

Rigid-Body Dynamics Project

Rigid-Body Spring Pendulum

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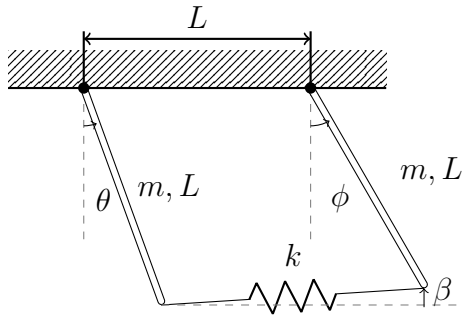
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1 Conceptualize the Problem



The pendulum system consists of two rigid bars rotating about one end, attached at the opposite ends by a linear spring.

1.1 Constants and Assumptions

Constants:		Assumptions:	
Bar Mass:	$m = 0.25\text{kg}$	No Losses	
Bar Length:	$L = 0.5\text{m}$	Released from Rest	
Gravity:	$g = 9.81\text{m/s}^2$	Slender Bars	
Linear Spring:		Planar	
Spring Coefficient:	$k = 25\text{ N/m}$	Rigid-Body Dynamics	
Unstretched Length:	L		

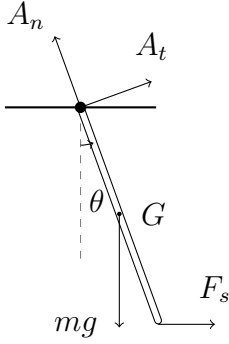
We are asked to determine the following:

1. The 6 Equations / 6 Unknowns for the system to solve for the Equations of Motion.
2. Integrate the Equations of Motion using various initial conditions.
 - (a) $\theta_o = \pi/12\text{ rad}$, $\phi_o = \pi/12\text{ rad}$
 - (b) $\theta_o = -\pi/12\text{ rad}$, $\phi_o = \pi/12\text{ rad}$
 - (c) $\theta_o = \pi/36\text{ rad}$, $\phi_o = \pi/12\text{ rad}$
3. Linearize the Equations of Motion assuming small angular positions and velocities (i.e. small angle approximation $\sin(x) \approx x$, $\cos(x) \approx 1$)
 - Determine the A matrix below.

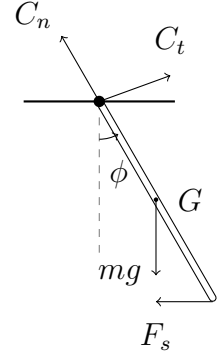
$$\begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} = [A] \begin{bmatrix} \theta \\ \phi \end{bmatrix}$$

4. Find the natural frequencies of the system and their respective eigenvectors using the eigenvalues and eigenvectors of $[A]$.
5. Using information from (5), solve for the analytical solution to the linearized Equations of Motion and plot them for the initial conditions defined in (2).

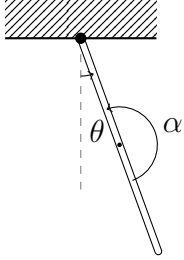
2 Free Body Diagram



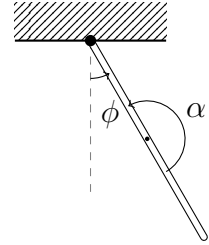
F_s : Force onto bar by the spring
 mg : Mass \cdot gravity, weight of each bar
 G : Center of gravity of each bar
 θ, ϕ : Angle of bar relative to vertical
 A_n, C_n : Reaction forces in the normal direction at pin
 A_t, C_t : Reaction forces in the tangential direction at pin



Acceleration Diagram

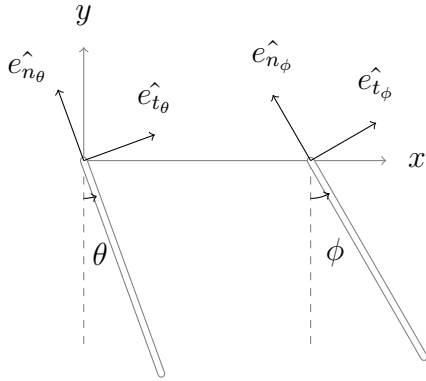


α : $\ddot{\theta}, \ddot{\phi}$ respectively

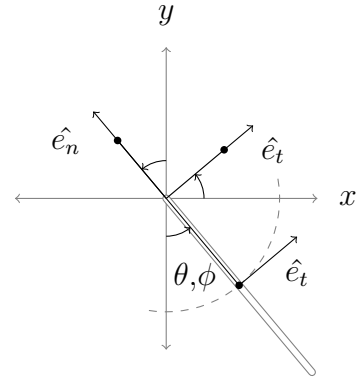


3 Coordinate Frame

(a) Separate Coordinate Frames



(b) Unit Vector Calculations



$$\begin{aligned}
 \hat{e}_n &: [-\sin(\theta)\hat{i} + \cos(\theta)\hat{j}] \\
 \hat{e}_t &: [\cos(\theta)\hat{i} + \sin(\theta)\hat{j}]
 \end{aligned}$$

