STUDIA UBB PHYSICA, Vol. 68 (LXVIII), 1-2, 2023, pp. 67-81
(RECOMMENDED CITATION)
doi:10.24193/subbphys.2023.07

COMPARATIVE STUDY ON THE SPEED OF SOUND MEASUREMENT IN METALS BASED ON COLLISION TIME

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ABSTRACT. Several electrical measurement methods based on impact time measurements are presented in order to determine the sound propagation velocity in different metals. The sound impulses were initiated by dropping metal rods or tubes on a rigid anvil, and the speed of sound was determined by measuring the impact time and the time needed for the wave to propagate from the impacting end to the free end. Several electric methods are presented and compared, the results obtained for the speed of sound being in fair agreement with theory. The experiments described in this paper could be successfully used as undergraduate Physics experiments leading students towards better understanding of phenomena regarding sound propagation in solids.

Keywords: *sound propagation in solids, impact time, electric methods, comparison*

INTRODUCTION

The physics of mechanical wave propagation plays an important role in the education process of both physicists and engineers. It provides the first introductory steps to wave phenomena and will support, from both phenomenological and mathematical point of views, further more complex subjects such as optics, quantum mechanics or electromagnetism.

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More and more accurate measurements of speed of sound in different propagation media have a very long, almost 400 years old history [1].

The development of measurement techniques from Kundt's tube to the use of sophisticated microphones made the measuring of speed of sound in air to become a relatively easy task. Meanwhile, the measurement of sound speed in solids, especially in metals, using electrical methods can be more difficult and complex, from both theoretical and experimental point of views, and it is an excellent inter- and multidisciplinary subject for undergraduate research for Engineering Physics students

This work describes and compare several electric methods based on impact time used to determine the speed of sound in metals. It was proposed as a graduation project for Engineering Physics specialization, at Babeș-Bolyai University, Faculty of Physics [2].

The paper is organized as follows: in the first section some general considerations are presented about sound propagation with a short review of measuring techniques for propagation in metals, a simple experimental set-up based on the impact time measurement between a metallic rod or tube and a compact anvil is described in the subsequent sections together with several appropriate measurement techniques. Finally, results are presented and conclusions are made.

SOUND VELOCITY AND ITS MEASUREMENT TECHNIQUES

The physical phenomenon of sound is defined to be a disturbance of matter that is transmitted as a wave from its source outward, through a transmission medium that surrounds the source, with a well-defined velocity called speed of sound.

According to standards, sound may be defined as being an "oscillation in pressure, stress, particle displacement, particle velocity, etc., propagated in a medium with internal forces (e.g., elastic or viscous), or the superposition of such propagated oscillation" [3, 4].

Sound can propagate through a medium (gas, liquid, solid or plasma) as longitudinal wave and as a transverse (shear) wave, but only in solids. At a fixed distance from its source, the pressure, velocity, and displacement of the medium will vary in time and at a given moment in time, the pressure, velocity, and displacement may vary in space.

The sound propagation is generally affected by the relationship between the density and pressure of the medium (affected also by temperature), the motion of the medium itself (being subject to Doppler-Fizeau effect) and the viscosity of the medium (causing attenuation).

Sound, like all waves, travels at a certain speed through the propagation medium and has the properties of frequency and wavelength. Direct evidence of the speed of sound can be observed while watching some phenomena implying both sound and light, thundering and lightning for instance. The flash of the lightning is seen well before the sound of the thunder is heard, implying that sound travels at a finite speed, much lower in value than light.

The speed of sound depends on the medium the sound waves pass through; it is a fundamental property of the material and is given by a Newton–Laplace type equation:

$$c_s = \sqrt{\frac{K}{\rho}} \tag{1}$$

where c_s is the speed of sound, ρ is the mass density of the medium and K describes the stiffness of the medium (modulus of bulk elasticity for gases and liquids and Young's modulus for solids, respectively).

