A Brief History of the Speed of Sound

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The meaning of the speed of sound at which sound waves travel through a medium (usually air) was derived from the Latin concept "celerita", meaning "velocity"[9].

Historically speaking the speed of sound was one of, if not the first effects relating to the study of acoustics and variables relating to sound propagation outdoors. Due to the fact that the speed of sound is one of the most historically significant factors in acoustics and sound propagation this section of the report discusses a brief history essential to the subject.

It is possible that as long ago as the 6th century BC, the Greek mathematician Pythagoras was aware that sound was a vibration transmitted from a source to the ear.

Written records dating from the time of the Greek philosopher Aristotle (350 BC)[10] show a rudimentary knowledge of sound propagation, as he wrote:

> *"All sounds are produced because air is set in motion by expansion or compression or when it is clashed together by an impact from the breath or from the strings of musical instruments"*

Pythagoras thought that high frequencies were transmitted through air more rapidly than low frequencies. In addition to Pythagoras comments, the Roman architect Vitruvius (25 BC)[11] wrote:

> *"Voice is breath, flowing and made sensible to the hearing by striking the air. It moves in infinite circumferences of circles as when, by throwing a stone into still water, you produce innumerable circles of waves increasing from the centre and spreading outwards."*

The first explicit mention of sound velocity appears to be by Francis Bacon[12]. He discussed the possibility of comparing the velocity of sound with that of light (which he knew at the time to be immeasurably high) by comparing the time taken for the sound of a church bell to travel one mile (1.6km) with that taken by a simultaneous light signal (an interrupted lighted taper) over the same distance by using his own pulse as the timing mechanism.

However, the first actual quantitative determination was by the French mathematician Mersenne[13] , working under the influence of Galileo.

Mersenne used both musical instruments and gun fire as sound sources and estimated the distance travelled by sound in one second to be equal to 230 French Toises; this corresponds to 448 m/s and is thus higher than the known true value.

Mersenne incorrectly asserted that the same speed was observed by night and by day, either with wind or against it[14].

By comparing the speed of travel of sound produced by a large weapon such as a cannon with that produced by a small weapon such as a musket, Gassendi[15] demonstrated the "surprising" fact that the time taken for sound to traverse a given distance is independent of both pitch and intensity, but as with Mersenne he erroneously concluded that wind had no effect on the velocity of sound. (Refer to Lenihan[16] for a discussion of the roles of Mersenne and Gassendi in determining the velocity of sound.)

The importance of air as the medium through which sound is transmitted had yet to be established. The far-reaching work on barometric pressure by Torricelli[17] led to his successful demonstration of a vacuum and soon a number of experiments with air pumps were under way[18]. During the 17th century Sir Isaac Newton[19] showed that in an elastic fluid the speed at which sound waves are propagated is proportional to the square root of the elasticity divided by density. In fact, the reasoning which led to this result was so obscure that few have claimed to be able to follow it.

The noted mathematicians d'Alembert and Bernoulli both concluded that this was the most obscure and difficult part of the whole of Newton's Principia, whilst at one time Lagrange[20] actually claimed the derivation to be illogical.

Illogical or obscure it may have been, the work marked an important step forward and Newton went on to use Boyle's Law, which holds true only for constant temperature, to derive the speed of sound in air as $\mathbf{c = \sqrt{p/e}}$, leading to a calculated value of 968 ft/s, or approximately 295 m/s.

Newton concluded that experimental data then available indicated that the velocity lay between 280 and 330 m/s, and in the first edition of Principia he appears satisfied with the order of magnitude agreement between theory and experiment.

A number of experimental determinations of the speed of sound were reported about this time but a particularly detailed study including a review of pervious determinations was reported by the Reverend William Derham in 1708. He arranged for guns (called sakers) to be fired from various church towers and other eminences in the neighbourhood, covering distances of up to 12.5 miles (20.1 km) from his own church tower at Upminster, observed the flash (in daylight using a telescope for this purpose) and timed the interval to the arrival of the report using an accurate portable movement with pendulum beating half seconds. In this way he confirmed that velocity was independent of level (i.e. independent of distance from the source) and arrived at an accurate mean value of 348 m/s[21].

In a further series of tests over a fixed distance of 12.5 miles Derham investigated various effects on the velocity of sound and, contrary to suggestions by previous workers, Derham concluded that favourable winds accelerated sound propagation whilst opposing winds retarded it.

