Research Report:

# On an *Experimentum Crucis* for Optics

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*Abstract*
Formulated almost 150 years ago, Thomas Young's hypothesis that light might be a transverse wave has never been seriously questioned, much less subjected to experiment. In this article I report on an attempt to prove experimentally that Young's hypothesis is untenable. Although it has certain limitations, the experiment seems to show that sound in air, a longitudinal wave, can be "polarized" by reflection just like light, and this can be used as evidence against Young's hypothesis. Further refinements of the experimental setup may yield clearer results, making this report useful to those interested in the important issue of whether light is a transverse or a longitudinal wave.

**Introduction**

In the course of development of science, there has always been a close connection between sound and light [1]. Acoustics stimulated research and discovery in optics and vice-versa.

Reflection and refraction being the first common points observed between the two, the analogy between optical and acoustical phenomena has been proven also in the case of interference, diffraction, Doppler effect, and even in their mode of production: sounds are produced by the vibration of macroscopic objects, while light is produced by vibrating molecules and atoms.

The wave nature of sound implies that light is also a wave and, if matter must be present for sound to be propagated, then aether must exist in order to account for the propagation of light through spaces void of all the matter known to chemistry.

However, there is today a critical point in which light seems to be different from sound: polarization.

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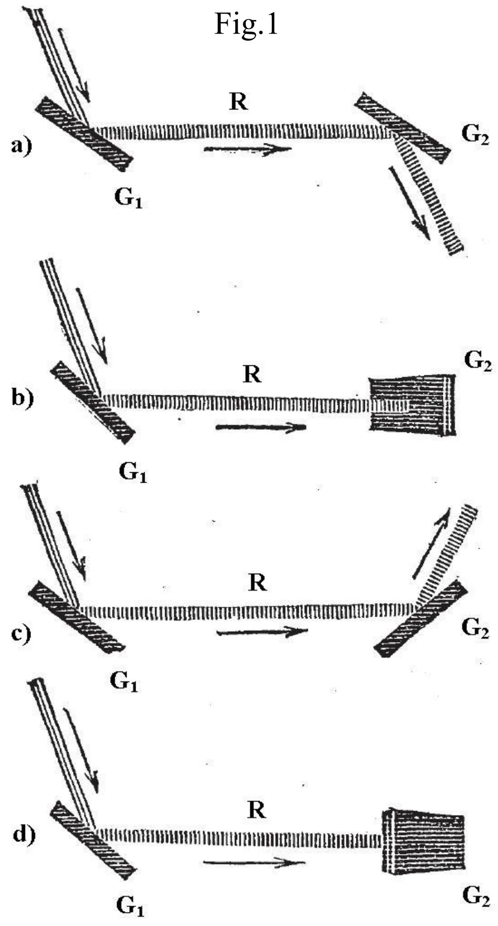
[1]. A. Zarembowitch, *Ultrasonic Waves And Optics*, Imaging Processes and Coherence in Physics, Lecture Notes in Physics, Vol. 112, (Springer Science, 1980), p. 57-63.

Light is said to be polarized when it is reflected from glass at an angle of 56 degrees. You cannot notice any change in the beam of light reflected in this way, except for a reduction in its intensity due to the fact that not all the incident beam is reflected at the glass surface - part of it enters the glass plate refracted.

However, as shown in Fig.1, if this beam of light (R), reflected once from the first glass plate (G1), is reflected again from another identical glass plate (G2) at an angle of 56 degrees, something new becomes apparent: reflection from the second plate ($G_2$) will be observed only when the planes of reflection of the two glass plates coincide - cases a) and c) - and will cease completely when the two planes of reflection are perpendicular to each other - cases b) and d). (Fig.1 is reproduced and adapted from [2]).

Fig.1




This behavior of the beam of light (R) is quite remarkable because normally beams of light reflect from glass plates no matter on which side of the beam the glass plate is and irrespective of the angle of incidence. Still, in this case, the light beam (R) reflects or not from the second glass plate ($G_2$), depending on the side of the beam on which the glass plate is placed for reflection and on whether the angle of incidence is different from or equal to 56 degrees.

This phenomenon has not been given any name yet, but I will take the liberty to call it **Malus effect** because its discovery was based on the observations made by Etienne Louis Malus.

