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Life and work of E.F.F. Chladni

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Abstract. Ernst Florens Friedrich Chladni, the son of the rector of the University of Wittenberg, studied law and philosophy at the Universities of Wittenberg and Leipzig, wrote a dissertation in each of these disciplines and became an experimentalist concerned with sound and vibrations. Chladni's name is associated with the *Chladni figures*, and this is the first real effort to experimentally investigate the nature of sound. In the lecture the publications of Chladni are presented and, cursorily, his new instruments, designed and built by the physicist. Chladni began to tour half Europe in his own coach with sufficient space for his musical instruments. He gave lectures on the physics of plate and rod vibrations and included demonstrations of the figures and his musical instruments. Chladni's work has had a profound influence on the experimental advances in acoustics, room acoustics, in the verification of theories of superposition of waves, in elasticity, vibrational modes, sound velocities in various media, and much more. The lecture presents a portrait of the scientist Chladni, the times, and his contributions to experimental acoustics which influenced research for many decades.

1 The youth

In Thomas Mann's novel *Doctor Faustus* (1947) it is reported from the father of the hero of the novel, Adrian Leverkühn: "I should like to know with what eyes one would have looked on the man from Wittenberg who ... a hundred and some years before had invented the experiment of visible music, which we were sometimes permitted to see. To the small amount of physical apparatus which Adrian's father had at its command belonged a round glass plate, resting only on a peg in the centre and revolving freely. On this glass plate the miracle took place. It was strewn with fine sand and ... by means of an old cello bow which he drew up and down the edge from top to bottom made it vibrate, and according to its motion the excited sand grouped and arranged itself in astonishingly precise and varied figures and arabesques. This visible acoustics, wherein the simple and the mysterious, law and miracle, so charmingly mingled, pleased us lads exceedingly; we often asked to see it, and not least to give the experimenter pleasure[1]."[1]

Life and work of Chladni in many respects is non-typical for a physicist at the time of Goethe. The university of Wittenberg, founded in 1502, had its golden age in the decades, when Martin

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[1] "Ich möchte wissen, mit welchen Augen man damals den Mann aus Wittenberg angesehen hätte, der ... vor hundert und einigen Jahren das Experiment der sichtbaren Musik erfunden hatte ... Zu den wenigen physikalischen Apparaten, über die Adrians Vater verfügte, gehörte eine runde und frei schwebende, nur in der Mitte auf einem Zapfen ruhende Glasplatte, auf der dieses Wunder sich abspielte. Die Platte war nämlich mit feinem Sande bestreut, und vermittelst eines alten Cellobogens, mit dem er von oben nach unten an ihrem Rande hinstrich, versetzte er sie in Schwingungen, nach welchen der erregte Sand sich zu erstaunlich präzisen und mannigfachen Figuren und Arabesken verschob und ordnete. Diese Gesichtsakustik, worin Klarheit und Geheimnis, das Gesetzliche und Wunderliche reizvoll genug zusammentraten, gefiel uns Knaben sehr; aber nicht zuletzt um dem Experimentator eine Freude zu machen, baten wir ihn öfters, sie uns vorzuführen."

Luther and Philipp Melanchthon were academic teachers there. In the 18th century its flowering time was long ago. Nevertheless, in the first part of the 18th century its number of 800 students was still above average of the German universities. This changed in the seven-year war when the number of the students fell below 400. After this minimum in 1760 the university recovered due to the presence of a number of excellent lawyers. During this time Ernst Martin Chladni (1715–1782) acted as a full professor at the faculty of laws. His ancestors came from Slovakia. In 1673 the persecutions of the Protestants forced Georg Chladni to leave the country because of his Protestant faith. His grandson Ernst Martin married Johanna Sophia Clement in 1753. On November 30, 1756 their only son Ernst Florens Friedrich was born in the house Mittelstr. 5 (Fig. 1). Chladni's sister passed away when she was a baby, and Ernst Florens Friedrich grew up as the only child. In 1761 his mother died, and his father later entered into a second marriage. In 1824 Chladni described in an autobiographical article in the journal *Caecilia* his childhood and youth full of restrictions and the strict bringing up by his father. This retrospect of the nearly 70 years old physicist explains many specific features in Chladni's life and activity. Chladni mentioned as his hobby the study of natural history, and he was also very interested in music. But his father allowed his son to learn a musical instrument not before he was 19 years old.

Fig. 1. Chladni's birth house, Wittenberg, Mittelstr. 5 (photograph: U. Kuhl).

