PHY321: Harmonic oscillations: Time-dependent Forces and Fourier Series

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Aims and Overarching Motivation

Driven oscillations and resonances with numerical examples.

Monday, March 14. Summary of analytical expressions from February 28-March 4 (see slides at https://mhjensen.github.io/Physics321/doc/pub/week9/html/week9-reveal.html. Discussion of resonances and other examples like the mathematical pendulum and other systems.

Reading suggestion: Taylor sections 5.6-5.8.

Wednesday. Examples of oscillations and Fourier analysis applied to harmonic oscillations.

Reading suggestion: See lecture notes at https://mhjensen.github.io/Physics321/doc/pub/week10/html/week10-reveal.html

Friday. Work on homework 6 and discussions of harmonic oscillation examples and systems.

Numerical Studies of Driven Oscillations

Solving the problem of driven oscillations numerically gives us much more flexibility to study different types of driving forces. We can reuse our earlier code by simply adding a driving force. If we stay in the x-direction only this can be easily done by adding a term $F_{\mathrm{ext}}(x,t)$. Note that we have kept it rather general here, allowing for both a spatial and a temporal dependence.

Before we dive into the code, we need to briefly remind ourselves about the equations we started with for the case with damping, namely

$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx(t)=0,$$

with no external force applied to the system.

Let us now for simplicty assume that our external force is given by

$$F_{\mathrm{ext}}(t)=F_0\cos{(\omega t)},$$

where F_0 is a constant (what is its dimension?) and ω is the frequency of the applied external driving force. **Small question:** would you expect energy to be conserved now?

Introducing the external force into our lovely differential equation and dividing by m and introducing $\omega_0^2=\sqrt{k/m}$ we have

$$\frac{d^2x}{dt^2}+\frac{b}{m}\frac{dx}{dt}+\omega_0^2x(t)=\frac{F_0}{m}\cos{(\omega t)},$$

Thereafter we introduce a dimensionless time $\tau=t\omega_0$ and a dimensionless frequency $\tilde{\omega}=\omega/\omega_0$. We have then

$$\frac{d^2x}{d\tau^2}+\frac{b}{m\omega_0}\frac{dx}{d\tau}+x(\tau)=\frac{F_0}{m\omega_0^2}\cos{(\tilde{\omega}\tau)},$$

Introducing a new amplitude $\tilde{F}=F_0/(m\omega_0^2)$ (check dimensionality again) we have

$$\frac{d^2x}{d\tau^2}+\frac{b}{m\omega_0}\frac{dx}{d\tau}+x(\tau)=\tilde{F}\cos{(\tilde{\omega}\tau)}.$$

Our final step, as we did in the case of various types of damping, is to define $\gamma=b/(2m\omega_0)$ and rewrite our equations as

$$\frac{d^2x}{d\tau^2}+2\gamma\frac{dx}{d\tau}+x(\tau)=\tilde{F}\cos{(\tilde{\omega}\tau)}.$$

