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Teaching and Research in Acoustics at Ecole Centrale de Lyon (France)

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ABSTRACT

Acoustic facilities at the Ecole Centrale de Lyon offer the opportunity for graduate students in MS or PhD programs to work in several areas: aeroacoustics, hydroacoustics, active control of noise and flow instabilities, and propagation of acoustic waves through turbulent and inhomogeneous media. Both theoretical and applied aspects are considered. Experimental and numerical predictions are developed concurrently. Detailed examples are described in the text.

1 INTRODUCTION

Research in acoustics has been conducted for over 20 years in the Laboratory of Fluid Mechanics and Acoustics at the Ecole Centrale de Lyon (ECL). Beginning with research support from the Direction des Recherches of Electricité de France (EDF) in the 1970's to investigate the noise emitted by airfoils and fans, the Laboratory has built a comprehensive aeroacoustics research program. With the help of the CNRS, facilities were expanded so that they now include two large anechoic rooms—one with a quiet, high speed, wind tunnel.

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Presently, most research is conducted in close cooperation with large governmental organizations, national companies and private industries: CNRS, DRET, DCAN, CNES, Aérospatiale, Turboméca, Solyvent-Ventec, Peugeot, Renault, Thomson, Metraflu to name a few. Technology transfer to industry benefits from special agreements with the French Minister of Education. European collaboration is also present through the well known Brite Euram Program.

The graduate program in Acoustics is open not only to French students, but also to foreign students who are registered in any of the universities with which the ECL has an exchange agreement. Currently, these universities include the Imperial College of Science and Technology in London, The Technische Universität in Berlin, The Technische Hochschool of Darmstadt, the Université Technique of Lodz, Cornell University and Pennsylvania State University. In one year, these students can obtain the Diplôme d'Etudes Approfondies (equivalent in the USA to an MS). The Doctorat Nouveau Régime (equivalent to a PhD) usually requires 3 years. Because official recognition of the Acoustics program includes the University Claude Bernard Lyon I and the Institut des Sciences Appliquées de Lyon, the number of special courses goes beyond those offered at ECL. Flow induced vibrations, ultrasound, piezoelectric-transducers, image processing, and psychoacoustics are therefore additional possible choices.

With regard to continuing education, our main program, 'Eur'Acoustics, Idee Force 92', has received formal recognition by the French Ministry of Education. The program is offered every year, usually in July, as a one-week course supplemented by a workshop. The topics, steering committee, and instructors, are chosen with a focus on current industrial needs.

Professors in Acoustics have close ties with the national community through examination boards and meetings of the Société Française d'Acoustique. Colleagues from abroad are often invited to participate in collaborative research during their sabbatical leaves, with partial financial support from either ECL or the Région Rhône-Alpes. International meetings are also held at the ECL, e.g. the IUTAM meeting on Aero- and Hydro-Acoustics in 1985, the first European Turbulence Conference in 1986, the Euromech Colloquium 132 on Hot-wire Anemometry, and the European Colloquium 142 on Aeroacoustics.

2 RESEARCH ACTIVITIES

The main research activities span the fields of physics, fluid mechanics, numerical modeling and experimental techniques. Turbulence is often at the crossroads of the work because turbulent flows generate noise or disturb the propagation of acoustic waves. Understanding the mechanisms of sound generation, identification of the location of sound sources, and noise control are, of course, our ultimate engineering goals.

2.1 Jet noise

Various configurations are used to investigate the noise emitted by turbulent jets: single jets, excited jets, and coaxial jets such as the by-pass engines used in modern aeroplanes. Presently, the flows being studied experimentally are subsonic (up to 180 m/s) but extensions up to a Mach number of 1·5 are under development. Experiments generally involve frequency spectra, azimuthal correlations and directivity patterns of the radiated noise, and maps of acoustic energy fluxes. The aim is to locate the sources, to characterize their preferred direction of emission, to find their temporal intermittency, and to interpret the physical mechanisms of the noise emission in terms of the growth of jet instabilities and the subsequent evolution of the large-scale turbulent structures of jets.[1–3]

Water injection is an additional topic being considered to reduce acoustic emission from rockets of the Ariane Space industry. A new experimental facility has recently been built which allows water to be injected into an air jet at a mass rate up to three times that of the air jet itself. Injection is symmetrical and can be introduced at different distances along the jet. Figure 1 shows an example of the experiment. We find that noise is reduced at high frequencies and at high jet speeds. The effect of water injection on noise from propane flames will be also investigated.

