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Studies of Free Falling Object and Simple Pendulum Using Digital Video Analysis

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Abstract

The motion of a free falling object and a simple pendulum were analyzed by digital cameras and computer programs (Sony Vegas, Adobe Photoshop and Microsoft Excel). The positions of the moving objects were evaluated every 33 ms from a series of images and experimental results were compared with fundamental equations in mechanics to verify the technique. For the free falling experiment, the displacement was proportional to the time squared and the velocity can be averaged from the change in position during each 33 ms interval. From the simple pendulum experiment, the angular displacement had a periodic variation with the time. This oscillation exhibited damping amplitudes and a constant time period. The time period squared had a linear relationship with the length of the pendulum. The agreements between the experimental results and the theory led to the acceleration due to the gravity with an acceptable level of accuracy. From this demonstration, a simple setup consisting of a conventional camera and software can not only be applied in the context of simple problems but also shows a potential in the teaching of advanced mechanics.

Keywords: Digital camera, video analysis, free falling, simple pendulum, harmonic oscillation

Introduction

In recent years, digital video analysis has been increasing implemented in physics education. Images captured by digital cameras or webcams prove to have positive effects on the attitude and achievement of students [1,2]. In mechanics, the motion of objects can be visualized and analyzed. Time dependent positions captured by cameras lead to average velocity and acceleration. Commercial packages such as Vernier's Logger Pro and CMA's Coach have been developed for students to collect motion data and fit them to the theoretical models. Tracker is also available as freeware [3,4] but its accuracy is reduced in the case of objects with high velocity. Page *et al* suggested that a high precision measurement can be achieved by video analysis when possible sources of errors from projections, lens distortion and marker positions were controlled [5]. Physics learning by digital video analysis has been continuously improved in terms of hardware and software as well as content. Some intermediate concepts in physics including centrifugal force [6], rigid body [7,8] and damping [9] have successfully been analyzed using video files. To enhance the appeal of physics learning, some lessons were related to popular sports. For example, Cross explained the behavior of a bouncing tennis ball [10]. Heck and Ellermeijer used Coach to analyze the sprinting of runners [11] whereas Chanpichai and Wattanakasiwich employed Tracker to analyze the throwing of a basketball [12]. Nowadays, the data may be automatically acquired by incorporating computer vision and image recognition techniques [13-15]. Stereoscopic filming has also been used to obtain 3-D data [16,17].

Free falling and simple harmonic motion are familiar lessons in high school physics. Still, new analytical and experimental techniques have been proposed to enhance the understanding of these concepts [18-23]. In this work, we use a simple setup composed of a digital camera, Sony's Vegas and Adobe's Photoshop software to track the positions of a free falling object and a simple pendulum. Analyzing the variations of their position and time period in Microsoft's Excel, the acceleration due to gravity is evaluated in order to examine the accuracy of the technique. To our knowledge, such a setup has never been reported in the literature.

Experimental procedure

In the free falling experiment, a ball was manually released from a height of 2.16 m. The process of falling was captured by a digital camera (Sony DSC-T1500, 10.1 megapixels) in video mode. With the aid of the Sony Vegas 7.0 program, 30 sequential images per second from the video file were stored as jpeg files (96 dpi) in a computer. The movement of the ball was followed frame by frame with a time interval of 33 ms using the Adobe Photoshop CS3 program. Positions were measured by identifying the middle pixel of the ball in each frame and its coordinates (x,y) were recorded as a function of falling time. Any 'sideways' motion (deviation in x) can also be inspected by drawing a vertical line in the program.

In the simple pendulum experiment, a metal bead attached to the end of light string was oscillated in a vertical plane. The periodic motion exhibited by the pendulum was recorded with a digital camera (Sony DSC-W170, 10.1 megapixels). By a similar procedure using Sony Vegas Pro 9.0 and Adobe Photoshop CS3, the coordinate (x,y) of the bead in each frame was obtained. The angular displacement of the pendulum can be computed from the arctan of x over y. To study the time period and the amplitude in a non-simple harmonic oscillation released from 20 degrees, the angular displacement was plotted as a function of the oscillating time. To further verify the setup, the time periods of oscillations for varying length of the pendulum (0.20 - 0.60 m) were measured. Initial angular displacements in this case were kept at 5 degrees corresponding to a simple harmonic motion.

Before recording each experiment, the image plane was carefully arranged to be parallel to the plane of motion in order to minimize systematic errors from the projection. The distances between the camera and the wall as well as the height of the wall were measured to relate to the length scale in the images. By choosing vivid colors (e.g. red, blue) for the objects, the effect of blurred images for the moving object is kept at an acceptable level and the error due to the marker position in the Photoshop program was approximately 1 pixel. Besides, the center of the sphere may not coincide with an individual pixel but fall between pixels. Overall, the uncertainty of the marking and uncertainty in locating the center of the sphere led to a systematic error in this manual tracking not exceeding 2 pixels. To reduce random errors, repeated measurements were carried out in the free falling experiment and each time period in the simple pendulum experiment was averaged from 50 cycles.

