RESEARCH IN AEROACOUSTICS AT THE CENTRE ACOUSTIQUE OF ECOLE CENTRALE DE LYON

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1 Introduction

The Centre Acoustique of the Ecole Centrale de Lyon is a research group of the Laboratoire de Mécanique des Fluides et d' Acoustique, a unit associated with the CNRS (UMR 5509), specializing in aeroacoustics. In a broad sense, aeroacoustics can be defined as the study of the interactions of sound and flow. Sound generation by unsteady flows is of course one of the primary goals of aeroacoustics, but sound propagation through flows, development of passive or active techniques to control flow noise are also typical components of aeroacoustics. In our group for example the main activities focus on :

- Sound generation by "free flows", i.e. subsonic and supersonic jets, grazing flows over cavities, … both from an experimental and from a numerical point of view.
- Sound generation by lifting surfaces, fixed, like high lift devices, or rotating, like fans and propellers.
- Sound propagation through non homogeneous and/or random media in the linear or non-linear regime (N-waves)
- Wall pressure fluctuations under turbulent flows and the related vibro-acoustic response of flow-excited structures
- Hybrid (active/passive) strategies to design acoustic liners with application to aircraft noise reduction at take-off and landing
- Development of flow control strategies to reduce the noise of unstable flows (for example grazing flows over cavities).

The experimental facilities of the Centre Acoustique consist, mainly, of a large anechoïc room (10m*8m*8m) associated with "quiet" open wind tunnels, one devoted to the study of subsonic flows up to a maximum Mach number of 0.4 (depending on the tunnel section, maximum mass-flow rate 15kg/s), and a second one to the study of supersonic jets (up to M=1.7; maximum mass-flow rate 1 kg/s). Figure 1 gives an illustration of the anechoïc facility, used in this particular case to study the mechanisms of noise reduction due to the injection of water in a supersonic air-jet, a device used during the lift-off of space launchers [1].

In the following pages, two specific items will be described in some more detail, putting forward respectively experimental and numerical aspects :

- The laboratory simulation of the propagation of high intensity acoustic waves through random fluctuations of temperature or velocity
- The "direct" computation of the noise generated by turbulent flows, specifically high Mach number, high Reynolds number subsonic jets, using "acoustic" LES.

More information on the experimental facilities and on the other research topics of the team can be found on our web site : http://acoustique.ec-lyon.fr.

Figure 1 : Injection of water in a supersonic air-jet to reduce the generated noise (Mach=1.3)

2 Laboratory simulation of sonic boom propagation through turbulence

In the near field of an aircraft in supersonic flight, the pressure signal displays a characteristic N-wave form. When propagating to the ground this N-wave is distorted due to several physical phenomena : competition of non-linear effects with frequency-dependent absorption, bending of acoustic trajectories by temperature gradients and wind shear, resulting in the formation of shadow zones, and atmospheric turbulence. Atmospheric turbulence affects the perceived loudness of sound, mainly by changing its amplitude (peak pressure), rise time and total duration. Predicting the modification of these parameters induced by turbulence is important, because perceived loudness of the sonic boom when heard outdoors is a key factor in determining the acceptability of supersonic flight. Field measurements of sonic booms are expensive and are conducted in an environment very difficult to control. Laboratory experiments with small-scale N waves produced by electrical sparks with a downscaled atmosphere, offer an attractive alternative. Several parameters can influence the propagation of sonic booms and it is impossible to realise an experiment completely representative of atmospheric propagation. However the most important parameter seems to be the ratio of the N-wave length to the outer scale of turbulence [2]. In the experiments conducted at ECL the duration of simulated N-waves was considerably shorter than that of sonic booms, but the turbulence length scales have been adjusted so that the ratio mentioned above is approximately conserved (see Table 1); it is therefore possible to model sonic boom propagation over distances of several kilometres with ultrasonic waves propagating over distances of 1-4 m in well-controlled conditions both from a fluid mechanic and an acoustic point of view. Looking at the various waveforms obtained in the experimental set-up for different realisations of the turbulent field, and comparing with “real” traces of sonic booms, is the only way of being confident that the experiment is correctly downsized. Such a comparison is given in Fig.2, showing indeed that similar types of waveforms are obtained, for example multi-peaked, U wave shapes associated with the random focusing of sound, or “messy” waveforms..

