ca. 1910

Ernst Mach

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CONTRIBUTIONS OF ERNST MACH TO FLUID MECHANICS[1]

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Often I am asked why the Ernst-Mach-Institut bears the name of a famous philosopher of the 19th century. The question is certainly justified, because my institute deals with research in experimental gas dynamics, ballistics, high-speed photography, and cinemaphotography. We are not in any way doing philosophical studies. In this article, I describe the contributions of Ernst Mach to experimental physics, especially to gas dynamics and ballistics, and thus not only explain our institute's name but also serve a great physicist's reputation for noteworthy discoveries in natural science.

1. ERNST MACH THE UNIVERSALIST

The wideness of Ernst Mach's intellectual world enabled him to influence many branches of physics and medicine, and, as we shall see, to relate his findings to philosophy and to strongly influence that branch of philosophy known as positivism.

One of the fields, for instance, in which he was especially interested, was the analysis of the human senses. By analyzing the sensations of bodily movement, he was the first to explain correctly the function of the labyrinth of the inner ear. In the course of his studies, he constructed a chair that could rotate about two perpendicular axes (see Figure 1), which is noticeably similar to modern devices for training astronauts.

During his investigations of the physiology of the human eye, he discovered a phenomenon of visual contrast that is today called "Mach bands."

[1]The author gratefully acknowledges the assistance of Prof. Raymond J. Emrich, Lehigh University, Bethlehem, Pa., in preparing and editing this article.

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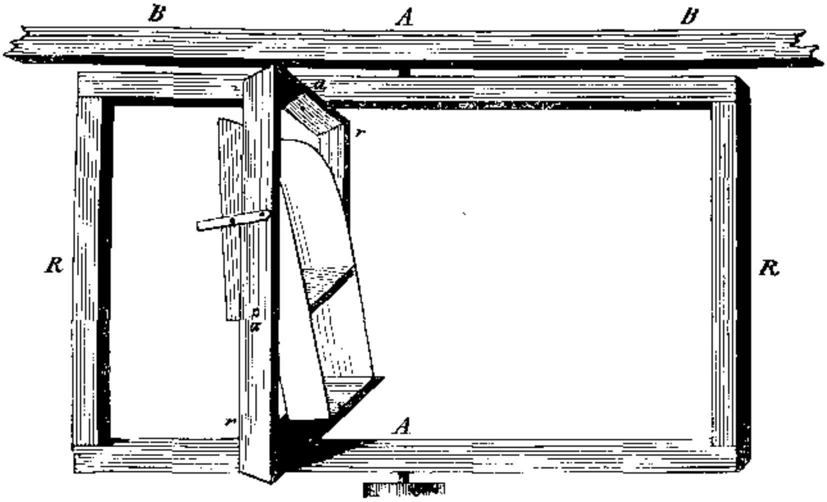


Figure 1 Mach's chair to study human sensations of movement (Mach 1875).

Mach was even more interested in epistemology than in the physiology of the senses, however, because he believed that things only existed if they could be perceived by the senses. The interaction between observer and observed object fascinated him especially. This interest also formed the basis of his critical analyses of the foundations of science.

It is well known that Mach's criticism of Newtonian mechanics and his proposal for relativistic mechanics provided the basis of Einstein's theory of gravitation and general relativity. In a letter of 1901, Einstein called himself a student of Mach. In his commemorative address on Ernst Mach, Einstein surmised that Mach could have stated the special theory of relativity fifty years earlier if physicists had taken more seriously the constancy of the speed of light experimentally evident at that time. It was also Einstein who introduced the name "Mach's principle" for the hypothesis that it is not Newton's *absolute space* but distant masses in the galaxies that form the origin of Coriolis and centrifugal forces.

Mach's epistemology has had enormous influence on science. His theory of knowledge originates in the principle of economy of thought. Following this principle, science must keep away from all metaphysical constructions. Natural laws are, for Mach, only useful abbreviations that make a repetition of measurements or calculations unnecessary.

2. MACH NUMBER

Today in the era of supersonic flight and space flight, the term "Mach number" has become a household word. Every schoolboy and schoolgirl indulges in the romance of flying at Mach 1 or Mach 2, or whatever his or her counting ability permits. It was, however, J. Ackeret (1929), in his thesis submitted for the certificate of *Habilitation*, who suggested calling the ratio of flow speed to local sound speed the Mach number:

$$M = v/a.$$

If one looks at a modern textbook on aerodynamics or gas dynamics, the name Mach appears also in "Mach angle," "Mach wave," and "Mach reflection." Ernst Mach carried out the fundamental research explaining and defining these terms. He can properly be considered the originator of supersonic aerodynamics.

He was also innovative in his pioneering work in ballistics and in ballistic measurement technique. He detected and visualized the bow shock wave in front of a projectile moving with speed higher than the speed of sound.

It was more than a hundred years ago that Ernst Mach found the essential difference between subsonic and supersonic flight speeds. He was first to recognize the real nature of shock waves in air and to study their reflection from boundaries and from other shock waves. He was also first to recognize what the various gas elements are doing as they emerge from a supersonic nozzle and encounter the shock fronts that are needed to accommodate the surrounding gas to the jet. To carry out these studies, Mach had to invent new experimental techniques such as trigger events, delay circuits, and time-interval measurements at a time when even the electron tube had not yet been invented.

Mach's experimental work should not be considered in isolation from his philosophy and his whole life's work. His experimental methods exemplify his philosophy, for many of the phenomena he investigated are not visible with the naked eye. By means of new experimental techniques, he made physical processes perceptible to the human senses, and found, in many cases, a correct physical interpretation. He practiced what he preached.

3. A SKETCH OF MACH'S LIFE

Ernst Mach was born on 18 February 1838 in Chirlitz-Turas, Moravia, not far from Vienna, Austria. His father, Johann Mach, was tutor for the family of Baron Breton. He had studied philosophy at Prague and was interested in animal psychology and in agriculture. One of his achievements was starting silkworm culture in Europe. Ernst inherited his stubborn personality from his father.

Josephine Mach (*nee* Langhans), Ernst's mother, was artistic, having a talent for music, drawing, and poetry. Both parents were idealistic and solitary people.

Mach described himself as a "weak pitiful child who developed very slowly." At the age of ten, he entered the lowest class of a classical secondary school (*Gymnasium*) directed by Benedictine monks, but his intellect and temperament were not well suited to such an education. He had not the slightest taste for Latin and Greek. The clerical teachers found the boy to be "very much without talent" and "unfit for study." They advised his father to let him learn a trade or business. Like many original thinkers, Ernst Mach found no purpose in the meaningless parroting of facts. He preferred to try to discover for himself the origins and causes of things.

Disappointed with his son's failure, Mach's father resumed teaching him Latin, Greek, history, algebra, and geometry at home.

After the suppression of the revolution of 1848, Austria entered a reactionary clerical period. Mach's liberal family thought for a time of emigrating to America, and Ernst asked permission to learn a trade to be able to earn money in the New World. For two years he was apprenticed to a cabinet maker in a neighboring village. This was a pleasant period in his life, since he always enjoyed making things with his own hands. But in the end, the family remained in Austria.

In 1853, when he was fifteen, Mach entered the sixth class of the *Gymnasium* at Kremsier in Moravia, also directed by monks. He finished his studies two years later, and wrote afterwards, "I passed the examination only by pure chance."

In the same year, at the age of seventeen, he went to the university in Vienna to study mathematics and physics. Mathematics and natural sciences were rather poorly represented there, but Mach found the philosophy, philology, and history teaching to his liking. One wonders if this, combined with the inspiration of reading Kant's *Prolegomena to Any Further Metaphysics* and the early education by his father, is the reason for the antimetaphysical direction of Mach's thoughts and his special interest in physics, psychophysiology, and epistemology.

At the age of twenty-two, Mach took the degree Doctor of Philosophy with a thesis titled "On Electrical Discharge and Induction." In 1861, he qualified as *Privatdozent* in physics at the University of Vienna. His first lectures were "Physics for Medical Students" and "Advanced Physiological Physics."

In 1864, at the age of twenty-six, Mach was appointed to the chair of mathematics at the University of Graz. Incidentally he was considering at the same time accepting the chair in surgery at the University of

Salzburg. In 1867, Mach became Professor of Experimental Physics at the German University of Prague. Here he spent twenty-eight prolific years.

Important critical and historical books and papers were written in this period: *History and Root of the Principle of the Conservation of Energy*; *The Science of Mechanics*; *The Analysis of Sensations and the Relation of the Physical to the Psychical*; *Studies of Flying Projectiles*.

In 1895 Mach was appointed to a chair in Vienna created for him in "philosophy, especially the history and theory of the inductive sciences." In Vienna he published "Principles of Heat," a critical account of the science of heat.