Results and discussion

Visual display of the free falling process is illustrated in **Figure 1**. By analyzing the series of images, positions (y) of the ball every 33 ms are plotted against time squared (t^2) in **Figure 2**. Twenty one data points give rise to a straight line with a correlation factor of 0.997. This result is in a good agreement with the fundamental equation of motion:

$$y = v_0 t + \tfrac{1}{2} g t^2 \tag{1}$$

The acceleration due to the gravity (g) evaluated from the slope in **Figure 2** is 9.8 m·s^{-2}. Compared to the value of g measured at the nearby Songkhla province by the National Institute of Metrology (Thailand) as 9.78120 [24], the value from this free falling experiment differs from the standard value by only 0.19 %. Moreover, the projection of this line nearly passes the origin meaning that the initial velocity (v_0) introduced by the manual dropping is negligible. However, it has to be mentioned that 3 repeated experiments yield an average g value of 10.5 m·s^{-2}. The deviation from 1-D translation by uncontrollable 'sideways' motion is likely to be a major factor in this loss of accuracy.

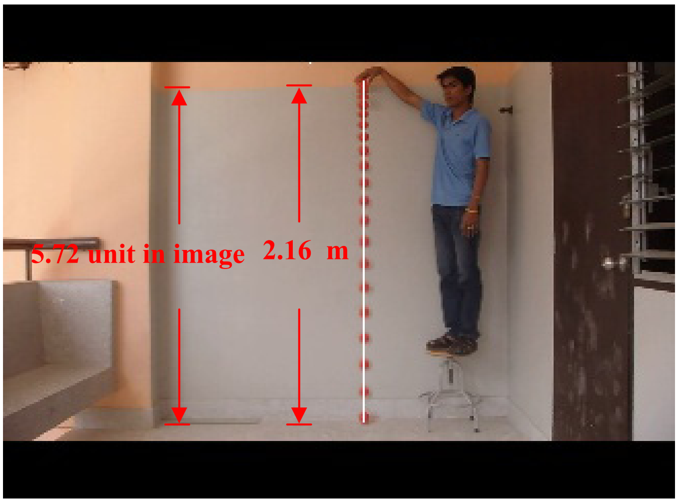

Figure 1 Composite image from the free falling sequences.

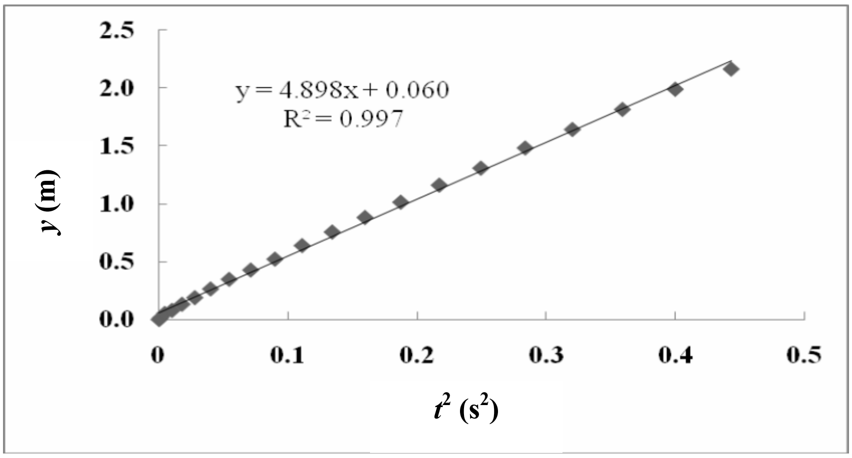

Figure 2 Plot of displacement against time from the free falling experiment.

Figure 3 compares the average velocity (v) at different times with the calculation from the well known formula:

$$v = v_0 + gt \quad (2)$$

The difference seen in **Figure 3** can be explained by pointing out that the velocity from Eq. 2 is an instantaneous velocity while the value from the experiment is averaged over the time interval of 33 ms. The deviation of the experimental values from the theory is more pronounced when the ball approaches the ground because of its increasing velocity. Otherwise, the average velocity from such a demonstration adequately represents the motion of free falling objects.

