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Making Acoustics Virtual

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ABSTRACT

Availability of multimedia-read software, in particular via internet communication, allows to enrich the educational process with „almost-real" but remote presentations. Among other subjects, in particular acoustics can be treated nicely – allowing to pass from hardware sources, to real listening, then spectra visualization and frequency analysis. In this way, elementary subjects can be illustrated step by step, then coming to more complex instruments and phenomena. In this paper we present analysis of sounds emitted by simple tubes (flutes) and then we identify these components in spectra of „thunder drums", together with modes of a membrane. A violin resonant box is an example of an "intelligent" membrane. All these elements will be presented on internet as a didactic, multimedia package.

Keywords: sounds, Fourier transform, acoustic waves

1. INTRODUCTION

Features of standing waves in sound sources are, or should be, a well known, simple subject. Teaching „Physics III – oscillations and waves" module at Engineering Faculty, Telecommunication Departments in Trento we learned that university students had no idea, how standings wave looked like and what their modes were. Therefore, the present material will be also developed as a didactic subsidiary at Trento University. Some selected subjects of these lessons will be of a wide-spread use and serve to stimulate interest in Physics. A final form of the present material will be a multimedia internet site [1] and a CD-ROM file.

The multimedia construction of the material includes: photos of the devices, sound registrations, films registrations of particular processes, like reverberation, wave spectra of sounds recorded with a virtual oscilloscope, movie files with Fourier analysis of spectra, and some additional movie files like coupled oscillators. A reference to a full movie has been adjoined illustrating construction of a „mathematical" violin.

We span over the simplest examples of standing waves, in an open and a closed flute tube, illustrating in particular overtones. Then, adding circular membrane modes we discuss the spectra of „thunder drum" with all complex phenomena, like coupling of vibrational modes and vibration damping. The other example of a standing wave., i.e. a fixed cord, is illustrated in its complex form - as all possible harmonics present in the spectrum of a good violin instrument.

Sound analysis have been done in two steps, by internet exchange of files: the sound registration was done on IBM PC 486-class computer with a 66-MHz Sound Blaster-type card and a cheap microphone. The registered sounds in *.wav form were sent to a Pentium III-class, 750 MHz clock computer with *freeware* Oscilloscope 2.51, program developed by K. Zeldovich. The program allows visualization of registered sounds and their *Fourier analysis*. An example of such an analysis for a "singing glass" has been shown in our preliminary internet publication http://lab.pap.edu.pl/~rajch/allplays.

2. SOUNDS OF A FLUTE

The easiest way to show overtones is to use a simple, plastic flute, like that in fig.1, with all holes (*registers*) closed, apart from the bottom one. In this configuration, as we blow at the top, wave-arrows are formed at both ends of the tube. As it can be easily deduced from the fig.2., the fundamental frequency can be obtained from the conditions for the wavelength $\lambda = 2L$, and higher harmonics are double, triple and so on of the fundamental one. The fundamental frequency $f = \upsilon / 2L$ with the sound velocity v=334 m/s and for the 28.5 cm long flute should be 586 Hz, in a perfect agreement with the measured frequency of 587 Hz (D_5 on a musical scale [2]).

Fig.1. A plastic flute (29 cm long)

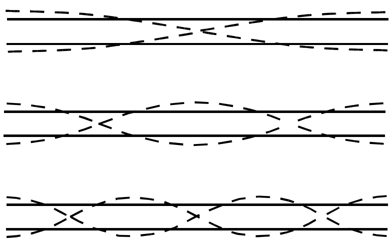

Fig.2. Standing waves modes for a tube opened on both ends: higher harmonics are integer multiplies of the fundamental frequency - 1:2:3 etc.

Higher harmonics of the open flute, by “ear”, are easily audible: the weakest blowing produces the lowest sound, a stronger one a sound 1175 Hz (D_6) which is exactly double in frequency (an octave above), the strongest one – a sound a little bit more complicated – the third harmonics 1765 Hz can be heard but dominates a higher frequency, 2720 Hz, not belonging to the harmonics progression, dominates.

