Teaching of the phenomena of free, damped and forced oscillations in physics through an all-inclusive java applet

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Abstract

A java applet has been created for use as an all-inclusive online as well as offline learning object to teach the phenomena of free, damped and forced oscillations in physics in an entirely novel way. Subtle, yet very important features of the above phenomena, which can be difficult to make young learners understand through conventional classroom teaching, can be made easily understandable with the applet's help, through demonstration of animated plots, as well as through the provision for virtual experimentation with appropriate controls. The learner can keep track of the relevant theory including all pertinent equations, which come into focus in synchronization with the dynamic plots in real time. A topical quiz has been embedded inside the applet itself to examine the improvement, if any, in his understanding of the topic. Quantitative as well as interview-based studies to test the effectiveness of the applet have also been carried out. The results indicate that the applet can be most effective when used in conjunction with proper guidance from the teacher and when made part of a well thought-out curriculum.

1. Introduction

The phenomena of free, damped and forced oscillations are amongst the most frequently encountered topics in physics. Students are introduced to the topics when learning the mechanics behind the swinging pendulum. They come across the topics in acoustics as also when studying alternating currents in circuits. Later on they encounter the topics in atomic and nuclear physics as well. The mathematical formulation used to teach the topics however remains more or less the same. It usually involves the solution of second order, homogeneous and inhomogeneous ordinary differential equations. It is imperative that the students, coming out of school and entering college to study physics, have a fair idea of solving differential equations in general. As is often the case, this does not happen and the teacher has to write all the steps of the mathematical formulation on the blackboard, explaining them alongside. He may have to repeat the same when teaching the topics under the different heads. This kills the enjoyment of understanding the physics inherent in the topics. It also stretches the time required to finish the topic in class. In the process, the subject has the potential of becoming boring as well. I recall encountering the yawns and drooping eyes of a few of my students as I frenetically go about performing all of the mathematical deductions on the blackboard. This has led me to think if there could be another way the topics could be taught to make them more interesting and through which the relationships shared by the topics could be made more apparent. With computers and the Internet becoming more and more pervasive and accessible, I thought upon creating an e-learning tool in the form of an all-inclusive educational applet to accomplish this task. The applet would facilitate engaged exploration in the students through the inclusion of interactive and animated simulations, using which they would be encouraged to pose questions to themselves and seek answers from the applet. To that end, I would be guided in some measure by the results of earlier research [1-4] on creating effective educational simulations. In the process, I would also be building upon an applet [5] created by me earlier to teach the topic of resonance, as well as a few other applets [6,7] to teach some other topics as well.

2. Theory of oscillations in lumped systems

I have chosen oscillations in simple, lumped systems like the mass-spring system and its electrical analogue, the series-LCR circuit, as the subjects of this study. In the mass spring-system, the total energy is lumped as kinetic and potential energies in the mass (m) and the spring (represented by the spring-constant k) respectively. In the series LCR circuit, the total energy is lumped as electric and magnetic energies in the coil (of self-inductance L) and the capacitor (of capacitance C) respectively. Let us consider the mass-spring system first. The motion of the mass, displaced initially from its position of rest and constrained only by viscous-damping, is governed by the second-order, homogeneous, ordinary differential equation,

$$m\frac{d^2x}{dt^2} + kx + b\frac{dx}{dt} = 0 \quad (1) .$$

x is the displacement at time t and b is the damping-constant, the damping force being proportional to the velocity. The solution of Eq.1 subject to the initial conditions,

$$x(t=0) = x_0 \quad (2a)$$

$$\frac{dx}{dt}(t=0) = 0 \quad (2b),$$

can be obtained for three different cases:

(i) For small damping: $b < 2\sqrt{km}$,

$$x(t) = x_0\frac{\omega_0}{\omega_1}\exp(-\frac{b}{2m}t)\cos(\omega_1 t - \theta) \quad (3)$$

where $\omega_0 = \sqrt{\frac{k}{m}} \quad (4)$

$$\omega_1 = \sqrt{\frac{k}{m} - (\frac{b}{2m})^2} \quad (5)$$ and

$$\theta = \cos^{-1}(\frac{\omega_1}{\omega_0}) \quad (6) .$$

The motion is under-damped or oscillatory with an oscillation-frequency ω_1.

(ii) For critical damping: $b = 2\sqrt{km}$,

$$x(t) = x_0(1 + \frac{b}{2m}t)\exp(-\frac{b}{2m}t) \quad (7).$$

The motion is said to be critically-damped. The system does not oscillate at all and the initial displacement decays to zero in the least possible time.

(iii) For large damping: $b > 2\sqrt{km}$,

$$x(t) = B_1 \exp\left(\left(-\frac{b}{2m} + \sqrt{(\frac{b}{2m})^2 - \frac{k}{m}}\right)t\right) + B_2 \exp\left(\left(-\frac{b}{2m} - \sqrt{(\frac{b}{2m})^2 - \frac{k}{m}}\right)t\right) \quad (8),$$

where B_1 and B_2 are arbitrary constants that may be determined from the initial conditions. Note that the terms under the square roots are real. The system, in this case too, does not oscillate and the initial displacement decays to zero, albeit slowly. This motion is referred to as over-damped or dead-beat.

The above solutions pertain to the free, natural motion of a damped system not subject to any external force. If the same system is driven by a sinusoidal-external -force of amplitude $F_{\max}$ and frequency ω_2, then the equation of interest would be

$$m\frac{d^2x}{dt^2} + kx + b\frac{dx}{dt} = F_{\max}\sin(\omega_2 t) \quad (9).$$

Its steady state solution would yield

$$x(t) = -\frac{F_{\max}}{D}\cos(\omega_2 t - \phi) = \frac{F_{\max}}{D}\sin(\omega_2 t - \chi). \quad (10).$$

$$D = \sqrt{m^2(\omega_2^2 - \frac{k}{m})^2 + b^2\omega_2^2} \quad (11),$$

and

$$\chi = \phi + 90^0. \quad (13).$$

The steady state velocity can be found to be

$$v(t) = \frac{\omega_2 F_{\max}}{D}\sin(\omega_2 t - \phi) \quad (14),$$

by taking the time-derivative of Eq. 10. From Eqs. 10 and 14, we find that the motion is that of forced oscillation with both the displacement $x(t)$ and the velocity $v(t)$ oscillating with a frequency ω_2 equal to that of the external driving force. $x(t)$ lags the driving force by the phase angle χ while $v(t)$ lags the driving force by the phase angle ϕ. We also note that the amplitude of both $x(t)$ and $v(t)$ vary with ω_2. The amplitude of $x(t)$ becomes maximum when D becomes minimum. This occurs when

$$\omega_2 = \sqrt{\frac{k}{m} - \frac{b^2}{2m^2}} \quad (15)$$

and the situation is referred to *amplitude resonance.* On the other hand, the amplitude of $v(t)$ becomes maximum when $\frac{D}{\omega_2}$ becomes minimum. This occurs when

$$\omega_2 = \sqrt{\frac{k}{m}} = \omega_0 \quad (16)$$

and the situation is referred to *velocity resonance.* In this case, the phase angle ϕ, at resonance, becomes zero and consequently the velocity oscillates in phase with the driving force.

It is important to bear in mind that

solution for $x(t)$ given in Eq. 10 (and also for $v(t)$ given in Eq. 14 for that matter) correspond to the state of the system after it has reached a steady state. In the intervening period between $t=0$ and this time, the actual solution for $x(t)$ would be the sum of this steady state solution and any one of the transient solutions for $x(t)$ given in Eqs. 3, 7 and 8. However the transient solutions, true to their name, die out quickly, enabling the system to be in the true steady state described only by Eqs. 10 and 14.

