Redesigning the Helmholtz Resonator with Reeds and the Vocal Folds : Expanding Helmholtz's writings on aerophones

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Introduction

2021 marks the bicentennial of Herman Helmholtz. More than a historical figure, Helmholtz is a surprisingly contemporary name. His name appears in many topics of music acoustics: periodic motion of bowed strings; modes of vibration of reed instruments; analysis of complex tones; principles of hearing and music perception; the structure of musical scales and the theory of harmony. Many of his observations are not trivial remarks, and they laid the foundations of many of the theories and models of the functioning of musical instruments.

The 19th century Prussian researcher had a broad understanding of the behaviour of wind instruments driven by reeds, which he sometimes calls "tongues". In many aspects his theories were not fundamentally improved in later research. His cunning experimental techniques are inspiring lessons in inventiveness and resourcefulness and produced many observations which were merely confirmed later with more advanced methods. Examples of these important observations that will be used later in this article are (1) The role of the reed as a modulator of air flow (2) Many sound sources share the same basic principles, such as harmonium reeds, mechanical reeds and lips (when playing a brass instrument) and vocal folds (3) Operating differences exist between reeds that impose their own vibration frequency and reeds that follow the frequency imposed by a coupled resonator (4) and between reeds that close when blown into and those that open. (5) The spectral richness of a sound is related to the more or less abrupt way the reed closes the air intake into the resonator. (6) the musical sounds should be split into an attack, a permanent and a termination phase.

Helmholtz also had a deep understanding of the resonator that carries his name, however he employed the cavity resonator as a mere tool for enhancing sinusoidal partials when carefully attached to the ear canal. In his works the Helmholtz resonator is never referred to in conjunction with a musical instrument.

Several ethnic instruments are based on a Helmholtz resonator, such as the ocarina, the renaissance gemshorn, the Chinese xun, the blown bottles, nose whistles, the african udu, the Brazilian percussive moringa and the jew's harp, found in many world cultures. Several whistles, and the way individuals whistle with their hands, or just the mouth, can be described as Helmholtz resonators. The Brazilian berimbau, a single string instrument with a gourd, contains a Helmholtz resonator. Furthermore, most stringed instruments rely on an air resonance to amplify their lower register. Yet, there is little mention in the literature of Helmholtz resonators driven by reeds.

Aim: redesigning the ocarina

In this article we describe a work in progress aimed at designing new instruments based on the Helmholtz resonator, when excited by different "reeds" or "tongues" and even by human voice, based on the main observations derived from Helmholtz's treatise and separate papers. The first question that triggered our research was "Why isn't there a Helmholtz resonator with reeds?" Even though some attempts are patent in internet fora [1], there is no report on whether these were successful, or what exactly was tried.

We will briefly report the use of five methods to excite a resonator: (1) a single reed with a truncated clarinet mouthpiece; (2) a bassoon double reed directly attached; (3) the use of the lips as in the conch or trumpet; (4) the attachment of an accordion free reed; (5) voice production inside the resonator.

Materials and methods

The following setups were prepared to evaluate the potential coupling between the different excitation methods and the Helmholtz resonator represented by a percussive moringa: a clay recipient with an internal volume of 1550 ml , a neck of length 73 mm and diameter 33 mm. A hole of diameter 39 mm and a wall thickness of 7 mm, see figure 1.

The Brazilian moringa is similar to the Nigerian udu, most probably inspired by that, and is generally played by tapping with the hand directly on the hole. There are two main sounds: a deeper one, resulting from the permanence of the hand on the hole; a tone with higher pitch, that results from a quick removal of the hand. In the first case, the response corresponds to the conventional Helmholtz resonator, consisting of the vessel air column and the single neck. The frequency of this resonance was measured at 138 Hz, and its Q-factor 57. In the latter case, the resonance results from the adding of a second "neck", represented by the hole itself.

1. a single reed with a truncated clarinet mouthpiece – figure 1

2. a bassoon double reed directly attached to the

Figure 1: The Brazilian moringa (left) with a truncated clarinet mouthpiece and reed (right). In all excitation methods the reeds and mouth were adapted to the lateral hole

moringa

3. the use of the lips as in conch or trumpet
4. the attachment of an accordion free reed
5. voice production inside the resonator

The experiments took place at the respective authors' home workshops, rather than in a laboratory environment, due to the access restrictions in Australia and Brazil, during the pandemic period.

