Predicting Interior Noise due to Fluctuating Surface Pressures from Exterior Flows

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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. While CFD is used routinely for external aerodynamics, its application to the characterization of exterior fluctuating surface pressures for broadband interior noise problems is relatively new. Accurate prediction of both the convective and acoustic wavenumber content of the flow across a broad frequency range 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. This therefore opens up the possibility of describing a complex windnoise source in terms of the superposition of two simple analytical sources that can be fit to CFD data.

Spatial Correlation

Consider the simplified side mirror shown in Figure 1. This example was used in a recent benchmark study that compared aero-acoustic predictions from various commercial CFD codes [1].

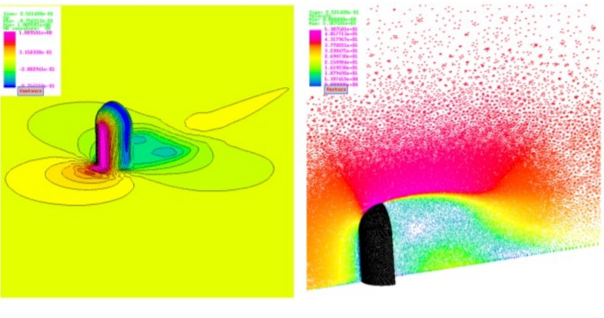

Figure 1. CFD data: (a) Cp distribution and (b) velocity vectors

It is often found that a prediction of the exterior radiated noise and/or the overall magnitude of the surface pressure is not sufficient to fully characterize interior wind noise. One explanation for this is that the structure acts as a spatial filter and preferentially transmits certain wavenumbers in the fluctuating surface pressure [2]. This can be demonstrated using a simple numerical example. Figure 2 shows two glass panels of dimension 1 x 1 x 4e-3m. Each has a constant damping loss factor of 6% and is placed in contact with a 1 m^3 acoustic cavity. A Diffuse Acoustic Field (DAF) excitation is applied to the first panel and a Turbulent Boundary Layer (TBL) 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 (SPL) of each cavity [3]. It can be seen in Figure 2 that even though both loads have the same exterior 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.

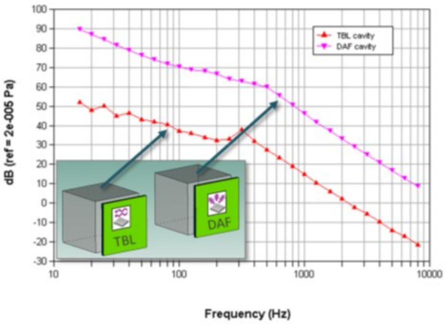

Figure 2. Interior SPL for normalized loads: TBL and DAF.

Flow past simplified side mirror

An unsteady CFD analysis was performed for flow past the simplified side mirror described in [1]. Figure 1 shows examples of the unsteady flow due to a free-stream velocity of 50m/s (computed using the commercial code in [4]). The fluctuating wall pressures were recovered for a rectangular region of dimension 0.45m x 0.2m downstream of the side mirror as shown in Figure 3. A time segment of length 0.05 seconds was recorded using an average time step size of approximately 1e-5 seconds.

The time domain data was converted to frequency domain and averaged over 8 segments with 50% overlap. The magnitude of the auto-spectra at 100Hz and 1kHz are plotted in Figure 3. The shorter spatial structures in the flow at higher frequencies are clearly visible.

Spatial Correlation of CFD data

Visualization of 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 [3].

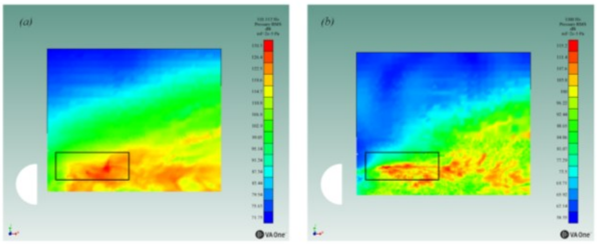

Figure 3. Fluctuating Surface pressure: (a) 100 Hz and (b) 1kHz.

