E.F.F. Chladni

Treatise on Acoustics

The First Comprehensive English Translation of E.F.F. Chladni's Traité d'Acoustique

Translated By
Robert T. Beyer

ASA Press

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Since its first meeting in 1929, The Acoustical Society of America has enjoyed a healthy growth in membership and in stature. The present membership of approximately 7,000 includes leaders in acoustics in the United States of America and other countries. The Society has attracted members from various fields related to sound including engineering, physics, oceanography, life sciences, noise and noise control, architectural acoustics; psychological and physiological acoustics; applied acoustics; music and musical instruments; speech communication; ultrasonics, radiation, and scattering; mechanical vibrations and shock; underwater sound; aeroacoustics; macrosonics; acoustical signal processing; bioacoustics; and many more topics.

To assure adequate attention to these separate fields and to new ones that may develop, the Society establishes technical committees and technical groups charged with keeping abreast of developments and needs of the membership in their specialized fields. This diversity and the opportunity it provides for interchange of knowledge and points of view has become one of the strengths of the Society.

The Society's publishing program has historically included the *Journal of the Acoustical Society of America*, the magazine *Acoustics Today* (www.acousticstoday.org), a newsletter, and various books authored by its members across the many topical areas of acoustics. In addition, ASA members are involved in the development of acoustical standards concerned with terminology, measurement procedures, and criteria for determining the effects of noise and vibration.

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Note on the Translation

This work was translated by Robert T. Beyer, Ph.D. (1920–2008), noted acoustician, Professor of Physics at Brown University, and Gold Medal recipient of the Acoustical Society of America. Along with other projects, Dr. Beyer worked on this translation over the last 10 years of his life. As a labor of love, this project was prepared for publication by his children and grandchildren.

The original text includes eight fold-out plates of all of the figures referenced in the text. Since Chladni does not reference the figures in strict numerical order, we have followed the original, and included them at the end of the text, for reference, in 16 standard pages.

Footnotes from the original manuscript have been retained. Additional footnotes have been added to clarify the translation for the modern reader. The key for authorship of the newly added footnotes is as follows:

RTB — Robert T. Beyer, Ph.D.
MAB — Margaret Anne Beyer
CBH — Catherine Beyer Hurst
RRB — Roberta Rea Beyer
TDR — Thomas D. Rossing, Ph.D.
JPC — James P. Cottingham, Ph.D.
GB — Guillaume Bouchoux, Ph.D.

With special thanks to Margaret Beyer, who began assisting her father with this project in 2003, for spearheading this effort and organizing the manuscript, to Rick Beyer for reproducing the plates, to Roberta Beyer for assistance with the French, and to Catherine Beyer Hurst for copy editing the final manuscript. We would also like to thank the Acoustical Society of America for their support, and especially Ken Foote for his unflagging enthusiasm. And, finally, thanks are also due to Thomas Rossing, Ph.D., who applied his depth of knowledge in musical acoustics

to a thorough review of the translation; to Guillaume Bouchoux, Ph.D., a bilingual acoustician, who checked passages in the original French when needed; and to James Cottingham, Ph.D., Chair of The Acoustical Society of America Press Editorial Board, who also reviewed the text, monitored and coordinated changes suggested by the other readers, and answered numerous editorial questions. It really does take a village!

In loving memory of our father
and grandfather.

Catherine Beyer Hurst
Margaret Beyer
Rick Beyer
Mary Beyer Trotter
Brian Hurst
Tim Hurst
Roberta Beyer
Andy Beyer
Julie Trotter
Rachel Trotter
Faith Trotter

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Translator's Introduction: Chladni and the State of Acoustics in 1800

[This introduction is adapted and has been modified from the material on Chladni found in the introductory chapters of *Sounds of Our Times: Two Hundred Years of Acoustics* by Robert Beyer. ISBN 978-0-387-98435-3. Reproduced with permission]

In 1802, Ernst F.F. Chladni (1756–1827) published, in German, *Die Akustik*.[1] Chladni himself translated the book into French, a book "in which I have abridged, changed and added a great deal." He published this volume in 1809 as *Traité d'Acoustique*, dedicating it to Napoleon (a wise choice, no doubt, during that "sun of Austerlitz," especially since the French government contributed funds to support the translation and revision). It is the translation of this French language volume that is presented here.[2]

By just glancing through *Traité d'Acoustique*, we can see several features that distinguish the book from a modern one. The first is the almost complete absence of mathematics. Acoustics, as it was studied at the time, at least, in the mind of Chladni, and aside from music and vibrating structures, was largely a science of observations and descriptions. Magnificent mathematics had been developed by Euler, d'Alembert, and Lagrange in the eighteenth century and applied by them to acoustical problems, but Chladni clearly passed over the details of this mathematics in writing his treatise.