This is the equation we will code below using the Euler-Cromer method.

```python
# Common imports
import numpy as np
import pandas as pd
from math import *
import matplotlib.pyplot as plt
import os

# Where to save the figures and data files
PROJECT_ROOT_DIR = "Results"
FIGURE_ID = "Results/FigureFiles"
DATA_ID = "DataFiles/"

if not os.path.exists(PROJECT_ROOT_DIR):
    os.mkdir(PROJECT_ROOT_DIR)
```

```python
if not os.path.exists(FIGURE_ID):
    os.makedirs(FIGURE_ID)

if not os.path.exists(DATA_ID):
    os.makedirs(DATA_ID)

def image_path(fig_id):
    return os.path.join(FIGURE_ID, fig_id)

def data_path(dat_id):
    return os.path.join(DATA_ID, dat_id)

def save_fig(fig_id):
    plt.savefig(image_path(fig_id) + ".png", format='png')


from pylab import plt, mpl
plt.style.use('seaborn')
mpl.rcParams['font.family'] = 'serif'


DeltaT = 0.001
#set up arrays
tfinal = 20 # in dimensionless time
n = ceil(tfinal/DeltaT)
# set up arrays for t, v, and x
t = np.zeros(n)
v = np.zeros(n)
x = np.zeros(n)
# Initial conditions as one-dimensional arrays of time
x0 =  1.0
v0 = 0.0
x[0] = x0
v[0] = v0
gamma = 0.2
Omegatilde = 0.5
Ftilde = 1.0
# Start integrating using Euler-Cromer's method
for i in range(n-1):
    # Set up the acceleration
    # Here you could have defined your own function for this
    a =  -2*gamma*v[i]-x[i]+Ftilde*cos(t[i]*Omegatilde)
    # update velocity, time and position
    v[i+1] = v[i] + DeltaT*a
    x[i+1] = x[i] + DeltaT*v[i+1]
    t[i+1] = t[i] + DeltaT
# Plot position as function of time
fig, ax = plt.subplots()
ax.set_ylabel('x[m]')
ax.set_xlabel('t[s]')
ax.plot(t, x)
fig.tight_layout()
save_fig("ForcedBlockEulerCromer")
plt.show()
```

In the above example we have focused on the Euler-Cromer method. This method has a local truncation error which is proportional to Δt^2 and thereby a global error which is proportional to Δt. We can improve this by using the Runge-Kutta family of methods. The widely popular Runge-Kutta to fourth order or just **RK4** has indeed a much better truncation error. The RK4 method has a global error which is proportional to Δt.

Let us revisit this method and see how we can implement it for the above example.

Differential Equations, Runge-Kutta methods

Runge-Kutta (RK) methods are based on Taylor expansion formulae, but yield in general better algorithms for solutions of an ordinary differential equation. The basic philosophy is that it provides an intermediate step in the computation of y_{i+1}.

To see this, consider first the following definitions

$$\frac{dy}{dt} = f(t, y), \tag{1}$$

and

$$y(t) = \int f(t, y)dt, \tag{2}$$

and

$$y_{i+1} = y_i + \int_{t_i}^{t_{i+1}} f(t, y)dt. \tag{3}$$

To demonstrate the philosophy behind RK methods, let us consider the second-order RK method, RK2. The first approximation consists in Taylor expanding $f(t, y)$ around the center of the integration interval t_i to t_{i+1}, that is, at $t_i + h/2$, h being the step. Using the midpoint formula for an integral, defining $y(t_i + h/2) = y_{i+1/2}$ and $t_i + h/2 = t_{i+1/2}$, we obtain

$$\int_{t_i}^{t_{i+1}} f(t, y)dt \approx hf(t_{i+1/2}, y_{i+1/2}) + O(h^3). \tag{4}$$

This means in turn that we have

$$y_{i+1} = y_i + hf(t_{i+1/2}, y_{i+1/2}) + O(h^3). \tag{5}$$

However, we do not know the value of $y_{i+1/2}$. Here comes thus the next approximation, namely, we use Euler's method to approximate $y_{i+1/2}$. We have then

$$y_{(i+1/2)} = y_i + \frac{h}{2}\frac{dy}{dt} = y(t_i) + \frac{h}{2}f(t_i, y_i). \tag{6}$$

This means that we can define the following algorithm for the second-order Runge-Kutta method, RK2.

$$k_1 = hf(t_i, y_i), \tag{7}$$

and

$$k_2 = hf(t_{i+1/2}, y_i + k_1/2), \tag{8}$$

with the final value

$$y_{i+i} \approx y_i + k_2 + O(h^3). \tag{9}$$

The difference between the previous one-step methods is that we now need an intermediate step in our evaluation, namely $t_i + h/2 = t_{(i+1/2)}$ where we evaluate the derivative f. This involves more operations, but the gain is a better stability in the solution.