	Sonic Boom	**Scaled experiments**
Source	aircraft	electrical spark source
Duration	200 – 300 ms	30-50 µs
Rise time	~ 10ms	2-5 µs
Peak pressure at the bow shock	up to 500 Pa	100 – 800 Pa
Distances of propagation in the turbulence	~ 1or 2 km	1 – 4,5 m
Outer scale of turbulence	~100-200m	10-20 cm
Extent of the inertial zone	Several decades	~2-3 decades
Type of turbulent medium	Atmospheric boundary layer turbulence	Velocity (turbulent plane jet) Temperature (heated grid in air)

Table 1 : Experimental parameters of the laboratory scaled experiments for N wave propagation through turbulence.

In the laboratory, both scalar fluctuations (temperature fluctuations obtained by free convection above a heated grid in air), and vectorial fluctuations (velocity fluctuations in a plane turbulent jet) were studied, as their influence on acoustic wave propagation is different (for the same r.m.s. value of the induced random index of refraction), especially due to a more rapid formation of caustics in the case of vectorial perturbations [3].

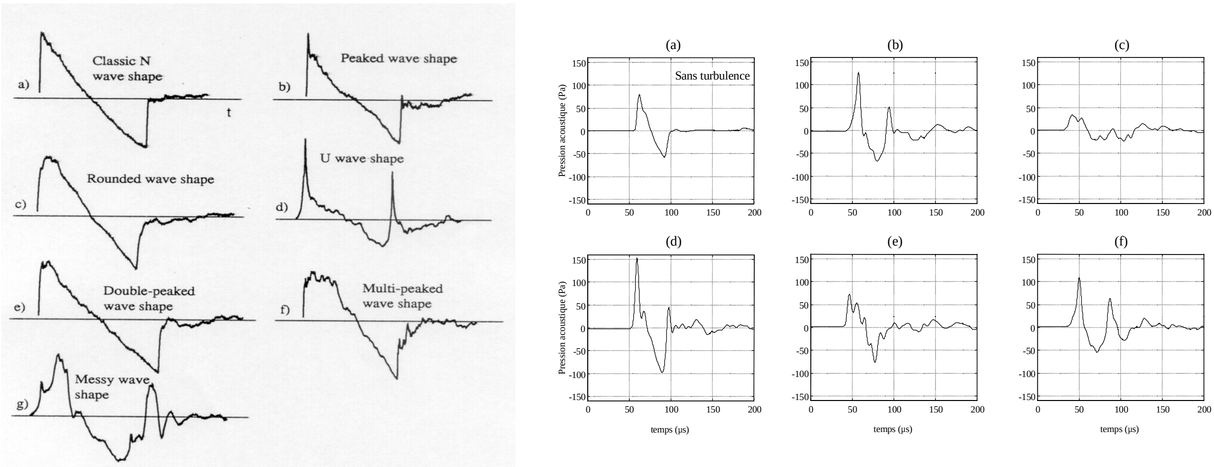

Figure 2 : Snapshots of characteristic N-wave shapes :
Left : recorded during the steady flight of an F-16 aircraft (Mach number=1.3, altitude=4.3 km) by Lee & Dowing [5]
Right : measured in the downscaled experiment after propagation through a plane turbulent jet (mean velocity 11.2 m/s, r.m.s. value of longitudinal velocity fluctuations 2.7 m/s, distance of propagation 1.2m)

From these snapshots statistical properties of the distorted N-waves can be deduced; the main conclusions are the following. In the presence of turbulence one can notice :

- a decrease of mean peak pressure
- an increase of the mean rise time
- an increase of the mean N-wave duration
- a clear correlation between the occurrence of random caustics and the distortion of N-waves.

It is important to note that occasionally the individual behaviour of each quantity can be quite different from the averaged behaviour. For example the peak overpressure can be much stronger with turbulence than without, and in this case the sonic boom will cause much more annoyance, a non trivial result. So it is also important to determine the probability distribution function of the characteristic parameters of the N-waves. This has been done both experimentally and by numerical simulations using a series of realisations of a random field to represent the action of turbulence and propagating non-linearly acoustic waves through each of these realisations before forming the relevant statistics [4].

