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The Acoustic center of the École Centrale de Lyon: A historical perspective

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Abstract – The research team in acoustics at the École Centrale de Lyon was founded 50 years ago by Prof. Geneviève Comte-Bellot. In this paper we describe the growth of this team, now known as the Acoustic center of the École Centrale de Lyon (or Centre Acoustique in French), from the early 1970s to the present day. We highlight the evolution of the research interests and experimental facilities, and provide a selection of "historical" references at the end of the paper. The main current research topics are listed and illustrated, and are complemented by a partial list of recent references.

Keywords. Aeroacoustics, Vibroacoustics, Sound propagation, Active control, Nonlinear acoustics

1 Historical perspective

1.1 The early years (1970–1980)

The acoustic team of the Laboratory of Fluid Mechanics and Acoustics (LMFA) of the École Centrale de Lyon was established by Prof. Geneviève Comte-Bellot (born in 1929; see Fig. 1), a world-renowned expert in the study of turbulent flows, at the very beginning of the 1970s. This creation was the result of her vision that the new discipline of aeroacoustics, resulting from the intersection of fluid mechanics and acoustics, was destined for significant development in both its fundamental aspects and its applications, particularly in the aeronautical industry. On the practical side, the construction of a silent wind tunnel associated with an anechoic chamber [1] was rapidly finalised, a first in France in the university context. The installation was completed by two coupled reverberation chambers used to measure the absorption coefficient of acoustic materials and the transmission loss of panels placed in the large opening connecting the two rooms. Figure 2 shows the layout of the experimental installation, which is located in a basement to minimise the transmission of parasitic noise. A first experimental paper [2] was published very quickly, in which cross-correlations between surface pressure fluctuations and acoustic farfield were used to characterise airfoil noise. The initial research topics focused on the noise of fans and of their basic components, airfoil or blade profiles. At that time, the operational team consisted of only two members, Prof. Michel Sunyach and a young Assistant Prof., Henri Arbey. In 1974, the installation was completed with the construction of a wind tunnel intended for studying the noise generated by subsonic jets [3].

The research topics quickly expanded to include the diffusion of sound by turbulence, as studied by D. Juvé and M. Sunyach in 1976. This was further expanded in 1978 by Philippe Blanc-Benon and D. Juvé, who investigated the propagation of high-frequency sound waves through an extended zone of kinematic or thermal turbulence (see [4]). Initial research activities focusing on airfoil noise were supplemented in 1980 by the study of aircraft compressor noise (see [5]).

1.2 The birth of vibroacoustics at the École Centrale de Lyon

In 1969, Lionel Gaudriot and Jacques Martinat, co-founders of the company Metravib (Mesure et Traitement des Vibrations), were invited to the École Centrale by its director, Paul Comparat. Interaction with teachers and researchers at the École was important, and L. Gaudriot was integrated into Jean Mathieu's fluid mechanics laboratory. He collaborated actively with G. Comte-Bellot on several vibroacoustic and aeroacoustic projects [6]. In vibro-acoustics, the two coupled reverberation chambers mentioned above were used to measure the transmission loss and acoustic radiation efficiency of

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Figure 1. Professors Geneviève Comte-Bellot and Jean Mathieu (founder of the Laboratory of Fluid Mechanics) in 1983.

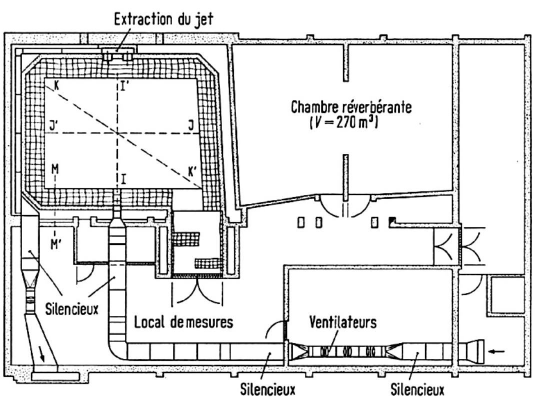

Figure 2. The experimental facility in the early 1970s, see [1].

