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Measuring longitudinal wave speed in solids: two methods and a half

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Abstract

Three methods to analyse longitudinal wave propagation in metallic rods are discussed. Two of these methods also prove to be useful for measuring the sound propagation speed. The experimental results, as well as some interpretative models built in the context of a workshop on mechanical waves at the Graduate School for Pre-Service Physics Teacher Education, Palermo University, are described. Some considerations about observed modifications in trainee teachers' attitudes to utilizing physics experiments to build pedagogical activities are discussed.

1. Introduction

The physics of mechanical wave propagation plays an important role in the education of physicists and engineers. In fact, it provides a simple introduction to wave phenomena and can be helpful in making sense of more complex subjects such as physical optics, quantum mechanics and electromagnetic radiation.

It has been shown [1–3] that many students, also at university level, have many difficulties in understanding the basic concepts of mechanical wave phenomena such as, for example, what a wave is and how propagation is influenced by the properties of the medium. This fact can be surely related to significant time constraints in today's undergraduate mechanics college courses, which make it difficult to treat this subject in detail and to deepen understanding of the relevant conceptual points. However, we think that more 'structural' educative issues can bias the students' understanding of mechanical wave phenomena. For example, the rigid body is very often not described as a model of real bodies and its study is rarely followed by deepening the understanding of the fundamental role of wave propagation in the motion of real, elastic bodies [4].

It is generally acknowledged that laboratory activity has to be a standard component in physics courses in schools and universities and many experiments related to mechanical waves can be easily carried out, allowing students to better understand wave properties. Moreover, the use of computer-assisted data acquisition systems (often known as MBL systems [5–7]) can greatly enhance students' learning and stimulate their interest, mainly when these are connected to pedagogical methods that engage students in activities which address the cognitive difficulties identified by physics education research [8].

The measurement of sound speed in air is a routine task [9], but the measurement of sound speed in solids, especially in metals, can be more difficult due to the much higher values with respect to air. Some papers report measures of longitudinal wave speed in solids based on the method of vibrating rods [10, 11]. A thin rod is clamped at its midpoint and an acoustic wave is generated at one end of the rod by a sound generator or by rubbing it by the thumb and the forefinger fingertips. In this way, stationary longitudinal waves are established and the rod oscillations can be detected and analysed in their frequency components. An estimate of the speed of longitudinal waves is then given by using the well-known resonance relation between the wavelength and the length of the rod itself.

This experimental method, although easy to implement, is based on the understanding of many relevant concepts of wave physics, such as the spectral analysis of signals or the relationship between stationary and progressive waves. Moreover, many students, also at university level, do not understand how the speed of progressive waves can be measured by using a method based on the idea of stationary waves.

In this paper, we describe three different experimental methods to measure the acoustic wave speed in metallic rods and present the related experimental results, obtained by using commercial MBL systems for data acquisition. The sound speed is obtained by directly measuring distances travelled by longitudinal pulses and the related times. Some relevant implications will be drawn about the relationships between experimental methods and construction of appropriate models to describe and explain mechanisms of functioning. Considerations about observed modifications in trainee teachers' attitudes to utilizing physics experiments and performing data analysis will be presented in the last part of the paper.

The experiments were performed during the mechanical wave lab section of the Graduate School for Pre-Service Physics Teacher Education curriculum, at Palermo University, where the lab work is aimed at giving explanations of observed practical and real-life situations as well as at introducing and/or deepening the understanding of relevant physics topics [12].

2. Longitudinal wave propagation in elastic bodies

It is well known that the theory explaining the motion of elastic bodies has to take into account wave propagation inside the bodies. This theory has received detailed treatment in the scientific literature [13, 14], but the role of wave propagation in the motion of elastic bodies is a topic usually not well dealt with in introductory physics courses, as well as in courses for teacher preparation.

A recent paper [4] describes the motion of solid bodies, under the action of impulsive forces, in terms of motion of wave pulses propagating to and fro into them. In particular, the authors describe the time dependence of the centre-of-mass position in an elastic rod of length L, cross-sectional area S and mass density ρ, on which a compressional constant force, F, acts at one of its ends (say the left) for a time interval Δt and then drops instantaneously to zero.

The impulse generates at $t = 0$ a compressional wave pulse that propagates along the rod with velocity c. We assume the rod length L to be much greater than the length $c\Delta t$ of the

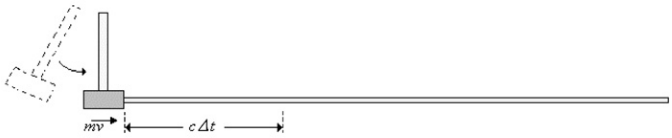

Figure 1. A hammer, of head mass m, colliding at velocity v with a rod of length L, and producing a compressional wave pulse travelling along the rod with velocity c.

rod part involved in the wave pulse. The change in the length of the rod due to either the compression or extension is assumed to be small in comparison with the rod length. Taking into account a generic particle, p, internal to the rod, placed at a distance d with respect to the left end of the rod, the propagation of the compressional pulse produces a particle motion along the direction of propagation. At $t = d/c$ the particle starts to move, with velocity u, for the time interval Δt and then stops. It is assumed $u \ll c$. The wave pulse reaches the free end of the rod at the instant $T = L/c$ and it is partially reflected and partially transmitted.

