Modeling interior noise due to fluctuating surface pressures from exterior flows

V. Cotoni[1], D. Blanchet[2], P.J. Shorter[1]
[1] ESI Group
12555 High Bluff Drive, Suite 250, San Diego, CA 92130, USA
e-mail: **vco@esi-group.com**

[2] ESI Group
Werner-Eckert.Str 6, Munich, 81829, Germany

Abstract

There are many applications in which exterior flow over a structure is an important source for interior noise. In order to predict interior “wind noise” it is necessary to model both: (i) the spatial and spectral statistics of the exterior fluctuating surface pressures (across a broad frequency range) and (ii) the way in which these fluctuating surface pressures are transmitted through a structure and radiated as interior noise (across a broad frequency range). One approach to the former is to use an unsteady CFD model. The use of compressible CFD to characterize exterior fluctuating surface pressures for broadband interior noise problems is relatively new; the accurate prediction of both the convective and acoustic wavenumber content of the flow can therefore present some challenges. This paper presents a numerical investigation of the spatial and spectral statistics contained in the flow downstream of a simplified side-mirror. Two distinct concentrations of energy are observed in wavenumber space at the convective and acoustic wavenumbers. Using wavenumber filtering it is then possible to describe a complex windnoise source in terms of the superposition of two simple analytical sources (that can be fit to CFD data). An example is presented in which the fluctuating surface pressures are applied to a side glass and a SEA model is used to predict interior noise.

1 Introduction

The term ‘windnoise’ is often used to describe interior noise that is generated by unsteady exterior flows. In transportation applications, excessive windnoise affects interior comfort and can result in negative perceptions of vehicle quality [2]. There is therefore significant interest in being able to predict windnoise upfront in the design process in order to reduce source content and modify paths (to meet cost, weight and noise targets). In order to model windnoise it is necessary to understand the source (the fluctuating surface pressures on certain exterior regions of a structure), 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 (in particular, the frequency range(s) in which windnoise provides an audible contribution to the interior noise in the occupant headspaces). While many regions of a vehicle can contribute to windnoise, the fluctuating surface pressures on the front sideglass (due to vortices and separated flow generated by the A-pillar and mirror) are often an important contributor. This paper therefore considers an analysis of the fluctuating surface pressures downstream of a simplified side mirror as shown in Figure 1. The mirror is mounted in the floor of a windtunnel and was used in a recent JSAE benchmark study that compared (exterior) aero-acoustic predictions from various commercial CFD codes [3] (additional details about the flow conditions and geometry can be found in the reference). In a previous publication, the authors have investigated the 1D wavenumber content of the fluctuating surface pressures in the flow and cross-flow directions for this example [1]. Some sections of the previous paper are summarized here for completeness and the work is then extended to include predictions of transmission through a simplified sideglass.

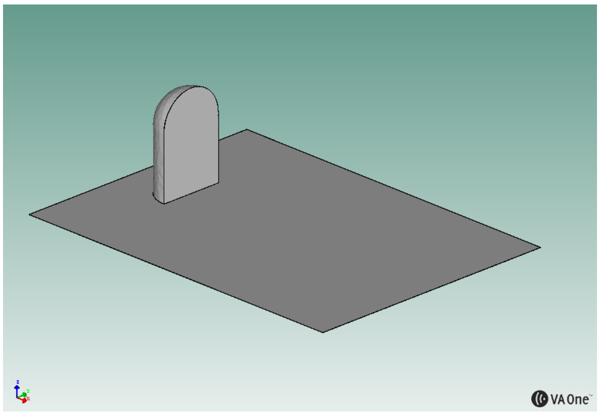

Figure 1: Simplified side-mirror located in the floor of an (anechoic) windtunnel