Recording and analysis

All sounds were recorded with a microphone connected to the PC soundcard, using Praat [2], at 44100 samples per second, a single channel. They were analysed in Python, using a short-time Fourier method. Spectrograms were extracted with a Hann window 2048 samples in length, which corresponds to 46ms at the recording sampling rate of 44.1 kHz.

Power spectra were obtained using the Welch method with a window length of 16384 samples, or 372ms, allowing for a resolution of 2.7 Hz. Fundamental frequency estimations were obtained from the power spectrum and the estimation of the decay rate by fitting a linear function to the filtered signal of a slap on the side hole of the resonator.

Results

In this section we describe how the different types of exciters behaved when attached to the moringa. When applicable, the playing frequency is stated, otherwise these results are mainly qualitative and we relate them to Helmholtz observations on reed operation.

Voice

For the voice, a glissando was produced from roughly a G below the resonance of the moringa up to the G above. It was clear that a smooth glissando cannot be produced, having a break slightly above the resonance frequency. The sensation while singing into the resonator is somewhat similar to that of playing a didgeridoo or a brass instrument: the vocal fold vibration locks somehow to the resonance. Vocal folds, usually working as a strong reed that vibrates with their own frequency independently of the resonator they're attached to, are here in a weaker position due to a better impedance matching to the resonator.

Interestingly, this locking frequency coincides with the resonance of the moringa, that is about 138 Hz. Instead, we were expecting that the volume of the moringa would add to the volume of the vocal tract to produce a slightly lower resonance frequency.

Otherwise, the moringa provides an interesting filter for the voice, highly attenuating overtones and producing a deep pure tone from the fundamental. In perceptive terms, we could say that this technique provides a "disguise" to the voice, since the listener will hardly distinguish the modified voice from other instrumental sounds, such as the trumpet-like sound described below.

Lip valve moringa

When blown into using lip vibration with a technique similar to that used in the conch [3], the instrument responds easily with a relatively loud sound with a large dynamic range of about 20 dB. The feeling is that the lip vibration locks easily to the resonance, as happens in a digeridoo. Although the playing frequency can be changed in a narrow range, the best efficiency and comfort is achieved at 140.0 ± 1.3 Hz. Further adjustments of the playing frequency are possible using the technique of reducing the neck cross-section by introducing the hand or just a finger, the lip vibration tending to follow the changes in the frequency of the resonator. Even if the change in resonance won't strongly drive the lip behavior, as it would be with a mechanical reed and a pipe, a trained player will easily feel the change in resonance and do the proper adjustments to play in tune with the resonator.

Single and Double Reed moringa

The single reed setup, shown in figure 1, was blown by approaching the mouth to the reed, while covering all air gaps between reed and wall of the moringa. Since the lips did not press the reed directly, the tongue was used to control reed damping and mass. Despite all efforts, this reed could not be made to vibrate at a frequency near the resonator's, although squeaks could be produced.

The only beating reed that could play the moringa at its resonance was the double reed. The correct setting for this oscillation could not be reproduced later, as the reed that played the resonance proved to be cracked during the successful trial. Intact reeds tried later could not play the resonance. A tentative explanation to the relative success of the double reed is provided in the section below about the model.

Despite the difficulties in finding the appropriate reed to work together with the moringa, the double reed appears here as a weak, outward striking reed that couples to a resonator far below its own frequency as described by

Helmholtz.

Both the lip valve and the reed show poor spectral content, probably because they do not have the support of any higher resonances in the moringa, unlike a normal bore instrument. The reed harmonics are slightly richer (harmonic to fundamental ratio around 100 for the reed and 300 for the lip valve). This is consistent with Helmholtz's observation about spectral richness: Lip valves close smoother than double reeds, due to their geometry but also the softness of the tissue. The resonator does not have resonances that are harmonically related to the main resonance of the resonator, at least in the first few multiples of the latter. Any harmonics are thus related to the nonlinearity of the exciter. Notice that the amplitude of the fundamental is about the same in both cases.

Free reed moringa

Three accordion reeds were tested on the side hole of the moringa and blow with the mouth pressing against the wall of the moringa. The reeds corresponded to the notes C3 (below the resonance), C#3 (close to the resonance) and D3 (above the resonance). This was aimed at testing the behavior around the resonance of the moringa.

All 3 reeds were able to produce a tone with much higher spectral content than either the lip or the reed excitation. No adjustments to the reed frequency were tried at this point.

