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Simple Harmonic Oscillation using Computer Simulation: Compilation of Experiments for Classroom Investigations

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Abstract

The Simple Harmonic Oscillation (SHO) is a fundamental concept in physics, as it describes a large variety of phenomena that occur in nature, such as the motion of pendulums, mass-spring systems, and atoms. A thorough understanding of SHO can provide a good foundation for learning more advanced topics in physics, making it an essential topic for students to learn. Computer simulation technology provides an effective way to model SHO phenomena in the classroom. This technology allows students to explore SHO concepts visually and to replicate experiments that would be cumbersome or impossible to conduct otherwise. However, there are few compilations of SHO simulations appropriate for classroom use. This paper presented a compilation of SHO experiments that utilize computer simulation of PhET. The compiled experiments cover a broad range of SHO concepts, including proving the relationship of energy and amplitude, velocity and displacement, acceleration and displacement and types of damping. These experiments are suitable for classrooms of all levels and can be used to broaden and enrich students' understanding of SHO. Overall, the simulation-based experiments presented here offer a valuable resource for educators seeking to improve their students' understanding of SHO.

Keywords: physics education, physics teaching and learning, simple harmonic motion, computer simulations, experimental method

INTRODUCTION

Simple Harmonic Oscillation (SHO) is a type of periodic motion where an object repeats the same motion over again in a fixed path. This oscillation occurs when an object moves back and forth around an equilibrium position due to a restoring force, such as gravity or a spring force. Examples of simple harmonic motion include pendulums swinging back and forth and the vibration of strings on musical instruments.

Simple harmonic oscillations are important for many real-world applications including engineering, seismology and physics related studies. In engineering applications like mechanical systems or electrical circuits, these types of cycles lead to higher system efficiency by providing sustained energy conversion between storing energy during one part of its cycle then dissipating it during another portion [1]. Additionally, [2] described that these oscillations are used as modeling tools in certain physical phenomena such as sound waves traveling through space and time-dependent biological processes like human heartbeats.
Simple harmonic oscillation experimentation is a great way for students to explore the world of physics in the classroom. It can help them understand how objects respond to force and motion, as well as the relationships between acceleration, velocity and displacement [3]. With some fun hands-on activities designed to highlight these concepts, even younger kids can begin to gain an appreciation of calculus-level

topics such as energy transfer, work and impulse. One way to introduce SHO in the classroom is by exploring the fundamental frequency of a mass-spring system. Students can investigate what happens when they change the length or mass of the setup or add an external force like gravity. For upper-level classrooms, a teacher could use various mathematical models to model sinusoidal functions that can explain this behavior more accurately.

Experiments involving pendulums also let students explore SHO behavior in an interesting way. Discussing kinetic and potential energy in this context helps bring concepts from physics alive for learners by providing a tangible example that does not require complex calculations and formulas to analyze [4]. Tinkering with the angle and height at which the pendulum swings from its point of origin further adds evidence that demonstrates how non linearity shapes its path through space, despite obeying a sinusoidal function. Moreover, exploring damped oscillations provide a great opportunity for testing ideas related to damping factors in amplitude decay over time as well as reflection on how devices possessing conservative forces play out complex behaviors due to their "memory" regarding certain previous configurations (i.e., stored energy). By comparing reflections between different materials attached on a spring (for instance Styrofoam versus steel) students may began delving deeper into damping behavior while developing creative solutions towards managing undesirable vibrations caused by unbalanced systems or harmonic resonance phenomena created under various conditions like resonant cavities or acoustic feedback loops resulting after setting up many loudspeakers connected together in series.

Having said all about SHO, this paper is a compilation of experiments that can be conducted in PhET's simulation on SHO. The experiments are mostly about proving theories and formulas on SHO. For instance, proving that acceleration is directly proportional to the negative of the displacement of oscillation. Additionally, graphs would be presented to showcase the relationships. This compilation would be beneficial to teachers since they can already view most classroom level experiments in one document such as this. They can easily replicate the experiment in their classroom.