Figure 1: Visual Representation of Coordinate Frame Unit Vectors

Due to the complexity of the system if it were to be defined in cartesian coordinates, we determined that the motion of the system would most effectively be represented by two separate normal-tangential coordinate frames because the motion of each bar is purely rotational, where the center of mass of each bar is following a curve. As seen in Figure (1a), two coordinate frames were used, one for each bar. Similarly, Figure (1b) shows how the unit vectors are calculated as well as the path the center of mass travels.

4 Sum of Forces

The six equations that represent the forces on the system are comprised of four force summations and two moment equations,

$$\sum F_n = m \frac{L}{2} \dot{\theta}^2 = F_{s_n} + A_n - mg \cos(\theta) \quad (1)$$

Sum of Normal Forces on the left bar (θ)

$$\sum F_t = m \frac{L}{2} \ddot{\theta} = F_{s_n} + A_t - mg \sin(\theta) \quad (2)$$

Sum of Tangential Forces on the left bar (θ)

$$\sum F_n = m \frac{L}{2} \dot{\phi}^2 = F_{s_n} + C_n - mg \cos(\phi) \quad (3)$$

Sum of Normal Forces on the right bar (ϕ)

$$\sum F_t = m \frac{L}{2} \ddot{\phi} = F_{s_n} + C_t - mg \sin(\phi) \quad (4)$$

Sum of Tangential Forces on the right bar (ϕ)

$$\sum M_A = - \left(\frac{L}{2} \cdot mg \sin(\theta) \right) + (F_{st} \cdot L) = \frac{1}{3} mL^2 \ddot{\theta} \quad (5)$$

Sum of Moments about A (θ)

$$\sum M_C = - \left(\frac{L}{2} \cdot mg \sin(\phi) \right) + (F_{st} \cdot L) = \frac{1}{3} mL^2 \ddot{\phi} \quad (6)$$

Sum of Moments about C (ϕ)

Where:

- θ : Position of the left bar.
- ϕ : Position of the right bar.
- $\dot{\theta}$: Angular velocity of the left bar.
- $\dot{\phi}$: Angular velocity of the right bar.
- $\ddot{\theta}$: Angular acceleration of the left bar.
- $\ddot{\phi}$: Angular acceleration of the right bar.
- A : Reaction force in the normal or tangential direction on the left bar.
- C : Reaction force in the normal or tangential direction on the right bar.
- F_s : Force due to the spring in either the normal or tangential direction.
- m, L, g : Mass, length of each bar, and gravity, respectively.

5 Knowns and Unknowns

Knowns:		Unknowns:	
Mass:	$m = 0.25\text{kg}$	Reaction Forces:	A_n, A_t
String Length:	$L = 0.5\text{m}$		C_n, C_t
Gravity:	$g = 9.81\text{m/s}^2$	Angular Accelerations:	$\ddot{\theta}, \ddot{\phi}$
Linear Spring:			
Spring Coefficient:	$k = 25 \text{ N/m}$		
Unstretched Length:	L		
State Variables:			
Angular Position:	θ, ϕ		
Angular Velocity:	$\dot{\theta}, \dot{\phi}$		

Since there are six equations and six unknowns, we can solve for the equations of motion analytically using Matlab.

6 Constraints

No constraint equations were needed to find a solution to the system.

