Development and demonstration of Helmholtzian instruments

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Introduction

Hermann von Helmholtz started employing the cavity resonator in the early 1860's, as a tool for enhancing the partials of complex tones. It was basically a research instrument, originally made in glass, later on produced in metal by Rudolf König, a German instrument maker established in Paris. Helmholtz argued that the great advantage of such device was the fact that it presented a basic frequency that was much lower than the next resonance value, thus ensuring a more reliable detection of external sounds. It required a physical explanation, which was provided in his classic book [1], and later improved by Lord Rayleigh's formulation [2]. However, more than a tool for sound observation, the Helmholtz resonator may be regarded as a fundamental structure in several musical instruments and other acoustical sources.

During 2021, the 200$^{\text{th}}$ anniversary of Hermann von Helmholtz, a major activity was initiated by co-authors Leonardo Fuks and Malte Kob to produce a number of new musical instruments that feature Helmholtz resonance effects. The idea of the collection was to feature the various concepts of resonance and perception that Helmholtz featured in his publications, including *On the sensations of tone* and, perhaps, going beyond, providing new instruments. A rather large collection of items was designed from scratch or selected among ethnic and folk instruments. A part of this elaboration and testing took place during past winter at the Erich Thienhaus Institute at Detmold University of Music using a 3D printer and manual production techniques. The instruments ranged from simple shapes, such as the Platonic solids (tetrahedron, cube, octahedron, dodecahedron, and icosahedron), up to the complex Klein bottle, turned into a resonator. It is relevant to mention that Helmholtz was a friend of mathematician Felix Klein, who conceived the famous surface. Acoustic analysis methods such as overtone and impedance measurements on the instruments demonstrated the validity and limitations of the idealised resonator models.

Two groups of resonators are focused on this paper: (1) a family of six stepped-tube resonators that combine different portions of a neck – with diameter D1 – and a cylindrical cavity - with diameter D2, all of them with the same natural frequency, called Morphed Resonators; (2) a set of five neckless resonators, i.e. having just a hole across the thin wall of the body, four of them being Platonic Solids – tetrahedron, cube, dodecahedron and icosahedron – and a cylindrical resonator, all of them with close natural frequencies. The Morphed objects were conceived to provide different timbres for resonators with the same fundamental frequency.

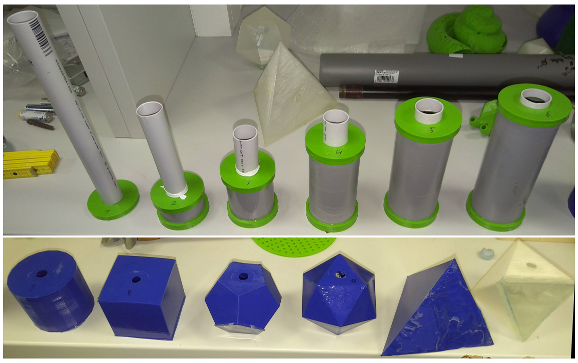

Figure 1: Built resonators: top - Morphed resonators (stepped-tube); and bottom - Platonic bodies (neckless resonators), numbered from left (1) to right (6).

Within the structured session at DAGA 2021 the newly created instruments (see Figure 1) were displayed, their features characterised by measurements, and a set of instruments was available for playing live at a round table.

Production

The two resonator families were manufactured at ETI from CAD models using a 3D printer. The five Platonic solids are available online: in sites such as thingiverse.com, there are several files for download, in different sizes and degrees of filling: some are massive, others are hollow, with various wall thicknesses. We downloaded a set of solids in STL file format and changed the thickness and dimensions to match the same internal volume for all of them. After printing, a hole was made in the center of one face from each solid.

Exciting these resonators with an air jet at the narrow tube outlet or the cavity hole makes them sound near their Helmholtz resonance frequency. Being adjusted to the same fundamental frequency, it is interesting to investigate differences in the sound spectrum of these instruments, related to their resonance spectrum.

Blowing Mouthpiece

To provide a comparable jet excitation for all resonators, a flow channel with a cross section 10 x 2 mm^2 and 6 cm length has been built by a sandwich of 3 CD-ROM disks, the middle one of which has a slit towards the center hole (see Fig. 2). This standardized excitation method assures that the open end impedance at the excitation end is exactly the same for all resonators.

When jet-excited, the fundamental frequency f_0 was at 309 Hz ± 1 semitone.