In 1898 Mach suffered a paralytic stroke. His right side was paralyzed, but fortunately he remained mentally alert. Even after his illness he finished the book *Perception and Error*.

In 1901 he finished his active career. In the same year, Emperor Franz Joseph appointed Mach a member of the Austrian *Herrenhaus*, but Mach refused to be ennobled. For him only science was nobility.

In 1913 Mach moved to Vaterstetten near Munich to live with his son Ludwig. Together they worked on his last major book, *The Principles of Physical Optics*. However, he could not finish this work. The volume was first published in 1921.

Mach died one day after his seventy-eight birthday, on 19 February 1916.

By this short sketch of his life, we see that Ernst Mach belonged to an era where universality and broad education were a matter of course for a scientist. He was among the great scholars who had the privilege of actively searching for and assessing the wealth of scientific knowledge appearing in many fields in his time.

Many books and articles have been written about the personality of Ernst Mach. Most of these have analyzed and criticized the importance of his contribution to the fundamentals of science and the philosophical value of his work. Unfortunately most publications, with some exceptions (Merzkirch 1966, 1970, Kutterer 1966), barely mention his research in gas dynamics and other parts of experimental physics.

Let us now pick out some examples of his experimental contributions to physics, especially to gas dynamics and ballistics.

4. DOPPLER EFFECT

When he was only a twenty-two-year-old student, Mach contributed to the understanding of the Doppler effect. Christian Doppler (1803–1853), *Assistent* at the Polytechnic Institute in Vienna, observed in 1841 that at the approach of a whistling train a stationary observer hears a higher frequency sound than the natural tone of the whistle, and then hears a lower frequency after the train has passed.

Doppler's discovery, however, was not appreciated at the time, as he had included some untenable ideas about the color of stars. In particular, the respected Viennese mathematician Petzval, famous for his work in photographic optics, did not accept Doppler's discovery and explanation. Together with the astronomer Mädler, he quarreled with Doppler for years (Herrmann 1966). Ernst Mach was successful in producing the Doppler effect in the laboratory by means of a simple piece of apparatus and in demonstrating the correctness of Doppler's formula for the dependence of the sound-wave frequency on the movement of the source. This report was published in 1860 under the title "On the Change of Color and Tone by Movement" (Mach 1860). Here he acknowledged the correctness of Doppler's interpretation and disproved Petzval's theory (Mach 1861). Obviously, Mach, even in his youth, was more respectful of facts than of authority.

In order to make the change in the received frequency audible, Mach constructed the device shown in Figure 2. A 1.8-m rod A-A' turns in bearings C-C' about axis B-B'. A hole F bored in A and connecting through B' and C' to bellows H supplies air to whistle G of known frequency f. The arm A-A' is rotated by a cord passing over pulley D. An observer standing in the plane of rotation of the whistle hears a frequency f' alternately higher and lower than f as the whistle approaches and recedes. Mach reported that the amount of the frequency change clearly depends on the whistle speed.

Some years later in Prague, Mach initiated further experiments to test the correctness of the Doppler formulas (Mach 1878a). Our institute has two hand-written documents in which it is mentioned that Ernst Mach was present, with some colleagues, at an experiment conducted with two trolley cars passing on adjoining rail tracks. On one car was a whistle, and on the other were the observers. In a second experiment, the observers stood near the track and listened as the trolley with the whistle passed. Those present certified by signature on the documents that in the second case they perceived a smaller Doppler frequency shift than in the first.

Concerning the astronomical consequences of the Doppler effect, Mach proposed to analyze the spectrum of a star and to determine the speed of the star from the displacement of the spectral lines (Mach 1878a). Mach informed Kirchhoff of this idea. In a reply letter of October 1860, of which we have the original, Kirchhoff shares Mach's

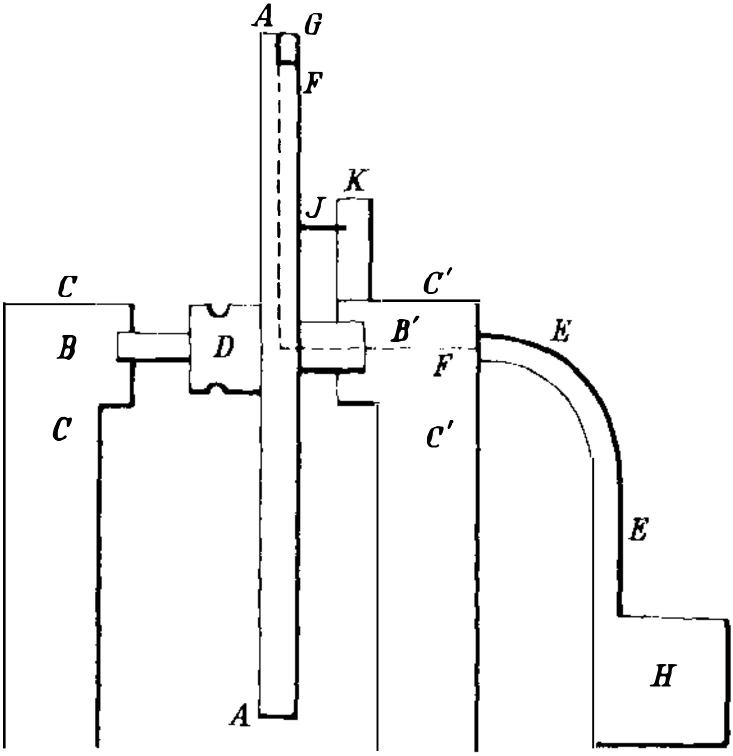


Figure 2 Mach's device to illustrate and explain the Doppler effect (Mach 1860).

opinion that by study of the spectrum one can determine the motion of the source. Kirchhoff points out that the spectra of sodium and magnesium have characteristic lines that could be easily identified in a shifted recording. No doubt Mach was one of the pioneers in spectral astronomy.

5. WAVES GENERATED BY ELECTRIC-SPARK DISCHARGES

One sound source Mach used for his physiological and physical studies in acoustics was the electric spark (Mach & Fischer 1873). He was quite interested to learn from his assistant Dvorak of a publication by K. Antolik (1875) that dealt with acoustic phenomena of spark discharges. Inspired by the work of Antolik, a Hungarian high school teacher, a number of experimental studies (Mach & Wosyka 1875, Mach & Sommer 1877, Mach et al. 1878, Mach 1878b, Mach & Grüss 1878, Mach & von

Weltrubsky 1878, Mach & Simonides 1879, Mach & Wentzel 1885) were made during the years 1875 to 1885 at the Prague Physical Institute. In addition to the development of ingenious experimental methods, two significant advances in shock wave physics were made, namely (*a*) the elucidation of the properties of propagating shock waves in air, and (*b*) the discovery of the irregular reflection of shocks.

The experimental procedure was to detect the air motion induced by shock waves reflecting from a sooty glass plate. A thin layer of soot is deposited on a glass plate by holding it over a smoky flame, such as a candle. The glass plate is laid on a table, soot side up, and above it two small spark discharges are produced simultaneously. Figure 3 is a drawing of successive positions of the shock fronts as they reflect from the

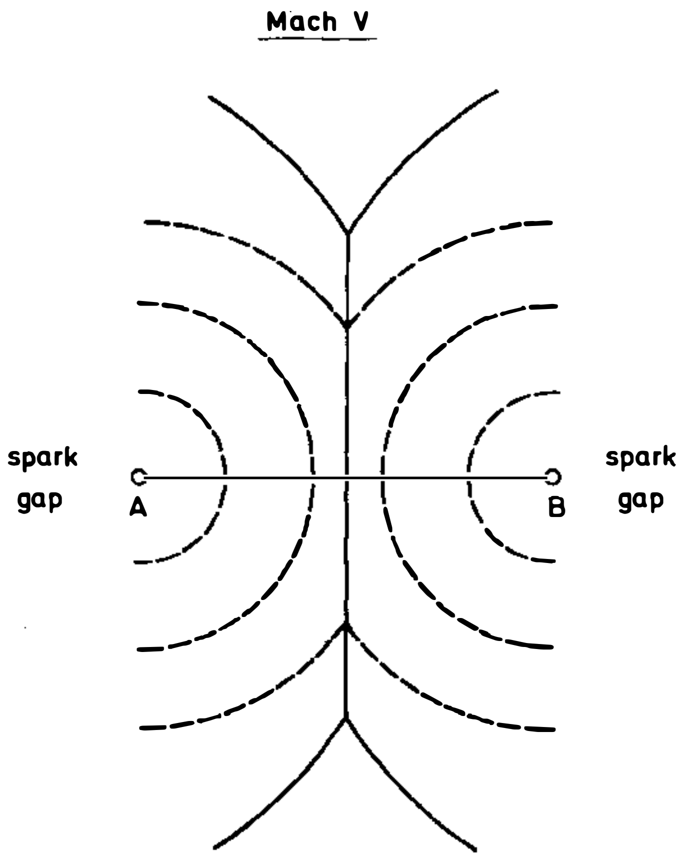


Figure 3 Schematic drawing of shock fronts and the trace of their reflection left on a sooty plate (Mach 1878b).

plate surface (*dashed lines*) and the trace of their mutual reflection from each other (*solid lines*). As the separate shocks reflect from the glass surface, the air next to the surface is put into motion and the soot is blown off; however, when two equal shocks moving oppositely mutually reflect from each other and the surface, the gas next to the surface remains at rest and the soot is not removed.

