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Vibroacoustic simulations with non-homogeneous TBL excitations: Synthesis of wall pressure fields with the Continuously-varying Uncorrelated Wall Plane Waves approach

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ABSTRACT

In this paper, a numerical method is presented to predict the vibroacoustic response of a vibrating structure excited by a spatially inhomogeneous turbulent boundary layer. It is based on the synthesis of different realizations of random pressure fluctuations that can be introduced as loadings of a vibro-acoustic model (such as a finite element model). The vibro-acoustic response is finally deduced by averaging the responses for the different loads. To generate the pressure fluctuations of the non-homogeneous turbulent boundary layer, the Uncorrelated Wall Plane Wave (UWPW) approach used so far for homogeneous boundary layers is extended. On a first step, this extension is based on a decomposition of the excited surface into sub-areas and on the averaged parameters of the boundary layer on each sub-area. In a second step, it consists in considering the interaction between the sub-areas and a refinement of the sub-area decomposition. This leads to the Continuously-varying Uncorrelated Wall Plane Waves (C-UWPW) approach. The accuracy of the proposed approach is investigated on a rectangular panel of variable thickness and excited by a growing turbulent boundary layer triggered at one edge of the plate. Comparisons with the spatial approach, usually used but with very long computation times, are presented. The interests of the proposed approach in terms of accuracy and computation time are discussed. An illustration of the proposed approach to predict the radiated noise from a blade immersed in a water flow will be proposed during the oral presentation.

1. INTRODUCTION

Vibrations induced by the wall pressure under a turbulent boundary layer is a major concern in the design of vehicles. Such vibrations cause structure wear and are a source of disturbing interior noise. Predicting the vibroacoustic behaviour of structures excited by a turbulent flow is an important issue for improving vehicle longevity and passenger comfort.

Most of the literature dealing with the vibratory response of structures excited by turbulent boundary layer (TBL) consider a spatially homogeneous excitation as in [1-7] for plate cases and [8, 9] for cylindrical shell cases. However, many industrial applications show vibrating structures underneath a growing TBL or with curved surfaces for which the pressure loading can no longer be considered homogeneous spatially. Few attentions have been carried out to this topic whereas the influence of an inhomogeneous TBL cannot be negligible on the vibroacoustic behaviour of the structure. This has been have recently highlighted by the present authors on a rectangular plate with a variable thickness and excited by a TBL triggered at the upstream edge of the plate [10]. In this context, this article aims to propose an efficient and versatile process for predicting the vibratory response of a structure excited by a non-homogeneous TBL. This process relies on an extension of the Uncorrelated Wall Plane Waves (UWPW) method developed some year ago for homogeneous TBL [11] and validated against others numerical results and experimental results in [12-13]. It consists in the synthesis of different realizations of the TBL wall pressure field considering the spatial variations of the TBL parameters. These realizations can then be easily used as loadings of any vibroacoustic model. The theoretical developments of this extension have been recently presented in [14]. We describe and illustrate the different steps of this process in the present paper. The accuracy of the proposed approach is investigated on a rectangular panel of variable thickness and excited by a growing turbulent boundary layer triggered at one edge of the plate. Comparisons with the spatial approach are proposed. The interests of the proposed approach in terms of accuracy and computation time are discussed.

2. THE CONTINUOUSLY-VARYING UNCORRELATED WALL PLANE WAVES (C-UWPW) METHOD

Let us illustrate the application of the C-UWPW approach [14] on a rectangular panel excited by a growing turbulent boundary layer triggered at one edge of the plate as shown in Fig. 1. The plate thickness is linearly varying in the stream-wise direction to stress the effect of the spatial evolution of the TBL.

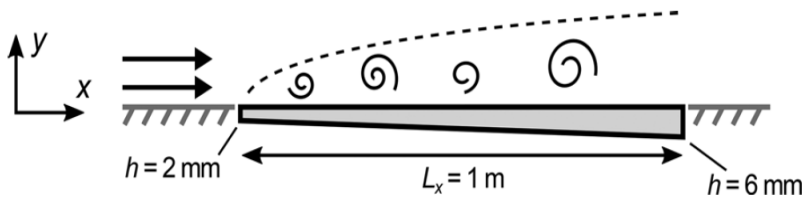

Fig. 1. Plate excited by a growing turbulent boundary layer triggered at the leading edge

The TBL is assumed triggered by a strip of sandpaper at the plate edge x=0 m. For this academic case, the TBL parameters are estimated with an analytical model for a flat smooth plate [15]. This model for 2-D incompressible flow supposes a zero pressure gradient and external velocity constant and equal to the free stream velocity. The laminar and transitional regions are neglected. For more complex geometries, computational fluid dynamics simulations can be used to estimate the TBL parameters at the surface of the vibrating structure. Figure 2 illustrates the TBL parameters obtained with the analytical model and for a flow speed of 40 m/s.

