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Simple Pendulum and Mass Spring System Using Video Based Motion Analysis

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***Abstract*—Simple pendulum and mass spring system are studied using video based motion analysis in Tracker software. These seemingly simple experiments are very non-intuitive and are extremely fundamental to any classical mechanics laboratory. Here, little innovative explorations are introduced to extend the study of these so as to enhance student learning and experimental skills, at very low cost. The videos of the experiments performed are captured using a web cam and are then analyzed using Tracker software and the results are compared to the theoretically expected outcomes. This is very good illustration of utilizing ICT to enhance laboratory experiments.**
Index terms - Video based motion analysis, ICT, Tracker software, Simple Pendulum and Mass Spring System

I. Introduction

A greater part of classical mechanics laboratory typically involves studying various types of oscillations such as pendulums and mass spring systems. The crucial measurements to be made are the time taken for a certain number of oscillations which is obtained using a stop watch and the amplitude information which is usually obtained using a scale. Generally, these experiments are performed manually and the errors involved are minimized by taking a large no of measurements. Unfortunately, the experiments do not provide simple understanding as to why the trajectory of a bob in a pendulum or a mass executing oscillations in a mass-spring system are simple harmonic in nature as it is very non-intuitive and we do not have the position information at regular time intervals. This major disadvantage can be overcome when we use technologies for computerization of these experiments. Two such approaches are sensor based data acquisition termed as micro-computer based laboratories [1-3] and video capture and analysis, which is termed as video motion based analysis [4,5]. The first approach even though very interesting and educative has a greater learning curve and involves more set up cost whereas the second approach is easier to learn and is available at low cost and is what is employed in setting up these innovative experiments in classical mechanics laboratories.

A. Video Motion based Analysis

A web cam can be used to capture videos of the experiments being performed. Typically, the motion of the object of interest in the experiment is recorded as a video, which can be analyzed using a software such as Tracker. These video analysis softwareallow the object's position to be tracked frame by frame thus providing the position and time information required for analysis in classical mechanics experiments. This simple technique can be used to perform many computerization experiments [1-6] with good accuracy and precision. All the experiments can be extended because of the availability of the large number of parameters on Tracker which can be altered. Visualization can evolve student interest to understand Physics and explore the different possibilities. Lesser time in experimentation means that the student has more time for analysis and inference of results.

B. Video Capture

Today from any corner of the world, we can see each other and have a chat using a web cam that is connected to a computer. To obtain a quality video using a web cam, one should ensure good focus, proper lighting and a plain background for the experimental apparatus, so that it becomes easy to track the object. Recording a video helps us in two ways:

- Less time is needed to perform the experiment.
- Stored videos can be analyzed later.

C. 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 we track an object's motion using the video footage shot by web cam. Features include:-

1. Object tracking with position, velocity and acceleration overlays and graphs,

2. Special effect filters,

3. Multiple reference frames,

4. Calibration points and

5. Line profiles for analysis of spectra and interference patterns.

D. Overall Implementation Strategy

The students were introduced to this technique and the way to perform error analysis through a simple experiment on simple pendulum. This was followed by giving them instructions as to how they can vary the parameters in a given experiment and how they can make changes to a given system so that newer systems can be constructed and studied. For example, the students are asked to vary the initial angle from small angle to larger angles all the way up to 90 degrees for the simple pendulum experiment. The small angle approximation is no

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more valid, but they would get to study the time period variation for larger angles. Then, they are asked to change the mass of the bob to understand the concept of damping. To further innovate they are asked to add an extra constraint to the system which completely changes the nature of oscillations and it provides a different insight. Similarly, they have been given spring of larger mass so that its effective mass would need to take into account for time period calculation. In this fashion, the level of the experiments was slowly but constantly raised and the results were compared with the expected outcomes by asking them to figure out the appropriate theoretical model to be considered. The results were very encouraging and these innovations are performed using this technique for the first time.

II. EXPERIMENTS AND RESULTS

1. Simple Pendulum

A. Small Angle Oscillations:

The bob is given an initial angular amplitude of 16 degrees and the oscillations were captured using web cam. The captured video is opened in Tracker and the time period and its error were determined as follows:

Time Period Calculation:
First we pick a new 'point mass' for analysis from the Track sub-menu in tracker. Then we play the video and pause it when the mass reaches close to one of the extreme positions. Using the forward and backward frame buttons we decide the exact extreme location (the bob will move either ways towards the center of oscillation here). We need to press 'Shift' button and hold it as we click to mark the position of the bob. Now, the video is played and after counting 7-8 oscillations, we pause close towards the same extreme position and repeat the process to mark the exact extreme position of the bob. The time difference between these two frames, which can be obtained by taking the difference of the times tabulated in the table view available on the bottom right window, divided by the no. of oscillations gives the time period 'T' of the oscillation.

