4-2016

The singing cymbal: Is it really photon momentum?

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Published In

S. Collin, N. Etchenique and T. Moore, "The singing cymbal: is it really photon momentum?," The Physics Teacher 54, 209-211 (2016). http://dx.doi.org/10.1119/1.4944358

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I. Introduction

A simple demonstration that is occasionally used in the classroom to show that light carries momentum involves making an orchestral cymbal audibly ring using light from a common photoflash. A metal plate or a piece of foil can also be used, however, it appears that many people use a cymbal because the sound is easily heard at a reasonable distance. It is such an impressive example of the effects attributable to photon momentum that it is posted on the CERN website for educational under the name "singing cymbal." [1] Although it is an impressive demonstration, a series of simple classroom experiments can show that the sound of the singing cymbal is not due to the transfer of photon momentum.

II. Estimation of Photon Momentum

It is true that illuminating a cymbal using a photoflash produces an audible sound, however, it seems surprising that such a small amount of light can move a mass as large as an orchestral cymbal. The likelihood that other effects are responsible has been expressed by several people, and at least one series of experiments were performed in an attempt to determine the origin of the phenomenon;[2] unfortunately the results were inconclusive.

A close examination of the demonstration leads one to propose at least four possible causes for the effect, only one of which is that the momentum of the photons is transferred to the cymbal. Three other possibilities are: 1) acoustic excitation of the object by the sound of the capacitor discharging and subsequent ignition of the bulb; 2) thermal radiation from the bulb inducing a rapid expansion of the air near it that propagates to the cymbal, and 3) absorption of the light by the cymbal, which then induces vibration due to rapid thermal expansion of the metal.

To determine the feasibility of photon momentum inducing an audible sound in a cymbal, one can calculate an estimate of the momentum of the light produced by a common photoflash. The flash used in the experiments described below was a Vivitar 283 photoflash, which according to the manufacturer has an optical output of 2,900 beam candlepower seconds. Assuming all of the light from the flashbulb is incident on the cymbal, the total energy reaching the metal is approximately 54 J. This assumes 100% efficiency in the reflector and 100% transmission. Both of these assumptions are idealistic, and measurements indicate that less than 15% of the energy is actually radiated in the direction that the flash is pointed. However, for purposes of calculation we will assume that 54 J of optical energy is indeed incident on the cymbal.

The total photon momentum incident on the cymbal can be determined from the relationship

$$p = E_T/c, \tag{1}$$

where E_T is the total energy and c is the speed of light. For the assumed energy the maximum momentum of the photons is approximately 1.8×10^{-7} kg • m/s. Because cymbals are highly reflective, but not completely reflective, and because the light is not entirely normal to the surface, the total momentum transferred to the metal will be between one and two times the total photon momentum. A good estimate may be a factor of 1.5, resulting in a maximum value of the transferred momentum of 2.7×10^{-7} kg • m/s.

At this point it is instructive to compare the estimated momentum with a quantitative example. For instance, a reasonable estimation of the mass of a grain of salt is approximately 100 μg. As a kinematics problem it is possible for students to estimate the height from which a grain of salt would be dropped in a vacuum to produce this momentum. The answer is approximately 35 cm and it is a good exercise for students to determine if one can hear the effect of dropping a single grain of salt onto a cymbal from a height of approximately one foot. This experiment can be easily performed in the classroom; however, even without doing the experiment the students should be skeptical.

What follows is a description of several experiments using an ordinary photoflash and a crotale, which is a tuned brass cymbal found in the percussion section of most orchestras. The results of these experiments indicate that the acoustic effects produced by exposing a cymbal to the light from a photoflash are not due to the transfer of momentum from the photons to the metal. Instead, the sound is produced by the absorption of the light by the metal, which rapidly heats the cymbal thereby generating a thermally induced impulse. The absorbed energy is sufficient to produce oscillations that result in an audible sound.

III. Experiments

The experiments described here were performed using an ordinary photoflash and an orchestral crotale tuned to C6. To estimate the actual output of the flash a broadband optical energy meter was used to determine the energy output at wavelengths between 400 nm and 2 μm at several places on the face of the flash. The area of the detector was 0.79±0.02 cm^2 and the area of the face of the flash was 16.1±0.02 cm^2. The detected energy varied from approximately 0.335 J to less than 0.075 J depending upon where the detector was placed on the faceplate. A realistic estimate of the total output energy in the optical region of the spectrum is therefore less than 7 J rather than the theoretical value of 54 J cited above, making the claim that the sound of the ringing cymbal is due to photon momentum even less likely. During the experiments the transparent flash face was held approximately 7 mm from the cymbal so that all of the light leaving the flash was incident on the back of the cymbal.

The resonances of this type of cymbal have high Q values and the lowest mode is preferentially excited when struck. Therefore, when the cymbal is struck almost all of the acoustic energy originates from a single mode of vibration.[3] The shape of this mode has no nodal circles and two nodal diameters, and for the cymbal used in these experiments the resonance frequency was 1047 Hz. Power spectra of the sound produced by the cymbal when it was excited by the flash and when it was struck indicate that almost all of the sound power results from the oscillation of this mode in both cases.

