1

A Bit of History

In the beginning, there was music... So could begin a history of acoustics, a very old science that has played a primordial role in the process of scientific development. As a matter of fact, it appears that music was one of the first elaborate means of communication. The oldest known instruments date back to 35,000 years ago (lower Paleolithic era called aurignacian) and were simple flutes carved in bones. We had to wait until Greek antiquity to understand the fact that sound is produced by a deformation movement of the body that creates it. However, the process of transmission of sound from the instrument to the ear was unknown to these people. The "Theory of Sound", published in 1895 by Lord Rayleigh [STR 45] and which inspired this short introductory chapter, established what is known as classical acoustics.

Conventionally, acoustics is split into three parts: the production of sound, its propagation and reception. For each of them, it can be useful to present a brief historical primer, focusing particularly on the period which witnessed the birth of the basic concepts, between the 16th and 19th Century.

Finally, we will conclude this chapter by mentioning aeroacoustics, a very recent science that has gained momentum only with the pioneering works of Sir James Lighthill in the 1950s.

1.1. The production of sound

It is commonly accepted that, as early as the 6th Century BC, Pythagoras was the first Greek to study the origin of musical sounds. He showed that the highest pitches are produced by the shortest strings and that a string half as long as another emits a pitch an octave above. The method of plucking the strings was gradually developed, although without its relationship to the concept of frequency being established. It does not appear that this approximation had been made before Galileo (1564–1642). In his treatise, he discusses the influence of the length, tension and density of the string. He further observes that those sounds whose frequencies are integers multiple of the lowest frequency combine pleasantly to the ear.

In 1636, the Franciscan friar Mersenne (1588–1648) carried out, in Paris, the first serious publication about the vibration of strings. He was the first to measure the frequency of a musical sound.

The pioneer of experimentation on the connection between the frequency of the sound and the way the string is plucked was Sauveur (1653–1716), who incidentally suggested the term "acoustics" for the science of sounds. Sauveur, as well as Wallis (1616–1705) at the same time in England, observed that vibrating strings showed motionless points which he named "nodes", while others were animated by a maximal amplitude motion called today "antinodes". The English mathematician Taylor (1685–1731) built the first strictly dynamic solution to the problem of the vibration of strings. His calculations were in adequate agreement with Galileo and Mersenne's experiments. Although he had focused on a specific problem, Taylor has paved the way for Bernoulli (1700–1782), d'Alembert (1717–1783) and Euler's (1707–1783) more elaborate mathematical techniques (partial differential equations).

The phenomenon of the succession of nodes and antinodes on a string characterizes multiple frequencies of the simple vibration frequency of the string. The latter produces a fundamental sound, while the former were baptized harmonics. Experimentally, Sauveur noted that a plucked string emitted a sound with a complex structure in which many harmonics were present. The theoretical explanation of this phenomenon was given by Bernoulli in 1755. The resulting vibration is the algebraic sum of the partial vibrations, an idea that will be later called superposition principle. This drove Fourier, in 1822, to build his famous decomposition theorem whose scope of application is much wider than that of acoustics.

Lagrange (1736–1813) gave an elegant analytical explanation in 1759 to the problem of the strings. He focused on the sounds produced by pipe organs and woodwinds, facing the problem of boundary conditions.

The extension of the methods previously described requires knowledge of the relation of the behavior of the body that relates its deformation to the stress that is imposed on it. This issue had been experimentally addressed on solid bodies, between 1660 and 1676 by Hooke who derived on this occasion the concept of elasticity. This law, more comprehensive than that introduced by Hooke, forms the current basis of the concept of linear elasticity, either in the static (strength of materials), dynamic (viscoelasticity) or quasi-static (vibration) fields. This last field is the basis for the study of noise emissions. Hooke's law was used for theoretical means for the first time in 1744 by Euler, and then in 1751 by Bernoulli in cantilevers or supported beam vibration problems. They based their studies on the deformation energy which later led Rayleigh (1842–1919) to the well-known fourth-order spatial differential equation. This equation, which governs the vibration behavior of the beams, is known as Euler's equation.

