PREDICTION AND MEASUREMENT OF TURBULENT BOUNDARY LAYER WALL-PRESSURE FLUCTUATIONS ON THE SURFACE OF A SINGLE PANEL AT LOW MACH NUMBERS

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1 Introduction

The characterization and prediction of Turbulent Boundary Layer (TBL)-induced sound for aircraft applications has been investigated for several years [1]. It has been shown that a primary source of cabin noise during cruise conditions is induced by TBL wall-pressure fluctuations [2]. Early investigations provided insights into the characteristics of wall-pressure fluctuations, and several researchers developed semi-empirical models to predict the wall-pressure spectra at a single point. Such models have become integral components in advanced analytical frameworks for continuum models [3], and numerical approaches, such as Statistical Energy Analysis (SEA), as they provide the frequency distribution of the TBL excitation over the structure in question. Two semi-empirical, single-point frequency spectrum models, are reviewed and compared to experimental wall-pressure fluctuations measured on a rigid panel, in a wind tunnel facility, for Mach numbers (M) of 0.06, 0.09 and 0.12. The measured wall-pressure spectra are normalized by TBL variables to investigate spectral similarity over the range of Mach numbers.

2 Semi-Empirical Models

2.1 Efimtsov's Model [4]

Efimtsov developed two models using extensive flight testing and wind tunnel experiments, covering a range of subsonic and supersonic Mach numbers. His most recent model has the form of Eq. (1). In Eq.(1), f is the frequency, δ is the predicted TBL thickness, ρ is the freestream density, $U_\tau = U_\infty\sqrt{C_f/2}$ is the friction velocity, C_f is the friction coefficient, U_∞ is the freestream velocity, $Sh = 2\pi f\delta/U_\tau$ is the Strouhal number, $Re_\tau = \delta U_\tau/\nu_w$ is the Reynolds number based on wall shear stress, and ν_w is the kinematic viscosity at the wall. The empirical constant, α, has a value of 0.01, $\beta = [1 + (Re_{\tau o}/Re_\tau)]^{1/3}$, and $Re_{\tau o} = \delta U_\tau/\nu$.

$$\Phi(f) = (2\pi)^2\alpha {U_\tau}^3\rho^2\delta \frac{\beta}{(1+8\alpha^3 Sh^2)^{\frac{1}{3}} + \alpha\beta Re_\tau\left(\frac{Sh}{Re_\tau}\right)^{\frac{10}{3}}} \tag{1}$$

2.2 Goody's Model [5]

More recent efforts by Goody were directed at modifying the Chase-Howe model to better agree with experimental measurements from a collection of sources. Goody's model has the form of Eq. (2).

In Eq. (2), τ_w is the wall shear stress, ν is the freestream kinematic viscosity, and $R_\tau = (U_\tau\delta/\nu)\sqrt{C_f/2}$ is the ratio of unsteady pressure time scales.

$$\Phi(f) = \frac{6\pi(2\pi f\tau_w)^2\left(\frac{\delta}{U_\infty}\right)^3}{\left(\left(\frac{2\pi f\delta}{U_\infty}\right)^{\frac{3}{4}} + 0.5\right)^{3.7} + \left(1.1{R_\tau}^{-0.57}\left(\frac{2\pi f\delta}{U_\infty}\right)\right)^7} \tag{2}$$

3 Method

A thick acrylic panel (thickness of 0.019 m) was simply-supported within the lower chamber of a custom, two-piece, noise reduction test section. The panel-chamber combination created a smooth lower surface for the test section with overall dimensions of 0.80 m x 0.48 m x 1.83 m. The upper chamber is lined with an acoustic foam to reduce the noise intensity from the wind tunnel motor and its control unit. Wall-pressure spectra were measured with a flush-mounted microphone, located 0.86 m from the start of the test section. A second, reference, microphone was placed at the same streamwise location, but spaced 50.8 mm in the spanwise direction, to temporally filter propagated noise from the wind tunnel fan and structure. The microphone array consisted of two, ¼ in.-diameter, Brüel and Kjaer 4944A type microphones. The microphones were outfitted with standard grid caps and custom caps with 0.5 mm pinhole diameters. Wall-pressure spectra measured with the grid cap configuration are truncated above 3 kHz, due to resonance. Only pinhole measurements were corrected using the Corcos correction [6] based on the condition that $\delta^+ = \delta U_\tau/\nu \leq 160$ [7].

