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Acoustic Michelson-Morley Experiment with an Ultrasonic Range Finder

By Norbert Feist

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Acoustic Michelson-Morley Experiment with an Ultrasonic Range Finder

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Abstract- **An ultrasonic range finder was mounted on a horizontally rotatable rail at fixed distance, s, to a reflector on the top of a car. The change of the distance reading, s, determined the two-way velocity of sound as a function of the car's velocity and direction. As a result of this experiment, the out and back velocity c_2 was determined to be isotropic – as in the optical case of the Michelson-Morley experiment. Within the experimental error, the velocity was found to vary as c_2 $(c^2-v^2)/c$.**

I. The Original Michelson-Morley Experiment (MMX) In Retrospect

At the end of the 19th century, light was assumed to propagate isotropically in the Ether at rest, independent of the source velocity, at a constant speed of c. Similar to sound, measurements should reveal a vector addition of c and v when performed with a detector moving at velocity v in the medium. That means the expected results were c-v in the forward direction and c+v and in opposite direction. In this case, the harmonic mean, $c_2 = (c^2-v^2)/c$, serves as two-way velocity.

The general equation for any angle ϕ between rail direction and car velocity reads:

$$c(\phi) = \sqrt{c^2 - v^2 \sin^2 \phi} - v \cos \phi \quad (1)$$

This dependence on direction should determine Earth's velocity v with respect to Ether. But the measuring accuracy was not sufficient for a direct determination.
The two-way velocity is anisotropic as well:

$$c_2(\phi) = \frac{c^2 - v^2}{\sqrt{c^2 - v^2 \sin^2 \phi}} \quad (2)$$

Michelson managed to compare two two-way velocities with sufficient accuracy by means of an interferometer. According to Eq. (2), the optimum difference is given in the case of two bars of equal length oriented at right angles. Upon rotation of the interferometer, however, no fringe shift was detected. The Michelson-Morley result thus was: The two-way velocity of light is isotropic in moving systems. The conflict with the Galilei transformation was explained by assuming a length contraction in the forward direction.

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II. An Acoustic Analogue of MMX

There are many analogies between electromagnetic and acoustic wave propagation. Examples include the constancy of c, the Doppler Effect, interference, diffraction, and refraction. For practical reasons, an analogous length contraction could be ruled out in the case of measuring the velocity of sound along the same measuring gauge.

During the graphical analysis of the MME, the question arose whether sound complies with Eqs. (1) and (2) -- which are assumed to be valid for light. No evidence was found in the literature of an acoustic analogue of the MME with sound waves. After SRT decoupled both fields, developing sound ray sources and experimenting with them would not have produced a stimulus equivalent to those performed with lasers.

At the end of the 20^{th} century, however, the development of inexpensive ultrasonic range finders offered hobby physicists the opportunity to perform these experiments without requiring a wind tunnel. Such an MME analogue needs only one arm because the two-way velocity of sound can be calculated directly.

III. Description of the Experiment

a) Principle

The pulse-echo method measures the time of flight, t, of an ultrasonic pulse from the converter to a reflector at an unknown distance, s, and back. A built-in micro processor calculates the unknown distance s from 2s = ct, using the programmed fixed sound velocity of 343.37 m/s in air at 20^0C (68^0F). For constant s, this method yields a variable sound velocity as the distance changes.

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As mentioned above, the two-way velocity of sound parallel to the forward direction [φ = 0 or 180 degrees] in a moving system should be $C_{2\,(0^0/180^0)} = (c^2 - v^2)/c$. Assuming the head wind velocity to be equal to that of the car (100 km/hr or 27.78 m/s), the measured outside parallel two-way velocity of sound should only be 341.12 m/s (or 99.34% of the sound velocity for the car at rest). The pulse time-of-flight should increase correspondingly.

Assuming Eq. (2) to hold, the distance reading would be:

$$s(v)/s0 = c/c_2 \qquad (3)$$

For example, at v = 100 km/hr, the distance equals 1358.7mm. This compares to a distance of 1350 mm with the car at rest.

Perpendicular to the forward direction, Eq. (2) yields the two way velocity $C_{2(90^0/270^0)} = C\sqrt{1 - \vartheta^2/C^2}$ as for the MMX. At 100 km/hr (or v = 27.78 m/s), this corresponds to 342.24 m/s as two way velocity of sound and a distance reading of 1354.5 mm instead of 1350 mm for the car at rest.