7 Solve for the Equations of Motion

The equations of motion for this system are (from Eqs. (1-6))

$$\ddot{\theta} = -3 \frac{gm \sin \theta - 2kL \cos \theta - 2kL \sin \phi - \theta + \frac{2kL^2 \cos \theta}{\sqrt{L^2(\sin \phi - \sin \theta + 1)^2 + L^2(\cos \phi - \cos \theta)^2}} + \frac{2kL^2 \sin \phi - \theta}{\sqrt{L^2(\sin \phi - \sin \theta)^2 + L^2(\cos \phi - \cos \theta)^2 + L^2(\cos \phi - \cos \theta)^2}}}{2Lm}$$

$$\ddot{\phi} = -3 \frac{gm \sin \phi - 2kL \cos \phi - 2kL \sin \theta - \phi + \frac{2kL^2 \cos \phi}{\sqrt{L^2(\sin \phi - \sin \theta + 1)^2 + L^2(\cos \phi - \cos \theta)^2}} + \frac{2kL^2 \sin \phi - \theta}{\sqrt{L^2(\sin \phi - \sin \theta)^2 + L^2(\cos \phi - \cos \theta)^2 + L^2(\cos \phi - \cos \theta)^2}}}{2Lm}$$

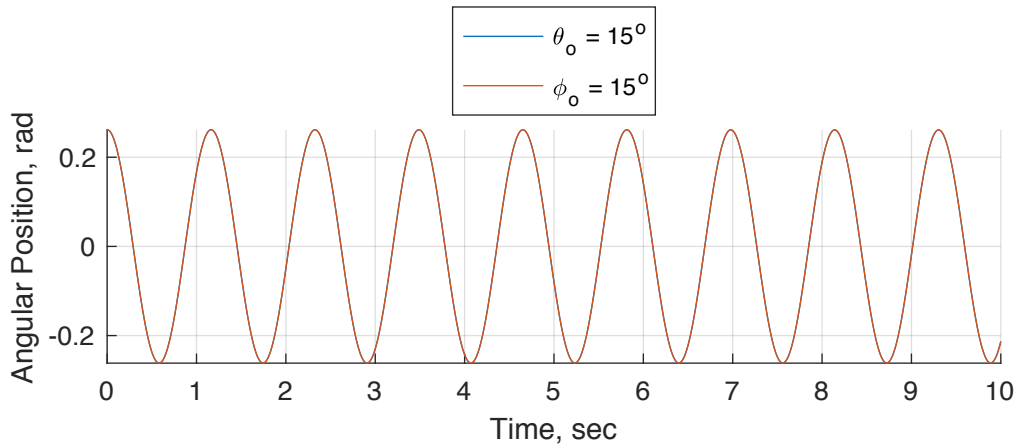


Figure 2: Angular Position vs. Time ($\theta_o : 15^\circ$, $\phi_o : 15^\circ$)

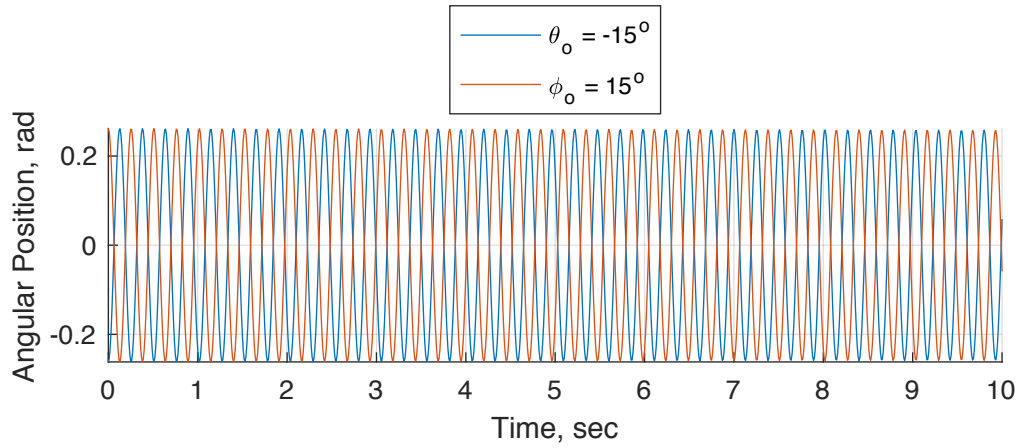


Figure 3: Angular Position vs. Time ($\theta_o : -15^\circ$, $\phi_o : 15^\circ$)

