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Resonance phenomena in dielectric media: A review and comparison of acoustic and electromagnetic modes

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The theory and application of resonances and vibrational modes are part of the foundation of science. In this contribution, examples of acoustical resonators are highlighted, and compared to electromagnetic modes. As an example from architecture, we describe the phenomenon of whispering galleries; such modes are nowadays known in dielectric and optical resonators. A specimen of a semicircular whispering bench in Park Sanssouci in Potsdam is acoustically investigated and demonstrated to show low losses for sound propagation. A special acoustical bug is discussed which was used for the espionage of the U.S. ambassador in Moscow. The Sovyets could interrogate this passive device by radio waves. Its working principle was based on the electromagnetic resonance of the cavity that the sound-sensitive membrane was part of. The underlying relation between excitation and resonance is compared to the sound production in flue organ pipes. A stopped flue organ pipe was investigated using a piezoelectric film sensor inside the pipe body. The results show that even-numbered modes, which are usually suppressed in the radiated sound of a stopped pipe, are still present in the vibrations inside the resonator.

Keywords: Whispering gallery; dielectric resonator; passive wireless microphone; flue organ pipe; ferroelectret sensor.

1. Introduction

In the history of the natural sciences, there has always been a tendency to draw inspiration from acoustic phenomena. The fascination probably arises because there are normally at least three senses involved, namely touch, sight, and hearing: A sound-producing instrument like a bell is palpable and so are its vibrations. But the bell and its actions are also visible, as well as audible.

The Greek philosopher Pythagoras is one of the first to have studied harmonic relations. According to Boethius,[1,2] he noticed that certain hammers at a blacksmith's shop produced consonant sounds. He then found out that the masses of these hammers were in whole-number relations or proportions. By extending his investigations to string instruments, he concluded that consonances in general were related to integer proportions of physical quantities as, for example, the string length.[1] Today, we talk of these acoustical phenomenona in terms of resonances. The word "resonance" is related to the Latin verb *resonare* and still preserved in the corresponding English word "to resound". But the term has long been extended to similar effects with all sorts of waves. This is also the motivation of this paper: In this case, we have juxtaposed examples of acoustical and electromagnetic resonators to compare the respective resonance phenomena.

This paper is partly a review and partly a report of our own investigations on the topic. It is structured in the following way. First, acoustic and electromagnetic whispering-gallery modes are reviewed. By an experimental study of a semi-circular whispering bench, we will demonstrate the effect of low-loss sound transmission by the structure. This is followed by the review of an espionage bug in which an electromagnetic resonator is sensitively coupled to sound waves and wirelessly interrogated by radio waves. In comparison with this device, the resonances of flue organ pipes and their interaction with the sound-generating air flow are discussed. Finally, measurements of the vibrations inside a flue organ pipe by means of a ferroelectret film sensor are presented.

2. Whispering Galleries

Originally known from large architectural structures, like St. Paul's Cathedral in London, whispering galleries are arched, circular or spherical structures by which sound and, in particular, whispered words can be transmitted over impressively large distances.

This effect was explained by Rayleigh, first in terms of acoustical rays that are reflected repeatedly and equidistantly along the walls, and thus confined to an annulus air layer close to the wall.[3] Similar to other kinds of surface waves, these excitations had path losses proportional to $1/r$

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in contrast to $1/r^2$ as for a point source in free space, where r is the distance of the source. Rayleigh later extended his explanations using wave theory.[4] By comparing the whispering-gallery problem to a circular membrane and, thus, using Bessel functions, he showed that the "clinging of vibrations to the immediate neighbourhood of a concave reflecting wall may become exceedingly pronounced". Sabine noted that most whispering galleries were accidentally built, without the intention to exhibit the acoustic effect.[5]

2.1. *Dielectric and optical resonators*

Whispering gallery modes can be observed and are exceedingly exploited on a much smaller scale. Dielectric resonators in the centimeter range are be interrogated with microwaves,[6,7] with applications, e.g., as wireless passive strain sensors.[8] For sensing, the resonance frequencies, which are sensitive to physical quantities like temperature or strain, are determined by exciting the resonance by electromagnetic waves like, e.g., a windowed sinusoid.[9] The high Q-factors of whispering gallery modes and the corresponding long decay of the excited resonances are advantageous for frequency determination. The loaded quality factor can be as high as 80000 as reported for a 9.51 GHz mode of a sapphire resonator.[10]