Next we dwell on the series LCR circuit. The corresponding equation of motion for the system driven by an external sinusoidal voltage source of amplitude $V_{\max}$ and frequency ω_2 is given by

$$L\frac{d^2q}{dt^2}+\frac{q}{C}+R\frac{dq}{dt}=V_{\max}\sin(\omega_2 t) \quad (17).$$

With the voltage source removed and the system left to itself, the equation of motion becomes

$$L\frac{d^2q}{dt^2}+\frac{q}{C}+R\frac{dq}{dt}=0 \quad (18).$$

If we compare Eq. 17 with Eq. 9 and Eq. 18 with Eq. 1, we find that the equations are exactly analogous if the self-inductance L corresponds to the mass m, the capacitance C corresponds to inverse of the spring-constant k, the resistance R corresponds to the damping constant b and the charge q corresponds to the displacement x. The velocity $v=\frac{dx}{dt}$ would now correspond to the current $i=\frac{dq}{dt}$.

The voltage across R ($V_R = iR$) would now correspond to the damping force (bv), the voltage across C ($V_C=\frac{q}{C}$) would now correspond to the restoring force provided by the spring (kx) and the voltage across L ($V_L = L\frac{di}{dt}$) would now correspond to the net force on the mass ($m\frac{dv}{dt}$). What this implies, is, that we need not strain ourselves trying to solve the equations all over again for the electrical system as we have already found the solutions for the mechanical one, evidenced through Eqs. 3,7,8, 10 and 14. We only need to replace the values of the lumped parameters in the mechanical system with those of their electrical counterparts. We would then have found that velocity resonance corresponds to current resonance wherein the amplitude I_0 of the alternating current i becomes a maximum when the frequency of the external alternating voltage source ω_2, equals

$$\omega_0=\frac{1}{\sqrt{LC}} \quad (19),$$

the natural frequency of the resistance-less motion. The current is then in phase with the source voltage, and the corresponding impedance Z is equal to R. The circuit then behaves as if it is a purely resistive one. We may also observe voltage resonance in the LCR series circuit, corresponding to amplitude resonance in the mechanical case. The amplitude of the oscillating charge q on the capacitor and equivalently that of the oscillating voltage across the capacitor $V_C=\frac{q}{C}$ would then be a maximum at a value of the source frequency

$$\omega_3 = \sqrt{\frac{1}{LC} - \frac{R^2}{2L^2}} \quad (20),$$

which, importantly, is different from both ω_0 and ω_1. In conclusion, all features of the oscillations in the mechanical system, which may or may not have been discussed above, would also have their exact analogues in the electrical system.

3. Educational applets: What are they and how they may be improved upon?

Virtual simulations of theoretical concepts and laboratory experiments have long been used as supplements to conventional classroom teaching. Many an initiative [8-13] has been taken in this regard, especially in the last few years. Most of these initiatives take the help of Flash or java applets, which are small programs that are temporarily downloaded onto the user's computer and executed. These applets, through which the simulations may be carried out, are embedded inside a parent html page. In some cases the applets may be downloaded and saved onto the local computer and executed offline. It is important to note that more often than not, the applets are designed more as tools to supplement the theoretical understanding. As a consequence, very little theory, which may include the working formula, is provided alongside the applet. This little bit of theory, along with the instructions on how to use the applet, are incorporated in the html page housing the applet or in separate files, which may be downloaded for offline use. Hyper-links, which enable the user looking for more information to navigate to other websites, web-forms through which the teacher may collect feedback and queries from the students, sets of questions and answers as well as other features, may be found inside the parent html page. However, with the rapid rise in both the speed of the internet and its affordability, there is no reason why we cannot create and make use of larger sized applets with bigger file-sizes, housing all of the features stated above in neatly arranged panels and dynamically link the contents of the different panels. The benefit that would accrue from such a design is manifold. Since the applet would have a size not greater than that of the display-screen-area, all the main components of the applet stacked in the different panels, would be clearly visible to the learner at all times. The learner would then be able to watch a simulation of an experiment in one panel and browse through the related theory, which crops up simultaneously in another panel, all at the same time and without losing focus.

This would also help the learner to relate the experiment to the theory, better and faster. The notion of a subject-topic being segregated into a theoretical part and an experimental part would also cease to haunt the young minds. This, in turn would lead to a better and a more complete understanding of the topic. The all-encompassing design of the applet would also help foster intuitive links between different aspects of a given topic.

4. Existing applets on damped and forced oscillations

One of the simplest applets on damped oscillatory motion is that of Eric Woolgar [14], wherein the values of the parameters pertaining to mass, spring-constant and damping factor may be inserted in the corresponding text-boxes and the resulting plots of different types of motion may be visualized. One also finds a set of questions related to a few interesting situations pertaining to the solution of Eq. 1, a fact not surprising, given the author happens to be a mathematician. With Walter Fendt's applet [15] on forced oscillation, one may change the frequency ω_2 of the driving force and view, in addition to the displacement versus time plots, also the plots pertaining to displacement's amplitude versus ω_2 and displacement's phase versus ω_2. Michael Bergdorf and Stephan Kaufmann's applet [16] is functionally and feature-wise similar to Fendt's applet, but has an additional provision for letting the user change the value of the initial displacement. Thanks to MIT's open courseware project, we have another applet [17] on forced and damped vibration. In the applet, apart from being able to observe both the transient and steady-state temporal plots for the displacement (x) for different values for the parameters chosen by the user, one can also observe how the corresponding phase-space trajectories (x versus velocity v) evolve with time. Wee Loo Kang's applet [18], hosted under NTNUJAVA Virtual Physics Laboratory [7], has many extra controls and the ability to display the values of many more variables related to the simulation. However, it takes some time and effort getting to learn how to use it. Last but not the least, the Physics Education and Technology Project (PhET) team at the University of Colorado, Boulder, have designed a resonance applet [19], which, in spite of not having been designed to produce plots like those found in the other applets discussed above, would appeal to first-time learners of the topic. The use of Flash in addition to java makes the applet closely resemble a real-world mass-spring resonating system and makes it easier for the student to relate to the phenomenon.

5. Research related to the design of effective simulations and studies to test their efficacy

In recent years, a lot of insightful research [1-4] has been carried out, primarily by the PhET team at Colorado, to find out the most effective ways to design and use educational simulations that may be carried out through applets.Wieman et al.[1] have discussed strategies like using the simulations in the form of simple animated illustrations, in concept tests or in the form of interactive classroom demonstrations. They have also suggested using the simulations in different settings: as group activities in the class where students may be put through question-answer sessions; as simulation-based homework assignments as tools to conduct virtual experiments in situations where performing actual experiments is not possible and also as a pre-lab or post-lab supplement to the conventional laboratory class. Adams et al.[2,3] have conducted over two-hundred student interviews and thereafter come out with recommendations on both the design as well as qualitative aspects related to creating effective simulations. They have opined that the simulations should be research-based, engaging, interactive, animated, encourage exploration, promote learning and should relate to the real world. Podolefsky et al.[4], on the basis of interviews with students exposed to a wave-interference simulation, have analyzed the factors that promote engaged exploration.