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 function in the flow direction is shown in Figure 4.

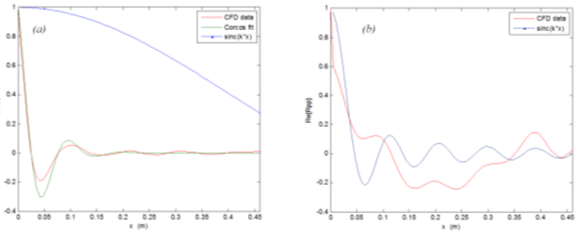

Figure 4 – Spatial correlation in flow-direction: (a) 300Hz & (b) 3.25k Hz. red: CFD, blue: DAF. green: Corcos

For comparison, the analytical expression for the spatial correlation in a diffuse field is also shown by the blue curves (with acoustic wavenumber k = 5.3 rad/m). It can be seen that at low frequencies, the spatial correlation in the CFD results decays much more rapidly than would occur in a diffuse acoustic field. It can be seen that a Corcos TBL model with a convection wavenumber k_c = 62 rad/m provides a good fit to the spatial correlation in the CFD data. This convection wavenumber is physically plausible and represents a convection velocity of ~60% of the free stream velocity. At higher frequencies, oscillations in the spatial correlation match those of a propagating acoustic wave. The decay in the spatial correlation does not exactly match that of a spatially homogenous diffuse-acoustic field. However, this is perhaps to be expected since the fluctuating surface pressure is not homogenous and is therefore likely to exhibit non-uniform acoustic directivity.

Wavenumber Content

The wavenumber content in the flow and cross-flow directions can be obtained by calculating the wavenumber transform of the spatial correlation functions obtained in the previous section. The magnitude of the wavenumber transforms are plotted in Figure 5. The wavenumber of a freely propagating acoustic wave is also plotted. It can be seen that there is a distinct concentration of energy associated with acoustic wave propagation across the frequency range of interest. In the flow direction, this energy is spread across several angles of incidence (and at all wavenumbers < kacoustic). A slight Doppler shift can also be seen in the acoustic wavenumbers in the flow direction. Acoustic waves travelling upstream have a slower overall wavespeed and hence higher wavenumbers than acoustic waves that travel downstream. It can also be seen that there are relatively few acoustic waves that propagate directly in the cross-flow direction. Instead, the waves tend to travel at an angle to the cross-flow direction. This suggests a directional acoustic source.

The convection wavenumber for a typical TBL has also been plotted. It can be seen that at low frequencies there is a distinct concentration of energy at the convective wavenumber in the flow direction. However, 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 (and due to difficulties resolving the short spatial correlation lengths at higher frequencies with a given mesh size). As expected, there is little evidence of any convection in the cross-flow direction.

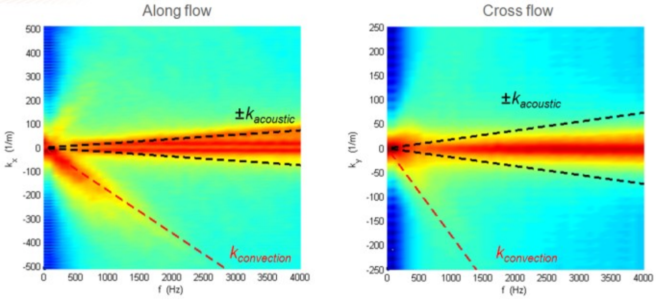

Figure 5 – Wavenumber of spatial correlation (scale ~30dB)

While not discussed explicitly here, it is possible to fit simple TBL and acoustic loads to the energy in wavenumber space. The accuracy of this approach is currently the subject of ongoing work and will be reported in separate publications.

Conclusions

An unsteady CFD analysis was performed for flow past a simplified side mirror. In wavenumber space, clear concentrations of energy were seen at the convective and acoustic wavenumbers. This opens possibility of fitting analytical TBL and DAF loads to CFD results in order to provide simple windnoise sources in vibro-acoustic models.

References

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