24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

EFFICIENT METHOD FOR CAR EXTERIOR NOISE PREDICTION BASED ON STEADY CFD INPUT

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The numerical methods to solve aeroacoustic problems requires as input data an accurate description of the turbulent flow inducing the noise sources. Typically, unsteady CFD simulations is used to feed aeroacoustic code. Unfortunately, the CPU cost associated to such CFD simulation is incompatible with automotive industry time scale, especially if multiple designs must be evaluated. At a design stage, the CFD simulations should be computationally less expensive while still providing good estimates and correct comparisons between different flow designs.
The time averaged (RANS) solutions fit to this last requirement and are generally already available for other selection criteria (aerodynamics, thermal). In this paper, the authors present a stochastic method which synthesize several realizations of turbulent sources fitting to the statistics output by the RANS simulation. These sources are then injected in an acoustic propagation solution, providing the averaged acoustic solution and the variance of the turbulent noise in a limited time frame. In this paper, the SNGR method available in Actran commercial package is used to demonstrate the benefits of the approach in the framework of an industrial design. The results are calibrated and compared to high fidelity unsteady flow simulations.

Keywords: Aeroacoustic, exterior noise, side mirror noise, SNGR

1. Introduction

Following the definition of aeroacoustics, noise sources exist in the presence of unsteady flows and aerodynamic forces. Therefore a computation of aeroacoustics (CAA) first starts with a computation of fluid dynamics (CFD) and requires an unsteady aeroacoustic excitation.

Unsteady compressible CFD solutions provide access to the pressure fluctuations, which are accurate for acoustic purpose if the set-up is designed to capture acoustic fluctuations accurately. In an industrial framework, this process can be human time and resources consuming. Moreover, it is limited to a maximal frequency first driven by the cut-off frequency of the unsteady CFD (frequency above which the unsteady structures are no longer resolved) and by the propagation speed of the acoustics which is much bigger than the local flow velocity in subsonic applications.

The hybrid methods, solving the unsteady turbulent flow first and the acoustic propagation in a separate solver are more appropriate, because they reduce the constraints and the computational cost to resolve the acoustic field. However, the CPU cost associated to such the unsteady CFD simulation is incompatible with industrial time scale, especially if multiple designs must be evaluated.

At a design stage, the CFD simulations should be computationally less expensive while still providing good estimates and correct comparisons between different flow designs. RANS based flow simulations fulfil the requirements to shorten the design cycle and test a maximum number of different aerodynamic concepts.

In the present paper a stochastic method is used to synthesize the time dependence of the exterior aeroacoustic sources based on RANS input. The first section recalls the main theoretical aspects. Then, as example, the paper focusses on the wind noise modelling. It introduces the numerical model and process used to solve the exterior acoustic field starting from the preliminary work accomplished in 2015 [6]. Then, the last part of the paper is devoted to the comparisons of the results and performances to the numerical results obtained with a LES based flow simulation and the experimental measurements, performed in a wind tunnel.

2. Stochastic Velocity Generation

The stochastic noise method developed in this paper is based on Fourier modes representation of turbulent velocity fluctuations. The approach considered in this paper is based on the work of Bailly et al. [4].

The turbulent velocity is given by the following relation:

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

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 and discussed in [4].

The turbulence spectrum $E(K^n)$ is derived from experience or from knowledge of the configuration. In the present paper, the von Karman-Pao spectrum is used as illustrated in Figure **1**:

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

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 $K = \int_0^\infty E(k)dk$.

The current implemented procedure in the commercial software Actran requires to feed the model with:

1 A CFD RANS computation for macroscopic turbulence parameters (mean flow fields, turbulent kinetic energy and turbulent dissipation rate),
2 A number of modes representing the turbulent spectrum.

As turbulence is not a deterministic process, several realizations of the synthetic velocity field are generated to compute the aeroacoustic sources for the acoustic simulation.