It can be easily shown that the particle velocity due to the reflected wave pulse is related to the characteristic impedance, $Z = \rho c$, of the materials on both sides of the boundary [15]. If u_i indicates the particle velocity due to the incident wave pulse and u_r the particle velocity due to the reflected pulse, we have

$$u_{\mathrm{r}} = \frac{Z_{\mathrm{m}} - Z_{\mathrm{a}}}{Z_{\mathrm{m}} + Z_{\mathrm{a}}} u_{\mathrm{i}}, \qquad (1)$$

where Z_{m} and Z_{a} are the characteristic impedances of the metallic rod and air, respectively. Because $Z_{\mathrm{m}} \gg Z_{\mathrm{a}}$, u_{r} has the same direction of u_{i} and $u_{\mathrm{r}} \approx u_{\mathrm{i}}$. So, the reflected pulse is an extensional wave and when it reaches p, the particle again starts to move during the time interval Δt with velocity $\approx u$ along the x-axis in the same direction as before. Finally, at $t = 2T$ the extensional wave pulse reaches the left end of the rod and a compressional wave pulse arises, propagating again along the rod, as happened at the instant $t = 0$.

Kaufmann *et al* [4] show that the velocity of particle p during each period T is either zero or u and that a relationship can be established between the velocity of the rod centre of mass, V, the mean velocity of particle p during each period T and the value of the particle speed, u.

We now consider the impulse, $F\Delta t$, as exerted by a massive body (for example a hammer head of mass m), colliding at velocity v with the end of the rod along the x-axis, as shown in figure 1.

We assume that the force exerted by the hammer on the rod rises instantaneously from zero to a constant value F then after a time, Δt, it drops instantaneously to zero again. We also assume that the hammer can be considered a rigid body (a good approximation for non-rod-shaped, massive hammer heads, small with respect to the rod's length). Since the force on the rod's end is constant for a time Δt, the particle velocity, u, in the rod is the same over the entire length $c\Delta t$ and we assume that $u \ll c$.

In order to find a relationship between the speed, v, of the colliding body and the particle velocity in the rod, we consider the simple case in which the colliding body, of mass m, comes totally at rest after the stroke (i.e. after the time Δt). Conservation of momentum requires that the body initial momentum, mv, is transmitted to the wave in the rod. So we can write

$$mv = \rho Scu\Delta t, \qquad (2)$$

where $\rho Scu\Delta t$ represents the momentum of the wave pulse.

The wave pulse energy is $\rho Scu^2\Delta t$, and from the conservation of energy we can write

$$\frac{1}{2}mv^2 = \rho Scu^2\Delta t.$$

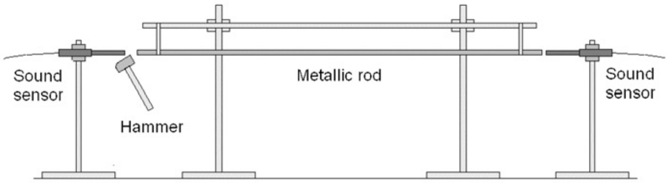

Figure 2. Method 1 experimental apparatus. The two sound sensors are connected by an MBL interface for data collection.

Combining these two relations, we obtain

$$u = \frac{v}{2}, \tag{3}$$

that is, when the hammer comes totally at rest after the stroke, the particle velocity is half the initial velocity of the colliding body. By (2) and (3), we can now obtain the value of the body mass producing a total transmission of momentum to the wave pulse

$$m = \frac{\rho S c \Delta t}{2}. \tag{4}$$

This value is equal to half the mass involved in the wave pulse and is independent of the velocity, v, of the body colliding with the rod.

If we use a colliding body of mass in accordance with (4), after the stroke the body is at rest, in contact with the rod where the wave pulse is propagating. This contact will be lost when the extensional pulse arrives at the struck end and the extreme metal layers move away from the colliding body.

The estimated value of collision times between a hammer and a metallic rod is $\Delta t \approx 10^{-4}$ [15]. As a consequence, a portion of length $l = c\Delta t \approx 0.5$ m of an aluminium rod ($c_{al} = 5 \times 10^3$ m s^{-1} [16]) is influenced by the wave pulse. If we consider a thin rod of the same metal ($S = 8\times10^{-5}$ m^2, $\rho_{al} = 2.7\times10^3$ kg m^{-3}), it is also possible to find a value of the rod mass, M, involved in the wave pulse and, consequently, the mass of the colliding body producing a total transmission of momentum to the wave pulse: $M = S\rho c\Delta t \approx 0.10$ kg; $m \approx 0.05$ kg.

By considering a colliding mass velocity equal to 3 m s^{-1} (as is in our experimental setting, see section 3.2 for detail), the particle velocity due to the wave pulse should be $u = 1.5$ m s^{-1}. During the time Δt, the end of the rod should displace $u\Delta t = 1.5 \times 10^{-4}$ m to the right.

3. Experimental methods

3.1. Method 1

The speed of sound, c, in a solid rod of length L can be easily calculated by evaluating the time, t, in which a longitudinal wave pulse goes from one end of the rod to the other. A very simple way of measuring t is to generate a wave pulse at one end of the rod, for example by means of a hammer stroke, and make use of two sound sensors placed at the rod ends to detect signals, as shown in figure 2.

The sound sensor placed near the end of the rod hit by the hammer should detect a signal before the other one. The delay time, t, between the two signals represents the travelling time of the longitudinal wave pulse, generated by the stroke. A greater delay time should be expected for the wave pulse propagating in air. Measurements are performed using 3 m long metallic rods (much longer rods are not easily manageable in school laboratories).

