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Helmholtz in the kitchen: a frying pan as a volume resonator

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Abstract

Helmholtz resonators are an interesting, widespread phenomenon, which can spark students' interest in acoustics and more generally in applying physics to the phenomena of everyday life. Using a smartphone as an experimental tool to measure and analyze acoustic data, this work presents an investigation of the sizzling noise of something frying in a pan, and also of the change of this sound when the lid of the pan is opened and closed. We adapt the general resonance frequency result of the Helmholtz resonator (1) to the case of a real lid-pan system (2) and to a better controlled case using an artificial lid with a rectangular opening and a white noise source (also provided by a smartphone) inside the pan. Experimental spectra obtained for both cases show satisfactory agreement with the theoretical prediction. We conclude with a discussion of the limitations and perspectives of the experiment.

Keywords: acoustics, mobile technologies, Helmholtz, resonator

(Some figures may appear in colour only in the online journal)

1. The phenomenon

Ssshhhhshshh … everybody knows the appetizing sizzling noise of something frying in a pan ('frying sound'), and maybe also the *change* of this sound when the lid of the pan is opened and closed. In case you do not know, have a look at figure 1 and try yourself: the pitch of the sound is lower when the lid is almost closed, and gets higher when the lid is opened.

Beyond interest in the content of the pan, the 'hungry mind' [1] endeavours to know where this curious change comes from, and this is the subject of the present contribution.

Figure 1. The 'Helmholtz pan' with lid at 10° ('closed', left) and at 30° ('open', right).

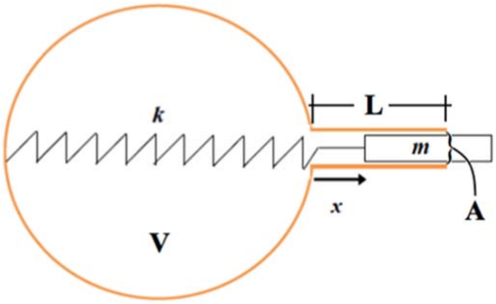

Figure 2. Geometry of the Helmholtz resonance. Adapted from [2].

2. Theory

The basic idea is to understand the sound from the pan as a Helmholtz resonance (HR), i.e. as the lowest mode of an open acoustic cavity, with the frequency determined by the cavity volume, the opening cross-section and diameter, and velocity of sound. The principle of the HR is shown in figure 2: an air mass in the opening is coupled to the 'spring' of compressible air within the cavity.

Helmholtz resonances are responsible for many acoustic phenomena in everyday life (musical instruments, e.g. the fundamentals of guitars and violins; ([3], 9.4, 10.5.2), bottle resonances; [4], buffeting or booming sounds in vehicle interiors [5], etc). A resonance frequency without damping is given by ([6], 8.5)

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{A}{L_H V}}. \tag{1}$$

The effective length L_H (Helmholtz length) is not the geometric length, but given by

$$L_H = l + \Delta l \tag{2}$$

where Δl is the so-called 'end' or 'mouth' correction, due to the motion of gas outside the geometric boundaries of the opening [7, 8]. For a flat opening in a wall (i.e. without a neck), Ingard [9] has shown that $\Delta l = \alpha\sqrt{A}$, where α is a numerical constant close to 1 depending on geometry, which in his paper he calculates for a variety of cases. For the present purpose of an approximate understanding of the frying sound, we use

$$\Delta l = \alpha\sqrt{A} \sim \sqrt{A}. \tag{3}$$

Now, if the effective length for a flat opening is inserted in the resonance frequency, the following expression is obtained:

$$f_0 = \frac{c}{2\pi\sqrt{\alpha}}\sqrt{\frac{\sqrt{A}}{V}} = \frac{c}{2\pi\sqrt{\alpha}}\frac{\sqrt[4]{A}}{\sqrt{V}}. \tag{4}$$

The first expression on the RHS shows that there is $1/\text{length}^2$ under the square root, as it should be on dimensional grounds. The second highlights the dependency of the frequency on the 4th root of the opening surface, in which we will mainly be interested in the sequel. If the pan really behaves like a Helmholtz resonator we should find this dependency, at least approximately.

