Goal of Experiment

The goal of my experiment is to run a dynamic test of the decided joint material of polyethelyene sheet. From this experiment we hope to fit the data for the damping and stiffness constant.

Process and Procedure

Process

In order to isolate the joint properties, I manufactured a 2 link, 5-layer laminate structure with 0.002" polyester film as the flexible layer and 6 layer cardstock as the rigid material. I then conducted a dynamic test by constraining one of the links vertically between two plates and pulled unconstrained link to the side, released and let it come to rest. I recorded this experiment with my phone so that I could import the data into tracker, track the position of the blue dot at the end of my segment, and record the position data over time. This data was then imported into python so that I could fit the data to a simulated experiment.

The assumptions I made for this experiment is that the system is exactly vertical. Since I am in a configuration that is meant to negate gravity, but if there was any warping or if the links were not exactly vertical, some forces due to gravity would have an effect. Additionally, I am treating the rigid segments as rigid bodies have no flexure for my model.

Pictures of Experimental Setup

Set up of experiment from above. One link is constrained allowing only one segment to move.

Side profile of experimental set up. A small blue ball was added to the end of the link to track the motion of the segment as it oscilatted.

Video

0:00

Video of experiment that was used for tracker.

Model Fitting

The model I used to fit for this experiment was a single link that had a torsional spring and damping force applied to the point of rotation. The reason that the model was built like this is because only one link in the experiment had free motion and the cause of motion was the felxure joint.

The optimization method used for my assignment was the scipy.optimize.minimze function. The reason that this method was used was because I was trying to tune the b and k values of the model to best fit the experimental data. Since there was no relationship between these variables, I went with the fastest method of fitting the data. For the purposes of this assignment, the script will not run the fitting to decrease the amount of outputs but the values of the damping and spring constant are calculated from the the optimization.

Importing Libraries

Adding libaries to build dynamic model and fitting algorithms

In [1]:

```
%matplotlib inline
```

In [2]:

```
import pynamics
from pynamics.frame import Frame
from pynamics.variable_types import Differentiable,Constant
from pynamics.system import System
from pynamics.body import Body
from pynamics.dyadic import Dyadic
from pynamics.output import Output,PointsOutput
from pynamics.output_points_3d import PointsOutput3D
from pynamics.particle import Particle
import pynamics.integration
```

```python
import numpy
import matplotlib.pyplot as plt
plt.ion()
from math import pi,sin
import sympy
from sympy import sqrt
import math
import logging
import pynamics.integration
import pynamics.system
import numpy.random
import scipy.interpolate
import scipy.optimize
import cma
import pandas as pd
import idealab_tools.units

system = System()
pynamics.set_system(__name__,system)
```

Running Optimization and Importing Data

Setting variable to True to run fit or false to just run a single simulation. Importing the xlsx file of exerimental data and plot the data. The data was cut at two seconds to focus on the dynamics of the system and to optimize the simulation time so that it would run faster.

In [3]:

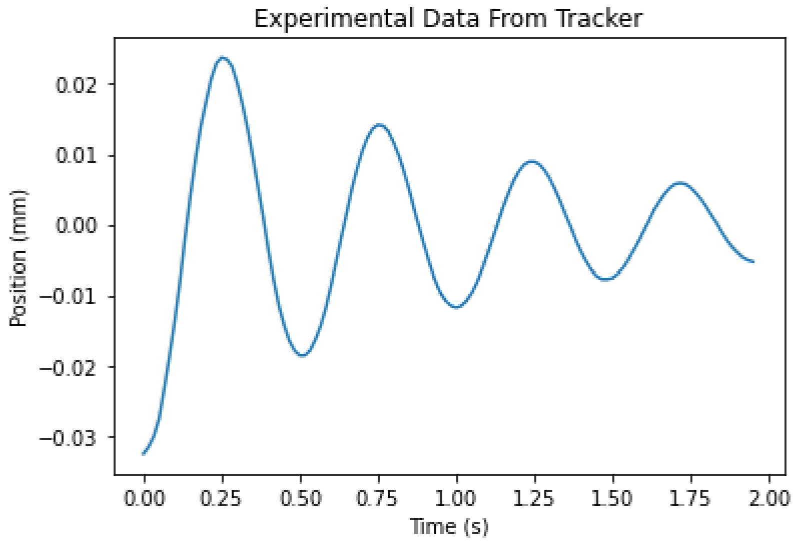
```python
#Run SciPy Opitmization regession fit
run_fit = False

#import test data and convert to numPy arrays
data = pd.read_excel(r'damping data_cut.xlsx')
df = data.to_numpy()
length = df.shape[0]

fig = plt.figure()
plt.plot(df[:,1],df[:,3])
plt.title('Experimental Data From Tracker')
plt.xlabel('Time (s)')
plt.ylabel('Position (mm)')
```

Out[3]:

```
Text(0, 0.5, 'Position (mm)')
```



Constants of Model

Adding dimensions and interias of segment based off of physical laminate structure. Link dimensions were 50mm x 30 mm x 1 mm. Mass of the tracker was 0.0588 grams and mass of the segment was 1 gram. These values were gotten from teammates from their parameterization documents.