In an attempt to give an explanation for the unusual behavior of the light beam (R), scientists conceived this light beam to be in a special state, contended that this special state is produced by the reflection of a normal beam of light on the first glass plate ($G_1$), called this new state of the light beam “polarized”, and referred to any beam of light behaving like the beam of light (R) as being in a “polarized state”.

Finding a complete and thorough explanation of what we have called Malus effect has been a priority for scientific men from the very discovery of this phenomenon. After long hesitations and influenced by the results of interference experiments performed with beams

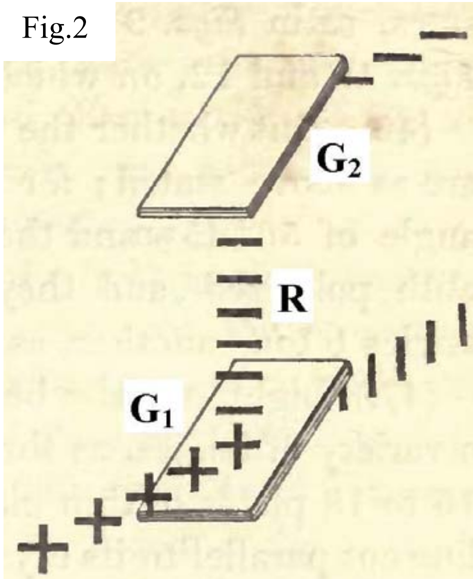
[2]. Edward L. Youmans, *A Class-book Of Chemistry*, (D. Appleton and Company, 1863), p. 150.

of light like (R) obtained by other methods, Thomas Young advanced a hypothesis that was, in his own words [3], “imperfect” and without any “physical foundation”: that light might be a transverse wave.

According to this hypothesis, the beam of light incident on the first glass plate ($G_1$) was composed of transverse waves oscillating in all possible directions across the beam (Fig.2).

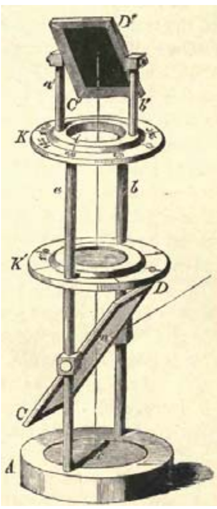
Upon hitting on the glass plate ($G_1$), only the oscillations parallel to the surface of the glass were reflected, while all the others were absorbed by or entered in the glass plate, so that the light beam (R) contained only transverse waves oscillating parallel to the glass surface. Precisely how this selective reflection took place was not specified.

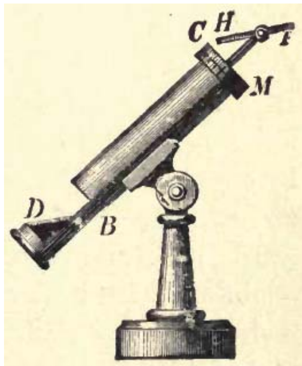
Fig.2




Then, following the same logic consistently, it was argued that, upon incidence on the second glass plate ($G_2$), reflection will take place according to whether the glass surface was parallel or not to the oscillations composing the beam of light (R). (Fig.2 is reproduced and adapted from [4]).

Malus effect described in Fig.1 can be best observed with a Norremberg polariscope shown in the left figure [5], which is a variation of Biot’s original polarizing apparatus, shown at right [6]. In both cases, a beam of light is reflected by one glass plate onto a second glass plate, as explained above.





The angle between the planes of reflection of the two glass plates can be changed by rotating the second glass plate around the beam of light reflected by the first.

I have constructed such an apparatus (Fig.3) at the beginning of this

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[3]. E. T. Whittaker, *A History Of The Theories Of Aether And Electricity From The Age Of Descartes To The Close Of The Nineteenth Century*, (Longmans, Green, And Co., 1910), p. 122.

[4]. Charles Woodward, *A Familiar Introduction To The Study Of Polarized Light*, 2nd Ed., (John Van Voorst, Paternoster Row, 1851), p. 25.

[5]. Eugene Lommel, *The Nature Of Light*, (D. Appleton and Company, 1898), p. 309.

[6]. Ibid., p. 307.

year and I have verified that, indeed, reflection from the second glass plate is not observed when the planes of reflection of the two glass plates are perpendicular to each other, but only when they are coincident [7].

The effect is very striking and powerful in that it can be observed easily how the intensity of the beam reflected from the second glass plate is reduced to zero in the former case and changes to maximum in the later.

