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Publication Date
1972-09-01

Submitted to
Am. J. of Physics
"Notes and Discussions"

LBL-1090
Preprint

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September 1972

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AEC Contract No. W-7405-eng-48

SIMPLE DEMONSTRATIONS OF DOPPLER EFFECT, INTERFERENCE, AND RADIATION RESISTANCE USING A SONALERT*

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Stimulated by a note in The Physics Teacher,[1] I bought for about $6 a Sonalert[2] that emits a loud steady note at 2.9 kHz, which is approximately the F-sharp three and one-half octaves above middle C on the piano. I scotch-taped the Sonalert, a 9-volt transistor battery power supply, and a battery clip (used as a switch) into a self-contained package the size of a 2-inch cube.[3] With this package and essentially no other equipment I can get the best demonstration of Doppler effect I have ever heard, as well as very nice demonstrations of interference and beats, and a striking demonstration of radiation resistance.

Doppler Effect

The Sonalert package may be taken outside and thrown like a baseball back and forth between two people. (It helps if they use baseball mitts. I also add extra scotch tape to keep the battery clip on and to soften the package.) This gives a very pleasant demonstration of the Doppler effect. I call it "Doppler ball." With an easy throw one hears a pitch decrease of about a minor second (from F-sharp to F on the piano); when receiving, one hears a corresponding increase to G. A person standing between the players hears first an increase (as the

package approaches) and then a decrease (as it recedes). A person standing at some distance, transverse to the line of flight hears no effect (transverse Doppler effect). After a few minutes practice a friend and I using baseball mitts achieved pitching speeds that gave a Doppler shift of nearly a major second (from F-sharp either up to G-sharp or down to E). By determining the musical interval one can measure the pitching speed of the players. A major second on the equal temperament scale corresponds to a fractional change in frequency f given by $|\Delta f| / f \doteq 0.12$. The theory of the Doppler effect gives

$$|\Delta f| / f = v/c, \qquad (1)$$

where $c = 332$ m/sec is the velocity of sound in air, and v is small compared with c for the approximate formula (1) to hold. My friend and I thus achieved nearly $v = 0.12 \times 332 = 40$ m/sec = 90 miles per hour! Of course, musical intervals are not easily determined with great accuracy by ear. Perhaps we achieved 100 miles per hour.

Another impressive exercise that can be done by one person is for him to throw the package straight upwards into the air with all his might, catching it when it returns. (The package is very rugged. I have often missed catching it but it still works. During the throw the pitch suddenly decreases from F-sharp to E, for a sufficiently strong throw. During the entire up and down flight the pitch increases uniformly with time, reaching G-sharp just before the catch. During the catch it suddenly decreases back to F-sharp. Since the pitch increase is uniform with time during the entire flight, one can <u>hear</u> that the acceleration due to gravity is constant!

Another demonstration that does not demand baseball mitts is to tie the package to a long piece of twine and whirl it around one's head. This is also best done outside. I can easily achieve 1 revolution per second with 4 meters of twine, and 2 per second with 2 meters. Either of these gives $v = 25$ m/sec, yielding a Doppler shift $|\Delta f|/f = 25/332 = 0.076$. For a person standing outside the orbit the total shift between the approaching and receding package is thus 0.15, which gives a musical interval midway between a major second (C to D) and a minor third (C to E-flat). This is easily heard. Of course the person whirling the package hears no Doppler shift at all (transverse effect). Ordinary strong twine is sufficiently strong: The package weighs only 90 grams. For 2 revolution per second at 2 m, the acceleration is about 38 g, so the string must support about 3.4 kg, or $7\frac{1}{2}$ lb.

Interference and Beats

When the Sonalert is turned on inside almost any room the room becomes filled with standing waves due to reflections from floor, walls, and ceiling. One easily hears these by setting the Sonalert in one place and walking around. (It helps to cover one ear. The standing wave maxima are closer together than the distance between your two ears.) One hears striking maxima and minima in intensity. Alternatively, one may hold one's head fixed and holding the Sonalert package move it towards or away from a nearby floor, wall, or table top. One hears a sequence of successive maxima and minima in intensity as the standing-wave pattern changes. The changes in intensity occur rapidly or slowly, depending on how fast you move your hand.