The two higher pitched reeds produced richer tones than the C3 reed, and the latter had a tone that was not as stable as the other two. The C3 reed sounded at 131 Hz for the C3, similar to its free oscillation frequency of 132 Hz. The other two reeds dropped their frequency, with C#3 sounding at 133 Hz instead of its natural 139 Hz, and D3 sounding at 135 Hz whereas its natural frequency is 148 Hz

A mathematical model for the reed ocarina

In this section we use some of Helmholtz's results regarding the Helmholtz resonator and newer results to try to understand some of the behaviours in particular those of the single and double reeds, in particular: Why was the reed ocarina difficult to set in vibration? Why did it vibrate with the double reed? Can we explain that with a simple model of the reed and the Helmholtz resonator?

As valves, reeds have characteristic curves characterising how much flow U they admit for a particular value of the pressure difference between the mouth and the resonator $P_{\text{blow}} - P_{\text{res}}$, through their opening area S. A simple model for this relationship is according to the following formulas:

$$P_{\text{blow}} - P_{\text{res}} = k(S_0 - S)$$

The flow is simply calculated with a Bernoulli formula:

$$P_{\text{blow}} - P_{\text{res}} = \frac{1}{2}\left(\frac{U}{xw}\right)^2$$

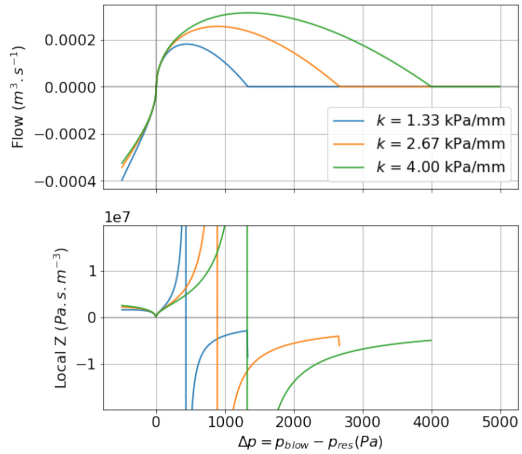

Figure 2: Top: pressure/ flow characteristic curve of the single reed. Bottom: Derivative of the top curve, corresponding to the equivalent resistance of the reed

S_0 represents the opening area when the reed is left to rest. Such model provides one of the top curves in figure 2 shown for a typical clarinet reed.

The bottom axes in figure 2 shows the resistance corresponding to each of the curves $u(p)$ plotted in the top axes $R = \frac{dp}{du}$, the inverse of the tangent of the top curve. When the instrument is playing the reed will swing back and forth on the right-hand side where the slope of the top curve (flow vs pressure) is negative. This is because the reed has to have a negative resistance, corresponding to an element that causes the oscillation to grow instead of dampening it. The values are for a reed mouthpiece typical of a clarinet (1 mm opening with a width of 1 cm)

The resistance (or more generally the impedance) of the reed is important because for a given change in pressure in the resonator the flow has to adapt accordingly to this curve. Because the resonator also has particular ratios of pressure to flow variation (or impedance) at each frequency, the impedances of both the reed and the resonator have to match at the playing frequency. If they cannot match at all then the oscillation cannot happen.

The absolute value of impedance of the resonator can be determined with the knowledge of the geometric dimensions and two parameters determined earlier, the frequency and Q factor of the resonance of the moringa. Using an equivalent electroacoustic circuit we can show that the decay rate $\alpha = -\frac{1}{2CR}$, and we have $R = -\frac{1}{2C\alpha} = 6 \times 10^6 Pa \cdot s \cdot m^{-3}$. This is the maximum impedance expected to be seen by an exciter placed on the side wall of the resonator.

By comparison, the clarinet has a maximum impedance in most of the resonances above $10^7 Pa.s.m^{-3}$ as can be seen from impedance measurements on real clarinets, for example in `https://newt.phys.unsw.edu.au/music/clarinet/E3.html`

We see there is a minimum value of impedance that the reed can provide and this is slightly less than $10^7 Pa \cdot s \cdot m^{-3}$, which is fine for the clarinet but still above the

