VIDEO-BASED MOTION TRACKING AND ANALYSIS OF SIMPLE PENDULUM OSCILLATIONS

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Abstract: In this paper, we report a very basic experiment on "Oscillatory motion of a simple Pendulum" using Tracker video analysis and a smartphone camera. Tracker software is fundamentally an ICT-based learning tool and is favoured as it is free, user-friendly, and supports effective learning and teaching. By integrating a smartphone camera into the laboratory setup, the analysis of oscillations is performed at a large angle rather than the traditional small-angle approach. This study findings highlight the feasibility of this approach in studying the motion of a simple pendulum while being simultaneously interactive and inexpensive. Here, the value of "g" (acceleration due to gravity) is determined and the damping coefficient is also calculated. We found that the large-angle approximation did not cause too large an error compared to the original value of "g".

Keywords: tracker; motion-tracking; simple pendulum

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1 Introduction

In any Physics undergraduate curriculum, the general mechanics laboratory course typically concerns studying various types of oscillations such as a simple pendulum, a compound pendulum, Maxwell's needle, etc. The crucial measurements involved in these experiments are the time taken for a certain number of oscillations which is obtained using a stopwatch. However, manual execution of these experiments evokes lots of human errors which are minimized by recording a large number of observations or measurements[1]. But these pendulum experiments generally deal with the calculation of "g" from the $\mathrm{L}^2 - \mathrm{T}$ curve only and do not provide information whether the oscillations are simple harmonic in nature, as it is very non-intuitive. Furthermore, no information regarding position can be obtained at various time intervals from this plot. It is therefore essential to involve the students in a more engaging way of doing practicals which would pave the way for adding to their theoretical knowledge and make it more thought-provoking. That can be achieved by the integration of information technologies into the teaching and learning process [1]. In pendulum experiments, the calculations are usually done with the small-angle approximation, but in many cases of compound pendulums, the angle of oscillation is to be considered larger so as to obtain any oscillation at all. This major disadvantage can be overcome using ICT-based approaches such as sensor-based data acquisition termed as micro-computer-based laboratories [2-4] and video capture and analysis, which is termed as video motion-based analysis [5,6]. The first approach while being fascinating and educative, requires a greater learning curve and involves more set-up cost whilst the second approach is easier to learn and available at low cost.

A. Video Motion-based Analysis

A simple smartphone camera with high picture quality can be used to capture videos of the experiments being performed. The motion of the object of interest which is the bob of simple pendulum in our case is recorded as a video followed by further analyses using a motion tracking software called Tracker. Tracker allows the bob's position to be tracked frame by frame thus providing the position and time information required for analysis with good accuracy and precision.[2]. This technique involves less time in experimentation, thereby granting the student more time for analysis and inference of results.

B. Analysis using Tracker software

Tracker is a video analysis package built on the Open Source Physics (OSP) [7] Java framework. It is a user-friendly software where an object's motion is tracked using the video footage shot by web cam/mobile camera. The software is enriched with several features including[2]

1. Tracking the object with position, velocity and acceleration overlays and graphs
2. Multiple reference frames
3. Calibration scales
4. Line profiles for analysis of spectra and interference patterns

C. Theory of Simple Pendulum Oscillations

A simple pendulum consists of a small mass (m), also known as the pendulum bob which is suspended from an inextensible string of negligible mass to a pivot as shown in the figure below,