Theoretical Background

Simple harmonic motion is a type of periodic motion in which an object moves back and forth along the same path and at a constant speed [5]. The acceleration of an object undergoing simple harmonic motion is directly proportional to its displacement along the x-axis. This is known as the restoring force, since it is the force that restores the object back to equilibrium position; when the object deviates from equilibrium, a restoring force will act on it, causing it to return. As such, acceleration is related to displacement by an equation:

$$a = -\omega^2 x \qquad (1)$$

Here a is the acceleration, ω^2 stands for angular frequency squared and x is equal to the displacement. Thus, as the displacement increases, so too does acceleration. The negative sign indicates that acceleration acts in the opposite direction to its displacement.

The angular frequency is equal $2\pi f$ where f is the frequency. Since $f = 1/T$ where T is time period of the oscillation, the equation 1 could be written as.

$$a = -4\pi^2 f^2 x \qquad (2)$$

$$a = -\frac{4\pi^2}{T^2} x \qquad (3)$$

Equations 3 tell us that if the time period decreases then the acceleration will increase. Equation 2 demonstrates that frequency is also directly proportional to the acceleration when displacement is constant.

The velocity of the oscillation can be computed as

$$v = \omega\sqrt{x_o^2 - x^2} \qquad (4)$$

In equation 4, v is the velocity at any point of the oscillation, x_o is the amplitude of oscillation, and x is the displacement. This equation implied that v is proportional to the displacement. The longer the displacement of the oscillator, the faster is the oscillation.

The velocity is maximum when the displacement is at equilibrium or at x = 0. The equation now becomes

$$v_o = \omega x_o \qquad (5)$$

The equation 5 gave us the idea that the velocity of the oscillation is directly proportional to the amplitude.

The kinetic energy of the oscillation is maximum when displacement is zero since at this point velocity is maximum as well. The potential energy is maximum when $x = \pm x_o$.

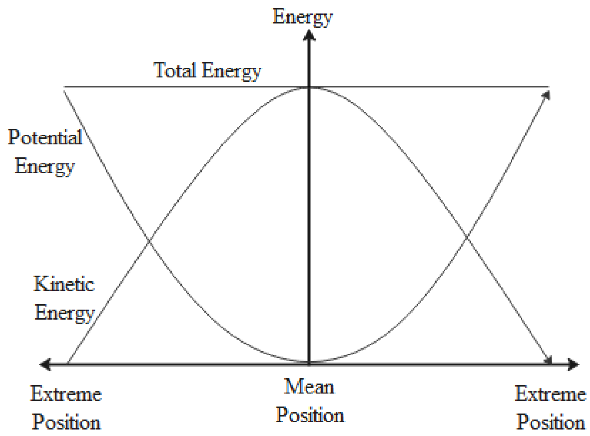

Figure 1. The kinetic and potential energies of the oscillation. Photo from https://www.vedantu.com/question-answer/a-pendulum-is-oscillating-on-either-side-of-its-class-11-physics-cbse-5f982e77e5ee356aec25acca

Based on figure 1, the total energy is equal to the sum of kinetic energy and potential energy and this is the case at any point of the oscillation. At x = 0, the total energy is equal to

$$E = \tfrac{1}{2} m v_o^2 \qquad (6)$$

Substituting equation 5 to equation 6 give us

$$E = \tfrac{1}{2} m\omega^2 x_o^2 \qquad (7)$$

Equation 7 describes that energy of the oscillation is directly proportional to square of the displacement when mass and angular frequency are constant. The energy is also proportional to the square of the angular frequency when displacement and mass are constant.

MATERIALS AND METHOD

The primary tool for this experiment is a computer. Additionally, the PhET simulation on SHO requires an internet connection and web browser capable of running Javascript, an Adobe Flash Player installed on the computer for running the simulations, and a monitor or other display device with resolution of at least 1024 x 768 or higher recommended for best performance when running the simulations.

The simulation is equipped with a ruler, stopwatch, and period timer. There is also length, mass, gravity, and friction lever to adjust the quantitative measure of these three quantities. The play bottom is located at the bottom and can be adjusted as normal or slow. These features can be view from figure 2.

