In the footsteps of Ernst Mach – A historical review of shock wave research at the Ernst–Mach–Institut

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Abstract. The aim of this paper is to recall some of the historical work on shock waves and to give a brief survey of research activities at the Ernst-Mach-Institut (EMI). Some fundamental results of Ernst Mach (1838 – 1916) are demonstrated and historical remarks are given to the shock tube as an important tool in shock wave research. The activity at EMI in this field was initiated by Prof. H. Schardin (1902 – 1965) in 1955 and has since been continued. Propagation processes of shock and blast waves, blast loading phenomena, shock attenuation, shock reflection at various surfaces, development of new types of blast simulators, electromagnetically driven T-tubes, precursor and decursor phenomena are only a few examples of research topics at EMI that will be discussed.

Key words: Historical review, Ernst Mach

1. Introduction

Shock waves are a fascinating and exciting phenomenon. They are common and important occurrences in our lives. One may assume that the origin of life on earth was only possible in concurrence with shock waves and ultraviolet radiation from lightning discharges and/or meteorite impact. Glass (1974) from UTIAS gave an excellent survey of this genesis in his book “Shock Waves and Man”.

In our daily life, we are surrounded by shock waves. They develop, for example, if high explosives detonate, if pressure vessels explode or even if champagne bottles are opened. Shock waves from lightning can be enormously fearsome. The destruction of buildings and structural members by shock or blast waves can be tremendous as we know from war times and from detonation disasters or explosions in coal mines. Since the beginning, the world has had contacts and experiences with shock waves and their effects, but it was a long time before systematic research work on shock waves started.

Today, with the help of sophisticated high speed cameras, with optical and holographic visualization techniques, with electronic measuring devices, and with numerical simulation methods using powerful computers, most of us have forgotten that our working field started with very simple but highly ingenious methods and test equipment. The purpose of the present paper is to remember some of these historical aspects.

The first speculation that pressure jumps may propagate in a compressible medium with a velocity higher than the speed of sound seems to be that mentioned by Stokes in 1848. First attempts for a mathematical description were made by Airy in 1849 and Earnshaw in 1859. The transformation of a compression wave to a shock wave was described for the first time by Riemann (1860), but he did not consider the adiabatic coefficient in the sound speed formula.

Theoretical calculations concerning the change of the gas state in a compression shock were made by Rankine (1870) but it was Hugoniot (1887) who discovered the increase of the entropy in a compression shock. Today, both names stand for the set of differential equations describing the change of the gas state across a shock front – the famous Rankine–Hugoniot equations.

The experimental validation of theoretical calculations and descriptions created difficulties for several reasons. Shock waves are transient phenomena which are not visible to the naked eye. Therefore special techniques must be applied to make them visible and measurable. An ingenious scientist was needed who was not only skilled in experimental techniques but also in theoretical interpretations of experimental observations. A person who fulfilled these conditions was Ernst Mach (Fig. 1).

2. Some contributions of Ernst Mach

Ernst Mach (1838 – 1916) was a universalist of science in the classical sense and was the first who recognized the character of shock waves and invented various high speed visualization and shock wave diagnostic methods. His life and his contributions to philosophy and physics
The discovery of Mach reflection is certainly his most important contribution to fluid dynamics and even today this phenomenon is not completely understood in all details. In the first issue of this journal, Krehl and van der Geest (1991) reported on the discovery of the Mach reflection effect and described the experimental setup used by Mach. The Mach effect was discovered in 1875 at the Physical Institute of the German University in Prague. Figures 2 and 3 show the institute and Mach's office, respectively.

In an ingenious experiment, an exploding wire was used as the source of a strong acoustic wave which today we would call a shock wave. Figure 4a illustrates an arrangement with a fine wire forming an angle so that two cylindrical shocks start out from the exploded wire and their intersection can be studied. A Leyden jar as a capacitor was charged by a hand operated electrostatic induction machine until the spark gap fired, thus closing the circuit. Most of the stored electrical energy was delivered to the wire. A sooted glass plate below the wire revealed the intersection of the shock waves and the so called Mach V into which the line of intersection bifurcated. This can be seen in Fig. 4b, which is a reproduction of an original photograph by Ernst Mach.

During the decade 1875 to 1885, a number of fundamental experimental studies were performed at the Prague Physical Institute (Mach and Wosyka 1875; Mach and Sommer 1877; Mach et al. 1878; Mach 1878; Mach and Grüss 1878; Mach and von Welturbsky 1878; Mach and Simonides 1879; Mach and Wentzel 1885). By interpreting numerous experiments, with waves produced by sparks, Mach succeeded in giving the correct gasdynamic interpretation of the Mach V and gave a criterion for the occurrence of irregular reflection of shock waves. The Mach V is the trace of the moving triple point where the incident, reflected and Mach waves intersect.

Long before its development by Paul Vieille, Mach (Mach and Sommer 1877) used a setup which today we would call a shock tube driven by electric discharge in a T-tube, similar to that used by Fowler (Fowler et al. 1951) to study luminous fronts at electrical discharges. In 1877, Mach measured the wave front speed of a spark discharge. To do this, two channels, ab and ac (Fig. 5), were bored in a wooden block P. A spark between the electrodes E-E was produced at point a, the junction of the two channels. A cover plate D covered the upper end of the holes. At the outlets of channels b and c, a rotating, circular sooted plate detected the arrival of the pressure pulses. The difference in the arrival times at the sooted disk from the two channels was determined by the angular displacement of the marks relative to the calibration marks impressed on the disk at rest. By extending the length of the channels in thicker blocks, successive additional travel times were determined. As a result, Fig. 6 shows a copy of Mach's original speed distance curve of the wave front propagation. Near the source he measured a blast wave speed of 756 m/s (shock Mach number \( M_s = 2.2 \)). Although Mach clearly recognized that the spark produced wave was different from a sound wave, he did not employ the word shock wave (Stoßwelle). For him it was a sound wave with finite amplitude. Neither did Mach recognize that he had a powerful tool in hand - a shock tube - to study the behavior of shock waves, reflection phenomena and attenuation in tubes.