The state of aeroacoustics modelling: challenges and trends

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Abstract. Modelling and simulation of aeroacoustic phenomena has progressed massively since the introduction of Lighthill's analogy. New simulation methods and larger access to computational power allow large corporations in the automotive and aerospace sector to tackle problems such aircraft exhaust noise, side mirror noise, HVAC (Heating, Ventilation, and Air Conditioning) noise. On one side, the aeroacoustic community is very active on improving the accuracy and maturity level on these applications; on the other side, the community looks as well to new technologies which would be better suited to tackle markets which have a larger variety of products and combination of system which are not affordable at reasonable cost with combined unsteady flow and acoustic simulations. A representative important market for the last category is electronics where the combination of components and cooling fans are almost infinite. Challenges such as better fan noise prediction, complete system simulation including structures and acoustic treatments and high frequency accuracy will require new methods and workflows to be part of the design process of engineering companies. This paper will perform an overview of the aeroacoustic modeling techniques and methods, discuss the challenges that companies are facing when using aeroacoustic simulation, address the gaps in processes for making aeroacoustic simulation more accessible and examine the trends for the decades to come.

Keywords: Aeroacoustics, Acoustic analogies, FEM.

1 Industrial aeroacoustic context

In recent reports, World Health Organization has quantified traffic noise pollution as one of the biggest pollutions impacting the health of humans in the surrounding. The noise issues are therefore a big constraint on the growth of the transport sector and might limit the deployment of new mobility solutions like drones or eVTOL as they will increase the population being affected by these new sources.

The industry has been highly active considering the acoustic comfort of new products emerging on the market as a top priority. This includes a comprehensive understanding of the noise sources and their propagation mechanisms and a design which reduces the sources or damps the propagation. These efforts focused on the dominant noise sources as thermal engines, allowing to increase the traffic without increasing the global noise level in cities.

However, to further reduce the overall noise level, the industrial designs now target a reduction of other sources unveiled once the dominant noise source were reduced such as tire noise, cooling fan noise, e-motor noise, side mirror noise. These noise problems are current challenges for acoustic engineering teams to address. These sources are triggered by mechanisms with several interaction levels. Aeroacoustics typically represents this class of problems, where the flow turbulences generate the noise sources, producing acoustics waves that may trigger the creation of new turbulent structures (self-noise) or may induce some surface vibrations requiring the use of a coupled structural-fluid-acoustic approach.

This paper will review different levels of assumptions, leading to different numerical solutions to tackle aeroacoustic problems in general highlighting the advantages and limitations of each approach. In the paper's later part, numerical techniques more appropriate for broadband noise predictions in industrial context have been discussed with examples.

2 Direct methods

Acoustics is part of the flow solution and satisfies the compressible Navier-Stokes equations. Both the flow turbulence and acoustics are solved simultaneously in a CFD (Computational Fluid Dynamics) solver, but the associated length and time scales are very different:

- Acoustics propagates over large distance (several wavelengths) at the speed of sound $c = {}^{v}/_{M}$ where v is flow velocity and M is the Mach number
- Turbulent eddies are convected with the mean flow and decay very rapidly over the distance.

Based on this difference of length and time scales, the computational cost scales as Re^3/M^4 where Re refers to Reynolds number and M refers to Mach number. Acoustics is also a very small amplitude pressure fluctuation (80dB would lead to 0,2Pa pressure fluctuation which is several orders of magnitude compared to the fluctuations driving the mean flow) and is therefore complex to capture accurately in full unsteady compressible Navier-Stokes solution.

So, for applications involving high Reynolds number and low Mach number application such as side mirror noise in automotives, the computational cost is huge and is not appropriate for industrial applications even with current computational resources. Apart from these, the acoustic pressure fluctuations are much smaller in magnitude compared with aerodynamic or turbulent pressure fluctuations. This requires less dissipative spatial schemes to properly solve for acoustic fluctuations.

