Acoustic characterisation of double-orifice configurations by means of an LES-SI approach

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Summary
A numerical study of the aeroacoustic properties of a pair of orifices placed in a duct is presented. Two configurations with two different distances in between the orifices have been analysed to consider conditions with or without tonal noise sources. Large Eddy Simulations have been performed and validated with respect to experimental measurements for both aerodynamic and acoustic predictions. Data series from an acoustically excited LES have been post-processed through System Identification techniques to concurrently model noise sources and acoustic scattering. The model of the noise obtained has been used as to confirm the good prediction of the acoustic scattering.

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1. Introduction

Noise modeling and reduction are of primary importance in many industrial applications. Duct elements like contractions, edges, valves are often characterized by whistling or self sustained oscillations when a proper acoustic feedback is established. The understanding of the physical features, as well as their relative modeling, of these phenomena is therefore of fundamental interest. A common approach to study the acoustic propagation and the noise generation in duct system is based on the so-called Multiport method [1]. Thereby, the acoustic properties of a generic duct system are represented mathematically by means of an acoustic scattering matrix and of a noise vector [2]. The coefficients of the latter may be assessed analytically, experimentally or numerically. Experimentally, the acoustic scattering matrix is identified by measuring the acoustic response to given external excitations. Once the acoustic scattering of the geometry and the impedance of the surrounding environment are known, the noise sources are identified by performing measurements of the acoustic pressure fluctuations.

Within this study, we aim to assess both the acoustic scattering and the noise generated by turbulence, by employing the so called LES-SI method [3]. The latter consist in a combination of a highly resolved compressible Large Eddy Simulation with System Identification Techniques [4]. At first an acoustically excited LES is carried out. Afterwards, the acoustic data series extracted from LES are post-processed through SI procedures to assess the acoustic active (noise) and passive (scattering) properties of the system under study. The LES-SI method has been successfully employed to identify the acoustic scattering of multiple ducted configurations such as sudden area expansion [5], T-junction [6] or orifice [7]. Subsequently the aforementioned procedure has been extended by [8] to concurrently assess both the acoustic scattering and the noise sources by means of a single excited LES. Thereby, by introducing a new identification approach based on the so-called Prediction Error Methods (PEM) it is possible to completely characterize both active and passive acoustic properties of a given configuration. Within this work we aim to assess the acoustic scattering of a duct in which two orifices have been placed inside, often called, "double-orifice" or "double diaphragm" configuration. The same configurations have been already analysed by means of LES by Sengissen et al. [9] to numerically predict the noise, generated by turbulence by measuring pressure fluctuations in the region near the orifices.

Nevertheless, a correct identification of the aeroacoustic noise may be achieved only if the acoustic scattering of the domain has been assessed in the identification procedure. Indeed, the acoustic pressure fluctuations measured in a duct system are due to a superposition of acoustic waves generated by turbulence and their propagation in the domain. To the authors knowledge, a complete study to assess and model both the acoustic active and passive properties of the present duct system is still missing. Finally, the complete characterization of the aeroacoustic proper-

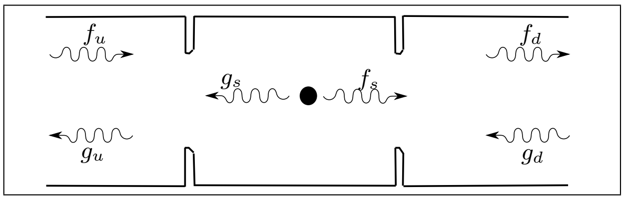

Figure 1. Multiport schema

ties of simple duct sections, like double orifice configurations, let to build low order network models of more complex duct systems by connecting different discrete acoustic elements. Thereby ,it is possible to analyse various acoustic environments where several sources of noise may be present.

