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# PHYSICS 105 NOTES

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TYPESET NOTES FOR PHYSICS 105: ANALYTIC MECHANICS  
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# Introduction

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- Instructor: Prof. Dan McKinsey
- Office Hours: Tuesdays, 2:30pm in 441 Physics South
- Grading:
  - 30% Homework
  - 20% Midterm 1
  - 20% Midterm 2
  - 30% Final

The grade bins for this class are fixed, and they will not be altered throughout the semester.



# Lecture 1 (01/17)

This lecture was held on **January 17, 2023**. It covered equations for simple harmonic motion in one and two dimensions.

## 1.1 Why Do We Study Oscillations?

We study oscillations because they are very common in physics – they happen any time we have a system with a stable equilibrium point. When we nudge our system away from this point, a restoring force  $F_x(x)$  tries to bring our system back to equilibrium.

Although  $F_x(x)$  could potentially be functions of more variables, we can let it be  $x$  for now. We will also assume that  $F_x(x)$  has continuous derivatives everywhere so that we can expand it as a Taylor series. Thus:

$$F_x(x) = F_0 + x \left( \frac{dF_x}{dx} \right)_0 + \frac{1}{2} x^2 \left( \frac{d^2 F_x}{dx^2} \right)_0 + \dots$$

Then, since the origin is also an equilibrium point, then  $F_0$  must equal 0 at the equilibrium point. Then, neglecting higher order terms, we get the approximate relation that:

$$F_x(x) = -kx$$

where  $k \equiv -\left(\frac{dF_x}{dx}\right)$ . Since the restoring force always points toward the equilibrium position, then  $dF/dx$  is always negative, so  $k$  is a positive constant.

Alternatively, we can also write the force in terms of the potential:

$$U(x) = \frac{1}{2} kx^2$$

where  $U(x) = U(0) + U'(0)x + \frac{1}{2}U''(0)x^2 + \dots$ , with  $U'(0) = 0$  using the same logic as before. These oscillations can be damped or driven, which we will revisit later.

## 1.2 Simple Harmonic Oscillator

Here we will look at different ways to represent the oscillatory equations of motion for simple harmonic oscillators. To start, let's use Newton's second law to get the differential equation:

$$-kx = m\ddot{x}$$

Then, we can define  $\omega^2 \equiv \frac{k}{m}$ , then we get the equation

$$\ddot{x} + \omega^2 x = 0$$

which is the standard differential equation for simple harmonic motion. This differential equation has the solutions:

$$\begin{aligned}x(t) &= A \sin(\omega t - \varphi) \\x(t) &= A \cos(\omega t - \delta)\end{aligned}$$

where  $|\delta - \varphi| = \pi/2$ . The kinetic energy can also be calculated:

$$\begin{aligned}T &= \frac{1}{2}m\dot{x}^2 = \frac{1}{2}m[A\omega \cos(\omega t - \phi)]^2 \\&= \frac{1}{2}mA^2 \frac{k}{m} \cos^2(\omega t - \varphi) \\&= \frac{1}{2}kA^2 \cos^2(\omega t - \varphi)\end{aligned}$$

Since  $U(x) = \frac{1}{2}kx^2$ , then we get:

$$U(x) = \frac{1}{2}kA^2 \sin^2(\omega t - \varphi)$$

Adding the two, we get:

$$T + U = \frac{1}{2}kA^2(\sin^2(\omega t - \varphi) + \cos^2(\omega t - \varphi)) = \frac{1}{2}kA^2$$

which is a constant for all  $\theta$ . We expect this result, since we know that the total energy of an isolated oscillatory system doesn't change. The period  $\tau$  can also be expressed as:

$$\tau = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}}$$

And we also have the relation that  $\nu = 2\pi\omega$ .

