Chronological summary of the work performed during my Thesis

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TU Delft

Ansys

- The first couple of weeks consisted mostly of getting familiar with Ansys and starting some small parameter sweeps run from MATLAB. Some errors I ran into:
  - Extra singularity for atand(L33/L11) = Alpha
  - Output of the simulations consisted of double data for the area u_in > 0

Clear resin

- Use flexural modulus? (2.2 GPa)
- Data on yield strength? (calculate through elongation at failure?)

	METRIC[1]		IMPERIAL[1]		METHOD
	Green[2]	Post-Cured[3]	Green[2]	Post-Cured[3]	
Tensile Properties					
Ultimate Tensile Strength	38 MPa	65 MPa	5510 psi	9380 psi	ASTM D 638-10
Tensile Modulus	1.6 GPa	2.8 GPa	234 ksi	402 ksi	ASTM D 638-10
Elongation at Failure	12 %	6.2 %	12 %	6.2 %	ASTM D 638-10
Flexural Properties					
Flexural Modulus	1.25 GPa	2.2 GPa	181 ksi	320 ksi	ASTM C 790-10
Impact Properties					
Notched IZOD	16 J/m	25 J/m	0.3 ft-lbf/in	0.46 ft-lbf/in	ASTM D 256-10
Temperature Properties					
Heat Deflection Temp. @ 264 psi	42.7 °C	58.4 °C	108.9 °F	137.1 °F	ASTM D 648-07
Heat Deflection Temp. @ 66 psi	49.7 °C	73.1 °C	121.5 °F	163.6 °F	ASTM D 648-07

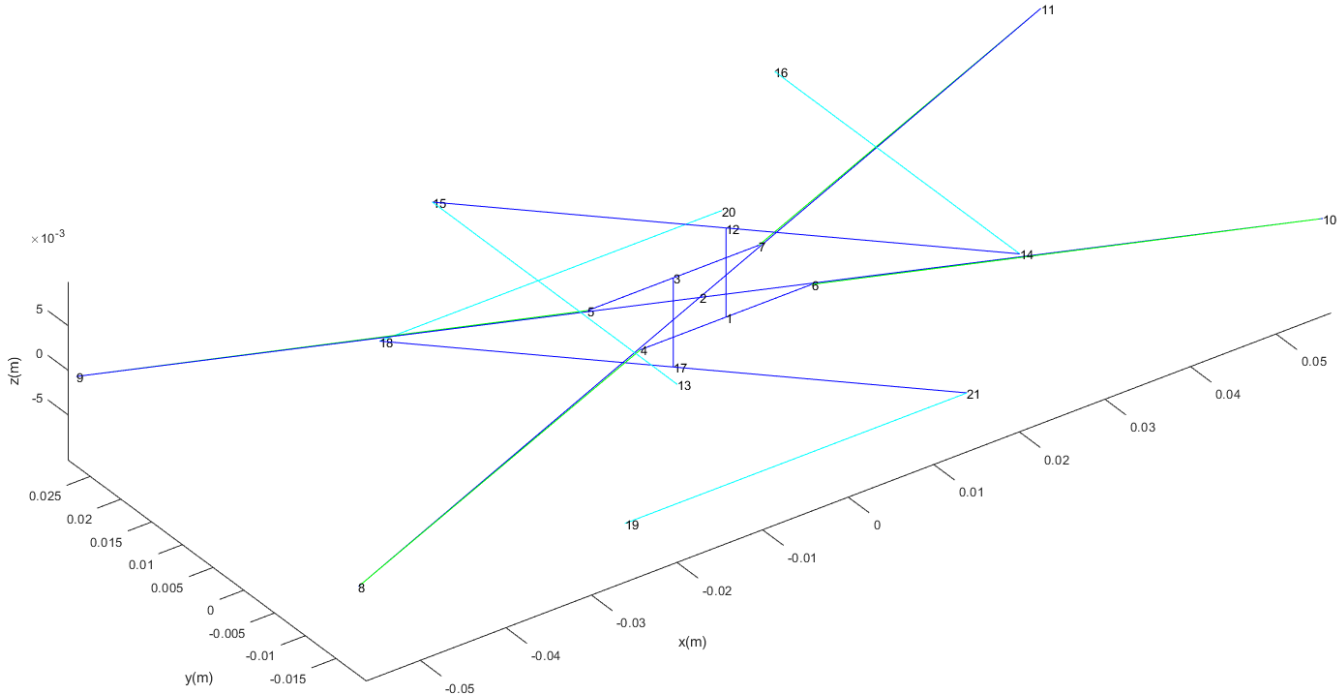
[1] Material properties can vary with part geometry, print orientation, print settings, and temperature.

[2] Data was obtained from green parts, printed using Form 2, 100 µm, Clear settings, washed and air dried without post cure.

[3] Data was obtained from parts printed using Form 2, 100 µm, Clear settings, and post-cured with 1.25 mW/cm^2 of 405 nm LED light for 60 minutes at 60 °C.

Kinematics

- Behavior when atand(L33/L11) = Alpha.
  - When the flexures create a rotation point in the middle of the system.
- How to deal with this?
- 1) Run check before – dependent on parameters + limit computations
- 2) Check if Ansys produces error



Handling of data

Data handling

- Overview of all tested possibilities. Add new cases.
- Avoid running an existing solution again.
- Makes sure all data is saved.

Solution?:

- Object oriented
  - Save textfiles with all data per case, or save objects with data as property.
  - How to check for duplicates

Implementing Criteria

Optimization

- How extensive should the search be?
- Should I investigate using optimization algorithms?
  - What should the objective be?
  - Constraints?

Yield strength

- Ultimate strength, 65 MPa
- Highest a viable design gets to is

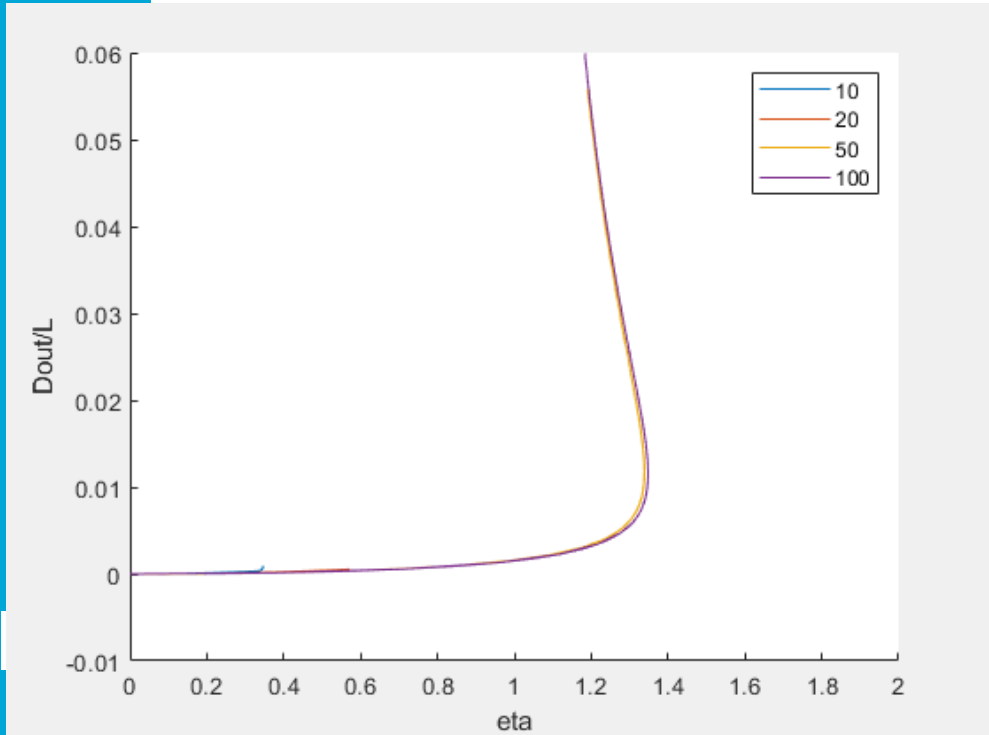
  <30 MPa

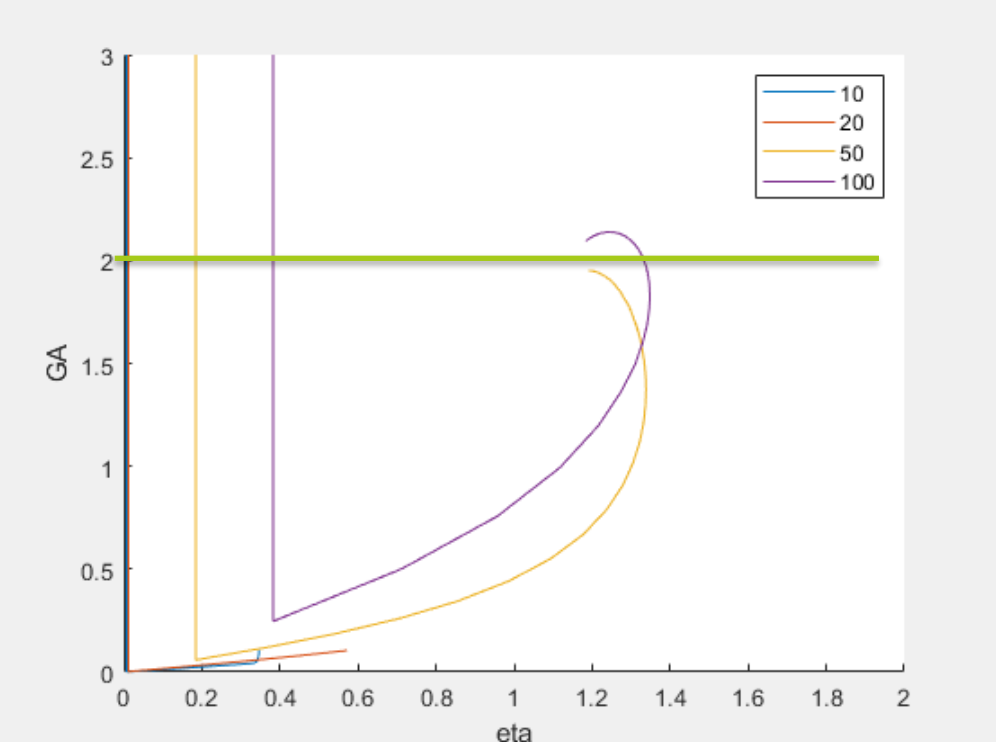
Kinetoelastic map

- To Non-Dimensionalize a compliant mechanism
- $\eta = \frac{Fs^2}{Ebd}, s = \frac{L}{d}$ All are average values. S

s, was determined by changing d. By increasing the force eta changes.

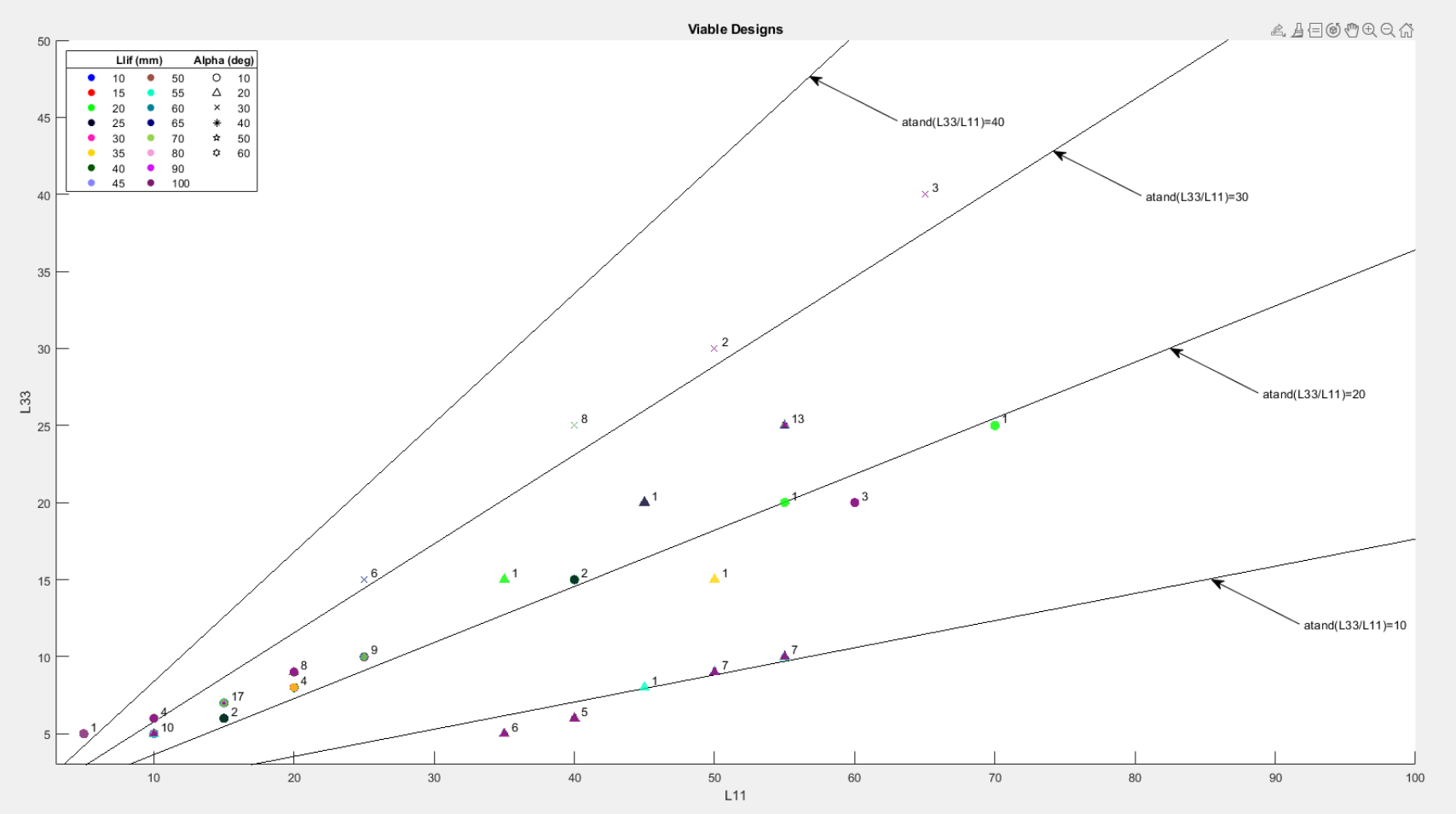
(Did have to increase b(out of plane thickness), to counter out of plane displacement)





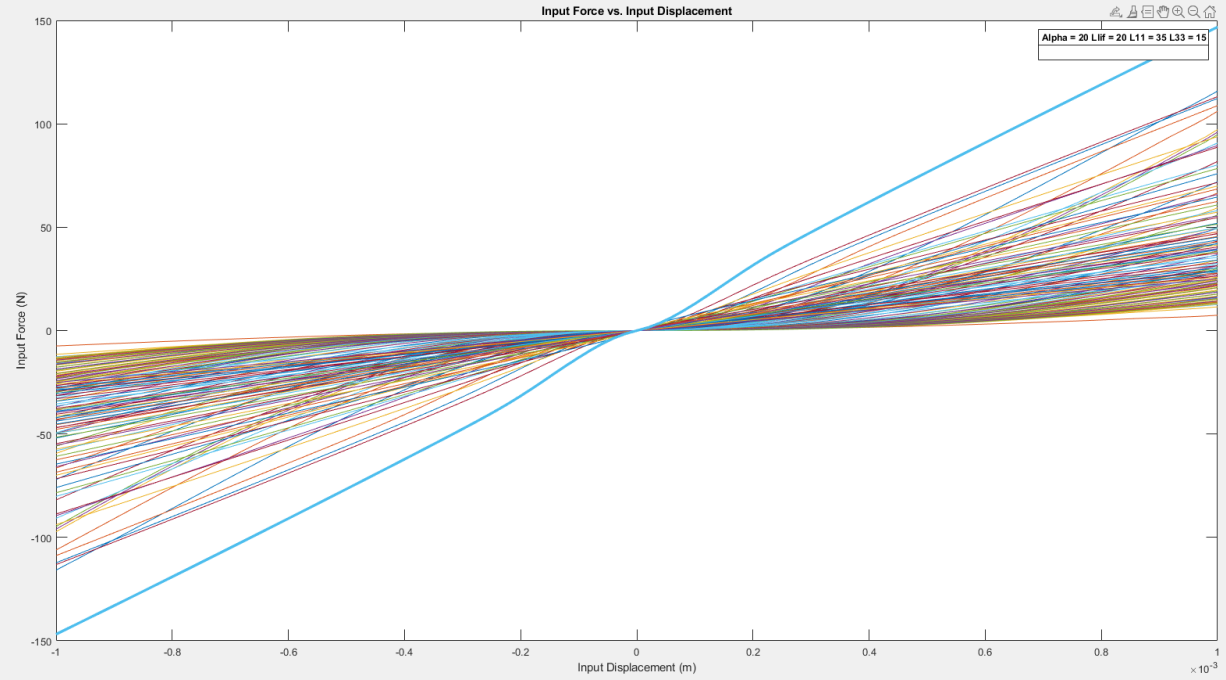
Viable designs

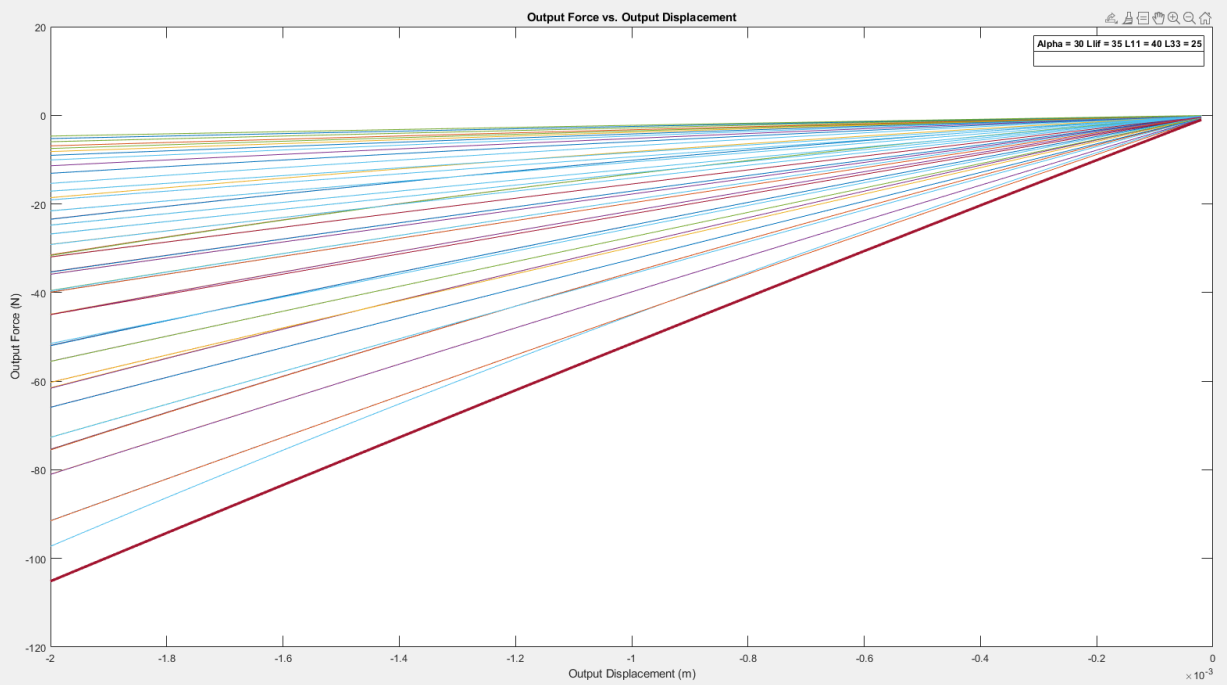
```
Alpha = [10,20,30,40,50,60,70]; %deg 22, angle
Llif = [10,15,20,25,30,35,40,45,50,55,60,65,70,80,90,100]*Dinput;
Lll = [5,10,15,20,25,30,35,40,45,50,55,60,65,70]*Dinput; %mm 18, w
L33 = [5,6,7,8,9,10,15,20,25,30,35,40,45,50]*Dinput; %mm 8.6, hei
```



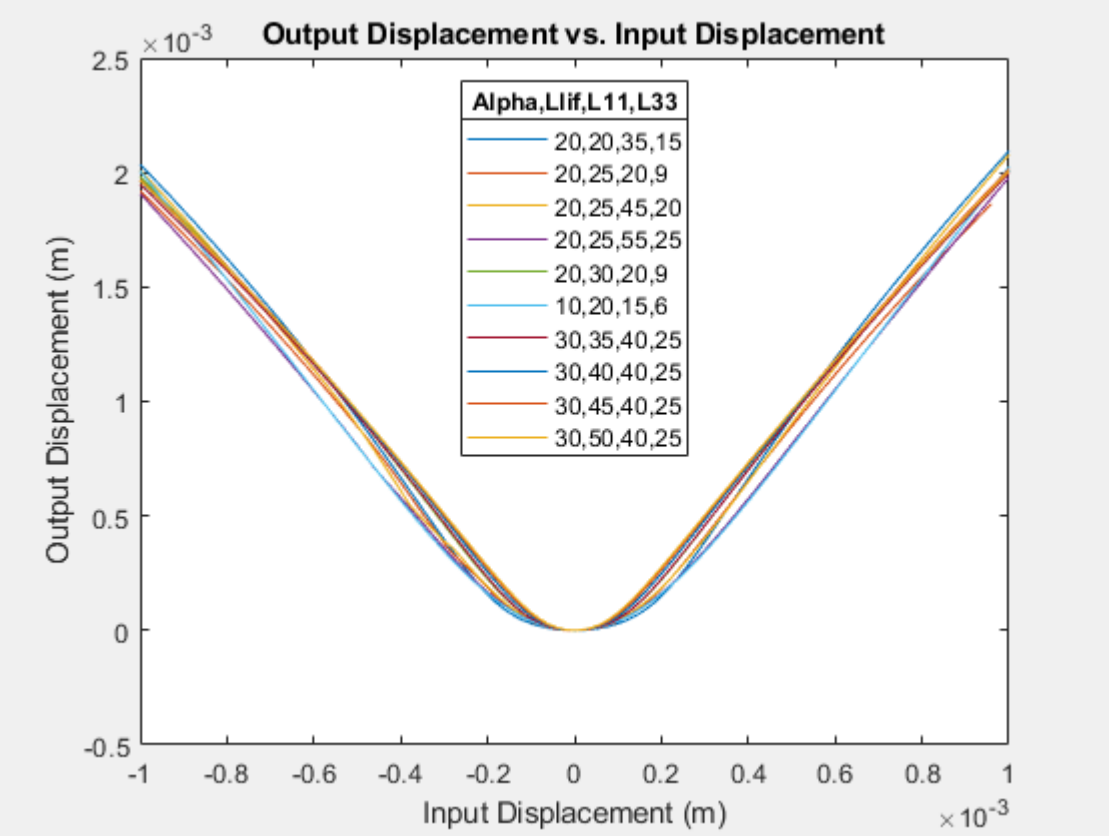
Viable designs

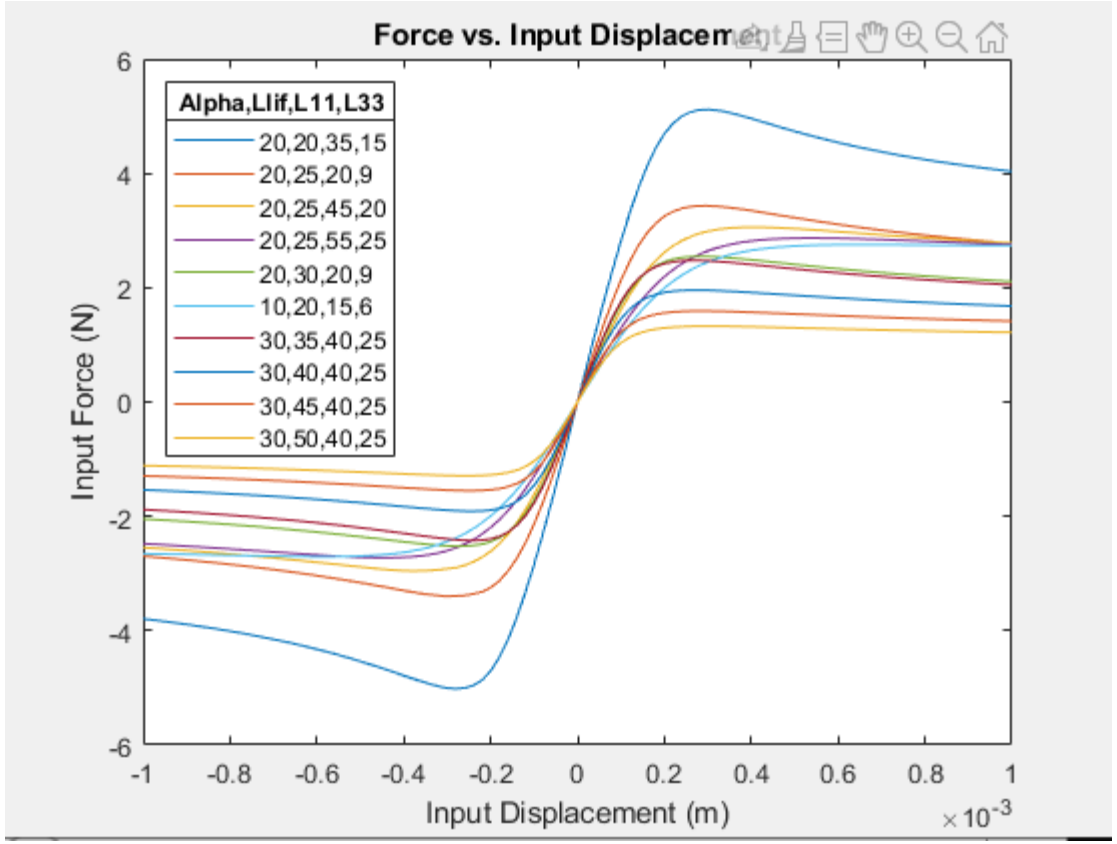
- Testing input and output stiffness





~10 best designs

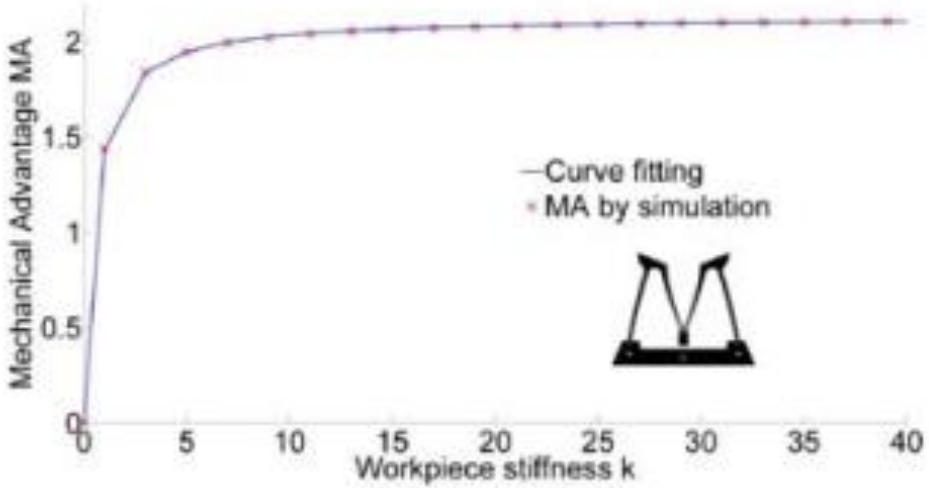




- Next step?
- How to make sure this is the global optimum

MA

- Did not find any formulae for MA with components of input/output stiffness and actuation stiffness.



$$\mathbf{MA} = \mathbf{MA}_x\left(\frac{k_w}{\sigma + k_w}\right)$$

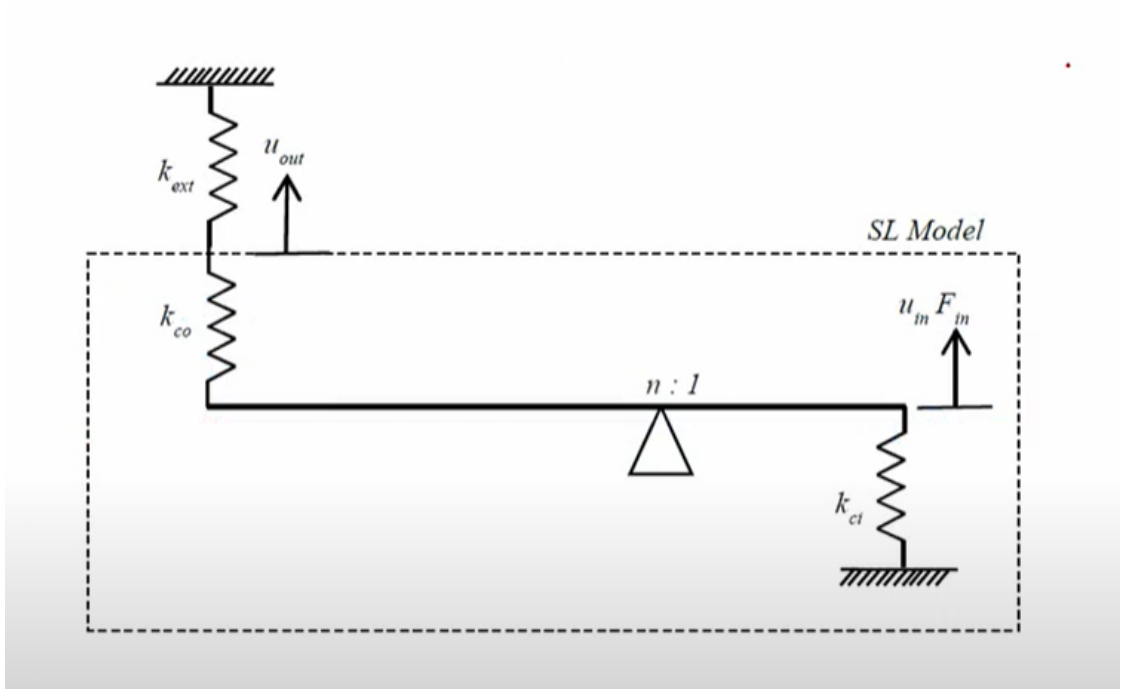
MA

$$\mathrm{MA} = \mathrm{MA}_s\left(\frac{k_w}{\sigma + k_w}\right)$$

- In one of his lectures Prof. Ananthasuresh does discuss some work of a master student with the following formula's:

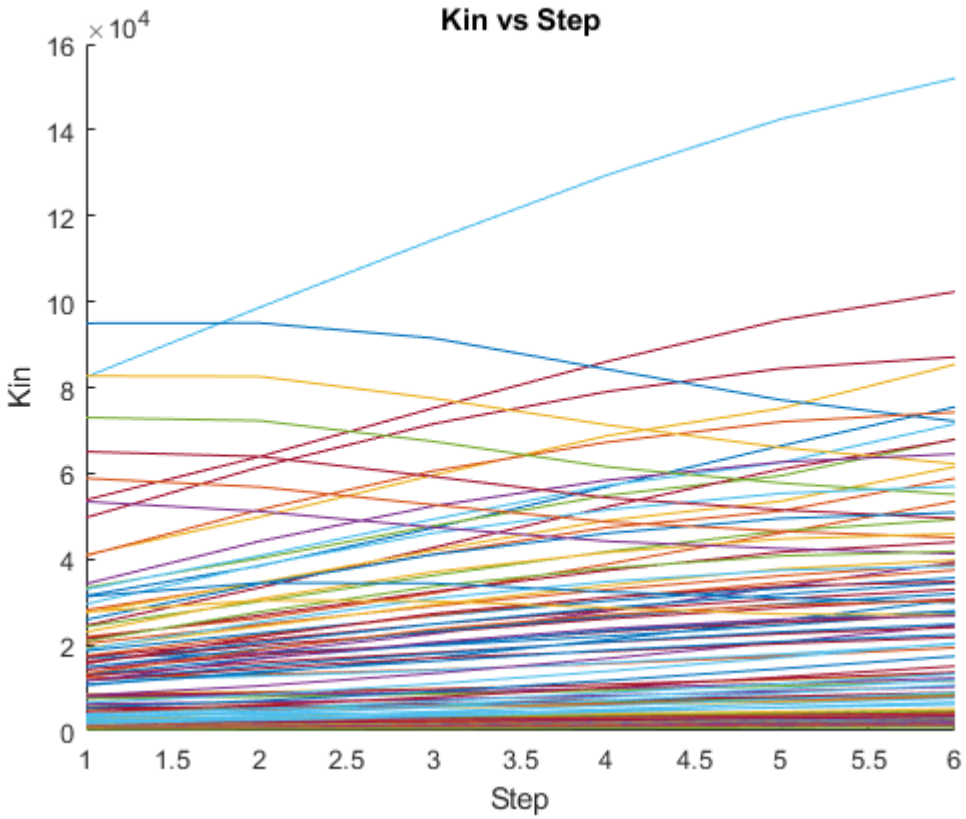
$$MA = MA_s\left(\frac{k_{ext}}{s_k + k_{ext}}\right)$$

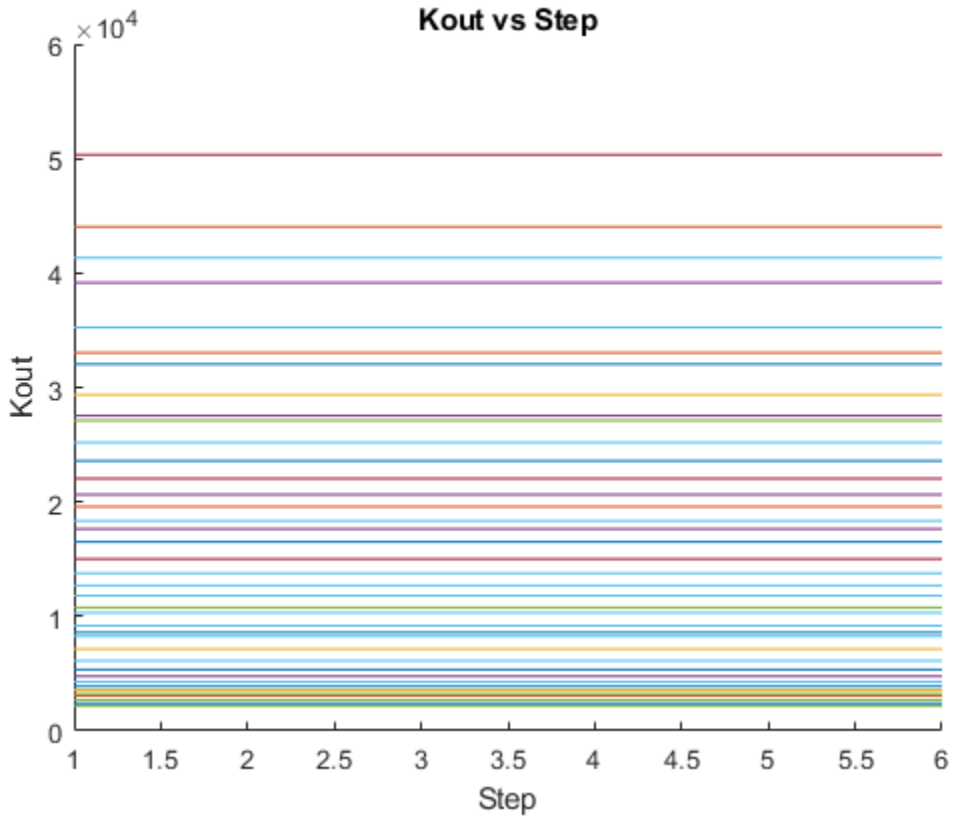
$$\left\{\begin{array}{l} MA_s = \dfrac{nk_{co}}{k_{ci} + n^2 k_{co}} \\ s_k = \dfrac{k_{ci}k_{co}}{k_{ci} + n^2 k_{co}} \end{array}\right\}$$



Visual investigation

- What are some reasonable values: Now have 0.3N 1% discrepancy of input, as that would result in a reasonable number of solutions





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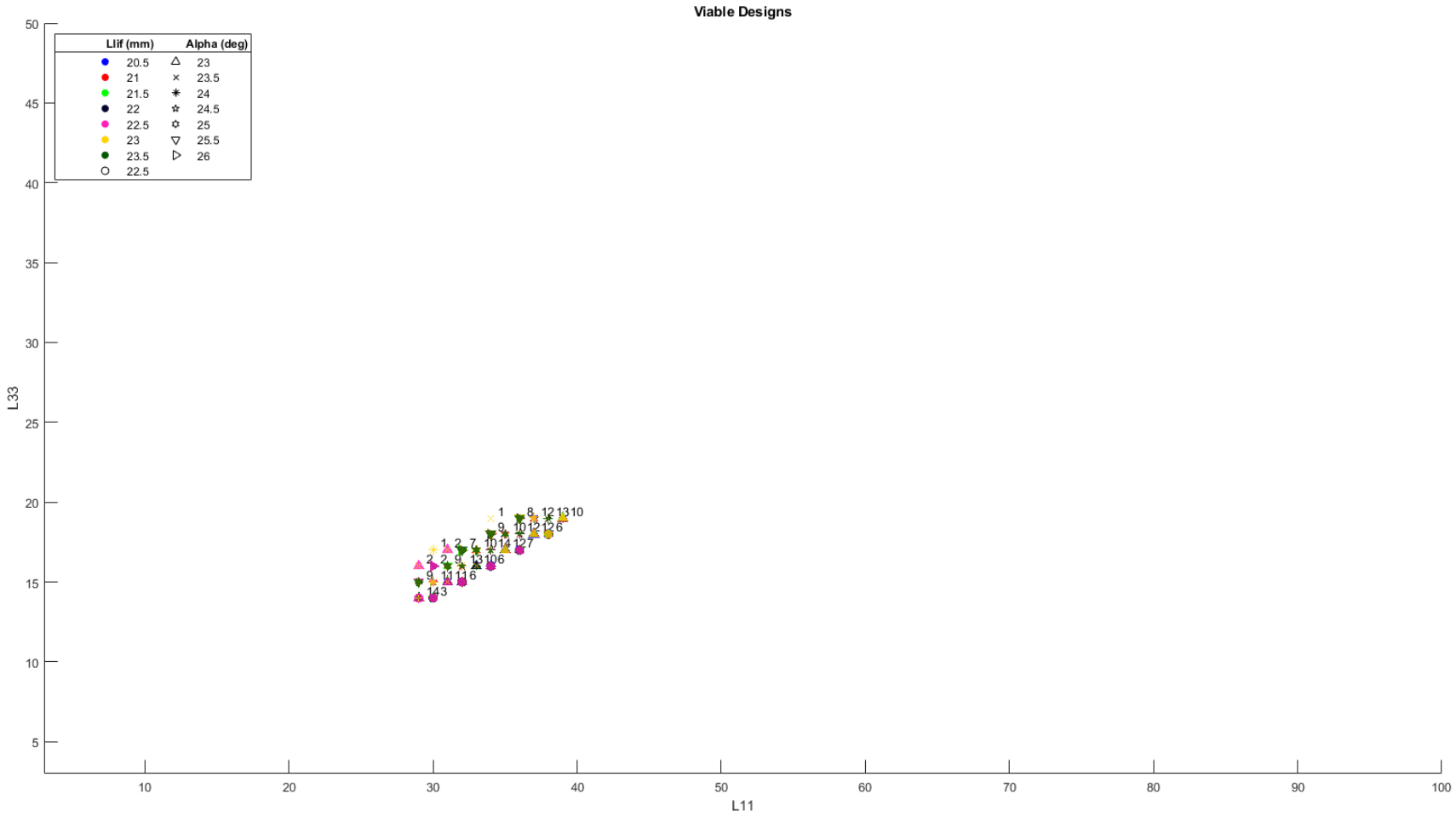
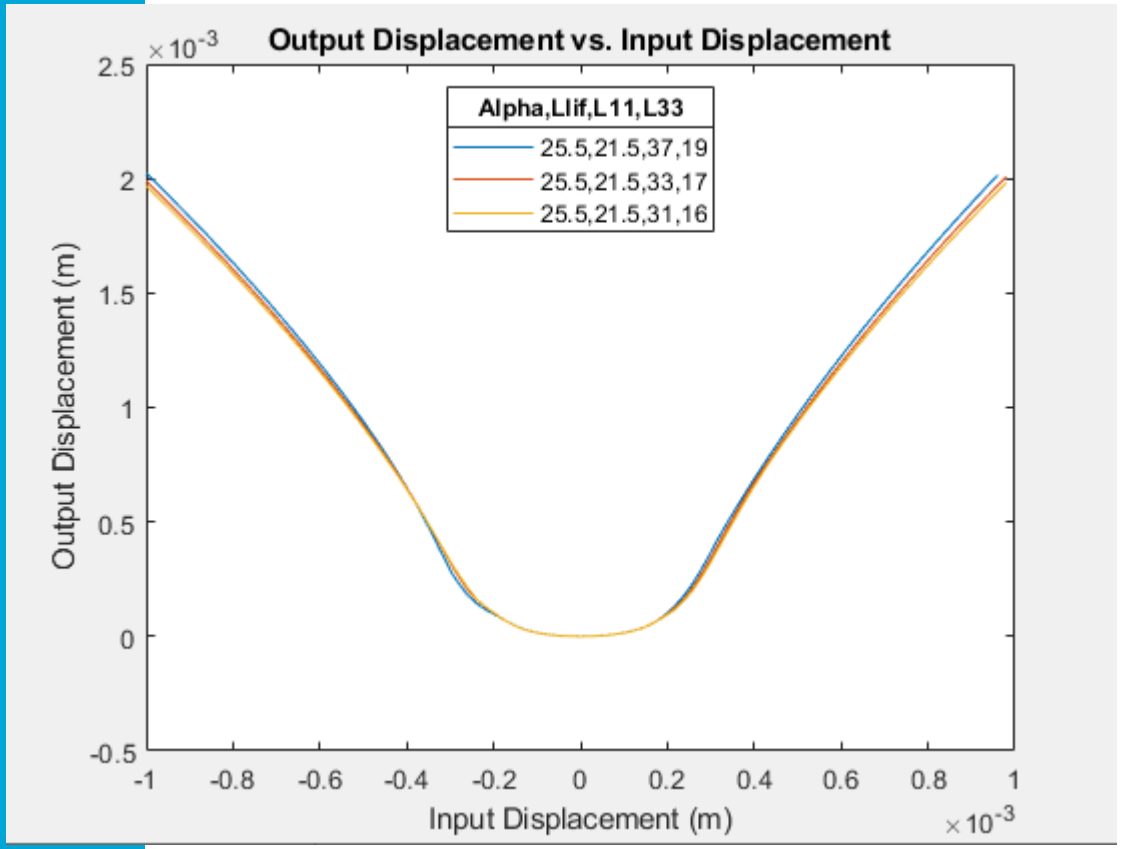
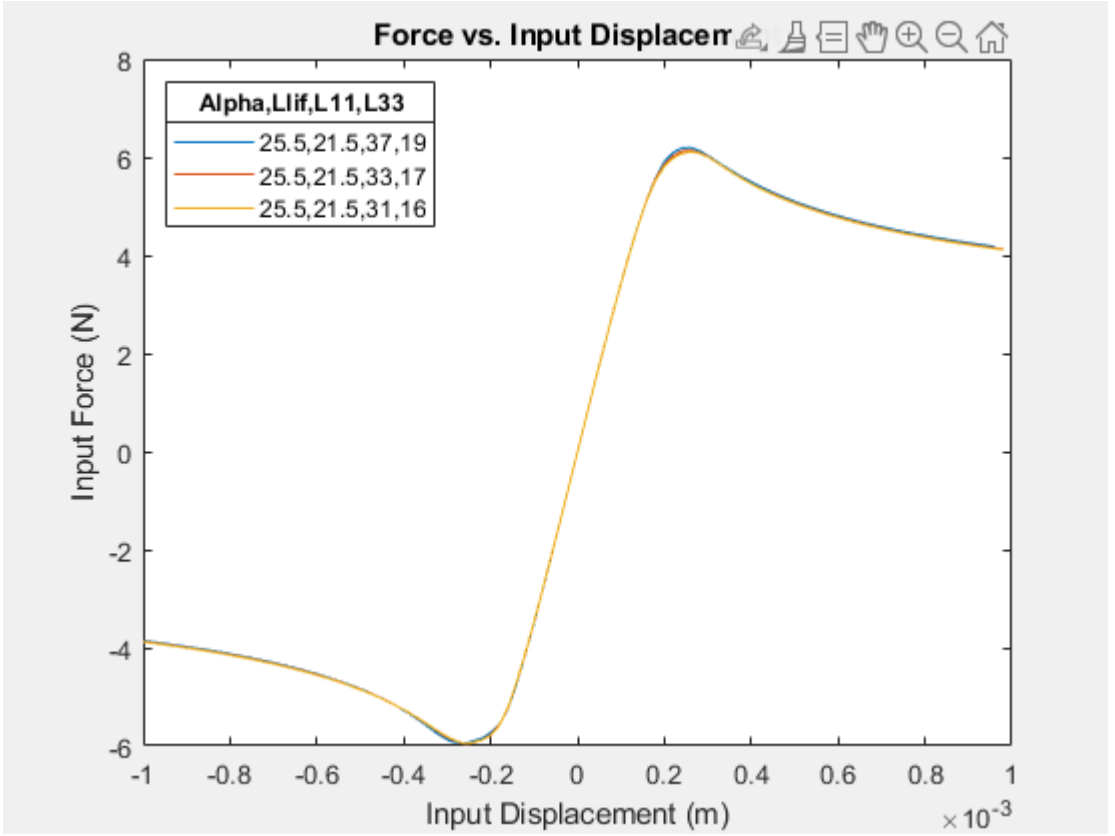
Result after 3 iterations