2. Duct Acoustic

The propagation of plane acoustic waves in an element can be described by means of the so called Multiport formulation [1]:

$$\begin{Bmatrix} f_d \\ g_u \end{Bmatrix} = \underbrace{\begin{bmatrix} T^+ & R^- \\ R^+ & T^- \end{bmatrix}}_{\text{Scattering Matrix}} \begin{Bmatrix} f_u \\ g_d \end{Bmatrix} + \underbrace{\begin{Bmatrix} f_s \\ g_s \end{Bmatrix}}_{\text{Source Vector}} \tag{1}$$

The terms f_u and g_d represents two characteristic acoustic waves entering the domain, whereas f_d and g_u are two characteristic waves leaving the configuration analysed. Subscripts u and d indicate the region immediately upstream or downstream the element of interest. The acoustic propagation in Eq. (1) is described by means of the so-called scattering matrix, where the coefficients $T^{\pm}$ and $R^{\pm}$ represent the transmission and reflection at the up- and downstream end of the element, respectively. The noise generation due to aero-acoustic phenomena is modeled through a source vector $\{f_s, g_s\}$. In linear regime, the noise source acts like an additional terms on the outgoing acoustic waves f_d and g_u. The acoustic scattering is therefore not influenced by the presence of additional noise due to turbulent pressure fluctuations.

3. The LES-SI Method

The numerical method adopted to characterize the acoustic properties of the double orifice configurations under analysis is the so-called LES-SI Method [3]. This method consists in a combination of a highly resolved compressible Large Eddy Simulation (LES) with System Identification techniques (SI) [4]. At first an acoustically excited LES is carried out. Subsequently, acoustic data series extracted from the computational domain are post-processed by means of SI to characterize the acoustic properties of the ducted system. In the present study, the acoustic scattering matrix and the noise source of Eq. (1) are identified by means of the so-called Prediction Error Method (PEM) [4]. Indeed, under the hypothesis of a linear, time invariant system, Eq. (1) can be modeled through the Box-Jenkins model (BJ)[8]:

$$y_{BJ}(t) = \frac{B(q,\Theta)}{F(q,\Theta)}u(t) + \frac{C(q,\Theta)}{D(q,\Theta)}e(t), \tag{2}$$

where $u(t)$ represents the system input (LES external excitation), $y_{BJ}(t)$ the output and $e(t)$ a Gaussian White Noise (GWN) of variance σ_e^2. The term q represents the time-shift operator:

$$y(t-1) = y(t)q^{-1}. \tag{3}$$

On the one hand, the polynomials B, F of parameters Θ model the acoustic propagation. On the other hand, the noise source is taken into account by means of the polynomials C, D. These last two polynomials filter an unpredictable error term $e(t)$ (GWN), in order to properly describe the noise generated by turbulence.

Since $e(t)$ is unpredictable, Eq. (2) is rewritten in the prediction form [4],

$$\begin{aligned} \hat{y}_{BJ}(t,\hat{\Theta}|t-1) = & \frac{D(q,\hat{\Theta})B(q,\hat{\Theta})}{C(q,\hat{\Theta})F(q,\hat{\Theta})}u(t) \\ & + \frac{C(q,\hat{\Theta}) - D(q,\hat{\Theta})}{C(q,\hat{\Theta})}y_{LES}(t), \end{aligned} \tag{4}$$

where $\hat{\Theta}$ represents the estimation of the parameters Θ and $y_{LES}(t)$ are the acoustic data series extracted from LES. The identification process consist in finding a proper parametrization $\hat{\Theta}$ to model the acoustic propagation from LES by means of Eq. (2). With PEM, this is achieved by minimizing the error between the acoustic response measured from LES and the acoustic response modeled by the BJ model:

$$\hat{\Theta} = \arg\min_{\hat{\Theta}} \left\{ \left(y_{LES}(t) - \hat{y}_{BJ}(t,\hat{\Theta}|t-1) \right)^2 \right\} \tag{5}$$

4. Geometries and Flow Conditions

The configurations analysed consist in a pair of orifices placed in a duct. The downstream edge of the orifices is chamfered. Two different distances L have been investigated to consider both resonant and non resonant conditions. Within this work we use the same notation as used in [9] to refer to the cases considered: L1D and L2D respectively. Geometrical details are reported in Fig. (2) and Table I. The Bulk Velocity has been fixed to $4.1m/s$ for both the cases analysed to match the velocity measurements (Laser Doppler Anemometry, LDA) performed at LMFA *Ecole Centrale of Lyon*.