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### 1.2.1 | Method 2: Summation of sines and cosines

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Looking at the second solution more closely, we note that

$$\begin{aligned}A \cos(\omega t - \delta) &= A [\cos(\delta) \cos(\omega t) + \sin(\delta) \sin(\omega t)] \\&= A \left[ \frac{B_1}{A} \cos(\omega t) + \frac{B_2}{A} \sin(\omega t) \right] \\&= B_1 \cos(\omega t) + B_2 \sin(\omega t)\end{aligned}$$

with  $A = \sqrt{B_1^2 + B_2^2}$ . This form of the solution is particularly nice since it allows us to deal with initial conditions very easily. For instance, if the oscillation started at the peak, then we know that  $B_2 = 0$  and so we're left with a pure sine wave which is really easy to deal with.

### 1.2.2 Method 3: Exponentials

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We can also formulate the solution as

$$x(t) = C_1 e^{i\omega t} + C_2 e^{-i\omega t}$$

This form is useful since integrals and derivatives are especially easy. You can also check that this solution satisfies the differential equation by plugging in  $x(t)$  into our differential equation. To show that it's consistent with our previous form, we use Euler's identity  $e^{i\theta} = \cos(\theta) + i\sin(\theta)$ :

$$\begin{aligned} x(t) &= C_1 e^{i\omega t} + C_2 e^{-i\omega t} \\ &= (C_1 + C_2) \cos(\omega t) + i(C_1 - C_2) \sin(\omega t) \\ &= B_1 \cos(\omega t) + B_2 \sin(\omega t) \end{aligned}$$

And so naturally in this form we assume  $B_1 = C_1 + C_2$  and  $B_2 = i(C_1 - C_2)$ .

### 1.2.3 Real Part of Exponentials

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Since  $x(t)$  is a real quantity, then we can actually make a couple simplifications to our solution in the previous section. Firstly, we note that since  $x(t)$  is real, then  $B_1, B_2$  must also be real. Therefore, this enforces  $C_1 = C_2^*$ , so we now have

$$x(t) = C_1 e^{i\omega t} + C_1^* e^{-i\omega t}$$

And since we know that  $z + z^* = 2\Re(z)$ , then letting  $z = C_1 e^{i\omega t}$ , we get:

$$x(t) = 2\Re(C_1 e^{i\omega t})$$

Then as one final simplification, if we let  $C = 2C_1$ , then  $C = B_1 - iB_2 = Ae^{i\delta}$  so we can write:

$$x(t) = \Re(Ce^{i\omega t}) = A \cos(\omega t - \delta)$$

As an illustration of this expression, we can imagine moving around a unit circle:

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### 1.2.4 Summary

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To summarize, we have the following equivalent ways of writing solutions to these oscillations:

$$\begin{aligned} x(t) &= A \cos(\omega t - \delta) \\ &= B_1 \cos(\omega t) + B_2 \sin(\omega t) \\ &= C_1 e^{i\omega t} + C_2 e^{-i\omega t} \\ &= C_1 e^{i\omega t} + C_1^* e^{-i\omega t} \\ &= \Re(Ce^{i\omega t}) \\ &= \Re(Ae^{i\omega t - \delta}) \end{aligned}$$

These solutions are all equivalent, each having its own benefits when it comes to solving problems. It's our job to figure out which form is the most convenient for our problem at hand.

## 1.3 Oscillations in 2 Dimensions

How do our equations for oscillations generalize in 2 dimensions? Well, now our restoring force is slightly more complicated to account for a new dimension:

$$\vec{F} = -k\vec{r}$$

And we can split this up into component form:

$$\begin{aligned} F_x &= -kr \cos \theta = -kx \\ F_y &= -kr \sin \theta = -ky \end{aligned}$$

This then generates the same set of differential equations as before, and they are independent so we can solve them separately. Therefore, we generate the equations:

$$\begin{aligned} x(t) &= A_x \cos(\omega t - \delta_x) \\ y(t) &= A_y \cos(\omega t - \delta_y) \end{aligned}$$

