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Aircraft Noise Prediction via Aeroacoustic Hybrid Methods - Development and Application of Onera Tools over the Last Decade : Some Examples

This article focuses on advanced noise prediction methodologies, in regard to aircraft noise mitigation. More precisely, the so-called aeroacoustic hybrid methodology is first recalled here, before illustrating its potentialities through several examples of application to realistic aircraft noise problems. Among other things, this paper highlights how Onera has contributed to the development of reliable computational methodologies over the last decade, which can now help in solving aircraft noise issues.

Introduction

A few years ago, noise annoyance by aircraft was officially identified as the major obstacle to sustainable air traffic growth. Therefore, all stakeholders involved in the development of aircraft systems or components are now focusing on practical ways to reduce the acoustic signature left by their products. On the other hand, since acoustics is a complex discipline, they are often bound to make intensive use of numerical simulation, which constitutes a powerful tool for R&D, when combined with experimentation. This, however, requires a continuous development and a proper application of advanced modeling and solving techniques, which are mandatory for simulating the noise generation and/or propagation phenomena occurring in realistic situations.

Aircraft noise prediction via aeroacoustic hybrid methodologies

Aircraft noise prediction

The noise signature of aircraft includes two main contributions, respectively of propulsive and non-propulsive origins. The first one, namely the *engine noise*, is due to all engine propulsive devices (turbofan or turboprop), whereas the second one, namely the *airframe noise*, is induced by the airframe and its appendages (fuselage, wings, slats, flaps, landing gear, cavities, etc.). Although the engine noise accounts for a dominant portion of the overall aircraft noise during take-off, the airframe noise component becomes equally important during the approach for landing, when the engine thrust is considerably reduced.

From a more phenomenological point of view, such a distinction between engine and airframe noises vanishes at some point, since both components result from the contribution and combination of a large number of acoustic sources and phenomena. Indeed, noise originates from numerous source mechanisms, such as structural vibrations, fluidic motions, flow interactions with structures, gas combustions or explosions, and so on. Once they have been generated by these sources, acoustic waves propagate within the surrounding environment, which is generally constituted by one or several media of various complexity (e.g., comprising solid bodies and/or medium heterogeneities, etc.). During this propagation phase, acoustic waves may be subjected to numerous and important alterations in terms of amplitude, phase or frequency. Such effects all result from mechanisms as diverse as reflection and diffraction effects by solid structures, convection by fluidic motions, refraction by the medium heterogeneities, diffusion by the medium turbulence, absorption by the medium viscosity and so on.

Many of the acoustic generation processes and most of the acoustic propagation mechanisms are relevant to the physics of fluid dynamics and can thus be simulated by numerically solving the Navier-Stokes equations. At the present time, however, and despite the continuous development of computational tools and resources, it is still extremely challenging to solve aeroacoustic problems following a direct manner, that is to say, via a single calculation. Indeed, except in particular situations (e.g., simplistic configurations, academic cases, etc.), it is nearly impossible to simulate at the same time the noise generation and its subsequent propagation, whose underlying mechanisms greatly differ by their intrinsic characteristics (e.g., energy, length scales, etc...). As an example, most of the noise annoyances due to modern aircraft come from the so-called aerodynamic noise, which results from either the interaction of airflow with the structure itself (e.g., airframe noise), or from its ingestion by the engines (e.g., fan and/or turbine noises, etc...). On the other hand, the aerodynamic noise physics is made up of complex phenomena covering a broad range of spatiotemporal scales, with noise generation processes that are driven by turbulent structures of high amplitude and small space-time correlations, while propagation ones are associated with sound waves of low amplitudes and large space-time correlations. Thus, and although both phenomena are ruled by the same compressible Navier-Stokes equations, they cannot be easily predicted via a single calculation, because the computational resources required to resolve all of the relevant scales would be far too high.

Therefore, to make the numerical approach tractable in a practical context, the overall acoustic problem is usually broken down into a set of coupled sub-problems that focus on individual sub-regions of the overall spatial domain. Each sub-problem has a specific range of amplitudes and physical scales that can be addressed using a numerical method that is customized to the dominant physics occurring at this stage. Thus, methods involving a mix of techniques are classified as *hybrid* approaches for the acoustic prediction.

Aeroacoustic hybrid approach for aircraft noise prediction

In general, aeroacoustic hybrid methods are comprised of two to three stages (see figure 1), which are respectively devoted to :

- the noise generation and near-field propagation (over regions where the aerodynamic flow is unsteady, e.g., turbulent) ;
- the mid-field propagation (over regions where the aerodynamic flow is steady but heterogeneous) ;
- the far-field propagation (over regions where the aerodynamic flow is steady and virtually homogeneous).

The acoustic generation and early propagation (Stage #1) can be simulated with a compressible unsteady CFD approach, whether it involves DNS (Direct Numerical Simulation), LES (Large Eddy Simulation), unsteady RANS (Reynolds Averaged Navier-Stokes equations), or a judicious mix of these techniques, such as DES (Detached Eddy Simulation). The main advantage offered by these CFD techniques is that they are very close to the physics, with an accuracy level that is proportional to the costs that they entail (in terms of computational time and memory consumption)[*].

The acoustic far-field radiation (Stage #3) can be predicted with an Integral Method (IM), such as those relying on Kirchhoff [25], Lighthill [29] or Ffowcs-Williams & Hawkings (FWH) [21] integration techniques. The main advantage offered by these methods is that they are relatively cheap (in terms of computational resources), while being rigorously exact - provided however that their underlying hypotheses are strictly verified. Indeed, these various IM techniques all assume that the acoustic propagation phase can be modeled by an elementary Green function, which allows meshing and computing the propagation medium to be avoided - and, thus, offers to greatly lower the computational time and memory requirements.

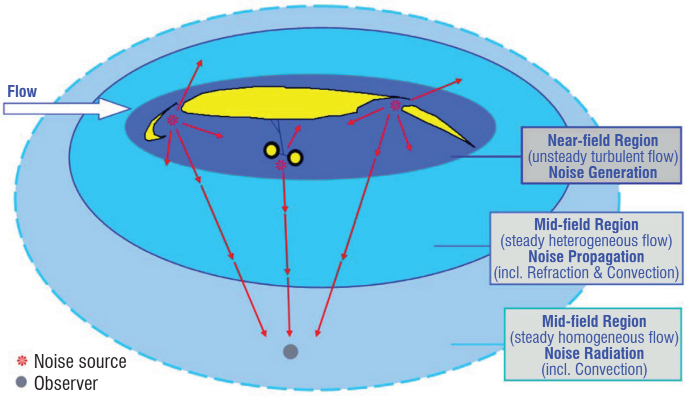

Figure 1 - Aircraft noise emissions by high lift wing and undercarriage systems; sketch of the overall problem and splitting of the latter into several distinct sub-problems, to be addressed following an aeroacoustic hybrid approach

Concerning now the acoustic mid-field propagation (Stage #2), this step can be neglected in particular situations, such as for instance when the noise source radiates in an unbounded medium at rest. This step cannot however be ignored when the noise emission is to be followed by other phenomena, such as acoustic reflection / diffraction effects by solid obstacles or acoustic refraction effects by the medium, which is something likely to occur in many aircraft noise problems [47]. As an example (see figure 1), when installed under a wing, landing gear is located within a region where acoustic waves may be subjected to both strong reflection effects (induced by the undersurface of the wing) and non-negligible refraction effects (induced by the mean flow gradients, which generally extend up to one chord away from the wing surface). As mentioned above, due to the variety and complexity of all of the physical phenomena involved, numerically simulating such a propagation phase is not a trivial task[*]. In particular, although they do not need to account for turbulent fluctuations nor viscous effects, computational techniques required for handling this noise propagation step must accurately simulate the propagation of acoustic waves over relatively large distances across possibly heterogeneous media, while accounting for the possible presence of solid obstacles (e.g., when the configuration is installed). This may typically be accomplished with higher fidelity acoustic propagation approaches, such as a Computational Aeroacoustics (CAA[†]) method relying on the Euler equations, or a linearized version thereof [43, 44]. Indeed, one can here recall that only a CAA method[‡] can simultaneously account for both

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[*] Here, one can notice that, in some situations, the acoustic near-field generation can also be mimicked with less sophisticated (and, thus, less accurate / expensive) methods, such as those relying on semi-empirical models (to be calibrated through experiments), or on stochastic/statistical techniques [39, 27, 6, 26]. These alternative approaches are however of more restrictive use, since their underlying assumptions generally narrow their range of validity and/or applicability.

[*] Although this would constitute an ideal solution, this mid-field acoustic propagation phase cannot be incorporated within Stage #1, because of the increased cost of extending the viscous, nonlinear CFD computations to include refraction by the medium heterogeneities and reflection by solid obstacles away from the noise source region(s).

[†] Here, it should be noted that the generic name "CAA" was first introduced to denote this young and rapidly growing discipline devoted to the numerical simulation of acoustic propagation within complex aerodynamic flows. This specific label is now often used in a wider sense and has been extended to simpler techniques, such as Integral Methods (e.g., Acoustic Analogy). Such extension could be seen as inappropriate, since most of these techniques belong more to the linear acoustic domain than to the non-linear aero-acoustic one, which CAA originally comes from.