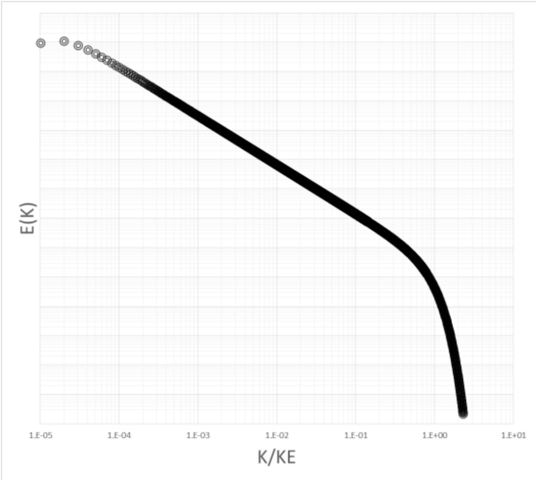

Figure 1 : Von Karman-Pao Turbulent Energy Density Spectrum

3. Case Study

The statements presented in previous section are now applied to a real case application. The configuration is similar to the one already investigated in 2015 [6] (see Figure **2**) with unsteady CFD results. A car is rolling at 140km/h (Mach number 0.114). The exterior acoustic propagation is considered and the acoustic response is recorded at 4 probes locations.

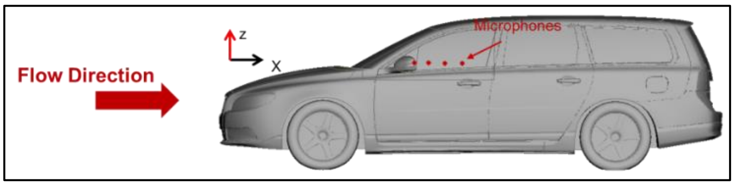

Figure 2. Geometry of the car and intensity probes location

The acoustic intensity along the Y axis is the variable of interest. Comparisons are performed with the numerical results obtained with a LES based flow simulation and validated against experiments conducted in a wind tunnel. The CFD mesh is refined close to the side mirror to have a better flow resolution in this region and provide a good input for the aeroacoustic simulation.

4. Numerical Set-up

4.1 Numerical process overview

A coupled CFD/CAA computational sequence based on the Lighthill analogy is used, following the original idea of Lighthill [1]. The noise radiated is computed using a hybrid method where the unsteady velocity field is synthetized following the stochastic noise method described above.

The SNGR approach relies on a three-steps procedure:

1. The mean flow is computed by solving the Reynolds Averaged Navier-Stokes equations (RANS) in a CFD solver. The mean flow and turbulent statistics are exported at the end of the computation and used as input for the second step.
2. The turbulent velocity field is synthesized to compute the aeroacoustic sources in the Actran SNGR module.
3. The propagation around the side mirror in the frequency domain, is then ensured by the Actran Aero-acoustic solver.

The finite element formulation developed in the commercial software Actran was originally suggested by Oberai in [2]. The theory and equations have been extensively described in [3]. An experimental validation of the strategy to predict the car acoustic exterior field was done in [6], where the authors also highlight the influencing parameters for an accurate prediction at a limited CFD cost.

4.2 Description of the Aero-Acoustic Simulation

4.2.1 Hydrodynamic Setup

The CFD model is built and solved with ANSYS Fluent. The mean flow field and turbulent statistics are computed using a RANS type simulation combined to a k-ε turbulence model. The steady solution is exported at the end of the RANS calculation over the complete CFD domain (as illustrated in the left image of Figure **3**) in the ANSYS Fluent native format. However, only a sub-part of the CFD results are read and used by Actran to generate the unsteady velocity field and compute the SNGR sources (as illustrated in the right image of Figure **3**).

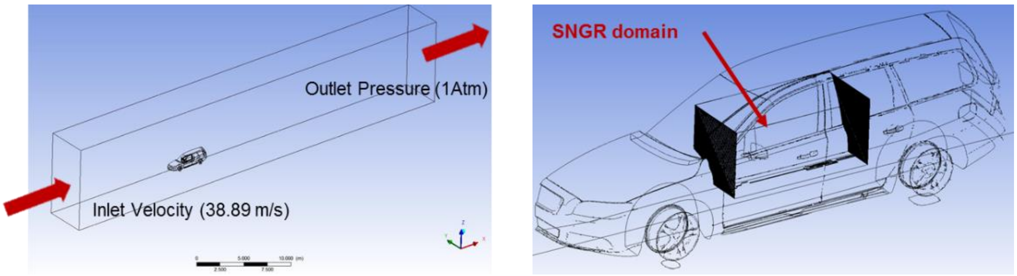

Figure 3. CFD set-up and domain of the SNGR sources computation

The size of the sub-box follows the best practices rules defined in [6]. In addition, the mesh is refined in this zone compared to the rest of the CFD domain (4mm is considered).