This explains the straight line marking the plane of symmetry of the two explosions. But beyond a certain point, the soot line diverges into two branches and forms a "V" at each end, the so-called Mach-V. This unexpected result, which Mach called irregular reflection, is today called Mach reflection.

Recently I duplicated this experiment. A photograph of the sooted plate after the two shock waves met and reflected from it appears in Figure 4.

In addition to various spark gaps, exploding wires were used as sources of shock waves by Mach. A straight fine wire absorbs the electrical energy stored in a capacitor, raising the wire's temperature and pressure in a very short time, so that a finite pressure wave propagates out from a line. Figure 5*a* illustrates an arrangement with a wire forming an angle so that two cylindrical shocks start out from the exploded wire and their intersection can be studied. The capacitor—a Leyden jar—was charged in Mach's experiments by a hand-operated influence machine until the spark gap fired, thus closing the circuit. Most of the stored electrical

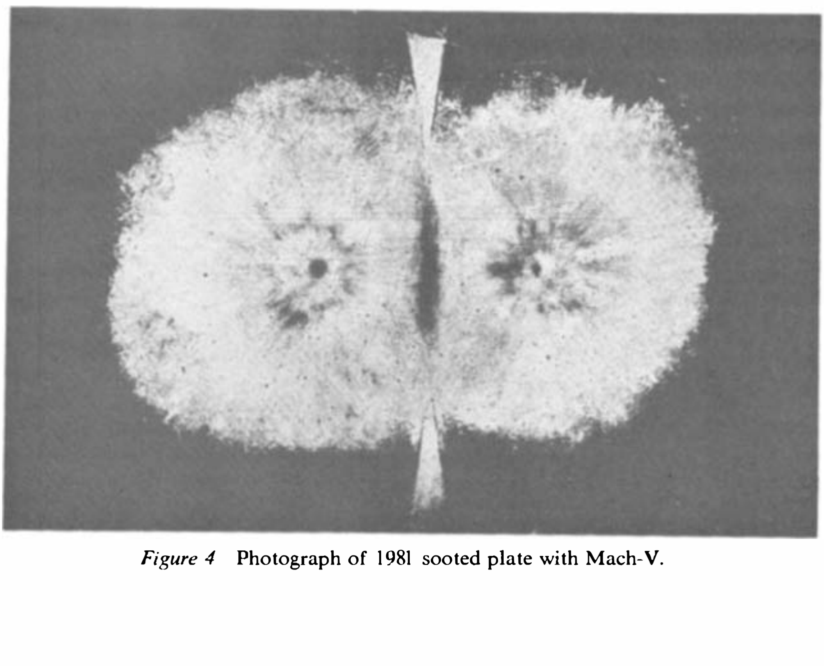
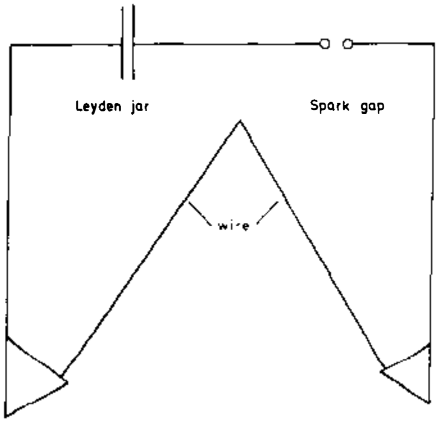


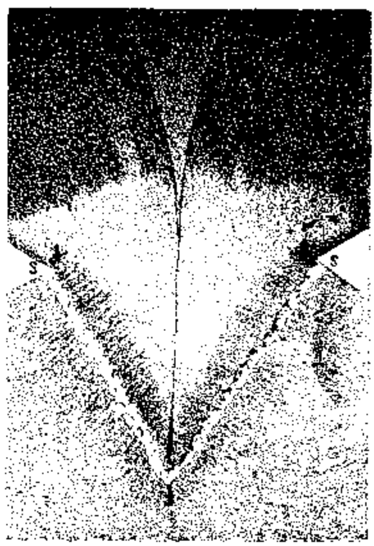
Figure 4 Photograph of 1981 sooted plate with Mach-V.

energy was delivered to the wire. A sooted glass plate below the wire revealed the intersection of the shock waves produced and the Mach-V into which the line of intersection bifurcated. This can be seen in Figure 5*b*, which is an original photograph by Ernst Mach.

Antolik was convinced one could learn from such soot patterns something about the features of the electric discharge. Mach realized very



a



b

Figure 5 Study of two cylindrical shock waves meeting at an angle. (*a*) Exploding wire circuit; (*b*) Mach's photograph of the sooted plate beneath the exploded angle wire (Mach & Wosyka 1875).

early that it was not electrical phenomena but mechanical-acoustical phenomena that were revealed by the soot patterns. Two small, simultaneous chemical explosions at points *A* and *B* (see Figure 3) give the same soot pattern as the discharge of two spark gaps.

Mach and his colleagues were successful in gathering speed-distance data on the wave-front progression from a spark discharge by use of a rotating disk chronograph (Mach et al. 1878). Two channels, *ab* and *ac*, were bored in a wooden block *P*, down which pulses were started simultaneously by discharge of a spark at *a*, as shown in Figure 6. The spark was produced between electrodes *EE* and confined with cover plate *D*. At the outlet of the channels *b* and *c*, a rotating, circular sooted plate detected the arrivals of the pulses. The speed of rotation of the sooted disk was adjusted until it was synchronized audibly with a 63.05-Hz tuning fork. The difference in the arrival times at the sooted disk was determined by the angular displacement of the marks relative to calibration marks impressed on the disk at rest.

By extending the lengths of the channels in thicker blocks, successive additional travel times were determined, so that a composite speed-distance curve of the wave-front propagation could be constructed. Figure 7 shows the results of these measurements. Near the source, a blast wave such as is produced by a spark differs considerably in its propagation speed from an acoustic wave, i.e. a small-amplitude wave. Mach concluded that the spark-produced wave is a compression wave of finite amplitude. He writes (Mach & Sommer 1877):

> It does not contradict the theory [of sound] to assume that the speed of sound is independent of the amplitude. But this is not valid for oscillations of finite amplitude

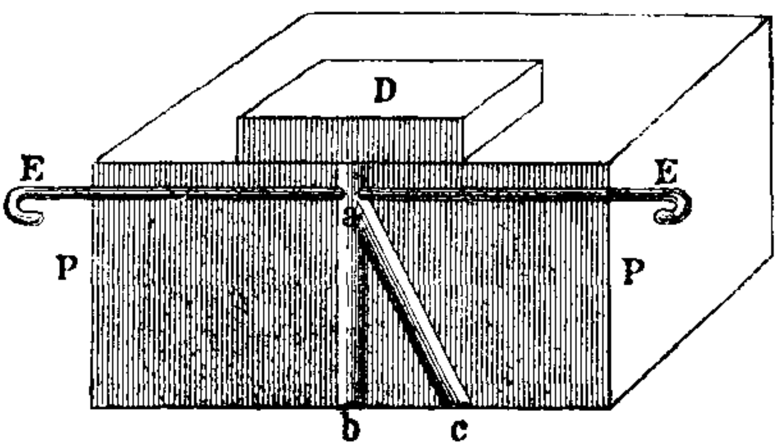


Figure 6 Apparatus for measuring travel times of a blast wave (Mach et al. 1878).

as has been shown by Riemann, 1860. Speed of sound has, for finite amplitudes, a quite different meaning; it is different at different places in the wave and alters during the wave motion. It appears that we deal in our experiments with such waves as are described by Riemann.

Although Mach clearly recognized that the spark-produced wave is different from a sound wave, he did not employ the expression "shock wave" (*Stosswelle*).

Mach obtained other quantitative results on spark-produced blast waves while photographing them with a Jamin interferometer. A reproduction of his results published in 1878 can be seen in Figure 8. The relative density change is about 50 times the change that Toepler, Boltzmann, and Mach himself had measured in the sound wave from a whistle.