For the simple pendulum experiment, images from a few frames are exemplified in **Figure 4**. The angular displacement (θ) of the pendulum of length 0.50 m and initial amplitude 20 degrees, captured by the camera and analyzed by the programs, is plotted over the time of 26 cycles in **Figure 5**. The sinusoidal-like motion with a damping is observed in the graph as the decay of the amplitude is visible to the naked eye. The damping is unavoidable because the pendulum oscillates in air. Any viscous media including air imposes drag on the pendulum in which the drag coefficient (β) is dependent on the medium and the shape of the pendulum. The time period of the oscillation (T) incorporating the effects of drag and initial angular displacement (Θ) is expressed by Eq. 3 [23].

$$T = T_0\left(1 + \frac{\Theta^2 e^{-2\beta t}}{16}\right) \quad (3)$$

where T_0 is the time period for an ideal simple pendulum of length l given by Eq. 4.

$$T_0 = 2\pi\sqrt{\frac{l}{g}} \quad (4)$$

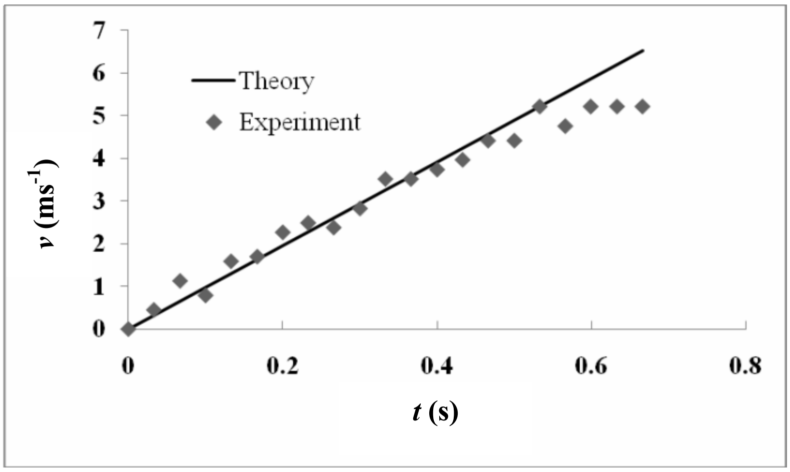

Figure 3 Comparison of averaged velocity from the free falling experiment and instantaneous velocity from the calculation.

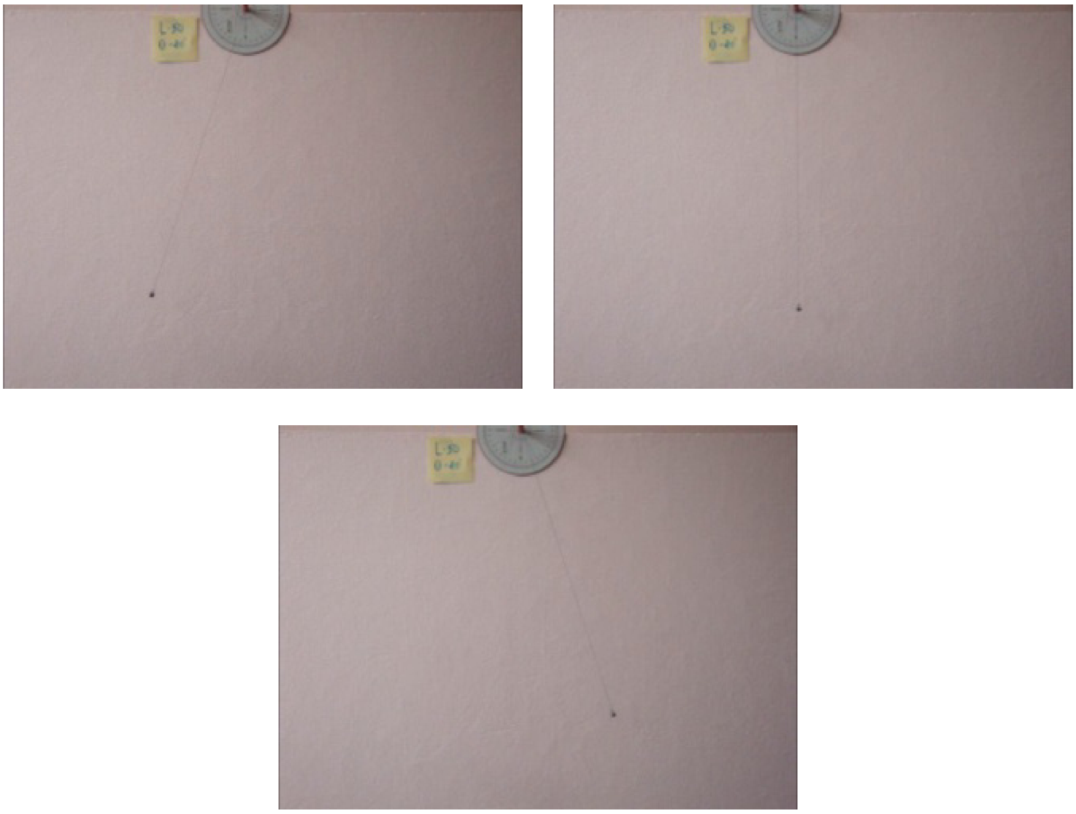

Figure 4 Sequential images from the simple pendulum experiment.