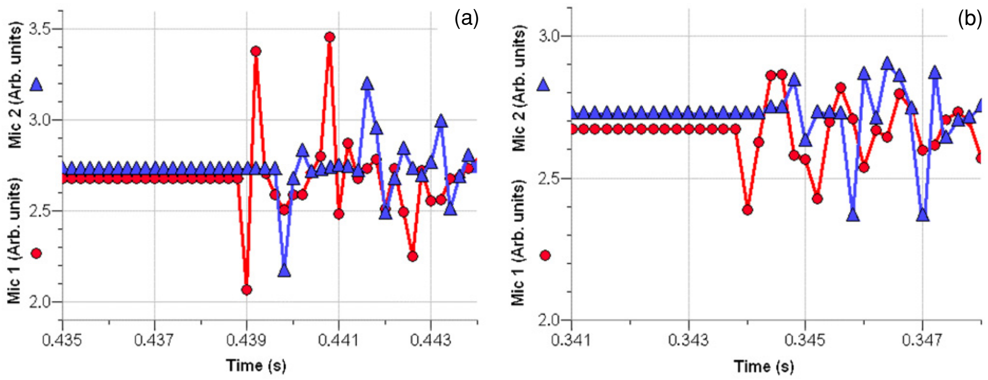

Figure 3. Typical signals detected by the sound sensors of the apparatus as shown in figure 2. Measurements are performed with (a) a brass rod and (b) an aluminium rod, 3 m long. Circles and triangles represent data taken by the sensors placed near the end of the rod hit by the hammer and near the rod's other end, respectively.

(This figure is in colour only in the electronic version)

From the known values of the sound speed in metals, typical values expected for t are of about 10^{-3} s or less. As the uncertainty of the time intervals measured with an MBL system is equal to a sampling point, we should use a sampling rate of at least 20 000 points s^{-1} in order to have an acceptable experimental error (of about 5%). On the other hand, the commercial data acquisition systems available in schools are limited to data sampling rates of about 5000 points s^{-1}, when two sensors are used. As a consequence, the experimental uncertainty on time measurements is $\delta t = 2 \times 10^{-4}$ s, corresponding to a percentage error of about 20% or more. However, in our opinion this experiment can still be considered conceptually effective in order to show the lowering of time of pulse propagation in solids, when compared with the time of propagation in air, that can be measured with the same set-up, with an accuracy of about 10 times higher.

Typical results are shown in figures 3(a) and (b), obtained by using a brass (measured density $\rho_{br} = 8400 \pm 100$ kg m^{-3}) and an aluminium ($\rho_{al} = 2800 \pm 30$ kg m^{-3}) rod. The rods are cylindrical, 3 m long and have a cross-sectional diameter equal to 1 cm.

The figures show that the delay times, t, are of four and two sampling intervals in brass and aluminium rods, respectively. These results give values of $t = (8 \pm 2) \times 10^{-4}$ s in brass and $t = (4 \pm 2) \times 10^{-4}$ s in aluminium. As considered before, these values are affected by large percentage errors, 25% in the case of brass rods and 50% in the case of aluminium.

Measurements show reliable delay times but, being affected by relevant uncertainty, they can only give qualitative evidence of the dependence of the travelling times from the material.

3.2. Method 2

A nice demonstration of the mechanical wave propagation in metallic rods can be obtained by producing a shock wave at one end of a fixed rod and observing a small pendulum bob, initially in contact with the rod's other end, displacing after a definite time interval.

With this method it is possible to give an estimate of the propagation speed of wave pulses in the metal by measuring the length of the rod and the time interval the wave pulse takes to travel along the rod. In order to obtain reproducible measurements we arranged the colliding body as a pendulum falling from a given height, so as to control the impulse on the rod. The

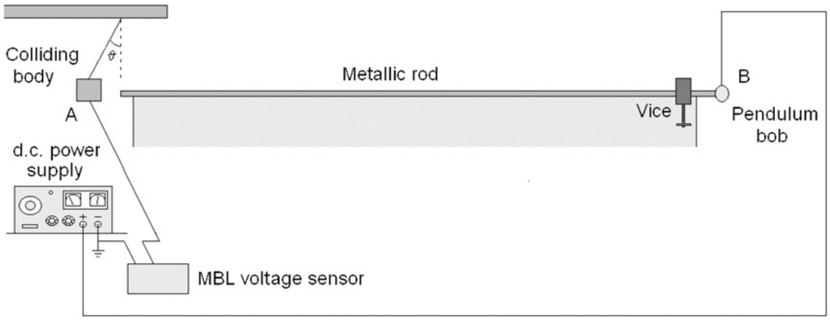

Figure 4. Method 2 experimental apparatus. A small metallic pendulum bob (B), initially in contact with the right end of the rod, is displaced by the perturbation generated by a body (A) colliding with the left end of the rod.

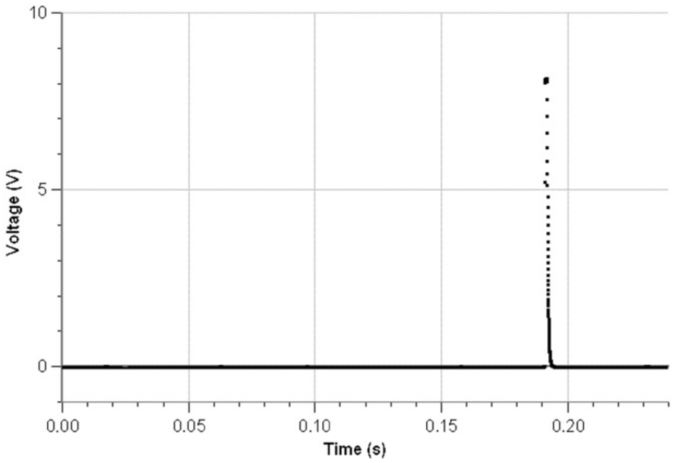

Figure 5. Typical signal detected by the voltage sensor in the experiment of figure 4. The sampling rate is 50 000 samples s^{-1}.

time measurement can be performed by using a voltage sensor to detect a signal in the electric circuit composed by the colliding body, the metallic rod and the pendulum bob, all conductive, as shown in figure 4.