In the case of plasmas, sound velocity is given by a much-complicated relationship, depending on electrons kinetic temperature and charge state and mass of ions from plasma.

Regarding speed of sound measurements, traditionally two fundamental directions are commonly used. Either the travelling time between two reference points is measured or the measurement of frequency (the inverse of propagation time) or wavelength is performed. The implemented measurement techniques are various.

The first ever reasonably accurate estimate of the speed of sound in air was performed by W. Derham: the time interval was measured between the sight of a fired gun smoke and hearing firing [1].

Probably the most well-known historical experiment for the measurement of the speed of sound in a gas or a solid rod was performed in 1866 by German physicist A. Kundt using the tube later named after him [5].

This type of experiment uses a metal rod held in midpoint and excited to vibrate along its length at one end, and a movable piston blocking the other end, capable to adjust the length of the tube. When the length of the tube is a multiple of half wavelength, the sound waves in the tube are in the form of standing waves, and the fine powder deposited previously inside tube is rearranged in a very specific pattern (nodes and antinodes). The distance between the neighboring nodes is one half wavelength of the sound. By measuring the distance between the nodes, the wavelength can be found, multiplying it by the frequency the speed of sound is found. Modern experimental demonstrations usually use a loudspeaker attached to a signal generator producing a sinusoidal wave.

The modern, weaponless version of Derham's experiment uses two microphones and a fast-recording device (digital storage scope). The sound source and the two microphones are arranged in a straight line, with the sound source at one end. The oscilloscope records the delay between the signals given by the two microphones, the distance between them divided by delay time will give the velocity of sound. A more sophisticated versions implies the use of PC sound cards and adequate software for recording and processing [6]. This technique is a single-shot timing type method or it may be regarded as a time-of-flight technique.

Another widely used measurement technique implies the use of a laboratory made "giant make-and-break switch": one part of the "switch" will be the metal rod or tube in which we want to determine the speed of sound, the other component is a hitting hammer, a colliding body or a large metallic base. When contact is made for a short period of time (cause by a hit or a single drop), the compression pulse travels along the rod or tube to the far end and is reflected as a rarefaction pulse to the near end. The sound path will be twice the length of the rod and the speed of sound will be equal to this distance over contact time. In the scientific literature there are several techniques used to measure this contact time:

a) by partially discharging a capacitor through a resistance or speaker during contact and then determining the residual charge [7-9]
b) by using a digital timer [10]
c) by sound sensor or the movement of a pendulum bob [11].

Other time-of flight techniques use gongs, bells, and hammers with oscilloscopes [12, 13] or PC audio cards [12] or 555 timer-based circuitry and piezoelectric sensor [14] or oscilloscope [15].

Speed of sound might be determined using Lissajous figures [16)] or smartphone and cardboard too [17].

EXPERIMENTAL DETERMINATIONS

A simple experimental set-up was built up to measure the impact time between a metallic rod or tube and a large compact metallic anvil (Fig. 1).

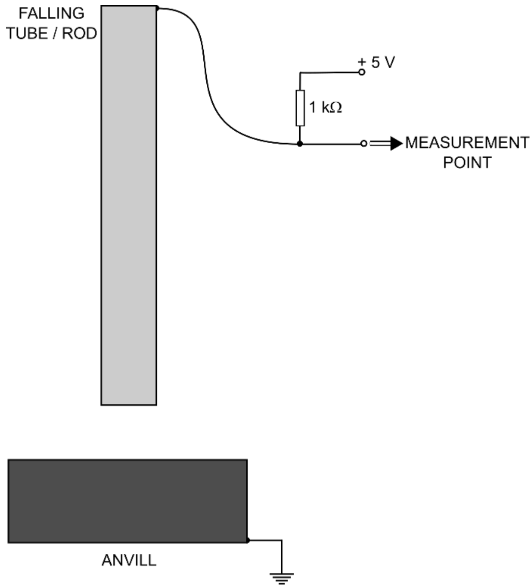

Fig. 1: The experimental set-up

As one can see, the set-up is a make-and-brake switch incorporated in a voltage divider, the voltage at the measurement point would be the supply voltage (+ 5 V) when there is no contact between the tube or rod and the anvil, and 0 V if the collision takes part.