Judged by today's standards his results appear highly creditable and remarkable accurate. Unfortunately it is not certain that he established the correct quantitative relation between effective sound speed and wind speed, for this was before the invention of the anemometer (although the ingenious experimenter Hooke had in fact invented a swinging-plate wind velocity indicator in 1667).

Derham's estimates of wind speed were largely based on an arbitrary fifteen point scale and attempts to translate to true wind speed had not been successful[22].

Although graduated air thermometers had been in use since the time of Galileo, thermometry was still being established; Fahrenheit's scale based on mercury in glass thermometer was not published until 1724[23] although probably established around 1714, the Celsius scale not until 1724[24].

Derham did not actually measure the prevailing temperature but concluded that the speed of sound was the same in winter as in summer and, although this false conclusion has been held against him, this was surely but a major lapse.

In 1738 Cassini and others from the Académie des Sciences[25] made measurements over a distance of approximately 28km. They used cannons as sources, pendulum clocks for timing, and worked at night so that stable meteorological conditions prevailed[26]. They were the first to state definitively that with a prevailing wind speed denoted as "u", in the direction of the wind sound is propagated with speed (c + u) but that against the wind the effective speed of sound is (c – u).

They used reciprocal firing from either end of the baseline and adopted the mean traverse time in order to minimise intrusive wind effects and arrived at a value of 337 m/s for the speed of sound[27].

Although Cassini concluded that temperature does affect the velocity of sound, the first quantitative study of the influence of temperature was undertaken by Biancon[28] at Bologna by comparing velocities determined in winter and in summer. It was correctly concluded that an increase in temperature produces an increase in the velocity of sound.

The remainder of the 18th Century was essentially a period of consolidation. In view of the difficulties encountered with Newton's derivation, several theoreticians tackled the problem and a reasonably clear treatment was eventually produced by Euler[29], whilst Lagrange revised Newton's reasoning and generalised the treatment to cover sound waves of arbitrary character (i.e. not just simple harmonic waves). However, all the calculated values were seriously discrepant from the experimental data[30].

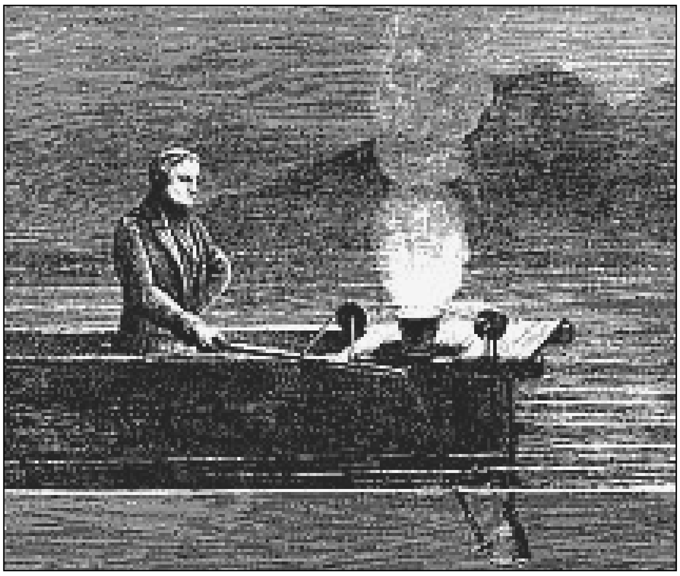
It was not until Laplace[31], following the observation by Dalton that a sudden compression produces heating of a gas, pointed out that setting the volume elasticity of the air equal to the static pressure implied that isothermal conditions existed, whilst due to the rapidity of the pressure fluctuations, adiabatic (an adiabatic process is a process in which no heat is gained or lost in the working fluid) conditions probably prevailed.

This led to the revised relation $c = \sqrt{yp/e}$, where y is the ratio of the specific heat at constant pressure to that at constant volume.

It is understood the inclusion of y immediately brought calculated and observed values for the velocity of sound into substantial agreement. Although at this stage it was not entirely obvious that sound propagation took place completely adiabatically.

Any lingering doubts were largely resolved when Stokes[32] showed that sound propagation must occur either substantially adiabatically or substantially isothermally, as otherwise large damping factors would prevail and a comparatively high attenuation rate would be observed[33].

As Herzfeld and Rice[34] have shown, in an unbounded wave the time required for temperature equilibration to occur is proportional to the square of the wave length, whereas the time actually available for this to occur is only directly proportional to wave length. Thus propagation becomes more truly adiabatic as the sound frequency decreases whilst, at normal atmospheric pressure, adiabaticity is expected to persist up to the highest attainable frequencies[35].



