

Rigid-Body Dynamics Project

Rigid-Body Spring Pendulum

November 15, 2018

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Submitted to:
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In Partial Fulfillment of the Requirements of
ES204 Dynamics - Fall 2018



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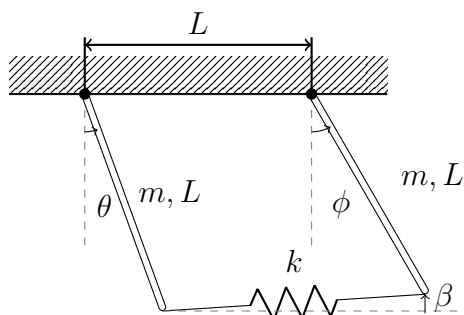
Contents

1	Conceptualize the Problem	1
	1.1 Constants and Assumptions	1
2	Free Body Diagram	2
3	Coordinate Frame	2
4	Sum of Forces	3
5	Knowns and Unknowns	4
6	Constraints	4
7	Solve for the Equations of Motion	4
8	Solve the Equations of Motion	5
9	Does it Make Sense?	5
	9.1 Units	5
	9.2 Magnitude	5
10	Appendix	5
	10.1 Attributions	5
	10.2 Analytical Solution	6
	10.3 Numerical Solution	7
	Non-Linearized	7

List of Figures

1	Visual Representation of Coordinate Frame Unit Vectors	2
2	Meow.	4
3	Meow.	5
4	Meow.	5

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		

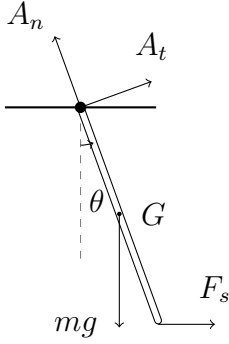
We are asked to determine the following:

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.

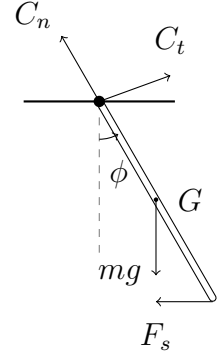
$$\begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} = [A] \begin{bmatrix} \theta \\ \phi \end{bmatrix}$$

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).

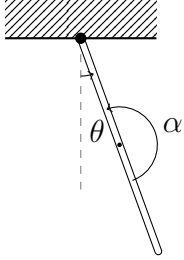
2 Free Body Diagram



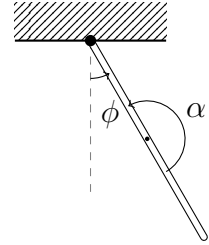
F_s : Force onto bar by the spring
 mg : Mass \cdot gravity, weight of each bar
 G : Center of gravity of each bar
 θ, ϕ : Angle of bar relative to vertical
 A_n, C_n : Reaction forces in the normal direction at pin
 A_t, C_t : Reaction forces in the tangential direction at pin



Acceleration Diagram

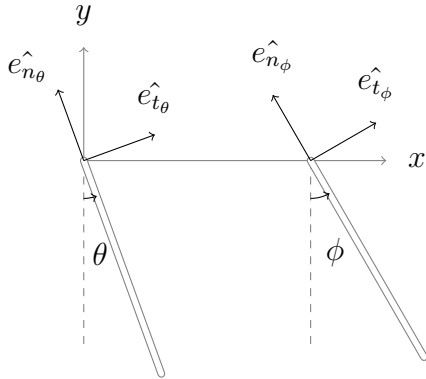


α : $\ddot{\theta}, \ddot{\phi}$ respectively

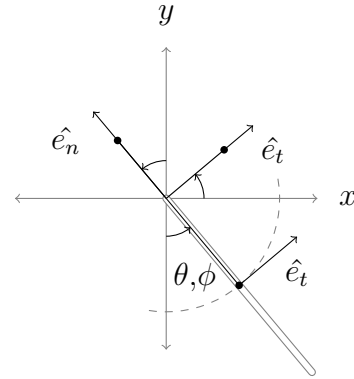


3 Coordinate Frame

(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))

