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Shock Waves

The life and work of Pierre-Henri Hugoniot

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Abstract. You, a fervent member of the shock-wave community, who day after day use the word "Hugoniot" to refer to a relationship, a curve, an elastic limit, what do you know about the man, who just over a hundred years ago, showed you the way?

Thus heckled, how many among us know his real first name? Very few, I fear.

This article is addressed to all those who wish to know more about the life and work of Pierre-Henri Hugoniot. It is both a homage to the man, enamored of his country and of doing public service, and to the physicist who ranks among the builders of modern science.

Key words: P.-H. Hugoniot, Shock wave theory

1. The child prodigy

On the 5th of June, 1851 at ten o'clock in the evening, in Allenjoie, a small city in the Doubs Département, a boy was born who was named, Pierre-Henri. His father was Pierre Hugoniot (a metal worker), his mother was Suzanne Catherine Nardin (no profession) and his brother was Pierre-Louis, his elder by five years.

His family was of modest means, as was the norm in this hamlet of a few hundred inhabitants located at the limits of the Jura, about ten miles from Belfort, which some twenty years later was a center for resistance to the German invaders.

The people of his native village do not know about his childhood, his brother, his family, or his studies, nor is the posthumous glory of this child prodigy celebrated. For prodigy he must have been in order to succeed scholastically in this period when compulsory, free, secular education was yet to be instituted.

In 1869, at the age of eighteen, he was already titular of a degree in mathematics. In 1870, He was accepted first in his class at the "Ecole Normale Supérieure". However, it was the "Ecole Polytechnique", where he was accepted the same year, that he chose to attend. The reasons for this choice must be left to conjecture. Can it be attributed to the nationalistic and rebellious spirit that took hold of a part of the student population during the summer of 1870; students who saw France declare war against Germany the 19th of July, and Napoleon III lose at Sedan the 2nd of the following September? The projects and the career chosen by Pierre-Henri Hugoniot upon graduating from the Ecole Polytechnique lend credence to this hypothesis. But let us wait and see!

2. Pour la patrie, les sciences, ... et la gloire

2.1. The student

The Ecole Polytechnique entrance documents constitute one of the most precious sources of information concerning the young man.

Let us first linger over the photograph of Pierre-Henri Hugoniot with his fellow students. What is it that both surprises and makes him different? Is it the fact that he is bare-headed or his faraway look? The photograph is of mediocre quality, and a portrait could only be made from it by using an image processing technique specially designed for the purpose (Dinten and Tatard 1989). Luckily, the archives of the school can help us recreate his face and figure:

brown hair and eyebrows,
hooked nose,
brown eyes,
average mouth,
round chin,
height 176 cm.

The student Hugoniot went up from second to first division, 54th out of 145 students. He was declared acceptable for public service in 1872, 38th out of 141 students. Finally, he was accepted in the marine artillery service, first out of

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Fig. 1. A photograph of the young Hugoniot Cliché Ecole Polytechnique

six students. From then on, it was to this service that he devoted body and soul for the next fifteen years, as he died suddenly during a trip from Paris to Nantes at the age of 36.

2.2. The gunner

There is a description of the scientific works of Pierre-Henri Hugoniot in the archives of the Ecole Polytechnique. It tells us of the ease with which the student reached the level of his teachers. It was thus that he became: professor of mechanics and ballistics at the Lorient Artillery School, from 1879 to 1882 and assistant director of the Central Laboratory of Marine Artillery, from 1882 to 1884. On the 15th of January 1884, he was appointed Captain of the Marine Artillery.

This period was marked by the assistance he provided to Monsieur Helie, professor of the Lorient Artillery School, in the publication of a second revised and corrective edition in 1884. Here, in a few words, the author expresses his gratitude to his colleague: "*A second edition of this work was requested of me, but this required research which the weakness of my sight appeared to forbid. Luckily, I found in M. Hugoniot, Captain of the Marine Artillery, a colleague with whom I have always found myself in perfect agreement, with the result that he shares with me the responsibility for this work*" [1]

The work received an award by the Paris Academy of Sciences in 1884.

[1] Italic typewriting is used wherever the text is a quotation either of English or English translation of French sentences.

