The rotating mirror

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The rotating mirror

The 19th century physicist did not have our sophisticated electronic techniques to aid him in his research, but he devised ingenious and simple mechanical, electrical, and optical devices to allow him to examine and analyze phenomena. For example, the nineteenth century analogue of the oscilloscope was the rotating mirror. Both instruments are used frequently in two modes: studying repetitive events which are occurring too fast for the senses to follow, and measuring short intervals of time. This note will discuss the theory of the rotating mirror, and then show how it was used to measure the velocity of the electrical signal in wires, and the velocity of light. It will conclude with a description of the manometric flame apparatus which was developed for the analysis of sound waves.

The rotating mirror

Consider a mirror mn (Fig. 1) rotating about its axis. The observer is at o, and an event of very short duration (say a spark) takes place at a. The virtual image of the spark appears at a' on the circumference of the circle whose radius is ac. A short time later the event is repeated, and, since the mirror has turned, the new image is at a''. It is a straightforward geometrical proof to show that the arc of the event; the image sweeps around the circle at twice the rate at which the mirror is rotating. Once this rate is known, a calibrated time base is established. Finding the elapsed time between two or more events then becomes a matter of measuring the angle between successive images.

Measurement of short time intervals

The proposal of Charles Wheatstone (1802-1875) to use a rotating mirror to measure the velocity of a signal in a single-wire transmission line was announced by Faraday in 1830. In his 1834 paper, "An Account of some Experiments to measure the Velocity of Electricity and the duration of Electric Lights," Wheatstone described how he first attempted to study the duration of a spark passing between two spherical electrodes by observing the gap as it rotated. He then made the fundamental shift to the simpler and more general device of observing stationary sparks in a rotating mirror; the same mirror apparatus could be used in a number of experiments.

The rotating mirror was also used to examine the oscillations of a hydrogen flame burning in an upright glass tube. This experiment was later repeated by Tyndall in 1857.

Wheatstone's measurement of the velocity of electricity used a half-mile length of bare copper wire with spark gaps at the middle and at the ends. The rotating shaft on which the mirror was mounted was arranged to trigger discharges of a Leiden jar connected to the wire, and the mirror used to examine the resulting sparks at each of the three gaps. (Note the analogy with the triggering mechanism of the oscilloscope.) The angular displacement of the leading edges of the images of the sparks from each other (a maximum of a half degree of arc) was used to determine the time between sparks, and the velocity of the signal was found to be 288,000 miles per second. Later experiments reduced this figure to something below the velocity of light in air.
About 1835, Wheatstone proposed that a rotating mirror might be used to measure the velocity of light. In one scheme, light from a spark followed two paths to the rotating mirror and hence to the eye: one beam was direct, and the other was reflected from a distant mirror before returning to the revolving mirror. The time lag of the second beam relative to the first would be indicated by an angular displacement of the images of the two sparks. Once the extra distance traveled by the second beam was known, the velocity of light could then be calculated directly.

François Arago (1786-1853) in 1838 proposed an experiment, using a rotating mirror, to determine the relative velocities of light in air and water. This would provide a definitive comparison of the undulatory and wave models of light. This proposal was taken up by the gifted experimenter, Leon Foucault (1819-1868) in 1850. Foucault, using the apparatus shown schematically in Fig. 2, proved that the ratio of the velocity of light in air to that in water is $4/3$, which is consistent with the undulatory model.

In Fig. 2, sunlight from the left illuminates a thin wire, $o$, which serves as an object. Rays from the object pass through the achromatic lens $L$, and reflect from the plane mirror $m$. They then reflect from concave mirror $M$, and retrace their path. A diagonal glass plate at $V$ reflects part of the beam downward to eyepiece $P$, where the image of the wire is viewed by the eye. Mirror $m$ now starts to rotate, and at angular velocities of more than 30 rev/sec, the image is seen without flickering, and is shifted to the side. The velocity of light is found from the rotation rate of the mirror, and the lateral displacement of the image. Foucault repeated the experiment with the concave mirror at $M'$, causing the light to travel twice through a 3-m long water-filled tube.

The illustration is from Ganot’s Physics (1875), but it is identical (except for a reversal of black and white tones) with the one in the first edition of Silliman’s Physics (1858). The original owner of the copy of Silliman which I use has written in pencil in the margin by the description of Foucault’s work, “This is a recent determination.”

Observation of wave-shapes

In 1862, Rudolph Koenig (1832-1901) developed the manometric flame apparatus, which was used into the first decade of the 20th century to examine the wave-shapes of sounds. The diagram which Koenig published to illustrate his apparatus is reproduced as Fig. 3. The heart of the apparatus is the manometric capsule, shown in cross-section in the upper left-hand corner. The capsule, whose body is turned from wood, is divided into two halves by a thin, flexible membrane. Gas entering through the stopcock burns at the tip of the small orifice at the right; the flame is typically a centimeter or two high. Acoustic vibrations from a tuning fork, a siren, or any other source, are collected by the funnel, and the vibrations pass down the rubber tube where they impinge on the membrane, causing it to
oscillate. The vibrations of the membrane cause a periodic change in the supply of gas to the burner, and the flame oscillates up and down at the same frequency as the sound.

The oscillating flame is viewed in the rotating mirror, which spreads out the images of the flame, and also provides a time base for calculating the frequency of the oscillations. A pure frequency produces a series of images of the same height, similar to the upper two drawings in Fig. 4. The sound which produced the upper waveshape is half the frequency of the sound responsible for the lower waveshape.

Within limits, the manometric flame could also be used to make a Fourier analysis of a complex wave. For example, the waveshape which is second from the bottom in Fig. 4 is made up of a fundamental and a second harmonic, while the bottom waveshape was produced by a fundamental sounding simultaneously with a third harmonic.

Readers who wish to see a more extended account of the manometric flame should see the 1946 article by Stephenson and Schoepfle. I recently had the opportunity to examine the collection of historical scientific instruments at the College of Wooster (where Professor Stephenson taught for many years) and the three pieces of apparatus mentioned and illustrated in his article are still in a good state of preservation.

A modern application of the rotating mirror which is reminiscent of the manometric flame has recently (1970) been published by Kirschman. He describes the construction of a homemade “oscilloscope” which displays repetitive electrical signals by using them to drive a 6FG6 electron-ray tube. This tube, designed for use as a tuning indicator, has a fluorescent region whose height is proportional to the applied potential. The display is then viewed in the rotating mirror.

References

7. The collection of instruments at the Museum of History and Technology of the Smithsonian Institution has a Köenig capsule which is exactly like the one in the illustration: Köenig was also an instrument manufacturer.
10. Ref. 6, p. 225, Fig. 1 may also be found on p. 224 of Ganot.