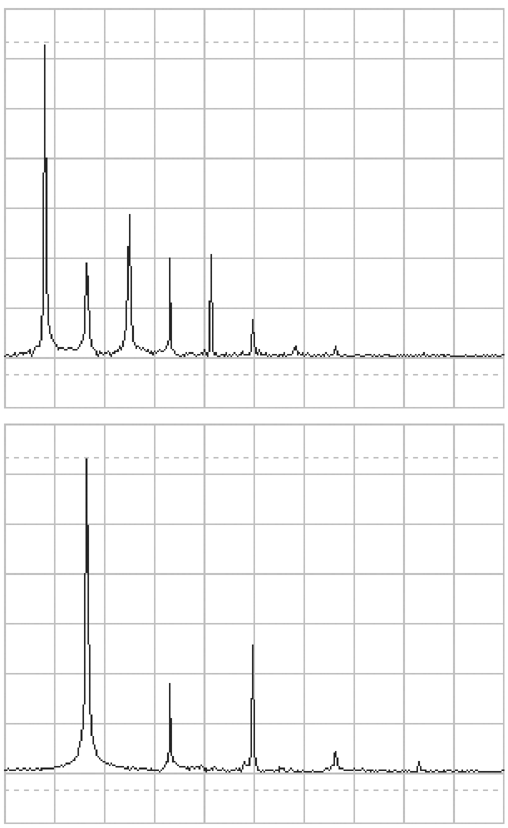

Fig.3a and 3b. Fourier transform analysis of flute spectra - the „weak" and „intermediate blowing”. Two figures differ by the OY scale (a lower amplification factor was applied in fig. 3b), OX scale is the same (f=0–7046.4 Hz). Note that widening of the lines is not an instrumental effect, as for example for a vibrating glass an almost „Dirac-delta" spectra can be obtained [1].

Really, as it shows the Fourier transform of the sounds, even in the fundamental tone, higher frequencies are present and, furthermore, in quite complex interdependencies. Say, for the weakest blowing, even the 7th harmonics is visible in the spectrum, with the 3rd and 5th one higher than corresponding even ones, see fig.3a. For the intermediate blowing we observe five, equidistant peaks of frequencies, all of them multiples of the 1175 Hz one, see fig.3b. These frequencies remain still multiplies of the lowest mode, compare, for example, the position of the 6th peak in fig. 3a with the 3rd peak in fig. 3b.For the strongest blowing into the open flute, the peaks are much broader and not equidistant any more, indicating non-linear effects, see fig.3c.

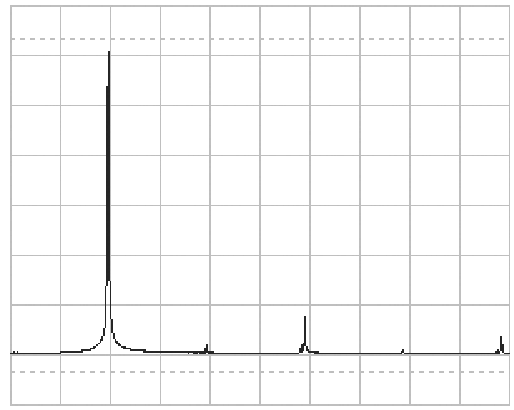

Fig.3c. Fourier transform analysis of flute spectra - the „strongest" blowing for the **open** flute. Note the doubled OX scale (f=0-14048.5 Hz) compared to fig. 3a and 3b and an expanded OY scale. Lack of the even frequency multiplies, as on this figure, should be typical for a tube **closed** on one end, and not open on both ends – it seems that with a high power density of the sound the tube gets capped.

Apart from the Fourier transform, also the very wave-spectra, as registered, are quite informative: the „weakest" blowing produces a kind of a triangular wave, a stronger one – a kind of a square (in amplitude maxima) and triangle (at wave minima) form. (These forms are obviously „hidden" in Fourier transforms, but the picture like below is more appealing).