McKagan et al. [20] have developed a curriculum pertaining to the photo-electric effect which includes, apart from an interactive computer simulation, interactive lectures, peer instruction and home assignments. They have then designed two exam questions to test the efficacy of the curriculum and found that it indeed helps the students to correctly predict the results of photoelectric experiments. In another work, McKagan et al.[21] have used student interviews to gain new insights into student thinking related to the PHET–simulations [10] on quantum theory and quantum mechanics and made use of the results to help refine the simulations as well. Frenkestein et al. [22] and later Keller et al. [23] have studied the effectiveness of another computer simulation: the 'Circuit Construction Kit', as a substitute for real laboratory equipment. Based on statistical analysis, they have found that in situations where students were exposed to the simulation, their performance improved remarkably.

Statistical studies to test the effectiveness of simulations have also been carried out by the likes of Tambade and Wagh [24], who have used the methodology of pre-test and post-test to study the positive effect of computer simulations and animations in improving the understanding of the concepts of force, field and potential in electrostatics. Tadesse [25] has also used student pre-test and post-test results to show how students' performance was enhanced in theoretical as well as practical classes through the use of computer simulations.

6. Design and working of the all-inclusive oscillations applet

The creation of my java applet on free, damped and forced oscillations has been motivated by my ideas, discussed in section 3, related to teaching the topic in a novel and useful way. The recommendations emanating from research on designing physics simulations, discussed in the previous section, have also been very helpful in putting my ideas to work. As it has turned out, my applet is fundamentally different from the other applets on the same topic discussed in section 4. It has an innovative and visually appealing layout. It is more feature-rich and is more fun to use. As we shall see, it can also prove to be much more useful.

The applet has been created using the Java Standard Edition Development Kit (JDK) version 5.0. Since the applet would be executed inside the browser of the host computer, Java Runtime Environment (JRE version 5.0 or later) must be installed in the host computer. One may note that both the JDK and the JRE are available as free downloads [26]. Fig. 1 is a screenshot of the applet when it is run for the first time. As can be seen, it is divided into four panels, one containing an option-box to select different tasks, another to house the controls to perform the simulations, and the remaining two to primarily display the results of the simulations. Clicking on the 'Read complete theory' option in the option-box in the top-left panel, opens up a text-pane in java, containing all the pertinent theory, including all the equations. The pane has two scrollbars in the horizontal and vertical directions, which make it possible to pack in as much theoretical material as required. The user can smoothly navigate through the theory with the scrollbars without losing focus on the simulations. This is made possible because of the fact that the box can cover only an area, which is no greater than that of the top-left panel. All the other panels continue to be displayed. The bottom-left panel contains the slider controls using which one may change the values of different variables governing free and damped oscillation. One can use the sliders corresponding to the parameters *m* (or *L*) and *k* (or *1/C*) to fix the value of the angular frequency ω_0 of free un-damped oscillation and in addition use the slider for the parameter *b* (or *R*) to fix the angular frequency ω_1 of damped

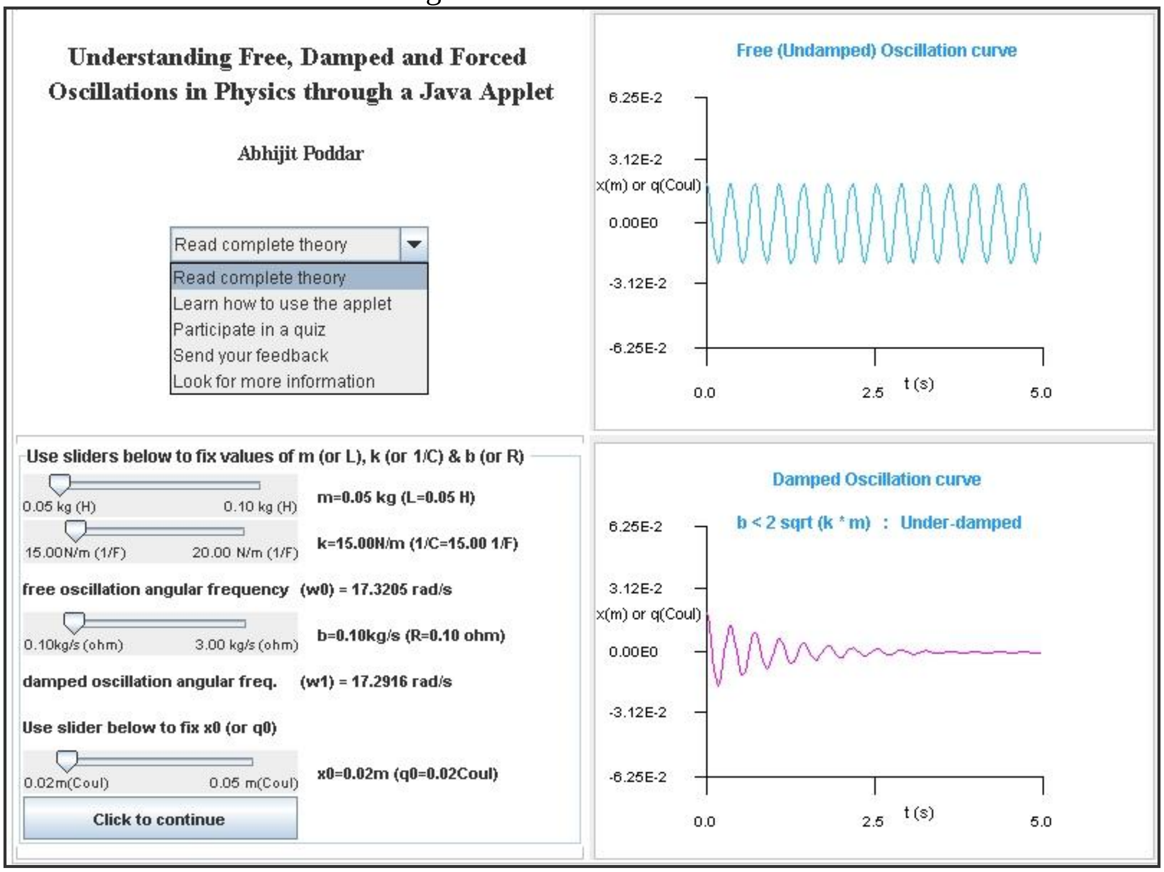

Figure 1: A view of the applet as it is run for the first time.

oscillation. An additional slider has been introduced to fix the value of the initial displacement x_0 (or the initial charge q_0). For each set of slider positions in the bottom-left panel, the corresponding waveform for free oscillations of the displacement *x* (or charge *q*) and also that for the damped oscillations of the same *x* (or *q*) can be visualized in the top-right and in the bottom-right panels respectively, as is shown in Fig. 1. The student or learner can read the relevant theory on free and damped oscillations, which comes into focus in the top-left panel, the moment he starts to drag any of the four sliders. At the same time he can explore around by playing with the slider controls, observe the resultant visualizations and find out, just as predicted by theory,

(a) how ω_0 changes with *m* and *k* in the mechanical case and equivalently, with *L* and *1/C* in the electrical case ;

(b) how ω_1 changes with *m*, *k* and also *b* in the mechanical case and equivalently, with *L*, *1/C* and also *R* in the electrical case;

(c) how ω_0 and ω_1 are not affected by changes in x_0 ;

(d) how, slowly increasing the value of *b*, results in under-damped oscillatory motion (for which $b < 2\sqrt{km}$ or equivalently $R < 2\sqrt{L/C}$) giving way to critically damped motion (for which $b = 2\sqrt{km}$ or equivalently $R = 2\sqrt{L/C}$) which again gives way to over-damped