[‡] Whether it relies on high-order Finite Difference (FD) schemes operating on multi-block structured grids [28, 30, 56, 57] or on the so-called Discontinuous Galerkin Method (DGM) [1], which is based on unstructured grids.

the reflection/diffraction effects by solid obstacles and the refraction effects by the medium heterogeneities, contrary to other techniques that can only model the former (such as the Boundary Element Method, BEM), or even none of them (such as Integral Methods, IM).

Coupling processes of the aeroacoustic hybrid methodology

A critical aspect of developing aeroacoustic hybrid methodologies corresponds to the coupling process, i.e., the information exchange occurring between the various stages respectively associated with the individual sub-problems.

The nature of this coupling is problem dependent, because of significant variations in the inter-dependencies between the various stages from one problem to another. However, except in problems involving acoustic feedback (e.g., screech tones, in jet aeroacoustics), the coupling between these stages is weak, i.e., primarily unidirectional. Under this scenario, feedback from a given stage to the previous one can be ignored and the successive stages of an aeroacoustic hybrid calculation can be coupled in a *weak* sense, all possible retro-actions from a given step to the previous one being then neglected [47].

Such a weak coupling process occurring between two successive stages of an aeroacoustic hybrid approach is constituted with a data transfer, whose role is to transmit all of the acoustic information gathered at each step to the next level. Needless to say, such an operation must be properly achieved, so that it does not degrade the acoustic signal information to be transferred. This requires the weak coupling technique to both rely on sound physical principles and offer sufficient numerical robustness, especially in regard to an application within a realistic context [47, 12].

Two- to three-stage aeroacoustic hybrid methods

When circumstances allow the acoustic mid-field propagation (Stage #2) to be neglected, one ends up with the so-called two-step aeroacoustic hybrid method, which addresses only Stages #1 and #3 via a weak coupling of CFD and IM calculations (see top of figure 2).

Over the last decades, such 2-step aeroacoustic hybrid approach became one of the most popular techniques for simulating applied problems of external noise and use is now often made of 2-step hybrid calculations that couple CFD and IM modules, whether the latter IM module is based on the Acoustic Analogy by Lighthill (e.g., for an isolated jet) or by Ffowcs-Williams and Hawkings (e.g., for an isolated rotor). In particular, over the past decade, Onera widely promoted such a 2-step aeroacoustic hybrid approach by jointly developing CFD solvers (such as the *els*A platform [3, 4]) and IM tools (such as the *KIM* code [41, 40]), which it later applied to realistic aircraft noise problems, as will be partially illustrated in the following paragraphs.

On the other hand, more recently, the three-step aeroacoustic hybrid approach also emerged, which combines Stages #1, #2 and #3 via a weak coupling of CFD, CAA and IM calculations (see bottom of figure 2). As was mentioned, and although it is more complicated to handle, such a 3-step aeroacoustic hybrid approach allows more complex problems to be simulated, since its CAA-based propagation stage can account for refraction and/or scattering effects that may occur in the midfield. As an illustration, the internal noise propagation problems that occur in nacelle and exhaust ducts of engines can be exemplified. Indeed, here, once their generation has been properly simulated via a numerical method (e.g., Computational Fluid Dynamics, CFD) or modeled by analytical means (e.g., duct mode theories [61]), acoustic waves can then be transferred to a CAA solver, for the latter to propagate them through the duct, while accounting for all internal effects to be possibly induced by the presence of flows, solid devices or any other disturbing elements (such as noise absorbing panels, etc.). Another typical situation for which an aeroacoustic hybrid approach relying on a CAA-based Stage #2 is mandatory concerns those external noise problems whose propagation phase occurs within a complex environment, such as for instance the airframe noise emissions by aircraft appendages (e.g., landing gear, etc.). Indeed, here again, once their generation has been properly simulated (usually via an unsteady compressible CFD method), acoustic waves can then be transferred to a CAA solver, for the latter to propagate them up to the far-field, while accounting for all of the installation effects induced by either the aircraft structure (e.g., reflection/diffraction) or the air flow surrounding the latter (e.g., convection/refraction).

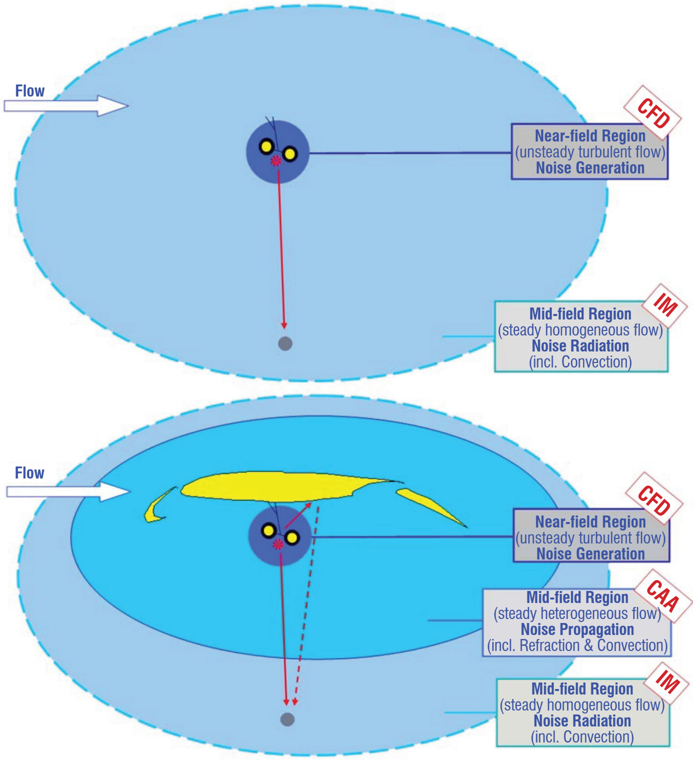

Figure 2 - Numerical prediction of the noise emission by landing gear in isolated (top) or installed (bottom) configuration, via either a 2-step (CFD-IM, top) or a 3-step (CFD-CAA-IM, bottom) aeroacoustic hybrid approach.

Here too, over the past decade, Onera largely promoted such a 3-step aeroacoustic hybrid approach, by both i) developing the CAA solver *sAbrinA* [43, 44, 46, 50, 42, 6], before ii) allotting it with proper CFD-CAA weak coupling features [43, 44, 58, 47, 48] and iii) applying it to various (either isolated or installed) aircraft noise problems (see the next paragraphs). At this stage, one can recall that alternative three-step aeroacoustic hybrid approaches also exist, such as those based on the combination of CFD, CAA and BEM methods. In this case, the IM stage is simply replaced with a BEM one, which allows the far-field noise to be predicted, while taking into account additional scattering agents located in the far field region. This approach was also promoted by Onera, through dedicated joint projects [45, 37] conducted in collaboration with Airbus.

Two-step aeroacoustic hybrid method : noise predictions based on CFD and IM calculations

A few examples of aircraft noise predictions that were achieved following a two-step hybrid approach relying on CFD and IM weakly coupled calculations are presented hereafter. The latter were all conducted with the help of Onera tools; more precisely, the CFD calculations (Stage #1) were handled with either *els*A [3, 4] or CEDRE [5] codes, which are two unsteady compressible CFD solvers that operate on structured and unstructured grids, respectively. On the other hand, the far-field noise extrapolations (Stage #3) were all achieved with the help of the KIM code [41, 40], which relies on a time domain IM (Integration Method) based on the FWH acoustic analogy [21]. Please note that the few examples presented hereafter are here for illustration purpose only; in particular, they do not claim at presenting the entire portfolio of application works that were achieved thanks to the two-step hybrid approach and tools developed at Onera.

Noise emission by an isolated CROR engine, via CFD (uRANS)-IM(FWH) weakly coupled calculations

Within the framework of an Airbus/Rolls-Royce project whose long term objective is to assess the sustainability of CROR*-powered aircraft with respect to noise regulations, a dedicated action was recently conducted by Colin et al. (Airbus). The aim here was to further assess and validate existing CROR-noise prediction methodologies, in regard to a use within an industrial context. With that view, joint experimental measurements and numerical calculations were performed, in order to characterize the aeroacoustics of a CROR engine, which was allotted either a high or a low speed flight condition; the aeroacoustic test campaign was performed at DNW† , whereas its numerical counterpart was performed at Airbus. All computations relied on a 2-step aeroacoustic hybrid approach and consisted in CFD-IM weakly coupled calculations [7-9].

The CFD computations were achieved with the help of a structured unsteady RANS approach, for which the Onera solver *els*A was used. Some of these CFD(uRANS) calculations were handled via a full 3D approach relying on a Chimera technique (that is, with overlapping grids), which allowed part of the experimental set-up to be accounted for (see figure 3, left side) and, thus, its potential aerodynamic installation effects to be assessed. On the other hand, alternative CFD(uRANS) computations were performed using a chorochronic technique ‡ (see figure 3, right side), which permitted the meshing / computing efforts to be lessened, but however prevented any of the test set-up devices (and subsequent installation effects) from being accounted for.