Measurement of the propagation speed of sound in water of the Lake Geneva in 1828 (observation point 1) according Guillemin (1868)

A definitive determination of sound velocity was undertaken in 1822 by a commission appointed by the Bureau des Longitudes which included Prony, Arago, Bouvard, Mathieu, Gay-Lussac and Humboldt[36]. They used accurate chronometers, an accurately surveyed distance of 18.6223km and again used reciprocal firing of cannons to minimise wind effects. They arrived at a mean time for sound to travel the measured distance of 54.63 s at 16 °C, leading to a speed value of approximately **c_0 = 331.2 m/s**.

As time passed, other techniques for determining the velocity of sound were put forward. It had now become obvious that in the open air the accuracy of speed determination, particularly when made over the long base lengths necessary to ensure adequate time resolution, was limited by uncertainties regarding the temperature and the wind velocity.

For instance a relatively low wind speed of 5 miles per hour (8km/hr) corresponds to a possible error of 2.2 m/s; although a substantial part of this error could be eliminated by reciprocal firing, at least part would remain unless exact synchrony were achieved.

Also, a change of temperature of 1°C produces a speed change of about 0.6 m/s. Besides carrying out open-air measurements at Versailles, Regnault[37] therefore carried out an elaborate series of experiments in the newly-laid water pipes under the city of Paris using sources consisting of pistols, explosions, and musical instruments. Now when confined in pipes the speed of sound is less than in free space but by using pipes of different diameter he managed to extrapolate to free-field conditions and arrived at a value for dry air of c_0 = 330.7 m/s[38].

Tackling the problem in an entirely different way Hebb[39], while working at the Ryerson Physical Laboratory in the USA, made direct measurement in free air of the wavelength of sound corresponding to a signal of known frequency. The technique, which had been proposed by Michelson, is said too be almost too well known to require description.

Two paraboloidal reflectors (focal length approximately 0.38 m, diameter 1.5 m) were arranged coaxially, one of them being moveable on a parallel track. A pure-tone air-whistle source whose frequency f = 2376.5 Hz was found by comparison with a tuning fork, was placed at the focus of one of the mirrors whilst a carbon microphone was placed at the focus of each of the mirrors. Using a split-primary transformer the outputs of the two microphones were combined in such a way that when the output from the secondary was monitored using headphones the sound heard was proportional to the vector sum of the two microphone outputs.

By progressively changing the separation between the mirrors the relative phases of the two signals varied so that at certain points they cancelled whilst at other points they reinforced each other. This method therefore provided a direct determination of wavelength and, as the frequency was known, this yielded the sound velocity.

The experiment was carried out in a hall 36m long, thus no wind was encountered and the temperature was found to remain very constant. The separation between mirrors could be increased to as much as 100 λ and the positions of the minima could be located to within about 1 cm, so that an accuracy of the order of 0.1% was achieved. In this way Hebb reported a value of c_o = (331.29 ± 0.04) m/s but subsequently[40] he revealed that this result was slightly in error due to the method he had used to correct the velocity measured in air containing moisture to obtain the dry-air value.

His revised estimate for dry air was remarkable c_o = 331.41 m/s.

The development of instrumentation during World War 1 for use in connection with sound ranging of enemy guns, notably the hot-wire microphone in the neck of Helmholtz Resonator developed by Tucker, led to further open-air determinations of sound velocity.

Among these were experiments reported by Esclangon[42] and a particularly detailed study by Angerer and Ladenburg[43], but the day of open-air measurements was long since past and their determinations were doubtless more accurate as methods for measuring the mean temperature along the sound path than as primary determinations of speed of sound[44].

Measurements of velocity of sound using a piezoelectric transducer and interferometric technique were reported by Pierce[45] who appears to be the first to report velocity dispersion (i.e. frequency-dependent velocity of sound) in air, based primarily on the laboratory studies and reviews of previous work reported by Hardy, Telfair and Pielemeier[46] supplemented by the work of Smith[47].

At 1 kHz and 1 atmospheric pressure the velocity of unbounded progressive plane waves in dry air containing 0.03% carbon dioxide and at 0 °C is given as (331.4 ± 0.05) m/s.

Harris[48], who made careful measurements of relative sound velocity, has shown that at room temperature it reaches a minimum value at a relative humidity of about 14% at which point it is approximately 0.2 m/s lower than the dry-air value: at 100% Relative Humidity (RH) the velocity is about 1.1 m/s higher than the dry-air value[49]. It is this value of 331m/s which is commonly referenced to in text books today.