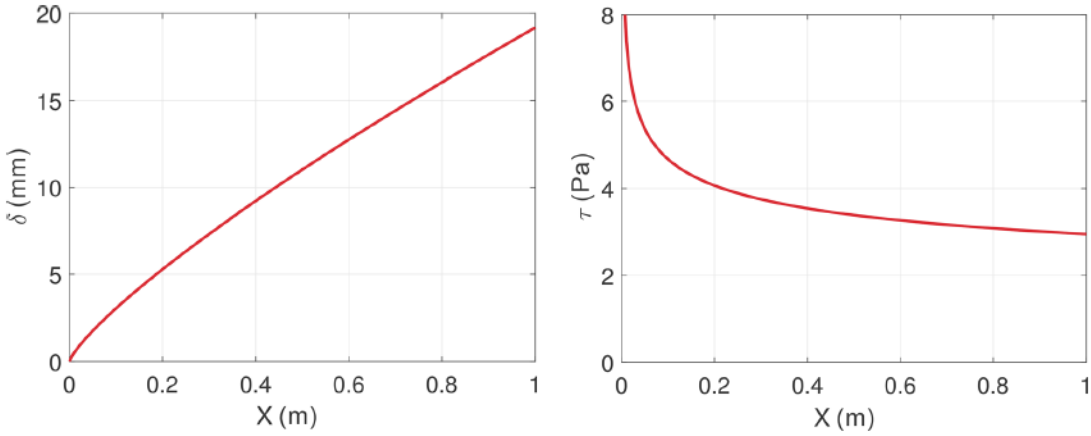

Fig. 2. TBL thickness and shear stress variations along the x-axis for a flow speed of 40 m/s.

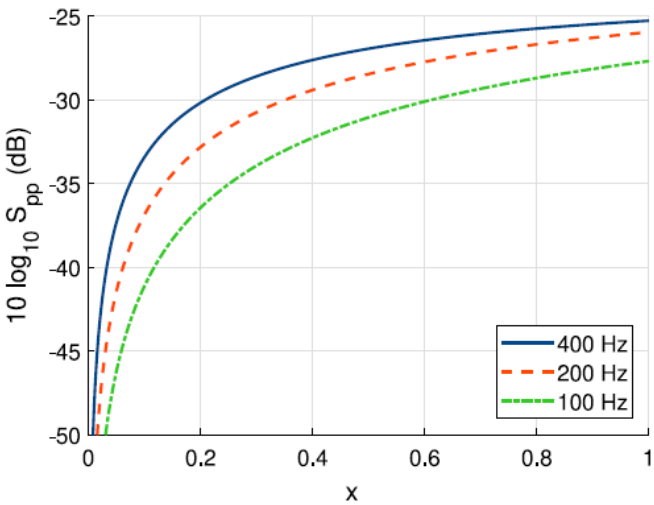

Fig. 3. Variations of the auto-spectrum of the wall pressure induced by the TBL.
Results of the Goody model using the TBL parameters of Fig. 2.

The cross-spectrum density of the wall pressure field (WPF) induced by the TBL, $\Phi_{pp}^{X}(\mathbf{k},\omega)$ should then be estimated at any point X on the plate area in the wavenumber-frequency space $(\mathbf{k},\omega)$. To do that, the Goody model [16] and the Mellen model [17] are considered to define, respectively, the autospectrum and the normalized cross-spectrum density of the wall pressure. The spectrum of these models are evaluated by considering the TBL parameter values at the point X to give us $\Phi_{pp}^{X}(\mathbf{k},\omega)$. An illustration of the pressure auto-spectrum variations is given in Fig. 3.