The electric circuit is closed when both the colliding body and the pendulum bob are in contact with the metallic rod, secured to a heavy desk by means of a single vice placed near the right end of the rod. The idea is to exert a stroke to the rod when the pendulum bob is at rest; the action closes the circuit, so that a dc voltage is detected by the voltage sensor. The signal lasts until the wave pulse arrives at the other end of the rod and makes the pendulum bob displace, actually opening the electric circuit. An estimate of the time interval that the pulse takes to travel between the two rod ends can be obtained by the duration of the voltage peak detected by the voltage sensor.

Measurements are performed by using several brass and aluminium rods of different lengths and cross sections. Figure 5 reports a typical signal detected by the MBL system when a colliding mass equal to 398.0 ± 0.1 g, falling from a well-defined position ($\theta = 30^\circ \pm 1^\circ$, see figure 4), hits an aluminium rod of length $L = 2.995$ m and cross-sectional diameter

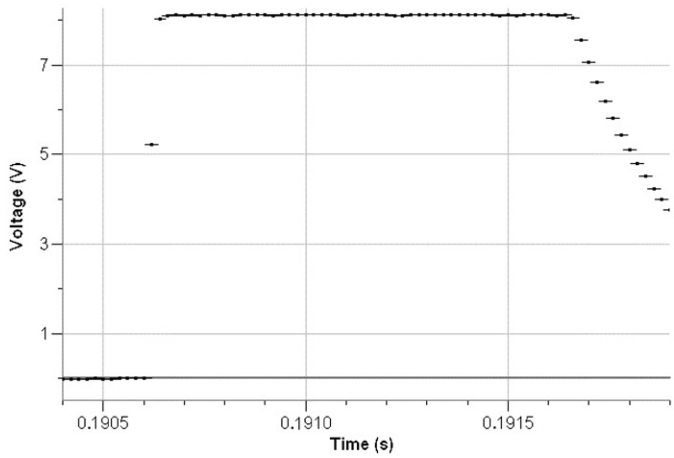

Figure 6. An enlargement of the voltage peak reported in figure 5. The error bars are equal to 2×10^{-5} s.

$D = 1.00$ cm. All rod lengths are measured using a 5 m long metric tape, with 1 mm sensitivity. The rods' diameters are measured using a vernier calliper, with 1/10 mm sensitivity.

The sampling speed is set to 50 000 points s^{-1} (the maximum available with our data acquisition system when using a single sensor set-up). An enlargement of the detected voltage peak is reported in figure 6.

The travelling time, τ (i.e. the time the wave pulse takes to travel through the rod and make the pendulum bob displace, actually opening the measuring electric circuit), can be easily measured by considering the time interval corresponding to the constant part of the peak. We also take into account the two points belonging to the leading edge of the voltage peak, since they are due to electric latency in MBL hardware circuits. The value of τ for the data depicted in figure 6 is $\tau = (1.06 \pm 0.02) \times 10^{-3}$ s, the experimental error being calculated as a time interval between two successive data points.

3.3. Method 3

An experimental approach to the measurement of sound speed in solids is suggested in the teacher's guide of the classic textbook [10]. We modified the suggested method in order to utilize commercial devices and performed different kinds of experiments in order to deepen the students' understanding of the pulse propagation process.

The experimental apparatus can be considered as a variation of method 2 apparatus. Here the metallic rod, of length L, is hung on non-conductive elastic bands below another rod supported by stands. A dc power supply is connected, through an MBL voltage sensor, to one end of the suspended rod and to a metallic body, arranged as a pendulum and set to collide with the rod, as shown in figure 7.

If the electric circuit is closed by making the colliding body come into contact with the rod's left end, a voltage signal can be detected by the data logger. The body, of mass m, falling from a given height will collide with the rod's end, exerting an impulse on it. The body remains in contact with the rod while a compression pulse travels along the rod. Because the right end of the rod is free, the reflected pulse is an expansion pulse and when it reaches the rod's left end, the contact is broken, actually triggering the end of signal detection.

The signal duration is related to the distance travelled by the pulse (two times the rod's length), so the speed of the acoustic waves in the rod can be easily calculated.

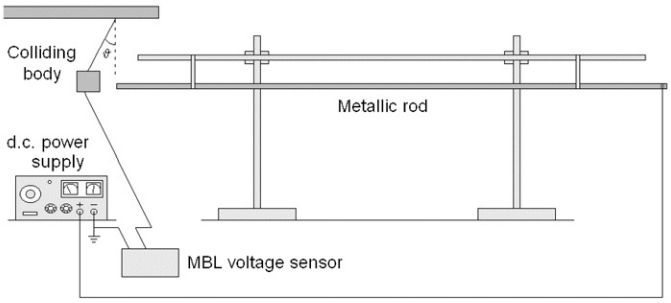

Figure 7. Method 3 experimental apparatus. The voltage sensor detects the dc power supply voltage when the colliding body is in contact with the rod.

