Chapter 6
Aeroacoustics Structure Interaction Experiment in a Rectangular Duct with a Flush Mounted Panel

Daniele Fabbri, Carlo Rosso, Fabio Bruzzone, Francesco Avallone, Lucas A. Bonomo, and Julio A. Cordioli

Abstract This work presents a preliminary study motivated by the need to design and conduct controlled experiments on the aeroacoustics response of a flush mounted flexible panel embedded in an otherwise rigid rectangular duct. The overarching goal is to understand how structural flexibility influences the generation and propagation of aerodynamic sound through fluid structure interaction. While the full experimental campaign will involve the characterization of different panel materials and thicknesses under grazing flow, this contribution focuses on outlining the proposed test rig and reporting preliminary numerical simulations that guide the design process. The simulations presented here highlight the expected frequency shifts with respect to the in vacuo structural modes and emphasize the differences between purely acoustic structure interaction and aeroacoustics structure interaction cases. These results provide an initial indication of the coupling regimes that will be most relevant for subsequent experiments. Ultimately, the study aims to establish a controlled benchmark test case and generate reference datasets for the validation of multiphysics numerical approaches in aeroacoustics fluid structure interaction.

Keywords Multiphysics · Aeroacoustics · Structure · ASI · FEA

Introduction

The need of couple different physics in the same framework was well described by *Korobkin* et al. in [1] describe the multiphysics coupling in hydroelasticity and emphasize a key principle that also applies to aeroacoustics: "to make significant progress ... we need stronger interaction and better collaboration between computational, experimental and theoretical researchers." In the same spirit, the purpose of this paper is to describe the experimental set up of an aeroacoustics structure interaction case describing also some preliminary numerical results. The theoretical basis of aeroacoustics originates from *Lighthill's* acoustic analogy [2], which models aerodynamic sound generation as turbulence induced quadrupole sources in a compressible fluid. While effective for free space turbulence such as jets, *Lighthill's* formulation excludes the effects of solid boundaries. This limitation was addressed by *Curle* [3], and later by *Ffowcs Williams* and *Hawkings* [4], who introduced dipole and monopole source terms to account for stationary and moving surfaces. These extensions enabled the modeling of sound generated by flow structure interactions, including panel flutter and traveling wave instabilities, where wall motion directly contributes to acoustic radiation. Although nonlinear effects and complex geometries lie beyond the reach of such analytical models, their contribution to the foundations of fluid–structure interaction is significant. This multiphysics approach can be crucial to find strategies useful in the noise reduction as the comfort is increasingly important in engineering design, as it directly affect workers' performance and well being. In the same way, appropriate illumination plays a central role in ensuring human comfort [5, 6]

Early analytical studies of aeroacoustics structure interaction relied on simplified flow representations to clarify the underlying mechanisms. *Zolotarev* [7] analyzed the dynamics of a thin elastic plate in a fluid channel using potential flow

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theory, enforcing continuity of velocity and pressure at the interface. His formulation showed that even a light fluid can noticeably alter plate frequencies and, in the case of near coincident acoustic and structural resonances, produce mode splitting into two coupled branches. He also identified critical flow velocities associated with flutter instability, where no real valued natural frequencies exist. In a complementary approach, *Tang* et al. [8] investigated the interaction of a single vortex with a flexible wall, modeling the vortex as a singularity in an irrotational background flow. Their results highlighted that wall vibration primarily radiates sound through a monopole mechanism linked to volumetric flux, with dipole effects playing a secondary role when the vortex passes very close to the surface. Together, these works establish both the global modal coupling and the local vortex excitation aspects of aeroacoustics structural phenomena, serving as useful theoretical references for more advanced Navier–Stokes-based models.

