogeneous mean flow to be taken into account should affect strongly the acoustic nearfield propagation behavior, and thus modify the resulting airfoil' shield efficiency in a non negligible way. All these particular points will be investigated in an immediate future.

5. CONCLUSIONS

In this study related to the installation effects, we numerically studied the potential acoustic shield that an empennage airfoil could constitute regarding the aft fan noise of a coaxial engine. After a brief description of both the CFD/CAA platform *sAbrinA* and its new overlapping feature, an illustration of the latter was given through a 3D simulation of the aft fan noise emitted by an installed engine, firstly considered within a medium at rest. This led to the conclusion that the RFN configuration could be very efficient in terms of aircraft noise reduction. It also demonstrated that the *sAbrinA* solver is definitely up to face complex problems out. The next step will be to extent the present investigation to other fan noise material (in terms of modal content and/or frequency) and background mean flows (approach and take-off flight conditions). This should be made in the next few months, if not weeks.

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