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The reproduction of the response of an aircraft panel to turbulent boundary layer excitations in laboratory conditions

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ABSTRACT

One important topic in the aeronautic and aerospace industries is the reproduction of random pressure field, with prescribed spatial correlation characteristics, in laboratory conditions. In particular, the random-wall pressure fluctuations induced by a Turbulent Boundary Layer (TBL) excitation are a major concern for cabin noise problem, as this excitation has been identified as the dominant contribution in cruise conditions. As in-flight measurements require costly and time-consuming measurement campaigns, the laboratory reproduction has attracted considerable attention in recent years. Some work has already been carried out for the laboratory simulation of the excitation pressure field for several random fields. It has been found that TBL reproduction is very demanding in terms of number of loudspeakers per correlation length, and it should require a dense and non-uniform arrangement of acoustic sources due to the different spanwise and streamwise correlation lengths involved. The present study addresses the problem of directly simulating the vibroacoustic response of an aircraft skin panel using a near-field array of suitably driven loudspeakers. It is compared with the use of an array of shakers and piezoelectric actuators. It is shown how the wavenumber filtering capabilities of the panel reduces the number of sources required, thus dramatically enlarging the frequency range over which the TBL vibro-acoustic response is reproduced with accuracy. Direct reconstruction of the TBL-induced panel response is found to be feasible over the hydrodynamic coincidence frequency range using a limited number of actuators driven by optimal signals. It is shown that piezoelectric actuators, which have more practical implementation than shakers, provide a more effective reproduction of the TBL response than near-field loudspeakers.

INTRODUCTION

The problem of simulating multivariate and multidimensional random processes with prescribed spectral density characteristics has been extensively addressed in the past decades [1] both theoretically and experimentally for the synthesis of real-world acoustic or vibration environments. These methods have been assessed within different areas for the experimental synthesis of partially correlated signals, like the reproduction of pseudorandom time histories of the response of a four-track vehicle to the Gaussian excitation induced by road surface roughness [2], or for simulating the spatial variation of seismic ground motions recorded over extended areas [3]. Although there exists theoretical [4] and analytical [5] studies in the scientific literature, these methods are not sufficiently developed for the simulation of the spatial properties of random process partially correlated, like the acoustic excitation due to a diffuse pressure field or aerodynamic excitations like Turbulent Boundary Layer .

As an example, a common problem in building acoustics is the variability of the characterisation of the isolating properties of the partitions. The laboratory characterisation is affected by the modal behaviour of the transmission facility. To make the measurement of the incident power more reliable at low frequencies, the applicants have proposed a novel approach based on the reconstruction of the statistical properties of an acoustic diffuse field over the surface of a test partition. This method uses a near-field array of suitably driven loudspeakers acting over a grid of microphones in the proximity of the structure under study [6]. Theoretical results have shown that this approach is efficient in providing a measure of the sound reduction index that only depends on the properties of the panel itself [7].

In the aeronautical and aerospace industries, there is a timely interest in the laboratory simulation of random loads over components subject to high fluctuating pressure levels (embarked satellites at take-off) or over the fuselage (jet noise). Acoustic Progressive Wave Tube (APWT) facilities are currently used for simulating the dynamic response and the sonic fatigue of aeronautical structures. They are able to reproduce the spectral excitation distribution at high levels, but not the spatial correlations [8]. Therefore, the authors have investigated how the proposed control system could synthesise propeller-induced noise excitations, readily modelled as a grazing incident plane wave of random phase and amplitude [8].

The aeronautical industry is also concerned with cabin noise problems and their impact on discomfort and the integrity of the electronic equipment. The noise induced by the TBL pressure fluctuations developed over the fuselage of well-streamlined aircraft is important during cruise conditions. The use of design modifications and noise control measures provides some opportunity for reducing the boundary layer noise in the cabin assuming that a characterization of the TBL-induced noise can be made either from flight tests or low-noise wind tunnel experiments. Initially, a diffuse sound pressure field was used to mesure the TBL-induced response [9], but, for pressure fields of the same intensity, a diffuse field is more efficiently exciting the panel resonances [10]. Other authors have also proposed the use of an array of loudspeakers [4], driven to reproduce the TBL excitation on the panel under study, or to optimised a set of punctual forces applied over the surface of the partition [5]. The theoretical results outlined from the study indicated that it was possible to reproduce the TBL excitation, but the physical implementation was not possible due to electronic limitations at this time.