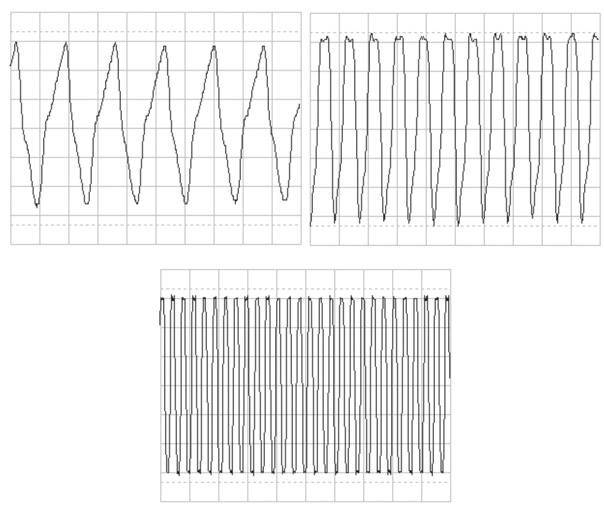

Fig.4. Waveforms of the three modes of an open flute, depending on the „strength" of blowing, from the weakest to the strongest, (OX = 10 ms).

When we close also the *bottom* hole of the flute, the standing wave picture changes, and the harmonics progression passes through only *odd* multiplies of the fundamental one. Therefore, relations between frequencies of harmonics are not more integer but 5/3 (i.e. *sesta maggiore* for musicians) 7/5 and so on. The fundamental frequency for the closed flute should be a half of that for the open one, compare fig. 2 with fig. 5, but it is difficult to excite such a low frequency in practice. Additionally, the lowest (λ =3L/2) frequency excited (835 Hz) is slightly different than the theoretical one, 880 Hz. This is due to so called „effective" length of the tube, which is somewhat bigger than the geometrical one (see ref. [3], for example). We do not present relative spectra but appeal to Reader's ear to recognize the lowest (835 Hz) frequency, generated with the slightest blowing, 5/3 of the lowest frequency (=1396 Hz) generated with the intermediate blowing and 1975 Hz (=7/3 of the lowest) with the strongest blowing.

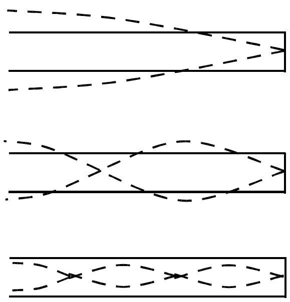

Fig.5. Standing waves in a tube closed on one end (i.e. the flute with all holes closed). Note that the lowest possible frequency corresponds to the wavelength $\lambda = L/4$ and higher harmonics are odd multiplies of the fundamental one.

We indicate in fig.6. only the „lowest frequency" spectrum of the closed flute (keeping in mind that this is *not* the *fundamental mode*, i.e. $\lambda = L/4$), which shows that the odd (i.e. times three) multiple of the lowest tone dominate over the even ones.

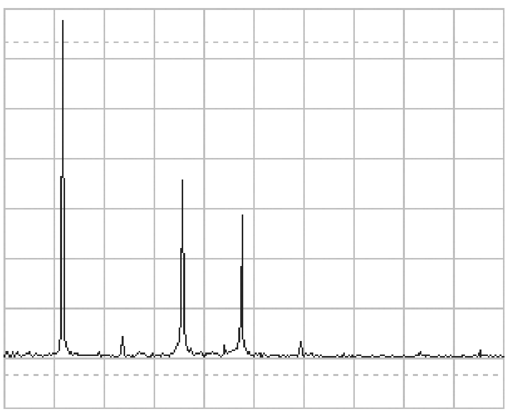

Fig. 6. The lowest mode excited ($\lambda = 3L/4$) in the closed flute. Note the almost absence of the second harmonics, see also the whole dynamics of the sound on the internet movie file.