Before discussing the fluctuating surface pressures for the mirror example in detail, it is useful to first investigate how different loads are transmitted through a typical sideglass. In particular, it is often found that the glass acts as a spatial filter and preferentially transmits certain wavenumbers in the fluctuating surface pressure [4]. The spatial filtering of different exterior fluctuating surface pressures can be demonstrated using a simple numerical example. Figure 2 shows two glass panels of dimension 1 m × 1 m × 4 mm. Each has a constant damping loss factor of 6% and is placed in contact with a 1 m3 acoustic cavity. A Diffuse Acoustic Field excitation is applied to the first panel and a Turbulent Boundary Layer (with a 50 m/s free stream velocity) is applied to the second panel. The magnitude of the exterior fluctuating surface pressure of each load has been normalized to have unit amplitude. An SEA model is then used to predict the interior sound pressure levels of each cavity [5]. It can be seen in Figure 2 that even though both loads have the same exterior fluctuating surface pressure level, the interior sound pressure level due to the Turbulent Boundary Layer is approximately 30dB lower than that due to the diffuse acoustic field (it is noted in passing that the peak in the interior SPL around 3kHz is associated with the glass coincidence frequency).

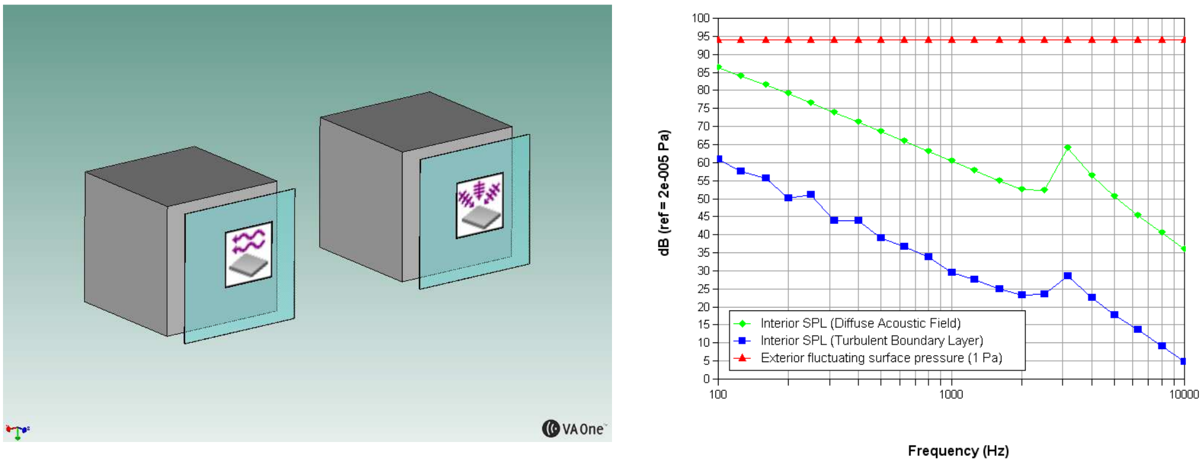

Figure 2: Glass panel of dimension 1x1x4e-3m in contact with a 1m3 acoustic cavity and excited by (a) Turbulent Boundary Layer (with a 50 m/s mean flow) and (b) Diffuse Acoustic Field. Prediction of interior SPL when each exterior load is normalized to have a unit exterior fluctuating surface pressure. Note large differences in interior SPL due to the different spatial correlation characteristics of each load.

The reason for the difference in interior SPL is due to differences in the "spatial correlation" of the two loads. The cross-spectra Spp between two locations in a spatially homogenous fluctuating surface pressure can be written as

$$S_{pp}(x,x') = F(\omega)R(x,x',\omega) \tag{1}$$

Where F is a function of frequency (that does not depend on location) and R represents a spatial correlation function. A diffuse acoustic field has a spatial correlation function R of the form [6]

$$R(x,x') = \sin(kr)/kr\,;\;\; r = |x - x'| \tag{2}$$

where k is the acoustic wavenumber and r is the distance between two locations x and x' on the surface. A Turbulent Boundary Layer (modeled using a Corcos type model) has a spatial correlation function R of the form [7]

$$R(\Delta x,\Delta y) = \exp\left(-\alpha_x|\Delta x| - \alpha_y|\Delta y|\right)\exp\left(-ik_c\Delta x\right) \tag{3}$$

where Δx is the separation between two points in the flow direction, Δy is the separation in the cross flow direction, α_x and α_y are decay coefficients in the flow and cross-flow directions and k_c is the convection wavenumber.