2.2 Rotor noise

Our first effort in the study of rotor noise centered on the noise emitted by a single blade for a large range of speeds and for both smooth and perturbed incident flows. Of interest is the location of the noise source, either at the trailing edge (for a low speed laminar flow) or at the leading edge (for an incident turbulent flow). Noise levels are also highly dependent on the inhomogeneities of the incident flow. Measurements are usually made with an array of tiny microphones embedded in the blade surface. Piezo-electrical materials will be used in the near future.

There is a large variety of noise sources associated with multi-blade rotors. Upstream turbulence, wake/rotor interactions, and potential disturbances due to supports or other azimuthal inhomogeneities produce flow unsteadiness, which in turn causes noise emission. Our current experimental investigations involve accurate measurements of the flow, wall pressure

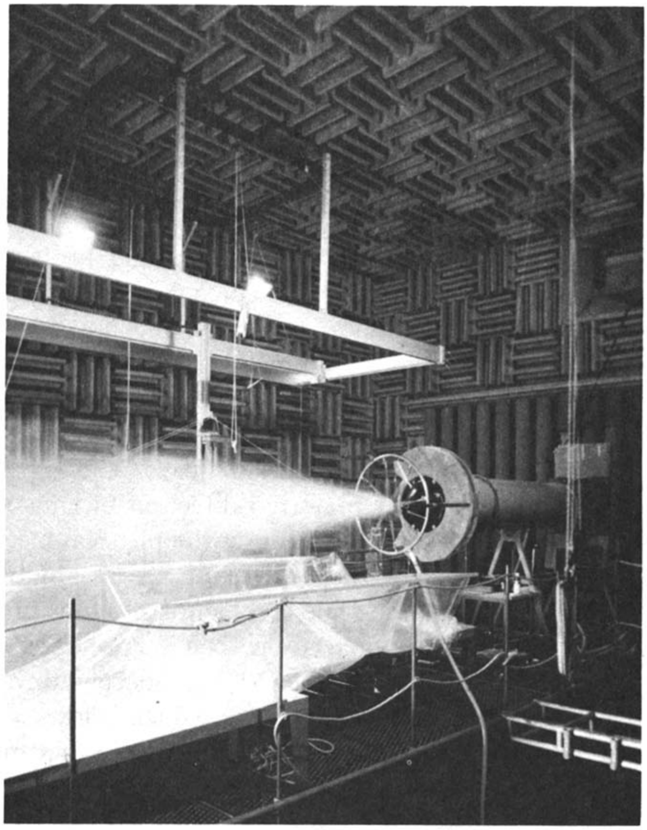

Fig. 1. An air jet with water injected to attenuate noise, speed 180 m/s.

fluctuations, and radiated noise. Provisional noise estimates are made (from existing theories) in the early stages of aerodynamic rotor design. Currently underway are studies of the noise emitted from the secondary rotors of helicopters.[4]

Also we investigate both experimentally and numerically the noise diffraction due to rotor casings, for application to helicopter rotors and marine propellers. In the experiments a circular array of loudspeakers with relative phase differences generates spinning modes (Fig. 2). Numerical studies using a finite element method are being carried out for simple geometrical shapes for comparison with the experiments.[5]

2.3 Wall pressure fluctuations under boundary layers

One of the major facilities of the laboratory is a quiet blowdown wind-tunnel that exits into a large anechoic room. Its characteristics are given in Section 4. For the study of wall pressure fluctuations, a square rigid wall