In dielectric resonators, whispering gallery modes occur as so-called hybrid electromagnetic modes or HEM. Illustrations of the modes $\mathrm{HEM}_{1,1,1}$, $\mathrm{HEM}_{3,1,2}$ and $\mathrm{HEM}_{16,1,2}$ of a cylindrical dielectric resonator are shown in Fig. 1. The indices correspond to the mode order in angular, radial, and z direction, respectively. Calculations to obtain the modes shapes are based on Ref. 11, Chapter 3: The method is based on Maxwell's equations from which Helmholtz equations are derived yielding the standing-wave pattern associated with the cylindrical geometry of the resonator.

The above-mentioned effect described by Rayleigh that the annulus of vibrations becomes thinner with increasing mode number is nicely illustrated here.

Optical resonators like semiconductor microdisks with the size of a few micrometers[12] or expoxy-resin bottle-resonators,[13] equally small, show whispering-gallery modes which can be used for lasing if filled with dye and pumped with laser light. Even single-mode lasing[13] could be achieved due to the special radiation characteristics of whispering-gallery modes. Another example are optical modes of nanomembranes which can be rolled up to show a circular cross-section.[14–16] The modes of these micro-tubular cavities can even be coupled to localized plasmon resonances.[17]

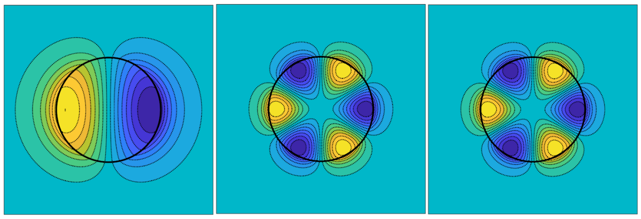


Fig. 1. Hybrid electromagnetic modes (HEM) in a disk resonator, from left to right: $\mathrm{HEM}_{1,1,1}$, $\mathrm{HEM}_{3,1,2}$ and $\mathrm{HEM}_{16,1,2}$. Images were created by Taimur Aftab.

2.2. *Exedra or whispering bench in Park Sanssouci*

In Park Sanssouci in Potsdam, Germany, semicircular benches or exedrae can be found which exhibit a whispering-gallery effect. The bench shown in Fig. 2 is part of the Charlottenhof castle gardens.

Approximately at the height of the head while sitting down, there is a rectangular frame recessed into the wall of the bench. The frame has an iron boundary of 2.5 cm width in top view. The distance between the outer edges of the frame is 48.5 cm, and the inner distance is 43.5 cm, accordingly. The diameter of the circle, measured at the recess in the wall, is 11.3 m. If two people sit down at the two ends of the bench, they can talk to one another at ease at very low volume, even whispers are transmitted around the semicircle clearly — this makes a great impression on everyone trying it.

To study this effect, a loudspeaker (Bose SoundLink Flex) was located at one end of the bench at the height of the iron frame (Fig. 2(c)) and a recording device (ZOOM H2 with a sampling rate of 44.1 kHz and a bit depth of 24 bit) at the other end, cf. Fig. 2(b), corresponding to the whole semi-circle,