Non-resonant excitations could be generated using an array of acoustic sources. They would produce acoustic waves impinging on the test panel with a range of trace velocities, thus being able to synthesize decaying correlation functions such as the one due to a TBL. Maury *et al*. have presented a simulation study that assumes an array of near-field loudspeakers driven by optimal signals in order to generate a random pressure field able to reproduce the statistics of TBL wall-pressure fluctuations [11]. The target pressure field was specified in terms of the Cross-Spectral Density (CSD) matrix between the outputs of an array of sensors when subject to a TBL excitation. It was observed that, due to the exponential decay of the correlation area with frequency, it would be limited to the very low frequency range given a reduced set of loudspeakers.

The authors have recently shown the practical feasibility of a multichannel simulation of a TBL excitation over a plane grid of microphones using a near-field array of acoustic sources [12]. By means of the exact proper orthogonal decomposition of the random process associated to a TBL, a theoretical lower bound has been established on the number of uncorrelated components required for an accurate approximation of a TBL pressure field, at least 2.1 sources per unit spanwise correlation length. An experimental set-up has been designed for the synthesis of an acoustic diffuse field, a grazing incident plane wave and a TBL using a near-field array of 4×4 loudspeakers driven by an Arbitrary Waveform Generator [12]. The optimum drive signals were determined from knowledge of the spatial correlation characteristics to be reproduced and prior identification of the acoustic transfer functions between the loudspeakers and an array of 13×16 microphones close to the simulation surface. The array of loudspeakers was situated inside a semi-anechoic chamber to assess the physical limitations of the synthesis technique.

The methodology has shown to be successful for the laboratory simulation of an acoustic diffuse field and a grazing incident plane wave, up to 1 kHz and 650 Hz, respectively. However, for the TBL reproduction, the synthesis technique has shown acceptable accuracy only up to about 200 Hz. A greater and denser number of loudspeakers could enlarge the upper frequency limit, but for a typical aircraft skin panel, this would require small-sized loudspeakers with necessarily reduced performances in the low frequency range.

The present study proposes an alternative methodology based on the direct synthesis of the TBL-induced panel response. Next section presents the framework for synthesizing the TBL or the velocity response of a panel subject to a TBL together with the determination of the optimum drive signals to an array of actuators. Computer simulation results are discussed then, when reproducing the TBL or the TBL-induced response using a near-field array of loudspeakers or structural actuators. The performance of the different strategies is then compared for a given number of actuators. Finally, we provide recommendations concerning the implementation of such strategies.

THEORETICAL BASIS

In this section we provide the methodology proposed for the synthesis of the vibro-acoustic response of the panel subjected to a TBL. We will start with the description of the TBL excitation model, to continue with the determination of the optimum signals to drive the array of transducer used for the synthesis.

TBL excitation model

The reproduction of the TBL pressure field needs a model to describe mathematically the spatial correlation characteristics to be reproducted. Most of the works dealing with a TBL field uses the Corcos model [13], that provides a $\mathbf{S}_{dd}$ matrix which is particularly well suited to describe the statistics of TBL wall-pressure fluctuations induced by high-speed subsonic flows such as for aircraft boundary layers:

$$S_{dd}(r;\omega)=S_0(\omega)\,\mathrm{e}^{-|r_x|/L_x}\,\mathrm{e}^{-|r_y|/L_y}\,\mathrm{e}^{-\mathrm{j}\,\omega\, r_y/U_c}\,, \qquad [1]$$

where U_c is the flow convection velocity, L_x and L_y are the correlation lengths along the spanwise (or *x*-direction) and streamwise (or *y*-direction) respectively. They are assumed to be inversely proportional to frequency, and have the form

$$L_x=\frac{\alpha_x\,U_c}{\omega}\,, \qquad [2]$$

$$L_y=\frac{\alpha_y\,U_c}{\omega}\,, \qquad [3]$$

where α_{x} and α_y are empirical constants taken to be respectively 1.2 and 8. Unless otherwise stated, the convection velocity is assumed to be 92 ms^{-1}, which corresponds to a flow Mach number of 0.45.