Figure 3. Equipment for vibro-acoustics measurements in the early 1970s.

Figure 4. The D2S team on the ECLyon campus in 1990 (L. Jézéquel is in the center of the image).

sandwich panels, using a power-based method (Statistical Energy Analysis) that was at the beginning of its development (in the USA) and is now standardised for predicting the acoustic performance of buildings (EN ISO 12354 series). Loudspeakers and an electrodynamic shaker were used in the transmission chambers to excite the room and the panel respectively. At the beginning of the 1970s, random noise generators were available, but the measurement equipment was analogue (Fig. 3), in particular frequency analyzers and even the correlator used to calculate the vibration power injected into the panels.

After leaving the École Centrale de Lyon premises in 1974 (although maintaining a research laboratory there until 1981), Metravib experienced significant growth. Louis Jézéquel (see [7]) was subsequently appointed Professor at the École. He began his career in building dynamics at a new school near Lyon (ENTPE, École Nationale des Travaux Publics et de l'Équipement) in Vaulx-en-Velin in 1976. In 1985, he established a leading research team in structural vibrations (D2S, Dynamique des Structures et des Systèmes), focusing on topics such as the dynamics of rotating machines, the stability of friction systems, vibroacoustics, and active control. The team experienced strong and regular growth and its vibroacoustics research activities led the D2S team (Fig. 4) to join forces with the acoustics team to form a center of excellence in this field.

In 1992, the D2S team joined the Laboratory of Tribology and Systems Dynamics (LTDS, UMR5513).

1.3 Creation of the Acoustic center (1980s)

Very quickly, the characteristics of the initial installation proved to be too limited for the applications foreseen: the Mach number was restricted to 0.4 for small diameter jets (with a typical diameter of 2 cm), and to 0.2 for the noise of airfoils placed in the potential core of a rectangular jet (with a section of 30 cm × 10 cm).

From the end of the 1970s, G. Comte-Bellot sought the necessary funding to create a world-class facility, complete with the measurement rooms and offices required to increase the size of the team. Construction of the new building began in 1980 and the official inauguration of the Acoustic center of the École Centrale de Lyon took

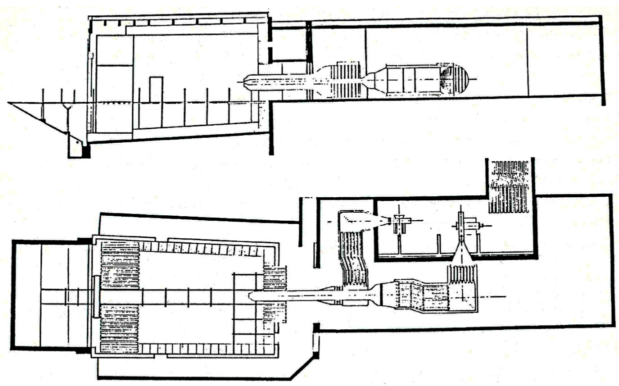

Figure 5. The experimental facility of the Acoustic center in the 1980s [8].

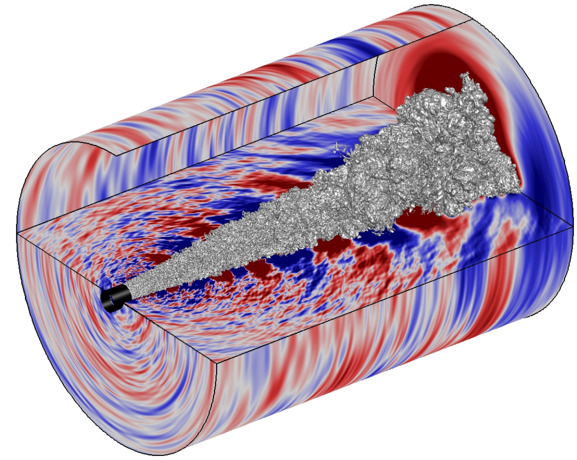

Figure 6. Direct numerical simulation of the vorticity and sound pressure of a jet at high Reynolds and Mach numbers.

place in 1985 on the occasion of the holding of the IUTAM symposium "Aero and Hydro-Acoustics", organized by G. Comte-Bellot and J.E. Ffowcs-Williams.

