Experimental application of pseudo-equivalent deterministic excitation method for the reproduction of a structural response to a turbulent boundary layer excitation

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Abstract. The use of wind tunnels for studying the vibrational response of structures subjected to turbulent flows presents various challenges, such as background noise and complex setup requirements. This work introduces an alternative experimental method called X-PEDEm (eXperimental Pseudo-Equivalent Deterministic Excitation) that aims to reproduce an equivalent structural response to a Turbulent Boundary Layer (TBL) excitation without the need for a wind tunnel. X-PEDEm involves coupling the experimental acquisition of the structure's vibrational response with deterministic forces, such as an impulse force from a hammer, followed by post-processing. The method has been validated for different boundary conditions and flow speeds, offering versatility in recreating various types of TBL. While not an exact reproduction of turbulent flow-induced responses, X-PEDEm provides an optimal approximation with low time and resource requirements, making it easy to implement experimentally.

Introduction

In the field of transportation vehicle design and production, such as aircraft, ships, trains, and automobiles, there is ongoing research on the sound emissions caused by the interaction between fluids and structures. A key area of focus is predicting how structures respond to Wall-Pressure Fluctuations (WPFs) generated by a Turbulent Boundary Layer (TBL).

Currently, researchers rely on semi-empirical models, often represented as 2-points Cross-Spectral Density (CSD) functions like the Corcos model [1]. However, these models can be computationally intensive when applied in Finite Element Analysis (FEA) and have limitations in representing responses across a broad frequency range [2]. Consequently, there is a growing interest in alternative experimental methods for predicting the structural response to TBL excitation. Many researchers have used loudspeakers as a means to reproduce a TBL-like pressure field, but this approach can also present challenges [3, 4].

In this study, the authors aim to experimentally validate an alternative method based on the Pseudo-Equivalent Deterministic Excitation method (PEDEm) [5]. The potential of PEDEm and its numerical validation for experimental purposes have been previously presented [6]. Here, the focus is on experimentally validating the application of PEDEm, referred to as X-PEDEm, considering different sample panels under different boundary conditions and subjected to TBL excitation at various flow velocities.

Background theory and methodology

Leaving the reader free to explore how PEDEm was created and developed [5, 6], here the main formulations are presented in Eq. 1-3 and discussed.

$$[S_{FF}(\omega)] = \sum_{i=1}^{NG} d_i(\omega)\{\Theta^{(i)}\}\{\Theta^{(i)}\}^T \tag{1}$$

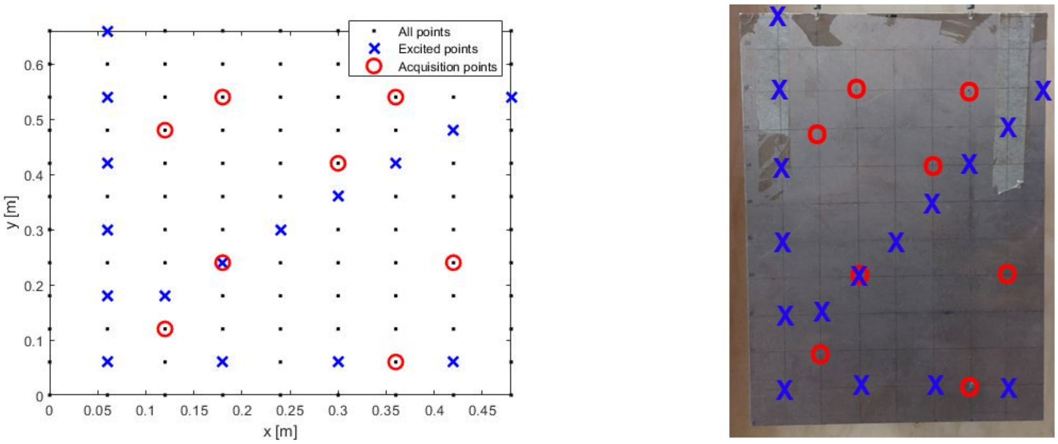
$$\{w(\omega, i)\} = [\Phi][H(\omega)][\Phi]^T\{\Theta^{(i)}\}\sqrt{d_i(\omega)} \tag{2}$$

$$[S_{WW}(\omega)] = \sum_{i=1}^{NG}\{w(\omega, i)\}^*\{w(\omega, i)\}^T \tag{3}$$