For the sideglass problem, the acoustic wavenumber is typically much lower than the convection wavenumber across much of the frequency range of interest (the diffuse acoustic field has a much longer spatial correlation length than the Turbulent Boundary Layer). The two different excitations therefore result in very different distributions of energy in wavenumber space, and this preferentially excites different structural mode shapes of the glass. The diffuse acoustic field has a concentration of energy at low wavenumbers (wavenumbers that are contained within the 'acoustic circle'). Below coincidence, this typically excites the 'non-resonant' (mass controlled) modes of the glass. Since these modes are also efficient acoustic radiators, the mass controlled modes are typically the dominant transmission path below coincidence. Above coincidence, the resonant modes become the dominant transmission path but these modes are also well excited by the wavenumber content of a diffuse acoustic field. In contrast, a Turbulent Boundary Layer typically has a concentration of energy at the convective wavenumber of the flow and has much smaller concentrations of energy at the wavenumbers associated with the resonant and mass controlled modes of the panel. The net result is that a diffuse acoustic field is transmitted through the glass much more efficiently than a Turbulent Boundary Layer for the same RMS fluctuating surface pressure.

In summary, in order to characterize an exterior fluctuating surface pressure it is necessary to be able to characterize not only the magnitude of the fluctuating surface pressure but also the wavenumber content. One approach to characterizing the wavenumber content is to use a CFD model to predict the fluctuating surface pressures. If an incompressible simulation is performed, the acoustic component of the fluctuating surface pressure field can be computed using standard aero-acoustic analogies. If a compressible CFD simulation is performed, various signal processing techniques can be used to characterize the wavenumber content of the fluctuating surface pressures. This approach is discussed in more detail in the following sections.

2 Flow past simplified mirror

An unsteady CFD analysis was performed for flow past the simplified side mirror described in [3]. Figure 3 shows examples of the unsteady flow due to a free-stream velocity of 50 m/s (computed using the commercial code in [12]). Additional details about the CFD model and boundary conditions can be found in [3]. The fluctuating wall pressures were recovered for a rectangular region of dimension 0.45 m × 0.2 m downstream of the side mirror as shown in Figure 4. A time segment of length 0.05 seconds was recorded using an average time step size of approximately 10^{-5} seconds. The pressure time history data was then imported into the commercial vibro-acoustics software in [5]. The time domain data was converted to the frequency domain and averaged over 8 segments with 50% overlap (the resulting cross-spectral data was then integrated onto a 1/12th octave frequency domain). The magnitude of the auto-spectra in the 100 Hz and 1000 Hz 1/12th octave bands are plotted in Figure 4. The shorter spatial structures in the flow at higher frequencies are clearly visible.