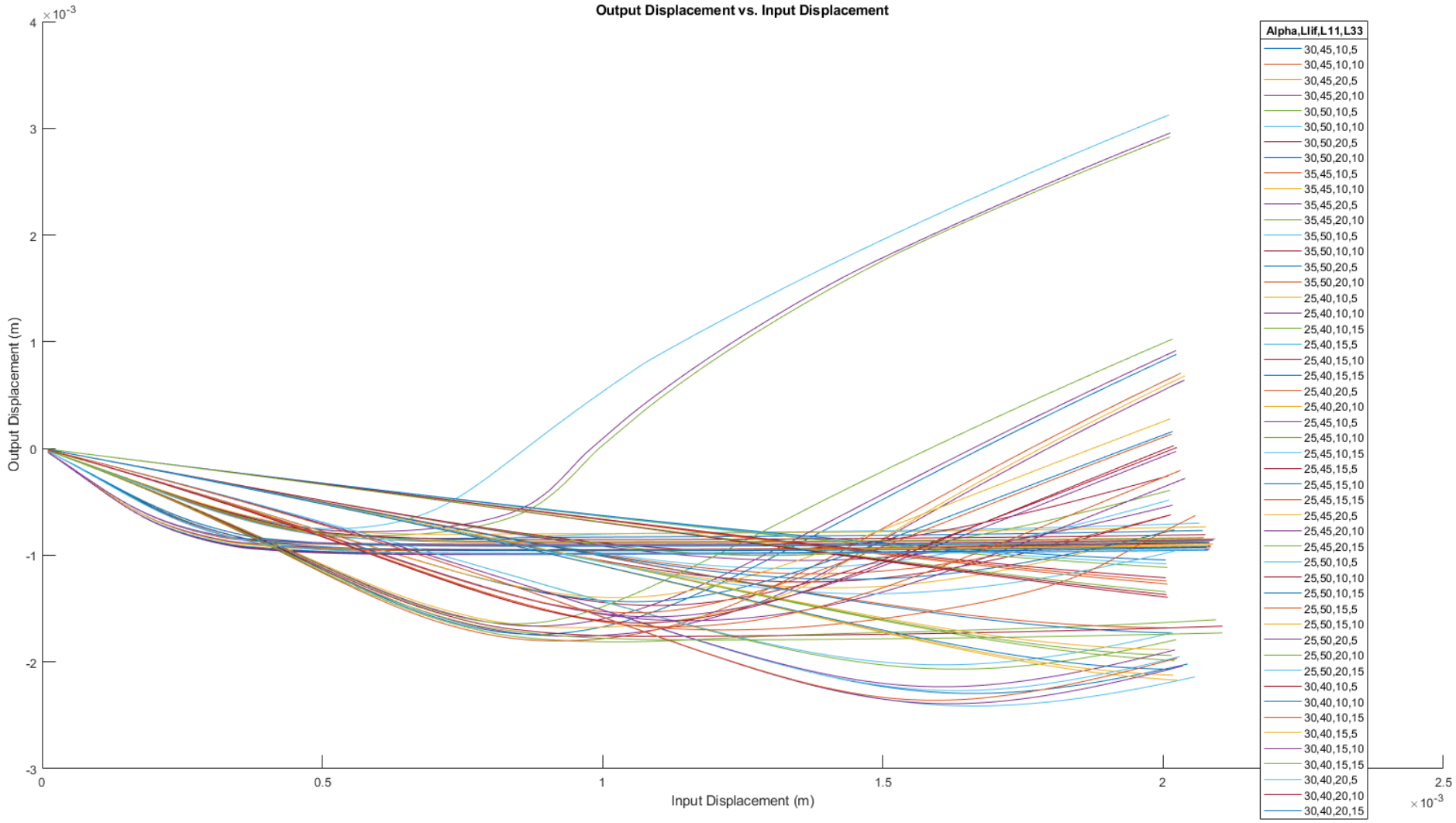


Din/Dout and Fin/Din of best designs





Cosinusoidal



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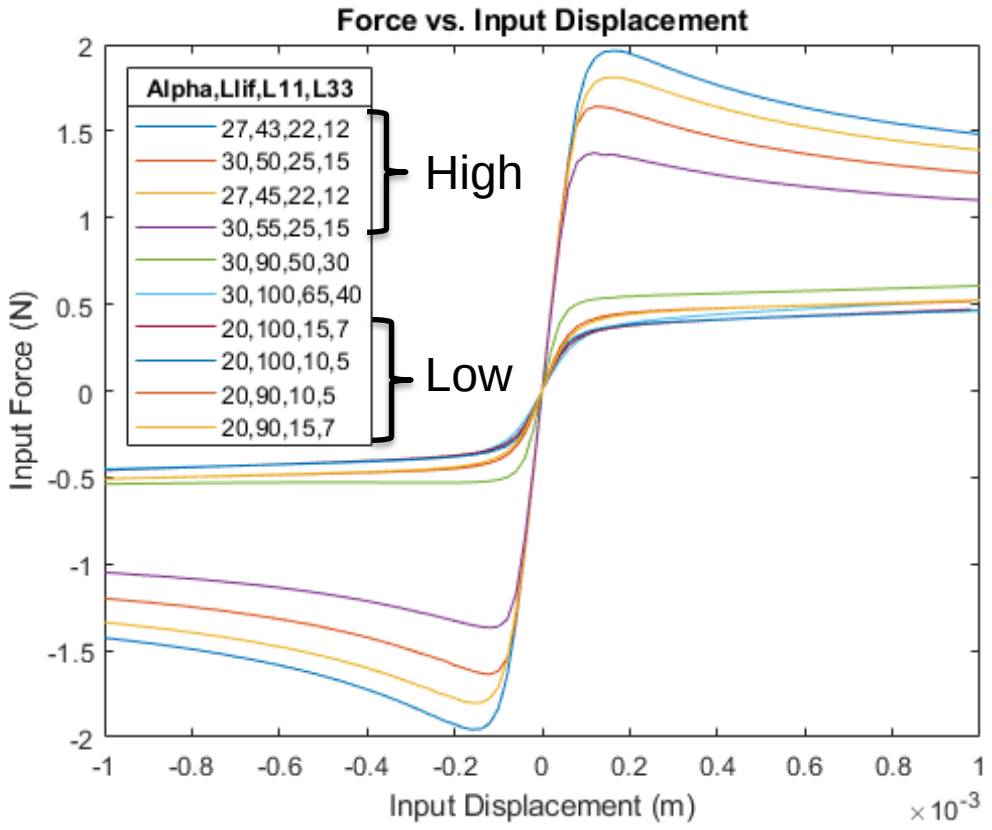
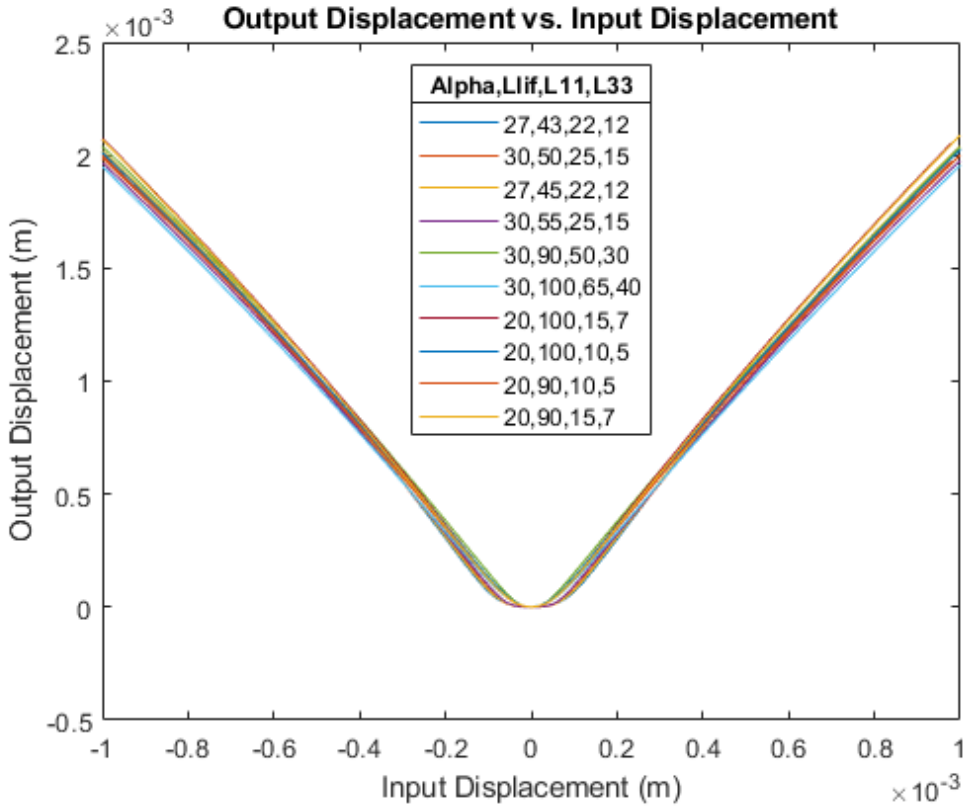
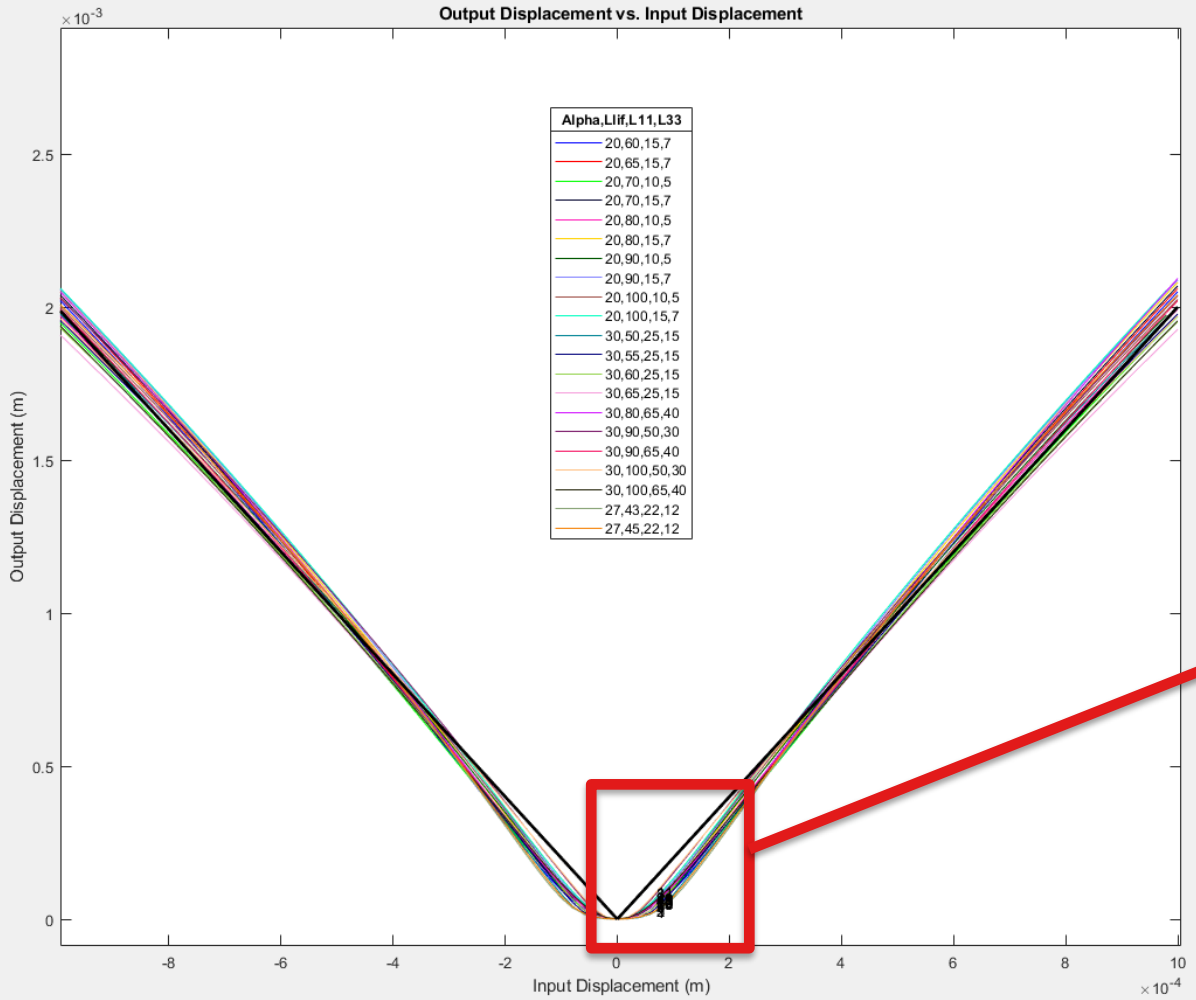
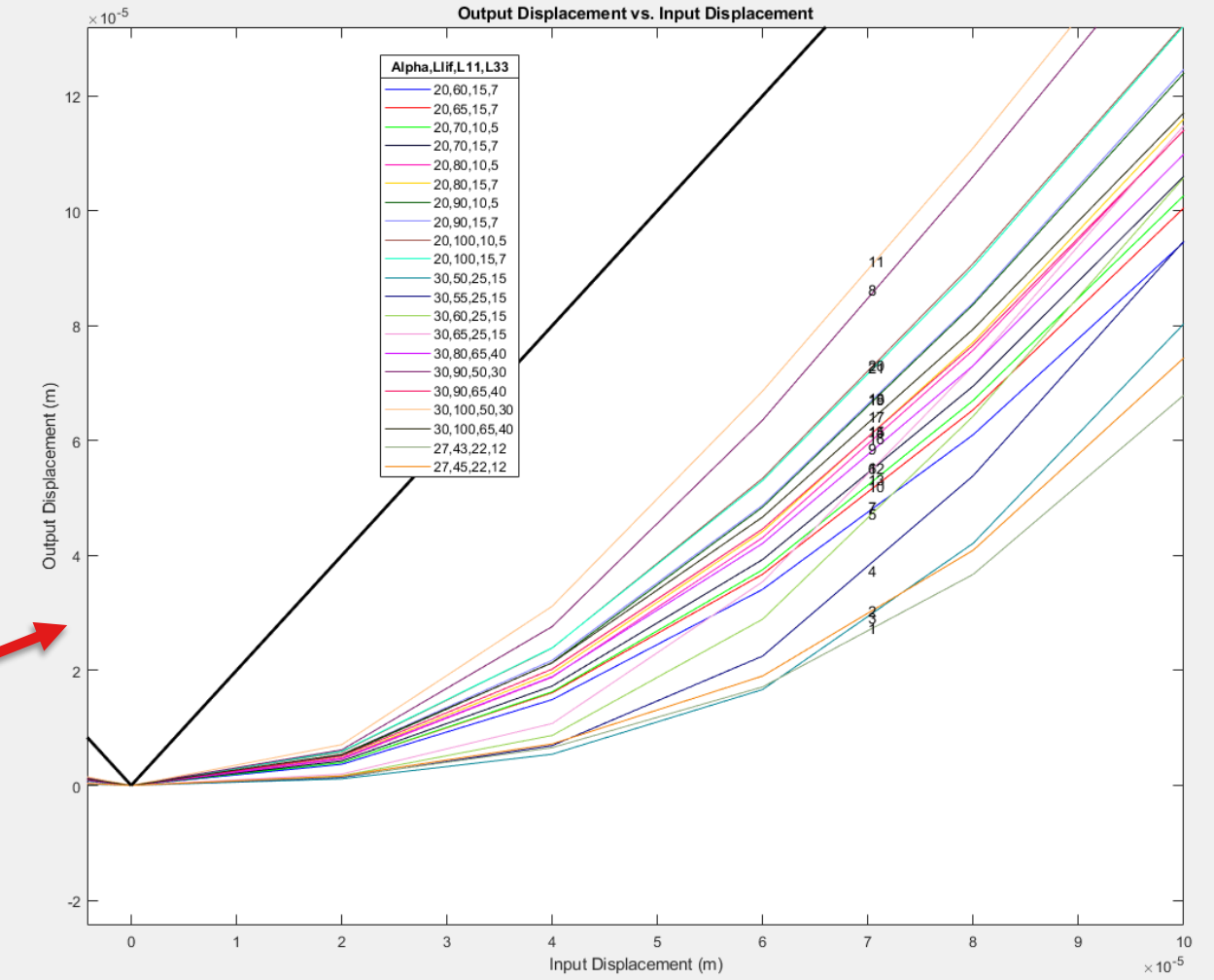
Stiffness Differences





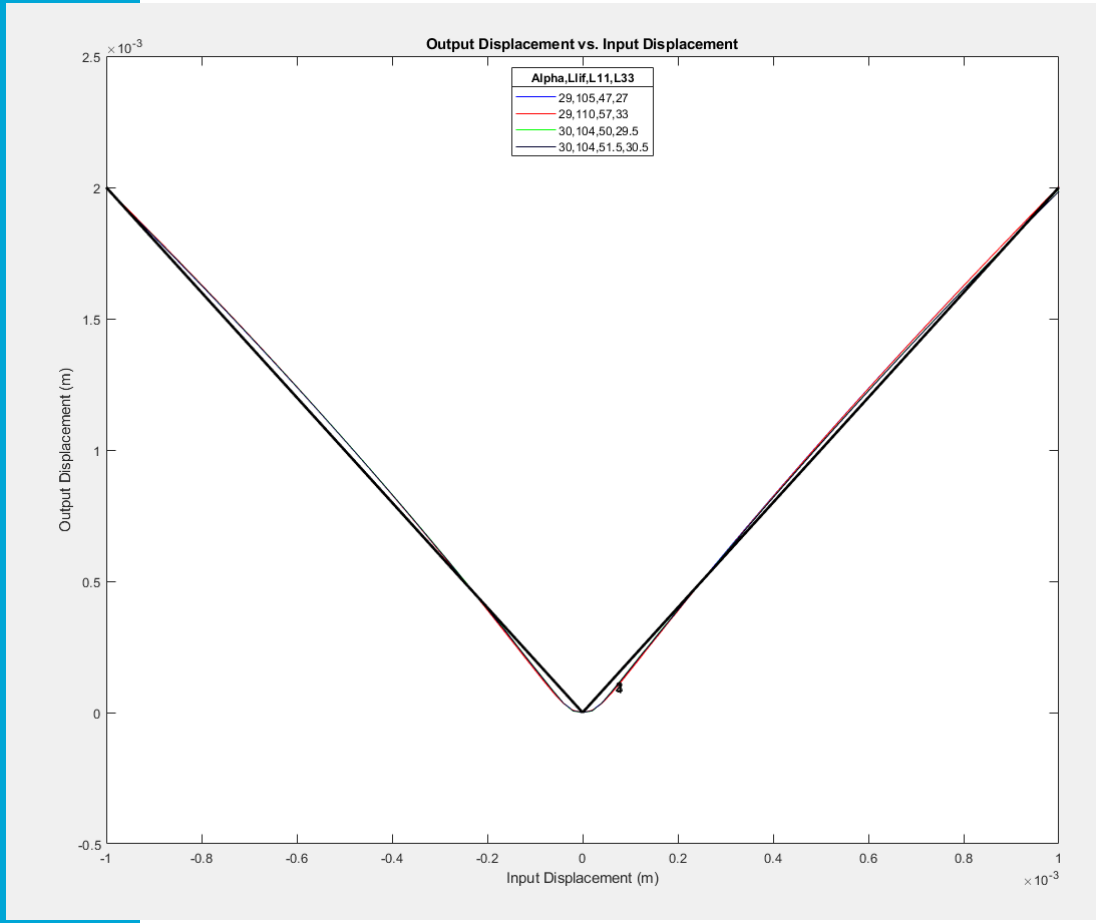
New criteria added

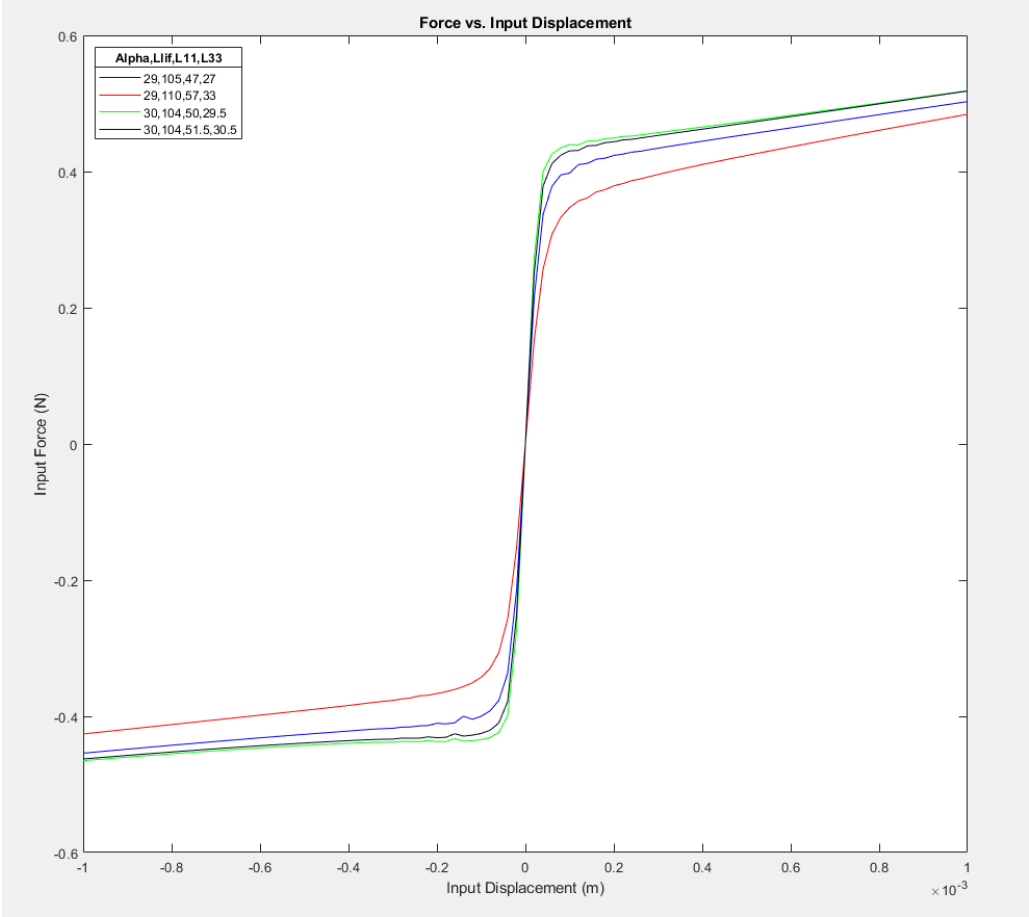




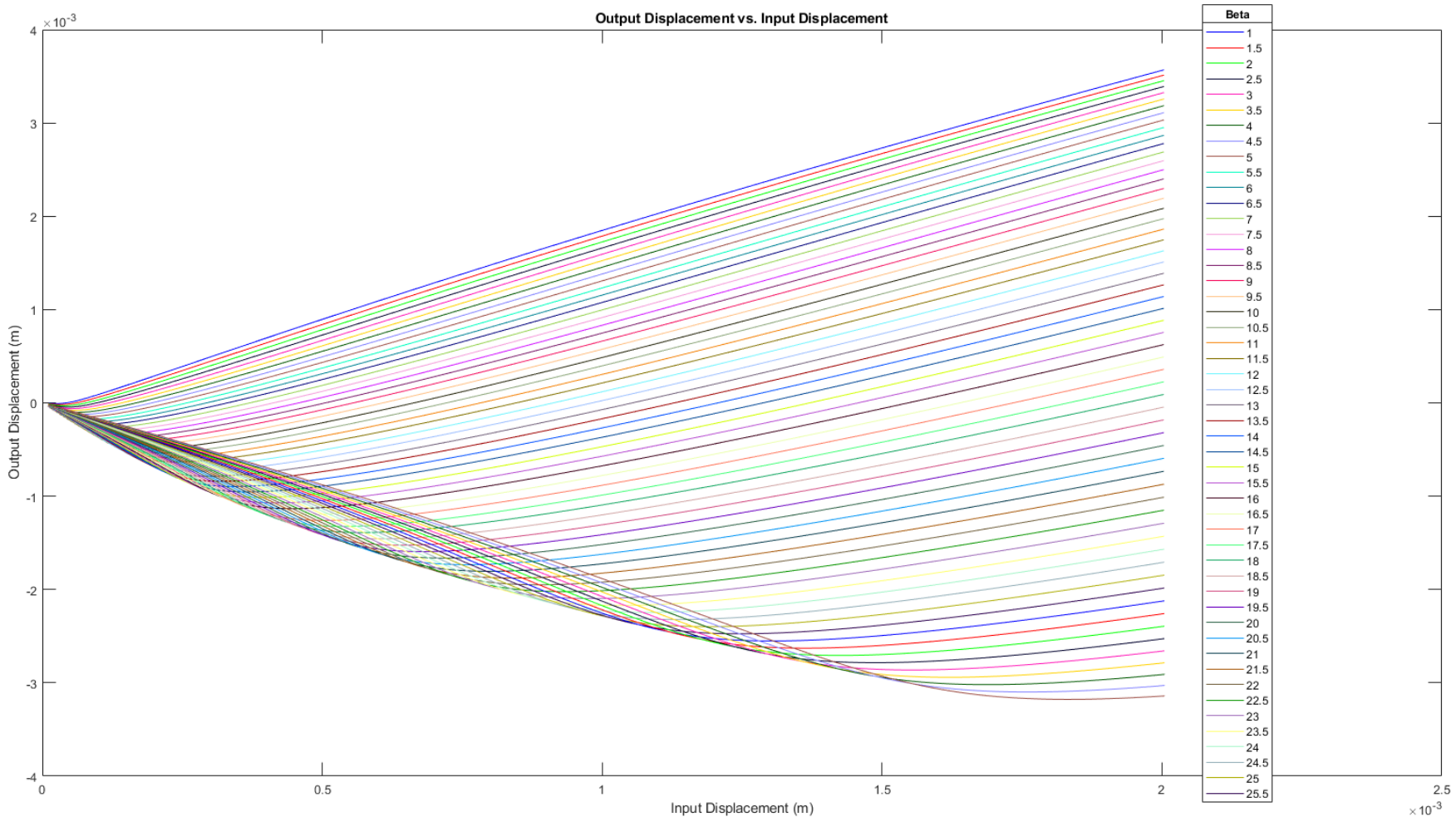
For now

- To converge, and to make sure not too many solutions exist the criteria bounds to check linearity of the GA decrease every

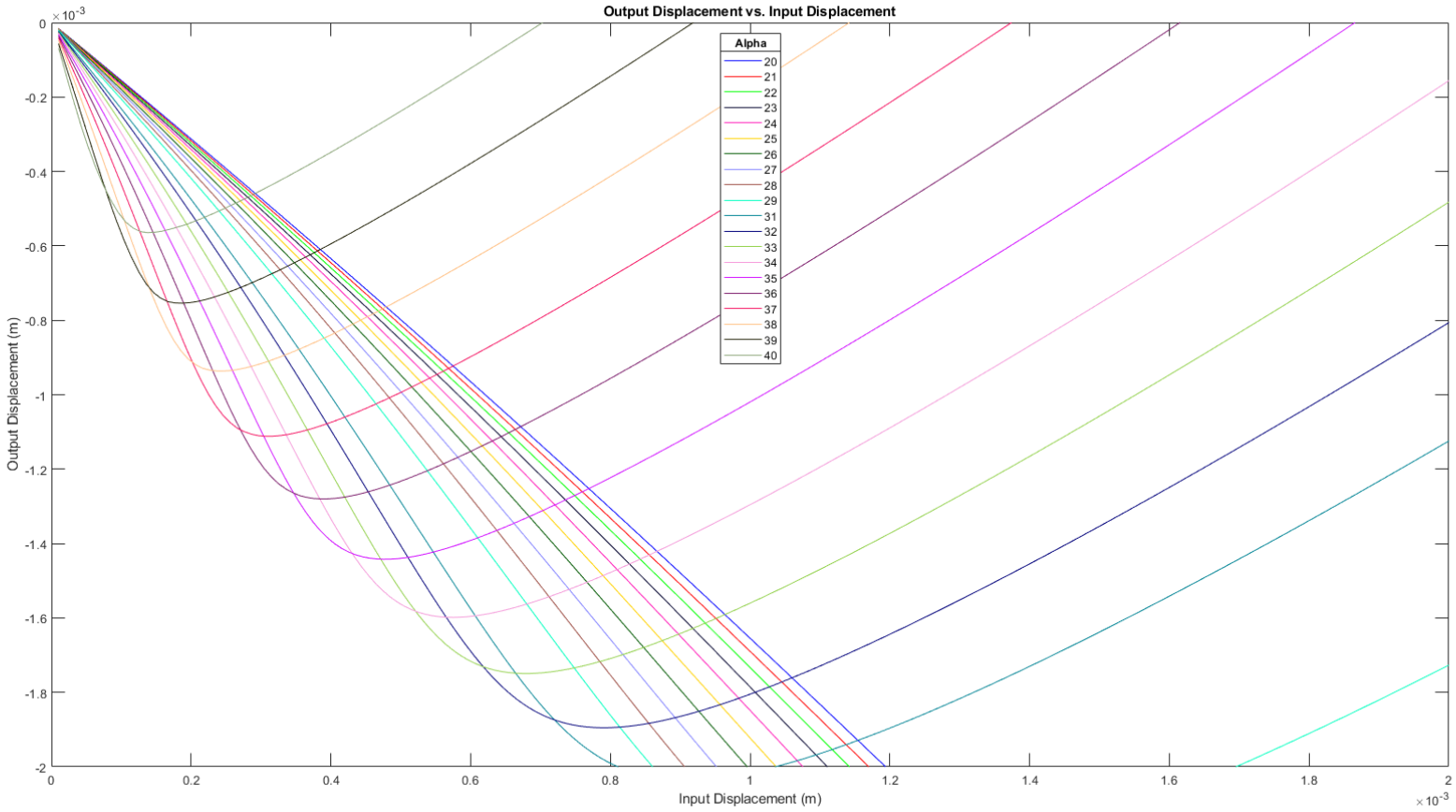




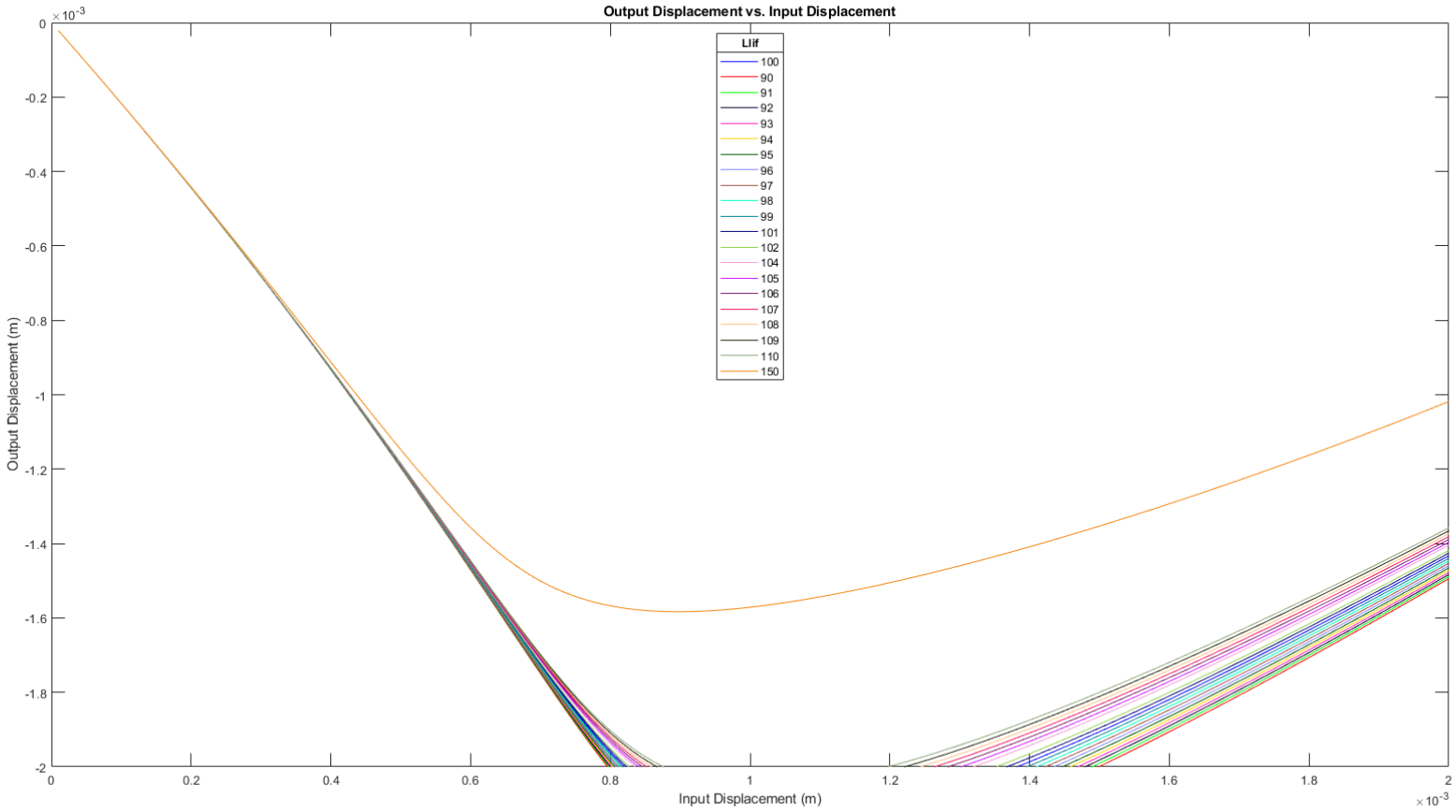
Sinusoidal → Cosinusoidal



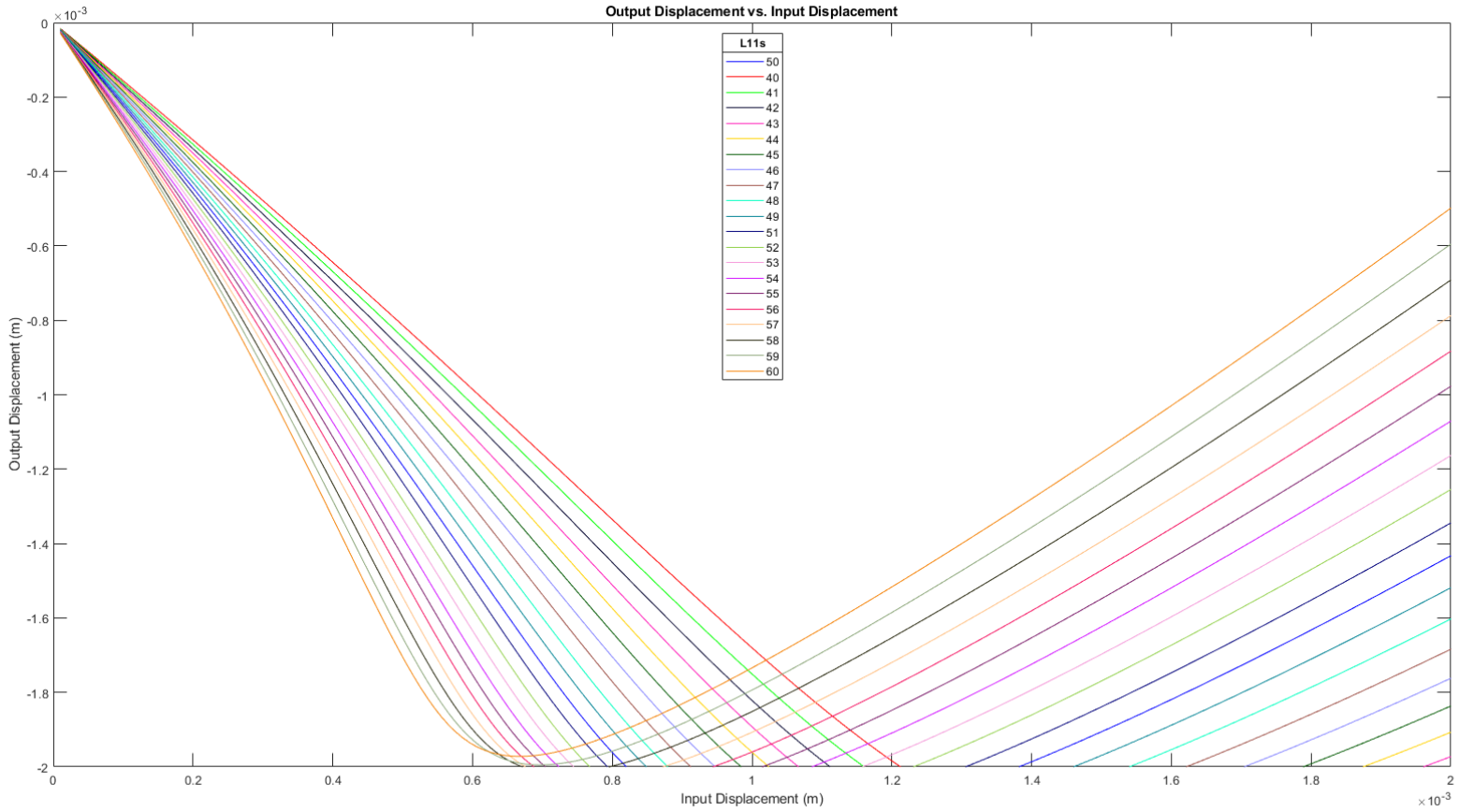
Sinusoidal → Cosinusoidal, Alpha



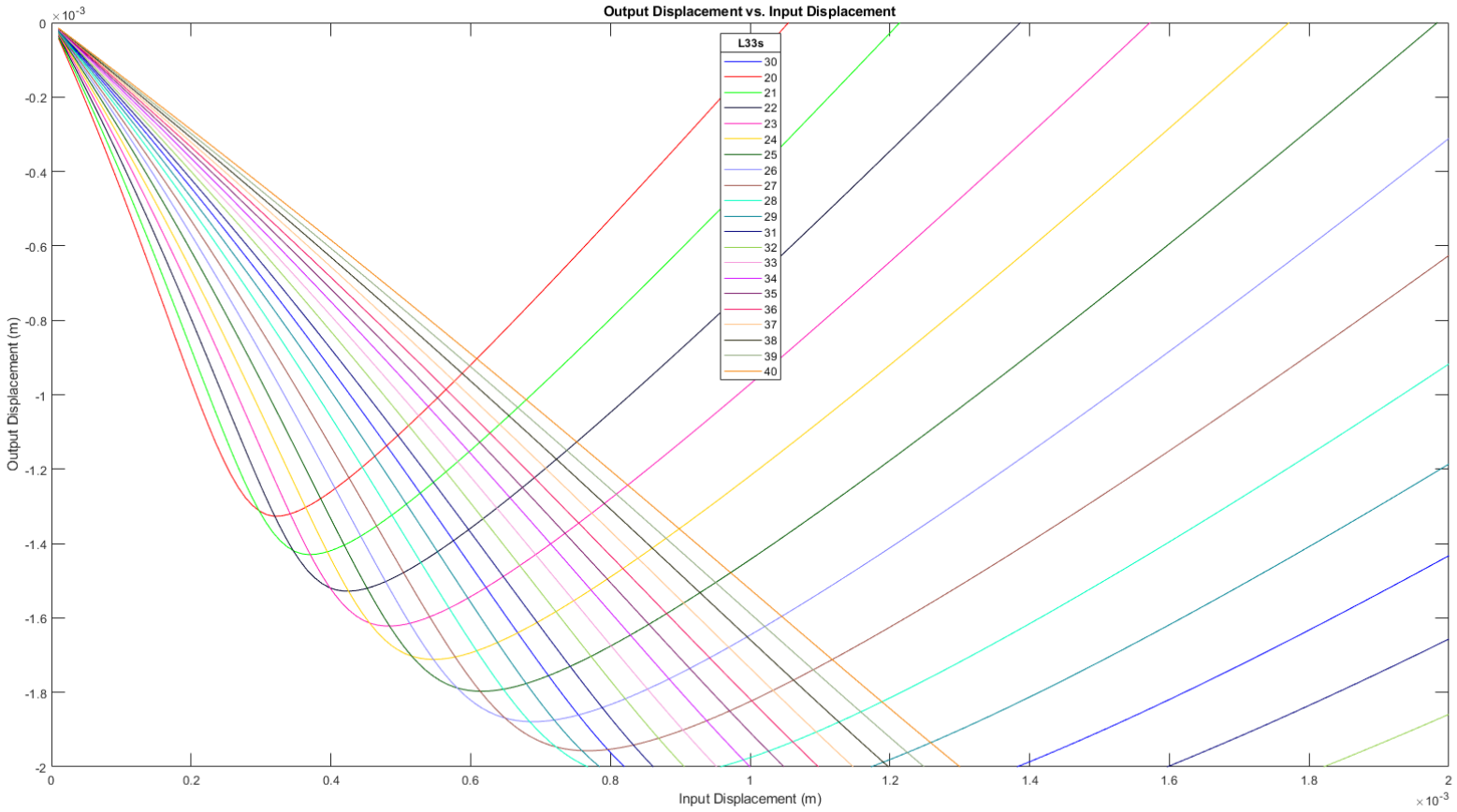
Sinusoidal → Cosinusoidal, Llif



Sinusoidal → Cosinusoidal, L11



Sinusoidal → Cosinusoidal, L33



Conclusion

- Cosinusoidal mechanism can not simply be made by picking the same parameters and altering the alpha over all flexures.

Static Balancing

- Started searching for literature about static balancing.
- Not a lot of examples which use buckling beam
- Is there somewhere where Force-displacement diagrams can be found?

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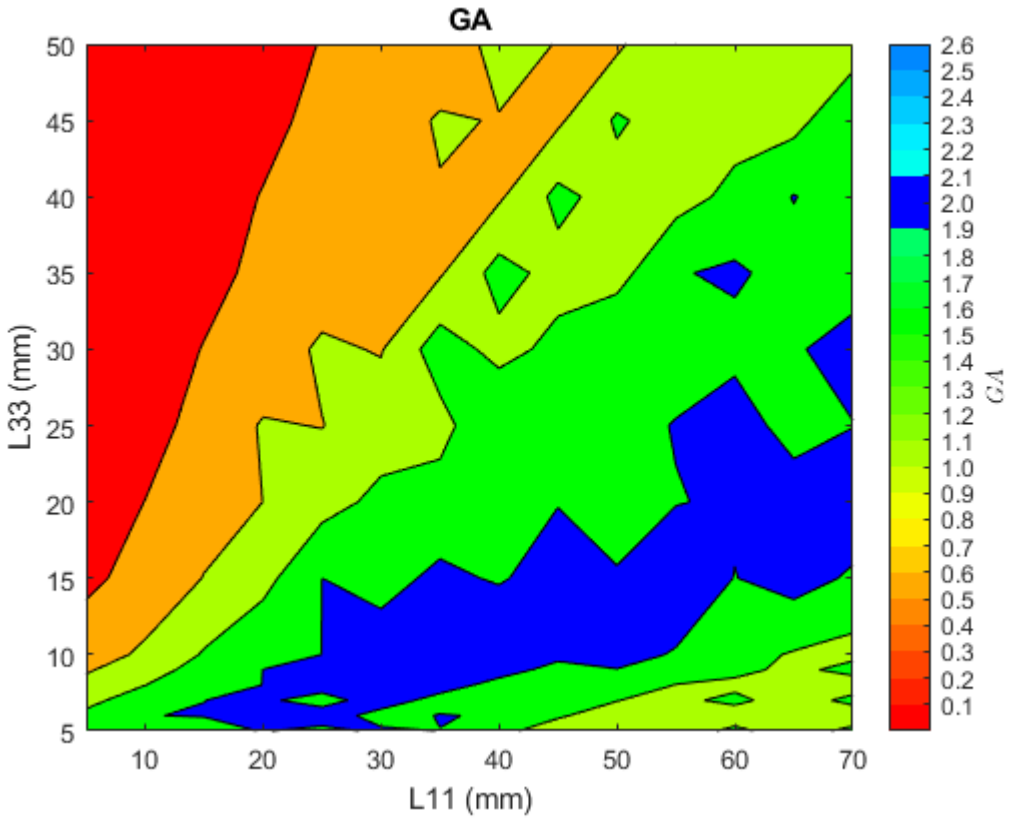
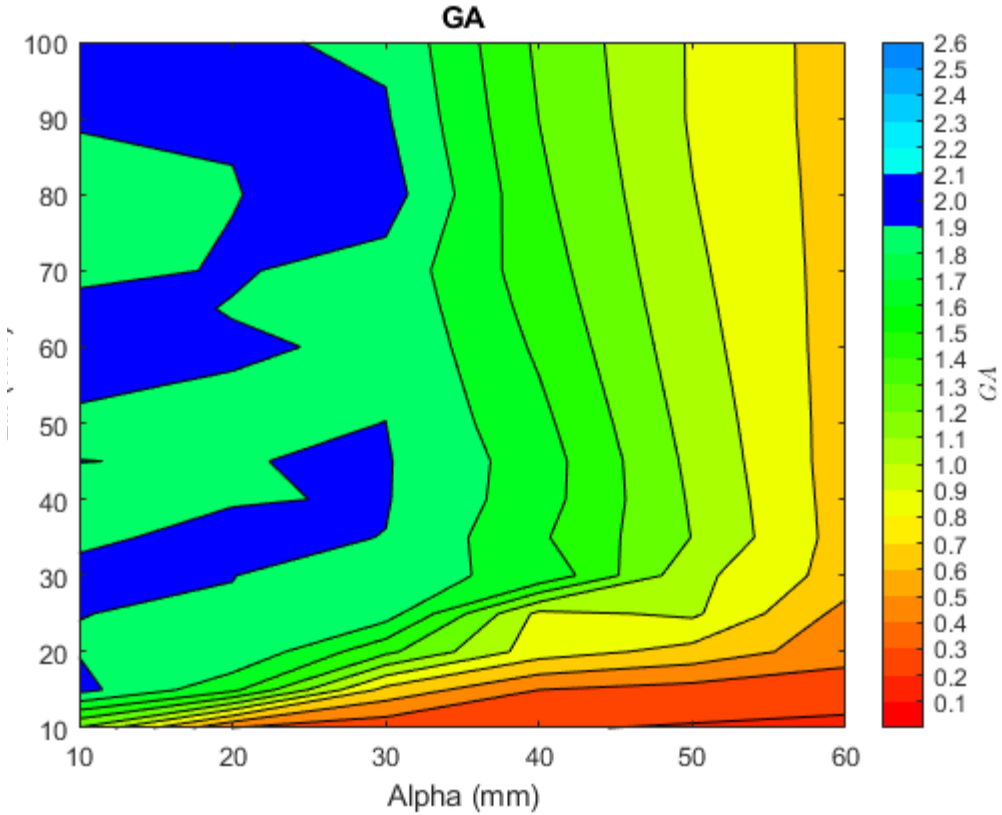
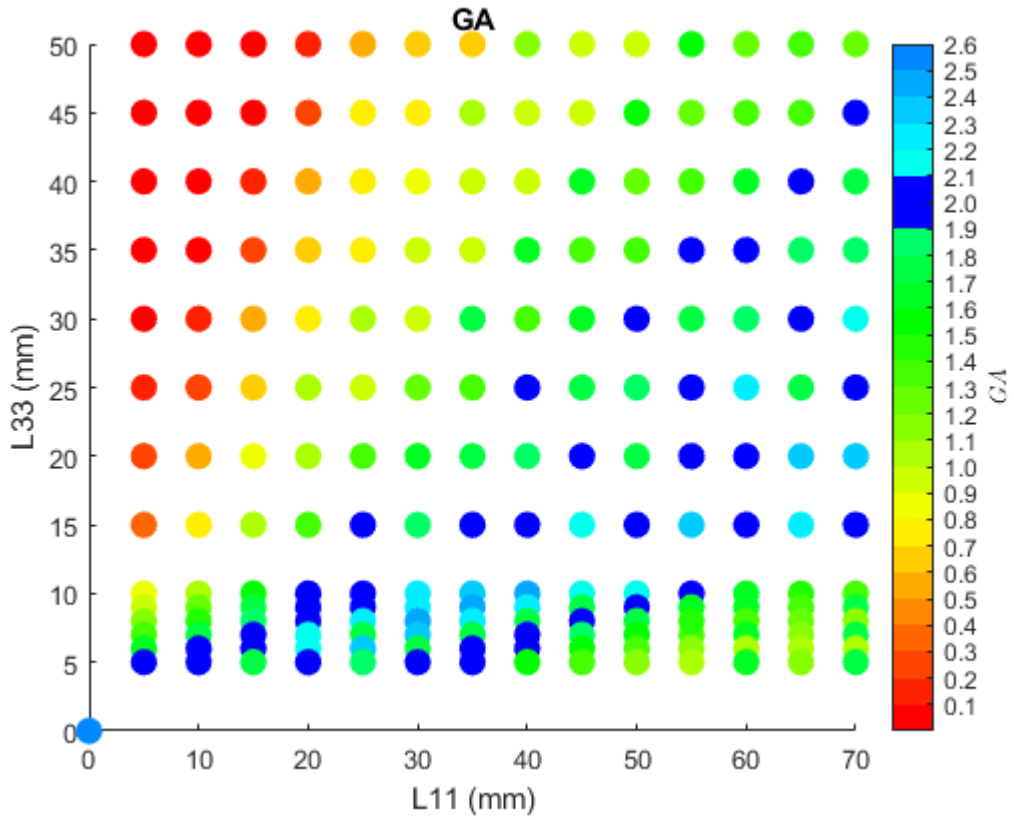
GA Contour plot

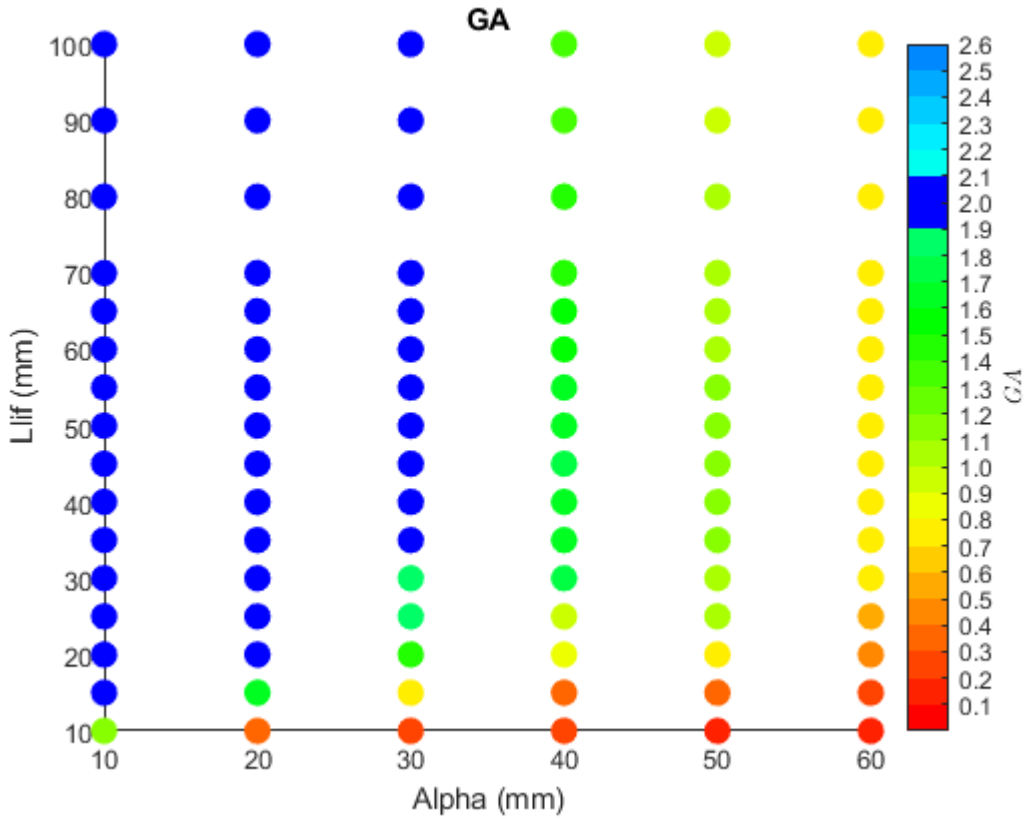




- Also made contour plot of every graph, but these do not perfectly show the behaviour due to the lack of datapoints and inter/extrapolation in between these.

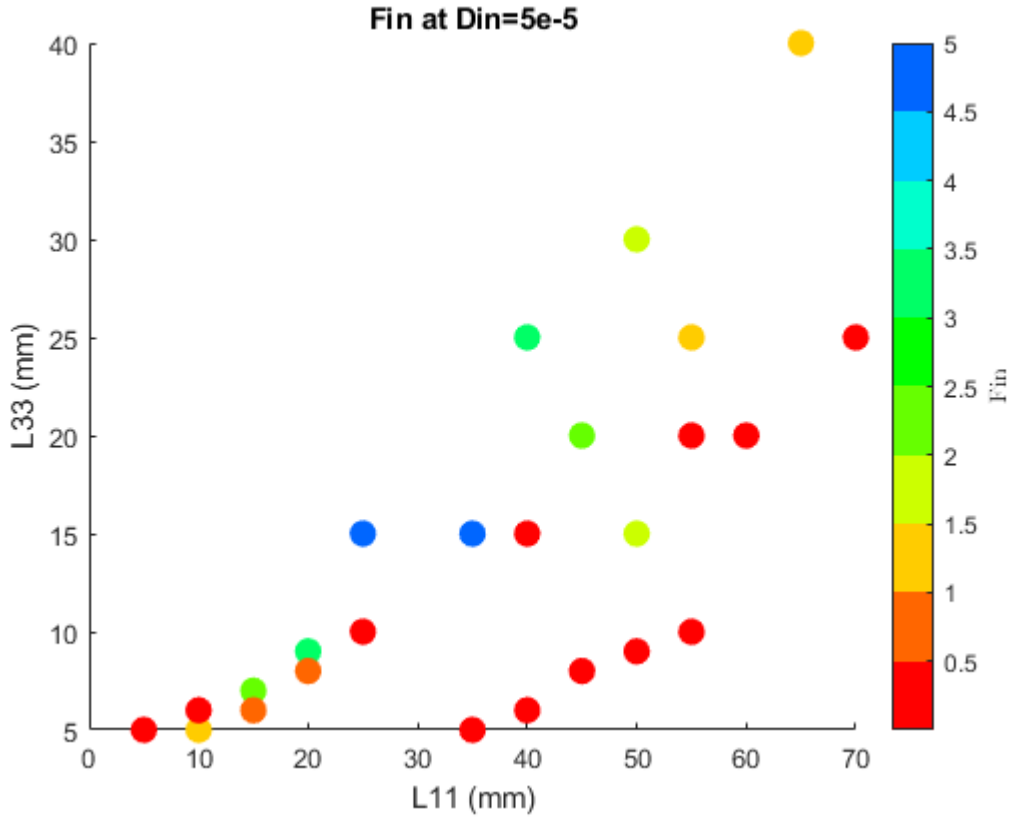
GA

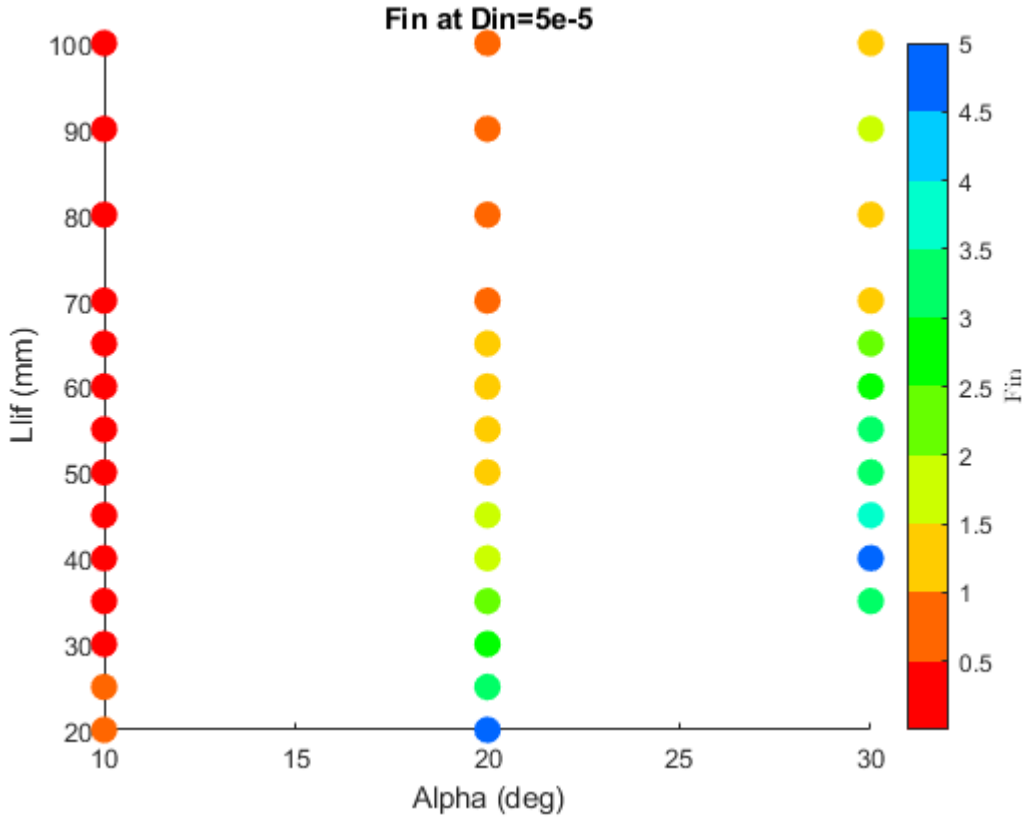




- Best points are taken to plot the graphs, (here: closer to 2 the better). Otherwise, there is overlap and only the last points plotted are visible
- This also means that you can not just take the best results from the two graphs and combine these.

