6-BAR SUSPENSION DESIGN REPORT

Introduction

The following report outlines the analysis of a 6-bar suspension meant for off road vehicles. The analysis of the linkage was made on a scaled down model which is 8 times less than the realistic model.

Phase 1:

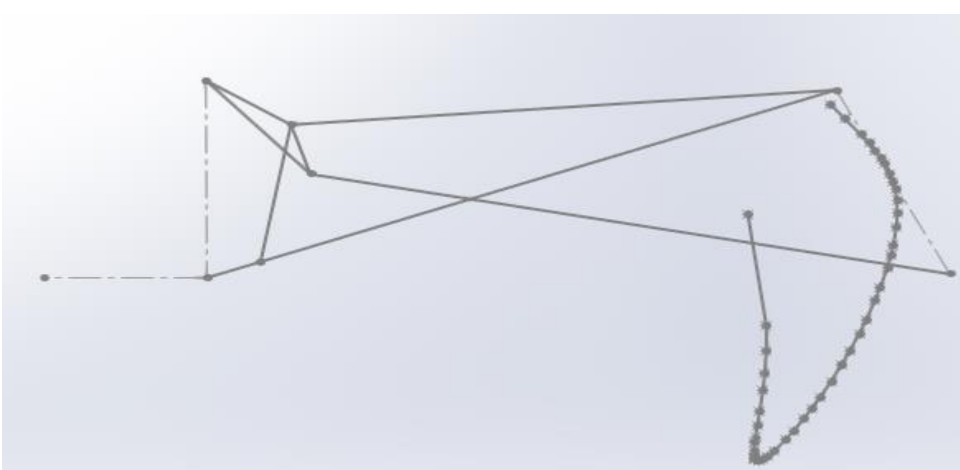
The aim and purpose of the suspension linkage is to obtain an approximately straight path; the reason that lies behind the suspension semi straight path is to be able to compensate to displacements under rotation, and in addition, the path of the displacement of the tire is limited (i.e. it represents around 10 to 20 percent of the total crank input rotation)

A. The linkage starts at the natural position has a higher range above the natural point of 25 mm, and with crank input increasing its return to its initial position in a semi straight motion while ensuring that the output angle of the coupler with the ground does not exceed 20 degrees. The linkage will need to change directions at the base of its output range so the output position 25 mm below the lower ground will have a velocity of 0 mm/s and a as low an acceleration and jerk as possible leading into this point.

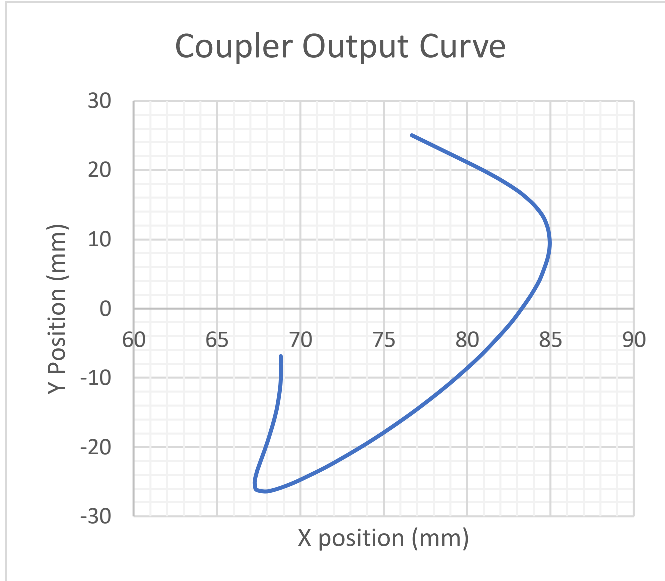
Therefore, the design aim is to obtain:

- Semi straight path
- Transmission angle below 20 degrees
- Zero velocity at the extremes of the path required
- Low acceleration and jerk at the endpoint boundaries

The output path of the linkage is shown on the diagram of the linkage below.



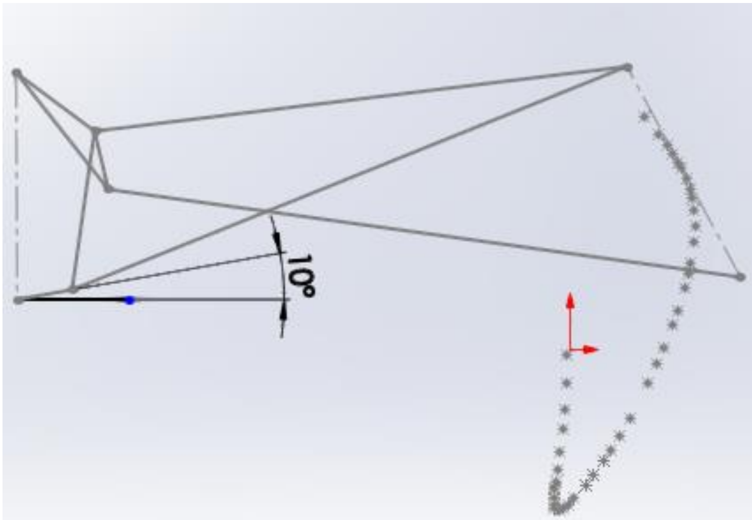
B. The midpoint of the coupler has a total range of motion from -5° to 210° and has a vertical displacement range from -26 mm to 25 mm (totaling 51mm) and a horizontal range of displacement from 67mm to 85 mm (totaling 18 mm).

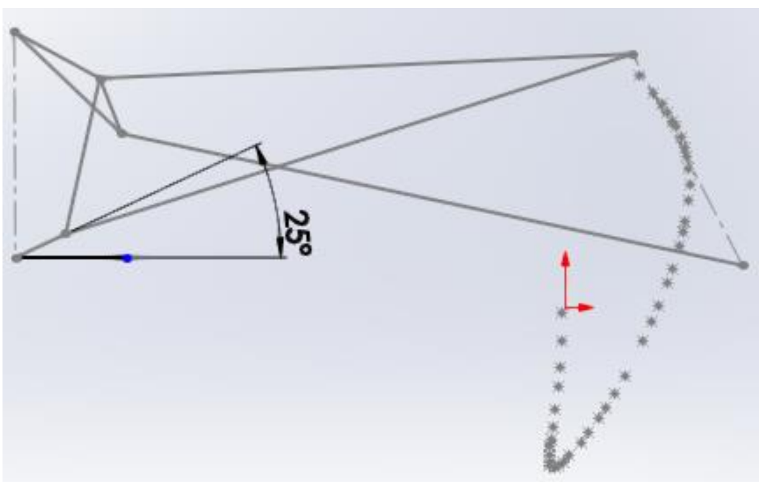


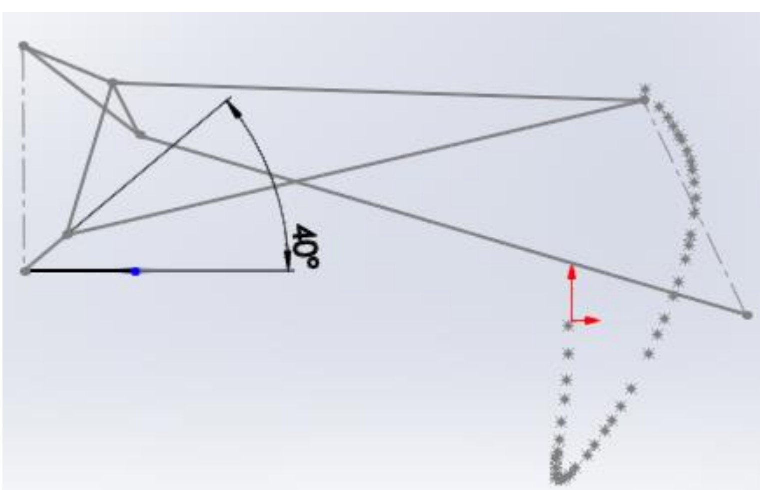
input angle	*x/mm*	*y/mm*	*trans angle/degree*
-5	76.69	25.04	57.63
0	78.56	22.84	56.29
5	80.42	20.65	55.03
10	81.44	19.37	53.82
15	82.23	18.28	52.68
20	82.95	17.17	51.59
25	83.37	16.41	50.58
30	83.98	15.09	49.63
35	84.43	13.78	48.75
40	84.68	12.73	47.94
45	84.89	11.17	47.21
50	84.96	9.25	46.55
55	84.83	7.25	45.97
60	84.44	4.6	45.47

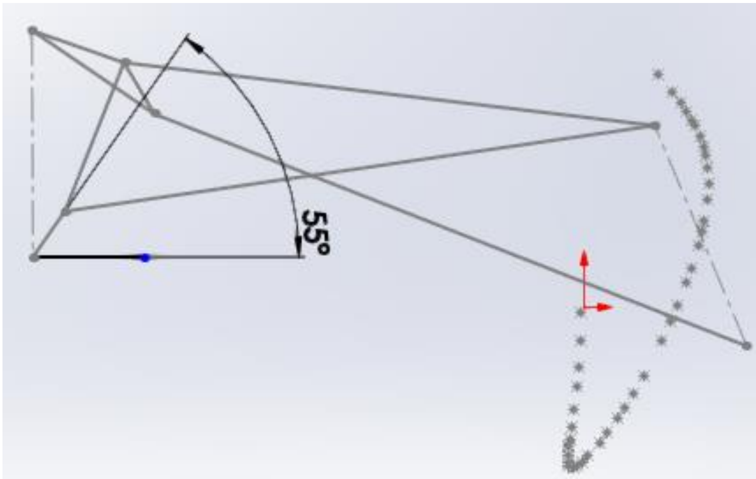
65	84.14	3.16	45.04
70	83.68	1.37	44.7
75	82.84	-1.44	44.43
80	82.19	-3.3	44.23
85	81.11	-6.08	44.12
90	80.28	-8.01	44.08
95	79.11	-10.5	44.11
100	78.06	-12.57	44.22
105	76.78	-14.92	44.41
110	75.48	-17.13	44.67
115	74.39	-18.86	45.01
120	73.44	-20.28	45.43
125	72.2	-22.02	45.92
130	71.24	-23.27	46.5
135	69.83	-24.91	47.15
140	69.05	-25.68	47.87
145	68.39	-26.2	48.68
150	67.91	-26.41	49.55
155	67.42	-26.22	50.49
160	67.3	-25.88	51.51
165	67.27	-24.9	52.58
170	67.38	-23.72	53.72
175	67.5	-22.83	54.92
180	67.73	-21.3	56.18
185	68.04	-19.18	57.51
190	68.41	-16.24	58.92
195	68.64	-13.84	60.41
200	68.82	-10.6	62.06
205	68.83	-6.86	64.04

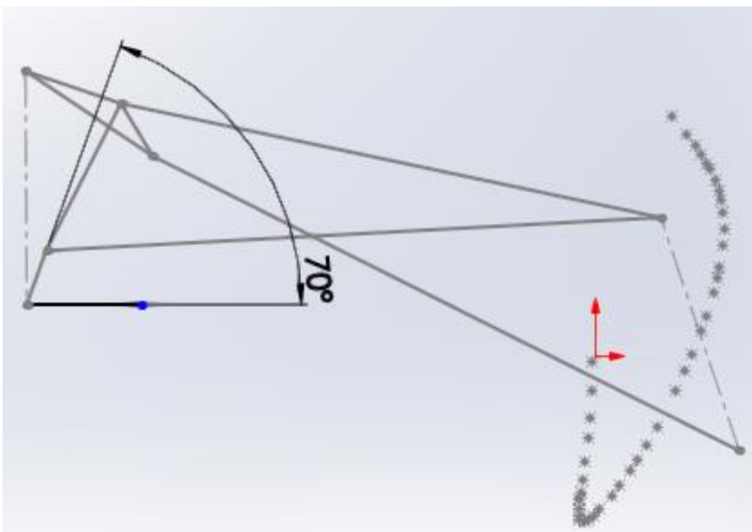
C. Range of Motion in 15° increments of crank input