This spatial correlation function is presented in Figure 1 along the spanwise and streamwise directions. As it can be appreciated, it is an exponentially decaying function of frequency and oscillates along the streamwise direction due to the convection effect. The time decay is more rapid along the spanwise with respect to the streamwise direction. When reproducing the excitation pressure field, this is the “ideal” target function that will be considered in the optimisation procedure.

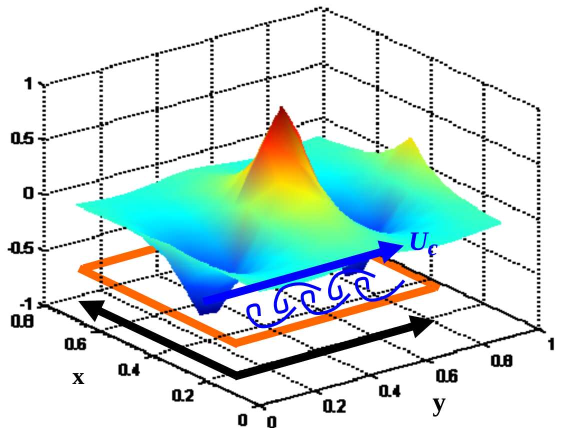

Figure 1: Theoretical correlation as a function of the normalised separation distance between two microphones of a TBL pressure field

Simulation approach

In this section we will outline the main equations for the determination of the optimum drive signals to a near-field array of loudspeakers, depending on the physical quantities to be reproduced, namely the velocity or the acoustic panel response. Futher details can be found in the references [6, 7, 11, 12].

The general synthesis method for the reproduction of random forcing pressure fields with given spatial correlation characteristics considers an array of near-field loudspeakers, driven with signals optimised for the simulation of the desired pressure field, $\mathbf{d}$, over an array of regularly spaced microphones located in the proximity to the panel surface, as shown in Figure 2.

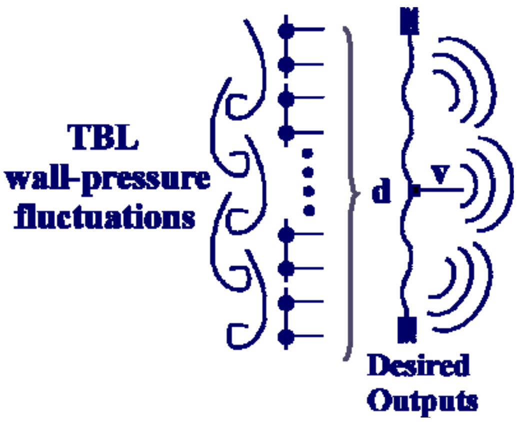

Figure 2: Block diagram showing the measured TBL signals for the reproduction of the excitation and of the induced-velocity response

The expression for the CSD matrix between the target pressure signals reads

$$\mathbf{S}_{dd} = \mathrm{E}\left[\mathbf{d}\,\mathbf{d}^{\mathrm{H}}\right] = \mathbf{D}\,\mathbf{S}_{xx}\,\mathbf{D}^{\mathrm{H}} = \mathbf{D}\,\mathbf{D}^{\mathrm{H}}, \qquad [4]$$

where it is assumed that the vector $\mathbf{d}$ is generated from a set of uncorrelated white noise reference signals, $\mathbf{x}$, *via* a matrix of shaping filters, $\mathbf{D}$, E denotes the expectation operator, and $^{\mathrm{H}}$ the Hermitian, complex conjugate transpose.

For the reproduction of the excitation over the grid of microphones over the panel, a matrix of control filters, $\mathbf{W}$, is determined that generates the optimum input signals to the array of loudspeakers, which drive the microphone outputs $\mathbf{y}$, *via* the plant transfer matrix $\mathbf{G}$, to be statistically equivalent to the target pressure field $\mathbf{d}$. At each frequency, the vector of error signals is defined to be

$$\mathbf{e} = \mathbf{d} - \mathbf{y} = (\mathbf{D} - \mathbf{G}\,\mathbf{W})\,\mathbf{x}, \qquad [5]$$

and the optimum least-squares matrix of control filters $\mathbf{W}$ is given by

$$\mathbf{W}_{\mathrm{opt}} = [\mathbf{G}^{\mathrm{H}}\mathbf{G}]^{-1}\mathbf{G}^{\mathrm{H}}\mathbf{D} = \mathbf{G}^{\dagger}\mathbf{D}, \qquad [6]$$