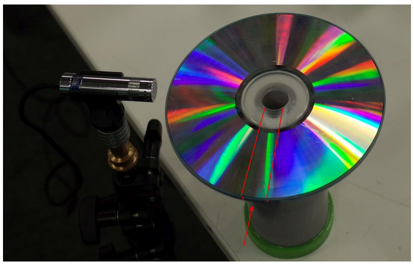

Figure 2: Blowing experiment setup for morphed Helmholtz resonators. Note the blowing mouthpiece made of 3 CD-ROMs, here mounted on top of the Helmholtz resonator 4. The flow channel cut into the center CD-ROM of the sandwich is indicated by red lines.

Morphed resonators

The classical formula universally applied for the Helmholtz resonator, for a given gas and temperature, calculates the lowest frequency as a function of the cavity volume and the two neck dimensions: diameter and length, see formula at the Interpretation section. This implies that if we use the same volume and replace appropriate necks with varying diameters and lengths, we might obtain resonators with the same tuning. But will they sound exactly the same if blown like a bottle? Also, if all the necks have the same diameter, but varying lengths, and are attached to different cavity volumes, so as to play the same pitch when blown, will they have identical sound qualities? We followed the second strategy to build a family of resonators, and analysed the sounds and acoustic responses using the blowing method described above. We decided to include an extreme case of resonator: a cylinder, representing a single tube panpipe. It is obviously a "non-Helmholtz" resonator, and the natural frequencies are easily calculated as the odd multiples of a fundamental. However, this raises the question about how comparatively long can the resonator's neck be and how should we correct and model this extremely large neck. It will certainly be part of further investigations.

Platonic resonators

As mentioned, all bodies were adjusted to have equal internal volumes and dimensions of the opening, i.e., the neck. After printing them out, we measured the volumes filling the bodies with water, and having the liquid weighed for an accurate measurement. The smallest among them was taken as a standard and all other bodies were filled with a corresponding amount of resin to achieve the same value for the whole collection of resonators.

Analysis

The instruments were analysed using two methods: sound spectrum analysis of the blown resonators recorded by a microphone, and impedance analysis using an acoustic impedance analysis system [3].

Sound pressure

Sound pressure recordings were carried out by blowing the resonators with the slitted CD-ROM flow channel described above (see Fig. 2). A calibrated 1/2" measurement microphone (NTI MA2010) was placed at 90 degrees to the flow channel to reduce jet noise portions in the sound recording. Thanks to the blowing mouthpiece, all resonators could easily be excited in a reproducible manner, expect for the morphed resonator variant (1), which did "speak bad, meaning that the evolution of a stable pitch took some delay after starting blowing.
The spectra of the blown morphed Helmholtz resonators are shown in Fig. 3. The sounds of these morphed

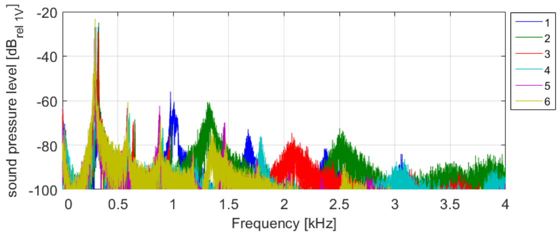

Figure 3: Sound pressure spectra of blown Morphed Helmholtz resonators

Helmholtz instruments all differ from one another in their timbre. Some of the tones sound a bit lighter, airier and thinner, while others sound duller and deeper. This is due to the different overtone distribution within the sounds. Each of these sounds has different overtones that are present together with the fundamental tone. Neither the number of overtones per frequency range nor their amplitudes are equal in all sounds, causing differences in the timbre of a sound. The sound of the first resonator (the one with the longest neck) has a more light, airy and thin timbre. The timbre of this sound can also be explained from the spectrum, where odd overtones, i.e. the fifth and third, are more pronounced there, and the even overtones (octaves) are missing.

Acoustic impedance

In addition to the sound pressure the acoustic impedance has been measured using a device similar to the one described in [3].

The sound spectra shown in Fig. 3 reveal formants near the measured impedance peaks shown in Fig. 4. Whereas

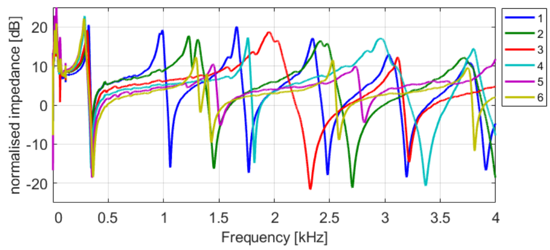

Figure 4: Impedance measures obtained above the open neck of morphed Helmholtz resonators

the impedance peak related to the fundamental frequency is very similar for all variations of the morphed instruments, the higher resonances vary significantly among the instruments.