A large anechoic chamber ($10\,\mathrm{m} \times 8\,\mathrm{m} \times 8\,\mathrm{m}$) was coupled to a wind tunnel enabling a Mach number of 0.5 to be achieved in $0.4\,\mathrm{m} \times 0.2\,\mathrm{m}$ section. A second fan fed a half-velocity flow into jets adjacent to the main stream and intended to enhance the emergence of the noise from airfoils placed in the potential core of the primary jet (Fig. 5). The detailed characteristics of the facility are described in reference [8]. A compressor to power a supersonic jet stream was part of the original plan but could not be installed due to insufficient funding.

Studies of the noise generated by fans, airfoils and obstacles of more complex shapes were supplemented by studies of the excitation of structures by flows. This involved measuring wall pressure fluctuations under turbulent boundary layers, as well as the resulting vibrations from flexible plates and, somewhat later, pipes [9, 10]. In parallel, under the impetus of M. Sunyach, the possibility of active strategies was developing to reduce noise in ducts or control combustion instabilities [11–13].

1.4 The development of numerical simulation (1985–2005)

Initially, the research conducted at the Acoustic center focused on experimentation and theoretical modelling. This gradually extended to numerical simulations. The first works were directed towards the propagation of acoustic waves in random media, first using ray techniques and subsequently parabolic approximations. Examples of this work include the interaction of acoustic waves with kinematic turbulence [14], sound propagation in the atmosphere [15] and nonlinear effects [16].

Following the arrival of Christophe Bailly in 1995, who was soon joined by Christophe Bogey, the team quickly turned to the simulation of acoustic wave propagation in high-speed flows [17]. The team then developed the direct simulation of noise generation by turbulent flows, based on the resolution of the compressible Navier–Stokes equations using high-precision discretisation schemes in time and space developed by the team. The flows studied were high Mach number subsonic jets [18] (Fig. 6), but also cavity flows [19]. The team then considered supersonic jets, airfoils and turbulent boundary layers.

2 Current experimental facilities

While the structure of the buildings has remained essentially the same over the years, the experimental facilities have constantly been upgraded to expand research possibilities. In 1994, the installation of a centrifugal compressor enabled the study of supersonic jets with a Mach number of up to 1.5, with applications in the aeronautics and space sectors. Very recently, the replacement of the coating on the walls of the anechoic chamber and the installation of a two-stage high-pressure blower has enabled the study of airfoil noise and of wall-pressure fluctuations under turbulent boundary layers in the high subsonic regime (Mach number up to 0.7), where compressibility effects become very important. Combined use of the blower and the centrifugal compressor also enables the study of the noise generated by coaxial jets, with subsonic or supersonic primary streams. A 3D schematic view of the new facility is given in Figure 7. The interior of the anechoic chamber is also shown in Figure 8, which shows the exhaust sections of both the subsonic and supersonic wind tunnels.

Other additional facilities have also recently been built. For fundamental studies, a low Mach ducted fan test rig was instrumented with both external and internal large microphone arrays (LP3 test bench, displayed on Fig. 9). Another facility (Caiman wind tunnel) is also used to study the performance of passive and active materials in ducts with flow (Mach < 0.3) under multimodal excitation.

An innovative facility has been developed for studying nonlinear sound propagation. It uses Schlieren and Mach–Zehnder interferometry to characterise weak shock

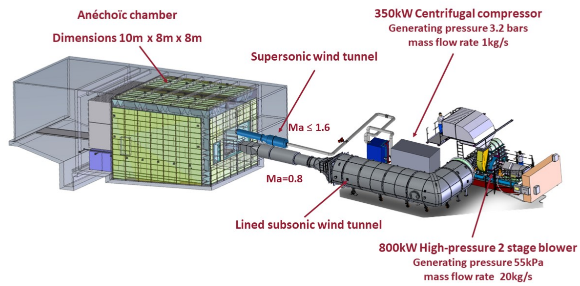

Figure 7. 3D schematic view of the main experimental facility of the Acoustic center (blower and compressor, wind tunnels and anechoic chamber).