Huang et al. [9, 10, 11] carried out a series of analytical and experimental studies on acoustic–panel interaction in ducts without flow, demonstrating how panel length, tapering, and damping influence transmission loss and providing strategies for passive low-frequency noise control. Building on this, D'Elia [12] developed a compact, tunable liner concept that combines vibrating beams with micro slit cavities, validated through analytical impedance models and experiments. More recently, *Hessenthaler* et al. [13] proposed a comprehensive analytical framework for FSI with sixteen canonical cases intended as benchmarks for validating numerical schemes. The simplifications of analytical methods, however, limit their applicability, to capture nonlinearities and complex geometries, numerical approaches are required. Building on the analytical work of Huang et al. [9], Fan et al. [14] introduced a fully coupled time-domain numerical framework for aeroacoustics–structural interaction (AASI) in ducts and pipes. Their method combines a compressible Navier–Stokes solver based on the Conservation Element/Solution Element (CE/SE) scheme [15] with a one dimensional membrane model of the flexible panel, coupled through a predictor–corrector partitioned scheme. This approach captures acoustic, vortical, and entropy fluctuations without linearization, making it suitable for studying nonlinear panel–flow interaction in confined geometries. The model reproduces Huang's frequency domain results in the absence of flow and then explores Mach dependent effects. Simulations identify nonlinear modal transitions, shifts in acoustic radiation from upstream to downstream dominance, and mode excitation at supersonic speeds induced by shock. Transmission loss exhibits four regimes, from rapid decay in the very low subsonic range to partial recovery in the low-supersonic regime. These results confirm that in tube and pipe systems, accurate prediction of aeroacoustics structural coupling requires fully time resolved numerical simulations to capture the regime dependent dynamics of panel vibration and wave radiation. Other numerical method which. Several studies have explored the interaction between turbulent flows and flexible panels, often through experimental campaigns or simplified numerical models [16, 17, 18]. However, their direct application to configurations inside ducts remains only partially clarified. As also noted by Lam in his thesis, current numerical methodologies can capture aeroacoustics structural interaction at low flow speeds but neglect convective terms at the wall boundary, making them unsuitable for higher flow regimes where curvature effects and instabilities such as divergence or Kelvin–Helmholtz waves may arise. Moreover, existing approaches often fail to account for large structural deformations, rely on two dimensional assumptions, and do not systematically address the influence of panel material properties, duct geometry, or multiple panel configurations commonly encountered in practice. These limitations underscore the need for further research into fully coupled, three dimensional turbulent flow panel interaction within duct systems, in order to better explain and predict their aeroacoustics response.

Methodology

The aeroacoustic structure–interaction experiment is conducted in the UFSC Grazing Flow Acoustic Impedance Facility [19, 20], composed of modular rectangular ducts with a cross section of 40 × 100 mm². A 3 dimensional schematic of the test rig is shown in Fig1. Quasi anechoic terminations at the inlet and outlet minimize acoustic reflections, while eight compression drivers are distributed both upstream and downstream of the test section to generate sound fields up to 150 dB propagating with and against the flow. Grazing flow is supplied by an external compressed air system, sustaining Mach numbers up to 0.7. Flow speed is controlled by differential pressure transmitter connected to a 2 mm diameter pitot tube at the inlet, calibrated according to ISO 3966:2008 [21], with temperature monitored by a transmitter.

In the present study, the conventional sample holder is replaced by a flush-mounted flexible panel, enabling direct investigation of aeroacoustic structure interaction (AeroASI) mechanisms under grazing flow. An array of eight equally spaced flush mounted pressure field microphones is located downstream the panel section to capture the acoustic field for modal decomposition of incident, reflected, and transmitted waves. Panel vibrations are measured with a scanning laser Doppler vibrometer, while structural parameters are characterized independently through bench-top modal testing. In addition to the acoustic measurements, the downstream flow field will also be characterized. To capture the velocity profile, hot wire prob and a Pitot tube will be considered, allowing direct comparison between mean and fluctuating flow quantities. These measurements will provide key data on boundary layer perturbations and on the possible development of shear layer instabilities

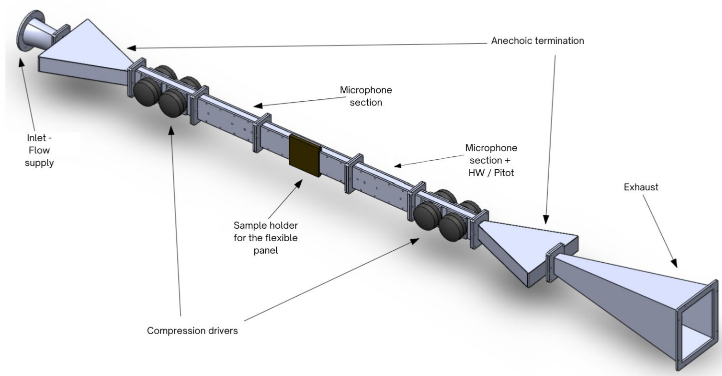

Fig. 1 USFC Impedance Tube Test rig

downstream of the panel, as well as some vortex acoustic coupling, thereby supporting a more complete understanding of the coupled aeroacoustics structure coupling. The configuration used is figured in 2