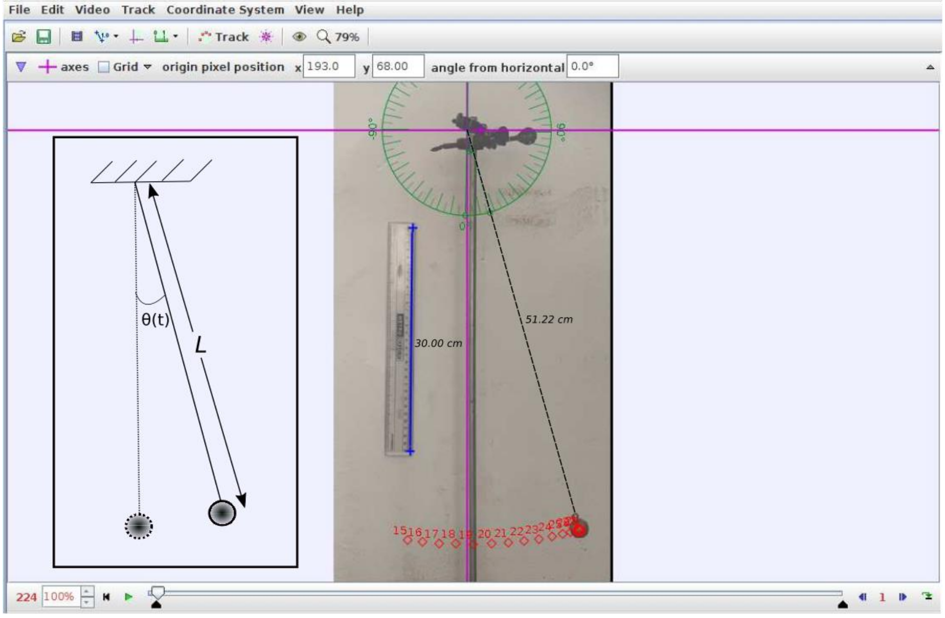

Figure 1: Schematic of a simple pendulum overlaid on a screenshot of a video frame in Tracker

When the bob is released with an initial angle (θ), the oscillation of the pendulum can be described using the following differential equation[1]

$$\frac{d^2\theta}{dt^2} + \frac{g}{L} sin\,\theta = 0 \tag{1}$$

where g is the acceleration due of gravity, L is the length of the pendulum and θ is the amplitude of the angular displacement. While considering small angle approximation, we can consider $sin\theta \simeq \theta$. Using small-angle approximation in the above equation, we get,

$$\frac{d^2\theta}{dt^2} + \frac{g}{L}\theta = 0 \tag{2}$$

which is a linear second-order differential equation and its solution is obtained as

$$\theta = A\, sin\, \omega t\ + B\, cos\, \omega t \tag{3}$$

where ω is the angular frequency of oscillation and given by

$$\omega^2 = \frac{g}{L} \tag{4}$$

$$\omega = \sqrt{\frac{g}{L}} \quad (5)$$

$$T = 2\pi\sqrt{\frac{L}{g}} \quad (6)$$

Generally, for this experiment, the time taken for at least 20 oscillations is recorded using stop watch, and then this step are repeated 3-4 times, following which the average time period is calculated and then the acceleration due to gravity g, is calculated from the slope of $L^2 - T$ the curve. But for experiments involving the large angle oscillations this measurements would result in significant error. For such cases, α - sin θ curve can be plotted and the slope would give the g.

2 Damping Coefficient

In reality, the pendulum cannot keep on oscillating forever due to resistive forces such as air resistance and the amplitude of oscillation will decline due to the frictional force between the string and pivot[1]. Generally, the frictional force is neglected due to the negligible mass of the string and only the air resistance is considered. The equation of motion can be rewritten as

$$\frac{d^2\theta}{dt^2} + \gamma\,\frac{d\theta}{dt} + \frac{g}{L}\,sin\,\theta = 0 \quad (7)$$

where γ is the damping coefficient. Using multiple linear regression fit, we can be obtain the damping coefficient along with acceleration due to gravity.

3 Experiment and Analysis

In our experiment, we set up a small bob suspended from a hinge using a very thin white thread, as shown in figure-1 to observe the oscillations of a simple pendulum. The bob was displaced from its equilibrium position, inducing initial oscillations, and it was confirmed that the motion stays within a plane perpendicular to the direction of observation. A smartphone camera was used to record the oscillations with utmost care taken to minimize errors in capturing the in-plane motion. As shown in the figure, we used a 30 cm scale for calibration to set the distance scale within the video frames. The recorded video was then trimmed to preserve only the relevant portion required for further analysis. The initial angular amplitude was found as approximately 15°, gradually decreasing due to damping.

The recorded video of the pendulum oscillation was imported into Tracker software. Before commencing the tracking process, a coordinate system was assigned to the video frames, where the origin was placed at the point of suspension of the pendulum. As depicted in the figure-1, a measuring tape and a protractor were used to gauge distances and angles within the video frames. After setting the tracking point in a key frame, the software automatically tracked the remaining frames, embodied by red diamond-shaped points with tracking sequence number on top, as shown in the figure-1. These provide x, y position coordinates of the pendulum bob. Each frame was separated by 0.033 seconds, as the video was recorded at 30 frames per second. After obtaining the coordinates of the pendulum bob as a function of time, they were further analysed to determine the angular displacement from the mean position using

$$\theta(t) = tan^{-1}\frac{-y(t)}{x(t)} \quad (8)$$

3 Results

The time variation of angular displacement is plotted in the figure-2. As evident from the plot in the figure-2, the amplitude of oscillation is found to be decreasing with time, analogous to damped pendulum motion. The lower panel in Figure 2 shows the simple harmonic angular displacement of the pendulum for a short time span from *t = 100 sec to 110 sec* where amplitude reduction is not so significant apparently; however, reduction in amplitude due to damping present in the system can not be ignored in longer time scale. Thus, this video-based experiment provides the opportunity for studying the pendulum oscillation in a time range from a few oscillations to hundreds of oscillations, which is not possible in a typical manual laboratory setup.