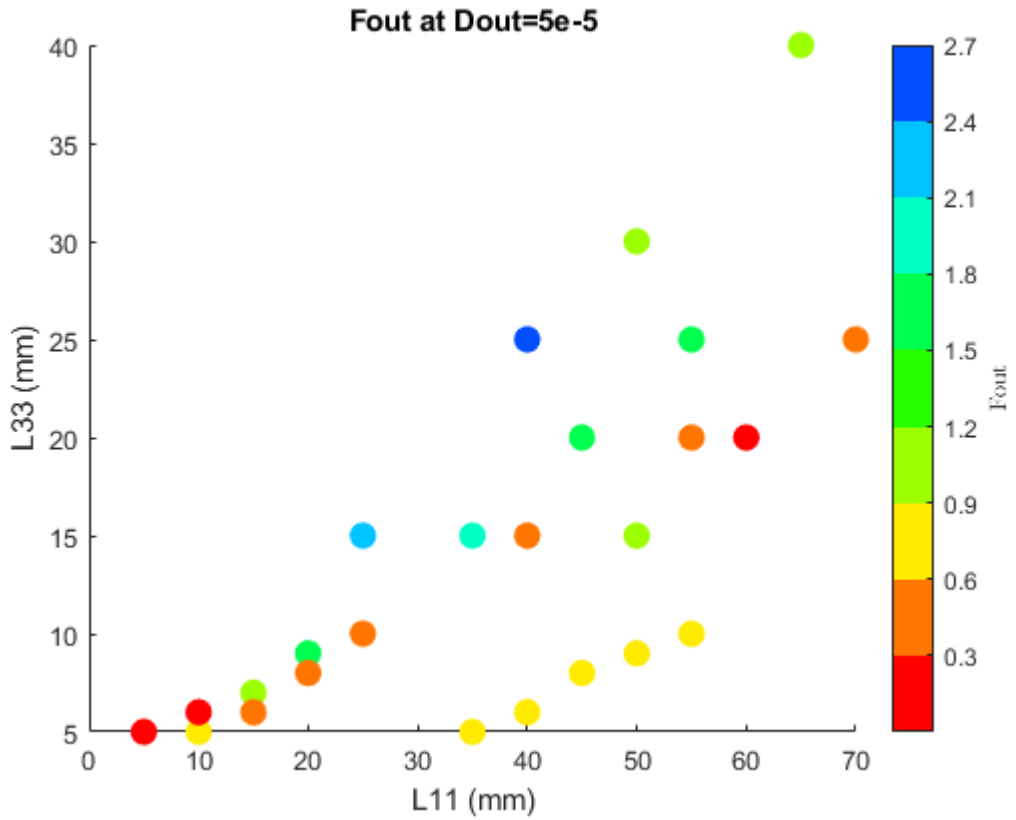
Kin

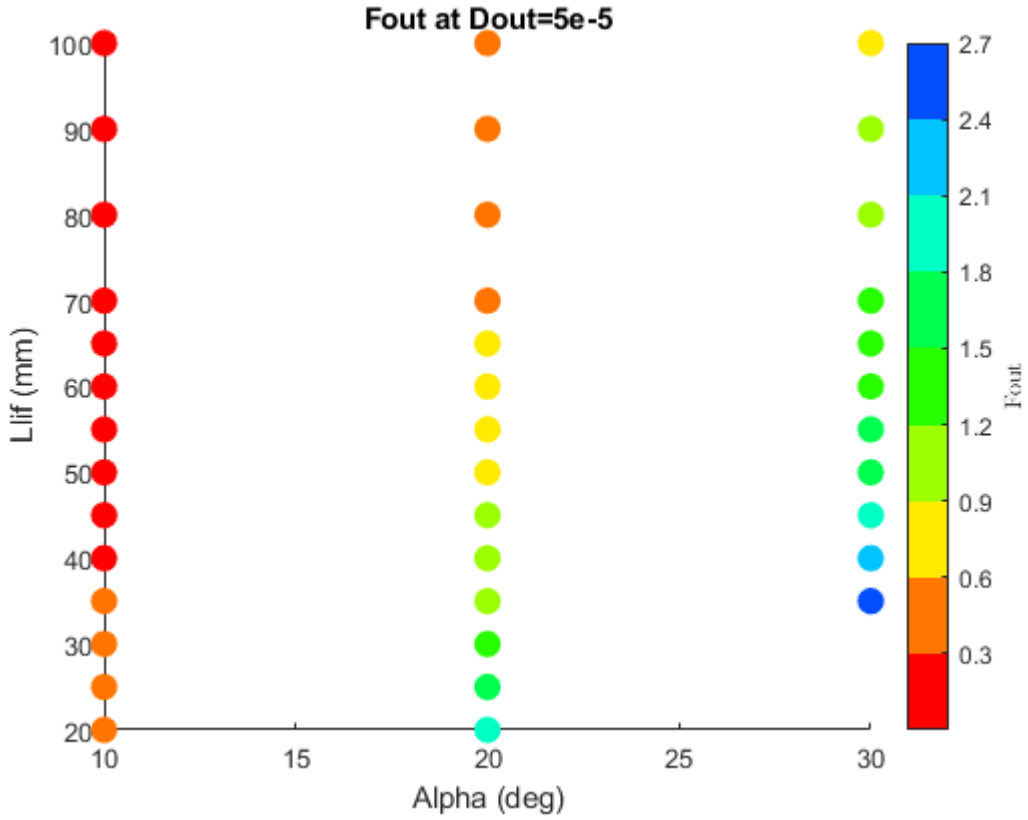




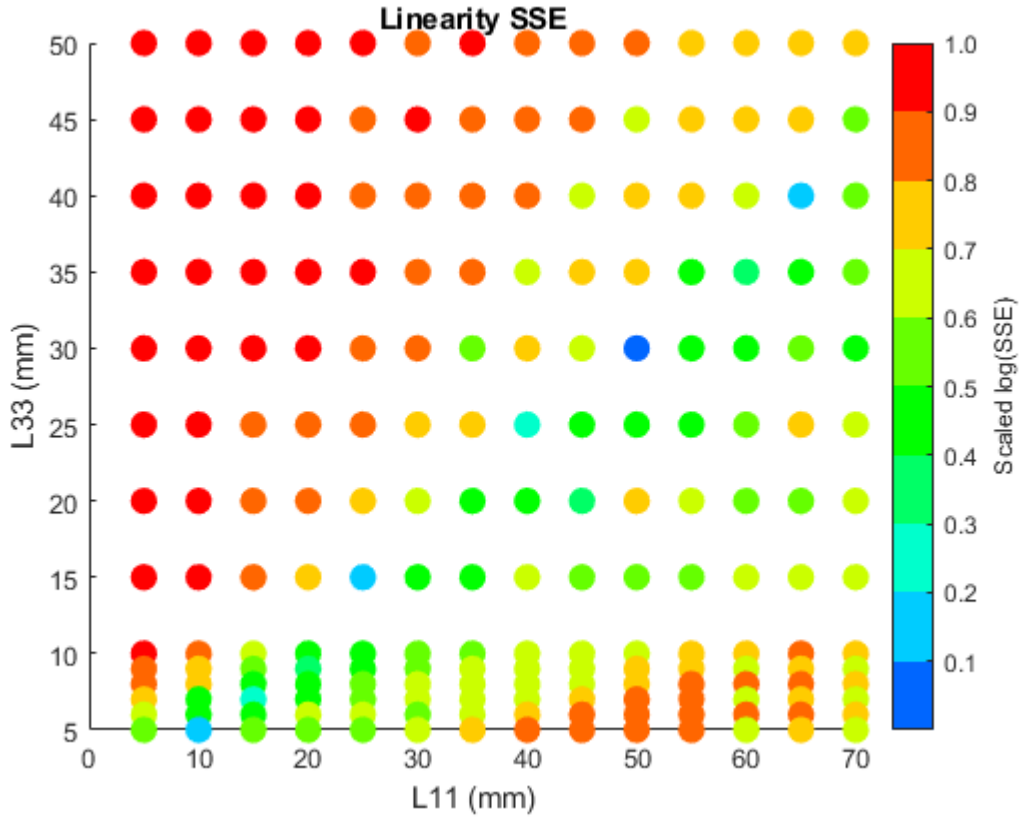
- Only solutions with 1.9 < GA < 2.1 are investigated and plotted
- Force is checked at 10% of total displacement

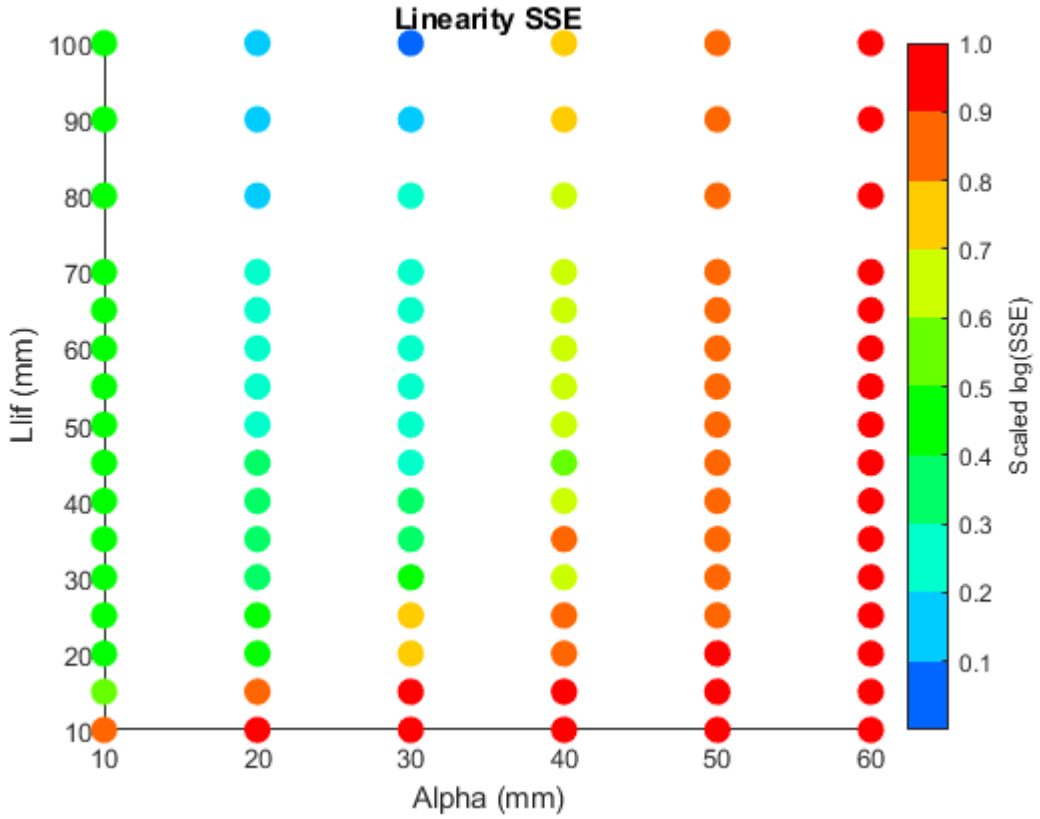
Kout


Fout at Dout=5e-5
L33 (mm)
L11 (mm)
Fout
0
10
20
30
40
50
60
70
5
10
15
20
25
30
35
40
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7


Fout at Dout=5e-5
Llif (mm)
Alpha (deg)
Fout
10
15
20
25
30
20
30
40
50
60
70
80
90
100
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7

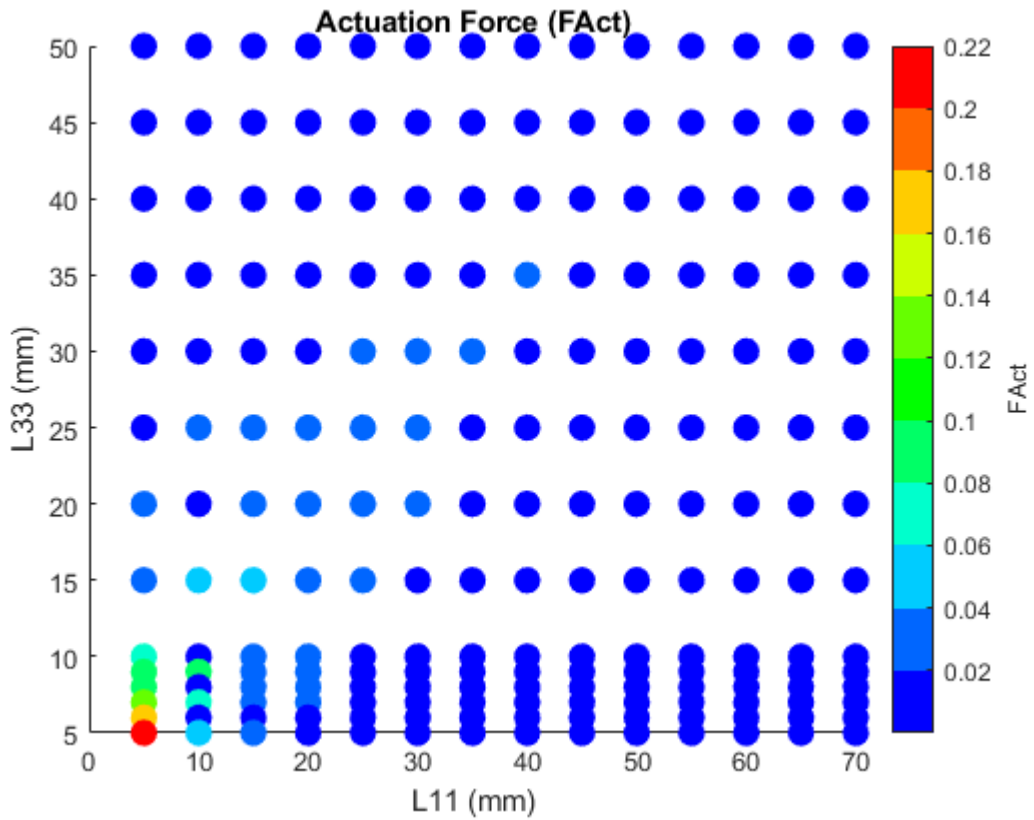
Linearity

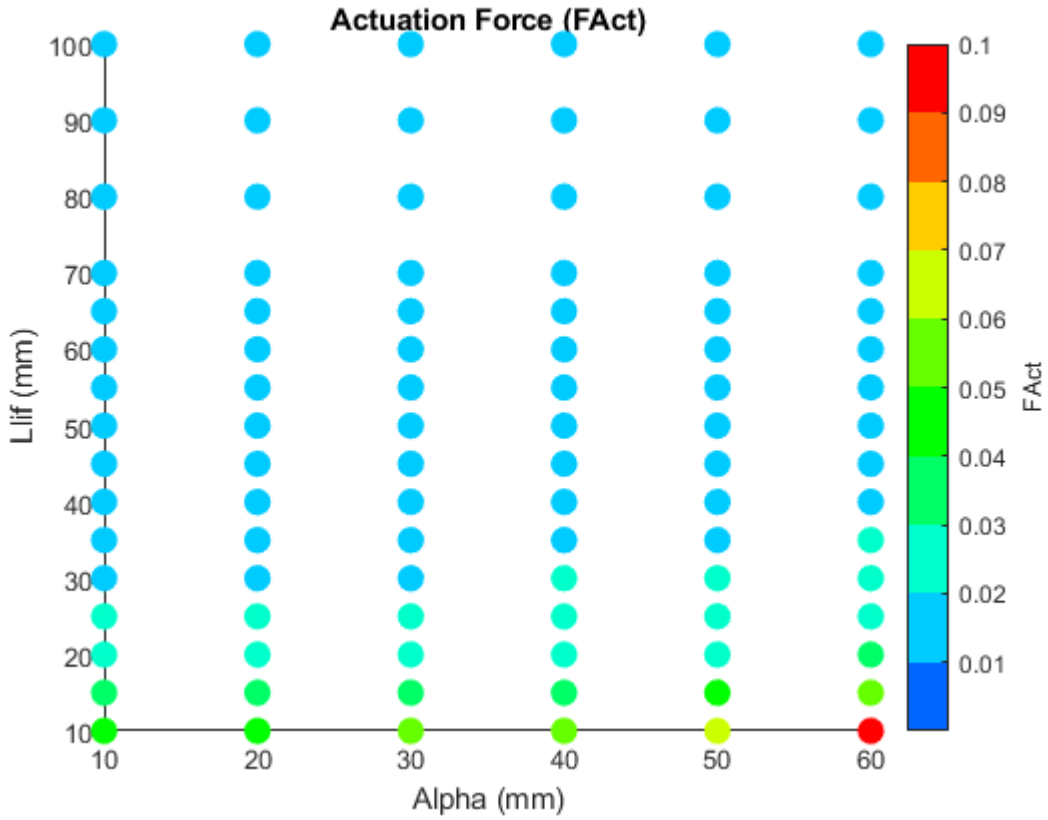




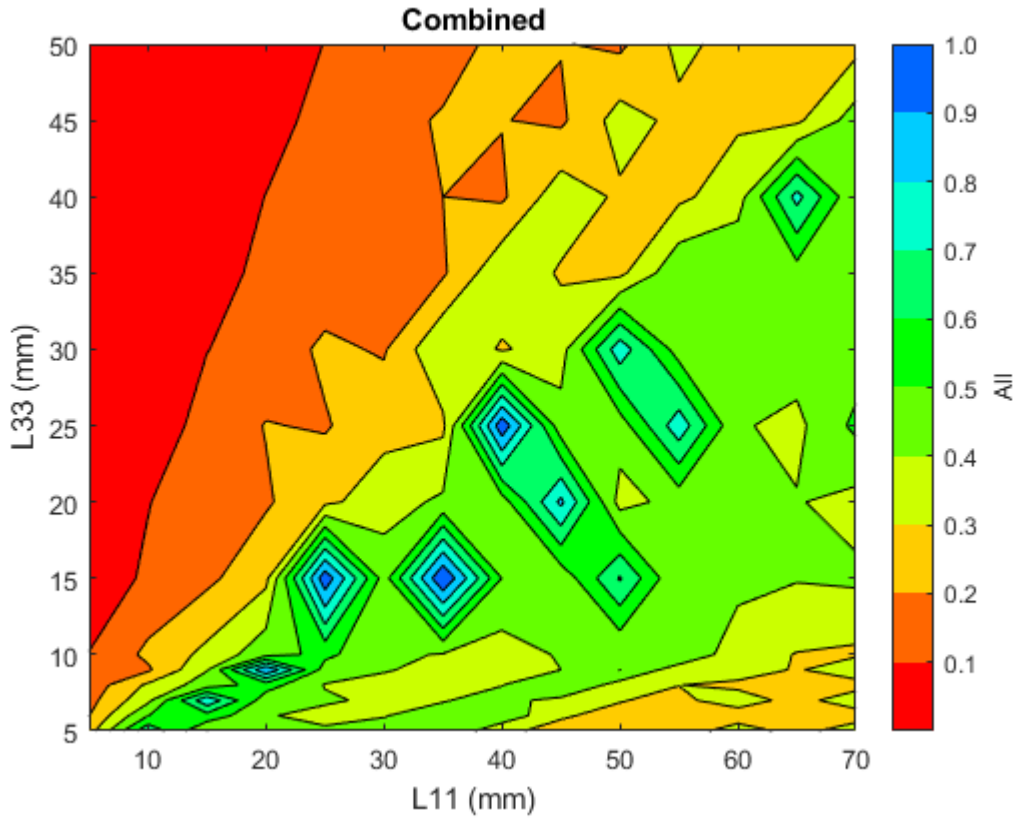
- Used sum of square error (SSE) to calculate how close a system was to linearity.
- Log10(SSE) to get order of magnitude of error
- Rescaled from 0 to 1

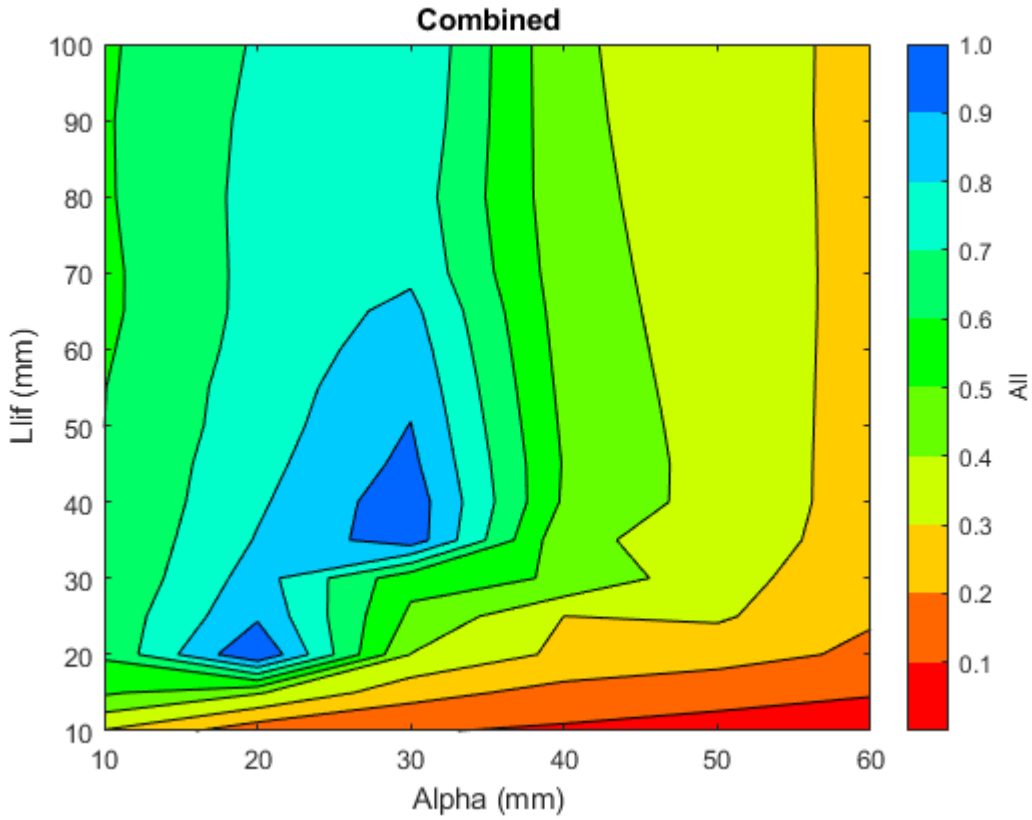
Kact


Actuation Force (FAct)
L33 (mm)
L11 (mm)
FAct
50
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02


Actuation Force (FAct)
Llif (mm)
Alpha (mm)
FAct
100
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01

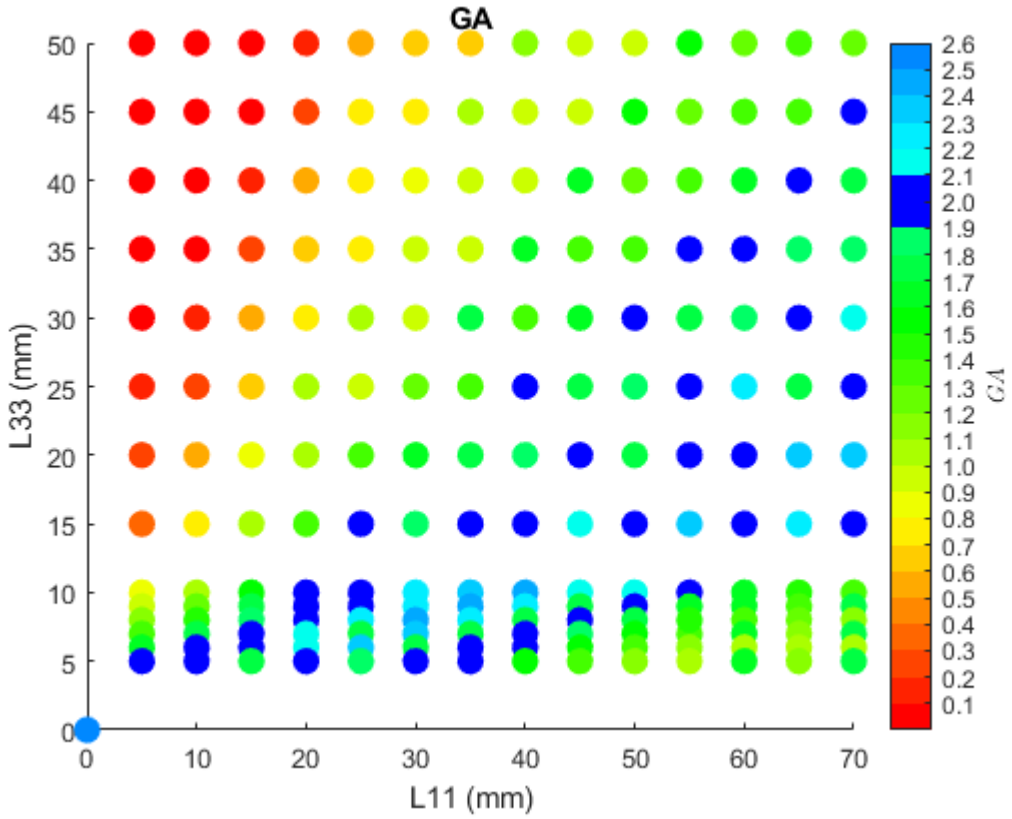
Combined

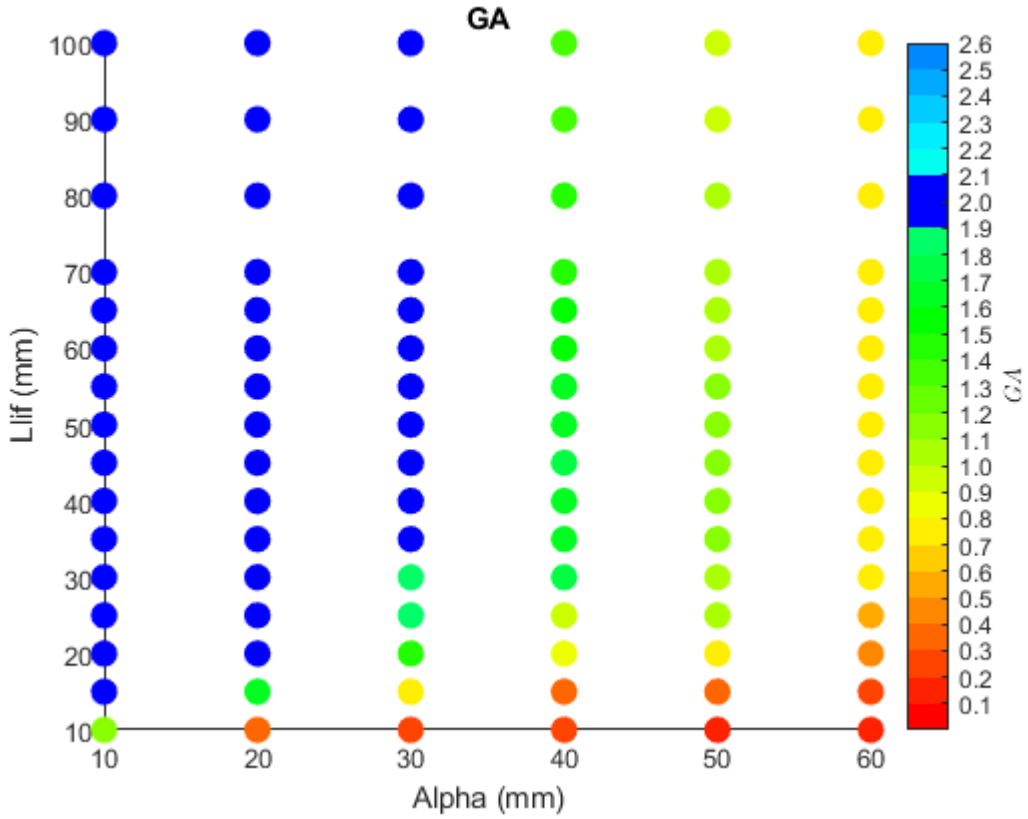




- Just to get an idea, weights per criteria are arbitrary (1,0.9,0.8,0.7,0.6) : (GA, Kin, Kout, Lin, Kact)

GA



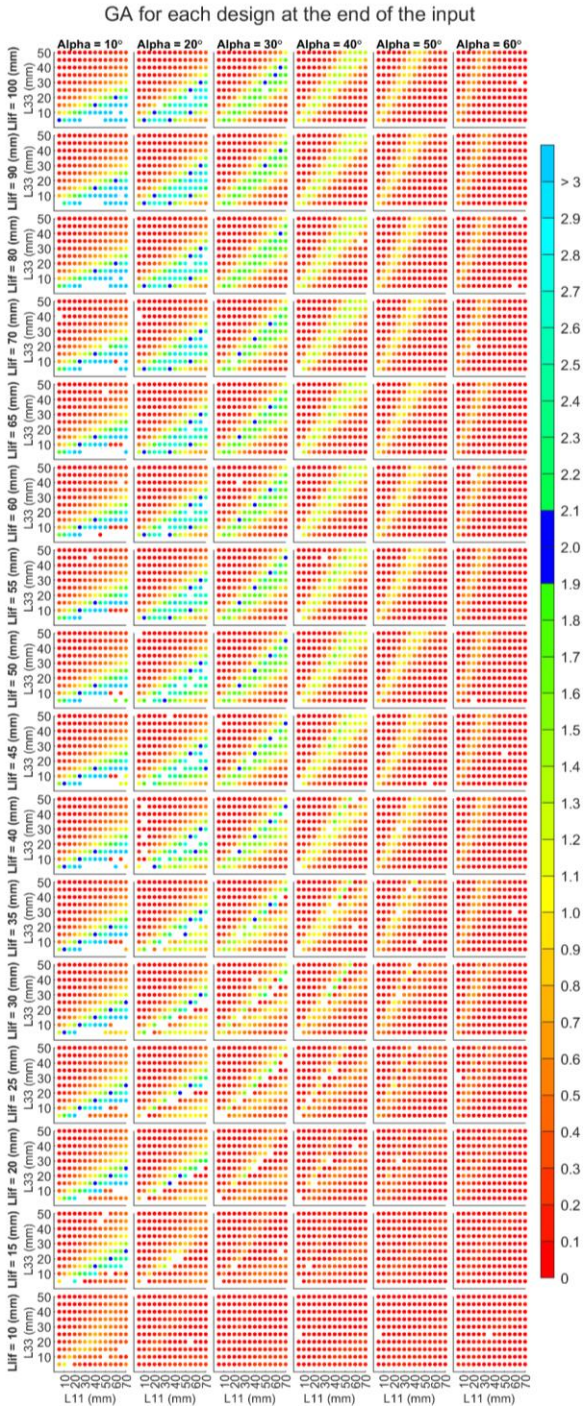


This was data first, but problem with showing 4-parameters + 1 criteria. As each point in this graph is essentially the best point chosen from all the points with the same L11 and L33 (in the first figure).

Also, more points in between the data were needed to get a better idea of where the optimum is.

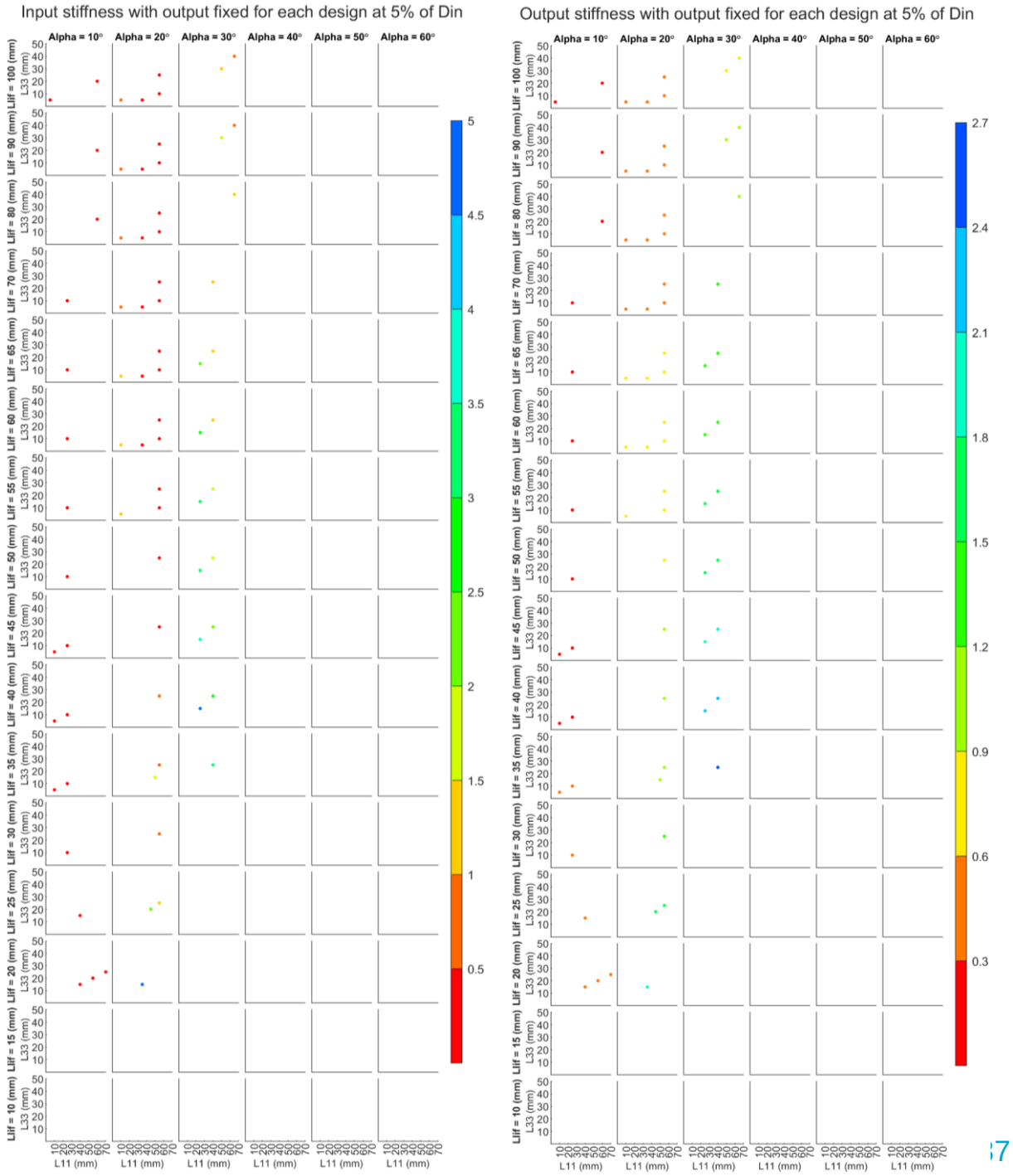
GA

A solution I used, to show all dimensions was to make subplots and use the extra axes to show two more dimensions. The figures shown here are using the old data.



Fin/Fout

Here only the points that have a 1.9 < GA < 2.1 are shown. The points are taken for the input force/ output force at 5% of the total input displacement.

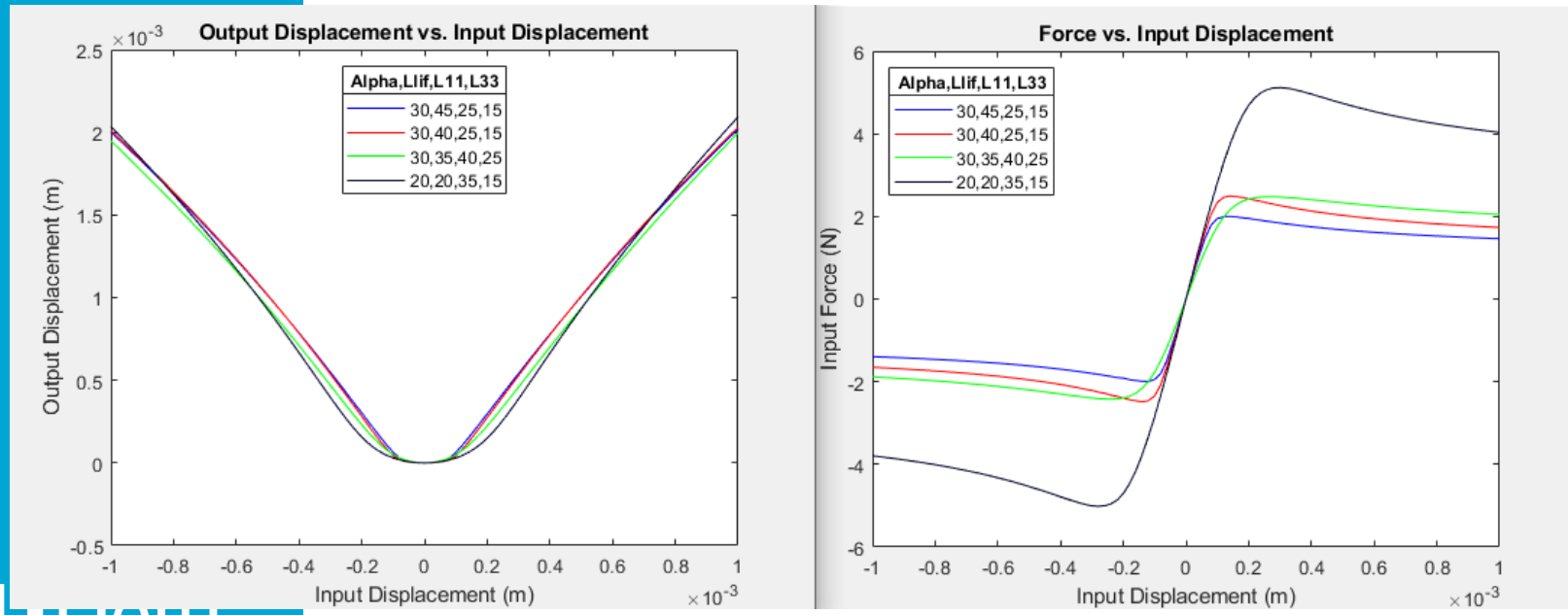


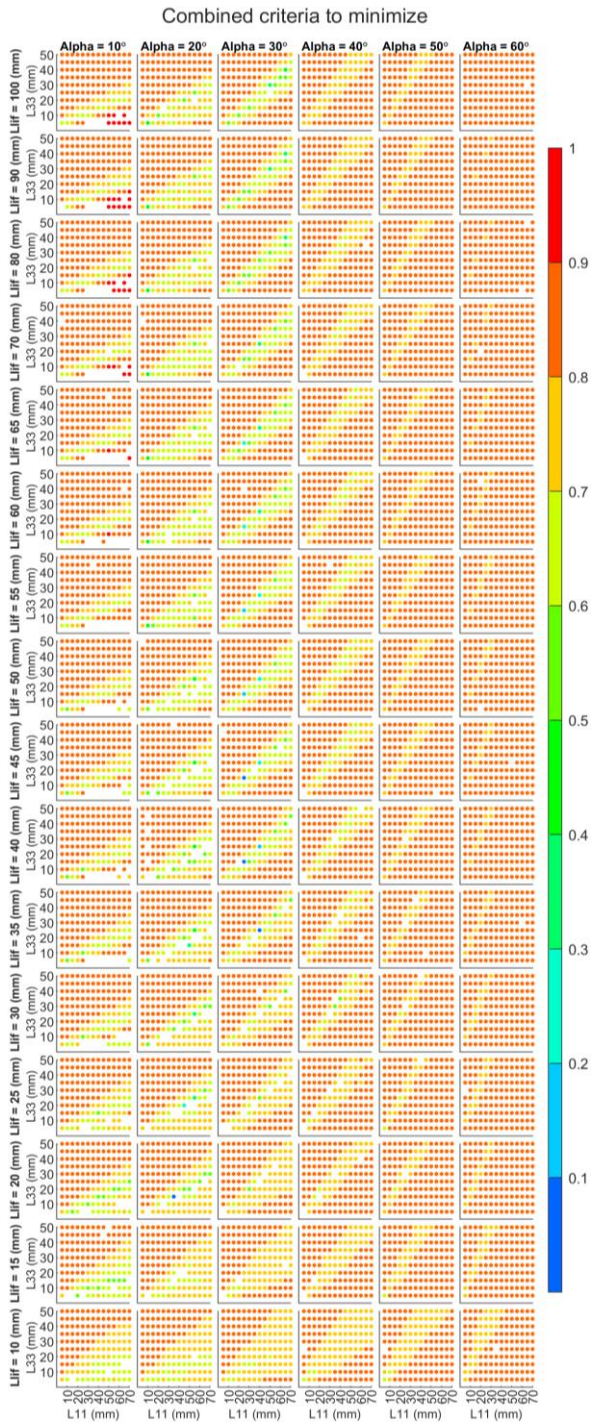
Linearity


Scaled log(SSE) for each design at the end of the input
Alpha = 10°
Alpha = 20°
Alpha = 30°
Alpha = 40°
Alpha = 50°
Alpha = 60°
Liff = 10 (mm)
Liff = 15 (mm)
Liff = 20 (mm)
Liff = 25 (mm)
Liff = 30 (mm)
Liff = 35 (mm)
Liff = 40 (mm)
Liff = 45 (mm)
Liff = 50 (mm)
Liff = 55 (mm)
Liff = 60 (mm)
Liff = 65 (mm)
Liff = 70 (mm)
Liff = 80 (mm)
Liff = 90 (mm)
Liff = 100 (mm)
L33 (mm)
L11 (mm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Weights?

Here I combined all the criteria and minimized the objective. All criteria are scaled before and have a weight attached. In this figure the weights were all set to 1. The displacement and force-disp of the 4 best results are plotted below.



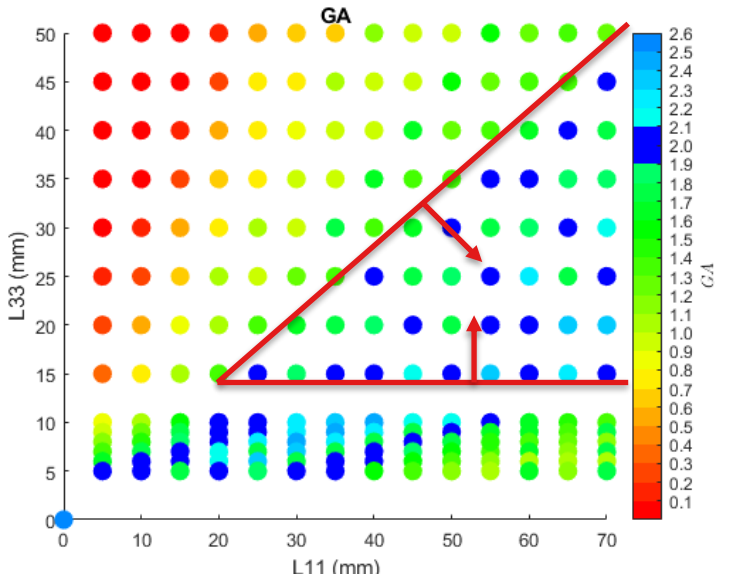


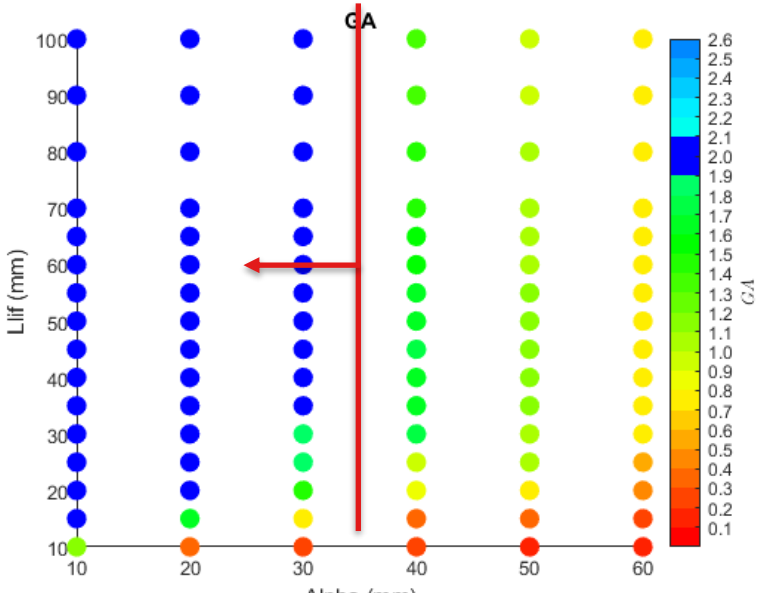
Extra simulations

Did extra simulations in the red areas.

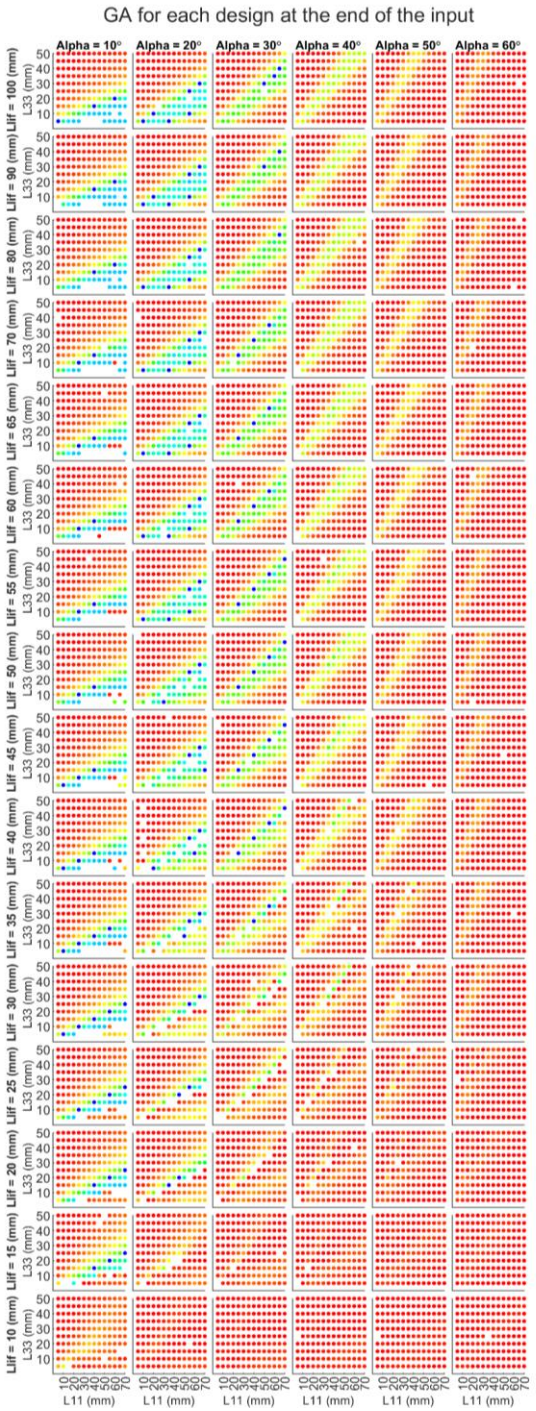
Results of this will come later.

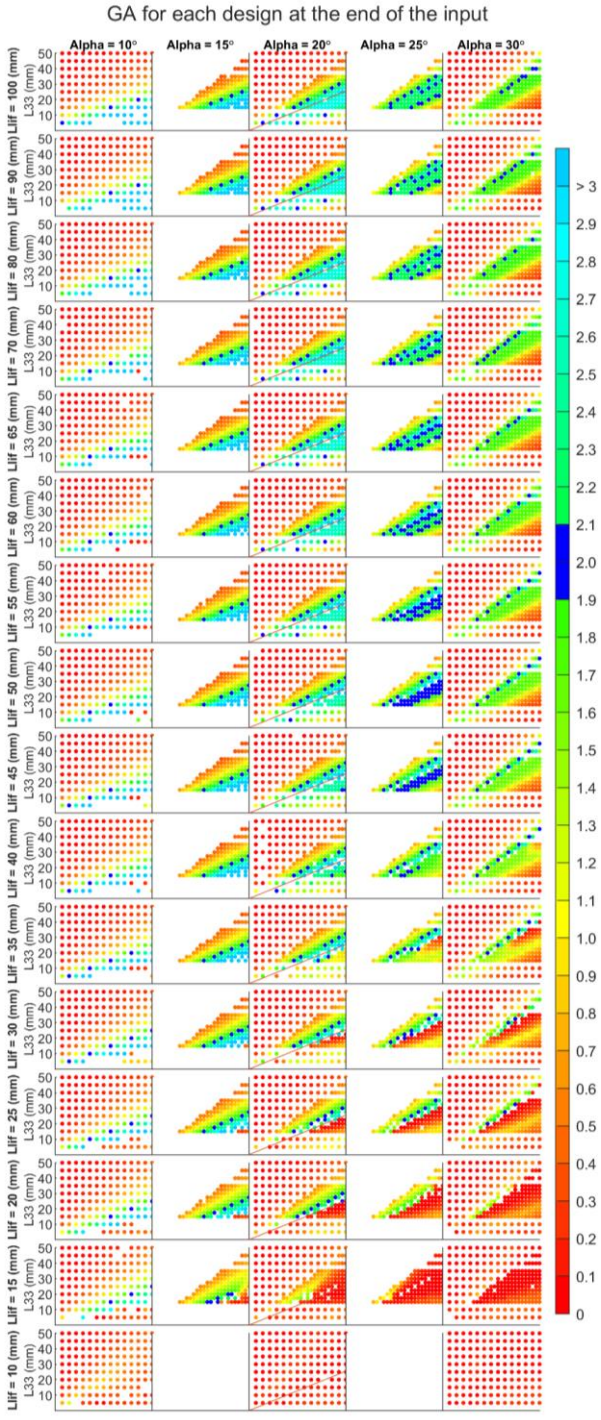
- `Alpha = [15:2.5:35];`
- `Llif = [15:2.5:110];`
- `Range of L11=f(L33) res(2.5)`
- `L33 = [15:2.5:45];`

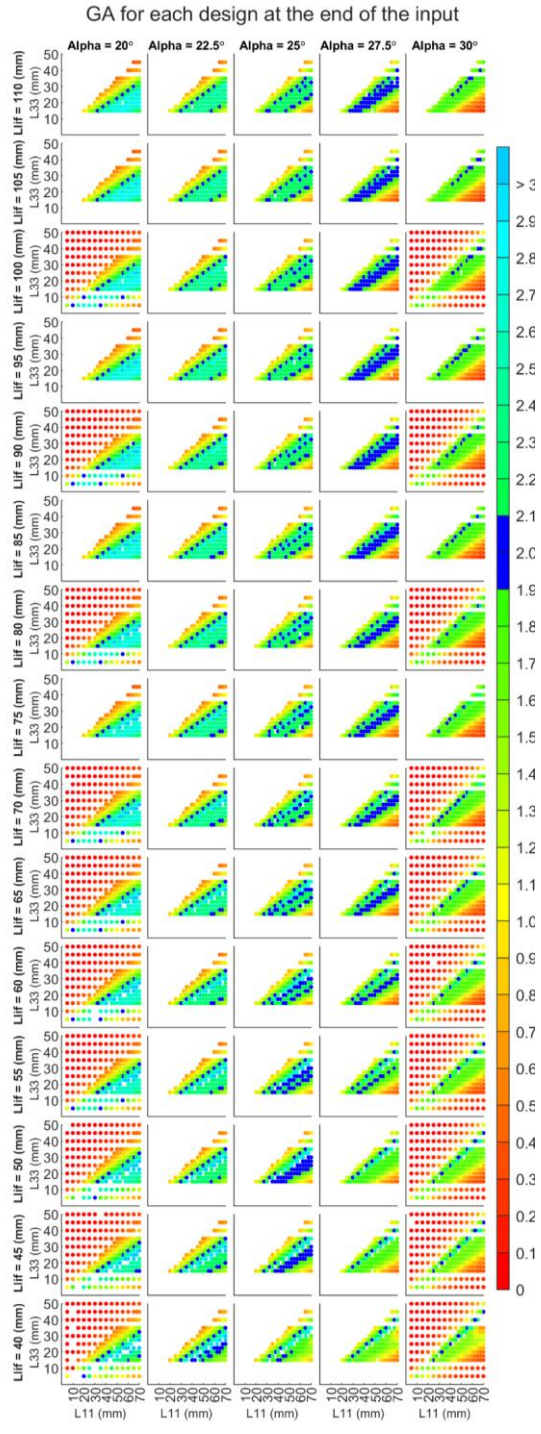




GA


GA for each design at the end of the input
Alpha = 10°
Alpha = 20°
Alpha = 30°
Alpha = 40°
Alpha = 50°
Alpha = 60°
Liff = 10 (mm)
Liff = 15 (mm)
Liff = 20 (mm)
Liff = 25 (mm)
Liff = 30 (mm)
Liff = 35 (mm)
Liff = 40 (mm)
Liff = 45 (mm)
Liff = 50 (mm)
Liff = 55 (mm)
Liff = 60 (mm)
Liff = 65 (mm)
Liff = 70 (mm)
Liff = 80 (mm)
Liff = 90 (mm)
Liff = 100 (mm)
L33 (mm)
L11 (mm)


GA for each design at the end of the input
Alpha = 10°
Alpha = 15°
Alpha = 20°
Alpha = 25°
Alpha = 30°
Liff = 10 (mm)
Liff = 15 (mm)
Liff = 20 (mm)
Liff = 25 (mm)
Liff = 30 (mm)
Liff = 35 (mm)
Liff = 40 (mm)
Liff = 45 (mm)
Liff = 50 (mm)
Liff = 55 (mm)
Liff = 60 (mm)
Liff = 65 (mm)
Liff = 70 (mm)
Liff = 80 (mm)
Liff = 90 (mm)
Liff = 100 (mm)
L33 (mm)
L11 (mm)


GA for each design at the end of the input
Alpha = 20°
Alpha = 22.5°
Alpha = 25°
Alpha = 27.5°
Alpha = 30°
Liff = 40 (mm)
Liff = 45 (mm)
Liff = 50 (mm)
Liff = 55 (mm)
Liff = 60 (mm)
Liff = 65 (mm)
Liff = 70 (mm)
Liff = 75 (mm)
Liff = 80 (mm)
Liff = 85 (mm)
Liff = 90 (mm)
Liff = 95 (mm)
Liff = 100 (mm)
Liff = 105 (mm)
Liff = 110 (mm)
L33 (mm)
L11 (mm)

TU Delft

Extra simulations

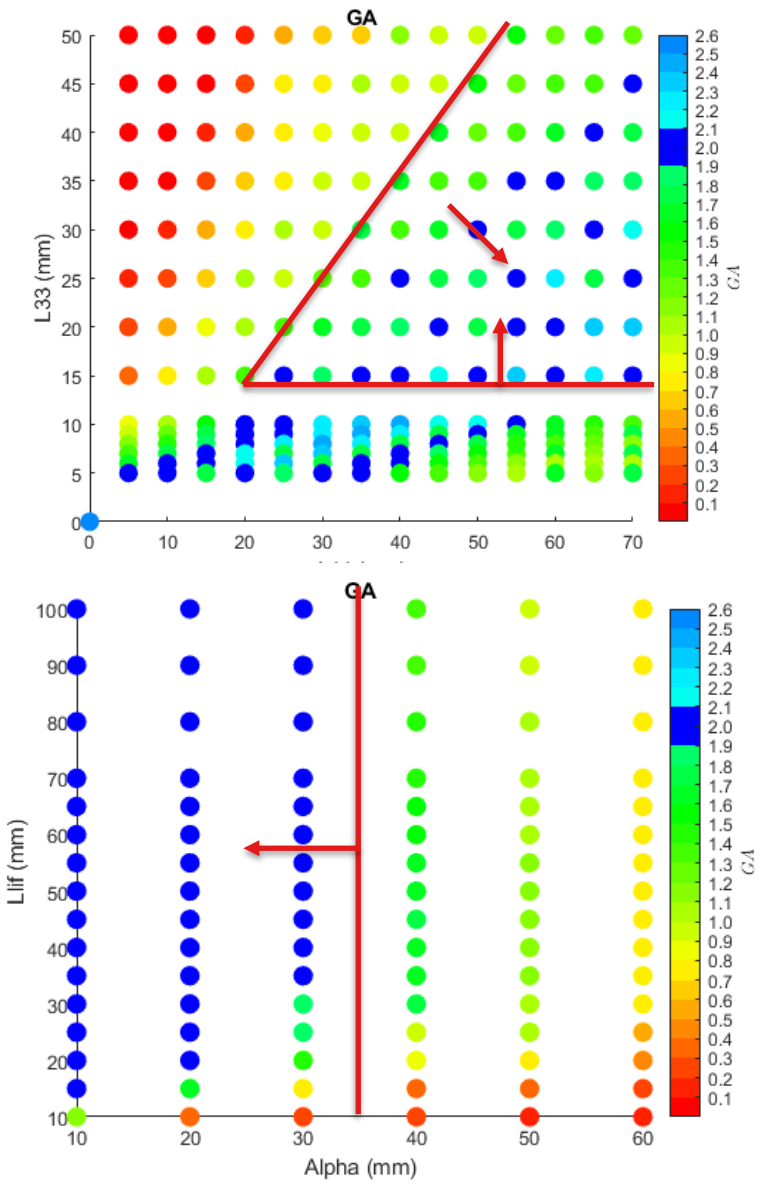
Did extra simulations in the areas indicated with the red arrows.
Results of this will come later.