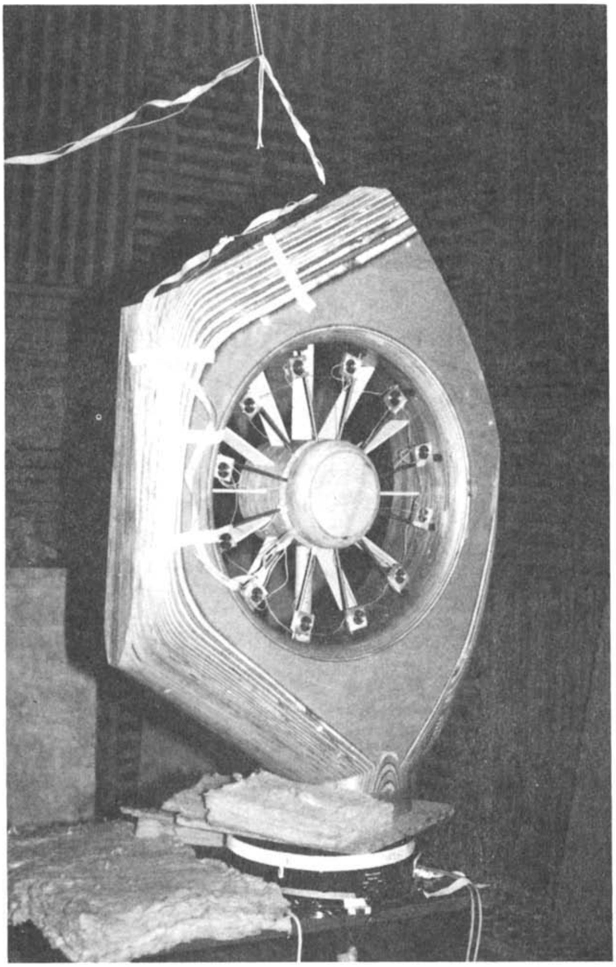

Fig. 2. A circular array of loudspeakers generating spinning acoustic modes.

duct is mounted at the exit of the wind tunnel. The lower wall is used for wall pressure measurements under fully turbulent boundary layers.[6] The duct can also support a vertical airfoil for investigating the flow field and wall pressure near a wing-body junction. When wall pressure under transitional boundary layers is investigated, a splitter plate is mounted at mid-height in the duct. An adjustable pressure flap at the trailing edge controls the flow. Up to 48 microphones are embedded in the wall to measure the primary characteristics of the wall pressure field: variances, frequency spectra, maps of space correlations and maps of space–time correlations. Simultaneous flow measurements are made using 5-hole Pitot probes and hot-wire anemometry. Visualizations of the flow using sheets of light are also possible. Presently our emphasis is on a better understanding of the relationship between the wall pressure fluctuations and the flow structures within the turbulent boundary layers creating the wall pressure fluctuations. We use conditional sampling techniques to associate pressure fluctuations on the wall with specific 'events' occurring within the boundary layer.

Complementary measurements are made in a water-tunnel in the Laboratory and also in lakes from buoyant bodies released from the lake bottom. These offer a large range of investigations in different laboratory contexts and in real life.

2.4 Chaotic emission of noise

The complexity of turbulent flows has recently motivated us to investigate the noise generated by simple systems of potential vortices. The motion of the vortices, due to their mutual interactions, can become chaotic. An example is the case of three line vortices orbiting around each other in the presence of a solid wall. Chaotic motion occurs when the three vortices initially form a rather flat isosceles triangle, creating noise over a wide band of frequencies. Both the far field noise and time traces of the wall pressure have been computed, revealing large irregular oscillations.[7] Our current efforts are aimed at a better understanding of the vortex trajectories, velocities and accelerations in relationship to the generation of large pressure fluctuations. The addition of a uniform shear flow and the consideration of finite core vortices will be the next step in the study of more realistic turbulent boundary layers.

2.5 Propagation of acoustic waves through inhomogeneous flows

The atmosphere and the oceans contain velocity and temperature (or salinity) disturbances which significantly alter the propagation of sound waves. Because of these inhomogeneities, acoustic rays are bent from their linear trajectories and travel times between source and receptor are variable.