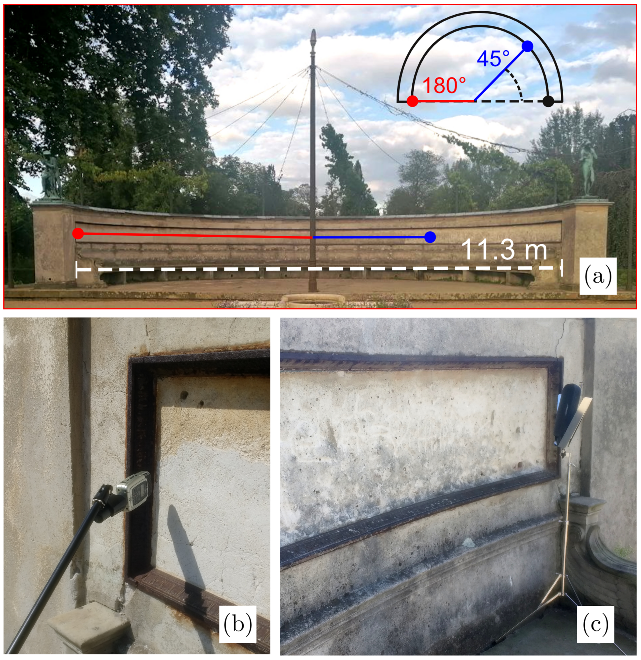


Fig. 2. Exedra or semicircular bench (a) in Park Sanssouci in Potsdam exhibiting an acoustic-waveguide phenomenon: A conversation can easily be held by two persons whispering from one end of the bench to the other end. The inset shows the two positions of the recorder (b) as red and blue dots at angles of 180° and 45°, respectively. The loudspeaker (c) is shown as a black dot.

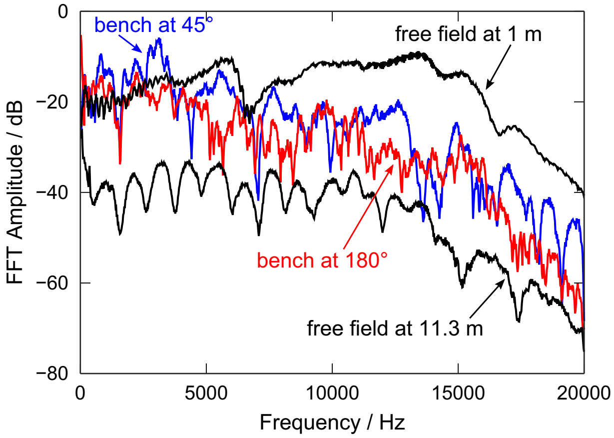


Fig. 3. Spectra of a chirp measurement with the setup at the whispering bench in Fig. 2 and in free field at distances 1 and 11.3 m, the latter corresponding to the diameter of the bench. Angles at the bench denote the position of the recorder on the bench with respect to the sound source.

or to an angle of 180°. The axis of the microphones of the recorder was at an angle of approximately 10° with the tangent of the semi-circle at the recording position in order to capture the waves travelling along the circumference.

An additional measurement was carried out with the sound source at an angle of 45° of the semi-circle. The angles are illustrated in the inset in Fig. 2(a). For comparison, the output of the loudspeaker was measured with the same recorder in free field at a distance of 1 m and 11.3 m, the latter corresponding to the diameter of the bench. A 10-second chirp from 20 to 20000 Hz was used as a test signal; this measurement was repeated three times, respectively. The resulting spectra are given in Fig. 3.

Apart from variations in the spectra that are due to the measurement equipment, it can nicely be seen that even for the angle of 180° on the bench, the sound pressure level is always well above the reference measurement recorded in free field at the corresponding distance of 11.3 m. Even more interestingly, in the range below 3.5 kHz, at both positions on the bench, the signal level is in the same range or even higher than for the reference recording at 1 m. For speech communication, this is well known to be the most important frequency range. This explains why the whispering-gallery effect is so convincing at the location.

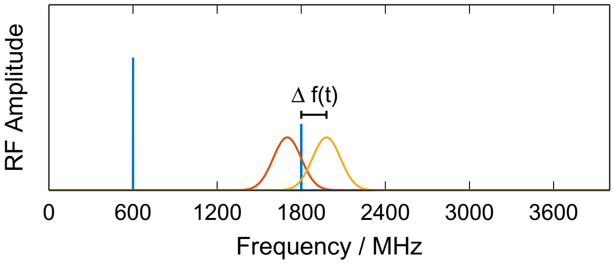
3. The Great Seal Bug by Lev Termen

According to Ref. 18, in August 1945, a great carved seal was given as a present to the U.S. ambassador in Moscow. It hung on the wall behind the ambassador's desk until, during a bug sweep in 1951, a bug was discovered inside the seal. This passive bug in the seal, which was used for recording conversations in the office, was invented by the Russian Leon Theremin — or Lev Termen — who is well known for the invention of the electronic music instrument named after him.[19]

