The 'shell effect': music from environmental noise

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Abstract
The 'shell effect' can be used to play music with a pleasant and characteristic timbre. If you place a sensitive microphone at the rim of pipes of suitable length and diameter to obtain resonance frequencies, ambient noise will produce musical notes. The corresponding optical effect, i.e. extracting visible light from ambient radiation considered dark by the human eye, is also discussed.

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Introduction

In all probability, some of our ancestors noticed that it was possible to listen to the sound of the canebrakes only on particularly windy days. Then one of them, listening to a higher sound emitted from a particular cane, discovered that the cane had a hole or was broken, forming a cylinder with one end open. He decided to try to imitate Nature. He took a piece of cane, blew inside and succeeded in hearing one of the first sounds produced by man using a flux of air. Flutes, clarinets, trumpets, horns, organs and all other wind instruments can be considered to be the offspring of that first observation. The generation of sound in these instruments is due to the vibrations of air columns, which generate longitudinal stationary waves.

If that musical investigator, on a quiet and totally windless day, had placed a piece of cane or a shell, or simply a cupped hand, to his ear, he would have heard either 'the voice of the cane field' or 'the voice of the sea'. This is interesting: in an environment where we do not hear any sound or noise, near the open ends of the tube we *can* hear a sound. The best-known method for obtaining a sound from environmental noise, used especially by children on the beach, is to put a shell to one's ear to listen to 'the voice of the sea', so we call this effect the 'shell effect'. The shell effect is not used to construct musical instruments. Its extreme weakness and the presence of other frequencies in addition to the fundamental one make it unsuitable. In this paper we present a pipe-organ in which audible sounds—musical notes—are generated without any flux of air into the pipe.

Explaining the shell effect

The air molecules in an open and quiet environment move in random directions. In a cylindrical container the air molecules, bouncing elastically on the inner walls, are forced to assume, statistically, an oscillation direction parallel to the cylindrical surface. The cooperative action among molecules generates an 'air tube' vibrating at a frequency f due to the characteristics of the container, in this case the length and diameter of the cylinder. Of the many waves propagating in the environment, the air column inside the tube responds to waves whose frequency f can generate resonant oscillations.

There is an increase in sound level near the end of the tube. This increase is not due to an interaction between the tube and our auditory apparatus. Outdoors, when the ambient noise level

Figure 1. View of Stromboli Volcano in the Mediterranean. This volcano generates whistles due to air fluxes along its ducts. Photograph by B Chouet (US Geological Survey).

was about 15 dB, we found an average increase of 5 dB near the open ends of tubes. A demonstration of the sound so obtained is available from the electronic version of this journal.

In addition, by eliminating some higher frequencies from the original, it is possible to obtain 'pure' notes that sound more agreeable. The electronic version also offers several pieces of music that were inspired by a CD entitled '*Stromboli*'. We dedicate this music, together with the words, to that wonderful Italian volcano, since it generates whistles due to air fluxes along its ducts.

Experiment

The length and internal diameter of a cylinder are the principal parameters that determine the characteristics of the emitted sound. The fundamental frequency of resonance f_0 for an open pipe is calculated from the formula

$$f_0 = \frac{c}{2l} \quad (1)$$

where l is the length of the tube and c is the velocity of sound in the medium inside the pipe (331.45 m s^{-1} in dry air).

Empirically it was found that an 'end correction' must be introduced to make equation (1) more closely fit the frequency really emitted by the tube:

$$f_0 = \frac{c}{l + 2(0.61R)} \quad (2)$$

where R is the internal radius of the tube [1, 2]. Initially we used this formula.

We started from the C above middle C, at 523.2 Hz, and went down to the C at 130.8 Hz, below middle C. Frequencies of the lower notes were determined by considering the semitone interval given by the rule

$$\Delta f = f\left(1 - \frac{1}{2^{1/12}}\right).$$

So, for example, we have

$$f(\mathrm{B}_\flat) = \frac{f(\mathrm{A})}{2^{1/12}}$$

and so on.