+/- 66000 data points

- `Alpha = [15:2.5:35];`
- `Llif = [15:2.5:110];`
- `Range of L11=f(L33)`
- `L33 = [15:2.5:45];`

NEW

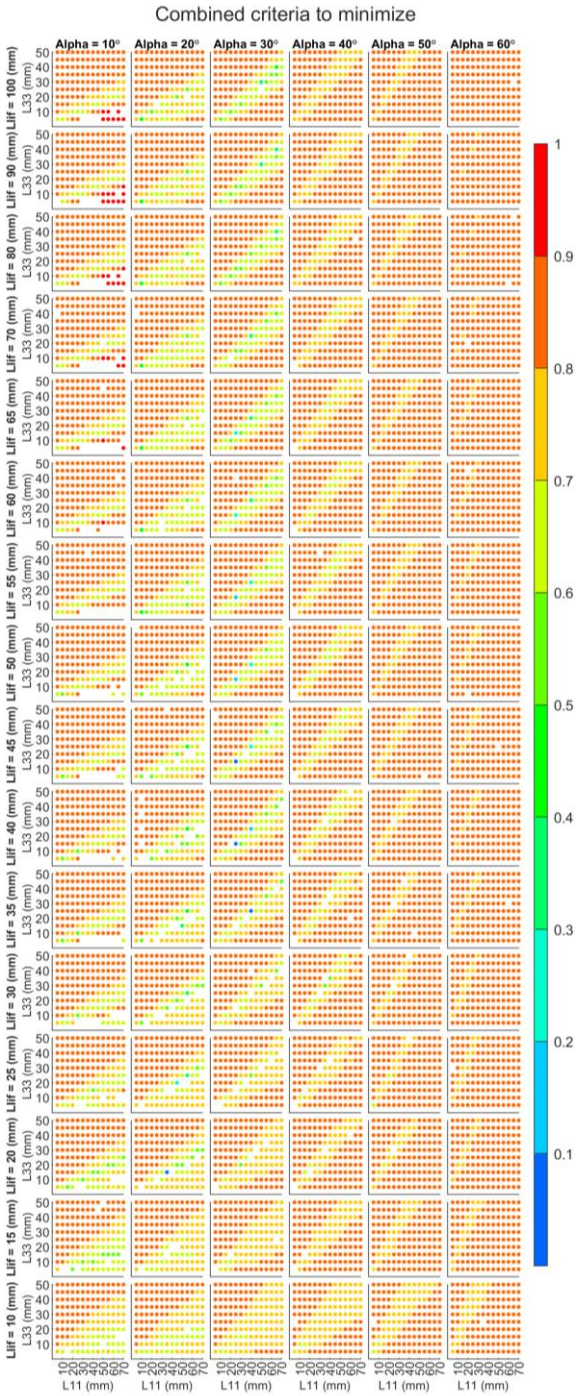
- `Alpha = [15:2.5:45];`
- `Llif = [15:2.5:110];`
- `Range of L11=f(L33)`
- `L33 = [15:2.5:45];`



Criteria Combined

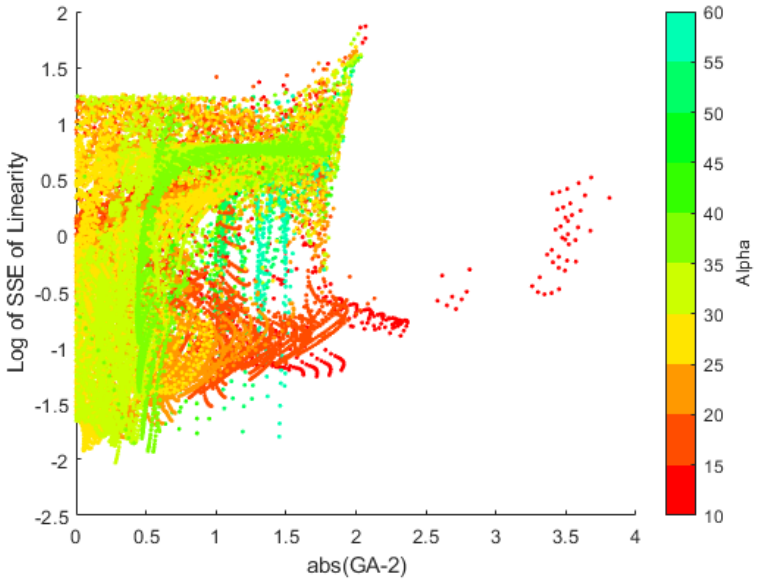
- There is no clear best point, from just looking at individual plots, so I scaled each criteria from 0-1 and added these up.
- How to determine weights/ how to determine the objective to minimize?

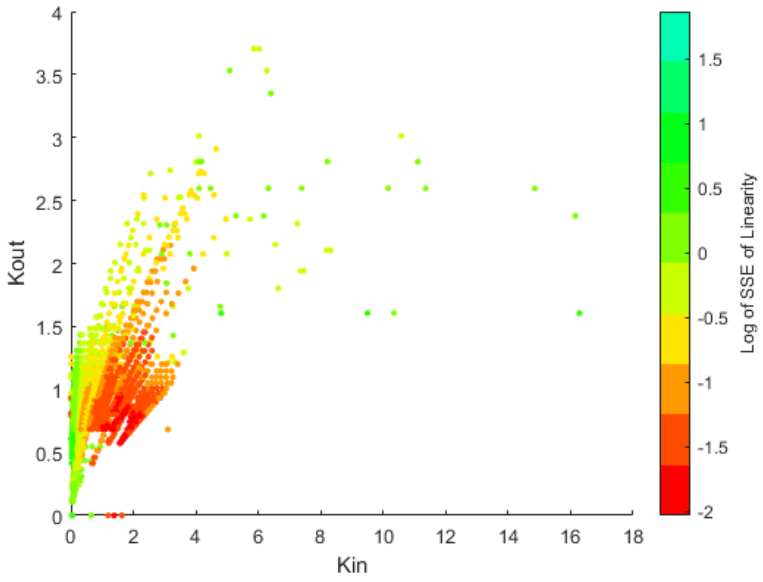
- Also wrote a script to find the optimal point by minimizing an objective.

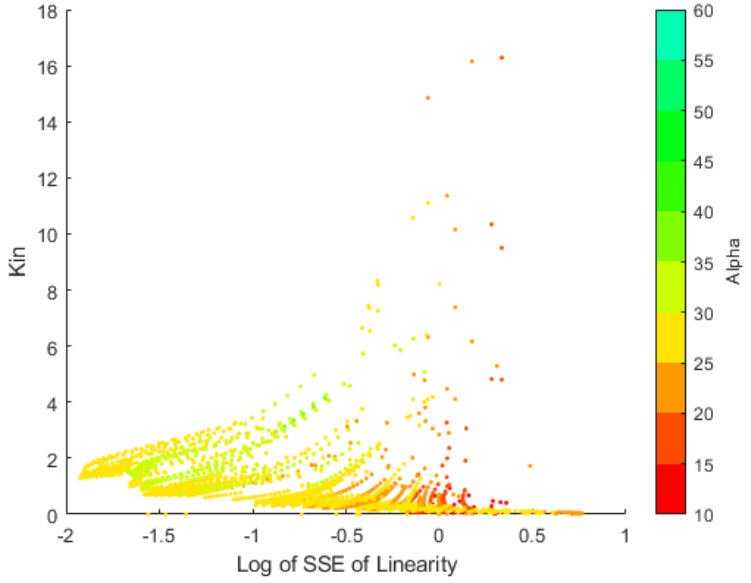


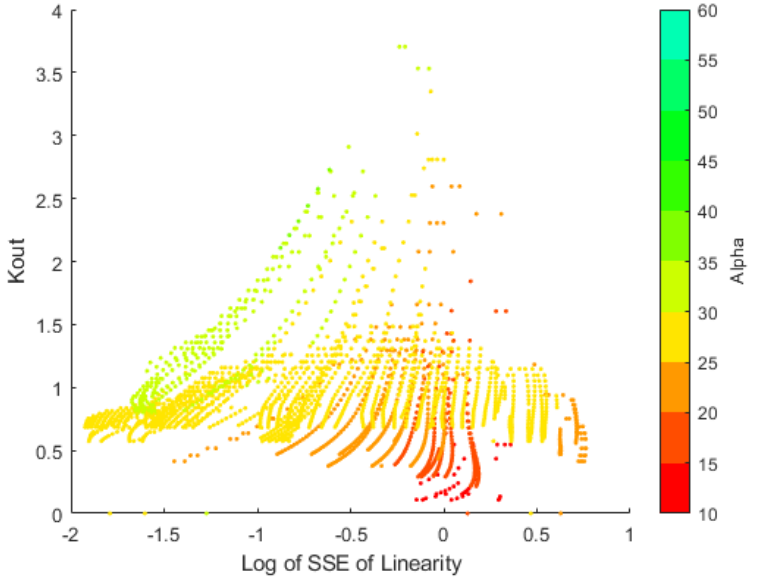
- No clear optimum
- More criteria to plot
- Dimensionless parameters?

- GA
- Linearity x
- Kin
- Kout
- Kact x





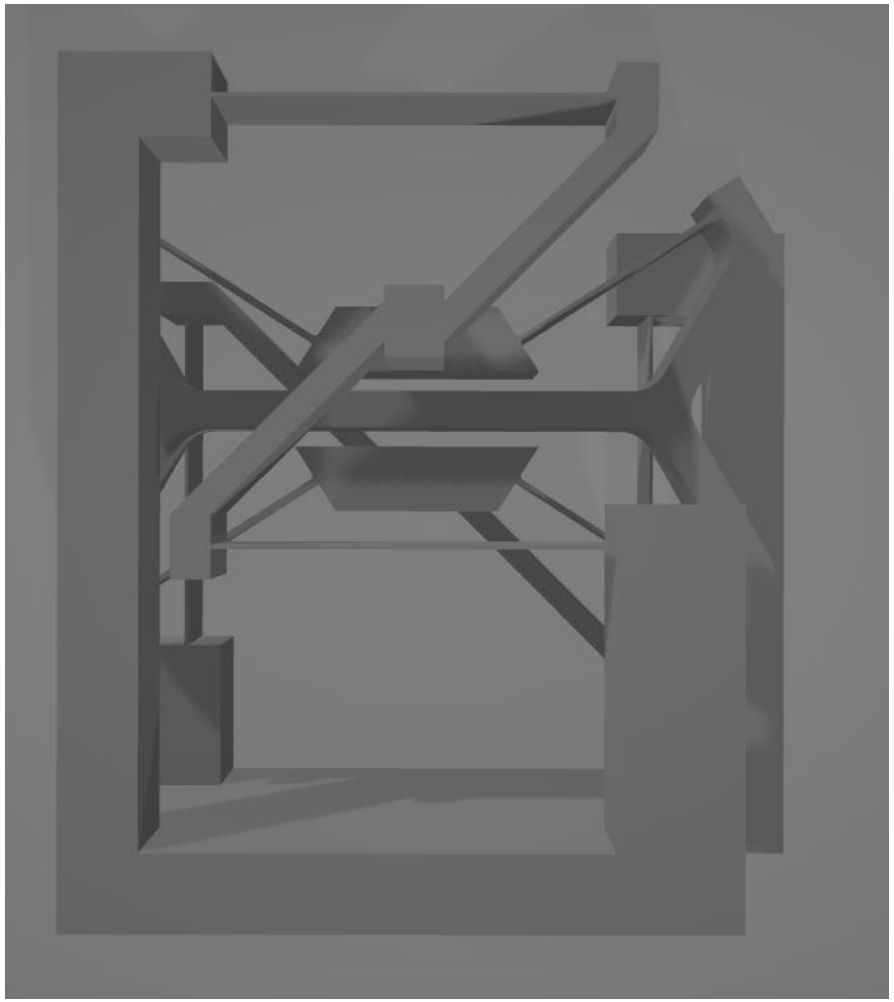




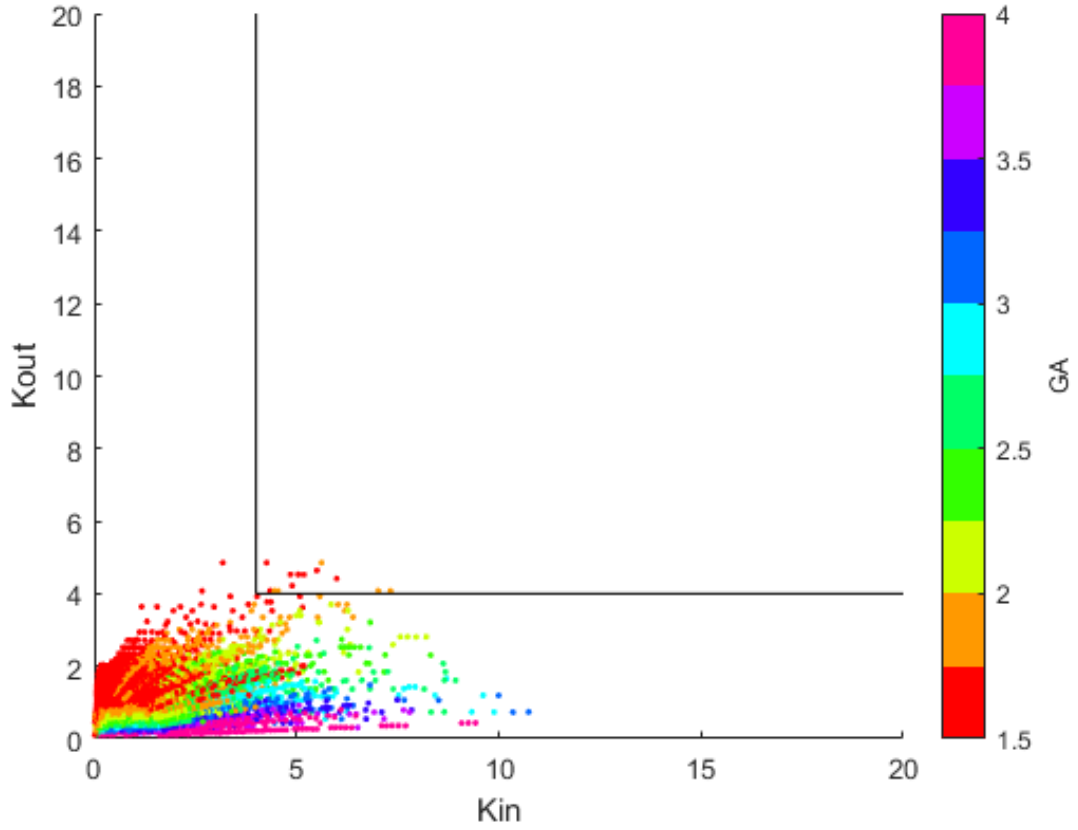
Cosinusoidal mechanism

- Still not really have a clue how to optimize for the extra parameter. Without it taking an insane amount of time.
- Maybe some sort of regression algorithm to find a relationship for the tilted angle in relationship with the other parameters.

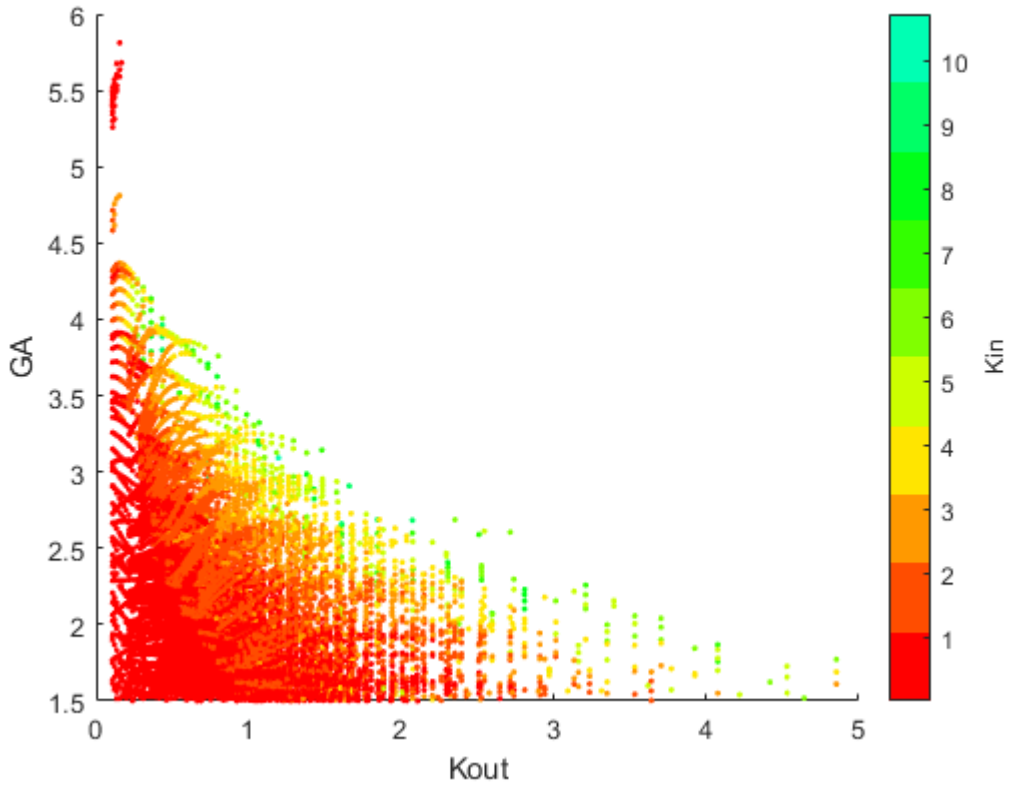
Iteration 1 using SLA printer

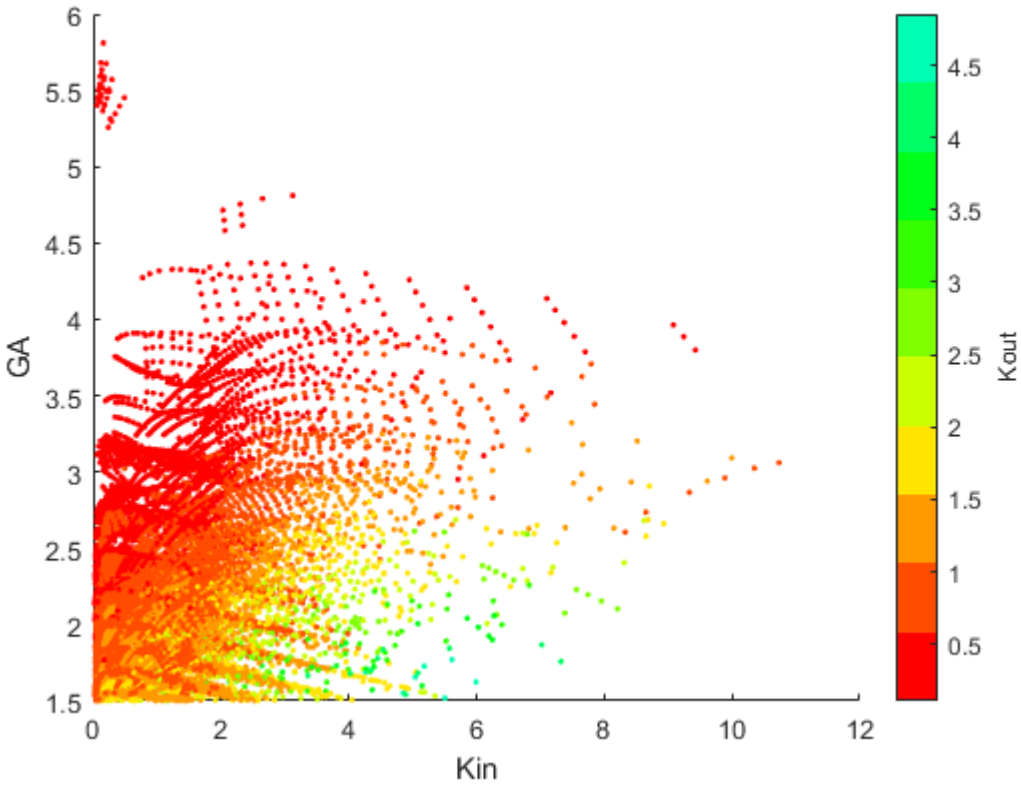


13 points that have min(Kin,Kout)>4

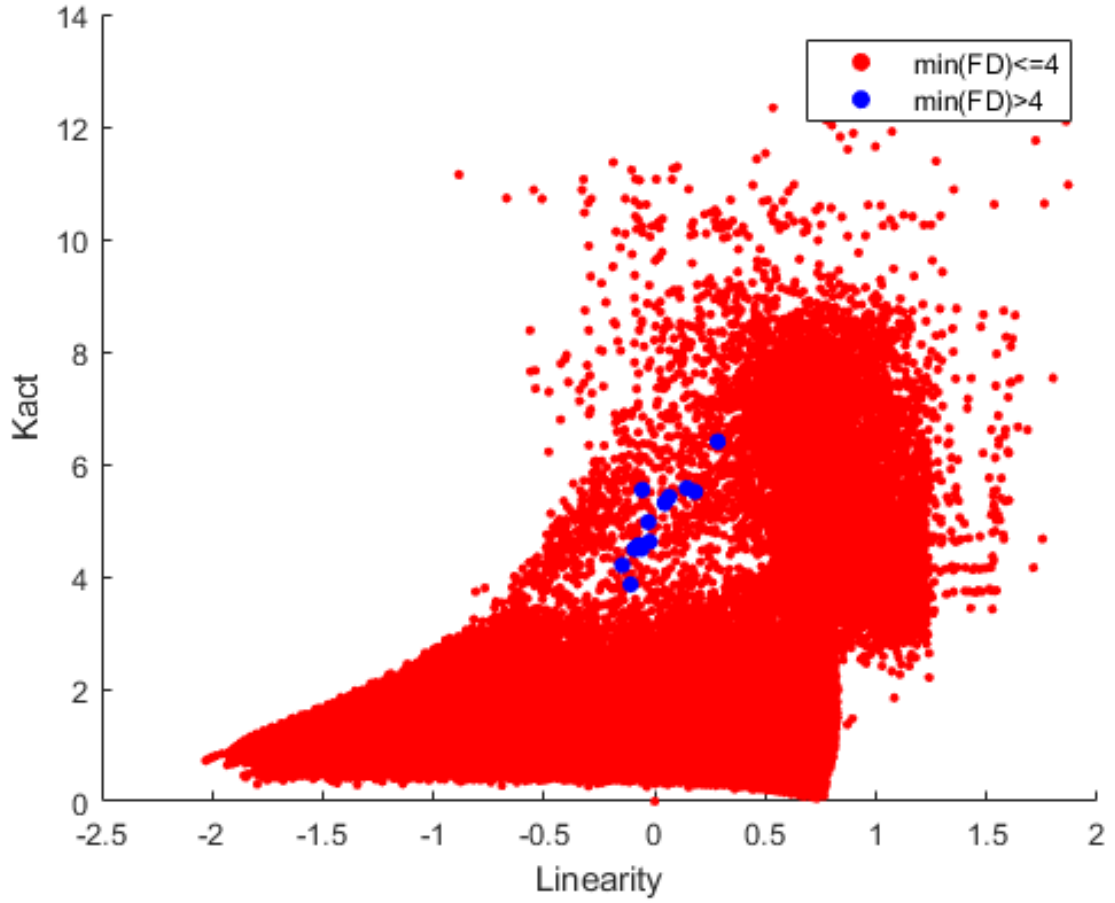


Clear that for a large GA a small Kout is necessary

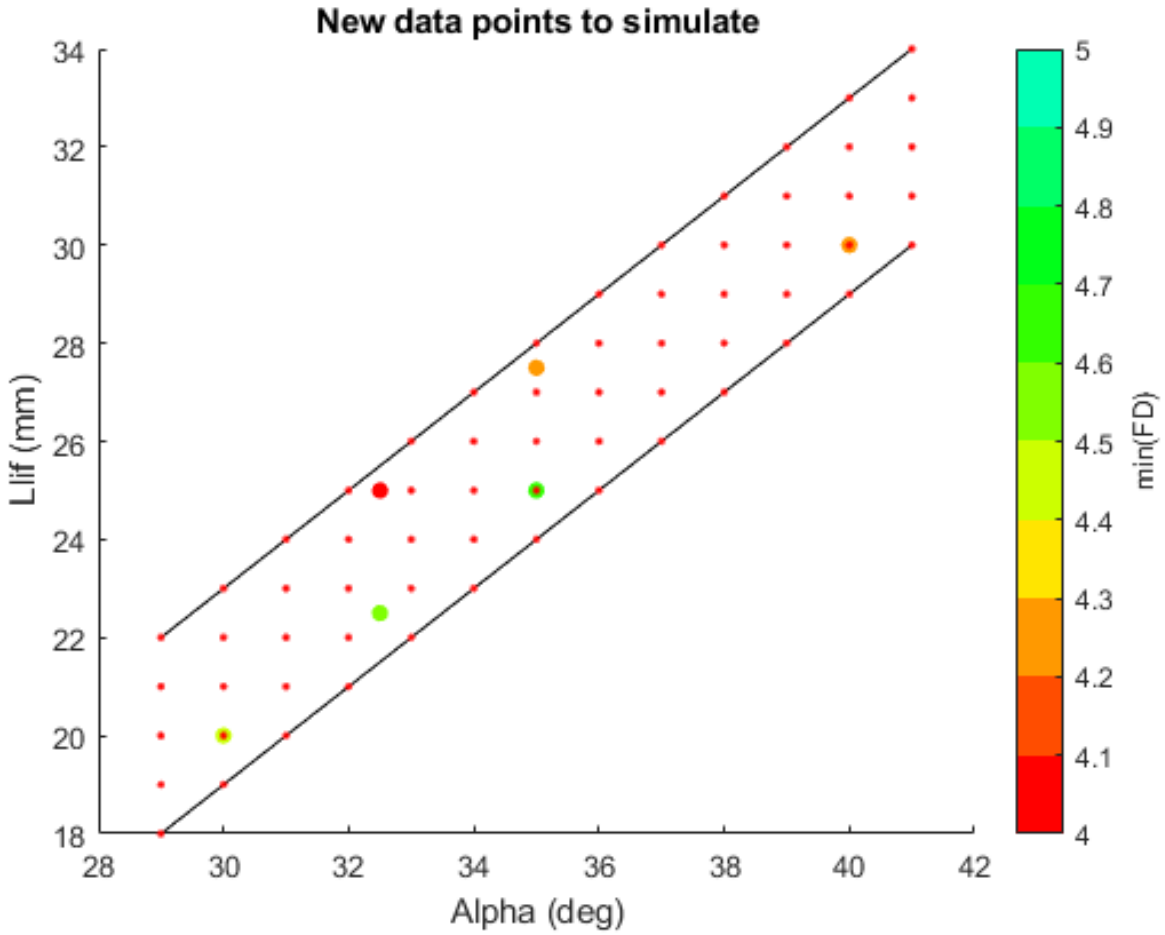


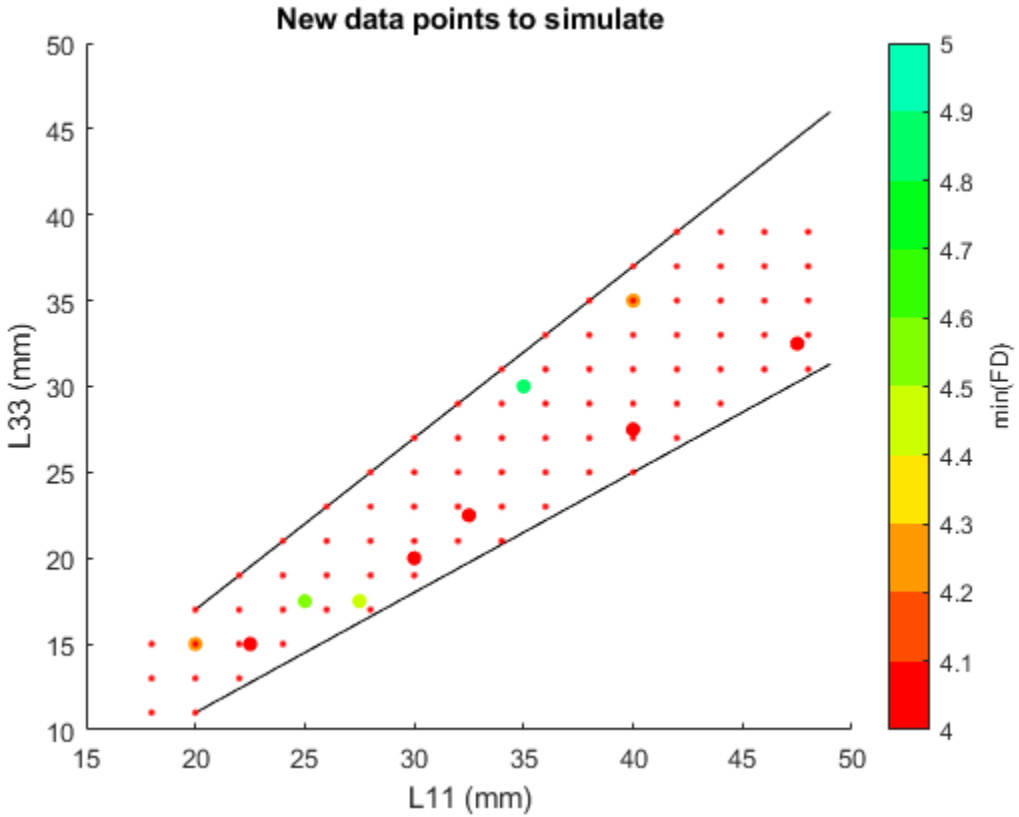


Linearity and KAct for the the points with min(Kin,Kout)>4.
Mostly middle of the pack.

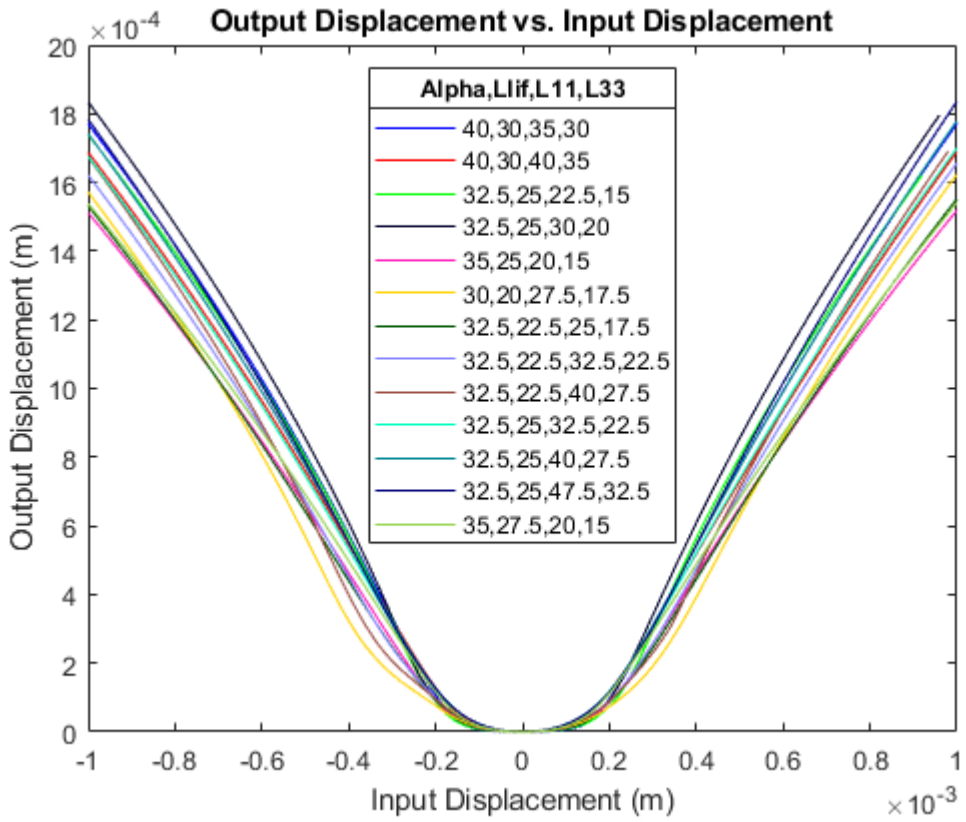


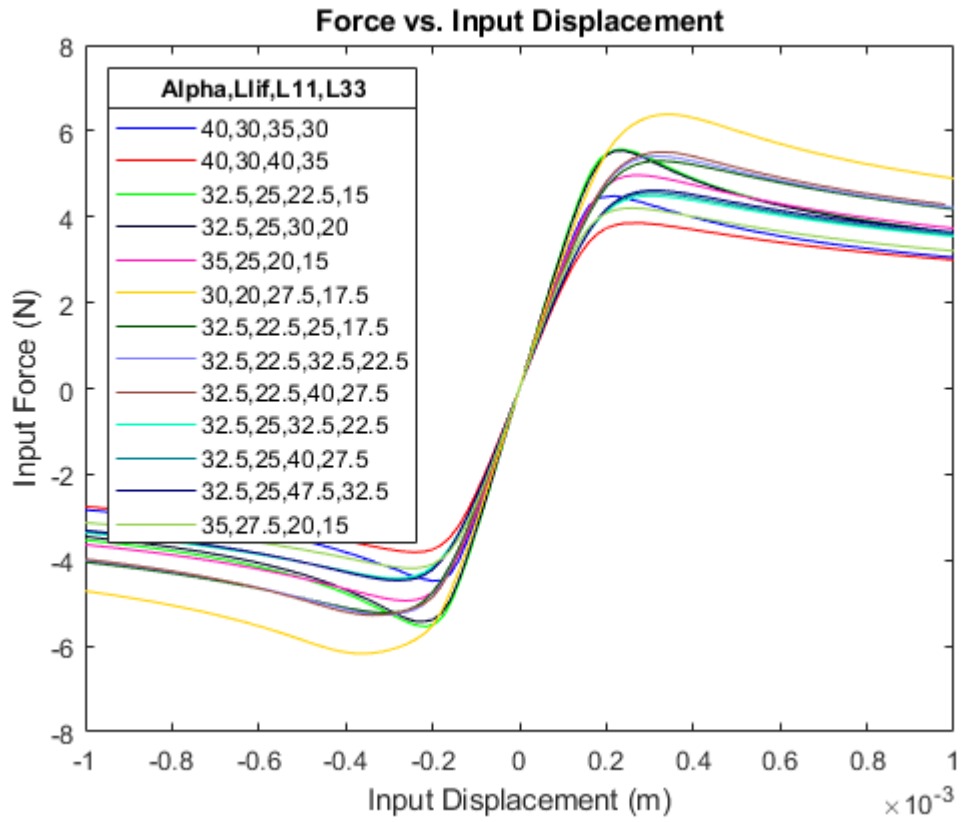
For the points min(Kin,Kout)>4, there is a clear relationship between Alpha-Llif and L11-L33. This was used for determining where more data points will be evaluated.





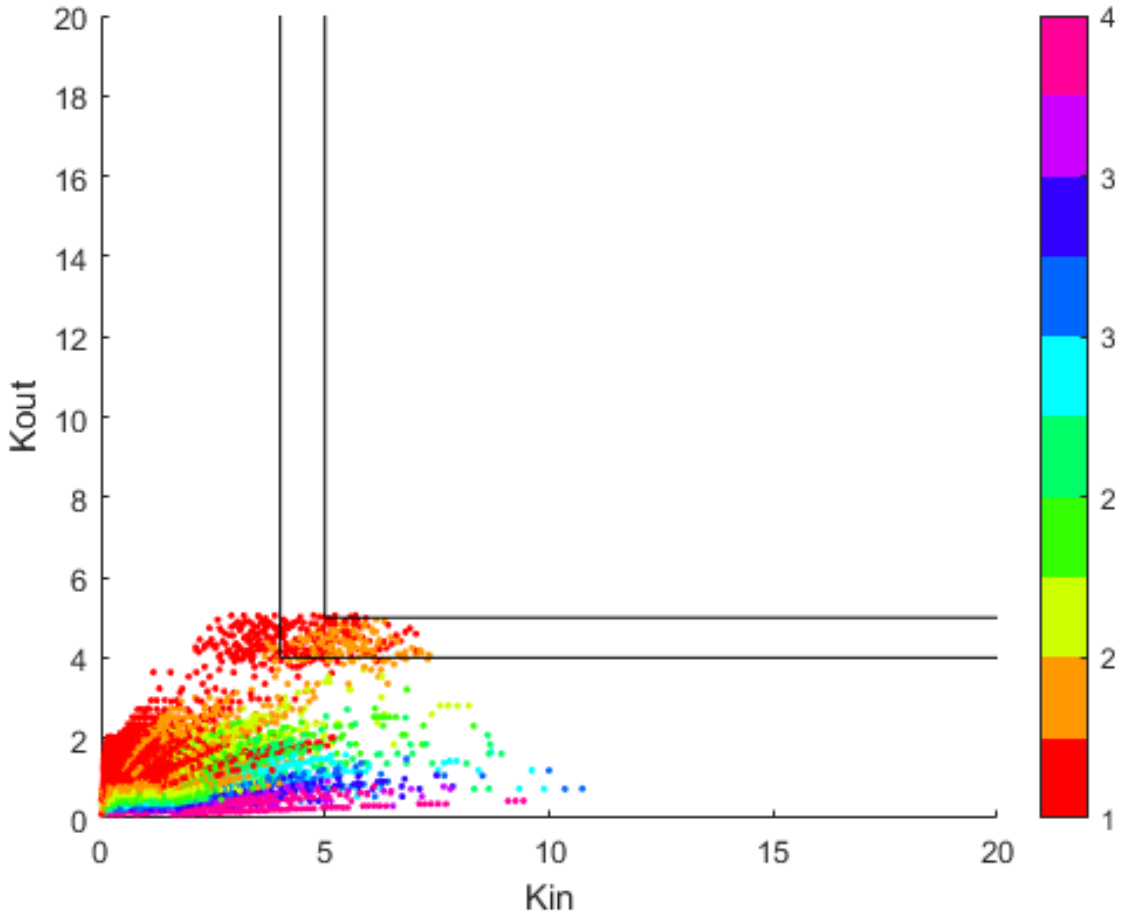
DD and FD diagram for the mechanisms that have min(Kin,Kout)>4

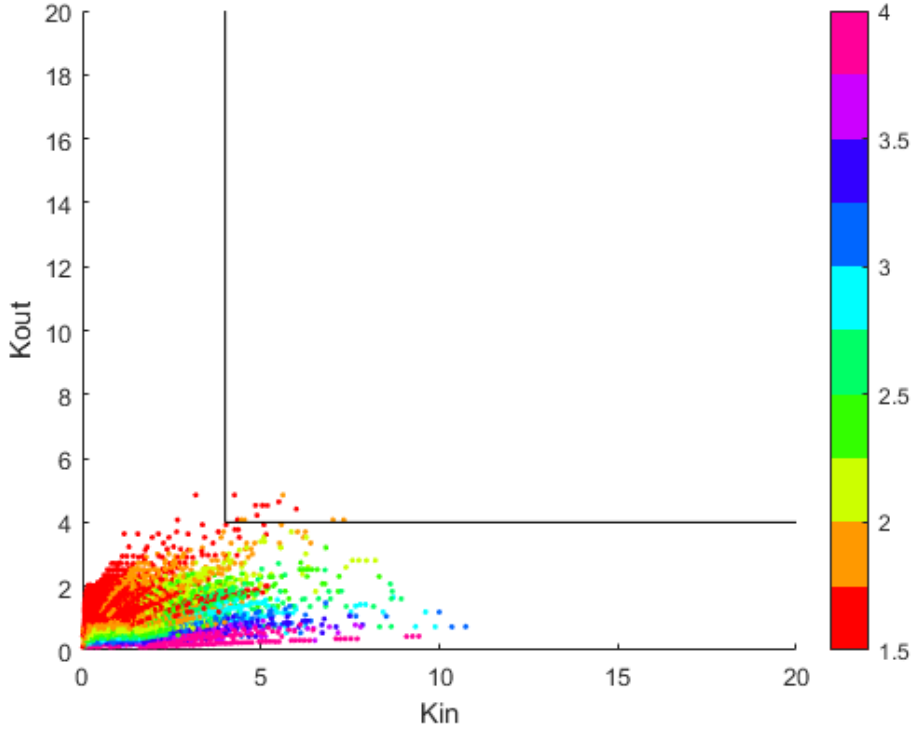




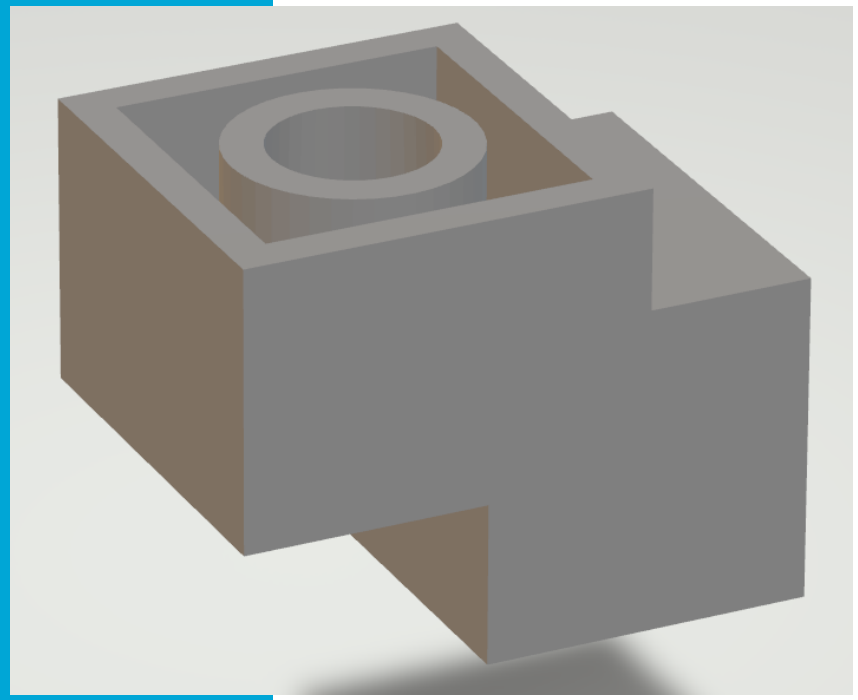
New Data, now 226 points have min(Kin,Kout)>4, and 4 even >5

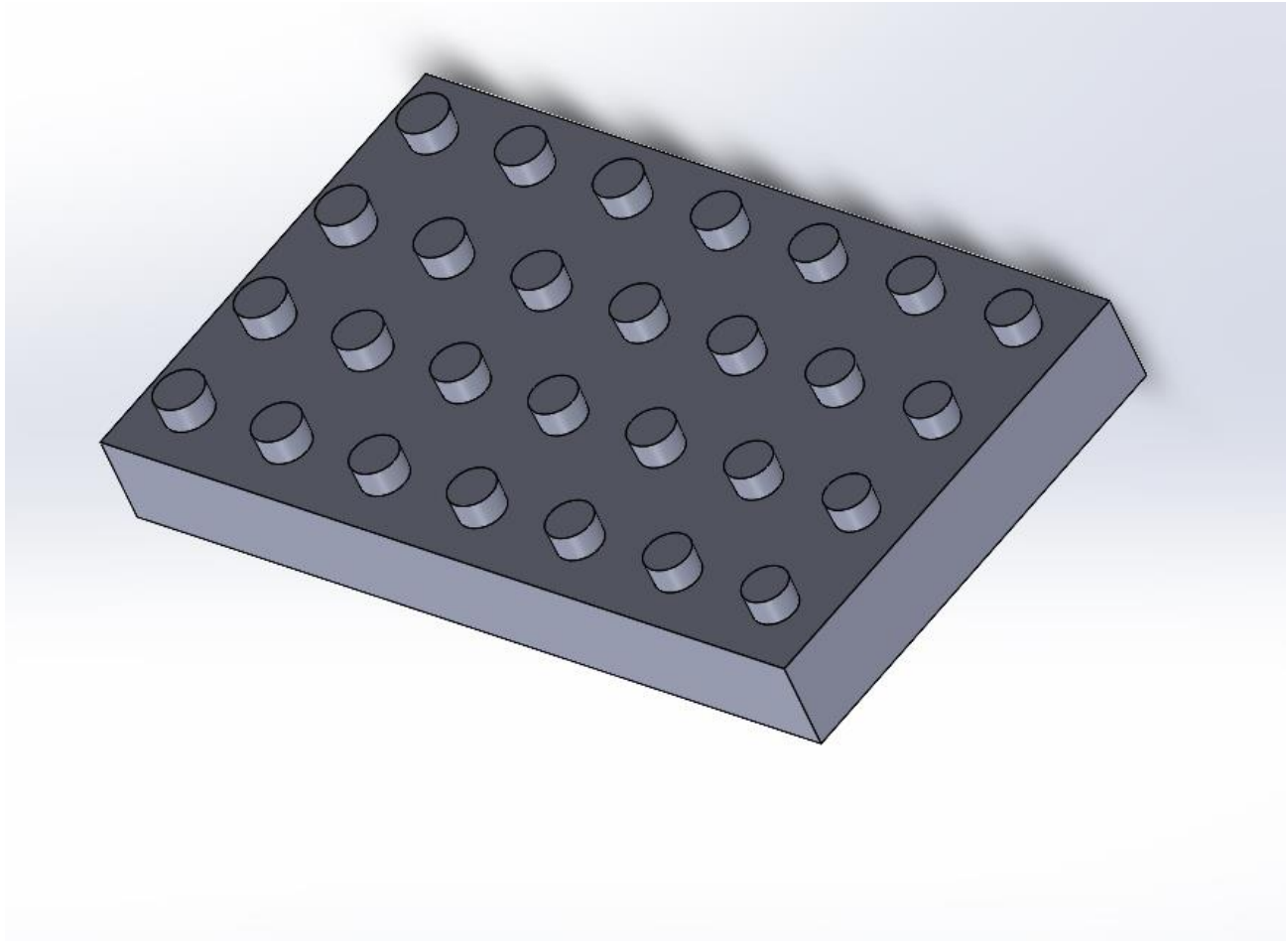
Best point: [Alpha, Llif, L11, L33] = [41, 30, 26, 23]