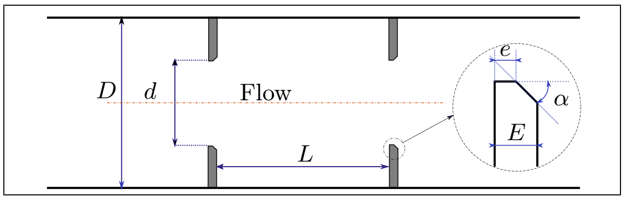

Figure 2. Geometriy sketch

Table I. Geometry details

Case Name	L1D	L2D
D	$50mm$	$50mm$
L	$1D = 50mm$	$2D = 100mm$
d	$28mm$	$28mm$
E	$1.8mm$	$1.8mm$
e	$0.9mm$	$0.9mm$
α	49.7°	49.7°
h	$11mm$	$11mm$

5. LES and Validations

The CFD solver adopted within this work is AVBP, developed by CERFACS and IFP-EN. This solver allows to perform a highly resolved Large Eddy Simulation on orthogonal and non-orthogonal meshes. The spatial and temporal discretization adopted consists in a second order Lax-Wendroff scheme. In order to assess accurately both the acoustic scattering properties and the noise generation, the wall has been resolved. Therefore, the first cell element has been positioned at $y^+ = 4$ unit wall. Moreover, the computational grid has been axially refined in proximity of the edges of the orifices to afford a better resolution of the small vortical eddies. The meshes adopted contain around 6.0Mio elements and 6.5Mio elements for the L1D and the L2D case respectively. The time step has been fixed to ensure a CFL number of 0.7, once a steady flow condition has been reached. Acoustically non-reflecting boundary conditions, based on a modified version of the Navier Stokes Characteristic Boundary Conditions [10] and a Plane Wave Masking have been adopted [11]. These boundary conditions afford completely acoustically non-reflecting boundaries, improving the quality of the identification results.

The LES solution has been validated w.r.t the measurements carried out at LMFA, by considering both aerodynamic and acoustic properties of the simulated flow field. On the one hand, aerodynamic characteristics, fundamental for a good prediction of the acoustic scattering, have been compared with experiments at 11 different measurement plane sections. On the other hand, the acoustic pressure fluctuations have been assessed and compared with the measurements from a microphone M positioned in the middle of the two orifices. The position of the measurement planes and of the microphone are reported in Fig. (3) The aero-

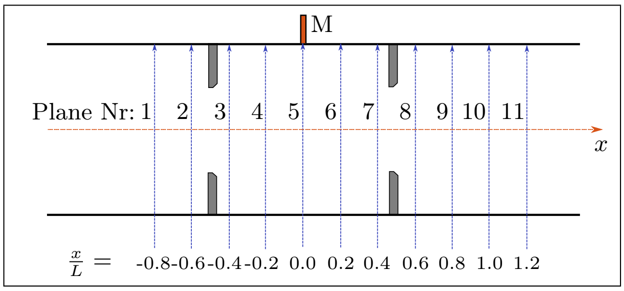

Figure 3. Plane and microphone positions

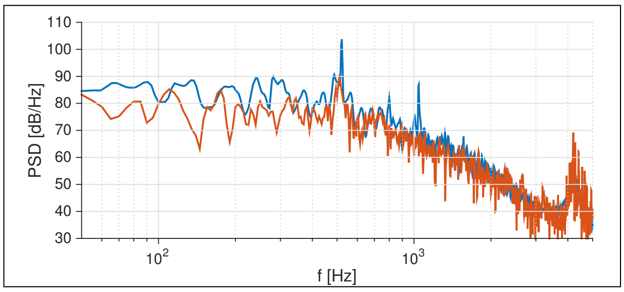

Figure 6. PSD of pressure fluctuations at microphone M for the L1D case: blue line experiment, red line LES results