Here, we can “zero out” one of these phases (by simply starting at one of the phases), so this changes our equations to:

$$\begin{aligned} x(t) &= A_x \cos(\omega t) \\ y(t) &= A_y \cos(\omega t - \delta) \end{aligned}$$

where  $\delta$  now refers to some *relative phase* between the two oscillations. Now we ask ourselves, what is the path of this particle? To do this we eliminate  $t$ . First, we can expand out  $y(t)$  without introducing the relative phase:

$$\begin{aligned} y(t) &= A_y \cos(\omega t - \delta_x + (\delta_x - \delta_y)) \\ &= A_y \cos(\omega t - \delta_x) \cos(\delta_x - \delta_y) - A_y \sin(\omega t - \delta_x) \sin(\delta_x - \delta_y) \\ &= A_y \cos(\omega t - \delta_x) \cos(\delta_x - \delta_y) + A_y \sin(\omega t - \delta_x) \sin(\delta_y - \delta_x) \end{aligned}$$

In the last line we've used the identity that  $\sin(-x) = -\sin(x)$ . Now, we can use the relative phase  $\delta \equiv \delta_y - \delta_x$  and  $\cos(\omega t - \delta_x) = \frac{x}{A_x}$  to get:

$$y = \frac{A_y}{A_x} x \cos \delta + A_y \sqrt{1 - \left(\frac{x}{A_x}\right)^2}$$

We can alternatively write this as

$$A_x y - A_y x \cos \delta = A_y \sin \delta \sqrt{A_x^2 - x^2}$$



So squaring this, and simplifying, we get:

$$A_y^2 x^2 - 2A_x A_y xy \cos(\delta) + A_x^2 y^2 = A_x^2 A_y^2 \sin^2 \delta$$

Then, if  $\delta = \pm \frac{\pi}{2}$ , then we get an ellipse:

$$\frac{x^2}{A_x^2} + \frac{y^2}{A_y^2} = 1$$

If  $\delta = 0$  (i.e. no phase), then we get  $(A_y x - A_x y)^2 = 0 \implies y = \frac{A_y}{A_x} x$ , which is a straight line! Visually, it looks like this:

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### 1.3.1 | Lissajous Curves

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Note that in the previous derivation we used the same  $k$  in both the  $x$  and  $y$  directions. However, in the most general case this isn't actually required! Therefore, the general set of equations are:

$$\begin{aligned} x(t) &= A_x \cos(\omega_x t) \\ y(t) &= A_y \cos(\omega_y t - \delta) \end{aligned}$$

If  $\frac{\omega_x}{\omega_y}$  is rational, then the motion is periodic, called a Lissajous figure (or a Lissajous curve). If it is irrational, then the curve will eventually fill out a rectangle over time.



# Lecture 2 (01/)

This lecture was held on **January 19th, 2023**. It covered the equations of motion for damped and driven oscillators, as well as their applications in modern circuits.

## 2.1 Last time: The Free Oscillator

On Tuesday we explored oscillatory mechanics where there were no other forces besides the restoring force. However, in most systems, we will always have some kind of *damping force* which impedes motion. This doesn't always have to be the case, but we will first explore a damping force which is proportional to the velocity:

$$\vec{f} = b\vec{v}$$

Under this, we now have the restoring force and the damping force, so Newton's second law now reads:

$$m\ddot{x} + b\dot{x} + kx = 0$$

And so if we let  $\beta = \frac{b}{2m}$  (we'll see later why this substitution is useful), then we can write

$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = 0$$

The nature of these differential equations is that due to their linearity, if we find two independent solutions  $x_1(t)$  and  $x_2(t)$ , then in general their solution will be a linear combination of the two:

$$x(t) = C_1 x_1(t) + C_2 x_2(t)$$

We saw that exponentials worked before, let's have that as our main guess. Let

$$x(t) = e^{rt} \implies \dot{x}(t) = r e^{rt}, \ddot{x}(t) = r^2 e^{rt}$$

Plugging this in, we get:

$$\begin{aligned} r^2 e^{rt} + 2\beta r e^{rt} + \omega_0^2 e^{rt} &= 0 \\ \therefore r^2 + 2\beta r + \omega_0^2 &= 0 \end{aligned}$$

