Wind noise modeling in separated and reattaching boundary layers

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ABSTRACT

The Chase model for the pressure fluctuations in a fully developed turbulent boundary layer is expanded to cover the cases of separated and reattaching boundary layers. Wind tunnel measurements are used to validate the model for flows with positive and negative pressure gradients and flows over discontinuities causing separation. The outer variables of the boundary layer are used to determine a two-dimensional surface wavenumber spectrum to be used as an excitation source in an SEA model. The flow over a vehicle is modeled and the predicted panel vibration and interior noise are compared to test data. The results indicate that the cross spectral densities obtained from pairs of surface mounted microphones are sufficient for determining the wind noise excitation in the SEA model.

Keywords: Flow Noise, SEA
I-INCE Classification of Subjects Numbers: 21.6.4, 75.2

1. INTRODUCTION

The turbulent flow excitation of structures and the associated sound transmission through panels depend on both the spatial and temporal matching of the pressure and vibration fields. Typically this is described by functions of wavenumber, $k$, and frequency, $\omega$, which are Fourier transforms of the spatial and temporal fields, respectively. A typical example of the function $\Phi_p$ describing the pressure field in a fully developed turbulent boundary layer (TBL) is given by Chase (1)

$$
\Phi_p(k, \omega) = \frac{C \rho^2 u_c^3 k^2}{\left[ k^2 + \left( \frac{\omega}{u_c} - k \right)^2 + \frac{1}{\delta^2} \right]^{2.5}} (1)
$$

where $\rho$ is the fluid density, $u_c$ is the convection flow velocity, $\delta$ is the boundary layer thickness, and $C$ is a constant.

Of particular interest in the development of Eq. (1) was the low wavenumber component of $\Phi_p$ which plays an important role in the structural response to TBL pressures in some cases. This is illustrated in Fig. 1 where typical wavenumber spectra of a TBL pressure field (at Mach 0.1) and a glass panel vibration response function are compared for a frequency of 500 Hz. The panel vibration is determined by the product of these two spectra which is dominated by two wavenumber regions: near the TBL convection peak and near the panel response peak. The latter is considered to be in the low wavenumber region of the TBL spectrum.

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The single point frequency spectrum of the TBL pressure is obtained by integrating Eq. 1 over wavenumbers, resulting in Eq. 2 and shown by the solid curve in Fig. 2. Goody (2) and others (3, 4) have modified the Chase model to better model the high frequencies by the addition of an additional term in the denominator, as shown in Eq. 3 ($\delta^*$ is the TBL displacement thickness) and by the dashed line in Fig. 2. Recent wind tunnel and road test measurements of the TBL pressure on automobile surfaces (5, 6) have indicated that this modified Chase model is also applicable to regions where there are separated and reattaching flows.

$$\Phi_p(\omega) = \frac{C \rho^2 u_c^4}{\omega \left[ 1 + \left( \frac{\omega \delta}{u_c} \right)^2 \right]^{1.5}}$$  \hspace{1cm} (2)

$$\Phi_p(\omega) = \frac{C \rho^2 u_c^4}{\omega \left[ 1 + \left( \frac{\omega \delta}{u_c} \right)^2 + \left( \frac{\omega \delta^*}{u_c} \right)^2 \right]^{1.5}}$$  \hspace{1cm} (3)

Figure 1 – Wavenumber spectra

Figure 2 – Single point TBL pressure spectrum
In this paper the modified Chase model is used to develop source terms for the SEA model of a vehicle. Surface microphone measurements are used to determine the exterior turbulent flow pressure spectra. The SEA model predictions are compared to panel vibration and interior sound level measurements.

2. TURBULENT FLOW PRESSURE SPECTRUM MEASUREMENTS

The wavenumber dependence of the TBL pressure spectrum in Eq. 1 is difficult to measure. The TBL spectrum drops off rapidly at low wavenumbers as illustrated in Fig. 1. To accurately measure this with a microphone array the wavenumber filtering characteristics must have a sharper roll off than this. Fig. 3 shows a typical wavenumber filter shape of a 16 microphone array. Using this microphone array in a fully developed TBL at Mach 0.1 give the results shown in Fig. 4 at 500 Hz. In this example $k_c = 143 \text{ rad/m}$, For a 3.2 mm glass panel, $k_b = 25 \text{ rad/m}$, where there is an overestimate in the measurement by a factor of 3. The low wavenumber measured values are probably contaminated by acoustic pressure which has a wavenumber of $k_o = 9.2 \text{ rad/m}$ in this case.

![Array Filter Response](image)

Figure 3 – Wavenumber spectrum of microphone array filter

![Wavenumber Spectrum](image)

Figure 4 – Wavenumber spectrum of TBL pressure at Mach 0.1

An alternate approach is to measure the cross spectral density between two microphones and infer the parameters of the modified Chase model. As an example, Fig. 5 shows the TBL pressure measured by two microphones spaced $d = 12.7 \text{ mm}$ apart in the direction of the air flow on a passenger car front side window in a wind tunnel with a flow speed of 44 m/s. The time delay between signals gives a phase response in the cross spectral density of $\phi = -360 \frac{fd}{u_c}$, as shown in Fig. 6. By fitting a curve
to the data a value of \( u_c = 35 \text{ m/s} \) is obtained which is about 75\% of the free stream velocity. Fig. 7 shows the magnitude of the cross spectrum which is fitted with Eq. 3 using \( \delta = 75 \text{ mm} \) (and \( \delta^* = \delta/8 \)) which indicates a large separation zone caused by the flow over the A-pillar.

Figure 5 – Measured pressure signals on front side glass

Figure 6 – Phase of cross spectral density on front side glass

Figure 7 – Magnitude of cross spectral density on front side glass
Measurements on the rear side glass (Figs. 8 and 9) indicate a secondary reattaching boundary layer as seen by a high frequency hump in the magnitude of the cross spectrum.

![Figure 8 – Phase of cross spectral density on rear side glass](Image)

![Figure 9 – Phase of cross spectral density on rear side glass](Image)

### 3. SEA MODEL

The SEA model for sound transmission through a vehicle window is shown in Fig. 10.

![Figure 10 – SEA model for sound transmission though plate](Image)
The measured TBL pressure level is input to the “Turbulent” subsystem. This subsystem has the density of air but with the “wave speed” equal to the convection velocity. This provides the correct spatial pattern for the coupling to the acoustic and structural subsystems. Fig. 11 shows the results for the acoustic scattering predicted by the SEAM model at the side glass. The acoustic levels are too low to measure. However, they are an important source of the window vibration at high frequencies, as shown in Fig. 12.

Fig. 11 – SEA model calculation of exterior scattered acoustic levels

Fig. 12 – SEA model calculation of the window vibration levels

Fig. 13 shows the measured and SEA model results for the interior sound levels. The turbulent excitation dominates low frequencies while the scattered acoustic source dominates high frequencies.

Fig. 13 – SEA model calculation of the interior vehicle sound levels
4. CONCLUSIONS

The cross spectral density of two microphones gives the necessary information to determine the parameters of the modified Chase model for TBP pressures in separated and reattaching flow regions on a vehicle. These parameters can be used as source terms in n SEA model to obtain accurate estimates of the surface vibration and transmitted sound.

REFERENCES