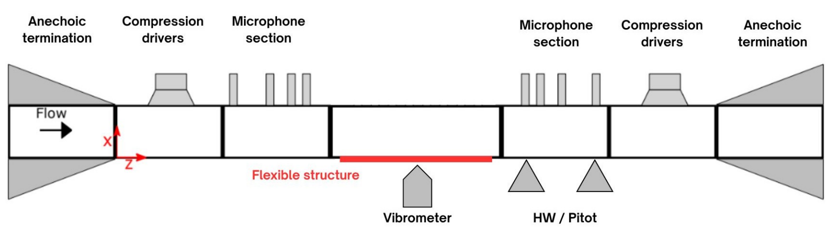

Fig. 2 Experimental scheme

In this work, the structure is considered the central object in the aeroacoustics fluid–structure interaction. The vibrating plate is not treated as a passive boundary, but rather as a dynamic element whose flexibility and material properties fundamentally govern the coupling mechanisms. To investigate this, three different structural materials will be studied for the plate. By systematically varying the elastic modulus, density, and damping characteristics, we will alter the flexibility of the structure and thus its ability to interact with the surrounding fluid and acoustic fields. This approach follows the consolidated understanding that the structural response dictates not only the modal behavior but also the efficiency of energy transfer between flow, vibration, and sound radiation.

Results - preliminar numerical case

A preliminary numerical investigation of the test rig was performed to quantify the influence of the mean flow on the aeroacoustic–structural interaction comparing it with an acoustic structure interaction (ASI) case. The computational domain consists of the central section of the duct, where the flexible plate is mounted, with perfectly matched layers (PMLs) applied at both inlet and outlet to avoid spurious reflections (Fig. 3). The plate, modeled as an aluminum structure with a thickness of 1 mm, is clamped at both ends and located at the center of the domain.

The analysis was carried out in two stages. First, the mean flow field was obtained by solving the steady turbulent flow using the SST model. A fully developed velocity profile was imposed at the inlet, while a zero pressure condition was prescribed at the outlet. This velocity profile was subsequently mapped into the acoustic domain, which was represented by two fluid regions adjacent to the plate. A background flow acoustics coupling was employed to account for the convective effects of the mean flow. On the structural side, the flexible plate was coupled to the acoustic field through an aeroacoustic–structure boundary condition, ensuring continuity of pressure and normal velocity across the interface. To assess the role of mean flow, two configurations were compared: the full aeroacoustic–structural interaction with background flow, and a vibroacoustic case without mean flow (ASI). The acoustic excitation was introduced using a plane wave source imposed at the inlet, allowing for the study of the structural response under incident sound waves both with and without the influence of the mean flow.

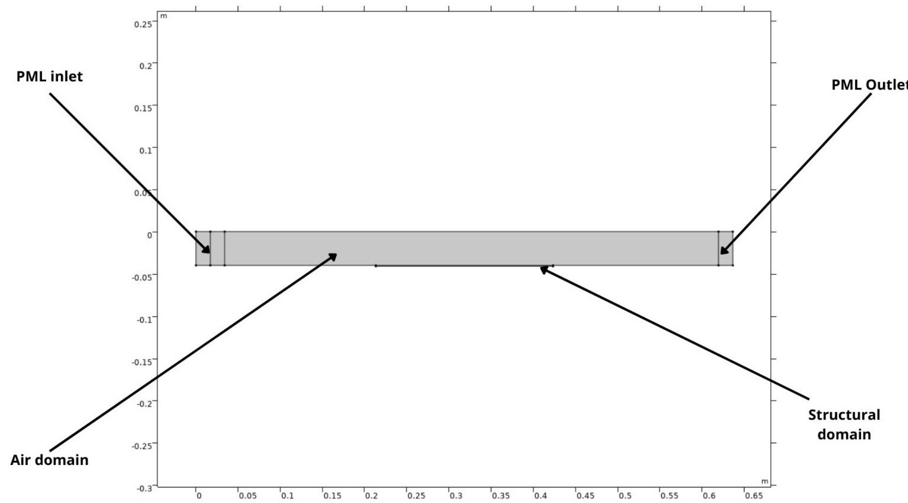

Fig. 3 Numerical geometry

In the low frequency range of interest (20–1000 Hz), the simulations were conducted and the results showing the sound pressure level (SPL) over the plate 4, downstream of the duct 5, and the Y component displacement response of the plate 6. The uncoupled natural frequencies of the plate are indicated in the next figures by vertical dotted red lines. These lines mark the positions of the first three in vacuo frequencies, providing a direct reference for comparison with the coupled vibroacoustic and AeroASI results. For clarity, the first natural frequencies are also summarized in Table 1.

