

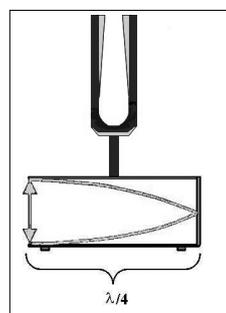
# The Sound Field Around a Tuning Fork and the Role of a Resonance Box

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A typical two-tine tuning fork is barely audible when held vibrating at an arm's length. It is enough, however, to touch its base to a table or, better, to a resonance box and the emitted sound becomes much louder. An inquiring student may pose questions:

- Why is a bare tuning fork such a weak emitter of sound?
- What is the role of the resonance box?
- Where does energy connected with larger intensity of emitted acoustic waves come from?

Simple and convincing answers come from observations of the experiment described below aided by computer software. Experimental observations of acoustic waves emitted by a tuning fork are discussed quantitatively using a linear quadruple model, but even qualitative conclusions are accurate enough to allow students to formulate answers to the posed questions.



**Fig. 1. Coupled resonant system of tuning fork and air column in resonant box. The oscillation mode of the fork<sup>2</sup> is marked with lighter shade. The back of the box is not included in the  $\lambda/4$ .**

## The role of a resonance box

A tuning fork<sup>1</sup> mounted on a resonance box forms a coupled system with the box (Fig. 1). The box dimensions are designed to enable formation of a standing wave in an air column contained in the box. The smallest length of the box allowing for accommodation of such a wave is approximately equal to a quarter of a wavelength  $\lambda$ . For a typical tuning fork of frequency  $f = 440$  Hz and for speed of sound  $v = 340$  m/s, it is 19 cm:

$$\frac{\lambda}{4} = \frac{1}{4} \frac{v}{f} \approx 19 \text{ cm.}$$

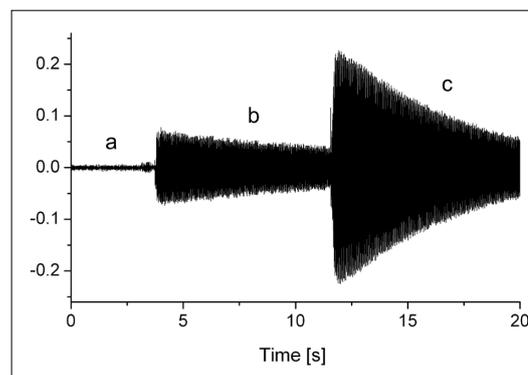
Energy is transferred between the fork and the resonance box. The intensity of sound emitted by such a coupled

system is much larger than that emitted by the fork alone, so the resonance box is a more effective emitter of acoustic waves than the fork. To register acoustic waves, we used the software Coach<sup>3</sup> (Fig. 2).

The sound registered for the fork held in hand and then mounted on the closed resonance box, and the effect of opening this box at one end, is shown in Fig. 3. One can notice not only the short-term fluctuations of the registered acoustic pressure but also the longer-term changes of amplitude with time. For the fork alone, the amplitude is small and its change



**Fig. 2. Tuning fork on a resonance box, sound detector, and a measuring console CoachLab II.<sup>3</sup>**



**Fig. 3. Acoustic pressure vs time in arbitrary units (a) for the fork alone, (b) effects of mounting the vibrating tuning fork on the closed resonance box, and (c) opening this box.**

within the time of observation is unnoticeable. Placing the vibrating tuning fork on the closed resonance box causes a strong increase of amplitude and its slow diminishing in time. Opening the resonant box causes not only a further increase of amplitude of the registered wave but also a much faster decrease of amplitude with time. This observation is crucial for understanding the source of energy needed to produce a large intensity of sound emitted by the coupled system. The energy is attained at the expense of shortening the time of emitting the wave. If the amplitude of the emitted wave is larger, the energy stored in the vibrating fork is utilized faster, which results in a faster decrease of amplitude of the acoustic wave with time. In other words, the fork on a box sounds louder but for a shorter time.

## The sound field near a tuning fork

If the vibrating fork is placed close to the ear and we rotate the fork around the longer axis, the sound almost disappears



Fig. 4. Setup for registering sound amplitude as a function of angle of fork rotation.