4.2.2 Exterior Aero-acoustic Setup

The exterior aero-acoustic model has been extensively described in [6] and is subdivided in three parts, as illustrated in Figure **4**:

1. A source zone: Where the Actran SNGR module will compute the aeroacoustic sources.
2. A buffer zone: Zone without sources acting as a buffer region before applying the non-reflecting boundary condition.
3. A non-reflecting boundary condition: The buffer region is bounded by a PML layer whose benefits in combination to the PARDISO solver have been demonstrated against infinite elements for other exterior acoustic studies [5]. It ensures a free propagation and the prediction of the acoustic solution in far field for a reduced cost.

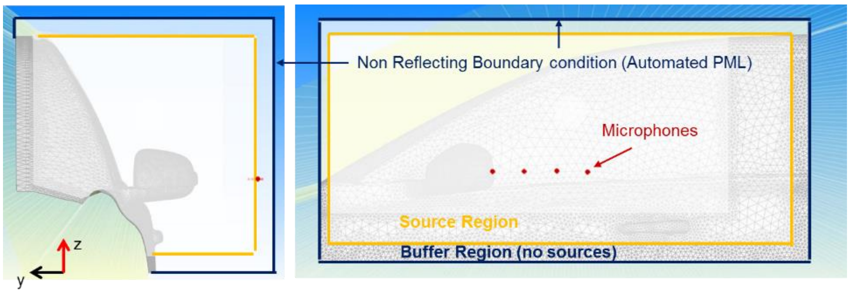

Figure 4. Actran Aero-acoustic set-up

The computational time per frequency has been reduced by a factor 3, and a gain of 50% was observed on the memory consumption compared to the model using infinite elements in [6]. Thanks to these last improvements, for the same accuracy level, the aeroacoustic propagation can be solved fully In-Core with the Automated PML and the PARDISO solver in 10min (using 5 threads) per frequency for a peak memory consumption of 50GB.

To prevent any source truncation at the end of the acoustic source domain a weighting function is applied during the acoustic propagation step to smoothly damp the sources before reaching the buffer region.

The SNGR module provides several realisations of the source field which are handled simultaneously by the acoustic solver using a multiple load analysis. The acoustic intensity is averaged over the different realisations.

5. Influence of SNGR parameters

5.1 Focus on high turbulent zones

To improve CPU usage and memory, the synthesis of turbulent velocity field is reduced to the CFD cells with the most important energetic turbulent contributions. The selection is automatic and based on the threshold level provided by the user.

The average intensity in dB over the four intensity probes is compared in Figure **5** for different selection level.