The theoretical shape of the signal at the measurement point is presented in Fig.2.

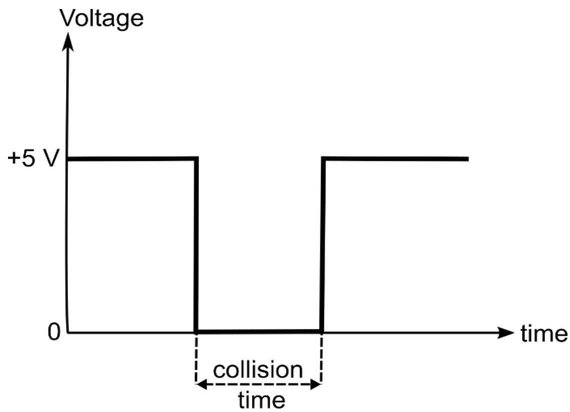

Fig. 2: Theoretical signal shape

The rod or the tube was freely dropped on the anvil and caught after the first spring up to avoid further contacts with the anvil. The time dependence of the voltage at the measurement point could be measured or recorded and the value of the collision time deduced.

The different tubes and rods used during experiments are presented in Table 1.

Table 1. Tubes and rods used in experiment

Material	Type	Diameter (cm)	Thickness (mm)	Length (cm)
Cu	tube	3	1	20.1
				32.2
				51.5
				84.0
				110.4
Al	tube	1.2	1.5	23.1
				33.7
				42.1
				51.4
				60.2
				72.1
	rod	2	-	25.4
				51.2
				75.0
				99.6

Five different measurement techniques were applied to analyze the voltage at the measurement point.

Method 1: An Arduino Uno [18] microcontroller was used to analyze the signal by means of a build in function called *pulseIn* [19]. Particularly in our experiments, the so-called LOW pulse read method was applied using the digital pin 7 of the Arduino. The + 5 V supply voltage was ensured by the microcontroller.

It was observed that with this method the measurements were sensitive to dropping and surface shaping, the emerging noise having an unwanted influence on the shape of the signal. The *pulseIn*() method from Arduino framework is not able to handle multiple edges which are present in the real experiment, due to imperfect contact between the dropped rod and the sitting anvil.

Method 2**:** The same Arduino Uno was used, this time the detection was made using Falling interrupt in conjunction with the Timer1 from the Atmega328. The Timer1 was configured to run in NORMAL mode with an input clock prescaler of 1. Considering the 16 MHz quartz crystal, from the Uno, the Timer1 is incremented every (1/16) µs. This counting is used to measure the time between the first falling edge and the last rising edge of a contact pulse as describer earlier. The routine is presented in the figure from below where the first part of the code is responsible with the detection of the first falling edge and the second part of the code is responsible to catch the last rising edge of the pulse and to store that value of the timer in the "ui16PulseEndTime" variable.