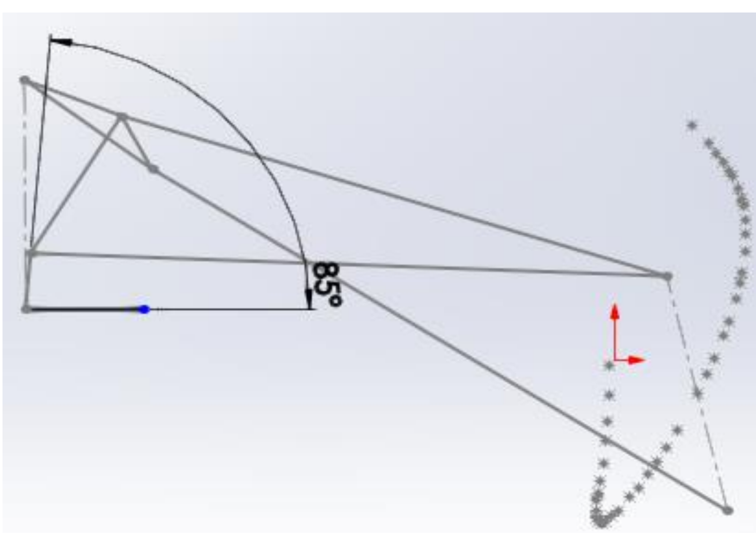


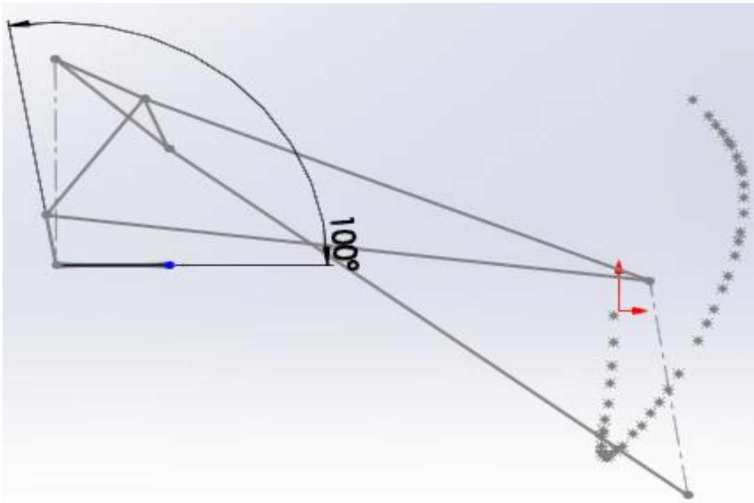


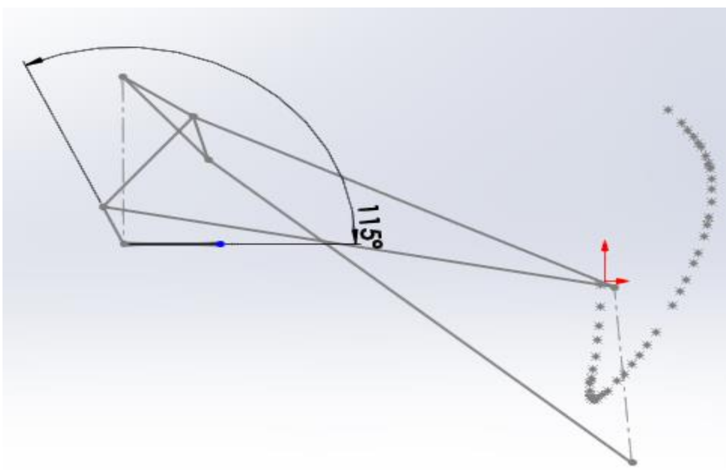


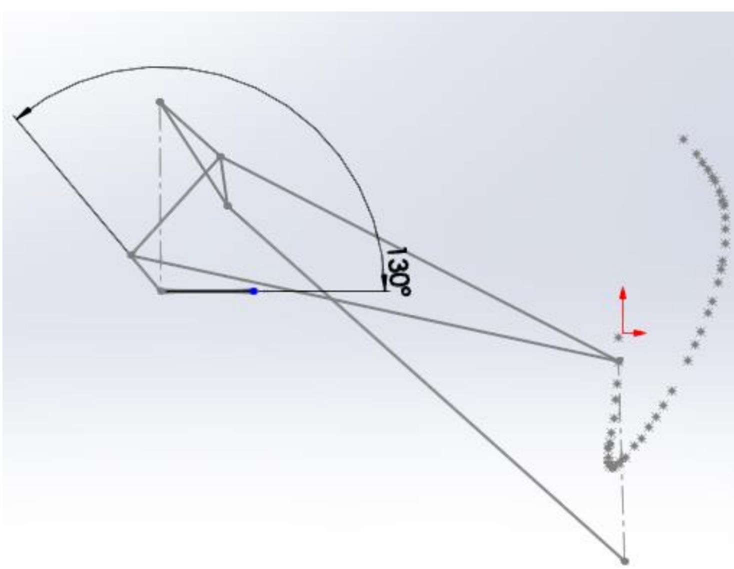

55°

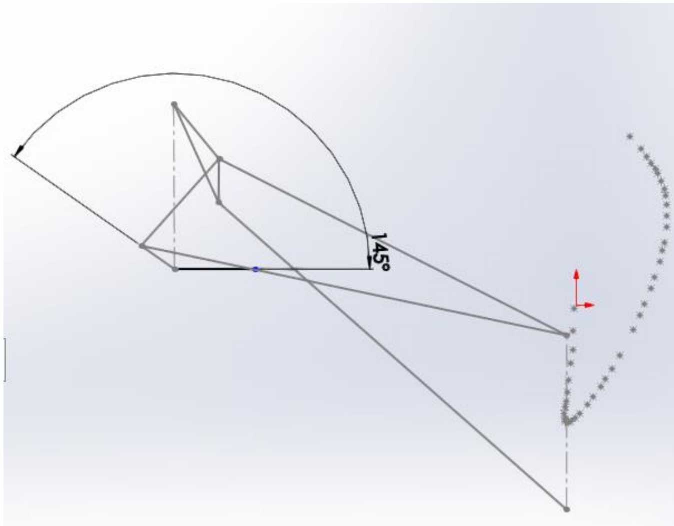

70°

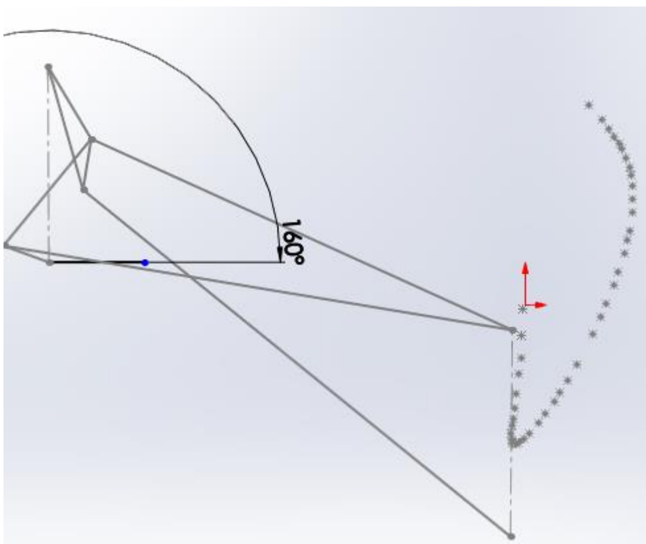

85°

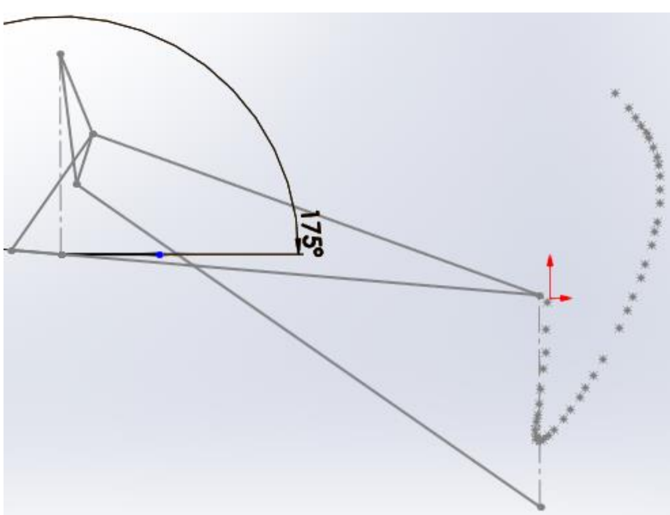

100°

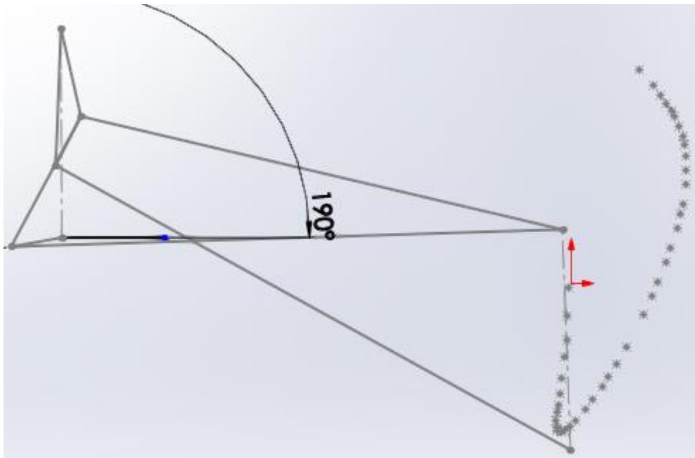

115°

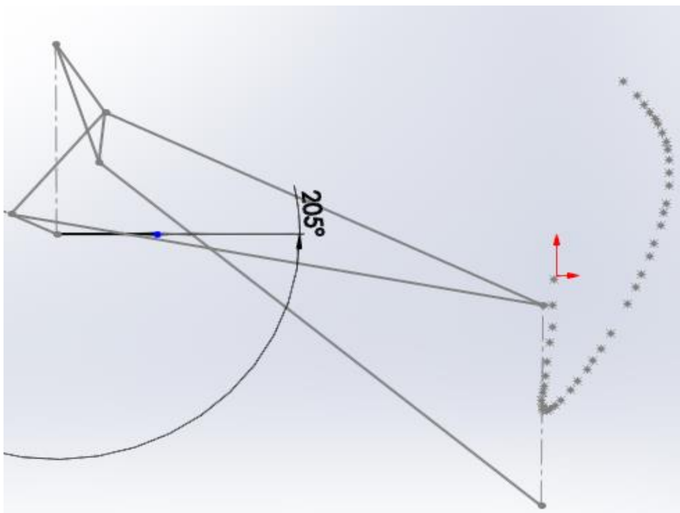

130°


145°

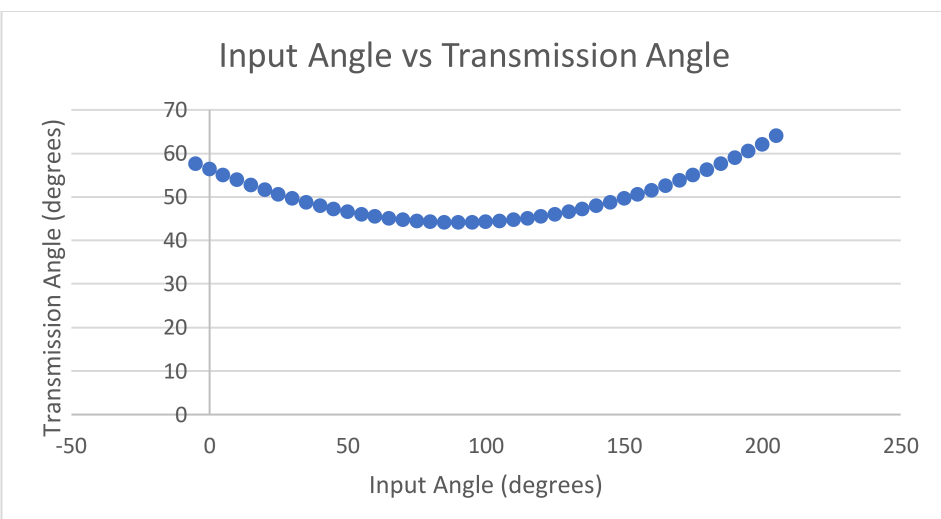

160°


175°





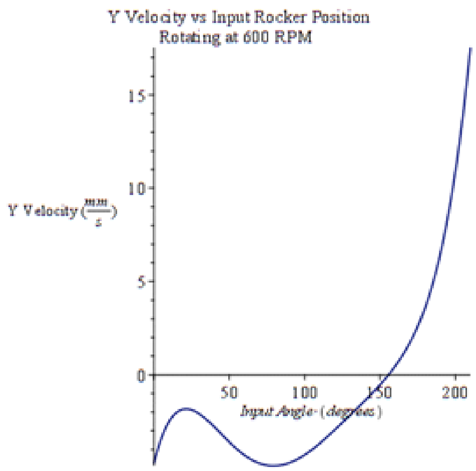
This initial linkage has a single circuit, as such it crossed over configuration, which it cannot be observed without disassembling the linkage.

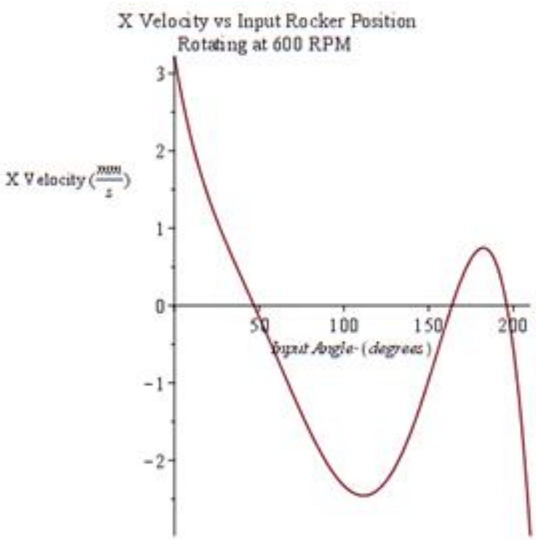


As we can notice above the transmission angle is not exceeding a difference of 20 degrees that results in NO toggle points that will enhance the durability and performance.

D. For the modelled suspension linkage, a speed of 1 radian/second was selected as the operating speed of the crank. This is a realistic value that was chosen by comparison to the movement of a real long-throw suspension mounted on a travelling vehicle as it maneuvers through a bump as the contact period between the tire and the bump occurs for a short period of time. As such, a peak speed, at the top of the range of motion of 15mm/s seemed.

<u>Velocity Analysis</u>



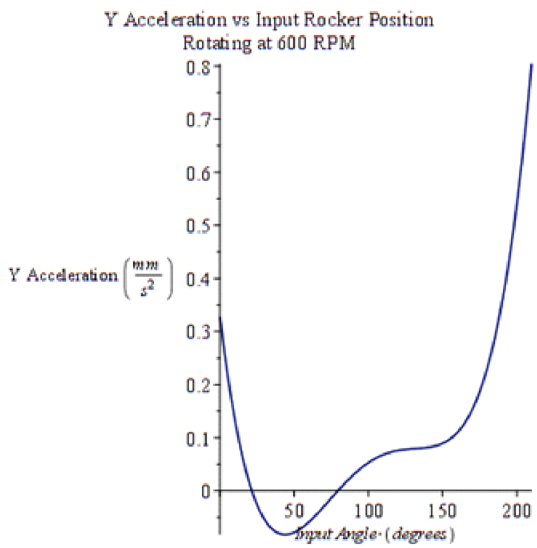


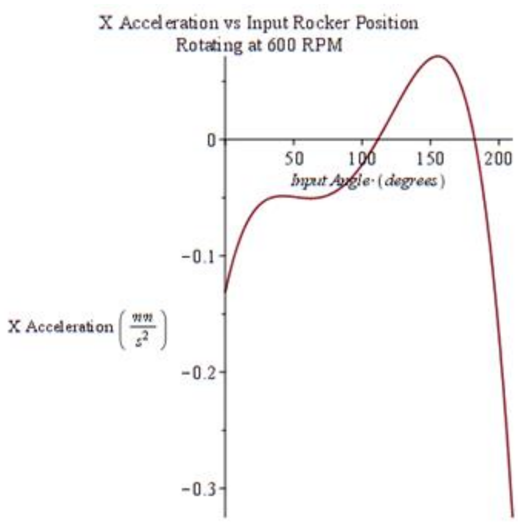
The velocity of the coupler in the x direction reaches 0 when the input angle is approximately 150 degrees and the velocity in the y direction reaches 0 when the input angle is approximately 165 degrees. These positions correspond to the midpoint of the coupler changing directions in both x and y. These positions both occur at the extreme points.

Input Angle	**X Velocity (mm/s)**	**Y Velocity (mm/s)**
0	3.885182	-6.24728
5	3.240283	-5.05716
10	2.69596	-4.27809
15	2.227947	-3.84035
20	1.815833	-3.68052
25	1.442798	-3.74118
30	1.095362	-3.97065
35	0.763125	-4.32276
40	0.438512	-4.75651
45	0.116517	-5.23588
50	-0.20556	-5.72949
55	-0.52835	-6.2104
60	-0.8507	-6.6558
65	-1.16992	-7.04676
70	-1.48201	-7.36794
75	-1.78197	-7.60737
80	-2.06401	-7.75613
85	-2.32183	-7.8081
90	-2.54887	-7.75973
95	-2.73858	-7.60971
100	-2.88463	-7.35874
105	-2.98125	-7.00928
110	-3.0234	-6.56522

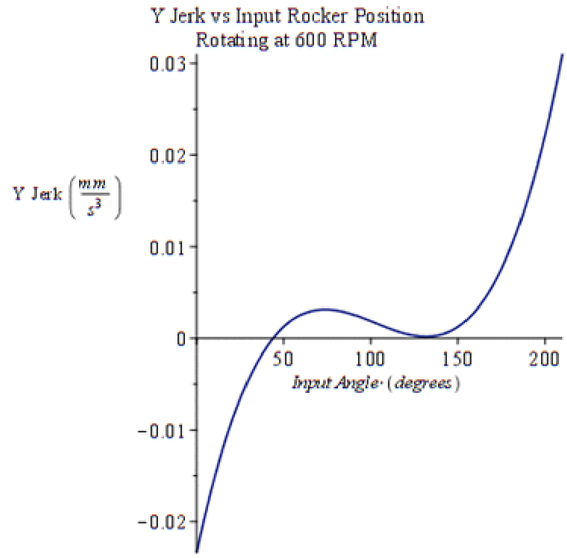
115	-3.00709	-6.03169
120	-2.92957	-5.41473
125	-2.78969	-4.72106
130	-2.58803	-3.9578
135	-2.32726	-3.13219
140	-2.01236	-2.25134
145	-1.65084	-1.32198
150	-1.25306	-0.35014
155	-0.83246	0.659058
160	-0.40578	1.701721
165	0.006613	2.775409
170	0.380524	3.879427
175	0.68765	5.015083
180	0.89533	6.185957
185	0.966284	7.398171
190	0.858362	8.660652
195	0.52428	9.985401
200	-0.08863	11.38776
205	-1.03868	12.88669

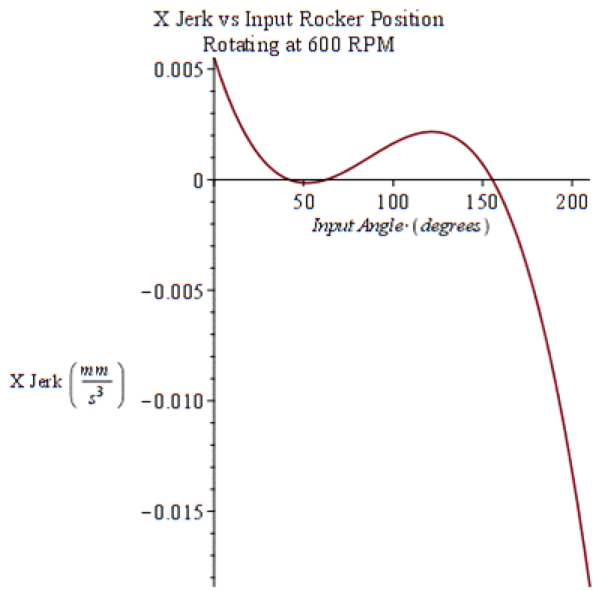
E. The acceleration analysis shows how much force is required to move the linkage through its range of motion based on Newton's second law. The acceleration plot shows the acceleration increasing as the linkage reaches its terminal points at either extreme. Despite the linkage reaching a maximum speed of 15 mm/s, the acceleration remained low at 0.8mm/s^2 and 0.3 mm/s^2 in the x and y directions.





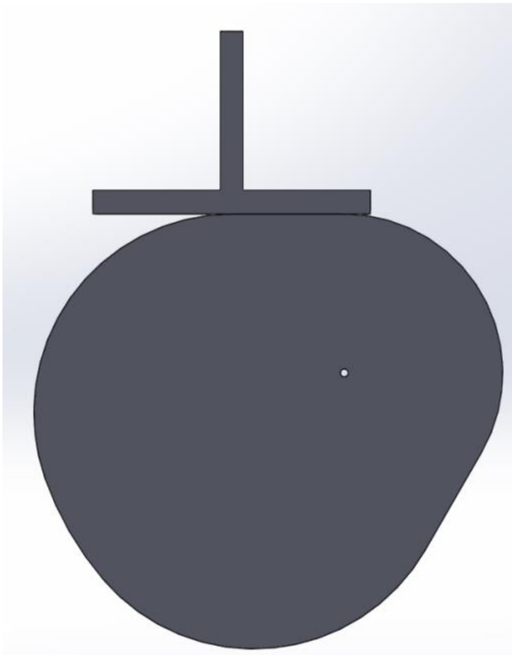
F. The jerk analysis shows the rate of change of acceleration. Jerk is also proportional to the rate of change of the output force and should be as low as possible to ensure smooth operation of the suspension and prevent damage due to the impact of components within the mechanism.



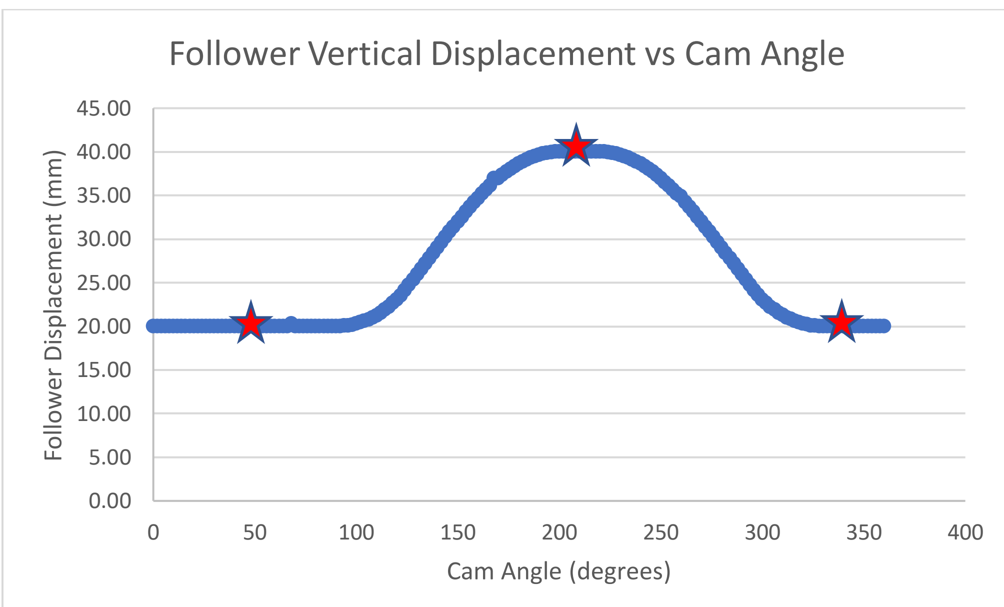


Phase 2

A. Design a cam and follower that will mimic your linkage output. The cam and follower can be of any type (roller, mushroom, flat plate) and any joint type (force or form closed).



B. Illustrate the shape of the cam clearly and give the polar coordinates of the cam surface in an Excel table. Show the cam-follower mechanism in the configurations that make the output match the three precision points from Phase 1.



The cam was designed to travel from a low-level dwell (20 mm above the starting position), to high-level dwell (40 mm above the starting position), back to the same-low level dwell in a continuous cycle.

