Using HPC BEM to Resolve Large Wind Noise Problems

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Abstract

The coupled structural-acoustic Boundary Element Method (BEM) has been widely used in vibro-acoustic analysis for decades now, due to its ease of model set up and low dispersion error characteristics. Recently, evolutions of BEM to solve Aero-Vibro-Acoustic (AVA) problems have been introduced. However, the large-frequency range of excitations, sometimes compounded by the large-size nature of the models at hand implies that such problems have a large number of degrees of freedom. As a consequence, while BEM can provide an accurate solution, the time and memory requirements related to model size and frequency range tend to create practical limitations.

The advent of affordable large-scale distributed memory computing power enables a new generation of BEM solvers to push these limitations away. It enables coupled indirect BEM problems to be solved on large clusters and distribute all CPU-intensive steps on a large number of CPUs. In this paper, the theory behind DMP for BEM will be introduced, and applications to Aero-Vibro-Acoustic will be shown based on work done over several years with a German wind noise workgroup of car manufacturers including Audi, Mercedes, Porsche and Volkswagen.

Introduction

In order to model wind noise it is necessary to understand the source, the paths which typically involve direct vibro-acoustic transmission through certain regions of the structure, transmission through nearby leaks/seals and isolation and absorption provided by the interior sound package and the receiver and in particular, the frequency range(s) in which wind noise provides an audible contribution to the interior noise in the occupant's ears. While many regions of a vehicle can contribute to wind noise, the fluctuating surface pressures on the front side glass due to vortices and separated flow generated by the A-pillar and mirror are often an important contributor.

This paper presents an overview of different approaches that can be used to efficiently predict wind noise contribution to overall SPL at the driver's ear. After describing the physical phenomena involved in wind noise simulation, a review of major wind noise source characterization methods will be presented. Following is a description of vibro-acoustics methods used to predict interior SPL for a given wind noise source model. Finally, the latest validation cases for Aero-Vibro-Acoustics (AVA) are presented.

From turbulent flow to vehicle interior SPL

A turbulent flow generated outside a vehicle can potentially be transmitted to the interior of a vehicle and be detrimental to the sound quality experienced by occupants (Figure 1). The turbulent flow outside a vehicle generates a fluctuating surface pressure field on the side glass which includes a convective and an acoustic component. The convective component is related to the pressure field generated by eddies travelling at the convection speed. The acoustic component is related to acoustic waves travelling within the flow and being generated on various surfaces before reaching the side glass.

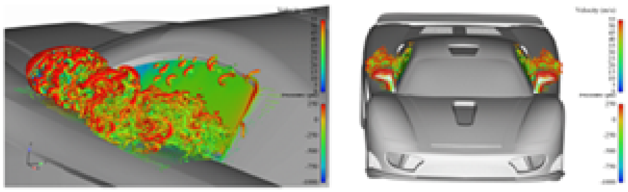


Figure 1: Turbulent flow generated behind side mirror and A-pillar

The acoustic component is typically very small in amplitude compared to the convective component and as will be shown later in this paper, can be the major contributor at coincidence frequency of the side glass. Furthermore, the acoustic waves reaching the side glass are highly directional. The turbulences at the rear face of the mirror and on the A-Pillar create acoustic waves that travel rearward towards the side glass with a specific heading.

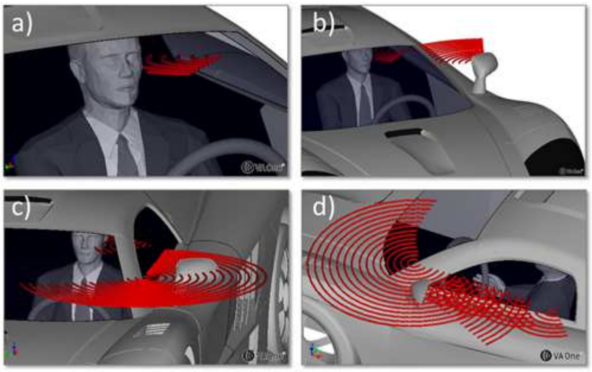


Figure 2: Sketch of acoustic waves propagating a) from side glass to driver's ear, b) from side mirror to driver's ear, c) from A-Pillar to driver's ear, d) away from A-Pillar, side mirror and side glass and interfering with each other before reaching side glass.