In 1771–1774 Chladni visited the *Landesschule* in Grimma (Saxony). These *Landesschulen* had been established in secularized monasteries after the reformation, and served as colleges of the Saxonian state for the future government officials, teachers and Protestant preachers. The severe education at home continued in Grimma. Chladni was not allowed to stay at a hostel like the other pupils, but he had to live in the flat of one of his teachers, and therefore he was again under permanent supervision.

After school attendance in Grimma Chladni was induced by his father to start studies of law in Wittenberg, where he was again under control of his father. In 1778 Chladni changed the university and went to Leipzig to escape his father's sphere of influence. Leipzig was an ideal place for active and passive occupation with music and acoustics, and there were many concerts and musical events. With two doctoral theses, one in philosophy and one in laws, Chladni finished in 1782 his studies in Leipzig and returned to Wittenberg.

2 First acoustic experiments

In March 1782 Chladni's father died, and his life changed fundamentally. After his father's death, Chladni felt responsible for his stepmother. Initially this was the main motivation to stay in Wittenberg, although his financial situation was difficult. At the university of Wittenberg one of the two professors in mathematics passed away in 1784, and Chladni applied for the vacant position. But the position was cancelled, and he had to abandon his hopes. In 1783–1792 Chladni announced lectures, first on legal subjects, from 1784 on geometry and mathematical geography, and from 1786 in his real field of research, acoustics.

In 1782 Chladni started with extensive experiments in his flat. Chladni wrote: "For a long time it was my main activity to analyse such sound sources, which had not yet been studied. Up to now only vibrations of strings and vibrations of air in wind instruments were the subjects of studies. And now I performed experiments on transversal vibrations of rods, which had been the subject of theoretical studies of Leonhard Euler and Daniel Bernoulli, and then on the vibrations of plates, which were an unknown field[2].[2]"

First Chladni investigated transversal vibrations of rods with different boundary conditions. The violin bow was the instrument for the mechanical excitation. The idea for this came from a publication on the glass harmonica by the Bach biographer Nicolaus Forkel (1749–1818). This source intimately influenced Chladni's work on instrument making. The essential idea to the sound patterns came from the study of the works by Georg Christoph Lichtenberg (1742–1799). In 1777 Lichtenberg succeeded in making spark discharges in dielectrics visible by decorating the objects with sulphur and minium powders. This motivated Chladni to apply fine sand to his plates and rods. With this method of sound patterns he could confirm the formulas for the characteristic frequencies of rods, which had been derived theoretically. Chladni had a sensitive ear. He could discriminate frequencies differing by less than a semitone. With experiments with vibrating plates with flexural rigidity - the two-dimensional counterpart to rods - Chladni opened a field, which had hardly been studied neither theoretically nor experimentally. Existing theories by Euler and Michael Golovin (?–1790) had been in contradiction to Chladni's experiments.

Chladni studied systematically the sound patterns of circular, quadratic, and rectangular plates, by fixing them with his fingers at different points, thus enforcing at these points the occurrence of nodal lines. The results were published in 1787 in *Entdeckungen über die Theorie des Klanges* with 11 plates and a total of 166 figures. At the end of this book Chladni reminded of the unsolved problem of the mathematical treatment of flexural vibrations of plates. I shall deal with this problem later in detail.

Chladni dealt with sound patterns all his life. In his books in 1802, 1817, and 1827 he came back to this problem. Also in many special papers he discussed this problem. Stimulated by his research on flexural vibrations of rods and plates Chladni had the idea to invent a new musical instrument. This is suggested by several remarks in his first book. Chladni's financial situation was poor. Probably, the income from his private lessons were modest. Already as a child, Chladni wished to travel to faraway places, and so came the idea to demonstrate the sound patterns in Germany and neighbouring countries and to give a popular-science introduction to acoustics for the educated classes. To expand the lectures, Chladni demonstrated his new musical instrument and could demonstrate its mechanism with the results of his acoustical research work (Fig. 2). After many experiments the first musical instrument was finished in 1790 and was called *Euphon*. In 1799 a second instrument, the *Clavicylinder*, was finished (see Ref. [3]).

[2] "Ich sah es geraume Zeit hindurch als ein Hauptgeschäft an, solche klingenden Körper genau zu untersuchen, die vorher noch gar nicht gehörig untersucht waren, indem die damals vorhandenen Untersuchungen sich meistens blos auf Saiten und auf die Schwingungen der Luft in Blasinstrumenten bezogen. Zuerst stellte ich über die von L. Euler und Daniel Bernoulli theoretisch untersuchten Transversalschwingungen eines Stabes Experimente an, und sodann über die, noch von Niemanden untersuchten Schwingungen einer Fläche."