The fourth-order Runge-Kutta, RK4, has the following algorithm

$$k_1 = hf(t_i, y_i) \qquad k_2 = hf(t_i + h/2, y_i + k_1/2)$$

and

$$k_3 = hf(t_i + h/2, y_i + k_2/2) \qquad k_4 = hf(t_i + h, y_i + k_3)$$

with the final result

$$y_{i+1} = y_i + \frac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right).$$

Thus, the algorithm consists in first calculating k_1 with t_i, y_1 and f as inputs. Thereafter, we increase the step size by $h/2$ and calculate k_2, then k_3 and finally k_4. The global error goes as $O(h^4)$.

However, at this stage, if we keep adding different methods in our main program, the code will quickly become messy and ugly. Before we proceed thus, we will now introduce functions that enbody the various methods for solving differential equations. This means that we can separate out these methods in own functions and files (and later as classes and more generic functions) and simply call them when needed. Similarly, we could easily encapsulate various forces or other quantities of interest in terms of functions. To see this, let us bring up the code we developed above for the simple sliding block, but now only with the simple forward Euler method. We introduce two functions, one for the simple Euler method and one for the force.

Note that here the forward Euler method does not know the specific force function to be called. It receives just an input the name. We can easily change the force by adding another function.

```
def ForwardEuler(v,x,t,n,Force):
    for i in range(n-1):
        v[i+1] = v[i] + DeltaT*Force(v[i],x[i],t[i])
        x[i+1] = x[i] + DeltaT*v[i]
        t[i+1] = t[i] + DeltaT

def SpringForce(v,x,t):
#   note here that we have divided by mass and we return the acceleration
    return  -2*gamma*v-x+Ftilde*cos(t*Omegatilde)
```

It is easy to add a new method like the Euler-Cromer

```python
def ForwardEulerCromer(v,x,t,n,Force):
    for i in range(n-1):
        a = Force(v[i],x[i],t[i])
        v[i+1] = v[i] + DeltaT*a
        x[i+1] = x[i] + DeltaT*v[i+1]
        t[i+1] = t[i] + DeltaT
```

and the Velocity Verlet method (be careful with time-dependence here, it is not an ideal method for non-conservative forces))

```python
def VelocityVerlet(v,x,t,n,Force):
    for i in range(n-1):
        a = Force(v[i],x[i],t[i])
        x[i+1] = x[i] + DeltaT*v[i]+0.5*a*DeltaT*DeltaT
        anew = Force(v[i],x[i+1],t[i+1])
        v[i+1] = v[i] + 0.5*DeltaT*(a+anew)
        t[i+1] = t[i] + DeltaT
```

Finally, we can now add the Runge-Kutta2 method via a new function

```python
def RK2(v,x,t,n,Force):
    for i in range(n-1):
# Setting up k1
        k1x = DeltaT*v[i]
        k1v = DeltaT*Force(v[i],x[i],t[i])
# Setting up k2
        vv = v[i]+k1v*0.5
        xx = x[i]+k1x*0.5
        k2x = DeltaT*vv
        k2v = DeltaT*Force(vv,xx,t[i]+DeltaT*0.5)
# Final result
        x[i+1] = x[i]+k2x
        v[i+1] = v[i]+k2v
        t[i+1] = t[i]+DeltaT
```