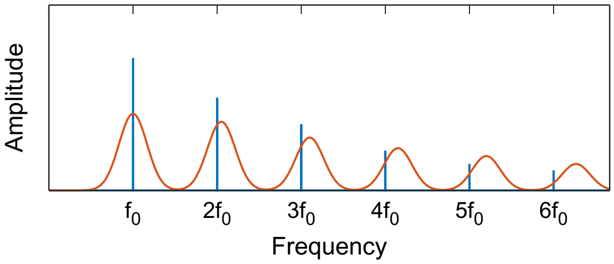
The bug consisted of a metal cylindrical can with a diameter of 20 mm and a height of 13 mm covered with a conductive diaphragm on one side. Inside the cavity, a metal backplate on a rod was attached to the bottom of the cavity parallel to the diaphragm. The resonance frequencies of this diaphragm-covered cavity depend on the distance between the diaphragm and the backplate. By incident sound waves from the room, the resonance frequencies become modulated.

For the interrogation of the bug, a Marconi-type antenna with a length of 228 mm was attached, reaching into the cavity through an electrically insulated inlet. By careful analysis of the possible modes of operation, Brooker and Gomez[18] arrived at the conclusion that the Sovyets must have interrogated the bug with a radio signal at about 600 MHz. The antenna was coupled to the cavity, in which harmonics of the 600 MHz signal were generated by nonlinearities of the bug materials, possibly due to the contact of the different materials used for the can and the diaphragm, for example. The relevant cavity mode must have been around the third harmonic of the illumination frequency of 600 MHz, i.e., at 1800 MHz. Thus, due to the coupling between the cavity and the antenna, the radio signal returned by the antenna contained a component at 1800 MHz, cf. Fig. 4(a).

However, the frequency of the cavity mode was changing depending on incident sounds as illustrated by two possible resonance peaks in Fig. 4(a). Therefore, the emitted third harmonic contained an amplitude modulation: Depending on the frequency difference $\Delta f(t)$ between the cavity mode and the generated third harmonic of the signal, the amplitude of



(a)



(b)

Fig. 4. Spectra of excitation signal (blue) and resonator (orange/yellow): For the great seal bug (a), adapted from Ref. 18, and a flue organ pipe (b).

the third harmonic varied, becoming smaller with increasing $\Delta f(t)$. The width of the resonance peak in the spectrum of the cavity also influenced the amplitude modulation.

In this example, the vibrating air modifies the cavity modes mechanically, while dielectric properties do not play a role. In contrast, the aforementioned Theremin is operated by hand gestures, which are detected by two antennas controlling the pitch and amplitude of the sound-generating oscillators.[19] In this case, the high permittivity of the human body due to its high water content is used for changing the antennas' resonance frequencies.

4. Resonances in Organ Pipes

4.1. *Pipe resonances and sound*

The effect described in the previous section about the relation of the harmonic of an interrogation signal and the resonance has parallels in the physics of musical instruments. In particular, in woodwind instruments, e.g., in flue organ pipes, the emitted sound as well as the standing waves inside of the resonator tube contain strictly harmonic components. This is due to the air jet which, coming out of the windway, is deflected periodically out of the mouth of the pipe and into the resonator, with the upper lip in between, cf. Fig. 5.

The dynamics of the air jet are determined by the design or the geometric dimensions of the flue, the mouth, and the upper lip as well as their relative position. This constitutes a "nonlinear relationship between the jet flow […] into the pipe and the acoustic flow into the mouth".[20] By this nonlinear effect, a certain mixture of higher harmonics is generated by which higher resonances of the resonator can be excited.