For a 1 mm resolution, the expected two-way velocities of sound should be distinctly measurable. (Later experiments show that the standard deviation equalled 0.6 mm at rest.)

The first test rides used a standard supersonic distance range finder with cm resolution, a 2m gauge length mounted on the top of the car, and an assistant to check the car's speed and distance. This validated the measuring principle.

b) Diagram and Equipment

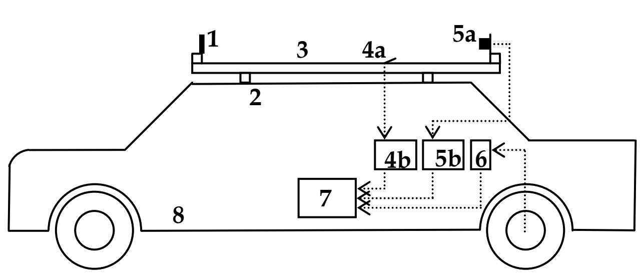

Fig. 1: Acoustic MMX Setup

1. Aluminium Reflector 8 cm x 8.5 cm
2. Carrier Mounted on Top
3. Gauge Length, Al Square Section Pipe

4a. Thermoelement, 0.5 mm Diameter, Time Constant 0.025 sec.
4a. Thermometer, Type Gulton-Tastotherm D700
5a. 50 kHz Foil Supersonic Converter With Factory Quality Control Combined With 5b
5a. Basic Equipment for the Supersonic Distance Finder Type LRS 3, Manufactured by Format Messtechnik, Resolution 0.1 mm („On top of a high time resolution, expressed in nanoseconds, a phase sensitive discrimination of the reflected ultrasonic pulse is essential")
6. Universal Meter Type Fluke 743B as Frequency Meter for the GAL Signal
7. Floppy Disk Operated Data Logger, Type Memograph by Endress+Hauser
8. Car, Type BMW 520i, Fig. 9

Remark concerning 4a:

In air, the velocity of sound rises with temperature. This was tested separately with the gauge length at rest – by 0.18% per K in the relevant measuring range.

The temperature sensor was not sensitive enough for this application. Therefore, the temperature control of the device was disabled. Hence, according to the manufacturer's recommendation, the micro-processor was set to a constant air temperature of 20°C (68°F). A more sensitive external thermometer system was used as a replacement. Because of this, the recorded distance values s_0 (at rest) and s(v) (at velocity v) were multiplied by the factor:

$$k = \left[1 - (20 - \vartheta) \cdot 0{,}0018\right] \qquad (4)$$

Eq. (4) uses the separately determined temperature ϑ. Because of this, temperatures must be normalized to a reference of 20°C before applying Eq. (6).

Remark concerning 6:

This car's speedometer was calibrated between 0 and 100 km/hr by means of direct rear wheel drive at a motorists' association. This calibration was verified by driving on a highway while using a GPS system. These values then represented the reference for the SCV (Speed Compensated Volume) signal. After obtaining good data as the car accelerated, the signal temporarily dropped out at 63 km/hr. (See the red curve in Fig. 8.) This was taken into account by cancelling the corresponding value. Moreover, a possible error in estimating the car's velocity wouldn't alter the result "The two-way velocity of sound is isotropic for *all* velocities of the moving system" – in accordance with the MMX.

c) Experiment and Evaluation

The rides were performed in externally calm conditions. On the carrier, the gauge length was oriented with the front reflector at angles of $\phi = 0, 22, 45, 68$ and 90^0 with respect to the car's longitudinal axis. (See the diagram Fig. 1 and attached photo Fig. 9.) The car's velocity was increased until the moment when the distance finder "quit" empirically. That was followed by a slow deceleration to a complete stop.

After a short stop, a return journey was recorded with the same procedure. The red curve in Fig. 8 shows that. Once every second, results were recorded for temperature, car velocity, v, and distance, s. The thermal factor, k, and the s values, were normalized to 20^0C as described above.