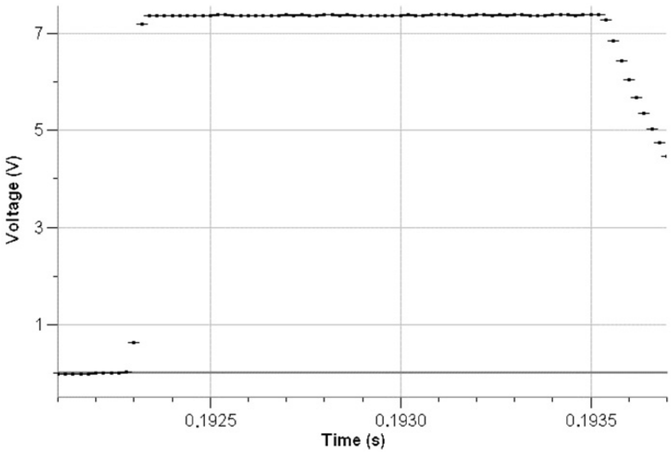

Figure 8. Signal detected by the voltage sensor with the experimental apparatus sketched in figure 7. The MBL sampling rate is 50 000 samples s^{-1}. The error bars are equal to 2×10^{-5} s.

Measurements are performed using the same cylindrical aluminium and brass rods of method 2. Figure 8 shows the enlargement of the voltage signal detected by the MBL system when using the same colliding body used in method 2, falling again from $\theta = 30^\circ \pm 1^\circ$ (see figure 7). Here we use an aluminium rod of length $L = 2.995$ m and cross-sectional diameter $D = 1.00$ cm.

The travelling time, τ (i.e. the time the wave pulse takes to travel through the rod and then back to the end that was hit, actually opening the electric circuit), can be easily measured by considering the time interval corresponding to the constant part of the peak. In the case reported in figure 8, we obtain $\tau = (1.24 \pm 0.02) \times 10^{-3}$ s, a value that is in good agreement with expected travelling times in a 3 m long aluminium rod.

More measurements have been performed using aluminium and brass rods of different lengths and cross-sectional diameters and they will be discussed in the following section.

4. Sound speed calculation

Travelling times obtained with rods of different lengths and cross-sectional diameter $D = 1.00$ cm are reported in figures 9 and 10 for brass and aluminium rods, respectively. Similar results are obtained for sets of rods with different D.

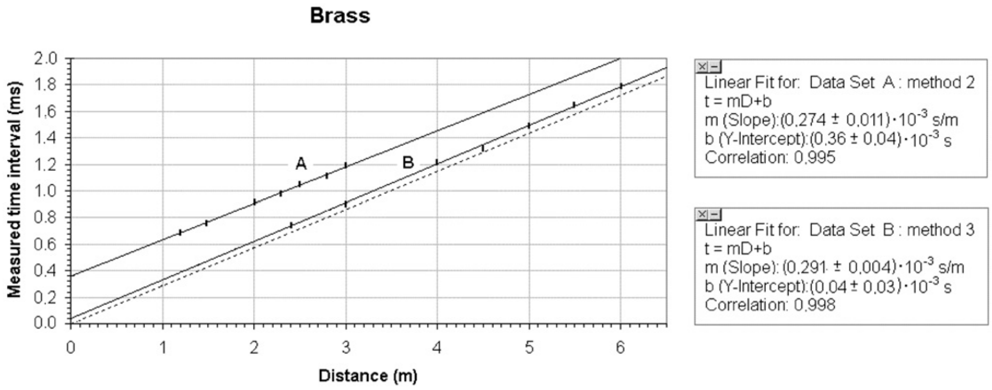

Figure 9. Time interval versus travelled distance measured by using brass rods of different lengths and cross-sectional diameters equal to 1.00 cm. Continuous lines are experimental data fittings. The dashed line is the linear relation of time versus distance for the accepted value of sound speed in brass rods.

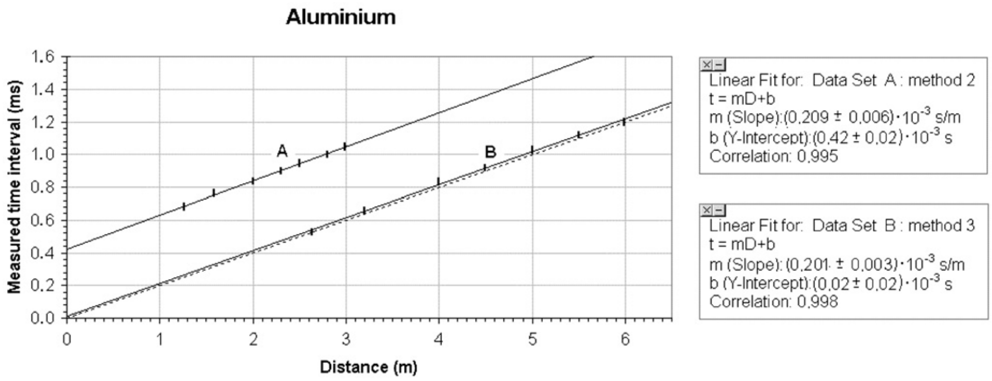

Figure 10. Time interval versus travelled distance measured by using aluminium rods of different lengths and cross-sectional diameters equal to 1.00 cm. Continuous lines are experimental data fittings. The dashed line is the linear relation of time versus distance for the accepted value of sound speed in aluminium rods.