The UWPW method [11] consists in generating different realizations of the WPF induced by the TBL and to use them as loadings of a vibroacoustic model, typically a FEM model [12, 13]. The pressure fields are synthetized by considering a set of uncorrelated wall plane waves mimicking the TBL. In the case of an inhomegenous TBL, the amplitudes of the wall plane waves should vary continuously to represent the spatial variations of the excitation strength. It is carried out using the Continuously-varying Uncorrelated Wall Plane Waves (C-UWPW) method [14]. The blocked pressure of a realization *r* is then given by:

$$p_b^r\left(\mathbf{X},\omega\right)=\sum_{\mathbf{k}\in\mathbf{\Omega}_\mathbf{k}}\sqrt{S_{A_\mathbf{k}A_\mathbf{k}}\left(\mathbf{X},\omega\right)}\exp\left[\mathrm{i}\left(\mathbf{k}.\mathbf{X}+\varphi_\mathbf{k}^r\right)\right], \tag{1}$$

where :

- $S_{A_\mathbf{k}A_\mathbf{k}}$ is the autospectrum the space-varying wave amplitudes given by $S_{A_\mathbf{k}A_\mathbf{k}}\left(\mathbf{X},\omega\right)=\dfrac{\Phi_{\mathrm{pp}}^{\mathrm{X}}\left(\mathbf{k},\omega\right)\delta k^2}{4\pi^2}$;
- $\varphi_\mathbf{k}^r$ are random phases uniformly distributed in $\left[0;2\pi\right]$ expressing the fact that the waves are uncorrelated;
- $\mathbf{\Omega}_\mathbf{k}$ define the sets of wavenumbers inside the considered truncated wavenumber space with a wavenumber resolution δk in the streamwise and crosswise directions.

An illustration of two realizations of the pressure field is given in Fig. 4. The increase of the pressure amplitude along the streamwise direction can be noticed as well as the small wavelengths related to the convection of the vortices.

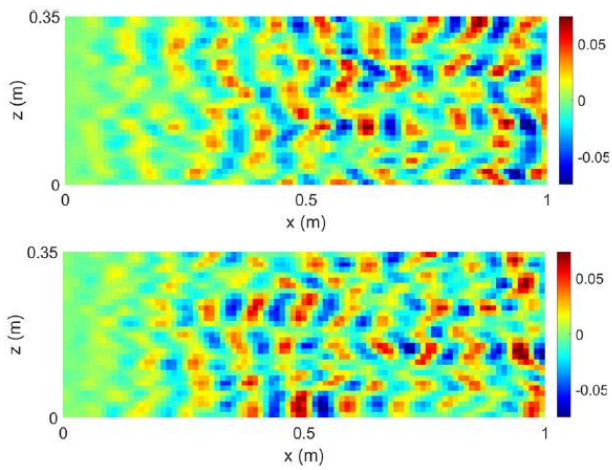

Fig.4. Two realizations of the wall pressure field at 277 Hz.
Results of Eq. (1) using the cross-spectrum density of the WPF evaluated with the TBL parameters of Fig. 2.

For each realization *r* of the synthetized pressure field, the panel velocity response at the point M, $v_M^r\left(\omega\right)$ can be computed using the vibroacoustic model of the considered system (for instance, FEM for the present plate). An illustration of the responses of the plate to the two synthesized pressure fields of the Fig. 4 is shown in Fig. 5. It can be noticed that the plate responses are different for the two loadings for this frequency (i.e. 277 Hz) corresponding to an anti-resonance, halfway through the fifth and sixth natural modes. Moreover, the wavelengths are larger than those of the synthetized pressure field and they can be associated to the flexural motions of the plate.

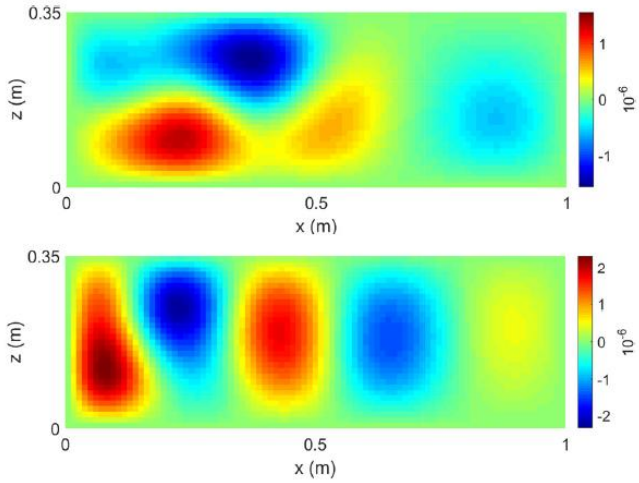

Fig. 5. Velocity response of the plate for the two pressure loadings shown in Fig. 4.