Concerning now far-field acoustic extrapolations, all IM calculations were achieved following a FWH approach, for which use of Onera's solver KIM was made.

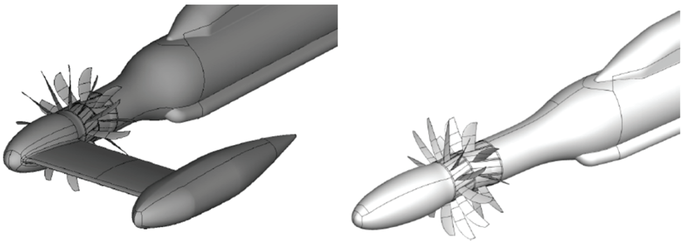

Figure 3 - CROR engine considered under either a facility installed (left) or an isolated (right) configuration. Reproduced from [9] with permission. Courtesy of Airbus

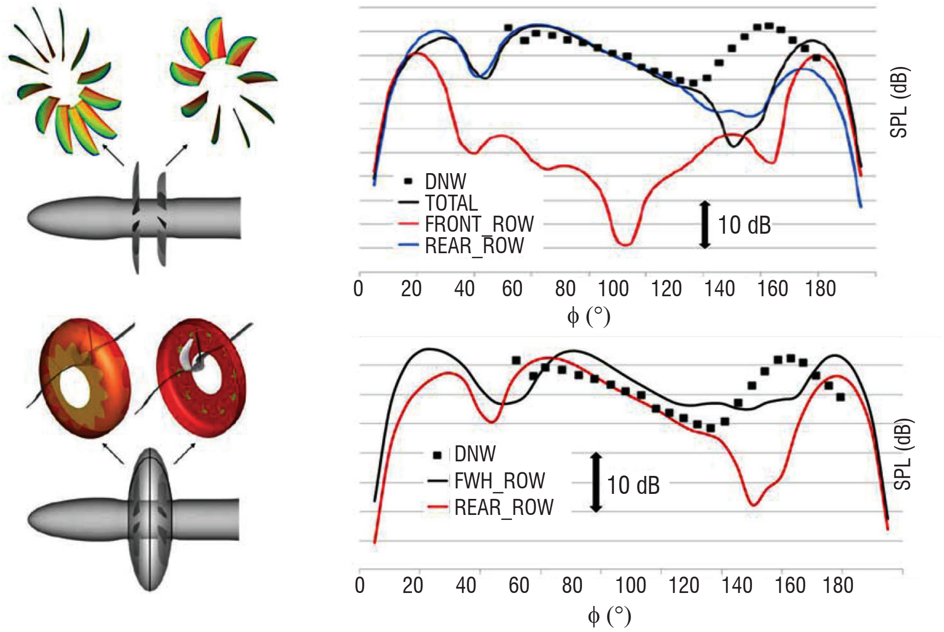

Figure 4 - Noise emission by an isolated CROR engine at take-off, predicted via a CFD(uRANS)-IM(FWH) hybrid calculation based on either a solid (top left) or a porous (bottom left) surface integration. Right side; far-field radiation of noise emissions associated with the BPF (Blade Passing Frequency) and its first harmonic, as extrapolated in a 'solid' (top: black line, bottom: 'FWH-SOL') or a 'porous' (bottom; 'FWH_PERM') surface sense. Numerical (solid lines) against experimental (black dots) results. Reproduced from [9] with permission. Courtesy of Airbus

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* Counter-Rotating Open Rotor

† German-Dutch Wind Tunnels, established by the German Aerospace Center (DLR) and the Dutch National Aerospace Laboratory (NLR)

‡ that is, relying on space/time azimuthal periodicity

Some of these IM (FWH) computations were based on the *solid* surface approach, with only the noise emission coming from the blades (loading noise, etc.) being accounted for (see top of figure 4). On the other hand, alternative IM (FWH) calculations relied on the porous (or permeable) surface strategy, with all noise emissions coming from the immediate vicinity of blades being integrated also (see bottom of figure 4). As one can see in figure 4, results delivered by these CFD(uRANS)-IM(FWH) weakly coupled computations were favorably compared to experimental data.

In addition to this, specific parametric and/or comparative studies were conducted, which provided key insight of either phenomenological or methodological nature; concerning in particular methodological aspects and regarding first the CFD stage, results have shown that, whenever installation effects are to be accounted for, making use of the full 3D approach is mandatory, despite the increased meshing/computing costs that such an approach may involve. On the other hand, making use of the (lighter and cheaper) chorochronic approach is effectively to be privileged, as long as installation effects can be considered as negligible enough. Regarding now the IM stage, results have shown that the FWH porous (or permeable) surface integration approach allows far-field acoustic extrapolations to fulfill a higher degree of fidelity to the physics, since it incorporates additional effects[*], compared to its solid surface counterpart. The latter, however, appears to be more flexible to use, since it avoids some of the issues of the former[†], whereas it allows the noise generation mechanisms to be investigated further (here, by discriminating the various radiating parts of blades). For more details about this study, the reader is referred to [7-9].

Noise emission by a double stream jet with pylon, via CFD(LES)-IM(FWH) weakly coupled calculations

The so-called AITEC research project focused on the jet noise emissions by a double stream nozzle (of By-Pass Ratio value 9), which i) included a pylon and ii) was running under high power conditions. Within this context, near-field aerodynamic and far-field acoustic measurements had been gathered during a dedicated dual aero+acoustic campaign, which was conducted in the Onera wind tunnel *CEPRA 19.*

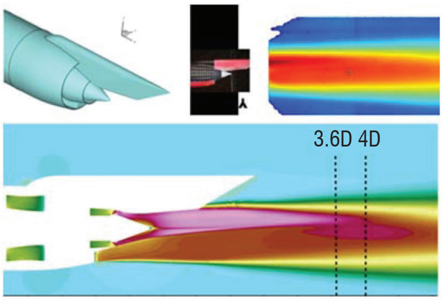
The configuration was then simulated by Vuillot et al. following a 2-step aeroacoustic hybrid approach, that is, via weakly-coupled CFD and IM calculations [62] ; the CFD computation consisted in an unstructured LES, which was achieved with the help of the Onera solver *CEDRE*, whereas the far-field noise was IM-extrapolated using a time domain/porous FWH calculation, for which the Onera code *KIM* was used.

As can be seen in figure 5, both aerodynamic and acoustic predictions were very favorably compared to experimental data. In particular, and although the turbulent transition was not perfectly reproduced by the CFD calculation, the latter succeeded in correctly capturing the aerodynamic installation effects (such as the flow deviation) due to the pylon's presence. More importantly, the latter's effect on acoustic far field radiation was properly predicted, both in terms of directivities and amplitude (absolute levels). In addition, despite the fact that the CFD grid had induced some filtering of the near-field acoustics, its low frequency content $(St < 1)$ could be correctly captured by the FWH extrapolation. Finally, a proper investigation of the latter results allowed the tonal noises observed to be related to the pairing of jet vortices. For more details about this study, the reader is referred to [62].

Noise emission by a nose landing gear, via CFD(ZDES)-IM(FWH) weakly coupled calculations

To better predict the physical mechanisms associated with landing gear noise emissions, the so-called LAGOON research program was initiated by Airbus a few years ago. The objective of the project was to acquire an extensive experimental database associated with elementary landing gear configurations, so that computational methods dedicated to landing gear noise predictions could be accurately and thoroughly validated.

Within this framework, combined experimental and computational campaigns were thus carried out, focusing on both the aerodynamics and the acoustics of a simplified nose landing gear (see figure 6). The model geometry was that of a nose gear of an Airbus A320 aircraft, with a scale factor of 1:2.5 and with only the main elements (leg, wheels, etc.) considered. Such geometry was taken as isolated, and allotted either a take-off or an approach flight condition.



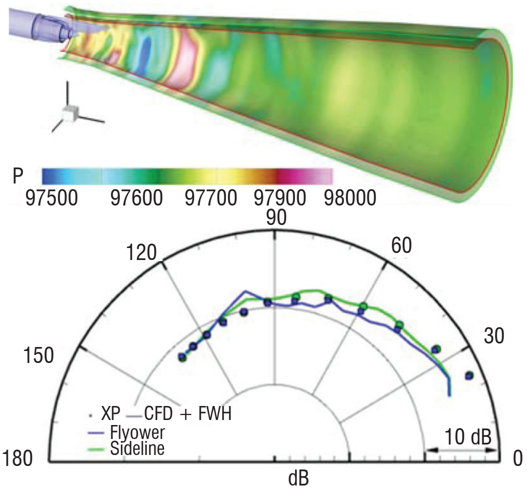


Figure 5 - Noise emission by a double stream jet, via a CFD(LES)-IM(FWH) hybrid calculation. Left : steady flow, as measured (top) and CFD-computed (bottom). Right side : far-field acoustics, as measured (dots) and IM-extrapolated (lines) from the CFD-IM weak-coupling surface (top). Reproduced from [62] with permission

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[*] such as the so-called quadrupolar noise sources, the near-field flow refraction phenomena, etc...