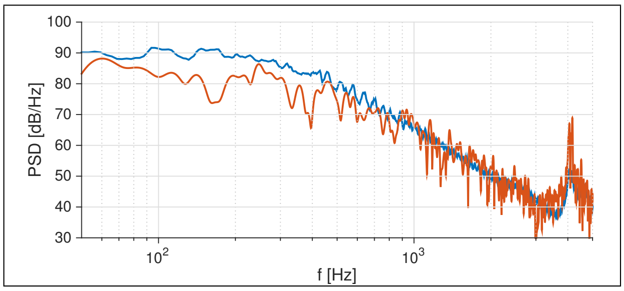

Figure 7. PSD of pressure fluctuations at microphone M for the L2D case: blue line experiment, red line LES results

dynamic axial flow velocity reported in Fig. (4) and Fig. (5) show a good agreement between the LES results and the LDA. The axial velocity profile imposed in the simulations at the Plane 1 coincides with the ones measured in experiment. The most important deviations from experiments may be seen at Plane 5 in between the two orifices for both cases analysed. This is indeed a region of high turbulence fluctuations due to the intense vorticity generation that takes place at the first diaphragm. Therefore, a possible reason of this disagreement in the mean axial velocity is mainly a too short averaging time, in this case, $t_{av} = 0.1$s. The acoustic power spectral density of wall pressure fluctuations measured at microphone M are reported and compared with LES results in Fig. (6) and Fig. (7) for the L1D and L2D case, respectively. The decay of broadband noise is well predicted for both cases. The spectral densities predicted by LES at low frequencies (around $100-300$Hz) are slightly lower than the experiment. This is mainly due to the non-reflecting boundary conditions adopted in the LES. Indeed, the

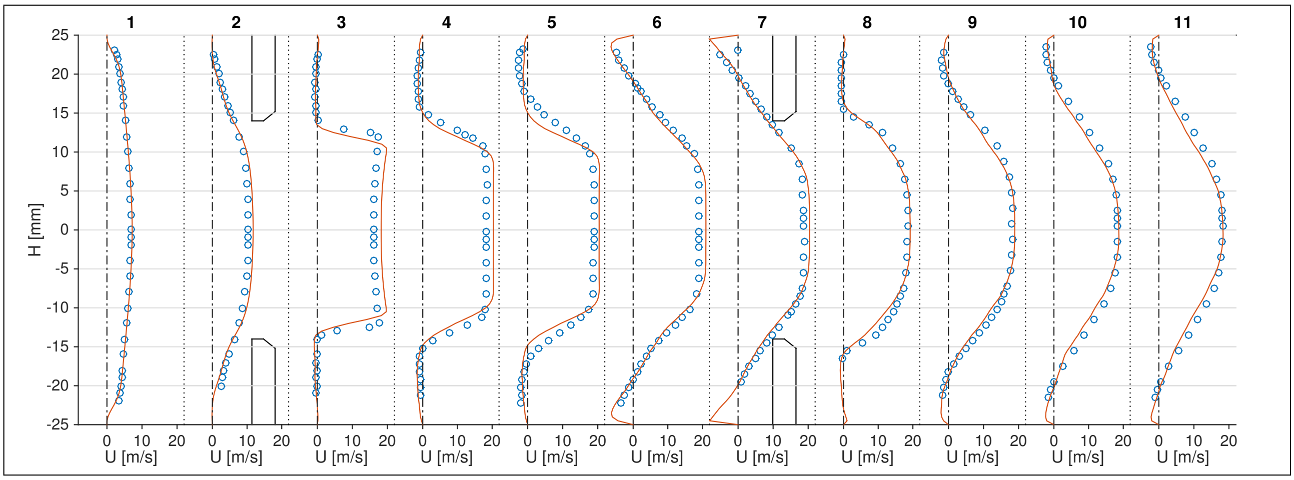

Figure 4. Mean axial velocity profiles at different plane sections for the L1D case. Blue circle: experiment LDA measurements. Red lines: LES results

