Section 2: On the Propagation of Sound Through Liquids and Solids

212. All Possible Materials Propagate Sound

The vibrations of a sounding body are transmitted to all contiguous material, directly or indirectly. Air is the ordinary conductor of sound and the most proper medium for transmitting the sensation of sound to the exterior organs of hearing to man and to all types of land animals. But all liquid and solid materials also propagate the sound with a great deal of intensity; the same with all of the modifications to the sound propagated by these materials.

213. Propagation of Sound in Water

The propagation of sound in *water* may be concluded from the fact that aquatic animals also possess organs of hearing; it is noted also in the experiments. When under water, one can hear sounds that are produced in the air, but one hears more strongly the sounds that are produced under water. (*Journal des Savants,* 1678, p. 178; Hawksbee, *Philos. Transact.* No. 321; Arderon, *Philosoph. Transact.* No. 486; Nollet, *Mém. de l'Acad. de Paris*, 1743 and *Leçons de Physique expérimentale*, vol. III, p. 417; Musschenbroek, *Introd. ad Philos. nat.*, vol. II, Sect. 226; Monro, *Physiology of fishes, etc.*, Ch. IX).

Sound produced in the water is also heard in the air. The air does not contribute at all to the propagation of sound in water; if the air contained in water is carefully separated, the propagation is the same, according to the experiments of Nollet and Musschenbroek. But, unlike air, water is not compressible when an enormous force is applied, except to a very small degree, according to the experiments of Canton, Abich, Zimmermann, and Herbert. One will not be able to apply the theory of the propagation of sound in air, to determine the way in which one particle of water transmits the pulse to another, which is not consistent in compression and

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expansion. These differences between liquids and expandable gases are also shown in that liquids never make the same sound vibrations as the air or other gaseous material contained in a pipe.

214. The Resistance of Water Delays the Vibrations of a Sounding Body

When a bell or a sounding vessel is full of water, or when a sounding body is plunged into water, the sound is graver than that produced in the air, because of the delay of the vibrations by the resistance of the water as a denser fluid. This delay increases when the vessel is filled with water, or when the sounding body is plunged more deeply under water. At an even greater depth, sound vibrations cease, and only an imperceptible clacking is produced. Some other liquids, for example, oil, milk, foaming champagne, etc., resist even more sound vibrations than water.

215. The Velocity of Sound Through Liquid Matter is Unknown

The velocity with which sound is propagated in water, or in other liquids, is completely unknown. One can nevertheless presume that it will not be the same at different depths, because the density does not increase due to the pressure, as in the expandable fluids. It would be difficult to do experiments on this subject.

216. The Intensity of Sound Propagated Through Water and Through Other Liquids

The intensity of the propagation of sound through water, when it is produced in the water, greatly surpasses that of the propagation of sound in the air. Nollet observed that the effect of two rocks striking against each other was almost unbearable. A sound produced in the air is also heard under water, but it is weaker, because of the lesser action of a less dense fluid[1] on a denser fluid.

Mr. Perolle did many experiments on the intensity of sound in different liquid materials, which he published in the *Mém. de l'Acad. de Turin,* 1790–1791. He used a watch hanging by a thread in a vessel filled with the liquid material to determine the distance at which one can still hear it ticking. In the air, this distance was 8 ft, in

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[1] Gas, for example.—*MAB*

water 20 ft, in olive oil 16 ft, in oil of turpentine 14 ft, and in ethanol 12 ft. When repeating these experiments, he did not always obtain the same results. We cannot demand in these experiments the same exactitude that would be required if there were a continuation of the same material between the sounding body and the ear; yet we can see that these fluids vibrate with more strength than air; even the vessel and the table it was placed on were noticeably vibrating; the surface of the water stayed still. Each fluid is distinguished by a different tone.

Mr. d'Arnim (*Annal. de Gilbert*, vol. iv, ch. 1, p. 113) notes that the intensity of sounds must be due to the specific gravities of fluids, if the other factors remain the same, and that the results that Mr. Perolle obtained do not differ very much in these specific gravities.