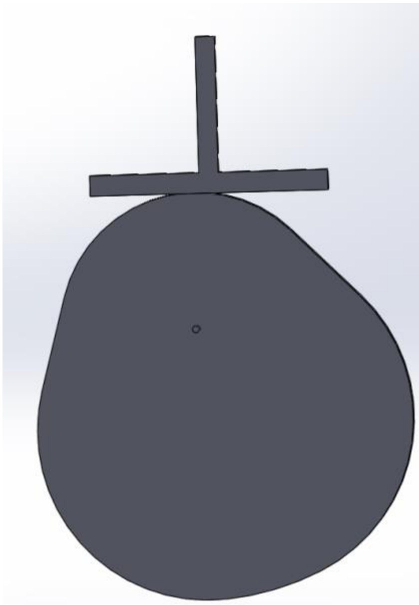


Figure 1: Low-Level Dwell Configuration

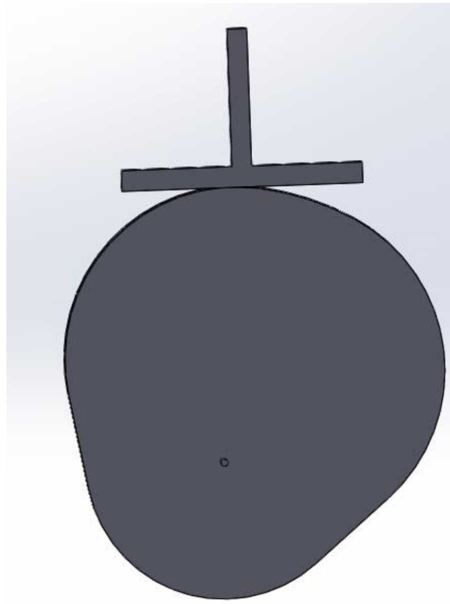
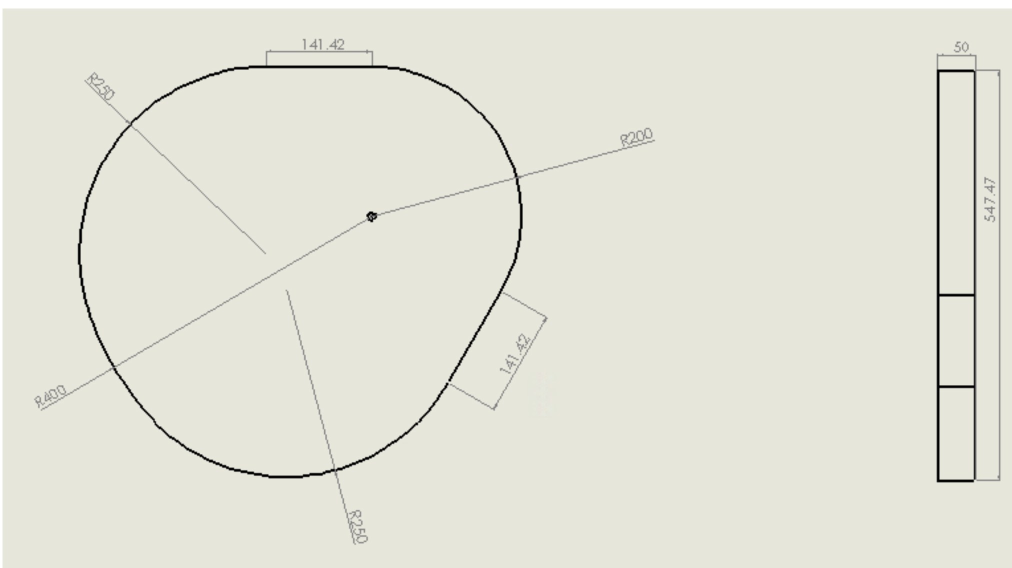


Figure 2: High-Level Dwell Configuration



C. Decide on a cam rotation speed and calculate the SVAJ curves for your cam and follower mechanism

A rotation speed of 100 degrees per second was selected based on observing the response of the velocity curve and selecting a speed that will result in a speed that would emulate the suspension being simulated hitting a large bump and reacting at realistic speeds. Scans of the Maple worksheet used to derive the SVAJ curves can be found on the next page.

$$f(x) := \frac{2500}{25 \cdot \mathrm{sqrt}(2 \cdot 3.141592)} \exp\left(-\frac{(x-200)^2}{2 \cdot 25^2}\right)$$

$$f := x \mapsto \frac{100\, e^{-\frac{(x-200)^2}{1250}}}{\sqrt{6.283184}} \qquad (1)$$

$$g(x) := \frac{2500}{25 \cdot \mathrm{sqrt}(2 \cdot 3.141592)} \exp\left(-\frac{(x-220)^2}{2 \cdot 25^2}\right)$$

$$g := x \mapsto \frac{100\, e^{-\frac{(x-220)^2}{1250}}}{\sqrt{6.283184}} \qquad (2)$$

$k(x) := 39.89$

$$k := x \mapsto 39.89 \qquad (3)$$

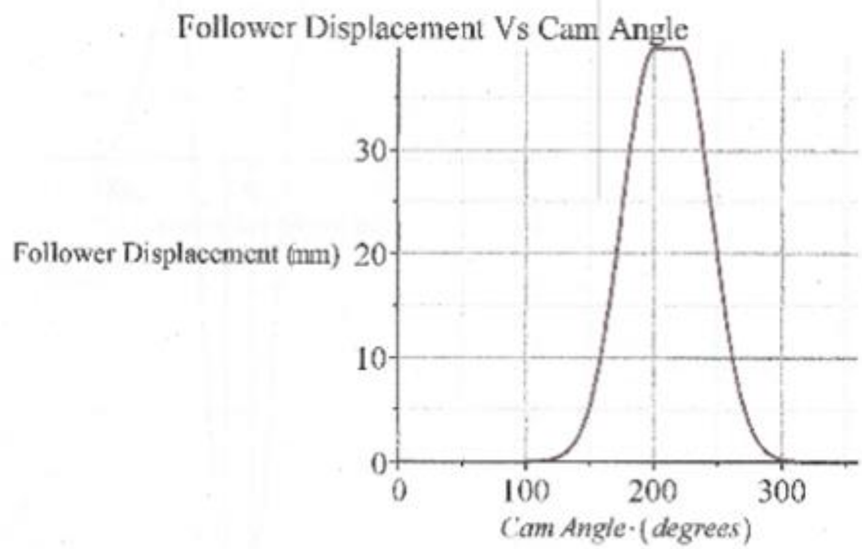
$w := 100$

$$w := 100 \qquad (4)$$

$s(x) := piecewise(x \leq 200, f(x), 200 < x < 220, k(x), x \geq 200, g(x))$

$$s := x \mapsto \begin{cases} f(x) & x \leq 200 \\ k(x) & 200 < x < 220 \\ g(x) & 200 \leq x \end{cases} \qquad (5)$$

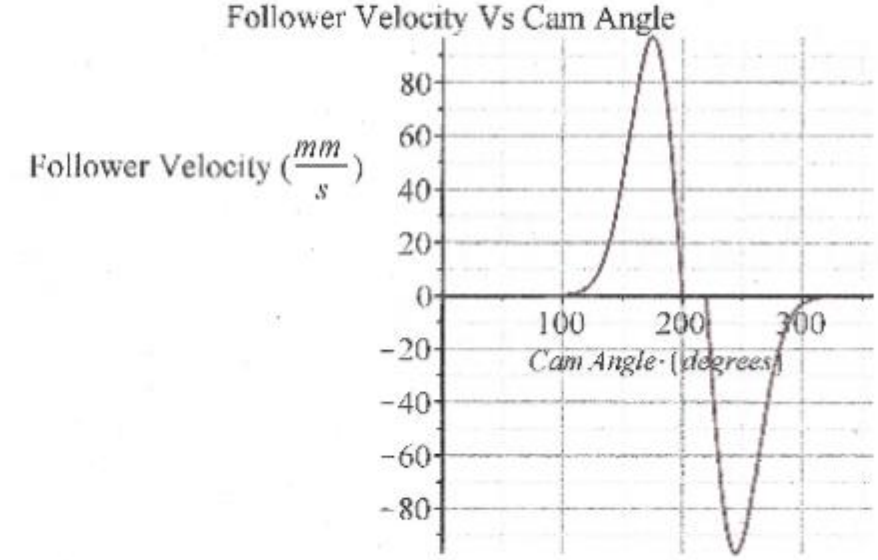
$plot(s(x), x = 0..360)$



$v(x) := w \cdot diff(s(x), x)$

$$v := x \mapsto w \left(\frac{d}{dx} s(x)\right) \qquad (6)$$

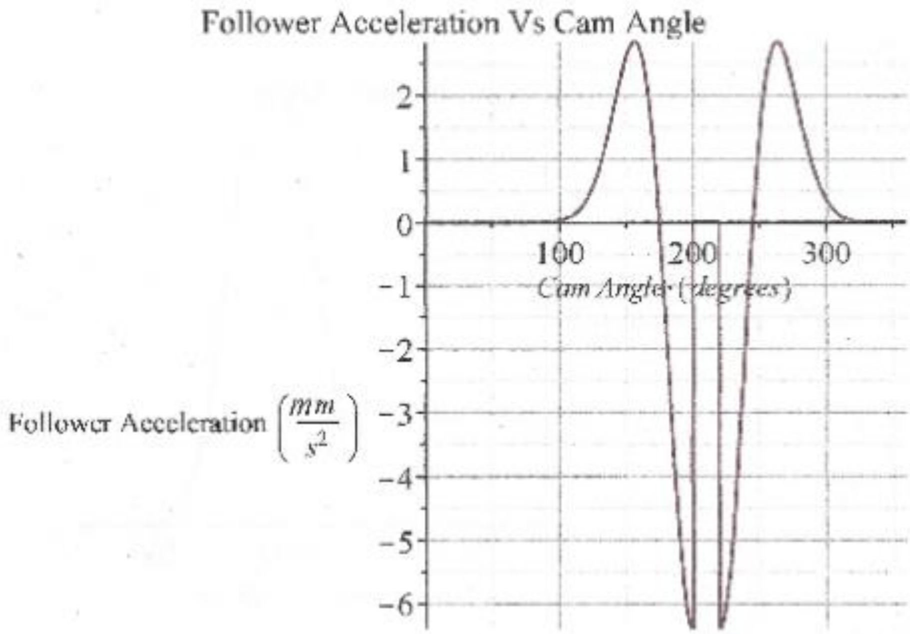
$plot(v(x), x = 0..360)$



$a(x) := diff(v(x), x)$

$$a := x \mapsto \frac{d}{dx} v(x) \tag{7}$$

$plot(a(x), x = 0..360)$

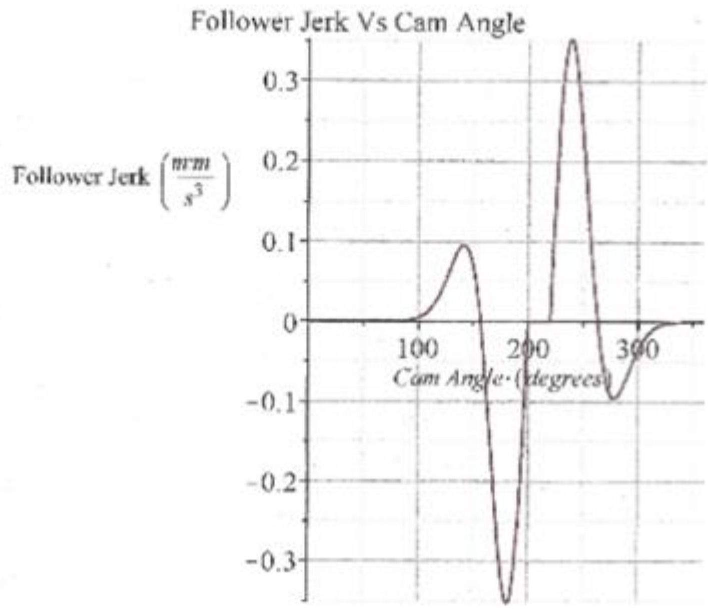


$j(x) := diff(a(x), x)$

$$j := x \mapsto \frac{d}{dx} a(x) \tag{8}$$

$plot(j(x), x = 0..360)$

Next page



D. Make sure the velocity at the one precision point matches the specification from Phase 1? How closely does it match? Does changing the cam rotation speed influence the accuracy of the other precision points?

The velocity of our precision point (in the low-level position) matches our specified velocity of 0. The discontinuity is because the modelling functions of the rise and fall are based on the two Gaussian equations (the equations used to model the circular path on the cam) due to the limitation in the modelling approach the two fitted Gaussians resulted in a discontinuity that lasts for a minimal period . Changing the rotation speed will affect the peak velocity of the follower and the peak magnitudes of the acceleration and jerk.

E. What does your acceleration output tell you? What does your jerk output tell you?

The acceleration and jerk both have discontinuities where the displacement curve becomes constant at its maximum dwell. This is due to the small fraction of the cams movement allocated for the follower to decelerate. If the cam was manufactured, the cam could be filleted (as in the Solidworks model) to allow for a longer deceleration period, but such modifications greatly complicate the modelling equation making the provided model a good approximation.

Originally, concerns about the cam and follower losing contact due to the high changes in acceleration as well as damage to the cam due to the sudden changes in force. However, the maximum magnitudes of acceleration and jerk are 0.006 $\frac{m}{s^2}$ and 0.0003$\frac{m}{s^3}$ respectively, and as a result the potential damage to the cam is minimal, especially if the cam was to be constructed from metal.

Phase 3

A. Go back to your linkage from Phase 1. Now you will fully specify the geometry of each link in your mechanism. For each link: what is its thickness? What material is it made of? Where is its center of mass? How are the joints positioned relative to one another? What is the mass and moment of inertia for each link?