Figure 8. Internal view of the anechoic chamber and of the exhaust sections of the subsonic and supersonic wind tunnels.

waves generated by electric arcs. The facility is primarily used to simulate sonic boom propagation in the atmosphere and their interaction with buildings and realistic ground topography. A comparison between measurements and numerical simulations using nonlinear Euler equations is shown in Figure 10.

On the more applied side, the team is strongly involved in studies carried out on the Phare-B2 test bed. This facility, engineered in partnership with Safran Aircraft Engines, reproduces the operation of an aeronautical fan at 1/3 scale, and develops a power of 2 MW (Fig. 11). Thanks to the anechoic environment, the external radiated noise can be measured and correlated with internal in-duct sensors. The innovative array techniques developed on the LP3 rig can then be transferred to this quasi-industrial installation.

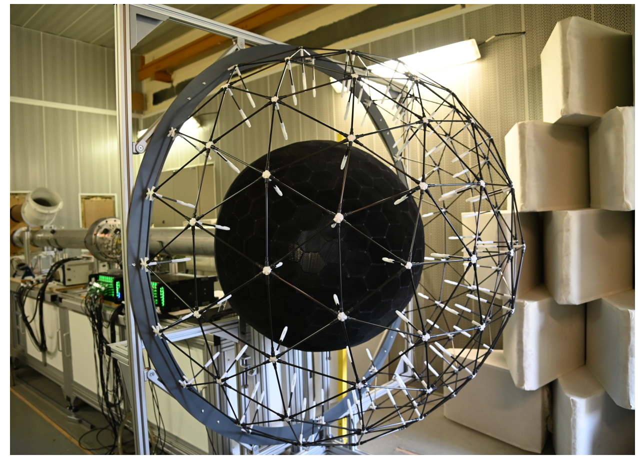

Figure 9. Partial view of the LP3 test bench, with emphasis on the 89 microphone external array (The black half sphere is a porous Turbulent Control Screen used to reduce incident fluctuations in the sucked flow).

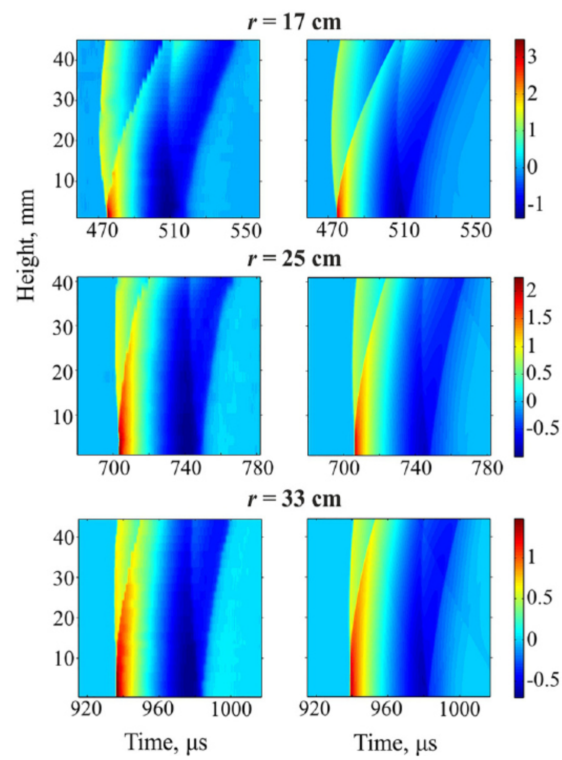

Figure 10. Reflection patterns of spark-generated shock pulses measured by a Mach-Zehnder interferometer (left) and numerically simulated (right) [20].