The surface of water stays still because the motion of each particle happens only in an extremely small space, such that it is impossible or almost impossible to perceive. The motions of the surface of the water, represented in Figs. 252 and 257, do not apply to the object I am talking about right now, because they are caused by sounding vibrations of the vessel itself, which pushes back the contiguous/surrounding water.

217. Solid Matter Also Propagates Sound

Solid materials propagate sound very strongly, especially if their shape is favorable to vibrations; but to better perceive the sound propagated by such a material, it is useful to press it against the firm parts of the head, which can transmit the impressions to the interior organs of hearing. A simple wire made of such a material will suffice to propagate sound; for example, when two people stretch out a wire, while holding the ends between the teeth, they can hear each other by covering their ears and speaking very low. If one hangs a large silver spoon at one end of the wire and holds the other end between the teeth, it sounds, when one's ears are covered, like the sound of a large bell. With the ear held to one end of a long beam, one distinctly hears the impact of a pin hitting the opposite end, whereas the same sound transmitted by air cannot be heard at the same distance. A rod of any length, thickness, and material transmits sound, and even words, very well if one of the ends is held against the sounding body and the other is held by the teeth or at another firm part of the head, especially when the material of the rod is somewhat elastic. The effect is almost the same if the person who is speaking holds the rod to their teeth, their throat, or even a button on their clothes, held tightly against their chest. Instead of a single rod one could also use an extension of several rods, even if they are joined at different angles. Words are heard even more distinctly if the rod is held against a metal, glass, or porcelain vessel, and if the speaker directs his voice toward the inside of the vessel. The intensity is even greater if the vessel itself is held against the teeth, or another suitable part of the head. The sounds of an instrument are heard very well, when the ears are blocked, and the end of the rod is pressed to the resonant table or against the walls of the instrument. In the same way, it would also be possible to hear the sound of a tuning fork pressed against an instrument, after its vibrations, propagated by the air, stop being perceptible to the ear. This method of hearing sounds produces a sensation almost as if the sound were coming from the rod itself. Every material changes the tone differently.

Deaf people, or those who are hard of hearing, could use this method to hear words or the sound of an instrument, if the cause of their hearing loss is located in the exterior organs; but if the interior organs are the cause, it would not be helpful to them.

This propagation of sound through all solid materials also allows the miner digging a passageway to hear the blows of the miner on the opposite side and thereby judge his own direction.

Many observations about the propagation of sounds by solid materials can be found in a dissertation by J. Jorissen, *Nova methodus, surdos reddendi audientes,* Halle, 1757; and in another by Winkler: *de Ratione audendi per dentes,* Lips. 1759; in Kircher's *Musurgia*, book 1, sec. VII, ch. 7; in *Boerhavii Praelect. in Institut. Rei medicae*, vol. IV*, de auditu*, *etc.* More recent studies include those of Perolle, Biot, Herhold, and Rafin.

218. Direction of Motions

One can presume that the longitudinal or transverse direction of the motion of a propagating body, when it is pushed by the vibrations of a sounding body, depends in part on the form of the propagating body, and in part on the direction in which the sounding body acts on the body that propagates the sound. The nature of the vibrations of the sounding body (if they are transverse or longitudinal) will be indifferent.

219. Velocity of Sound Through Solids

It seems to me that the *velocity of the propagation of sound in solid materials,* as long as it is made by longitudinal vibrations, can be determined by the following method. Sound is propagated by a length of open air in the same amount of time as that of a column of air of the same length, enclosed in a pipe, which makes a longitudinal vibration (Par. 185). The longitudinal vibrations of rigid bodies (Pars. 77–83) follow the same laws as air; we can thus suppose that the sound is propagated by each rigid or expandable material at the same time that that material, as a sounding body, makes a longitudinal vibration. The propagation of sound by rigid materials would thus be all the more rapid as the longitudinal sound gets more acute, supposing that the length is the same. Therefore, roughly the same correlation will exist between these velocities and the velocity of the air, as the sounds presented in Par. 82. However, the length being the same, the longitudinal sound of tin is more acute than that of air by two octaves and a major seventh. That of silver is more acute by three octaves and a tone, and that of copper by almost three octaves and a fifth. Those of iron, glass, and fir, whose vibrations are more rapid, surpass that of air by at least four octaves and a semi-tone, etc. So if there were a sufficiently long and homogeneous continuation of such a material, the speed of the propagation of sound by air would be surpassed by that of tin approximately 7.5 times, silver 9 times, leather almost 12 times, iron and glass almost 17 times, different types of wood 11–17 times, and terracotta roughly 10–12 times.