Eq. (3) was rearranged as follows:

$$c_2 = c(s_0/s(v)) \quad (5)$$

By setting the sound velocity at rest, c, to 100 %, the equation may be represented as follows:

$$c_2 = 100(s_0/s(v)) \quad (6)$$

These percentages are shown in Figs. 2 to 7 (see attachment). The red line represents theoretical anisotropy according to Eq. (3). Rather than matching the red lines, the measured data agrees more closely with the black curves represented by

$$c_2 = (c^2 - v^2) / c \quad (7)$$

d) Discussion of the Result

The results confirm the hypothesis that the two-way velocity of sound is isotropic in a moving system – as in the case of the optical MME.

Considering the unknown flow conditions above the car and "data clouds" in the wind, this potentially important result should no doubt be checked again.

In 2006 there was an attempt to determine the directionality of the one-way velocity of sound in a wind tunnel with known flow conditions, Fig. 10. The noise in the tunnel thwarted the measurements in the range of audible sound by means of loudspeaker, microphone, and maximum length sequences.

After 2000, the mechanical wind detectors in the weather stations were successively replaced by acoustic anemometers with measuring errors below 1% [1]. This, however, was only achieved by programmed corrections (see [2] for 5 additional links) which should be known for a successful reproduction of the experiment.

At present, to reproduce the experiment, superpose the signals from the continuous wave (CW) source, sent and received back from the reflector, on a phase-sensitive oscilloscope. Then, check whether the wind causes a mutual drift upon rotating the measuring gauge.

Acknowledgements

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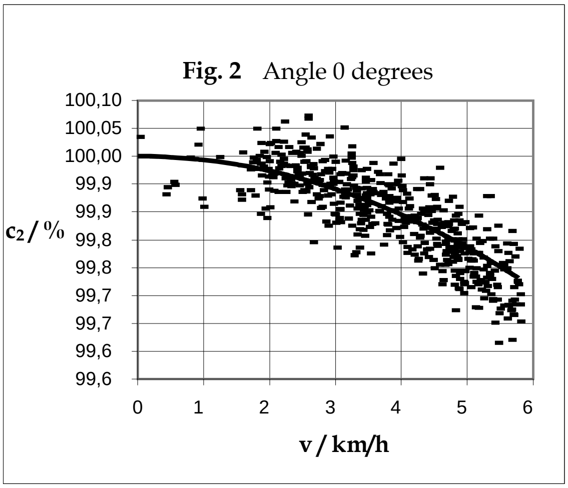