However, the resonance frequencies of the pipe body are not in a strictly harmonic relation. This detuning is caused by an effective change of the measurable resonator length L_0 by so-called end corrections, which arise due to the open end of the pipe, and the mouth.[21] The effective resonator length is then expressed as

$$L' = L_0 + \Delta_e + \Delta_m, \tag{1}$$

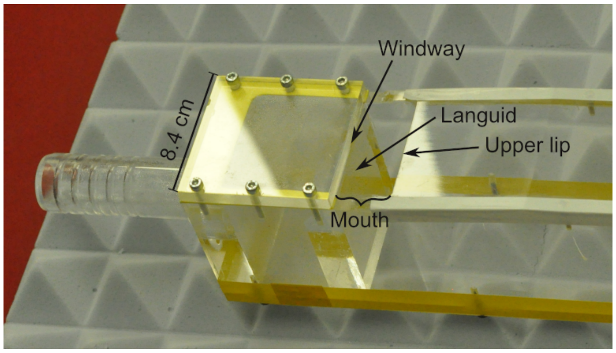


Fig. 5. Foot of a Poly(methyl methacrylate) or PMMA flue organ pipe for lab experiments.

where Δ_e is the end correction of the open end, and Δ_m is the correction of the mouth. Both corrections, Δ_e and Δ_m, decrease with frequency. Accordingly, the effective length L' of the resonator is smaller for higher frequencies, giving rise to higher resonance frequencies for the n-th harmonic:

$$f_n = n \cdot \frac{c}{2L'}, \tag{2}$$

with the speed of sound c. In Fig. 4(b), the spectra of the harmonic excitation and of the pipe are depicted, respectively. The fundamental frequency of the excitation spectrum is related to the effective length of the fundamental frequency of the resonator f_1. The sound or timbre of the pipe is determined by the frequency matching of excitation and resonator together with the widths or Q factors of the resonance peaks.

The detuning in cylindrical pipes is stronger for a larger radius in relation to the length L_0. Consequently, these thicker pipes have weaker harmonics and sound dull in comparison with brighter-sounding thinner pipes.[21,22]

4.2. *Stopped pipe measured with a piezoelectric polymer sensor*

For pipes with an open end, as considered above, a half-wavelength or $\lambda/2$ condition is normally assumed for the resonances: For the standing waves, both ends are considered to be open, yielding the relation between length and resonance frequency given in Eq. (2). In this section, measurements on a stopped pipe are discussed, the end of which is closed with a stopper as shown in Fig. 6. Stopped pipes are normally regarded as $\lambda/4$-resonators with the open end at the mouth. Accordingly, they have a fundamental frequency which is half that of the open counterpart of the same length, while the even-numbered harmonics are suppressed.

The stopped pipe studied here was made of PMMA and equipped with a piezoelectric polymer sensor made out of charged cellular polypropylene (PP), a material also known as a ferroelectret.[23–26] The sensor is custom-made from cellular PP film which is charged and subsequently metallized from both sides with a patterned mask to obtain quadratic

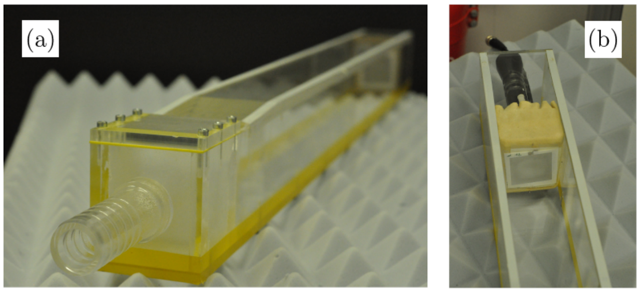


Fig. 6. PMMA flue organ pipe (a) with a cellular polypropylene sensor at the stopper inside the resonator (b).

electrodes. This sensor was taped to the surface of the stopper inside the pipe resonator, cf. Fig. 6.

Thin wires and medical cannulas were used to guide the electric sensor signal through the stopper to the outside of the pipe. Thus, the pressure variations inside the resonator could be measured.

Simultaneously, the air pressure p_{air} with which the pipe was operated was measured with a water column. For a standard musical operation of the pipe, the pressure was $p_{\mathrm{air}} = (657 \pm 10)$ Pa, corresponding to (6.7 ± 0.1) cm H_2O where the uncertainty stems from the reading of the millimeter scale at the water column. The sound pressure amplitude inside the pipe was calculated by

