The Acoustics of Beethoven's Hearing Machine

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When the piano builder André Stein persuaded Beethoven to construct a *Gehörmaschine* in 1820, the foundations of what is now known as the science of acoustics had yet to be fully laid. The German scientist Hermann von Helmholtz would not publish his *On the Sensations of Tone* until 1863, followed in England by Lord Rayleigh's *The Theory of Sound* in 1877. That was the era when the first electro-acoustic devices—loud-speakers, microphones and telephones—were being conceived by inventors like Alexander Graham Bell, Werner von Siemens, and Thomas Edison.

Yet long before those cornerstone scientific works appeared, certain professionals must have had a good intuitive approach to the behavior of sound. Violin makers, organ and piano builders, and other musical instrument manufacturers were probably among the most knowledgeable in acoustic matters because of the hands-on experience they had acquired over the years in their workshops. While they did not yet understand that sound propagates like waves, they would certainly have realized that one can guide sound traveling in air toward a certain direction by letting it bounce off hard surfaces. Many early pianos and harpsichords

CD-booklet for Tom Beghin, *Inside the Hearing Machine: Beethoven on His Broadwood - Sonatas Opus 109, 110 and 111*. Evil Penguin Records Classic, EPRC 0025 , 1 compact disc, 2017.

were provided with lids that were hinged to the spine of the instrument. The piano lid would either be closed in order to temper the sound level in small rooms (the common situation for keyboard music up to Beethoven's time), taken off altogether (the norm for more formal performances in larger rooms or in a theater), or tilted open (the position that gained importance over the course of the nineteenth century with the advent of modern piano recitals and dedicated concert halls).

The norm today is for the inclined lid to be open on the right side of the piano, facing toward the audience. The obvious reason for this is that the inclined lid projects the sound radiated by the soundboard toward the audience, like a mirror reflects rays of light, increasing its loudness and clarity. When we design new concert halls, we make use of the principle of sound reflection that we call Snell's law. To give but one example, the acoustic canopy of reflector panels hung above a concert hall stage is designed and optimized to project the sound of the orchestra—and especially the strings—as efficiently as possible to the audience, as well as back to the musicians so they can hear themselves better.

When Stein started conceiving of the hearing machine, he must have realized that guiding as much sound as possible toward the pianist's ears was the main key to amplifying sound for the almost-deaf Beethoven. First, he would have recognized that keeping the piano closed (as Beethoven would have) was not optimal: a closed lid leaves the sound little opportunity to escape. As revealed by his comments in Beethoven's conversation books, Stein knew intuitively that the lid needed to be partially removed and replaced by a device that allowed the contained sound to be released at the pianist's end while at the same time projecting it toward Beethoven's ears.

Second, Stein seems to have been aware of the principle of focusing sound by means of a curved surface. Concave curvature tends to concentrate sound in a focal point at which the sound level is several decibels louder than at other points the same distance from the sound source. Decades before the advent of electro-acoustic reinforcement, Stein could implement this natural means of sound amplification by giving the device a concave shape, which could have taken the form of a cupola or a horn. Unfortunately, no image exists of Beethoven's original *Gehörmaschine*, but the word *Kuppel* (cupola) is mentioned by one witness. It is therefore plausible that at least part of the hearing machine was curved.

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As far as the material of the hearing machine is concerned, wood and sheet metal both come to mind, and both materials were indeed mentioned in Beethoven's written conversations with Stein. From an acoustic point of view, both materials are sound-reflective in the piano's main frequency range (going up to 2000 Hz for the fundamental tones), although at high frequencies (higher than 2000 Hz, corresponding to the multiple harmonics) metal sheets are slightly more reflective than wood due to the open pores of the latter material. In addition, as the *Gehörmaschine* was most likely connected to the Broadwood, the radiation of vibrational energy present in the piano case played a role as well: for maximum radiation efficiency, a panel should be stiff and lightweight, both conditions being best fulfilled by thin metal sheeting. Despite the fact that Beethoven seems to have preferred wood over tin, and regardless of any acoustic arguments, it would have been entirely logical for Stein's hearing machine to be made of sheet metal because it is much more straightforward to construct a complex curved geometry out of bendable metal sheets than out of wood panels—a point that was recorded by Franz Oliva in the conversation books.