The analysis of the impedance shown in Fig. 5 reveals only the resonance related to f_0 and more or less expressed resonances near 2.8 kHz which corresponds to the $\lambda/2$ resonance caused by opposing walls within the resonators.

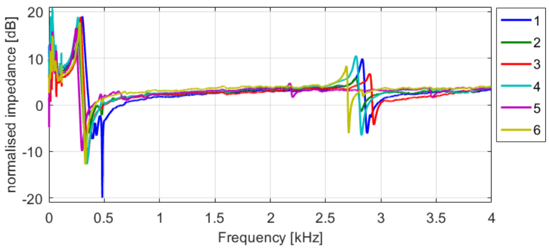

Figure 5: Impedance measures obtained above the opening in the Platonic bodies

Interpretation

The two families of Helmholtzian instruments exhibit interesting differences despite their general similarity according to the Helmholtz resonator theory [4] that determines one resonance frequency:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S_0}{V_0 \cdot L}}$$

with the speed of sound c, the area S_0 and length L of the neck, the volume V_0 of the cavity.

(1) Morphed Helmholtz resonators

These instruments are built such that they have the same f_0 according to the Helmholtz resonator equation above but also feature a cross section jump at the transition between neck and volume which separates two longitudinal resonators. Consequently, the extreme configurations represent approximately a $\lambda/4$ resonator (1: long neck and almost zero volume) and a $\lambda/2$ resonator (2: almost no neck and long volume which is closed on one and almost closed on the other side) on top of the Helmholtz resonator characteristics. This can be seen in Fig. 6 from the bold lines that represent the first and last constructions. The variant (6) exhibits two resonances around

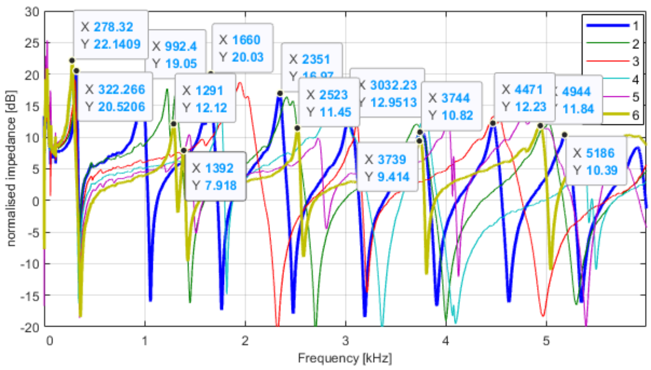

Figure 6: Impedance measures of the morphed Helmholtz resonators, highlighted are variations with long neck (1) and almost no neck (6)

1.3 kHz which is possibly due to the additional cross section jump that occurs by partial covering of the resonator neck opening with the excitation device. This device also was present during measurement of the impedance. The CD has a slightly smaller inner diameter that reduces the neck opening further at a larger distance in comparison to the first section jump between volume and neck.

In the constructions between these extremes the two sections on either side of the constriction between neck and volume vary in effect and superpose according to theory, resulting in additional resonances. We plan to address in the future if the formula for the frequencies of a Helmholtz resonator applies to a considerably long neck, such as in morphs 2 and 3 (Fig. 1). Analytic or numerical models could be used to explain more details of the experimental findings.

(2) Platonic resonators

As a consequence of their similarity in volume and opening, their fundamental frequencies are very close, as expected. However, their symmetric shape provokes internal standing wave patterns that correspond to $\lambda/2$ resonances. These are clearly identified in the spectral plots as equidistant peaks that correspond to multiples of the distance ΔD between the opposite walls according to $f_n = n\frac{c}{2\Delta D}$, independent from the fundamental frequency f_0. For the objects that were created the first resonance due to the opposing walls occurs at ca. 2.8 kHz which corresponds to $\Delta D = 6$ cm. Since the segments differ in size and distance the resonance frequencies also vary slightly. An exception is the tetrahedron (number 5) which does not have opposite walls and therefore does not show a resonance peak around 2.8 kHz.

Conclusions

These experiments show how equal-pitched Helmholtz resonators have different timbres when blown, due to their shapes. The results may be helpful in the development of new instruments and stimulate fruitful discussion in the realms of music acoustics and pedagogy.

Acknowledgements

Benedikt Klein is acknowledged for his work on the analysis of the sounds during his internship.The help by Theresa Jensch and Walter Buchholtzer in the design and printing of the 3D prototypes was much appreciated.

References

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4 Joe Wolfe's web page with interpretation and derivation of the Helmholtz resonator equation: `https://www.phys.unsw.edu.au/jw/Helmholtz.html`