We may remark at this point that Ernst Mach later developed, with his son Ludwig, a modification of the Jamin interferometer that has been widely used for aerodynamic studies. As seen in Figure 9, the Mach-

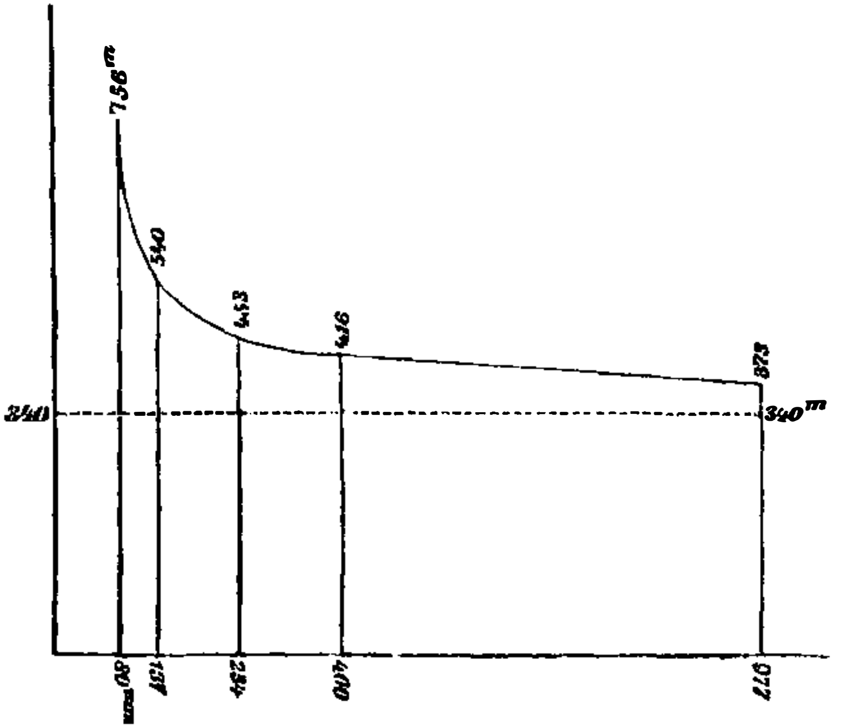


Figure 7 Distance dependence of speed of wavefront produced by spark discharge (Mach et al. 1878).

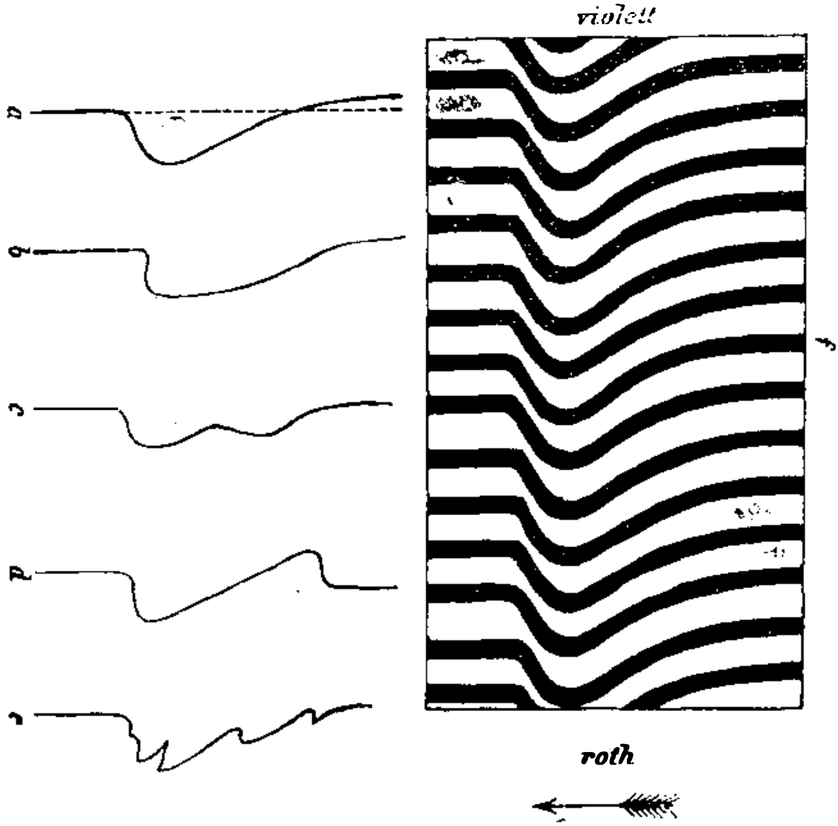


Figure 8 Density profiles in a blast wave as obtained from a Jamin interferogram (Mach & von Weltrubsky 1878).

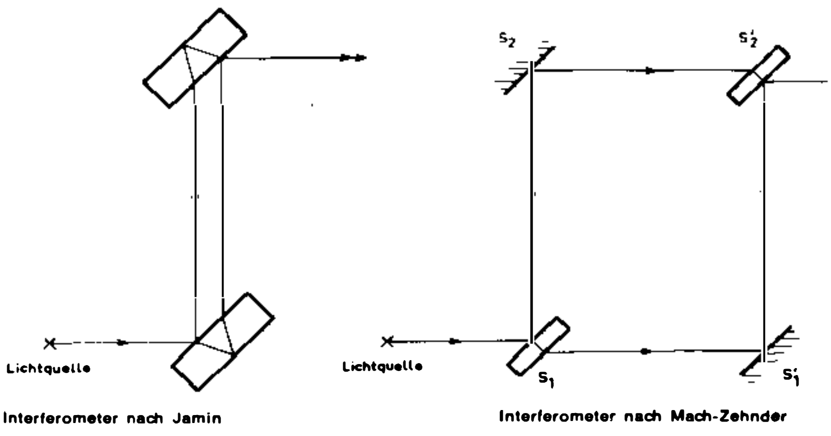


Figure 9 Jamin and Mach-Zehnder interferometers.

Zehnder modification, with four optically flat glass plates instead of two, permits an arbitrarily great separation of the coherent beams, thus furnishing a large field of view.

As well as recognizing the greater speed of propagation of shock waves, Mach's studies in the 1870s with sooted plates gave other information on the physical properties of shock waves. When he mounted a second glass plate over and parallel to the sooted plate, Mach observed that a cylindrical wave is converted into a plane wave as it propagates in the channel formed by the two plates (Mach & Grüss 1878). The arrangement has features of the present-day shock tube with electric driver.[2]

By interpretation of a number of experiments such as the ones described, Mach succeeded in giving the correct gas-dynamic interpretation of the Mach-V and thus of the criteria for the occurrence of irregular Mach reflection of shock waves. By examination of the reflected light from the sooted plate, Mach surmised that in the flow after the Mach-V the pressure is higher than in the flow behind the regular reflection. But how could Mach demonstrate the existence of a more intense wave after irregular reflection?

Mach used the arrangement shown in Figure 10. A straight wire source *i-g* and an angle wire source *b-c-d* are initiated by discharge of separate capacitors. A time delay between the explosions is varied in successive "exposures" of sooted plates, giving the intersection patterns traced in Figure 10.

These intersection paths give a lot of information about the propagation of the colliding cylindrical waves emanating from the two arms of the angle wire. The successive patterns, recorded when the counter-moving waves intersect, depict in a rough way successive shapes in time of the colliding cylindrical waves as they propagate away from the angle wire. It is almost as if we have snapshots of the wave front reflecting obliquely from a rigid boundary represented by the line of symmetry leaving *c* and bisecting *i-g* in Figure 10.[3] If we think of the incident wave reflecting from a rigid boundary, after the Mach-V forms we can pick out the incident shock and the reflected shock meeting at the triple point, and a new wave appears that is today called a "Mach stem." Furthermore, the trace of the triple point appears in Figure 10 and coincides

[2] The modern shock tube is described in a number of books and articles. See, for example, Bershader (1981).

[3] The traces sketched in Figure 10 are not truly snapshots of the wave front(s), because the counter-moving wave from *i-g* does not intersect with the wave system under study at all places at the same instant.

with the edge of the Mach-V, which appears so clearly in the original soot-plate experiments. (See Figures 4 and 5.)

Nowadays, by using modern apparatus, particularly the shock tube (Bleakney et al. 1949), the phenomenon of Mach reflection can be even more directly demonstrated photographically. Figure 11 is an example. It was only in 1944 that R. J. Seeger (Keenan & Seeger 1944) named the irregular oblique reflection of shock waves "Mach reflection."