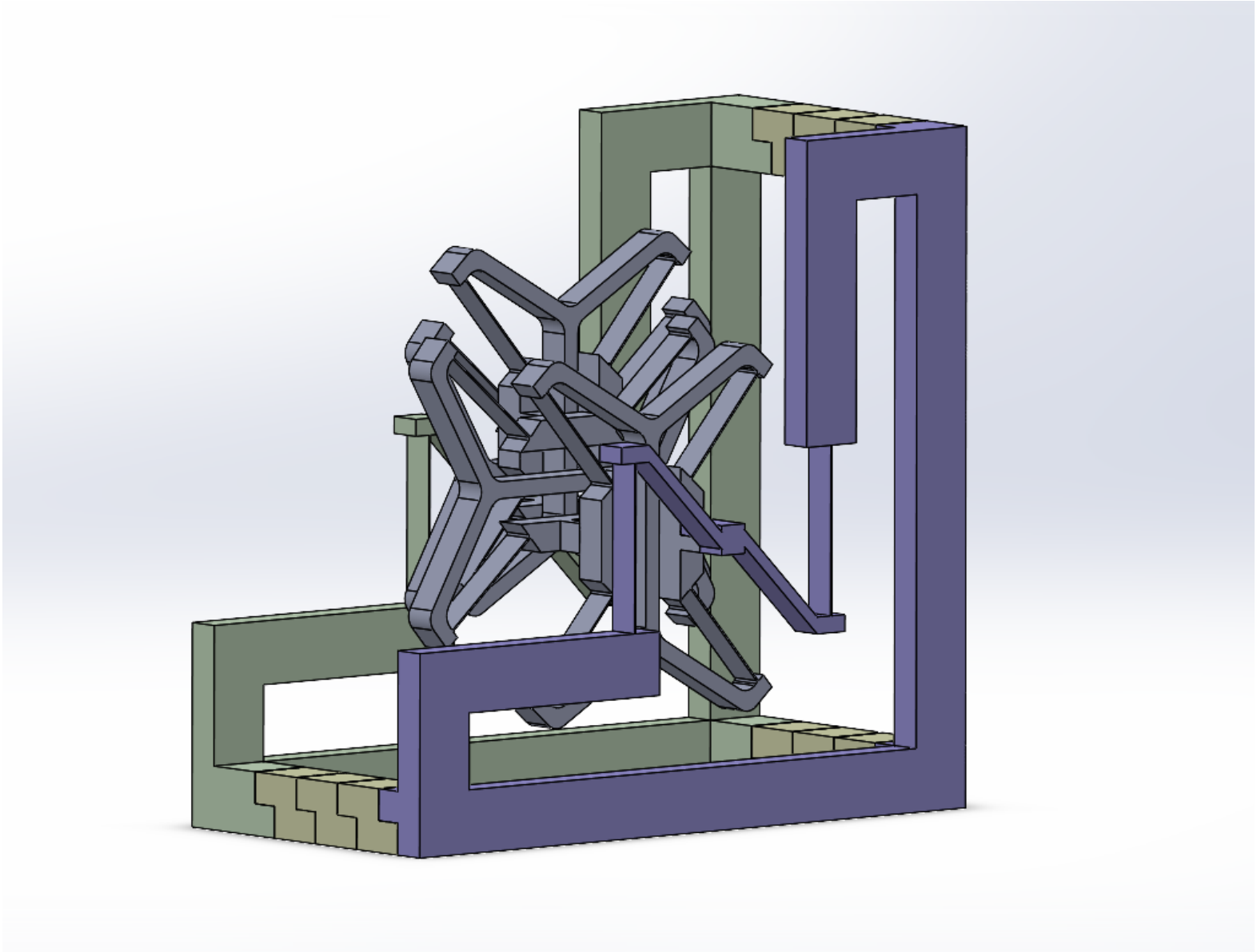


To test pin-hole sizes to connect mechanisms

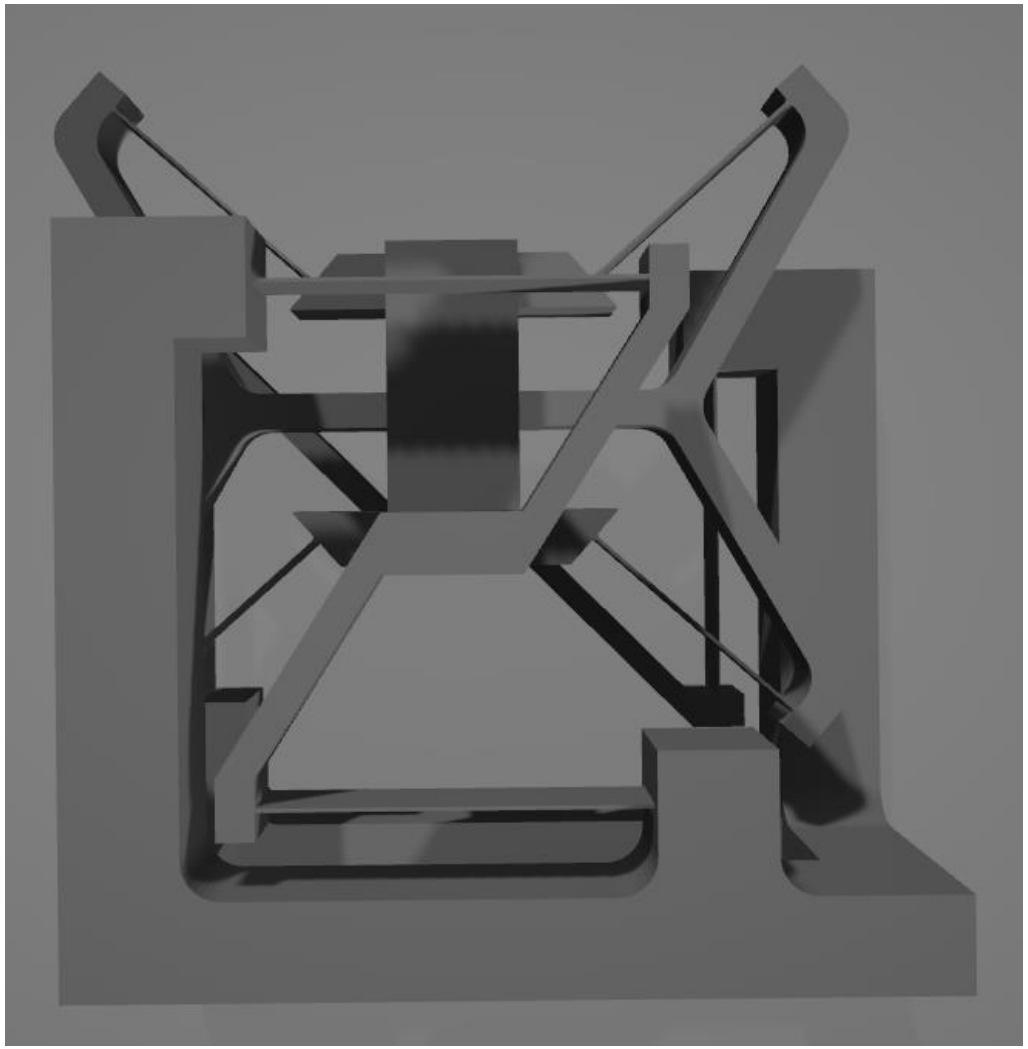




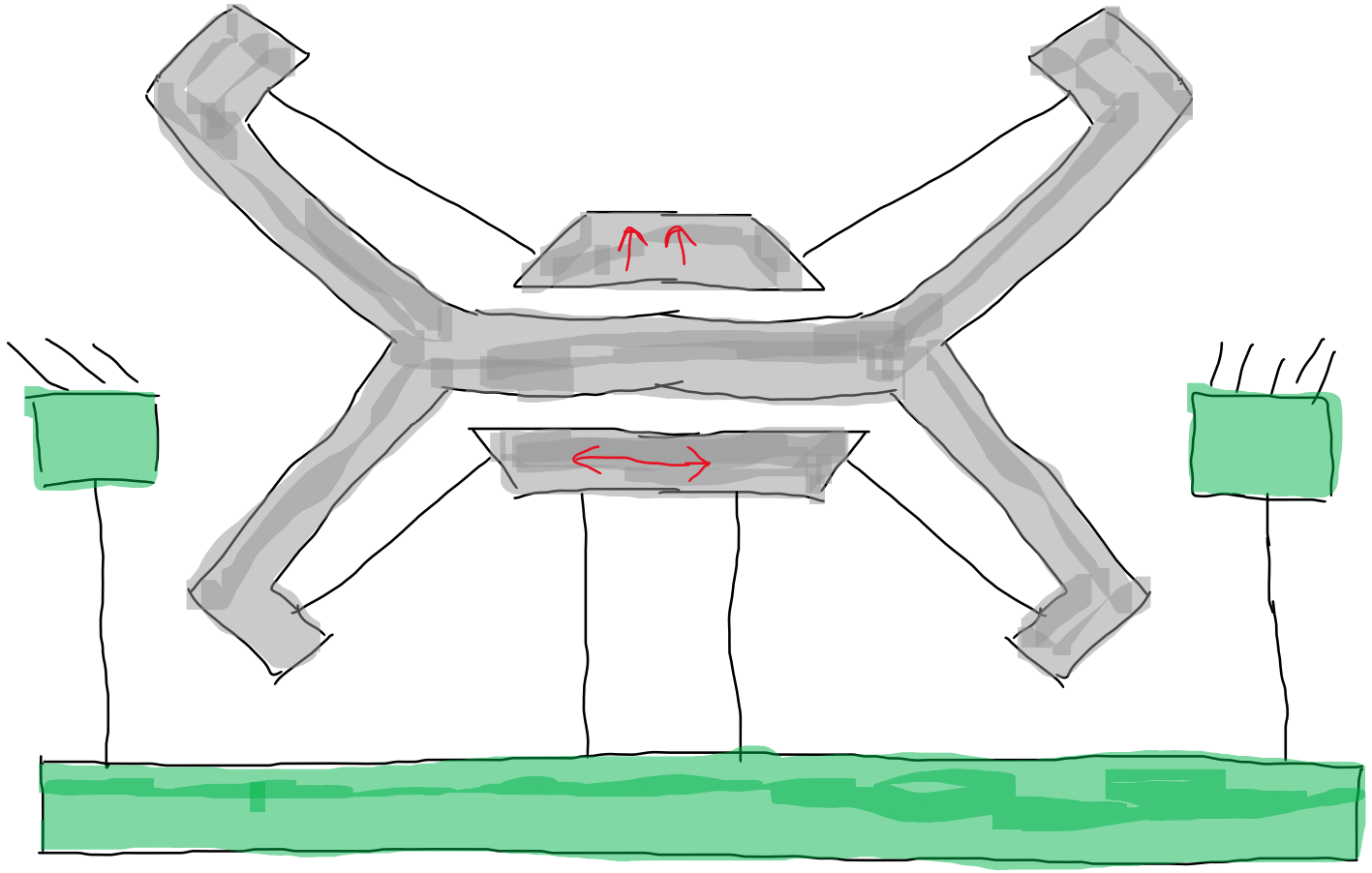
Solidworks: - Made it tileable
- Easy manipulation with functions



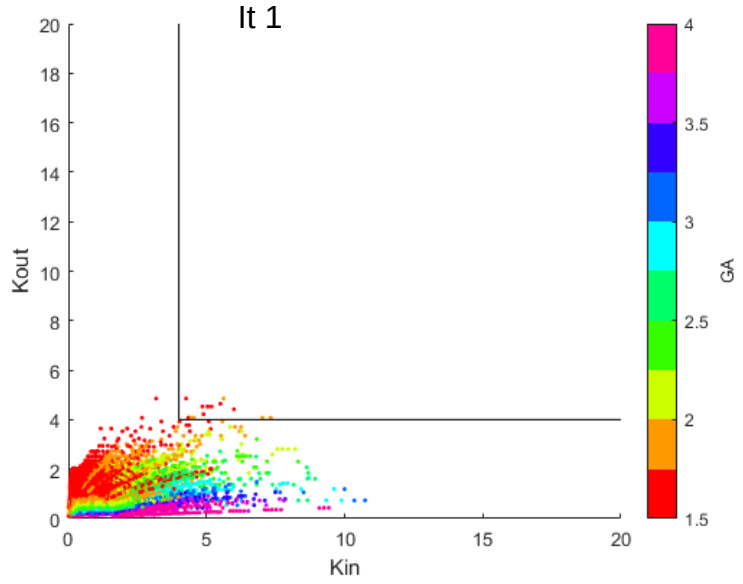
Iteration 2 SLA printer

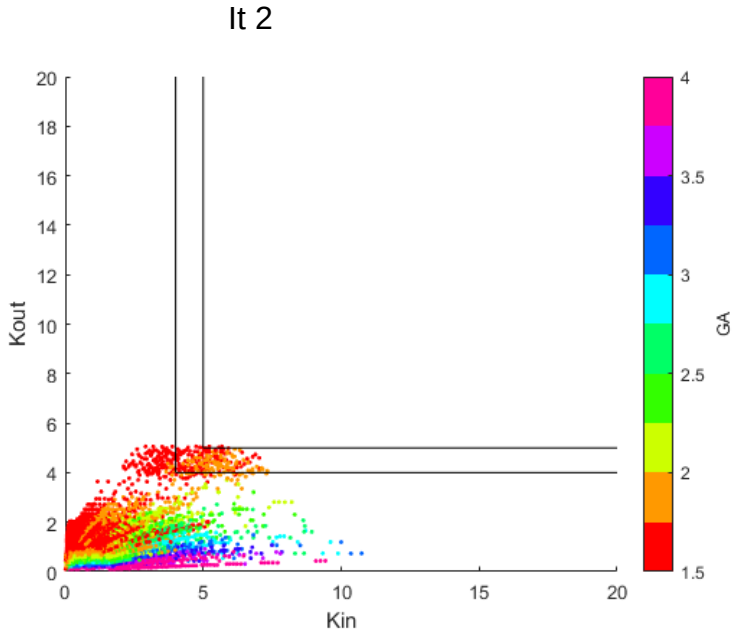


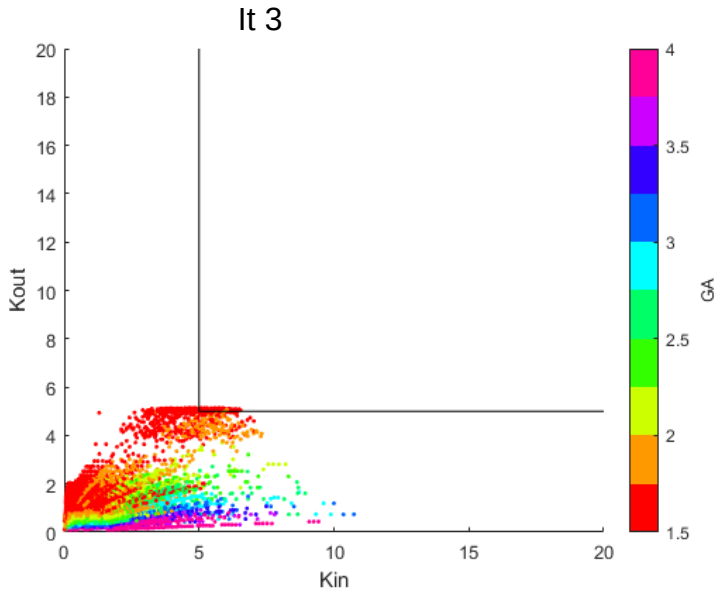
Prototype for new mechanism to not have large moment from input



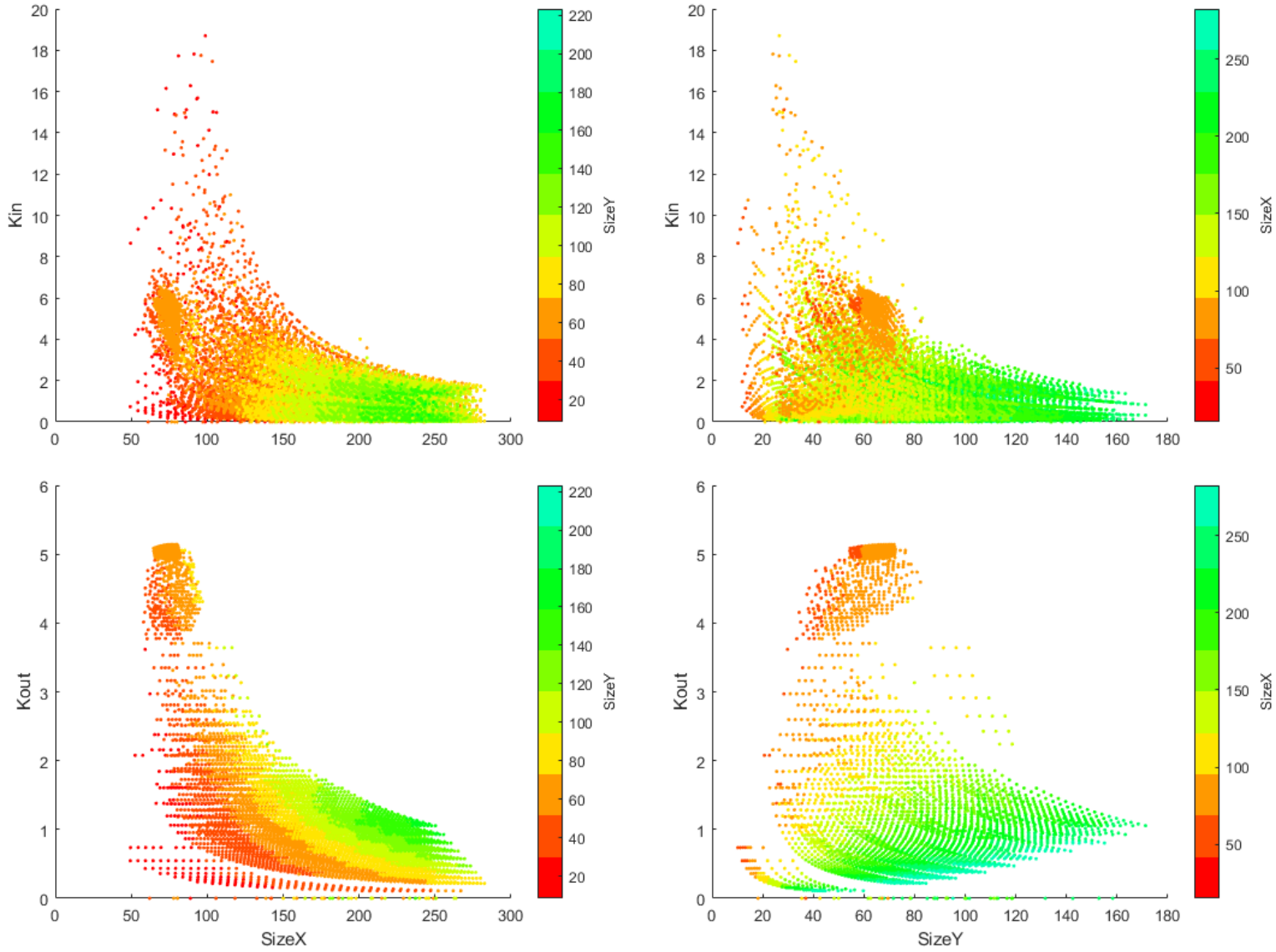
Kout does not seem to improve, but more points with high force capabilities





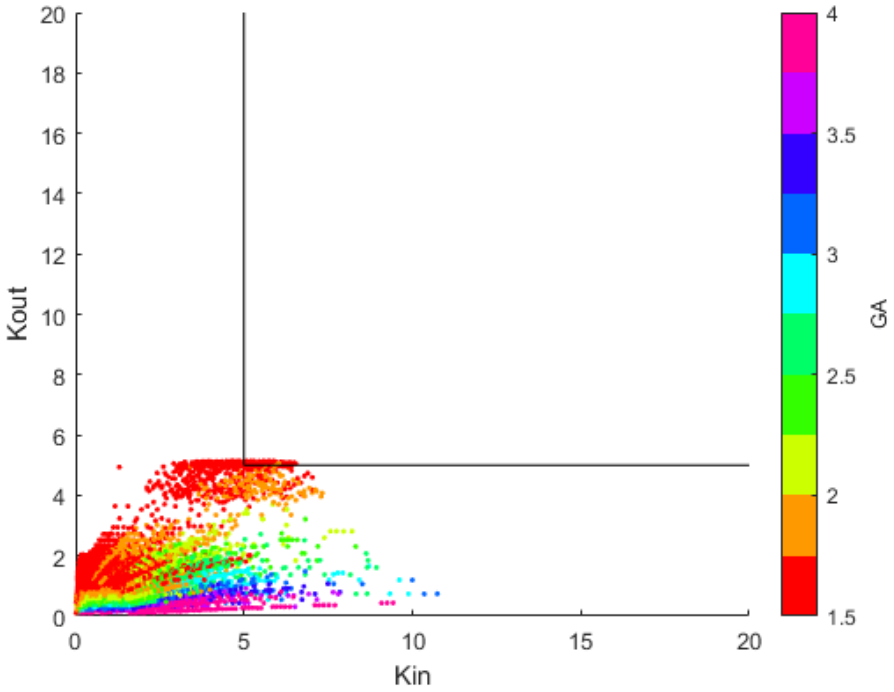


Size dependency, smaller seems better and limited by manufacturing



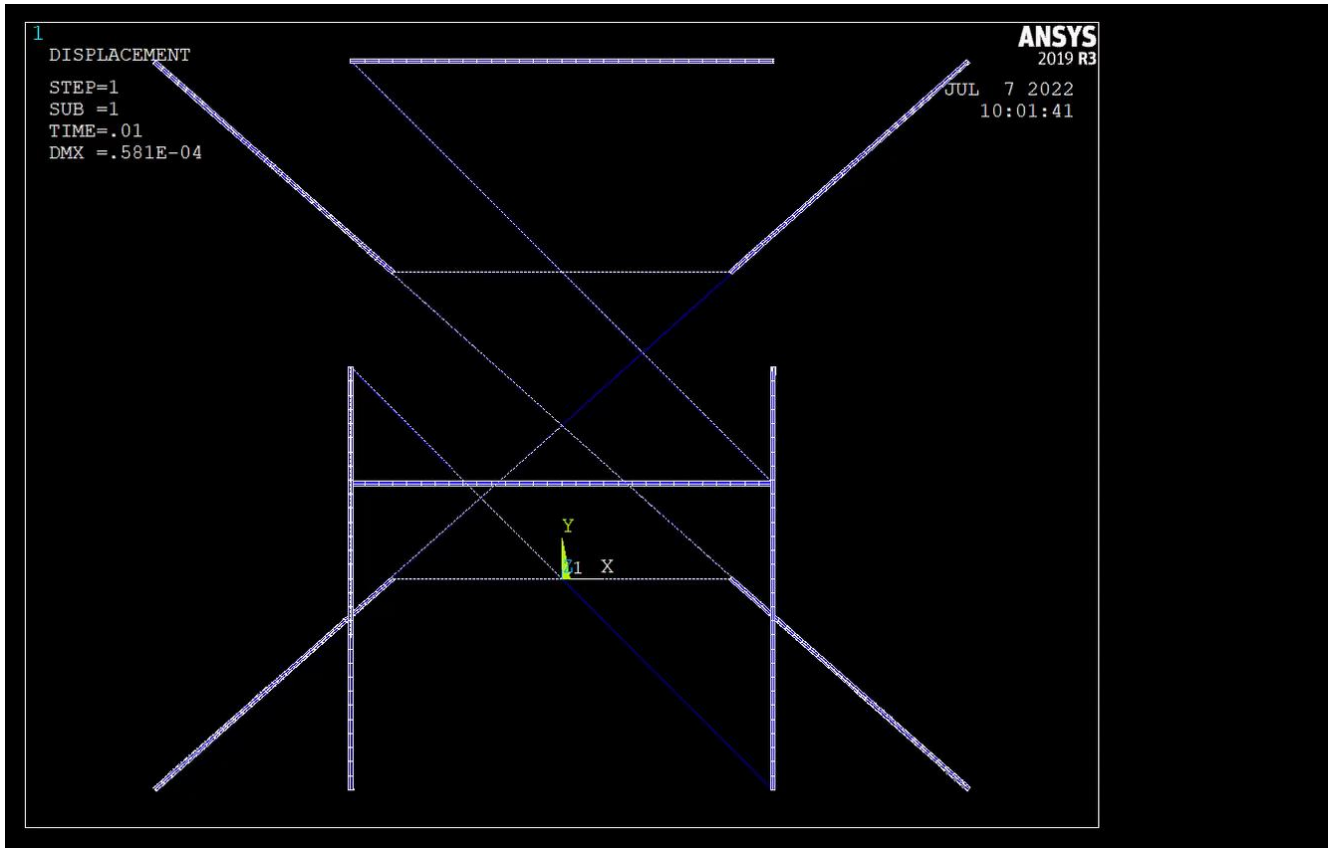
Some notes

- Sharing files
- Behavioral analysis approach
- Testing?
- Still have to run stress analysis
- Linear guidances between mechanism?

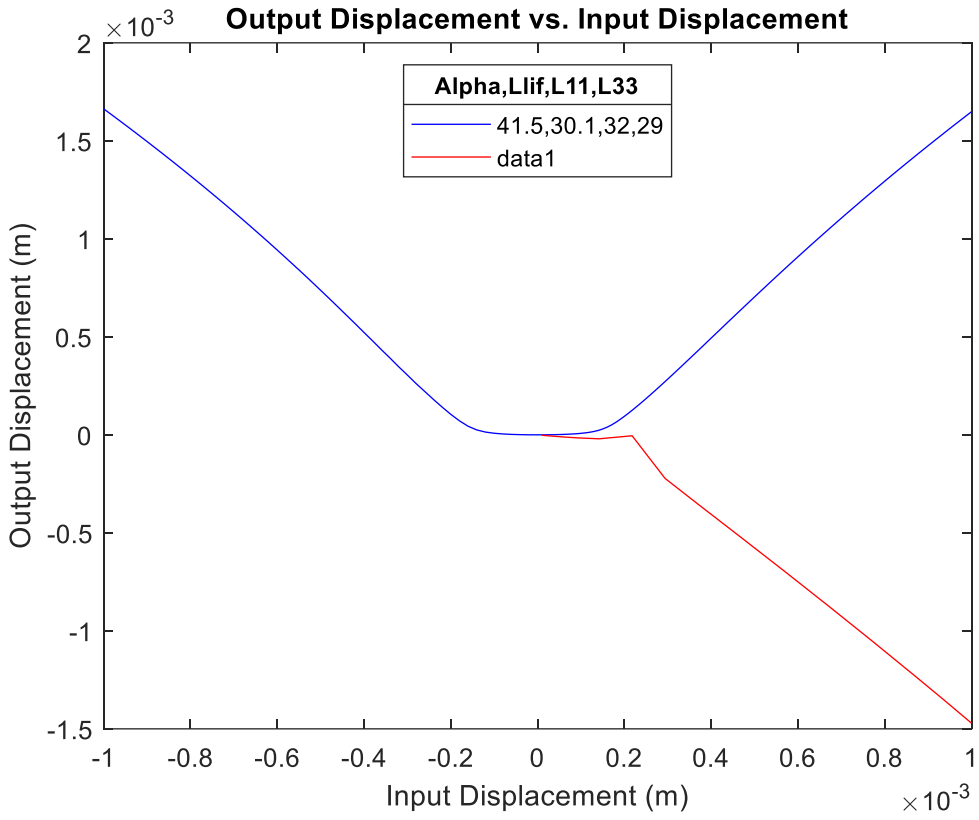


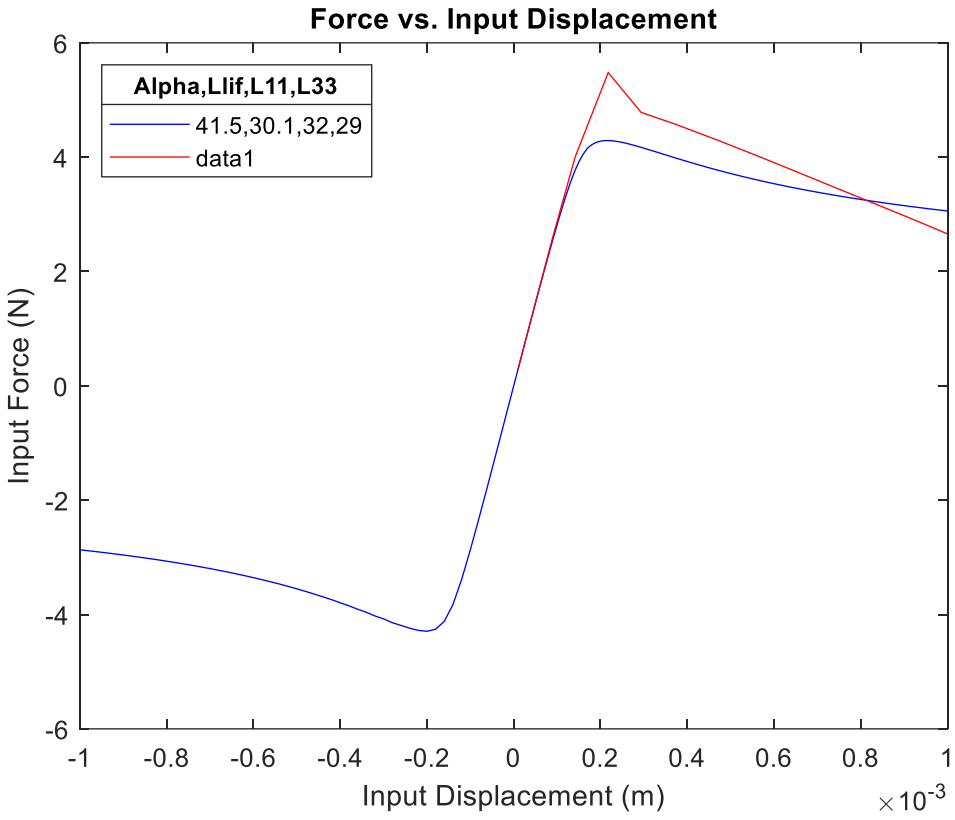
Comparing Stress

- Output fixed looking at 5% of Din
  - Smax = 3.32 MPa
  - F = 4.11893 N
- Load at output
  - Smax = 38 MPa
  - Opposing force?
  - Too high

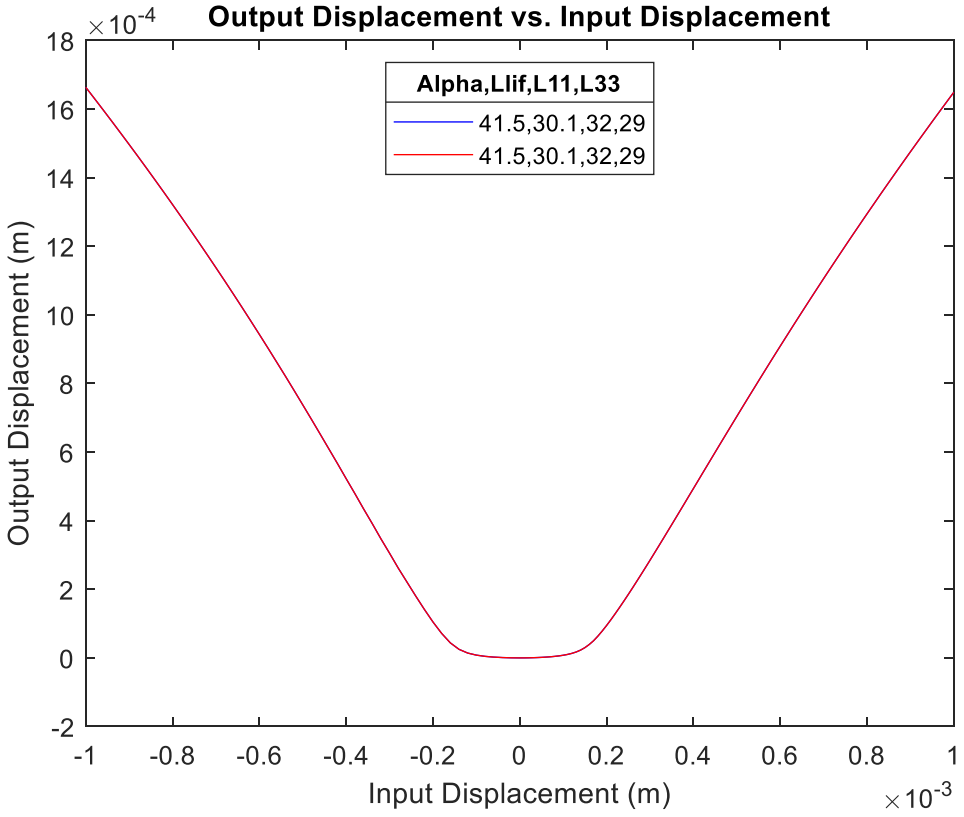


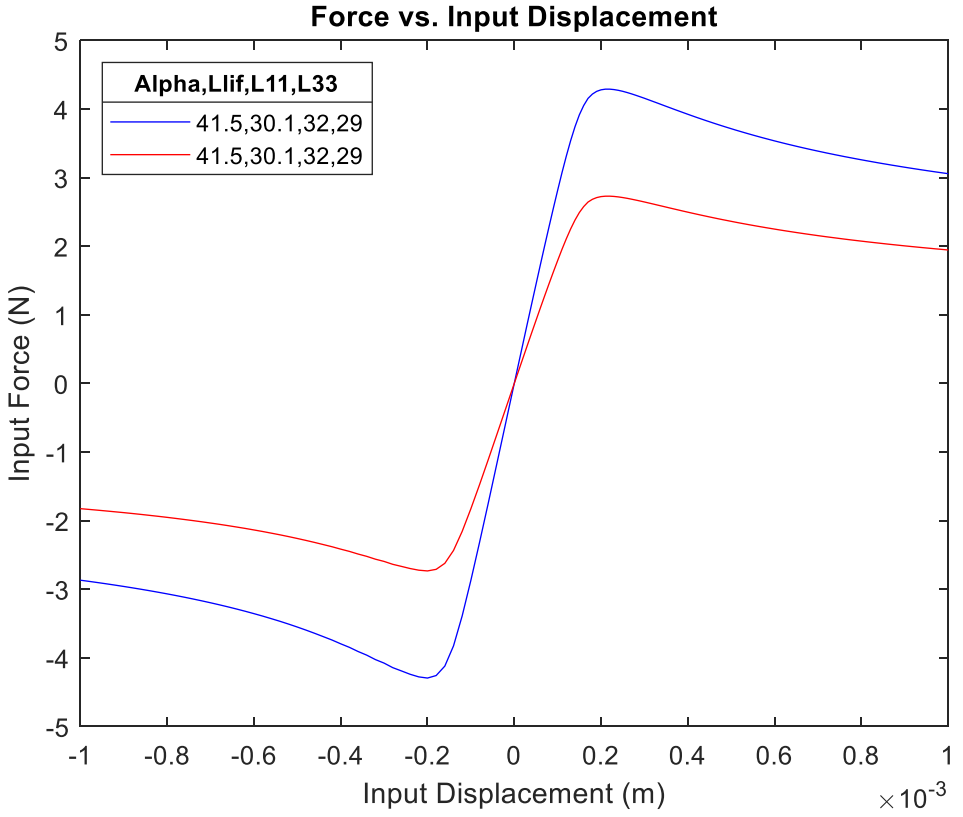
DD and FD graph of mechanism with added load





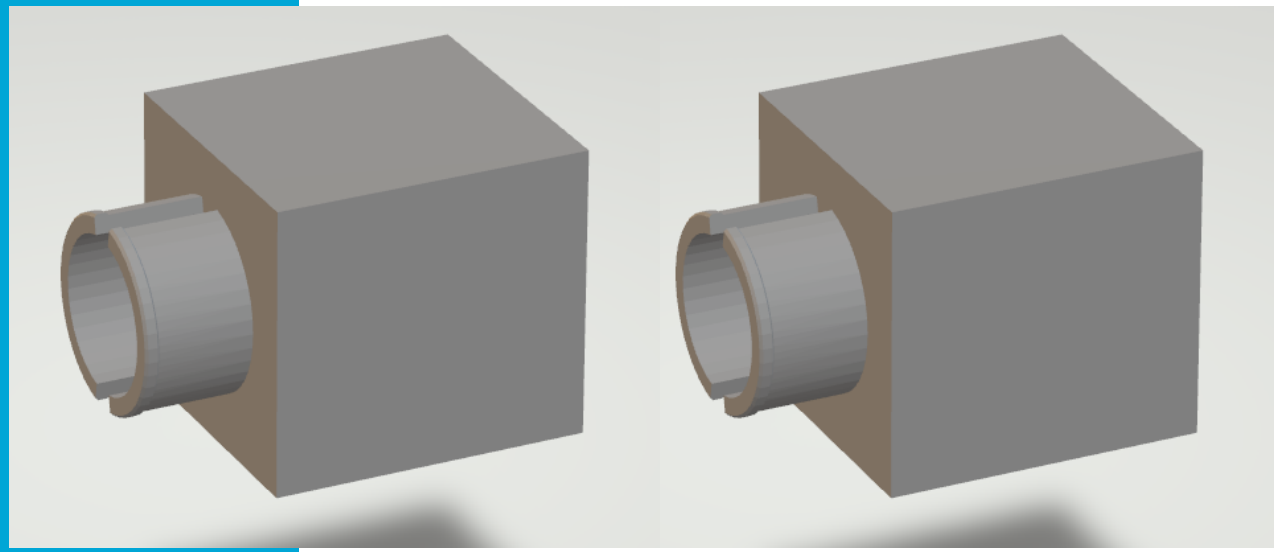
Blue: Clear resin, Red: Tough1500 resin

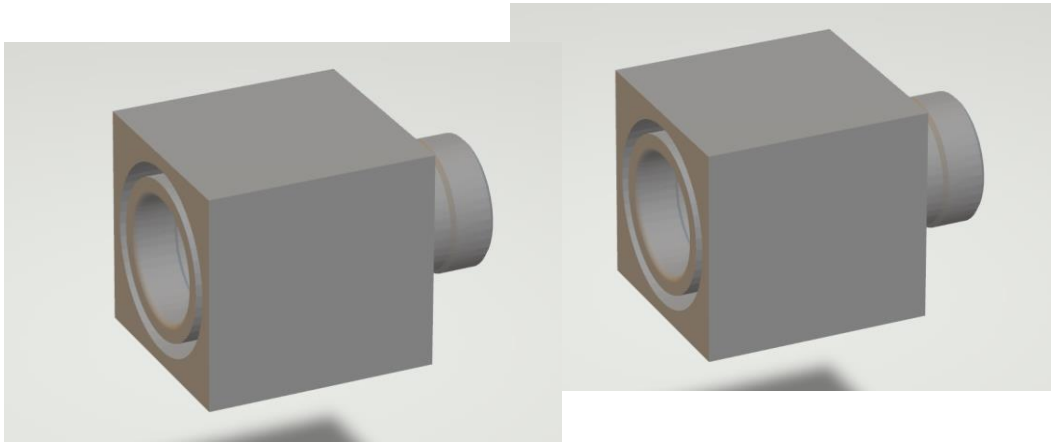




Combining the planes

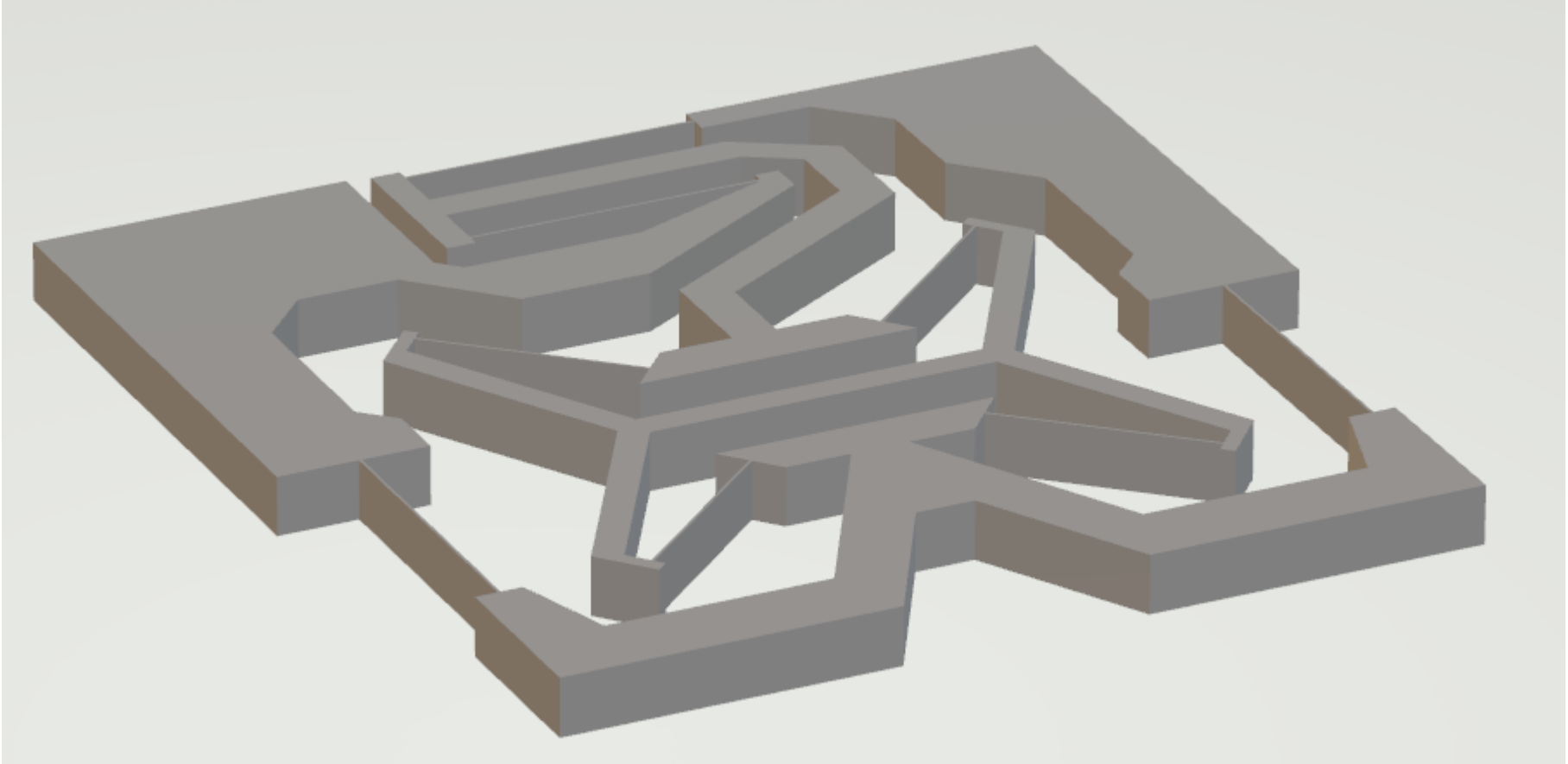
- Some ideas to attach the input shuttle to butterfly flexures and output shuttle



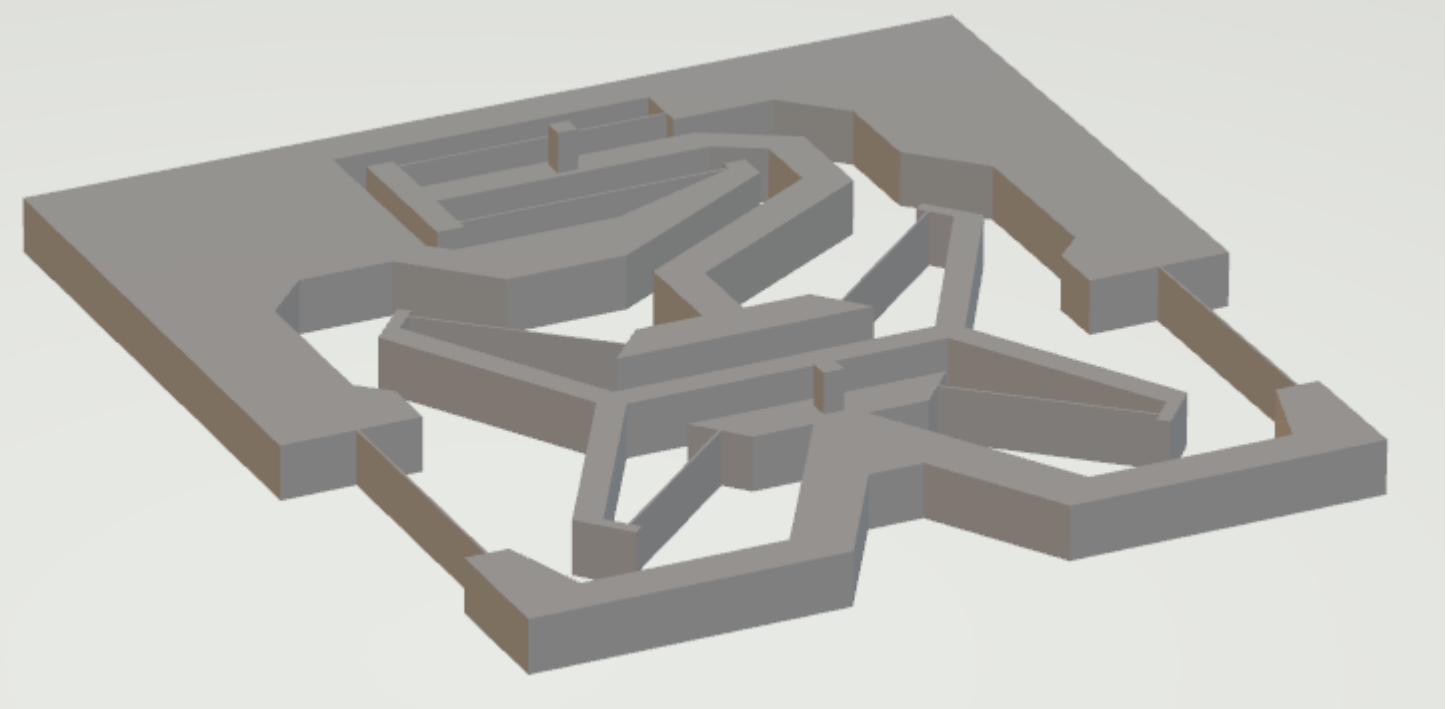


Trying to make manufacturing work

- Iteration 1 planar mechanism



- Iteration 2 of planar mechanism



- Matlab figures for behaviour now working
- Adding stiffness to linear design?
- Is linearity preferred?
- Kinetoelastic (non-dimensional analysis)
  - 1. Take only flexures into account
  - 2. The whole mechanism

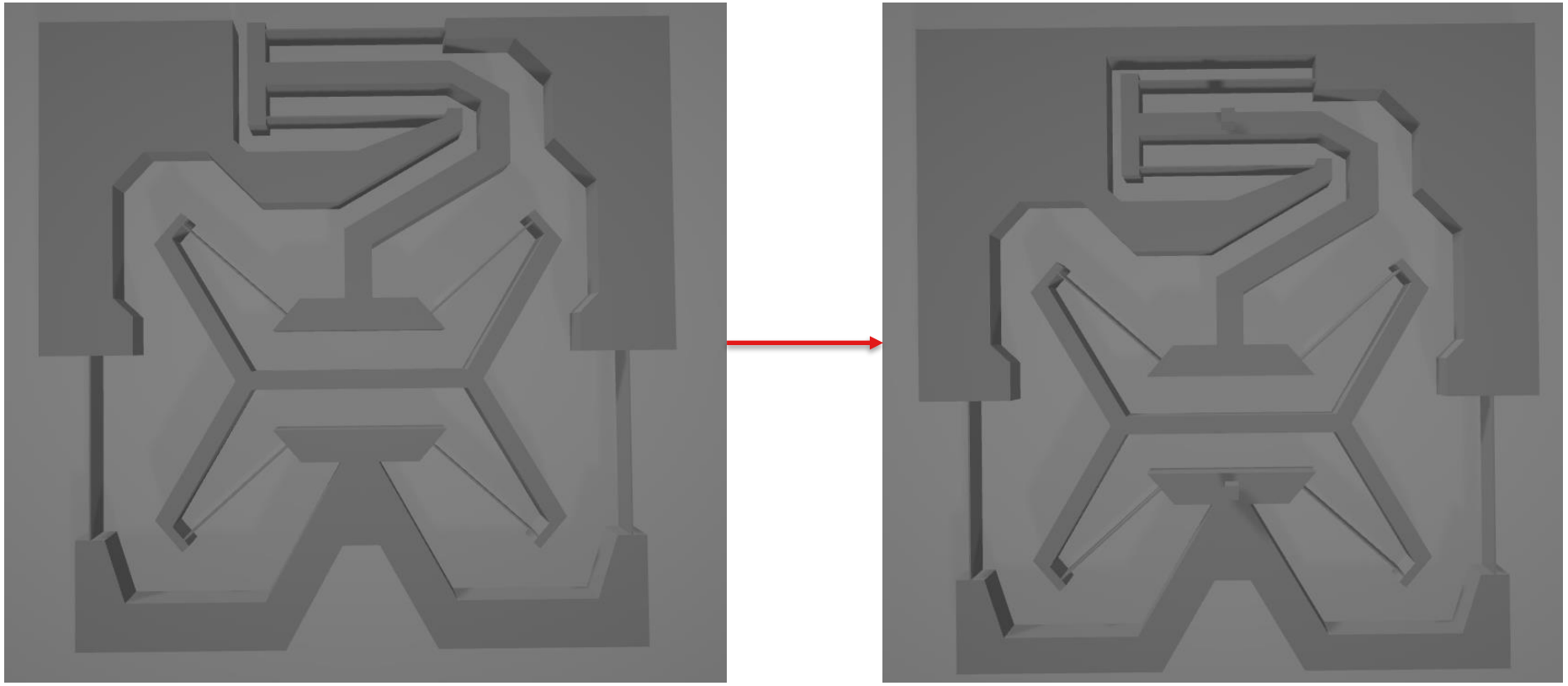
$$s = \frac{\bar{L}}{\bar{d}}$$

$$\eta = \frac{Fs^2}{E\bar{b}\bar{d}}$$

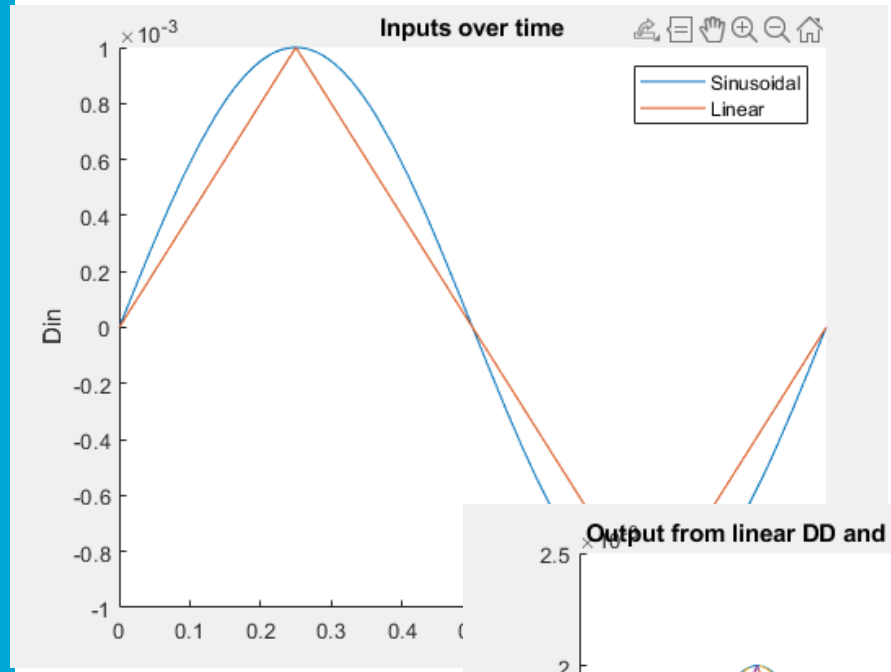
Problem is that for same s and eta the mechanism still behaves different

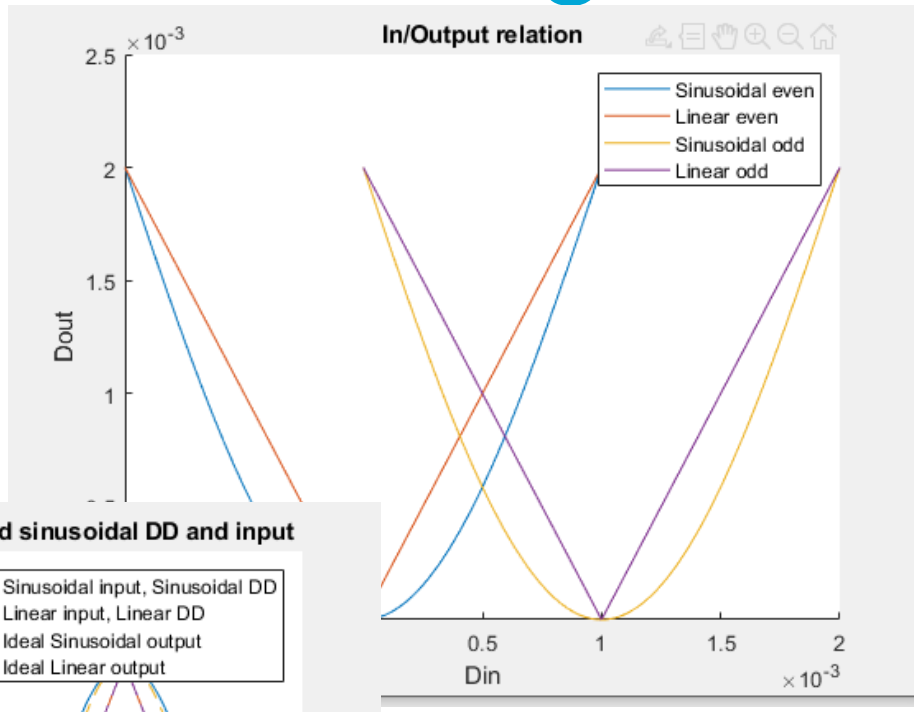
- Planar design just for manufacturing?