Fig. 2. Chladni, demonstrating his experiments in the palais of the prince of Thurn and Taxis, Regensburg 1800.

3 The travels

In 1791, Chladni started with a travel period, and he travelled - with interruptions - over great parts of Europe. To this end he had an own coach with sufficient space for his musical instrument. Between these journeys he was living in Wittenberg, and since 1813 in the little town Kemberg near Wittenberg. In 1792 he sold his home in Mittelstr. 5, but he lived in this house until the death of his stepmother in 1801. In 1801 Chladni moved into the house Schloßstr. 10 (*Zur Goldenen Kugel*) (*To the Golden Ball*). In this house the future physicist Wilhelm Weber was born in 1804. It is imaginable that the frequent contact between Chladni and the young Weber evoked the interest of the young man in acoustical problems.

The first travel led him first to Dresden, then to Berlin. In 1792 he visited Göttingen, where he met Georg Christoph Lichtenberg. This contact with Lichtenberg was the beginning of Chladni's interest in meteors. This interest culminated in Chladni's second scientific work, the theory of the extraterrestric origin of meteors. But this subject is not my topic here.

When the bow had an acute angle to the string, Chladni heard notes which were 3 to 5 octaves higher than the usual tones. At first he examined the phenomenon with strings and then with rods from different materials. Rubbing the material with a cloth in longitudinal direction he could produce vibrations. Thus Chladni discovered longitudinal vibrations (or dilatational vibrations) of bodies. In 1796 he gave a lecture in Erfurt at the *Kurfürstlich Mainzische*

Akademie nützlicher Wissenschaften and presented first results of his experiments on this subject. Chladni now distinguished between transversal and longitudinal vibrations as it is usual today.

Looking into Chladni's last book from 1827, one notes a confusion of notation on this subject in papers of other authors. Chladni found that the frequencies are reciprocal to the length of the string or the rod. If the diameter or the tension of the string is changed there are only negligible variations of the frequency for the longitudinal vibrations. Chladni had difficulties to find the dependence of the frequency on the density of the material.

When Chladni investigated cylindrical rods, he discovered torsional vibrations of such rods. In the first publication in 1796 and 1797 on this topic one gets the impression that he classifies this type of vibrations as a third class of vibrations in addition to the transversal and longitudinal vibrations. But in the later publications he argues against this possible misunderstanding and denotes these vibrations a special form of transversal vibrations.

Wilhelm Weber and his brother Ernst Heinrich Weber in 1825 had an idea, how to make longitudinal vibrations visible. They used glass tubes, and distributed dry sand in the interior of the tubes. The tube was hold horizontally and excited to longitudinal vibrations by rubbing the tube. The grains of sand started to move and formed little piles. This method was further developed by August Kundt (1839–1894) in 1866 to the well-known method of dust figures.

Chladni must have noticed quickly that the technique of longitudinal vibrations can be used to measure the sound velocity in solid bodies. To this end he applied an indirect method. At that time only the velocity of sound in air was known. Chladni was assuming that the longitudinal vibrations of air in cylindrical form (e.g., in an organ pipe) are analogous to the longitudinal vibrations of a rod. Rods of a material which is examined will be fixed in the centre, i. e., for the fundamental vibration the length of the rod is half the wavelength of the tone. This tone is now compared with the fundamental vibration of an organ pipe with the same length, it shows the same vibrational state. With the velocity of sound in air, Chladni could measure the velocity of sound in several solids (tin, silver, copper, glass, iron, several kinds of woods). He published the results in 1797.

In 1798 Chladni visited the chemist and botanist Franz von Jacquin (1766–1839) in Vienna, and in his laboratory he performed experiments to determine the velocity of sound in gases. In Wittenberg Chladni lacked the necessary equipment to carry out difficult scientific experiments. Therefore he often used the devices of other scientists when he visited them on his journeys. In this time scientific devices usually belonged to the private property of the professors. Their salary at the university was low, and scientific equipments constituted a big investment. To determine the velocity of sound of gases Chladni used the same idea he applied earlier for the determination of the velocity of sound in solids. He compared the tone of an organ pipe in a special gas with the tone of this pipe in air. Thus he obtained the velocity of sound in oxygen, nitrogen, carbon dioxide, nitrogen oxide and hydrogen.

