Sonic boom, more than two centuries of investigation !

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ABSTRACT

Seven-five years ago, in 1947, Charles Yeager on board of experimental aircraft Bell-XS1 became the first human to break the mythical sound barrier. Five years later, in 1952, Gerald Whitham published his seminal paper relating the sonic boom pressure level and waveform to the shape of a supersonic projectile. Only ten years more were sufficient for the French and British government to sign in 1962 the cooperation agreement officially launching Concorde programme. Its first flight took place in 1969, two months after Tu-144 one. Concorde commercial exploitation between 1976 and 2003 remains until now a unique adventure in civil aviation, a technological achievement and an economical failure. Growing environmental concerns partly explain this one. Among them, sonic boom remains one of the main drags on future supersonic aviation. In this paper, I sketch a brief historical landscape of the elements and scientists that lead to our modern understanding on sonic boom, focusing my attention on pioneering research before the age of supersonic aviation.

1. INTRODUCTION

Seventy-five years ago, on October 14th 1947, the so-called "sound barrier" was broken officially for the first time by a manned vehicle, the Bell XS-1 experimental aircraft (K-561). Dropped from a Boeing B-29 Superfortress at an altitude of about 7,260 m over the Mojave Desert, it reached Mach 1.06 during an 18 seconds long level flight. The young US Air Force pilot, Charles "Chuck" Yeager described later his supersonic experience "as smooth as a baby's bottom". Despite this, the myth of a physical sound barrier, or sound wall, coined by British physicist William Frank Hilton in 1935 (K-505) referring to the sharp drag increase when approaching Mach 1, became a popular myth among the public. Most people believe this noise emanates from the "destruction" of some invisible sound "wall" when the needle of the speedometer reaches Mach 1. During its commercial service (1976-2003), most passengers of Concorde were somewhat disappointed to experience nothing special ! One sensible element feeding this myth however is the sonic boom, or the loud, impulsive and startling noise perceived on the ground by populations overflown by supersonic aircraft. Commercial supersonic overland flight is currently banned by many countries, in particular the United States who enacted a strict regulation in the wake of French-British Concorde programme and rising concerns about its environmental impact (take-off and landing noise, sonic boom, depletion of ozone layer). Despite active research to design low-boom supersonic aircraft, there is today no adopted international regulation on what could be a sufficiently quiet sonic boom level. General Assembly of International Civil Aviation Organization simply requests that "no unacceptable situation for the public is created by

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sonic boom from supersonic aircraft in commercial service". The future NASA demonstrator aircraft X-59 is designed to reproduce at the ground the low boom levels achievable with most advanced design technologies. Community studies evaluating its annoyance, are expected to provide within the current 2020 decade sufficient data on human response to adopt a technology-feasible and measurable threshold for quantifying what would be an "acceptable" boom level. This could pave the way to a new era for aviation, definitely cleared of the myth of the sonic barrier. Or, alternatively, repeating more or less Concorde scenario of the 70's, the supersonic dream could collapse one again facing a combination of international political turmoil, volatility of energy costs and increasing environmental concerns. In particular, the worrying prospect of global warming will undoubtedly make some people estimate this high-speed technology dream heading in the opposite direction of a desirable lower-carbon economy.

In this paper, I propose to review some historical observations regarding sonic boom mostly *before* the age of supersonic aviation. I date the birth of this one between Bell-X1 first supersonic flight in 1947 and Gerald Whitham seminal papers founding sonic boom theory between 1950 and 1956. An extensive review of sonic boom research since has been achieved recently by NASA [1] and does not need to be summarized here. Therefore I will speak mostly about *prehistory of sonic boom*, at a time when supersonic aircraft did not exist, but sonic boom indeed did. After some historical considerations about the sound celerity, natural sonic booms from meteoroids will first be detailed. Whip-cracking, the oldest human-made sonic boom will then be briefly discussed, before examining the knowledge about supersonic projectiles since the 18th century, that paved the way to modern sonic boom understanding. Many information provided here is extracted, I hope as correctly as possible, from the extraordinary book of Peter Krehl, *History of shock waves, explosions and impact* (Springer, 2009) [2]. I can only recommend the reader to access this book, for a delightful intellectual travel within it through time, space and ideas. Most references I found in this book are simply referred as (K-XXX) where XXX is the page number. Only the few additional references I added are listed in the present bibliography.