The speed (velocity =speed with

Substance	Temp (°C)	Speed (m/sec)	Speed (ft/sec)
CO_2	0	258	816
CO_2	35	274	900
Air	0	331.5	1,087
Air	20	344	1,130
Water Vapor	35	402	1,320
Helium	20	927	3,040
Hydrogen	0	1,270	4,165
Water	15	1,437	4,714
Steel	20	5,000	16,400

Figure 22: Speed of sound in various substances and temperatures.

direction) of sound in dry air is generally given as:

$V_{\text{sound in air}} \approx 331.6 + 0.6\ T_c$ (m/s) (Equation 20)

The speed of waves is affected by the density of the medium and the density is affected by the temperature and pressure, the speed of sound through air varies depending on these (and other) factors.

Bieler-Butticaz[50] appears to have been among the first to note that the attenuation of sound in air is strongly dependent upon temperature and humidity although she gave no quantitative data. The speed varies depending on atmospheric conditions; the most important factor is the temperature.

Bieler-Butticaz noted:

> *"The humidity has very little effect on the speed of sound, while the static sound pressure (air pressure) has none. Sound travels slower with an increased altitude (elevation if you are on solid earth), primarily as a result of temperature and humidity changes."*

Einstein[51] discussed the velocity of sound in mixtures of dissociated and non-dissociated molecules of a diatomic gas and showed that it is possible to calculate the rate of energy transfer between the two kinds of molecule from a determination of the velocity of sound as a function of frequency.

This concept was applied to the calculation of sound attenuation in a gas by Herzfeld and Rice and soon afterwards Kneser[52] showed their analysis adequately explained the sound dispersion previously observed in carbon dioxide.

In a non-dispersive medium the speed of sound is independent of frequency, therefore the speed of energy transport and sound propagation are the same. Air is a non-dispersive medium. In a dispersive medium the speed of sound is a function of frequency. The spatial and temporal distribution of a propagating disturbance will continually change. Each frequency component propagates at each its own phase speed, while the energy of the disturbance propagates at the group velocity.

Water is an example of a dispersive medium.

The speed of sound (c) in a medium depends on the mediums elasticity (E) and its density (p) according to the relationship **$c = \sqrt{(E / p)}$**.

It is noted that the speed of sound increases with the stiffness of the material, and decreases with the density. In solids, the velocity of sound depends on density of the material, not its temperature. Solid materials, such as steel, conduct sound much faster than air.

Propagation speeds for other media are given in figure 22. For each degree Centigrade increase in temperature, the speed of sound increases by 0.61 m/sec. It appears apparent from the data available, that the precision achieved by field determinations, laboratory studies, and calculation of the velocity of sound is adequate.

References

9. Velocity is speed with direction.

10. Aristotle, De anima (On the soul), Vol. 11, 350 BC English translation in M. R. Cohen and I. E. Drabkin, A source book in Greek science. Harvard University Press, 1948.

11. Vitruvius (Marcus Vitruvius Pollio). De Architectura, Vol. 3 & 5. (For translation see "Ten book on architecture". Dover, London 1914.

12. Bacon, F., Sylva Sylvarum 1627.

13. Mersenne, M., De l'utilité de l'harmonie, part de l'harmonie universelle. Cramoisy, Paris 1636. (English translation in J.Hawkins, General history of the science and practice of music (3 Vol.). Novello, London 177; supplementary volume 1852, 6th edition 1875).

14. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

15. Gassendi, P., opera Omina, Vol. I, Lyons, 1658. (Abridged but corrupt text published in French by Bernier in 1684; see Lenihan).

16. Lenihan, J. M. A., Mersenne and Gassendi: A early chapter in the history of sound. Acustica 1 [1951], 96.

17. Torricelli, E., The barometer. A letter to Michelangelo Ricci in Rome, 1644. (See Collected works of Torricelli, Vol. 3, 1919, p. 186.).

18. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

19. Newton, I., Philosophaiae naturalis principis mathematica, Lodon 1687. (F. Cajori's revision of the translation by A. Motte of the 3rd edition, 1725, Univ. Cal. Press 1962.).

20. Lagrange, J. L., Recherches sur la nature, et la propagation du son. Miscellanea Turinensis 1 [1759], 1.

21. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

22. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

23. Fehrenheit, D. G., Experimenta circa gradum caloris liquorum nonnullorum ebullientium institute. Philos. Trans. Roy. Soc. 33 [1724], 1.