This is quadratic in  $r$ , so therefore we have solutions  $r = -\beta \pm \sqrt{\beta^2 - \omega_0^2}$ . Now, we can then write

$$\begin{aligned} r_1 &= -\beta + \sqrt{\beta^2 - \omega_0^2} \\ r_2 &= -\beta - \sqrt{\beta^2 - \omega_0^2} \end{aligned}$$

so the general solution now becomes:

$$x(t) = C_1 e^{r_1 t} + C_2 e^{r_2 t} = e^{-\beta t} \left( C_1 e^{\sqrt{\beta^2 - \omega_0^2} t} + C_2 e^{-\sqrt{\beta^2 - \omega_0^2} t} \right)$$

This equation makes sense intuitively, since a large value of  $\beta$  generates a faster decay, which makes sense since  $\beta$  refers to the damping constant.

Now we have 3 cases that we want to analyze:

- (a) Underdamped:  $\omega_0^2 > \beta^2$
- (b) Critical damping:  $\omega_0^2 = \beta^2$
- (c) Overdamped:  $\omega_0^2 < \beta^2$

As it will turn out, only the overdamping will give us oscillatory motion.

### 2.1.1 Case 1: Underdamped Oscillation

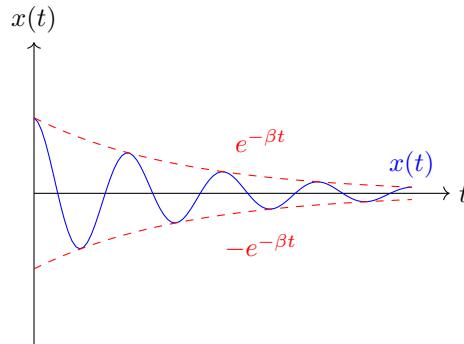
Here we look at the case where  $\omega_0^2 > \beta^2$ . If this is the case, then we can write  $\sqrt{\beta^2 - \omega_0^2} = i\sqrt{\omega_0^2 - \beta^2} = i\omega_1$ , with  $\omega_1 = \sqrt{\omega_0^2 - \beta^2}$

**Insight:** if  $\beta = 0$ , then we exactly recover the solution that we got last time:

$$x(t) = C_1 e^{\sqrt{-\omega_0^2} t} + C_2 e^{-\sqrt{-\omega_0^2} t} = C_1 e^{i\omega_0 t} + C_2 e^{-i\omega_0 t}$$

This is a good way to check that what we're doing still makes sense.

There's also the case where we get *weak underdamping*, where essentially we have  $\beta \ll \omega_0$ , so we get instead  $x(t) = e^{-\beta t} (C_1 e^{i\omega_1 t} + C_2 e^{-i\omega_1 t})$ . Here, the  $e^{-\beta t}$  term goes to zero over time, and the second term is just oscillation with  $\omega_0 \rightarrow \omega_1$ , so we can interpret this as an oscillation with an envelope of a decaying exponential. A diagram representation:



Here, the red dashed lines represent the envelope, and the  $x(t)$  represents the actual motion. As we can see, the oscillation goes to zero over time, which makes sense since the damping force is constantly taking away energy.

### 2.1.2 Case 2: Damped Oscillation

Now we look at  $\omega_0^2 < \beta^2$ . Here, the exponentials are real, so we can write:

$$x(t) = C_1 e^{-(\beta - \sqrt{\beta^2 - \omega_0^2})t} + C_2 e^{-(\beta + \sqrt{\beta^2 - \omega_0^2})t}$$

On large time scales, we can see that the oscillation is dominated by the slower of the two exponentials (the faster one just dies out quicker, so we don't see it for large times). Interestingly, the rate of decay is lower if  $\beta$  is larger, and we can see that since the exponentials get larger.

When solving these problems, there are three cases we need to specifically look at if we let  $x(0) = x_0 > 0$ :

- $\dot{x}_0 > 0$  such that we reach the maximum then the pendulum comes back.
- $\dot{x}_0 < 0$  but we approach  $x = 0$  but we do not go past.
- Same as the previous case, but we do end up going past  $x = 0$ .