Finally, we can now add the Runge-Kutta2 method via a new function

```python
def RK4(v,x,t,n,Force):
    for i in range(n-1):
# Setting up k1
        k1x = DeltaT*v[i]
        k1v = DeltaT*Force(v[i],x[i],t[i])
# Setting up k2
        vv = v[i]+k1v*0.5
        xx = x[i]+k1x*0.5
        k2x = DeltaT*vv
        k2v = DeltaT*Force(vv,xx,t[i]+DeltaT*0.5)
# Setting up k3
        vv = v[i]+k2v*0.5
        xx = x[i]+k2x*0.5
        k3x = DeltaT*vv
        k3v = DeltaT*Force(vv,xx,t[i]+DeltaT*0.5)
# Setting up k4
        vv = v[i]+k3v
        xx = x[i]+k3x
        k4x = DeltaT*vv
        k4v = DeltaT*Force(vv,xx,t[i]+DeltaT)
# Final result
        x[i+1] = x[i]+(k1x+2*k2x+2*k3x+k4x)/6.
        v[i+1] = v[i]+(k1v+2*k2v+2*k3v+k4v)/6.
        t[i+1] = t[i] + DeltaT
```

The Runge-Kutta family of methods are particularly useful when we have a time-dependent acceleration. If we have forces which depend only the spatial degrees of freedom (no velocity and/or time-dependence), then energy conserving methods like the Velocity Verlet or the Euler-Cromer method are preferred. As soon as we introduce an explicit time-dependence and/or add dissipitave forces like friction or air resistance, then methods like the family of Runge-Kutta methods are well suited for this. The code below uses the Runge-Kutta4 methods.

```
DeltaT = 0.001
#set up arrays
tfinal = 20 # in dimensionless time
n = ceil(tfinal/DeltaT)
# set up arrays for t, v, and x
t = np.zeros(n)
v = np.zeros(n)
x = np.zeros(n)
# Initial conditions (can change to more than one dim)
x0 =  1.0
v0 = 0.0
x[0] = x0
v[0] = v0
gamma = 0.2
Omegatilde = 0.5
Ftilde = 1.0
# Start integrating using the RK4 method
# Note that we define the force function as a SpringForce
RK4(v,x,t,n,SpringForce)

# Plot position as function of time
fig, ax = plt.subplots()
ax.set_ylabel('x[m]')
ax.set_xlabel('t[s]')
ax.plot(t, x)
fig.tight_layout()
save_fig("ForcedBlockRK4")
plt.show()
```

Example: The classical pendulum and scaling the equations

Let us end our discussion of oscillations with another classical case, the pendulum.

The angular equation of motion of the pendulum is given by Newton's equation and with no external force it reads

$$ml\frac{d^2\theta}{dt^2}+mgsin(\theta)=0, \tag{10}$$

with an angular velocity and acceleration given by

$$v=l\frac{d\theta}{dt}, \tag{11}$$

and

$$a=l\frac{d^2\theta}{dt^2}. \tag{12}$$

We do however expect that the motion will gradually come to an end due a viscous drag torque acting on the pendulum. In the presence of the drag, the above equation becomes

$$ml\frac{d^2\theta}{dt^2} + \nu\frac{d\theta}{dt} + mgsin(\theta) = 0, \tag{13}$$

where ν is now a positive constant parameterizing the viscosity of the medium in question. In order to maintain the motion against viscosity, it is necessary to add some external driving force. We choose here a periodic driving force. The last equation becomes then

$$ml\frac{d^2\theta}{dt^2} + \nu\frac{d\theta}{dt} + mgsin(\theta) = Asin(\omega t), \tag{14}$$

with A and ω two constants representing the amplitude and the angular frequency respectively. The latter is called the driving frequency.

We define

$$\omega_0 = \sqrt{g/l},$$

the so-called natural frequency and the new dimensionless quantities

$$\hat{t} = \omega_0 t,$$

with the dimensionless driving frequency

$$\hat{\omega} = \frac{\omega}{\omega_0},$$

and introducing the quantity Q, called the *quality factor*,

$$Q = \frac{mg}{\omega_0 \nu},$$

and the dimensionless amplitude

$$\hat{A} = \frac{A}{mg}$$

More on the Pendulum

We have

$$\frac{d^2\theta}{d\hat{t}^2} + \frac{1}{Q}\frac{d\theta}{d\hat{t}} + sin(\theta) = \hat{A}cos(\hat{\omega}\hat{t}).$$