To account for the effect of mean gradients and large scale disturbances, we solve the propagation equations simplified so as to emphasize forward propagation ('the parabolic approximation'). This simplified set of equations is much more tractable than the full equations and can be numerically treated using the split step Fourier algorithm.

For the effects of velocity and temperature disturbances whose scales are of the order of the acoustic wave length, we are currently developing two complementary approaches:

(1) First, experiments in well-controlled laboratory conditions are carried out (i) in a two dimensional jet to investigate effects of velocity-field fluctuations, and (ii) above a large heated grid to investigate effects of temperature fluctuations within thermal plumes.[8] These two facilities permit us to analyse the most important parameters of the acoustic-turbulence interaction: frequency of the acoustic wave, distance of propagation, type of the source, and intensity and scale of the turbulent media. From a theoretical point of view, the range of perturbations extends from 'single scattering', to 'multiple scattering', to 'saturation'. Measurements of the transmited waves are carried out with arrays of up to eight microphones. We focus these studies on the attenuation of the wave, spatial coherence, acoustic intensity fluctuations, and instantaneous phase fluctuations, all of which express the wave front wrinkling as the wave progresses through the turbulent field.

(2) Second, numerical simulations of the acoustic propagation through isotropic turbulent fields are carried out.[9] A realization of the turbulent field is generated by superposition of random Fourier modes with random orientations, each with a velocity or temperature Fourier contribution fixed by a prescribed spectrum. Acoustic waves are then initiated at a given location and the equations of propagation (i.e. rays, parabolic approximations) are solved to give the transmitted acoustic field.[10,11] Figure 3 illustrates what typically takes place. The random bending of the rays gives rise to concentrated (or depleted) zones of acoustic intensity. Ensemble averaging permits us to generate statistical characteristics which can be compared with experimental data. Extensions of this technique to anisotropic turbulent fields is in progress.

2.6 Active control

Active control of systems for noise control is receiving increasing attention because it can now be carried out using microprocessors. When applied to fluid systems, active control can be used to suppress flow instabilities.

In our laboratory we are currently working on active control algorithms for noise reduction in ventilation ducts, hydraulic pumps, car interiors, gasoline powered electrical generators, and aircraft cabins. Noise reductions of the order of 15 dB are typically achieved in a 10–1000 Hz interval, however every application requires its own specific technique. For wide band noise, recursive filters are necessary. For periodic noise components, adaptive filters based on an external reference signal are used. These filters, designed in our laboratory, are effected digitally as numerical algorithms and run in real time on microprocessors.[12] Our present efforts focus on noise reduction when several dominant modes are present, such