[†] such as spurious noise sources due to an improper handling of wake vortices convected downstream from the blades

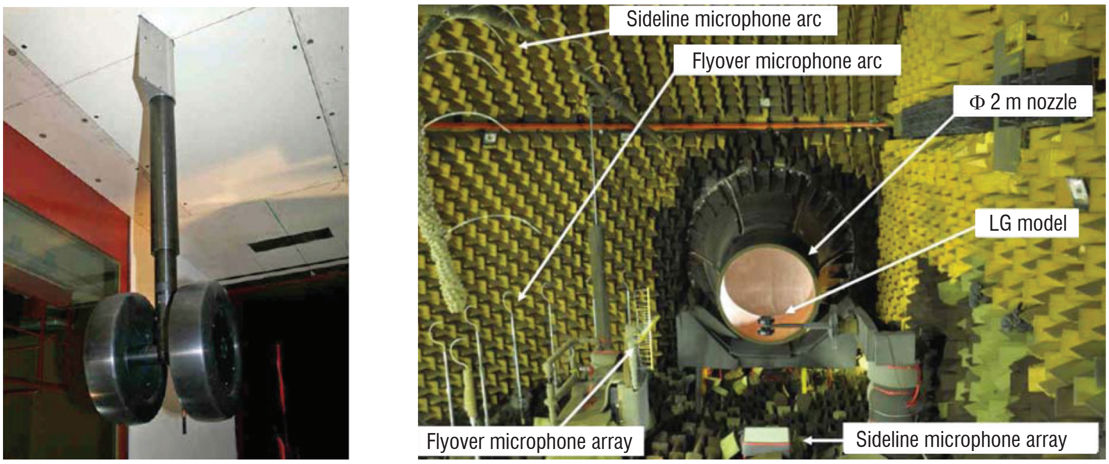

Figure 6 - Noise emission by a simplified nose landing (NLG) under approach flight conditions (LAGooN program). NLG model (seen from behind), as installed in both the aerodynamic facility (left side) and the open jet anechoic wind tunnel (right side) of Onera. Reproduced from [55] with permission. Courtesy of Airbus

The aero+acoustic dual experiments were performed by Manoha et al. in Onera's aerodynamic (*F2*) and anechoic (*CEPRA 19*) facilities, respectively [32, 33] (see figure 6).

The computational counterpart of this aero+acoustic experimental campaign was conducted at Onera, following a 2-step aeroacoustic hybrid approach [55]; unsteady aerodynamics predictions (Stage #1) relied on structured CFD calculations that were based on a ZDES approach [18, 19] and that were conducted by Ben Khelil et al. using the Onera solver *elsA* (see left side of figure 7). As can be seen on the left/bottom side of figure 7, those calculations were favorably compared with the aerodynamic measurements through direct comparison of near-field results (this, to the exception of mismatches over the low and high frequency ranges, which can be reasonably attributed to the high pass filtering induced by the experimental acquisition and the numerical simulation techniques, respectively). In particular, both experimental and numerical outputs exhibited tonal noises (with frequencies of approx. 1 kHz and 1.5 kHz), whose emission was inferred to be associated with resonances coming from the inner cavities of the wheels.

These unsteady CFD results were then acoustically extrapolated to the far-field by Sanders et al. via an IM(FWH) approach, which was based on either a porous or a solid surface integration and for which the Onera code *KIM* was used. These CFD-FWH weakly coupled calculation results were also favorably compared to the experimental measurements recorded in the far-field (see right/bottom of figure 7). Depending on the far-field location, however, an overestimation of acoustic levels could be observed for results that had been obtained via IM(FWH) calculations relying on a porous (rather than a solid) surface integration, this being due to side-effects coming from the FWH-integration of vortices convected by the wake of the landing gear. More details about this study can be found in [55].

Three-step aeroacoustic hybrid method : noise predictions based on CFD and/or CAA calculations

A few examples of aircraft noise predictions that were achieved following a 3-step hybrid strategy, that is, via CFD and/or CAA calculations are presented hereafter. These computations were mostly conducted with the help of Onera solvers. In particular, all CAA calculations were handled with the help of the Onera solver *sAbrinA* [43, 44, 46, 50], which is a highly-accurate time-domain CAA solver operating on multi-block structured grids. Here again, please, note that the application examples presented hereafter constitute a non exhaustive list excerpted from the range of works that were achieved thanks to the three-step hybrid approach and tools developed at Onera.

Aft fan noise emission by an engine at take-off, via CAA calculations

Fan noise is a major harmful aircraft sound source, especially during take-off and approach flight phases. For a long time, engine or aircraft manufacturers mainly focused on the numerical prediction of fan noise upstream components, which are emitted by the air intake of the engine. Over the past few years, however, they have also focused on the more complex problem of predicting their downstream counterparts, which propagate through the exhaust and its highly heterogeneous jet flow.

Within such framework, several collaborative Airbus-Onera studies were carried out, which consisted in performing out computations following the 3-step aeroacoustic hybrid philosophy, with a noise generation step (Stage #1) that was handled via analytical means (based on the modal theory* [61]), whereas the noise propagation step (Stage #2) was conducted using CAA calculations.

Among others, a study was conducted by Redonnet et al. a few years ago [50], with the purpose of assessing how far a time domain structured CAA method (such as the one underlying *sAbrinA* solver) could predict the noise propagation phase associated with aft fan noise emissions by a realistic bypass exhaust. Besides its realistic geometry (which incorporated the pylon and internal bifurcations of the nozzle), such exhaust was assigned representative thermodynamic conditions (take-off conditions) and relevant fan noise contents. The latter were analytically derived according to the modal theory* [61], being then CAA-forced at the upstream of the secondary exhaust, for the CAA solver (*sAbrinA*) to numerically propagate them up through the bypass exhaust.

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* which delivers the elementary solutions of the acoustic propagation problem within an infinite annular rigid duct and a homogenous medium, with these solutions being characterized by an azimuthal periodicity of order m and a given radial distribution of order n [61].

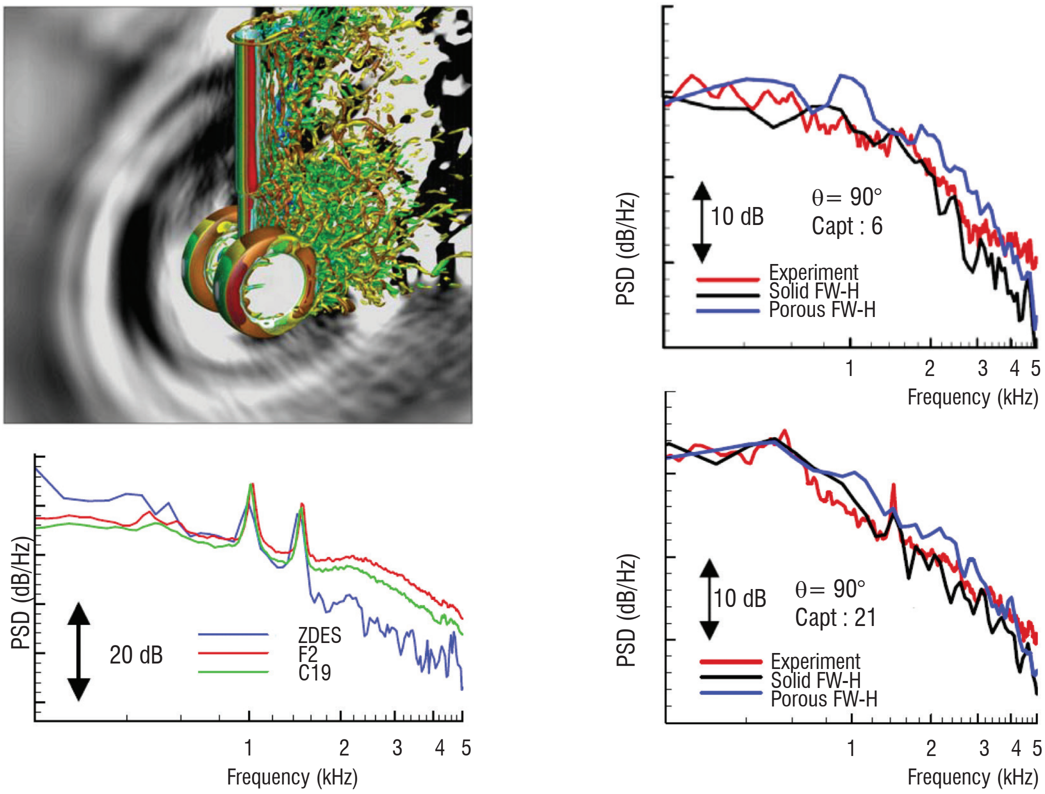

Figure 7 - Noise emission by an isolated nose landing gear (NLG) under approach flight conditions, via a CFD(ZDES)-IM(FWH) hybrid calculation. Left side: near-field aerodynamic results (top: Q-criterion iso-surfaces colored by the stream wise velocity component and instantaneous pressure fluctuation field), with validation (bottom) via direct comparison of the Power Spectral Density (PSD) computed by CFD (in blue) and recorded in the experiments (in red and green), for a probe of the right wheel. Right side; validation of the far-field acoustic results, via direct comparison of the PSD predicted by CFD-FWH (black and blue) and measured in the experiments (red), for two microphones located at 90° from the model in the flyover (top) and side line (bottom) directions. Reproduced from [55] with permission

As an illustration, figure 8 provides the acoustic field radiated by the exhaust at take-off, as CAA-predicted for an aft fan noise mode of azimuthal / radial orders $(m, n) = (13,1)$ emitted at the Blade Passing Frequency (BPF).