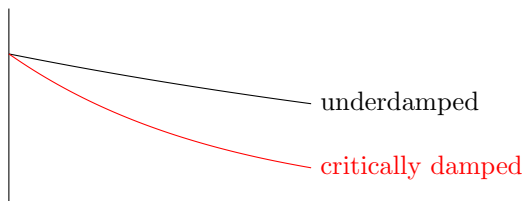
### 2.1.3 Case 3: Critical Damping

Now we look at  $\omega_0^2 = \beta^2$ , the most interesting case. Here, this means that the roots of  $r^2 + 2\beta r + \omega_0^2 = 0$  are equal, so our solution becomes

$$x(t) = e^{\beta t}$$

Well we know that this differential equation has two solutions, and there is indeed a second solution,  $x(t) = xe^{\beta t}$ . We can check that it satisfies the differential equation by plugging it in (you can do this on your own time)

A critically damped oscillator will approach equilibrium the fastest. This has important design consequences – in times where we want to reduce oscillation, critically damped systems are especially useful. Below is an illustration of this:



Both of these curves are exponential decay curves, but the critically damped one goes to zero much faster than any other damping.

## 2.2 Driving Forces

Now imagine instead of a resistive force, that we have a driven force instead. That is, our equation of motion now looks like this:

$$F = -kx - bx + F_0 \cos(\omega t)$$

where  $F_0 \cos(\omega t)$  denotes the driving force, with  $\omega$  being the angular frequency of the driving force. Therefore, we have the differential equation:

$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = f_0 \cos(\omega t)$$

where  $f_0 = \frac{F_0}{m}$ , and  $\beta$  is defined in the same way as before. This differential equation has two solutions:

- A homogeneous solution  $x_h(t)$ , which solves the differential equation when the right hand side is 0.
- A particular solution,  $x_p(t)$ , which solves the differential equation while replicating the right hand side.

Then, if we can find these two solutions, then we can combine them together:

$$x(t) = x_h(t) + x_p(t)$$

We already know  $x_h(t)$  from the earlier section, so if we can find an  $x_p(t)$ , then we have the full solution to the problem. We've seen before that sines and cosines seem to work well with oscillations, so why not try the solution  $x_p(t) = A \cos(\omega t - \delta)$ . Plugging this in, we get:

$$\begin{aligned} -A\omega^2 \cos(\omega t - \delta) - 2\beta A\omega \sin(\omega t - \delta) + \omega_0^2 A \cos(\omega t - \delta) &= f_0 \cos \omega t \\ f_0 \cos(\omega t) - A(\omega_0^2 - \omega^2) \cos(\omega t - \delta) + 2\beta A \cos(\omega t - \delta) &= 0 \end{aligned}$$

Now we use the trigonometric identities:

$$\begin{aligned} \cos(\alpha - \beta) &= \cos \alpha \cos \beta + \sin \alpha \sin \beta \\ \sin(\alpha - \beta) &= \sin \alpha \cos \beta - \cos \alpha \sin \beta \end{aligned}$$

Doing so we get the equation:

$$\{f_0 - A[(\omega_0^2 - \omega^2) \cos \delta + 2\omega\beta \sin \delta]\} \cos(\omega t) - \{A[(\omega_0^2 - \omega^2) \sin \delta - 2\omega\beta \cos(\omega t)]\} \sin(\omega t) = 0$$

Since  $\sin(\omega t)$  and  $\cos(\omega t)$  are linearly independent functions, this equation is only satisfied when both terms are zero. From the first term, we get:

$$\begin{aligned} \tan \delta &= \frac{2\omega\beta}{\omega_0^2 - \omega^2} \\ \therefore \delta &= \tan^{-1} \left( \frac{2\omega\beta}{\omega_0^2 - \omega^2} \right) \end{aligned}$$

Therefore,

$$\sin \delta = \frac{2\omega\beta}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\beta^2}} \quad \cos \delta = \frac{\omega_0^2 - \omega^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\beta^2}}$$