PEDEm is based on the reformulation of the CSD displacement matrix $[S_{WW}(\omega)]$ as shown in Eq. 2 and Eq. 3 by considering the modal decomposition of the CSD load matrix $[S_{FF}(\omega)]$ in eigenvectors $\{\Theta^{(i)}\}$ and eigenvalues $d_i(\omega)$ as expressed in Eq. 1. In particular, PEDEm considers two asymptotic behaviors of these eigensolutions:

- in a low frequency (LF) domain, the eigensolutions represent a spatial distribution totally correlated, for which the eigenvector matrix $[\Theta]$ is an all-1 matrix and only the first eigenvalue is non-null;
- in a high frequency (HF) domain, the eigensolutions represent a spatial distribution totally uncorrelated, for which the eigenvector matrix is an identity matrix, and all eigenvalues are equal and non-null.

X-PEDEm uses the same equations and the same asymptotic behaviors of PEDEm for the post-processing phase of experimental data that can be obtained with an easy experimental campaign as a hammer test. Indeed, X-PEDEm requires just the acquisition of the experimental Frequency Response Functions (FRFs) between acquisition points and excitation points. The acquisition points can be chosen randomly, and they should not be less than five, while the excitation points must respect the position configuration shown in Fig. 1a and they should not be less than ten.