when the cost functions being minimized is the sum of the Mean Square Error signals normalized by the sum of the corresponding mean-square sensor outputs. where $\mathbf{G}^{\dagger}$ denotes the pseudo-inverse of $\mathbf{G}$. We note that synthesis of the TBL simulation with acoustic sources requires knowledge of the transfer function matrix $\mathbf{G}$ between all pairs of loudspeakers and microphones, and the matrix of shaping filters, $\mathbf{D}$, calculated from Eq. [4] using an eigen-decomposition of $\mathbf{S}_{dd}$.

The optimal value of the objective function for the field reproduction takes the form

$$J_{\mathrm{opt,d}} = \frac{\mathrm{Tr}\left[\left(\mathbf{I} - \mathbf{G}\mathbf{G}^{\dagger}\right)\mathbf{S}_{dd}\right]}{\mathrm{Tr}\left[\mathbf{S}_{dd}\right]}, \qquad [7]$$

We can also consider as the objective function the simulation of the TBL-induced velocity response, using a set of equations analogous to Equations [5-7]. We can define an error function as the difference between the desired signal, the TBL-induced velocity, and the ones reproduced by the array of actuators as

$$\mathbf{e}_v = \mathbf{v} - \mathbf{y}_v = \mathbf{G}_v\left(\mathbf{D} - \mathbf{G}\mathbf{W}\right)\mathbf{x} \qquad [8]$$

and the optimum least-squares matrix of control filters $\mathbf{W}_v$ is given by

$$\mathbf{W}_{\mathrm{opt},v} = \left(\mathbf{G}_v\mathbf{G}\right)^{\dagger}\mathbf{G}_v\mathbf{D} \qquad [9]$$

In this case, the simulation of the TBL-induced velocity response requires knowledge of $\mathbf{G}_v\mathbf{G}$, the transfer function matrix measured between all pairs of loudspeakers and velocity sensors, of $\mathbf{D}$, the target filter matrix, and of $\mathbf{G}_v$, the transfer mobility matrix, associated to the panel velocity response due to a unit point force excitation. This latter quantity can be determined from modal analysis of the panel vibrations and can be modelled as series of the panel normal modes. The optimal value of the objective function for the induced-response reproduction takes the form

$$J_{opt,v} = \frac{\mathrm{Tr}\left[\left(\mathbf{I} - \mathbf{G_v G}\left(\mathbf{G_v G}\right)^{\dagger}\right)\mathbf{S}_{vv}\right]}{\mathrm{Tr}\left[\mathbf{S}_{vv}\right]} \quad . \qquad [10]$$

In this context, the use of structural actuators such as miniature shakers or piezoelectric patches has also been investigated. The shakers exert normal forces over the rod-panel contact surfaces, and so can be used to simulate both TBL forcing pressures at these discrete positions, but also the TBL-induced velocity response. In this case, $\mathbf{G}$ in Equations [5-7] is the plant matrix between all pairs of input drive signals to the shakers and the applied normal forces measured by the shakers impedance heads. It is a diagonal gain matrix which might also account for off-diagonal cross-coupling effects through the shakers inertial back-reaction to the panel vibrations.

The piezoelectric rectangular elements are distributed actuators symmetrically bonded on either side of the panel surface and activated 180° out-of-phase, so that they cause uniform bending moments along their edges over the panel surface [14]. Therefore, they cannot be used in order to simulate wall-pressure fluctuations. However, they are suitable candidates to reproduce the vibrating response of a panel to a TBL excitation, as shown in the next section.

SIMULATION RESULTS

The analytical simulations presented here consider the two previous reproduction strategies: the simulation of the excitation TBL pressure field or the reproduction of the induced-vibroacoustic response of the partition under study. For both strategies, different types of actuators can be used for the reproduction of the desired signal. We will consider here the use of an array of loudspeakers and the use of an array of the same number of shakers, both optimised according to Equations [6] and [9].

The physical configuration taken to study the performance of the synthesis methodology corresponds to a typical aircraft structure, an aluminium panel, with simply supported boundary conditions. The parameters values are summarised in Table 1.