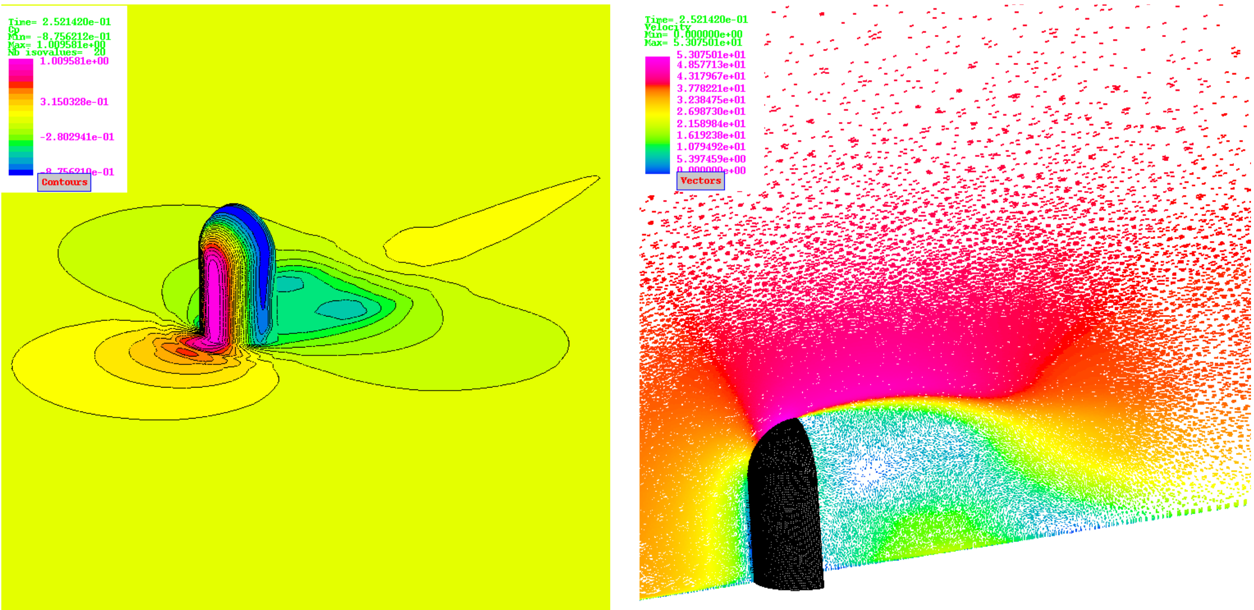

Figure 3: Visualization of flow predicted by CFD code: (a) Cp distribution and (b) velocity vectors.

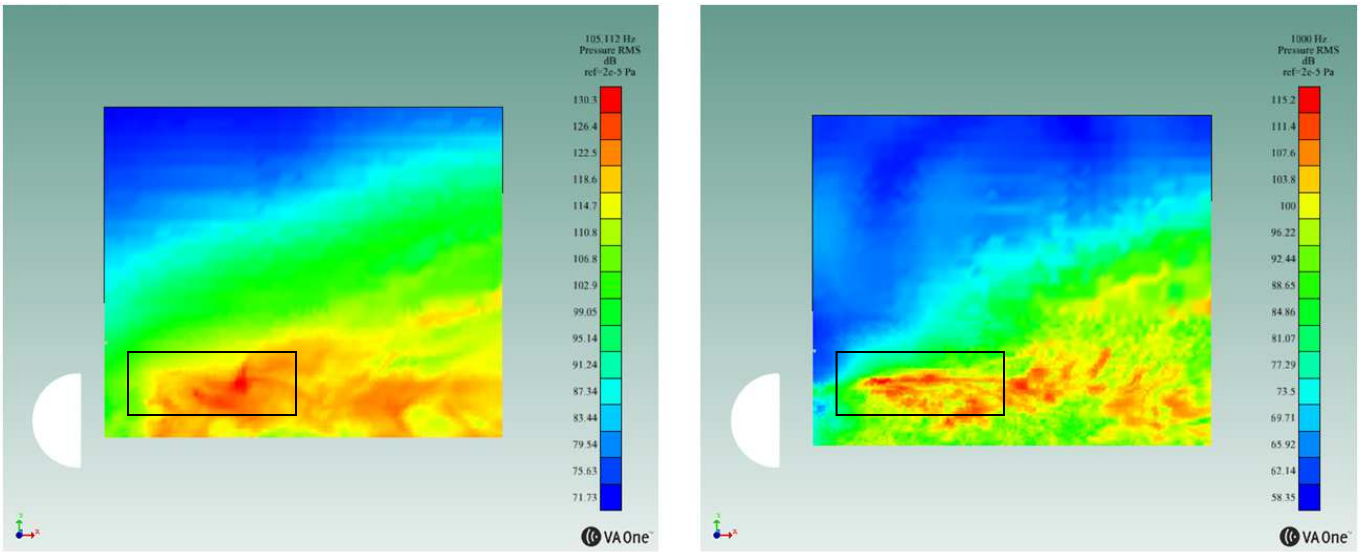

Figure 4: Magnitude of Fluctuating Surface pressure at: (a) 100 Hz and (b) 1000 Hz. Region of interest (of dimension 0.45m x 0.2m) used for analysis of Fluctuating Surface Pressures is shown with black rectangle. Note the shorter spatial structures in the flow at higher frequencies