220. Experiments That Have Been Performed on This Subject

The experiments that have been done up until now note a greater speed of the propagation of sound through solid materials than through air. Mr. Wunsch, Professor at Frankfurt-on-Oder, published experiments (in his *Mémoires allemands, présentés à l'Académie de Berlin* 1793) on the propagation of sound by a very extended expanse of wooden boards. Sound is propagated much more rapidly than by air; but we cannot agree with him when he claims (like Hook in the preface of his *Micrographia*) that sound propagates itself through solid bodies instantaneously, or at least as quickly as light. Mr. Herhold and Mr. Rafin in Copenhagen performed experiments (published in Reil's *Archiv für die Physiologie*, vol. III, ch. 3, p. 178) on the propagation of sound by a cord with a length of 300 ells or 600 Danish feet. One of the ends of this twisted linen cord was tied to a wooden stake, and a silver spoon was attached near that end, so that they hit each other; the other end was pressed against the ear, or held in the teeth, while holding the cord. The sound was heard through the cord much quicker than through the air; the difference seemed to them to be almost a second, which seems to be too much for that distance. The most interesting experiments on this subject are those of Mr. Biot, which I mentioned in Pars. 201 and 205, described in vol. II of *Mémoires de la Société d'Arcueil*, p. 403. For these experiments, he used pipes in a Parisian aqueduct, made of cast iron, that altogether formed an uninterrupted length of 951 m (488 toises). In the last pipe, he placed an iron ring of the same diameter as himself, wearing at his center a bell and a hammer that could be dropped at will. So at the other end it must have been possible to hear two sounds, one transmitted by metal and one transmitted by air. He went on to verify these experiments with two demonstrations where, after a certain time, someone delivered a blow at each end. Mr. Hassenfratz (*Traité de Physique par M. Haüy,* sec. 479), having gone down into one of the quarries located underneath Paris, tasked someone to hit a hammer against a rock mass that forms the wall of one of the passageways, in the middle of the quarries. He always distinguished two sounds, one of which, transmitted by the rock, arrived earlier than the other, transmitted by air; but it also got weaker more rapidly as the observer got farther away.

221. Intensity of Sound Propagation Through Solids

The intensity of the propagation of sound through solids greatly surpasses the intensity of the propagation of sound through open air (Par. 216). The best experiments on this subject are those of Mr. Perolle, published in the *Mém. de l'Acad. de Turin*, 1791–1792, and in the *Journal de Physique,* vol. XLIX, p. 382. He used various materials, with one end touching a watch and the other touching one of the firm parts of the head; assuming the ear was not blocked, the sound was heard much better than if the sounding body had been placed in the air at a much lesser distance. The intensity of the propagation by cylinders of different types of wood seemed to decrease in the following order:

1. Fir
2. Campeche wood
3. Boxwood
4. Oak
5. Cherry
6. Chestnut

In general, the metal cylinders propagated the sound a bit less than the wood cylinders. The intensity seemed to follow this order:

1. Iron
2. Copper
3. Silver
4. Gold
5. Tin
6. Lead

The strings propagated it with less force than the solid bodies, and the intensity seemed to follow this order:

1. Catgut
2. Hair
3. Linen
4. Silk
5. Hemp
6. Wool
7. Cotton

The pieces of zinc, antimony, glass, rock salt, gypsum, and dried clay were also good conductors of sound; marble was noticeable for the small amount of force with which it transmitted the motion.

In the experiments that I performed on this subject, I observed the greatest intensity when the sound was propagated by glass rods or by thermometer or barometer tubes, and by rods of fir wood.