4 Results and Discussion

The measured spectra are normalized using a mixed combination of inner and outer boundary layer parameters: τ_w, U_τ, and δ, to investigate spectral self-similarity for M = 0.06, 0.09 and 0.12. The normalized spectra, measured using the pinhole and grid cap microphone configurations, are shown in Fig. 1a and Fig. 1b, respectively. The non-dimensional spectra, measured with both configurations, collapse well over the mid-frequency range ($10 < 2\pi f\delta/U_\tau < 100$), but less so for low frequencies. The outer-layer scaling set ($\Phi(f)U_o/q_o^2\delta^*$ as a function of $2\pi f\delta^*/U_o$), were found to be equally acceptable over these ranges. A Mach number dependence is shown by the normalized spectra in Fig. 1a, for $2\pi f\delta/U_\tau \geq 10^2$, as the spectra did not collapse under any combination of inner, mixed or outer scaling variables. The spectra in Fig. 1b exhibit a much stronger self-similarity for $2\pi f\delta/U_\tau > 10$; however, this may be a result of scalable microphone

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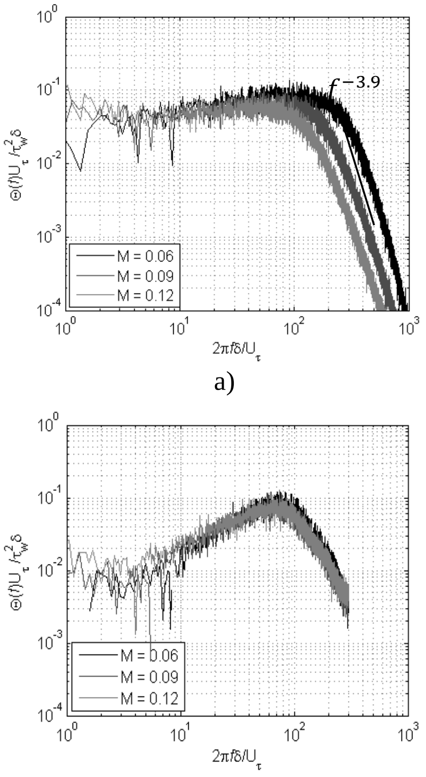
attenuation, disguised as flow-similarity. The steep spectral decay for $2\pi f\delta/U_\tau \geq 10^2$ shown by both data sets, is an indication of a not fully-developed boundary layer. This region, describing wall-pressure energy from the logarithmic region of the boundary layer, should exhibit a much shallower decay ($\propto f^{-1}$) but instead, the spectra exhibit a decay rate proportional to $f^{-3.9}$ (Fig. 1a). This decay rate is typical of the transition from overlap to high-frequency regimes.



a)

b)

Figure 1: Normalized single-point wall-pressure spectrum as measured with a) pinhole cap, and b) grid cap configurations

Figure 2 shows a comparison between measured and predicted spectra at $M = 0.12$. One can observe that low- and mid-frequency (f < 1 kHz) spectrum is best predicted by Efimtsov's model. Goody's model over-predicts spectral energy above 50 Hz, but most accurately captures the decay rate over higher frequencies (f > 1 kHz). No model accurately predicts the steep roll-off beginning around 1 kHz, and only Goody's model predicts a spectral peak. Both models account for an appreciable contribution from the overlap region (1 kHz < f < 50 kHz), which is not exhibited in the measured spectra; the absence of which, is believed to be the root cause for the discrepancies between experimental and predicted spectra above 1 kHz. Although Efimtsov's model less accurately predicts spectral decay rates above 1 kHz, it shows a much better agreement with experimental data over the low- and mid-frequency ranges and therefore, appears to be most appropriate for predicting wall-pressure fluctuations at low Mach numbers.

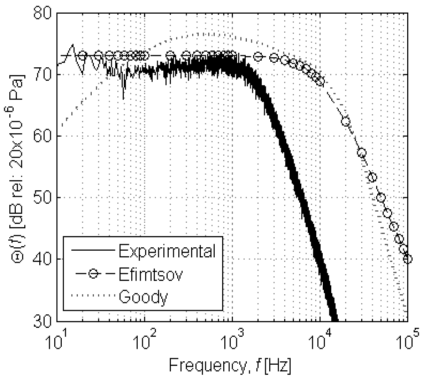


Figure 2: Wall-pressure spectrum for $M = 0.12$, as measured with the pinhole microphone, compared to existing semi-empirical models

Conclusions

The Efimtsov model is shown to best predict spectrum levels over the low- and mid-frequency ranges, while the overlap spectral energy decay rate is best predicted by the Goody model. For future work, the applicability of models by Goody and Efimtsov, and other models, will be re-evaluated with a fully developed TBL. A trip system is being installed in the wind tunnel to artificially develop the boundary layer, so that scaling variable dependencies can be better evaluated.

Acknowledgements

The authors are grateful for the support from the Natural Sciences and Engineering Research Council of Canada, and collaboration with Bombardier Aerospace.

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