The previous steps (i.e. generation of the WPF and calculation of the plate response) are repeated for N^r realizations (typically 30, see [12-14]). The auto-spectrum of the plate velocity at point M in response to the TBL excitation is then deduced by an ensemble average over the responses, $v_M^r(\omega)$ for $r \in [\![1, N^r]\!]$:

$$S_{v_M v_M}(\omega) = \mathrm{E}\left[v_M^r(\omega) \overline{v_M^r}(\omega) \right]_r = \frac{1}{N_r} \sum_{r=1}^{N_r} \left| v_M^r(\omega) \right|^2 \tag{2}$$

Fig 6 shows the response for 30 realizations and the ensemble average. For a validation purpose, the response of the plate to the growing TBL excitation calculated by the present C-UWPW process was compared to the response calculated with the spatial approach (see [14]). An excellent agreement was observed. In terms of computing time, the spatial method required 32 min per frequency point whereas only 1 min was necessary for the C-UWPW method.

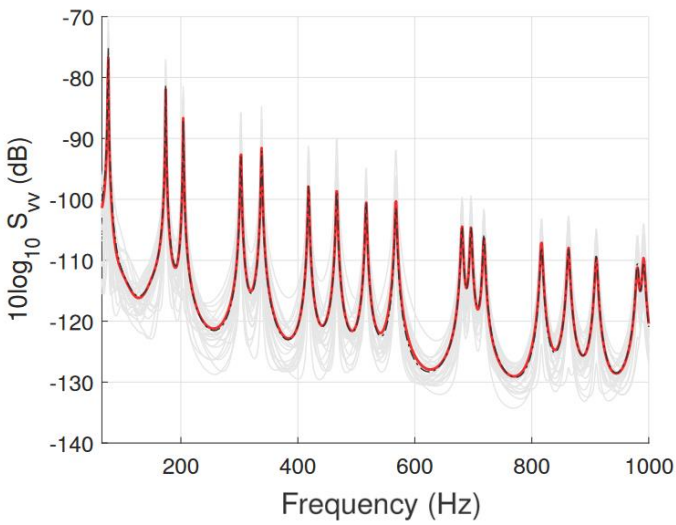

Fig. 6. Illustration of the mean square velocity response of the plate:
Gray, responses for the 30 realizations; Red, response to the TBL excitation (i.e. ensemble average of the 30 realizations)

Finally, to highlight the interest for taking the spatial variations of the TBL parameters in the vibroacoustic calculations, the differences of plate mean square velocities between the inhomogeneous TBL case and a supposed homogeneous TBL case are plotted in Fig. 7. The TBL parameters of the supposed homogeneous case correspond to an arithmetic average of the parameters shown in Fig.4 for the inhomogeneous case. Three observations can be made:

- first, the curve related to the spatial approach and the one related to the C-UWPW approach are very close on the whole frequency range. This shows that the C-UWPW approach is well adapted to describe the effect of the spatial variations of the TBL on the plate vibrations.
- Second, significant differences (between 2 and 6 dB) can be observed on the whole frequency range between homogeneous and non- homogeneous cases. This shows that assuming the TBL as homogeneous can lead to important errors.
- Finally, the differences are not monotonic in frequency. For some particular frequencies (around 250 Hz and 510 Hz), the absolute differences can be significantly higher than for the other frequencies. When looking at the modal frequencies, these two frequencies correspond to the 5th and 13th modes. The modal shapes of these two modes are plotted in Fig. 8. The first half (i.e. $0 < x < L_x/2$), where the plate is thinner, the deformation of the plate is significant, while the second half (i.e. $L_x/2<x<L_x$), remains undeformed. As highlighted in Fig. 5, the TBL excitation is maximum near the trailing edge (x close to L_x) whereas it is negligible near the leading edge (x close to 0). The exciting pressure fails to excite these modes and so their response is lower compared to the one obtained supposing a homogeneous TBL.

