Prediction of interior SPL caused by the Wind Noise.

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Abstract

Evolution of simulation methods used to predict interior sound pressure caused by the wind noise have opened a variety of new possibilities to improve the quality of the results. The better understanding of the noise generation parameters and transmission process allows engineers to bring in various methods (such as Statistical Energy Analysis (SEA), Finite Elements Method (FEM), Boundary Elements Method (BEM) and hybrid couplings (FEM/SEA)) in the wind noise simulation. This paper demonstrates the physical mechanisms of wind noise generation, common workflow used in wind noise applications, and shows the results obtained with different simulation methods. Improved surface pressure mapping technic and method of extracting acoustics and convective pressure out of the turbulent flow is demonstrated within Aero-Vibro-Acoustic toolbox in VA One software.

Introduction

'Wind noise' term is used to describe the interior noise that is generated by exterior flows. In the transportation applications, 'wind noise' influences on the interior comfort and might impact the overall perception of the vehicle quality. For the automotive industry, 'wind noise' is dominates in interior pressure for mid to high driving speeds [1]. In the moving vehicle the fluctuating surface pressure (FSP) on the front side glass due to vortices and separated flow generated by the A-pillar and side mirror is major 'wind noise' contributor. Numbers of technique has been discussed in the past [2], [3], [4] to predict the contribution of the "wind noise" to interior SPL. The different approaches to predict wind noise contribution inside vehicle is demonstrated in this paper along with brief descriptions of the physical mechanisms involved in wind noise simulations and explanation of vibro-acoustic methods that is used to obtain interior SPL. The improved mapping technique used to associate fluctuating surface pressure with vibro acoustic mesh is described in "Mapping of CFD results on vibro-acoustic mesh" part. Wavenumber decomposition of the fluctuating surface pressure is used to eliminate the energy that corresponds to the convective and acoustic parts of the flow. Finally the latest simulation results presented, compared to measurements and discussed.

From turbulent excitation to interior SPL

Physical mechanism of the wind noise

A turbulent flow generated outside of vehicle consists of two different components: convective and acoustic parts. Convective part associated with hydrodynamic pressure of the turbulent flow. This pressure field generated by eddies that travels at the convective speed. The acoustic part associated with exterior acoustic sound field, and related to acoustic waves that are generated by pressure fluctuating at different obstacles and travels within the flow. For example turbulences at the rear face of the side mirror creates an acoustic waves that travels towards the side glass. The acoustic pressure is typically much smaller in the amplitude compare to convective component, but it can be the main contributor to the interior noise due to better coupling with side glass. Both convective and acoustic components of the flow contributes to the interior SPL and should be considered.

Overview of available AVA approaches

Development of various numerical simulation methods has opened a new possibilities in aero-vibro-acousti problems. Method that allows to couple time domain turbulent flow data with vibro-acoustics model shows an accurate results and can be used during design change stage. The overall workflow using aero-vibro-acoustic toolbox is illustrated in figure 1.

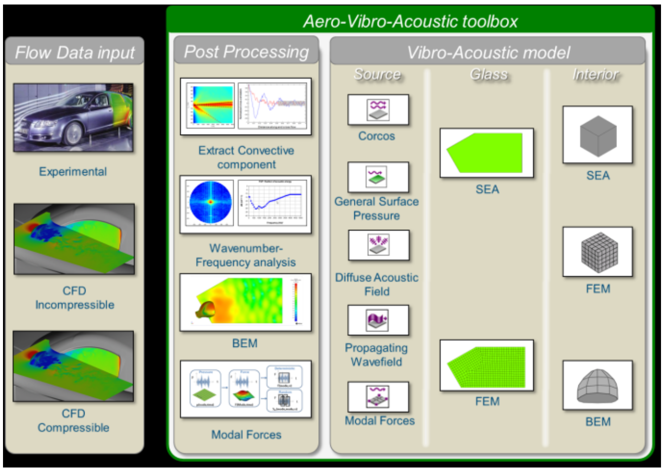

Figure 1: The overall workflow from surface pressure data to interior using different post processing techniques and vibro-acoustic models.

This illustration is used to describe the available methods of post processing the flow data and ways to couple it to the vibro-acoustic model. The left side of this figure shows the input of surface pressure data in time domain. The input data can be obtained from measurements of fluctuating surface pressure on the side glass. Surface microphones capture pressure that contains both convective and acoustic component. Such measurements should be done with care to ensure that the both components are well sampled, the measurements points are close enough to sample convective wavelengths and microphones are small enough to avoid "microphone size effect" at high frequencies.

Surface pressure post processing

The input data can be represented using compressible or incompressible CFD simulation. The post processing techniques would be different for those types of CFD since compressible CFD contains both acoustic and convective components, while incompressible CFD contains only convective component, since fluid cannot transport the acoustic waves through compression and decompression.