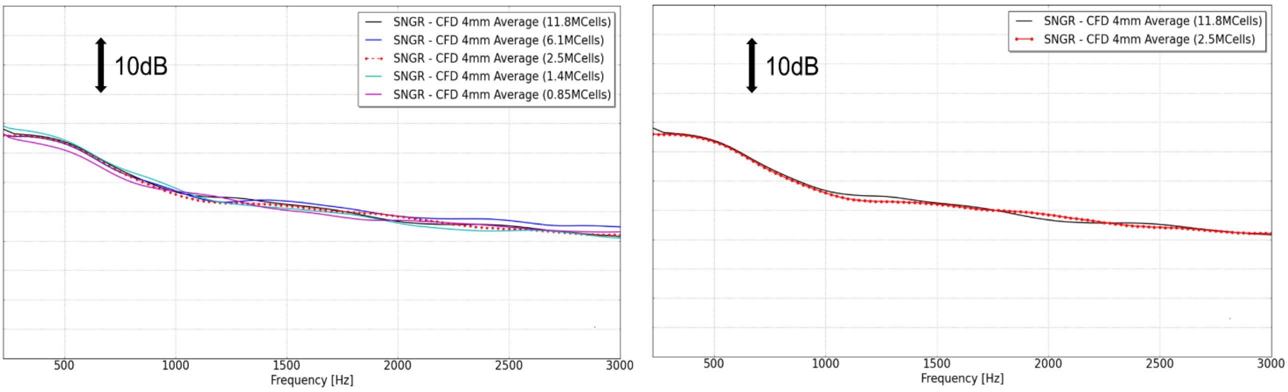

Figure 5. Average Acoustic Intensity in dB for several turbulent thresholds

The curves show a maximal absolute difference of 2dB between the results. An illustration of the turbulent zones considered for the computation of the turbulent sources is presented in Figure 6 for the 2.5MCells model, and mapped in the plane section of the intensity probes.

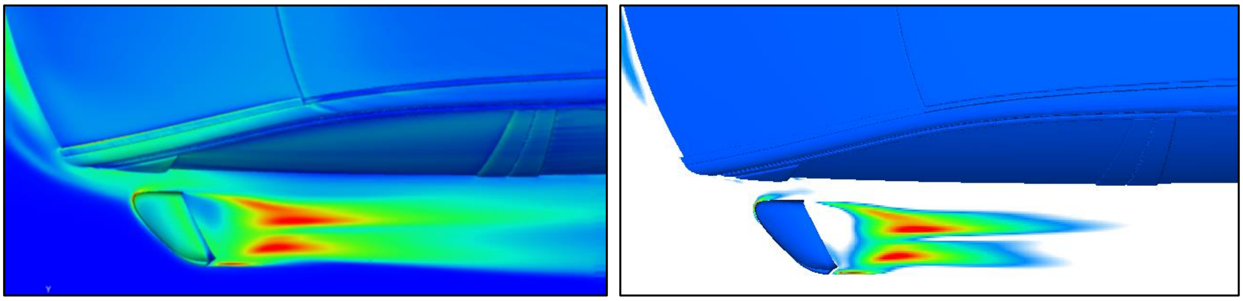

Figure 6. Map of the TKE field in the microphone plane. Before VS After Threshold

The performances for the generation of 1 realisation of the turbulent sources are reported in Table 1. They are obtained with a 2x Intel(R) Xeon(R) CPU E5-2697 v4 @ 2.30GHz processor using 8 threads.

Table 1: Performance Review of the SNGR calculation

Number of CFD Cells (MCells)	11.8	6.1	2.5	1.4	0.85
Computational time per Realization	4h30	2h25min	55min	33min	20min
Memory Consumption	117GB	68GB	36GB	27GB	23GB

The SNGR set-up based on 2.5MCells already provides a good level of accuracy as shown in the Figure **5** (right) for a highly reduced computational cost. In addition, as the curves are smooth with respect to the frequency, the frequency step could be increased to 50Hz (factor 2), reducing the computational time per realization to 30min for the 2.5MCells configuration.

5.2 Convergence of the random process

Several realisations of the aeroacoustic sources are generated by the different sets of random numbers in the SGNR formula. The acoustic results based on these different realisations are averaged. This section focus on the convergence rate of the acoustic results in order to define the minimum number of realisations required to get a satisfying accuracy level. The 1.4MCells configuration is used to reduce the computational cost. The convergence of the average acoustic result for different number of realizations is presented in Figure **7**.

The main differences are observed at low frequencies where the turbulent structures are larger and have a better acoustic radiation efficiency.

A numerical convergence of the random process is however observed between the different tests. The absolute difference between each configuration indeed reduces while the number of loadcase increases. The maximum error observed at 500Hz is 3dB between 20Loadcases and 60Loadcases.

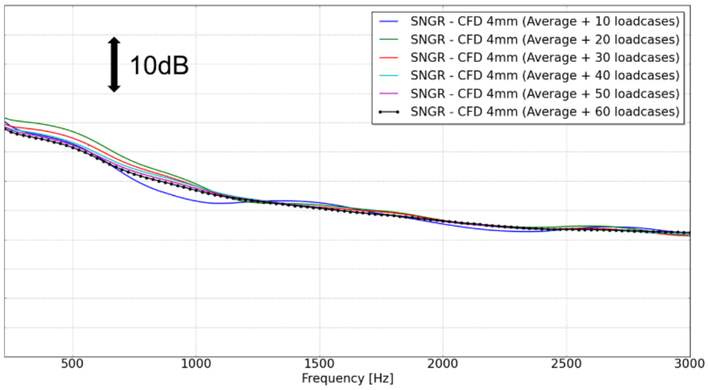

Figure 7. Convergence of the acoustic intensity in dB Vs number of realizations

As the computational time increases linearly with the number of realizations to compute, the cost associated to the SNGR process is fixed by the maximal error level tolerated. 30 loadcases can be chosen to target 2dB of error. 40 loadcases and further can be preferred to target less than 1dB of error.