3 Characterization of Fluctuating Surface Pressures

3.1 Spatial correlation

The auto-spectra of the flow is useful for understanding the flow characteristics, however, as discussed in the opening section it does not provide any information about the spatial correlation or wavenumber content of the fluctuating surface pressures. Additional signal processing was therefore performed using the Aero-Vibro-Acoustics module in [5]. In particular, the full cross-spectral matrix was calculated for a (dense) grid of points across the surface region of interest. This surface region was divided into a (coarser) orthogonal grid and a reduced cross-spectral matrix obtained by averaging the auto-spectra and cross-spectra within each cell of the coarse grid. Spatial correlation functions *R* were then obtained by averaging overall all pairs of cells with the same separation distance in the flow and cross-flow directions.

The resulting space averaged correlation functions were used to fit the parameters of a Corcos TBL model using the algorithms implemented in [5]. A Corcos TBL model with a convection velocity of 30 m/s provided a good fit to the spatial correlation in the CFD data. This convection velocity is physically plausible and represents a convection velocity that is approximately 60% of the free stream velocity. The decay coefficients ($\alpha_{x,y}$ in Eq. (3)) were found to be approximately independent of frequency with values of 0.7 and 0.8 in the flow and cross-flow directions.

3.2 Wavenumber content

The wavenumber content in the flow and cross-flow directions can be obtained by calculating the 2D wavenumber transform of the spatial correlation functions obtained in the previous section (at each frequency of interest). The magnitude of the 2D wavenumber transforms for two frequencies are plotted in Figure 5 (the scale of the contour plot is approximately 30 dB). The acoustic circle is shown in white in the Figure, and the convection wavenumber for a 30 m/s flow is plotted as a straight line segment. It can be seen that at low frequencies, there are two distinct concentrations of energy in wavenumber space at the convective wavenumber and at acoustic wavenumbers. At higher frequencies, there is little evidence of any energy at the convective wavenumber. This may be physical but it may also perhaps be an artifact of the CFD calculation.

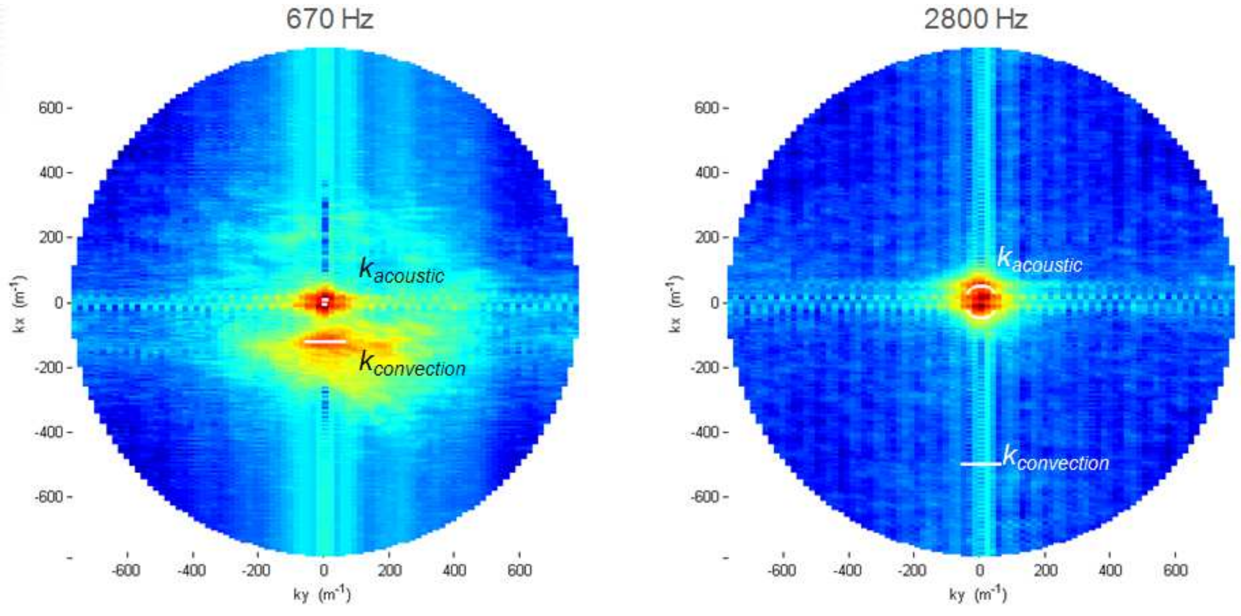

Figure 5: Wavenumber content of spatial correlation at two frequencies.