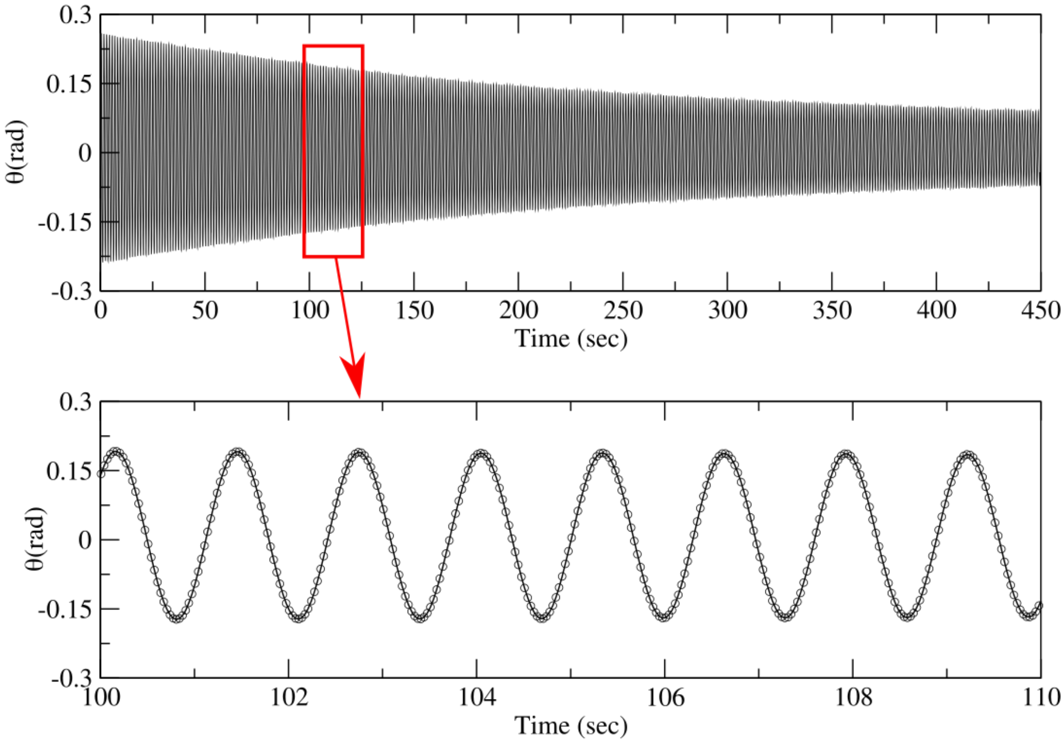

Figure 2: Variation of angular displacement w.r.t time

Using the $\theta(t)$ data, we calculated the angular velocity $\omega = \frac{d\theta}{dt}$ and angular acceleration $\alpha = \frac{d^2\theta}{dt^2}$ and plotted them versus time as shown in Figure 3. The time series ω and α data, obtained in the process, are used to calculate the damping constant γ and $\frac{g}{L}$ term using multiple regression fit. Similar to the lower panel of Figure 2, Figure 4 shows variation ω and α with time from *t = 100 to 110 sec*, where variation of ω is seen to be a smooth sinusoidal function; however, the numerical noise associated with derivative calculation reduces the smoothness for α-time graph.

Overall, as expected, both angular velocity and acceleration reduce with time due to damping. Now using expressions of angular velocity and acceleration, the equation
(7) can be rewritten as

$$\alpha + \gamma\,\omega + \frac{g}{L}\sin\theta = 0$$

$$\Rightarrow \alpha = -\gamma\,\omega - \frac{g}{L}\sin\theta$$

We implement multiple linear regression fit on the available time series data of α, ω and $\sin\theta$ to obtain the coefficients γ and $\frac{g}{L}$. Analysis of our data resulted in a damping coefficient $\gamma = 2 \times 10^{-3}\ kg/s$ and $g = 10.1\ m/s^2$. This analysis was carried out by running a small script using an open-source computation tool named Octave.