The vibration of elastic plates had been studied by Chladni (1756–1824). The results, published in 1787, show the existence of nodal lines that are the two-dimensional equivalent of the vibration nodes of strings. The experiment consists of sprinkling very fine sand on a plate. When it is subjected to vibrations, for example using a violin bow, the sand gathers at the vibration nodes of the plate, the nodal lines. A few examples of one of the plates proposed by Chladni in his book [CHL 09] are presented in Figure 1.1. Following these works, Napoleon in 1802 granted the Institut de France 3,000 F with the subject of the prize being to "present the mathematical theory of vibrations of elastic surfaces, and compare them to the experiment" [CHL 09]. The winner, Sophie Germain (1776–1831), who was the first French self-taught female mathematician, gave an exact fourth-order equation in 1816.

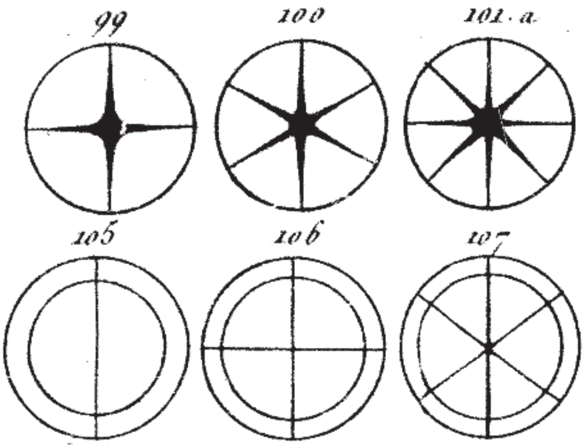

Figure 1.1. *A few examples of Chladni's figures (engraving from [CHL 09])*

Currently, only the structures with a simple form can possibly be solved analytically. This mainly concerns plates (circular, elliptical and rectangular) and shells (cylindrical and spherical), which is sufficient in most industrial applications. All these models are originating from the three-dimensional elasticity equations in which a simplification is introduced assuming that a dimension is small compared with the others, usually the thickness. The complexity of the obtained models suggests that it is unrealistic to expect that geometrical structures of complicated form be addressed in a simple way. It is necessary to resort to approximate numerical methods such as finite elements, and there again, models do not guarantee entire satisfaction. Needless to say that nonlinear elasticity, anisotropic or coupling (interaction) problems between the vibrating structure and the fluid that surrounds it are still the focus of research.

1.2. The propagation of sound

As has already been stressed, the Greeks were aware of the importance of the air in the propagation of sound, without, however, understanding by which mechanism fluids intervened. Since, during observations, the air remains motionless during the "transportation" of acoustic waves, some philosophers did not admit this point of view. For example, Gassendi from France (1592–1655) thought that sound spreads using beams of fine particles capable of impressing the ear. During this time, experiments related to the propagation of sound in a rarefied atmosphere did not invalidate the ideas of Gassendi. These latter were only challenged by Boyle (1627–1691) who carried out a significant experiment that allowed the observation of the decay of the sound intensity transmitted with the intensification of the vacuum. He concluded that the air conveys sound, without being the only material to exhibit this property. The question was to know how fast the air conveys the sound. By using firearms, Gassendi came up with a speed of 480 m/s. Better experiments driven by Mersenne gave 450 m/s. While Aristotle argued that treble pitches were more rapidly transmitted than low ones, Gassendi achieved an important observation by highlighting the fact that the speed of sound is independent of its tonal pitch. In 1656, the Italians Borelli (1608–1679) and Viviani (1622–1703), without specifying the air temperature nor its dampness, found a value of 350 m/s. In 1740, the Italian Branconi showed that the speed of sound increases with the temperature. The first significant measurement in open air was without any doubt conducted in 1822 by the members of the Bureau des Longitudes in Paris by means of a cannon. The observers were divided into two groups situated at two stations distant from each other by 18,700 m. Each group determined the time interval between the perceptions of light and sound of the cannon fired by the other group and then fired a cannon shot in turn so that the first group could perform a similar measurement. Measurements invariably gave 55 s at 15 degree C (therefore, a speed of 340 m/s). Brought down to zero degrees Celsius, the results yielded 332 m/s. During the 18th and the first half of 19th Century, a very large number of experiments confirmed this value. The accepted value is 331.36 ± 0.08 m/s with air at rest at 0 C and 1013.25 HPa.