Rather than think in terms of changing patterns of standing waves as you move your hand, one can think in terms of interference between two waves, one that comes directly from the package to your ear, and the other that bounces off the wall before reaching your ear. The time-varying intensity you hear as you move the Sonalert towards the wall is then interpreted as being due to beats between two waves having slightly different frequencies. If the Sonalert is moving away from your ear and towards the wall, the reflected wave is Doppler shifted up in frequency, the direct wave down. One easily verifies this concept experimentally with no equipment as follows. Choose an easily audible beat frequency, say 4 beats per second. Rehearse what this tempo sounds like by counting aloud 1, 2, 3, 4, 1, 2, 3, 4, . . . while looking at the second hand of your watch. Now calculate the desired velocity v of the package towards the wall, using Eq. (1) and the fact that the beat frequency is the difference between the upshifted and downshifted frequencies. The desired v turns out to be about 23 cm/sec. This is easy to achieve while extending or retracting one's hand from near the shoulder to arm's length. By measuring one's reach one can decide on the tempo of extending and retracting one's hand towards the wall and can rehearse this with the Sonalert off while looking at one's watch. Now turn on the Sonalert and see whether the rehearsed v gives the rehearsed beat tempo. (Your ear must be behind your hand, not off to the side.)

It is interesting to make the connection between the two points of view: The beat frequency between the up- and down-shifted

Doppler frequencies is given by

$$\text{beats/sec} = f_{\text{beat}} = 2\ (v/c)\ f. \qquad (2)$$

The other point of view is that whenever the source is moved one-half wavelength closer to the wall the standing-wave pattern has been essentially reproduced and the detector has heard a transition from maximum to minimum back to maximum:

$$\text{beats/cm} = \text{one per half-wavelength.} \qquad (3)$$

Starting with (2), we have

$$\text{beats/sec} = (\text{beats/cm}) \times (\text{cm/sec}) = (\text{beats/cm}) \times v\,.$$

Thus

$$\text{beats/cm} = (\text{beats/sec})/v = [\,2(v/c)f\,]\,/v = 2f/c = 2/\lambda = \text{one per}$$

half-wavelength, which is Eq. (3).

Next we consider another simple interference demonstration that gives a fairly accurate measurement of the wavelength λ of the sound waves. (Since the frequency f is known, that measurement also yields the velocity of sound, c, through the relation $c = \lambda f$.) The demonstration makes use of the Sonalert package and a tube with a closed lower end. My best tube (because it is the most elastic) is a 1000-ml Pyrex graduated cylinder. A large cardboard mailing tube also works. One ties a piece of twine to the Sonalert package and lowers the package down the tube. One hears striking maxima and minima of intensity as the package changes its position. These are due to interference between the wave that comes directly up the tube from the Sonalert, and that which goes down the tube, reflects at the bottom, and then comes back up. If the Sonalert is suitably oriented these two waves have nearly equal amplitude and the null values of intensity are nearly zero. By measuring the length of string played out between any two successive nulls one finds the half-wavelength. It comes out right! One can also ask whether one expects a maximum or a minimum intensity when the Sonalert is at the very bottom of the tube, or where the first null will be in relation to the bottom of the tube, and can then find the experimental result immediately.

Radiation Resistance

A fascinating apparent paradox can be posed during the last-mentioned demonstration in which the Sonalert package is lowered down the glass tube. At the Sonalert positions that give minimum intensity, the sound intensity is very small everywhere in the room. (There will be large relative variations in intensity throughout the room because of the standing waves produced by reflections from the walls.) At the Sonalert positions that give maximum intensity, the intensity is large throughout the room (subject to the variations just mentioned). By walking around the room or moving one's head around near the tube one easily determines that the total sound energy in the room is much less when the Sonalert is at a position giving a minimum than when it gives a maximum. This seems to violate conservation of energy. After all, the vibrating diaphragm of the Sonalert should put out a certain amount of sound energy; the varying interference pattern should only redistribute that energy, with roughly twice the average energy density appearing at some places, and zero at others, so the average is unchanged. At least that is often the case, and is probably what we learned while studying interference patterns in optics, where the light source is usually unaffected by waves reflected back to it.

For example, the total energy in a two-slit interference pattern is the same as that in a single-slit pattern having the same total slit area. Energy is conserved; it is merely redistributed in the interference pattern. Thus you may pose the paradox: What happens to the sound energy emitted by the Sonalert when it is at a null position in the tube?