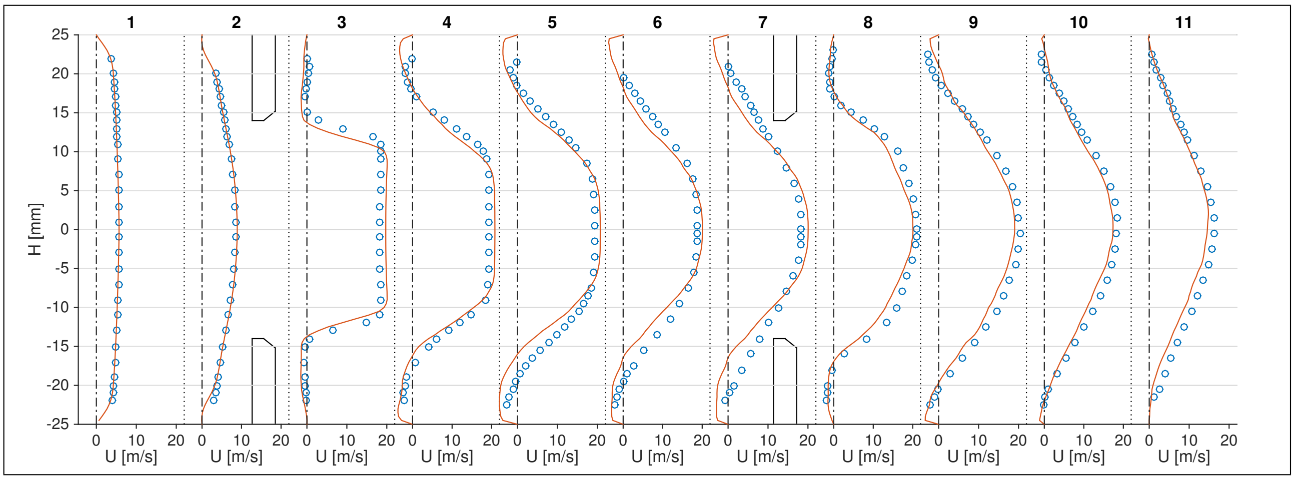

Figure 5. Mean axial velocity profiles at different plane sections for the L2D case. Blue circle: experiment LDA measurements. Red lines: LES results

experiment anechoic terminations present significant reflections at low frequencies [9], whereas the boundary conditions based on the Plane Wave Masking approach afford completely non-reflecting boundaries. The experimental power spectral density in Fig. (6) for the L1D case presents a tonal noise at 520Hz and a second tonality at 1050Hz. These tonalities are due to the vortexes released at the first orifice impinging the leading edge of the second orifice, as shown in [12]. The LES results present just a tonality at 510Hz but no tonality have been observed around 1050Hz. Here again, reflections at boundaries may play a central role on the amplitude of resonant frequencies. In spite of these differences, the noise spectra and the mean flow fields are overall well predicted by the LES. Therefore, the simulated noise predictions have been used as reference to apply the LES-SI method and characterize the acoustic propagation in the two cases as explained in the next section.

6. Results

In this section the LES-SI method presented in Sec. (3) is applied to the L1D and L2D configurations to determine both the noise sources and the scattering matrices. Results are validated against LES without external acoustic excitation, whose noise and aerodynamic predictions have been compared with experiments in the previous section. An acoustically excited LES has been carried out for both cases. The excitation imposed consists in a broadband signal with constant power spectral density in the plane wave frequency range: $[0-3000]$Hz. The upper frequency limit has been defined to not excite higher order acoustic modes. Moreover the amplitude of the excitation signal has been limited to 2% of the Bulk Velocity in order to not introduce non linear response of the shear layers developed at the orifice sections. The acoustic scattering matrix and the noise spectra have been modeled according to Eq. (2). Hereby, the use of a PEM to find a proper model parametrization as de-

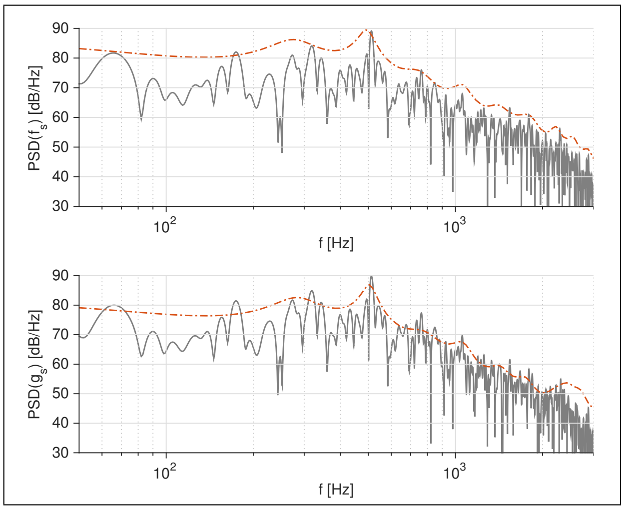

Figure 8. L1D case. PSD of pressure fluctuations of a non excited LES: grey line. Identified noise spectra from LES-SI: dash-dotted red line