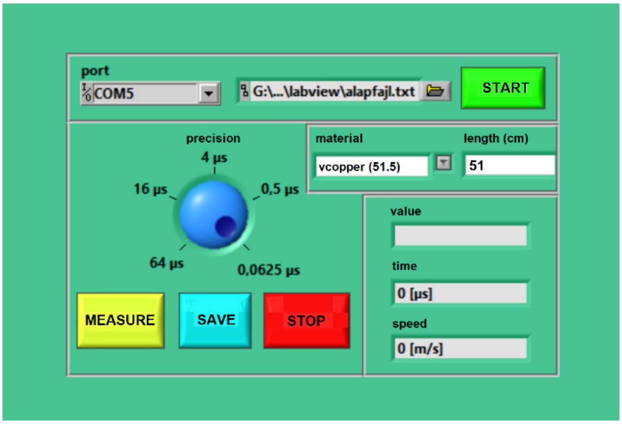

Fig. 3: The LabView interface

```
void LowEdgeInterrupt(void)
{ // called if a falling edge is detected

  // detecting the beginning of the pulse (the first falling edge)
  if(!bStartEdgeDetected)
  { // initial edge detected
    TCNT1 = 0;  // clear the timer counting register
    bStartEdgeDetected = true;
  }

  // detecting the last rising edge of the pulse (the end of the pulse)
  while(!(PIND & (0x01 << 2)))
  { // stay in this loop untill the PD2 is LOW => catch the last RISING transaction
    ui16PulseEndTime = TCNT1;
  }

  return;
}
```

Fig. 4: Sequence of the Arduino code

The interrupt reaction time will decrease the total contact pulse width value but this was measured and a correction can be added. A jittering effect in time measurement is also added due to the time spent inside the while loop depending when exact the last falling edge occurs and when the while loop condition is checked. These errors can be corrected by adding a 3.7 μs to the total time measured by the timer and the real times are obtained.

To check the methods precision, we have used an AnalogDiscovery2 to generate standard pulses and checked the length of the pulses using the Arduino. The results are discussed below.

For a 10 μs pulse generated with the AnalogDiscovery the Arduino measured 102 timer pulses and that means:

$$\frac{102}{16} = 6.375 + 3.7 = 10.075\ \mu s$$

For a 100 μs pulse generated with the AnalogDiscovery the Arduino measured 1542 timer pulses and that means:

$$\frac{1542}{16} = 96.375 + 3.7 = 100.075\ \mu s$$

For a 200 μs pulse generated with the AnalogDiscovery the Arduino measured 3138 timer pulses and that means:

$$\frac{3138}{16} = 196.125 + 3.7 = 199.925\ \mu s$$

This demonstrate that using a simple Arduino Uno board it is possible to measure the speed of sound even as an elementary physics teaching activity on a high school.

Method 3**:** Measurements are performed using a LCsoft Miniboard [20] and the *PulseView* software. The miniboard supplied the + 3.3 V for the divider, the HIGH and LOW signals were taken from digital pin 7 and the collision time was measured using cursors on the *PulseView* plot (Fig. 5).

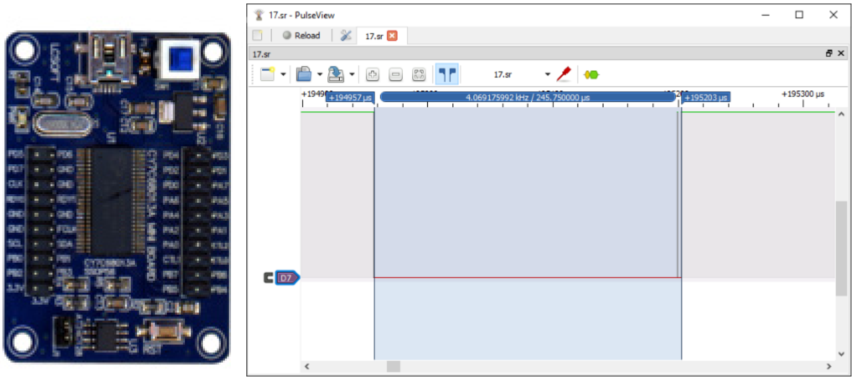

Fig. 5: The LCsoft Miniboard and PulseView window

Method 4: At the measurement point the voltage was monitored by a *Tektronix DPO3032* oscilloscope [21, 22]. The oscilloscope was programmed to expect a negative impulse and to measure its length (Fig. 6).

