Using high speed smartphone cameras and video analysis techniques to teach mechanical wave physics

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Using high speed smartphone cameras and video analysis techniques to teach mechanical wave physics

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Abstract
We propose the use of smartphone-based slow-motion video analysis techniques as a valuable tool for investigating physics concepts ruling mechanical wave propagation. The simple experimental activities presented here, suitable for both high school and undergraduate students, allows one to measure, in a simple yet rigorous way, the speed of pulses along a spring and the period of transverse standing waves generated in the same spring. These experiments can be helpful in addressing several relevant concepts about the physics of mechanical waves and in overcoming some of the typical student misconceptions in this same field.

Introduction
In the last two decades many experiments based on video analysis have been proposed in physics education research. Thanks to technological progress, old, expensive cameras have been replaced by relatively low-cost smartphone cameras. Video analysis making use of these devices [1] and based on dedicated tracking software [2–4], nowadays constitutes quite an established practice in the didactic physics laboratory [5, 6]. Recently, higher and higher speed and high resolution professional cameras have been used to improve the quality of data acquired, thus, grabbing aspects that typically escape observation to the naked eye. Also commercial smartphone cameras have very good capabilities, including the possibility of taking slow or very-slow motion videos which can be adopted to catch very fast events in kinematics, in optics and thermology, among other fields [7–9]. The use of video analysis techniques in the study of mechanical wave propagation, such as along ropes or springs, could constitute a further valuable case study [10]. More specifically, and as it will be further commented on in the following, wave physics is a field in which students still encounter troubles when asked to provide workable answers to apparently simple questions, such as those related to the correct relationships among speed, amplitude and the shape of travelling disturbances [11, 12].

The experiments
In the present work, we discuss some simple experiments about the physics of mechanical waves which do not need any sophisticated laboratory setup and make extended use of smartphone cameras as well as of tracking software.

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The possible addressees are both high school students and students attending introductory laboratory courses at undergraduate level. Two of our experiments are devoted to the measurement of the propagation speed of transverse and longitudinal pulses along a spring. A third experiment is devoted to the measurement of frequencies of standing waves. The apparatus required for these experimental activities makes use of a long, pre-loaded spring. As sketched in figure 1, one end of the spring is joined to the horizontal bar. The investigator can move the free end point of the spring to generate along it longitudinal (left), and transversal waves. Two kinds of transversal disturbances (a smooth, symmetrical packet (centre) and a plucked, triangular one (right)) are considered here.

Figure 1. Artist’s view of the experimental setup. A pre-loaded spring has one end locked to the horizontal bar. The investigator can move the free end point of the spring to generate along it longitudinal (left), and transversal waves. Two kinds of transversal disturbances (a smooth, symmetrical packet (centre) and a plucked, triangular one (right)) are considered here.

Figure 2. Superimposed snapshots taken from frames of slow motion videos for smooth (top) and plucked (bottom) transverse disturbances of the spring.

The spring used in our setup has rest length \( L_0 = (1.94 \pm 0.01) \) m and stiffness \( k = (2.2 \pm 0.2) \) N m\(^{-1}\). Pulses propagating along the spring were filmed using a smartphone camera (iPhone 6 plus, 240 fps, resolution HD 720p). Videos were analysed with Tracker [2, 3].

Transverse pulses

It is possible to observe that the speed of propagation of a travelling pulse does not depend on its shape nor its duration. In our first experiment, one generates transverse pulses with ad hoc shapes and durations by shaking by hand the free end of the spring. Typical results for some superimposed frames of the slow-motion videos for transverse pulses, of two kinds of shapes, are shown in figure 2. The analysis of the videos leads to the speed values \( v_S = (10.7 \pm 0.5) \) m s\(^{-1}\) and \( v_P = (11.0 \pm 0.5) \) m s\(^{-1}\) for the smooth, symmetric pulse and the plucked, asymmetric disturbance, respectively (see figure 3). These values (which are equal within their uncertainties) are compatible with the value \( v_T = (10.7 \pm 0.5) \) m s\(^{-1}\), evaluated according to the formula

\[
\text{Figure 2. Superimposed snapshots taken from frames of slow motion videos for smooth (top) and plucked (bottom) transverse disturbances of the spring.}
\]

\[
\text{Figure 3. Longitudinal coordinate of a given transverse displacement of the pulse measured with Tracker as a function of time, for plucked (blue circles) and smooth, symmetric (red circles) shapes. Continuous lines represent best-fit linear interpolations.}
\]
Using high speed smartphone cameras and video analysis techniques

\[ v_T = \sqrt{\frac{T}{\lambda}}, \]

where \( \lambda \) and \( T \) are the known linear mass density of the spring, \( \lambda = (0.123 \pm 0.002) \text{ kg m}^{-1} \), and its tension (measured using a dynamometer, \( T = (14 \pm 1) \text{ N} \)), respectively. In figure 4 we show the transverse displacement versus time of two points along the spring. This measure allows to estimate the duration of the disturbance, \( \tau_{\text{pulse}} = (0.19 \pm 0.01) \text{ s} \), for this particular pulse. To calculate its length we use \( L_{\text{pulse}} = v_T \tau_{\text{pulse}} = (2.0 \pm 0.2) \text{ m} \). This value is in full agreement with the direct measure of the pulse length obtained using the Tracker metering tool. One can see from figure 4 that the shape (including its duration) is basically unchanged along the spring. This result of course holds if one neglects longer times degradation of the pulse due to friction forces and other dissipative effects.