First, from a phenomenological point of view, this study allowed the installation effects to which acoustic waves may be subjected when propagating inside and outside an exhaust to be numerically characterized, thus highlighting how far the geometry and/or flow of a turbofan engine can affect its fan noise emissions. This conclusion is of importance, since it shows that a high fidelity to reality is required for numerically predicting the acoustic signature of an engine.

Secondly, and from a more methodological point of view, this study also proved that a time domain *structured* CAA method could be accurate and robust enough to offer both a high fidelity and a minimal flexibility, when applied to realistic engine noise problems. Indeed, for this study, special emphasis was placed on the validation stage, for which the results delivered by each CAA calculation were very favorably compared against those coming from alternative numerical techniques (BEM or DGM, see details in [50]). For more details about this work, the reader is referred to [50].

Here, it is worth mentioning that this particular study opened up the way to an intense applied research activity that was conducted at Onera since half a decade, and that aimed at numerically characterizing both the aft fan noise radiation in itself [50, 42], but also its possible mitigation via passive noise reduction devices - whether the latter relies on innovative installation concepts [45, 46, 38], novel exhaust designs [49, 37] or use of absorbing materials [52]. For instance, as a direct continuation of this study, more recently, alternative CAA calculations were conducted by Redonnet et al., to numerically assess the effect of acoustic absorbing materials on aft fan noise emission by realistic exhausts [52]. Indeed, nowadays, most of the engine noise reduction is achieved thanks to noise absorbing panels, which are set up inside intake and exhaust ducts. Therefore, the lined exhaust counterpart of the previous (rigid nozzle) simulation was conducted, with acoustic liner panels being modeled at end of the secondary exhaust (see top / left side of figure 9). The right side of figure 9 depicts the acoustic power emitted by both the rigid and the lined exhausts; as can be seen, the latter radiates much weaker acoustic levels than the former*, which obviously comes from the noise attenuation occurring within the downstream part of the secondary duct, due to the absorbing material.

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* with, in this particular case, a Sound Pressure Level radiated by the lined exhaust of approx. 6dB lower than the one emitted by its rigid counterpart [52]

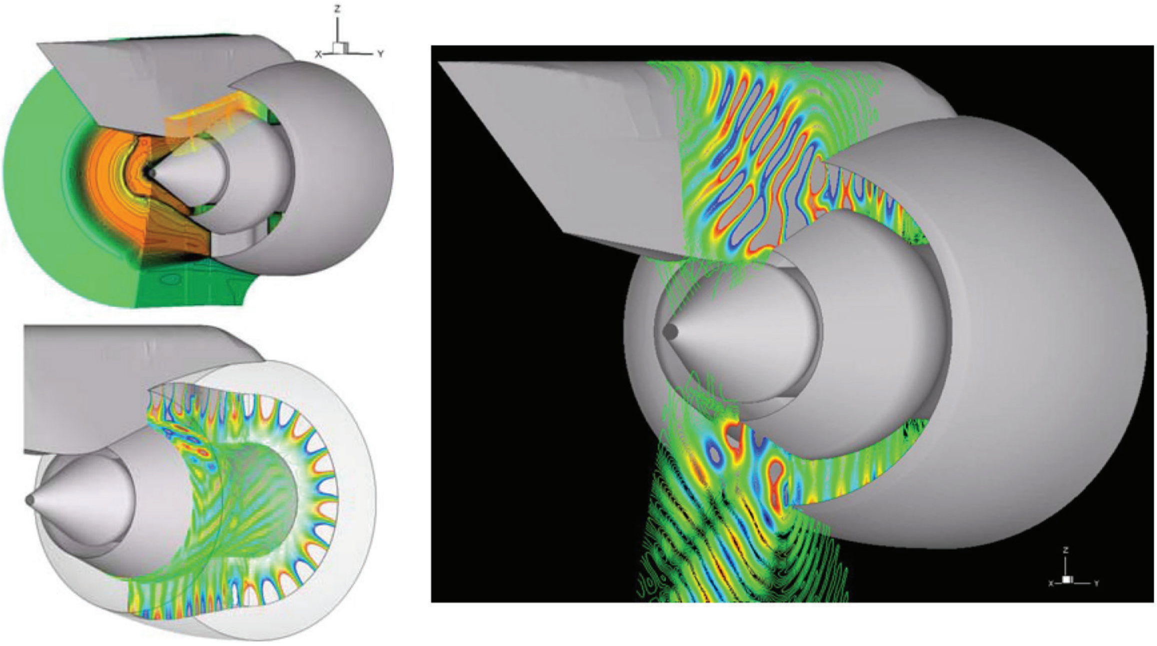

Figure 8 - Aft fan noise emission by an isolated exhaust at take-off, via a CAA calculation forced with analytical source contents. Counter-clockwise, from top left: steady mean flow field (axial velocity), internally propagated and externally radiated instantaneous perturbed pressure fields

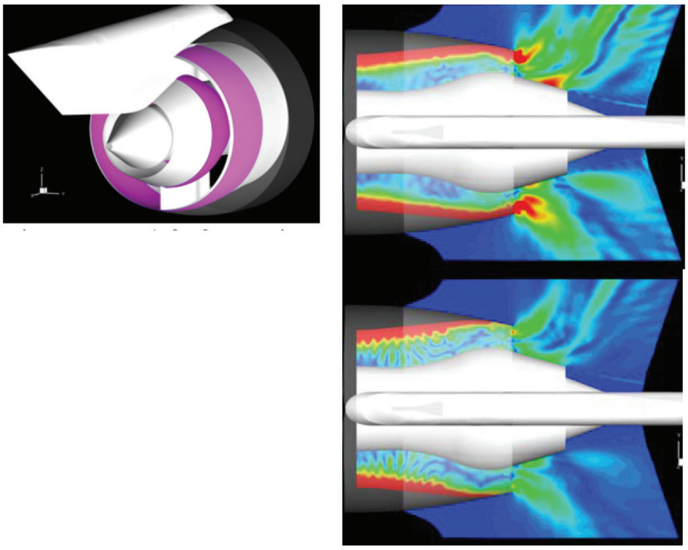

Figure 9 - Aft fan noise emissions by a possibly lined exhaust at take-off. Top left ; acoustic liner panels (in pink). Right side : Root Mean Square perturbed field radiated by the rigid (top) and the lined (bottom) exhausts

This alternative study allowed the efficiency of passive noise reduction technologies to be better highlighted, in regard to their application to engine noise problems. From a methodological point of view, this study has also shown that, once associated with proper post-processes, a CAA method could advantageously be employed to not only predict, but also to investigate some of the mechanisms that underlie the physics of acoustic liners (e.g., effects by ruptures of impedance or grazing flows - see [52]). Additional details about this study can be found in [52].

Aft fan noise emission by a partly installed engine, via CAA calculations

Over the past few years, several French national and European projects have been aimed at assessing how the aft fan noise emitted by engines could possibly be attenuated through the installation effects (or acoustic shielding) offered by structural elements (wing, empennage, fuselage) of non-conventional airplanes. As an illustration, figure 10 depicts an Airbus concept for a low noise aircraft, with the engines installed in RFN (Rear Fuselage Nacelle) configuration, so that the aft fan noise radiated through the exhaust is shielded by the rear fuselage and empennage.

Figure 10 - Low Noise Aircraft based on the Rear Fuselage Nacelle concept (courtesy of Airbus)

Within this framework, several experimental and numerical studies were conducted at Onera [46, 45, 37], all aimed at characterizing the shielding effect provided by a simplified empennage wing on the aft fan noise of a coaxial exhaust under take-off conditions. Some of the computations performed were achieved by Redonnet et al. [40] following the 3-step aeroacoustic hybrid philosophy, with a noise generation step (Stage #1) relying on analytical means [61], whereas the noise propagation one (Stage #2) was handled via CAA calculations (*sAbrinA* solver). The latter calculations directly benefited from an advanced Chimera technique developed by Desquesnes et al. [20] relying on the use of overlapping grids; this technique greatly helped in lightening the meshing tasks, while allowing the entire configuration to be simulated through simultaneously and strongly coupled CAA-CAA calculations.

First, the overall methodology was carefully validated by considering the installed exhaust as emitting within a quiescent medium, calculation results being then very favorably compared to those delivered by a reference BEM computation (see details in [46]). Then, the actual configuration (take-off flight conditions) was addressed, allowing the relevance of the RFN concept to be highlighted. As an illustration, figure 11 shows the instantaneous perturbed pressure field associated the acoustic emission of an aft fan noise mode (2, 2) emitting at one half of the BFP. By observing what occurs in the lower part of the domain (under the airfoil), one can observe that the empennage wing actually acts as an efficient shield, since only a fraction of the sound emitted in the aft direction succeeds in diffracting around the airfoil and propagating towards the ground.