The simulation results obtained for the synthesis method are presented in the next two subsections.

TBL reproduction with an array of loudspeakers

We will start analysing the performance for the proposed methodology when using an array of loudspeakers for the synthesis of the excitation TBL excitation field first, and the velocity induced response later. It should be noted here that although we have not optimised the positions for the actuators, it is desirable to perform also a proper selection of the number a position for the actuators.

Table 1: Airflow and panel parameters

Parameter	Value
Free-stream velocity	$U_\infty = 115\ \mathrm{ms}^{-1}$
Dimensions	$l_x = 0.314\ \mathrm{m}$ $l_y = 0.414\ \mathrm{m}$
Thickness	$h_p = 0.001\ \mathrm{m}$
Mass density	$\rho_p = 2700\ \mathrm{kg\ m}^{-3}$
Young's modulus	$E_p = 7 \times 10^{10}\ \mathrm{Pa}$
Poisson ratio	$\nu = 0.33$
Damping ratio	$\eta = 0.02$

In the work presented here, we have chosen a set of 3×4 loudspeakers, uniformly distributed over the panel surface, as indicated in Figure 3. The distance between the actuator and microphone arrays has been selected to ensure a good condition number for the transfer function matrix $\mathbf{G}$ between all pairs of loudspeakers and sensors.

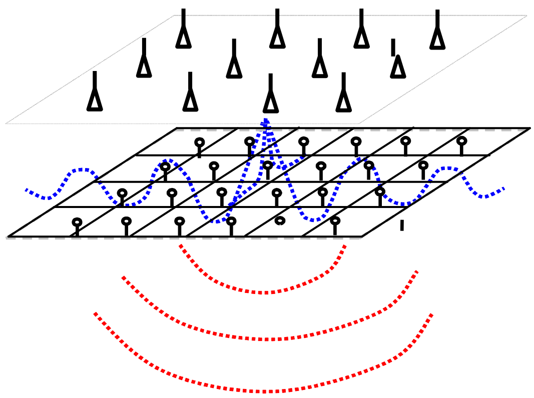

Figure 3: Physical configuration for the near-field array of loudspeakers and microphones for the synthesis of the TBL excitation field

The number of loudspeakers, as well as the number microphones and velocity sensors, has been chosen so that the corresponding 2D arrays are uniformly distributed and with an aspect ratio similar to the panel aspect ratio, $l_y / l_x \approx 1.12$. We simulated the TBL pressure field, with a free-stream velocity of $U_\infty = 115\ \mathrm{ms}^{-1}$ (Table 1) over the frequency range up to 3 KHz, covering the whole hydrodynamic coincidence frequency range, that extends up to 865 Hz in this configuration. To ensure proper convergence in the simulation, we have selected an array of 6×10 near-field microphones.

We have started analysing the simulation performance representing the panel kinetic energy due to an ideal TBL and when reproducing a number of target random fields, i.e. either the TBL excitation or the TBL-induced velocity response (Figure 4). Considering the theoretical criterion of 2.1 acoustic sources per unit spanwise correlation length for the TBL simulation [12], an array of 3×4 loudspeakers is only able to simulate the statistics of the TBL wall-pressure fluctuations up to 95 Hz along the panel *x*-direction, and up to 329 Hz along the panel *y*- direction. This is what is observed when comparing the theoretical TBL field, blue solid line in Figure 4, with the one obtained using the near field array of loudspeakers when reproducing the excitation, the black solid line. It can be verified that the reproduced curve shows significant differences from the theoretical one above about 300 Hz. With this methodology we are then limited to the low frequency range for the synthesis.

The induced-velocity response has been also superimposed in Figure 4 as a solid red line. We can observe that the performance has changed significantly, as we obtain an acceptable reproduction up to much higher frequency limit. The Mean Square Error between the theoretical value and the reproduced one (Equation 10), that provides a quantification of the accuracy simulation, stays below 5 dB up to 1.5 KHz. This error reaches its lowest levels at the panel resonance frequencies, as the panel velocity response coherence is more important and the plant response $\mathbf{G}_{\nu}\mathbf{G}$ (Equations 8-10) is well equalised by the control filters.

