Using high speed smartphone cameras and video analysis technique in teaching mechanical wave physics

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Abstract

We propose the use of smartphone based slow-motion video analysis techniques as valuable tools for investigating some physics concepts ruling mechanical wave propagation. The simple experimental activities presented here, suitable for high school and undergraduate students, allow 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 to students several relevant concepts about the physics of mechanical waves and in overcoming some of the typical students' 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 Thanks to technological progress, old, expensive cameras have been replaced by relatively low-cost smartphone cameras.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], constitute nowadays quite an established practice in the didactic physics laboratory [5,6]. Recently, higher and higher speed and high resolution professional cameras are 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 performances 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 to 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 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

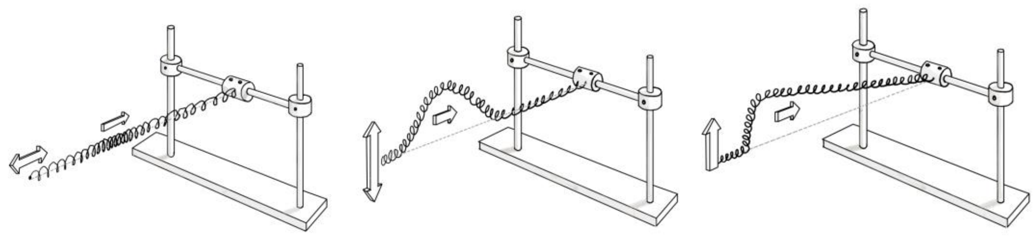

Fig.1 Artist's view of the experimental setup. A pre-loaded spring has one end locked to the horizontal bar. The investigator can move the free end point of the spring to generate along it longitudinal (left), and transversal waves. Two kinds of transversal disturbances (a smooth, symmetrical packet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

use of smartphone cameras as well as of tracking software. 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

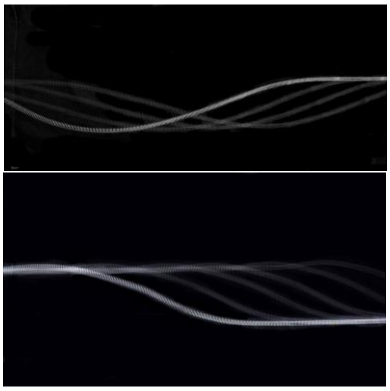

Fig.2 Superimposed snapshots taken from frames of slow motion videos for smooth (top) and plucked (bottom) transverse disturbances of the spring.

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, preloaded spring. As sketched in Fig.1, one end of the spring is joined to a transverse bar. The other spring endpoint can be shaken by the investigator thus creating pulses with various kinds of propagation modes, shapes, amplitudes and durations. The spring used in our setup has rest length L_0=(1.94±0.01) m and stiffness k=(2.2±0.2) N/m. 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 neither on its shape nor on 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 Fig. 2. The analysis of videos leads to the speed values v_S=(10.7±0.5) m/s and v_P=(11.0 ± 0.5) m/s for the smooth, symmetric pulse and the plucked, asymmetric disturbance, respectively (see Fig.3). These values (which are equal within their uncertainties) are compatible with the value v_T = (10.7±0.5) m/s, evaluated according to the formula

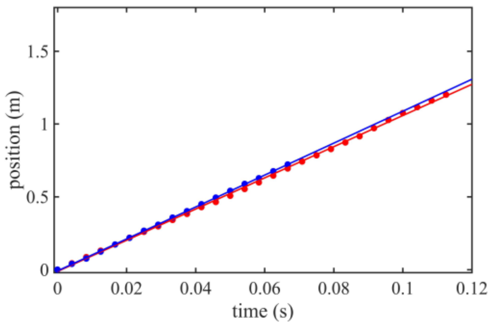

Fig.3 Longitudinal coordinate of a given transverse displacement of the pulse measured with Tracker as a function of time, for plucked (blue circles) and smooth, symmetric (red circles) shapes. Continuous lines represent best-fit linear interpolations.

$$v_T = \sqrt{\frac{T}{\lambda}},$$

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

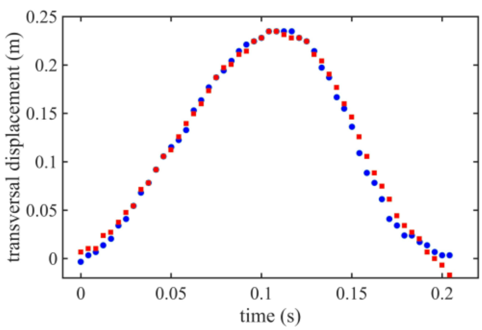

Fig.4 Transverse displacement versus time of two separate points of the spring for the smooth, symmetric pulse.