In [4]:

```
#Parameterization

#Defining Constants of System
seg_len = 0.050    #segment mass
seg_mass = 0.001 #segment mass
seg_h = 0.040 #segment height
seg_th = 0.001

#Set segment lengths
lA = Constant(seg_len,'lA',system)
lB = Constant(seg_len,'lB',system)

#Set masses
mA = Constant(seg_mass,'mA',system)
mB = Constant(seg_mass,'mB',system)
mM = Constant(.001/17,'mM',system) #17 trackers was 1 gram so divided to find mass of t

g = Constant(9.81,'g',system)
b = Constant(2.14176688e-06,'b',system) #values generated fro sciPy.minimize
k = Constant(1.59953557e-04,'k',system) #values generated fro sciPy.minimize
area = Constant(seg_len*seg_h,'area',system)
rho = Constant(1.059,'rho',system)

Ixx = Constant((1/12*seg_mass*(seg_h**2 + seg_th**2)),'Ixx',system)
Iyy = Constant((1/12*seg_mass*(seg_h**2 + seg_len**2)),'Iyy',system)
Izz = Constant((1/12*seg_mass*(seg_len**2 + seg_th**2)),'Izz',system)

#Define derivatives of frames
qA,qA_d,qA_dd = Differentiable('qA',system)

#set initial conditions
```

```
initialvalues = {}
initialvalues[qA]=-41*pi/180 #Initial state of experiment
initialvalues[qA_d]=0*pi/180

statevariables = system.get_state_variables()
ini = [initialvalues[item] for item in statevariables]

#Set simulation run time
tinitial = 0
tfinal = df[length-1,1]  #time of simulation to match time of experiment
fps = length/tfinal
tstep = 1/fps
t = numpy.r_[tinitial:tfinal:tstep]
```

Kinematics of Model

Adding kinematics of syste. Adding the body of the link and a particle mass of the tracker to the end of the segment.

In [5]:

```
#Kinematics

#Frames
N = Frame('N',system)
A = Frame('A',system)

system.set_newtonian(N)

A.rotate_fixed_axis(N,[0,0,1],qA,system)

#Vectors
pNA=0*N.x
pAB=pNA+lA*A.x

#Centers of Mass
pAcm=pNA+lA/2*A.x
pMcm=pNA+lA*A.x

#Angular Velocity
wNA = N.get_w_to(A)

#Velocity of Center of Mass
vA=pAcm.time_derivative()

#Interia and Bodys
IA = Dyadic.build(A,Ixx,Iyy,Izz)

BodyA = Body('BodyA',A,pAcm,mA,IA,system)
BodyM = Particle(pMcm,mM,'ParticleM',system) #Mass of blue dot tracker
```

Adding Force

Forces were added to the model. Gravity, Aerodynamic against flat plate, spring force and damping force.

In [6]:

```
#Forces

#Gravity
system.addforcegravity(-g*N.z)

#Aerodynamic Forces
f_aero_A = rho * vA.length()*(vA.dot(A.y))*area*A.y
system.addforce(-f_aero_A,vA)

#Spring Forces
system.add_spring_force1(k, (qA)*N.z, wNA)

#Damping Force
system.addforce(-b*wNA, wNA)
```

Out[6]:

```
<pynamics.force.Force at 0x260b29ca250>
```

Building Model

Solve for the equations of motion and run the opitimization algorithm if run_fit was set to true

In [7]:

```
#Constraints and Plots

f,ma = system.getdynamics();


tol = 1e-12
points = [pNA,pAB]

def run_sim(args):
    constants = dict([(key,value) for key,value in zip(unknown_constants,args)])
    states=pynamics.integration.integrate(func1,ini,t,rtol=tol,atol=tol,hmin=tol, args=
    return states

def calc_error(args):
    states_guess = run_sim(args)
    points_output = PointsOutput(points,system)
    y_guess =  points_output.calc(states_guess,t)
    error = df[:,3] - y_guess[:,1,1]
    error **=2
    error = error.sum()
    return error

pynamics.system.logger.setLevel(logging.ERROR)

if run_fit:

    unknown_constants = [b,k]

    known_constants = list(set(system.constant_values.keys())-set(unknown_constants))
    known_constants = dict([(key,system.constant_values[key]) for key in known_constant

    func1,lambda1 = system.state_space_post_invert(f,ma,return_lambda = True,constants

    guess = [3e-6,2.17e-4]
```

```
    pynamics.system.logger.setLevel(logging.ERROR)

    sol = scipy.optimize.minimize(calc_error,guess)
    print(sol.fun)
    result = sol.x

    error_f = calc_error(result)
```

```
2022-04-12 21:12:24,585 - pynamics.system - INFO - getting dynamic equations
```

Plots of Results

Plotting the results of the simulated tip of the simulation against the experimental tip.