The Aero-Vibro-Acoustic toolbox allows to post process surface pressure data and couple it with chosen vibro-acoustic method [5]. The convective component of the turbulent flow can be represented as a Corcos model. Using wavenumber transform method it is possible to visualize the spatial correlation function in terms of wavenumber/wavenumber or wavenumber/frequency map (see figure 2).

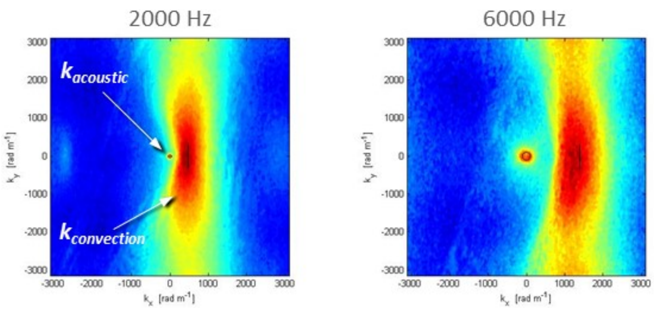

Figure 2: The wavenumber – wavenumber map of fluctuating surface pressure for 2000 Hz and 6000 Hz

This transformation shows that the energy is well distribute along the convective wavenumber and inside the acoustic circle. Energy inside acoustic circle can be integrated and fitted into equivalent acoustic source: diffuse acoustic field (DAF) or propagating wavefield (PWF). If fluctuating surface pressure obtained from incompressible CFD simulation then it is missing acoustic component. Acoustic component can be obtained from hydrodynamic load using acoustic analogy on Curle's integral version of the Lighthill equation for BEM.

When structure that is wetted by fluctuating surface pressure is represented by finite elements subsystem one can directly use the time domain data to convert it to modal forces.

Description of vibro-acoustic model

The vibro-acoustic model is consists of a source definition, transfer paths and receivers. The methods of coupling post processed flow data with vibro-acoustic model depends on the requirements in terms of accuracy, computation time, time needed to create a model, available input data, etc.

Vibro-acoustic sources represents the fluctuating surface pressure load on structural subsystem. The convective components from CFD or measurements can be described as a Corcos model which can be applied to SEA or FE panel. The acoustic component can be modelled as DAF or PWF. Acoustic RMS pressure of a turbulent flow can be obtained by wavenumber decomposition of measured data or compressible CFD, or a BEM computation if incompressible CFD data is used. The general surface pressure load which is defined by wavenumber-frequency spectrum of the fluctuating pressure excitation can represent pressure acting over an SEA structural subsystem. Modal forces can be used to project the fluctuating surface pressure on the modes of the FE structural subsystem.

Side glass panel can be modelled either using FE or SEA method. Typically side glass has a few hundred modes up to 7 kHz and do not represent a heavy computation expense. SEA glass permits a fast computation and reliable prediction in the frequency range valid for SEA method.

The interior of a vehicle can be modelled as a SEA, FEM or BEM fluid domain. Interior volume of the typical car counts more than 10 000 acoustic modes below 3 kHz. SEA methods allows to obtain response in such volume in a few minutes, while BEM method might take few days. SEA will provide the average SPL in defined volume, when BEM can be used to compute response at specific microphone locations.

If the objective of the study is to compute the wind noise contribution to the total SPL at driver's ear than there is no need to create a full vehicle VA model. The interior fluid cavity with the right surface absorption is sufficient. Appropriate approach of design prosecco depends on many factors, such as: available surface pressure data, available computation resources, available resources for model building, required accuracy etc.

Mapping of CFD results on vibro-acoustic mesh

The mesh size used in CFD simulation for the wind noise application is usually much smaller than size of the mesh required for vibro-acoustic simulation. A mapping operator is required to avoid impact of the aliasing effect on results when map from source mesh (CFD) to target mesh (structural).

Such mapping operator is formally defined as

$$P^t = TP^s \tag{1}$$

Where P^t and P^s are vectors gathering the pressure at the nodes of the target (i.e. coarser) and source (i.e. finer) mesh, respectively. The mapping operator T is thus a matrix that maps P^s in P^t. In doing so, it is necessary that the wavenumber content of the source signal (source mesh) is not altered when mapped onto the target mesh. For instance, if matrix T is computed by means of a simple nearest neighbour interpolation, then the pressure data would be simply undersampled. As a result, wavenumber content that is shorter than the target mesh will be interpreted as a long wavelengths, thus generating aliasing. This should be avoiding as aliased components can very well coupled with the structure and thus inject power into it. Therefore, matrix T should be designed to adequately smooth the original. This can be obtained by weight averaging the source mesh data to give the pressure at each point of the target mesh. Such average typically uses a compactly supported smoothing function centred on each target mesh point so that T is sparse. In this work the finite element shape function associated with each node of the target mesh is used to smooth the pressure data. Furthermore, T can be consistent ($\sum_j T_{ij} = 1$) or conservative. In the latter case, as area averaging is introduced to guarantee that the integral of the pressure over the surface is conserved.