2. THE SOUND VELOCITY: FROM LINEAR TO NONLINEAR ACOUSTICS

In 1636, the French friar Marin Mersenne (K-203) achieves the first measurement of sound velocity in air, noting the delay between a cannon muzzle flash and subsequent sound arrival, supposed to propagate at a much lower speed than light. He used his own blood pulse as a clock, assuming one beat every second, thus overestimating the value to 450 m/s. In 1687, Isaac Newton (K-223) in his *Philosophiae naturalis principia mathematica* proposes the first theory of sound, assuming (in modern language) propagation is isothermal. The resulting value of 298 m/s is underestimated. About half a century later, in March 1738 (K-236), a commission from the French Academy of Science (César François Cassini de Thury, Jean Dominique Maraldi and Nicolas Louis de la Caille) measures precisely the speed of sound, by the same method as Mersenne, but now using pendulum clocks, two cannons fired from two hills located North (Montmartre) and South (Montlhéry) to Paris by night. The experiment is repeated several days later with different wind conditions, and small temperature variations around 6^{o}C are noted. The mean reported value is of 173 toises per second, or 337.18 m/s, an error about half a percent. Also noted is the convection of sound by wind speed depending on its direction. Using the same methodology, but now relying on chronometers, a new series of experiments performed by Bureau des Longitudes in southern Paris region further improve this result in 1822 (K-284). On the theoretical side, Jean Le Rond d'Alembert (K-243) establishes the first mathematical solution of the one-dimensional wave equation in 1747. In 1802, Jean-Baptiste Biot (K-271) proposes the first correct theory for sound velocity in air. He acknowledges the assistance of Pierre-Simon de Laplace (K-283), who himself in 1816 points out sound propagation as an adiabatic process.

Abandoning the assumption of small perturbations (but assuming an isothermal motion), Siméon-Denis Poisson (K-276) proposes in 1808 a mathematical solution for sound waves of finite amplitude, noting a similar expression by Lagrange in 1784/85. During a polar expedition in 1824-1825, searching for northwest passage, a measurement campaign to investigate sound velocity at low temperature leads William Edward Parry (K-286) to observe a sound velocity from gun muzzles slightly larger than the voice one. Apparently unaware of Poisson's work, James Challis (K-310) in 1848 concludes that sound speed is dependent on wave amplitude, which could lead to the distortion of the wave profile with some parts overtaking other ones, a consequence that Poisson did not draw from his formula. Challis' paradox was solved the same year by George Stokes (K-311), assuming a surface of discontinuity is formed and applying the conservation of mass and momentum (but not of energy) across the shock front. In 1858, aware of Parris' observations, Samuel Earnshaw (K-324) establishes the first theory of finite amplitude sound, completing Poisson's work and providing an implicit solution in an adiabatic gas. Henri Regnault (K-335) measures in 1863 the velocity of small blast waves in very long tubes, the first quantitative evidence of sound velocity on wave amplitude. Stokes' laws are extended beyond nonlinear acoustics and to energy conservation by William Rankine (K-348) in 1869, who also measured the ratio of specific heats γ and coined the term 'adiabatic' (in 1859, K-329). Starting from a different point of view (Lagrangian coordinates and nonconducting gas), Pierre Henri Hugoniot (K-389) obtains independently in 1887 the equations of mass, momentum and energy conservation through shocks that now bear their two names and constitute the foundation of both modern shock theory and nonlinear acoustics, sonic boom being at the intersection of the two.

3. METEOROIDS, A NATURAL SOURCE OF SONIC BOOM

The notion of "sonic boom" is immediately associated to supersonic aircraft, though most people experienced it only rarely if ever, except those living around fighter training areas. Also few are aware that sonic boom is produced by any supersonic object, not necessarily an aircraft. However, supersonic bodies and therefore resulting sonic booms, either natural or human-made, are indeed rare. The natural phenomenon most similar to a supersonic aircraft is the hypersonic atmospheric entry of an extra-terrestrial meteoroid. Following the terminology of International Astronomical Union (IAU), the word 'meteoroid' denominates the solid body itself, the word 'meteorite' the solid remnant in case the meteoroid has not been completely vaporized, and the word 'meteor' all physical phenomena associated to its atmospheric transient phase, such as emission of light, heat, sound (including sonic boom) and ionization. Meteoroids are roughly of the size 30 μm to 1 m. Smaller objects are rather considered as interplanetary dust, larger ones are labeled as 'bolides'. The bigger the object, the rarer its occurence. The annual flux of extra-terrestrial objects through the Earth atmosphere can be estimated by combination of various techniques [3], including infrasonic observations. Nice N-wave like sonic booms small amplitude (of the order of 0.1 Pa) from small meteorites are observed [4]. In addition to their partial or complete vaporization, most bolides fragment in smaller pieces during their meteor phase. Therefore, ground recorded sound can be either due to their sonic boom, their fragmentation or their ground impact creating one or several craters. Among recently observed bolides, the meteorite of Carancas observed in Peru in 2007 has likely avoided fragmentation, an exceptional feature, and is a reference object for analyzing meteor sonic boom [5].