This source term is associated to a dipole source (surface terms). The acoustic waves travelling towards the side glass are likely to be transmitted inside the vehicle through the side glass and to the driver's ear as illustrated in Figure

3a,b,c. with any surfaces can also generate noise and therefore constitute acoustic sources. These sources act as quadrupole acoustic sources and are referred to as volume source terms. These acoustic sources are at close proximity to the side glass. At automobile speeds, these source terms are considered negligible since Mach number is below 0.3. Pressure fluctuations on the side glass also generate acoustic waves that propagate away from side glass. These waves can interfere with incoming acoustic waves from A-Pillar and mirror. It is believed to have a negligible impact on driver's ear SPL (Figure 3d).

Using BEM to propagate external acoustics

Several methods of representing the wind noise sources have been investigated over the past 10 years in the automotive industry. Empirical methods have shown their merits and limitations especially when the geometry of the structure changes significantly compared to previous computations [1,2,3,4]. A more predictive approach, based on the ability of coupling time domain turbulent flow data to a vibro-acoustics model has opened new possibilities. The computation process is illustrated in Figure 3. The left side of Figure 3 shows the source characterization section and the right side the vibro-acoustics methods that can be combined to compute the interior SPL. In this paper, the combination of the aero-acoustic (CAA) models and a vibro-acoustic (VA) model is called an aero-vibro-acoustic (AVA) model. The focus of this paper is on the use of BEM to add the acoustic component to an incompressible CFD simulation. A more complete description of the other methods available in Figure 3 is included in [5].

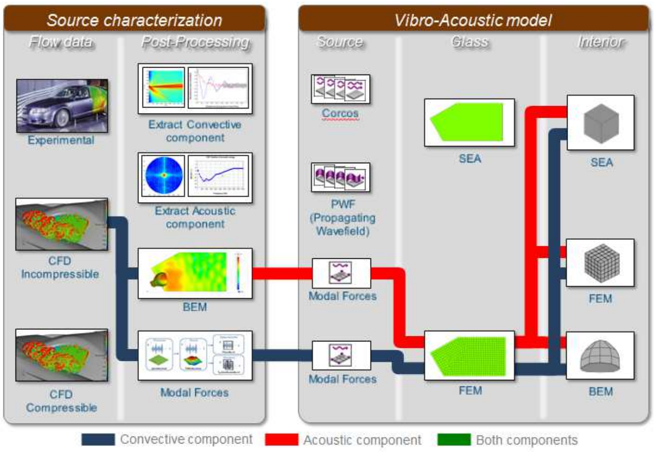


Figure 3: The computation scheme: Using BEM to add acoustics to an incompressible CFD computation.

The Navier-Stokes equations are notoriously difficult to solve numerically and a wide range of approximate strategies has been developed (LES, RANS, etc) to do so. In particular it is very difficult to solve for both turbulent flow and acoustic radiation at the same time, since turbulence is small scale and requires a very fine grid of computational mesh points and acoustic waves and sound radiation require a large spatial region to be modelled. Most CFD codes avoid this problem by assuming that the flow is incompressible which removes the acoustics. This section discusses how the acoustics can be added to an incompressible CFD simulation.

For wind noise automotive application, this means using BEM to propagate acoustic waves generated from the fluctuating surface pressure locations such as mirror and A-Pillar surfaces towards the side glass (see Figure 4).

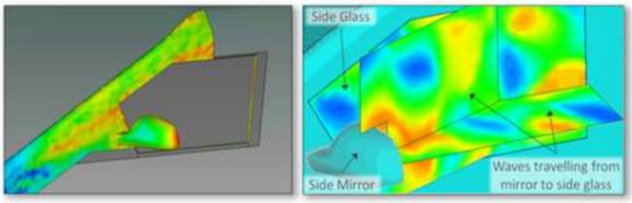


Figure 4: CFD fluctuating surface pressure imported on mirror and A-Pillar (left) applied as a boundary source term on a BEM model that propagates acoustic waves from mirror and A-Pillar to side glass (Right)

New derivation of the acoustic analogy based on Curle's integral version of the Lighthill equation for BEM allows the use of CFD incompressible analysis to model the turbulent flow.

Modal forces

When FEM is used to represent the side glass, one can directly use the time domain fluctuating surface pressure and convert them into modal forces. The process is illustrated in Figure 5. The time domain pressures are converted into forces and projected onto the modes of the side glass.

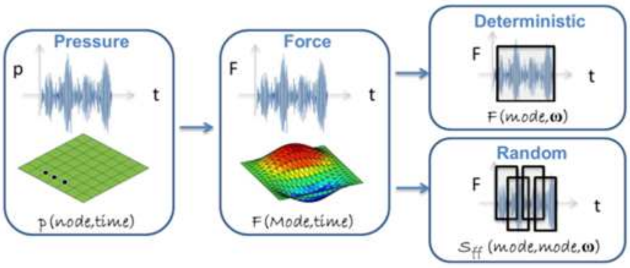


Figure 5: Using modal forces to represent forcing function from turbulent flow

The full time domain modal force signal is then either used in its entirety as a single window and used in the AVA model as a deterministic excitation or the time signal is post-processed and averaged using overlapping segments to generate a random source.