Recreating the hearing machine for Beethoven's Broadwood piano

Though Beethoven's conversation books give us a surprisingly detailed account of the process of building the hearing machine, in the end we were left to guess what shape it had, how big it was, where exactly it would have been placed on the piano, and so on. Early on in our discussions, we decided that a purely historical, reconstructionist approach would not be very meaningful. Instead Tom Beghin gathered a multidisciplinary team of specialists, including piano makers Chris Maene and Marc Loncke, Beethoven scholar Robin Wallace, and myself as acoustician. An iterative and creative design process gradually came into being in which historical, acoustic, and technical arguments were factored in as much as possible. The iterative process included producing prototypes of different possible hearing machines at the Pianos Maene workshop, evaluating them aurally and measuring them acoustically. This approach bears similarities with the original design process of 1820, even though Beethoven and Stein had less technical and acoustic expertise at their disposal.

At the start of the project in December 2015, the primary aim was to design a device that would amplify the sound of the piano for the pianist. The first prototype attempt, a cardboard model proposed by Chris, consisted of a simple funnel connected to a flexible hose that was to be held near one's ear. The funnel would be placed on top of the piano where it would collect the sound radiated by the soundboard and bring it to the ear of the listener or to one of Beethoven's multiple ear trumpets. (For a sequence of pictures, from prototypes to final versions, see figure 3.) Although this funnel turned out to be very effective in terms of sound amplification, the obtained tonal quality was too aggressive and too heavily filtered—that is, it lacked the entire frequency spectrum—for any artistic purpose. In addition, it did not correspond to a witness account in which a visitor describes Beethoven sitting a few steps behind the *Gehörmaschine* with his back to the piano, listening to his nephew Carl play the Broadwood and correcting Carl's errors. This suggests that the *Gehörmaschine* did not make use of any direct tube connection to the ear, but rather sent concentrated sound to the pianist purely over the air without using any kind of linking waveguide.

Subsequently, we made two more prototypes: a straight horn with a concave cross section, and the first version of what we started referring to as the box: a device consisting of flat surfaces, shallowly angled at the back and steeply inclined at the front. The sides had been closed off in order to contain as much of the sound energy as possible inside the box. On April 18, 2016, a first listening test was carried out at Pianos Maene with Tom playing the Broadwood. While the straight horn produced the highest amplification due to its concave

FIGURE 3. Retracing the design process: **1** funnel, **2** straight horn, **3** first box, **4** final horn, **5** final box, **6** flexible backward-projecting lid.

shape (as would be expected), the emanating sounds were unpleasantly boomy, cave-like, and nasal, and they had an unbalanced tone color. The box prototype sounded much richer and had a strongly present and beautifully sounding treble, but at the expense of overall amplification. Removing the sides further beautified the tone quality and resulted in a rounder and more spatial piano sound.

The main conclusions of the listening comparison between the straight horn and the box were that for maximum amplification a concave horn shape is indeed required, but for a more balanced quality of tone it is beneficial to keep as much of the lid as possible in place over the soundboard before opening up the angle of the device. And this is exactly what the conversation books imply: Stein replaced the original lid with another, presumably considerably shorter one to make room for the curving amplification device. Another of our conclusions was that while it is possible to estimate the degree of amplification on the basis of acoustic calculations (see figure 4), it is much more difficult to predict the subjective quality of the perceived piano sound purely on the basis of the available objective parameters, such as the results of calculations and computer simulations. A similar situation exists in the field of room acoustics.

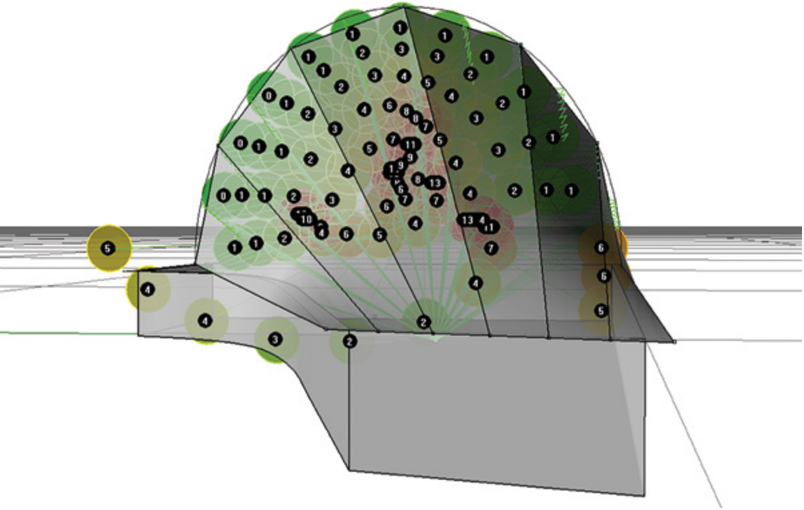


FIGURE 4
Acoustic simulation drawn during the design of the horn prototype, with the aim of maximizing the amplification effect; the numbers indicate increase in amplification due to the curved geometry in dB.