3 Collaborations and research philosophy

Since its establishment, the philosophy of the Acoustic center has been to achieve a harmonious balance between fundamental research and applications. The links with industry have always been very close, especially with the transport sector, whether automotive (Renault, Stellantis), rail (Alstom, SNCF) and of course aeronautics (Dassault, Airbus, Safran) and space (CNES, ArianeGroup). These links facilitate access to the sources of funding needed to develop experimental facilities, in addition to national or regional public funds. They are also a source of difficult and interesting academic problems to be solved, once a suitable schematisation has been found to highlight the physics of the main phenomena involved. In particular, our very close relationship with Safran has

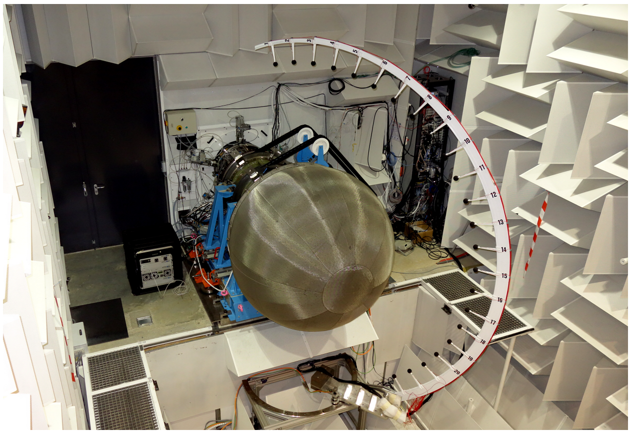

Figure 11. Phare-B2 facility. Partial view of the anechoic chamber and of the external microphone array (the inlet of the compressor is hidden by the Turbulent Control Screen).

enabled us to construct the Phare platform (a rotating machinery platform for environmental risk control) and to enhance the performance of our large anechoic wind tunnel through the creation of two industrial chairs co-funded by the French National Research Agency (ANR).

Many international collaborations have been established at university level over the years, for example with Cambridge, Johns Hopkins, Penn State, the University of Texas at Austin and Moscow State University, as well as with many European teams through participation in European programmes since the early 1990s. These close collaborations have enabled important international conferences to be organised, including Euromech 142 "Acoustics of Turbulent Flows" in 1982, the IUTAM "Aero- and Hydro-Acoustics" symposium in 1985, and several Long Range Sound Propagation symposia (LRSP, in 1996, 2008 and 2018). Other notable conferences include the International Symposium on Nonlinear Acoustics (ISNA 2015) and the Aeroacoustics 2016 conference, which was organised under the auspices of the Council of European Aeronautical Societies and the American Institute of Aeronautics and Astronautics.

Regional and national collaborations have always been in the spotlight with the aim of federating strengths and skills. In the 1980s, G. Comte-Bellot established a CNRS research group that brought together research teams from Lyon (LMFA and ICPI-now CPE Lyon), Grenoble (Cephag-now GIPSA-lab) and Marseille (Laboratoire de Mécanique et d'Acoustique, LMA). This desire for collaboration in Lyon led to the creation of the DEA (Diplôme d'Études Approfondies, equivalent to a Master's degree) in Acoustics in 1980, associating ECLyon with INSA and the University of Lyon I. In 2018, this was transformed into an international two-year Master of Science in Acoustics from the University of Lyon, taught in English. This Master of Science relies heavily on the teams of the CeLyA (Centre Lyonnais d'Acoustique) Laboratory of Excellence. Established in 2011, it is the only LabEx in France dedicated exclusively to

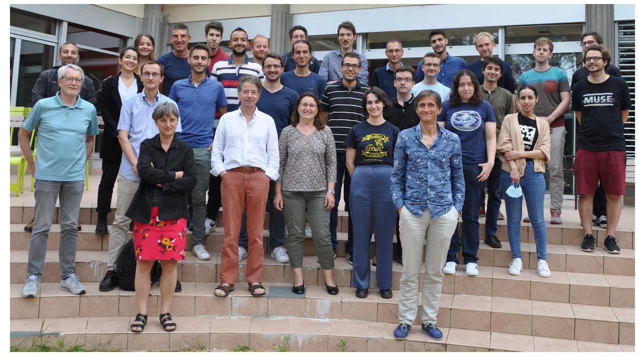

Figure 12. Team members at the occasion of a group seminar in July 2021.