For the real-life case (pan and lid) the geometry is non-trivial. First, the angle of the aperture is calculated with the law of cosines, given a diameter d and a distance h between the pan rim and the lid:

$$\theta = \cos^{-1}\left(1 - \frac{h^2}{2d^2}\right). \tag{5}$$

Then the surface A is calculated from θ utilizing the Pappus–Guldin [10] theorem for a toroidal geometry:

$$A = 2\sqrt{2}\pi d^2\sqrt{1 - \cos\theta}. \tag{6}$$

The system volume is given by $V_0 = 0.0016\ \mathrm{m}^3$ for the pan itself, $V_l = 0.0006\ \mathrm{m}^3$ for the lid and V_c for the (wedge-shaped) change of volume as the lid opens. The latter is also given by the theorem of Pappus–Guldin as

$$V_c = 2\pi r^3\theta. \tag{7}$$

Together the total volume is entered into equation (4) through V:

$$V = V_0 + V_l + V_c. \tag{8}$$

It is important to keep in mind that in the case of a common pan and lid system the surface A and the change of volume V_c are dependent of the aperture angle θ.

We now use the above results for two experimental cases, (i) the real-life system of a pan and lid, and (ii) a system with an artificial lid with an adjustable square opening, simplifying geometry.

3. Experimental procedure

Acoustical signals are measured by an iOS smartphone with the SpectrumView app (https://oxfordwaveresearch.com/products/spectrumviewapp/; see [11, 12] for alternatives). As a first qualitative example, consider in figure 4 the frequency change of a pan with frying oil, as the lid is gradually opened from 0° to 30° over some 20 s. The spectrogram shown in this figure is a representation of the evolution of the spectrum in time; the color (from blue to red) codes the level, in dB, of each frequency. A clear increase of the main frequency can be seen starting when the lid is opened (around 20 s) until a point when the acoustic energy is dispersed in all frequencies (around 40 s, more than 30°). This confirms the audible pitch change of the real-life kitchen phenomenon which inspired the present paper.

For quantitative measurements, we replaced the natural noise source (frying oil and fish croquettes) by another smartphone with the NoiseGenerator app (https://tmsoft.com/noise-generator/). In every measurement the frequency with the maximum sound level obtained by

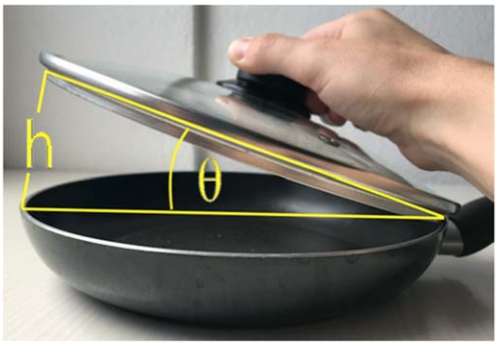

Figure 3. Pan geometry.

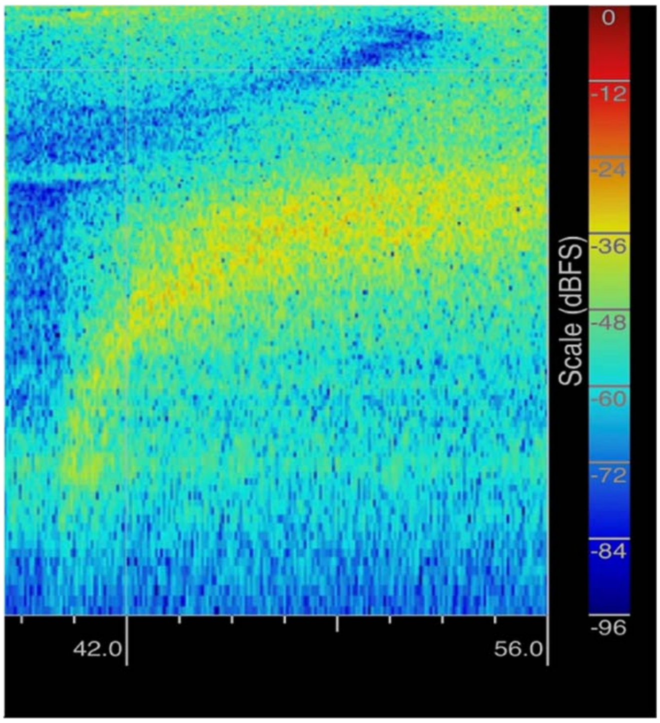

Figure 4. *f-A* dependency in a real-life kitchen setting (pan and lid and frying oil); the lid opens from 0° to 30° from left to right.