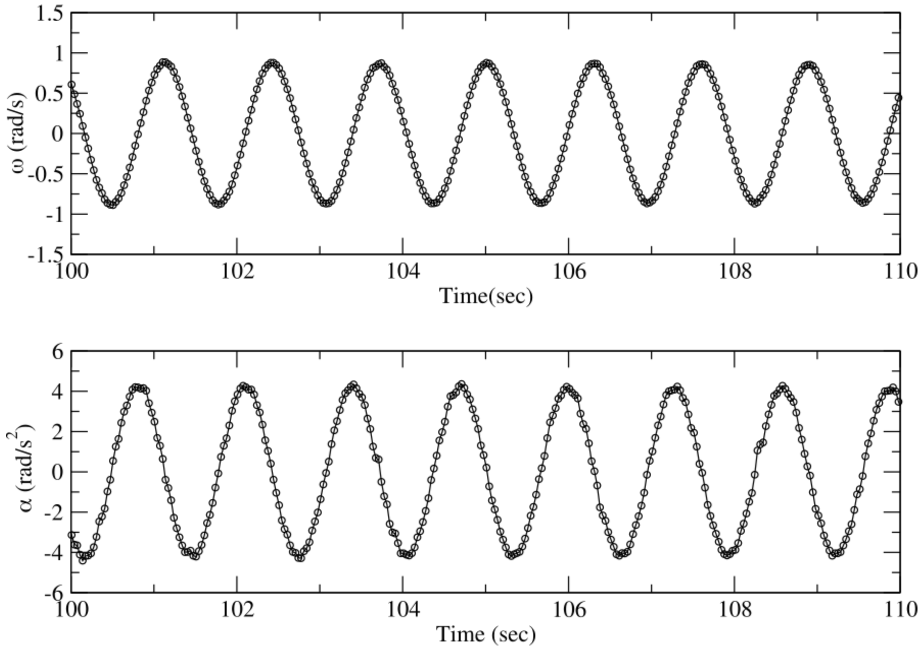

Figure 3: Angular velocity-time & Angular acceleration -time curve

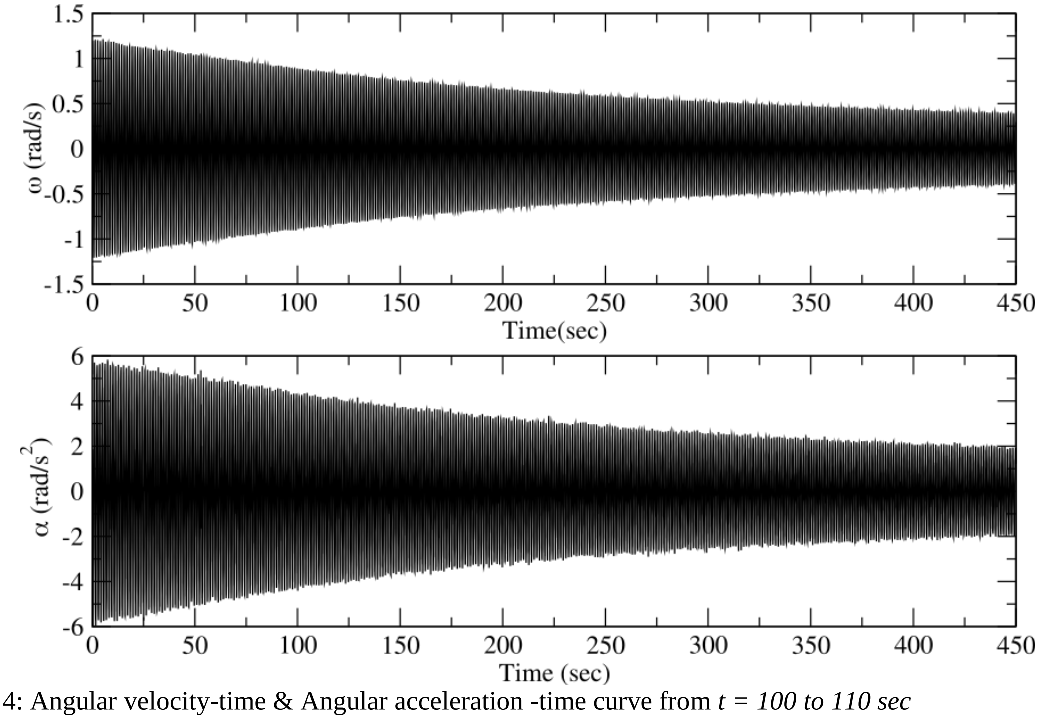

Figure 4: Angular velocity-time & Angular acceleration -time curve from *t = 100 to 110 sec*

4 Conclusion

Thus, in this work, we have employed a non-conventional method to determine the value of "g" and the damping constant γ using a simple pendulum oscillation. The obtained value of acceleration due to gravity is within 3% error, which can be attributed to the precision and accuracy involved in video analysis and the experiment itself. The damping constant lies within the expected range reported in earlier studies. The experiment reported in this article demonstrates a smart way of performing conventional laboratory experiments with a video-based analysis method using Tracker software. This technique can be extended to many other undergraduate-level laboratory experiments, accommodating a huge amount of data and aiding in the smooth and precise analysis of them.

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