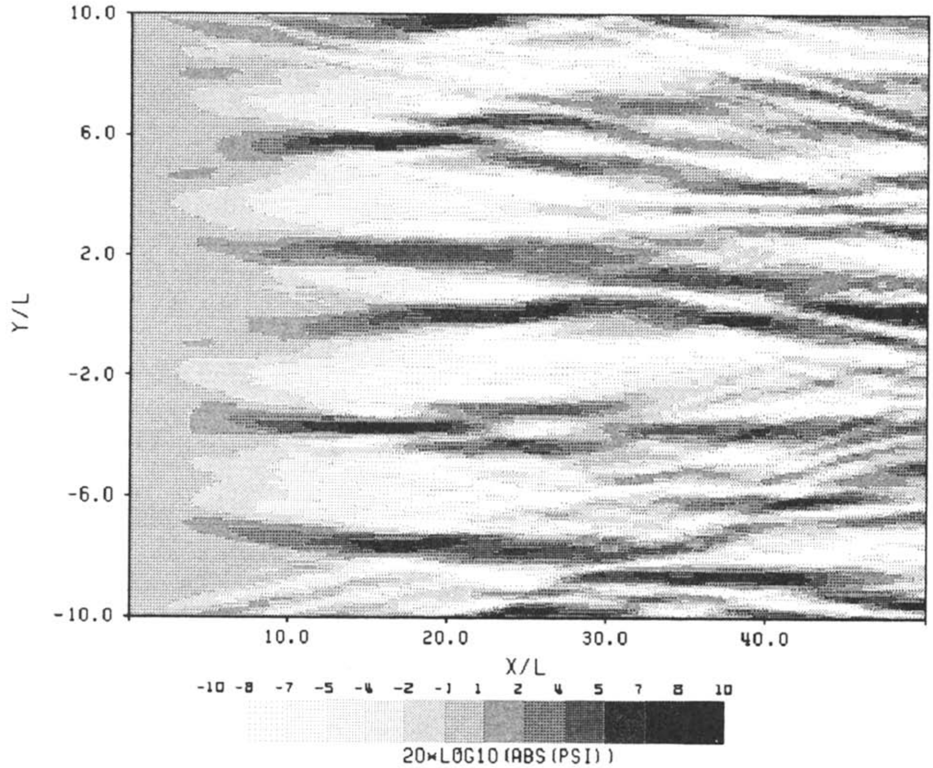

Fig. 3. Acoustic propagation through simulated turbulence: map of sound pressure levels (X is distance of propagation, L is the large eddy scale).

as typically occurs in large three dimensional enclosures. Here, multi-channel systems are needed. Whereas ten channel systems are not beyond reach, a careful analysis is necessary to account for all possible acoustic paths and to find proper criteria for optimizing the filter parameters. Also under development are techniques for active control of local acoustic wall impedances to alter sound propagation by the modification of wall boundary conditions. This approach can be applied, for example, to intake ducts of high speed airplane turbines.

Active control can also be applied to the suppression of flow instabilities and their coupling with near-by resonating systems (Fig. 4). This approach is particularly useful because the amount of power needed for this type of active control is very low. To date we have applied the approach to suppressing surge in fans, combustion instabilities in burners and the resonance of a Helmholtz resonator whose opening is exposed to a tangential flow.[13-15] Multi-channel control systems will be considered in the near future for more complicated situations, such as the control of flow separation and transition of laminar boundary layers.