Comparing Figure 4 and Figure 5, it can be seen that a complex distribution of energy in the spatial domain becomes a much simpler distribution of energy in the wavenumber domain. It is possible to fit a equivalent diffuse acoustic field to the CFD data by integrating the energy in the acoustic circle in wavenumber space. The RMS pressure spectrum for the total fluctuating surface pressure field and its acoustic component are shown in Figure 6. Below 350Hz there is less than one acoustic half wavelength across the dimension of the sideglass and so there is not resolution in the wavenumber transform to provide a good estimate of the acoustic wavenumber content. However, for windnoise applications interest typically lies in higher frequency content and so this is not a significant constraint. It can be seen that the estimated amplitude of the diffuse acoustic field is 5-30dB less than the amplitude of the overall fluctuating surface pressure. However, since the glass is 30dB more sensitive to a diffuse acoustic field than to a TBL load (as shown in the initial section), the diffuse acoustic field can often be one of the dominant contributors to interior noise.

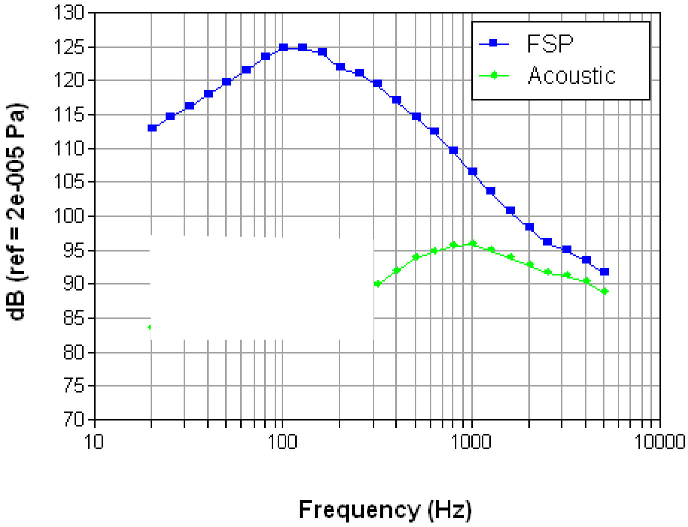

Figure 6: Space average RMS pressure of the fluctuating surface pressures (FSP) and of the acoustic component. Gray shaded area is below the resolution of the aperture used in the wavenumber transform.

4 Models of Noise Transmission

The discussion in the previous section can be illustrated by applying the two simplified loads to a simple flat plate (1 mm thick aluminium[1] with 3% damping) with dimension 0.45 m × 0.2 m. An SEA model was created in which the panel was described with an SEA plate subsystem, and the interior space as a semi-infinite fluid. TBL and diffuse acoustic field loads were applied to the panel and the parameters of both loads were fit to the CFD data using the procedures outlined in the previous section.

An analysis of the contribution of different transmission paths to the power radiated to the semi-infinite fluid is shown on the right-hand side of Figure 7. It reveals that (for this flat panel example), the transmission is dominated by resonant transmission below 600Hz (mainly due to the TBL load). Non-resonant (mass law) transmission from the acoustic component of the fluctuating surface pressures then dominates above 600 Hz. It should be noted that these conclusions are specific to the configuration studied, and in particular to the damping level in the panel (since this controls the resonant transmission), to the radiation efficiencies of the panel (flat vs curved) and to the CFD dataset used to describe the load.

[1] A thin aluminum panel was used in the example in this section rather than a glass panel because part of this work was performed while validating different experimental measurement set-ups that included different types of panel.