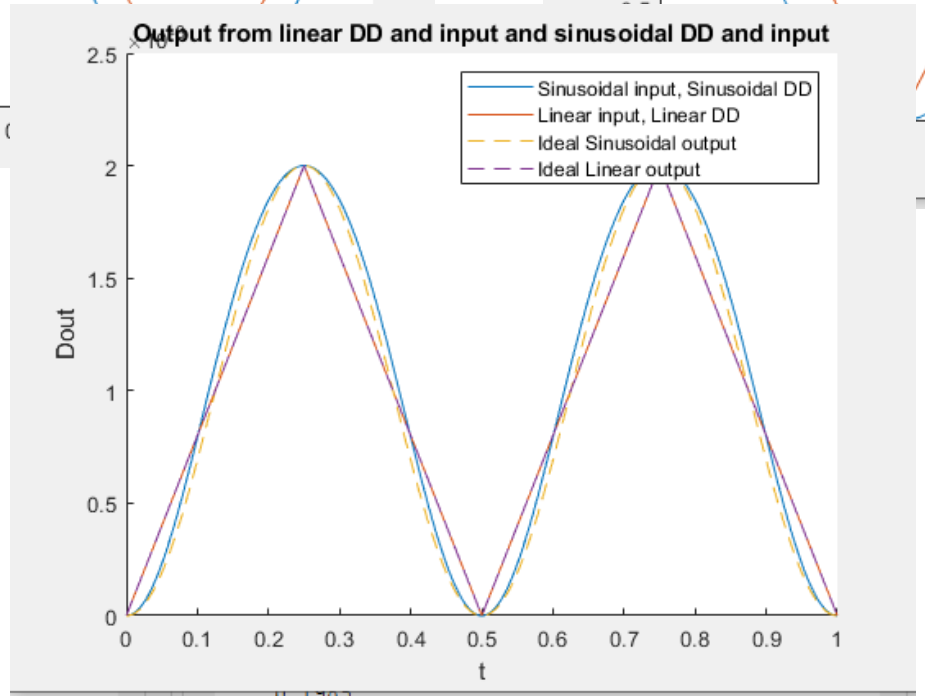
- Sent planar design for printing



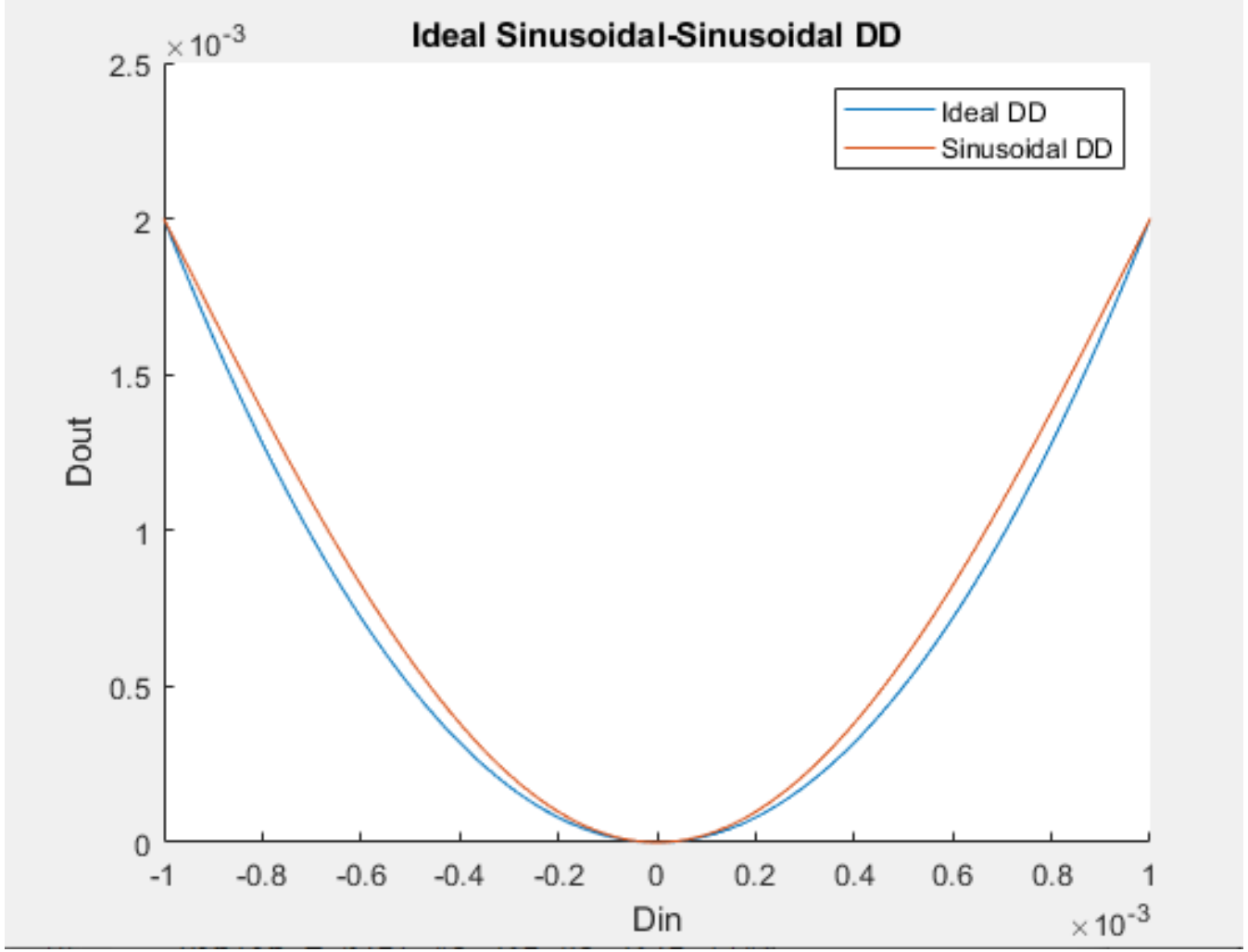
Linear vs Sinusoidal Design?



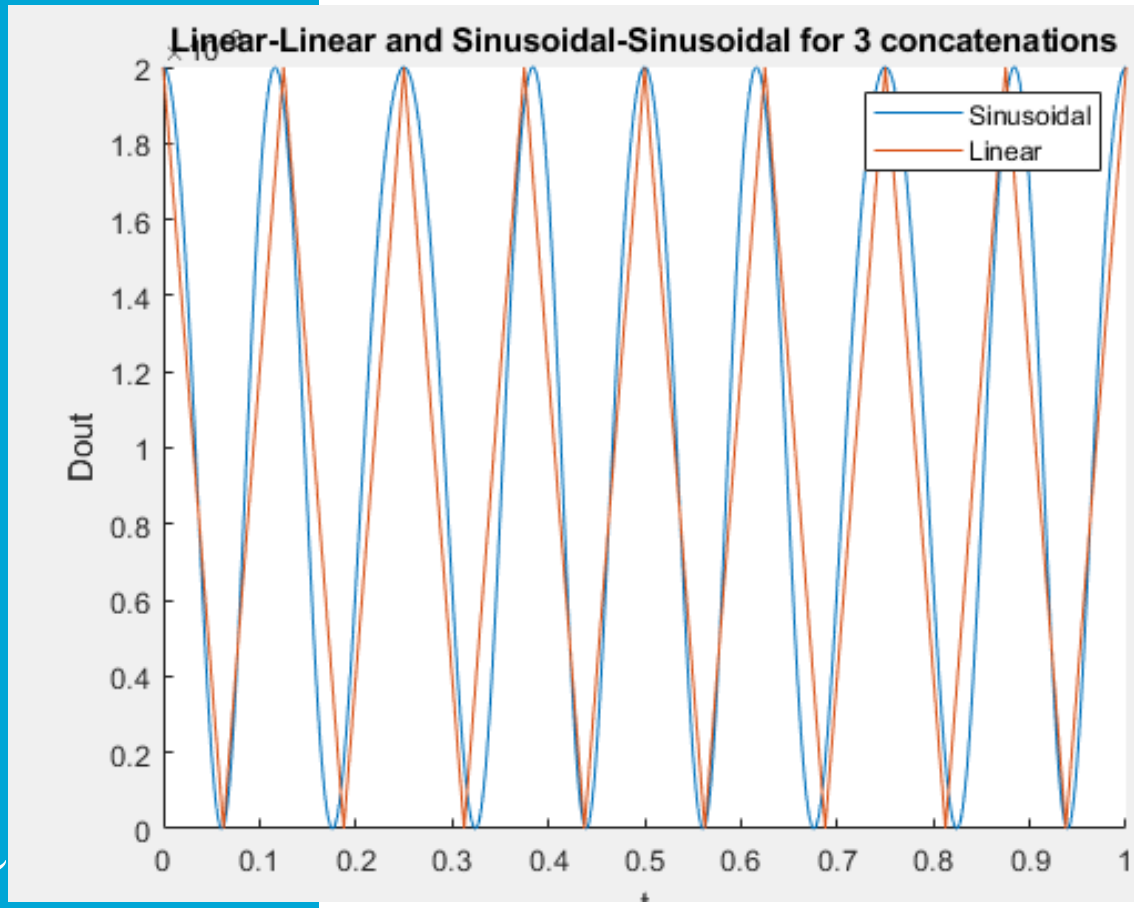


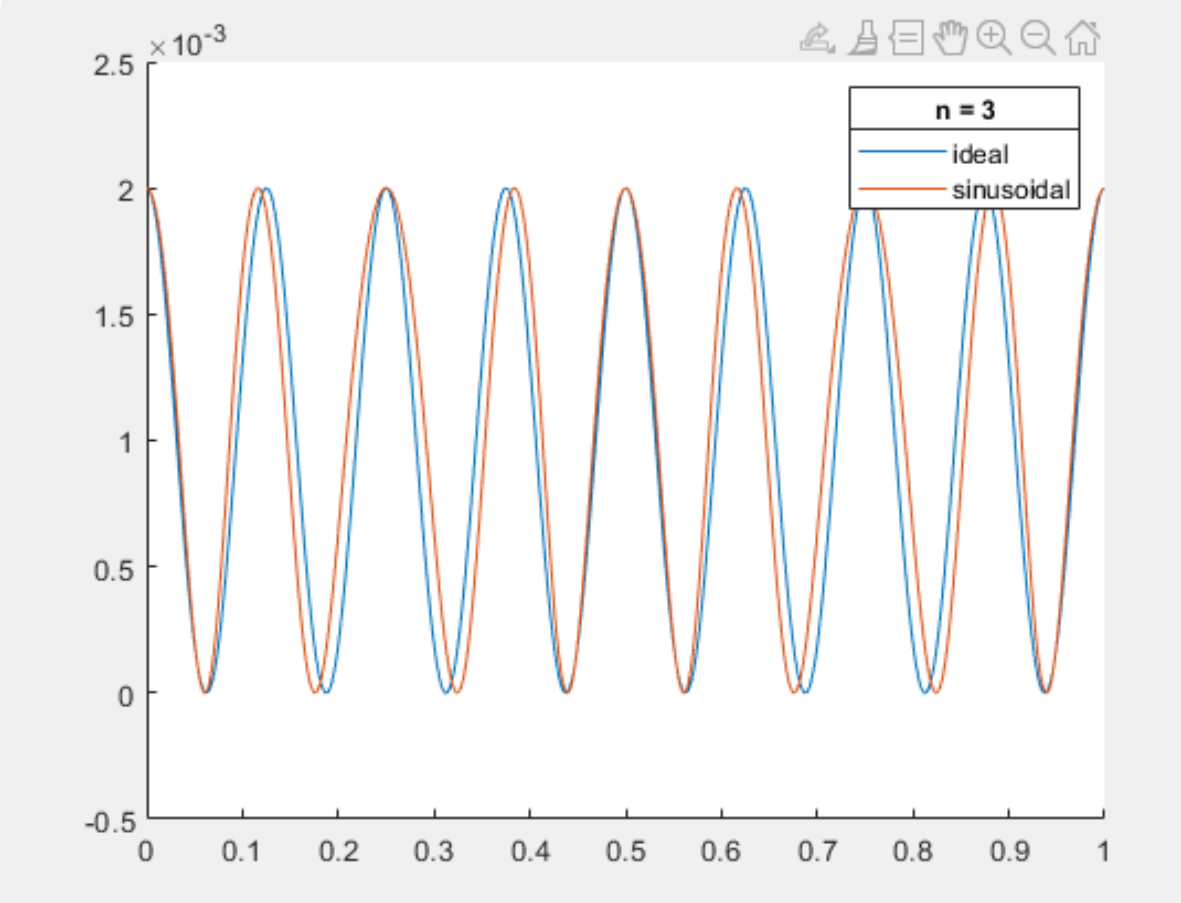


Input/Output relation GA=2

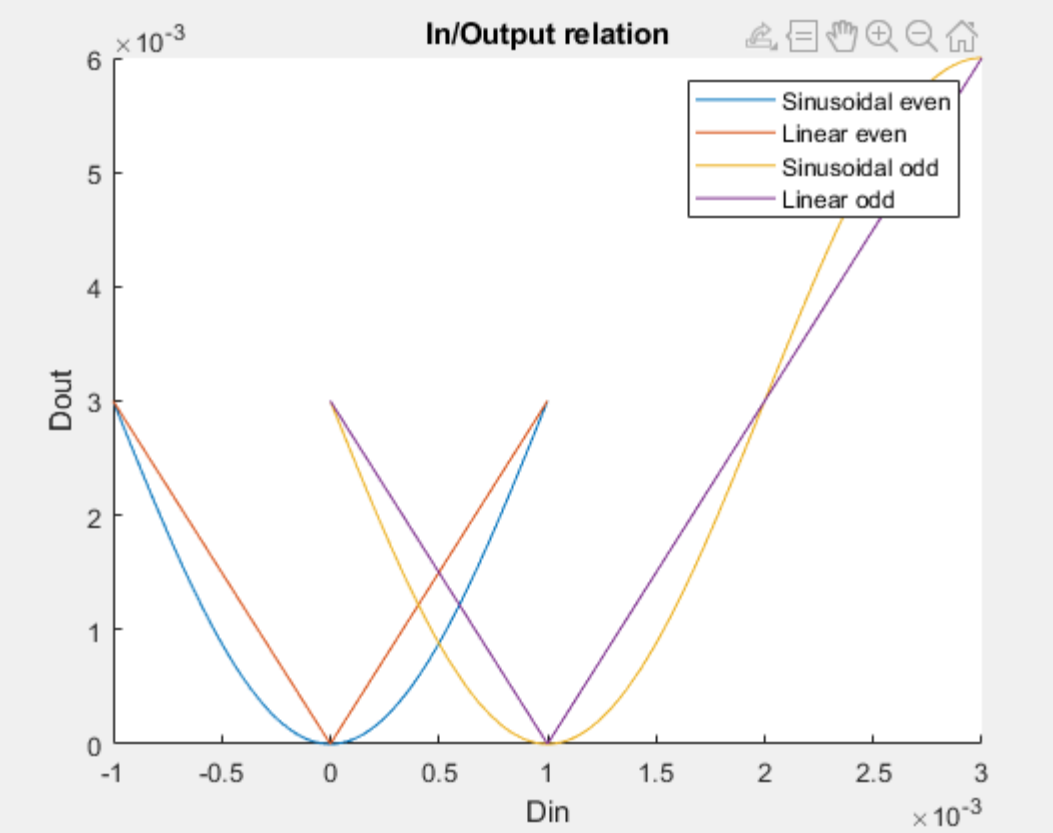


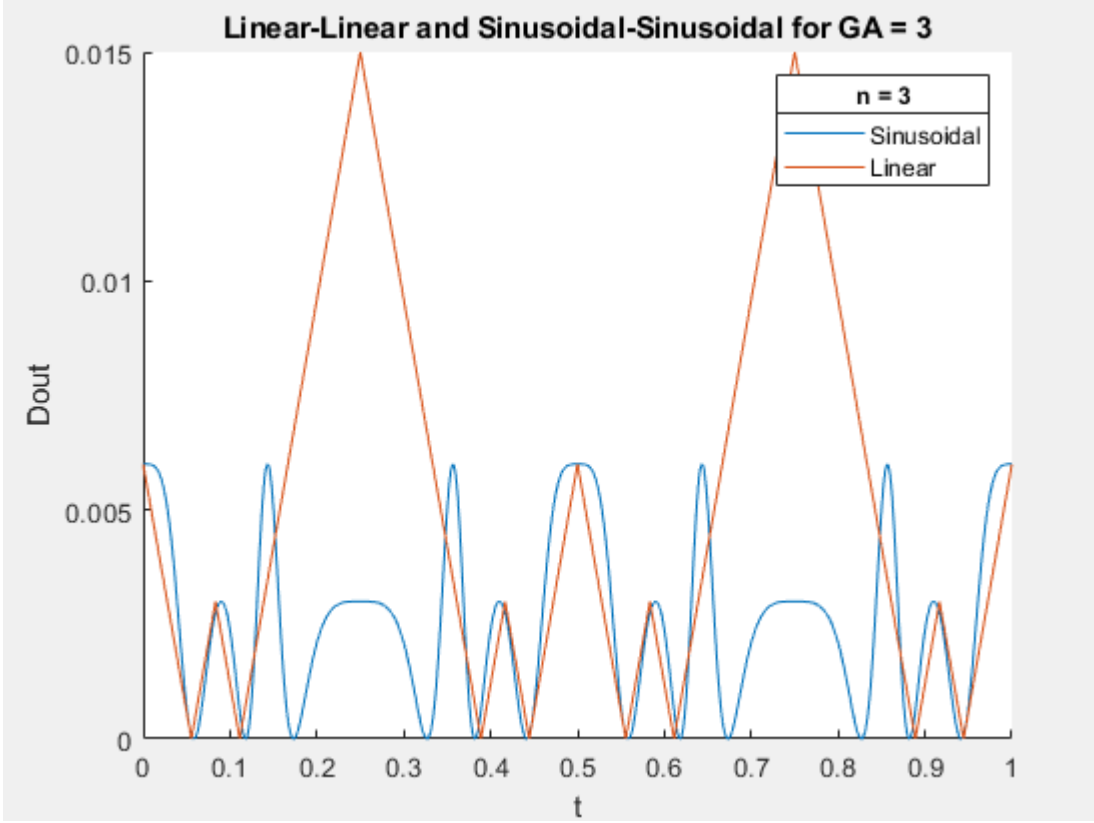
3 concatenations





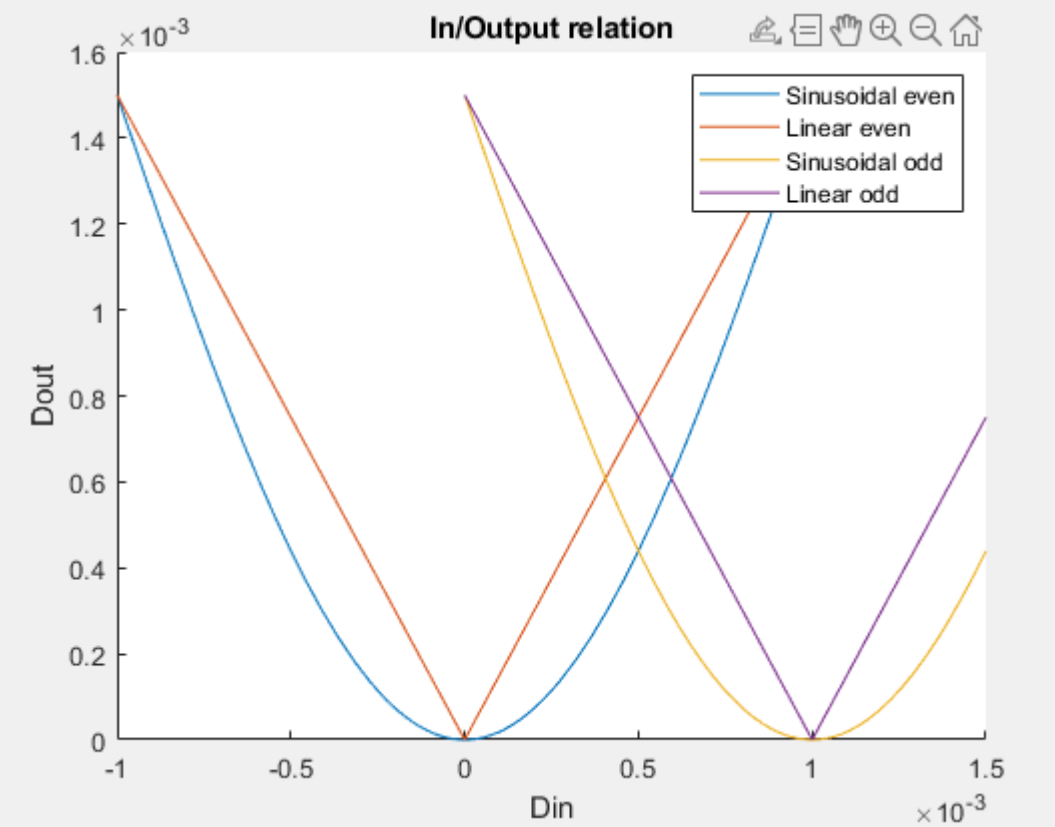
GA = 3

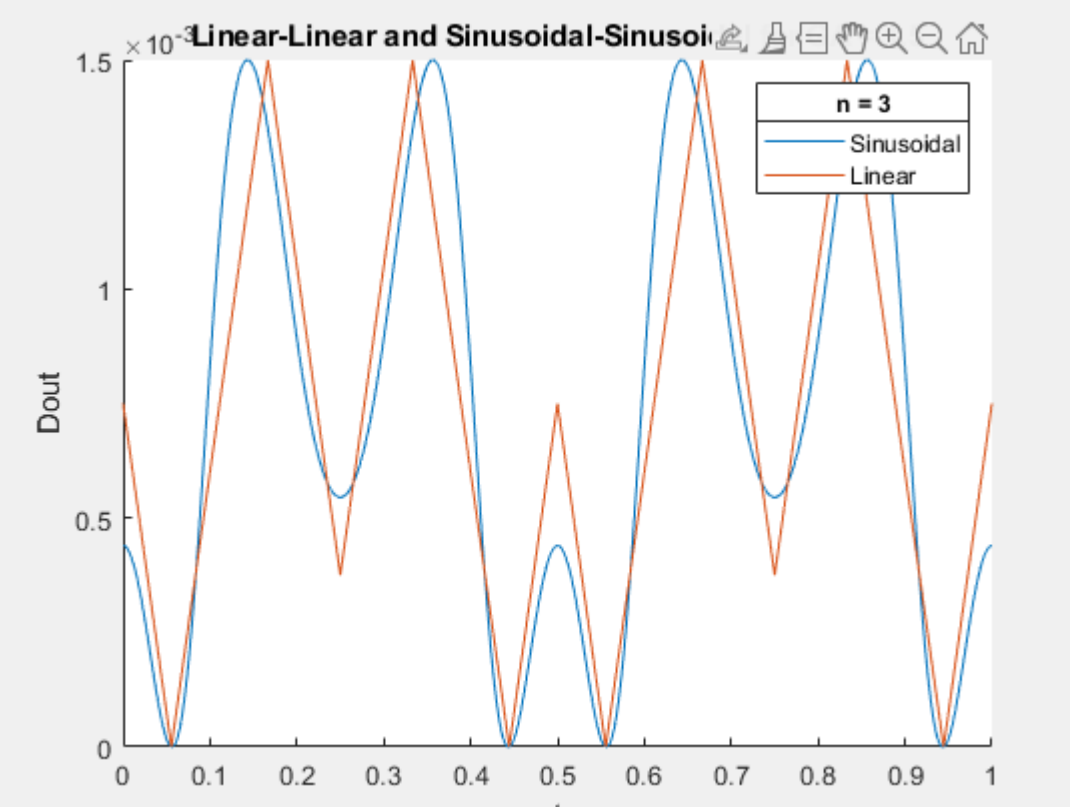




- How to deal with increase of output displacement?

GA = 1.5

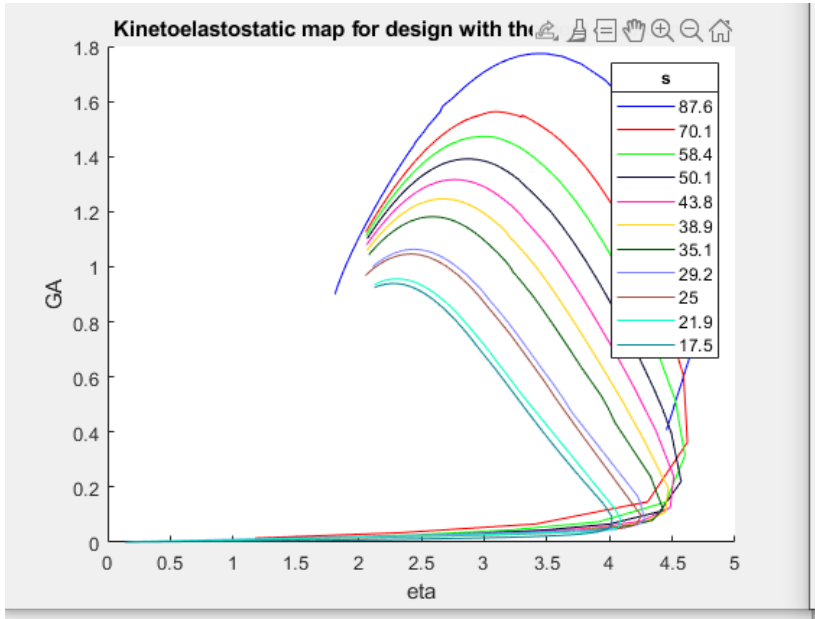


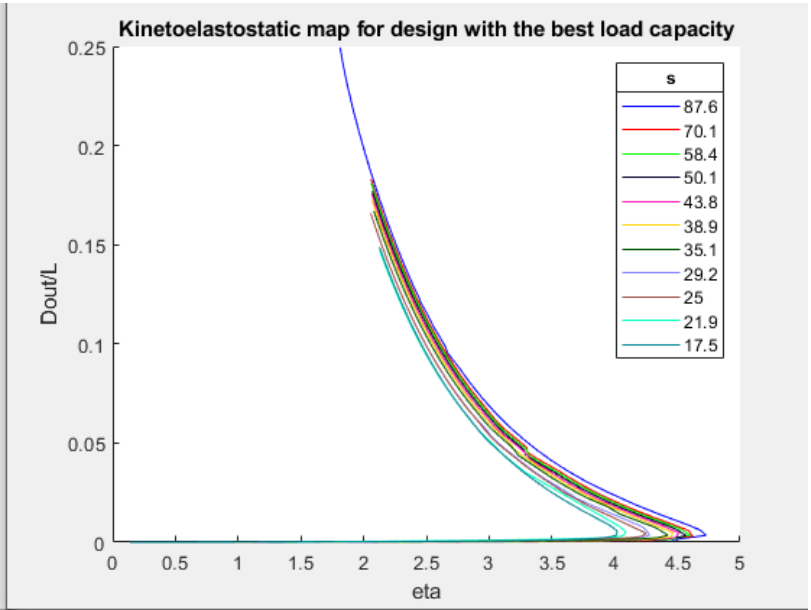


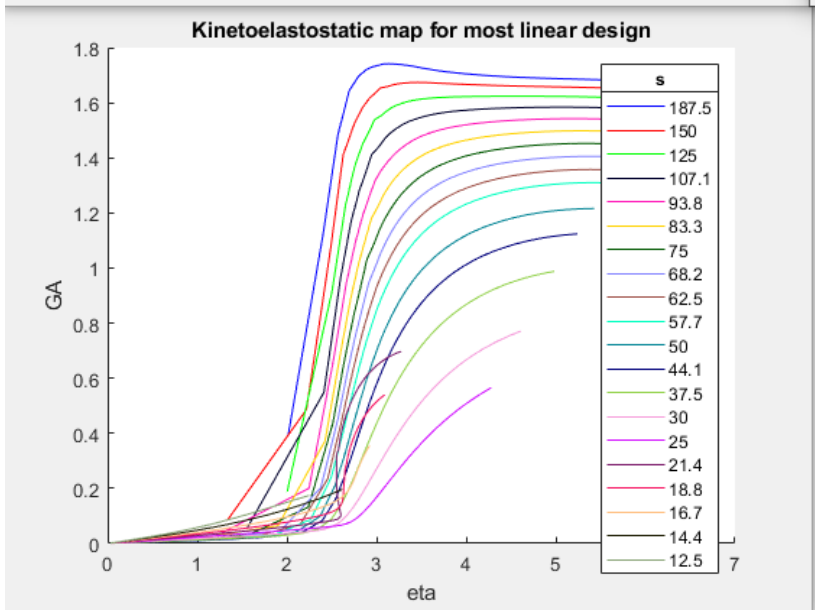
- Looks more manageable than GA=3

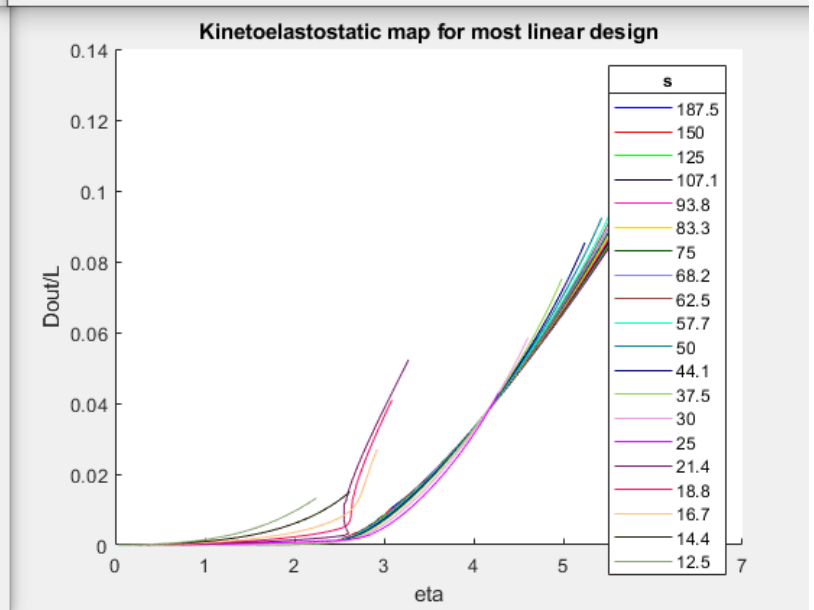
Kinetoelastic

$$\eta = \frac{Fs^2}{Ebd}, s = \frac{L}{d}$$



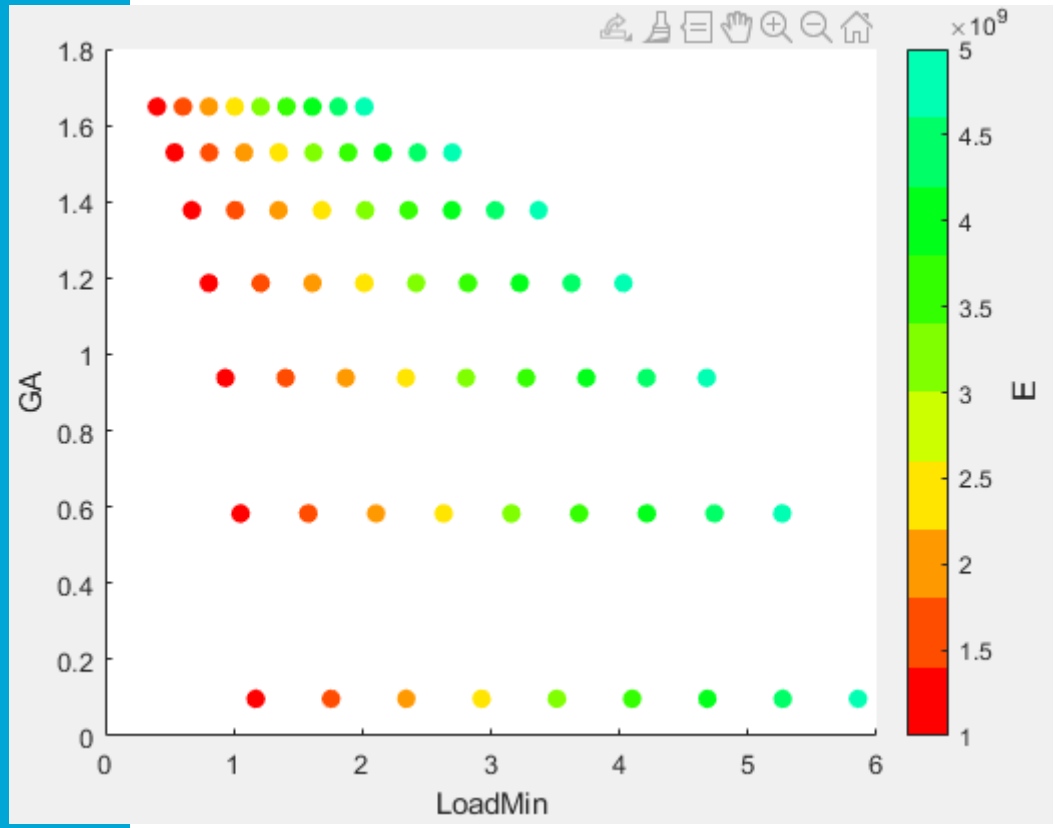


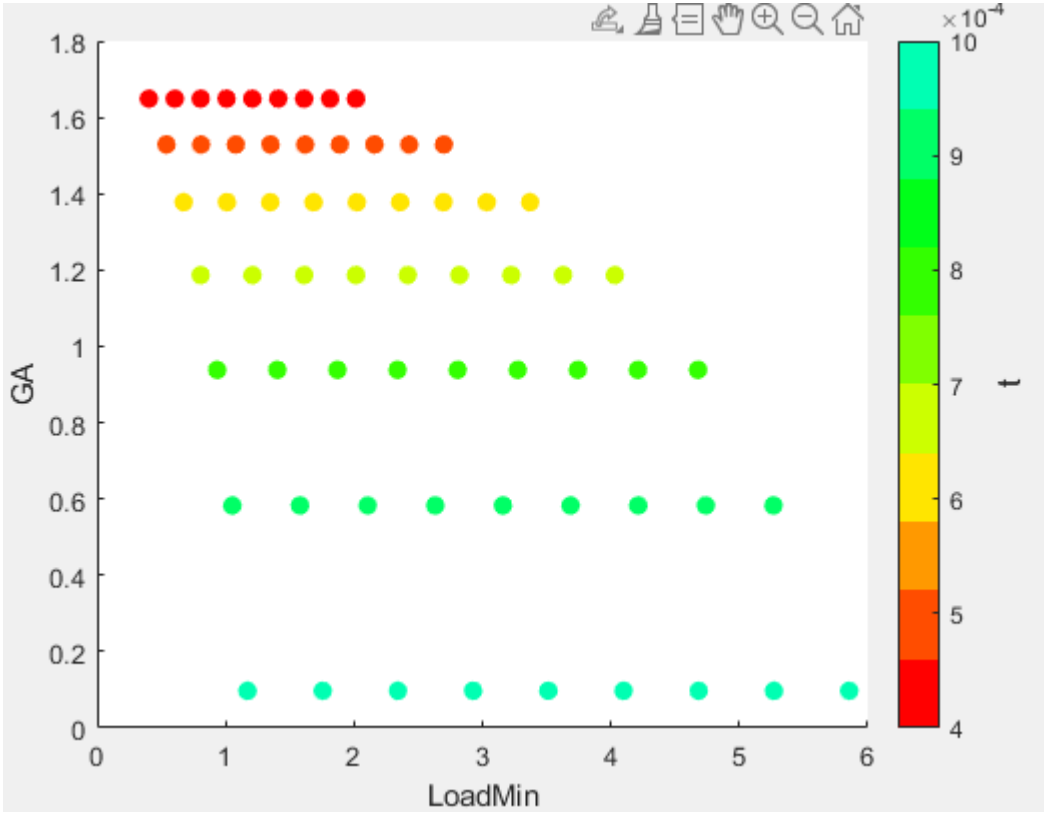




TU Delft

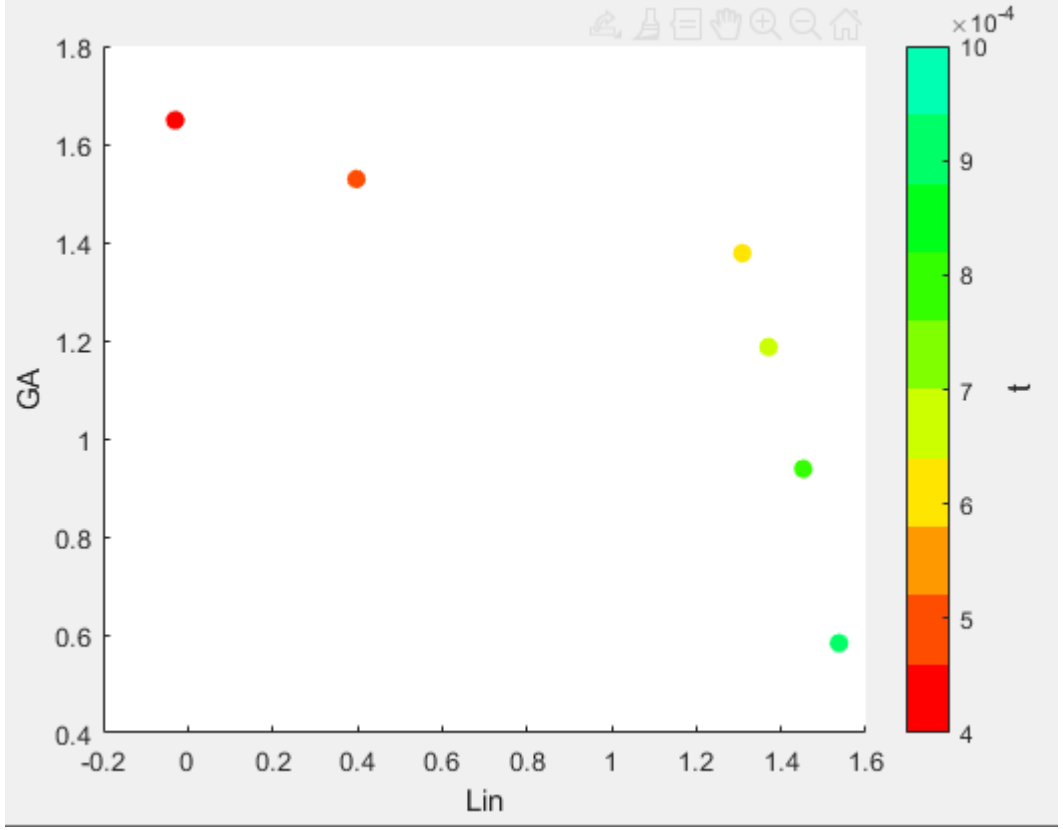
Varying material property E and flexure thickness t





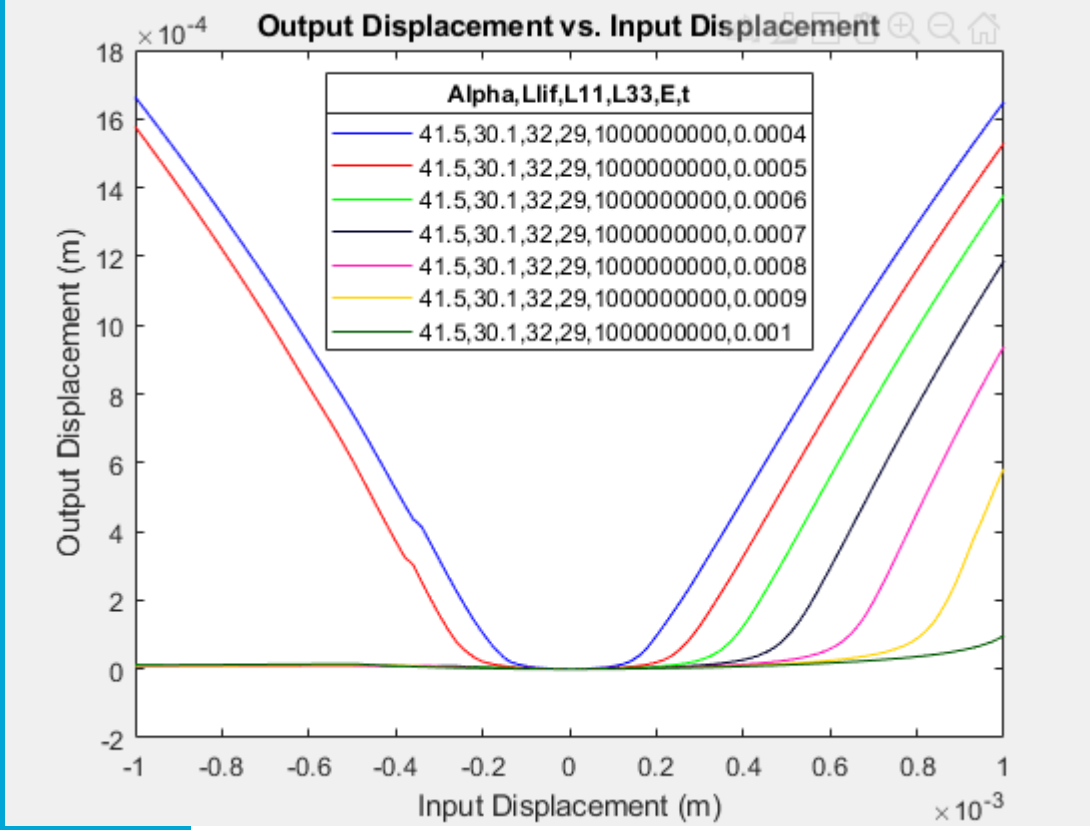
- ↑E means ↑ LoadMin
- ↑t means ↓ GA, E has no effect

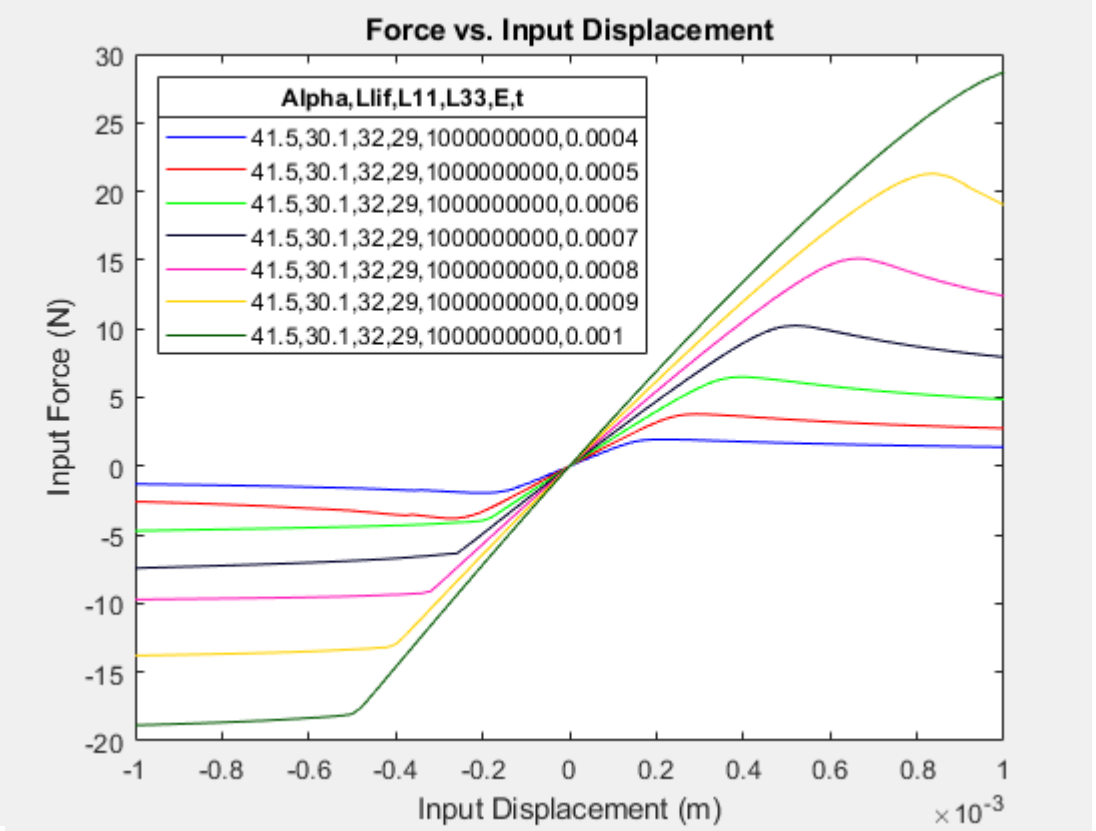
Varying E and t



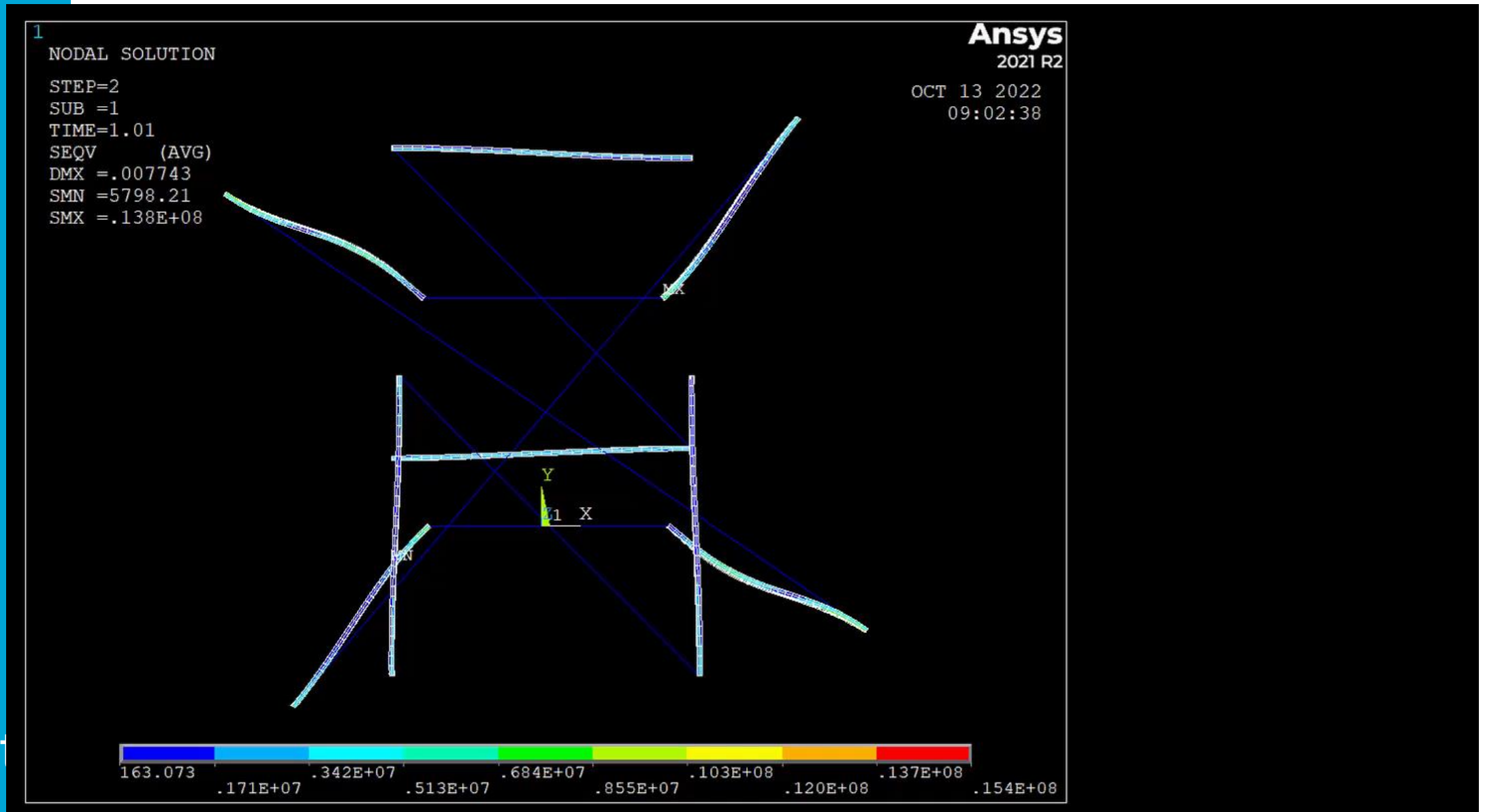
- ↑t means ↓ GA and worse linearity

Varying E and t

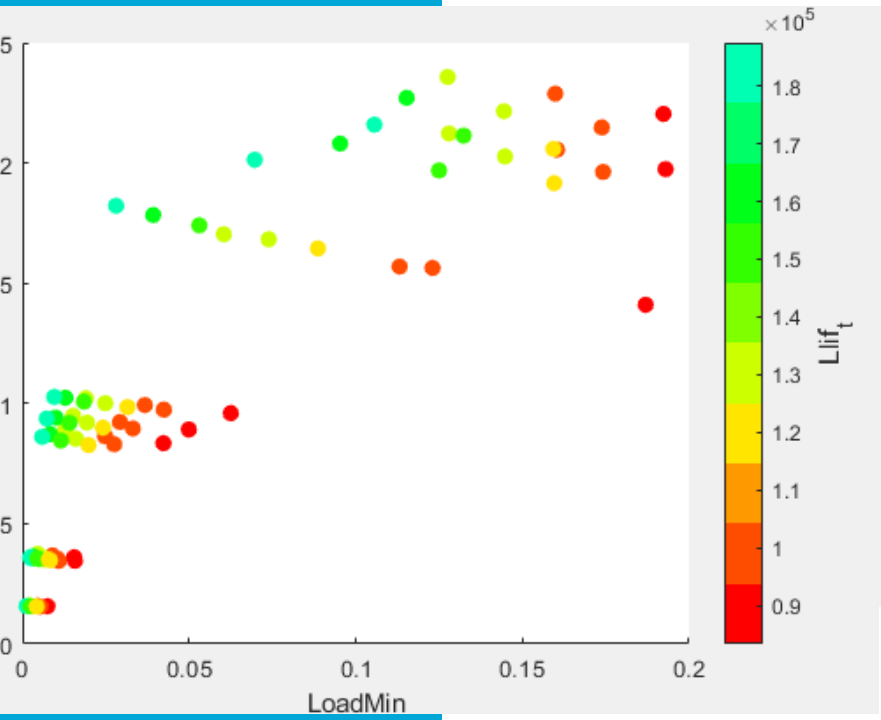


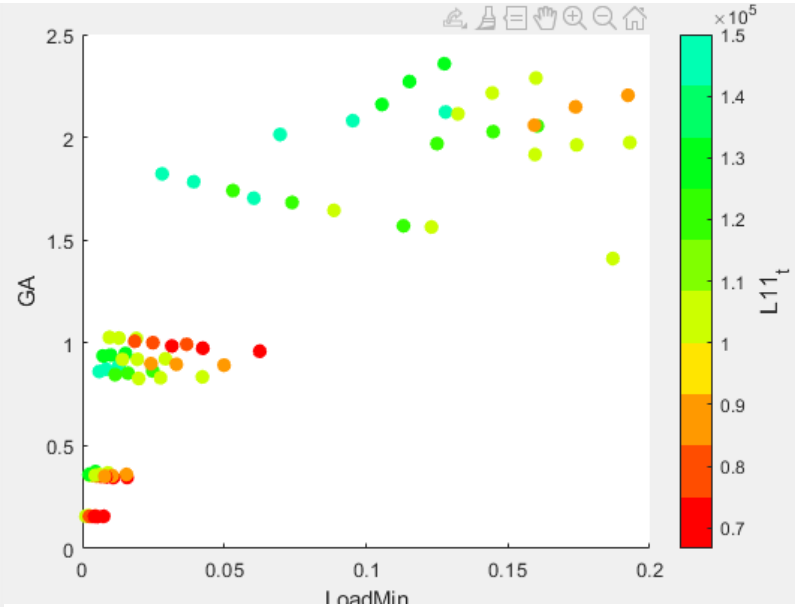


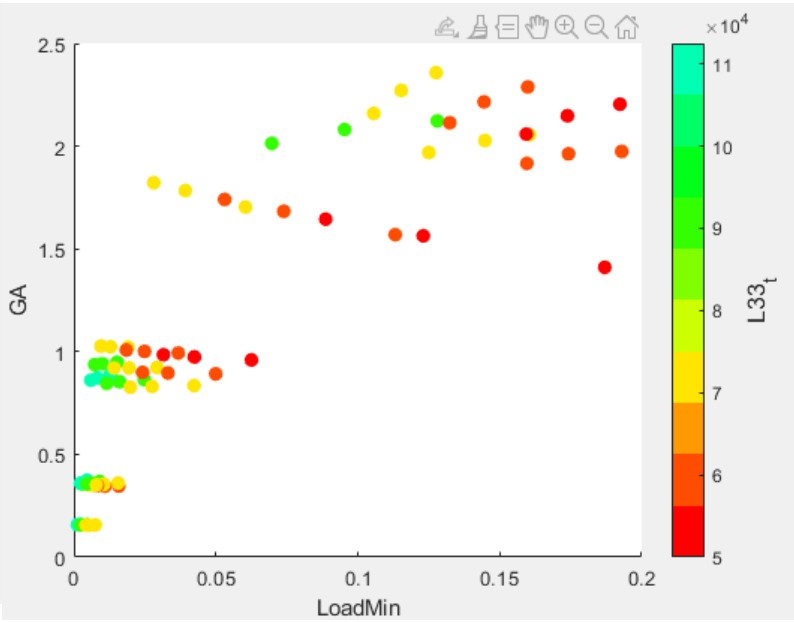
Varying E and t (buckling of output)



Llif/t, L11/t, L33/t constant







Resin Printer disadvantages

- Curvature due to curing.
- Not enough space for sufficient stiffness in case of planar design.
- And for non-planar design it is hard to remove flexures.
- Imperfections in the flexure, seemingly large.
- Long waiting time
- Pooling of resin
- Haven’t been able to make the design modular

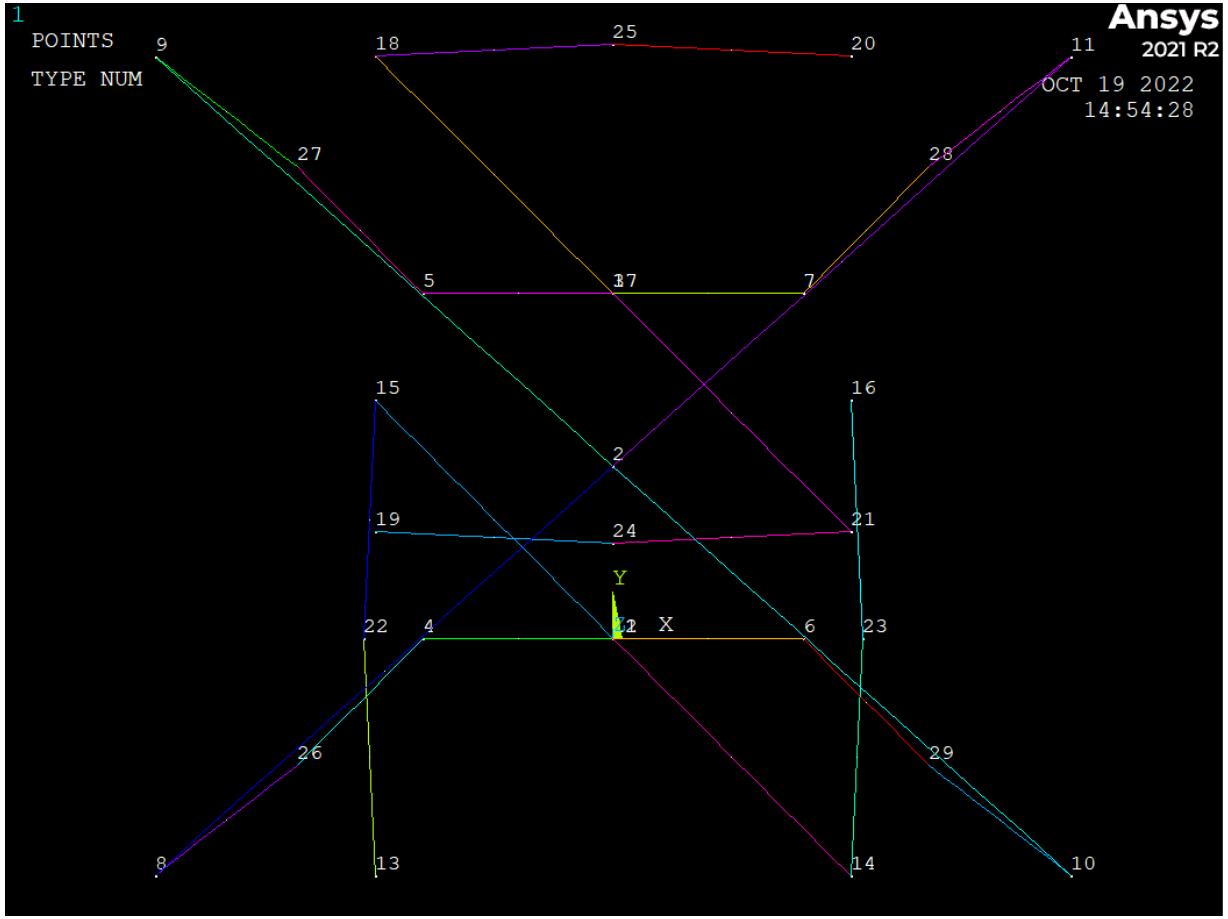
Options for printing?