A. Confirmation of an optical effect

Of the four explanations posited above, two require that the light be incident on the cymbal. If the vibrations are initiated by either thermal convection or by acoustic excitation it is not necessary for the light to impact the cymbal. However, if photon momentum or thermal shock due to absorption of the light produces the sound the cymbal must be exposed directly to the light. Therefore, a significant amount of information can be obtained by merely preventing the light from reaching the cymbal.

To demonstrate that it is necessary for the light to reach the cymbal, the flash was oriented so that the light was incident onto the back of the cymbal midway between the center and the edge. A microphone placed on the opposite side was used to detect the sound produced by the cymbal. The signal from the microphone was stored on a computer and used to calculate a power spectrum. The power associated with the vibrations at 1047 Hz was compared to the power produced at this frequency when a piece of 3 mm thick clear glass was inserted between the flashlamp and the cymbal. The average change in acoustic power caused by inserting the glass between the flash and cymbal was approximately -2.1 dB. This result indicates that the clear glass had a minimal effect on the amplitude of the induced vibrations, eliminating the possibility that a thermal impulse transmitted through the air initiates the vibrations of the cymbal.

The glass was then colored black to prevent light from being incident on the cymbal. The acoustic power recorded by the microphone with the colored glass in place did not exceed the noise level, which was more than 20 dB below the previous measurements. The result of this experiment indicates that the ringing of the cymbal is not primarily due to excitation from the sound of the photoflash and therefore the induced vibrations must be attributable to optical effects.

B. High-speed interferometry

The two remaining possible causes are the transfer of photon momentum and rapid thermal expansion of the metal due to absorption of the light by the cymbal. Distinguishing between these effects is not trivial, yet it is possible to do by observing the deflection of the cymbal during excitation. This was accomplished using high-speed electronic speckle pattern interferometry (ESPI).

High-speed ESPI has been used in previous investigations to measure the deflection of a flat circular plate after it has been struck.[4] Therefore, it is reasonable to expect that this technique will allow a comparison between the motion of the cymbal excited by light and the motion that occurs after being physically struck. If the cymbal is excited primarily by the transfer of photon momentum to the metal, the motion will be similar to that observed when it is physically struck by a solid object. On the other hand, if the excitation is primarily due to thermal expansion there will be a distinctly different deflection pattern.

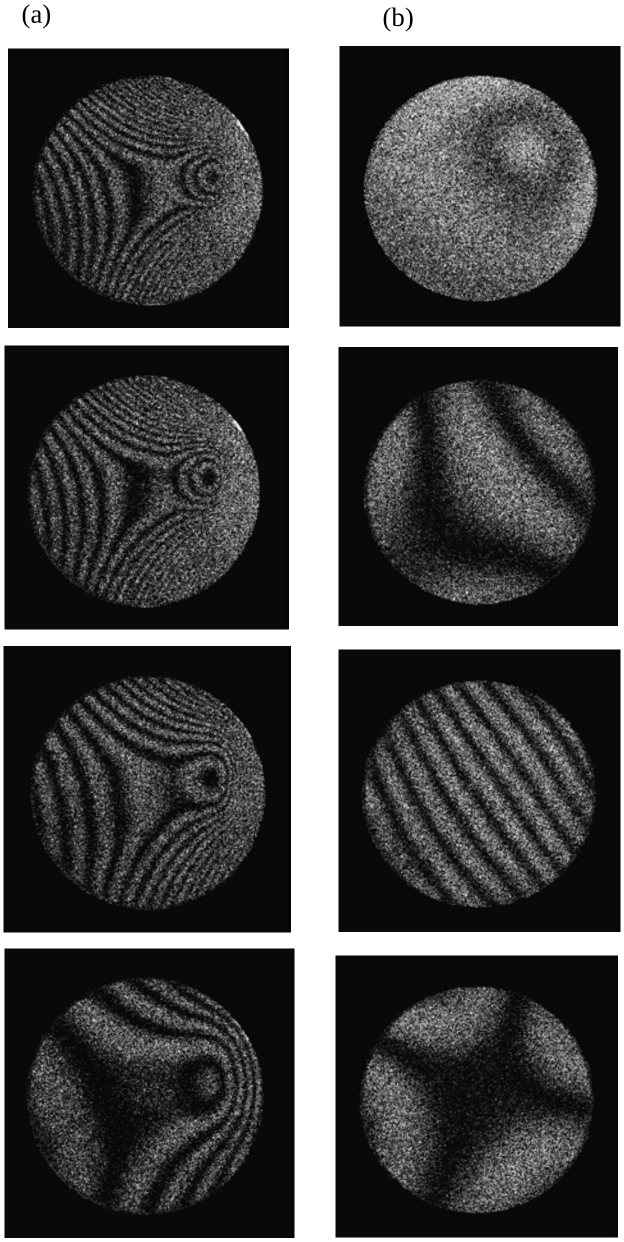

Fig 1. Images of the cymbal produced by high-speed electronic speckle pattern interferometry. The interferograms show deflection shapes after the crotale is excited with a) a photoflash and b) a physical strike.