How did Mach interpret the kind of reflection he discovered? He knew that waves of very small amplitude, i.e. sound waves, can pass through one another without being influenced by the meeting. When waves of finite amplitude intersect, however, the intersection becomes the starting point of a new wave, as illustrated in Figure 12. As the primary waves propagate, the angle α between their normals grows smaller and the new wave's speed must become larger in order to keep up with the point of intersection. When the speed w must be greater than $V/(\cos\alpha/2)$, the reflection is no longer regular, and irregular reflection with a Mach stem must occur. More than 100 years ago, Mach stated this criterion that allowed a computation of the limiting angle α_g. Below this limiting angle, regular reflection should not be possible. α_g is a function of the shock strength, because the speeds w and V depend on the shock strength. Actually the criterion for the start of Mach reflection is even today not

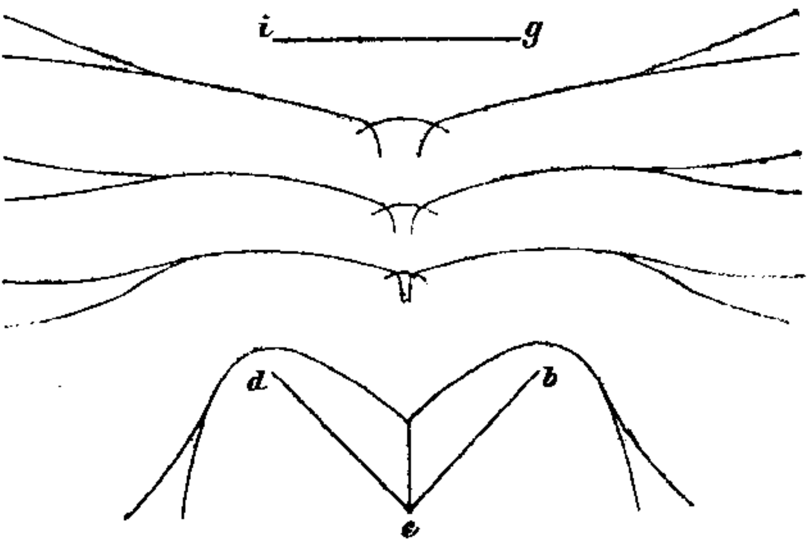


Figure 10 Sketch of intersection patterns of blast waves from a straight wire source and an angle wire source exploded at varying time delays (Mach 1878b). See text for explanation of symbols.

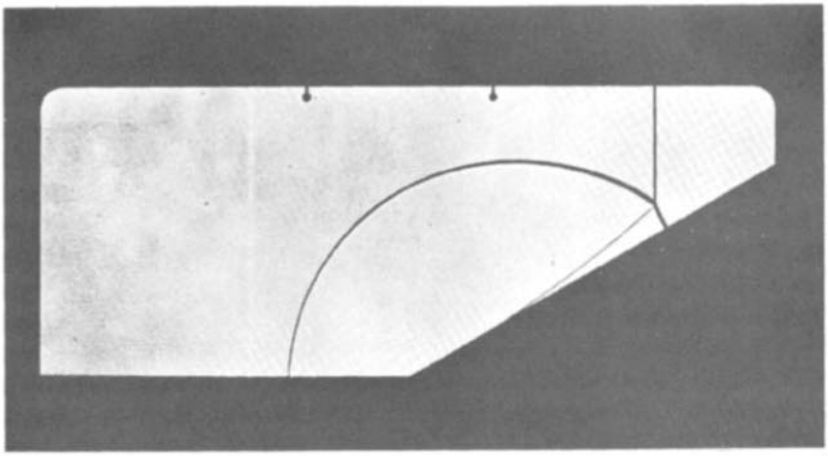


Figure 11 Snapshot with schlieren optics through shock tube windows of Mach reflection. A plane shock traveling to the right has met a sloping floor. The reflected shock is curved and intersects the incident shock at the triple point. The Mach stem extends from the triple point to the wall. The fourth line emanating from the triple point is not a shock but a contact surface separating gases with the same pressure but different entropies and densities.

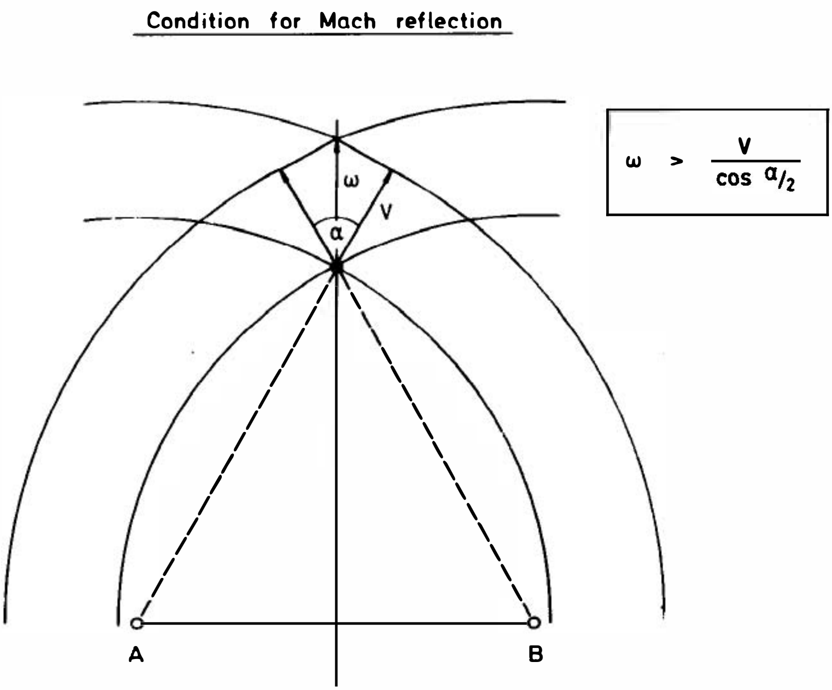


Figure 12 Cross-sectional drawing of two intersecting cylindrical waves from sources *A* and *B*. The wavefronts are shown at two positions reached a small time apart. A new wave starts and spreads continually from the intersection with speed *w*. The criterion for the start of Mach reflection is given by the formula (Mach 1878b).

completely clear in detail, and research is continuing (Whitham 1957, Ben Dor et al. 1980).

It is remarkable that Mach, without the help of apparatus that could give him pictures such as Figure 11, discovered the irregular reflection of shock waves merely by interpretation of soot patterns. It seems curious, on the other hand, that he was concurrently engaged in the first optical recording of blast waves using the Toepler schlieren method. The experimental problem consisted in producing the exact time delay between the spark discharge generating the blast wave and the spark discharge photographing the front of the blast wave. Electronic circuits did not exist; the electron tube had not yet been invented.

6. ELECTRIC DELAY CIRCUIT

Mach experimented with different arrangements of Leyden jars. One of these circuits (Mach & Grüss 1878), which worked well as an adjustable delay circuit, is shown in Figure 13. In Mach's circuit, the capacitor *A* is charged by an influence machine until the breakdown voltage of spark gap I is exceeded. Upon the discharge closing the circuit at I, the charge on *A* is shared with *B* and a blast wave emanates from I. By varying the resistance between *B* and *C*, the time for *C* to charge to the breakdown voltage of spark gap II can be varied. Spark gap II is the light source for photographing the blast wave generated at I. Mach used a thin, water-filled tube as resistor, varying the immersion depth of the electrodes.

A schlieren photograph made with this arrangement is shown in Figure 14. The resolution in this 100-year-old picture is not as good as one using

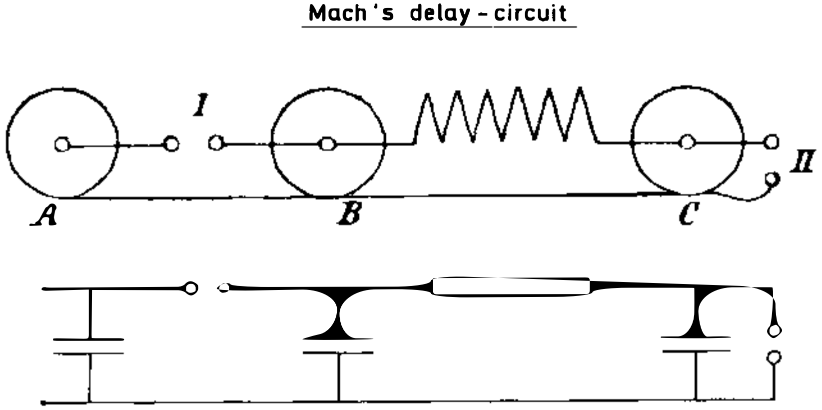


Figure 13 Mach's delay circuit (Mach & Grüss 1878). (*Below*) Same circuit in modern symbols.