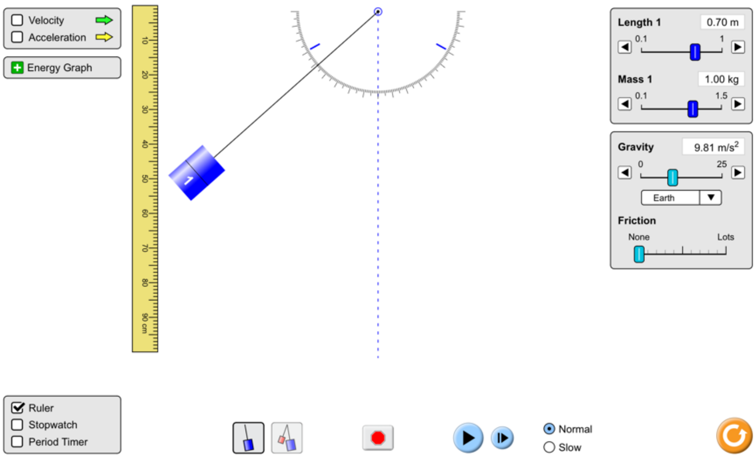

Figure 2. The Phet simulation on simple harmonic oscillation. From University of Colorado PhET Simulation, 2023 (https://phet.colorado.edu/sims/html/pendulum-lab/latest/pendulum-lab_en.html)

There are three experiments that are compiled in this paper. These are: acceleration against displacement; velocity versus amplitude; and energy against displacement. The summary of these experiments is found in table 1.

Table 1. The set-up of the experiments

Experiment	Independent variable	Dependent variable	Control variable
1	displacement	acceleration	length of string, mass, frequency, air resistance
2	amplitude	velocity	length of string, mass, frequency, air resistance
3	displacement	energy	length of string, Mass, frequency, air resistance

Each of these experiments has seven trials. Each experiment has graph to be plotted in the MS Excel. The graph showed that the relationship is correct. Displacement is measured from the equilibrium position, which is the starting point and reference, and it can be positive or negative depending on direction. There is no horizontal ruler on the simulation so this be measured by using trigonometric identity as x = length of string/rope x sin theta. The angle is given on the simulation. The acceleration is computed using equation 1 for experiment 1 and equation 3 for experiment 3. The amplitude is similarly computed as the displacement since the amplitude is the highest displacement. The velocity is computed using equation 5. The energy is computed using equation 7.

RESULTS AND DISCUSSION

Displacement vs Acceleration

The experiment one is about the displacement and acceleration of a simple harmonic oscillation. The base definition of an SHO is based on equation 1.

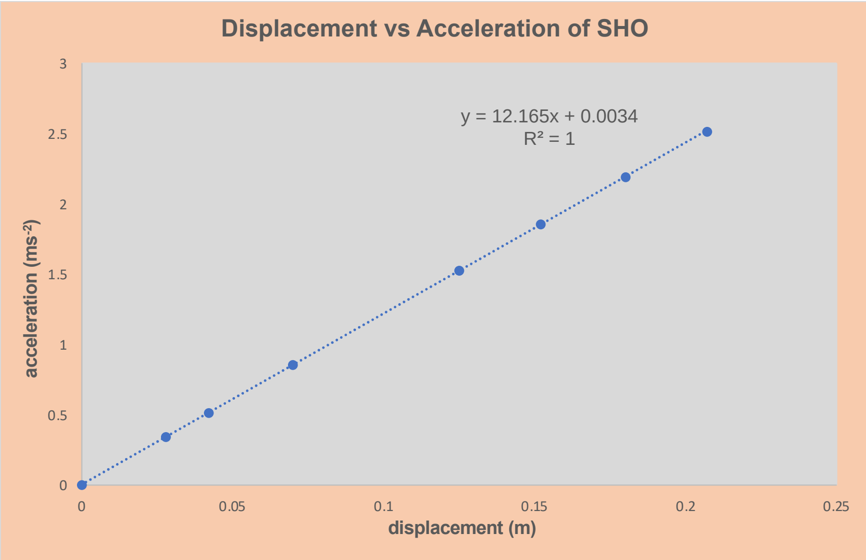

Figure 3. The displacement against acceleration forms a straight-line graph which indicates a direct relationship.