Transverse standing waves

Transverse standing waves have been generated in the same spring. The two endpoints of the spring have been connected to two fixed supports as sketched in figure 5. The spring has been stretched in order to maintain its tension at the same value as that of previous experiments. Stationary waves can be quite easily generated by shaking the spring with appropriate frequencies such that the fundamental mode and some higher harmonics show up, as depicted in figure 6. Videos were taken at high frame rate (240 fps) and once again analysed with Tracker to obtain the oscillation period. The frequency of a standing wave is described according to the well-known equation

\[ f_n = \frac{n \nu}{2L}. \]

This expression can be used to obtain the speed of wave propagation along the spring (see table 1) for the various harmonics. One can take as a representative speed for this experiment the average of these values, \( \nu_{\text{av}} = (10.4 \pm 0.4) \text{ m s}^{-1} \), which, in turn, compares well with the speed, \( \nu_L \) and \( \nu_P \), obtained in the previous experiment with the propagating transverse pulses.

Longitudinal pulses

The perturbation required to create a longitudinal pulse can be produced through the compression of a portion of spring and abruptly leaving it to expand freely. So, a segment of a spring becomes compressed and moves along it (see figure 7 for a typical frame of a slow-motion video of this kind of motion). Analogously to the case of transverse disturbance, one measures the speed of two pulses created with two different initial conditions (obtained by simply shaking with different vigour the hand holding the free end of the spring). One sees again, as depicted in figure 8, that the two longitudinal pulses propagate with basically equal and constant speeds, \( \nu_{\text{long}} = (8.4 \pm 0.4) \text{ m s}^{-1} \) and \( (8.5 \pm 0.4) \text{ m s}^{-1} \), respectively. This means that, in this kind of experiment, the speed of propagation does not depend significantly on the shape nor on the pulse duration. The measured speeds
are in agreement with the value \((8.8 \pm 0.9) \text{ m s}^{-1}\), obtained using the expression

\[v_{\text{long}} = \sqrt{\frac{Y}{\lambda}},\]

in which we make use of the linear mass density of the spring \(\lambda\) and of the Young’s modulus \(Y\), whose value is in turn obtained according to \(Y = k L_s\), where \(k\) is the elastic constant and \(L_s\) is the length of tensioned spring.

### Table 1. Measured period \(\tau\) and speed \(v\) of propagation for \(n = 1, \ldots, 5\) transverse modes.

<table>
<thead>
<tr>
<th>Mode ((n))</th>
<th>(\tau) (\pm 0.008) s</th>
<th>(v) (\text{m s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.192</td>
<td>10.4 \pm 0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.596</td>
<td>10.4 \pm 0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>11.0 \pm 0.6</td>
</tr>
<tr>
<td>4</td>
<td>0.308</td>
<td>10.1 \pm 0.6</td>
</tr>
<tr>
<td>5</td>
<td>0.242</td>
<td>10.2 \pm 0.7</td>
</tr>
</tbody>
</table>

### Conclusions

The simple experiments presented and discussed in this work are aimed to help students learn some fundamental concepts concerning the physics of mechanical wave phenomena. The video analysis of wave propagation along a spring can be very helpful in overcoming some of the typical student misconceptions, such as those relating to the propagation of the pulses, known from the literature [10–12].

Mainly two of these misconceptions inspired the proposed activities: (i) the connection between the speed of impulse propagation and the motion of the source and (ii) the relationship between the length of the pulses and the time duration of the disturbance. Physics education research showed that students generally believe that the speed of the propagation of the pulse can be modified through a change in the motion of the source [10, 11]. Students also tend to believe that the
Using high speed smartphone cameras and video analysis techniques

disturbance duration is proportional to the pulse propagation speed; it follows that the relationship between the length of the pulse and the oscillation duration is often misunderstood. The goal of the experimental activities, which we propose here, is the decomposition of these misconceptions: students should execute personal laboratory measurements with the aim of achieving, by themselves, results eventually contrasting with their own spontaneous understanding of these phenomena. As it generally happens in these contests, an autonomous achievement of logical solutions to the problem will lead to a unique choice between previous misconceptions and experimental results. Since the only logical, consistent, repeatable and robust solution is that based on actual activities in the lab, students will tend to rethink their original intuitions in favour of observed data. The simple experiments addressed in the present work further support the strategy of recognizing and limiting spontaneous interpretations of physical facts, including those pertaining to mechanical wave propagation. Moreover, the use of relatively cheap smartphones, allows for a very quick and detailed analysis of observed motions and of their fast behaving details. This approach is a definite gain when compared with other procedures making use, not a so-long time ago, of expensive cameras, stroboscopic lamps and the burden of film development and of its analysis.

References


Jacopo Bonato is graduate student at the physics Department in Trento. He is involved in the project of acoustics and mechanical wave physics teaching units at high school level. He is getting his academy diploma in classical guitar.

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