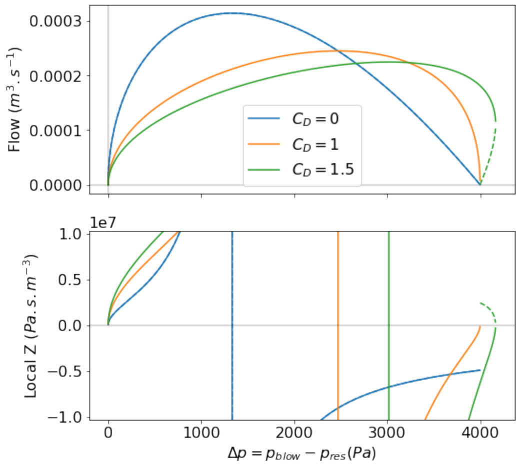

Figure 3: Pressure/ flow characteristic curves as the singular loss is increased in the "neck" of the reed as proposed by [9]. The negative slope of the curve can decrease to 0, bringing the reed resistance to match that of the moringa resonator

maximum impedance of the Moringa ($10^6 Pa \cdot s \cdot m{-}3$). The values of the reed opening can be changed by pressing on it with the lips, or by changing the reed stiffness k. To produce smaller impedances, or steeper $u(p)$ curves 2, a smaller stiffness is required, however this will also produce smaller pressure amplitudes, because the range of available pressures in the curve is also smaller.

Larger pressure amplitudes require an increase in the separation between the reed and the lay, or in the width of the reed.

Why does the resonator sound with a double reed?

Hirschberg [9] proposed that the double reed has a fundamental aerodynamic difference from the single reed. Many double reed geometries have a constriction past the reed that provides additional flow losses, although this doesn't seem to apply to all double reeds [10], it seems plausible that the narrow tube at the tail of the bassoon reed expanding into a large volume could provide a large singular loss. This means that the pressure forcing the reed to close is larger than the pressure that propagates acoustically into the instrument. The effect on the pressure/flow curve is to shift the maximum to the higher pressures, and this increases the slope of the curve, corresponding to a smaller local impedance. In extreme cases the pressure-flow curve can even exhibit hysteresis bringing down the minimum impedance to 0. Of course, the range of playable pressures is now very narrow.

Conclusions

The Helmholtz resonator may effectively be used as a component to a family of wind (and vocal) instruments with further research and manufacturing trials. Collaboration with instrument and/or reed makers might be required to build a reed with appropriate stiffness and dimensions. Furthermore, we also derived a functional spreadsheet [11] for calculating the natural frequencies of Helmholtz resonators with multiple necks, promptly applicable to ocarinas, udus and similar instruments, based on a paper by Langfelt and co-authors (Langfeldt et al., 2019). The reader is invited to check `https://thoughts4sounds.com/helmholtz-and-the-reeds/` for further observations on the topics of reeds and Helmholtz resonators.

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References

[1] `https://theocarinanetwork.com/reed-ocarina-sax-arina-t4390.html?amp=1`

[2] Boersma, Paul and Weenink, David (2021). Praat: doing phonetics by computer [Computer program]. Version 6.1.53, retrieved 8 September 2021 from `http://www.praat.org/`

[3] Rath, S. K. and Naik, P. C. (2009). A study on acoustics of conch shell. Current Science, 521-528.

[4] L. Li et al., Several explanations on the theoretical formula of Helmholtz resonator, Advances in Engineering Software (2017) J. Klaus , I. Bork ,M. Graf , G.-P.

[5] F. Langfeldt et al.Resonance frequencies and sound absorption of Helmholtz resonators with multiple necks. Applied Acoustics 145 (2019) 314–319

[6] Rayleigh L. The Theory of the Helmholtz Resonator, Proceedings of the Royal Society of London. Series A, Vol. 92, No. 638 (Feb. 1, 1916), pp. 265-275

[7] Pantalony D. Hermann von Helmholtz and the Sensations of Tone, Altered Sensations, Archimedes 24, DOI `10.1007/978-90-481-2816-7_2`, 2009

[8] Helmholtz H. On the Sensations of Tone as a Physiological Basis for the Theory of Music. Translated from the 3rd German edition by Alexander J. Ellis. London: Longmans, Green, 1875

[9] Hirschberg, A., Kergomard, J. and Weinreich, G. (1995). Mechanics of musical instruments. CISM courses and lectures, 355. (Chapter 5)

[10] Almeida, A., Vergez, C. and Caussé, R. (2007). Quasistatic nonlinear characteristics of double-reed instruments. The Journal of the Acoustical Society of America, 121(1), 536-546.

[11] `https://thoughts4sounds.com/helmholtz-resonators/`