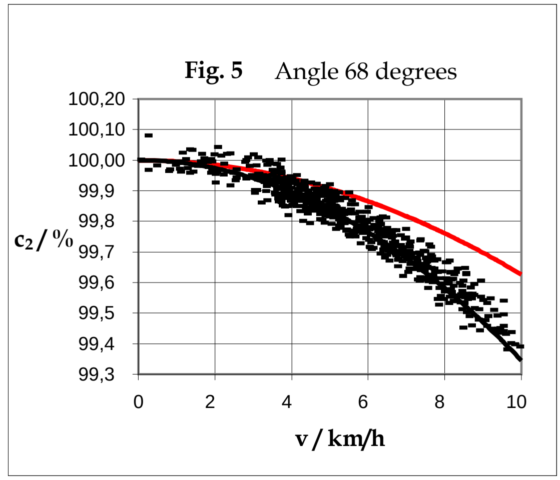

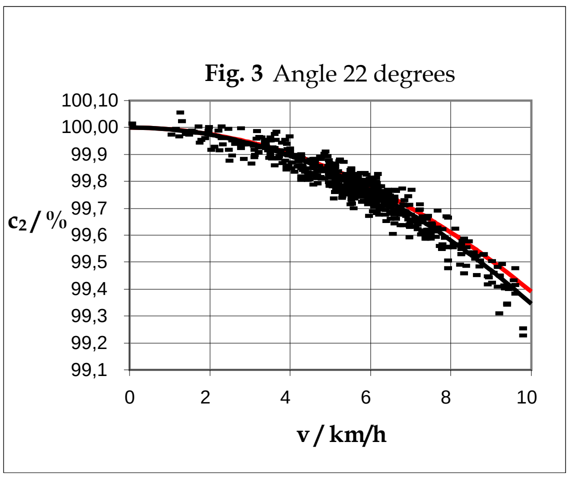

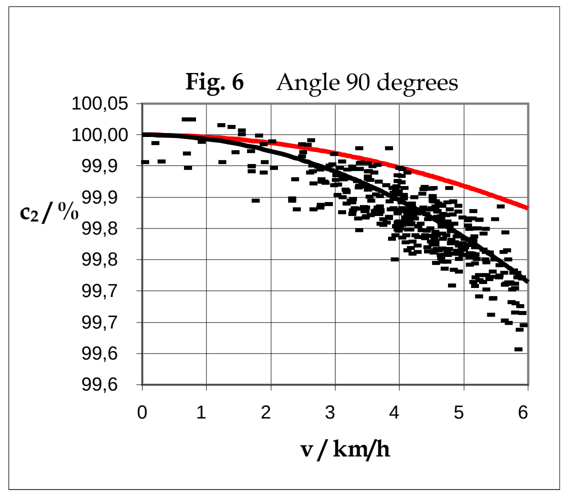

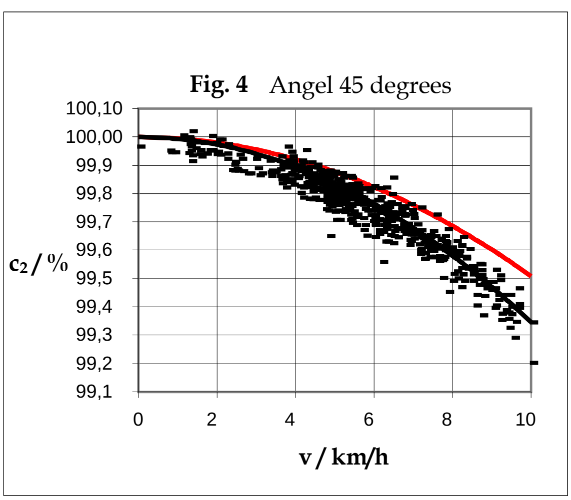

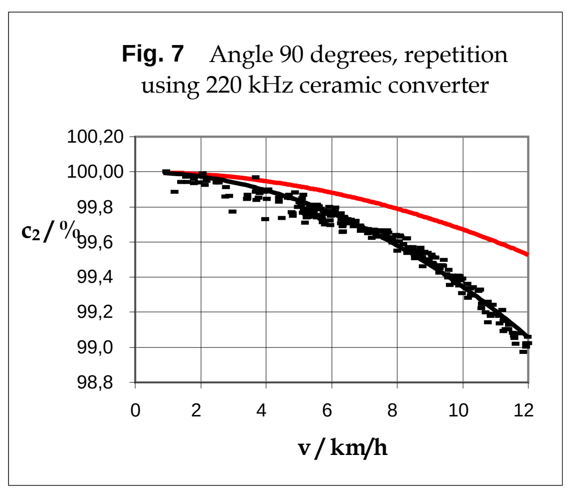

Fig. 2 – 7: Experimental Results on the Directional and Velocity Dependences of the Two-Way Velocity of Sound, c_2. Here, the latter is given in percentage of the velocity of sound at rest, c. The data shown in each Fig. are results of one test run to and fro. The red curves are "anisotropy curves" according to Eq. (2). The black curve was calculated according to Equation (7) $c_2 = (c^2\text{-}v^2)/c$. Therefore it is identical for all directions and figures.