Multimedia files and the *virtual oscilloscope* software allow to perform not only the static analysis of the sound, but also its full evolution. We refer the Reader to the internet site [1] for „observing by eye" and „hearing by ear", how non-linear effects develops when the (open) flute is excited by a strong blow.

4. SOUNDS OF A THUNDER

This elementary analysis of the open tubes makes possible identification of sound components in other, simple but quite funny devices, like for example „thunder tubes" [4], shown in fig. 7.

The „thunder tubes" produce a low-frequency, sinistrous and vibrating sound with long reverberation. Independently from differences in dimensions, both the big and the small tubes generate pretty strong sounds. Different modes of their excitation: by hard or soft hitting the spring or by its rubbering produce different effects (we will refer the Reader again to the internet site for hearing these different combinations).

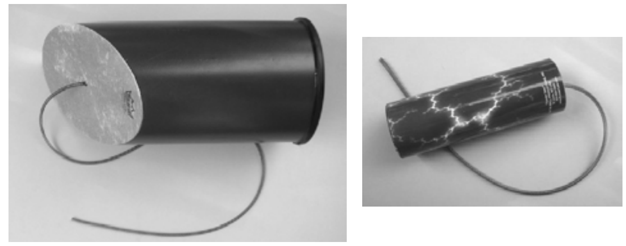

Fig.7. Thunder tubes: tubes open on one side and closed a semi-rigid membrane on the other one, with a flexible spring attached to it. Diameters are 15 cm and 5 cm and lengths 21cm (a shorter border) and 18 cm for the big and small tubes, respectively.

Frequency spectra of the thunder tubes, see fig. 8, are much broader and complex than of the flute but some common features can be identified. First of all one can identify the „odd-sequence" of harmonics, particularly well in the small tube (435, 1300 and 2200 Hz). The fundamental frequency is only slightly lower than the theoretical one (464 Hz) for a 18 cm-long, closed tube. For the big tube this progression (135, 355, 740, 1140, 1600 Hz) is not so clear – distances between higher frequencies rise. Note that the big tube is oblique and wide and we can not expect the approximation of a closed flute to be still valid.

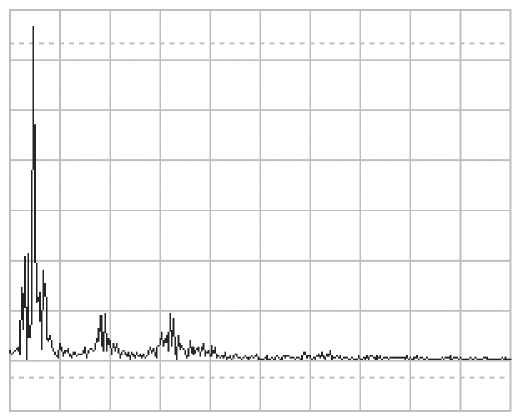

Fig.8a. Frequency spectrum of the small thunder tube obtained by the „virtual oscilloscope" program. [*small1.avi*].

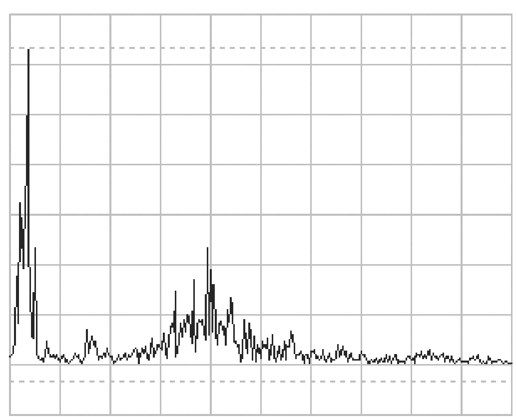

Fig.8b. Frequency spectrum of the big thunder tube obtained by the „virtual oscilloscope" program. [*big4.avi*]

Some broadening of the peaks is for sure to be attributed to the membranes. Differently from „linear" devices like flutes and strings, vibration modes of membranes do not constitute integer-numbers progressions. This is due to particular properties of the Bessel-equation solutions, see fig.9 for symmetric modes. Progression of frequencies, say for axially symmetric modes is 1: 2.29 : 3.6. If the membrane is elliptic, like for the big tube, a whole continuous spectrum of frequencies can be expected, like the wide maximum between 2 kHz and 4 kHz in fig. 8b.