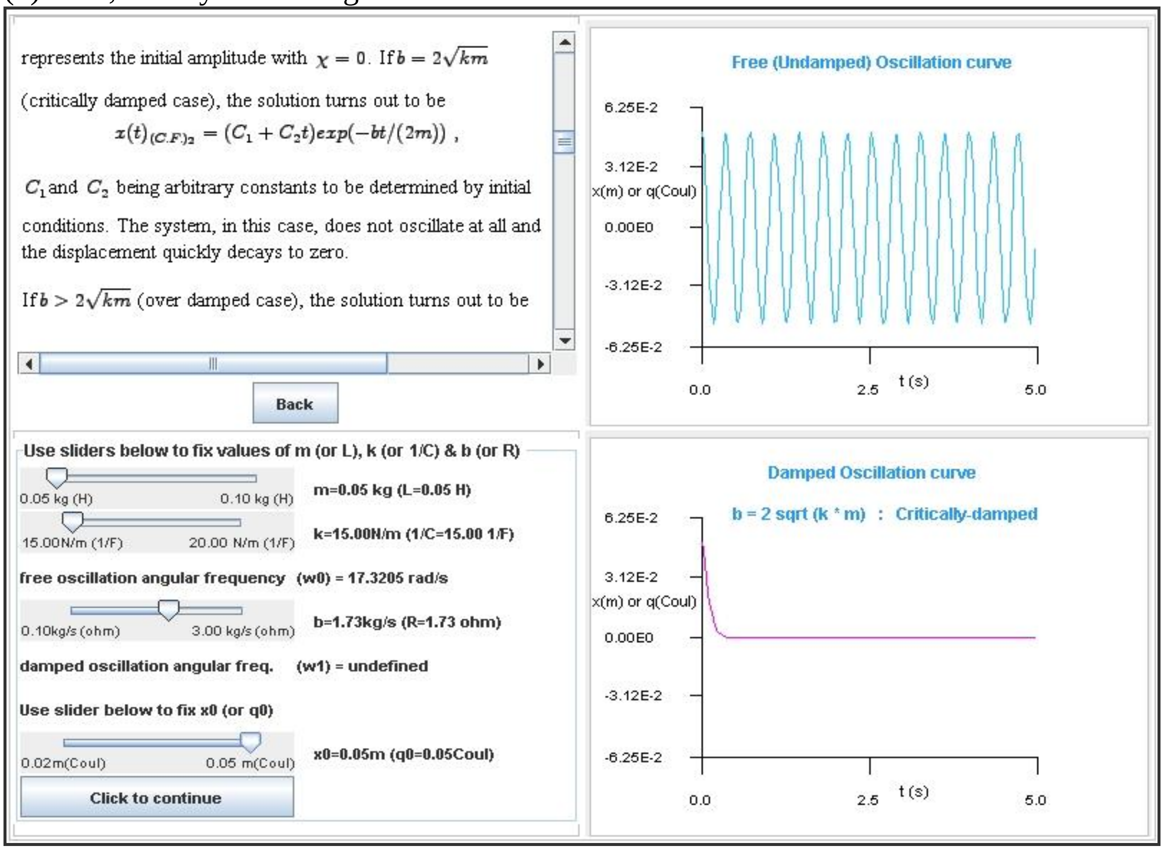

Figure 2: A screenshot of the applet showing, how, one may read the pertinent theory, simulate the case of critical damping with the slider-controls and observe the resulting plot at one and the same time.

motion (for which $b > 2\sqrt{km}$ or equivalently $R > 2\sqrt{L/C}$). If the student so desires, he may at first play around with the relevant controls and then look for explanations for the changes in the observed phenomena by going through the relevant theory, without losing focus. This feature of engaged exploration possible through the applet, is in

consonance with the conclusions drawn from earlier research on the requirements of creating an effective simulation [2,4]. A screenshot of the applet showing critical damping is presented in Fig. 2.
One may have observed the 'Click to continue' button at the bottom of the bottom-left panel in Figs. 1 and 2. Pressing this button opens up a set of new controls in the same panel, using which, one may simulate the phenomenon of forced oscillation and resonance for the same system. Both types of resonance, amplitude (or voltage) resonance and velocity (or current) resonance, talked about earlier in section 2, can be studied in detail at the same time. This is made possible through the use of multiple-representations of the same or related phenomena in the form of graphs, animations and pertinent text, in

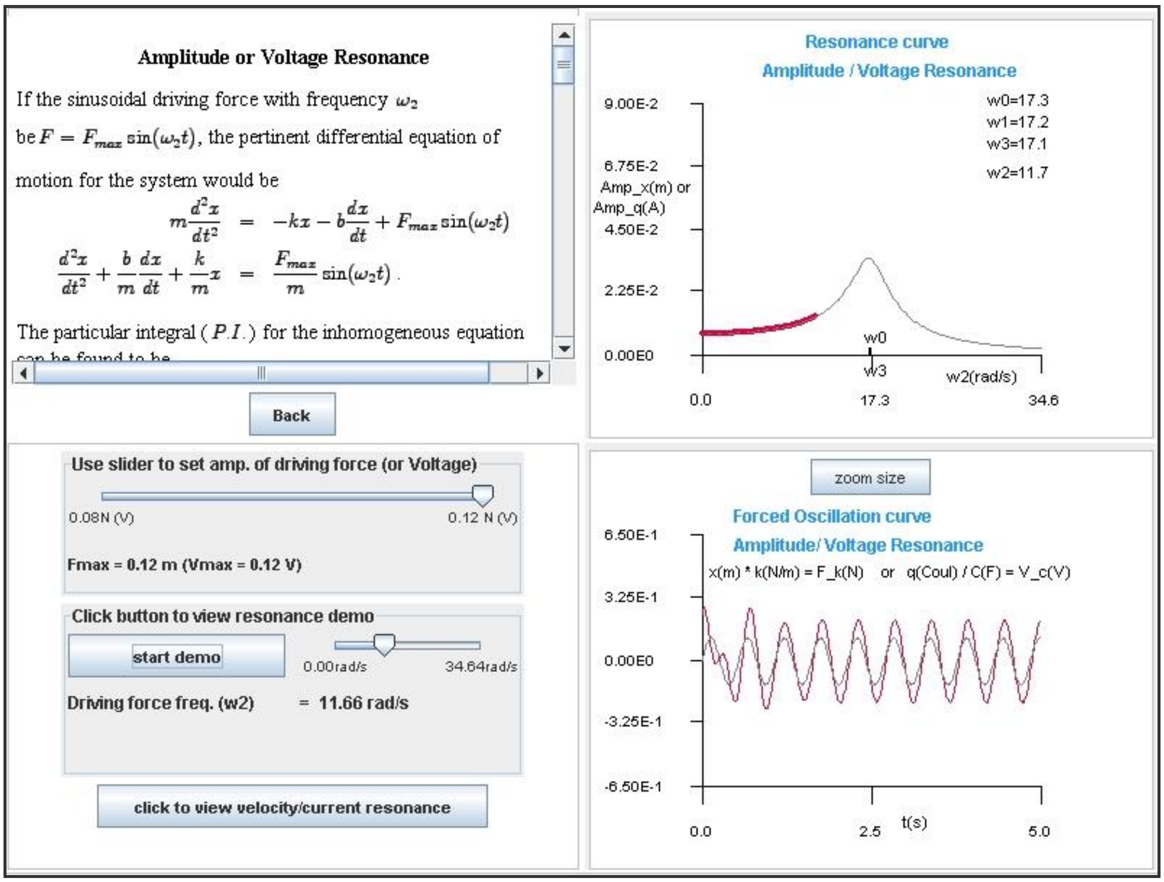

Figure 3: A screenshot of the applet showing, how, one may simultaneously refer to the theory and perform a virtual experiment to study the phenomenon of amplitude or voltage resonance.