3 Hybrid approaches

Hybrid approaches for computational aeroacoustics (CAA) typically refers to an approach where we decouple source generation and acoustic propagation into two different steps. For low Mach number flows, these approaches are very efficient as the computational cost is reduced and optimized (flow and acoustic solver are operating one after each other in the most efficient configuration). This approximation facilitates addressing CAA problem with a reasonable computational cost for low Mach number industrial applications compared with direct approaches. The separation is valid unless the acoustics interact strongly on the flow like close to shallow cavities that could create resonance impacting the fluid flow.

Following the original developments of Lighthill [1], several methods differ by the propagation part in the left-hand side and the source terms in the right-hand side. The region where the right-hand side is active is called the source region. The solution will fit to acoustics outside this region where the acoustic propagation matches the operator found in the left-hand side. As example, we reproduce in this section the derivation of Lighthill to illustrate the mathematical process and the underlying assumptions:

$$\frac{\partial^2 \tilde{\rho}}{\partial t^2} - \frac{\partial}{\partial x_i}\left(c_0^2 \frac{\partial \tilde{\rho}}{\partial x_i}\right) = \frac{\partial^2 \tilde{T}_{ij}}{\partial x_i \partial x_j} \quad (1)$$

, the term $\widetilde{T_{ij}}$ is the well-known Lighthill stress tensor given by

$$\tilde{T}_{ij} = \tilde{\rho} u_i u_j + (\tilde{p} - c^2 \tilde{\rho})\delta_{ij} - \sigma_{ij} \quad (2)$$

The right-hand side of Eq.1 represents the sound created by vortical motion of the fluid itself given by the first term $\tilde{\rho} u_i u_j$, the non-linear acoustic generation effect caused by deviations from adiabatic changes of state included in $(p - c_0\, \rho)\delta ij$ where c_0 is the speed of sound and the sound generation by shear represented by σ_{ij}. For a Stokesian perfect gas, in an isentropic, high Reynolds number and low Mach number flow, the Lighthill's stress tensor can be approximated to $\tilde{\rho} u_i u_j$.

3.1 Hybrid approach based on integral methods

To solve the equation derived in the section above, Lighthill, proposed an integral solution based on Green's function, denoted by G in the present section:

$$\rho_a(\vec{x}) = \int_V G(\vec{x}, \vec{y}) \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} dy^3 - c^2 \int_S \rho_a(\vec{y}) \frac{\partial G}{\partial n} - G \frac{\partial \rho_a}{\partial n} dy^2 \quad (3)$$

Where the Green's function $G(\vec{x}, \vec{y})$ is the solution at $\vec{x}$ due to an impulse in $\vec{y}$. To simplify the explanation, the formula (3) does not show the time dependence and the notion of retarded time. A variety of Green's function differs depending on the value on the boundaries of the problem:

- Tailored Green function satisfies $\frac{\partial G}{\partial n} = 0$ on the surface where density should be imposed and $G = 0$ on the boundaries where normal derivative of the density should be imposed, cancelling completely the boundary integral in equation. This Green's function is related to the boundaries of the problem and in general as complex to compute as solving the original problem and not used in practical applications.
- Free field Green's function is an analytical solution which vanishes in the infinity and is an easy valid choice which requires to compute the boundary integrals, leading to an implicit form (the density unknown is located in both sides of the integral equation) requiring to be solved for instance by a boundary element method (BEM). As the BEM technique creates dense algebraic systems, complex to invert, the method suffers an important computational penalty for large frequency or big problems.

As Lighthill focused on jet noise problem, the boundary integrals vanished as no near field surface were considered. Later, many researchers extended the Lighthill analogy to account additional effects like inclusion of solid boundaries performed by Curle [2]. In his study, the influence of solid boundaries is manifested by a dipolar distribution proportional to the force exerted by the solid boundary on the fluid per unit area. In the works of Ffowcs Williams and Hawkings [3], the effect of arbitrary motion of surface is included. In their approach, when both the bounding surfaces and the turbulence are compact relative to the radiated length scales, the turbulence is acoustically equivalent to a volume distribution of moving quadrupoles and the surfaces to dipole and monopole distributions.