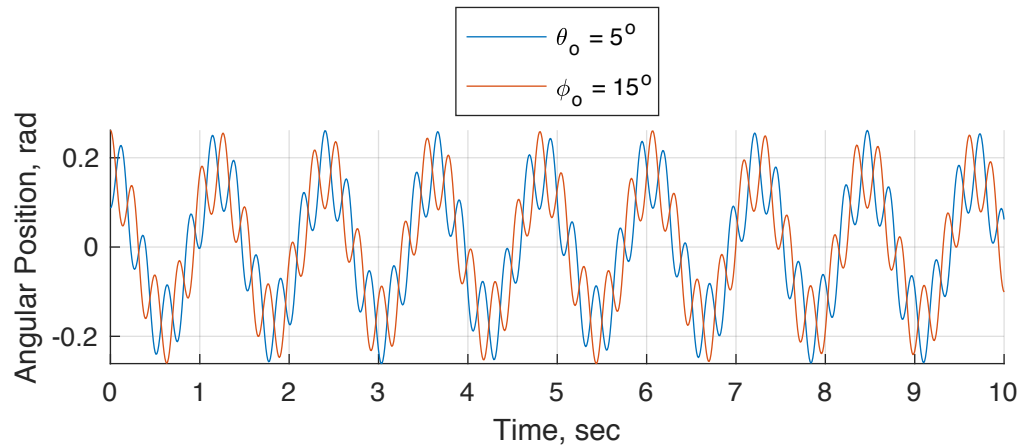


Figure 4: Angular Position vs. Time ($\theta_o : 5^\circ$, $\phi_o : 15^\circ$)

8 Solve the Equations of Motion

9 Does it Make Sense?

9.1 Units

Checking with the MATLAB symbolic units tool (from Section 10.3):

```

1 % Checking EOM Units
2 u = symunit;
3 m = m*u.kg;
4 g = g*u.m/u.s^2;
5 l = l*u.m;
6 k = k*u.N/u.m;
7 An = An*u.N;
8 At = At*u.N;
9 Cn = Cn*u.N;
10 Ct = Ct*u.N;
11 theta = 'theta';

```

```

12 thetadot = 'thetadot'/u.s;
13 thetaddot = 'thetaddot'/u.s^2;
14 phi = 'phi';
15 phidot = 'phidot'/u.s;
16 phiddot = 'phiddot'/u.s^2;
17
18 eqn = subs(eqn);
19 unitCheck = checkUnits(eqn)

```

```

unitCheck =
    struct with fields:

        Consistent: [1 1 1 1 1 1]
        Compatible: [1 1 1 1 1 1]

```

9.2 Magnitude

Looking at Figure (2), the amplitude and period of both ϕ and θ perfectly overlap with each other. This is expected due to the fact that two pendulums that begin oscillating when released from the same state will never have a change in their relative positions. This means that the spring connecting the two is neither stretched nor compressed throughout the system's oscillations. This is valid because the amplitude and period of oscillation never changes in this lossless system.

Looking at the generic linearization equation,

$$[m] \begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} + [k] \begin{bmatrix} \theta \\ \phi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

We can see that the solution to the system when $\theta_0 = \phi_0$ will be of the form,

$$-\omega^2 [m] \begin{bmatrix} \theta \\ \phi \end{bmatrix} \cos(\omega t + \Psi)$$

instead of the form,

$$-\omega^2 [m] \begin{bmatrix} \theta \\ \phi \end{bmatrix} \cos(\omega t + \Psi) + [k] \begin{bmatrix} \theta \\ \phi \end{bmatrix} \cos(\omega t + \Psi)$$

The fact that the equation takes the former's form supports our idea that this behavior makes physical sense when $\theta_0 = \phi_0$. For initial conditions where $\theta_0 \neq \phi_0$ or $\dot{\theta}_0 \neq \dot{\phi}_0$ we find a non-zero $[k]$, which lines up with the physical concept that the bars will inconsistently oscillate.

Lastly, in the special case where $\theta_0 = -\phi_0$, we can see a consistent oscillation in both variables where they remain equal and opposite to each other. Once again, envisioning this system will show that this behavior is aligned with what we would expect from a physical system with these initial conditions and without losses. The behavior is plotted in Figure (3).