- PTU,PTG? t = 0.6-0.7mm
  - Imperfections in flexures? Of what magnitude?
- Leaf spring steel? t = 0.1mm
  - No imperfections due to printing
  - A lot of evidence it works in literature

Imperfections

Exaggerated in the image

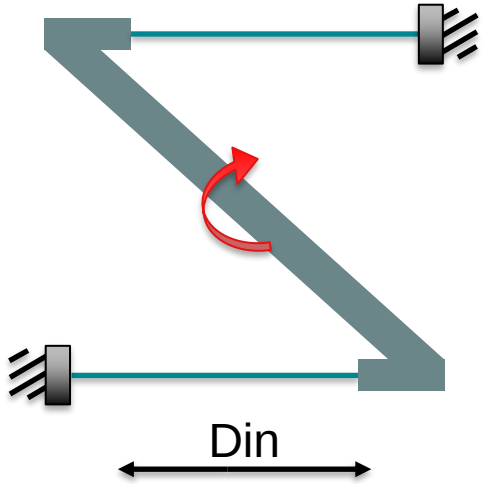
- Buckling of output happens earlier

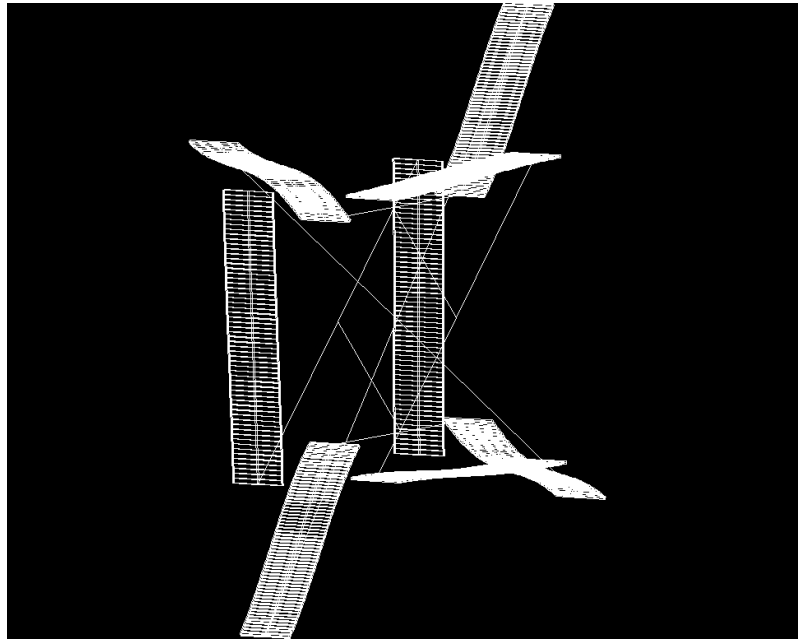


Improving stiffness of output

- Improve stiffness?
- Tried to displace output shuttle to not cause a resulting moment.
  - Output at same height as input. X
  - Output and Input both at same height as middle of

mechanism. Works!

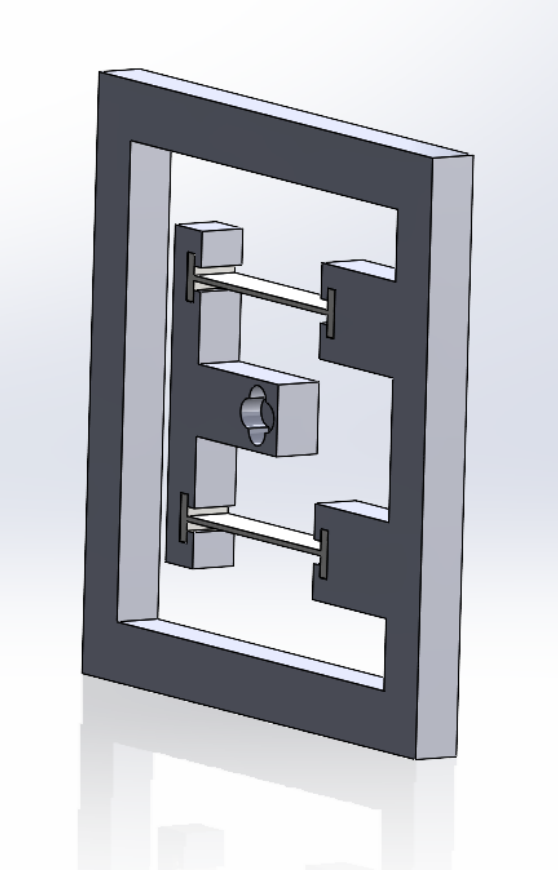


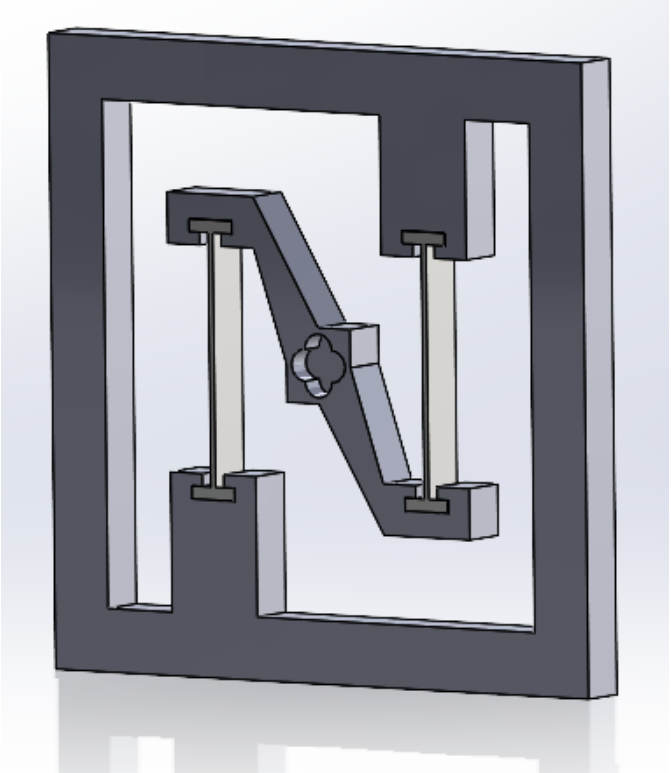


TU Delft

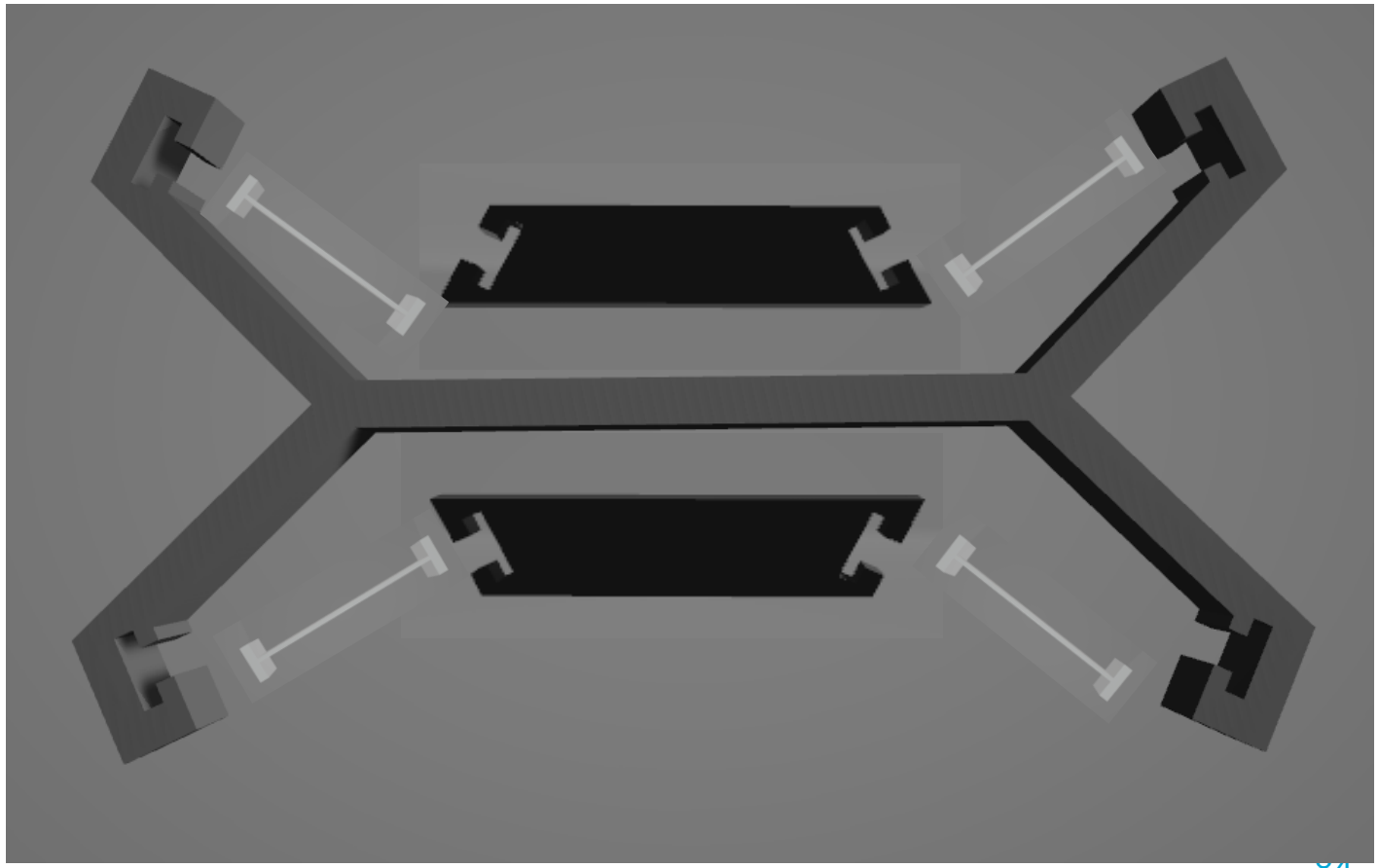
Modular design, to increase manufacturing robustness

- T-shaped input/output structure or diagonal?

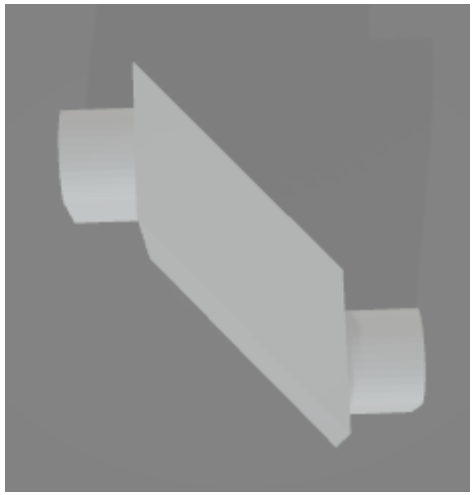


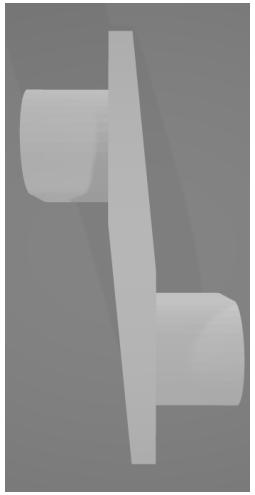


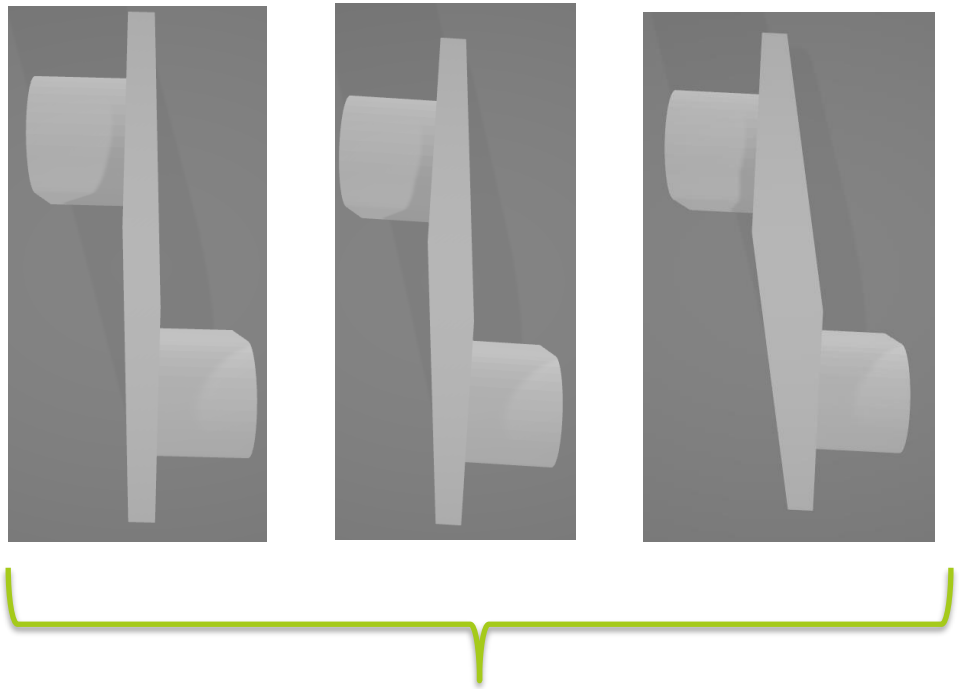
Butterfly flexure



Iteration process of connection piece







Material properties

- Poisson's ratio = 0.49
- Yield strength = 8 MPa

TPC Flex 45, Datasheet

Physical properties

Description	Testmethod	Typical value
Specific gravity	ISO 1183	1,14 g/cc
Melt volume flow rate	ISO 1133	39 cm³/10 min
Stress at break	ISO 527	24
Strain at break	ISO 527	530%
Tensile modulus	ISO 527	95 Mpa
Impact strength Charpy method 23°C	ISO 179	Notched No break
Shore D Hardness	ISO 868	45

TPU D45, edupack

TPU (Ether, aromatic, Shore D45)

Datasheet view: Materials data for simulation | Show/Hide | Find Similar

Composition overview

Compositional summary

(NH-R-NH-CO-O-R'-O-CO)n where R is from an aromatic diisocyanate, usually MDI or TDI (hard segment), and R' is from a short or long chain polyether diol (soft segment)

Material family	Elastomer (thermoplastic, TPE)			
Base material	TPU (Thermoplastic polyurethane elastomer)			
Polymer code	TPU			
Physical				
Density	1,13e3	-	1,15e3	kg/m^3
Elastic				
Young's modulus	0,0422	-	0,0546	GPa
Poisson's ratio	* 0,48	-	0,495	
Plastic				
Yield strength (elastic limit)	14,6	-	15,4	MPa
Tensile strength	41,3	-	47,9	MPa
Elongation	457	-	512	% strain

TPC D40, edupack

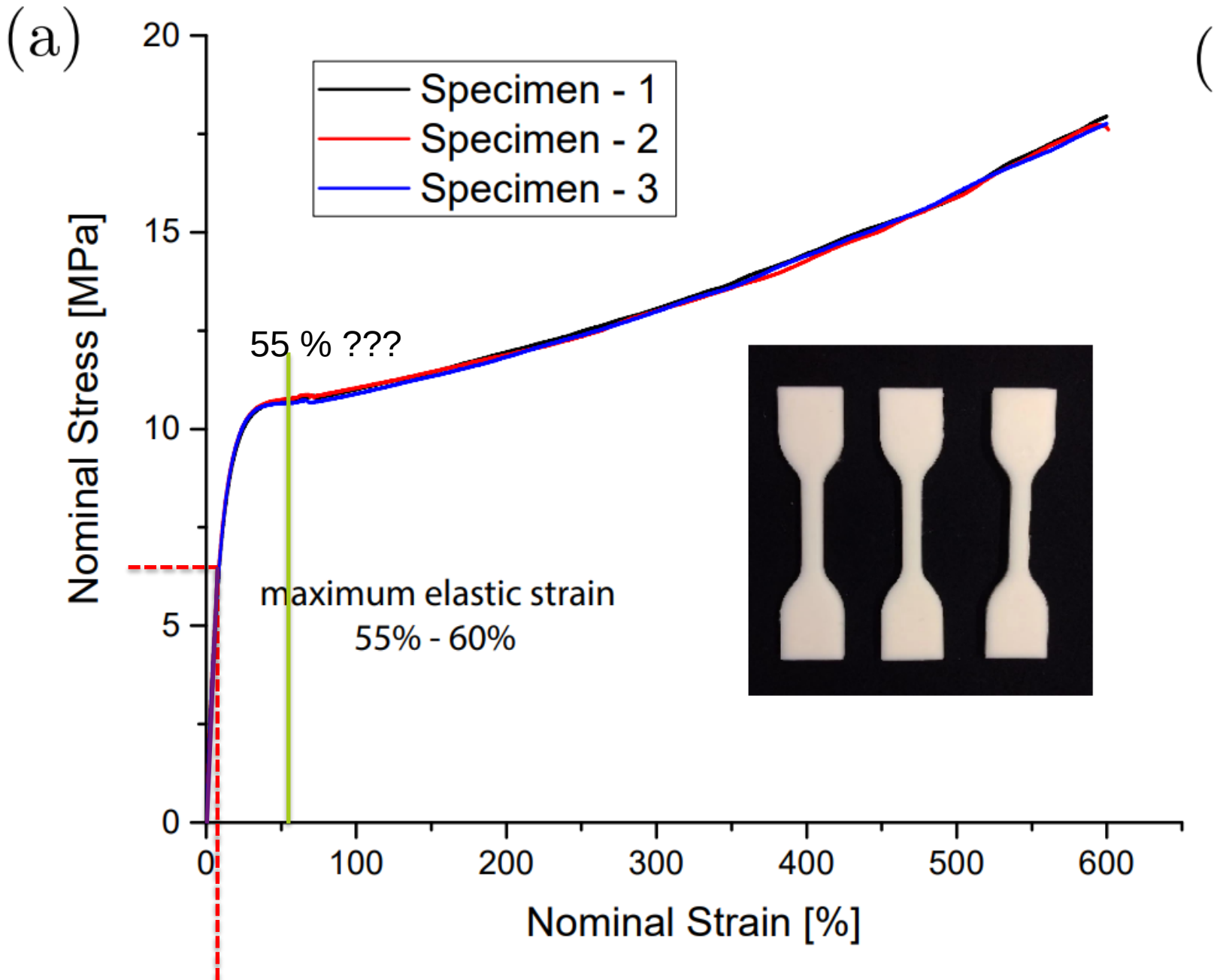
TPC (Shore D40)

Datasheet view: Materials data for simulation | Show/Hide | Find Similar

Compositional summary

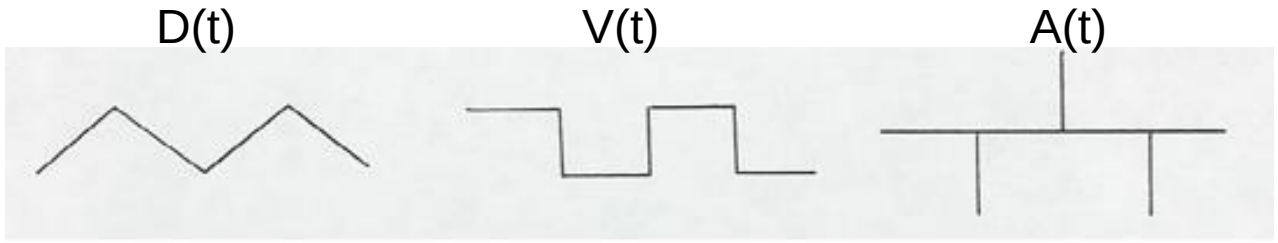
Block copolymer of a polyester (semi-crystalline hard phase - usually PBT, polybutylene terephthalate) and polyether (amorphous soft phase).

Material family	Elastomer (thermoplastic, TPE)			
Base material	TPC (Thermoplastic copolyester-ether elastomer)			
Polymer code	TPC			
Physical				
Density	1,14e3	-	1,18e3	kg/m^3
Elastic				
Young's modulus	0,0708	-	0,115	GPa
Poisson's ratio	* 0,476	-	0,495	
Plastic				
Yield strength (elastic limit)	6,64	-	9,48	MPa
Tensile strength	17,5	-	22,7	MPa
Elongation	226	-	324	% strain


(a)
Specimen - 1
Specimen - 2
Specimen - 3
Nominal Stress [MPa]
20
15
10
5
0
55 % ???
maximum elastic strain
55% - 60%
0
100
200
300
400
500
600
Nominal Strain [%]

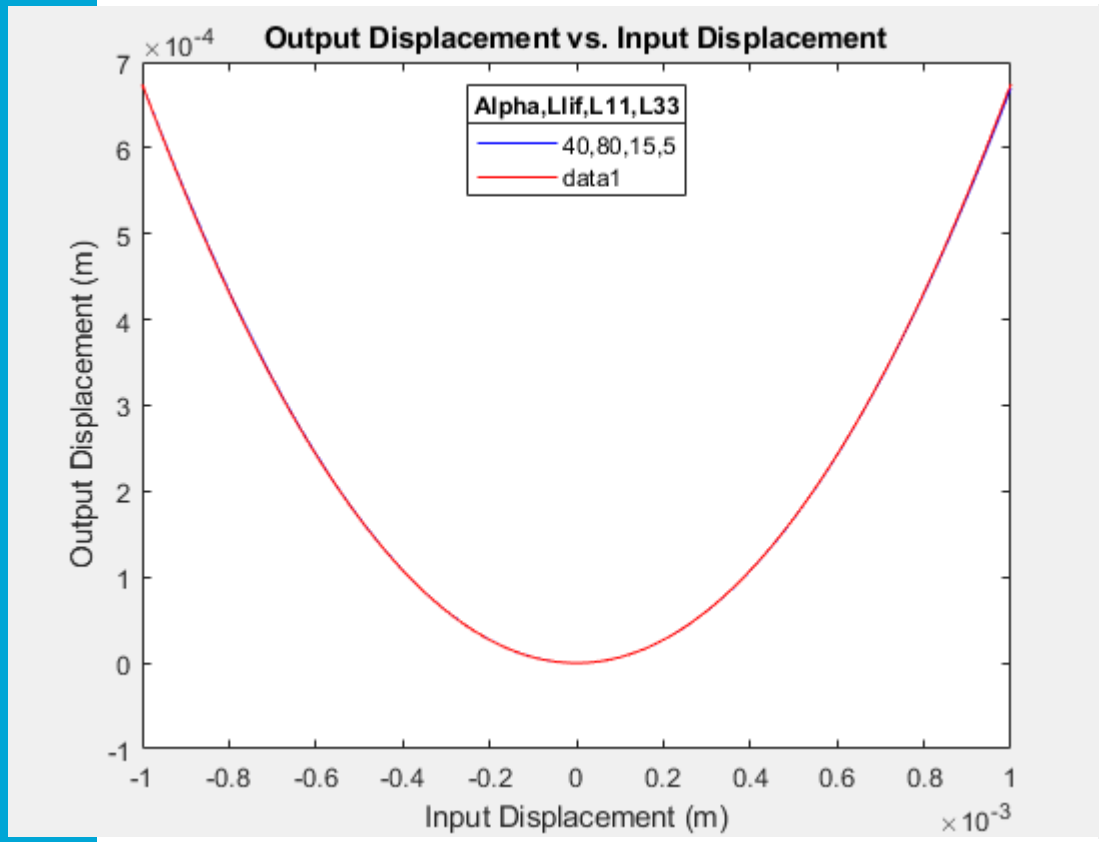
Sinusoidality Vs. Linearity

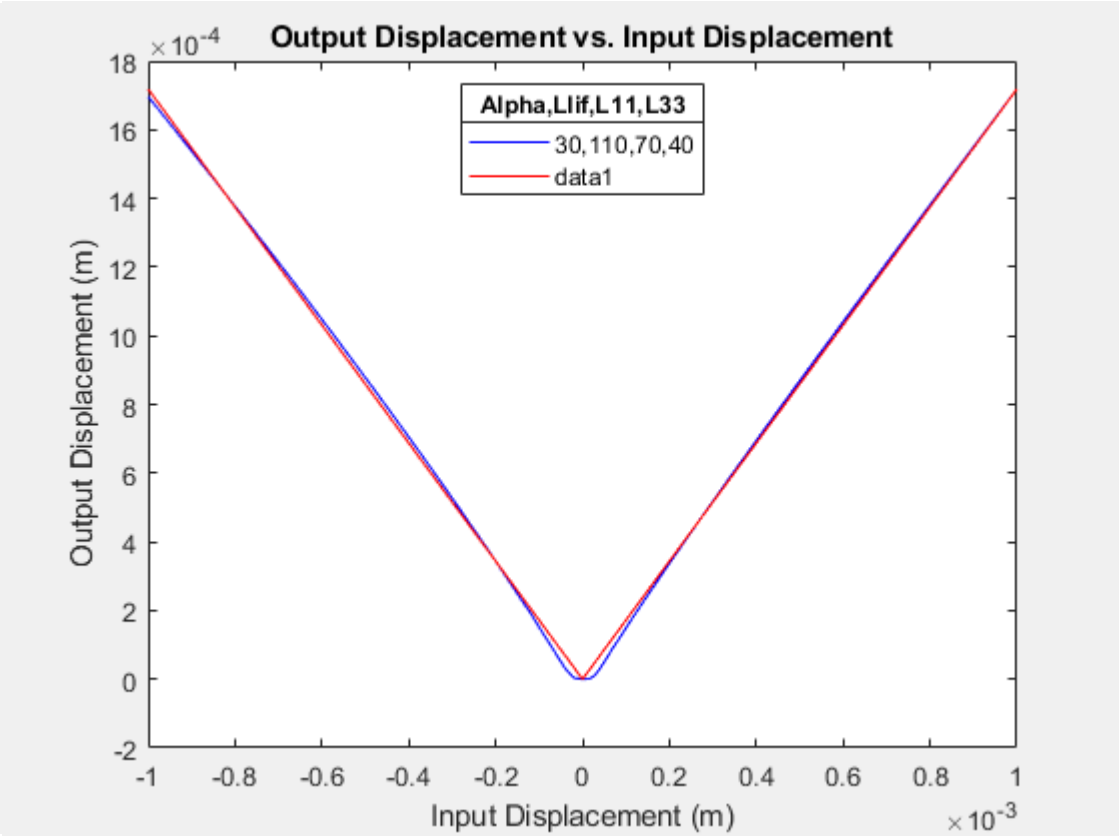
- More achievable (see next slide)
  - From available literature can already see the struggle to create perfect linear.
  - Harder to make due to infinite acceleration when input/output switch directions
  - Same for input, needs high harmonics to be created and will always be an approximation.
- More cyclical behavior
  - Would be preferable for a lot of applications
  - No high frequency harmonics and large scale of frequencies, which could drive an unwanted eigenmode of the system
    - https://en.wikipedia.org/wiki/Triangle_wave
    - For actuation would be big disadvantage



Achievable?

- Red = ideal, Blue = best sinusoidality or linearity

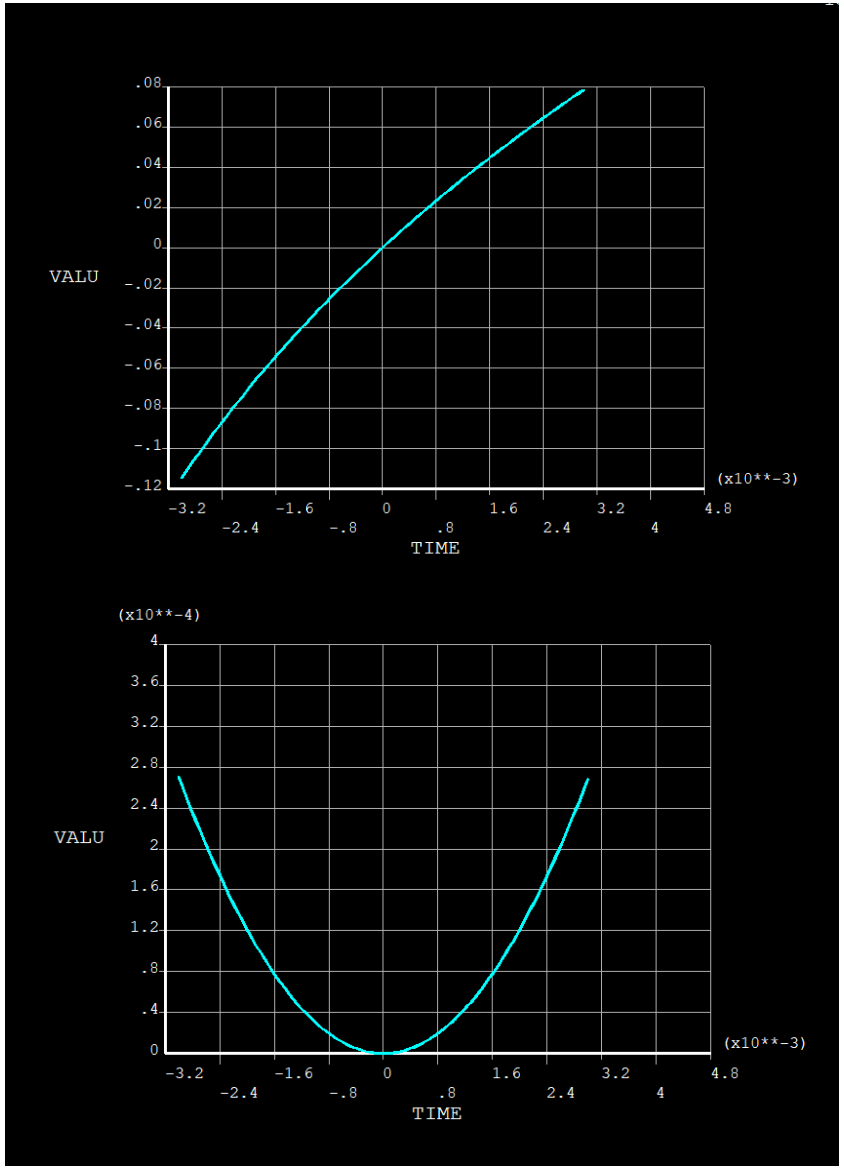




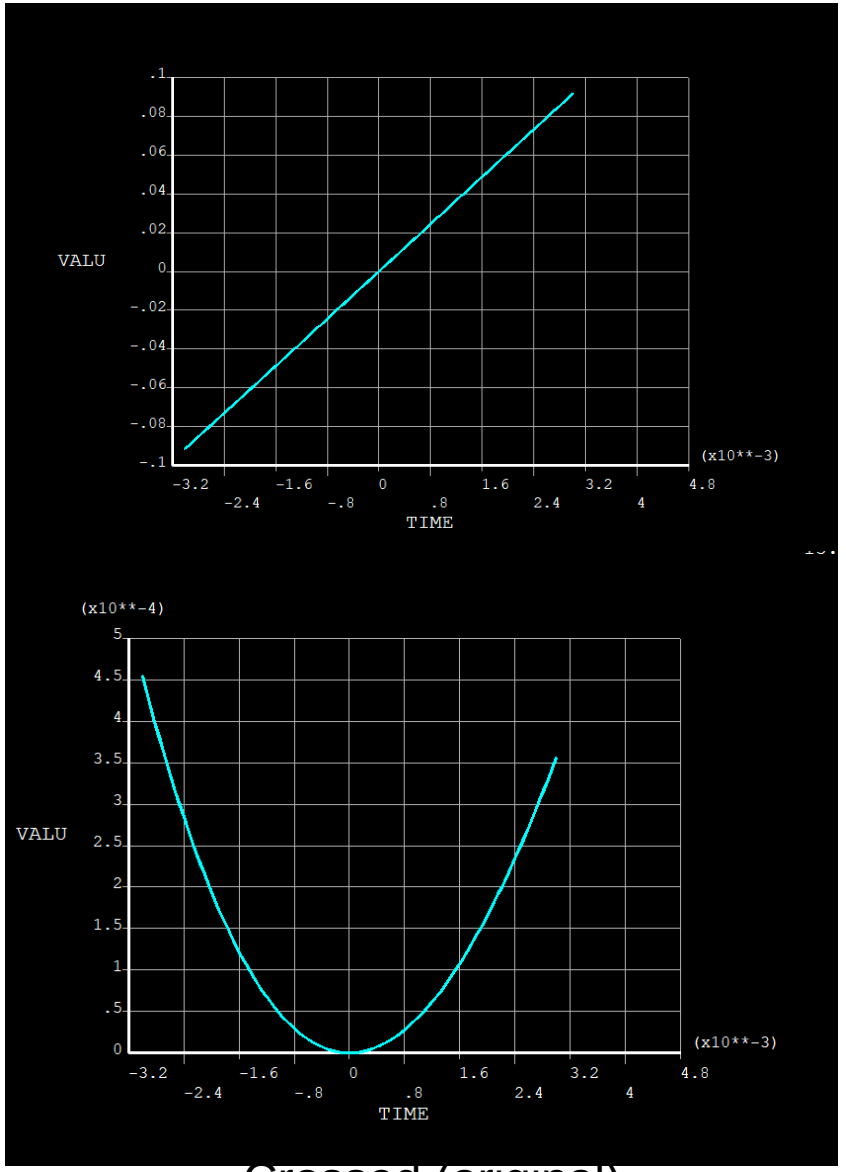
Show planning

- Only looking at Sinusoidal DD
- Manufacturing to concatenate once, might take too long

Parallel vs. Crossed [10,45,25,55]

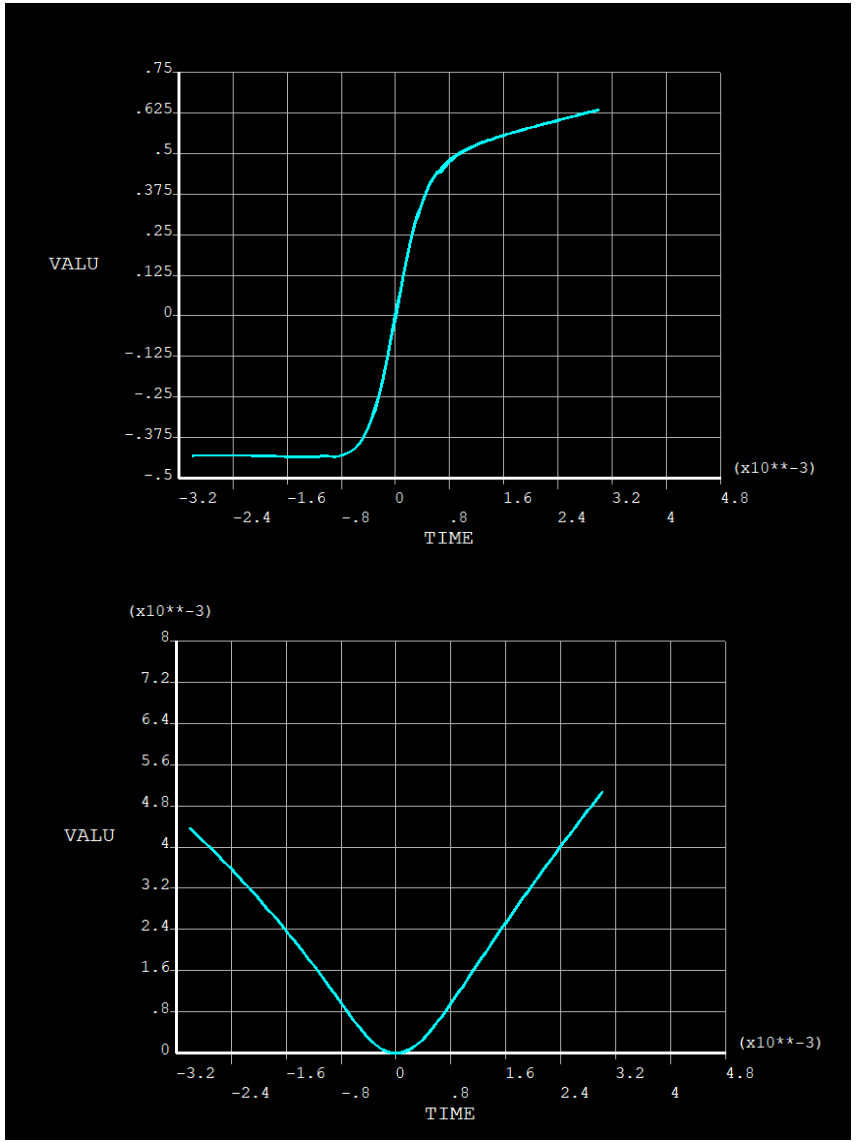


Parallel

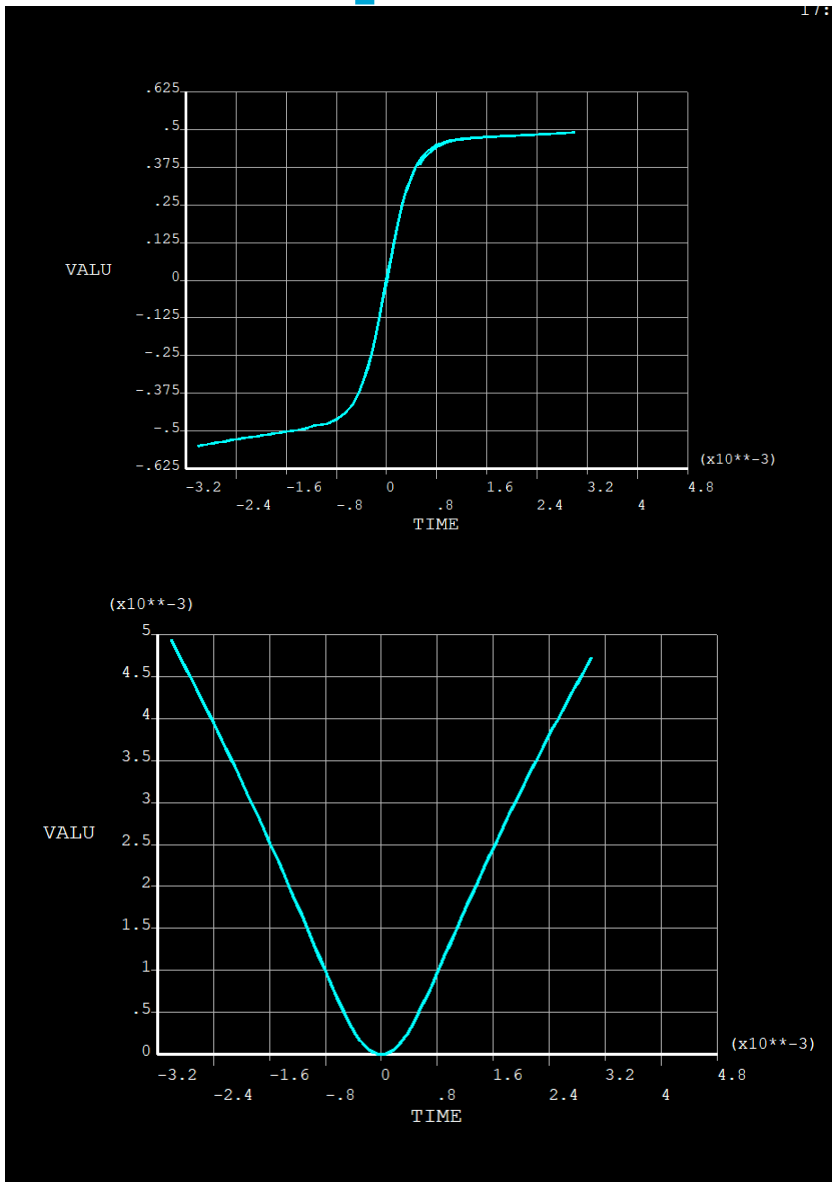


Crossed (original)

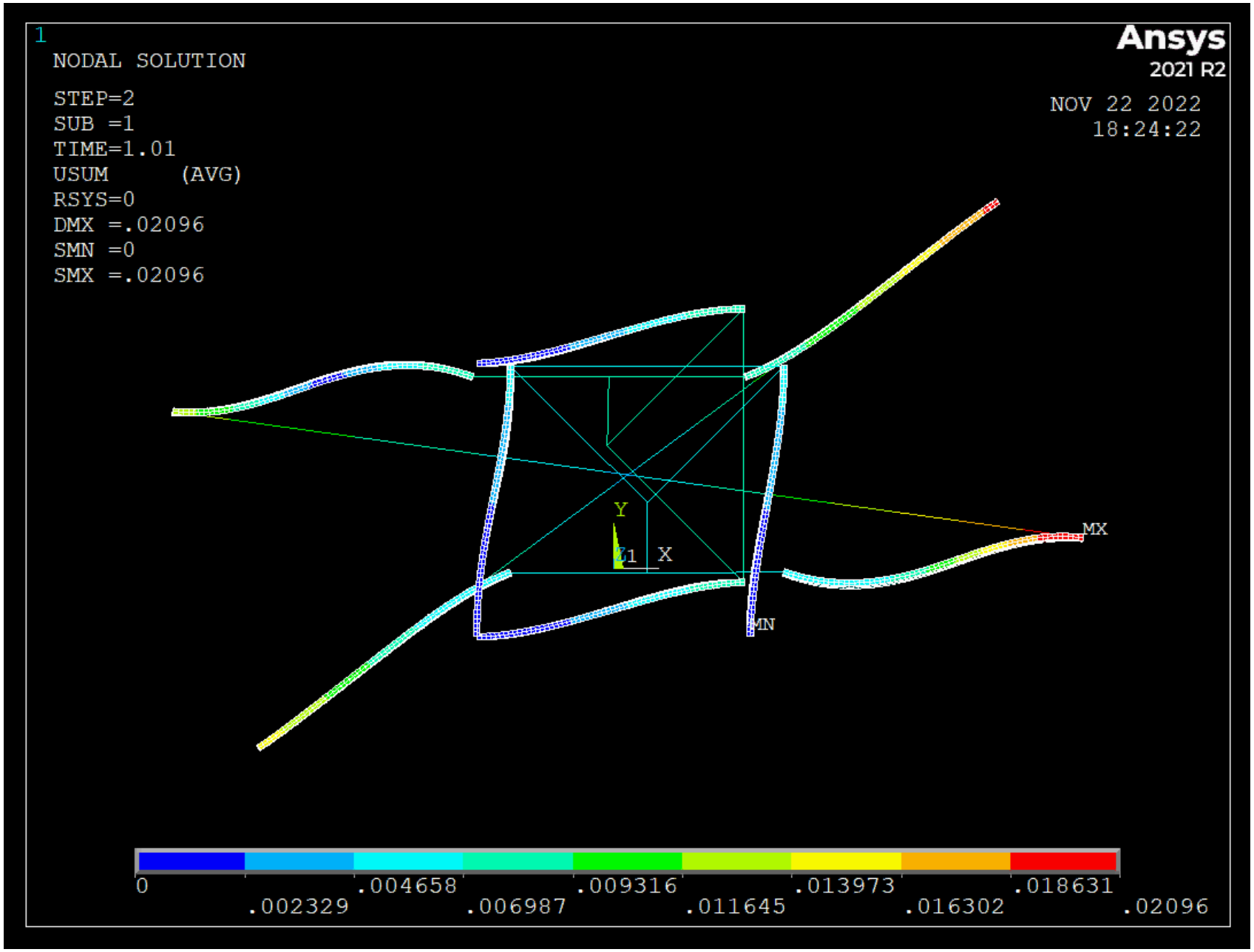
Parallel vs. Crossed [20,45,40,20]



Parallel



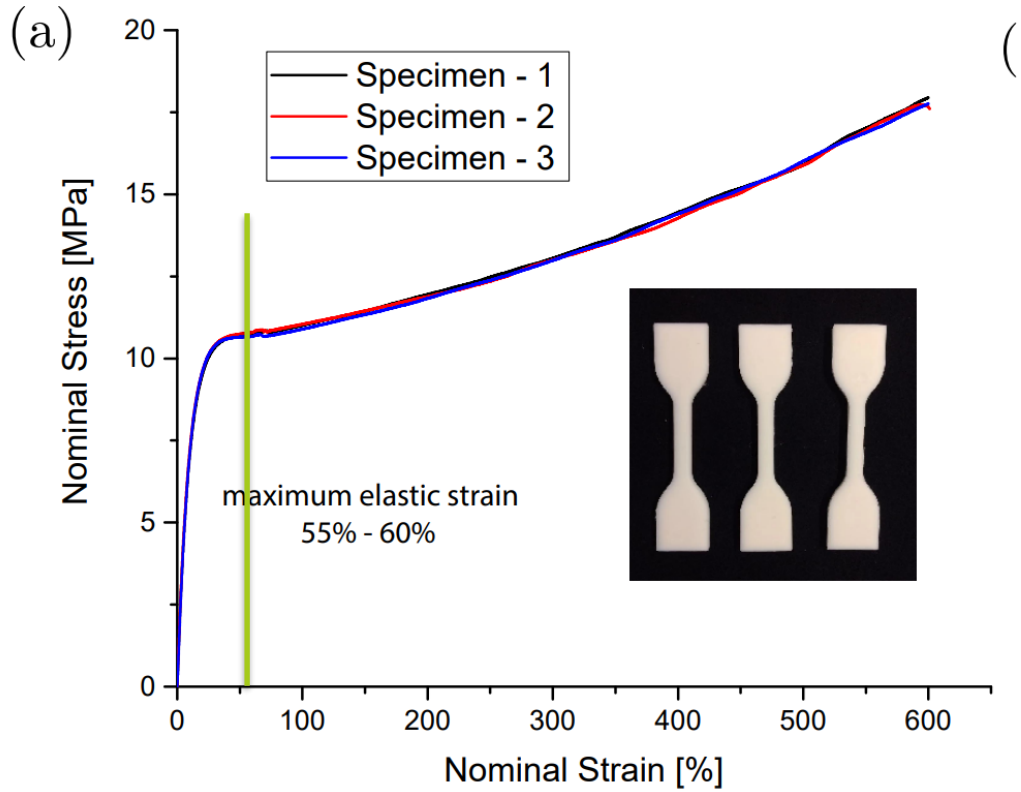
Crossed (original)


1
NODAL SOLUTION
STEP=2
SUB =1
TIME=1.01
USUM (AVG)
RSYS=0
DMX =.02096
SMN =0
SMX =.02096
Ansys
2021 R2
NOV 22 2022
18:24:22
Y
Z1 X
MX
MN
0
.002329
.004658
.006987
.009316
.011645
.013973
.016302
.018631
.02096