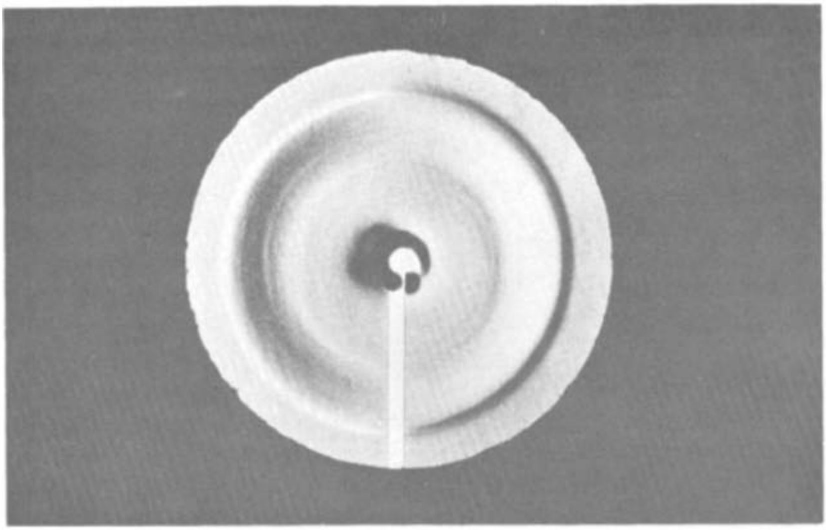


Figure 14 Schlicren photograph of blast wave emanating from spark gap at center (Castner 1892).

modern, high-speed electronic circuits and modern lenses and photographic film, but all features of interest are evident.

7. BALLISTIC EXPERIMENTS

In view of his having been the developer of the spark light source and delay circuits, it is not surprising that Ernst Mach performed the first basic experiments leading to the visualization of projectiles in flight. It is interesting how Mach himself describes his motivation in undertaking ballistic experiments. In a lecture in 1897 (Mach 1923), he told his audience:

> In the year 1881 I heard a lecture by the Belgian ballistician Melsens. He proposed that high speed projectiles push a considerable mass of compressed air ahead of them. In Melsen's opinion the compressed air may cause mechanical, explosion-like effects on the body it strikes. I wanted to investigate this idea experimentally and to make the processes perceptible, if they exist. My desire to do so was the more intense because all the means were available. I had previously used and tested them in other experiments.

It was his idea to photograph a high-speed projectile in flight in a darkened room by means of an electric spark of extremely short duration. The spark should be both light source and shutter. For detection of the compressed gas ahead of the projectile, the Toepler schlieren method was appropriate.

The first successful photographs of projectiles were made in 1886 by P. Salcher and S. Riegler, following Mach's suggestions. Salcher was a professor at the Naval Academy at Fiume (today, Rijeka, Yugoslavia). In the same year, Mach and Salcher described the event to the Vienna Academy. The leading page of the publication appears in Figure 15; this is a reproduction from Mach's personal bound volume of the academy proceedings. The two photographic prints—probably the oldest existing pictures of the bow wave ahead of a supersonic object—were apparently glued onto the page by Mach himself. This document can be considered as the beginning of the field of supersonic aerodynamics.

Intense discussion between Salcher and Mach took place by mail. Salcher reported the progress of the work weekly. In our library are 140 letters from Salcher, the first one written 14 February 1885. Unfortunately Mach's letters have never been located; from reading just one side of the correspondence, one can judge that Mach must have suggested tests and answered Salcher's questions. The first photographs that Salcher made of supersonic bullets displayed the characteristic bow wave. In his letter to Ernst Mach dated 23 May 1886, Salcher sketched what he saw in the photographs. This sketch is shown in Figure 16. To one familiar with the physics of shock waves, it is obvious how familiar Mach already was with these new supersonic phenomena. He interpreted the bow wave at once as the envelope of disturbances originating from the projectile, and he supposed it to be a shock front. Figure 17 displays the well-known construction illustrating the idea. The sine of the half-angle of the vertex of the cone is the ratio of the sound speed to the projectile speed, i.e. the reciprocal of the Mach number.

Two unsolved ballistics problems of that time could be answered by knowing of the existence of the bow shock ahead of a supersonic projectile.

Artillerists knew that two bangs could be heard downrange from a gun when high-speed projectiles were fired, but only one from low-speed projectiles. It was realized that in addition to the bang from the muzzle of the gun, an observer downrange would hear the arrival of the bow shock.

The second problem can be traced back to the Franco-Prussian war of 1870–1871. It was found that the new French Chassepôt high-speed bullets caused big crater-shaped wounds. The French were suspected of having used explosive projectiles and therefore of having violated the International Treaty of Petersburg prohibiting the use of explosive projectiles. As mentioned earlier, the Belgian Melsens had tried to refute the suspicion. Mach now gave the complete and correct explanation. The explosive type wounds were caused by the high-pressure air between the bullet's bow wave and the bullet itself.

Kaiserliche Akademie der Wissenschaften in Wien.

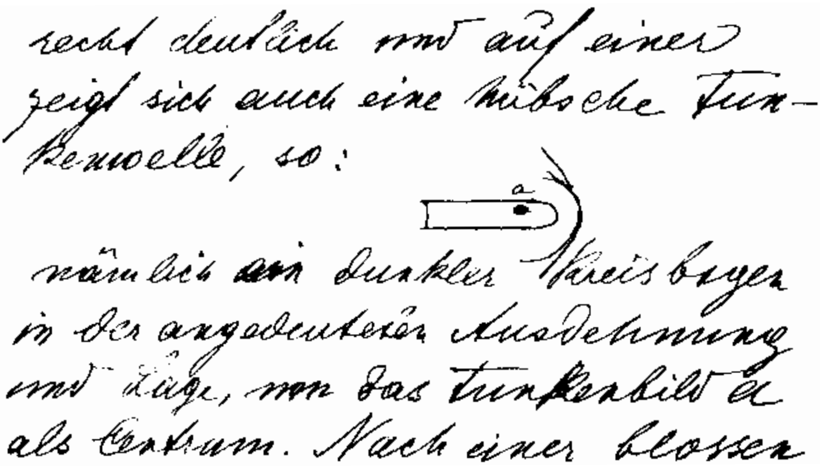
Sitzung der mathematisch-naturwissenschaftlichen Classe vom 10. Juni 1886.

(Sonderabdruck aus dem akademischen Anzeiger Nr. XV.)

Das w. M. Herr Regierungsrath Prof. E. **Mach** in Prag übersendet ~~folgende~~ vorläufige Mittheilung: „**Über die Abbildung der von Projectilen mitgeführten Luftmasse durch Momentphotographie.**"

Auf **Mach's** Bitte haben die Herren Professoren Dr. P. **Salcher** und S. **Riegler** in Fiume einen von **Mach** und **Wentzel** mit negativem Erfolg ausgeführten Versuch (Vergl. Akadem. Anzeiger 1884, Nr. XV und Sitzungsberichte 1885, Bd. 92, II. Abth., S. 636) mit **grösseren** Projectilen und **grösseren** Geschwindigkeiten (Infanteriegewehr, 11 Mm. Geschoss, 440 M. Geschwindigkeit) wiederholt, und haben das Resultat mit voller Schärfe erzielt. Die Luftmasse erscheint als ein das Projectil einhüllendes Rotationshyperboloïd, dessen Achse in der Flugbahn liegt. An den Bildern zeigen sich noch manche Einzelheiten, deren sichere Interpretation sich auf weitere Versuche gründen muss.

Figure 15 Reproduction of Mach's personal copy of the publication announcing the first successful photograph of a supersonic projectile in flight. The photographic prints were probably affixed by Mach himself.



recht deutlich und auf einer
zeigt sich auch eine hübsche Fun-
kenwelle, so:

nämlich ein dunkler Kreisbogen
in der angedeuteten Ausdehnung
und Lage, um das Funkenbild a
als Centrum. Nach einer blossen

Figure 16 Sketch of bullet and its bow shock in Salcher's letter to Mach.

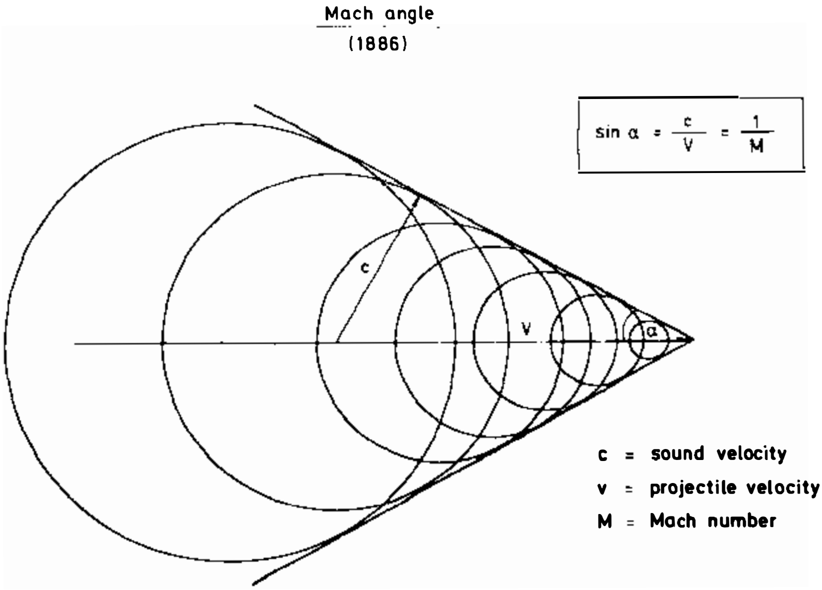


Figure 17 Concept of "Mach angle," 1886 (Mach 1923).