Figure 6 shows the averaged interior SPL obtained a from compressible CFD time domain fluctuating surface pressures coupled to a FEM side glass using modal forces while the interior fluid is modelled in BEM. It compares the simulation and measurements results for the cases with and without mirror. When an incompressible CFD simulation is performed, the acoustic component is not included in the time domain fluctuating pressure and BEM can be used to add this acoustic component. As shown in figure 3, the incompressible CFD time domain fluctuating pressures can be coupled to a BEM and the Curle's integral version of the Lighthill equation can be used to compute surface source terms to apply to the BEM fluid representing the external sound field of a car.

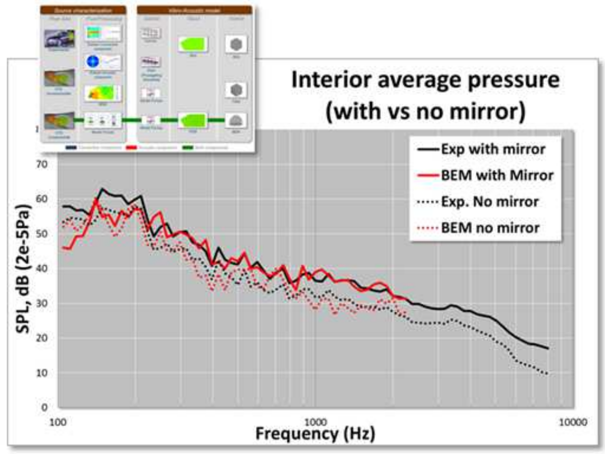


Figure 6: Interior averaged SPL for case with and without mirror using BEM for interior fluid modelling

HPC BEM

The Boundary Element Method (BEM) is a well establish technique for the solution of problems in engineering and applied science. The BEM is a technique which often presents important advantages over domain type solutions since it provides a great economy in computational efforts by discretizing only the boundary of the domains. Consequently, much smaller systems of equations are to be solved. However for complex geometry, as in the three dimensional case, dense meshes are required so that quite a large system of equations still remains, which make the solving step slow by a sequential approach. Development of parallel computer has received considerable attention by users of BEM to address more complex physics during an acceptable time. The best-adapted High Performance Computing (HPC) architecture to deal with large dense system of equations is for sure the Distributed Memory Processing. In this architecture, every unit of computation or processor works in parallel with its own memory and these processors do not have to be located in the same computer. The more common machine of this kind of system is the well-known Linux cluster with its nodes of CPUs.

There are essentially three phases in BEM: (i) The matrix set-up phase, (ii) The solution of linear equation phase and (iii) The calculation of external points phase.

The system equation set-up phase is a fine-grained process comprising a set of three nested loops. The inner loop, over the Gauss points, contains the straightforward calculation of the contribution to the global integral operators. The intermediate loop is over the target elements and finally the outer loop is over the source elements. In terms of complexity, this phase needs O(N2) operations with N the number of elements of the mesh. In terms of memory requirements, it is necessary to store the global integral operators so O(N2) Gb of RAM. The

solution of linear equation is based on Gauss elimination with partial pivoting like LU factorization. In terms of complexity, this phase needs O(N3) operations. The calculation of the external point phase is comprised of three nested loops. The inner loop, over the Gauss points is a sequential calculation of the approximation to the potential. The intermediate loop is over the target elements, and the outer loop is over the external points. In terms of complexity, this phase needs O(NxM) operations with N the number of elements of the mesh and M the number of data recovery.

For complex physics like wind noise on three dimensional geometry case, both constrains on CPU time and RAM requirements limit strongly the capacity of the BEM for a sequential approach on a single processor. By a parallel approach, these limitations are pushed further by introducing MPI instructions in the source code in those three time and memory consuming phases. During the matrix set-up phase, both intermediate and outer loops are distributed over a 2D-cyclic grid of processors to reduce considerably the CPU time. The O(N2) operations are dealed in parallel by the P processors; each one storing a part of the global O(N2) Gb of RAM. During the solution of linear equation phase, the well-known SCALAPACK linear algebra library is used to solve the dense system of equations efficiently on DMP architectures with a 2D-cyclic grid of processors. During the calculation of the external point phase, the intermediate loop is distributed over the P processors linearly.