In this experiment, the students can gather the data of the displacement by using the trigonometric identities the length of the wire being the hypotenuse. There were seven displacements that were taken into account. The equation for the acceleration is found in equation 1 but this equation contains angular frequency. To find the angular frequency, the time period must be taken. The simulation has time period tool found on the left side of the screen. From the seven displacements, seven time period should be noted as well. Now, the angular frequency is computed as $\frac{2\pi}{T}$, T as the time period. Finally, the acceleration is computed based on equation 1.

The data of displacement and acceleration were plotted in MS Excel and the line of best fit was generated as seen in figure 1. Equation 1 tell us that acceleration and displacement should be directly proportional. The line in figure 3 suggest this relationship. The gradient of this graph is the square of the angular frequency and the angular frequency is equal to the square root of the gradient. As seen on figure 1, the gradient is 12.165 s^{-2} and the square root of this is 3.49 s^{-1} which is exactly the same as the average angular frequency from the seven data.

However, there was an intercept found which was 0.0034 and the equation 1 suggest that the y-intercept should be zero. This error came from the calculation of the displacement based on the length of the wire. The significant figures of the number computed were another cause of this error.

Amplitude and Velocity

The experiment 2 explored the amplitude and velocity of the simple harmonic oscillation. The velocity of the oscillation can be computed using equation 5. The students can keep the data of the angular frequency that they computed from the previous experiment. The amplitude is defined as the maximum displacement so each of the seven measurement of displacement is the amplitude itself. The data of the velocity and the amplitude were graphed using the MS Excel and the line of best fit was generated. As seen in figure 4, the amplitude and the velocity formed a straight-line best of fit. This connotated that velocity and the amplitude is directly proportional to each other as exemplified by equation 5.

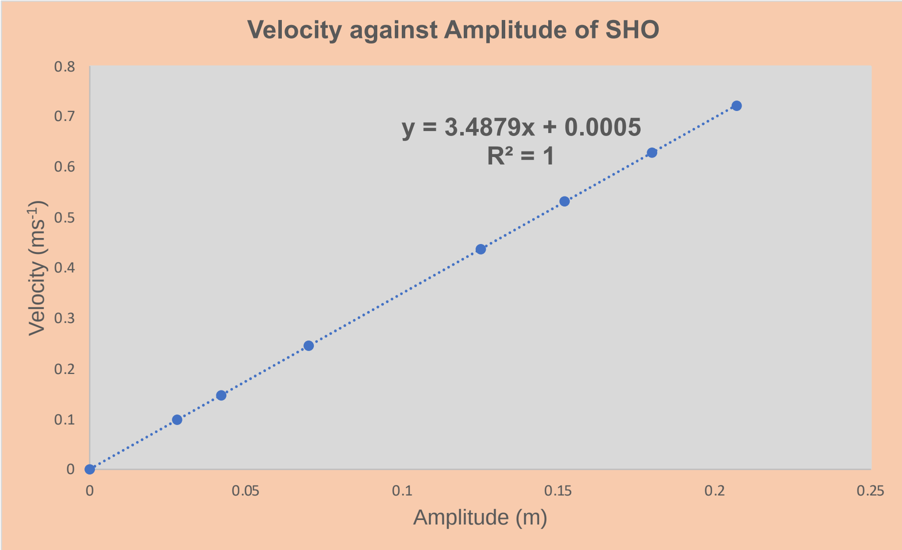

Figure 4. The relationship between velocity of the oscillation and its amplitude was found to be directly proportional.

It is also noteworthy that the gradient of this line, which is the angular frequency, is the same as the angular frequency in the previous experiment. This suggests that equation 1 and equation 5 is connected through the angular frequency. This angular frequency is equal to 3.49 s^{-1}.