Photographing of bullets in flight was continued by Salcher in Pola, Yugoslavia, and by Mach in Meppen, the ballistic range of the Krupp Steel Company. More details became visible, e.g. the Mach lines originating from the rough projectile surface, and the turbulent wake pattern behind the body. Mach gave the explanations for these (Mach & Salcher 1887, 1889a). Figure 18 shows the sketch of Mach lines in a letter from Salcher dated 21 May 1886. More details are in letters dated 26 June 1886, 31 March 1888, and 25 January 1889.

After Ernst and Ludwig Mach developed the interferometer to increase the amount of information beyond that obtained from Toepler schlieren photographs, they presented quantitative data on the change in density and pressure of the air behind the bow shock. One of the first photographs is shown in Figure 19.

The experimental arrangement giving such excellent photographs of supersonic projectiles in the 1880s may be of interest. An illustration in an 1889 publication is reproduced in Figure 20. A hand-cranked influence machine served as the high-voltage source. This machine had to be disconnected from the capacitor, a Leyden jar, after the capacitor received the required charge, and the trigger and spark-gap light source had to be connected to it. Moreover, the camera shutter had to be opened, the gun had to be fired, and finally the camera shutter had to be closed after the projectile arrived and triggered the spark light source.

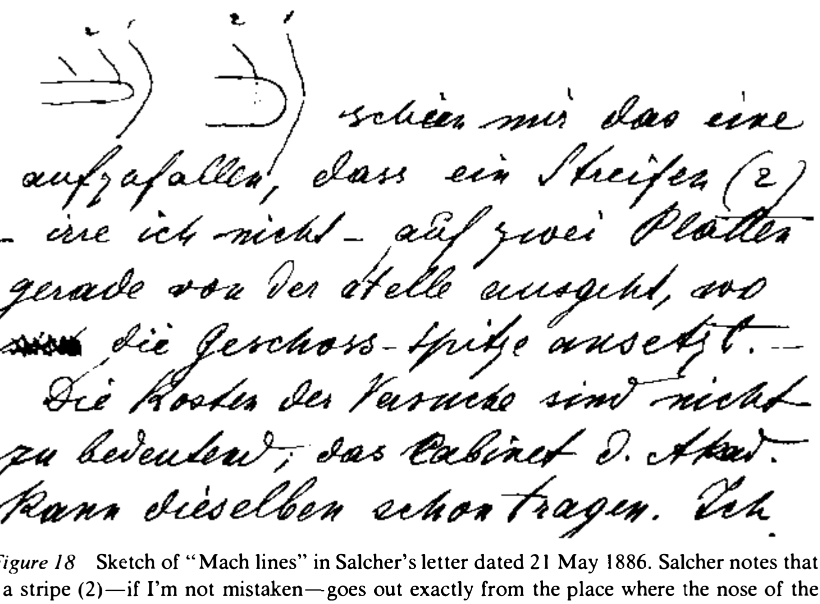

schien mir das eine aufzufallen, dass ein Streifen (2) – irre ich nicht – auf zwei Platten gerade von der Stelle ausgeht, wo die Geschoss-Spitze ansetzt. — Die Kosten der Versuche sind nicht zu bedeutend; das Cabinet d. Akad. kann dieselben schon tragen. Ich

Figure 18 Sketch of "Mach lines" in Salcher's letter dated 21 May 1886. Salcher notes that "a stripe (2)—if I'm not mistaken—goes out exactly from the place where the nose of the bullet begins."

Figure 19 Interferogram of flow field around a supersonic projectile (Mach 1923).

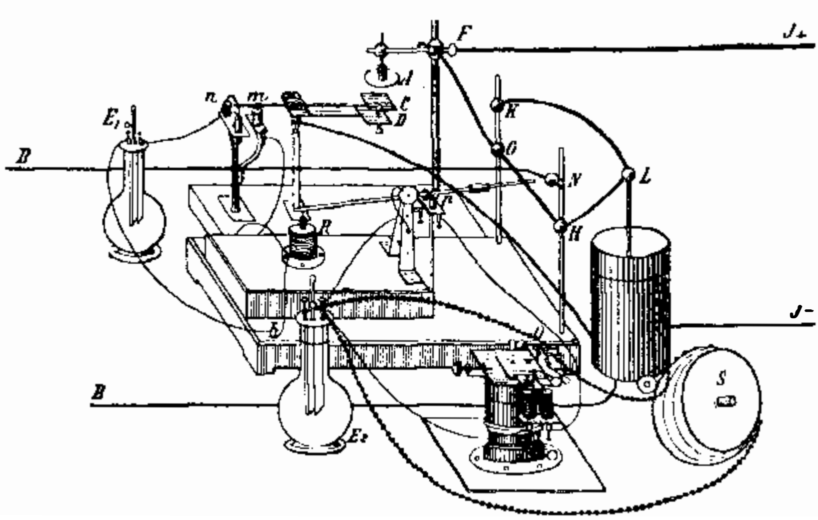


Figure 20 Illustration of experimental arrangement used by Mach in photographing projectiles in flight at Meppen (Mach 1889, Mach & Salcher 1889a).

Referring to Figure 21, in which Mach's circuit is presented in terms of today's symbols, the capacitor *L* is charged to a predetermined voltage by influence machine $J-J+$. The voltage is determined by the weight applied to the vane electrometer *ACD*; The vane *C* is attracted more strongly to *A* as the voltage of *A* rises, and when the attraction reaches the desired value, contact *n* closes, exciting relay *R* which switches the capacitor *L* from the influence machine to the light source gap and the trigger gap *B*. The relay *R* also closes contact *p* so that the camera shutter and igniter of the gun are triggered.

Parenthetically, I should like to remark that Mach was a very cautious experimenter. In connection with the procedures at the firing site where these photographs were made, he wanted to avoid any chance of unintentional firing, and introduced the following precaution: Instead of the relay actually firing the gun, it rang a bell. Upon hearing the bell, an artillerist fired the gun. Mach expressed pleasure at how well this precaution worked and was fascinated by the short reaction time of the soldier.

Returning to the circuit and the arrangement of the apparatus, the trigger for the spark light source consisted of allowing the projectile to short out two parallel wires in series with the capacitor and the spark gap. Exposure times of about 1 microsecond were obtained—a remarkable achievement.

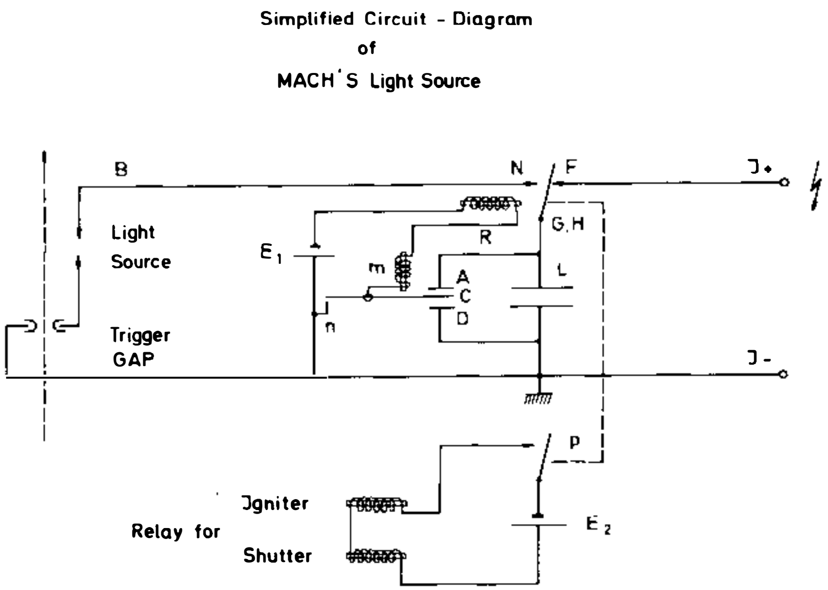


Figure 21 Circuit of arrangement shown in Figure 20.