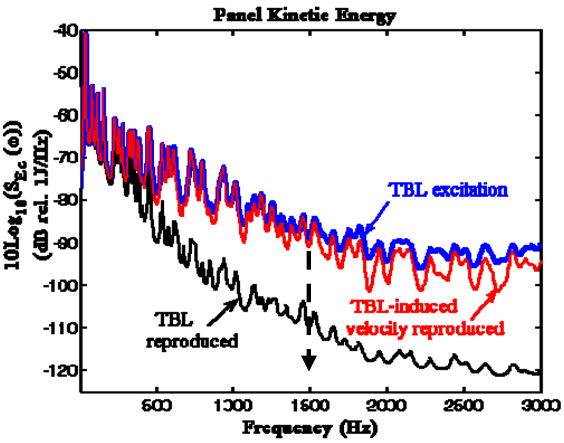

Figure 4: Panel kinetic energy due to a TBL (blue) and the one generated using a near-field array of 3×4 loudspeakers driven to reproduce the excitation (black) or the TBL-induced velocity response (red)

We have also analysed the system performance considering a spatial reproduction criterion. The spatial error calculated between the ideal target field and the one reproduced by the array of actuators can be calculated from the approximate correlation functions evaluated at the microphone positions. The spatial error, $\varepsilon_{\alpha,\beta}$, associated to the field α when reproducing the field β takes the form

$$\varepsilon_{\alpha,\beta} = \frac{\left\| \mathbf{S}_{y_{\alpha,\beta}y_{\alpha,\beta}} - \mathbf{S}_{\alpha,\beta;\alpha,\beta} \right\|}{\left\| \mathbf{S}_{\alpha,\beta;\alpha,\beta} \right\|}, \qquad [11]$$

where the subindices can refer to d , for the TBL excitation and to v for the induced velocity response.The norm of the correlation function matrices are defined as

$$\left\| \mathbf{S} \right\| = \sqrt{\mathrm{Tr}\left[\mathbf{S}^{\mathrm{H}}\mathbf{S} \right]} \ . \qquad [12]$$

The accuracy in the spatial reproduction of these corresponding correlation structures is presented in Figures 5, 6 and 7. We have plotted the CSDs approximated matrices at the panel surface calculated with respect to a sensor at the centerpoint of the simulation surface, for the driving pressures acting on the panel (left column) and for the velocity response induced on the panel (right column). The top row shows the correlation functions due to the ideal Corcos TBL model (Equation [1]), the mid row the one due to the least-squares approximation to the TBL pressure field (Equation [6]), and the bottom row the one due to the least-squares approximation to the TBL-induced velocity field (Equation [9]).

CSDs matrices have been plotted for three particular frequencies to highlight the limitations and advantages of the different reproduction strategies. Figures 5 and 6 show the results at 275 Hz and 634 Hz respectively, for which the modes (3,2) and (5,1) are highly excited by the TBL when they are resonant. These frequencies fall within the hydrodynamic coincidence frequency range. At 275 Hz, in accordance with the above theoretical criterion, a near-field array of 3×4 loudspeakers is sufficient to reproduce the TBL correlation function. This can be verified in Figure 5 for the middle left subplot. We can clearly appreciate that the TBL peak value is under-estimated for the excitation, but the corresponding approximate induced velocity response is much better reproduced (from Figure 5, middle right), as it requires a fewer number of sources for its reproduction, due to a correlation area larger than the TBL at this frequency.

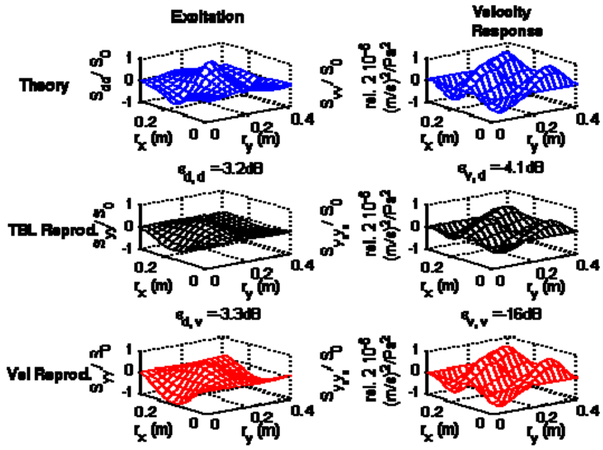

Figure 5: Spatial correlation structures at 275 Hz for the excitation (left) and the panel velocity response (right) due to a TBL (top) and when the TBL (middle) or the velocity are reproduced (bottom) using 3×4 loudspeakers