Error in Time Period:
The video is captured at the rate of 30 frames/sec and hence the least count is $1/30^{th}$ of a second, i.e. 0.033 sec. In this experiment, we know the extreme position of the bob to an accuracy of 0.033 sec, the reaction time of the camera, compared to the typical reaction time of a good experimenter, who takes about $1/10^{th}$ of a sec or 0.1 sec to start or stop a timer. That is why while doing manually, we take time for 20-30 oscillations so as to reduce the error in time period to less than 1%. By contrast, on computerization, we need just about 7 oscillations, that too one reading would suffice, to determine the time period to an error of less than 1% when we use the web camera for video capture. As the maximum error in time difference for 7 oscillations would be 0.066 sec, (0.033 sec for each extreme frame picked) which is distributed over 7 oscillations, the error in time period is 0.066/7 which is less than 0.01.

B. Large Angle Oscillations:

The advantage of getting good accuracy by determining the time period using just 5-7 oscillations allows us to extend the experiment to study large angle oscillations. If we perform manually, we will need at least 20 oscillations to get good accuracy and the oscillations of the pendulum would die down considerably due to damping. This would lead to error in time period as the oscillations will not correspond to the case of simple harmonic oscillator for the initial angle of oscillation but would require the treatment of a damped harmonic oscillator. Figure 1 shows the set up for performing a large angle oscillation of simple pendulum experiment.

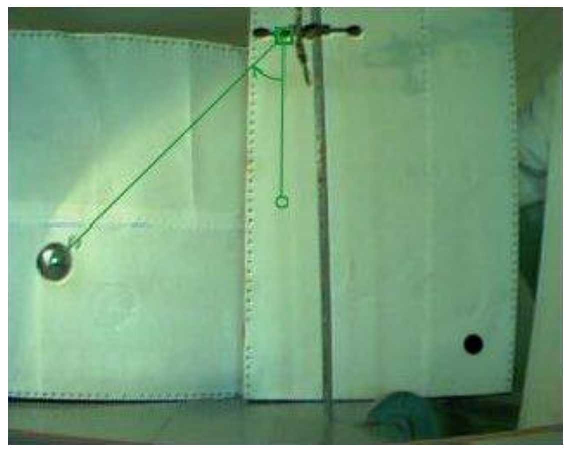

Figure 1: Setup image of simple pendulum for large angle oscillation amplitude of 46.5^{O}

The initial angle of oscillation can be obtained from Tracker, using which the expected time period is determined from the formula for large angle oscillations.

$$T_\alpha = T_0(1 + \frac{\alpha^2}{16})$$

Where T_0 is the time period for the small angle oscillation. The small angle approximation sin (α) ~ α is valid up to only about 15 degrees for an accuracy with less than 1% error. The time periods for various initial angles are obtained using Tracker as discussed above and are tabulated along with the errors.

Table 1: Determination of Time period for various initial angular positions of the bob

S. No	Initial angle of oscillation	Expected Time Period	Obtained Time Period

	(in degrees)	(in Sec)	(in Sec)
1	16.5	1.230 +/- 0.003	1.228 +/- 0.001
2	46.5	1.280 +/- 0.003	1.279 +/- 0.001
3	57.4	1.307 +/- 0.003	1.296 +/- 0.001
4	69.1	1.347 +/- 0.003	1.329 +/- 0.001
5	77.5	1.370 +/- 0.003	1.368 +/- 0.001

Discussion: One can observe that the discrepancy increases for larger angles. This is because the students have taken the time period for 10 oscillations instead of just about 5-6. The damping is very large for 10 oscillations and the angular amplitude would have decreased drastically for it to correspond to the theoretically expected value. Instead, it would be the average of time periods for a range of angular positions that the pendulum would have undertaken oscillations for, over 10 oscillations.