This equation can in turn be recast in terms of two coupled first-order differential equations as follows

$$\frac{d\theta}{d\hat{t}} = \hat{v},$$

and

$$\frac{d\hat{v}}{d\hat{t}} = -\frac{\hat{v}}{Q} - sin(\theta) + \hat{A}cos(\hat{\omega}\hat{t}).$$

These are the equations to be solved. The factor Q represents the number of oscillations of the undriven system that must occur before its energy is significantly reduced due to the viscous drag. The amplitude $\hat{A}$ is measured in units of the maximum possible gravitational torque while $\hat{\omega}$ is the angular frequency of the external torque measured in units of the pendulum's natural frequency.

The Pendulum code

We need to define a new force, which we simply call the pendulum force. The only thing which changes from our previous spring-force problem is the non-linearity introduced by angle θ due to the $\sin\theta$ term. Here we have kept a generic variable x instead. This makes our codes very similar.

```
def PendulumForce(v,x,t):
#   note here that we have divided by mass and we return the acceleration
    return  -gamma*v-sin(x)+Ftilde*cos(t*Omegatilde)
```

Setting up the various variables and running the code

```
DeltaT = 0.001
#set up arrays
tfinal = 20 # in years
n = ceil(tfinal/DeltaT)
# set up arrays for t, v, and x
t = np.zeros(n)
v = np.zeros(n)
theta = np.zeros(n)
# Initial conditions (can change to more than one dim)
theta0 =  1.0
v0 = 0.0
theta[0] = theta0
v[0] = v0
gamma = 0.2
Omegatilde = 0.5
Ftilde = 1.0
# Start integrating using the RK4 method
# Note that we define the force function as a PendulumForce
RK4(v,theta,t,n,PendulumForce)

# Plot position as function of time
fig, ax = plt.subplots()
ax.set_ylabel('theta[radians]')
ax.set_xlabel('t[s]')
ax.plot(t, theta)
fig.tight_layout()
save_fig("PendulumRK4")
plt.show()
```

Principle of Superposition and Periodic Forces (Fourier Transforms)

If one has several driving forces, $F(t) = \sum_n F_n(t)$, one can find the particular solution to each F_n, $x_{pn}(t)$, and the particular solution for the entire driving force is

$$x_p(t) = \sum_n x_{pn}(t). \tag{15}$$

This is known as the principal of superposition. It only applies when the homogenous equation is linear. If there were an anharmonic term such as x^3 in the homogenous equation, then when one summed various solutions, $x = (\sum_n x_n)^2$, one would get cross terms. Superposition is especially useful when $F(t)$ can be written as a sum of sinusoidal terms, because the solutions for each sinusoidal (sine or cosine) term is analytic, as we saw above.

Driving forces are often periodic, even when they are not sinusoidal. Periodicity implies that for some time τ

$$F(t + \tau) = F(t). \tag{16}$$

One example of a non-sinusoidal periodic force is a square wave. Many components in electric circuits are non-linear, e.g. diodes, which makes many wave forms non-sinusoidal even when the circuits are being driven by purely sinusoidal sources.

The code here shows a typical example of such a square wave generated using the functionality included in the **scipy** Python package. We have used a period of $\tau = 0.2$.

```
import numpy as np
import math
from scipy import signal
import matplotlib.pyplot as plt

# number of points
n = 500
# start and final times
t0 = 0.0
tn = 1.0
# Period
t = np.linspace(t0, tn, n, endpoint=False)
SqrSignal = np.zeros(n)
SqrSignal = 1.0+signal.square(2*np.pi*5*t)
plt.plot(t, SqrSignal)
plt.ylim(-0.5, 2.5)
plt.show()
```