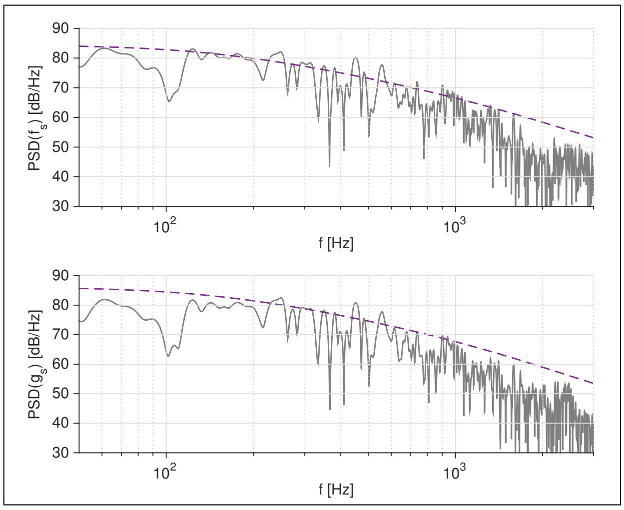

Figure 9. L2D case. PSD of pressure fluctuations of a non excited LES: grey line. Identified noise spectra from LES-SI: dashed viola line

scribed in Eq. (4) and Eq. (5) allows to identify concurrently both the Noise Sources and the acoustic scattering with just a single excited LES. Therefore a good prediction of the Noise properties of the configurations my means of LES-SI can only be achieved if and only if a good prediction of the acoustic scattering has been carried out. Indeed the output $y_{BJ}(t)$ of the BJ model in Eq. (2) depends on both noise terms and system response to a given input $u(t)$. Hence, the minimization of Eq. (5) determines a parametrization to describe completely the acoustic properties of the studied configurations. The models of the noise power spectral density for the L1D case and for the L2D case are reported in Fig. (8) and Fig. (9) respectively. The reader should take care that the PSDs of the noise reported in grey in the aforementioned figures, are not the same as the one in Fig. (6) and Fig. (7) . Indeed, acoustic waves are extracted from LES at the boundaries and not in the middle of the two orifices. Therefore, the identified noise models are compared with the acoustic pressure fluctuations assessed directly at the boundaries of the computational domain. The identified noise models are in overall good agreement with the power spectral density of the noise extracted from a non excited LES. The broadband noise decay is correctly captured for the L1D case, whereas a small deviation may be observed at high frequency ($f > 2000$Hz) for the L2D case. The tonal noise observed in the LES for the L1D case without excitation is identified by the LES-SI procedure (see Fig. (8)): a small increment in the power spectral density of the noise model is observed around 500Hz. The identified PSDs for the f_s source term in Fig. (8) it is shifted at slightly higher amplitude in the range of frequencies analysed. The reason of this discrepancy is still under investigation.

The gains and the phases of the acoustic scattering matrix identified by means of LES-SI are reported in Fig. (10) and Fig. (11). No experimental results on the acoustic scattering are available in the literature, therefore, a direct validation is not possible. Nevertheless the good predictions obtained for the noise, may be only achieved if both acoustic scattering and noise source are concurrently identified and modeled. In order to compute the phases reported in Fig. (11) the two configurations have been considered as compact. Therefore, the phase shifts for the reflection coefficients R^+ and R^- have been compute w.r.t the center point in between the two singularities. The phase of the coefficients of the scattering matrix T^+ and T^- presents almost a linear trend in frequency domain.

7. Conclusions

A concurrent System Identification of the noise sources and of the acoustic scattering of double orifice configurations has been carried out. Hereby, a correct characterization of the noise sources may be performed if both noise and scattering are correctly identified. The LES results have been successfully validated against the experimental campaign performed at LMFA *Ecole Centrale of Lyon* The LES-SI procedure yields a good model of the noise sources extracted from the LES. Finally the scattering matrix of both the configuration L1D and L2D has been successfully identified by means of the LES-SI method.

