LECTURE 1
AEROACOUSTICS - SOME THEORETICAL BACKGROUND
THE ACOUSTIC ANALOGY

I INTRODUCTION

I-1 Aerodynamic Noise Generation

Noise production from a mechanical system can be understood as a dissipation process by which the system looses a tiny part of its energy. The particularity of this acoustic dissipation, when compared to, for instance, viscous losses, is that the latter are roughly localised around the system, whereas the former propagates at large distances as sound. Furthermore, dealing with the orders of magnitude of usual sounds in the range of human hearing, the acoustic dissipation is negligible when compared to the total energy of the system, and often when compared to the other forms of dissipation. However it is received as a true nuisance. This makes the point of views of people concerned with the mechanical design of the system, and of scientists working in acoustics, quite different: the system can be described to the first order ignoring its acoustic dissipation, for what enters the scope of mechanical efficiency, losses, fuel consumption, and so on. The acoustic field is at much a higher level of accuracy.

This remark holds in particular for all systems involving unsteady flows, such as the ones encountered in aircraft applications, turbomachinery, heating and ventilating systems and ground transportation. Unsteady flows, both periodic and turbulent, will appear as the source of what is called the aerodynamically generated noise, to be distinguished from the noise radiated by vibrating structures. What will be clearly apparent is that the acoustic dissipation rate corresponding to the aerodynamic noise is a very rapidly increasing function of the characteristic flow speed, which makes aerodynamic noise dominate at high speeds. This is why it is a real issue in aeronautics. Vibrations are ignored below, as they are in most aeroacoustic investigations reported in the modern literature. It is probable that the study of the noise generated by blades experiencing aeroelastic instabilities, such as flutter, for instance, will be the matter for specific research in the future.

Another point related to the smallness of the acoustic waves in flows is the difficulty to simulate those using numerical tools. The Direct Numerical Simulation (DNS) of aerodynamic noise requires the solving of the full Navier-Stokes equations in unsteady, compressible situations and three-dimensional domains of space, with a level of accuracy that will maybe remain unachievable for the next decades. DNS is possible, however, though very time-consuming, in very simplified configurations, where it can help to better understand the basic noise generating mechanisms. Large-Eddy Simulation (LES) can be more appropriate but still remains far from industrial applications and requires a high level of expertise. Less sophisticated averaged approaches, such as steady or unsteady Reynolds-Averaged Navier-Stokes (RANS) computations, are currently used, but do not provide explicit description of the random fields that would be required to predict the broadband noise. This points out a first principle limit when going from heavy to simplified computational means, apart from the question of the achievable accuracy in existing Computational Fluid Dynamic (CFD) codes. A complementary approach to resort to is not to try and reproduce directly the sound field as something included in the flow, but rather to define some post-processing procedures, by which an evaluation of the acoustic dissipation is deduced from a flow simulation, the latter ignoring the acoustic dissipation. The acoustic analogy, defined later on in the notes, is a background formalism that can be used to justify this approach. It is only made possible by the large difference of amplitude between the acoustic motion and the other fluctuating motions, such as turbulence.

I-2 Aeroacoustics: Some History and Current Status

As a branch of acoustics, the theory of the noise generated aerodynamically is relatively new, since it was established in the sixties in connection with the noise from aircraft. At that time, the development of turbojet engines, meeting the requirements of aeronautical transports, involved a dramatic rise of acoustic nuisance in the environment. The progressive reduction in exhaust velocity in the jet, together with the transition to low by-pass ratio, next high by-pass ratio turbofan engines, led later to a substantial reduction in the jet noise, so that the rotating blades of the fan became in turn a significant source too. Furthermore, propellers have been currently used on aeroplanes and the development of helicopters induced specific problems related to the main rotor, as far crucial as a helicopter is actually devoted to operating in urban areas. So it appears that both open rotors and ducted rotors are of great importance in the more general context of rotating blade noise in aeronautics.

The pioneering work of Sir M.J. Lighthill in the fifties (1952) addressing the problem of turbulence and jet noise is the starting point of the theoretical background generally referred to for the investigation of the aerodynamic noise. This work was next extended by J.E. Ffowcs Williams and D.L. Hawkings at the end of the sixties (1969) to include the presence of moving surfaces, for application to the noise from aerodynamic rotors[1]. The basic idea is to define an acoustic analogy, by which the real problem involving a highly disturbed flow and moving solid surfaces is restated as a problem of linear acoustics in a medium at rest with some equivalent acoustic sources. The difficulty of solving exact, non-linear equations is then apparently avoided and replaced by the question of defining the equivalent sources, which is understood as a task of purely aerodynamic nature. In that sense, aeroacoustics is at the junction of aerodynamics and acoustics. However, the difficulty inherent to the equations of gas dynamics for three-dimensional, unsteady, compressible cases cannot disappear by just writing the equations in another way. The pseudo-wave equation of the acoustic analogy generally cannot be solved exactly and the advantage of the formalism is enlightened only if simplifying assumptions are accepted. This means that the neglected phenomena must be of secondary importance with respect to the problem to be solved, and that the dominant mechanism must be preserved.

Nowadays, because of the low noise levels required to meet the international standards around airports, some progress is still needed. Specific points to reduce the impulsive noise from high-speed propellers or helicopter rotors are to be investigated. The very recent performances in the field of aeronautics can be applied with benefit to much less sophisticated technologies. For example, cooling fans for automotive applications, small-size computer fans, as well as air-conditioning devices, are more and more present in everyday life. Human beings need and call for silence, not only during the fly-over of an aircraft, but when experiencing the flow of a hair-dryer too. Consequently, the range of practical applications of the theory of aerodynamic noise widens out, to include rotating machines of much simple design. Ground transports are also concerned with aerodynamic noise. The development of high-speed trains, with expected velocities up to 350 km/h, restates the question of aerodynamic noise from flat solid surfaces with grazing flow and geometrical singularities (cavities, steps, and so on). In another context, the noise from wind blowing on structures and the noise from wind turbines has become a topic of real interest. During more than twenty years from its beginning, the acoustic analogy has been used only as a dimensional tool, essentially because of the lack of efficient computational means for the accurate prediction of turbulent flows or their very high cost. Nowadays, the progress in computers makes some commercial codes reliable tools for industrial purposes, as far as they are aimed at predicting, not the sound itself, but the flow acting as the sound source. This has restored the original interest for the acoustic analogy by making possible true calculations using the compressible or incompressible description of an unsteady flow to infer the acoustic output.

On the methodological point of view, the present lectures are simply devoted to the statement of the acoustic analogy and to the progressive applications of the formalism to the noise-generating mechanisms related to periodic or turbulent flows, some illustrative examples and the technology of rotating blades. The emphasis is often on analytical methods, understood as a fast-running alternative dedicated to pre-design processes in an industrial context, till the numerical tools will be available at a reasonable cost. The analytical approaches also provide a clear physical understanding and allow performing parametric studies. They can be coupled to numerical simulations of a flow within the scope of the acoustic analogy. Some problems of major interest have only recently received analytical solutions, which suggest that the analytical approach is far from over. The most crucial point, however, is that analytical solutions are only made possible by introducing drastic simplifications in the geometrical description of a system or in the description of the flow. This defines their limitation, and the very details of the aeroacoustic phenomena will remain the matter for numerical developments. Both approaches have complementary advantages. Up to that point, let's hope that nobody will have the vanity of discarding any of them when investigating a problem of aeroacoustics.

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[1] Note that similar developments were made and published the same year by Möring, Müller & Obermeier.