C. Damped Harmonic Oscillations:

As a variation to the simple pendulum experiment, the mass of the bob is reduced by choosing a Table-Tennis (TT) ball as the bob and its oscillations were recorded using web cam. The auto-tracker option in Tracker was used to obtain the motion of damped pendulum and the trajectory of the TT ball is shown in Figure 2.

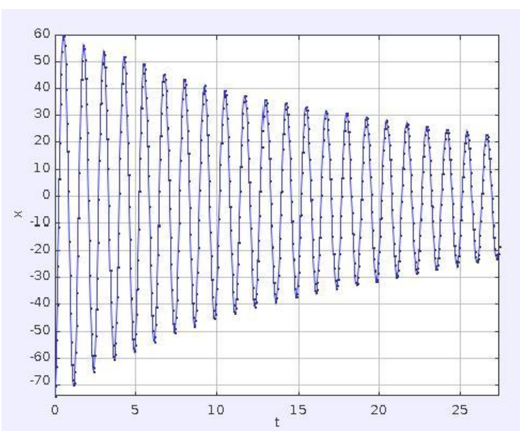

Figure 2: Damped oscillations for the TT ball suspended as a simple pendulum

The damping co-efficientμcan be obtained using the formula

$$\mu = \frac{ln(\frac{A_1}{A_2})}{(t_2 - t_1)}$$

Where A1 and A2 are the amplitudes w.r.t. equilibrium at times t1 and t2 respectively.

Results: The value of damping co-efficient from the experimental data (A1=70.22, t1= 0.5 sec; A2 = 33.11, t2 = 26.63 sec) was obtained to be: 0.013 +/- 0.002. The time period obtained from the experiment is 1.244 +/- 0.001 sec. The theoretically expected time period is 1.243 +/- 0.003 sec. As one can observe, there is no shift in the time period for the damped harmonic oscillator because the damping coefficient is too small to effect the time period in its second or third decimal position.

D. Simple Pendulum with Extra Constraint

The simple pendulum is of length, say L1. Now, we tie the bottom of the bob with another thread of length L2. Then, the bob was given a small displacement in the horizontal direction and its time period is determined. This was a homework problem to set up the equations of motion using Newton's second law and obtain the time period of oscillation, which the students wanted to cross-check by performing an experiment.

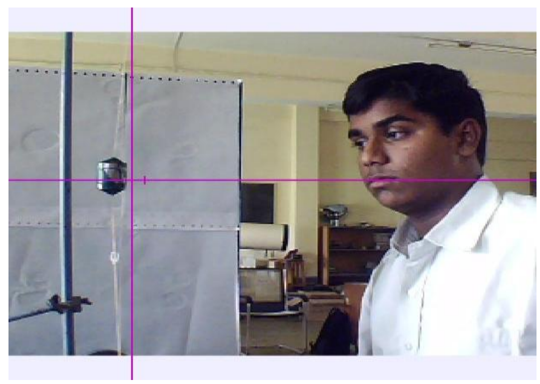

Figure 3: Setup of the constrained simple pendulum. Observe the mass tied at both ends by strings.

Results: The time period for the oscillating mass constrained with two strings of lengths L1 and L2 is determined to be **0.952 +/- 0.007**. Using this, the Tension in the strings is determined to be **2.310 +/- 0.003 N**. The theoretically expected value from the values of mass m, lengths L1 and L2, the initial displacement x given to the mass, gives the value for tension as **2.123 +/- 0.017**. The discrepancy can be explained if the experiment is repeated for different initial displacements.

2. Mass Spring System:

A. Simple Harmonic Oscillations:

A spring mass system was set up and was set into oscillations by giving small amplitude. A video of its motion is analyzed frame by frame in Tracker for obtaining the sinusoidal variation and its time period. The experiment was repeated for different masses and a graph of w^2 vs 1/m yielded a straight line. The spring constant was determined from the slope of the graph.

B. Damped Harmonic Oscillations:

The mass was submerged in water as shown in Figure 4 below. Then the oscillations were captured in a video.