In both figures, data marked as A and B represent the travelling times measured with methods 2 and 3, respectively. Each point is the mean value of ten measurements and the error bars are standard deviations of mean values. The lines are least-squares fittings of experimental data and the fit parameter values are reported in the tables on the right-hand sides of the figures. The dashed lines represent the travelling time–distance relation obtained by using accepted values for the sound speed in brass and aluminium rods reported in handbooks [16] and summarized in table 1.

The figures show that the slopes of all the fitting lines are in accordance with the accepted values. Moreover, the y-axis intercepts of fitting lines to method 3 data can be considered zero. The y-axis intercepts of fitting lines of method 2 data are significantly different from zero and this result deserves more attention.

The existence of non-zero y-axis intercepts of method 2 data fittings means that the measured time intervals, τ, are systematically higher than the expected values. This can be

Table 1. Values of the sound speed in aluminium and brass rods, calculated using methods 2 and 3, and accepted values, as reported in handbooks [15].

	Sound speed (m s^{-1})		
Rod material	Method 2	Method 3	Accepted values
Aluminium	4800 ± 120	4980 ± 80	5000
Brass	3600 ± 150	3440 ± 50	3480

explained by considering that the process of contact loss between the pendulum bob and the rod's right end involves some additional time, δt. The measured time intervals include the time taken by the wave pulse to travel along the rod plus a delay time δt that can be considered as the time needed by the bob to actually lose contact with the rod. A similar effect is reported by Mak *et al* [17], who use an experimental method similar to our method 2 to measure the speed of sound in metal rods. They employ a fast timer (sensitivity 1 μs) to measure the time required for a compressional pulse to travel along a rod from end to end and a crystal earphone as a pulse collector-detector. They also point out a lag time in the measured times and perform an end correction by comparing the timing of two rods of different lengths for each tested material.

An analogous delay time is not observed in method 3 data. Here the start and the end of data collection are triggered by the onset and loss of the electric contact of the colliding body with the rod, respectively. We can suppose that if a delay time exists at the creation of the shock pulse, an analogous delay time is present at the arrival of the reflected wave pulse at the left end of the rod. Since the start and end of data collection are triggered by the same body, it is reasonable to assume that these two delay times are almost equal and so cancel each other.

This 'symmetry' is not present in method 2, where the start of data collection is triggered by the onset of electric contact between the colliding body and the rod, but the end is controlled by the loss of contact between the rod and a different body, the pendulum bob.

Table 1 summarizes the sound speed values obtained in aluminium and brass rods with methods 2 and 3, together with accepted values. The error bars are calculated by using the uncertainties on the slope of the fitting lines, reported in figures 9 and 10.

Literature references [10, 17] use a hammer head to hit the rod and generate the wave pulse, without other considerations about its mass. A crucial point in this experiment is the mass value of the colliding body that makes it stay in contact with the rod for all the time the wave pulse takes to go from an end of the rod to the other and back to the first. Looking at (2) and (4), one can expect that if the colliding body mass is too small, it will bounce back before the reflected wave pulse can return to the rod end where the pulse originated. As a consequence, care should be taken in choosing the colliding body mass, as it depends on both the density and the section of the rods.

By following these considerations, more measurements have been performed with method 3 using different colliding masses falling from the same position ($\theta = 30°$). Figure 11 shows the plot of the measured travelling times as a function of the colliding body masses, detected in the brass rod with $L = 3.010$ m and $D = 1.00$ cm.

Figure 11 shows that by using colliding bodies of mass equal to or greater than 0.32 kg all the detected time intervals, τ, are almost constant, with a mean value of $\tau = 1.75 \pm 0.02 \times 10^{-3}$ s. If lower values of the colliding body mass are used, the detected values of τ appear to be remarkably smaller. By taking into account equation (4), we can infer the existence of a minimal value of the mass, m^*, for which the colliding body remains in contact

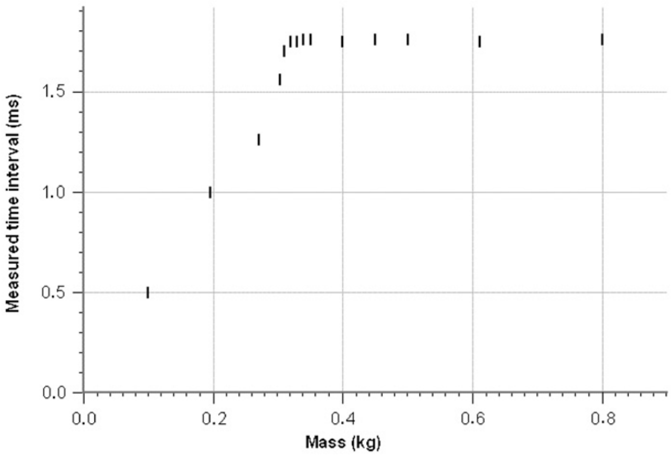

Figure 11. Plot of measured travelling time versus mass value of the colliding body in a 3 m long brass rod. Each point is the mean value of ten measurements performed using the same colliding body mass. Error bars are the standard deviations of mean values.