During the following months, we refined both prototypes on the basis of the conclusions from the first listening test. We flattened the horn at the back, starting with a much more shallow angle at the rear of the piano, only opening it up close to the keyboard at an angle that reflected the sound of the treble to the pianist. And we gave the box a curved end, adding some amplification due to its concave geometry. The new horn indeed sounded much less aggressive than its predecessor, while maintaining its strong amplification. The new box conserved the beautiful treble of the first box but generated a stronger overall sound level. Both have their own distinct sound character and may be considered plausible reincarnations of Beethoven's original hearing machine.

In order to quantify the amplification of the hearing machines, we carried out objective acoustic measurements on all final prototypes, but even before we took these measurements it was clear that very significant differences could be heard between the different hearing machines. Tom revealed that some of these devices stimulated his performance and increased the private pleasure of playing Beethoven sonatas on the Broadwood.

Toward a dedicated hearing machine for the present recording

As the recording session was approaching, an additional dimension emerged: how could the endeavor to recreate the sound environment of a deaf nineteenth-century pianist-composer translate into a meaningful audio recording for a normally hearing twenty-first-century listener? After all, when it comes to amplification of sound, a listener can simply raise the volume of the stereo system or portable music player. Through discussions between Tom, Chris, and myself it gradually became clear that an adapted approach was needed for the recording. We came up with a set of requirements, both conceptual and practical.

First, it seemed essential that the recording lid prioritize backward projection toward the pianist over upward diffusion (no lid at all) or lateral projection (the existing lid opened sideways). In addition to these direct acoustic differences, the indirect effect on the pianist's playing would need to be captured. The second requirement was that bass and treble should be treated separately. Not only had Tom expressed enthusiasm for the augmented clarity of the Broadwood's treble that was produced by the most successful prototypes, but during another test, in response to Tom's complaint about an overly boomy bass, Chris had moved the hearing machine approximately half a meter to the right, thereby freeing the strings of the leftmost octaves. The bass was now allowed to escape, and the overall sound became much lighter. The recording lid, we concluded, needed to have separate left and right parts to deal with the bass and treble independently. The third requirement was that this bipartite construction be flexible, meaning that bass and treble parts could be adjusted both to one another and within themselves. The resulting flexible backward-projecting lid, as we dubbed our contraption-to-be, would give Tonmeister Martha de Francisco and recording engineer Steven Maes additional options in their quest to obtain the most pleasing and appropriate sound, and would enable them to explore the various angles of the multipaneled lid with their carefully selected and positioned microphones.

Using the same software that we use for concert halls, I designed what became the final recording version of the hearing machine, which was constructed in Maene's workshop. Split into two panels, it has a cutting line that follows the curved shape of the piano bridge. In addition, both the bass and treble parts are themselves divided by a hinge in the middle, allowing their rear and front parts to be positioned at different angles. These four panels are suspended from a solid stand, arched above the piano. The inclination angles of all four panels were set at the beginning of the recording session to produce optimal clarity of the treble, a well-balanced bass, and an overall open sound. Everyone present was impressed by the impact that even minor changes to the recording lid had on the perceived sound of the Broadwood. After ray tracing the found settings, I was able to confirm that the sound produced by the treble strings was directly projected toward the pianist (see figure 5).

Acoustic measurements of the different prototypes

To obtain objective comparative results, we asked Tom to play six brief Beethoven fragments with each of the hearing machines. A calibrated Brüel & Kjær sound-level meter was mounted thirty centimeters behind the Tom's head. The equivalent continuous sound pressure level, corresponding to the average acoustic energy, was calculated for each of the five different cases: without lid, with