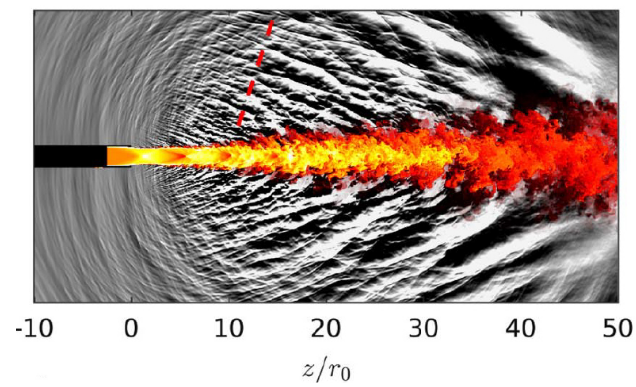

Figure 13. High Mach number supersonic jet: Snapshot of temperature fluctuations inside the flow and of pressure fluctuations outside [22]. The red dotted line shows the direction in which the Mach waves propagate.

acoustics. Initially directed by D. Juvé and, since 2018, by Étienne Parizet, it brings together all of the leading research teams in Lyon and Saint-Etienne. Its scope encompasses a wide range of fields, including physical acoustics (such as vibroacoustics, aeroacoustics and ultrasound), medical applications, sound perception, neuroscience and bioacoustics. Information about the CeLyA teams and their work can be found on the website: https://celya.universite-lyon.fr/.

4 The Acoustic center today and tomorrow

The Acoustic center started with just two researchers in 1973 and has grown to comprise 21 permanent staff and around 25 doctoral and postdoctoral students. A group photo of the team is provided in Figure 12.

To date, 183 PhD theses have been defended, and over 460 articles have been published in leading international journals. The complete list is available on the website https://acoustique.ec-lyon.fr/, where most of the texts of the articles and conference presentations texts can be found.

The main research topics currently being worked on are listed below, together with references to related

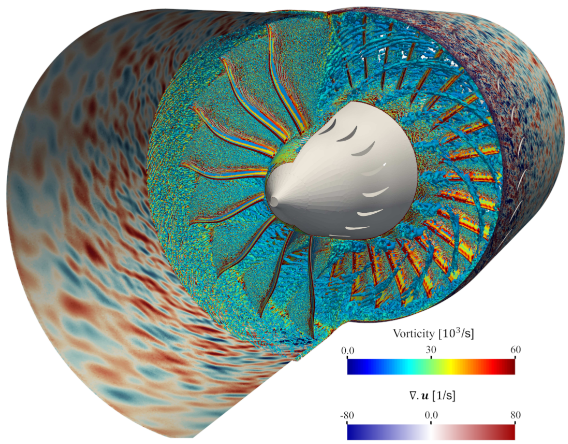

Figure 14. Ultrahigh bypass ratio fan. Instantaneous contours of the dilatation rate at 99% of the rotor span and an iso-surface of the Q-criterion coloured by the vorticity magnitude [24].

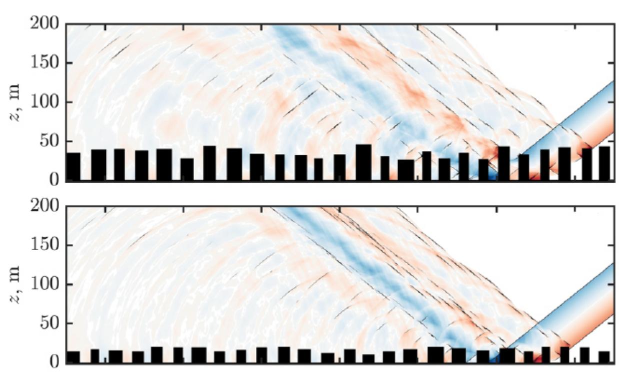

Figure 15. Numerical simulation of sonic boom propagation over urban areas (contour maps of the acoustic pressure) [27].