All the above strategies relied on the use of Green's function to solve the propagation equation. In most industrial problems, due to the presence of ducts, walls that impact noise propagation, the boundary integrals should be taken into account, leading to additional complexity (implicit formulation to be solved by a BEM technique).

The volume contribution is the only one remaining in tailored Green's function, showing that physical turbulent noise source is the volume contribution $\frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$. The boundary contributions are mathematical artefacts to take into account the presence of surface according to the selected mathematical formulation.

3.2 Hybrid approaches based on FEM techniques

To overcome the shortcomings of previous approaches and to facilitate the study of acoustic propagations in more complex acoustic environment, approach based on a Finite Element Method (FEM) is used to derive a frequency domain solution of the

Lighthill equation as detailed in Eq.4. In the FEM formulation, right hand side includes a volume contribution corresponding to the aeroacoustic sources present in the computational domain and a surface integral accounting for all sources present upstream and convected through a permeable boundary where normal flow velocity is non-zero.

$$\omega^2 \int_V N_a \rho dV - \int_V \frac{\partial N_a}{\partial x_i} c_0^2 \frac{\partial \rho}{\partial x_i} dV = i\omega \oint_S N_a \rho v_i n_i dS + \int_V \frac{\partial N_a}{\partial x_i} \frac{\partial T_{ij}}{\partial x_j} dV \tag{4}$$

where:

- ω is the angular frequency
- v_i is the i[th] component of the velocity
- ρ is the acoustic density fluctuation
- N_a is the finite element shape function
- $\widetilde{T_{ij}}$ is the Lighthill tensor

In this work, FEM method implemented in Actran software package are discussed where aeroacoustic source on right hand side of the equation is computed based on CFD data in source region. The volume contribution provides the noise generated by all turbulent noise sources present in the domain. The surface contribution differs from the Curle's solution and accounts for the presence of walls, impedance, or any other source exterior to the domain which needs to be supplied to the system.

The difference with respect to Curle's integral solution is the weighting functions as the Free field Green's function is used by Curle, while Galerkin shape functions are used in FEM. The source computation for this method is completely independent from acoustic propagation analysis, and this facilitates the use of incompressible CFD for source generation and as well different types of CFD inputs can be utilized as discussed in the following sections. Additional advantages of using FEM technique for acoustic propagation include modelling complex damping phenomena due to presence of absorbing material and coupling with structure vibration to study the impact of noise transmission loss.

Aeroacoustic source generation based on unsteady CFD data

The first approach is based on source computation using unsteady CFD that relies on turbulence modelling techniques like Large Eddy Simulations (LES), Detached eddy simulation (DES) etc. This approach had demonstrated very good correlation with measurement data (absolute comparison). It is necessary to properly account the right source region where high turbulent energy is expected and should ensure that CFD is refined enough to capture turbulent sources up to target frequency. In general, smaller eddies are responsible for higher frequency noise contributions, it is required that all small turbulent scales corresponding to the maximum frequency are resolved with good accuracy to generate a realistic noise source. As proposed in [4], the so-called mesh cut-off frequency (maximum frequency accurately resolved by a CFD mesh in LES simulation) is compared for 2 different meshes.

Hence in this workflow, it is crucial to identify the cut-off frequency of CFD mesh till which turbulence is properly resolved as illustrated in Fig.1 before launching LES simulation and this can be achieved using the relation provided in Eq.5 based on first RANS solutions.