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[1] E.F.F. Chladni, *Die Akustik*, Breitkopf & Hartel, Leipzig, 1802.

[2] E.F.F. Chladni, *Traité d'Acoustique*, Courcier, Paris, 1809.

Ernst F.F. Chladni (1756–1827) (From D. Miller.[3])

A second difference is the emphasis on vibrations. If one had any doubt that vibrations have long been recognized as an integral part of acoustics, a reading of Chladni would eliminate that misconception. Of the four sections of Chladni's book, the one devoted to vibrations comprises more than 60 % of the text. Propagation of sound through air and other gases covers about 15 %, while the remaining 25 % of the volume is divided among propagation in liquids and solids, musical scales, speech, and hearing. (Parenthetically we might note that, even though the period around 1800 was far from a quiet time in the world, there is virtually nothing in the book on noise).

In this book, Chladni divides the subject of acoustics into sources of sound, the passage of sound through matter, and its reception. Perhaps the first problem of sound propagation was the question of whether or not air (or other material) was necessary for sustaining its propagation. By 1800, this was thought to have been long settled. One of the oldest and most frequently repeated experiments in acoustics is the use of a bell or other mechanical source of sound in a chamber that had been evacuated to some extent. This experiment was first carried out by Sagredo in 1615, and repeated a number of times over the next 200 years, with the conclusion, as of 1800, that it had been proven that sound could not travel through a vacuum.

The next question was that of the velocity of propagation in air. By 1800, accurate measurements of the velocity of sound in air had existed for more than 150 years. However, the theoretical basis for calculation of the sound velocity in gases still remained a puzzle. For its calculation, the scientists of the day went back to Newton. Chladni, using Newton's method, cites velocities for a number of gases,

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[3] D.C. Miller, *Anecdotal History of the Science of Sound*, Macmillan, New York, NY, 1935, opposite pp. 24, 51.

such as oxygen and carbon dioxide, that come close to currently accepted values, but was far off in his estimate of the value in hydrogen—680–810 m/sec as against today's accepted value of 1240 m/sec. This problem was still not entirely settled in 1800. It must be remembered that much of our understanding of the behavior of gases, and of thermodynamics, stems from work done in the first quarter of the nineteenth century. Further progress in our knowledge of the velocity of sound had to wait for such a development.

The effect of the temperature on the velocity of propagation of sound was known qualitatively in 1800, but the precise connection had to await a better knowledge of the thermal properties of gases.

In 1800, there was virtually no knowledge of sound transmission in liquids. The velocity of sound in water had not yet been measured. However, a rather good theoretical value for this velocity is given by Young, who noted that the elasticity (we would call this the bulk modulus) of water had been measured by Canton in 1762 and found to be 22,000 times that of air. Using the elasticity data of Canton, Chladni is able to determine the sound velocity in a number of liquids with accuracy similar to that obtained for water.

A measurement of the velocity of sound in solids did exist in 1800, and is described by Chladni in this book. He compares the musical pitch emanating from a struck solid bar (undergoing longitudinal oscillations) with the pitch of the (standing) wave in a closed, air-filled pipe of the same length. Arguing that the difference is due to the difference in the two sound velocities, he comes up with values of the sound velocity. Chladni's wording is a bit obscure, and his values are too low by nearly 15 %. Nevertheless, he did demonstrate that sound velocity is considerably higher in solids than in gases or liquids.

In his discussion of echo, Chladni notes that it is possible (by having two reflecting surfaces facing one another) to have multiple echoes. He remarks that the ear is capable of distinguishing eight or nine different sounds in a single second. Therefore, when these repeated echoes take place more rapidly than eight or nine per second, he states that the phenomenon is known as resonance. We would define resonance somewhat differently today.

In considering sound intensity, Chladni notes that it depends on: the size of the sonorous body, the intensity of the vibrations of that body, the frequency of the vibrations, the distance at which the sound is heard, the density of the air, the direction in which the sound is heard, and the direction of the wind. We would recognize today that these dependences are a mixture of what we call the intrinsic intensity ($\frac{1}{2}\rho c {v_0}^2$, where ρ is the local gas density, c the speed of sound, and v_0 the amplitude of the displacement velocity), and such related quantities as the strength of the source, the directionality of the source, and the attenuation due to geometric spreading and sound absorption. All these quantities were not well sorted out in 1800.