24. Celsius, A., Observationer om tvenne beständiga grader på en thermometer. Vertensk. Acad. Hand. Stockholm 1742. See Ostwald, Klassiker der exakten Wissenschaften, No. 57, 1904.

25. Cassini, C. F., Sur la propagation du son. Mém. De l'Acad. Paris, 1738, 128.

26. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

27. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

28. Bianconi, G. L., Experimentum circa velocitatem soni, an aestate celerior quam hieme. Comm. Bonon 2 [1740].

29. Euler, L., De la propagation du son. Mém. De l'Acad. Sci. Berlin 15[1766], 185 (Also opera Omina, 3 (i), 428.)

30. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

31. Laplace, P, S., Sur la vitesse du son. Ann. Chim. Phys. 3 [1816], 238.

32. Stokes, G. G., An examination of the possible effect of the radiation of heat on the propagation of sound. Phil. Mag. (4) 1 [1851], 305.

33. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington England.

34. Herzfeld, K. F. and Rice, F. O., Dispersion and absorption of high frequency sound waves. Phys. Rev. 31 [1928[, 691.

35. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

36. Arago, D. F. J., Résultats des experiences faites en 1822, par ordre du Bureau des Longitudes, pour la determination de la vitesse du son dans l'atmosphére. Ann. Chim. Phys. 20 [1822], 210.

37. Regnault, V., Sur la vitesse de propagation des ondes dans les milieux gazeux. C. R. Acad. Sci. (Paris) 66 [1868], 209.

38. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

39. Hebb, T. C., The velocity of

sound. Phys. Rev. 20 [1905], 89.

40. Hebb, T. C., The velocity of sound and the ratio of the specific heats for air. Phys. Rev. 14 [1919], 74.

41. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

42. Esclangon, E., Su rune nouvelle determination de la vitesse du son á l'air libre. C. R. Acad. Sci. (Paris) 168 [1919], 165.

43. Angerer, E. and Ladenburg, R., Experimentelle Beiträge zur Ausbreitung des Schalles in der freien Atmosphäre. Ann. Phys. 66 [1921], 293.

44. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

45. Pierce, G. W., Piezoelectric crystal oscillators applied to the precision measurement of the velocity of sound in air and CO2. proc. Amer. Acad. Arts Sci. 60 [1925], 271.

46. Hardy, H. C., Telfair, D. and Pielemeier, W. H., The velocity of sound in air. J. Acoust. Soc. Amer. 13 [1942], 226.

47. Smith, P. W., precision measurement of the velocity of sound in air. J. Acoust. Soc. Amer. 25 [1953], 81.

48. Harris, C. M., Effects of humidity on the velocity of sound in air. J. Acoust. Soc. Amer. 49 [1971], 890.

49. M.E. Delany. Sound Propagation in the Atmosphere: A Historical Review. National Physical Laboratory, Division of Radiation Science and Acoustics, Teddington, England.

50. Bieler-Butticaz, Variation d'intensité du son pour différentes conditions atmosphériques á la montagne en hiver. Archives Sci. (Genéve) 3 [1921], 548.

51. Einstein. A., Schallausbreitung in teilweise dissoziierten Gasen. Sitz.-Ber. Preussischen Akad. Wiss. Berlin 24 [1920]. 380.

52. Kneser. H. O., Zur Dispersionstheoric des Schalles. Ann. Phys. (Leipzig) 5 [1931], 761.

53. Archè Publications. Handbook of Acoustic Ecology. 1978. ❑

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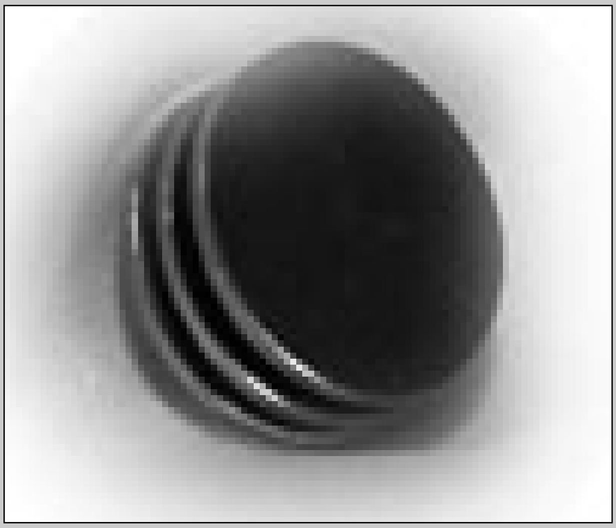

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