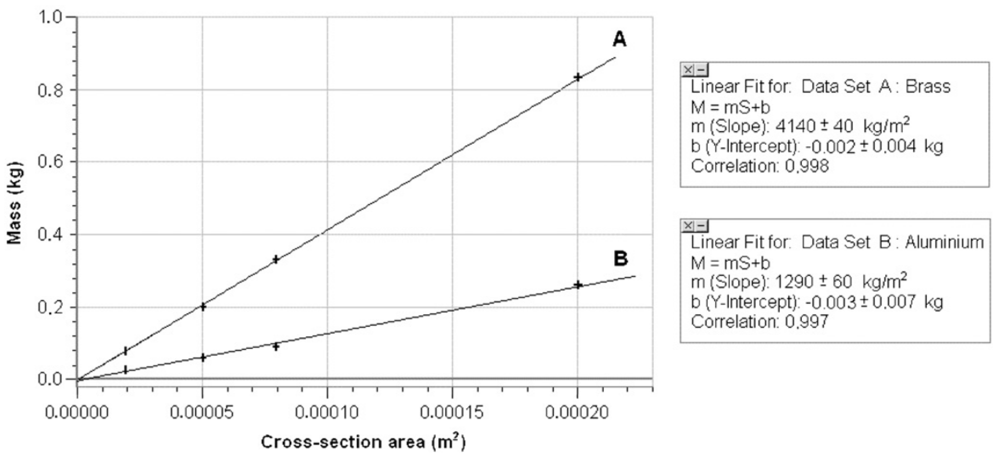

Figure 12. Plots of the minimal values of colliding body mass as a function of the cross-sectional area of 3 m long brass and aluminium rods.

with the rod for the whole pulse travelling time. This also happens for mass values greater than m^*, but not for smaller mass values.

Data reported in figure 11 allow us to give an estimate of this mass: $m^* = 0.32 \pm 0.01$ kg. The experimental uncertainty is due to the resolution used for the mass values in the zone at the beginning of the plateau in figure 11, where we increment the colliding body mass by 10 g steps. Time intervals detected when using colliding mass values greater than m^* give all sound speed values in good agreement with the accepted values for brass rods [16].

More data were obtained by performing measurements with brass rods of equal length (3.010 m) and different cross-sectional diameters (0.51 cm, 0.81 cm and 1.60 cm), with the colliding bodies falling from the same angular position. Measurements have also been performed with aluminium rods of similar lengths and cross-sectional diameters. The data obtained again attest to the existence of a minimal value for the colliding body mass. Figure 12

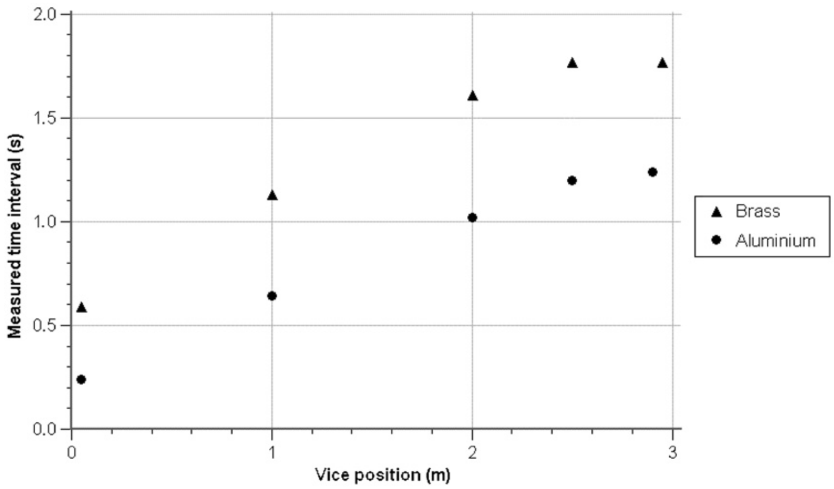

Figure 13. Plot of the pulse wave propagation time intervals as a function of the vice position, measured using method 3. Data refers to 3 m long aluminium and brass rods.

Table 2. Values of the colliding time intervals for mass m^*, in aluminium and brass rods.

Rod material	Δt ($\times 10^{-4}$ s)
Aluminium	1.9 ± 0.1
Brass	2.9 ± 0.1

shows plots of the minimal value of the mass, m^*, of the colliding body as a function of the cross-sectional area, S. Linear relationships between m^* and S are evident for both brass and aluminium, in accordance with (4).

By taking into account this equation and the slope of the best-fitting lines, it is possible to estimate the value of the time interval, Δt, necessary for a colliding body of mass m^* to transfer all its momentum and energy to the rods. Table 2 summarizes the values of Δt for brass and aluminium rods. The values are calculated from the slopes of the mass versus cross-sectional area in 3 m long rods. Error bar values are obtained from the uncertainties on the slopes of the fitting lines. Note that these time values are coherent with typical times for collisions given in the literature [15].

A modification of the experimental set-up of method 3 can be introduced by blocking the rod by means of vices to a very heavy laboratory desk. We verified that only by blocking the rods by means of a single vice, placed at the far end of the rod, do we obtain the same values of time intervals detected by using the suspended rods. If the vice is closer to the end of the rod hit by the body, the measured time intervals are smaller than those obtained with the freely suspended rod, as shown in figure 13. This behaviour can be explained by the action of the vice: when the wave pulse created by the stroke arrives at the vice, it is partially reflected. It returns to the left end of the rod and makes the colliding body displace, actually triggering the end of data detection. This happens well before the arrival of the wave pulse reflected by the right end of the rod. The action of the vice is not evident when the vice is placed at the right end of the rod because in this case both the reflected wave pulses are created almost at the same time.

The data reported in figure 13 seem to suggest a linearity in the propagation of the wave pulse in the rods. On the other hand, we found an appreciable scattering of the measured time values depending on the strength with which the vice is applied to the rod, i.e. from the 'efficacy' of the constraint. This prevented us using figure 13 data for further analysis.