Each link in the suspension mechanism is manufactured from solid titanium alloy to ensure a balance of tensile strength, fracture toughness, and ductility. The linkage uses primarily concentric mating techniques in its construction as well as to attach to the ground (being the frame of the vehicle on which the suspension is being used. The mass properties and drawings for each component of the mechanism are shown below.

```
Mass properties of coector rod
   Configuration: Default
   Coordinate system: Coordinate System1

Density = 0.00 grams per cubic millimeter

Mass = 0.03 grams

Volume = 25.45 cubic millimeters

Surface area = 114.37  square millimeters

Center of mass: ( millimeters )
    X = 0.00
    Y = 0.00
    Z = 20.00

Principal axes of inertia and principal moments of inertia: ( grams *  square m
Taken at the center of mass.
     Ix = ( 0.00,  0.00,  1.00)     Px = 0.00
     Iy = ( 0.00, -1.00,  0.00)     Py = 3.39
     Iz = ( 1.00,  0.00,  0.00)     Pz = 3.39

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
     Lxx = 3.39               Lxy = 0.00               Lxz = 0.00
     Lyx = 0.00               Lyy = 3.39               Lyz = 0.00
     Lzx = 0.00               Lzy = 0.00               Lzz = 0.00

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
     Ixx = 13.57              Ixy = 0.00               Ixz = 0.00
     Iyx = 0.00               Iyy = 13.57              Iyz = 0.00
     Izx = 0.00               Izy = 0.00               Izz = 0.00
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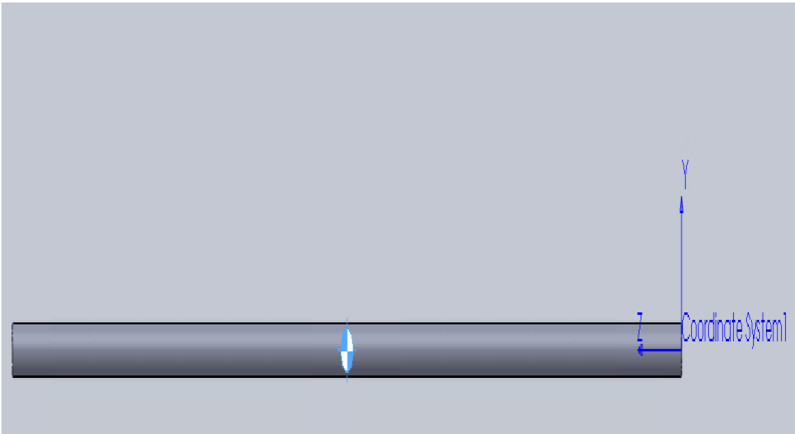


Mass properties of coupler_output
Configuration: Default
Coordinate system: Coordinate System1

Density = 0.00 grams per cubic millimeter

Mass = 1.55 grams

Volume = 342.79 cubic millimeters

Surface area = 577.29 square millimeters

Center of mass: (millimeters)
X = 4.51
Y = -9.21
Z = -1.20

Principal axes of inertia and principal moments of inertia: (grams * square n
Taken at the center of mass.

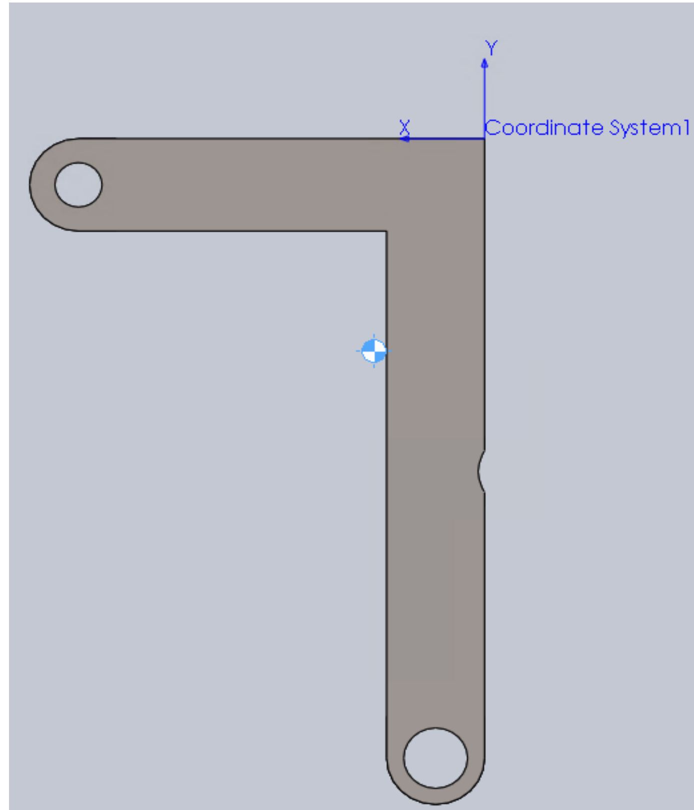
Ix = (0.33, 0.94, 0.00)	Px = 18.67
Iy = (0.94, -0.33, 0.00)	Py = 108.57
Iz = (0.00, 0.00, -1.00)	Pz = 125.69

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 98.90	Lxy = 27.85	Lxz = 0.00
Lyx = 27.85	Lyy = 28.34	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 125.69

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 232.31	Ixy = -36.34	Ixz = -8.36
Iyx = -36.34	Iyy = 61.98	Iyz = 17.09
Izx = -8.36	Izy = 17.09	Izz = 288.28



Mass properties of crank(orqange)
Configuration: Default
Coordinate system: -- default --

Density = 0.00 grams per cubic millimeter

Mass = 0.14 grams

Volume = 31.57 cubic millimeters

Surface area = 123.03 square millimeters

Center of mass: (millimeters)
X = 1.94
Y = 1.50
Z = 3.00

Principal axes of inertia and principal moments of inertia: (grams * square milli
Taken at the center of mass.

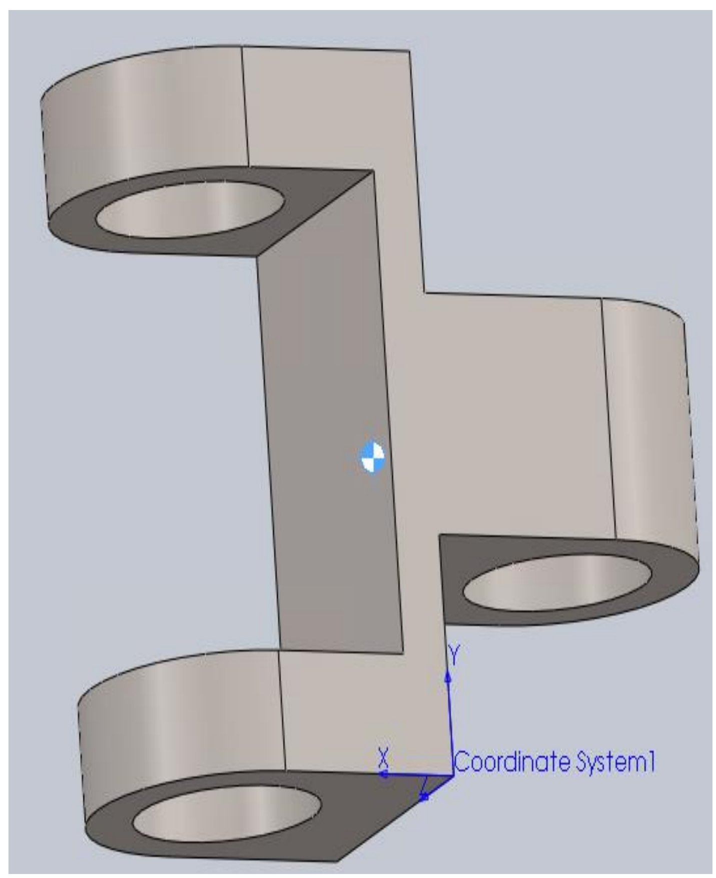
Ix = (0.00, 0.00, 1.00)	Px = 0.48
Iy = (1.00, 0.00, 0.00)	Py = 0.54
Iz = (0.00, 1.00, 0.00)	Pz = 0.77

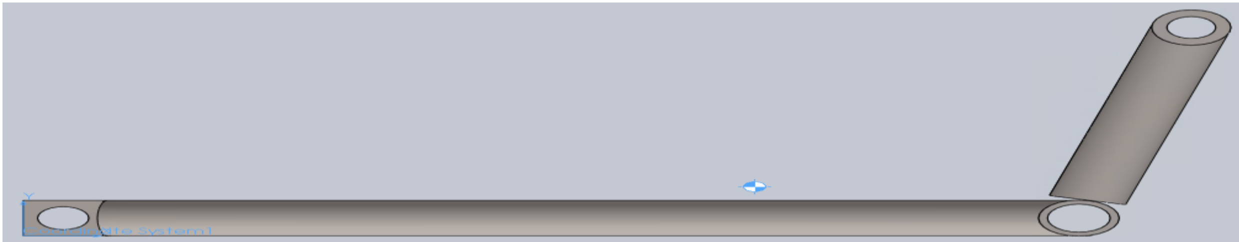
Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 0.54	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyy = 0.77	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 0.48

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 2.14	Ixy = 0.41	Ixz = 0.83
Iyx = 0.41	Iyy = 2.59	Iyz = 0.64
Izx = 0.83	Izy = 0.64	Izz = 1.34





Mass properties of greenpart_upper
Configuration: Default
Coordinate system: Coordinate System1

Density = 0.00 grams per cubic millimeter

Mass = 8.00 grams

Volume = 1774.06 cubic millimeters

Surface area = 2095.51 square millimeters

Center of mass: (millimeters)
X = 36.73
Y = 5.56
Z = -1.00

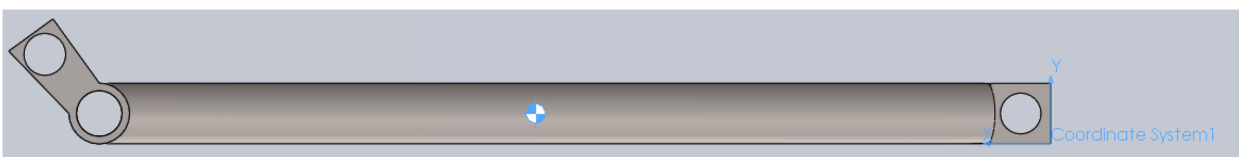
Principal axes of inertia and principal moments of inertia: (grams * square n
Taken at the center of mass.
Ix = (0.97, 0.25, 0.00)   Px = 924.08
Iy = (0.00, 0.00, 1.00)   Py = 2721.43
Iz = (0.25, -0.97, 0.00)   Pz = 3275.62

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1074.00	Lxy = 574.51	Lxz = 0.00
Lyx = 574.51	Lyy = 3125.71	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 2721.43

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 1329.48	Ixy = 2208.86	Ixz = -293.87