$$\hat{p}_{\mathrm{sound}} = \frac{C}{d_{33} \cdot A} \cdot \hat{U}, \tag{3}$$

where d_{33} is the piezoelectric coefficient of the sensor in thickness direction, A is the sensitive area of the sensor, and $\hat{U}$ is the voltage amplitude of the measured sensor signal. The piezoelectric coefficient was determined by dynamic measurements[27] of the sensor output at 2 Hz as $d_{33} = (208 \pm 8)$ pC/N at a confidence level of 95%. The capacity of the sensor was measured with an HP Precision LCR Meter at 1 kHz: $C = (216 \pm 1)$ pF. The sensitive area was $A = (24.0 \pm 0.5)$ cm^2 where the uncertainty is estimated based on the deviations of the electrode geometry due to the evaporation process used for metallization. With a voltage amplitude of $\hat{U} = (9.8 \pm 0.3)\,\mathrm{mV}$, the sound pressure amplitude can be calculated from Eq. (3) with Gaussian propagation of uncertainty as $\hat{p}_{\mathrm{sound}} = (4.2 \pm 1.3)$ Pa, which is less than one hundredth of the air pressure p_{air} used for driving the pipe. A spectrum of the signal recorded with the cellular PP sensor is shown in Fig. 7.

Astonishingly, above the fundamental at 97.7 Hz with −20 dB, there is also a clear second harmonic with −52 dB, as well as further even-numbered harmonics. These harmonics cannot be observed in microphone recordings. They are probably generated inside the pipe because the open boundary condition at the mouth is not ideal. Although the mouth itself is an opening in the resonator wall, a termination is still given by the languid. However, because the even-numbered modes are associated with a fixed termination or zero velocity at the languid, they do not radiate well.

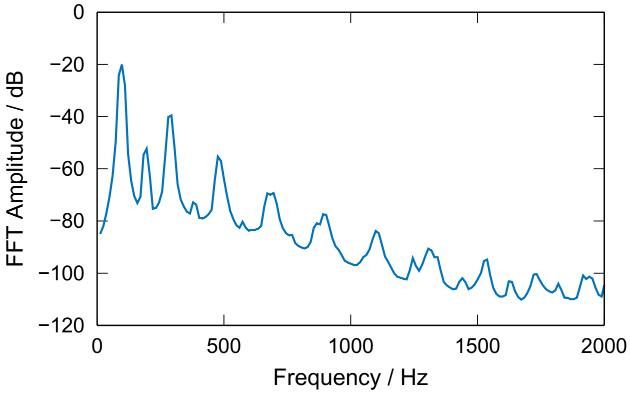


Fig. 7. Spectrum of a stopped flue organ pipe recorded with a cellular polyproylene sensor inside the resonator.

Previously, in the former group “Applied Condensed-Matter Physics” of Reimund Gerhard at the University of Potsdam, the wall oscillations of open flue organ pipes were studied, using piezoelectric electret sensors:[28,29] These film sensors were tightly wrapped around the outside wall of metallic organ pipes at different positions along the length. By these investigations, circumferential oscillations of the organ-pipe walls could be detected which were shaped by the standing waves of the air oscillations inside the pipe and also depended on the material and the wall profile (plane parallel or wedge shaped).

5. Conclusion

In this contribution, we compared acoustical whispering-gallery modes, and the resonances of a flue organ pipe to modes and applications of electromagnetic resonators. After a brief review of whispering-gallery modes in architecture, dielectric and optical resonators were given as an example of small-scale and even microstructures exhibiting whispering-gallery modes. Acoustic investigations of a whispering bench were presented. It was shown that the studied semi-circular bench will facilitate sound transfer with less propagation losses when compared to sound propagation in free field. This can be explained by the fact that whispering-gallery modes take the shape of surface waves.

A passive audio recording device was reviewed which was used by the Sovyets for espionage. In this bug, an electromagnetic cavity mode sensitive to incident sound waves was used. This cavity resonator was coupled to an antenna and, thus, modulated the amplitude of the radio-frequency signal that was used for interrogation of the bug. This working principle was demonstrated to have similarities to the sound production in organ pipes.

The vibrations inside a stopped flue organ pipe were detected using a ferroelectret film sensor. With this calibrated sensor, the sound pressure inside the pipe could be estimated; in comparison with the air pressure that is used to excite the pipe, these acoustic pressure variations are smaller by a factor of more than 100. In addition, we detected even-numbered modes inside the resonator, contrary to the common belief that these modes are suppressed in stopped pipes.

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