The extraterrestrial nature of meteorites is hypothesized by Ernst Chladni in 1794 (K-266), one of the fathers of acoustics. Before this date, sky origin of meteors was indeed previously reported by witnesses, but was dismissed as unreliable by scientific authorities. Chladni's assumption is substantiated a few years later, following a large meteorite fall in Normandy, France on April 26, 1803, with intense light and loud noise experienced by many observers in a large region. Their witnesses is collected by French physicist Jean-Baptiste Biot (K-272) along with several unusual stone samples, and his report is considered as the first scientific evidence of the celestial origin of meteorites. A definitive confirmation is proposed by Denison Olmsted [6], a professor at Yale. Following a Leonid meteor storm during the night of 12 to 13th November 1833, he collects public observations of this event after a call to public through newspaper, (this also marks the start of citizen science !), and concludes that the radiant point of the meteors is unaffected by Earth rotation, therefore is extraterrestrial. Following the 'Washington meteorite' observed in December 1873, Ernst Mach and Bruno Doss (K-411) assume in 1893 that the reported sharp meteor bang is a supersonic phenomenon due to the ballistic head shock wave they had observed in the lab for projectiles. The most ancient recording of meteor sound dates from 1908, resulting from the explosion of the great Siberian Tunguska bolide. Seismic signals show first a large amplitude, low frequency (< 0.03 Hz) arrival, followed by several high frequency ones [7]. In the absence of any crater, these are most likely an atmospheric internal wave, followed by sonic booms. Modern theory of sonic boom from meteorites is developed after World War II. The flight path of a meteorite is considered as a line source of self-similar strong shock wave described by Lin [8], transposing Taylor's [9] self similar, spherically-symmetric, strong shock solution for a point source nuclear explosion. Then transition from the source nearfield to the acoustic weak shock farfield is empirically proposed by Jones *et al.* [10] and later on numerically by Plooster [11]. Revelle [12] links the input energy of the model to the drag force of the meteoroid, establishing a consistent theory still in use today. Mimicking modern approach for supersonic aircraft coupling nearfield pressure evaluation by CFD to farfield propagation by ray theory, Henneton *et al.* [13] perform the first direct CFD evaluation of sonic boom from a meteoroid, incorporating real gas effects (dissociation and ionization) occurring at high hypersonic speeds (Mach 40).

4. WHIP-CRACKING, THE OLDEST SONIC BOOM OF HUMAN ORIGIN

Whips were probably designed by the most ancien humanity to direct animals. With proper handling, long whips can produce some cracking noise that is produced by their tip reaching supersonic speeds. This was speculated in 1905 by Otto Lummer (K-437), and experimental confirmation came from schlieren photographies by Zéphirin Carrière in 1927 (K-477). More recent high-speed shadowgraphs of Krehl *et al.* (K-796, K-914) point out tremendous accelerations and sonic boom emission when the speed of the whip tip is around Mach 2 (Concorde cruise velocity !). The dynamics of the cracking whip can be explained by the formation of a loop travelling along a tapered thong, see Goriely and McMillen, 2002 (K-796) who also described the shape of the emitted shock wave. It has also been hypothesized (Alexander, 1989, K-69) that sauropods such as diplodocus or apatosaurus could move the slender tip of their long tail at supersonic speeds, thus also creating a sonic boom.

5. FROM BALLISTICS TO SONIC BOOM

In 1644, Mersenne (K-155, K-208) estimates crudely the speed of a musket ball as comparable to the sound velocity. In 1707, Jacques Cassini II (K-156, K-231) invents the ballistic pendulum: the transfer of projectile momentum and energy induces an angular deviation of the pendulum that makes possible to measure the projectile speed. This was applied to the first measurement of supersonic speeds around Mach=1.5 by Benjamin Robbins in 1740 fur musket balls (K-237), and around M=1.87 by Charles Hutton (K-260) for larger cannon projectiles. In 1847, Christian Andreas Doppler (K-309, K-918) examines the acoustical consequences of Doppler effect, discusses the case of a supersonic source (either at constant, accelerating or slowing speed) and, using Huygens principle, draws the first supersonic cone and gives the formula for its angle. In 1886-87, Ernst Mach and Peter Salcher (K-387, K-920, K-921) make the first schlieren photographies of supersonic projectiles, outlining the head and tail shock waves recognized as such and approaching a conical geometry with Mach angle at the apex. The terminology 'Mach cone' and 'Mach angle' was proposed by Ludwig Prandtl in 1913 (K-454).