$$F_{cut-off} \approx \varepsilon^{1/3} \times \Delta_x{}^{-2/3} \qquad (5)$$

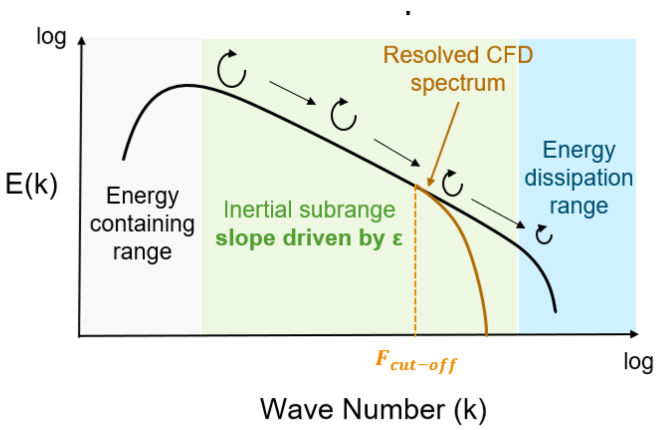

Fig. 1. Illustration of energy cascade and resolution in LES simulations.

Based on the RANS solution and CFD mesh, it is possible to detect the cut-off frequency of provided mesh using the tool implemented in Actran software. In the example illustrated in Fig.2, cut off frequency map detected for the CFD mesh for side mirror application is shown. It is crucial to ensure that in the main source region, the cut-off frequency is equal to or above the target frequency for acoustic solutions. To ensure this, turbulent kinetic energy map is used to ensure that CFD mesh is refined enough for targeted frequency in the region where high turbulent kinetic energy is observed.

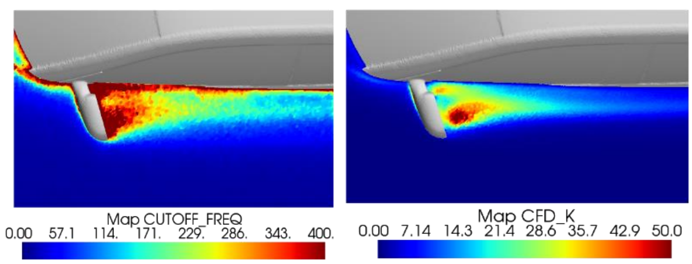

Fig. 2. Example of cut-off frequency map and associated CFD turbulent kinetic energy map for side mirror noise application

Aeroacoustic source generation based on steady CFD data

Despite the previous approach helps to reach accurate predictions with reasonable computational cost compared with direct approaches, relying on unsteady CFD for source generation could still be computationally expensive to iterate on multiple designs at the beginning of product development. At this design stage, the CFD simulations should be computationally cheaper while still providing correct predictions between different flow designs on a relative scale. A steady Reynolds Averaged Navier-Stokes solution (RANS) meets these requirements. As the acoustics are sensitive to time fluctuations, the frequency content needs to be synthetized for sources computed from RANS solution. The Stochastic Noise Generation and Radiation (SNGR) method implemented in the commercial software Actran is based on Fourier modes representation of turbulent velocity fluctuations and relies on the theory proposed by Bailly et al. [5].

The turbulent velocity is given by the following relation:

$$u'_i(x_j,t) = 2\sum_n \tilde{u}^n \cos\left(K^n k_j^n\left(x_j - U_j^C t\right) + \varphi^n + \omega^n t\right) \sigma_n^i \tag{6}$$

where,

- $\tilde{u}^n = \sqrt{E(K^n)\Delta K^n}$ with $E(K^n)$ the turbulent energy density spectrum
- U_j^C is the local mean velocity of the flow obtained from RANS
- ω^n is the angular velocity of the n^{th} mode
- σ_n^i is the orientation vector of the n^{th} mode with a random direction angle
- φ^n is the stochastic phase angle

The turbulent field is supposed to be incompressible, leading to some additional constraints on the random numbers. The turbulence spectrum $E(K^n)$ is derived from experience or from knowledge of the configuration.

$$E(k) = A\frac{2}{3}\frac{K}{k_e}\frac{\left(\frac{k}{k_e}\right)^4}{\left(1+\left(\frac{k}{k_e}\right)^2\right)^{\frac{17}{6}}} e^{-2\left(\frac{k}{k_\eta}\right)^2} \tag{7}$$

where

- k is the wave number;
- K the local Turbulent kinetic energy value;
- $k_\eta = \varepsilon^{1/4}\, \nu^{-3/4}$ is Kolmogorov wave number;
- k_e is the wave number corresponding the most energetic eddies;
- A is a scaling factor to satisfy the definition of $K = \int_0^\infty E(k)dk$.