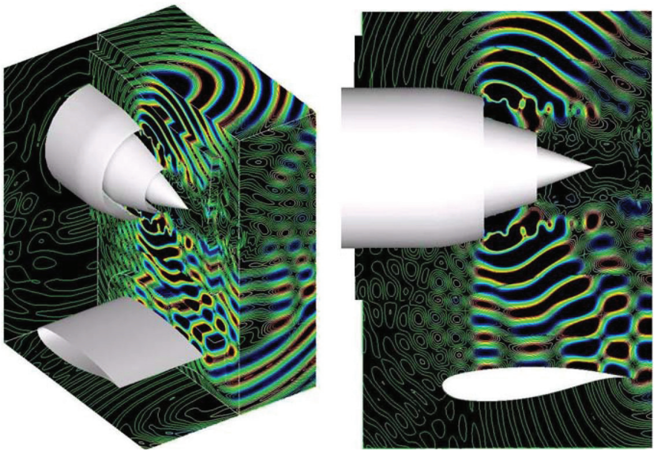

Figure 11 - Aft fan noise emission by a coaxial exhaust installed over an empennage airfoil, via a CAA calculation (fed with analytical source contents)

From a phenomenological point of view, the conclusions of this study were that RFN configurations are particularly efficient in regard to aft fan noise reduction, thus constituting a promising approach for diminishing acoustic signatures by aircraft. From a more methodological point of view, this study had further shown that a time domain structured CAA approach could allow realistic engine noise problems to be handled in an accurate and flexible manner, as long as some of its intrinsic constraints (e.g., meshing effort) could be relaxed through additional features (e.g. the Chimera-based CAA-CAA strong coupling technique used here). Main outcomes and conclusions of such work (which details can be found in [46]) were further confirmed by subsequent Onera studies devoted to the numerical and experimental characterization of the RFN concept [37].

Noise emission by the slat cove noise of a high lift wing, via partly decoupled CFD and CCA calculations

The leading edge slat is known as a major airframe noise source on large transport aircraft. Its underlying mechanisms are complex, as shown by several attempts to characterize slat noise emissions via unsteady CFD techniques [52, 2, 17-19].

Among other works, a few years ago, a dedicated research action was jointly conducted by Onera and Airbus; the computational tasks were based on a 3D-zonal unsteady CFD(LES) approach [36], calculations being performed by Ben Khelil et al. over the slat region of a 2D high-lift wing, which was considered in an as-like approach flight configuration [2]. Once they were properly post-processed by means of spectral analyses, the unsteady CFD results acquired over the slat region revealed the presence of strong local tonal sources within the cove area (see figure 12).

Although the final objective was to simulate the complete slat cove noise production chain following a 3-step hybrid aeroacoustic strategy based on a CFD-CAA weakly coupled calculation, the latter was first replaced by a analytical-CAA one; indeed, post-processes of the unsteady CFD data had delivered enough information about the noise generation stage for equivalent sources to be able to be analytically synthesized, based on the characteristics (location, frequency, relative magnitude, etc.) of the principal tonal emissions occurring within the cove area. Based on these elementary sources (harmonic monopoles), several CAA calculations [20] were then conducted by Desquesnes et al., enabling an interesting qualitative study to be achieved at a reasonable cost. Here, one can notice that, as for the computations presented in the previous paragraph, these CAA calculations directly benefited from the chimera-based CAA-CAA strong coupling technique (which was however used here in its *one way* version).

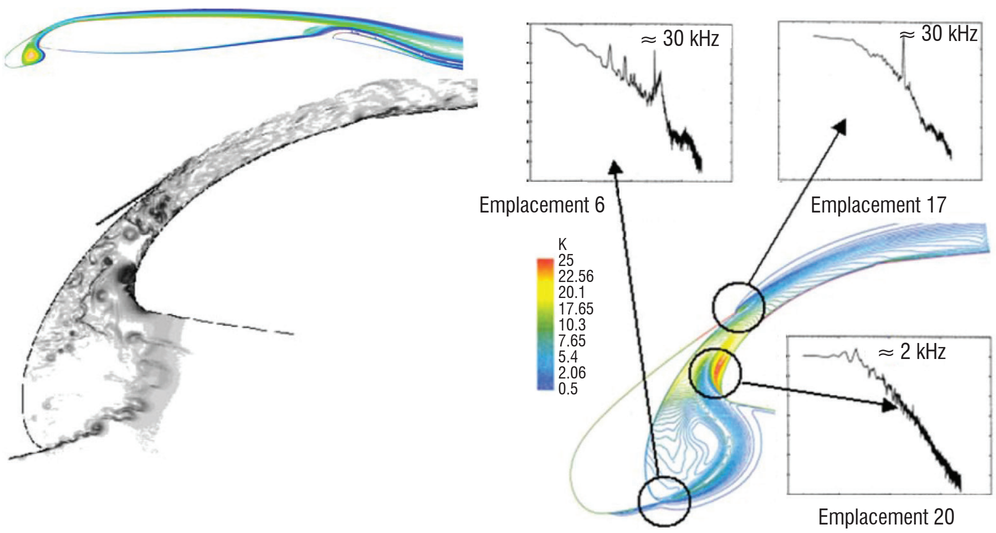

Figure 12 - Noise generation by a slat cove of a high lift wing at approach, via an unsteady CFD (zonal RANS/LES) calculation. Left side ; steady (top) and unsteady (bottom) aerodynamic fields. Right side : turbulent kinetic energy and acoustic spectra within the slat cove

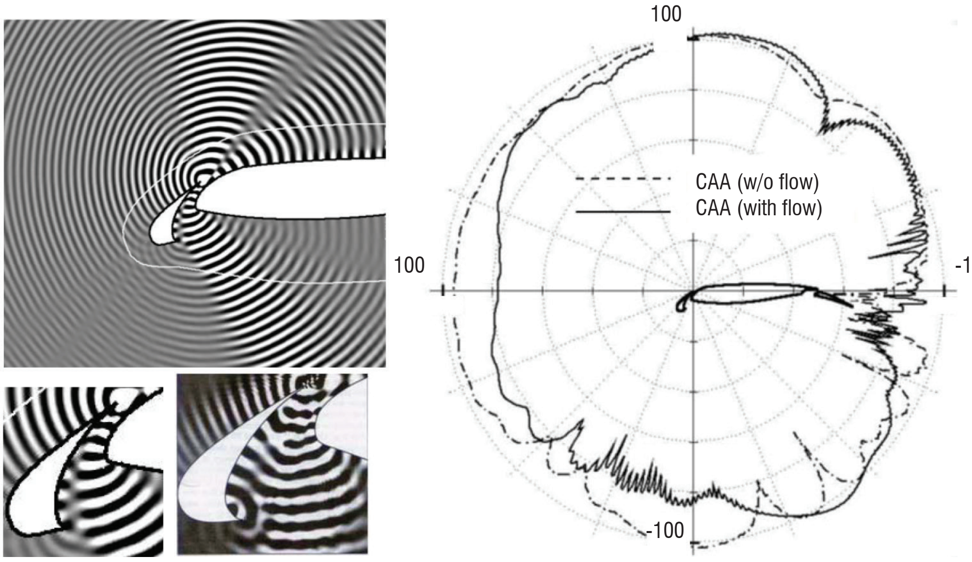

Figure 13 - Noise radiation by the slat cove trailing edge of a high lift wing at approach, as predicted by a CAA calculation based on an equivalent (analytical) source. Left side; instantaneous perturbed pressure field obtained over the domain (top) or within the slat cove (bottom left), to be compared with near-field CFD results obtained for an alternative configuration (bottom right, calculation by NASA). Right side; mid-field directivity diagram (in lines, to be compared with its quiescent medium radiation counterpart, in dashes). Reproduced from [20] with permission

Figure 13 presents the results associated with an (equivalent) noise source of 30 kHz, mimicking the acoustic emission by the slat trailing edge, due to the vortex shedding occurring at this location. As can be seen, the noise radiation patterns are very complex, resulting from the multiple interactions that occur between the acoustic waves and their environment; such interactions primarily come from the reflection/diffraction effects by the wing and the slat geometry, as was numerically highlighted here through a preliminary calculation conducted within a quiescent medium (whose results were very favorably compared to those delivered by a BEM computation, see [20]). These interactions also come from the convection/refraction effects by the associated steady flow, which were underlined here by comparison with results obtained for a quiescent medium (see right side of figure 13). Among other things, all of this leads the slat wing gap to act as an ‘acoustic focal’ device, which redirects part of the noise emission towards the ground direction in a very directive manner.

From a more methodological point of view, this study further showed the importance of accounting for realistic flows and associated refraction effects, when numerically predicting the acoustic propagation phase of airframe noise problems. This study also indirectly demonstrated the pertinence of handling such problems via a multi-stage aeroacoustic hybrid method based on *partly decoupled* CFD and CAA calculations, along with proper equivalent sources. For more details about this study and its outcomes, the reader is referred to [20].

Noise emission by truncated trailing edges, via weakly coupled CFD/CAA calculations

A few years ago, a couple of CFD-CAA weakly coupled computations were conducted, in order to assess the noise emission by airfoil truncated trailing edges; first, the numerical prediction of the noise emitted by the blunted trailing edge (TE) of an in-flight NACA0012 [35] was achieved by Manoha et al. following a 3-stages hybrid method strategy, via CFD-CAA-IM weakly coupled calculations [34, 59] (with an IM step consisting in a Kirchhoff extrapolation, see left side of figure 14).