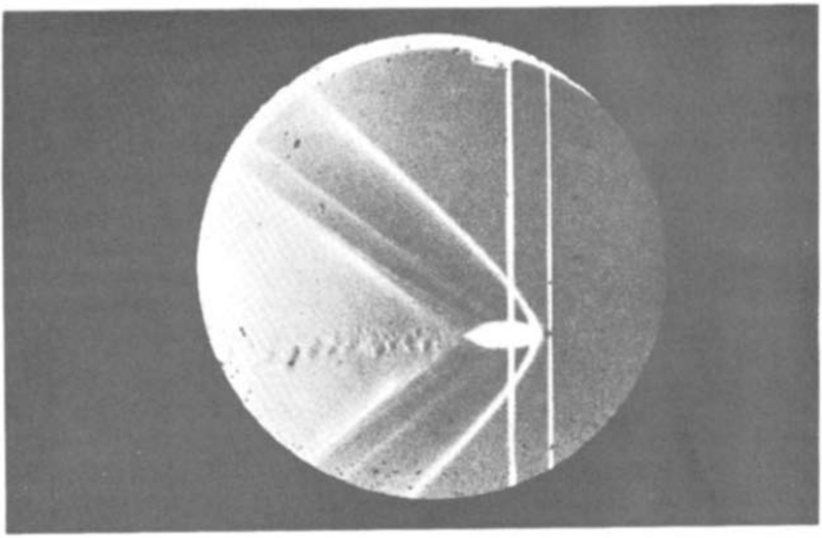


Figure 22 Shadowgram of projectile. Light source triggered by the projectile shorting the two wires seen in the photo (Castner 1892, Mach & Salcher 1887, Mach 1892).

It bothered Mach that important aspects were not visible because of the trigger wires appearing in the picture (see Figure 22). He therefore devised the delay mechanism shown in Figure 23. When the projectile's bow wave enters the open end of tube *r*, it progresses as a shock wave to the nozzle at the far end. When it reaches the end, a jet of air blows the flame of a burning candle through an orifice in a metal plate electrically connected to the tube and the spark gap. The ionized gas from the candle flame forms a conducting path to discharge the capacitor through the light source. By the choice of the length of the delay tube, the time delay between the projectile passing the mouth of the tube and the triggering of the light source can be regulated. It is chosen to catch the bullet in the visual field of the camera.

These devices are good examples of the experimental skill of Ernst Mach and illustrate that he was a physicist as well as a philosopher.

8. SUPERSONIC JET

Mach & Salcher (1889b) reported another gas-dynamic phenomenon. Tests in a torpedo plant in Fiume showed the formation of wave patterns in an air jet expanding into the atmosphere. Figure 24 is an excerpt of a letter Salcher wrote to Mach, dated 19 April 1888. Salcher described the succession of lines crossing the jet—Salcher used the word "Lyra" for them—and the changing pattern with increasing reservoir pressure. At

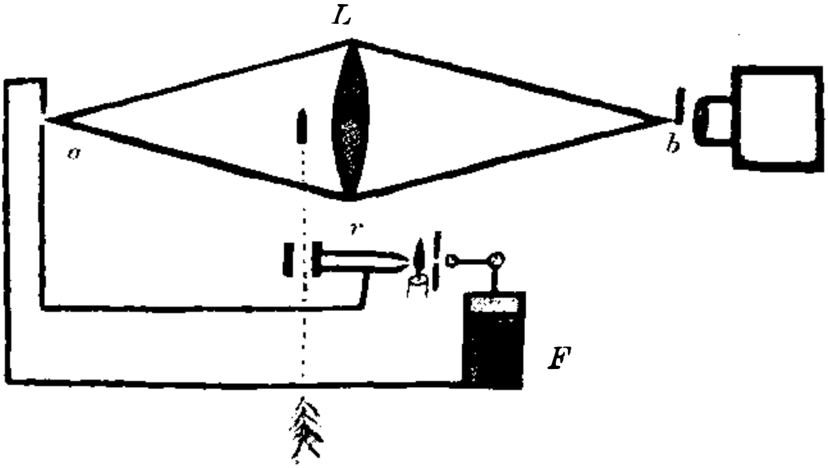


Figure 23 Optical arrangement and delay circuit (Mach 1923). Camera behind knife edge (b), lens (L), and source (a) comprise a schlieren arrangement. Delay tube (r), candle, orifice, and metal sphere comprise the trigger switch to discharge the capacitor (F) through the light source gap.

first Mach explained them as stationary acoustic waves, but later he recognized that some of the lines had to be shock waves. It is appropriate that the father of relativity theory recognized that instead of a projectile moving through air at rest, the body could be at rest and the air could move past with a speed greater than sound, producing the same shock-wave phenomena. Today this arrangement is called a "supersonic blow-down wind tunnel."

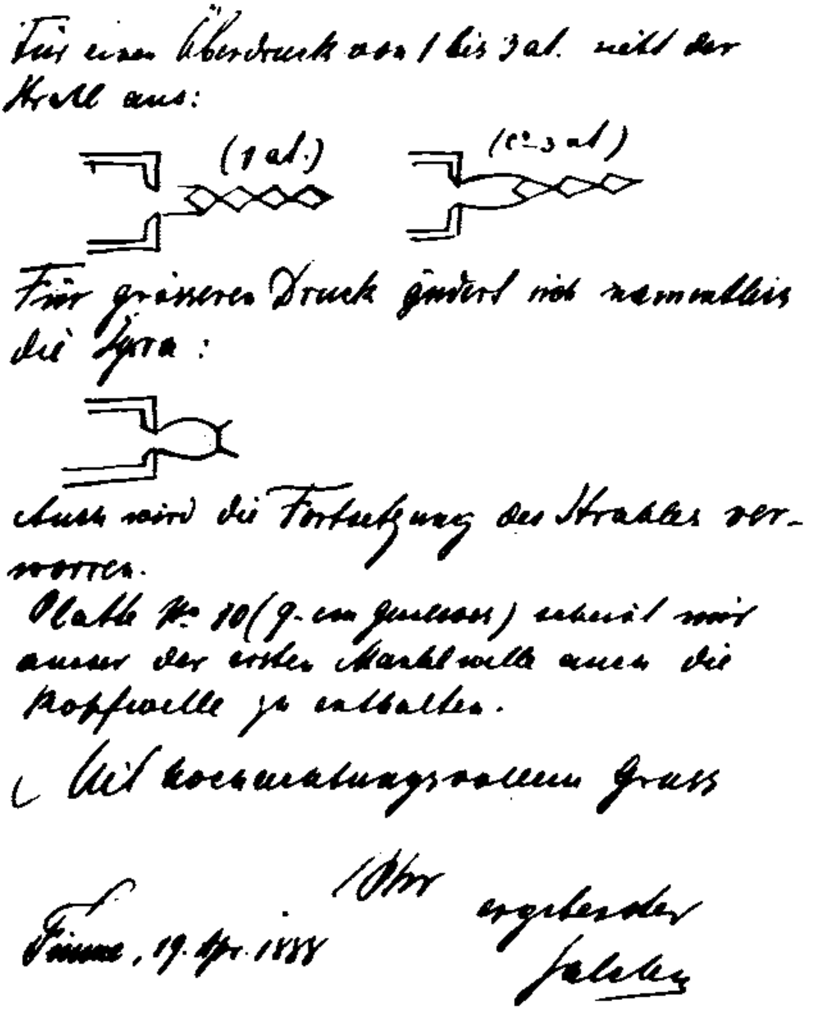
In one publication (Mach & Salcher 1889b), the authors state:

> At the time of the experiments involving photographing projectiles in flight, Salcher had the idea of investigating the reverse case of the air moving and the test body at rest in order to verify the results obtained.
>
> If the jet has a big enough cross-section, a phenomenon analogous to the bow shock becomes visible at the fixed body.

In spite of this early recognition of the possibility of the supersonic wind tunnel as an experimental facility, others denied that supersonic flow could exist in an exhausting jet. Finally Prandtl in 1904 convinced the doubters with his analytical treatment of the supersonic jet.

9. CONCLUDING REMARKS

The dominant theme in Mach's experimental research in gas dynamics and ballistics was the shock wave. With his methodical approach, his knowledge of optical apparatus, and his all-round experimental ability,


Für einen Überdruck von 1 bis 3 at. sieht der Strahl aus:

(1 at.) (c. 3 at.)

Für grösseren Druck ändert sich namentlich die Spitze:

Auch wird die Fortsetzung des Strahles verworren.

Platte No 10 (9 cm gemessen) scheint mir ausser der ersten Machschen Welle auch die Kopfwelle zu enthalten.

Mit hochachtungsvollem Gruss

Ihr ergebener Salcher

Fiume, 19. Apr. 1888

Figure 24 Sketch of jet patterns in Salcher letter dated 19 April 1888.

he made accessible a new field in physics—the field of supersonic flow of gases. His experiments opened the door to supersonic flight and modern ballistics, determining the trend for several decades. His optical arrangements are still regarded as optimum for visualizing supersonic phenomena (Merzkirch 1970).

Thus it is not surprising, in answer to the question posed at the beginning of this article, that the name of Ernst Mach has been chosen for a research institute devoted to optical visualization methods for its experimental work in fluid dynamics and ballistics.

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