3 “Direct” jet noise computation by Large-Eddy Simulations

Computing the noise generated by turbulent flows directly is a difficult challenge, especially for free flows like jets, as the conversion of mechanical energy into acoustic energy is a very inefficient process, even if the resulting sound is very loud for people living in the close vicinity of airports (for a sonic jet the ratio of energy radiated as sound to mechanical energy is estimated to be around 5.10^{-5}). In the past, most of the prediction schemes of jet noise have used crude statistical modelling using Lighthill’s acoustic analogy with inputs from RANS-type CFD codes. More recently a second type of approach (hybrid or two-step methods) was developed.

They start from unsteady CFD computations *in the flow region* and use an acoustic analogy to propagate the sound from the flow region to the acoustic far field. The interaction of the acoustic waves with the flow gradients can be partially taken into account by using more refined techniques than the classical Lighthill's analogy, for example Lilley's equation or the set of linearised Euler's equations. One of the shortcomings of these methods is the difficulty of defining the correct "source term" to be put in the R.H.S. of the acoustic propagator [6]. It is only very recently that the direct computation of noise (DNC) has become feasible. By DNC we emphasise that the noise emitted by the flow is obtained *without any acoustical modelling* (i.e. no analogy with the propagation of sound waves in a quiescent or moving fluid is introduced, no source term has to be more or less arbitrarily defined), by solving the full equations of motion for compressible and unsteady flows. For low-Reynolds-number flows solving the Navier-Stokes equations can be done by "acoustic" DNS, but for flows of real practical interest only "acoustic" LES can be used and it is in this direction that we have developed jet noise computations and, more recently, noise generated by grazing flow over cavities. The word "acoustic" in the above expressions is connected to the fact that to obtain the (very small) acoustic component in the flow field special care has to be taken concerning the accuracy of the numerical scheme and of the boundary conditions to simulate free-field conditions. The road has been paved by the pioneering work of Chris Tam and of Sanjiva Lele. DNS studies are useful to assess the techniques and compare different approaches (for example direct results and computation using an acoustic analogy). However for practical applications it is fundamental to consider flows at sufficiently high Reynolds numbers, and in this case one is forced to limit the resolution of the flow to the larger scales and so to use LES. Jets are a major source of aircraft noise at take-off. The most important parameter to consider in jet noise study is the Mach number; so we have concentrated on a jet at M=0.9, a typical value for real engine at take-off. In a first step we have computed the noise of jet for a moderate value of the Reynolds number (65000 based on jet diameter and exit velocity; for comparison, the DNS studies of jet noise by Freund have been conducted at Re=3600 [7]). Both the statistical results in the flow region (potential core length, turbulent intensity, self similarity properties) and in the acoustic field are in very good agreement with experimental results [8]. As an example, figure 3 compares the computed overall directivity of jet noise (mean acoustic level in the far field as a function of the angle measured from the downstream jet axis) with experimental data obtained for the same Mach number and for several values of the Reynolds number. The numerical prediction is within 2 dB of the experimental data. This was the first time that a numerical simulation was able to give, without any fitting constant, such an impressive agreement with experimental data at (relatively) high values of the Reynolds number. These results give sufficient confidence in the quality of the simulation to use these computations as a tool for investigating the sources of noise inside the jet, still a subject of controversy after more than 50 years of research. This study was limited to the downstream direction, where no significant Reynolds number effect is apparent. The main result is that the low-frequency noise radiated in this direction is connected to the intermittent breakdown of the shear layers in the jet at the end of the potential core. The noise generation mechanism appears to be associated to the almost periodic sudden acceleration of vortical structures when