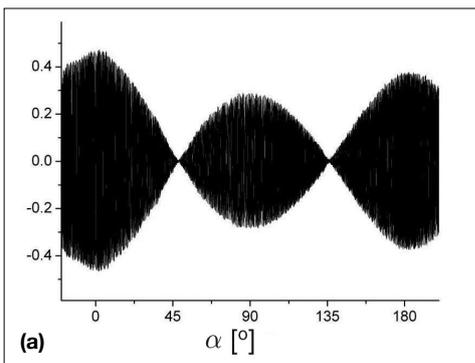
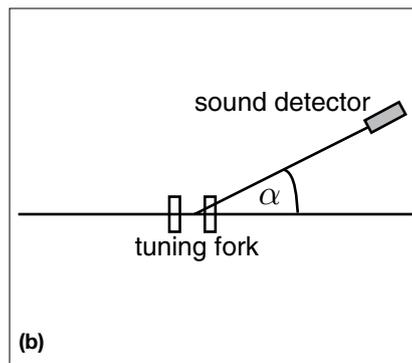


Fig. 5. (a) Registered acoustic pressure (arbitrary units) as a function of rotation angle  $\alpha$  of the tuning fork, at the detector distance of 4 cm from the fork. (b) Definition of angle  $\alpha$ . Angle  $0^\circ$  corresponds to detector alignment: both tines and detector in one line.



four times during a single rotation. One can confirm this observation using a sound sensor, angle sensor, and computer software such as Coach (Figs. 4 and 5). The muting of sound for certain directions (angle near  $45^\circ$  and  $135^\circ$ , Fig. 5) is due to interference effects that play an important role in the sound emitting by the fork.<sup>4</sup>

Each vibrating tine creates two longitudinal waves in the surrounding air. From one side it is, in a chosen moment, a wave of air compressions, and from the other side, low pressure regions (rarefactions). These are waves with opposing phases being emitted by sources located at a distance equal to the thickness of a vibrating element. Such waves propagating in the direction perpendicular to the tine direction of motion cancel themselves entirely. For a wave along the direction of motion, the cancellation is the weakest and depends on the relation between the thickness of the vibrating element and the wavelength. In our experiment, the thickness of the tine—and hence the distance between sources of waves—was 0.6 cm. It was a small distance in comparison with the emitted wavelength 77 cm. Such waves cancel themselves very strongly (destructive interference) (Fig. 6). This explains why the fork alone or a vibrating string are weak emitters of acoustic waves.

## Quantitative description of the wave emitted by a tuning fork

The interference picture of acoustic waves on the plane perpendicular to the long axis of the tuning fork was obtained assuming that each side of the two tines of the fork is a point source of the circular harmonic wave<sup>5</sup> (Fig. 7). The amplitude of an acoustic wave at a point  $x, y$ , which is the result of interference of four circular waves from point sources in Fig 7, is described by Eq. (1):<sup>5</sup>

$$A(x, y) = A_0 \left| \sum_{n=1}^4 \frac{1}{\sqrt{(x-a_n)^2 + y^2}} \cdot e^{i(\omega t - k\sqrt{(x-a_n)^2 + y^2} + \varphi_n)} \right| \quad (1)$$

- $a_n$  – denotes the position of  $n$ th source on  $x$ -axis,
- $\omega$  – frequency of acoustic wave,
- $k$  – wave number,
- $\varphi_n$  – phase of vibrations of  $n$ th source.

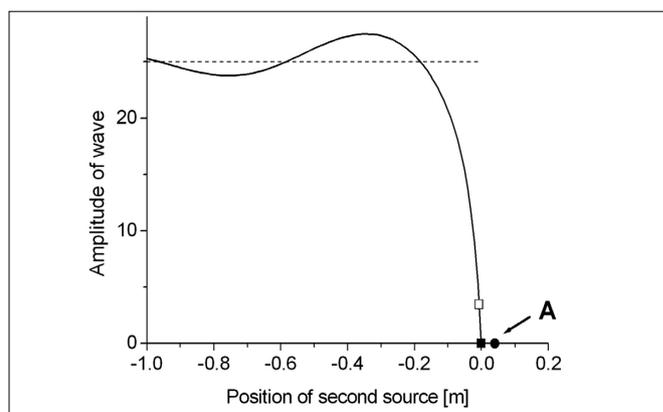


Fig. 6. Theoretical amplitude of a resulting wave (solid line) for two sources of a circular wave, vibrating in opposing phases, as a function of position of the second source. The first source is solidly mounted in 0.0 position (black square). The calculations were performed for a detector placed at a distance of 4 cm from the first source on the line joining both sources (position A), for the wave of frequency 440 Hz. The broken line represents the wave amplitude of only first source active. The open square denotes the amplitude of resulting vibrations for sources that model the vibrations of one tine of the used tuning fork. The amplitude for the open point is reduced by seven times due to partially destructive interference at short distances between sources. The calculations are based on Eq. (1), but only for one tine (two sources).