agreement with the conclusions drawn from earlier research [1,2]. At the very instant the student clicks the 'click to continue' button, the relevant theory on amplitude or voltage resonance comes into focus in the top-left panel as shown in Fig. 3. The corresponding simulation can now be started by fixing the value of the amplitude of the driving force (or voltage) using the relevant slider and clicking the 'start demo' button in the bottom-left panel shown in Fig. 3. The angular frequency of the driver ω_2 gets automatically incremented and for each value of ω_2, one may observe the displacement x (more specifically the restoring force kx) and equivalently the charge q (more specifically the voltage across the capacitor q/C) in the bottom right panel, as they evolve with time. The effect of the transient response dominates at the start but soon gives way to a fixed-amplitude steady-state oscillatory response with a frequency equalling the driving frequency ω_2. At each value of ω_2, the steady-state amplitude of x (or q) is plotted versus ω_2 in the top-right panel and this results in the so-called amplitude (or voltage)

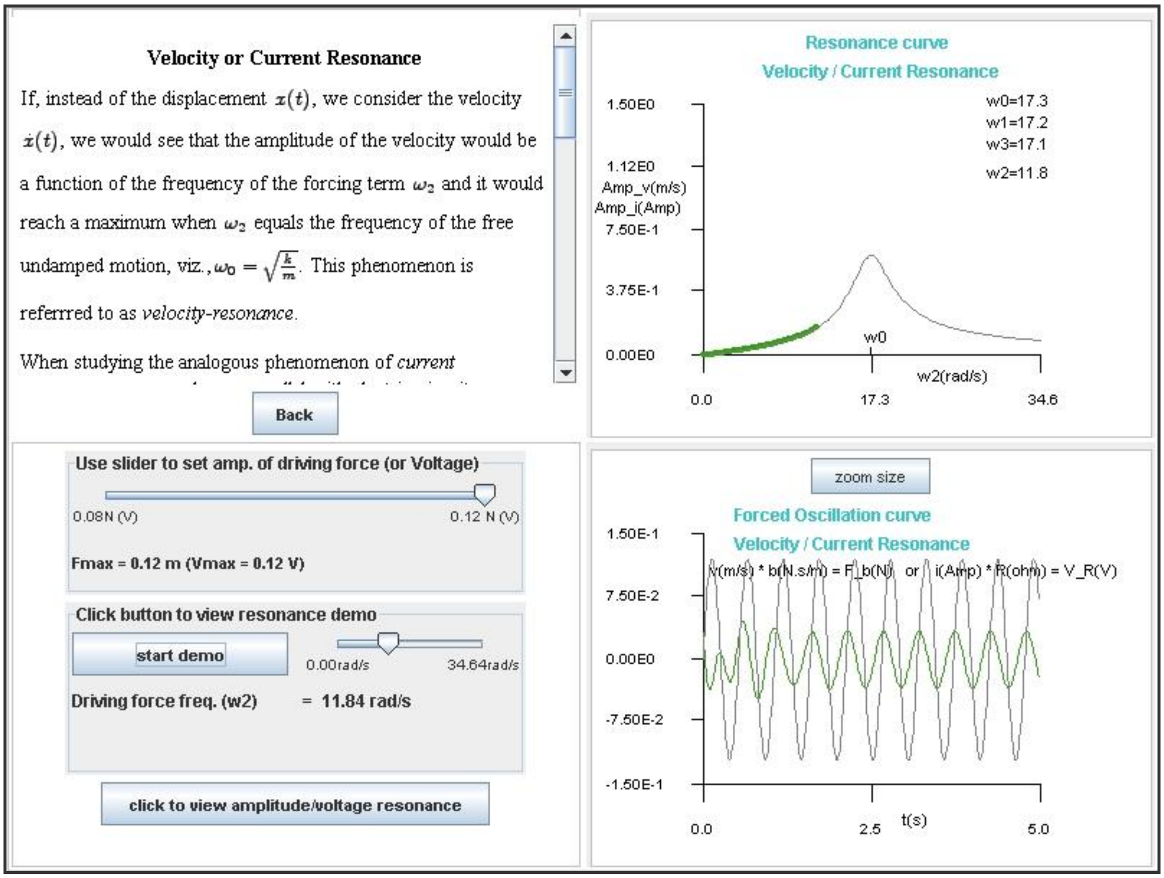

Figure 4: A screenshot of the applet showing the unfolding of the phenomenon of velocity or current resonance.

resonance curve, whose maximum is reached when ω_2 equals a frequency ω_3, as can be observed by following their values on screen. By playing with the respective controls, one may further explore

(a) how the amplitude of x (or q) changes with changes in m (or L), b (or R) and k (or C).

(b) how the amplitude of x (or q) changes with changes in the amplitude and frequency of the driving force (or voltage) .

(c) how the amplitude of x (or q) becomes maximum at a frequency ω_3, which is not only less than ω_0 but also less than ω_1 when the corresponding transient motion is oscillatory with frequency of oscillation ω_1. One may simultaneously look for explanations for the results of the above exploration by going through the relevant theory in the top-left panel, as can be seen in Fig. 3.

When one clicks the 'click to view velocity/current resonance' button at the bottom of the bottom-left panel shown in Fig. 3., he may now follow how 'velocity resonance' in the same mechanical system and its electrical counterpart: 'current resonance' in the same electrical system, occur. These correspond respectively to the amplitude of the velocity (v) of the mass or the amplitude of the current (i), reaching a maximum when the driving frequency ω_3 equals ω_0, giving rise to the so-called velocity (or current) resonance curve. The phenomenon can be best understood by