For orientations between these two positions, the reflected beam can be observed with intensities between zero and maximum.


Fig.3

Thomas Young's hypothesis that light might be a transverse wave marked the departure from the perfect analogy that existed between sound and light: for, up to then, both sound and light had been considered longitudinal waves of compression, the former in air, the later in aether. After Young, sound waves retained their longitudinal character, but light waves were taken as transverse.

This departure brought profound implications, and complications, for science: the first difficulty observed by scholars was in conceiving how the aether, a fluid, could possibly sustain transverse waves, since transverse waves cannot propagate other than through a solid medium. The most notable complication was that Young's hypothesis was used to support another hypothesis: that light was an electromagnetic wave in which the vectors representing the intensity of the electric and magnetic field oscillate across the beam of light perpendicular to each other. (It is often argued that Hertz' experiments proved that radio waves are electromagnetic waves. What Hertz has shown, in fact, was nothing more than that there was another way to produce aether waves - by electrical oscillations - besides heating matter to incandescence to emit light [8]).

The curious fact about Thomas Young's hypothesis that light might be a transverse wave is that it is, even today, accepted without any experimental evidence. For example, one way to check Young's hypothesis could have been an experiment to test whether a Malus effect like that seen in Fig.3 in the case of light can also be observed in the case of sound. I could not find, in the many references which I have seen, even a hint to the necessity of doing such an experiment.

Testing if an acoustical Malus effect exists is in fact testing if sound behaves like light in similar conditions and is of crucial importance because it allows us a direct verification of

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[7]. Ionel Dinu, *Research On The Nature Of Polarized Light*, (NPA Aether Group Seminar, April 23, 2010).

[8]. Heinrich Hertz, *Electric Waves, Being Researches On The Propagation Of Electric Action With Finite Velocity Through Space*, (MacMillan and Co., London and New York, 1893).

Thomas Young' hypothesis of light as a transverse wave: if sound is found to display a behavior similar to that of light (Fig.1), Young's hypothesis will be proven invalid because sound propagating in air is a longitudinal wave of compression. The existence of an acoustical Malus effect displayed by a longitudinal wave like sound in air will show that transverse waves cannot be invoked for the explanation of this phenomenon and will demand explanations of other nature, while requiring us to maintain the perfect analogy between sound and light as longitudinal waves of compression in their respective mediums of propagation.

A negative result of such an experiment is also highly relevant. The existence of an optical Malus effect and the inexistence of an analogous acoustical Malus effect will show that there is indeed a fundamental difference between light and sound. This fundamental difference will then be possible to be assigned to the different kinds of oscillations in the respective waves and, since sound in air is a longitudinal wave of compression, Young's hypothesis that light might be a transverse wave will have an indirect experimental support.

We can, therefore, conclude from the above that an experiment to check for the existence of an acoustical Malus effect is crucial for the verification of Young's hypothesis that light is a transverse wave. This is why, albeit being acoustical in character, it deserves to be called an *experimentum crucis* for optics.

**The acoustical Norremberg polariscope**

It is apparent from what has been said in the introduction that the acoustical Malus effect has to be searched for with an apparatus of Norremberg type, in which the glass plates are replaced with acoustical plates and sound is used instead of light. A proper name for such an apparatus would be acoustical Norremberg polariscope.

One of the key points in checking for the existence of an acoustical Malus effect is to ensure that the sound waves incident on the two acoustical plates are not only reflected but also refracted. This observation is very important since it is known that, in the case of light, the Malus effect occurs when the plates are made of glass and glass has this important property of splitting an incident beam of light into a reflected and a refracted beam. When metallic plates are used, the Malus effect is almost undetectable.

This important observation was made by David Brewster, who continued the work initiated by Malus. He discovered that the Malus effect is greatest when the beams reflected and refracted at the surface of glass are perpendicular to each other. The law named after him, Brewster law, is just what results from this observation, namely that the angle of incidence $i$ for which the Malus effect is greatest can be calculated as:

$$\tan(i) = n \qquad \text{Eqn.1}$$

where $n$ is the relative optical index of refraction of glass and air.

It can be seen that, in the case of glass, for which $n = 1.5$, the angle of incidence $i$ is indeed 56 degrees, since

$$\tan(i) = n = 1.5 \Rightarrow i = \tan^{-1}(1.5) = 56\deg$$

The relative optical index of refraction is defined as the ratio of the absolute refractive index of glass $n_{glass}$ and the absolute refractive index of air $n_{air}$.