SpectrumView in the detecting smartphone is determined. The empirical audible frequencies are obtained as an average of five measures for each opening angle. The recorded data are processed by Microsoft Excel.

A first group of measurements was taken on the 'natural' pan-lid system (see figure 3). Setting $G(\theta) = A\ (\theta)^{1/4}/V_0^{1/2}$, and $k = c/2\pi\alpha^{1/2}$, equation (4) reads as

$$f_0 = k\ G(\theta). \tag{9}$$

Here $G(\theta)$ is given by geometry, and is well known. However, k is less well known, first due to the sound velocity c (depending on the exact composition of the air-vapor mixture in the

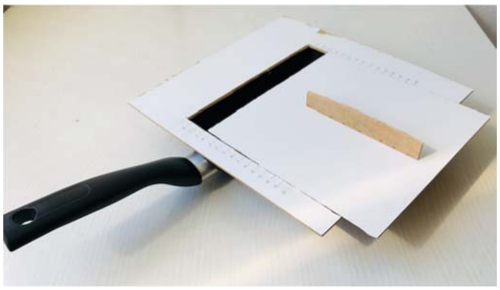

Figure 5. Pan with artificial lid.

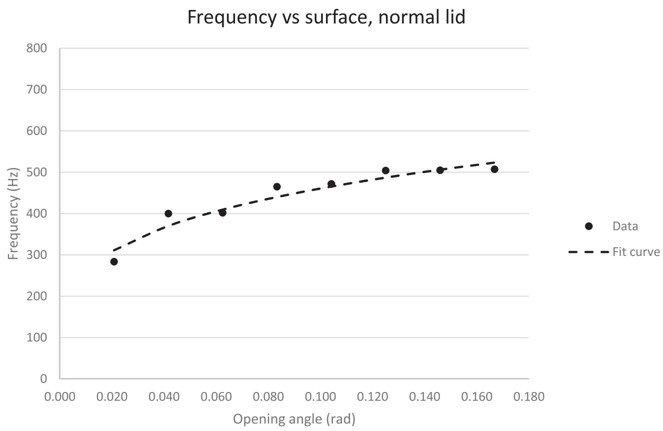

Figure 6. f_0 versus A for the pan with a normal lid; the curve shows a fit according to equation (8) ($R^2 = 0.92$).

pan and even more on its temperature, which we both do not know), and second due to the end correction parameter α (which is of the order of unity, but not known more exactly for this opening geometry). We thus look for an optimal fit of k (using Excel) so that equation (8) best describes the data.

A second group of experiments was undertaken on a system with an artificial flat lid with an adjustable rectangular opening, with simplified geometry: A is trivial (rectangle), $V_0 = 0.0016$ m^3 as above. For this case, equation (4) reduces to

$$f_0 = k\frac{\sqrt[4]{A}}{\sqrt{V_0}} \tag{10}$$

where $k = c/2\pi\alpha^{1/2}$ as above. We again infer an optimal fit value for it from the data, but in this case we know c (343 m s^{-1}, air at ambient conditions) and can further infer α.

4. Results

4.1. Pan with normal lid

The data are shown in figure 6. A best fit of equation (8) is obtained for $k = 49.3$ m s^{-1}. With this value, equation (8) yields the predicted curve, also shown in figure 6. The coefficient of