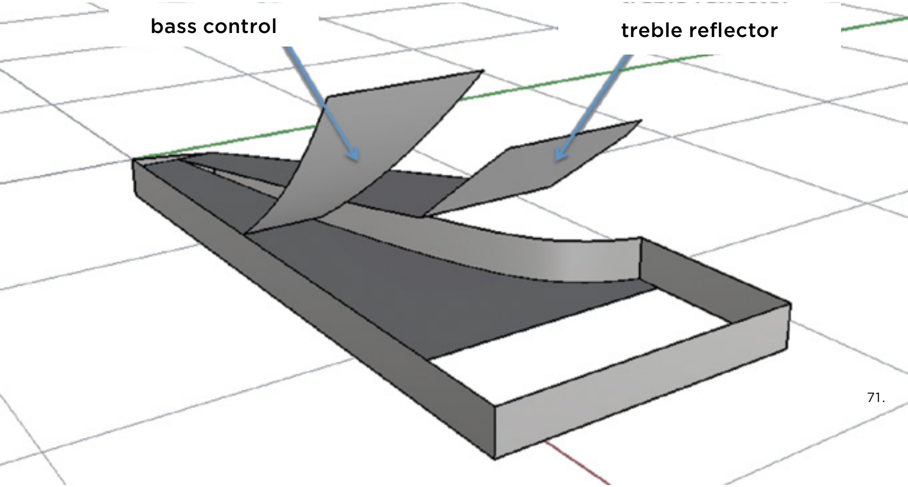
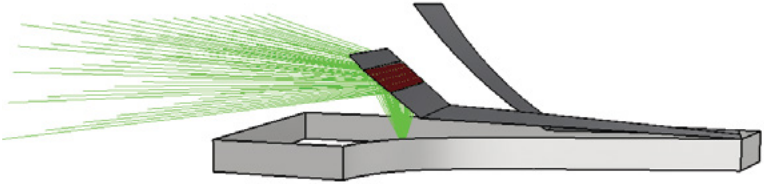


FIGURE 5 Acoustic concept (top) and raytrace of the flexible backward-projecting lid.



original lid, with the split lid (that is, the flexible backward-projecting lid), with the final version of the box, and with the final version of the horn. The results, summarized in figure 6, reveal the true acoustic effect of the different hearing machines (expressed in decibels) for different frequency bands (expressed in hertz). The first case—without lid—was chosen as our reference, corresponding to 0 dB, onto which the other four cases have been mapped.

With the original lid projecting sideways, the sound near the pianist is approximately 1 dB stronger than without the lid across the entire frequency range. With the split lid, however, a 4 dB boost occurs in the 4000 Hz band, corresponding to the first couple of harmonics of the treble strings. The box and the horn produce a similar but even stronger boost in the high frequencies: the box amplifies up to 7 dB, and the horn up to 10 dB, by far the highest result of all. In addition, the box and horn exhibit a peak of up to 7 dB in the bass frequencies (the 125 Hz band), explaining our impression of boominess. Overall, the measured results correspond well to our subjective impressions.

The analysis of the recorded excerpts revealed another interesting fact: the choice of hearing machine, as it turned out, had an influence on the speed of Tom's playing. The duration of the approximately one-minute fragments varied up to six seconds from one hearing machine to the other. The box and horn clearly slowed down Tom's playing, while the split lid had the tendency to speed it up. This suggests that whereas a boomy bass slows the pianist down, amplification of only the high frequencies, producing an increased clarity of tone, invites the pianist to play faster.

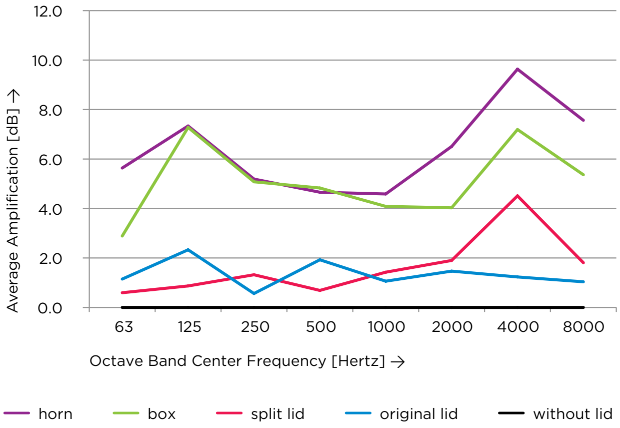


FIGURE 6 Amplification effects of the various hearing machines and lid settings.

In addition to sound-level measurements, we also carried out comparative binaural recordings by means of an artificial dummy head (*Kunstkopf*). The right and left ears of the head contained microphones set up to spatially reproduce the experience of the pianist. This recorded sound told us what Tom heard as he sat at the piano with its various hearing machines. Sure enough, it was clear that the split lid sounded much more open and spatially pleasant than the horn or box, confirming our final choice of hearing machine for the recording.