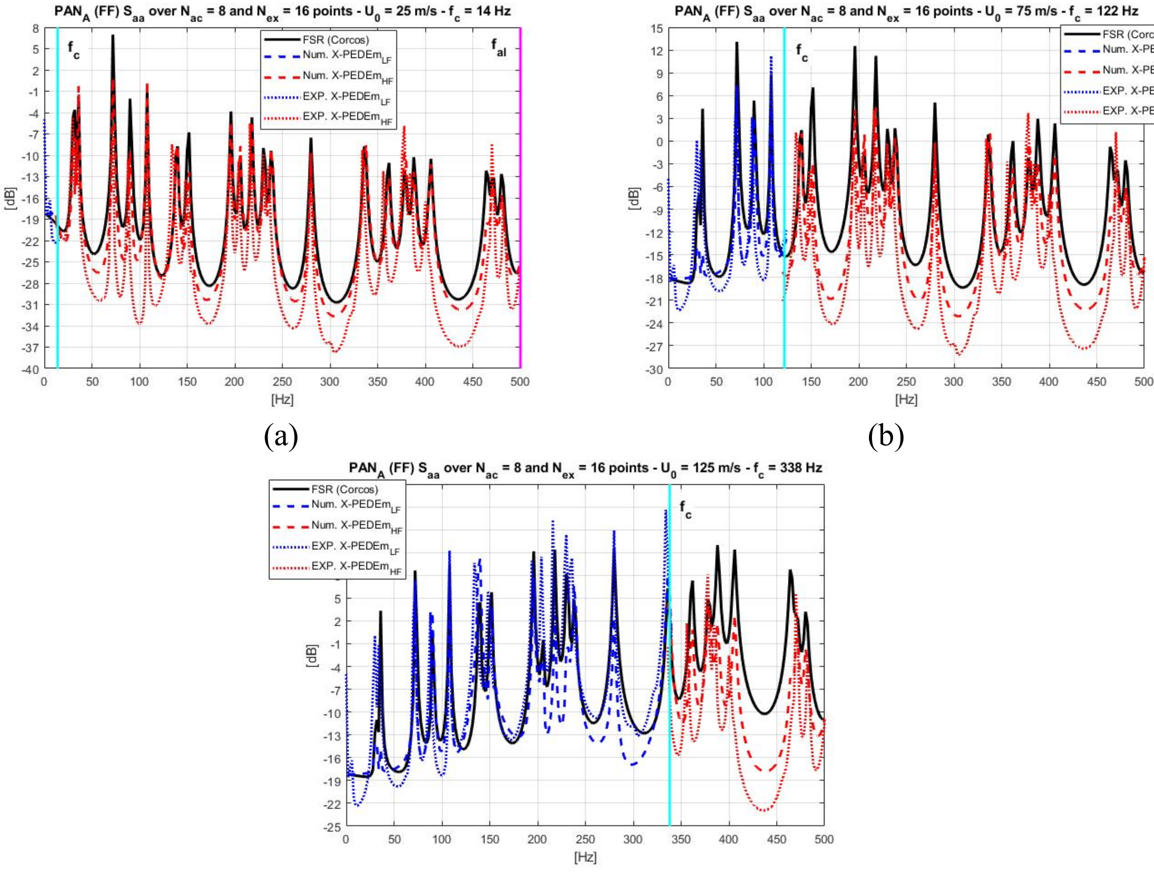


(a) (b)

Fig. 1 – Selection of acquisition points (red circles) and excitation points (blue crosses) over the structural mesh of sample panel "PAN_A". (a) Numerical mesh; (b) experimental mesh.

Experimental method validation

X-PEDEm has been experimentally validated with a hammer test campaign performed over three different sample panels, for three different boundary conditions and for different flow velocities. For a matter of space, only the results for panel "PAN_A" (Fig. 1b), with totally free edges as boundary conditions, are here shown in Fig. 2. The numerical FSR is here considered as reference solution and it is calculated by using the Corcos model [1] with the following empirical coefficients values: $\alpha_x = 0.116$, $\alpha_y = 0.700$ and $U_c = 0.8U_0$. X-PEDEm, on the other hand, has been evaluated by using the experimental FRFs collected during the hammer test campain by considering the acquisition and excitation points shown in Fig. 1b. The numerical formulation of X-PEDEm, developed with a MATLAB© code, is shown too for further validation. It is possible to appreciate how X-PEDEm (numerical and experimental) is able to follow the numerical FSR solution for three different flow velocities U_0. With the increase of U_0, the convective coincidence frequency f_c increases too. f_c is used as approximated indicator to establish which asymptotic behavior one should refer to: below the f_c, the asymptotic behaviour for LF domain is considered, while above f_c, it is chosen the asymptotic behavior for HF domain.



(a) (b)

(c)

***Fig. 2** – Comparison between the FSR calculated with Corcos model (solid black line), numerical X-PEDEm solution (dashed line) and experimental X-PEDEm obtained with a hammer test (dotted line); blue color for X-PEDEm in the LF domain, red color for X-PEDEm in the HF domain. (a) Solution for* $U_0 = 25$ *m/s; (b) solution for* $U_0 = 75$ *m/s; (c) solution for* $U_0 = 125$ *m/s.*

Conclusions

X-PEDEm proves to be valid as alternative experimental method for the reproduction of the structural response to a TBL excitation. It can be performed with an easy experimental set-up and with fast post-processing of the experimental data. It ensures versatility for what concerning type of panels, boundary conditions and asymptotic flow velocities. It may be pointed out that a hammer test is not able to maintain reliable FRFs in a broadband frequency region, but X-PEDEm can be performed with different experimental tools, as for example a shaker.

Nevertheless, there are still some open issues:

- It is important to find an accurate indicator that establish the frequency limits for the two asymptotic behaviors.
- A direct comparison between the experimental results obtained in a wind tunnel and the ones obtained with X-PEDEm is required for a final validation of the method.

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