Then, such TE noise simulation was extended to a thick plate configuration (see right side of figure 14), which was handled via a CFD-CAA weakly coupled calculation by Guenanff [22].

These studies first allowed an innovative CFD-CAA weak coupling procedure developed by Redonnet [43, 44] to be assessed and validated, in regard to its application to practical airframe noise problems. Beyond that, they also allowed specific key aspects of theoretical and methodological natures to be pinpointed, regarding the proper exploitation of unsteady CFD calculations via an acoustic-based method [34].

Lately, such aspects were addressed more thoroughly by Redonnet et al. [47, 48, 12, 13], which led to improving and optimizing the CFD-CAA weak coupling procedure, thus facilitating its application to real-life problems. As shown below, these recent works and associated outcomes helped to pave the way to the emergence of an accurate and robust 3-step aeroacoustic hybrid method.

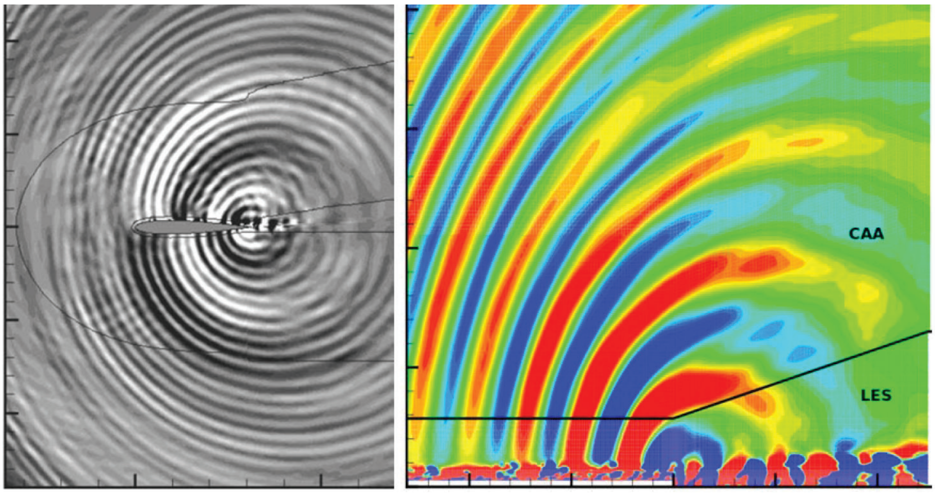

Figure 14 - Noise emission by either a blunted airfoil (left side) or a thick plate (right side) trailing edges, via a CFD-CAA-IM and a CFD-CAA weakly coupled computation, respectively. Right side image reproduced from [22] with permission

Noise emission by a facility installed tandem cylinder, via CFD-CAA weakly coupled calculations

With the view of better understanding landing gear noise sources, an experimental and numerical dual campaign was conducted by NASA Langley Research Center (LaRC), such campaign focusing on both the aerodynamics and the acoustics of a Tandem Cylinders (TC) configuration (see figure 15). To this end, extensive experimental data [24, 23] were collected, being then compared to results of CFD-IM weakly coupled computations [31] associated with a 2-step aeroacoustic hybrid method. Although such comparisons provided a very favorable experimental vs. numerical agreement, there was still concern about possible installation effects that could have been induced on acoustic data by the experimental set-up (see right side of figure 15), thus biasing such a validation exercise.

Therefore, a dedicated study was performed within the framework of a dedicated NASA-Onera collaboration*, whose objective was to numerically assess and investigate the various acoustic installation effects that could have been effectively induced by the experimental set up on the acoustic data gathered during NASA/LaRC experiments. To this end, several CFD-CAA weakly coupled calculations were conducted by Redonnet et al. [48], this being achieved through a weak coupling of (i) the CFD stage that had been performed by NASA/LaRC over the isolated TC and (ii) various CAA stages for which the TC configuration was considered as (either partly or fully) installed within the facility. All calculations relied on the so-called *Non Reflecting Interface* (NRI) [47, 54], which constitutes an improved version of the CFD-CAA weak coupling technique previously recalled, and whose non-reflective character allowed the acoustic backscattering effects that were expected to occur due to the facility devices (e.g., collector, side mounting plates, nozzle - see right side of figure 15) to be properly handled here. As an illustration, the right side of figure 16 displays the CFD-CAA results obtained for the fully installed TC configuration, which included all main devices of the facility, along with its confined and sheared jet flow.

All of these CFD-CAA calculations delivered results that were found to be closely consistent with outcomes previously acquired by NASA with the help of less advanced approaches, which either relied on the CFD-IM hybrid method previously recalled [31] or on alternative techniques (such as the so-called Equivalent Source Method, ESM – see [60]). On the other hand, compared to the latter approaches, the NRI-based CFD-CAA hybrid method allowed the fidelity of the TC noise

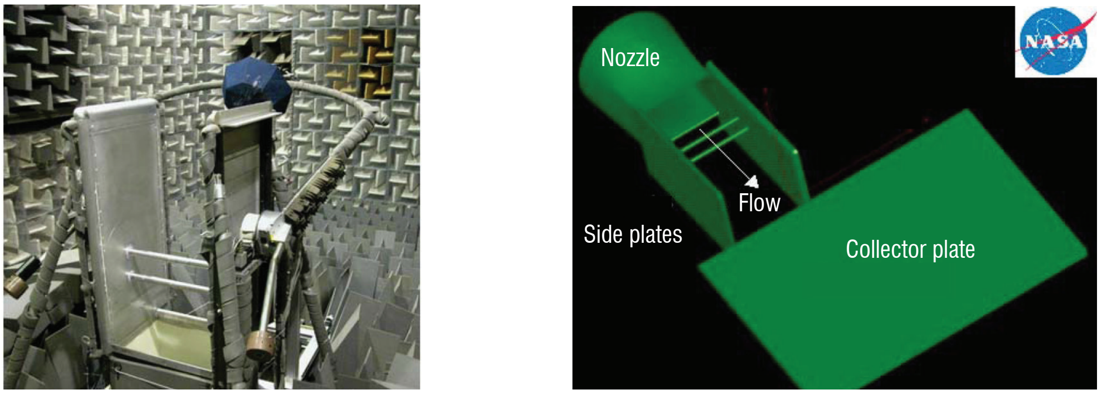

Figure 15 - Noise emission of a Tandem Cylinder (TC) installed within NASA/LaRC's Quiet Flow Facility (QFF). Left side: TC model, with some of the QFF devices (nozzle, mounting side plates). Right side: sketch of the whole installed TC set up, with all the QFF devices (nozzle, mounting side plates, collector plate). Courtesy of NASA

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* namely, the International Agreement between NASA and Onera on "Understanding and Predicting the Source of Nose Landing Gear Noise"

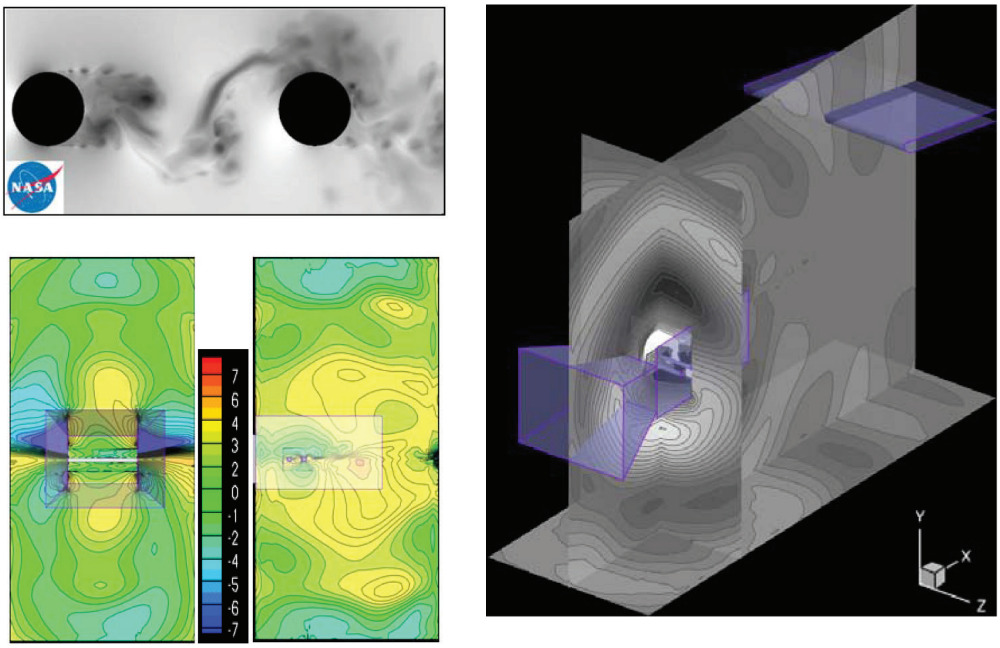

Figure 16 - Noise emission of a Tandem Cylinder (TC) installed within NASA/LaRC's anechoic facility QFF, via CFD-CAA weakly coupled computations. Clockwise, from top/left: instantaneous perturbed fields obtained via either i) the CFD calculation of the isolated TC or ii) the subsequent CFD-CAA computation of the QFF-installed TC, and iii) deltas (in dB) between the Sound Pressure Level fields associated with both configurations, as recorded in within two lateral planes (xy and yz)

propagation stage to be improved, by i) accounting for the acoustic emission that had been effectively predicted by the CFD stage (rather than by modeling it via equivalent sources, as is implicitly or explicitly done by IM or ESM techniques), as well as by ii) including the facility apparatus and associated (confined sheared) jet flow characterizing the experiment (rather than to consider a simplistic homogenous free field medium, as necessarily assumed by IM and ESM techniques).