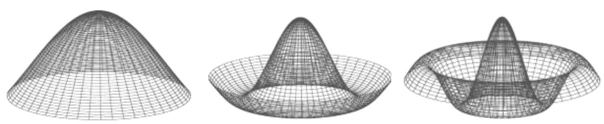

Fig. 9 Three lowest, axially symmetric vibrational modes of a circular membrane

In figure 8, remain to be identified sharp peaks at the lowest frequencies, 350 Hz and 265 Hz for the small and big tube, respectively. They can be attributed, probably, to the presence of the springs. A rough evaluation of the length of the wire forming the springs and assuming a longitudinal wave propagating inside the steel, we get approximately the above given frequencies.

Multimedia tools – movie files of Fourier transform, allow to identify also other particular features of sounds. In fig. 10 we present a sequence showing a reverberation effect – of rising and falling intensity of the sound.

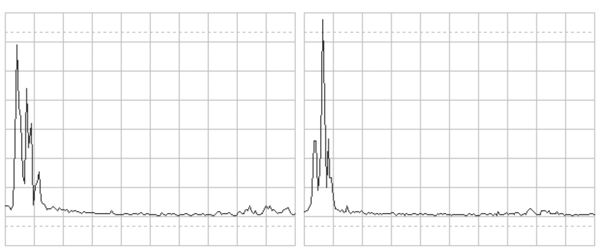

Fig. 10. Reverberation effects on the big thunder tube – intensities of different frequencies fall and grow in time Single pictures of the presented Fourier-analysis sequence were taken every 0.2 s.

This reverberation effect, is to be attributed to „coupled oscillators" – in the case of tubes consisting of the spring-membrane couple. Transverse waves of the (relatively heavy) spring, travel slowly along it and get reflected from the membrane, see fig. 11.

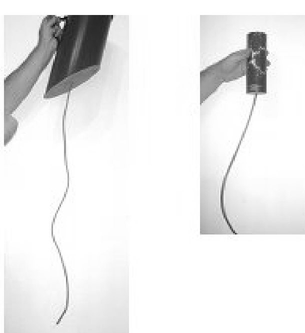

Fig. 11. Traveling waves along the spring, reflecting from the membrane produce "reverberation" effects - of a thunder inside the tube.

Another important physical phenomenon which can be identified only in multimedia approach is a quick damping of higher frequencies, see a sequence in multimedia version of the article. This effect for the „thunder tubes" reproduces a real, distance thunder, in which the low, sinistrous frequencies reverberate for a long time.

6. BEL SUONO

Finally, multimedia studies, easily to be reproduced by individual teachers with the experimental set-up we described at the beginning, allow studying real, professional instruments like a violin. Its is simply amazing to see, how a good violin produces sharp frequencies, and not only that, which is heard, but also the whole range of higher harmonics. In particular, note in fig.12a how higher harmonics, like the 5^{th} one, can dominate the entire spectrum. These higher harmonics are the effect of the complex, particular construction of the resonant case of violin. Note also in fig. 12b, that all elements of the violin, including the excitation mode, must be "proper" in order to obtain a "nice music".