Since

$$n_{glass} = \frac{c}{v_{glass}} \quad \text{and} \quad n_{air} = \frac{c}{v_{air}} \quad ,$$

where $c$ is the speed of light in vacuum (free aether), $v_{glass}$ the speed of light in glass and $v_{air}$ the speed of light in air, it follows that

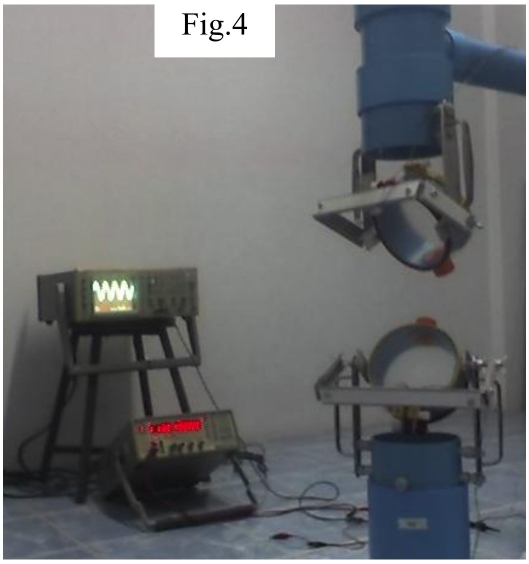
$$n = \frac{n_{glass}}{n_{air}} = \frac{\frac{c}{v_{glass}}}{\frac{c}{v_{air}}} = \frac{v_{air}}{v_{glass}} \qquad \text{Eqn.2}$$

Since both light and sound are waves, the above calculations are applicable also for the case of sound. Therefore, they will be used below to find the angle of incidence for which the acoustical Malus effect we are searching for should be observed.

**The experiment**

Figure 4 shows the acoustical Norremberg polariscope that I have built in order to search for the existence of an acoustical Malus effect analogous to that observed with light. The apparatus has two identical acoustic plates that reflect the sound produced by an ultrasound generator.

Fig.4



The acoustic plates are 50 mm thick and were made by cutting two lengths of 50 mm from a PVC pipe of 100 mm in diameter. The two rings obtained were covered at their openings with thin polyurethane membranes kept fixed in place by removable plastic rings.

The polyurethane membranes had a thickness of 20 μm and were chosen as thin as possible to ensure that the incident sound penetrates them [9] and enters the acoustical

[9]. Mak Se-yuen, *Wave Experiments Using Low-Cost 40 kHz Ultrasonic Transducers*, Physics Education **38** (5), 2003, p.441.

plate, so that the sound will not only reflect but also refract, just like light is both reflected and refracted at the surface of a glass plate.

Each acoustic plate is therefore like a 50 mm thick disk, or drum, having two parallel surfaces of thin elastic membranes that separate the interior of the plate from the exterior (left picture).

An airtight cap permits access to the interior of the plate. This was used for replacing the air inside the plate with a different kind of gas. A different gas will have a speed of propagation for sound different from that of air, and this will ensure that the sound beam coming from the air and entering the plate will change direction, i.e. will refract. This is similar with the situation in which a beam of light incident on a glass plate is refracted because light has different speeds of propagation in air and in glass.

The gas used to fill the acoustic plate was butane, available in liquefied form in cartridges for use in camping gas cookers. The gas was introduced through the opening of the acoustic plate displacing the air that existed inside. The acoustic plate obtained in such a way can be called a butane acoustic plate if the effects of the thin polyurethane membranes are neglected.

The speed of sound in butane at 0.1 MPa and 300K is 211 m/s [10], while the speed of sound in air in the same conditions is 349 m/s [11]. The relative acoustic refractive index of the butane acoustic plate in air can be obtained from equation 2 as:

$$n = \frac{n_{butane}}{n_{air}} = \frac{v_{air}}{v_{butane}} = \frac{349[m/s]}{211[m/s]} = 1.65 \qquad \text{Eqn. 3}$$

Using Brewser law (eqn.1) we find that the angle of incidence for which the acoustical Malus effect should be observed is

$$\tan(i) = n = 1.65 \Rightarrow i = \tan^{-1}(1.65) = 59\,\text{deg}$$

The sound used in experiments had a frequency of 40 kHz (ultrasound region) and was generated by a piezoelectric transducer built to operate at this frequency. Technical specifications of the transducer are available on producer's website [12].