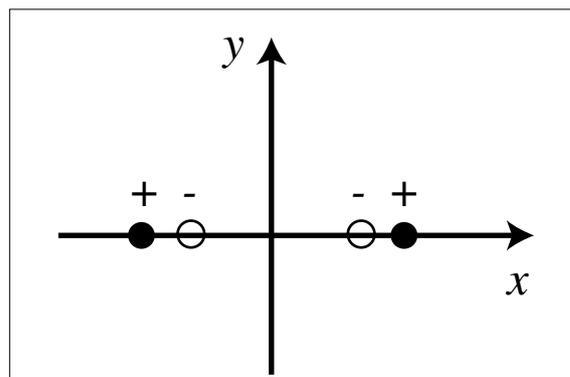


Fig. 7. Four point sources of circular waves forming a linear quadruple. The sources with opposite signs vibrate in opposite phases. Such a model was used to simulate acoustic waves emitted by a tuning fork.

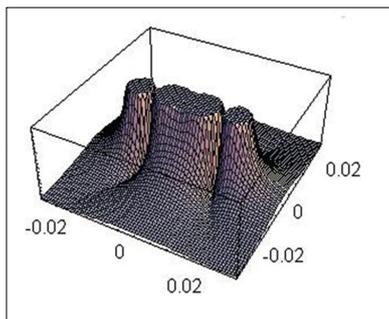


Fig. 8. Calculated [Eq. (1)] dependence of acoustic pressure wave amplitude on the position (in meters) on the plane perpendicular to the long axis of a tuning fork.

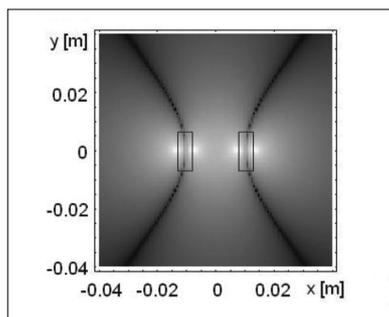


Fig. 9. Calculated [Eq. (1)] dependence of logarithm of acoustic wave amplitude on the position, on the plane perpendicular to the long axis of a tuning fork. The brightest areas correspond to the largest amplitude (four point sources of waves). Black regions denote positions of almost total damping of waves. Rectangles are the cross sections of tines of the tuning fork.

The thickness of the tines was 0.6 cm, the distance between the centers of the tines was 2.1 cm, and the frequency was 440 Hz. The result (Fig. 8) shows a very strong reduction (damping) of amplitude (and hence the sound intensity) with increasing distance from the tuning fork. Cancellation (destructive interference effects) for two vibrating tines, similar as that for a single tine or a vibrating string, is responsible for the tuning fork being such a weak emitter of acoustic waves.

In order to show exact positions where the total cancellation of sound occurs, the amplitude of the acoustic wave is shown in “shade scale” (Fig. 9). These positions form a hyperbola on the plot. Four minima and four maxima are clearly visible in the vicinity around the tuning fork at a distance of 4 cm from the fork.

If the distance from the fork is increased up to several tens of centimeters, then there is a change in spatial distribution of sound, and only two maxima and two minima are observed in a full turn of the fork.<sup>7</sup> This effect was demonstrated experimentally (Fig. 10) and theoretically (Fig. 11).

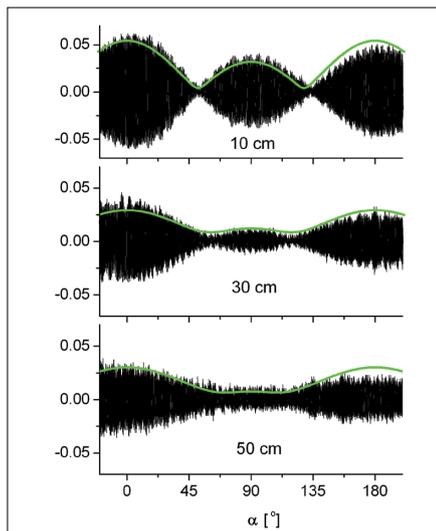


Fig. 10. Acoustic pressure as a function of angle for three different distances of the detector from the fork alone. The solid line represents the amplitude calculated assuming the presented model. Small asymmetry in experimental results is the consequence of diminishing amplitude in the course of the measurement with time.

The Mathematica Packet<sup>6</sup> was used to calculate the wave amplitude. The calculations were performed for the tuning fork that was used in the experiments. The thickness of the tines was 0.6 cm, the distance between the

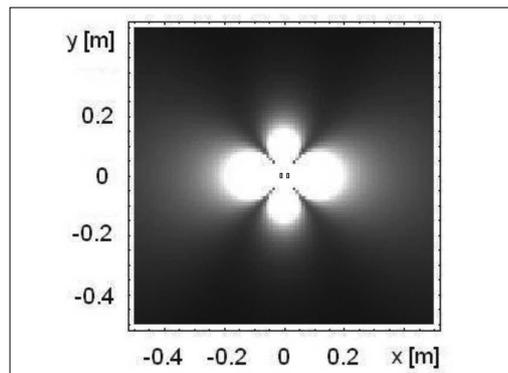


Fig. 11. Calculated [Eq. (1)] dependence of acoustic wave amplitude on the position on the plane perpendicular to the long axis for four point wave sources. The brightest regions correspond to the largest amplitude. Small rectangles in the center are the cross sections of tines of the tuning fork. For a full turn, at large distances only two sets of “louds” and “quiets” are observed, contrary to four sets observed at small distances.