For the sinusoidal example studied in the previous week the period is $\tau = 2\pi/\omega$. However, higher harmonics can also satisfy the periodicity requirement. In general, any force that satisfies the periodicity requirement can be expressed as a sum over harmonics,

$$F(t) = \frac{f_0}{2} + \sum_{n>0} f_n \cos(2n\pi t/\tau) + g_n \sin(2n\pi t/\tau). \tag{17}$$

We can write down the answer for $x_{pn}(t)$, by substituting f_n/m or g_n/m for F_0/m. By writing each factor $2n\pi t/\tau$ as $n\omega t$, with $\omega \equiv 2\pi/\tau$,

$$F(t) = \frac{f_0}{2} + \sum_{n>0} f_n \cos(n\omega t) + g_n \sin(n\omega t). \tag{18}$$

The solutions for $x(t)$ then come from replacing ω with $n\omega$ for each term in the particular solution,

$$\begin{aligned}
x_p(t) &= \frac{f_0}{2k} + \sum_{n>0} \alpha_n \cos(n\omega t - \delta_n) + \beta_n \sin(n\omega t - \delta_n), \qquad (19)\\
\alpha_n &= \frac{f_n/m}{\sqrt{((n\omega)^2 - \omega_0^2) + 4\beta^2 n^2 \omega^2}},\\
\beta_n &= \frac{g_n/m}{\sqrt{((n\omega)^2 - \omega_0^2) + 4\beta^2 n^2 \omega^2}},\\
\delta_n &= \tan^{-1}\left(\frac{2\beta n\omega}{\omega_0^2 - n^2\omega^2}\right).
\end{aligned}$$

Because the forces have been applied for a long time, any non-zero damping eliminates the homogenous parts of the solution, so one need only consider the particular solution for each n.

The problem will considered solved if one can find expressions for the coefficients f_n and g_n, even though the solutions are expressed as an infinite sum. The coefficients can be extracted from the function $F(t)$ by

$$\begin{aligned}
f_n &= \frac{2}{\tau}\int_{-\tau/2}^{\tau/2} dt\ F(t)\cos(2n\pi t/\tau), \qquad (20)\\
g_n &= \frac{2}{\tau}\int_{-\tau/2}^{\tau/2} dt\ F(t)\sin(2n\pi t/\tau).
\end{aligned}$$

To check the consistency of these expressions and to verify Eq. (20), one can insert the expansion of $F(t)$ in Eq. (18) into the expression for the coefficients in Eq. (20) and see whether

$$f_n \;=?\; \frac{2}{\tau}\int_{-\tau/2}^{\tau/2} dt\ \left\{\frac{f_0}{2} + \sum_{m>0} f_m \cos(m\omega t) + g_m \sin(m\omega t)\right\}\cos(n\omega t). \tag{21}$$

Immediately, one can throw away all the terms with g_m because they convolute an even and an odd function. The term with $f_0/2$ disappears because $\cos(n\omega t)$

is equally positive and negative over the interval and will integrate to zero. For all the terms $f_m \cos(m\omega t)$ appearing in the sum, one can use angle addition formulas to see that $\cos(m\omega t)\cos(n\omega t) = (1/2)(\cos[(m+n)\omega t] + \cos[(m-n)\omega t]$. This will integrate to zero unless $m = n$. In that case the $m = n$ term gives

$$\int_{-\tau/2}^{\tau/2} dt\ \cos^2(m\omega t) = \frac{\tau}{2}, \tag{22}$$

and

$$\begin{aligned} f_n &=? \quad \frac{2}{\tau}\int_{-\tau/2}^{\tau/2} dt\ f_n/2 \\ &= \quad f_n \checkmark . \end{aligned} \tag{23}$$

The same method can be used to check for the consistency of g_n.

Consider the driving force:

$$F(t) = At/\tau, \quad -\tau/2 < t < \tau/2, \quad F(t+\tau) = F(t). \tag{24}$$

Find the Fourier coefficients f_n and g_n for all n using Eq. (20).