Wavenumber frequency analysis

The wavenumber-frequency spectrum associated with the pressure signal is estimated by means of the averaged periodogram method. Therefore, the signal is broken into n_{seg} segments. A 50% overlap between segments is allowed. The periodogram estimate of each segment is then used to estimate the wavenumber-frequency spectrum of the source as

$$S_{pp}(k_x,k_y,f) = \frac{1}{n_{seg}} \sum_{s}^{n_{seg}} \left| P_s(k_x,k_y,f) \right|^2 \Delta f \Delta k_x \Delta k_y \qquad (2)$$

Where P_s is the wavenumber-frequency Fourier transform of the pressure signal while S_{pp} is the wavenumber-frequency spectrum.

The impact of mapping aliasing can be demonstrated using wavenumber representation of the surface pressure. The distribution of the surface pressure on the side glass is illustrated at figure 3.

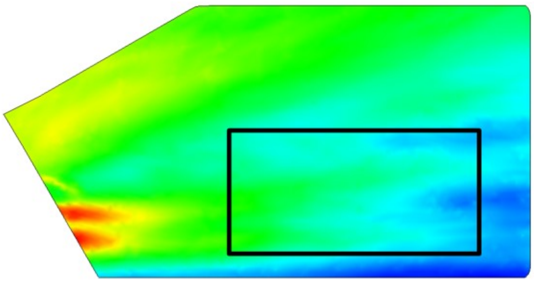

Figure 3: Fluctuating surface pressure distribution with post processing window

Rectangle box shows the window used for wavenumber decomposition processing. The size of the CFD mesh is 0.5mm, while the size of the target mesh is 5mm. The wavenumber frequency representation of two mapping methods is shown at figure 4.

The energy that associated with convective part of the flow has a higher wavenumber compare to energy that associated with acoustic part. For the nearest neighbour node mapping technique the convective energy is aliased and polluted the region of acoustic cone. Since the structure is more receptive to the low wavenumber spectral content, the overestimated energy inside acoustic cone leads to overestimated structural response.

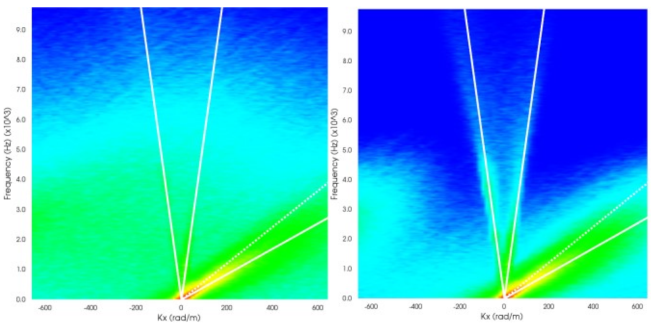

Figure 4: Wavenumber-frequency plots for nearest neighbour node (left) and conservative mapping operator (right).

Aero-vibro-acoustic results

Models descriptions

Validated vibro-acoustic model of the SAE body is used to perform aero-vibro-acoustic simulations. The details on creating and validation of vibro-acoustic model are describe [5], the details on wind tunnel measurements are described in [1]. The surface pressure results of CFD simulation was imported into the commercial vibro-acoustic software [6] and used for the prediction of the wind noise inside the SAE body.

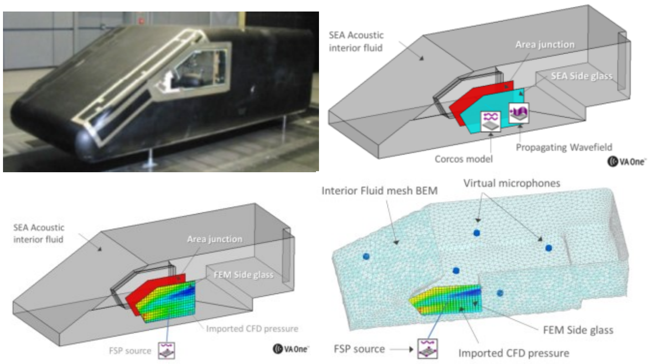

Figure 5: Photo of SAE body and pictures of vibro-acoustic models

The aero-acoustic simulations are done using several coupling methods. Hybrid FE/SEA coupled model containing the side glass subsystem represented with FEM and the interior domain represented with SEA fluid. The time domain fluctuating surface pressure is converted into frequency domain modal forces. The SEA model containing a side glass and interior fluid modelled using SEA method. The turbulent flow described using Corcos model for hydrodynamic part and PWF for acoustic part. Parameters for excitation were extracted from CFD data. In the BEM model the interior fluid domain is described with BEM method. This model allows to predict SPL at any sensor location or at recovery face. A time domain FSP source is used to excite the modes of the FE subsystem that represent the side glass.