Chladni also examined the vibrations of tuning forks. He found that a tuning fork in its fundamental oscillation may be looked upon as the flexural vibration of a rod with two nodal points. If this rod is bent to a fork, the nodal points in the middle approach each other. If the tuning fork is struck with a mallet, the higher eigenvibrations, being unharmonious to the fundamental vibration, are excited only weakly and decay very quickly. In 1826 Chladni published further studies on the tuning fork. Rotating a tuning fork about 360 degrees he noticed four maxima and minima of intensity. If the forks vibrate out of phase, he argued, the teeth periodically approach each other and depart from each other. In the latter case the air experiences a velocity in outward direction. At the same time the spacing between the teeth is extended, and the air moves to the inside. Between these regions there must be directions, where the air has the velocity zero. After a half-period all velocities change their signs, with an analogous change in the emission pattern.

In 1802, Chladni published in Leipzig the monograph *Die Akustik* [4]. The importance of this book for the development of acoustics in the first half of the 19th century can hardly be overestimated. It was the first systematic description of the vibrations of elastic bodies. The arrangement of the book in chapters on (i) sound generation, (ii) sound propagation, and (iii) sound reception was new, too. When Chladni stayed in Paris in 1808–1810, he translated the book into French, following a suggestion of Napoleon (for more details see Ref. [5]). In 1809 it was published with the title *Traité d'Acoustique* (2nd edition 1812, 2nd German edition 1830). Lorenz Oken (1779–1851) wrote in his review to this book in the journal *Isis*: "This is, and we know what we are stating, the only work of the German physicists, which had a revolutionary impact, and which had introduced a new branch into physics."[3] By means of the logical structure of this book, Chladni introduced acoustics as a discipline of its own, which, as a result of the presentation of acoustics as a theory of the vibrations of elastic bodies, was on a par with the other branches of physics.

In 1802 Chladni started his longest journey. Interrupted with only short stays in Wittenberg, Chladni visited half Europe until 1812. During one of his stays at home, October 14, 1806, there were the battles of Jena and Auerstedt. Napoleon's troops fought against the Prussians. On this day Chladni in Wittenberg heard the guns being fired. The distance between Jena and Wittenberg is nearly 150 km. It is known that also a landowner near Jüterbog (not far from Wittenberg) reported of this event. Chladni attributed the phenomenon to the conduction of the sound by the ground. Today it is known that sound propagation over great distances has its origin in the structure of earth atmosphere. In autumn temperature inversions in the atmosphere are frequent, which are responsible for the reflection of sound in great heights. Thus there is a region where we can hear the direct sound, followed by a region of silence, and from a distance above 120 km there is the second zone of audibility.

From December 1808 to March 1810 Chladni was in Paris, and in February 1809 he met Napoleon and produced the afore mentioned French translation of *Die Akustik*. After Paris Chladni went to Northern Italy. Florence was the most southern place, visited by Chladni. Via Munich and Vienna he came back to Wittenberg. When Napoleon returned from Moscow a part of his army entrenched in Wittenberg. Many professors moved to the surrounding towns. Chladni went to Kemberg, a town not far from here. After the congress of Vienna the University of Wittenberg was united with the University of Halle. Chladni stayed in Kemberg till the end of his life.

4 The last years

In 1815 Chladni started a new period of journeys. In his series of lectures he now included his theory of meteors. At the end of his life his collection of meteors comprised 41 meteors. To demonstrate his theory of the extraterrestrial origin of meteors he presented his meteors on his journeys. In these days Chladni got offers for fixed positions in Berlin, Jena, and Dresden. Now he was fairly advanced in years, and Chladni was not disinclined to accept such a position. But in the end his demand for independence was stronger. When Chladni was in Munich, he met Joseph von Fraunhofer (1787–1826) and this physicist sparked his interest in optics.

During a stay in Berlin in 1825 he met the architect Carl Theodor Ottmer (1800–1843), who made the drafts for the new building of the Singakademie in Berlin (today Maxim Gorki Theatre). On this occasion Chladni came into contact with room acoustics. In *Die Akustik*, a book with 310 pages, room acoustics took up only 7 pages, reflecting the state of the knowledge in 1802. At the beginning of the 19th century room acoustics was treated in terms of geometrical room acoustics. The importance of resonances had been recognized, and it was known that the ear can distinguish at most 9 different sound impulses per second. But on sound absorption and related questions there was a lot of obscurity.

About 1800 the problem of room acoustics was dealt with in particular by architects. The architect Carl Theodor Ottmer showed Chladni in 1825 the plan of the new building of the *Singakademie* in Berlin. The *Singakademie* of Berlin was a choir conducted by Carl Friedrich Zelter and devoted itself to the performance of works by Johann Sebastian Bach. Chladni examined the plan and expressed his positive expectation on the future acoustic properties of the hall in *Singakademie*. The hall was long and the ground plan was rectangular. In January 1827 there was the rehearsal in the new hall, and coincidentally Chladni was again in Berlin

[3] "Das ist, wir wissen was wir sagen, das einzige Werk der deutschen Physiker, das Epoche gemacht hat, das einen ganzen Zweig in die Physik eingeführt hat."

and visited the concert. Chladni's prediction became true. The *Singakademie* was one of the best music halls in Germany till its devastation in 1943.