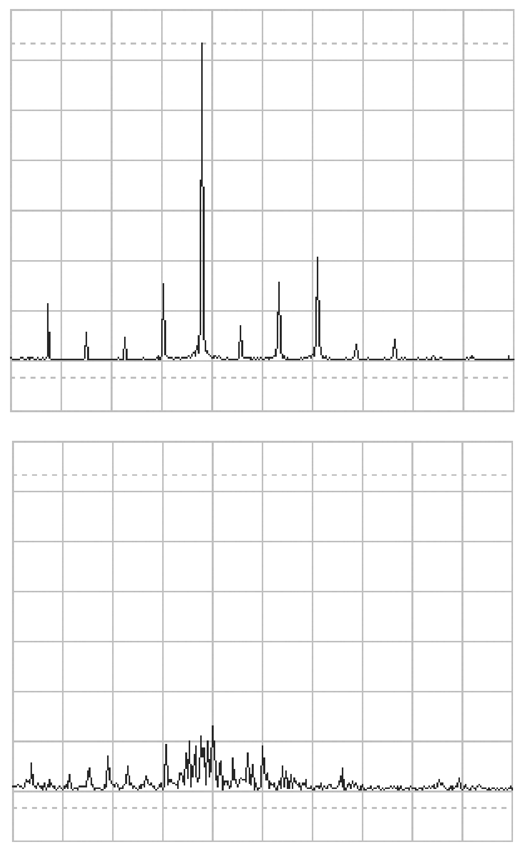

Fig. 12a and 12b. The Fourier transform spectra of a "good" violin – note narrow and perfectly distanced higher harmonics frequencies. The spectrum below has been obtained with the same violin, but with "non-professional" excitation – note the wide peak of "noise" at about 3 kHz.

To complete the range of multimedia resources used to illustrate simple sounds, we recall a presentation in a form of the didactical movie [5]: the story on a violin, done from the first mathematical principles, is described. Prof. Bogdan Skalmierski from Częstochowa Polytechnics tells, how he calculated the necessary tensions inside the resonant box, to obtain a "bel suono". The Reader can evaluate its sound "by ear" in ref. [5].

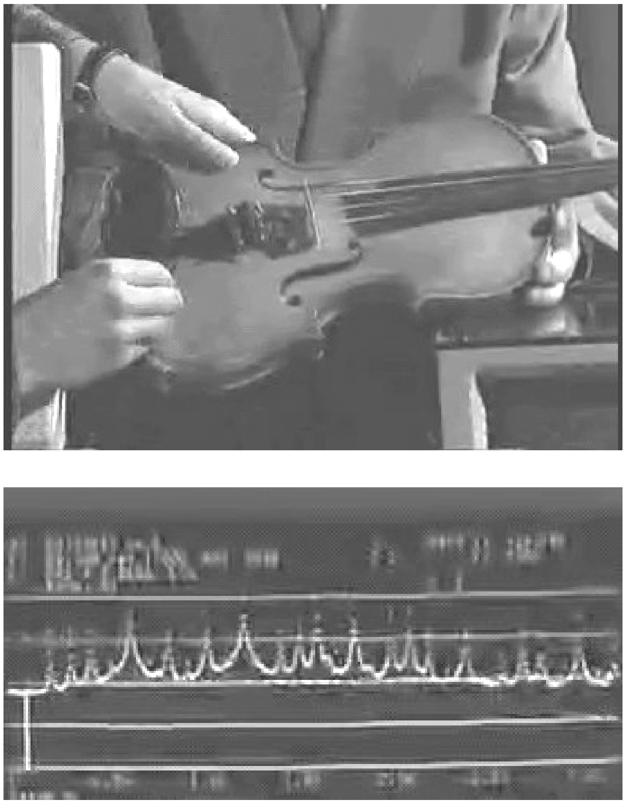

Fig.13. A "mathematical" violin in hands of its constructor, prof. B. Skalmierski. The sound produced by it, see below, is somewhat different from the "reference" violin, but the two spectra files has been obtained by different experimental and multimedia techniques.

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[2] **CRC Handbook of Chemistry and Physics**, 67th Edition, CRC Press. Boca Raton, FL (1986), p. E-44

[3] F.S. Crawford, **Waves and Oscillations** (Berkeley Physics Course), Vol. 3, New York, McGraw-Hill Book Company, 1965

[4] see, for example, Educational Innovations site http://www.teachersource.com/

[5] W. Niedzicki, **A mathematical violin**, http://www.ambernet.pl/Folder/MatematyczneSkrzypce.ram (in Polish)