## Resonance effect applied to improve sound detection

The intensity of sound emitted by the tuning fork alone is small. The detector used in the system (sound sensor 015 CMA<sup>3</sup>) could not register angular dependence of amplitude for distances larger than a few centimeters from the fork. To overcome this problem, a simple trick was applied: the use of a resonator enabled the measurements at larger distances. Simply, the detector was placed inside an open plastic pipe (Fig. 12) so that in front of it could be an air column (free space) equal to a quarter of the registered wavelength (19 cm for a 440-Hz wave). The results are shown in Figs. 10 and 13. The dependence of amplitude of the registered acoustic wave on the length of the air cavity in the resonator pipe placed in front of the detector points at resonance character of this phenomenon.

## Summary

Based on the results of the described experiments, it is possible to answer the questions posed in the first paragraph and understand the reason why string musical instruments are equipped with resonance boxes.

- A bare tuning fork itself is a poor emitter of sound due to destructive interference of acoustic waves that are produced by vibrating tines. Waves with opposite phases, emitted by two sources placed at a distance much smaller than the length of the emitted wave, mute almost entirely. Each tine emits two such waves.
- The role of a resonance box is the amplification of sound. A tine placed on the box forms a coupled system with the

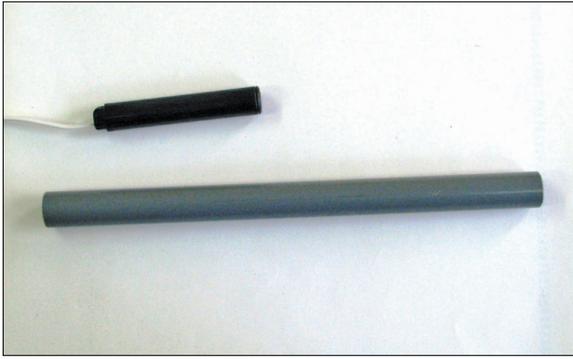


Fig. 12. Sound sensor 015 CMA and a resonator plastic pipe to accommodate the sensor.

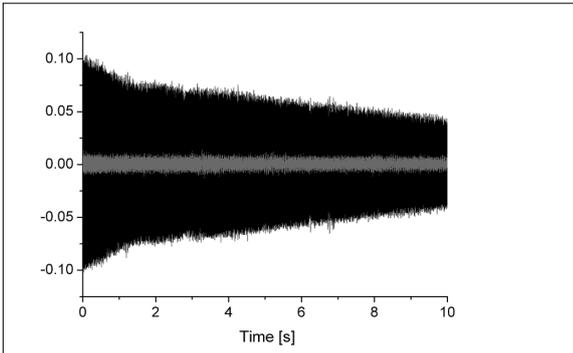


Fig. 13. Sound wave amplitude emitted by 440-Hz tuning fork registered by a detector with the 19-cm resonator (black) and the 10-cm resonator (grey).

box. Energy of vibrations can easily be transferred between tines and the resonance box, inside which a stand-

ing wave is formed. The resonance box is a good emitter of acoustic waves because there are no destructive interference effects in it.

- Observation that louder sound is emitted by a box but in a shorter period of time is a clear manifestation of the energy conservation principle.

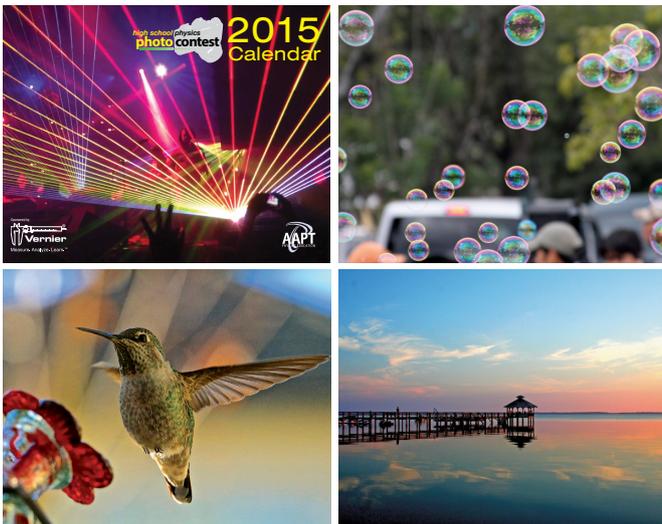
Experimental observations and quantitative description of tuning fork related phenomena are presented here in detail, but even qualitative results (without mathematical description) are adequate enough for students to understand the problem and formulate conclusions.

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