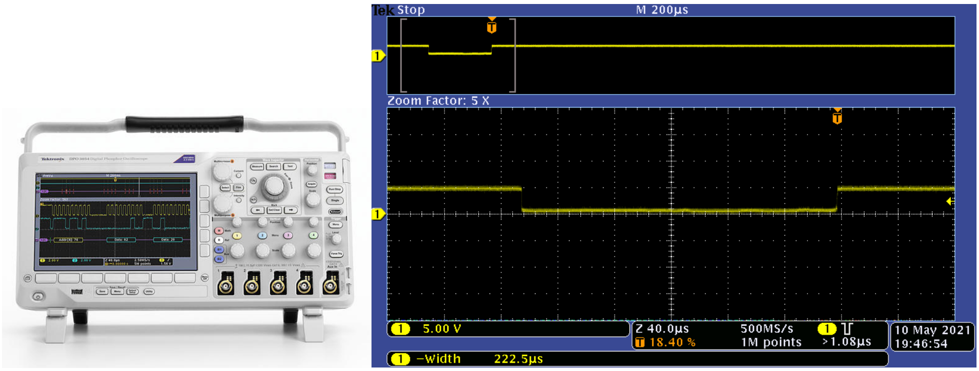

Fig. 6: The oscilloscope and the measuring window

All the above-mentioned methods will lead to the speed of sound in the metal (v) by means of the formula:

$$\mathrm{v} = \frac{2l}{t} \qquad (2)$$

where l is the length or the tube of the rod, and t is the collision time.

Method 5: The voltage divider was replaced by a piezoelectric sensor [23] attached to the free end of the rod or tube. The arrival of the shock wave to the sensor was detected by means of a voltage. This method does not measure the contact time between the two metallic parts, but the travelling time necessary for the sound to travel from the contact end to the free end (Fig. 7).

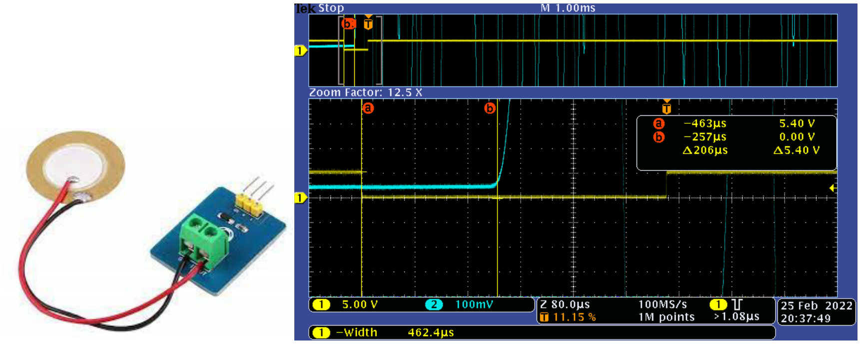

Fig. 7: The piezo sensor and the measuring window

In this case the shockwave has to travel only one length to reach the measurement point (sensor), thus the speed of sound in the metal (v) will be calculated by means of the formula:

$$\mathrm{v} = \frac{l}{t} \tag{3}$$

where l is the length or the tube of the rod, and t is the travelling time from the collision end to the free end.

As one can, the first three methods are somehow related, measuring the contact time via microcontroller, the fourth method uses a digital oscilloscope instead of the microcontroller and all methods lead to a speed of sound deduced by considering a back and forth travelling for the sound. For the fifth method, the sensor records a single length propagation from the contact end towards the free end where the sensor is placed.

RESULTS AND DISCUSSIONS

Performing some preliminary measurements, it was found that the collision times measured with the first four methods, as function of length, have the same order of magnitude for a given length and type of material, but the sound velocity calculated with equation (2) led to different values for each length. This result suggests that the speed of sound might depend on the length of the tube or rod, finding that could not be true, therefore further, and deeper analysis must be done.

Plotting the collision times as function of tube length, for both copper and aluminum tubes, obtained with the first three methods, the plots presented below are obtained (Fig. 8).