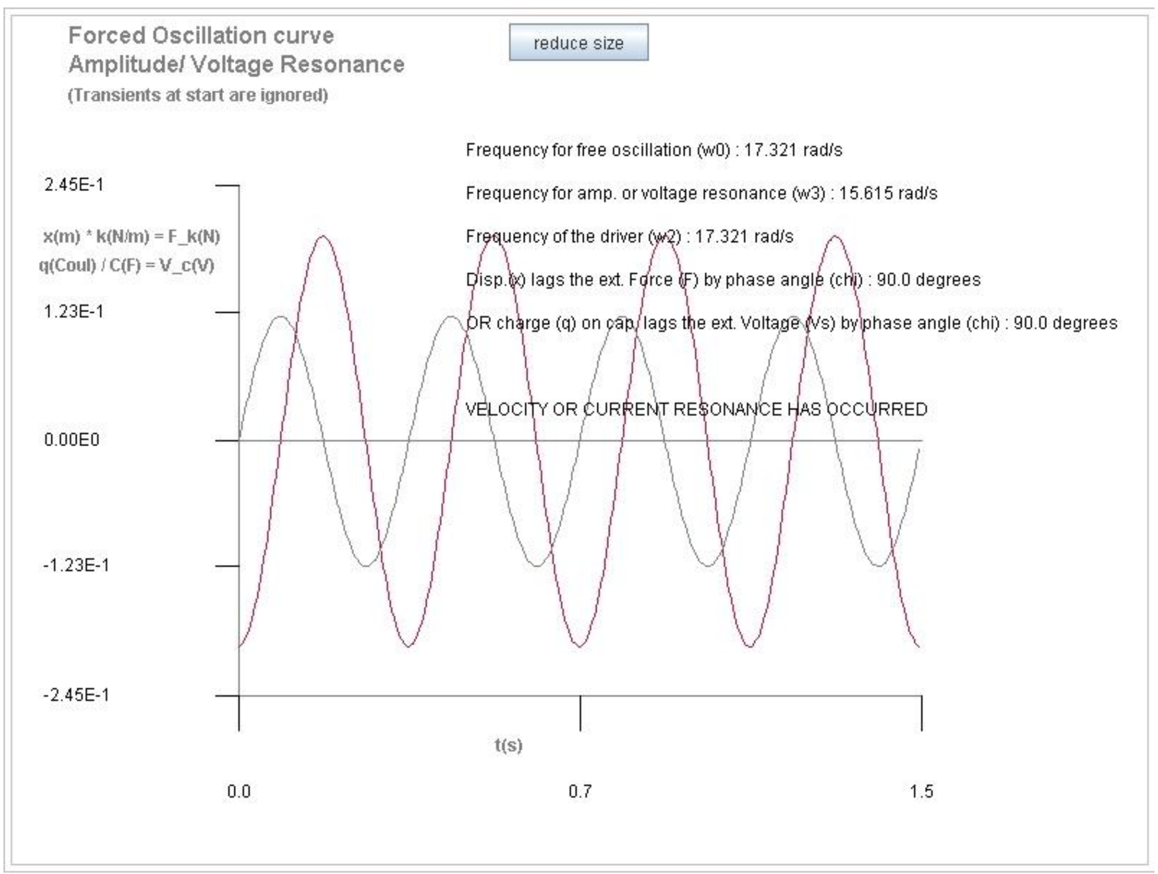

Figure 5: A screenshot of the zoomed bottom-right panel, showing the phase relationship between the driving force or voltage and the displacement or charge (more specifically the restoring force of the spring or the voltage across C) at the frequency ω_0.

following the corresponding animation in the top-right panel, as can be seen in Fig. 4. The variation of v (more specifically the damping force bv) and equivalently of i (more specifically the voltage across the resistor Ri) with time can also be followed in the bottom right panel. As in the amplitude-resonance case, one may change the values of the different parameters, explore their effect on v (or i), and seek explanations from the related theory at the same time.

One may have noticed the 'zoom size' button on the bottom-right panel of Fig. 3. Clicking the button zooms the panel-size, enabling us to follow more closely, the phase relationship between the driving force, whose time-variation is shown in grey, and the displacement x (more specifically the restoring force kx) whose time variation is shown in crimson. In the electrical case, this would correspond to following the phase relationship between the driving voltage

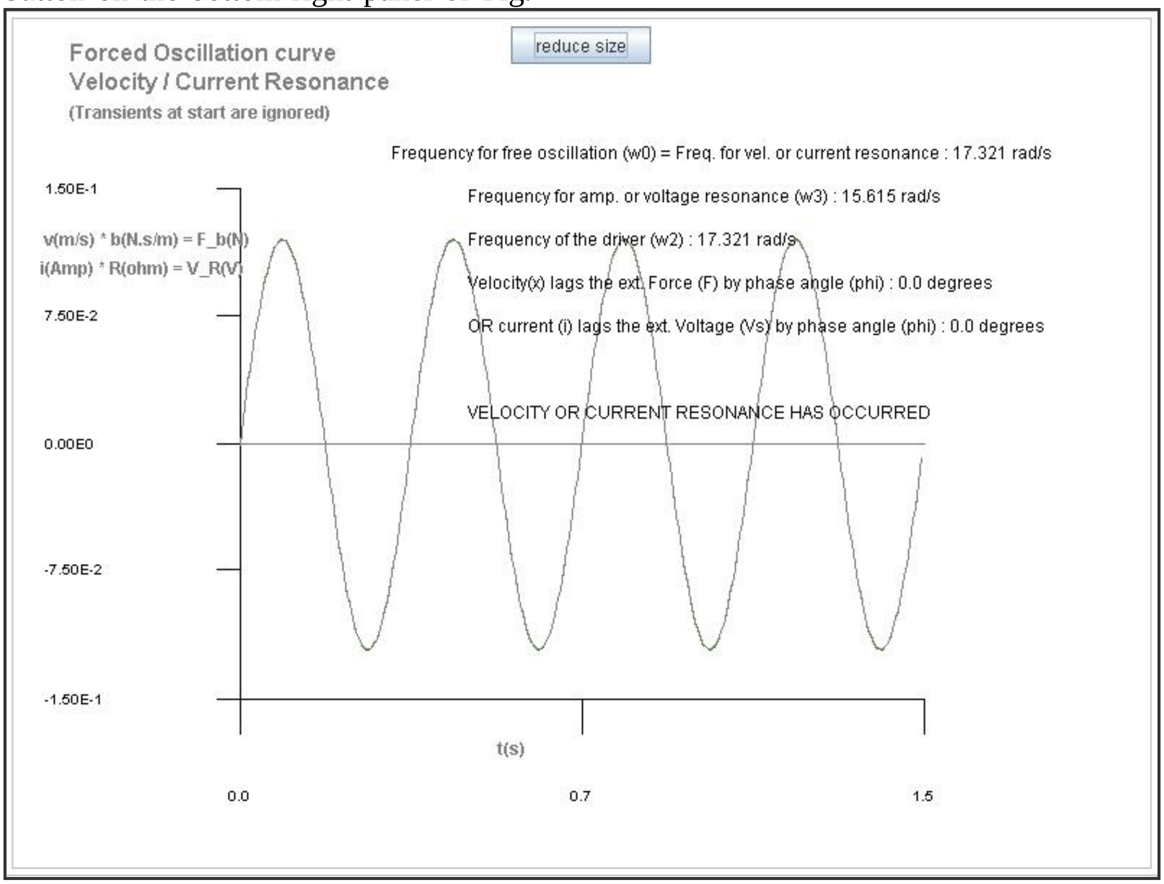

Figure 6: Another screenshot of the zoomed bottom-right panel, showing the in-phase relationship between the driving force or voltage and the velocity or current (more specifically the damping force or the voltage across R) at the frequency ω_0.

and the charge q (more specifically the voltage across the capacitor q/C). Of particular interest is the situation at the frequency of free oscillation ω_0, when x (or q) lags the driving force (or voltage) by 90 degrees as shown in Fig. 5. Similarly, clicking on the 'zoom size' button on the bottom-right panel shown in Fig. 4, helps us to visualize more closely the phase relationship between the driving force and the velocity v (more specifically the damping force bv). In the electrical case, this would correspond to following the phase relationship between the driving voltage and the current i (more specifically the voltage across the resistor Ri). Of particular interest is the situation at the frequency of free oscillation ω_0, when v (or i) is exactly in phase with the driving force (or voltage) as can be seen in Fig. 6.