In February 1827 Chladni went from Berlin to Breslau (today Wrocław). There he gave lectures and passed away on April 3, 1827. We are informed about his last hours, because in the evening before his death he met the mineralogist Henrik Steffens (1773–1845) and this scientist reported on this meeting in his memoirs [6].

5 Outlook

The work of all great scientists has implications in the future. The same is true for Chladni's work. Chladni was the initiator of a completely new branch in physics, acoustics. Comparing *Die Akustik* with the first edition of the book by Hermann von Helmholtz (1821–1894) with the title *Die Lehre von den Tonempfindungen* 60 years later, the great progress is evident. The influence of Chladni's *Traité d'Acoustique* on the scientific research in France shows up in the work by Felix Savart (1791–1841), who was the direct successor of Chladni in France in the field of experimental acoustics. With a gearwheel siren with a diameter of 82 cm and 720 teeth built by Savart a precise measurement of the frequency of tones became possible. Savart measured the upper limit of audibility and found the high value of 24 000 Hz.

An unsolved problem in Chladni's days was the tone quality, the timbre. For a long time it was known that a sound of the same pitch, produced with different musical instruments, has different qualities. Chladni assumed the coexistence of *weak noises* (*schwache Geräusche*) with each sound, being responsible for the different tone qualities. Georg Simon Ohm (1789–1854) solved the problem in 1843. He found that in the human ear a Fourier harmonic analysis of the tone takes place. In addition the ratio of intensities of harmonic fundamentals is important, whereas phase differences between the harmonics are irrelevant. Harmonics definitely had been a research field in acoustics, which was underestimated strongly by Chladni.

The mathematical treatment of bending vibrations of plates showed up to be an extremely complicated mathematical problem. After Chladni's demonstration of sound patterns in the presence of Napoleon in 1809 the *Institut de France* offered a competition for the mathematical treatment of bending vibrations of plates. The French Academy had set a first deadline for the solution of this problem (October 1, 1811). This date had to be extended first by two years and then by two other years (October 10, 1815) because the submitted papers were inadequate. The mathematician Sophie Germain (1776–1831) submitted a paper to each date, which she improved and refined each time. In 1816 she got the prize. But it turned out that the problem still was not yet solved. Sophie Germain had found the correct differential equation, but the hypothesis she applied for the derivation of this equation was partly incorrect leading to the wrong boundary conditions. Gustav Robert Kirchhoff (1824–1887) was the first to solve mathematically correct the problem of vibrations of circular plates with free rim.

In addition to Chladni's studies in acoustics there is his second activity on the origin of meteorites. Most noteworthy, Chladni was very successful in both fields. It may be allowed to end this article with a quotation by Goethe. Goethe dealt with natural sciences in many different fields, and was often criticized because of this diversification. In the periodical *Zur Morphologie* Goethe wrote in 1817 a paper titled *Schicksal der Handschrift*, and there at the end we read: "Who will criticize our Chladni, the proud of the nation? The world owes to him gratitude, since he made the sound visible. And what is more distant from this subject than the study of the meteorites? Where is the link between these activities? Is it the thunder produced by the falling meteorites? Not at all, but that an ingenious man feels the impetus to study two natural phenomena which are far away from each other, and investigates both of them continuously. Let us be grateful for the benefit we gained from it!" [4]

[4] "Wer darf mit unserem Chladni rechten, dieser Zierde der Nation? Dank ist ihm die Welt schuldig, daß er den Klang allen Körpern auf jede Weise zu entlocken, zuletzt sichtbar zu machen verstanden. Und was ist entfernter von diesem Bemühen, als die Betrachtung des atmosphärischen Gesteins ... Wodurch hängt aber dieses Geschäft mit jenem zusammen? Etwa durchs Donnergeprassel, womit die Atmosphärilien zu uns herunterstürzen? Keineswegs, sondern dadurch, daß ein geistreicher,

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aufmerkender Mann zwei der entferntesten Naturvorkommenheiten seiner Betrachtung aufgedrungen fühlt, und nun eines wie das andere stetig und unablässig verfolgt. Ziehen wir dankbar den Gewinn, der uns dadurch beschert ist."