4.1. What students learned from the experiments

All the reported experiments were performed by a group of trainee teachers (TTs) attending the pedagogical laboratory mechanical waves propagation course. They were graduates in mathematics and engineering. Their university curricula included two or three introductory physics courses dealing with theory, without any laboratory activity. Consequently, the TTs' attitude to experimental work was mainly oriented towards verification of already studied and well-formalized laws.

A comparison between results obtained by methods 1, 2 and 3 makes evident the role of the accuracy of experimental devices in measurements. The majority of the TTs declared that method 1 is conceptually effective at showing the time lowering of pulse propagation in solids when compared with the time of propagation in air, even if it is not suitable for giving quantitative estimates of sound speed in metals. For this reason, our students called it a 'half' measuring method.

Many discussions among the TTs were initiated by the experimental results of methods 2 and 3. In particular, the first lab results stimulated the TTs to read further examples reported in papers and textbooks in order to gain insight into the physics of collisions and the role of wave propagation in explaining the motion of real, elastic bodies.

It was initially not clear to the majority of the TTs that a sufficiently massive body, after colliding with the rod end, does not instantaneously rebound in accordance with the common interpretation of phenomena easily observed in real life and the rigid body mechanics studied in their introductory physics courses.

The plots of experimental data obtained with method 2 (see figures 9 and 10) led the TTs to discuss what they actually measured during the experiments performed. In particular, they did not understand why the fitting lines did not pass for the axis origin. They initially tried to repeat the measure many times, aiming to eliminate possible accidental error. The very fact that the measured time intervals were systematically higher than the expected values made the TTs suspect that the process of contact loss (between the pendulum bob and the rod's right end) added a delay time to the actual event they were studying. The search for an explanation of the results, and the analysis of the paper [17], suggested to them the possibility of a correction to the experimental data, as reported in the previous section.

Experiments performed using method 3 stimulated many discussions about the physics of wave propagation. The TTs found difficulty in understanding why the rod motion was not an instantaneous effect of the collision and why a massive body, after colliding with the rod end, can lose its contact only because of the reflected pulse returning from the free end of the rod. Moreover, the idea that in our experimental arrangement the reflected pulse is an extensional one was somehow passively accepted by the TTs; they recalled some previously studied theoretical concepts about waves (especially the transverse ones, the more widely studied in their university courses). On the other hand, the translation of this theoretical statement into the fact that the microscopic motion of the rod's particles is always in the same direction of the body stroke was not immediate for many TTs. This can be attributed to some unfamiliarity with longitudinal waves, but is more probably due to the way the TTs have learned physics in their introductory university courses: a set of formulae to memorize and general concepts treated simply as facts without meaningful understanding. The experimental evidence unquestionably contributed to clarifying the physical concepts involved, by supplying mechanisms of functioning that affected the TTs' understanding more than mere learnt formulae.

Other discussions were triggered by the experimental set-up for method 3: the metallic rods suspended by elastic bands. The TTs initially thought that firmly attaching the rod to a heavy body by means of vices could avoid the rod escaping from the colliding body before the reflected pulse returns back.

The experiments performed by applying method 3 with blocked rods (see figure 13) stimulated the TTs to reflect about the role of constraints in wave propagation and the general meaning of the constraint concept. They thought that the presence of the constraint, due to the vice, was sufficient to immediately bounce back a colliding body. The TTs did not understand that the constraint can only be detected by the colliding body when a compressional wave pulse, due to the action of the constraint, arrives at the end of the rod where the collision occurs. The awareness that the constraint can act only when it is 'informed' of the action of the colliding body by the wave pulse arrival contributed to the TTs' understanding.

All these considerations made the TTs make sense also of the shortening of time intervals measured when the vice was placed near the end of the rod hit by the body.

The TTs' behaviour, together with their interest in performing the experiments, allow us to make some conclusions about a new TT's attitude to approaching physics experiments. Many of them developed interesting discussions and reflections about what actually one measures when performing a physical experiment, by also reasoning on possible interpretative models of observed phenomena and quantitative results. This last point also represents a modification of the TTs' approach to modelling, which was initially mainly of a descriptive kind; they initially searched for a mere description of an observed phenomenon or for mathematical formulae making sense of the numerical results of measurements. After the lab part of the workshop, the TTs showed a renewed interest in searching for interpretative models, even involving microscopic interactions, explaining why a phenomenon develops in a given way or some specific experimental results are obtained.

5. Conclusions

In this paper, we discuss three different methods to analyse the acoustic wave propagation in metallic rods, also reporting experimental results. The method characteristics are described in the literature [10, 16] but the measurements have been performed by using different sensor and data logging devices. We adapted the experimental set-up to commercial microcomputer-based laboratory technology and developed a modelling of experimental results involving a pedagogical deepening of mechanical waves propagation concepts.

We show that two experimental methods give values of sound speed in metallic rods that are in good agreement with the accepted values reported in handbooks. The first experimental method can be considered only useful to give good qualitative evidence of differences in propagation times of wave pulses in rods of different materials. The hardware constraints of the commercial data acquisition systems, very affordable and available in high school laboratories, imply that acceptable estimates of the sound speed can be obtained only using sample rods of a length not easily manageable in a pedagogical laboratory.

The experimental data were obtained during the physics lab section activities of the mechanical waves propagation course, dedicated to trainee physics teachers of the Graduate School of Pre-Service Physics Teacher Education at Palermo University. The experiments performed and the discussions about the results allow us to conclude that trainee teachers have modified their initial attitude to physics laboratory activities and deepened their understanding of the physics content involved.

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