During World War I (1914-1918), ballistic noise from supersonic artillery shells was explored as a way to localize enemy guns, at a time when aerial observation was at is birth and highly risky. In

France, extensive researches were conducted in this way during the whole war by Ernest Esclangon. They were described in a series of reports during the war, and later published in a book in 1925 [14]. He distinguishes the low frequency sound emanating from the gun muzzle, to the higher frequency noise emanating from the ballistic shock wave, now named sonic boom. Clearly referring to the work of Mach and to the conical wavefront shape, he studies the influence of atmosphere on noise propagation, establishing the equations of linear acoustic ray tracing in presence of wind. Considering the parabolic shape of the projectile trajectory, he also outlines the resulting wavefront folding and caustic formation, a phenomenon now known as 'superboom' and occurring especially during aircraft acceleration [15]. Published in French and mostly ignored in the sonic boom community, his work can nevertheless be considered as a pioneering one regarding sonic boom. Viewed from a modern point of view, it establishes the basis of the geometrical theory of sonic boom propagation, though he apparently ignored the nonlinear aspects of sonic boom propagation. The works of Doppler, Mach and Salcher about the conical shape of the initial boom wavefront close to the supersonic body constitute the other fundamental background of the sonic boom modern view. Mach cone, nonlinear acoustical propagation and shock theory as established in the 19th century (see section II) were coupled to one another in 1946 by Jesse DuMond *et al.* (K-553) in the first comprehensive theory of sonic boom propagation for supersonic projectiles, outlining the characteristic N-shape of the boom pressure waveform and its amplitude decay as power -3/4 with distance in a homogeneous atmosphere. This theory is completed by Gerald B. Whitham (1950-1956), who relates under the slender body assumption (or linearized supersonic flow theory) the boom level and waveform to the shape of the projectile. The famous 'F' function of Whitham is extended shortly after in 1958 to wing-lifted bodies by Walkden [16]. At this date, all the key elements were now gathered for a deep and predictive understanding of sonic boom phenomenon.

REFERENCES

[1] D. J. Maglieri, P. J. Bobbitt, K. J. Plotkin, K. P. Shepherd, P. G. Coen, and D. M. Richwine. *Sonic boom: Six decades of research*. National Aeronautical and Space Administration (NASA), 2014.

[2] P. O. K. Krehl. *History of shock waves, explosions and impacts*. Springer, 2009.

[3] P. Brown, R. E. Spalding, D. O. ReVelle, E. Tagliaferri, and S. P. Worden. The flux of small near-earth objects colliding with the earth. *Nature*, 420(6913):294–296, 2002.

[4] W. N. Edwards. *Meteor Generated Infrasound: Theory and Observation*. in Infrasound Monitoring for Atmospheric Studies, Springer, 2010.

[5] O. Gainville, M. Henneton, and F. Coulouvrat. A re-analysis of carancas meteorite seismic and infrasound data based on sonic boom hypothesis. *Geophysical Journal International*, 209(3):1913–1923, 2017.

[6] D. Olmsted. Observations on the meteors of november 13th, 1833. *American Journal of Science and Arts*, 25(2):363–411, 1834.

[7] F. L. Whipple. Photographic meteor studies, i. *Proceedings of the American Philosophical Society,*, 79:499–548, 1938.

[8] S. C. Lin. Cylindrical shock waves produced by instantaneous energy release. *Journal of Applied Physics*, 25(1):54–57, 1954.

[9] G. I. Taylor. The formation of a blast wave by a very intense explosion i. theoretical discussion. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 201(1065):159–174, 1950.

[10] D. L. Jones, G. G. Goyer, and M. N. Plooster. Shock wave from a lighting discharge. *Journal of Geophysical Research*, 73(10):3121–3127, 1968.

[11] M. N. Plooster. Shock waves from line sources. numerical solutions and experimental measurements. *Physics of Fluids*, 13(11):2665–2675, 1970.

[12] D. O. Revelle. On meteor generated infrasound. *Journal of Geophysical Research*, 81(7):1217–1230, 1976.

[13] M. Henneton, O. Gainville, and F. Coulouvrat. Numerical simulation of sonic boom from hypersonic meteoroids. *AIAA Journal*, 53(9):2560–2570, 2015.

[14] E. Esclangon. *L'acoustique des canons et des projectiles*. Imprimerie Nationale, 1925.

[15] J. C. L. Wanner, J. Vallee, C. Vivier, and C. Thery. Theoretical and experimental studies of the focus of sonic booms. *The Journal of the Acoustical Society of America*, 52(1A):13–32, 1972.

[16] F. Walkden. The shock pattern of a wing-body combination, far from the flight path. *Aeronautical Quarterly*, 9(2):164–194, 1958.