As a result, this study primarily allowed the various acoustic installation effects that could have been effectively induced by the experimental apparatus on the acoustic data gathered during NASA/LaRC tests to be investigated (see left bottom of figure 16), highlighting not only the reflection / diffraction by the experimental set-up, but also the (partial) convection / refraction by its confined and sheared jet flow. From a more methodological point of view, the study allowed the innovative NRI-based CFD-CAA weak coupling procedure to be further assessed and validated, as well as making it possible to illustrate how far an aeroacoustic hybrid approach relying on the latter could effectively handle practical airframe noise problems involving installed configurations. More details about this work can be found in [48].

Noise emission by a nose landing gear, via CFD-CAA weakly coupled calculations

As was mentioned previously, the so-called LAGOON project [32, 33] focused on a simplified nose landing gear (NLG) in approach flight, in order to assess/validate the 2-step hybrid methodology by comparing to experiments the numerical results of CFD-IM weakly coupled calculations (see above).

Lately, such an assessment exercise was extended to the 3-step hybrid methodology, by completing these CFD-IM weakly coupled calculations with CFD-CAA ones. Here too, the objective was to further improve the fidelity of the acoustic propagation stage, by i) accounting for the acoustic emission that had been effectively predicted by the CFD stage (rather than to model it via equivalent sources, as implicitly done in the IM approach), as well as by ii) including the realistic jet flow characterizing the experiment (rather than to model it via a simplistic uniform mean flow, as is also done in the IM approach). To this end, CFD-CAA coupled calculations were conducted by Redonnet et al. [53], which were i) based on the unsteady aerodynamics data coming from the CFD computations previously achieved (see above), and ii) conducted with the help of the NRI-based CFD-CAA weak coupling technique.

First, CFD-CAA coupled calculation corresponded to an isolated NLG, that is, was allotted a computational set up similar to that of CFD-FWH computation (incorporating in particular a steady mean flow corresponding to a homogeneous free field). Such a calculation allowed the CFD-CAA outputs to be validated through direct comparison against both the numerical (CFD) and the experimental results, which had been acquired and/or processed under the same "homogeneous propagation medium" conditions*(see right side of figure 17). An alternative CFD-CAA calculation considered the NLG as installed in the anechoic wind tunnel, with a (heterogeneous) mean flow matching the sheared steady jet occurring in the facility. This alternative calculation (see left side of figure 17) made it possible to assess the sole mean flow effects that could have been induced by the facility jet on the experimental data.

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* with experimental data that had been corrected from the refraction effects by the open jet shear layers

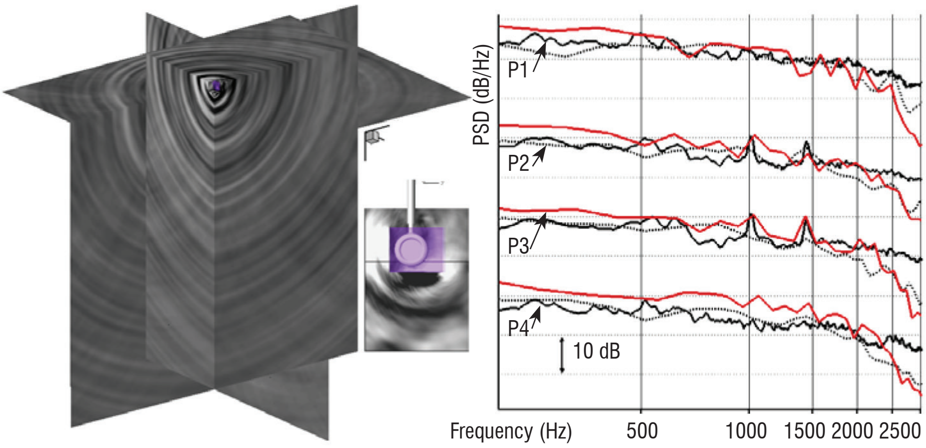

Figure 17 - Noise emission by Nose Landing Gear (NLG) installed within Onera's CEPRA19 anechoic facility, via CFD-CAA weakly coupled computations. Left side: instantaneous perturbed field radiated by the facility-installed NLG. Right side; validation of the isolated NLG calculation, via a cross-comparison of far-field results (Power Spectral Density recorded at four probes, P1-4) obtained for both the experiments (in black lines), the CFD-CAA (in red lines), and the CFD-FWH (in black dashes)

Here, it is worth mentioning that, beyond its sole applicative concerns, this study allowed the overall CFD-CAA coupled approach to be optimized further [11, 51, 12], so that it can be applied to realistic configurations in a safer and easier way. More precisely, the impact that its manipulation (sampling, interpolation, etc.) can have on an unsteady CFD dataset was studied from both a fundamental and a methodological point of view, allowing several innovative solutions to be proposed (including (i) specific guidelines for the preservation of aeroacoustic signals [13, 14], (ii) a novel interpolation method [10, 15] and (ii) a new class of finite difference derivative schemes [16]). Based on this, the CFD-CAA hybrid methodology was enhanced with key improvements (methodological guidelines, advanced methods, etc.), so that it can cope with all stringent constraints that are dictated by real-life problems without being jeopardized by some of their unavoidable side-effects (CFD data manipulation, acoustic signal degradation, etc.). For additional details about this work, the reader is referred to [53].

Conclusion and perspectives

This article focused on the so-called aeroacoustic hybrid approach, whose ultimate objective is the numerical prediction of realistic aircraft noise problems. More precisely, here, we recalled some of the efforts deployed over the last decade at Onera to improve aeroacoustic hybrid methods, through both the development of computational tools and their subsequent application to practical problems of aircraft noise.

With that view, it was first recalled here what aeroacoustic hybrid methods are about, whether the latter methods are composed of two or three stages. Their potentialities were then highlighted through various examples of application to practical problems of engine or airframe noise.

All this illustrates well the facts that i) two-stage aeroacoustic hybrid approaches (which rely more on Integral Methods) have now became the most popular means for numerically predicting the noise emission by aircraft components, whereas ii) their three-stage counterparts (which rely more on Computational Aeroacoustics techniques) now offer an even more promising alternative, thanks to the higher fidelity that they bring to the propagation phase of the hybrid scenario. Therefore, it turns out that, at the present date, aeroacoustic hybrid approaches constitute the best viable alternative to Direct Numerical Simulation, which is known to be inapplicable to industrial problems because of the excessive CPU time and memory requirements that it involves.

One can thus expect to see aeroacoustic hybrid approaches being more and more intensively applied to aircraft noise problems over the coming years. At that stage, there is no doubt that Onera will play a key role in helping these advanced noise prediction methods and underlying techniques to flourish within industrial environments ■

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Acronyms

AITEC	French national project (supported by DGAC) devoted to jet aeroacoustics)
BEM	Boundary Element Method
BPF	Blade Passing Frequency
CAA	Computational AeroAcoustics
CEDRE	Onera's CFD solver (unstructured approach)
CEPRA19	Onera's anechoic facility
CFD	Computational Fluid Dynamics
CROR	Counter-Rotating Open Rotor
dB	Decibel
DES	Detached Eddy Simulation
DGM	Discontinuous Galerkin Method
DLR	German Aerospace Center
DNS	Direct Numerical Simulation
DNW	German-Dutch Wind Tunnels
*els*A	Onera's CFD solver (structured approach
ESM	Equivalent Source Method
F2	Onera's aerodynamic facility
FWH	Ffowcs-Williams & Hawkings
IM	Integral Method
KIM	Onera's IM solver
kHz	Kilohertz
LAGOON	Transantional project (supported by Airbus), devoted to landing gear aeroacoustics
LaRC	Langley Research Center (NASA)
LES	Large Eddy Simulation
NACA	Airfoil profile geometry
NASA	National Aeronautics and Space Administration (USA)
NLG	Nose Landing Gear
NLR	Dutch National Aerospace Laboratory
NRI	Non Reflecting Interface
Pa	Pascal
PSD	Power Spectral Density
Q-criterion	Positive 2nd invariant of Jacobian
QFF	NASA/LaRC's anechoic facility
RANS	Reynolds Averaged Navier-Stokes
RFN	Rear Fuselage Nacelle
R&D	Research & Development
sAbrinA	Onera's CAA solver (structured approach)
St	Strouhal number
TC	Tandem Cylinder
TE	Trailing edge
uRANS	Unsteady RANS
ZDES	Zonal DES

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