2.3. The researcher

On the 3rd of April 1884, Pierre-Henri Hugoniot was appointed an auxiliary assistant in mechanics at the Ecole Polytechnique. Here, where the need for practical applications was less immediate, and where mathematics was the foremost discipline, he finally found the time and surroundings he needed to settle the question which he was constantly faced with as a gunner: "the propagation of movement in bodies, particularly in perfect gases." It only took him fifteen months to find the answer, as on the 26th of October 1885 he submitted a memoir to the secretariat of the Institute. This was finally published a few years later. It appeared in two parts in the proceedings of the Ecole Polytechnique, the first part in Volume 57 in 1887, the second in Volume 58 in 1889. The reason for this delay is clearly indicated in an editor's note in the proceedings "*... The author, carried off before his time, was unable to make the necessary changes and additions to his original text which it seems he had the intention of making;...*" Indeed, it is in the second part, in the fifth and last chapter, that the expression which has made Hugoniot famous is to be found:

$$e' - e = 1/2(p + p')(v - v') \qquad (1)$$

(N.B. Hugoniot only actually wrote (1) for an ideal gas of constant gamma. Nevertheless, the wording clearly implies the general expression).

3. What's new with the Hugoniot relationship

Those familiar with the works of Bernhardt Riemann (1826-1866) will have read the memorable pages in which he introduces the characteristic curves method-without naming it-when describing the formation of abrupt condensations (Verdichtungsstoss) and actually comes upon the formulae giving the relative speeds of propagation. However, in this approach, consideration is only given to the partial derivative equations expressing the conservation of mass and momentum, the conservation of energy being-erroneously of course-considered to be equivalent to the adiabatic law of Poisson according to which pressure is uniformly proportional to the gamma power of density. This incorrect hypothesis shows that Riemann has not even thought of the jump relationship (1).

Then one question remains: why is the name of Rankine so often associated with that Hugoniot, when designating relationship (1) or any of the geometric avatars of (1) in varied planes of representation?

Let us consider the work of William John Macquorn Rankine (1820-1872) in 1870, two years before his death. This already famous Scottish engineer was taking an interest in the permanent movement in planar sections of a dissipative fluid (conductive but nonviscous), and demonstrated relationship (1) as being necessary between the far upstream state and the far downstream state.

Then, what is the position of the work of Hugoniot with respect to this illustrious forerunner? Clearly his ambitions lay in another direction. Let us quote a few sentences from the introduction:

Hugoniot 1889, section 8; "*It is generally accepted, without being sufficiently demonstrated, that in the movement of a perfect gas, which receives no heat from outside and whose own conductivity is disregarded, the decompression of each section takes place according to the adiabatic law, whatever the variations in speed of the molecules. I rigorously establish, by means of the equivalence principle, that this hypothesis is true when the variation of speed takes place in a continuous manner*".

But the situation is very different when the movement is discontinuous. When a section is subjected to the effects of discontinuity, the original relationship between pressure and volume is suddenly changed".

Hugoniot 1889, section 13; "*In Chapter V, I shall examine the phenomena which occur when discontinuities of movement are introduced*".

Hugoniot 1889, section 15; "*When a discontinuity occurs in a perfect gas, all of the sections which are affected by it undergo sudden changes in pressure and subsequently density. I demonstrate that the relationship between the new density and the original density remains within two limits equal to (m-1)/(m+1) and (m+1)/(m-1), in which m represents the ratio of the specific heats. This theorem, which may appear to be paradoxical, is nevertheless a direct consequence of the first law of thermodynamics.*"

These passages suggest, and careful reading confirms, that Hugoniot covers the movement of non-dissipative media (elastic solids and perfect fluids) without excluding discontinuities and without postulating permanent flow. His subject, and also his methods, place him far closer to Riemann than to Rankine, which may explain him being unaware of the work of the latter. On the other hand, the reason for ignoring the former's work is more probably the linguistic barrier, being particularly strong in the years which followed the French defeat in 1870. Indeed, the first publication containing all the works of Riemann appeared in 1876 in German...and in 1897 in French.

4. After Hugoniot

4.1. Geometric representations

Today, Riemann's error is completely forgotten, and nobody imagines that a law other then Hugoniot's could have existed in the minds of 19th century physicists This is so much the case that today, the originality of the relationship (1) seems to lie less in the fact of having overcome the myth of the universality of Poisson's law than in the fact of having introduced a relationship between thermodynamics on both sides of a discontinuity, whether this occurs in one and the same fluid (shock wave) or, whether it separates two chemically distinct environments (reactive wave). It is clear to what degree this point of view is widespread when realizing the generality with which the name Hugoniot is attributed to all curves representative of relationship (1). In accrediting him with too much, is there not a risk of neglecting the merits of his successors, and creating a degree of confusion?

It must be emphasized that Hugoniot himself, in his memoirs, carefully avoided addressing the representation of relationship (1). He only takes advantage, in the case of the ideal gas of constant gamma, of the simple analytical nature and indicates the existence and magnitude of a compression limit.