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[10]. D. Bucker and W. Wagner, *Reference Equations of State for the Thermodynamic Properties of Fluid Phase n-Butane and Isobutane*, J. Phys. Chem. Ref. Data, Vol. 35, No. 2, 2006.

[11]. R.C. Hart, R.J. Balla, and G.C. Herring, *Optical Measurement of the Speed of Sound in Air Over the Temperature Range 300-650K*, ICASE Report No. 2000-20, NASA, Langley Research Center.

[12] Ceramic Transducer Design, Co., Ltd, www.ctdco.com.tw , part number 40T-16 (transmitter) and 40R-16 (receiver)

The piezoelectric transducer was connected to a Transmission Impairment Measuring Set (Hewlett Packard 4934A TIMS), which operated like a signal generator. The TIMS was able to excite the piezoelectric transducer with a sinusoidal electric signal having a frequency of 40 kHz and a maximum of 13.0 V peak-to-peak (4.6 V rms). When supplied with the maximum voltage of 13.0 V peak-to-peak (4.6 V rms), the voltage drop on a 10 Ω resistor in series with the transducer was 0.14 V peak-to-peak (50 mV rms), so the current flowing through the transducer was 5 mA rms. From these measurements the total electrical power absorbed by the transducer can be estimated at 23 mW (5 mA multiplied by 4.6 V).

The doubly reflected sound was detected with another piezoelectric transducer that matched the 40 kHz frequency of the first transducer. This receiving transducer was connected to an oscilloscope, allowing for a direct visualization of the intensity of the doubly reflected ultrasound.

Both the transmitting and the receiving transducers were mounted on supports that could place them at different angles with respect to the normal of each acoustic plate. Each acoustic plate could rotate both around the sound beam that traveled between them and around an axis perpendicular to the sound beam.

The distance between the transmitter and the center of the acoustic plate onto which it sent the ultrasound was 6 cm; the same was the distance between the center of the second acoustic plate and the receiver. The distance between the centers of the two acoustic plates was 16.5 cm, so the total distance traveled by the ultrasound between the transmitter and the receiver was 28.5 cm.

*Results*:

When operated in the above conditions, the ultrasound beam arrived at the receiver after two consecutive reflections on the two acoustic plates produced on the oscilloscope a signal of 0.8 V peak-to-peak, every time the planes of reflection of the two acoustic plates were coincident, i.e. in situations similar to cases a) and c) in Fig.1.

When one of the acoustic plates was turned 90 degrees around the beam traveling between the acoustic plates, the planes of reflection of the two acoustic plates became perpendicular to each other - similar to the cases b) and d) in Fig. 1 - and the signal arrived at the receiver and seen on the oscilloscope decreased to a value of 0.64 V peak-to-peak.

These results point to the fact that sound has a behavior similar to that of light and an acoustical Malus effect does exist, similar to that observed in optics. Although in the acoustic case the intensity of the doubly reflected wave does not vary between a maximum value and zero, the fact that there is a definite variation of its intensity between a maximum and a minimum value is remarkable.

## Conclusions

The present work is a report on the motivation for, and the results of, an experiment designed to test Young's hypothesis that light might be a transverse wave.

The experiment shows that an ultrasound beam reflected consecutively from two identical acoustic plates behaves similarly to that of a light beam reflected consecutively from two identical glass plates.

The intensity of the doubly reflected ultrasound beam changes between a maximum value when the planes of refection of the two acoustic plates are coincident and a minimum value when the planes of reflection are perpendicular to each other.

The effect is remarkable because the sound beam behaves as if it were partially polarized by reflection, just like light is considered to be polarized by reflection in an analogous setup.

However, since sound in air is a longitudinal wave of compression and cannot be polarized, this interpretation becomes unacceptable and it follows that this effect must be accounted for in other ways.

Most importantly, this result raises questions on the validity of Thomas Young's hypothesis that light might be composed of transverse waves because it shows that transverse waves cannot be invoked for the explanation of this effect. It seems then that we will have to consider both light and sound as longitudinal waves of compression - the former in aether, the later in air - and look for a different explanation of Malus effect that will be equally valid for these two types of waves.