5.3 Refinement of the CFD mesh

The turbulent threshold and the number of source realization are fixed in this section to respectively the same absolute level and 30loadcases. The comparison of the acoustic results for 2 different CFD mesh refinements (2mm and 4mm) is illustrated in Figure 8.

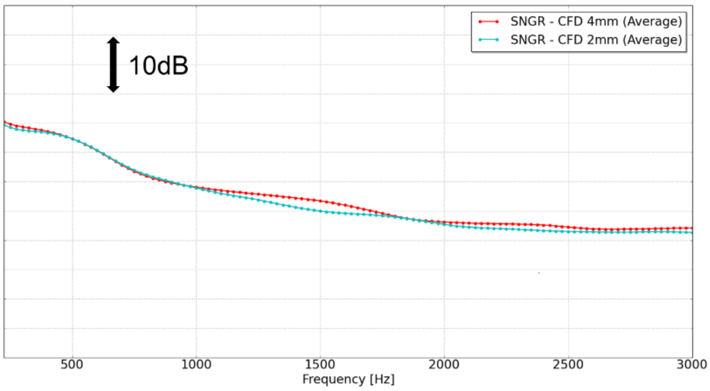

Figure 8. **.** Average Acoustic Intensity in dB for different CFD mesh refinement

Conversely to the LES based flow results, the SNGR prediction is not sensible to the refinement of the CFD mesh. The cut-off frequency predicted in [6] is not a determinant criterion for RANS based flow prediction to reach high frequencies. Indeed, the stochastic noise method provides a frequency content based on the spectrum defined for the application and does not rely on velocity fluctuations resolved on the CFD mesh as for unsteady flow simulations. The convergence of the mean flow and turbulent statistics on the mesh is the only requirement for these applications as for aerodynamic computations. The 4mm CFD mesh already provides a good level of convergence, as illustrated in Figure 9.

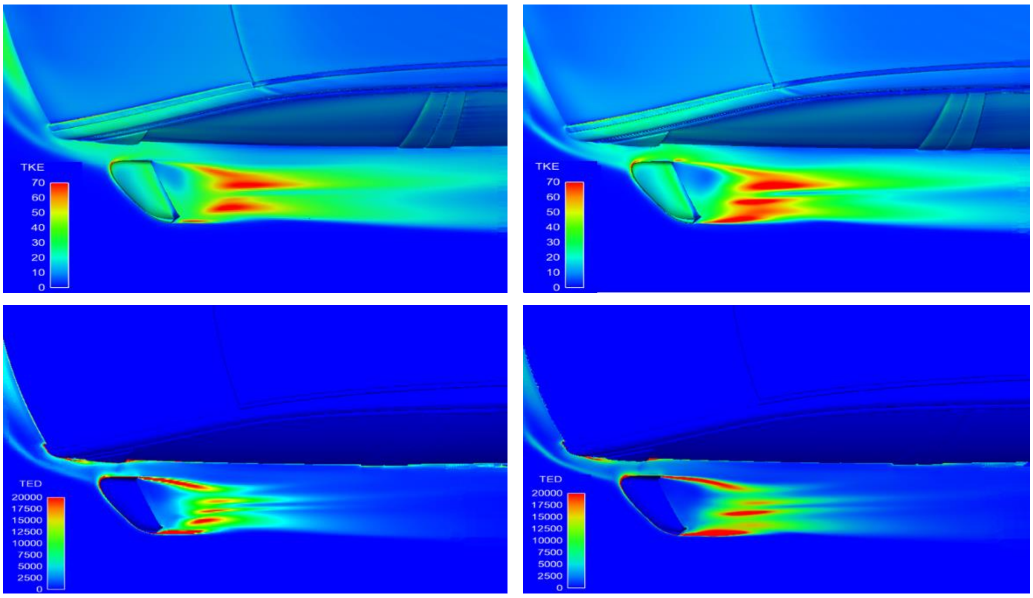

Figure 9. Map of the Mean Turbulent Fields for 2mm (left) and 4mm (right) in the microphone plane – Top: Turbulent Kinetic Energy - Bottom: Eddy Dissipation Rate