Consequently, the imaginative effort of Jules Crussard, vis á vis the significance of (1) in the case of the reactive wave, can be better appreciated. Moreover, this subject seemed important enough to Jouguet for him to state that: Jouguet 1917 page 267; "*We shall use a method of geometrical representation which we owe to Crussard 1907*".

It is also to him that we owe-again according to Jouguet in the preceding document-the statement of one of the essential properties of critical waves (Chapman-Jouguet waves).

Jouguet 1917 page 278 "*The two critical waves have an important property demonstrated by Crussard: the critical waves of maximum and minimum velocity are such that their velocity w is equal to the speed of sound a in the medium which follows them*".

On the other hand, it is effectively to Jouguet (1910) that we owe the correct analysis of the variation of the ratio w/a along the curve (H), and as a corollary the nature of the extremum of entropy at each of the critical points (minimum for detonation and maximum for deflagration) which Chapman had erroneously described in 1899.

These points may seem to be merely anecdotal. This is not the case. Indeed, they clearly show that more than twenty years were necessary for the understanding of specific features of relationship (1) with chemical change; they also show the significant difference between curves (h) and (H) respectively in the absence and the presence of chemical reactions, in the same way as an explosive wave differs from a shock wave. It is for this reason that I am profiting from the occasion of this homage to Hugoniot to attempt to convince the "shock wave community" to give Crussard his due, i.e. credit for the discovery of curve (H).[2]

4.2. Extensions

For more than half a century, the work of Hugoniot and Crussard was not the subject of any notable developments: there was nothing, in the period between the two wars, to encourage a movement away from the convenient framework of the ideal gas, or the finding of a solution to the problem of a global and coherent description of a fluid traversed by one or more waves. The Second World War and its flood of scientific challenges led to new light being shed on the Hugoniot relationship.

Thus it was left to H.A. Bethe (Bethe 1942) to track down the general properties of (1) for a shock wave in an arbitrary fluid. Bethe's own words as quoted in the follow-

2 For more details, the reader is referred to the text of the plenary lecture given in Albuquerque on the 14th of August 1989, at the opening of the sixth A.P.S. topical conference on "shock waves in condensed matter" S. Schmidt, J.N. Johnson, L.W. Davidson (editors) Elsevier Science Publishers B.V. 1990.

ing paragraph, which introduces his work, are clear: "*The theory of shock waves thus far has been developed mainly for ideal gases. Even for these, the question of stability of shock waves has received little attention. Recently the problem of shock waves in water has gained much practical importance. Therefore it seems worth while to investigate the properties of shock waves under conditions as general as possible*".

It is to Bethe that we owe the representation of (h) in terms of volume per unit mass v and entropy per unit mass s, and the analysis of the situation in the vicinity of the downstream state.

A review of the work directly derived from Hugoniot would be incomplete if we were not to consecrate a few lines to a note-now long forgotten-that Hermann Weyl wrote (Weyl 1944) concerning the same problem in 1944. Wartime circumstances explain why Weyl had no knowledge of the report written by Bethe two years earlier. Paradoxically, the fact that the research was carried out independently turned out to be an asset. Indeed, together with a first part (thermodynamics and the shock phenomenon) which is less rich than the wide ranging report written by Bethe, there is a capital second part (the problem of the shock layer) from which he derives the general concept of dissipation layer extended later by Cheret (1971) in the detonation layer theory.

5. Epilogue

The fame of Pierre-Henri Hugoniot could lead us to expect a life rich in events and anecdotes. In reality, he was anything but a personality. His choice at eighteen to enter the Ecole Polytechnique rather than the Ecole Normale-like everything he did in his lifetime (36 years)-can be explained by patriotism and the traumatic effect on the French nation of the defeat and surrender of Napoleon III at Sedan. If, upon graduation from the Ecole Polytechnique, he was the first to choose the marine artillery, it was due to patriotism. If he consecrated twelve years of his life to minor works unworthy of his talents, it can also be explained by his patriotism. In 1884, his work on ballistics was honored by the Academy of Sciences and he was, despite all his efforts to the contrary, appointed auxiliary master of mechanics at the Ecole Polytechnique. Was his failing health the reason for him exchanging his damp offices in Lorient for the comfort of the capital? No-one knows. Anyhow, in this new and prosperous environment, fifteen months were enough to enable him to solve the problem where Bernhardt Riemann himself had failed.

I hope that I have been able to share with you my thoughts on Hugoniot: a supremely gifted mathematician, promoted by his knowledge, but loyal in all of his choices to the ideal of service to his country. Of course, we can wonder what would have been his destiny if, in 1870, his choice had been different. The shock wave community would have lost a lot, science might not have.

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