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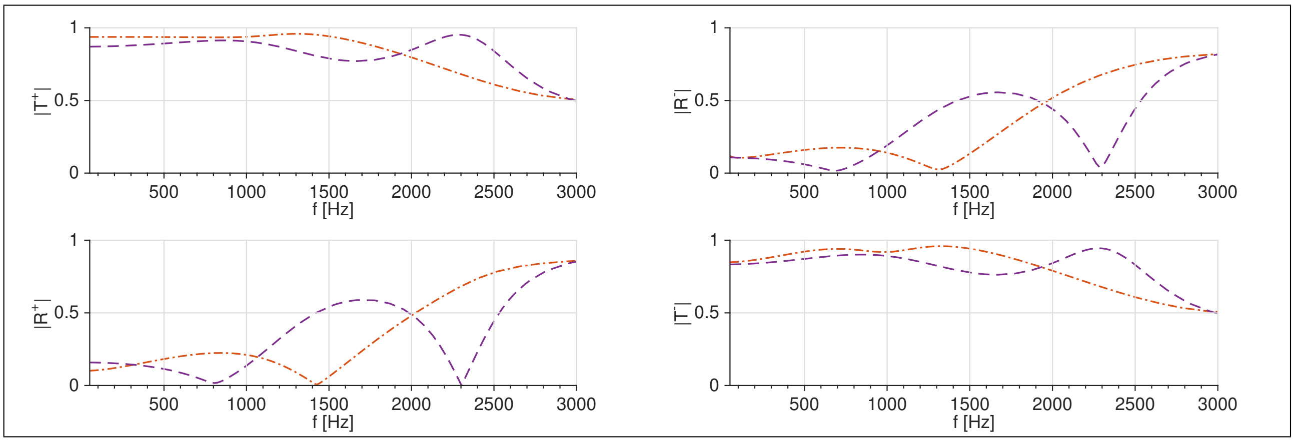

Figure 10. Gain of the identified acoustic scattering matrices. Dash-dotted red: L1D. Dashed viola: L2d

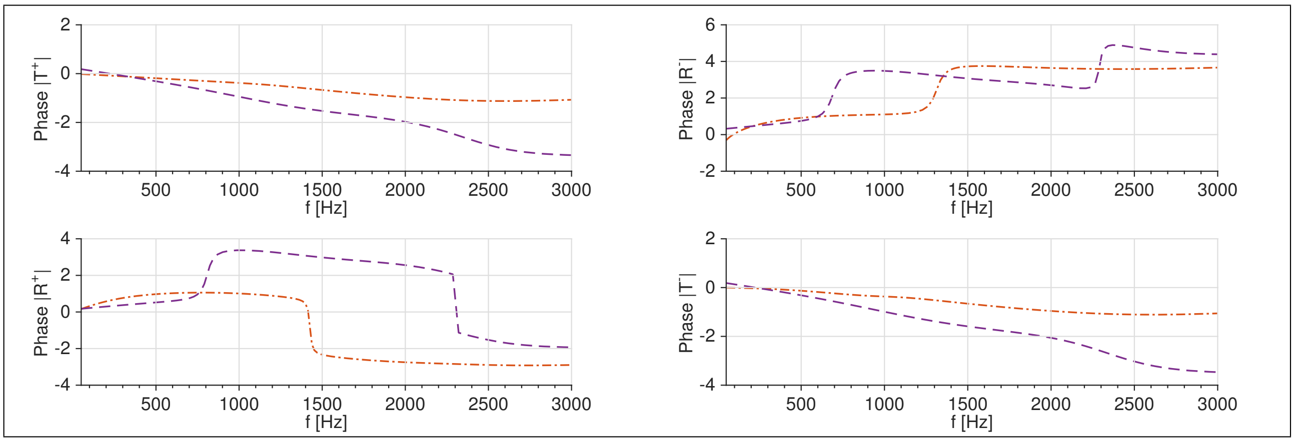

Figure 11. Gain of the identified acoustic scattering matrices. Dash-dotted red: L1D. Dashed viola: L2d

and experimental database. Finally the authors gratefully acknowledge the Gauss Centre for Supercomputing e.V. for funding this project by providing computing time on the GCS Supercomputer SuperMUC at Leibniz Supercomputing.

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