Only the odd coefficients enter by symmetry, i.e. $f_n = 0$. One can find g_n integrating by parts,

$$\begin{aligned} g_n &= \frac{2}{\tau}\int_{-\tau/2}^{\tau/2} dt\ \sin(n\omega t)\frac{At}{\tau} \\ u &= t,\ dv = \sin(n\omega t)dt,\ v = -\cos(n\omega t)/(n\omega), \\ g_n &= \frac{-2A}{n\omega\tau^2}\int_{-\tau/2}^{\tau/2} dt\ \cos(n\omega t) + 2A\frac{-t\cos(n\omega t)}{n\omega\tau^2}\Big|_{-\tau/2}^{\tau/2} . \end{aligned} \tag{25}$$

The first term is zero because $\cos(n\omega t)$ will be equally positive and negative over the interval. Using the fact that $\omega\tau = 2\pi$,

$$\begin{aligned} g_n &= -\frac{2A}{2n\pi}\cos(n\omega\tau/2) \\ &= -\frac{A}{n\pi}\cos(n\pi) \\ &= \frac{A}{n\pi}(-1)^{n+1}. \end{aligned} \tag{26}$$

Fourier Series

More text will come here, chpater 5.7-5.8 of Taylor are discussed during the lectures. The code here uses the Fourier series discussed in chapter 5.7 for a square wave signal. The equations for the coefficients are are discussed in Taylor section

5.7, see Example 5.4. The code here visualizes the various approximations given by Fourier series compared with a square wave with period $T = 0.2$, witth 0.1 and max value $F = 2$. We see that when we increase the number of components in the Fourier series, the Fourier series approximation gets closes and closes to the square wave signal.

```
import numpy as np
import math
from scipy import signal
import matplotlib.pyplot as plt

# number of points
n = 500
# start and final times
t0 = 0.0
tn = 1.0
# Period
T =0.2
# Max value of square signal
Fmax= 2.0
# Width of signal
Width = 0.1
t = np.linspace(t0, tn, n, endpoint=False)
SqrSignal = np.zeros(n)
FourierSeriesSignal = np.zeros(n)
SqrSignal = 1.0+signal.square(2*np.pi*5*t+np.pi*Width/T)
a0 = Fmax*Width/T
FourierSeriesSignal = a0
Factor = 2.0*Fmax/np.pi
for i in range(1,500):
    FourierSeriesSignal += Factor/(i)*np.sin(np.pi*i*Width/T)*np.cos(i*t*2*np.pi/T)
plt.plot(t, SqrSignal)
plt.plot(t, FourierSeriesSignal)
plt.ylim(-0.5, 2.5)
plt.show()
```

Solving differential equations with Fouries series

Material to be discussed during lecture (whiteboard)

Response to Transient Force

Consider a particle at rest in the bottom of an underdamped harmonic oscillator, that then feels a sudden impulse, or change in momentum, $I = F\Delta t$ at $t = 0$. This increases the velocity immediately by an amount $v_0 = I/m$ while not changing the position. One can then solve the trajectory by solving the equations with initial conditions $v_0 = I/m$ and $x_0 = 0$. This gives

$$x(t) = \frac{I}{m\omega'} e^{-\beta t} \sin \omega' t, \quad t > 0. \tag{27}$$

Here, $\omega' = \sqrt{\omega_0^2 - \beta^2}$. For an impulse I_i that occurs at time t_i the trajectory would be

$$x(t) = \frac{I_i}{m\omega'} e^{-\beta(t-t_i)} \sin[\omega'(t-t_i)]\Theta(t-t_i), \tag{28}$$

where $\Theta(t-t_i)$ is a step function, i.e. $\Theta(x)$ is zero for $x < 0$ and unity for $x > 0$. If there were several impulses linear superposition tells us that we can sum over each contribution,

$$x(t) = \sum_i \frac{I_i}{m\omega'} e^{-\beta(t-t_i)} \sin[\omega'(t-t_i)]\Theta(t-t_i) \tag{29}$$