For a mechanical system, the large displacement amplitudes that result at resonance could potentially damage the mechanical structure itself. For an electrical system, the large currents that result at resonance could burn the electrical circuit. It makes sense, therefore, to include some sort of sound to drive home this point and that is what

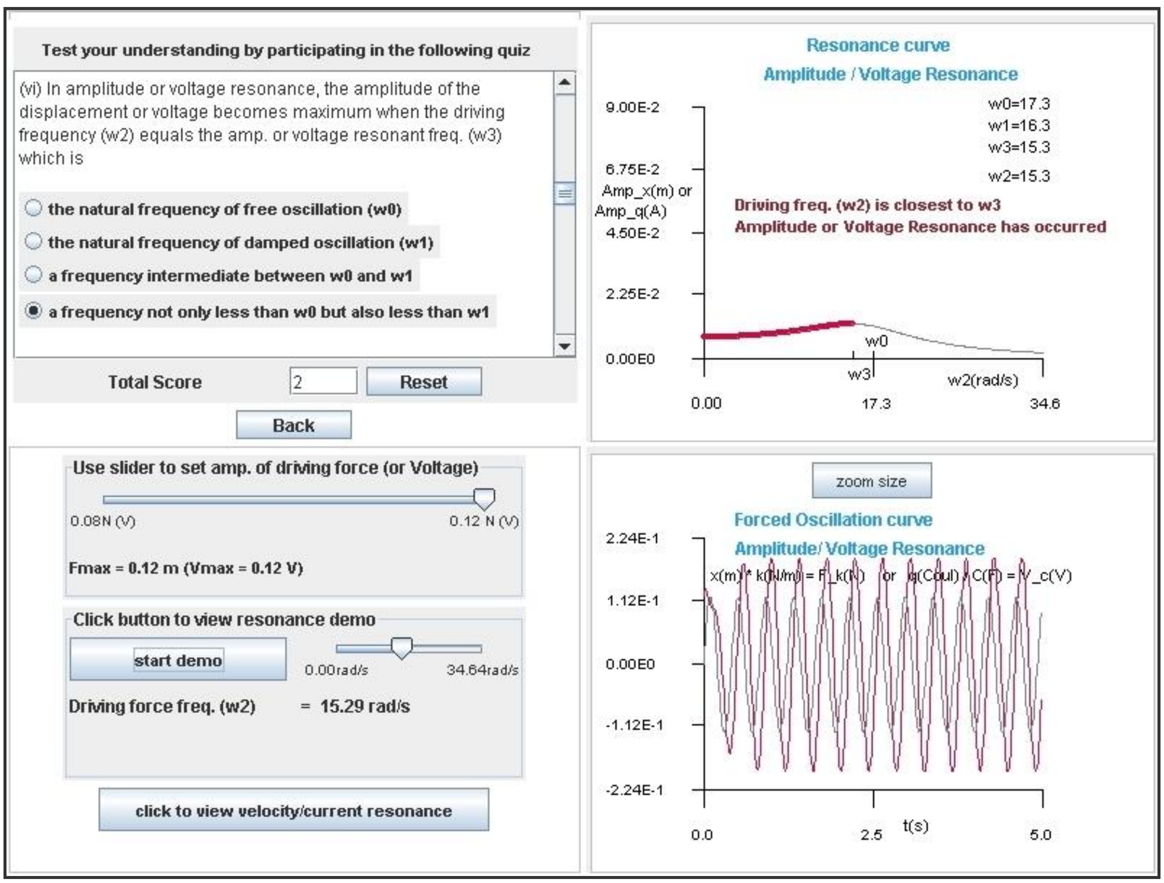

Figure 7: A screenshot of the applet showing how one may participate in a topical quiz and seek answers from within the applet itself, if required.

has been done. Calandra and co-workers [27] have shown that with increasing bandwidth of the Internet, digital audio is becoming more and more common in online courses and suggested ways how audio can be included in e-learning courseware. Taking a cue from their work, I have incorporated the sound of shattering glass and that of a fire alarm at the appropriate instant. Voice recordings have also been introduced at appropriate moments of the simulation to give it a real-world classroom-touch.

Another nifty feature of the applet is the inclusion of a set of quiz questions inside the applet itself, to facilitate the testing of ones understanding of the topic, at any time before, during or after its use. There is also a provision for keeping a score of the marks obtained for choosing the right answers. Questions seeking answers to subtle aspects on the topic have been included in the quiz. The student has the option of looking for the answer in the applet itself, at the same time. As an illustration, in order to seek the answer to a question, 'What would the value of the frequency for amplitude or voltage resonance be vis-à-vis the frequencies for free oscillation ω_0 and damped oscillation ω_1?', one can play around with the controls, watch the unfolding of amplitude-resonance in the top-right panel and note the values of ω_0, ω_1 and the frequency ω_3 at which amplitude resonance occurs. This is depicted in Fig. 7.

Earlier it had been pointed out that the goal of this work was primarily to create a 'self-contained' applet, which would depend very little on the web page to which it belonged. To this end, gathering feedback and being able to answer the queries of the users of the applet has been made possible from within the applet itself through the use of a PHP form. One may have noticed the 'Send your feedback' option in the drop-down list in the top-left panel shown in Fig. 1. Clicking this option would display a PHP form, asking the student to provide feedback regarding the applet and to send any question he may have regarding the topic. The student may view the response to his queries by clicking the link at the bottom of a confirmation page. Of course he has to wait till the teacher has noted down his response in a text file and uploaded it to the server hosting the applet. Alternatively, the teacher may send his response directly to the student at the email address provided by him in the PHP form itself.

Last but not the least, the student or learner should always be encouraged to look for more information, assimilating more knowledge in the process. To this end, a provision for linking to other web sites containing additional resources on the pertinent topic has also been made. This can be achieved by clicking the 'Look for more information' option in the drop-down list in the top-left panel shown in Fig. 1.

It bears mentioning that it would not be difficult to accommodate more features within the applet. The design of the applet has been deliberately made an open-ended one.

7. Assessment of the efficacy of the applet

To test the efficacy of my applet, I have made use of a simple pre-test – post-test study on ten of my students to study the effect of my applet in improving their understanding of the topic. The students were first lectured on the topic by myself for a couple of hours and then each of them were handed over a sheet of paper having fifteen multiple choice questions, each carrying two marks, which they were to answer in fifteen minutes. They were allowed to consult only their class notes if needed. This constituted the pre-test in my study. Next they were exposed to the applet by themselves, allowed to play around with it for an hour, and made to participate in the quiz embedded inside the applet for fifteen minutes. The quiz comprised the same set of fifteen questions and the students were at liberty to take the help of the simulations inside the applet in seeking the answers. This constituted the first post-test in my study. Subsequently the students were made to use the applet again for half an hour, but this time with my help and guidance, before participating in the same quiz again for fifteen minutes. This constituted our second and last post-test. As during the first post-test, the students were allowed to take the help of the simulations inside the applet, if required.
The use of the applet entailed very little expertise in the use of a computer, and all the students who were tested, did have that level of expertise. I therefore did not feel the need to factor in the effect of each student's computer proficiency in the study.

Statistical tests were carried out on the data (scores) by using the some of the statistical functions included in the spreadsheet program Gnumeric [28] and the results are shown below:

Table 1. M = Mean, σ = Standard Deviation

Test	M	σ
Pre-test	14.20	6.76
First post-test	16.00	6.86
Second post-test	21.6	6.10

Table 2. Paired (type-1) 2-tailed t-test probability (*P*) and Mean of Normalized Gain (<*G*>)

Comparing groups	P	$\langle G \rangle$
First post-test with pre-test	0.000725	0.15
Second post-test with pre-test	6.3E-06	0.52
First post-test with second post-test	0.000202	0.42

G = Normalized Gain [29]

$$= \frac{post\text{–}test\ score - pre\text{–}test\ score}{Max\text{–}score - pre\text{–}test\ score}$$

Post-test - pre-test combinations are as depicted in 1st column of Table 2 (When being compared to the 2nd post-test results, the 1st post-test plays the role of pre-test in the above formula)
Max-score = 30.