AVA validation results

The following results presented as illustration of correlation accuracy that has been achieved using different methods. It doesn't states recommendation of preferred approaches.

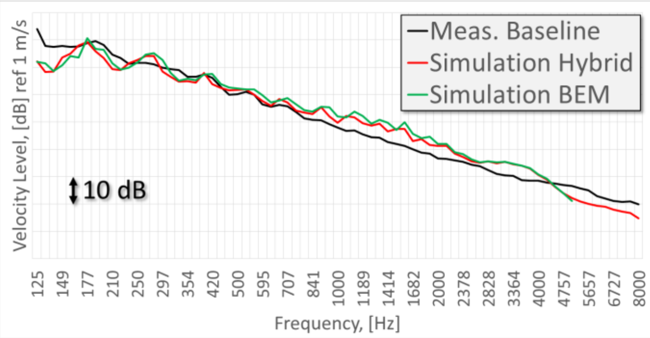

Figure 6: Average vibration of the FE side glass excited by modal forces

Figure 6 shows the average velocity response of the side glass excited by projecting pressure on the modes of FE panel in BEM and Hybrid FE/SEA model.

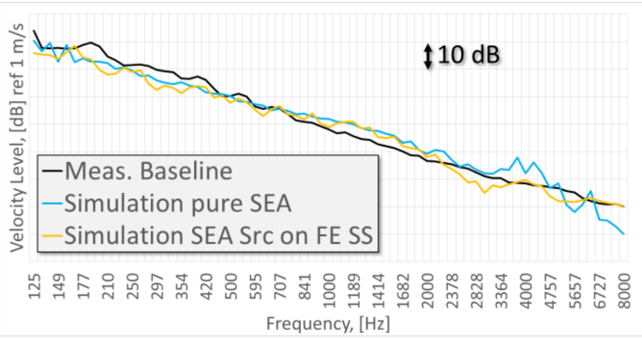

Figure 7: Average vibration of the FE or SEA side glass excited by analytical sources

Velocity response for the FE and SEA model of the side glass excited by SEA sources such as PWF and Corcos is shown on figure 7. The response in this model is a combination of the convective and acoustic sources. The acoustic component is contributing in high frequency region. 5 PWF with different settings are used to reconstruct the complexity of the acoustic field.

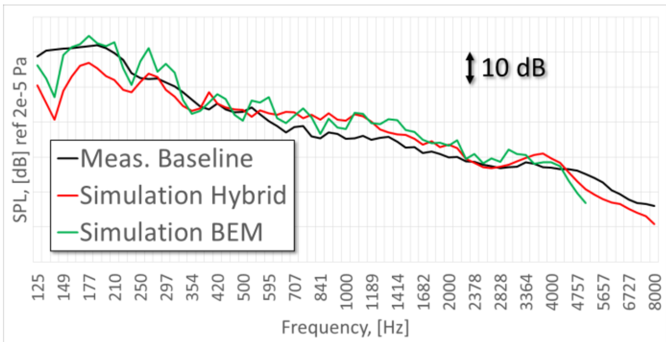

Figure 8: Average interior SPL

The average pressure obtained with deterministic and statistical methods of fluid descriptions shows a good correlation with experimental data (see figure 8).

Using analytical sources for wind noise excitation may predict less accurate results for certain frequency ranges. But this method is fast and maybe be used in design changes stage. Also database of used parameters for analytical source can be created to rapid study of wind noise impact.

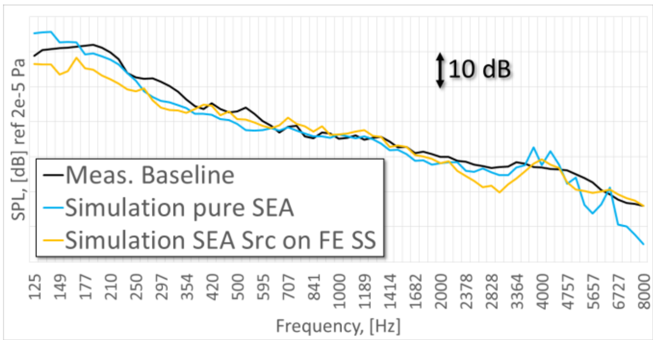

Figure 9: Average interior SPL

Conclusion

This paper has presented an overview of available approaches for characterizing wind noise sources in various vibro-acoustic models. The importance of proper mapping of surface pressure has been shown. Using wavenumber-frequency spectrums the analytical wind noise sources can be described. Obtained results of aero-vibor-acoustics simulation with help of different methods shows a good correlation with measurements and confirming that vibro-acoustics mechanisms are well modelled.

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