In 1800, the available means for the production of sound were the human voice, musical instruments, cannons and other explosive devices, and natural phenomena such as animal sounds and thunder. It is not surprising, therefore, that Chladni (and others of the time) used music as the basis on which to build almost all of acoustics. When dealing with vibrating strings, they were concerned with stringed musical instruments. Vibrating air columns were of interest because of organ pipes, and also various musical horns, while stretched membranes were related to drums. Almost every subject in Chladni's text is studied from the point of view of music. The great advances of theoretical acoustics in the eighteenth century were perhaps due to the common interests of music patrons, researchers, and the listening audiences.

Well before 1800, the understanding of music led to two great contributions to the science of sound. First, it emphasized the importance of ratios for different tones. The simple ratios appropriate for all the notes on the diatonic scale were known, and musicians with trained ears could easily identify the pitches of the various notes, starting from some accepted standard, such as middle C or, more commonly, the A above middle C. At the same time, it was also known that the pitch of a musical note was measured by its frequency of oscillation.

Because of earlier observations by Mersenne and Sauveur, Chladni is able to base his discussion of musical scales on the grounds of a knowledge of the frequencies involved in the tones of the scale, even though there remained some uncertainty as to what was the appropriate standard for middle C. One must note, however, that Chladni devotes most of his attention, in musical matters, to discussing ratios of frequencies of the different tones, where the quantities are far more accurate, rather than the absolute values of these frequencies. Chladni was aware that the human ear could hear tones as low as 30 Hz and up to 8000–12,000 Hz—which goes considerably beyond the range of frequencies achieved by most musical instruments.

Somewhere between the production and detection of sound is Chladni's own work on vibrating plates, since the study involved not only the production of sound by the vibrating plates, but also the experimental technique of identifying the vibrations. Chladni was well aware of the vibration of strings, and of the localization of nodal points in a standing wave, and the theoretical work of Lagrange and others gave a strong foundation to the subject. There was, however, no theory of vibrating plates.

Chladni was drawn to a study of the vibrations of plates from work done by Lichtenberg who scattered "electrified powder over an electrified resin-cake, the arrangement of the powder revealing the electric condition of the surface."[4] In Chladni's first work, reported in 1787, he held fixed one or more points on a plate and stroked the side of the plate with the bow of a violin. In order to render the effect of the vibrations visible, he placed a little sand on the plate. The sand "was thrown aside by the trembling of the vibrating parts (of the plate) and accumulated on the nodal lines." Chladni must have been fascinated by the patterns taken on by the sand particles, a fascination that these "Chladni figures" continue to generate. In those days before photography, he included hundreds of drawings of different

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[4] These "Lichtenberg figures" are what Chladni refers to as "electric figures" in the preface to *Traité d'Acoustique*.—*JPC*

modes of excitation for triangular, circular, square, and even elliptical plates, in this book.

The only instrument available for sound reception in 1800 was the ear. By the time of Chladni, the structures of the exterior and middle portions of the ear were quite well understood. Chladni recognized that the impulses of sound received in the outer ear were transmitted through the small bones (ossicles) of the middle ear, more or less faithfully, to the cochlea. While the gross features of the cochlea were well described by him, its role, so far as he was concerned, was very much that of a "black box." The sound impulses impinged on one end, and, somehow or other, the sensations were picked up by the auditory nerve at the other and transmitted to the brain. Chladni offered the (incorrect) opinion that the signals from the ossicles affected the cochlea as a whole rather than locally. Further developments in this area had to wait another century.

A phenomenon was observed in the eighteenth century that was later to have important consequences in physical acoustics, although this did not occur until much later. This is the phenomenon that was known as Tartini tones: When two musical sounds of different pitch are sounded simultaneously and loudly, a tone is heard with a pitch equal to the difference in the pitches of the two tones. Chladni and others studied the problem and concluded that it was a form of beats. Under the usual description of beats, when the difference in pitch is small (5–10 beats per second), we can distinguish them clearly. When the number of beats per second increases, we first distinguish the unpleasant sounds of dissonance, but as the number gets very large, they argued, we ultimately hear the pure tone of the difference frequency. While this interpretation was later proved to be incorrect, it satisfied the acoustics community for the next half-century.

In looking back over the period before the publication of *Traité d'Acoustique*, one is humbled by the accomplishments of acousticians who worked with an almost complete lack of anything we would call apparatus. What they had were the human voice and ear, musical instruments, bells and tuning forks, vibrating strings and plates, the basic equations developed over the years, and a great deal of ingenuity and resourcefulness. In a day when we can scarcely add numbers without a calculator, or perform an experiment without vast arrays of electronic equipment, we can only marvel at the success of their ingenuity and resourcefulness.

Robert T. Beyer

TREATISE
on
ACOUSTICS

(TRAITÉ D’ACOUSTIQUE)

by

E. F. F. CHLADNI

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PARIS – 1809