In [16]:

```
if run_fit:
    states2 = run_sim(result)
    points_output2 = PointsOutput(points,system)
    y2 = points_output2.calc(states2,t)

    fig = plt.figure()
    ax1 = plt.subplot(2,1,2)
    ax1.plot(t,states2[:,:1])
    ax1.legend(['qA'])
    ax1.set_title('State Positions')
    ax1.set_xlabel('Time (s)')
    ax1.set_ylabel('Position (mm)')

    ax2 = plt.subplot(2,1,1)
    ax2.plot(t,y2[:,1,1],df[:,1],df[:,3])
    ax2.legend(['pBtip_s' ,'pBtip_a'])
    ax2.set_title('Test vs CMA Tip')
    ax2.set_xlabel('Time (s)')
    ax2.set_ylabel('Position (mm)')

    fig.tight_layout()

    print(result)
    print(error_f)

else:

    func1 = system.state_space_post_invert(f,ma,return_lambda = False)
    states=pynamics.integration.integrate(func1,ini,t,rtol=tol,atol=tol,hmin=tol, args=

    points_output = PointsOutput(points,system)
    y = points_output.calc(states,t)

    fig = plt.figure(figsize=(8, 6), dpi=80)

    ax1 = plt.subplot(3,1,1)
    ax1.plot(t,states[:,:1])
    ax1.legend(['qA'])
    ax1.set_title('State Positions')
    ax1.set_xlabel('Time (s)')
    ax1.set_ylabel('Position (mm)')
    ax1.set_ylim([-1, 1])
```