In addition, equation 5 tell us that the y-intercept is zero but figure 4 has y-intercept which is equal to 0.005. This y-intercept is almost nothing but possibly this appeared because of the significant figures used.

Energy and Amplitude

The amplitude of a simple harmonic oscillator is defined as the maximum displacement of the oscillating object from its equilibrium position [6]. The amplitude determines the maximum velocity and acceleration of the system. The greater the amplitude, the greater the kinetic energy and momentum of the system will be at its maximum displacement. This relationship is mathematically expounded in equation 7.

Based on equation 7, velocity should be measured. The velocity was computed as maximum displacement or amplitude multiplied by the angular frequency as seen in equation 5. The angular frequency was already computed based from the previous experiments. Finally, the energy of oscillation was computed using equation 7.

The graph of energy versus the square of displacement was plotted in MS Excel and the line of best fit was generated. The figure 5 was this graph. As observed from this figure, the energy and amplitude are directly proportional to each other because of the straight line that was formed. This confirms that equation 7 is correct. In addition, the students can compute for the angular frequency based from the gradient and equation 7. Figure 5 tell us that the gradient is 6.0813. The gradient is equal to ½ mass times square of the angular frequency and so the angular frequency is equivalent to square root of 2 times the gradient divided by the mass. The angular frequency which is computed based from this equation yielded to 3.49 s^{-1} and this is exactly the same as the angular frequency in experiments 1 and 2.

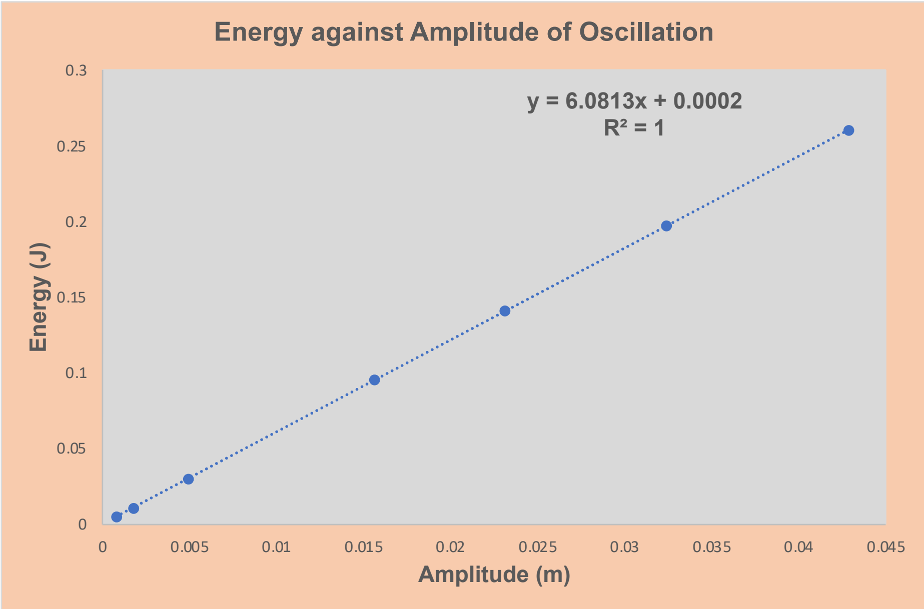

Figure 5. The plot of energy of oscillation and its amplitude formed a straight-line graph. This indicated a direct relationship between energy of oscillation and its amplitude.

However, equation 7 predicted that there should be no y-intercept but the generated graph in figure 5 contains a slim amount of y-intercept. The y-intercept from figure 3 is 0.0002 which is almost nothing and this is coming from the rounding off of the number [7].