In 1808, the physicist Biot (1774–1862) made the first experiments on the speed of sound inside a solid medium by using a 951-m long cast-iron pipe which had to be used to provide drinking water in the city of Paris. The observer measured a difference of 2.5 s in the travel times taken by sound through the metal and air. If c_0 and a refer to the velocities of the waves in the air and metal, Biot immediately obtained

$951/c_0 - 951/a = 2.5$ or $a = 10.5c_0$ that is a wave velocity in cast iron used to make the pipe 10 times greater than that of the air.

In 1827, Colladon and Sturm studied the speed of sound in Lake Geneva by measuring the time difference between the image of an inflammation produced by the shock of a hammer on a bell and the sound perceived by an observer located on the shore as indicated in the engraving reproduced in Figure 1.2. They found 1,435 m/s at 8°C.

A first theorization test was proposed by Newton in 1687. Circa 1760, Lagrange proposed another model which yielded once again Newton's results. However, the numerical value that they obtained is significantly different from that obtained experimentally. No significant progress was made before 1816, date at which Laplace criticized the isotherm hypothesis of his predecessors. He replaced it by an adiabaticity hypothesis that seemed to him more appropriate. The two velocities, obtained by Laplace and Newton, are in the ratio of specific heats. They showed the existence of a specific heat at constant volume and constant pressure whose values were known only with a very relative accuracy. Laplace used the numerical value of 1.5 for their ratio γ obtained by experimenters Laroche and Bernard. He obtained a value of the speed of sound of 346 m/s at 6 C. He estimated this value as almost identical to the experimental value of 337 m/s. A few years later, γ was again measured and the value still accepted nowadays of $\gamma = 1.41$ was obtained. This corresponds to a speed of sound in perfect agreement with the experimental values. It should be noted that if Lagrange had had full confidence in his theory, he could have indirectly measured γ very precisely.

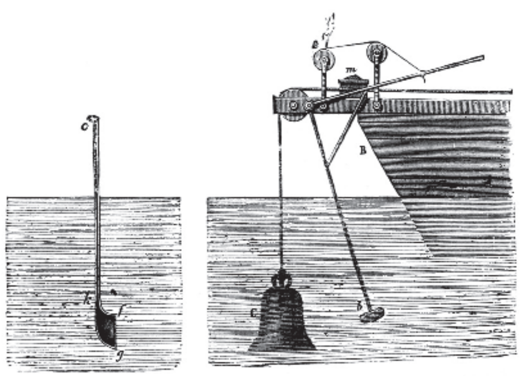

Figure 1.2. *Device setup for measuring sound in Lake Geneva (engraving from [DRI 73])*

Tests for solving the equation of propagation of sound followed d'Alembert's works on the vibration of bodies. In particular, at the end of the 18th Century, the problem of the propagation of sound in pipes started to be well known. Kundt (1839–1894) developed a method that enabled the measurement of the "speed" of stationary waves. Poisson derived in 1820 a theory of propagation in pipes for almost all cases. This work was finished by Helmholtz (1821–1894) in 1860. The particular case of the abrupt change in cross-section was studied by Poisson, as well as the reflection and transmission of sound under normal incidence at the boundary of two different fluids. The case of oblique incidence was treated by Green (1793–1841) in 1838. This had the purpose of bringing forward the similarities and differences between sound and light.

Nowadays, the interest is toward problems of propagation in limited (shallow-water propagation and cavity resonance) inhomogeneous media as well as in random media (turbulence).

1.3. The reception of sound

During the historical development of acoustics, the primary receiver of the studied sound was the human ear. However, no satisfactory or complete theory of hearing has been elaborated, leaving this psychoacoustics problem open, as are also most aspects that relate to the brain and its ability to interpret its environment.