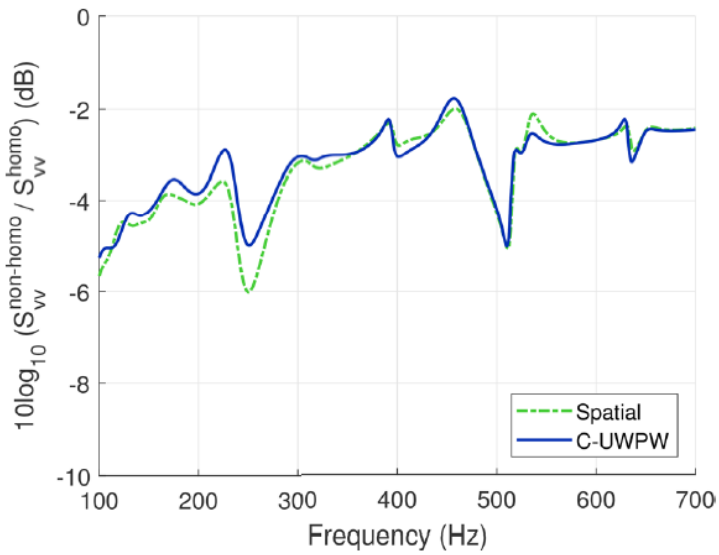

Fig. 7. Difference of mean square velocity (dB) between the non-homogeneous TBL case and the supposed homogeneous TBL case. Two calculations: the spatial approach and the presented C-UWPW approach.

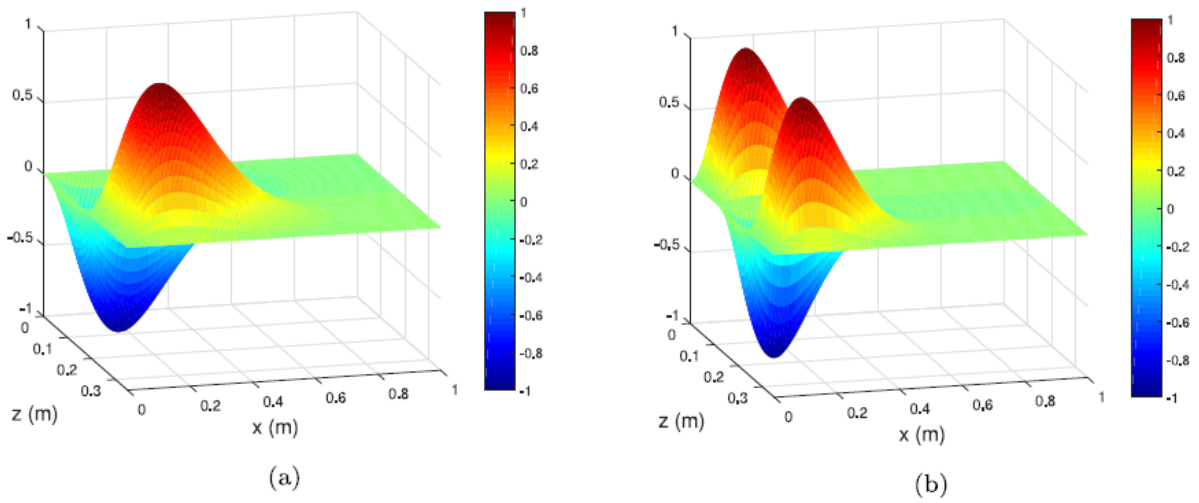

Fig. 8. Illustration of the two modes of the plate with a varying thickness having their natural frequencies at the dips of the spectrum of Fig.7 (i.e. around 250 Hz and 510 Hz).

3. CONCLUSION

A numerical process has been described for predicting the response of vibrating structures excited by a non- homogeneous turbulent boundary layer. The theoretical fundaments of this approach can be found in [14] (based on some works presented in [10]). This process makes it possible to consider the spatial variations of the TBL parameters in vibroacoustic simulations. The C-UWPW method is significantly less time consuming, in terms of computation, than the classical spatial approach because it is not necessary to achieve a double summation on transfer functions that should be estimated between many nodes of a FEM model. In the C-UWPW method, the number of vibroacoustic calculations is limited to the number of realizations considered (typically 30).
Comparison of a C-UWPW calculation describing the inhomogeneous TBL and another one supposing the TBL as homogeneous shows a significant difference (up to 6 dB) on the panel velocity response. This highlights the importance of taking the spatial variations of the TBL parameters into the vibroacoustic simulations with the proposed C-UWPW approach.

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