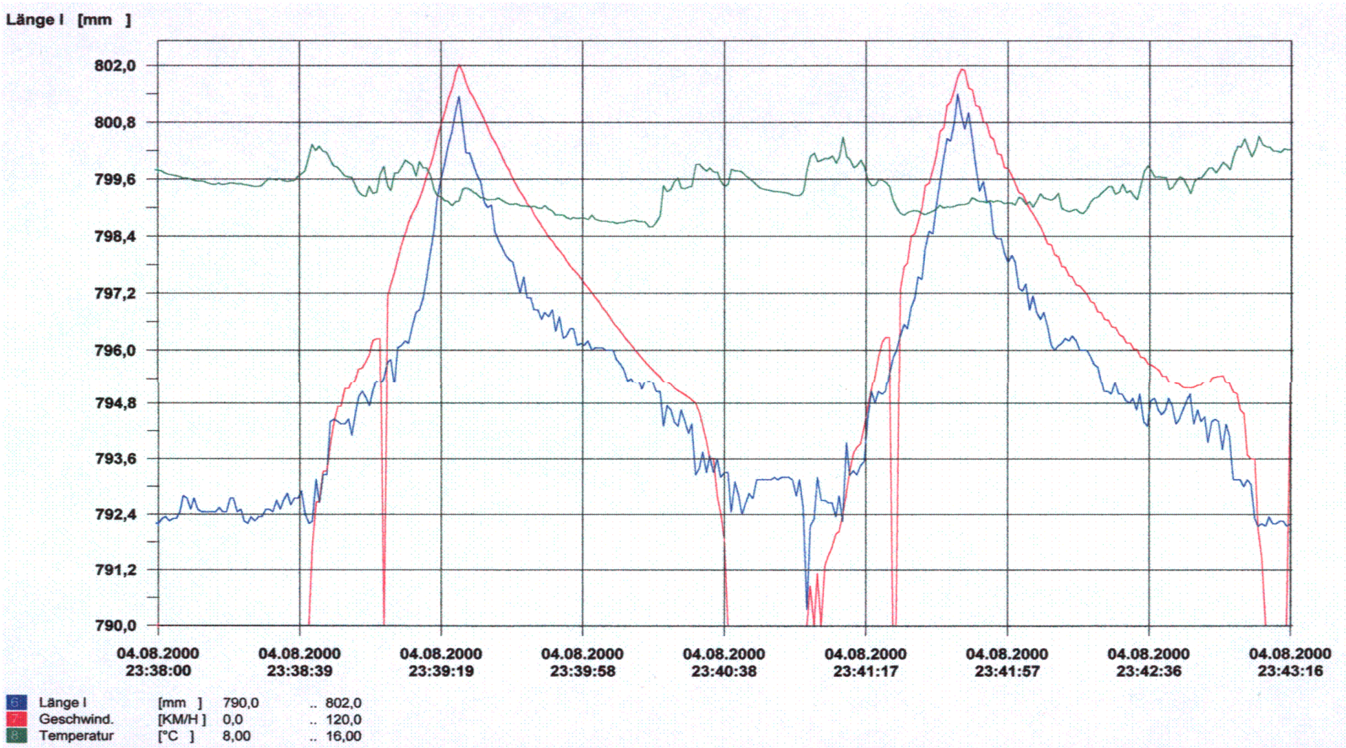

Fig. 8: Data Logger Plot: August 4, 2000, Data for Fig. 7

Fig. 9: Photo showing the Measuring Gauge Mounted on the Car's Top in 2000

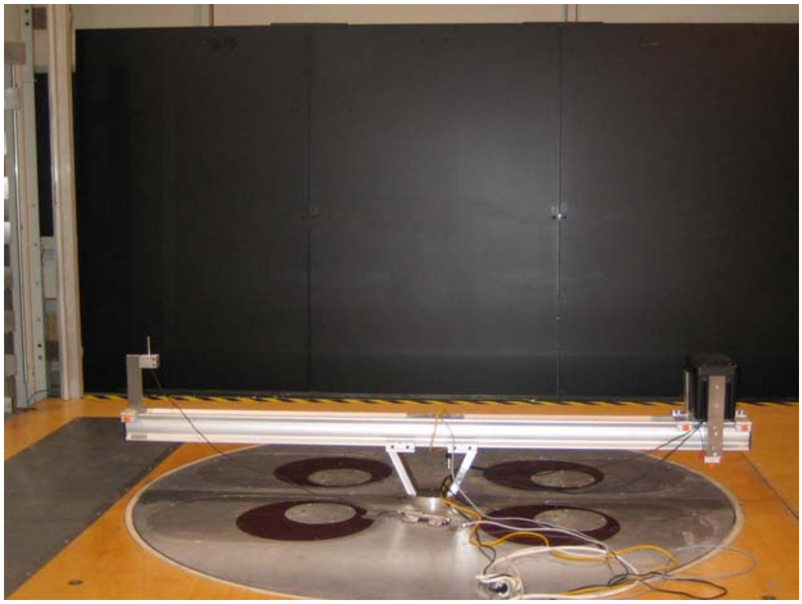

Fig 10: Futile Attempt for Reproduction in 2006 in a Very Noisy Wind Channel