After establishing the evidence of the relationship between the frequency and the plucking of strings, an important task was the determining of the frequency limits of human hearing. Savart (1791–1841) placed these boundaries between 8 and 24,000 Hz. Later Seebeck (1770–1831), using tuning forks, Biot, Koënig and Helmholtz obtained values between 16 and 32 Hz for low frequencies. Nowadays, an audible range between 20 and 20,000 Hz is commonly accepted.

In 1843, Ohm showed that the ear is capable of achieving a spectral analysis of complex sounds. This created a renewed interest in physiologic acoustics. Helmholtz, in 1862, proposed a theoretical model of the mechanism of the ear. It was during this work, called "Theory of Resonance", that he invented the resonator that now bears his name and which is presented in Figure 1.3. He developed the theory of summation and difference of pitches and laid the foundations for all the future research in this area [HEL 68].

From the middle of the 19th Century, acoustics has undergone considerable development and here it is impossible to continue our history of acoustics which would otherwise take us in too many different directions. The interested readers can refer to the historical book (and still actually relevant in many aspects) written by Strutt and Rayleigh [STR 45], as well as to the summary book edited by

Rossing [ROS 07] which contains a more complete historical introduction than this in addition to a list of historical references.

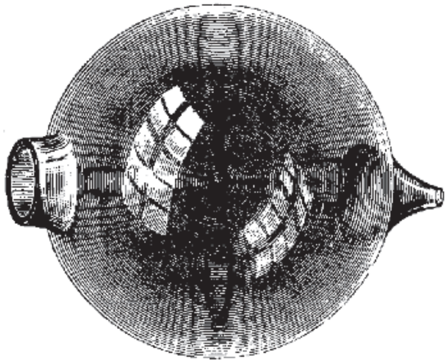

Figure 1.3. *Helmholtz resonator (engraving from [HEL 68])*

1.4. Aeroacoustics

Aeroacoustics is a discipline that involves varied aerodynamic and acoustic phenomena, which are in addition tightly coupled. Its real development as a special branch of physics is fairly recent, since it dates back to the founding works published by Lighthill in 1952. In general, two stages can be distinguished in the sound radiation by flows: the generation of noise in the areas of turbulence where nonlinear effects are very important, and the linear propagation of acoustic waves in a medium at rest until far-field. In order to identify the sources of noise, it is, therefore, necessary to have a good knowledge of turbulent flows; this explains why the progress of aeroacoustics was directly related to that of fluid mechanics, both at the experimental and the numerical level. However, in order to take into account the physical characteristics of acoustic fluctuations, a number of original techniques had to be also developed.

It is, therefore, in 1952 that Lighthill suggested an analogy from which most of the aeroacoustic theories have been developed. By recombining the fluid mechanics equations to show the noise produced by a flow as the solution of an equation of propagation in a medium at rest, Lighthill has enabled the foundation, on rigorous mathematical bases, of aeroacoustics, which then was stumbling a lot: in particular, in this framework, the experimental observation of the variation of noise radiated by a subsonic engine jet as a power eight function of the speed, previously of mysterious origin, is explained in a very simple way. In the context of the Lighthill analogy, the generation of noise is effectively identified by the term on the right of the Lighthill equation, by means of acoustic sources terms constructed from the velocity field and, in particular, from fourth-order correlations of turbulent velocity fluctuations which constitute, in the majority of cases, the primary source term by identifying the source to a quadripole.

The reduction, or even the control (passive or active), of the noise of aerodynamic origin constitutes today a major industrial challenge. Thus, for example, in the nuclear sector, the acoustic radiation produced in the pipes by fast flows is likely to severely damage the structures due to resonant effects being induced. Nonetheless, it is of course in the fields of aviation and land transportation that noises are more directly felt, such that gradually more stringent standards should be respected, and that the concept of acoustic comfort of users must be taken into account from the beginning by the manufacturers. It is, therefore, desirable to be able to accurately predict the sound field generated by turbulent flows if the main purpose is to address it efficiently.