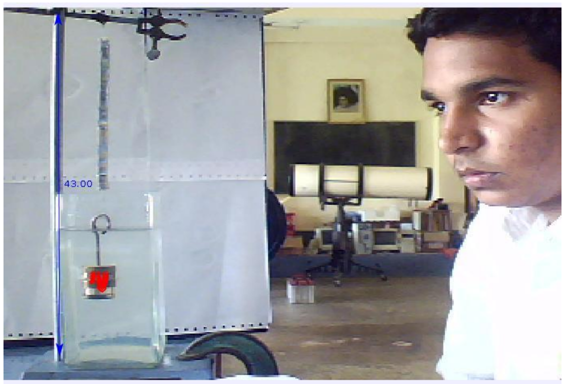

Figure 4: The mass spring system with the mass submerged in water in order to study damping

A red color tape is fixed to the mass so that it can be tracked easily in Tracker. In general, the web cams are sensitive to red color and the quality of video is improved, if we use red for the object to be analyzed in the video. The damped oscillations for the mass under water tracked from the video in Tracker are shown in Figure 5 below:

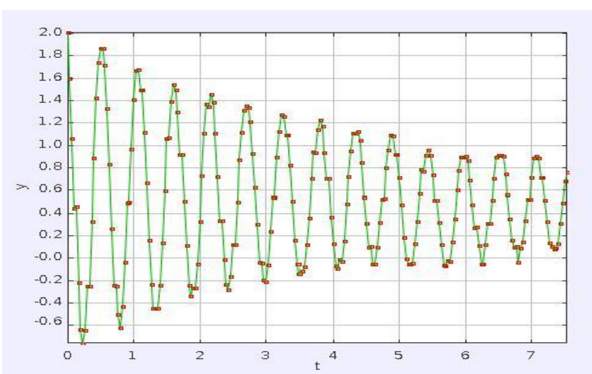

Figure 5: Damped oscillations for mass immersed in water obtained in Tracker using the point mass analysis

C. Springs in Series and Parallel:

The spring constants for two different springs were determined using the procedure outlined above in 2a. The springs were then coupled in series and parallel and the procedure was repeated to find the spring constants for the combination systems. Using the well-known formulae for combination of springs in series and parallel, the experimental results are compared with the theoretically expected results along with the error margins.

Observations:

Springs in series:

k1 = 50.3 +/- 1.8 N/m; k2 = 52.8 +/- 1.8 N/m
Theoretical value for keq = 25.8 +/- 0.9 N/m
Practical value for keq = 24.8 +/- 1.1 N/m

Springs in parallel:

k1 = 51.7 +/- 1.6 N/m; k2 = 11.66 +/- 0.17 N/m
Theoretical value for keq= 63.3 +/- 1.7 N/m
Practical value for keq= 62 +/- 2 N/m

As one can easily see, there is good overlap between the expected and obtained results. One more question that can be tested is what happens if the mass of the spring is not negligible compared to the mass that is hung? One would have to take into account the equivalent mass of the spring for the time period calculation and that is what is checked.

D. Equivalent Mass of spring:

A spring of heavier mass was procured so as to study the effect of mass of spring on the time period of the system. The spring constant was determined using the static method and then compared with that using the dynamic method for two different formulae, one involving the effective mass of the spring in the calculations and another without it. The accuracy involved in the experiment is able to distinguish between the two values to confirm the theoretical considerations. The spring constant was determined using the static method to be 10.5 +/- 0.7 Kg/sec^2. The results are tabulated.

Table 2: Determination of Time period for various masses attached to the spring m and comparison of practically obtained Time period Tprac with the theoretically obtained Time periods, without effective mass Tm and with effective mass of spring TM. Mass of the spring M = 59 gms.

m in gms	Tprac in sec	Tm in sec	TM in sec
200	0.895 +/- 0.009	0.85 +/- 0.02	0.90 +/- 0.02
250	1.024 +/- 0.009	0.95 +/- 0.03	1.01 +/- 0.03
300	1.128 +/- 0.009	1.04 +/- 0.03	1.10 +/- 0.03

Note: One can easily observe that there is no overlap for the time periods obtained when the mass of the spring is neglected and a good overlap when it is taken into account, perfectly verifying the theory.

III. Conclusions

Simple innovations have been implemented in the regularly performed experiments of simple pendulum and mass spring system using a low cost information technology technique of video based motion analysis to obtain an effective methodology for conducting classical mechanics laboratory. The effectiveness of the method comes fromits advantages of higher accuracy of data recording at regular times and the capabilities of obtaining amplitude information as well as angle information. Further, the videos captured can be analyzed at leisure and by multiple users. That is, even remote areas where good laboratory facilities are not available, the virtual experiment available as videos can be analyzed and the learning of concepts can be enhanced. This could be tested using the physics education research practices for its effectiveness.

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