Iyx = 2208.86	Iyy = 13926.94	Iyz = -44.50
Izx = -293.87	Izy = -44.50	Izz = 13762.14



Mass properties of lower_connection
Configuration: Default
Coordinate system: Coordinate System1

Density = 0.00 grams per cubic millimeter

Mass = 6.97 grams

Volume = 1545.78 cubic millimeters

Surface area = 1784.89 square millimeters

Center of mass: (millimeters)
X = 34.37
Y = 2.02
Z = 1.00

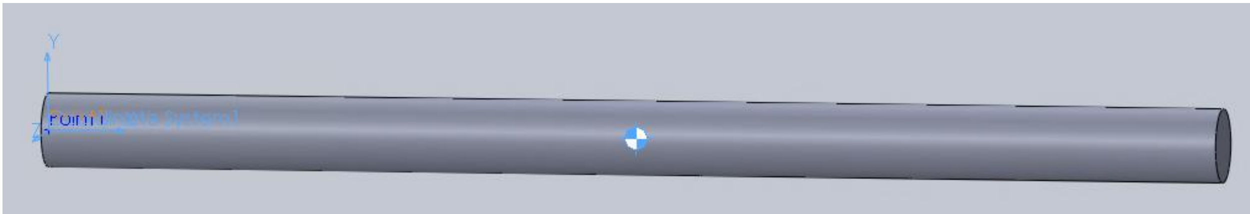
Principal axes of inertia and principal moments of inertia: (grams * square n
Taken at the center of mass.
Ix = (1.00, 0.00, 0.00)   Px = 634.88
Iy = (0.00, 0.00, 1.00)   Py = 2107.44
Iz = (0.00, -1.00, 0.00)   Pz = 2726.90

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 634.89	Lxy = 4.45	Lxz = 0.00
Lyx = 4.45	Lyy = 2726.89	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 2107.44

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 670.31	Ixy = 488.44	Ixz = 239.60
Iyx = 488.44	Iyy = 10969.07	Iyz = 14.08
Izx = 239.60	Izy = 14.08	Izz = 10371.10



Mass properties of lower_rod
Configuration: Default
Coordinate system: Coordinate System1

Density = 0.00 grams per cubic millimeter

Mass = 51.95 grams

Volume = 51954.40 cubic millimeters

Surface area = 13390.72 square millimeters

Center of mass: (millimeters)
X = 129.20
Y = 0.00
Z = 0.00

Principal axes of inertia and principal moments of inertia: (grams * square n
Taken at the center of mass.

Ix = (1.00, 0.00, 0.00)	Px = 1662.54
Iy = (0.00, -1.00, 0.00)	Py = 289916.65
Iz = (0.00, 0.00, -1.00)	Pz = 289916.65

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1662.54	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyy = 289916.65	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 289916.65

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 1662.54	Ixy = 0.00	Ixz = 0.00
Iyx = 0.00	Iyy = 1157172.79	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 1157172.79

Mass properties of suspensio_assembly, no counterbalance
Configuration: Default
Coordinate system: Coordinate System1

Mass = 17.65 grams

Volume = 4011.89 cubic millimeters

Surface area = 5397.46 square millimeters

Center of mass: (millimeters)
X = 19.57
Y = 26.89
Z = -16.22

Principal axes of inertia and principal moments of inertia: (grams * square milli
Taken at the center of mass.

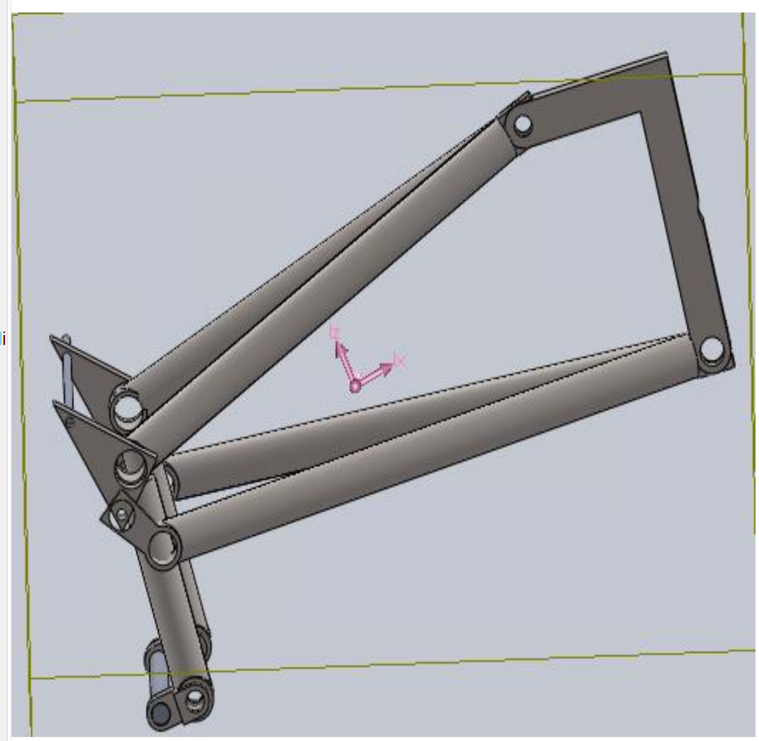
Ix = (0.91, 0.42, 0.00)	Px = 3094.63
Iy = (0.00, -0.01, -1.00)	Py = 9265.40
Iz = (-0.42, 0.91, -0.01)	Pz = 9415.56

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 4184.82	Lxy = 2387.97	Lxz = 7.18
Lyx = 2387.97	Lyy = 8325.38	Lyz = 4.73
Lzx = 7.18	Lzy = 4.73	Lzz = 9265.40

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 21584.45	Ixy = 11675.58	Ixz = -5594.17
Iyx = 11675.58	Iyy = 19726.90	Iyz = -7690.13
Izx = -5594.17	Izy = -7690.13	Izz = 28785.02



Mass properties of suspensio_assembly
Configuration: Default
Coordinate system: -- default --

Mass = 18.14 grams

Volume = 4080.66 cubic millimeters

Surface area = 5517.84 square millimeters

Center of mass: (millimeters)
X = 19.74
Y = 27.04
Z = -85.32

Principal axes of inertia and principal moments of inertia: (grams * square mill
Taken at the center of mass.

Ix = (0.89, 0.45, 0.00)	Px = 3277.95
Iy = (0.00, 0.00, -1.00)	Py = 9998.16
Iz = (-0.45, 0.89, 0.00)	Pz = 10155.79

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

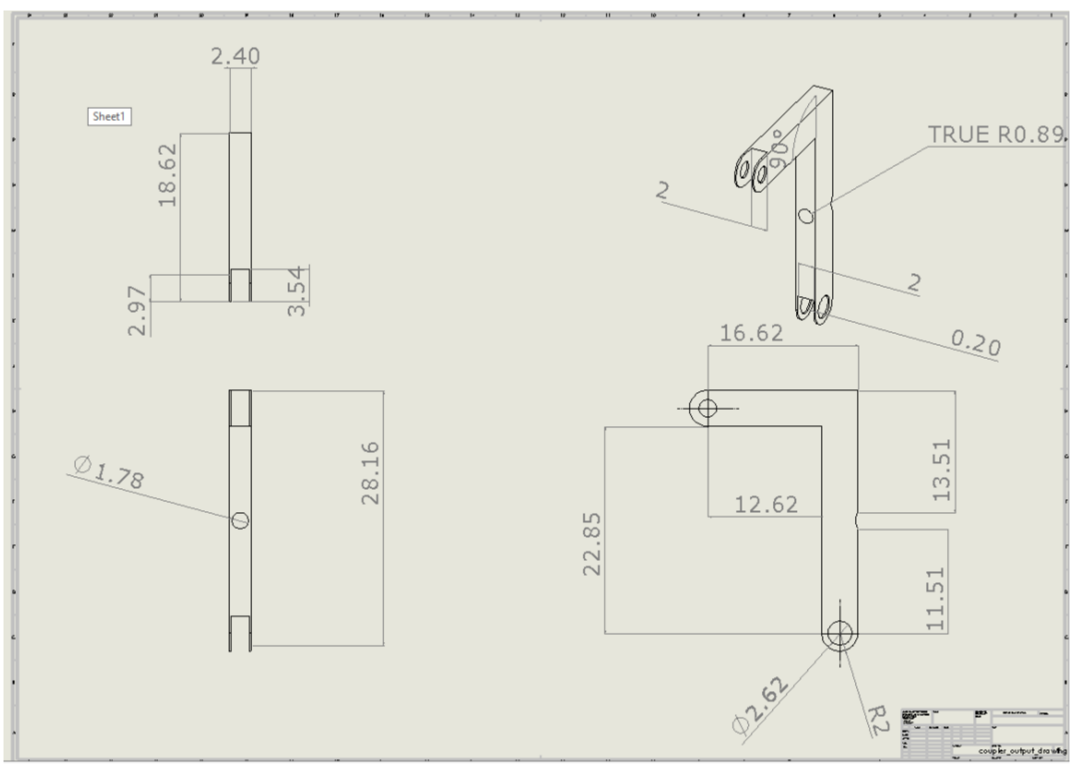
Lxx = 4657.05	Lxy = 2753.77	Lxz = 6.32
Lyx = 2753.77	Lyy = 8776.70	Lyz = 3.85
Lzx = 6.32	Lzy = 3.85	Lzz = 9998.16

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

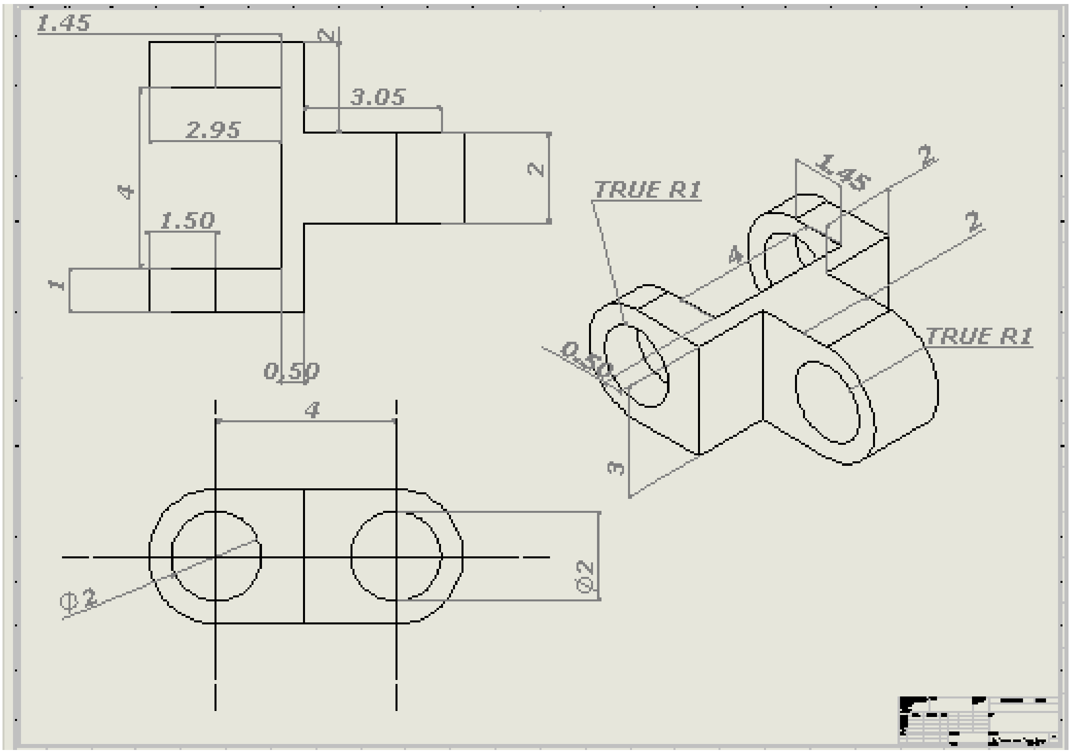
Ixx = 149950.14	Ixy = 12435.55	Ixz = -30542.19
Iyx = 12435.55	Iyy = 147875.97	Iyz = -41840.97
Izx = -30542.19	Izy = -41840.97	Izz = 30328.21

Drawings

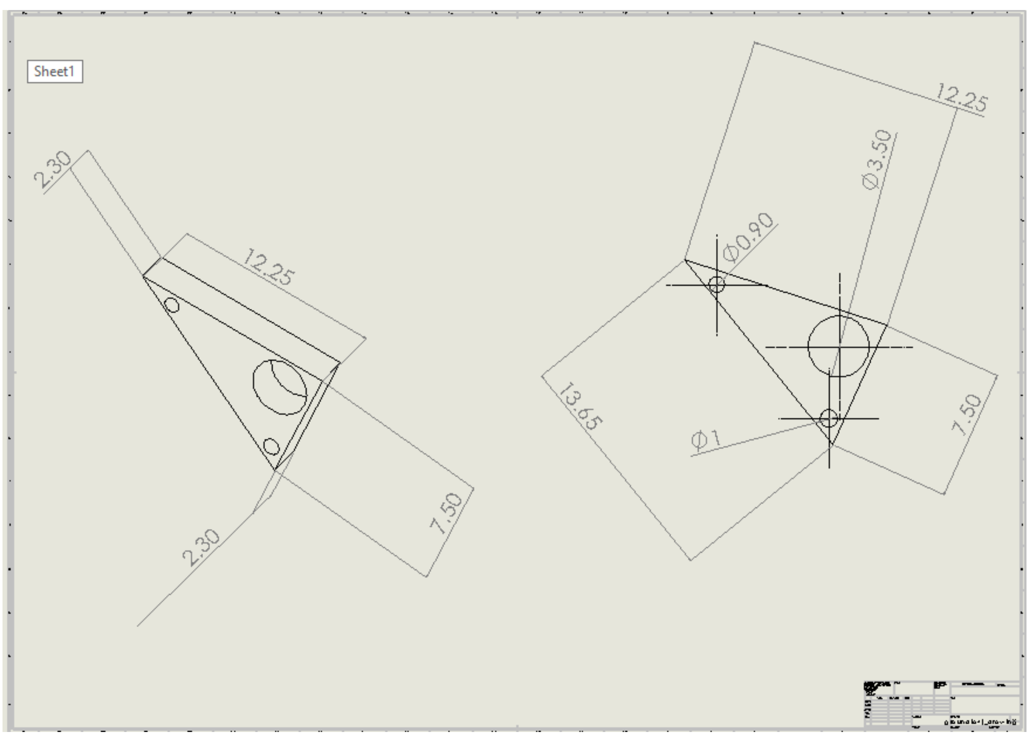
Coupler Output Link



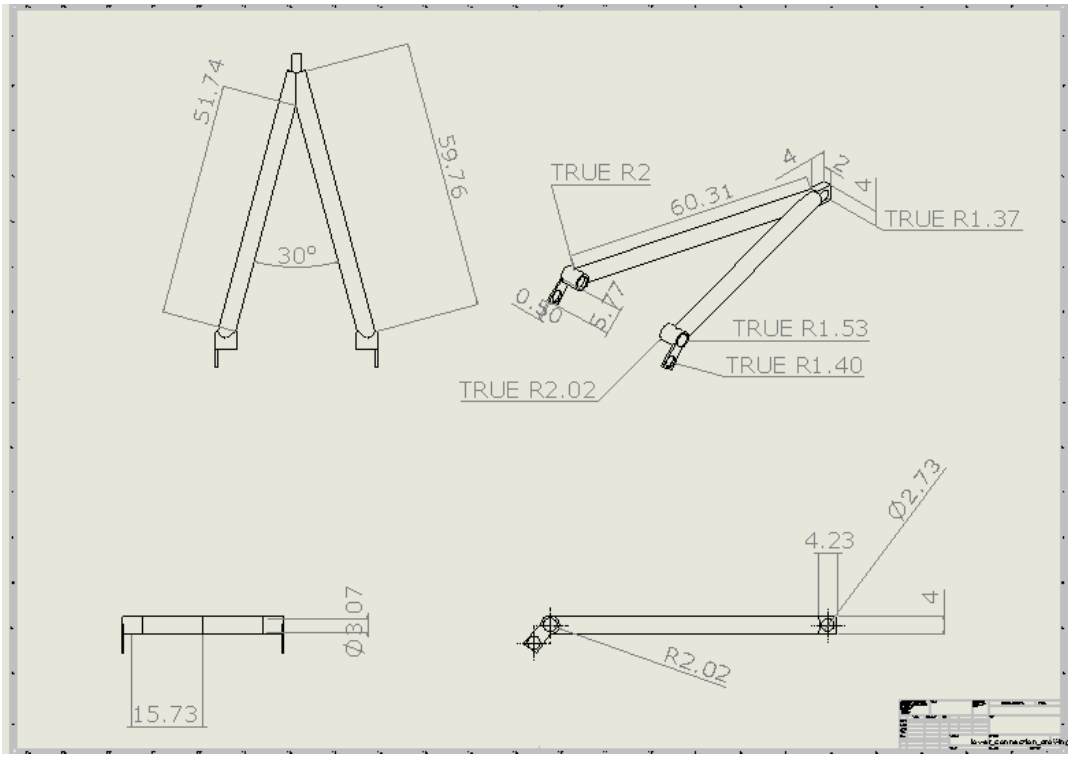
Crank Input Link



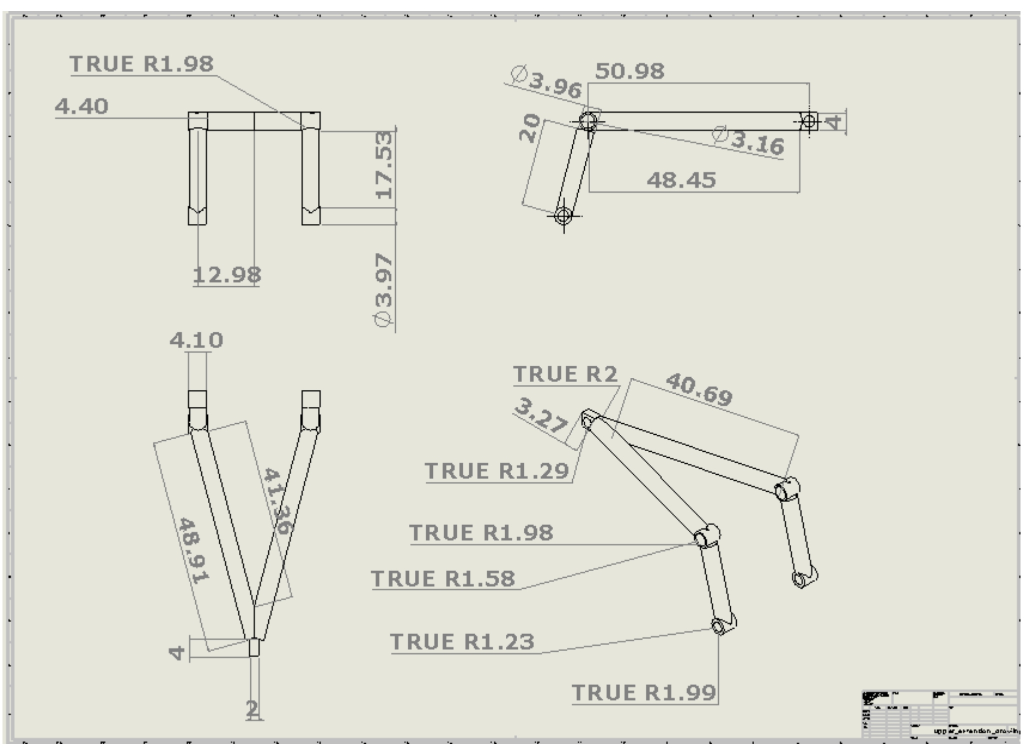
Upper Ground Tertiary Link



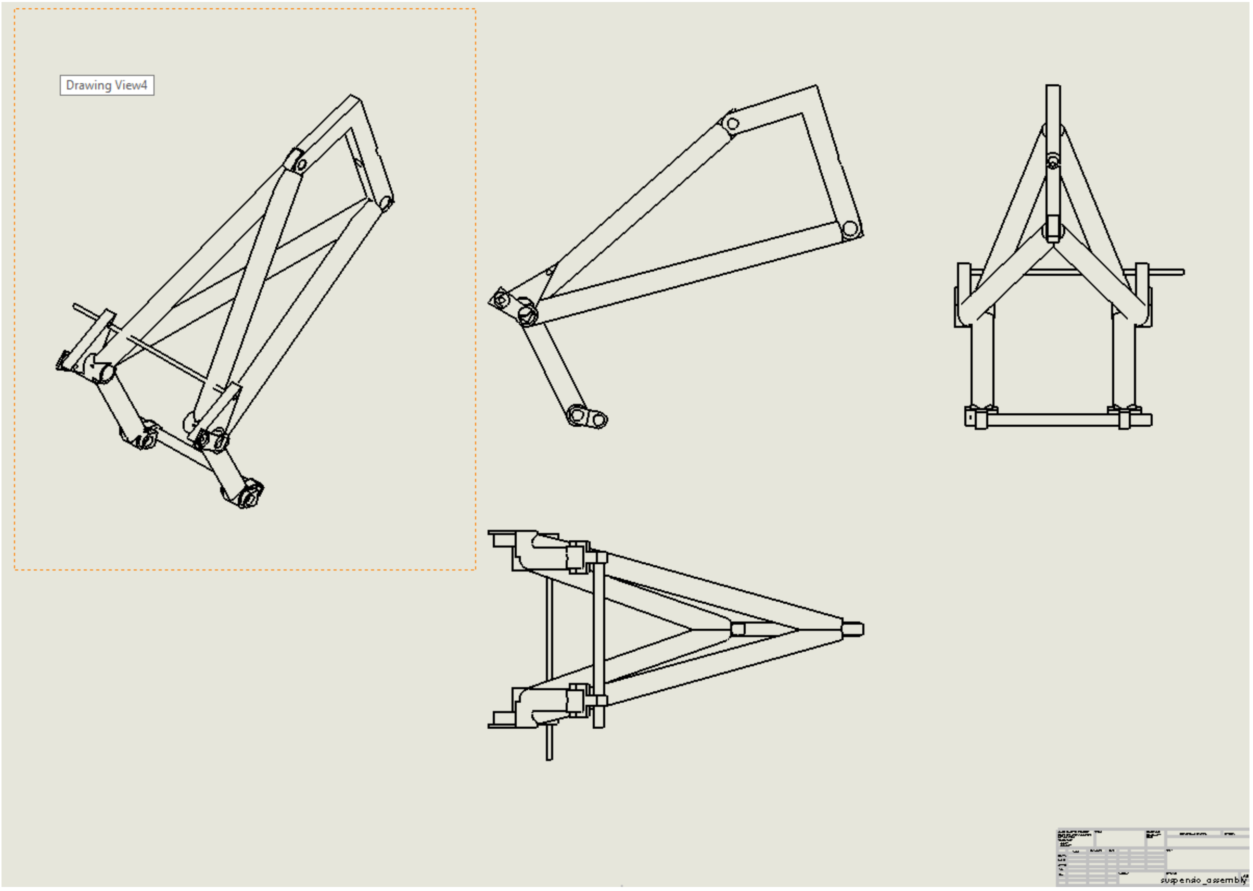
Lower Connection Link



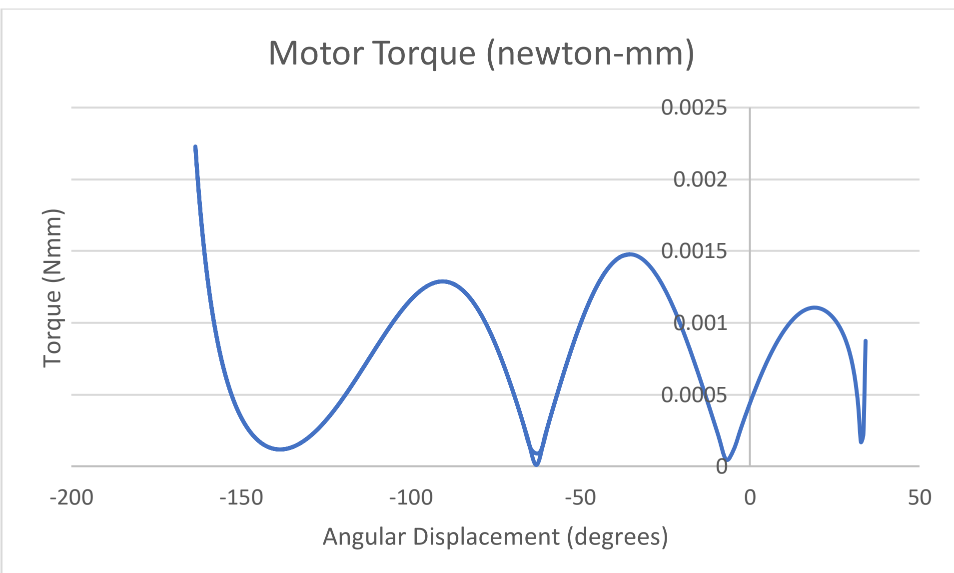
Upper Connection Link



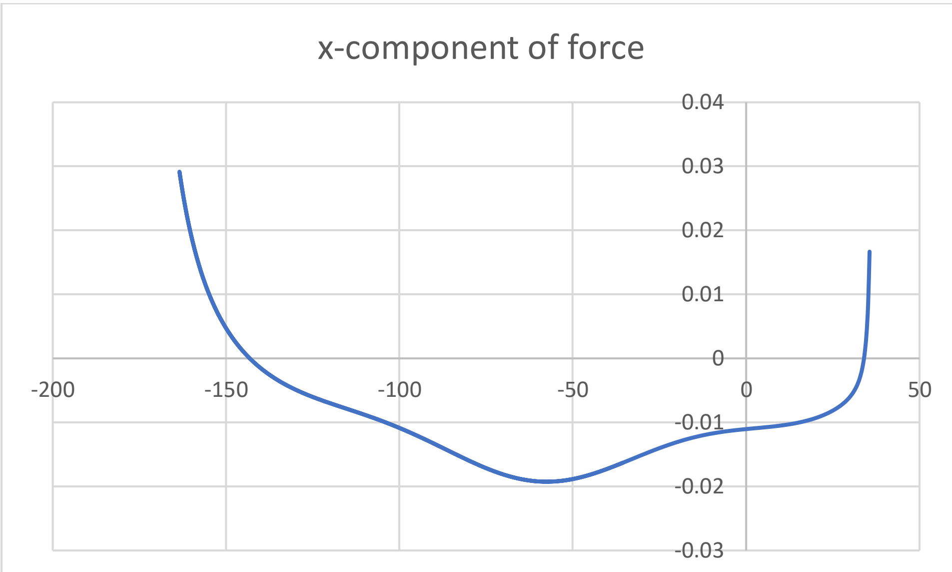
Assembly Layout Drawing

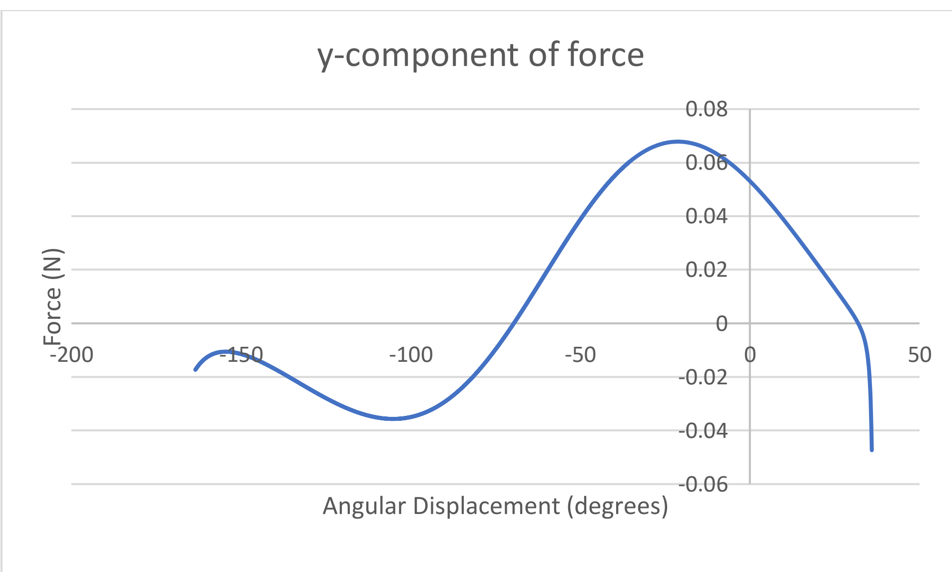