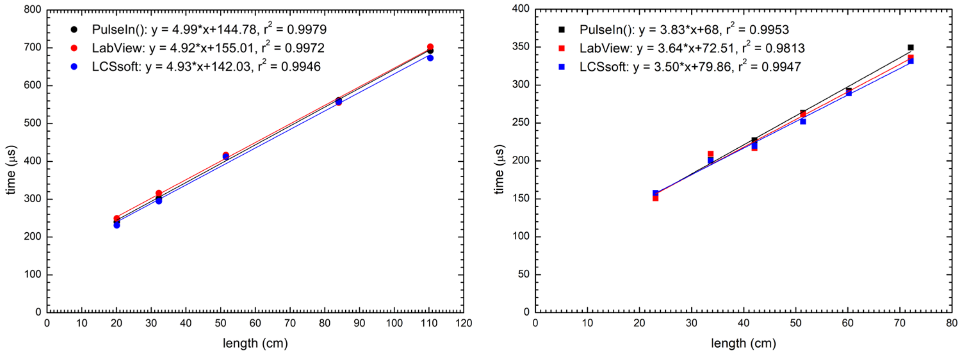

Fig. 8: The experimental results for the first three methods (Cu tube – left, Al tube – right)

The results obtained by oscilloscope measurements are presented in Fig.9 and those with the piezo sensor in Fig.10.

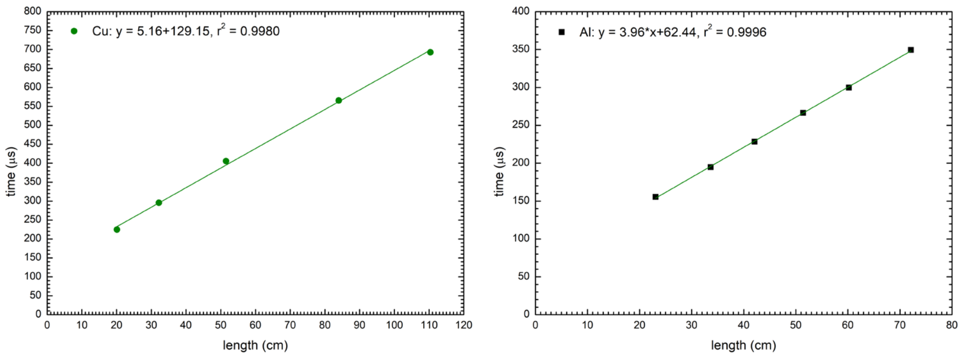

Fig. 9: Oscilloscope measurement results (Cu tube – left, Al – right)

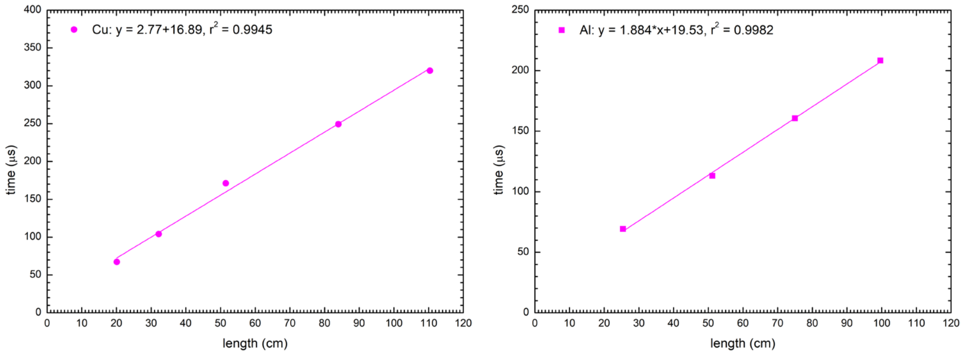

Fig. 10: Piezo sensor measurement results (Cu tube, Al rod)

As one can see, all plots demonstrate a good linear relationship between the collision time and the tube length (r-square > 0.99) and in all cases there is an offset time of about 100 μs when the first four methods are implemented, and less than 50 μs when the piezo sensor is used.