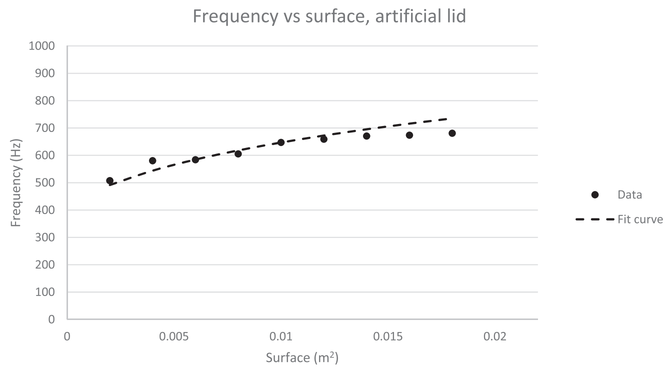

Figure 7. f_0 versus A, pan with artificial lid; the curve shows a fit according to equation (9) ($R^2 = 0.90$).

determination $R^2 = 0.92$ and the overall fit show acceptable agreement in view of the very simplified model used. Moreover, setting $\alpha = 1$, as a rough consistency check we can infer $c \approx 2\pi k = 310\,\mathrm{m\,s^{-1}}$, which is roughly 20% too low for the conditions in the pan (comparing to $c = 390$ m/s for air at 100° C). These findings in favor a Helmholtzian model for the frying pan noise go beyond the qualitative statement in section 3. In view of the uncertainty about α, we want to further corroborate the model by the following experiment with simpler geometry.

5. Pan with artificial lid

Measurements were taken as in the preceding case. Using the model according to equation (10) we make an Excel fit for k and obtain $k = 78.2\,\mathrm{m\,s^{-1}}$. Figure 7 shows that the measured frequency data versus surface and a $A^{1/4}$ fit curve with the k value just given again agreeing reasonably well ($R^2 = 0.90$; numerical values are given in table A1 in the appendix).

From the k value obtained one can infer $\alpha = (c/2\pi k)^2 = 0.51$ (with $c = 340\ \mathrm{m\,s^{-1}}$ known in this case). This result for α is comparable to previous work obtaining $\alpha = 0.4$ for a similar geometry ([13], based on [9]; note that this work accounts for very slim, slit-like rectangles having an end correction different from more square-like rectangles).

6. Discussion and conclusions

In this experiment a Helmholtz resonator description for frying pan noise was tested by smartphone measurements for two cases: first for a pan with a normal lid (figure 6), and second for a pan with an artificial lid, simplifying the geometry (figure 7). In both cases, the results show a satisfactory agreement with the Helmholtz resonator model ($R^2 = 0.92$ and $R^2 = 0.90$, respectively). Still, we have to admit that these models are quite rough approximations, as in the first case we do not take into account the complicated geometry of the opening, nor the temperature and composition of the air/vapour mixture in the pan, and in both cases the resonator formed by the pan has a quite flat shape compared to the more spherical cases of the original Helmholtz resonators.

In accordance with the scope of the journal, the present contribution aims at a new experimental exploration, illustrating a novel approach of general interest while using inexpensive equipment at the same time. It is intended for undergraduate students (and maybe also advanced upper secondary students) and physics lecturers interested in emphasizing the connection of physics to everyday life. Possible teaching contexts are student projects, or as a non-standard exploratory element of physics lab courses in the area of oscillations and waves. Specifically, we think that this contribution provides a further example of how the availability and mobility of smartphones (or tablets) allows one to investigate physics (science) phenomena in particular in everyday life, a kind of mobile 'flying circus of physics', to allude to a certain famous book about 'everyday science' [14]. Other examples of this kind concern cracking knuckles [8], tunnel pressure waves [15] and elevator oscillations [16]. For further exploration by the interested reader, inspiring activity collections are available (e.g. [17]), and the journal *The Physics Teacher* has maintained a column about the topic for several years [18].

Appendix. Numerical values for the pan with artificial lid

Table A1. Data for pan with artificial lid.

	Frequency f (Hz)	
Surface A (m^2)	Measured	Calculated (equation (10))
0.002	501	452
0.004	507	491
0.006	580	544
0.008	583	584
0.01	605	618
0.012	647	646
0.014	659	672
0.016	670	695
0.018	673	715
0.02	680	735

Note that the point with the smallest opening surface was excluded from the fit in figure 7, according to [9] and then [13] rectangular shapes that are thin enough are treated as a slot and the end correction is lower than the traditional rectangular geometry. In this case, the model for the smallest opening utilises a different end correction than the rest, and because of this does not follow the same fit curve and is treated independently.

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