At 634 Hz the accuracy in both the approximate TBL and induced velocity degrades (Fig. 6, mid row), due to an insufficient number of sources per unit correlation length in either case. In accordance with Figure 4, it can be seen that direct simulation of the TBL induced velocity response at these frequencies provides accurate results on the least-squares approximation to the panel velocity, with significant reductions of the spatial errors of about 16 dB and 5 dB, at 275 Hz and 634 Hz respectively (Figs. 5 and 6, bottom right). We note that simulating the velocity response at 275 Hz induces a beneficial backward effect on the approximate TBL (Fig. 5, bottom left), which is generated with about the same accuracy than the reproduced one (Fig. 5, middle left).

Finally, CSDs are plotted in Figure 6 at 1273 Hz that falls above the hydrodynamic coincidence frequency range and for which the mode (7,2) is resonant and weakly excited, but couples through the TBL with low-order modes which are non resonant, but highly excited. Clearly, simulating the TBL with 3×4 loudspeakers provides very inaccurate results (Fig. 6, mid row) as the panel width comprises 19 spanwise correlation lengths at this frequency. The theoretical criterion then predicts that an array of 40×52 acoustic sources would be required for an accurate TBL simulation, which is an unrealistically large amount of sources. However, a very reduced set of 3×4 loudspeakers is still able to generate with enough accuracy an approximate TBL-induced velocity response (Fig. 6, bottom right).

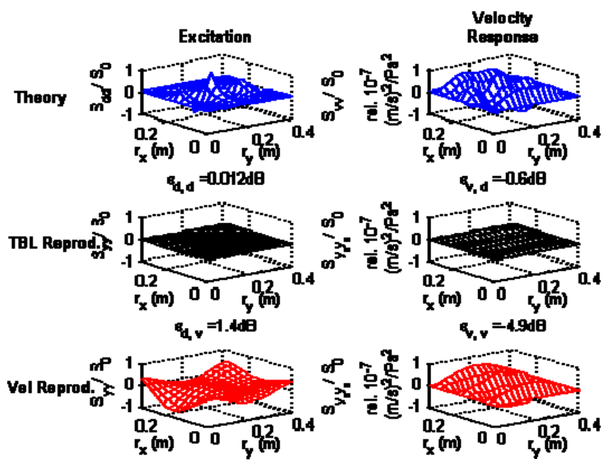

Figure 6: Spatial correlation structures at 634 Hz for the excitation (left) and the panel velocity response (right) due to a TBL (top) and when the TBL (middle) or the velocity are reproduced (bottom) using 3×4 loudspeakers.

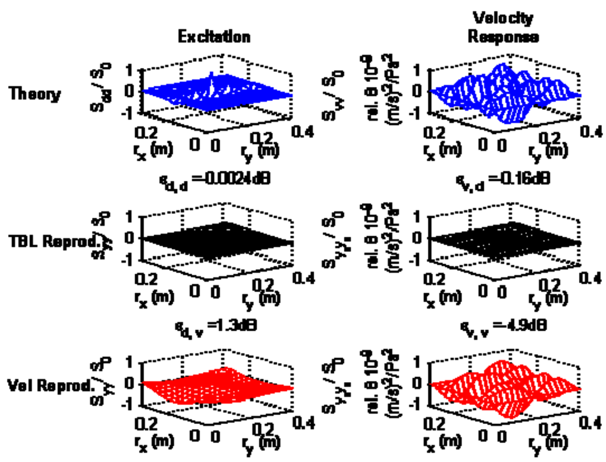

Figure 7: Spatial correlation structures at 1273 Hz for the excitation (left) and the panel velocity response (right) due to a TBL (top) and when the TBL (middle) or the velocity are reproduced (bottom) using 3×4 loudspeakers.