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

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

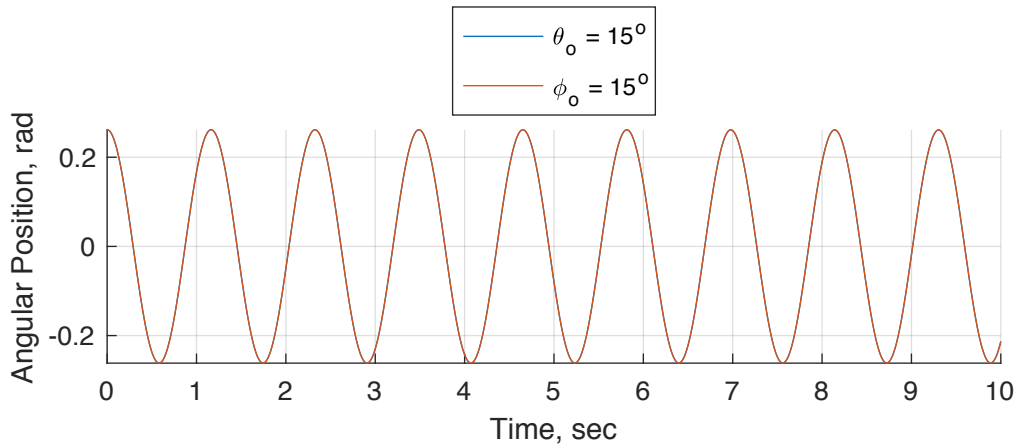


Figure 2: Meow.

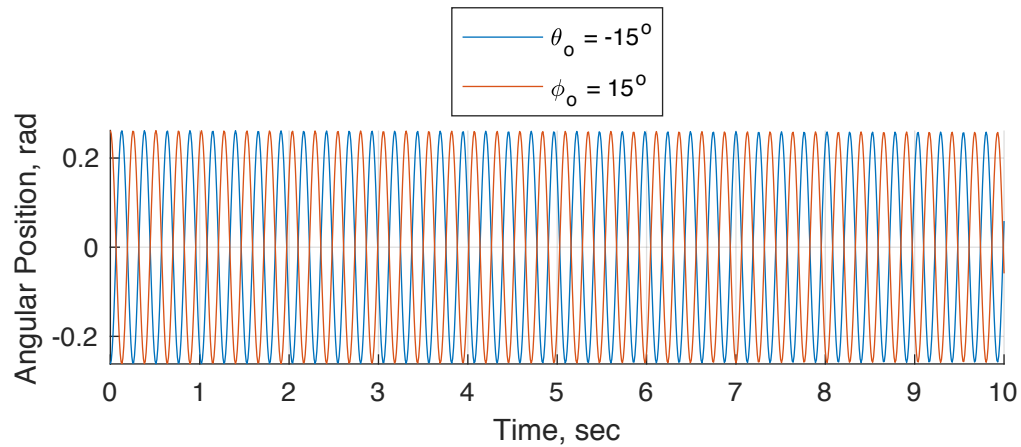


Figure 3: Meow.

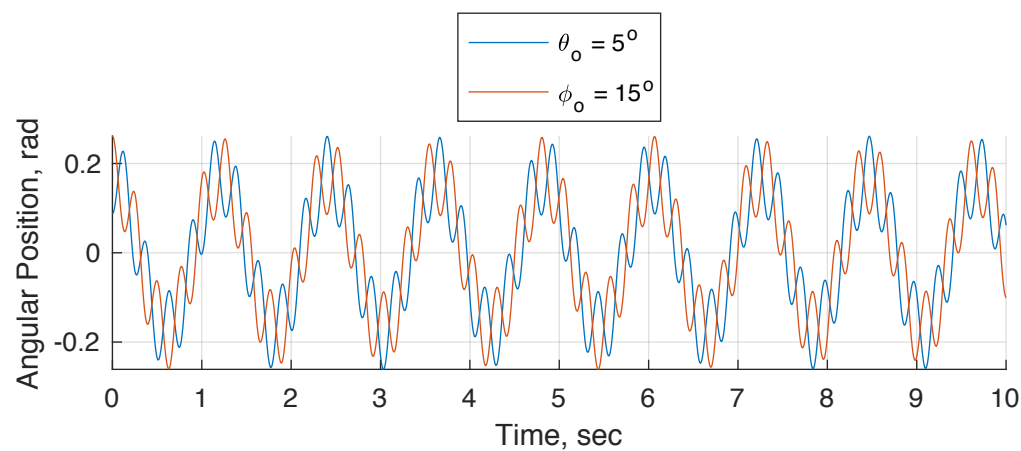


Figure 4: Meow.

8 Solve the Equations of Motion

9 Does it Make Sense?

9.1 Units

9.2 Magnitude

10 Appendix

10.1 Attributions

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Joint Effort

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:

```

```

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

```