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 Fig.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 shacking the spring with appropriate frequencies such that the fundamental mode and some higher harmonics show up, as depicted in Fig.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

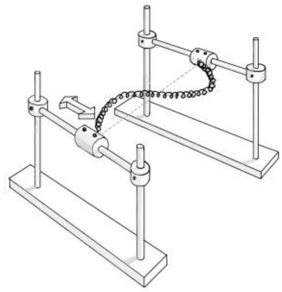

Fig.5 Artist's view of the setup for generating standing transverse waves.

$$f_n = n\frac{v}{2L}.$$

This expression can be used to obtain the speed of wave propagation along the spring (see Table I) for the various harmonics. One can take as a representative speed for this experiment the average of these values, v_{av}=(10.4±0.4) m/s, which, in turn, compares well with the speed v_S and v_P obtained in the previous experiment with the propagating transverse pulses.

Fig.6 Frames from 5 videos of the oscillating spring showing the fundamental mode (left) and the first four harmonics in transverse stationary motions.

mode (n)	τ [±0.008 s]	v [m/s]
1	1.192	10.4±0.4
2	0.596	10.4±0.5
3	0.375	11.0±0.6
4	0.308	10.1±0.6
5	0.242	10.2±0.7

Table I. Measured period τ and speed v of propagation for n=1, … ,5 transverse modes.

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 Fig.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

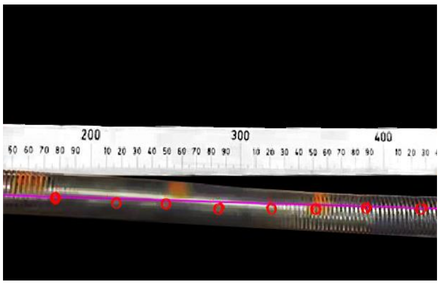

Fig.7 Snapshot taken from the video of a travelling longitudinal pulse. The red line/markers (corresponding with positions occupied by a selected spring disturbance – for instance its largest compression - in equally spaced instants of time) are used in the tracking process.

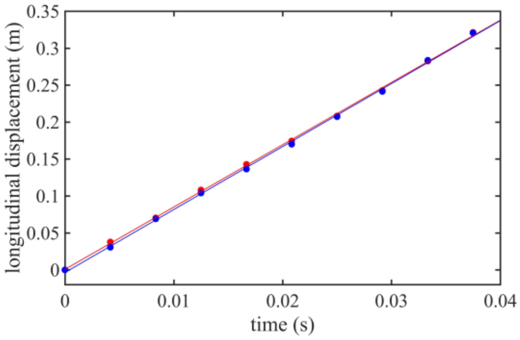

Fig.8 Position of two longitudinal pulses measured with Tracker as a function of the time. Continuous lines represent best-fit linear interpolations.

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 Fig.8, that the two longitudinal pulses propagate with basically equal and constant speeds, v_{long}=(8.4±0.4) m/s and (8.5±0.4) m/s, 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±0.9) m/s, obtained using the expression

$$v_{\mathrm{long}} = \sqrt{\frac{Y}{\lambda}},$$

in which we make use of the linear mass density of the spring λ 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.

Conclusions

The simple experiments presented and discussed in this work are mainly aimed to help students to learn some fundamental concepts concerning the physics of mechanical wave phenomena. The video analysis of waves propagation along a spring can be very helpful in overcoming some of the typical students' 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 disturbance duration is proportional to the pulse propagation speed; it follows then 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 decommissioning of these misconceptions: students should execute personally 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' choice 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 mechanical wave propagation. Moreover, the use of relatively cheap smartphones, allows a very quick and detailed analysis of observed motions and of their fast behaving details. This approach is a definite gain when compared with the procedures making use, not a so-long time ago, of expensive cameras, stroboscopic lamps and the burden of film development and of its manual tracking and analysis.

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