TBL reproduction with an array of structural actuators

The synthesis approach detailed before is applicable independently of the type of actuators used. It would be of interest to compare the results obtained when using a set of shakers and an array of piezo-patches for the reproduction of the TBL field. For that, we should maintain the physical configuration, in terms of number and positions of the transducer, identical to the previous configuration when using an array of loudspeakers, and change the corresponding transfer function matrices (Equation 5) between actuators and sensors. Piezoelectric actuators have shown to provide a good approach in other similar areas like active control of vibrating structures [15, 16]. Structural actuators can also be easily integrated into the partition under analysis, and have, then, a more practical implementation than the same array of loudspeakers of vibrating shakers.

Figure 8 shows a comparison on the performance of different actuators, using as the synthesis methodology the reproduction of the induced velocity due to a TBL field, that was shown to have better performance that the excitation reproduction. The panel kinetic energy due to an ideal TBL (solid blue line) and when using a uniform array of 3×4 loudspeakers (solid red line), shakers (solid green line) or PZT rectangular patches (solid yellow line) driven to reproduce the TBL-induced panel velocity response are compared. Results are presented up to a frequency of 3 kHz.

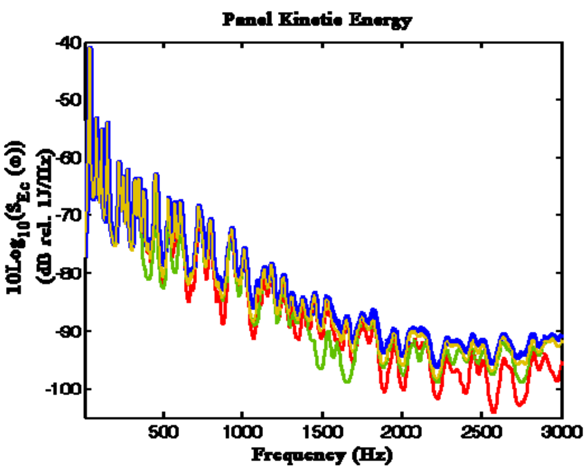

Figure 8: Panel kinetic energy due to a TBL (blue) and the one generated using an array of 3×4 actuators (loudspeakers: red; shakers: green; PZTs: yellow)

It can be seen from Figure 8 that the frequency range for simulating the TBL-induced velocity response is significantly larger when using structural actuators (up to 3 kHz) with respect to acoustic sources (up to 1.5 kHz), the most accurate results being obtained when using PZT patches. This trend occurs especially when the panel resonant contribution becomes more and more dominant with respect to the non-resonant contribution, as it is the case when the frequency increases, the difference being due to the nature of coupling between the efforts exerted by the actuators and the panel modes being excited.

It is observed in Figure 8 (green line) that the use of a uniform array of shakers is inefficient at simulating the velocity response at the resonant frequencies of the panel modes which have nodal lines at the shakers rod locations, and therefore do not couple with the point force actuators. When using PZT patches, there is still an effective moment around the nodal lines, so that the accuracy of the simulation is less selective than with an array of shakers, as clearly seen when comparing the green and yellow curves in Figure 8.

CONCLUSIONS

In this work, a framework has been presented to reproduce the induced vibro-acoustic response of a panel excited by a TBL pressure field in laboratory conditions. We have focussed on the comparison between previous investigations, reproducing the incident pressure field, and the simulation of the vibro-acoustic response of the aircraft panel. The first strategy is shown to be limited in the very low frequency range unless an unrealistic number of reproduction sources are used. In this work we have shown that the synthesis performance is greatly improved by considering the reproduction of the TBL induced-velocity field.

Numerical simulations have been performed with a typical aircraft panel configuration. Using an array of uniformly distributed loudspeakers with the same aspect ratio than the panel dimensions, i.e. 3×4 sources, one is able to simulate the panel velocity response over a broad frequency range, that extends beyond the hydrodynamic coincidence frequency.

We have also studied the use of other actuators, like vibrating shakers able to act directly over the panel dynamic characteristics, and a set of piezoelectric patches, that can be easily integrated into the structure. The performance comparison shows that the use of distributed PZT patches shows large potential for reproducing the statistics of the TBL-induced response over a broader frequency range including a large proportion of resonant modes.

Futher work in this area is directed towards the use of a cost function considering the induced-sound power radiated by the structure due to a TBL excitation, considering an array of microphones distributed on a semisphere surrounding the panel radiating side. We are also currently investigating the radiation of the structure into a cavity, to introduce into the synthesis method the influence of an enclosed sound field instead of radiation in free field, as we have considered until now.

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