Looking at the keyboard of a piano, we find there are 12 keys between each key and its successive octave. If f_0 is the frequency of the sound emitted by middle C, and f_1, f_2,..., f_{12} are the respective frequencies of the notes between middle C and the C an octave above it, the frequencies of the ratios of these notes are related as follows:

$$\frac{f_1}{f_0} = \frac{f_2}{f_1} = \ldots = \frac{f_{12}}{f_{11}} = k \text{ (constant)}.$$

Considering the logarithm of each ratio, we can write

$$\log f_{i+1} - \log f_i = \log k$$

with i from 0 to 12. So, adding up the right-hand and left-hand sides of the 12 ratios, we have

$$\log f_{12} - \log f_0 = 12 \log k$$

As $f_{12} = 2f_0$ (the relation between f_0, the frequency of a note, and the frequency of f_{12}, an octave above it), we obtain

$$\log 2 = \log(k^{12})$$

and then

$$2 = k^{12}$$

that is

$$k = 2^{1/12} \simeq 1.059\,463.$$

This means that the number of vibrations of a given sound, multiplied or divided by 1.059 463, furnishes the frequency of its superior or inferior semitone, respectively. But we also used another, simpler method, since it is possible to determine the right length of each pipe without a mathematical calculation. We made 'a trumpet extracting music from silence', that is a tube of variable length resonating with the environmental noise.

Two open pipes made of Plexiglas, of appropriate length and diameter, one inserted into the other, altered the total length of the 'trumpet' and enabled us to tune the 'extracted' sound from the non-audible environmental noise. The small variation, of approximately 2 mm, between the two internal diameters (31 mm and 29 mm) of the tubes produces negligible effects on the characteristics of the sounds.

By ear it is easy to recognize a given note, but we also used a spectral analyser to establish the exact length needed to optimize the musical result. We placed a microphone near the rim of each pipe. Each signal was amplified and sent to the corresponding key of a keyboard. Twenty-five switches were placed under the corresponding keys. Headphones were used to avoid feedback that would lead to saturation, but also so as not to introduce the amplified sound of the other tubes into the environment.

As the sound from a shell recalls the wind and sea, the musical sounds generated using this method suggest a mysterious, astral atmosphere, especially the lower notes.

The higher the noise level, the worse the 'purity' of the sound obtained, because of the appearance of higher harmonics. A decrease in ambient noise level causes the amplitude of the higher harmonics to decrease and gradually disappear. With an external noise of about 20 dB, only the fundamental frequency and the first three harmonics were excited in the longest pipe.

Some tests were performed with different artificial background noise, but no meaningful differences were revealed. We used sources of white, pink and brown noise. The spectrum of white noise is flat with respect to a linear frequency axis, while for pink or brown noise the horizontal axis is $1/f$ or $1/f^2$ respectively.

Conclusions

We have described a rather simple but clever musical instrument, based on the shell effect. Many other questions arise regarding the possibility of obtaining new and pleasant sounds by this method. Tests must be done to verify whether the emitted sound intensity changes with pipe direction and to examine how the environmental temperature and the material and shape of the pipe can change the intensity and timbres.

This electromechanical extraction of music from noise gives us the opportunity to emphasize one of the most important similarities between different fields in physics: the phenomenological correspondence between acoustic and electromagnetic properties. It is well known that what we call the shell effect is used routinely in making antennas that detect particular frequencies from ambient electromagnetic noise.

In writing this article we started with a very elementary and well-known observation: the shell effect. Many similar equations and mathematical expressions in these two fields demonstrate the existence of equivalent phenomena (reflection, refraction, diffraction, interference, Doppler effect). So, proceeding from the simple to the complex, we ask: does a device exist that 'extracts' visible light from ambient electromagnetic noise that is completely dark to a human eye? If so, what is it? If it does not exist, how can it be produced?

The dynamical Casimir effect [3] could be an 'almost equivalent optical Shell Effect'. 'Almost', because the two, parallel, oscillating metallic surfaces, which eventually generate visible electromagnetic waves, do not constitute a passive system like our pipe [4, 5]. They require energy to oscillate.

We think that the new nanotechnology will enable us to construct an equivalent optical effect. Nano-antenna structures, only a few nm long and in all probability made of carbon, will be able to resonate at optical frequency, so ‘extracting’ light from the environmental electromagnetic noise. These nano-antennas will allow light transmission and reception without optical fibres. We are aware of light being propagated, through its reflection from objects. Nano-antennas will resonate at optical frequencies and be conceptually identical to the acoustic resonating systems and electromagnetic antennas used at present for transmission and reception of radio and television.

Yet it should be possible to demonstrate that, since the human eye is sensitive even to just a single photon of a visible frequency, it is impossible to have a passive mechanism that ‘extracts’ visible photons from an ambient where visible photons do not exist.

In conclusion, in order to answer one of the questions arising from that first observation of canes in the wind, we must study and wait.

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