B. Calculate the torque required at the input to move the output through its three precision points at the velocity specified at one of the precision points.



C. What is the force at the output through the entire duty cycle of your linkage? You can calculate this in 5 degree increments of crank input. Plot the output force versus crank input angle in two-dimensions and given the list of coordinates in an Excel table. Compare the relative timing of the transmission angle (from Phase 1) with the force output. What does this tell you about how you might improve your mechanism?





Angular Displacement (deg)	*x-comp*	*y-comp*
35.93999894	0.016668	-0.04735
35.59436356	0.008433	-0.02881
35.17246287	0.003538	-0.01835
34.67462177	0.000436	-0.01197
34.10122362	-0.00165	-0.00773
33.45270997	-0.00315	-0.00463
32.7295802	-0.00427	-0.00215
31.93239118	-0.00516	-1.2E-05
31.06175677	-0.00588	0.001971
30.11834741	-0.0065	0.003898
29.10288958	-0.00704	0.005834
28.01616523	-0.00752	0.007821
26.8590112	-0.00795	0.009885
25.63231857	-0.00834	0.012044
24.33703194	-0.0087	0.014307
22.97414877	-0.00902	0.016679
21.54471855	-0.00932	0.01916
20.049842	-0.00958	0.021748
18.49067028	-0.00981	0.024435
16.86840402	-0.01002	0.027215
15.18429246	-0.01021	0.030074
13.43963246	-0.01037	0.032999
11.63576749	-0.01051	0.035973
9.774086626	-0.01063	0.038977
7.85602347	-0.01074	0.04199
5.883055031	-0.01085	0.044985
3.856700599	-0.01095	0.047937
1.778520578	-0.01106	0.050817

-0.349884721	-0.01118	0.053591
-2.526876314	-0.01132	0.056227
-4.750777797	-0.01149	0.058689
-7.019876649	-0.01169	0.060939
-9.332425539	-0.01192	0.06294
-11.68664368	-0.01221	0.064651
-14.0807182	-0.01254	0.066034
-16.51280553	-0.01292	0.067052
-18.98103283	-0.01335	0.067668
-21.48349944	-0.01382	0.067848
-24.01827832	-0.01434	0.067563
-26.58341755	-0.01489	0.066788
-29.17694184	-0.01547	0.065504
-31.79685403	-0.01606	0.0637
-34.44113666	-0.01664	0.061372
-37.10775348	-0.0172	0.058526
-39.79465105	-0.01773	0.055179
-42.49976032	-0.0182	0.051356
-45.2209982	-0.0186	0.047094
-47.9562692	-0.01892	0.042439
-50.70346702	-0.01913	0.037447
-53.46047615	-0.01925	0.032182
-56.22517356	-0.01924	0.026716
-58.99543028	-0.01913	0.021123
-61.76911306	-0.0189	0.015482
-64.54408602	-0.01856	0.009872
-67.31821228	-0.01812	0.004369
-70.08935561	-0.0176	-0.00095
-72.85538208	-0.01701	-0.00603
-75.61416171	-0.01636	-0.01079
-78.36357008	-0.01567	-0.0152

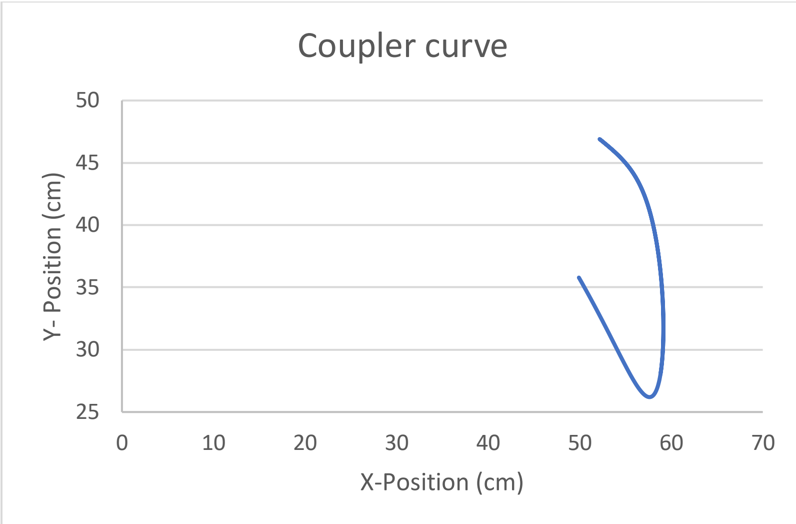
-81.10149	-0.01496	-0.01922
-83.82581312	-0.01424	-0.0228
-86.53444157	-0.01353	-0.02594
-89.22528956	-0.01283	-0.02863
-91.89628501	-0.01216	-0.03085
-94.54537108	-0.01152	-0.03263
-97.17050784	-0.01092	-0.03398
-99.7696738	-0.01035	-0.03492
-102.3408675	-0.00981	-0.03547
-104.8821089	-0.00931	-0.03567
-107.3914411	-0.00884	-0.03555
-109.8669319	-0.00839	-0.03514
-112.3066749	-0.00796	-0.03448
-114.7087915	-0.00754	-0.03361
-117.0714318	-0.00712	-0.03255
-119.3927766	-0.00669	-0.03134
-121.6710382	-0.00625	-0.03002
-123.9044622	-0.00579	-0.02861
-126.0913289	-0.00531	-0.02714
-128.2299542	-0.00479	-0.02563
-130.3186912	-0.00424	-0.02411
-132.3559316	-0.00364	-0.02261
-134.3401065	-0.003	-0.02113
-136.2696879	-0.0023	-0.01971
-138.1431901	-0.00155	-0.01835
-139.9591703	-0.00074	-0.01706
-141.7162302	0.00014	-0.01587
-143.4130166	0.001084	-0.01478
-145.048223	0.002097	-0.01379
-146.6205902	0.003183	-0.01293
-148.1289073	0.004342	-0.0122

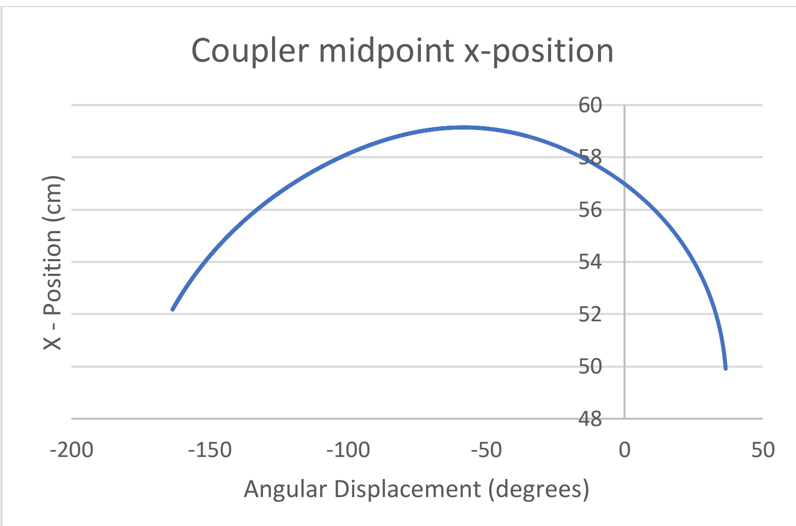
-149.5720129	0.005577	-0.0116
-150.9487958	0.006888	-0.01113
-152.2581956	0.008273	-0.01081
-153.4992042	0.00973	-0.01062
-154.6708658	0.011255	-0.01057
-155.7722783	0.01284	-0.01066
-156.8025934	0.014475	-0.01087
-157.7610178	0.016144	-0.01121
-158.6468134	0.017831	-0.01165
-159.4592982	0.019512	-0.01219
-160.1978465	0.02116	-0.0128
-160.8618894	0.022745	-0.01346
-161.4509158	0.024231	-0.01415
-161.964472	0.025584	-0.01484
-162.4021626	0.026766	-0.01549
-162.7636505	0.027742	-0.01608
-163.0486573	0.028482	-0.01659
-163.2569636	0.02896	-0.01698
-163.3884089	0.029162	-0.01723
-163.4428921	0.029078	-0.01734
-163.4203712	0.028713	-0.0173
-163.3208635	0.028079	-0.0171
-163.1444457	0.027198	-0.01676
-162.8912536	0.026097	-0.01631
-162.5614821	0.024811	-0.01575
-162.1553853	0.023376	-0.01511