Damping

Damping in oscillation refers to the gradual reduction of the amplitude or intensity of an oscillating system over time [8]. This reduction can be caused by various factors including friction, air resistance, viscosity, or other external forces acting upon the system. When a mechanical system undergoes damping, its energy dissipates due to frictional forces. If the damping force is too weak, the system will continue to oscillate with decreasing amplitude until it reaches equilibrium. On the other hand, if the damping force is too strong, the system will return to equilibrium too quickly, also known as over damping. However, when the damping force is precisely equal to the critical value, the system undergoes critical damping. [9] added that damping is an important concept in oscillation as it affects the behavior and stability of the system. In an undamped system, oscillations would continue indefinitely with a constant amplitude, but in reality, all real-world systems are subject to some form of damping.

Damping can be classified into three categories - overdamping, underdamping, and critically damped. Overdamping occurs when the system returns to equilibrium without oscillating, underdamping refers to the situation where the system oscillates around the rest position and the amplitude gradually decreases, while critically damped is the condition between overdamping and underdamping when oscillations decay as quickly as possible without oscillating. In the PhET simple harmonic simulator, the students can view these types of damping by increasing or decreasing the percentage of friction.

By placing the friction bar at the lowest percentage possible to medium, the students can observe light damping. In light damping, the amplitude of the oscillation decreases gradually over time rather than abruptly decreasing. This gradual decrease happens because the damping force that opposes the motion is relatively small compared to the driving force. As a result, the system's natural frequency is only slightly altered by the damping force which results in slow reduction of the amplitude. Light damping is commonly seen in certain mechanical systems like the oscillation of a pendulum or a mass-spring system moving through a viscous medium. [10] cited that light damping can be found in electrical systems like RLC circuits where resistive losses cause damping to occur.

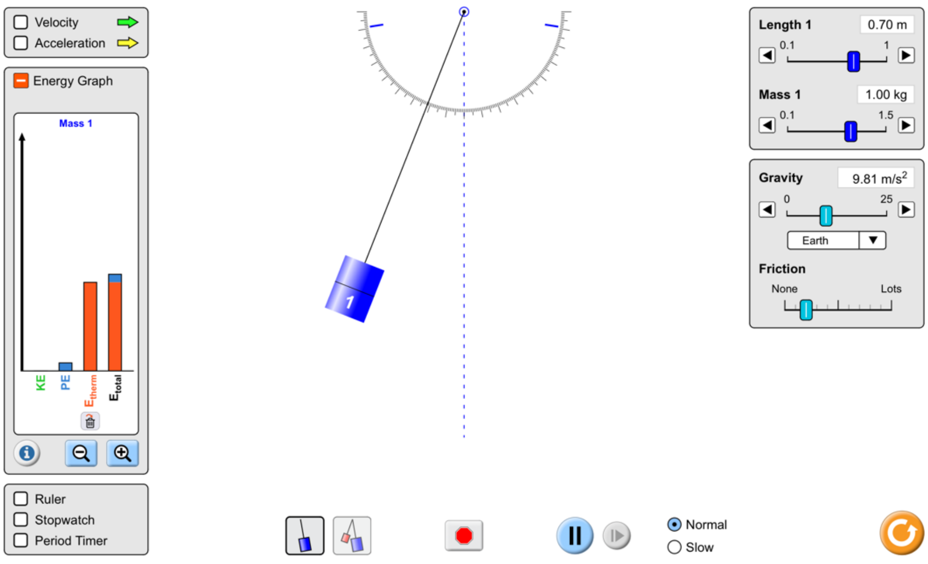

Figure 6. Light damping refers to the type of damping that occurs when an oscillating system loses energy slowly due to external factors such as air resistance, friction or other resistive forces. From University of Colorado PhET Simulation, 2023 (https://phet.colorado.edu/sims/html/pendulum-lab/latest/pendulum-lab_en.html)

If the students try moving the friction bar to the lots level, it will be observed that the oscillations decay as quickly as possible without oscillating. This is called critical damping.