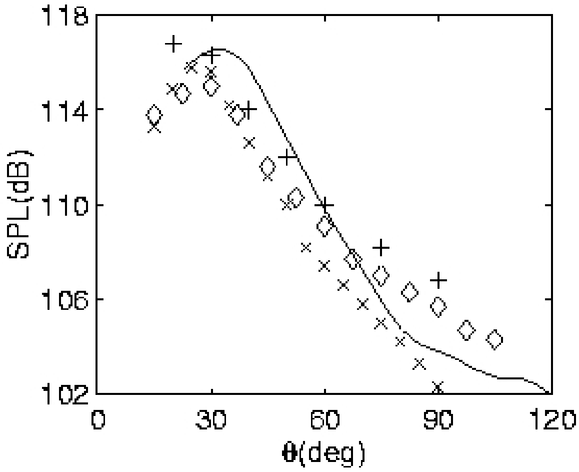

Figure 3 : Directivity of noise emission of a jet at Mach 0.9 (- numerical simulation, Re=65000; x experimental data, Re=3600, + and diamonds, Re=5 10^5). see ref. [8] for details

entering into the high speed jet core. On figure 3 it is however apparent that the dispersion of data points increases in the upstream arc. This is an illustration of the sensitivity of jet noise to Reynolds numbers. It is well known that the noise emission of jets and their sensitivity to upstream perturbation is very different at low and high Reynolds number. To obtain an "asymptotic" state it is necessary to exceed a threshold value of about 10^5. This sensitivity on the Reynolds number is clearly seen on acoustic spectra; while the low frequency part is not very much affected (these components are dominant in the downstream direction), the level in the medium and high frequency range (Strouhal number>0.5) is clearly related to the jet Reynolds number : the higher the Reynolds number, the higher the spectrum level in this range. This is why it was decided to simulate a jet at a Reynolds number of 4 10^5, well above the threshold value, and at M=0.9. Beside the question of numerical resources (the number of grid points is of the order of 16 million), it was necessary to develop new numerical schemes with very low dispersion and dissipation so that acoustic waves could be resolved with a very limited number of points per wavelength, typically 4 [9]. An impression of the results already obtained is given on figure 4, where a 3D snapshot of both the flow field and of the acoustic field is displayed. Careful analysis of converged statistical quantities confirms the relative independence of downstream sound emission with respect to the Reynolds number : levels, spectra and two-point correlations in the azimuthal direction are almost unchanged, so that it can be conjectured that the mechanisms of noise generation are independent of the Reynolds number. However in the direction normal to the jet axis the spectral content of the sound pressure as well as the azimuthal correlations are markedly different in the simulations as it is the case in experiments. A different mechanism for sound emission at large angles relative to the jet axis may be inferred, which can be thought to be related to the fine grained turbulence in the jet shear layers; this idea is reminiscent of the two-component model of jet noise already suggested by Tam from a systematic compilation of spectra of a very large database of experimental results. However this point is only conjectural at this time and further numerical simulations are clearly needed; among a number of questions to be studied in the near future, two appear as especially important :

- the role of upstream conditions (and the possibility of using the sensitivity to these conditions for developing strategies for active control of jet noise)
- the influence of the subgrid scale model used in the Large Eddy Simulation; what is the "effective" Reynolds number of the simulation both from the fluid mechanic and from the acoustic point of view? And how to model the acoustic emission of the unresolved turbulent scales in coherence with the directly computed part? [11]

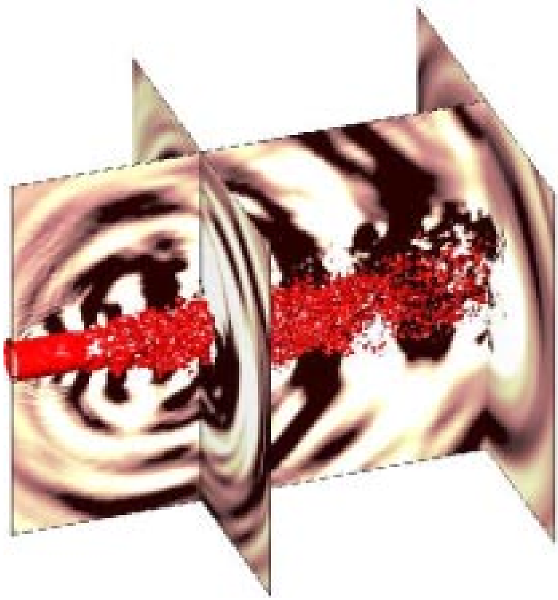

Figure 4 : LES simulation of a high Mach number, high Reynolds number subsonic jet. Visualisation of the flow region (norm of the vorticity vector) and of the acoustic region (pressure field).

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