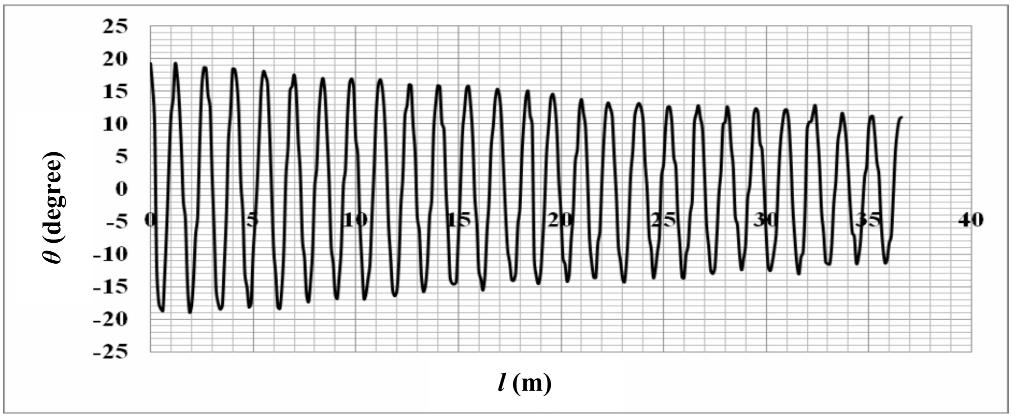

Figure 5 Plot of angular displacement against time from the simple pendulum experiment.

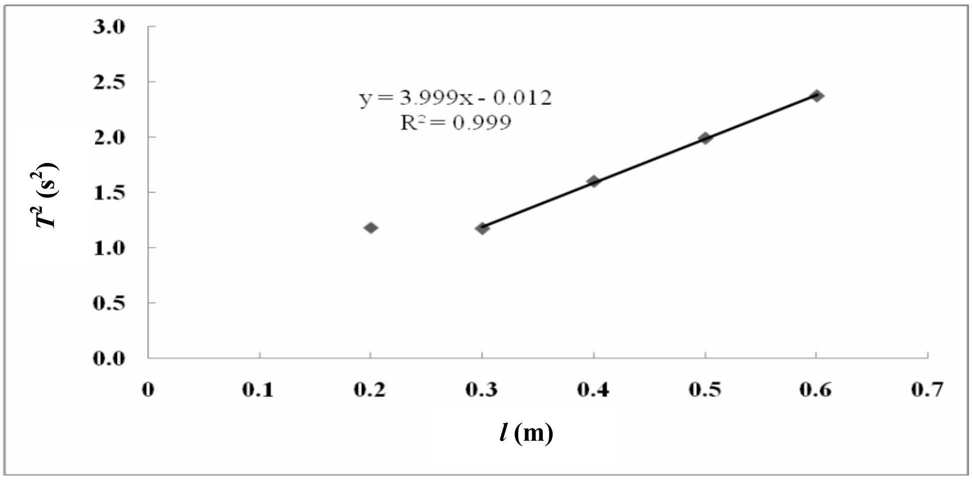

Figure 6 Plot of length of string against time period squared from the simple pendulum experiment.

The time period can also be deduced from **Figure 5** and it shows little variation over the time in spite of the damping (average value is 1.30 s with a standard deviation of 0.07). This experimental result is supported by the analysis that the variation of time period of the pendulum may be within the limit of experimental errors [23]. In the case of the small initial amplitude (5 degrees), this variation is reduced and the period for the pendulum of each length is therefore averaged from the time taken to complete 50 cycles. The standard deviation in the obtained period is about 0.060. In **Figure 6**, the period squared was shown as a function of the length of the pendulum. The data in the case of 0.3 - 0.6 m fall on a straight line with a correlation factor of 0.999 and the calculation from the slope gives rise to a value for *g* of 9.9 m·s^{-2}. When the length of the pendulum is 0.2 m, the increased uncertainty in determining the shortest period results in the value well above the trend line.

Conclusion

It was demonstrated that a conventional digital camera and computer programs can be used to analyze the free falling motion and simple pendulum oscillation. Without additional electronic equipment, both experiments yield an acceptable level of accuracy with g = 9.8 and 9.9 m·s^{-2}. This simple digital video analysis setup is a viable option in an educational context, providing an alternative to a stopwatch and a photogate in the studies of mechanics.

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