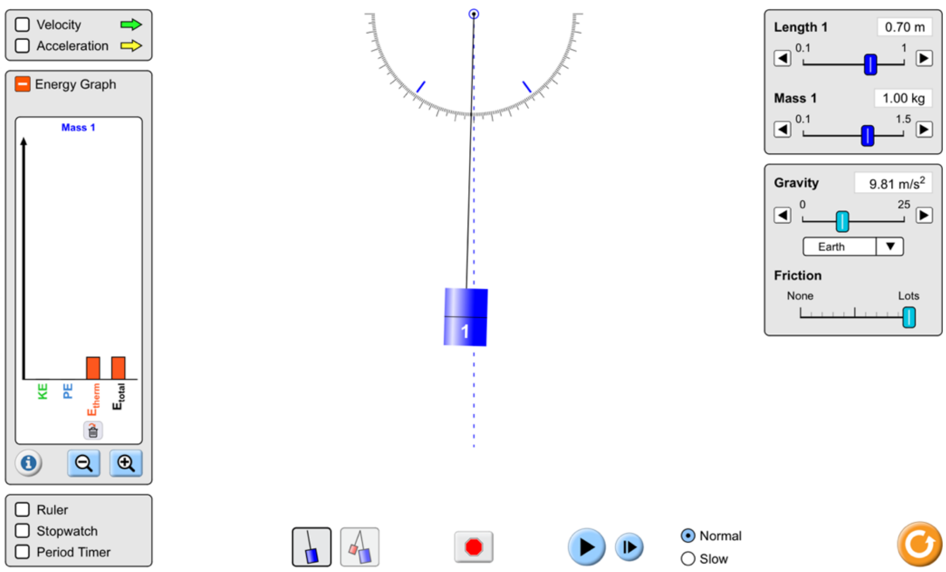

Figure 7. Critical damping is a type of damping where the oscillating system returns to its equilibrium position in the shortest possible time, without overshooting. From University of Colorado PhET Simulation, 2023 (https://phet.colorado.edu/sims/html/pendulum-lab/latest/pendulum-lab_en.html)

Critical damping is the point at which the oscillation ceases as quickly as possible without overshooting, and it minimizes the oscillation's frequency of vibration. Critical damping can occur in a variety of systems, including mechanical and electrical systems. For instance, a mass-spring damper system could have critical damping if the amount of damping is set such that the mass quickly comes to rest without any oscillation.

Critical damping is an important aspect of oscillation in engineering, physics, and other fields. [11] highlighted the use of critical damping in shock absorbers to bring them back smoothly to their original position without any overshoot, which could cause instability. [12] added that critical damping is used in machinery to prevent oscillations and vibrations, which can cause damage to the machinery and affect its performance. Some exercise machines, like treadmills, use critical damping to allow runners to run on the machine without affecting its operation.

Classroom Applications of Simple Harmonic Oscillations

We have conducted five experiments so far. These experiments have ended up learning the students about the relationships of amplitude and energy, displacement and acceleration, and amplitude and velocity. The students also learned about the damping and its types.

PhET simulations on oscillations can have several classroom implications. Using PhET simulations on oscillations, students can develop a better understanding of complex concepts related to oscillations such as amplitude, frequency, and period. [13] argued that PhET simulations allow for interactive learning, making it possible for students to experiment with different variables and observe the effects in real-time. This approach to learning can keep students engaged and help them retain information better. [14] highlighted that PhET simulations offer a risk-free environment for experimentation, allowing students to explore concepts without the need for expensive equipment or the risk of injury. In addition, With PhET simulations, students can actively participate in the learning process, which can facilitate better knowledge retention and understanding [15].

CONCLUSION

Based on the conducted experiments and simulations, it can be concluded that Simple Harmonic Oscillation can be effectively studied by using computer simulations. The compilation of experiments presented in this study serves as an excellent resource for educators to conduct classroom investigations on this topic.

The simulation demonstrated the principles behind Simple Harmonic Oscillation and how motion varies with amplitude, frequency, and initial displacement. Students can easily observe the oscillation of a spring and investigate different factors affecting it.

Overall, this study provided a valuable learning experience for students to understand this fundamental concept in physics. By utilizing computer simulations, they can visualize the oscillatory motion, which can enhance their understanding and make the learning process more engaging.

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