The role of vibrations in the Broadwood experience

An account of Beethoven's Broadwood would not be complete without a discussion of vibrations. Any piano tone starts with vibrations in the piano strings induced by the hammers. This vibrational energy is transmitted via the bridge to the soundboard, which in turn radiates a good portion of it as airborne sound waves. The remaining vibrational energy is dissipated within the piano structure itself, and can be felt by the pianist, who is touching the different parts of the piano. Tom told me that upon reception of his Broadwood replica from Chris, he was immediately struck by the overwhelming haptic experience: he could feel the keys vibrate strongly. We decided to measure the vibrational amplitude while Tom played by putting lightweight accelerometers—that is, vibration transducers—on different parts of the piano that are in contact with the pianist, including neighboring keys not used for a certain passage and the floor below the pedals, close to the pianist's feet. The same exercise was repeated with a Maene replica of a Viennese piano built by Graf in 1823, which was standing on the same floor as the Broadwood, allowing a like-for-like comparison.

The results were convincing: when we looked at the time plot of the vibration levels for both the Broadwood and the Graf during a crescendo passage in Opus 109, it was clear that the Broadwood vibrated more strongly than the Graf at almost any given moment (see figures 7 and 8). The sympathetic vibration of an unplayed key was between three and five dB stronger for the Broadwood, corresponding to two or three times the amount of vibrational

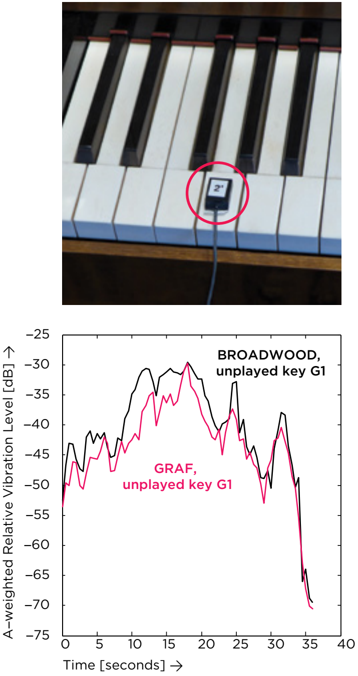


FIGURE 7 Vibration level measurements on Broadwood versus Graf, with accelerometer on an unplayed key. Opus 109, third movement, fourth variation, mm. 105²–112.

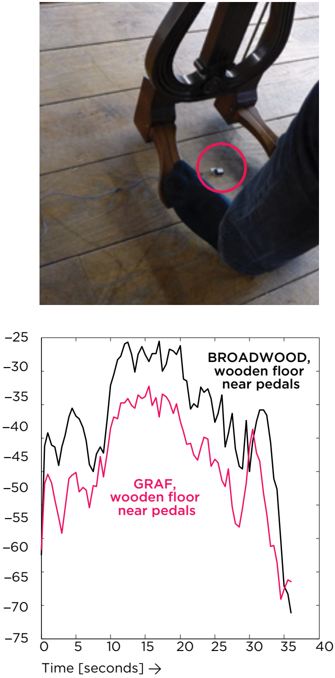


FIGURE 8 Vibration level measurements on Broadwood versus Graf, with accelerometer on the floor. Opus 109, third movement, fourth variation, mm. 105²–112.

energy than with the Graf. For the vibrations transmitted via the piano legs to the wooden floor, the results were even more striking: at a ten dB difference, there was ten times as much vibrational energy in the floor below the Broadwood than below the Viennese piano. The rise of the vibration level during the crescendo was also faster for the Broadwood, which could be explained either by a more sensitive dynamic behavior of the Broadwood compared to that of the Graf, or by a more complex process in which the strong haptic experience offered by the Broadwood invites the pianist to adjust more quickly to the changing dynamics.

Finally, when we listened to the signals acquired by the accelerometers—a process that can be compared to a doctor listening to a heartbeat with a stethoscope—we were surprised at just how fine and musical the vibrations sounded for the Broadwood, covering nearly the entire frequency range. Even a single unplayed key on Beethoven's piano contained all the vital information of the music, including the sympathetic resonance induced by vibrations coming from strings hit by keys on the other end of the keyboard. In contrast, the accelerometer signal acquired for the Graf sounded muffled and was disturbed by strong mechanical thumping at low frequencies, yielding an altogether much less musically satisfying experience. (Sound files may be found and compared at InsideTheHearingMachine.com.) Is it possible that Beethoven preferred the feel of the Broadwood's strong and more musically faithful vibrations over the lesser tactile experience he had been used to from Viennese pianos?

This recording is the culmination of our thrilling exploration into Beethoven's English Broadwood piano. May its unique resonances and vibrations be heard and felt!