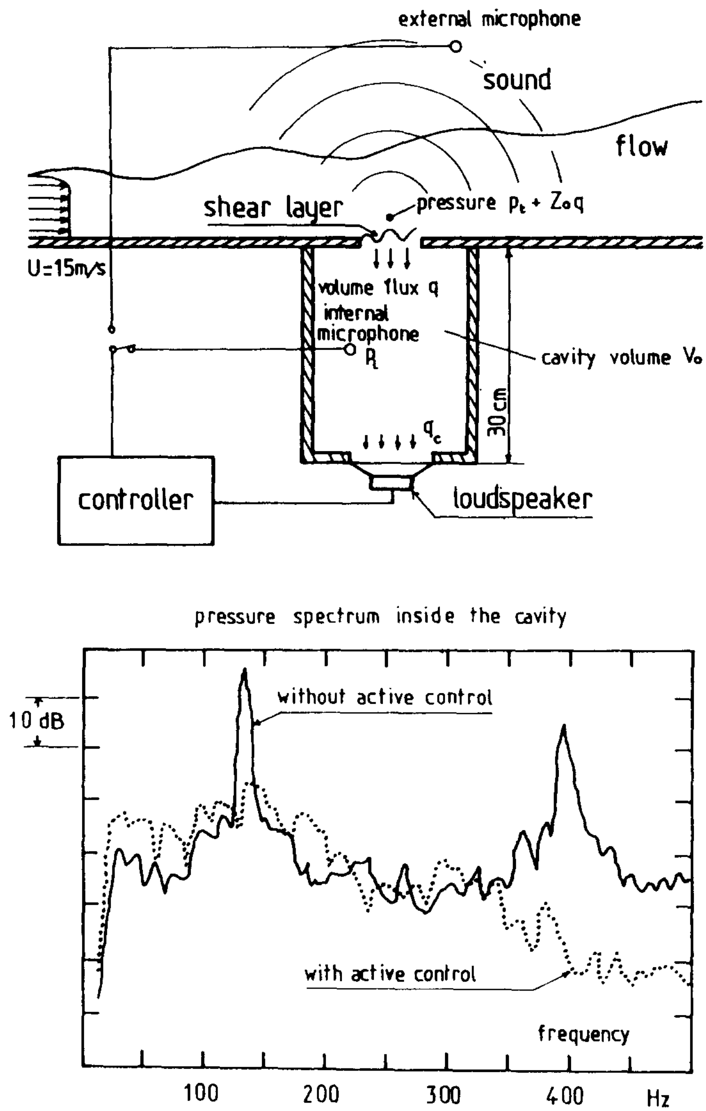

Fig. 4. Use of active control to suppress flow-excited cavity resonances.

3 GRADUATE COURSES OFFERED IN ACOUSTICS AT ECOLE CENTRALE

Each of the courses below contains 25 h of theoretical presentation and 16 h of laboratory work or study of engineering cases. Students usually take four or five of the following courses in a year:

—Fundamentals of acoustics
—Propagation of acoustic waves in inhomogeneous fluid media

—Underwater acoustics
—Aeroacoustics
—Turbulent flows
—Propagation of waves in solids
—Vibrations of continuous structures
—Random and non-linear vibrations
—Acoustic radiation from structures
—Numerical methods in acoustics
—Active control of noise, flow instabilities and vibrations
—Signal processing

During the one year program, a research project takes place in either a university or in a large company. This project is carried out concurrently with the courses and usually takes about 5 months to complete. It involves individual work and leads to a written report and an oral defence. Figure 5 illustrates a student project on acoustic intensimetry.

4 FACILITIES AND EQUIPMENT

4.1 Experimental facilities

Laboratory facilities include:

—Large anechoic room: $10{\cdot}3 \times 8 \times 7{\cdot}6$ m^3; cut off frequency 100 Hz.
—Small anechoic room: $6{\cdot}1 \times 4{\cdot}6 \times 3{\cdot}8$ m^3; cut off frequency 120 Hz.
—Quiet wind tunnel associated with the large anechoic room: 40 m/s in $1{\cdot}55 \times 0{\cdot}55$ m^2 cross-section; up to 160 m/s in $0{\cdot}40 \times 0{\cdot}20$ m^2 cross-section. Another arrangement gives the possibility of a secondary flow (up to 75 m/s) surrounding the high speed nozzle.[16]
—Quiet wind tunnel associated with the small anechoic room: 2–40 m/s in $0{\cdot}40 \times 0{\cdot}30$ m^2 cross-section.
—Adjacent reverberant rooms: $6{\cdot}75 \times 4{\cdot}8 \times 4{\cdot}5$ m^3 and $6{\cdot}2 \times 4{\cdot}6 \times 4{\cdot}5$ m^3; coupling through a 2×2 m^2 opening.
—Water tunnel: 2–12 m/s in $0{\cdot}20 \times 0{\cdot}10$ m^2 cross-section.

4.2 Data acquisition and processing systems

Associated data capture and processing devices include:

—Hot wire and hot film anemometry.
—Spectral analysers and real time correlators.
—Acoustic antenna: 1 or 2 dimensions, and acoustic intensity measurement system.

Fig. 5. Acoustic power measurement by intensimetry.

—Magnetic tape recorders, 4–8 and 14 channels.
—High speed data acquisition system; 8 channels, 12 bits, 500 kHz/channel, 64 kbytes/channel (Transiscope DIFA TS 9000).
—PC Spectrum/Network Analyzer (HP3565 S); 6 channels, 14 bits, 100 kHz/channel.
—Workstations for instrument control and data analysis (Hewlett Packard 9000 types 330 and 318, system HP UX).
—Microcomputers COMPAQ and Hewlett Packard type 486.
—Computer network with ALLIANT FX 2800 and Ethernet link.
—Evaluation and emulation modules for Analogue Devices ADSP 2100 microprocessors.
—Ansys and Sysnoise acoustic field simulators.