P gives the probability of the difference in the means being more due to chance than due to the effect of the applet (value < 0.05 is considered to be statistically significant). Each of the data sets was successfully tested for normality before applying the t-tests to the data-set pairs.

From the data presented in Table 1 we observe that the mean score from the pre-test increases by a meagre 12.7% after the first post-test and by a whopping 52.1% after the second post-test. Interestingly there is also a 35.0% increase from the first post-test mean score to the to the second post-test mean score. The standard-deviation values remain nearly equal. The results of the paired 2-tailed t-test shown in second column of Table 2 tells us that the increase in scores from one test to another is statistically significant in all three cases. However, the most significant increase in the scores occurs from the pre-test to the second post-test. The mean normalized gain <G> in the scores is also greatest after the second post-test when compared to the scores after the pre-test. From the above, we may infer that the use of the applet and its embedded simulations must have helped the students to have a better understanding of the topic. This is in tune with the outcome of similar studies on the positive effect of using computers [30,31] and computer simulations [20-25] on the teaching of different topics in physics. However, instructor guidance also seems to have played a major role in the process, corroborating the findings of earlier research [1].

The quantitative study of my applet's efficacy was somewhat constrained by my inability to test a larger number of students, at least for the time being, although I do believe that a larger statistical sample size would not have had a different effect on the overall conclusion. Nevertheless, I decided to also undertake a qualitative study, in tune with similar work [21] reviewed in section 5, on testing the effectiveness of simulations on the teaching of quantum mechanics. In the process I expected to gain deeper insights into students' questions on the topic and misconceptions, if any. I chose to have direct one-to-one interactions with a couple of students, one being the weakest and the other being the brightest boy in my class. Incidentally, but not surprisingly, they had had the lowest and the highest score respectively consistently in all the three tests, I had given them. A couple of questions I put to them were as follows:

The source voltage in a series LCR circuit equals the sum of the voltages across L, C and R.

(a) At the current resonant frequency ω_0, the voltage across R becomes a maximum and equals the voltage of the source. That would seem to suggest that the voltages across C and L would be zero at the resonant frequency. Is it correct? Explain your answer, both qualitatively and quantitatively.

(b) At the voltage resonant frequency ω_1, the voltage across the capacitor becomes a maximum. Explain intuitively, why, the voltage across the inductor cannot be a maximum at the same frequency ω_1, given that the maximum voltage across the inductor must equal the maximum voltage across the capacitor.

Both the students were allowed to take the applet's help in answering the questions. However, the weaker student failed to answer both the questions while the brighter student, in spite of being able to correctly answer only the first question after taking help from the applet, was yet to develop a complete understanding of the phase-relationships between the different waveforms, which is so vital in relation to the question. It was then that I intervened and spent some time explaining to the students with the help of the relevant animated plot in the applet, a screenshot of which is shown in Fig. 6, how, at the resonant frequency ω_0, the instantaneous waveforms for the voltages across C and L, not only are out of phase as always but also have equal magnitudes and therefore cancel out, as a result of which, the voltage across the resistor attains its maximum value which is equal to that of the source voltage. In the process I also used the applet to explain to them the concept of phase and phase difference. Thereafter, the students were able to comprehend why the answer to the first question was a no and seemed pretty relieved at that. Subsequently, they could use the relevant equations with greater confidence to verify the answer quantitatively.

As for the second question, I took the help of the animated plots in the applet once again to reason out and explain to both the students why voltages across C and L cannot be same at ω_1 as they would then cancel out (their phases being opposite at all times) resulting in the voltage across R becoming a maximum and equal to the source voltage at ω_1 in addition to the same happening at ω_0, which cannot be. Thus the maximum voltage across the inductance, which equals the maximum voltage across the capacitance, must occur at a frequency different from ω_1. The students were then instructed to apply the relevant theory to verify that this new frequency would be symmetrically placed on the other side of ω_0. To my satisfaction, it took little time thereafter, for the students to establish the theoretical correctness of the predictions by themselves.

The above interaction once again highlighted the importance of instructor guidance in the use of the applet to make it more effective. What it also showed was the necessity of integrating the applet with a well-designed curriculum that could include lectures, question–answer sessions and home assignments [1,20,21] and that is precisely what I did as a follow up exercise: designed an applet-centric curriculum to be used henceforth to teach the topic in question. Importantly, a few aspects related to the topic, which did not find place in the applet, were included in the lectures. Moreover, laboratory experiments, like that of the study of the resonance phenomena in a series-LCR circuit with the help of an oscilloscope, which were till now conducted independently, were now made part of the curriculum. In the process the students could relate the theory, simulations through the applet as well the results of real experimentation in the laboratory class, much better. In the near future, I also plan to include in the curriculum, actual experiments to study transient phenomena with the help of a PC and a data acquisition interface [32].

From the interactions I had with the students, I also realized how the applet could make seemingly queer phenomena like that of voltage magnification understandable. That the voltage across the capacitor (and also across the inductor, the two being equal and opposite at ω_0) could exceed the voltage of the source itself seemed intriguing, more so after they had collected the relevant data in a laboratory experiment to study resonance in a series LCR circuit a few days earlier. The animated visualization of the voltage waveforms for the source and the capacitor, a screenshot of which is shown in Fig. 6, helped remove their doubts. Through the applet, they could now also intuitively link the phenomena of voltage magnification in the electrical circuit to that of the analogous force magnification in the mechanical mass-spring system.

The interactions also brought out the fact that students suffered from a few misconceptions. One of the misconceptions was that the amplitude resonance and velocity resonance occur in different systems, while in actuality they refer to the same system at the two different values of the driving frequency, one equalling ω_3 and the other ω_0 respectively. By designing the applet in such a manner that one could toggle between observing either of the two resonance curves forming at any point while the animation was running, helped remove the misconception.

8. Summary and conclusion

To summarize, a self-contained java applet has been created to teach the phenomena of free, damped and forced oscillations in both mechanical and electrical systems at the same time and in a novel and interesting way. The applet contains all the relevant theory, simulated experiments and animations, an interactive quiz, provision for gathering feedback, posting questions and receiving answers, as well as linking to additional resources, neatly packed inside itself. The theory and experiment go hand-in-hand, with the relevant theory appearing in a panel in sync with the virtual experiment and visualization, taking place in another panel. While designing the applet, the recommendations coming out of earlier research on designing effective simulations have been followed as far as practicable. The efficacy of the applet has been studied quantitatively as well as through student interviews. It has been found that subtle yet important features of the topic can be more easily understood and the overall understanding of the topic can be remarkably improved through the applet, helped in no small measure by the timely intervention and proper guidance of the teacher. The applet must also be made part of a well-thought out curriculum to be most effective. The applet may be used online as well as offline at any time. In situations where laboratory experimentation is not feasible, the applet can help in virtual experimentation as well.

The eager look in the faces of the students in the class being taught with the applet's help betrays the interest and sense of participation generated in them. Teaching becomes all the more satisfying too. With the cost of computers and internet accessibility coming down fast, coupled with the increasing speed of the internet, applets such as these, as part of a well designed curriculum, have great potential in spreading the reach and scope of online-teaching, specifically of experiment based science topics.

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