It seems that the intensity also depends on the shape of the body propagating the sound, if it is more or less suitable for vibrating in different ways. A rod or a blade will propagate sound much better than a shapeless mass of the same material.

Descartes has already noted (in *Epist.* p. 2, ep. 72) that the intensity of the propagation of sound by solid bodies is greater than the intensity of the propagation of sound by air, due to the greater cohesion of these bodies.

222. Reinforcement of Sound by a Resonant Board

The resonance of solid bodies is used to increase the effect of a sounding body that, without this artificial means, would have too little intensity. The sound of a string, stretched on a narrow piece of wood, with no support, would be very weak; this is the reason why one stretches the string on a thin wooden board, to increase the effect of the vibrations that the string transmits to this bigger surface. Also, the sound of a very weak tuning fork or another type of fork is greatly increased when this body is leaned on a wooden board, or on another support that is sufficiently extensive and elastic. A similar resonant body must be looked at as being of indeterminate dimensions, since it vibrates in all possible intervals of time. In every sound, reinforced by vibrations transmitted to a larger surface, the whole body resonates in motion, in such a way that it is divided into vibrating parts, alternately above and below, separated by nodal lines, almost as in the characteristic vibrations of plates, described in Sect. 7 of the preceding part. If one wants a resonant board to reinforce all sounds, especially the gravest, it must not be too small or too thick, and it must be elastic enough to easily vibrate in all modes. In observing carefully, one will find that a resonant board often reinforces some sounds more than some others; this unequal reinforcement is most likely to take place if the sounds are the same as those that the board could render if it were the sounding body. One will be able to find the places that are more or less in motion in the reinforcement of a sound, while supporting a tuner that renders the same sounds, successively, at the different points of the board and while observing the different intensities of the sound. Any wooden box will serve for these experiments. The differences in intensity will again be greater if one sets up or supports a pointed iron wire in different places, in order to produce the modes of vibration described in Pars. 69 and 70.

A resonant board will reinforce several sounds at the same time, vibrating in different modes, when one does not prevent the other (Pars. 164–176).

Maupertuis (in the *Mém. de l'Acad. de Paris*, 1724) has better explained the intensification of all the sounds made by the same board, by claiming that each sound shook only some fibers endowed with an elasticity in compliance with this sound.

223. Sound Produced by Motions in all Bodies That Can Vibrate in the Same Time Intervals

A sound that is transmitted in the air, or in solid matter, puts in motion all of the bodies that can vibrate in the same time interval. If, in the same instrument, or in different instruments that can act on one another by the air or by a continuation of other material, two strings are in unison, and one of the strings is put in motion, the other will also vibrate; because in every time interval where it can make a vibration, it is pushed again by the vibrations of the other one. The same phenomenon will take place if one of the equal sounds, or both of them, result in divisions of the string into aliquot parts. One can render visible the nature of these vibrations by putting small papers on different points of the string (Par. 37).

Another reverberating sound will also produce more or less such a resonance, because one of these bodies, after a small number of vibrations, is pushed again by a vibration of another. A strong enough sound can rather easily shake windowpanes, walls, or other objects; this happens in the case where the nature of the shaking body permits it to vibrate in the same interval of time as the body that produces the sound.

224. Vessels Can be Broken by the Voice, According to Some Authors

Some authors, such as Morhof (*Stentor hyaloclastes, sive de scypho vitreo per vocis humanae sonom rupto*, Kil., 1683) and Bartoli (*Trattato del suono e de tremori armonici,* Bologna, 1780), talked of glass vessels, thin and convex, that were broken by a very strong and sustained voice, and that this phenomenon was preceded by a very strong quivering. The sound of voice then had to be the same each time; an octave that was suited to the vessel. I have also been told of a place in the *Talmud* (*Bawa Kama*, 18) that contains discussions on the damages that can be demanded when a vessel is broken by the voice of a domestic animal; which leads one to presume that, if a similar case had never happened, one would not have conceived the idea to take up discussion on this subject.