-161.6732758	0.021828	-0.01444
-161.1155249	0.020202	-0.01375
-160.4825621	0.018531	-0.01307
-159.7748748	0.016843	-0.01244
-158.993008	0.015164	-0.01186

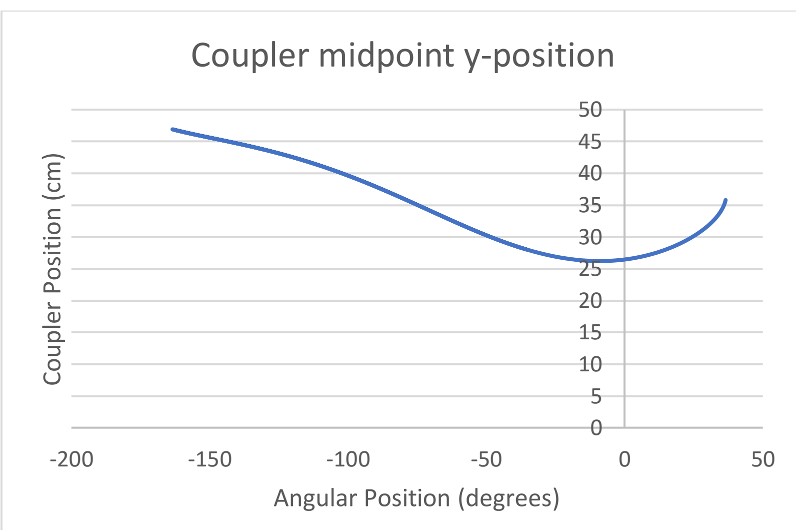
-158.1375637	0.013513	-0.01138
-157.2092007	0.011906	-0.011
-156.2086338	0.010356	-0.01073
-155.1366336	0.008869	-0.01059
-153.9940256	0.007454	-0.01058
-152.7816896	0.006112	-0.01071
-151.5005592	0.004846	-0.01098
-150.1516209	0.003655	-0.01139
-148.7359135	0.002539	-0.01193
-147.2545271	0.001496	-0.01261
-145.7086026	0.000524	-0.01342
-144.0993303	-0.00038	-0.01435
-142.4279494	-0.00122	-0.0154
-140.6957471	-0.002	-0.01655
-138.9040572	-0.00272	-0.0178
-137.0542595	-0.00338	-0.01913
-135.1477783	-0.004	-0.02054
-133.1860817	-0.00457	-0.02199
-131.1706804	-0.0051	-0.02349
-129.1031263	-0.0056	-0.025
-126.9850116	-0.00606	-0.02651
-124.8179673	-0.00651	-0.028
-122.6036622	-0.00694	-0.02944
-120.3438014	-0.00736	-0.03081
-118.0401251	-0.00778	-0.03206
-115.6944072	-0.00821	-0.03319
-113.3084542	-0.00865	-0.03414
-110.8841032	-0.00912	-0.0349
-108.4232213	-0.0096	-0.03541
-105.9277033	-0.01012	-0.03566
-103.399471	-0.01068	-0.03559

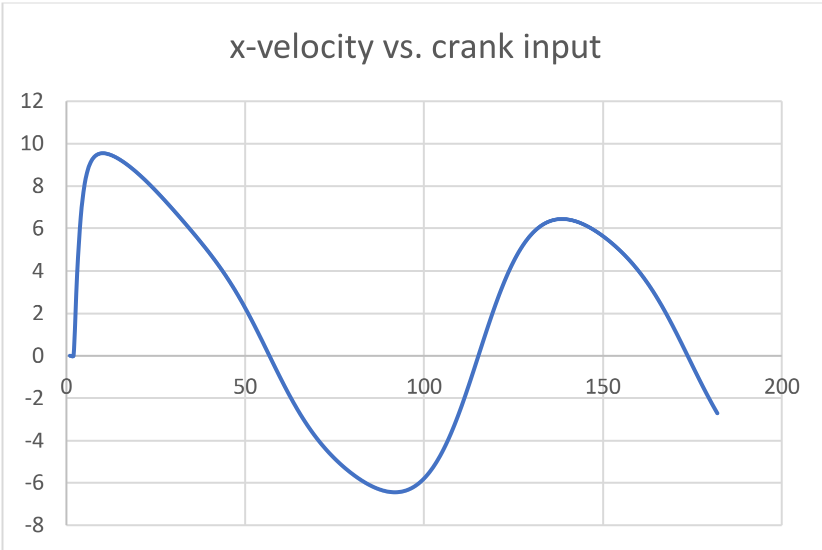
-100.8404713	-0.01127	-0.03519
-98.25267474	-0.01189	-0.03442
-95.63807402	-0.01255	-0.03324
-92.99868256	-0.01324	-0.03164
-90.33653283	-0.01395	-0.0296
-87.65367479	-0.01466	-0.02711
-84.95217445	-0.01538	-0.02416
-82.23411208	-0.01608	-0.02076
-79.50158073	-0.01675	-0.01692
-76.7566846	-0.01736	-0.01267
-74.00153742	-0.01792	-0.00805
-71.23826078	-0.01839	-0.00309
-68.46898257	-0.01877	0.002134
-65.69583527	-0.01904	0.00757
-62.92095437	-0.01921	0.013145
-60.14647666	-0.01926	0.018783
-57.37453865	-0.01919	0.024405
-54.60727487	-0.01902	0.029934
-51.84681627	-0.01874	0.035291
-49.09528855	-0.01838	0.040404
-46.35481054	-0.01793	0.045206
-43.62749255	-0.01743	0.049638
-40.91543476	-0.01688	0.053648

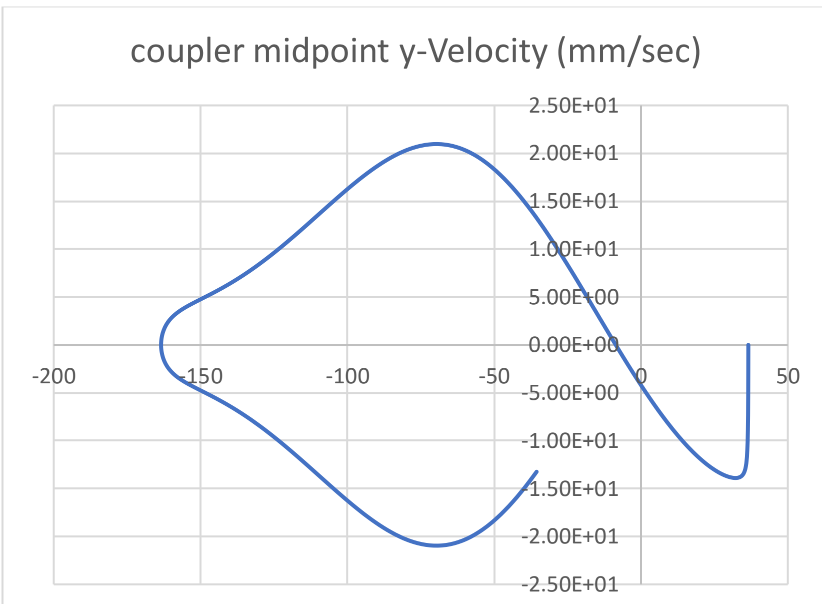
Comparing the timing of the force with the transmission angle shows that that the magnitude of the force varies with the cosine of the transmission angle (a transmission angle closer to 90 degrees results in better transfer of forces between linkages. As a result, the linkage was slightly iterated while being specified into three dimensional components. The recompleted position, velocity, and acceleration analyses are available below.

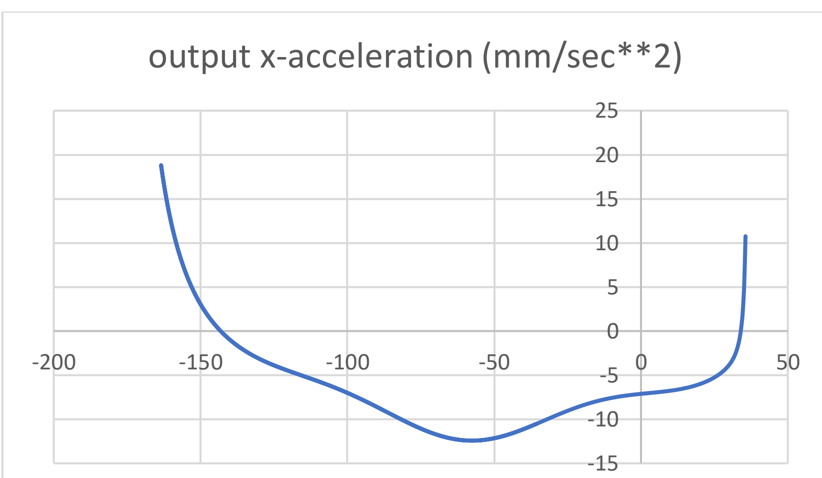

Coupler curve
Y- Position (cm)
50
45
40
35
30
25
0
10
20
30
40
50
60
70
X-Position (cm)

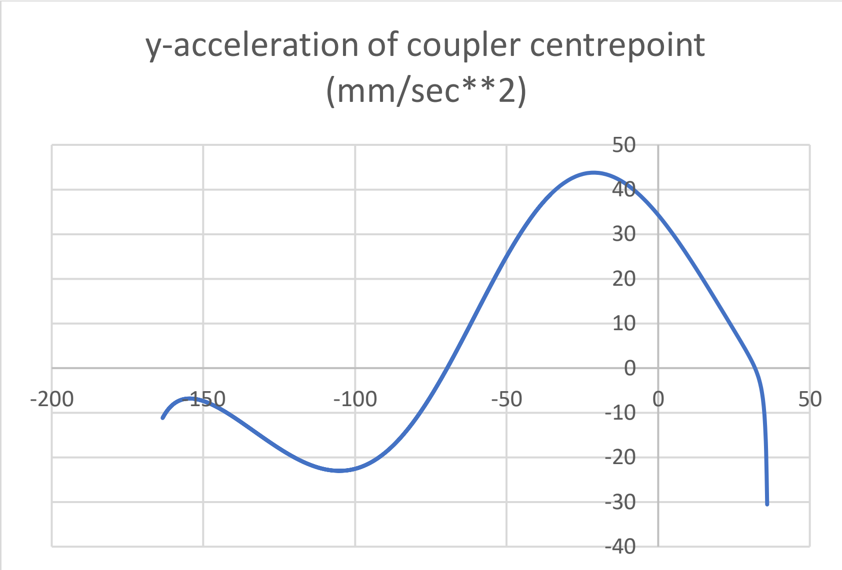

Coupler midpoint x-position
X - Position (cm)
60
58
56
54
52
50
48
-200
-150
-100
-50
0
50
Angular Displacement (degrees)

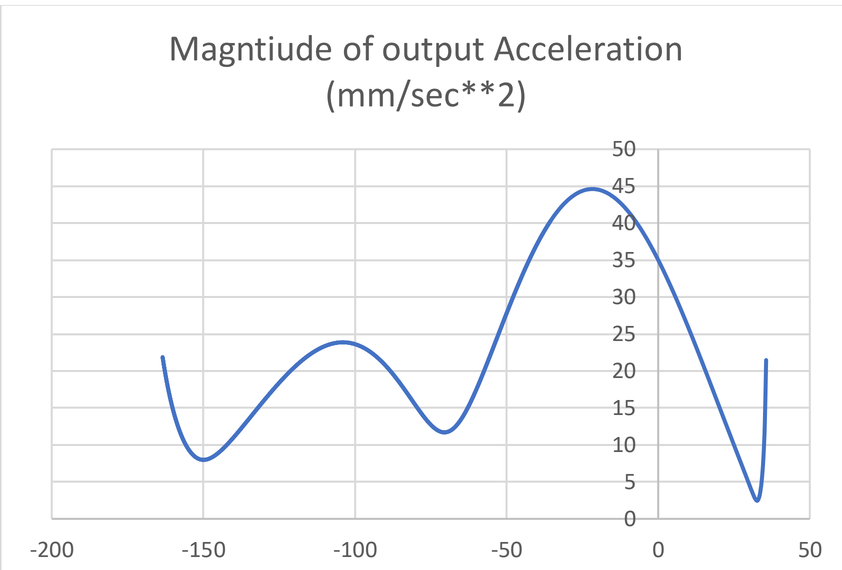

Coupler midpoint y-position
Coupler Position (cm)
50
45
40
35
30
25
20
15
10
5
0
-200
-150
-100
-50
0
50
Angular Position (degrees)


x-velocity vs. crank input
12
10
8
6
4
2
0
-2
-4
-6
-8
0
50
100
150
200

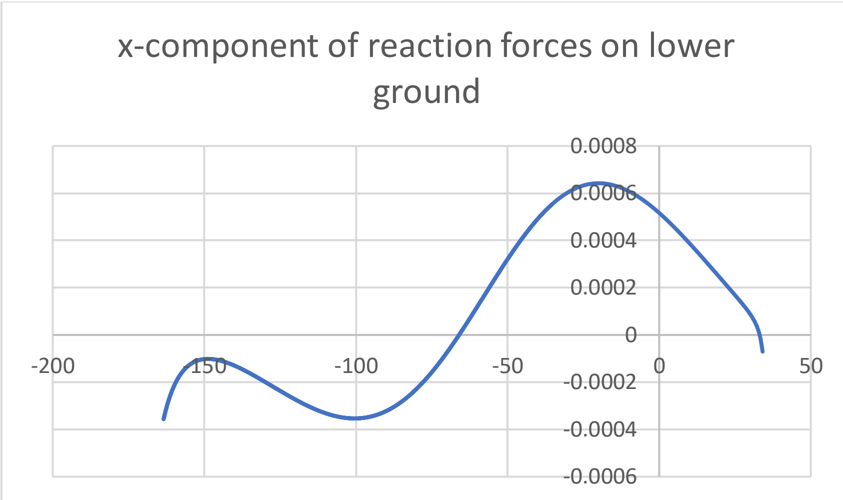

coupler midpoint y-Velocity (mm/sec)
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
-5.00E+00
-1.00E+01
-1.50E+01
-2.00E+01
-2.50E+01
-200
-150
-100
-50
0
50

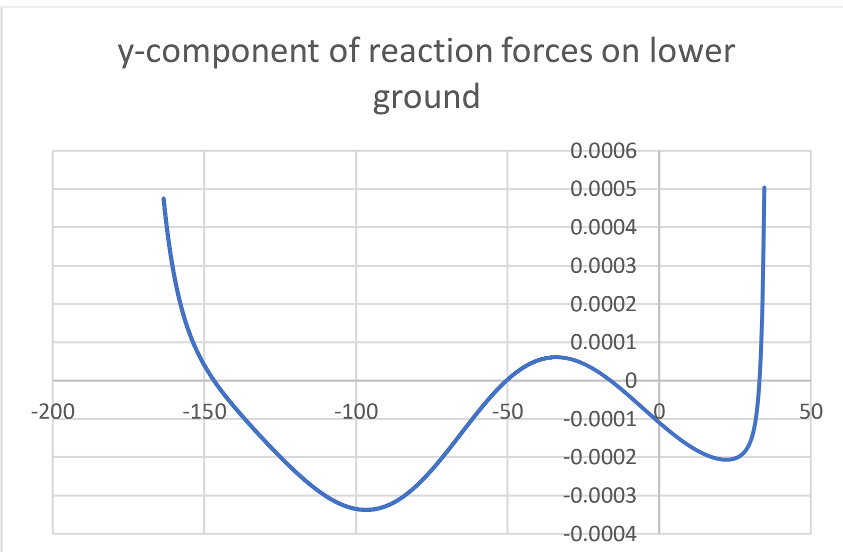

output x-acceleration (mm/sec**2)
25
20
15
10
5
0
-5
-10
-15
-200
-150
-100
-50
0
50

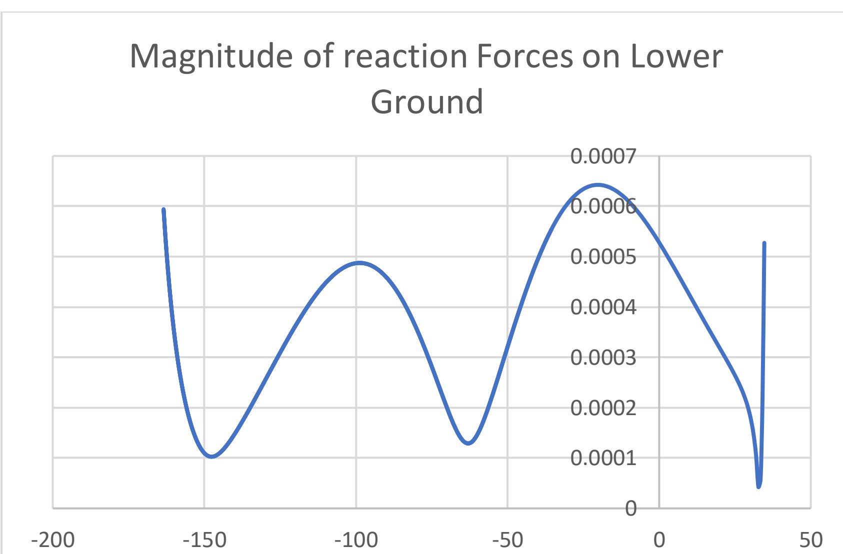


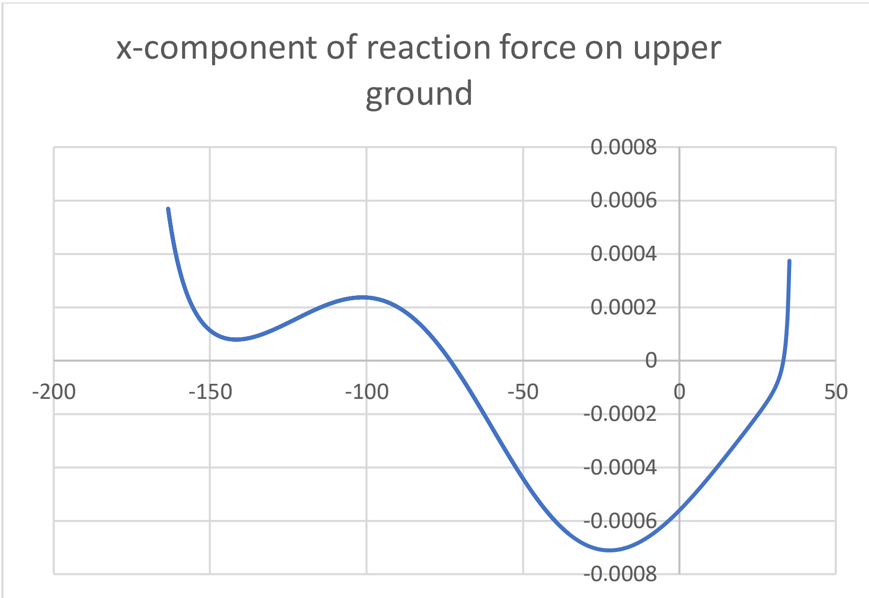


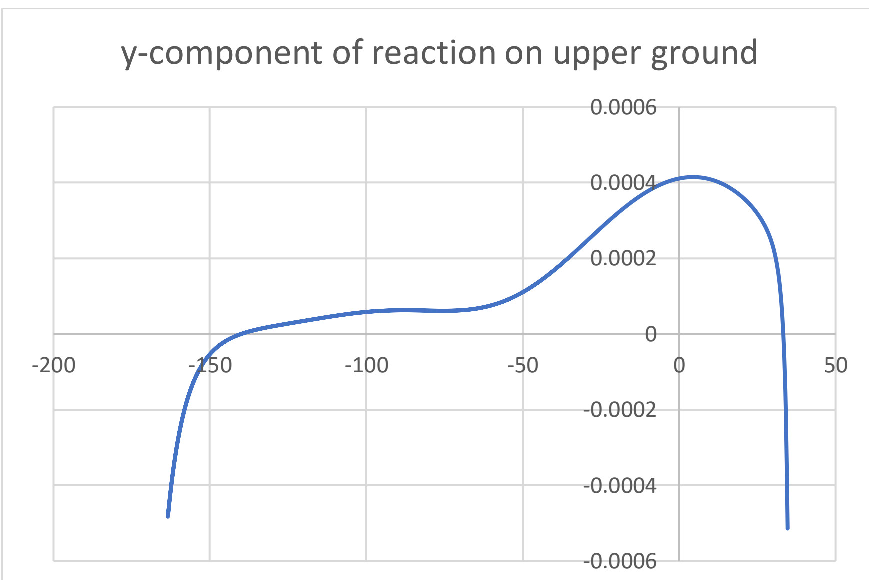
D. What are the shaking force and the shaking moment for your linkage? What are these quantities telling you about how to change your design to better balance the links? How might you balance your mechanism?

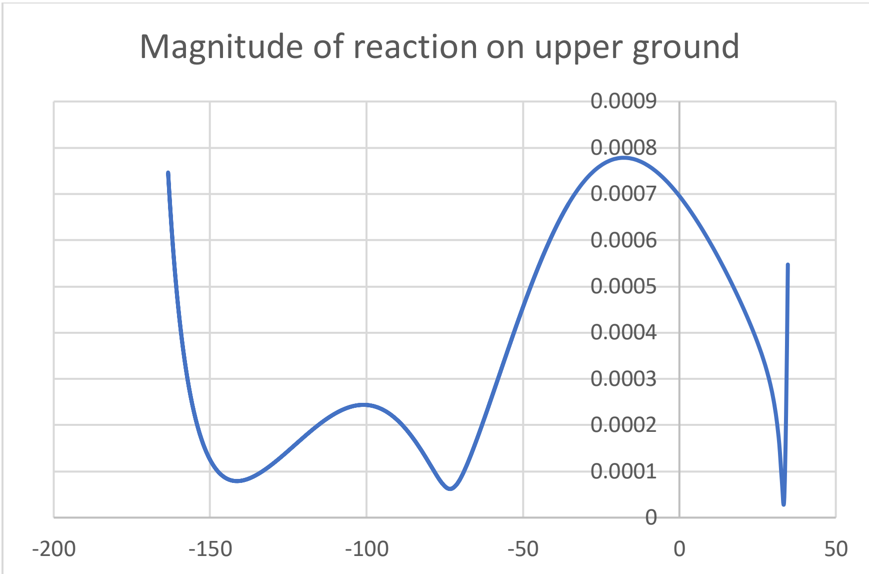

x-component of reaction forces on lower ground
0.0008
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-200
-150
-100
-50
0
50

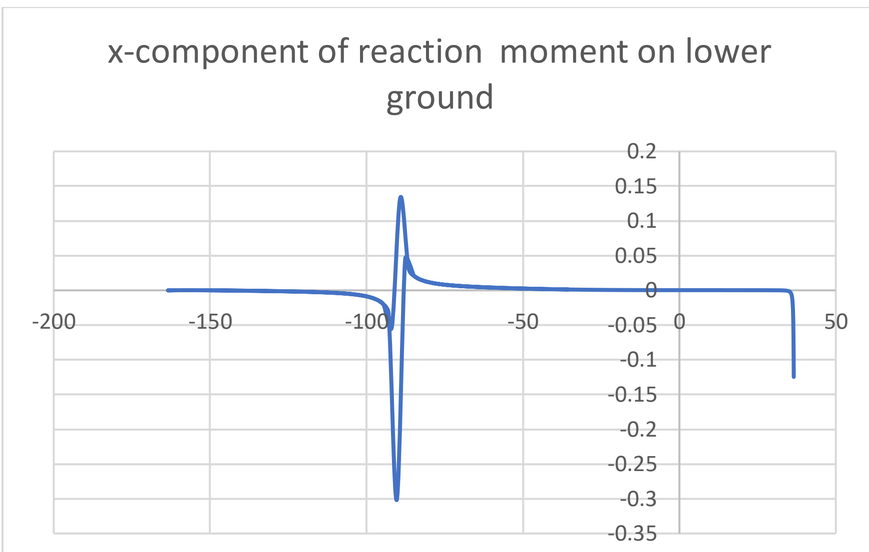

y-component of reaction forces on lower ground
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
-0.0002
-0.0003
-0.0004
-200
-150
-100
-50
0
50

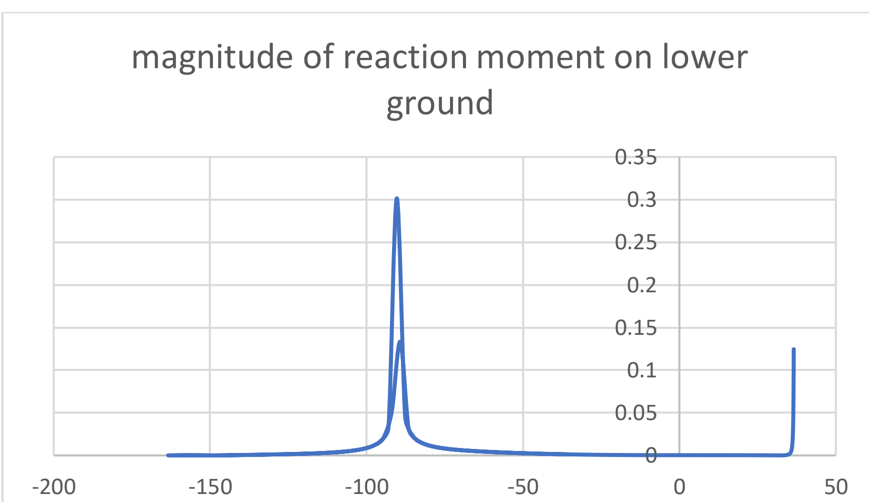

Magnitude of reaction Forces on Lower Ground
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-200
-150
-100
-50
0
50

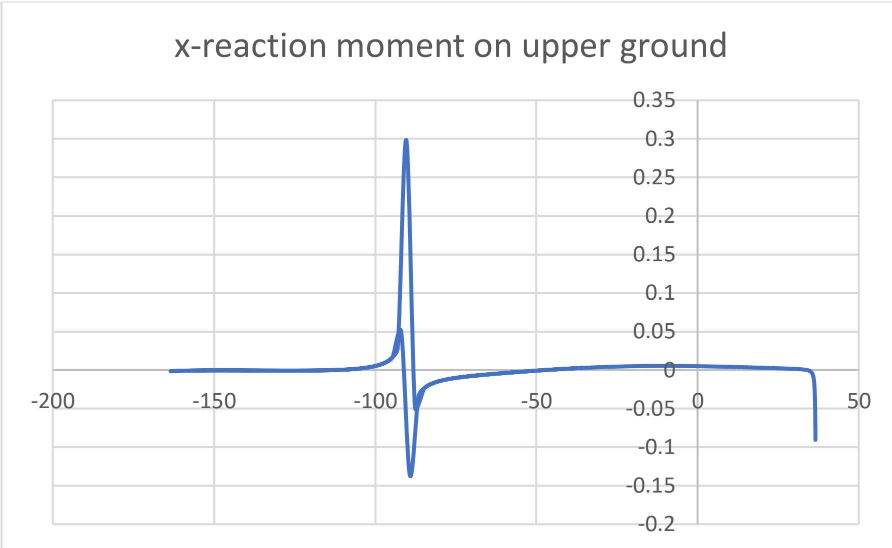

x-component of reaction force on upper ground