Although the theory of high-speed ESPI is complicated, the images produced by the interferometer are similar to those produced by Michelson and Twyman-Green interferometers. Displacement of the object under study is represented by a series of fringes of equal displacement, with each bright fringe representing an out of plane displacement of one-half wavelength of the illuminating light. That is, the interferograms can be read like a contour map.

High-speed ESPI was used to analyze the motion of a cymbal after inducing the vibrations in two different ways: once by being struck from behind with a mallet and once using a photoflash placed behind the cymbal. The laser used in the interferometer had a wavelength of 532 nm and the images were recorded with an exposure time of 0.1 ms at a frame rate of 9.9 kHz.

The high-speed images of the cymbal excited by both methods are shown in the series of images in Fig. 1, where the fringes represent out of plane deflection relative to the cymbal at rest. In Fig. 1 the left column (a) contains interferograms after excitation by the photoflash. Interferograms recorded after physically striking the cymbal are in the right column (b) of Fig. 1.

The topmost images in Fig. 1 a) and b) show the motion of the cymbal immediately following initiation of motion by the flash and the strike, respectively. The second set of images was captured approximately 0.3 ms after excitation, and the last two sets show deflection shapes 135 ms and 323 ms after the initial image. The images shown in Fig. 1 (a) indicate that the cymbal is distorted at the point of original excitation, with the metal slowly relaxing back toward the original shape over a period of several hundred milliseconds. The circular fringes at the point of excitation and the slow rate of relaxation indicate that the distortion is due to thermal expansion. Conversely, the series of images in Fig. 1. (b) indicate that when the cymbal is physically struck it begins to rock from side to side, which results in a series of uniform fringes. After approximately 250 ms the rocking motion has completely subsided and only the underlying motion responsible for the audible sound remains visible, i.e., the modal structure with two nodal diameters. A similar series of images would result if the motion was initiated by the transfer of photon momentum.

The lack of a whole-body rocking motion when vibrations are induced by the flash, combined with the obvious thermal expansion of the metal, indicates that thermal effects dominate any motion attributable to photon momentum. The distortion at the point of excitation, represented by the circular fringes centered on the position of the flash, indicates the presence of a thermal effect that not only initiates the motion but persists long after the flash. The lack of any evidence of rocking motion confirms that the transfer of momentum from the light can be neglected as a source of vibration and the audible sound is attributable to rapid thermal expansion at the position where the light is incident on the cymbal.

C. A simple classroom experiment

Most laboratories have the equipment necessary to perform the experiments in subsection A, so students have the opportunity to prove the optical origins of the effect. However, it would be unusual to find the equipment necessary to perform high-speed ESPI in a well-equipped university laboratory and extremely unlikely to find it in a high school classroom. Yet, it is probably more important for students to demonstrate the unlikeliness of photon momentum being responsible for the observed phenomenon than to be told the answer. Fortunately, there is a simple experiment that can conclusively demonstrate that the audible effects are not primarily due to the transfer of photon momentum. This experiment only requires the ability to record the sound using a microphone and input the signal into a computer.

To verify that the sound is primarily due to absorption and not to the transfer of photon momentum, the cymbal was colored black to increase thermal absorption of the object. Similar to the experiments described in subsection A, a flash was directed onto the back of the cymbal and a microphone placed on the opposite side recorded the audio signals simultaneously. The average acoustic power was approximately 8 dB higher than the acoustic power measured when the light was incident on the clean**,** reflective cymbal. This difference in power indicates that the amplitude of cymbal vibration increases when the object is colored black. Therefore, thermal absorption has a larger effect on the audible sound of the cymbal than the transfer of photon momentum. Had photon momentum been primarily responsible for the initiation of vibration, the sound power would have decreased when the cymbal was painted black due to the reduction in the transferred momentum that occurs when photons are absorbed rather than reflected.

It is important to note that this experiment does not demonstrate that the sound attributable to the transfer of momentum from the photons is completely negligible, only the interferometry allows one to make that conclusion. However, it does demonstrate that the thermal effect dominates the process.

IV. Conclusion

Although the ringing of a cymbal that occurs when it is illuminated by a photoflash is not due to the transfer of photon momentum as is commonly thought, it is still an excellent classroom demonstration. The effect is impressive and students can easily calculate a reasonable approximation of the photon momentum and compare it to the momentum transferred by dropping a small object on the cymbal. These calculations are well within the ability of the average student and should lead them to question whether photon momentum is indeed the driving mechanism.

The laboratory exercise of recording the sound of a cymbal induced by a photoflash, both before and after coloring it black, provides an excellent opportunity to discuss the fact that the momentum transfer is twice the incident momentum when light is incident on a reflecting surface. The surprising result that the sound increases when more photons are absorbed will lead to discussions of thermal effects, but more importantly it should lead to a discussion of how important it is to experimentally confirm conjecture. Although it has been generally accepted that this is a demonstration of the effects of photon momentum, and the idea promulgated by a world-class institution such as CERN, this does not necessarily make it so. It is a lesson that we all should be reminded of occasionally.

V. Acknowledgements

This work was supported by the National Science Foundation grant #PHY-1303251.

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