Table 1 First three natural frequencies of the plate

Mode	Natural Frequency [Hz]
1	124.9
2	344.3
3	674.7

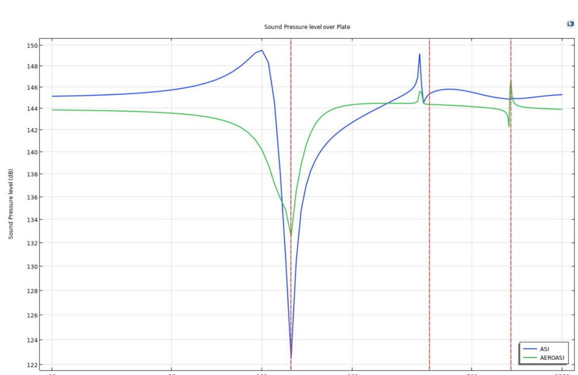

Fig. 4 SPL over the plate

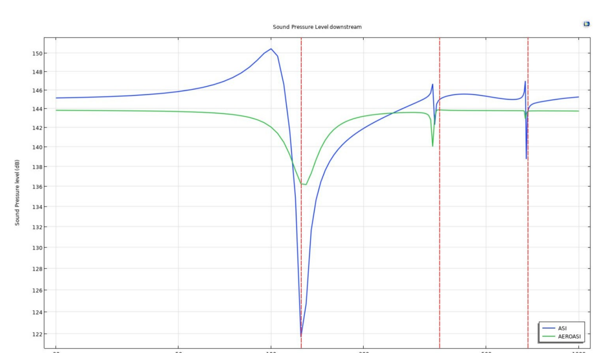

Fig. 5 SPL downstream

Examining the sound pressure levels, the ASI simulations display generally higher SPL values than the AeroASI results. This difference arises because in ASI the coupling is limited to the acoustic and structural domains, so the acoustic wave interacts directly with the plate. In contrast, in AeroASI the flow solution is first mapped onto the acoustic mesh, and the subsequent aeroacoustic–structure coupling leads to additional damping, which reduce the net SPL observed in the duct.

Moreover, in vibroacoustic case the SPL spectra show sharper peaks and deeper notches associated with the structural resonances, while when the background fluid is considered these features are smoother and shifted. The spikes are broadened by the interaction between the convected flow field, the scattered acoustic waves, and the vibrating plate. This highlights the fundamental difference between the two approaches: ASI emphasizes the direct acoustic–structure resonance, whereas AeroASI captures the more complex aeroacoustic feedback mechanisms that tend to dampen and spread out the resonance effects.

The comparison between the in vacuo natural frequencies of the plate and the coupled simulations highlights a systematic frequency shift. In the first mode, the coupled resonance appears slightly below the uncoupled structural frequency, which indicates that at low frequency the fluid mainly contributes through an added mass effect. Conversely, for the second and third modes the coupled resonances are shifted to higher values than the in vacuo frequencies. This trend is a well documented feature in fluid structure interaction problems [22, 9] and is mainly attributed to the additional stiffness introduced by the compressible fluid. Rather than acting as a pure added mass, the surrounding air modifies the effective impedance of the system, leading to a frequency dependent behavior: mass like at low frequency and stiffness like at higher frequencies.

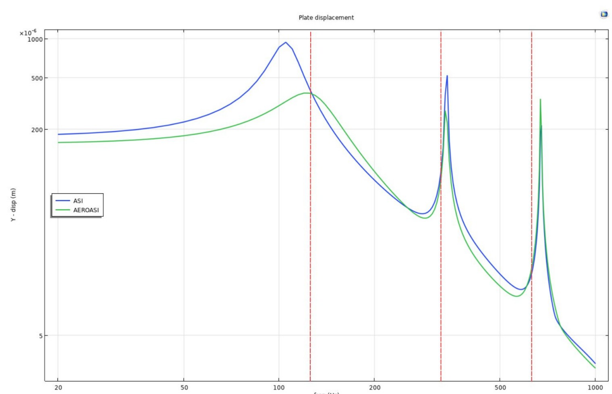

Fig. 6 Plate displacement - Y component

Conclusions

The present work has compared two configurations for a flexible plate in a duct: the acoustic–structure interaction case, where only the coupling between the acoustic wave and the structural response is considered, and the aeroacoustic–structure interaction case, where the presence of a mean flow is included through a stationary fluid solution mapped onto the acoustic structural domain.

The results highlight that the coupled resonance frequencies differ from the in-vacuo values: the first mode shifts slightly lower due to fluid mass loading, while the higher modes shift upward as a consequence of the additional stiffness introduced by the compressible fluid. Moreover, the sound pressure level distributions clearly show that ASI predicts sharper peaks and higher overall SPL compared to AeroASI, where the mean flow introduces damping, smoothing the spectral response.

This study is intended as a preliminary phase of a broader process aimed at understanding the impact of structural flexibility on noise propagation and reduction methods. The numerical analyses presented here serve to identify the type of behavior that can be expected when experimental investigations will be carried out, and to build the necessary knowledge for modeling more complex scenarios, such as the interaction between a grazing flow and a flexible structure in terms of aeroacoustic noise.

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