In the study made by Cabrol et. al.,[6] using SNGR approach for side mirror noise applications, very good correlation of acoustic trend has been observed with measurements and acoustic solution predictions based on LES approach. Different parameters involved in SNGR source prediction were discussed in this study. One of the advantages of this approach is that there is no limitation for maximum frequency based on CFD cell size unlike the approach based on LES method. It would help to attain acoustic prediction with much less computational cost for quick iterations for multiple designs.

Both the above approaches discussed based on RANS and LES based flow simulations are complementary processes targeting different objectives. The steady flow based aeroacoustic sources are dedicated to relative comparisons for a preliminary and fast pre-design, whereas the unsteady flow based aeroacoustic sources will be used afterward to assess accurately the absolute level of the acoustic pressure field for the most promising configuration. The first approach based on steady CFD simulations is expected to have computational time of the range of few hours for the complete workflow, whereas the latter approach could range from several hours to few days, with most amount of computational time is due to unsteady CFD simulation.

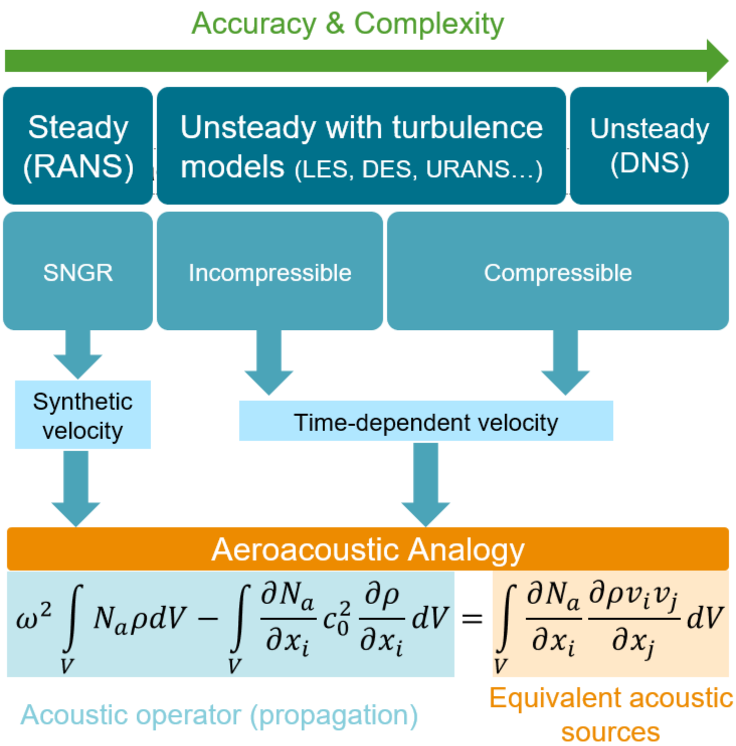

Fig. 3. Workflow for hybrid aeroacoustic source computation based on steady and unsteady CFD solutions.

4 Conclusions

In this paper, different numerical techniques to tackle aeroacoustic problems were discussed with relevant theoretical information to discuss the advantages and limitations. Hybrid approach for computational aeroacoustics is the most preferred method to address current aeroacoustic challenges in the transport industry. Earlier, integral solution based on Green's functions were used, however due to its limitation to represent properly acoustic propagation in complex environment, techniques based on FEM are used to address industrial aeroacoustic problem.

Depending on the design stage of the product, approach based LES solutions for aeroacoustic source computations can be used to achieve absolute results to be compared with measurements during the final stage of design cycle. Whereas SNGR approach can be helpful to compute aeroacoustic source based on steady state CFD solution to quickly rank different configuration based on relative comparison during early stage od design cycle. This approach also helps to extend the solution to higher frequencies without any limitation of cut-off frequency as in former approach.

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