In discussing this paradox it may occur to some student to challenge the idea that the Sonalert energy output is constant; perhaps it simply doesn't emit much energy when it is at a null. This may seem difficult to understand at first, but leads to a simple experiment: Will the battery run down faster with the Sonalert at a maximum intensity position than at a null position? Rather than run down a battery it is simpler to measure voltage and current and hence the power consumed by the Sonalert when it is at the two positions. This is easily done with an ordinary volt-ammeter. The student will find that the transistor battery voltage across the Sonalert remains constant as the position is changed, while the current changes from about 4 mA at the maximum to about 3.8 mA at minimum. Thus he finds not only that the Sonalert consumes less energy at the null, he also finds that the efficiency of the Sonalert for converting electrical to sound energy is only about 5%. The total power ($P = IV$) consumed is about 4 mA × 9 V = 36 mW. The sound power at a maximum is about 0.2 mA × 9 V = 1.8 mW.

More questions can be asked. Is the sound power twice as great at a maximum position in the tube as when the Sonalert is suspended in free space? How do you explain the variation in sound power? This can lead to a discussion of the concept of radiation resistance, as compared with the internal resistance of the circuit, and to a detailed consideration of the forces that resist and aid the motion of the Sonalert diaphragm. Is it possible that at a null the diaphragm is pushed in and out not only by the electrical forces provided by the Sonalert circuit, but also by the returning reflected sound waves emitted earlier, so that the battery has less work to do? For this to be so, the phase relation between the motion of the diaphragm and that of the returning reflected wave must be correct. Is it? How can one determine that relation experimentally by using the Sonalert and tube?

Another question: Is 1 mW sound power for a Sonalert a plausible result? How can we roughly calibrate the sound power actually emitted, so as to compare it with the 1-mW change in bettery output between the null in sound power and that emitted into free space?

One crude way is to look in a book to find what sound intensity feels painful to the average human ear. Then move the Sonalert closer to your ear until it begins to feel uncomfortable. I found I could put the Sonalert right over my ear and barely stand it. Assuming my electrical measurement was right, and taking the Sonalert area as 3 cm^2, that gives 0.3 $\text{mW cm}^{-2}\ \text{sec}^{-1}$ as my pain threshold at 2900 Hz. Some books give 1 $\text{mW cm}^{-2}\ \text{sec}^{-1}$ as a typical pain threshold. Thus, very crudely, the measured 1 mW of sound power is shown to be reasonable, without any use of equipment.

Finally, one may turn the student loose to see what other interesting demonstrations he can devise. For example, a hard flat table top can serve as a Lloyd's mirror for a Sonalert situated several inches above the table. He can explore the two-point source (the source and its virtual image in the mirror) interference pattern with one ear. Is the central fringe (the one in the plane of the table) a minimum or maximum? Is there a phase change upon reflection? Is it the pressure or the velocity that the ear responds to? As another example, suppose you are located between two separated Sonalert packages emitting slightly different frequencies. (Any two independent ones will have slightly different frequencies.) Without moving your head you hear beats. Now move your head towards one or the other Sonalert. What happens to the beat frequency? Can you tell which one has the higher and which the lower frequency simply by the behavior of the beats?[4]

Footnote and References

[*] This work was supported by the U. S. Atomic Energy Commission.

1. Vincent Mallette, The Physics Teacher 10, 283 (May 1972).

2. I bought one Mallory SC 628 Sonalert for $5.60, one 9 volt battery (RCA VS323) for $0.50, and a battery clip for $0.13, at Al Lasher's Electronics, 1734 University Ave., Berkeley.

3. I could have achieved a slightly smaller package and more than twice the sound power by using a 15-volt battery, RCA VS083.

4. This particular experiment was inspired by a demonstration at the Exploratorium (see Ref. 5) that uses low tones emitted by loudspeakers. The corresponding experiment using Sonalerts I found almost impossible to do inside a room, because of the ubiquitous standing waves due to reflections from walls. Even outside, the reflections from the ground gave standing waves and hence undesired spurious beats when moving one's head towards one source or the other.

5. Frank Oppenheimer, Amer. J. Phys. 40, 978 (July 1972).

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