6. Acoustic Results Validation

The SNGR prediction are now compared to the LES based flow results and the experiments. The RANS results are obtained with the 4mm CFD mesh. The turbulent threshold and the number of source realization are fixed respectively to respect 2.5MCells and 30loadcases. To better highlight the impact of the method on the acoustic results, the average intensity in dB over the four intensity probes is illustrated in Figure 10 per 1/12 octave bands.

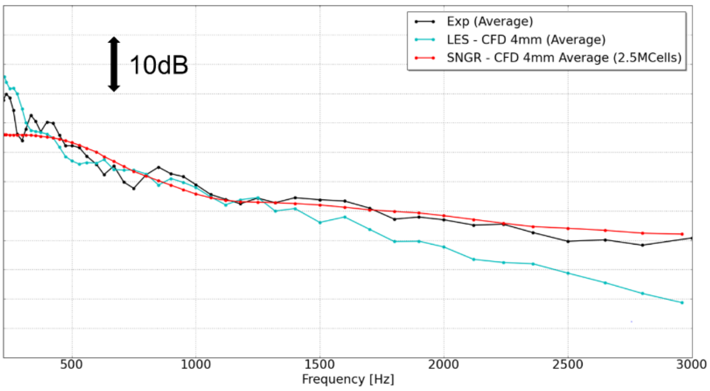

Figure 10. Average Acoustic Intensity in dB

The SNGR prediction has been rescaled to match the LES based flow results in terms of absolute levels.

As demonstrated in [6], the LES based flow results show the presence of a CFD cut-off frequency at 1250Hz with a CFD mesh refinement of 4mm in the source zone. Conversely, the SNGR method helps to retrieve the aeroacoustics sources generated by turbulent phenomena up to 3000Hz with a good trend compared to experiments.

Considering a frequency step of 50Hz (in regard to the smooth variation of the SNGR results), 30 loadcases and a turbulent threshold for treating 2.5MCells, the SNGR sources can be generated within 3.5 hours (30 loadcases distributed over 5 processors each with 36GB of RAM, each operating with 8 threads). These timings should be compared to the much longer timings for the unsteady flow based aeroacoustic sources which is dominated by the unsteady CFD process.

7. Conclusions

Using Reynolds-Averaged Navier-Stokes results exported from a standard CFD solver, this paper presents an efficient prediction technique to address side-mirror noise. The process is based on a hybrid CFD/CAA simulation using the Lighthill analogy implemented in Actran. The turbulent velocity field is synthetized based on statistical information and stochastic method, getting rid of the expensive unsteady CFD simulation.

The same guidelines derived in [6] are applied to set-up the Aeroacoustic propagation model, but the full acoustic process is based only on convergence of the mean flow and turbulent statistics from RANS simulation.

Depending on the accuracy level required, the cost the SNGR process can be reduced by:

- Focusing on the largest energetic turbulent contributions,
- Reducing the number of realizations of the stochastic source field.

These parameters are easily accessed in the turbulent field generation in Actran.

This process highly reduces the computational effort compared to aeroacoustic solutions based on unsteady flow simulation where the computational effort lies in the CFD computation. It allows to quickly sort out various different configurations based on their acoustic performance.

Moreover, the process can be used to extend the frequency range of aeroacoustic simulations based on LES-type CFD results. Indeed, the turbulent structures not resolved by the grid due to its limited size are modelled in SNGR process as decaying isotropic turbulence.

RANS and LES based flow simulations are actually complementary processes targeting two different goals. 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 configurations.

ACKNOWLEDGEMENTS

The authors thank Volvo Cars Corporation for their courtesy, providing the CFD data used in the present research. The Intel Corporation is also acknowledged for providing cutting-edge hardware technologies used in the framework of this paper.

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