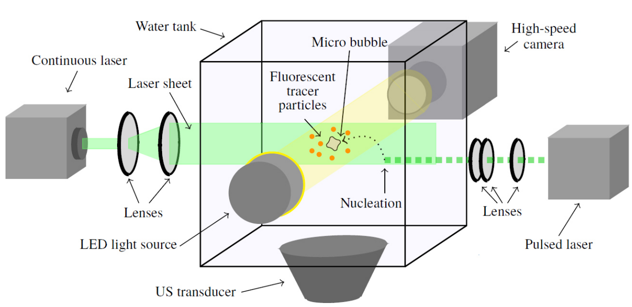

Figure 16. Microstreaming induced by oscillating microbubbles: Schematic of the experimental set-up [28].

work and illustrations from experiments or numerical simulations.

- Aeroacoustics of free flows [21, 22], Figure 13.
- Aeroacoustics of airfoils and turbomachinery [23, 24], Figure 14.

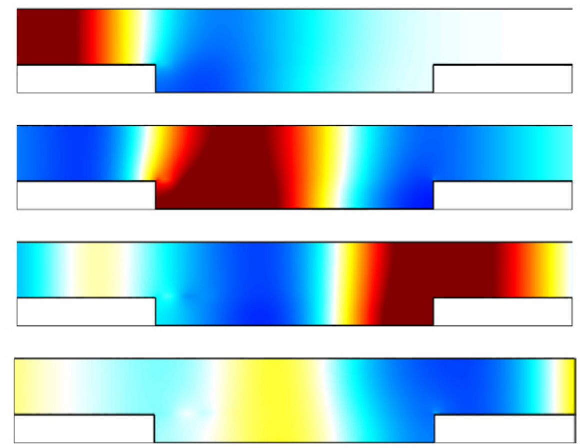

Figure 17. Time-domain simulation of sound propagation in a flow duct with extended-reacting liners: successive snapshots of the pressure field [30].

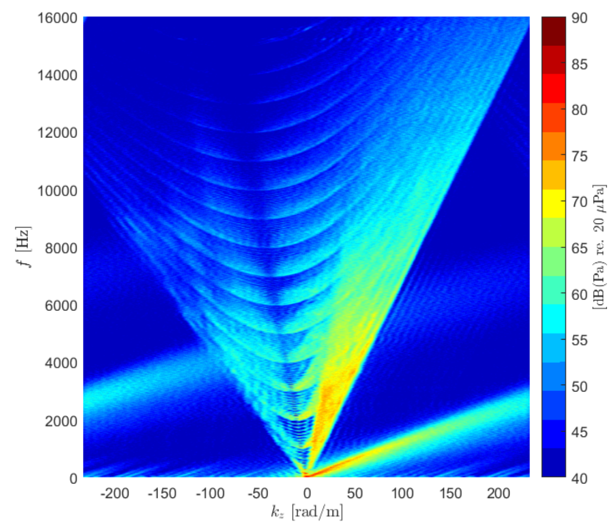

Figure 18. Wavenumber-frequency analysis of in-duct fan broadband noise using a Bayesian approach [36].

- Wall-pressure fields and excitation of structures by turbulent flows [25, 26].
- Linear and nonlinear acoustic propagation [20, 27], Figure 15.
- Bubble dynamics and medical applications [28, 29], Figure 16.
- Active and passive acoustic materials under grazing flow [30, 31], Figure 17.
- Innovative optical measurements: Schlieren imaging, interferometry, Rayleigh scattering [32, 33].
- Innovative microphone array techniques, inverse problems, 3D sound field synthesis [34–36], Figure 18.

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Conflicts of interest

The authors declare that they have no conflicts of interest in relation to this article.

Data availability statement

No new data were created or analysed in this study.

Author contribution statement

Both authors contributed to the selection of the material presented and to the writing of this paper.

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