10 Appendix

10.1 Attributions

Jeffrey Chen

Thorne Wolfenbarger Is just really really cool

Trey Dufrene

Joint Effort MATLAB Coding, Solving EOM's

10.2 Analytical Solution

10.3 Numerical Solution

Non-Linearized

```
1 clear;close all;clc
2
3 % Constants
4 c.m = 0.25; % kg
5 c.k = 25; % N/m
6 c.l = 0.5; % m
7 c.I = (1/3)*c.m*c.l^2; %kg.m^2
8 c.g = 9.81; % m/s^2
9
10 syms l g m k I theta phi thetadot thetaddot phidot phiddot...
11      An At Cn Ct
12
13 % Cartesian locations of bar ends
14 b = l*[sin(theta);-cos(theta)];
15 d = l*[sin(phi)+1;-cos(phi)];
16 rbd = d - b;
17 rbdSquared = rbd.^2;
18 % Spring Length (mag)
19 ls = simplify(rbdSquared(1) + rbdSquared(2))^(1/2);
20 % Spring Direction (Left and Right)
21 ehatsL = (d - b) / ls;
22 ehatsR = (b - d) / ls;
23 % Normal / Tangential for Theta
24 ehatnT = [-sin(theta);cos(theta)];
25 ehattT = [cos(theta);sin(theta)];
26 % Normal / Tangential for Phi
27 ehatnP = [-sin(phi);cos(phi)];
28 ehattP = [cos(phi);sin(phi)];
29 % Spring Force (Left and Right)
30 FsL = k*(ls-l)*ehatsL;
31 FsR = k*(ls-l)*ehatsR;
32
33 % Spring force in normal direction (Theta)
34 Fs_nT = simplify(FsL(1)*ehatnT(1)+FsL(2)*ehatnT(2));
35 % Spring force in tangential direction (Theta)
36 Fs_tT = simplify(FsL(1)*ehattT(1)+FsL(2)*ehattT(2));
37
38 % Spring force in normal direction (Phi)
39 Fs_nP = simplify(FsR(1)*ehatnP(1)+FsR(2)*ehatnP(2));
40 % Spring force in tangential direction (Phi)
41 Fs_tP = simplify(FsR(1)*ehattP(1)+FsR(2)*ehattP(2));
42
43 % Sum of Normal Forces, left bar (Theta)
44 eqn(1) = m*(1/2)*thetadot^2 == Fs_nT + An - m*g*cos(theta);
45 % Sum of Tangential Forces, left bar (Theta)
```

```

46 eqn(2) = m*(1/2)*thetaddot == Fs_tT + At - m*g*sin(theta);
47 % Sum of Moments, left bar (Theta)
48 eqn(3) = -(1/2)*(m*g*sin(theta)) + (Fs_tT)*(1) == (1/3)*m*(1
    ^2)*thetaddot;
49
50 % Sum of Normal Forces, right bar (Phi)
51 eqn(4) = m*(1/2)*phidot^2 == Fs_nP + Cn - m*g*cos(phi);
52 % Sum of Tangential Forces, right bar (Phi)
53 eqn(5) = m*(1/2)*phiddot == Fs_tP + Ct - m*g*sin(phi);
54 % Sum of Moments, right bar (Phi)
55 eqn(6) = -(1/2)*(m*g*sin(phi)) + (Fs_tP)*(1) == (1/3)*m*(1^2)
    *phiddot;
56
57 x = solve(eqn,[thetaddot,phiddot,An,At,Cn,Ct]);
58
59 syms theta(t) thetadot(t) phi(t) phidot(t)
60
61 thetaEOM = subs(x.thetaddot, {'theta', 'thetadot'}, {theta,
    thetadot});
62 phiEOM = subs(x.phiddot, {'phi', 'phidot'}, {phi, phidot});
63
64 eom = odeFunction([thetadot; thetaEOM; phidot; phiEOM],...
65     [theta; thetadot; phi; phidot],m,k,l,I,g);
66
67 theta_o = [pi/12 -pi/12 pi/36];
68
69 for i = 1:3
70     [T,S] = ode45(@(t,s)eom(t,s,c.m,c.k,c.l,c.I,c.g),linspace
        (0,10,1001),...
71         [theta_o(i),0,pi/12,0]);
72     figure
73     hold on
74     grid on
75     xlabel('Time, sec')
76     ylabel('Angular Position, rad')
77     plot(T,S(:,1),'DisplayName', ['\theta_o = ' num2str(
        rad2deg(theta_o(i))) '^o'])
78     plot(T,S(:,3),'DisplayName', '\phi_o = 15^o')
79     legend('show')
80 end
81
82 % Checking EOM Units
83 u = symunit;
84 m = m*u.kg;
85 g = g*u.m/u.s^2;
86 l = l*u.m;
87 k = k*u.N/u.m;
88 An = An*u.N;

```

```

89 At = At*u.N;
90 Cn = Cn*u.N;
91 Ct = Ct*u.N;
92 theta = 'theta';
93 thetadot = 'thetadot'/u.s;
94 thetaddot = 'thetaddot'/u.s^2;
95 phi = 'phi';
96 phidot = 'phidot'/u.s;
97 phiddot = 'phiddot'/u.s^2;
98
99 eqn = subs(eqn);
100 unitCheck = checkUnits(eqn)

```

```

unitCheck =
    struct with fields:

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    Consistent: [1 1 1 1 1 1]
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```