A qualitative explanation for the appearance of the offset time is given in the papers of Prowse and Brittoin [24, 25]. The variation of the pressure with time at the impact boundary is depicted below.

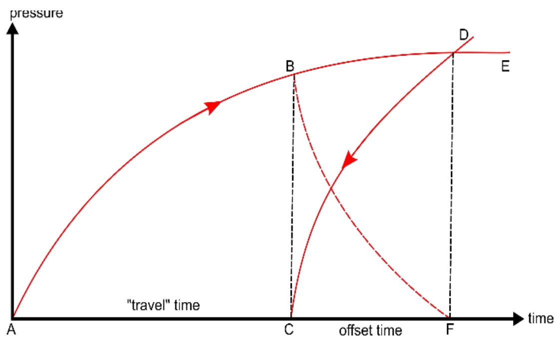

Fig. 11: Variation of pressure with time according to [24]

A compression pulse is initiated by the impact of the tube with the anvil. This will propagate along the tube towards the free and of it. Because of the finite length, the pulse will suffer a complete reflection with phase reversal. At this moment, the pulse will propagate from the free end towards the impact end with the velocity v and when arrives to the contact area (regarded as a rigid boundary) will suffer a perfect reflection but twice as fast. When the total pressure at the impact zone is reduced to zero, the tube will jump from the anvil and separates.

The initial growth in pressure at the impact end is represented by curve *AE* in Fig. 11. For the rod of length l, after a "travel" time $2l/\mathrm{v}$, the leading front of the initial stress pulse reaches the impact end (denoted point *C* on the time axes). The reflected pulse grows at twice rate of the initial pulse and it is depicted by curve *DC* in Fig. 11. This must be subtracted from the portion BE in order to obtain the resultant stress profile *BF*.

According to all these considerations, the total time of contact between the tube and the anvil will be given by the sum of two times, the travel time, and the time in the initial stress pulse necessary for the pressure to grow to half of its final value. This latter time corresponds to those offset times showed in Fig. 11.

Thus, the offset times deduced from the plots are subtracted from the measured impact times and with the resulted time twice of the length of the tube was divided in order to obtain the speed of sound (just the length in case of the piezo measurements).

The results (offset times and average velocities) of 30 time measurements for each tube or rod length given in Table 1, are summarized below (see Table 2).

Table 2. Tubes and rods used in experiment

Method	Material	Type	Offset time (μs)	Speed of sound (m/s)
#1	Cu	tube	155.01	4086.31
#2			144.78	4063.99
#3			142.03	4018.68
#1	Al	tube	72.51	5580.63
#2			68.00	5283.65
#3			76.86	5786.58
#4	Cu	tube	129.20	3940.77
	Al	tube	62.44	5066.29
		rod	154.41	5978.79
#5	Cu	tube	16.89	3661.40
	Al	tube	19.53	5295.79
		rod	1.49	4991.83

CONCLUSIONS

Five electrical methods based on the impact time measurement between a tub/rod and an anvil was implemented in order to determine the speed of sound propagation in metals.

It was experimentally demonstrated that, there is an offset time in the relationship of the measured impact time and the length of the tubes or rods. This offset time is not demonstrable if only one length is used and the deduced speeds will not be accurate.

The impact time is between 130 – 150 μs and the speed of sound between 3940 and 4087 m/s in case of copper tubes, and around 60 μs and 5000 – 5800 m/s in case of aluminum tubes, respectively. Larger values were found for Al rods.

These results are in good agreement with literature, 3810 m/s for Cu and 5000 m/s for Al [26].

The results obtained with the piezo sensor led to a relatively small offset time (less than 20 μs) and much better speeds, 3661 m/s for Cu and 4990 – 5300 m/s for Al, respectively.

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