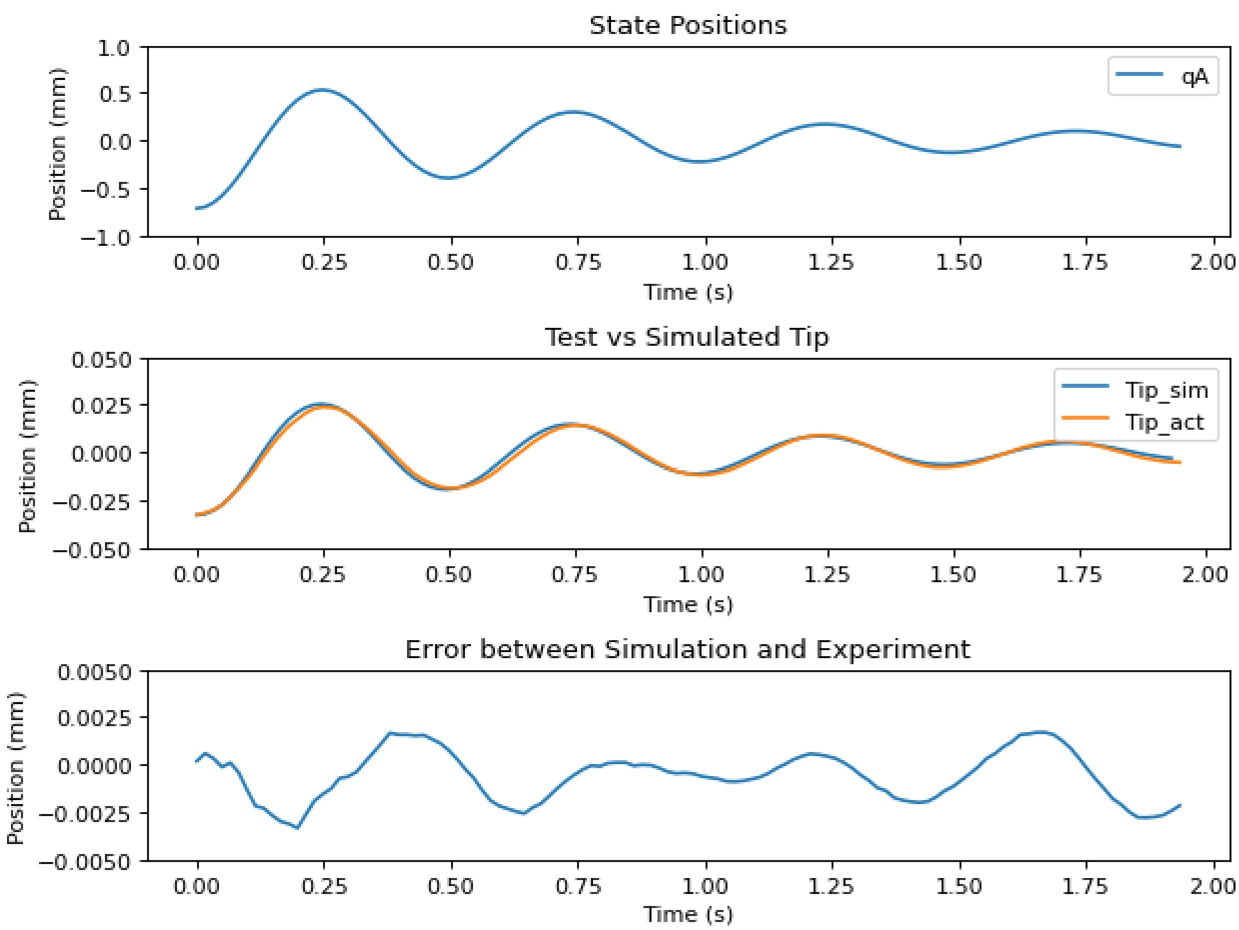
```
ax2 = plt.subplot(3,1,2)
ax2.plot(t,y[:,1,1],df[:,1],df[:,3])
ax2.legend(['Tip_sim' ,'Tip_act'])
ax2.set_title('Test vs Simulated Tip')
ax2.set_xlabel('Time (s)')
ax2.set_ylabel('Position (mm)')
ax2.set_ylim([-.05, 0.05])

ax3 = plt.subplot(3,1,3)
ax3.plot(t,(df[:,3]-y[:,1,1]))
ax3.set_title('Error between Simulation and Experiment')
ax3.set_xlabel('Time (s)')
ax3.set_ylabel('Position (mm)')
ax3.set_ylim([-.005, .005])

fig.tight_layout()

print('Dapming and Spring Constants Respectivly: [2.14176688e-06 1.59953557e-04]')
print('Squared Error from SciPy.Optimize: 0.0002384852610771121')
```

```
2022-04-12 21:20:01,370 - pynamics.integration - INFO - beginning integration
2022-04-12 21:20:01,550 - pynamics.integration - INFO - finished integration
2022-04-12 21:20:01,559 - pynamics.output - INFO - calculating outputs
2022-04-12 21:20:01,561 - pynamics.output - INFO - done calculating outputs
Dapming and Spring Constants Respectivly: [2.14176688e-06 1.59953557e-04]
Squared Error from SciPy.Optimize: 0.0002384852610771121
```



Discussion

1. The main improvement that could have been done on this experiment was to mount and constrain the stationary link better. Since the link was just sandwiched, there was still some room for the link to move which would contribute to not perfect motion of the unconstrained link.

1. The rationale behind the model that I used was to simplify the model as much as possible in order to get the optimization to run as fast as possible. In order to do this, only the unconstrained link was modeled and the joint damping and stiffness was modeled on the first point (pNA) of the link. The spring and damping varibles were based off the triple pendulum model that Dr. Aukes provided. Additionally, a point mass was added to the tip of the link (pAB) to represent the mass of the tracker that was attached to the system. Assumptions that I made were that the damping and spring constant were independent variables, the rigid laminate could be approximated as a flat plate, and that the aerodynamic forces were being generalized and applied to the center of mass instead of the entire length of the beam.

1. The method used for fitting the data was the scipy.optimize.minimize() function. The reason that this method was used was because I was trying to select the correct b and k values to generate closest simulated tip data as the experimental data. Through scipy.optimize.minimize(), the algorithm was an uncosntrained minimzation function based off calculating the error after every iteration. This method was used because I had gotten the k and b values close to the data through guess and check and then optimized the constants based off the hand tuned guesses. For this reason, using an unbounded algorithm is acceptable because i have converged the variables close to the desired result.

1. Summed squarred error is 0.000238 between the simulation and experimental data. The data fits very well. The simulation has some slight overdamping and the spring constant is slight too high. This can ben seen through the fact that the simulation peak is slightly before the experiment at 0.25 seconds and is after the experimental peak at 1.75 seconds. This could be due to not exact point masses or link masses. The slight discrepency is due to the interias of the simulated experiment not being exactly the same as the experimental inertias.

2. The limit of the model is to to the exact marker and segment dimensions used in the experiment. Since the polyester film is very soft, the interias and mass have a very large effect on the system. Therefore in order for the model to fit it requires that all the parameters to match the simulation. If those are the same then the model will match any single link pendulum that has gravity applied in the z direction.