From the cosine term, we get:

$$\begin{aligned} A &= \frac{f_0}{(\omega_0^2 - \omega^2) \cos \delta + 2\omega\beta \sin \delta} \\ &= \frac{f_0}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\beta^2}} \end{aligned}$$

so now we finally have the particular solution:

$$x_p(t) = A \cos(\omega t - \delta) = \frac{f_0 \cos(\omega t - \delta)}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\beta^2}}$$

So our general solution, (again  $x(t) = x_h(t) + x_p(t)$ ) is

$$x(t) = C_1 e^{r_1 t} + C_2 e^{r_2 t} + A \cos(\omega t - \delta)$$

Note that for large time, the  $x_h(t)$  terms die out, but the  $x_p(t)$  terms don't, and dominate for large time  $t \gg \frac{1}{\beta}$ . In other words:

$$x(t \gg \frac{1}{\beta}) = x_p(t)$$

### 2.2.1 | The phase difference

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Earlier we said that  $\delta$  represents the phase difference between the action and the resulting motion:

$$\delta = \tan^{-1} \left( \frac{2\omega\beta}{\omega_0^2 - \omega^2} \right)$$

For a fixed  $\omega_0$ , as  $\omega$  increases from 0, we get that the phase increases from  $\delta = 0$  to  $\delta = \pi/2$  at  $\omega = \omega_0$  and  $\delta \rightarrow \pi$  as  $\omega \rightarrow \infty$ .

### 2.2.2 | Amplitude

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At large times, it's useful to look at the effect of  $\omega$  on the amplitude by looking at  $x_p(t)$ . To find where  $A$  is maximized, we simply take  $\frac{dA}{d\omega} = 0$ , giving us  $\omega_2 = \sqrt{\omega_0^2 - 2\beta^2}$ , so the resonance frequency is lowered as damping  $\beta$  is increased. This makes sense intuitively, since the larger value of  $\beta$  means that our oscillation decays much faster.

**Insight:** Note that we don't get any resonance frequencies for  $\beta^2 > \omega_0^2/2$ , since that's when the square root becomes complex-valued.

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## 2.3 || Summary

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In summary, so far we've looked at free, damped and driven oscillations:

- Free oscillations:  $\omega_0 = \frac{k}{m}$
- Damped oscillations:  $\omega_1 = \omega_0^2 - \beta^2$
- Driven oscillations:  $\omega_2 = \omega_0^2 - 2\beta^2$

This set of relations gives us  $\omega_0 > \omega_1 > \omega_2$ . The maximum amplitude is given by

$$A_{max} = \frac{f_0}{\sqrt{4\omega^2\beta^2}} = \frac{f_0}{2\omega\beta}$$

This equation tells us that if we make  $\beta$  smaller, then  $A_{max}$  increases and also becomes taller and narrower. We define the *full width half maximum* (FWHM =  $2\beta$ ) to quantify this value.

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### 2.3.1 | Aside: Quality Factor

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We sometimes define a quality factor  $Q$  as the ration of the resonance position  $\omega_0$  to its width  $2\beta$ :

$$Q = \frac{\omega_0}{2\beta}$$

This means that large values of  $Q$  correspond to narrow resonance, and small values correspond to a wide resonance.

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## 2.4 || Application: LC Circuits

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We've learned in electricity and magnetism (and also 5BL) that a simple LC circuit also behaves like an oscillator, since it follows the equation:

$$L \frac{dI}{dt} + \frac{1}{c} \int I dt = 0$$

or in terms of the charge  $q$ :

$$L\ddot{q} + \frac{1}{c}q = 0$$

The solutions are of the same form since the only thing we've changed here are the variable names:  $q(t) = q_0 \cos(\omega t)$ . Overall, we can just perform the substitution of letters:

$$m \rightarrow L \quad x \rightarrow q \quad \frac{1}{k} \rightarrow c \quad \dot{x} \rightarrow I$$

Similarly, adding a resistance will give us the equivalent of a damping term, and adding an AC power generator is the same as adding a driving force to the system. Again, the nature of these system is the exact same as what we just solved for, so the equations of motion remain the same as well.