0.0008
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
-200
-150
-100
-50
0
50

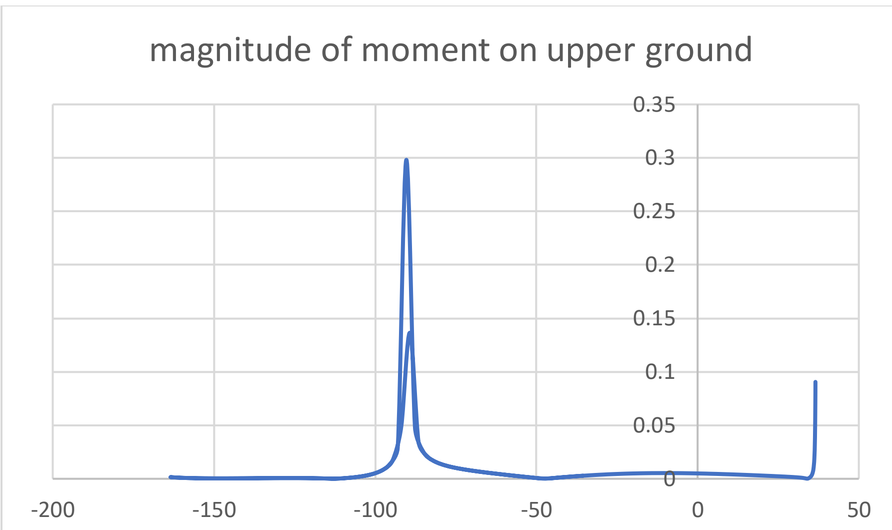

y-component of reaction on upper ground
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-200
-150
-100
-50
0
50


Magnitude of reaction on upper ground
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-200
-150
-100
-50
0
50


x-component of reaction moment on lower ground
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-200
-150
-100
-50
0
50


magnitude of reaction moment on lower ground
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-200
-150
-100
-50
0
50





The above moment plots show the magnitude of the shaking moment spiking at approximately -90 degrees. On both the upper and lower ground attachments, as these large magnitudes will cause damage to both the linkage and the attached structure it is important to attach a counter-weight to the linkage at the ground joints to counteract the moment and prevent potential damage.

Phase 4

A. Show each of the links with fully dimensioned geometries showing the location of the center of mass. Give the mass and moment of inertia of each link. Balance the links so that the shaking force and shaking moment are minimized (or at least made smaller than in Phase 3).

The final specifications of the linkages with the center of mass were unchanged between phases 3 and 4, however, a counterbalance was added to the o2 attachment point to counteract the large moments on the ground in phase 3.

Mass properties of suspensio_assembly
Configuration: Default
Coordinate system: -- default --

Mass = 18.14 grams

Volume = 4080.66 cubic millimeters

Surface area = 5517.84 square millimeters

Center of mass: (millimeters)
X = 19.74
Y = 27.04
Z = -85.32

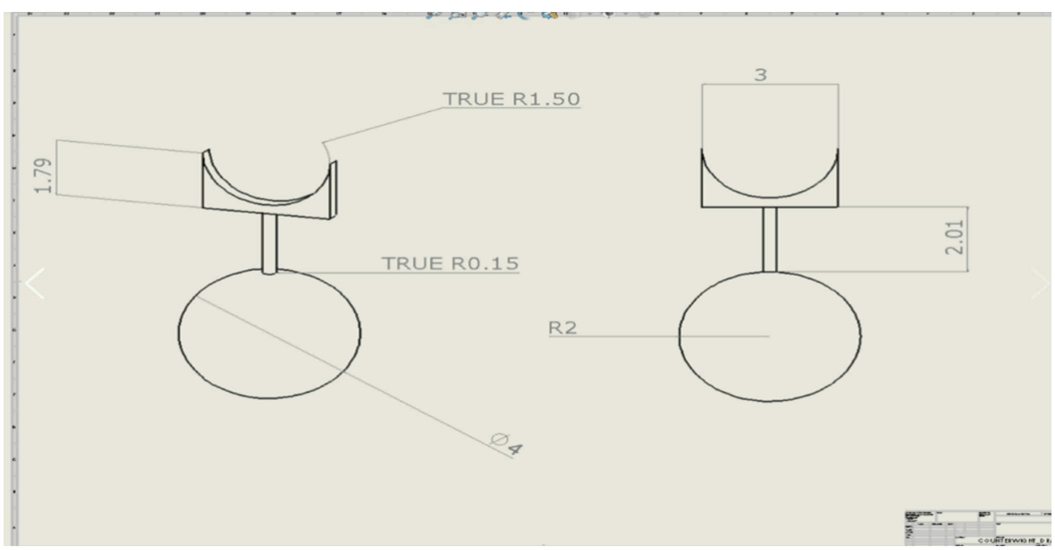
Principal axes of inertia and principal moments of inertia: (grams * square mill
Taken at the center of mass.
Ix = (0.89, 0.45, 0.00) Px = 3277.95
Iy = (0.00, 0.00, -1.00) Py = 9998.16
Iz = (-0.45, 0.89, 0.00) Pz = 10155.79

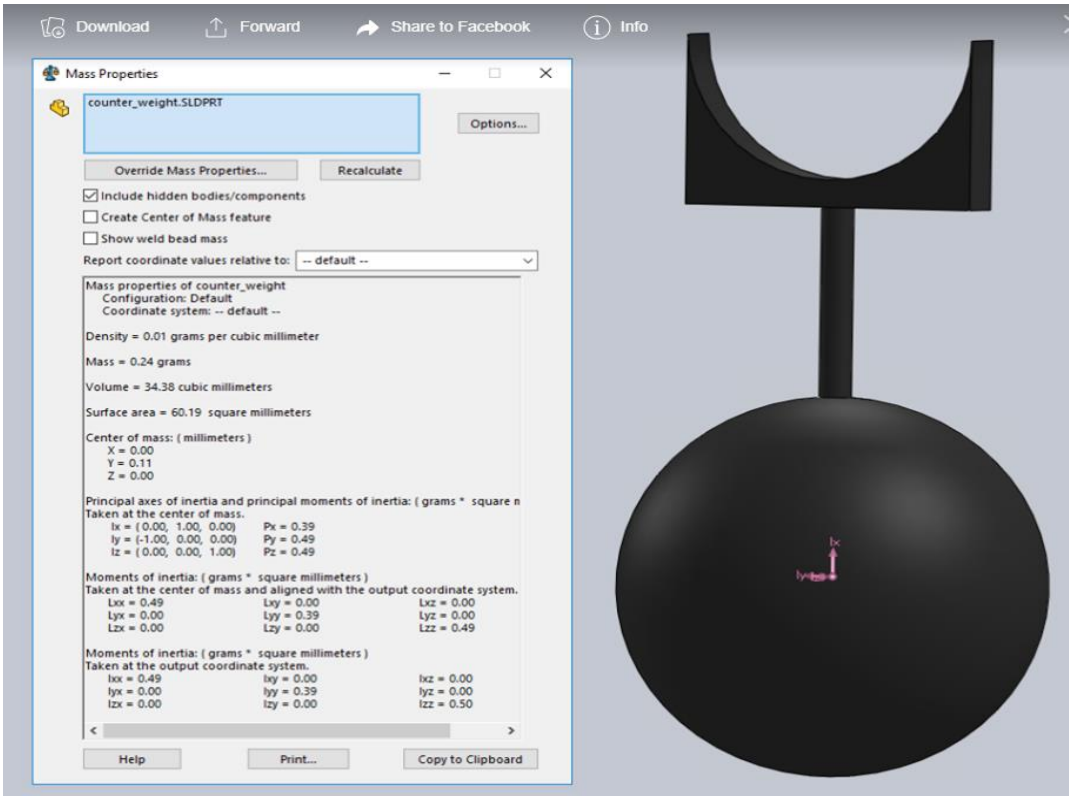
Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 4657.05	Lxy = 2753.77	Lxz = 6.32
Lyx = 2753.77	Lyy = 8776.70	Lyz = 3.85
Lzx = 6.32	Lzy = 3.85	Lzz = 9998.16

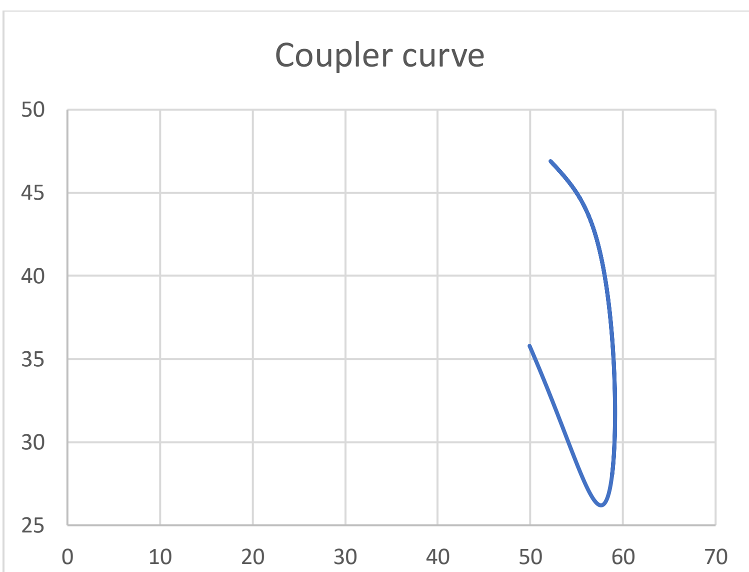
Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

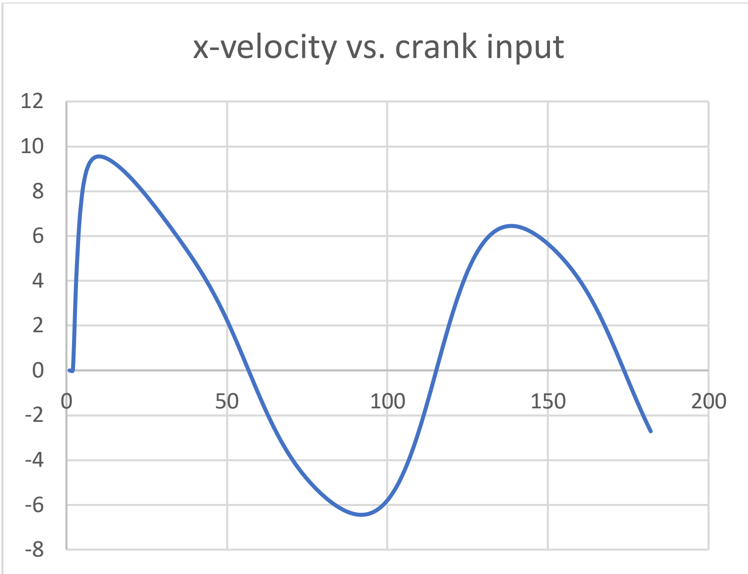
Ixx = 149950.14	Ixy = 12435.55	Ixz = -30542.19
Iyx = 12435.55	Iyy = 147875.97	Iyz = -41840.97
Izx = -30542.19	Izy = -41840.97	Izz = 30328.21

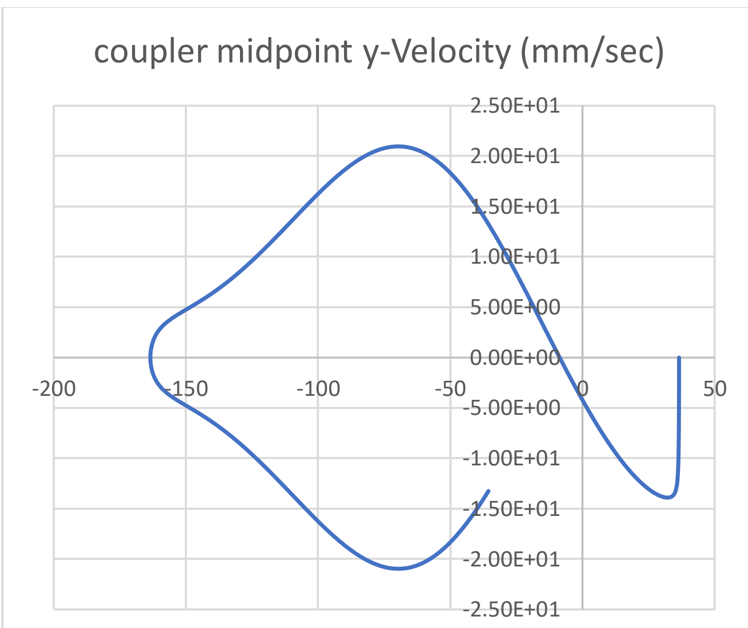




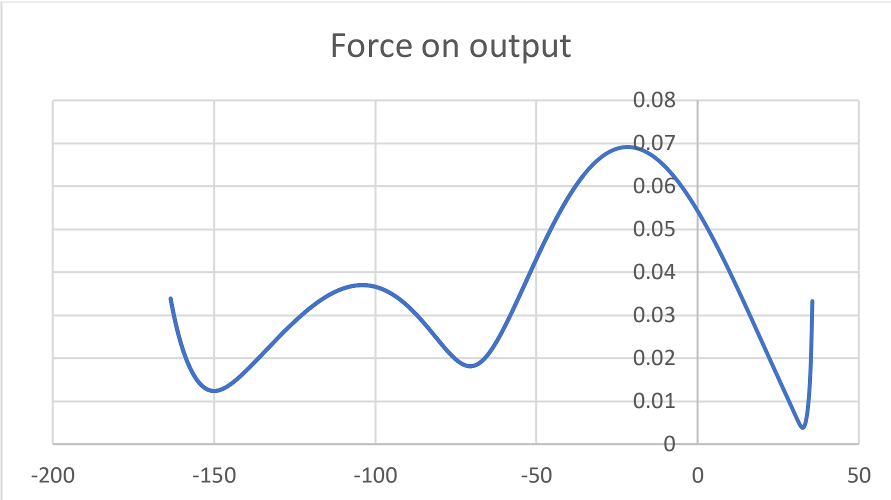
B. Show how closely your linkage comes to the three precision points and the one prescribed velocity by plotting the output pathway curve and the output velocity curve.



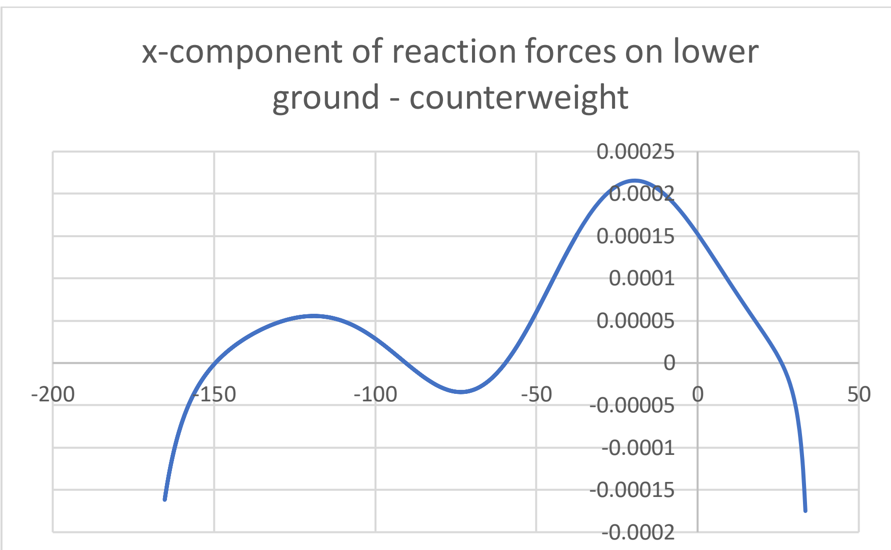


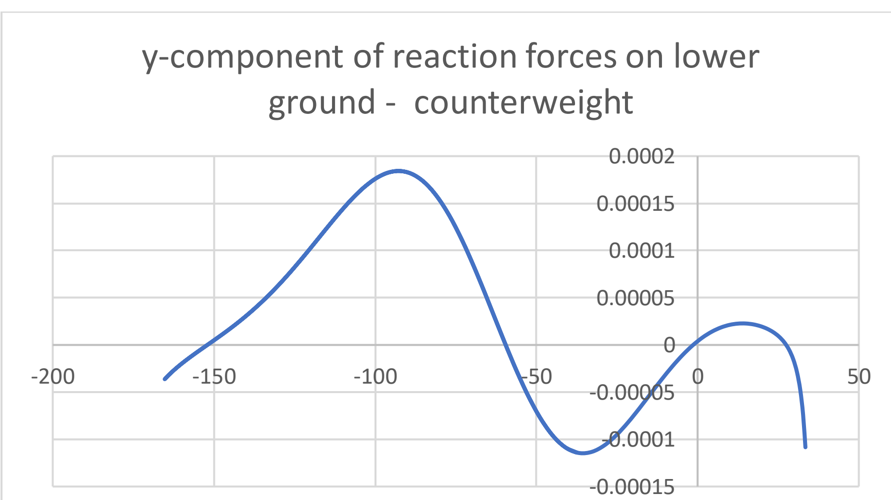


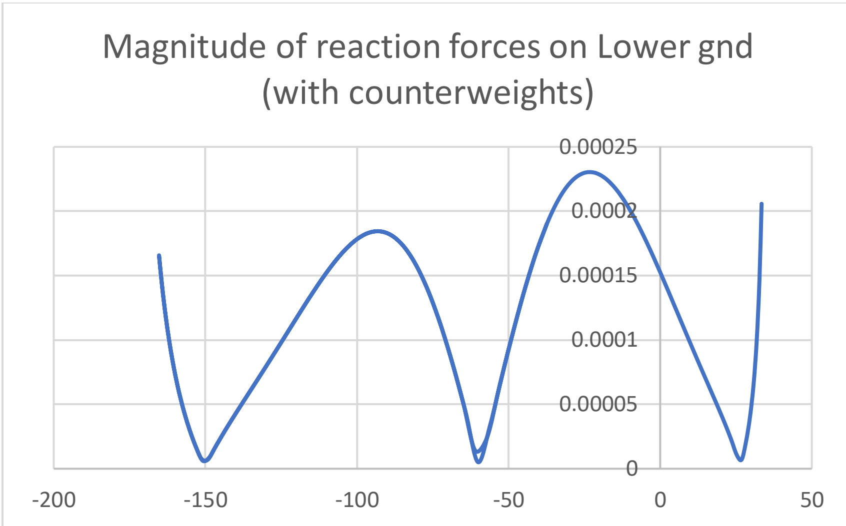
C. Plot the force output through the entire duty cycle:

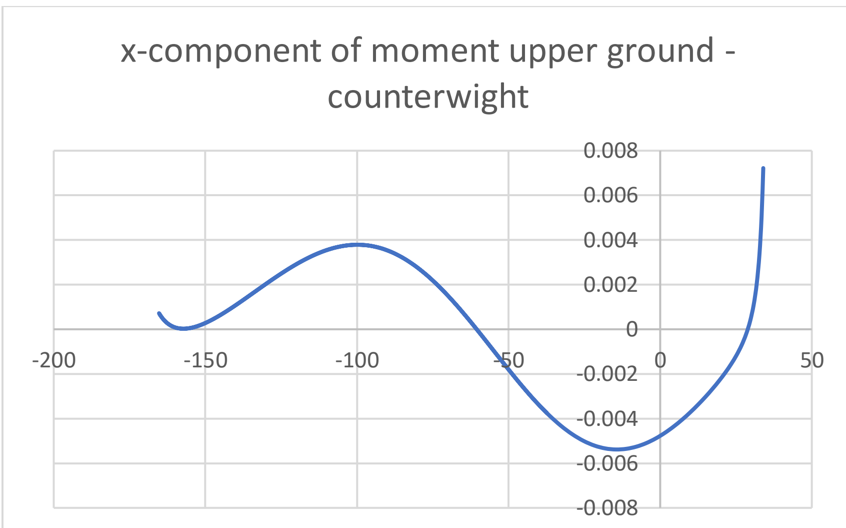


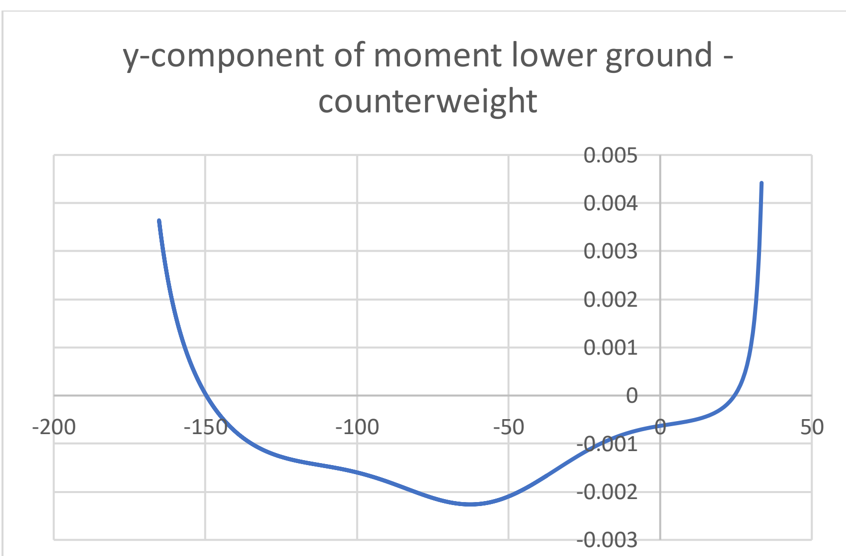
D. Show the shaking force and the shaking moment for your final design

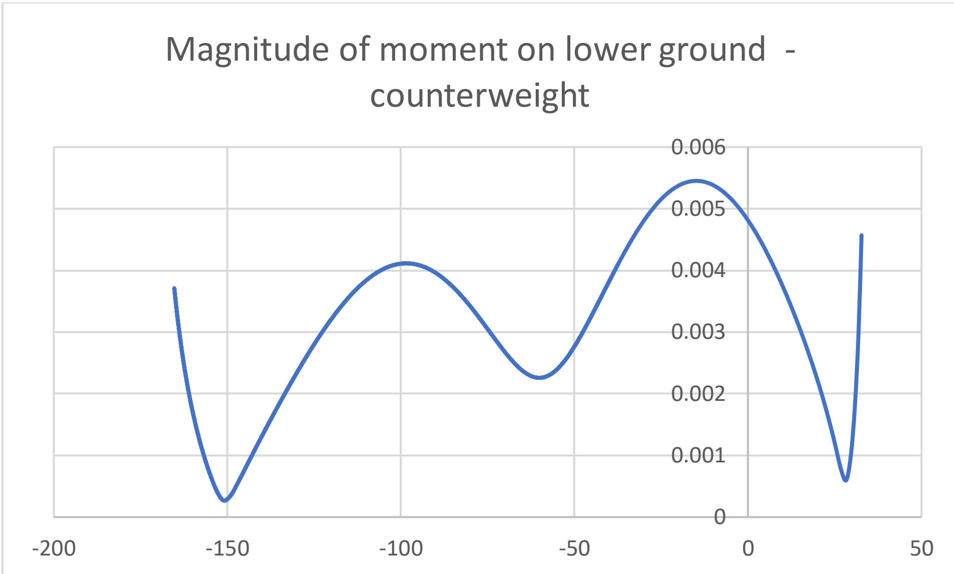


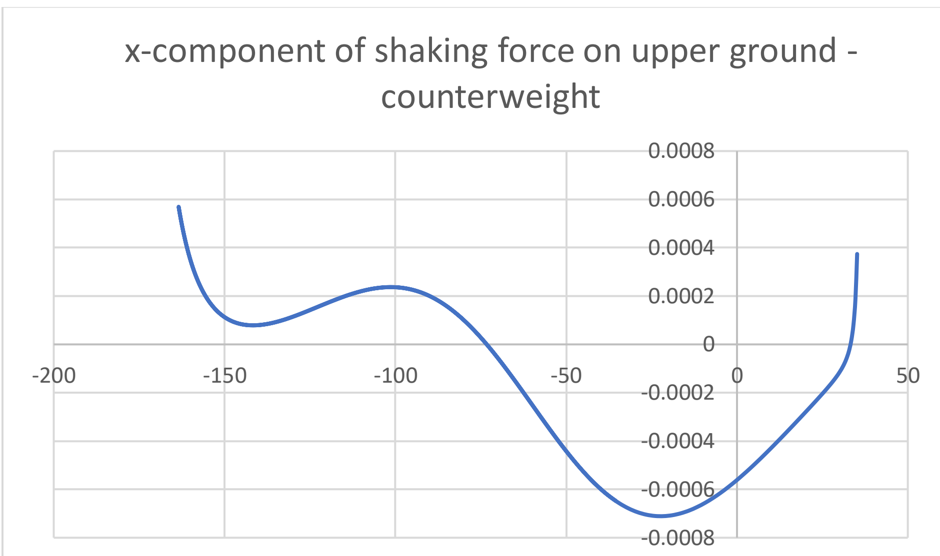


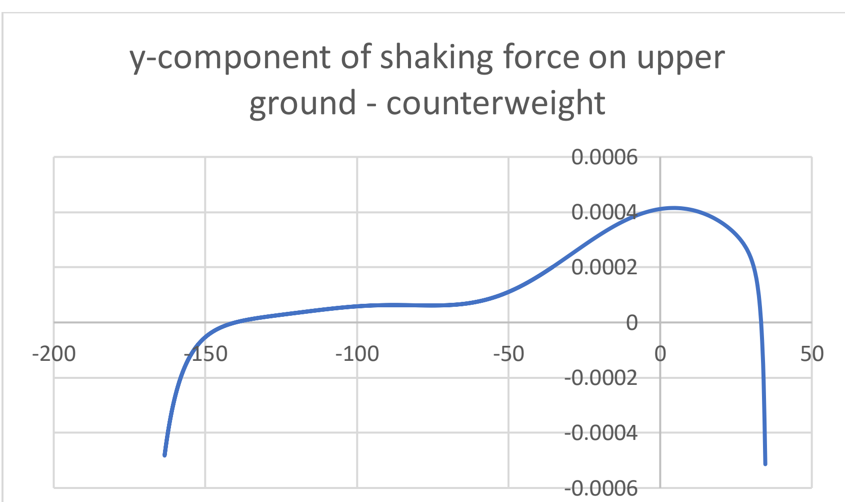

Magnitude of reaction forces on Lower gnd (with counterweights)
0.00025
0.0002
0.00015
0.0001
0.00005
0
-200
-150
-100
-50
0
50

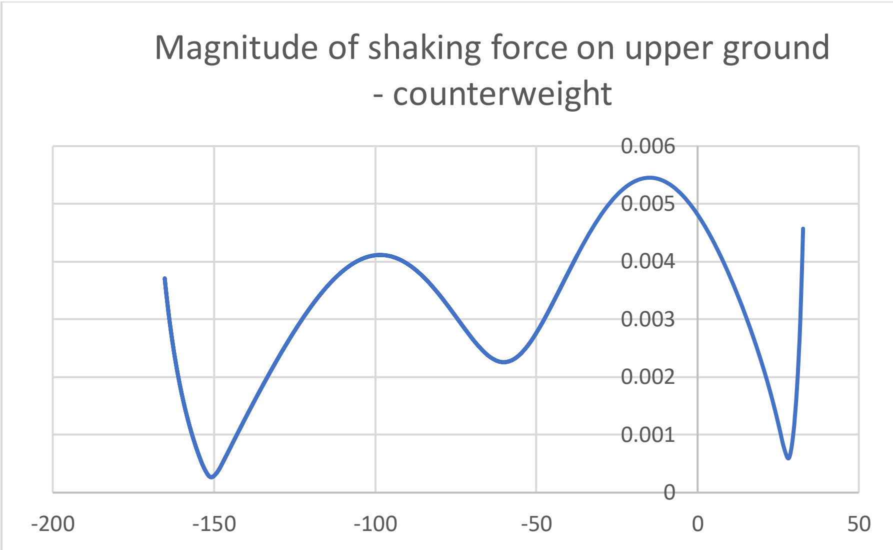

x-component of moment upper ground - counterwight
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-200
-150
-100
-50
0
50


y-component of moment lower ground - counterweight
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-200
-150
-100
-50
0
50


Magnitude of moment on lower ground - counterweight
0.006
0.005
0.004
0.003
0.002
0.001
0
-200
-150
-100
-50
0
50


x-component of shaking force on upper ground - counterweight
0.0008
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
-200
-150
-100
-50
0
50


y-component of shaking force on upper ground - counterweight
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-200
-150
-100
-50
0
50



Using the applied counterweights, the shaking moment previously measured on the upper ground joint was eliminated.