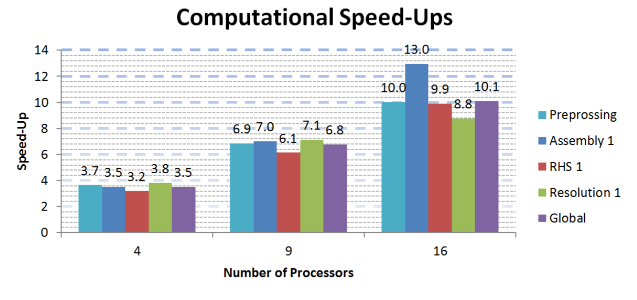
We illustrate the scalability of the BEM solver on a wind noise application solving the Lighthill-Curle analogy BEM equation. The number of nodes of the BEM mesh is 52 239. Usually, the scalability is presented through the speed-up Sp parameter. Sp is defined by:

$$S_p = T_{Seq} / T_{Para} \qquad [-] \qquad (1)$$

where T_{Seq} is the CPU time necessary for the computation in sequential approach i.e. using only one processor and T_{Para} is the CPU time necessary for the computation using P processors in parallel. The perfect scalability will lead to Sp = P meaning the CPU time is exactly divided by the number of processors. It is not possible in reality because the processors spend some time to communicate and exchange some data between them during the computation.

The table 1illustrates the scalability of the BEM solver for the wind noise application below on a Intel S2600CP/16x Intel Xeon E5-2680/2.7 GHz/128Gb computer.

Table 1: Scalability of HPC BEM implementation on a large wind noise problem



It is important to note every phase of the computation is dealed in parallel approach. Moreover, the speed-up for every step of the computation is very good. It enables to reduce considerably the global CPU time. For example, the speed-up is around 10 using 16 processors.

Finally, Figure 7 shows the propagation pattern of the acoustic waves generated on the A-Pillar, the side glass and the side mirror. This computation was performed using the HPC version of the BEM solver implemented in commercial software in [6].

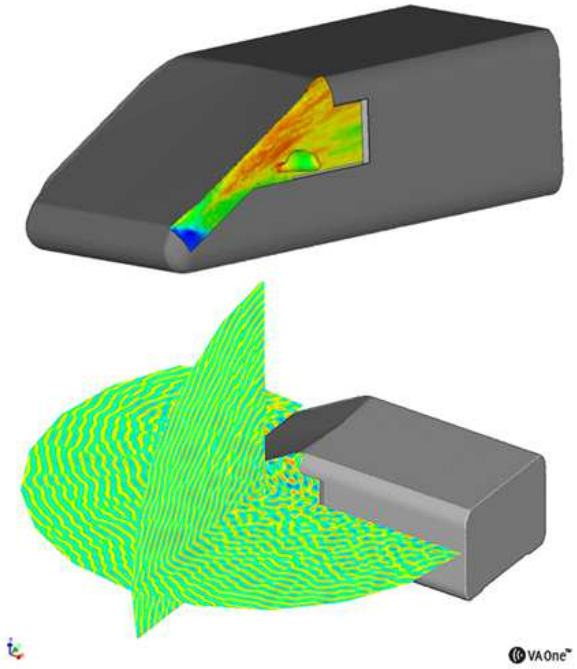


Figure 7: Top: Surfaces used to compute acoustic source terms using Curle formulation, Bottom: BEM acoustic waves propagation patterns from A-Pillar, side mirror and side glass source terms

Conclusion

This paper has presented an overview of available methods for characterizing windnoise sources. The ability to combine various vibro-acoustic methods such as FEM, BEM and SEA offers flexibility in the way wind noise can be modeled and has a positive impact on the time needed to build and run AVA models. The Aero-Vibro-Acoustics correlation results show a high level of accuracy for the case with and without mirror and confirm that today’s approaches can be used for design changes since the underlying physics are well represented by the CFD, VA and AVA models. Furthermore, a HPC implementation of BEM has been introduced and scalability results presented. Typically, a scalability of 10 can be expected for the case where 16 CPU are used for the large wind noise case presented.

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Definitions/Abbreviations

SEA	Statistical Energy Analysis
BEM	Boundary Element Method
FSP	Fluctuating Surface Pressure
TBL	Turbulent Boundary Layer:
PWF	Propagating Wave Field
FEM	Finite Element Method
DAF	Diffuse Acoustic Field
SPL	Sound pressure level
CFD	Computational Fluid Dynamics
HPC	High Performance Computing