REFERENCES

1. Juvé, D. & Sunyach, M., Near and far field azimuthal correlations for excited jets. AIAA 7th Aeroacoustics Conference, Palo Alto, 1981, Paper No. 81-2011.
2. Juvé, D., Sunyach, M. & Comte-Bellot, G., Intermittency of the noise emission in subsonic cold jets. *J. Sound Vib.*, 7(1) (1980) 319–32.
3. Juvé, D., A note on the use of intensity vector maps for source identification. *J. Acoust. Soc. Amer.*, **83** (1988) 1936–9.

4. Fournier, F. & Roger, M., Prédiction du bruit d'interaction rayonné par les fenestrons d'hélicoptères. *J. d'Acoustique*, **2**(4) (1989) 393–400.
5. Jacob, M. & Roger, M., Rayonnement acoustique d'une source ponctuelle située sur l'axe d'un écran mince de révolution. Etude théorique et expérimentale. *J. d'Acoustique*, **3**(2) (1990) 113–24.
6. Robert, G. & Ibars, Ph., Utilisation d'une plaque rectangulaire pour mesurer les petits nombres d'onde du champ pariétal de pression sous une couche limite turbulente. *J. de Physique*, **2**, C2 (1990) 1137–40 (also Ibars, Ph., Contribution des petits nombres d'onde au champ pariétal de pression dans une couche limite turbulente bidimensionnelle. Thèse ECL No. 90-15, 1990).
7. Collorec, L., Juvé, D. & Comte-Bellot, G., Wall pressure and radiated noise generated by three line vortices in chaotic motion close to a solid surface. In *Computational Aeroacoustics*, ed. J. C. Hardin & M. Y. Hussain. Springer-Verlag, New York, 1993, pp. 174–89.
8. Blanc-Benon, Ph. & Juvé, D., Statistical properties of acoustic waves propagating through turbulent thermal fields. AIAA 11th Aeroacoustics Conference, Palo Alto, 1987, Paper No. 87-2727.
9. Karweit, M. J., Blanc-Benon, Ph., Juvé, D. and Comte-Bellot, G., Simulation of the propagation of an acoustic wave through a turbulent velocity field: A study of phase variance. *J. Acoust. Soc. Amer.*, **89** (1991) 52–61.
10. Blanc-Benon, Ph., Juvé, D. & Comte-Bellot, G. Occurrence of caustics for high-frequency acoustic wave propagating through turbulent fields. *Theoret. Computat. Fluid Dynam.*, **2** (1991) 271–8.
11. Juvé, D., Blanc-Benon, Ph. & Chevret, P. Numerical simulation of sound propagation through a turbulent atmosphere. Fifth International Symposium on Long Range Sound Propagation, The Open University, Milton Keynes, UK, 1992, pp. 282–96.
12. Billoud, G., Galland, M. A. & Sunyach, M., Design of IIR filters for feedback-sensitive anti-noise systems. *Internoise 88*, (2) (1988) 1045–8.
13. Sunyach, M. & Ffowcs Williams, J. E., Contrôle actif des oscillations dans les cavités excitées par un écoulement. *Comptes Rendus Acad. Sci. Paris*, **303**, série II (1986) 1085–8.
14. Galland, M. A., Billoud, G. & Sebbani, M., Supression des oscillations auto-entretenues dans un résonateur de Helmholtz par contrôle actif auto-adaptatif. *Comptes Rendus Acad. Sci. Paris*, **312**, série II (1991) 695–700.
15. Billoud, G., Galland, M. A., Huynh Huu, C. & Candel, S., Adaptive active control of combustion instabilities. *Comb. Sci. Technol.*, **81** (1992) 257–83.
16. Sunyach, M., Brunel, B. & Comte-Bellot, G., Performances de la soufflerie anéchoique à grandes vitesses de l'Ecole Centrale de Lyon. *Revue d'Acoustique*, **73** (1985) 316–330.