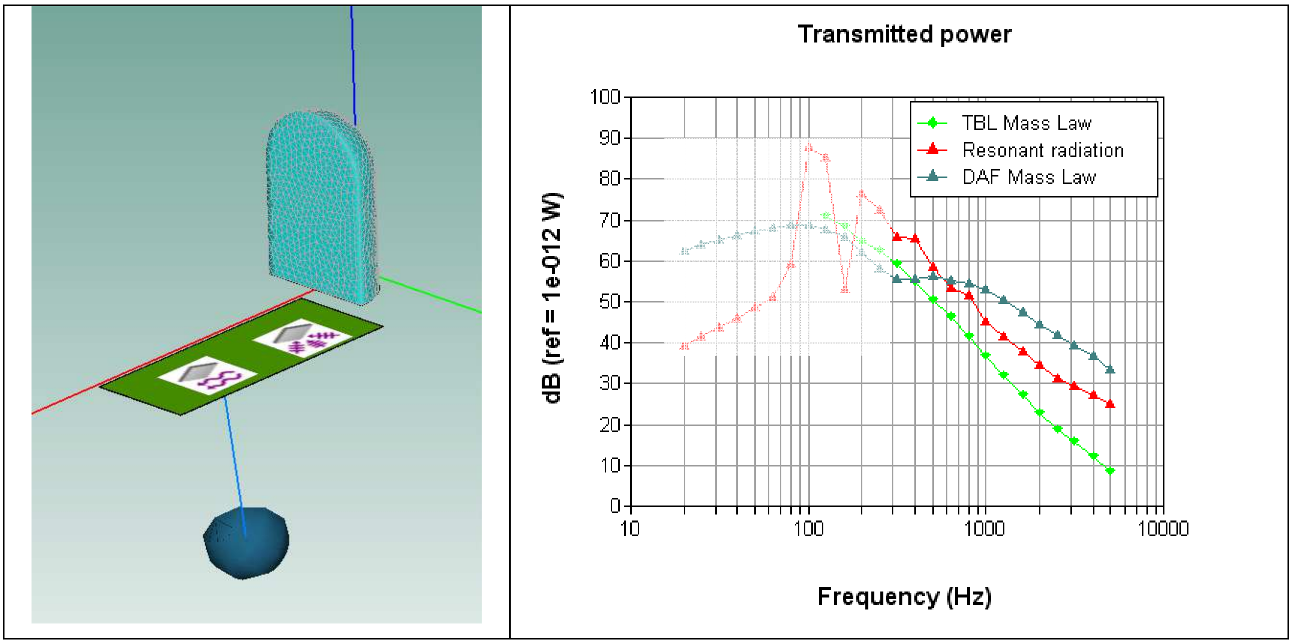

Figure 7: (Left) SEA model of noise transmission through a flat panel excited by a fluctuating surface pressure field downstream of a simplified mirror, (Right) Prediction of the contributions to the sound power from the various loads.

5 Summary/Conclusions

This paper has provided a numerical investigation of the spatial and spectral statistics of the fluctuating wall pressures downstream of a simplified side-mirror. The importance of spatial correlation when characterizing fluctuating surface pressures was emphasized using a simple example. The transmission of sound through a glass panel was compared when excited by a turbulent boundary layer and a diffuse acoustic field. For the same exterior pressure level, the turbulent boundary layer resulted in interior sound pressure levels that were 30 dB less than for the diffuse acoustic field. The fluctuating pressure levels downstream of a simplified side-mirror were then investigated. By performing a number of signal processing operations it was possible to plot the wavenumber content of the spatial correlation (averaged across a region of interest). Clear concentrations of energy were seen at the convective and acoustic wavenumbers. Wavenumber filtering was used to fit analytical turbulent boundary layer and diffuse acoustic field loads to the CFD data. These loads were then applied to an SEA model to analyze the different transmission paths through the panel. For the particular panel and flow conditions examined in this paper, the radiated acoustic power is dominated by non-resonant transmission acoustic transmission from 600 Hz to the coincidence frequency of the panel.

6 Reference

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