Now one can consider a series of impulses at times separated by Δt, where each impulse is given by $F_i\Delta t$. The sum above now becomes an integral,

$$\begin{aligned} x(t) &= \int_{-\infty}^{\infty} dt'\ F(t') \frac{e^{-\beta(t-t')}\sin[\omega'(t-t')]}{m\omega'} \Theta(t-t') \qquad (30) \\ &= \int_{-\infty}^{\infty} dt'\ F(t') G(t-t'), \\ G(\Delta t) &= \frac{e^{-\beta\Delta t}\sin[\omega'\Delta t]}{m\omega'}\Theta(\Delta t) \end{aligned}$$

The quantity $e^{-\beta(t-t')}\sin[\omega'(t-t')]/m\omega'\Theta(t-t')$ is called a Green's function, $G(t-t')$. It describes the response at t due to a force applied at a time t', and is a function of $t-t'$. The step function ensures that the response does not occur before the force is applied. One should remember that the form for G would change if the oscillator were either critically- or over-damped.

When performing the integral in Eq. (30) one can use angle addition formulas to factor out the part with the t' dependence in the integrand,

$$\begin{aligned} x(t) &= \frac{1}{m\omega'} e^{-\beta t}\left[I_c(t)\sin(\omega' t) - I_s(t)\cos(\omega' t)\right], \qquad (31) \\ I_c(t) &\equiv \int_{-\infty}^{t} dt'\ F(t') e^{\beta t'}\cos(\omega' t'), \\ I_s(t) &\equiv \int_{-\infty}^{t} dt'\ F(t') e^{\beta t'}\sin(\omega' t'). \end{aligned}$$

If the time t is beyond any time at which the force acts, $F(t' > t) = 0$, the coefficients I_c and I_s become independent of t.

Consider an undamped oscillator ($\beta \to 0$), with characteristic frequency ω_0 and mass m, that is at rest until it feels a force described by a Gaussian form,

$$F(t) = F_0 \exp\left\{\frac{-t^2}{2\tau^2}\right\}.$$

For large times ($t >> \tau$), where the force has died off, find $x(t)$.
Solve for the coefficients I_c and I_s in Eq. (31). Because the Gaussian is an even function, $I_s = 0$, and one need only solve for I_c,

$$\begin{aligned}
I_c &= F_0 \int_{-\infty}^{\infty} dt'\ e^{-t'^2/(2\tau^2)} \cos(\omega_0 t') \\
&= \Re F_0 \int_{-\infty}^{\infty} dt'\ e^{-t'^2/(2\tau^2)} e^{i\omega_0 t'} \\
&= \Re F_0 \int_{-\infty}^{\infty} dt'\ e^{-(t'-i\omega_0\tau^2)^2/(2\tau^2)} e^{-\omega_0^2\tau^2/2} \\
&= F_0 \tau \sqrt{2\pi} e^{-\omega_0^2\tau^2/2}.
\end{aligned}$$

The third step involved completing the square, and the final step used the fact that the integral

$$\int_{-\infty}^{\infty} dx\ e^{-x^2/2} = \sqrt{2\pi}.$$

To see that this integral is true, consider the square of the integral, which you can change to polar coordinates,

$$\begin{aligned}
I &= \int_{-\infty}^{\infty} dx\ e^{-x^2/2} \\
I^2 &= \int_{-\infty}^{\infty} dxdy\ e^{-(x^2+y^2)/2} \\
&= 2\pi \int_0^{\infty} rdr\ e^{-r^2/2} \\
&= 2\pi.
\end{aligned}$$

Finally, the expression for x from Eq. (31) is

$$x(t >> \tau) = \frac{F_0 \tau}{m\omega_0} \sqrt{2\pi} e^{-\omega_0^2\tau^2/2} \sin(\omega_0 t).$$