Material properties

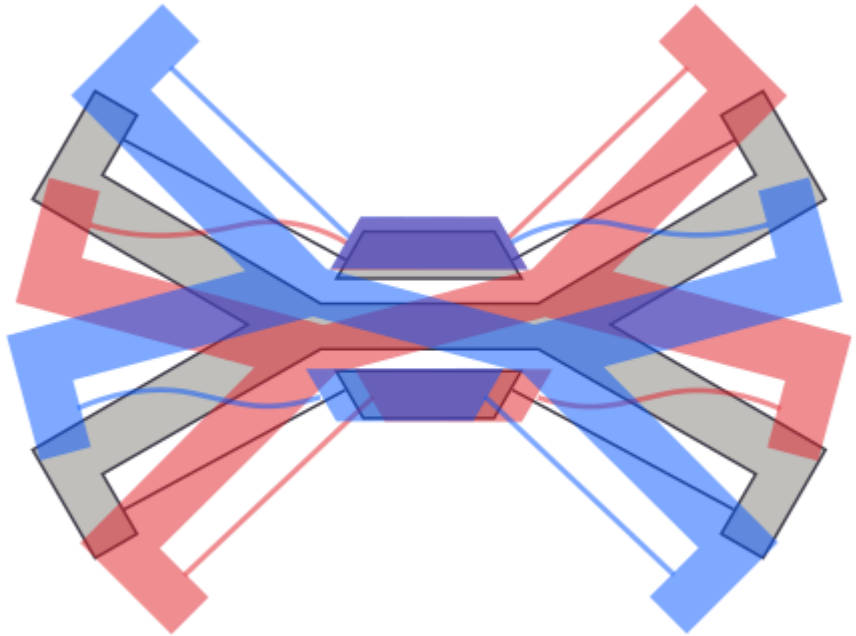
- Poisson's ratio = 0.4
- Yield strength = 7 MPa
- E = 95 MPa, only until

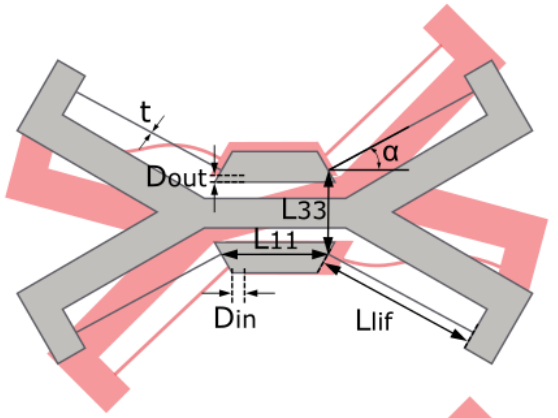
~7-8MPa

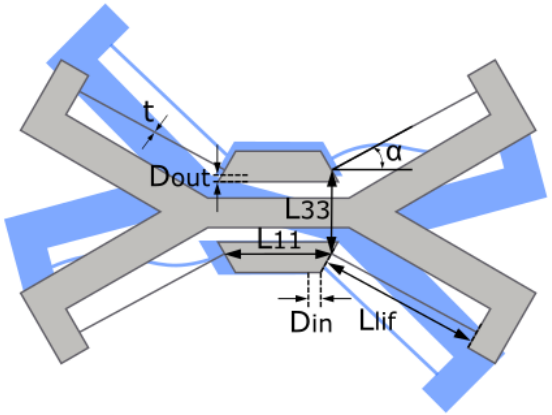


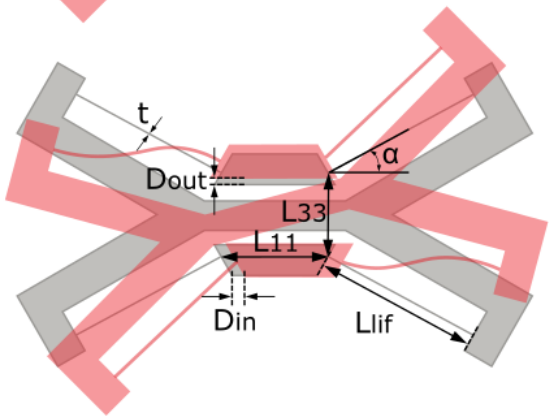
Zhang, Y., Tichem, M., & van Keulen, F. (2022). Concept and design of a metastructure-based multi-stable surface. *Extreme Mechanics Letters*, *51*, 101553. https://doi.org/10.1016/j.eml.2021.101553

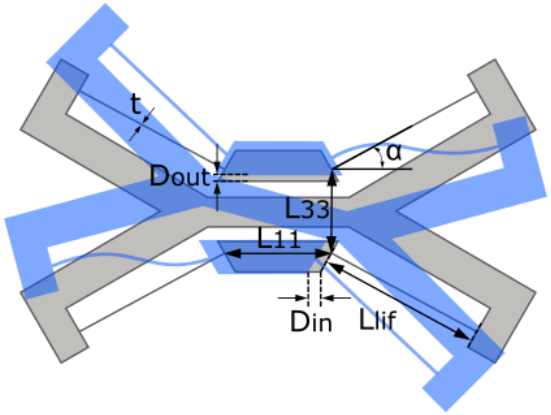
Figures

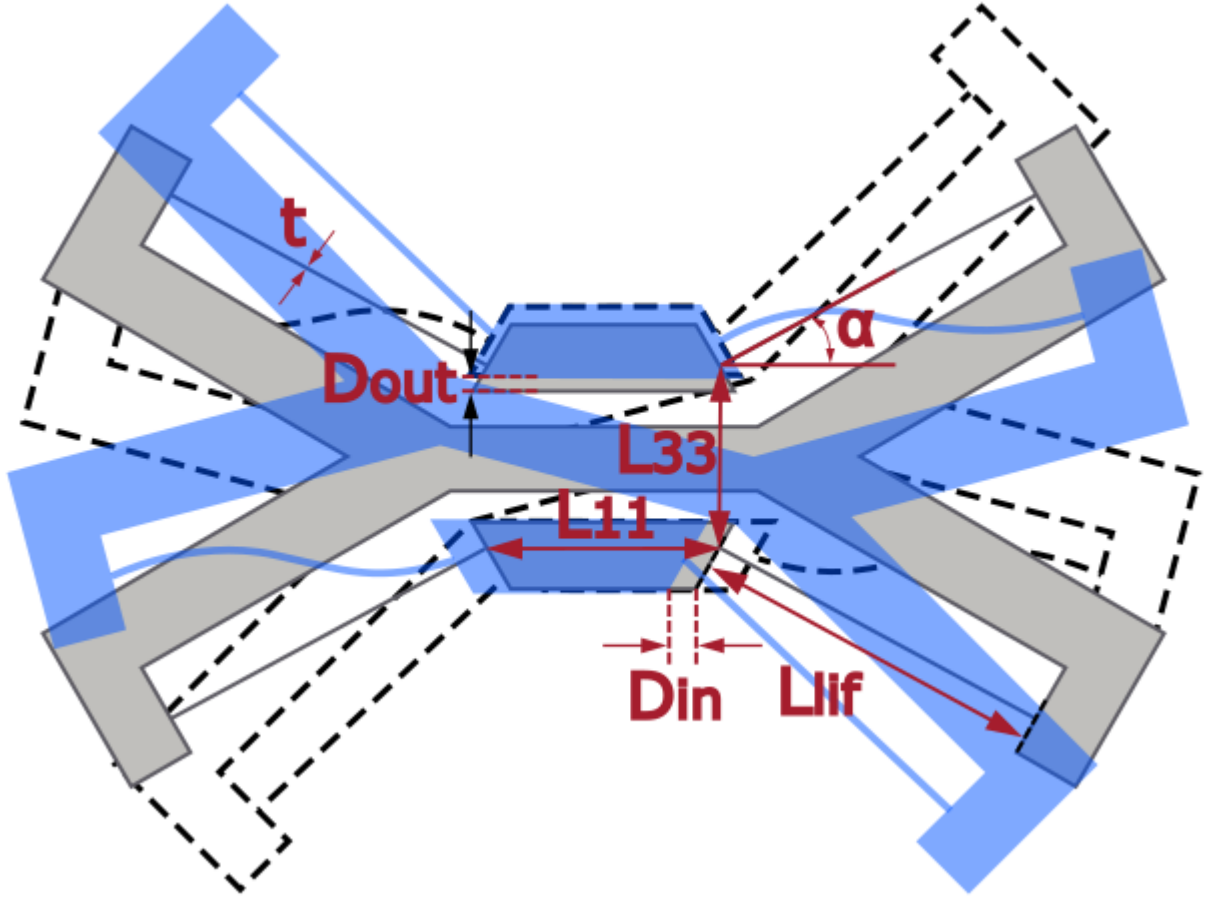



t
Dout
α
L33
L11
Din
Llif

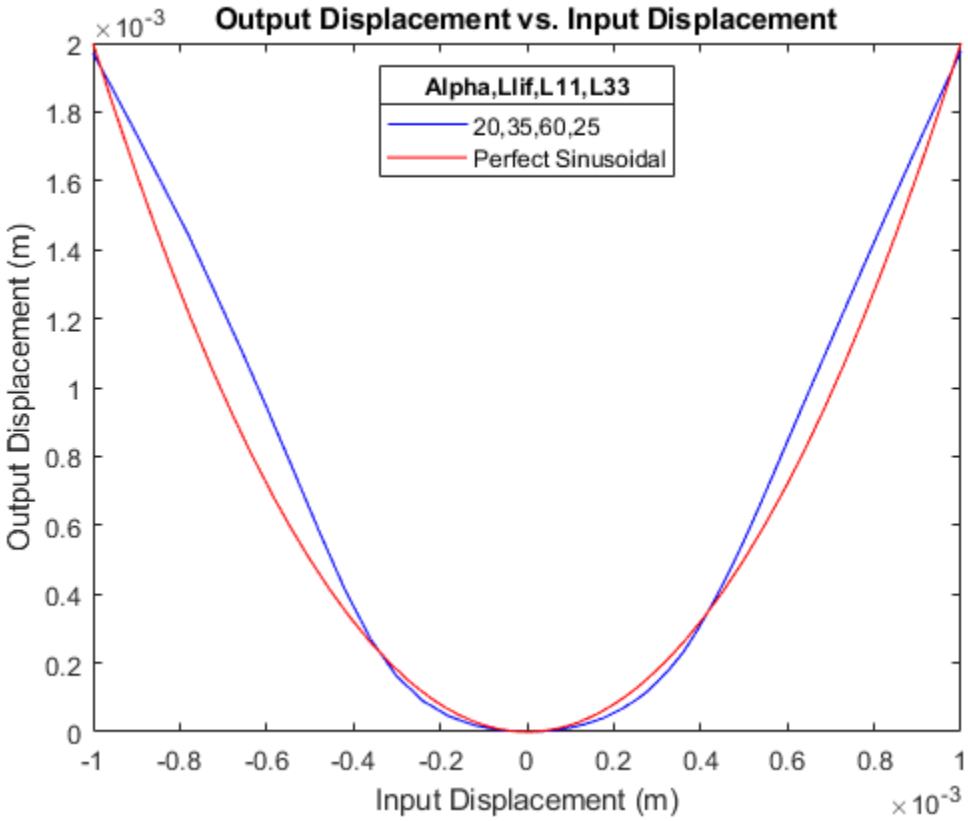

t
Dout
α
L33
L11
Din
Llif

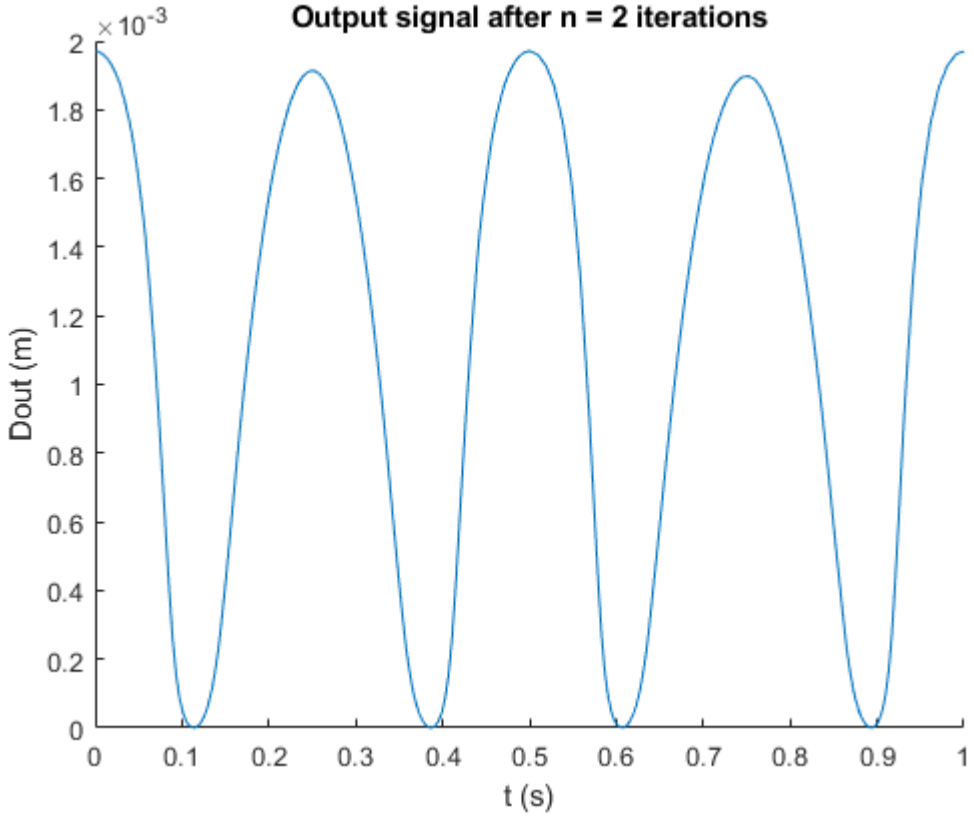

t
Dout
α
L33
L11
Din
Llif

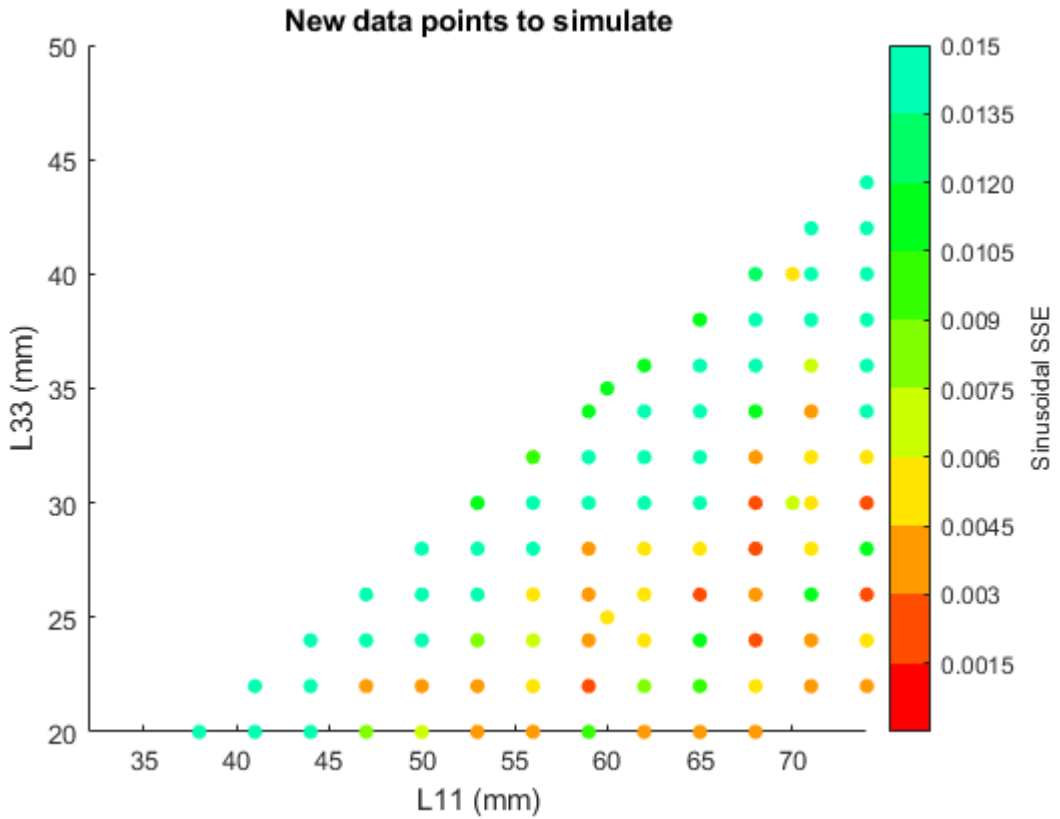

t
Dout
α
L33
L11
Din
Llif

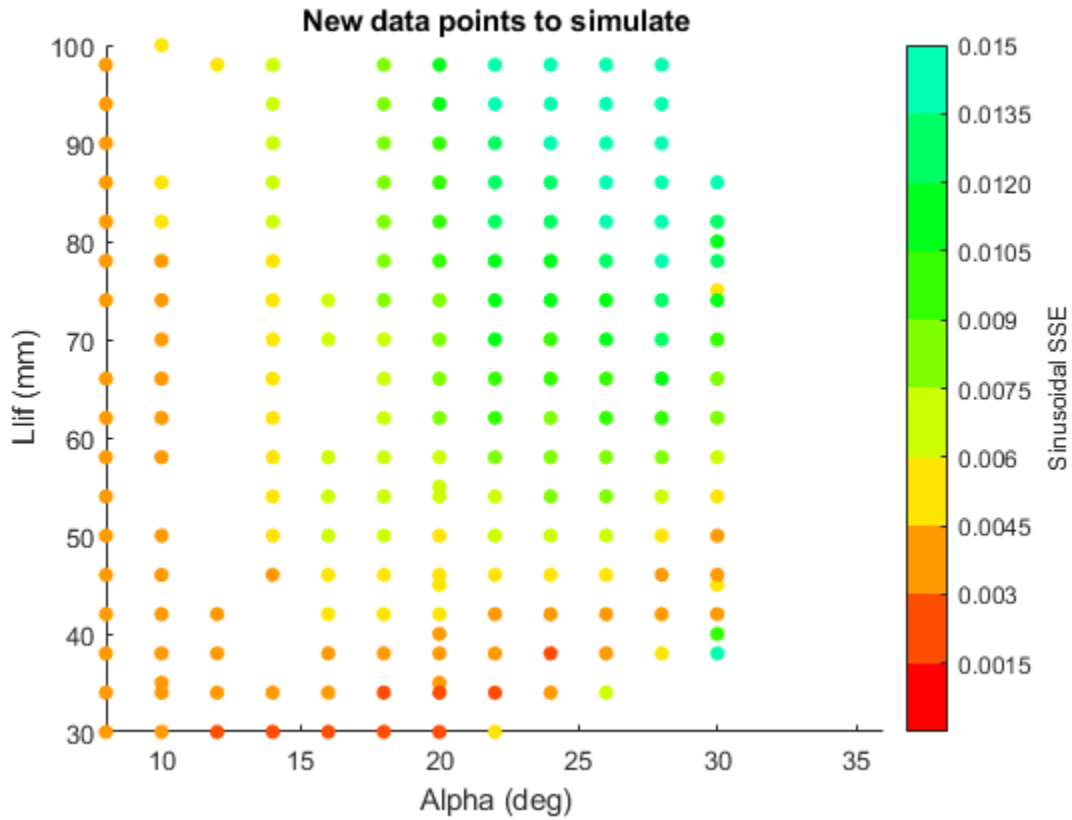

t
Dout
α
L33
L11
Din
Llif

After full investigation

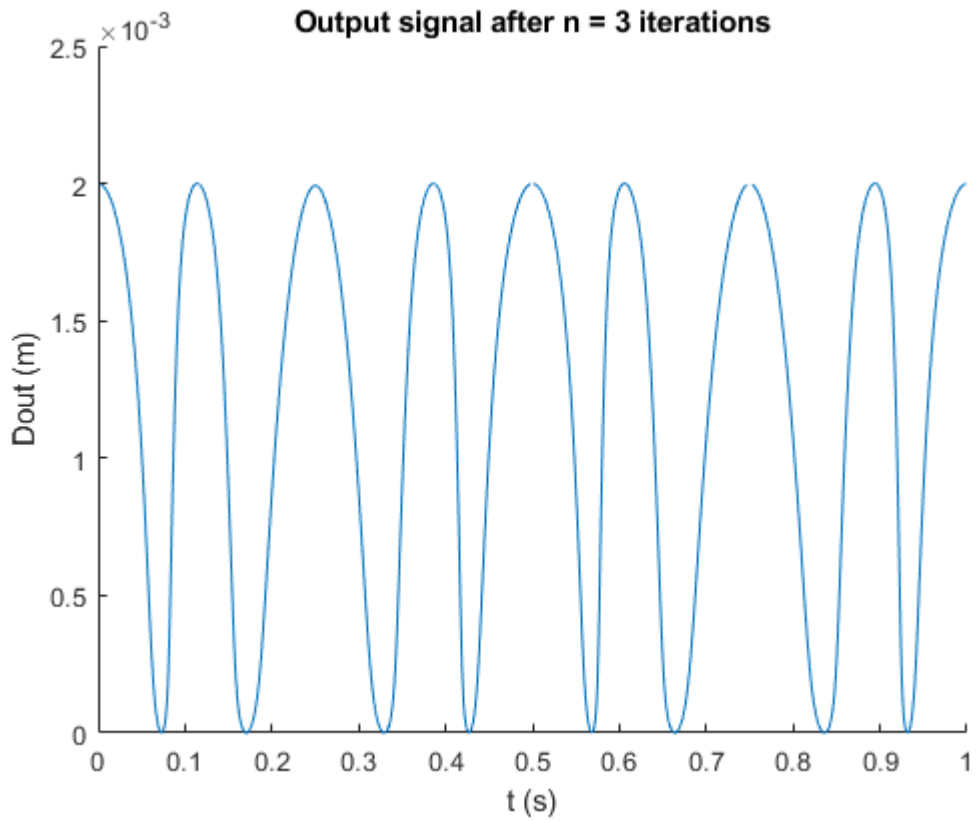


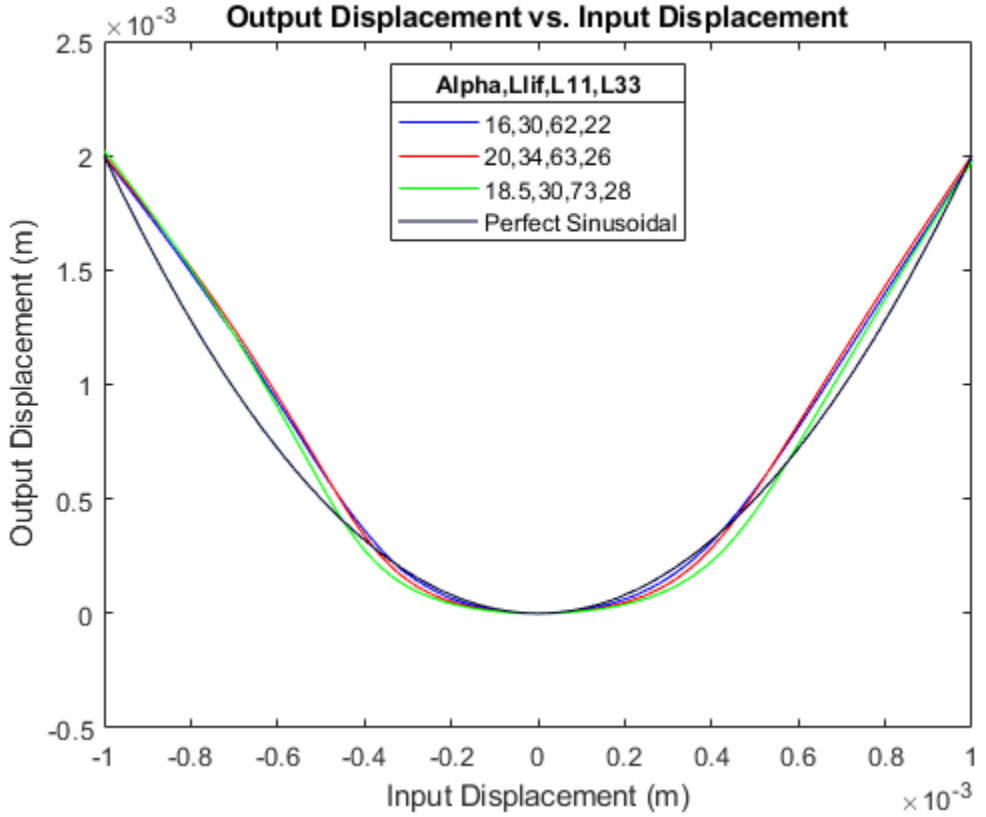



New data points to simulate
L33 (mm)
L11 (mm)
Sinusoidal SSE
50
45
40
35
30
25
20
35
40
45
50
55
60
65
70
0.015
0.0135
0.0120
0.0105
0.009
0.0075
0.006
0.0045
0.003
0.0015

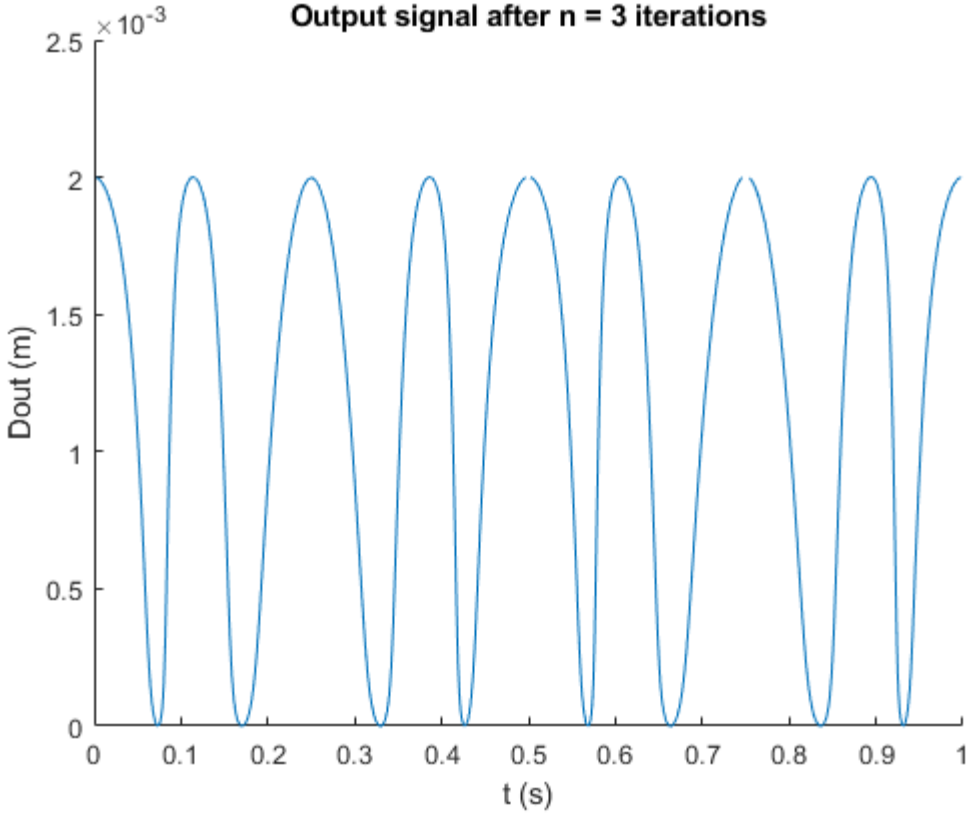

New data points to simulate
Lif (mm)
Alpha (deg)
Sinusoidal SSE
100
90
80
70
60
50
40
30
10
15
20
25
30
35
0.015
0.0135
0.0120
0.0105
0.009
0.0075
0.006
0.0045
0.003
0.0015

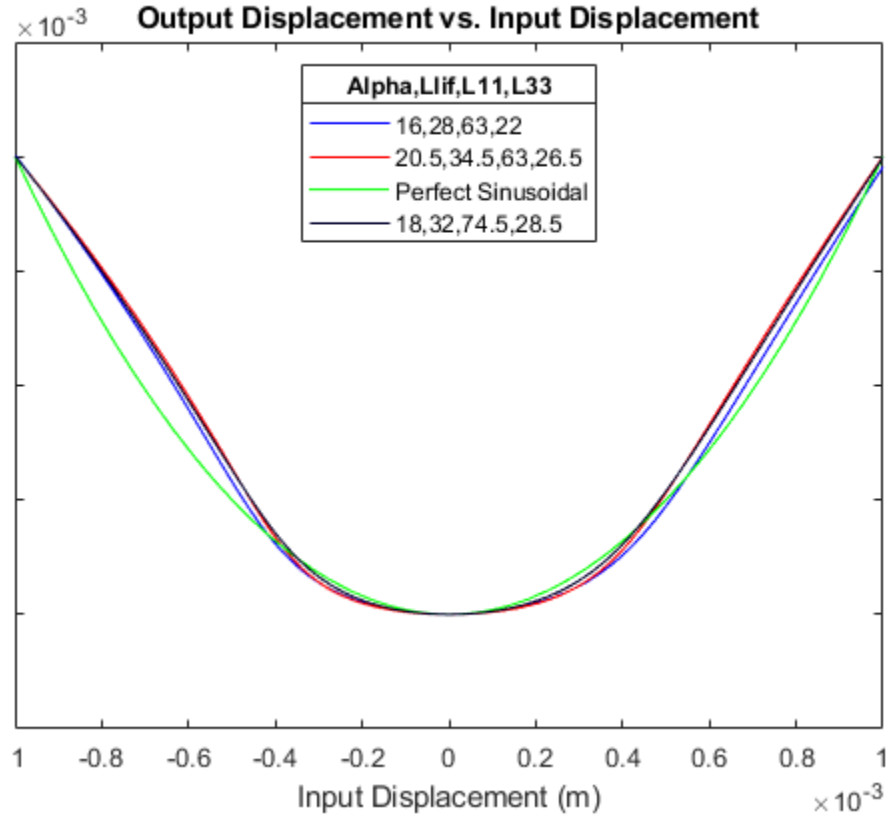
Iteration 1


Output signal after n = 3 iterations
×10^-3
2.5
2
1.5
1
0.5
0
Dout (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
t (s)

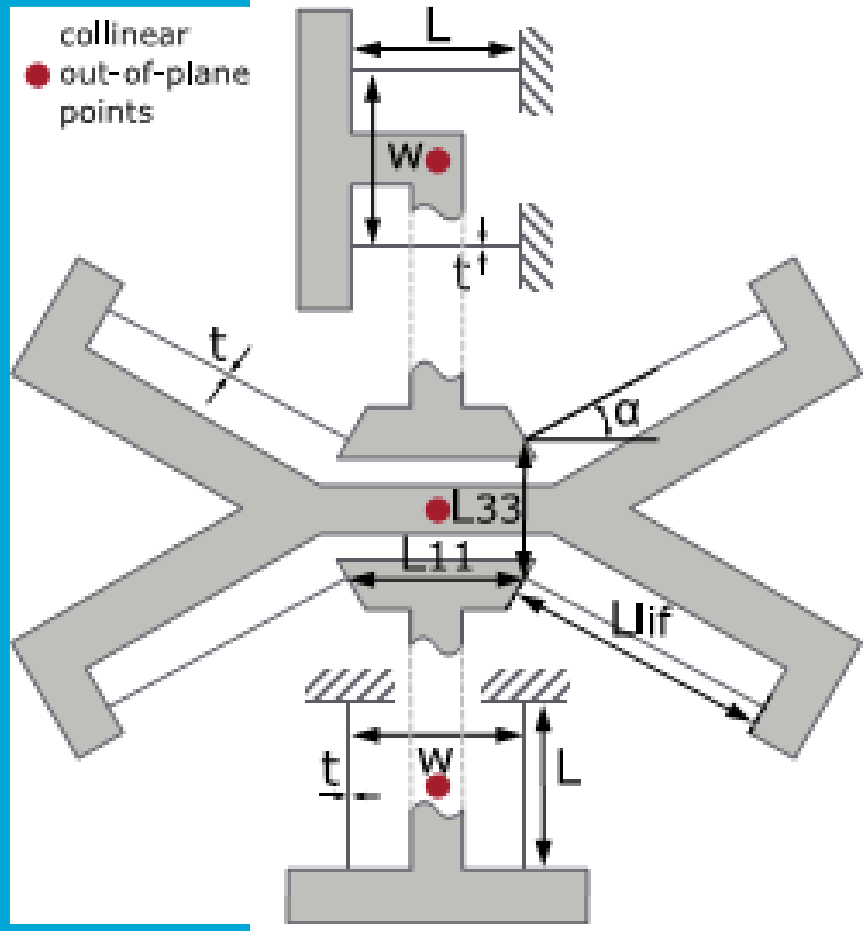

Output Displacement vs. Input Displacement
×10^-3
Alpha,Llif,L11,L33
16,30,62,22
20,34,63,26
18.5,30,73,28
Perfect Sinusoidal
Output Displacement (m)
2.5
2
1.5
1
0.5
0
-0.5
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Input Displacement (m)
×10^-3

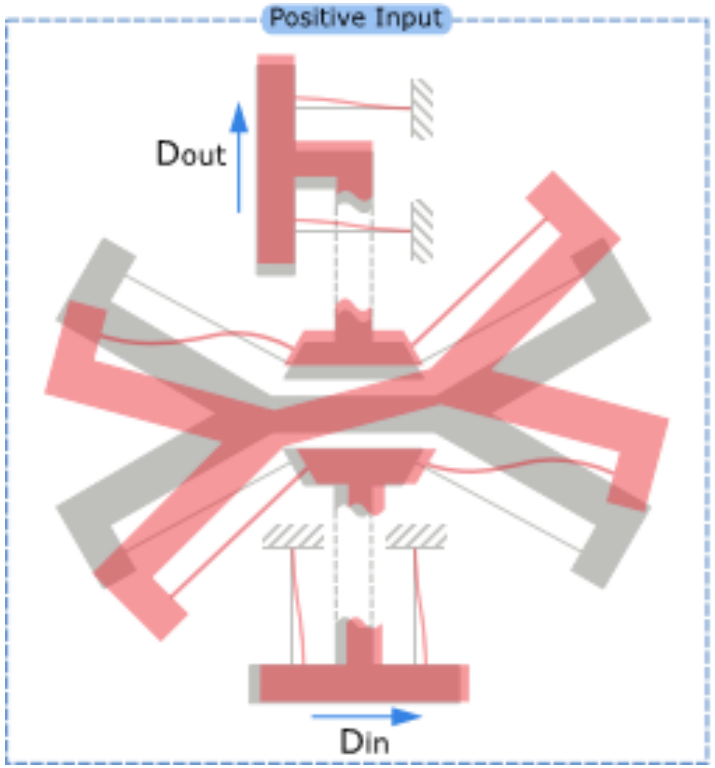
Iteration 2

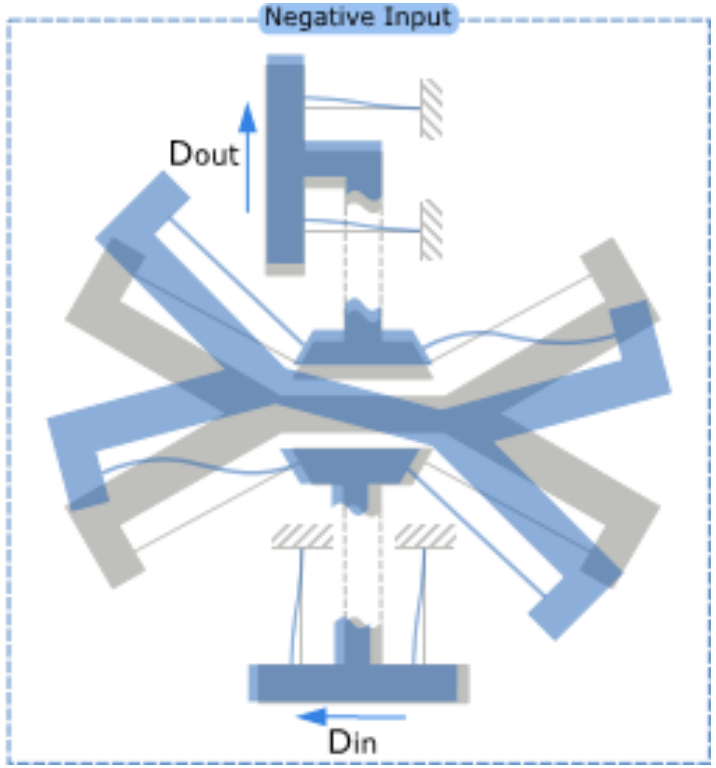

Output signal after n = 3 iterations
×10^-3
2.5
2
1.5
1
0.5
0
Dout (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
t (s)


Output Displacement vs. Input Displacement
×10^-3
Alpha,Llif,L11,L33
16,28,63,22
20.5,34.5,63,26.5
Perfect Sinusoidal
18,32,74.5,28.5
1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Input Displacement (m)
×10^-3

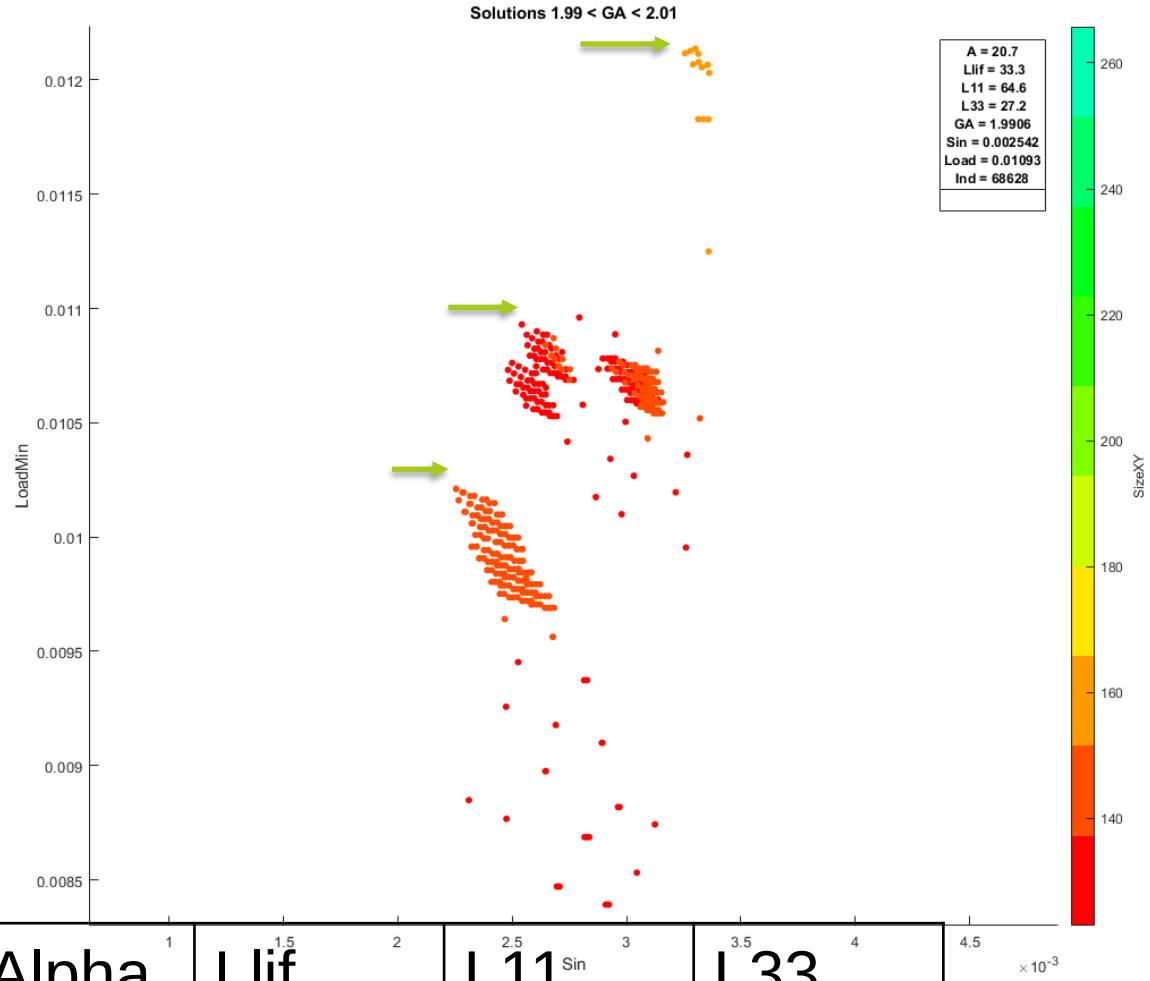
Figures


collinear
out-of-plane
points
L
w
t
t
α
L33
L11
Lif
t
w
L


Positive Input
Dout
Din


Negative Input
Dout
Din

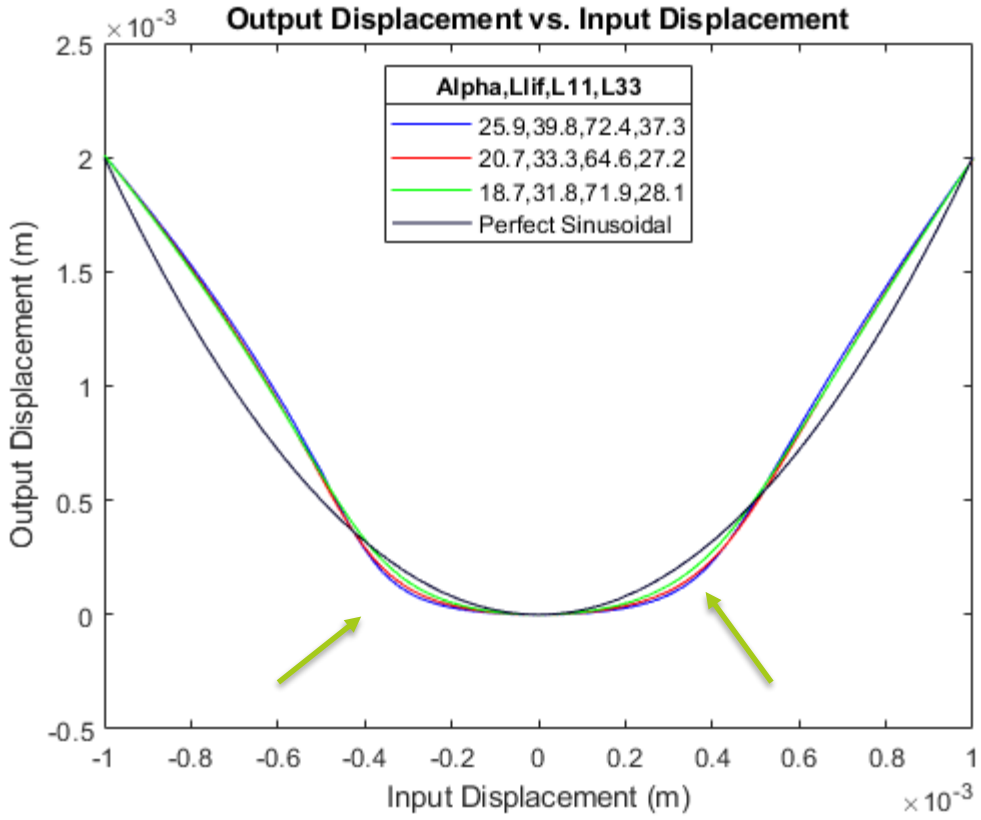
After 4 iterations



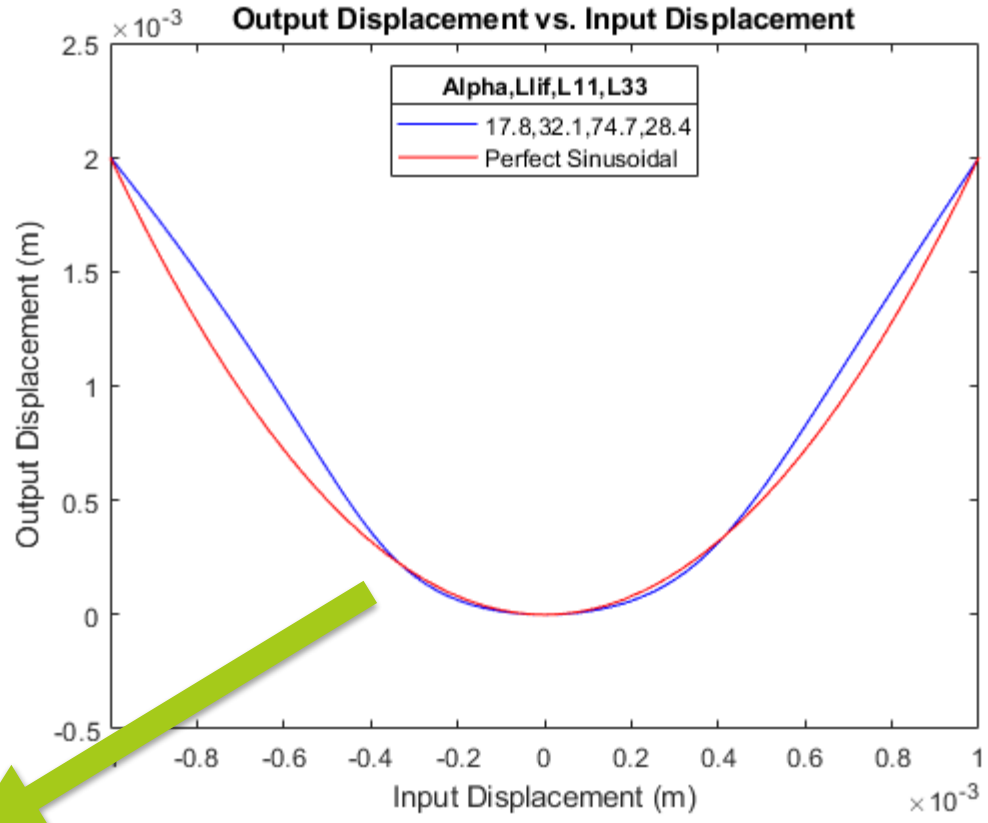
GA	Sin	Load	Alpha	Llif	L11	L33
2.0095	0.00325	0.0121	25.9	39.8	72.4	37.3
1.9906	0.00254	0.0109	20.7	33.3	64.6	27.2
2.0098	0.00225	0.0102	18.7	31.8	71.9	28.1

DD

New with load as criteria

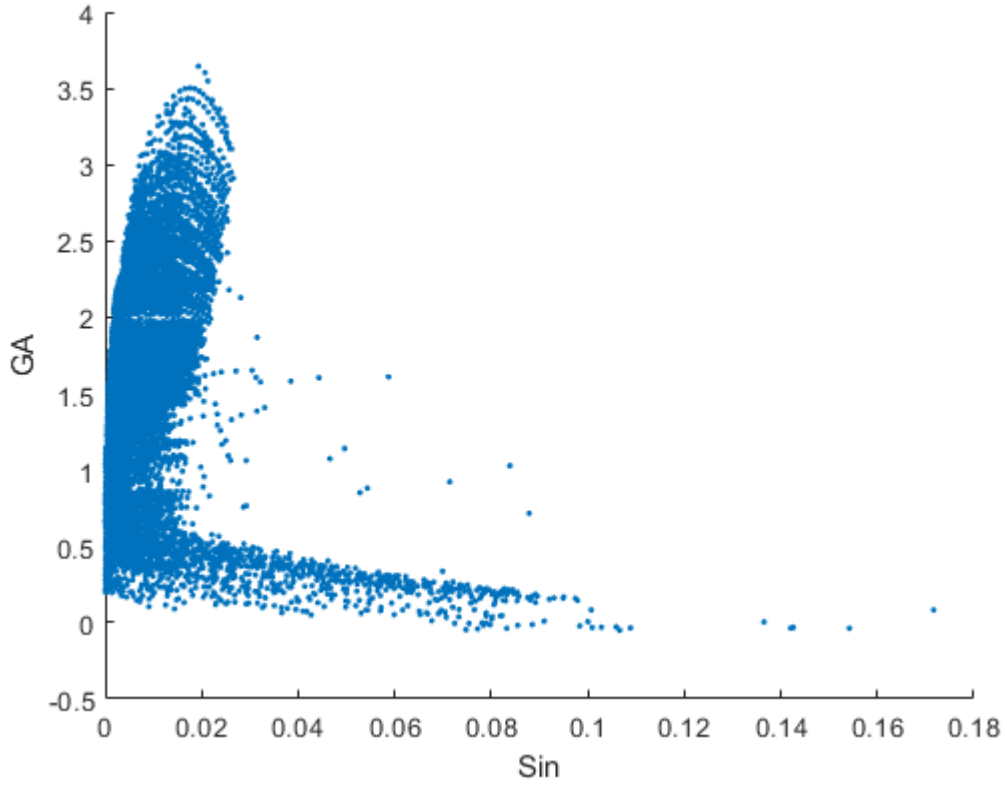


Old just looking at GA and Sin

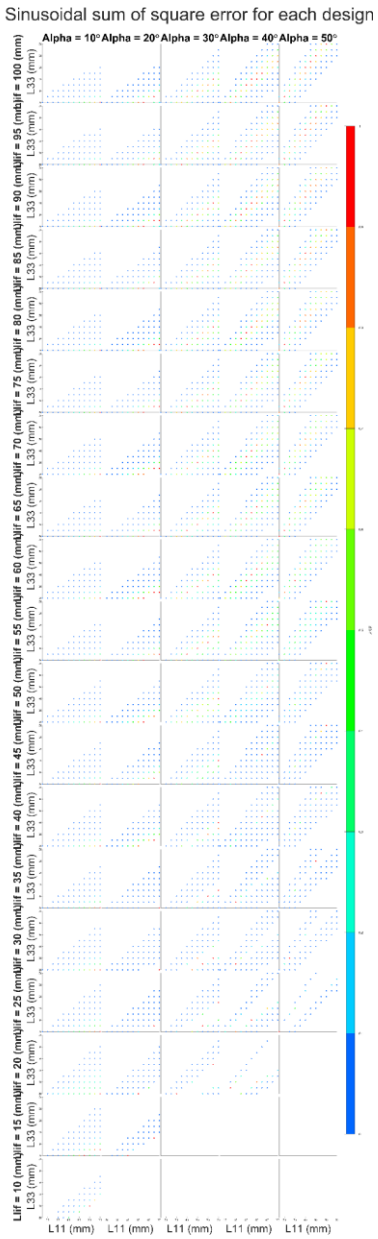


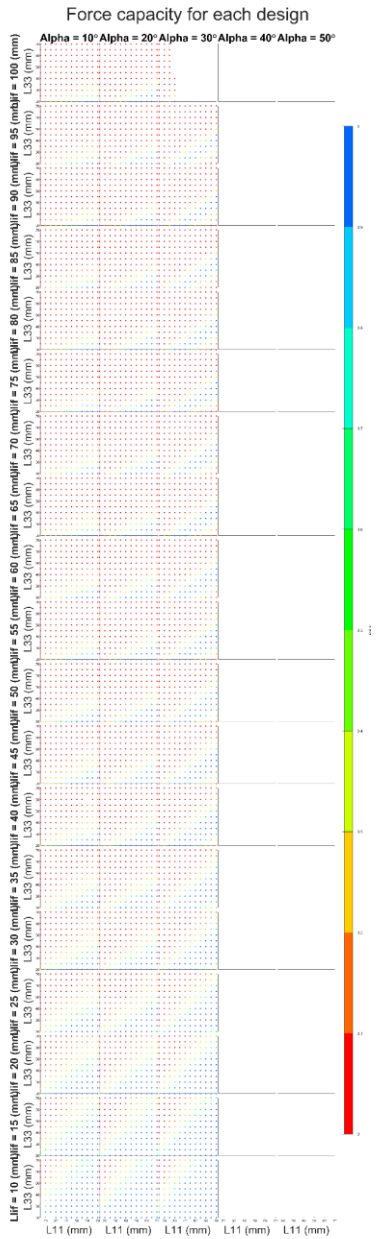
GA	Sin	Load	Alpha	Llif	L11	L33
1.9989	0.0026	0.0097	17.8	32.1	74.7	28.4

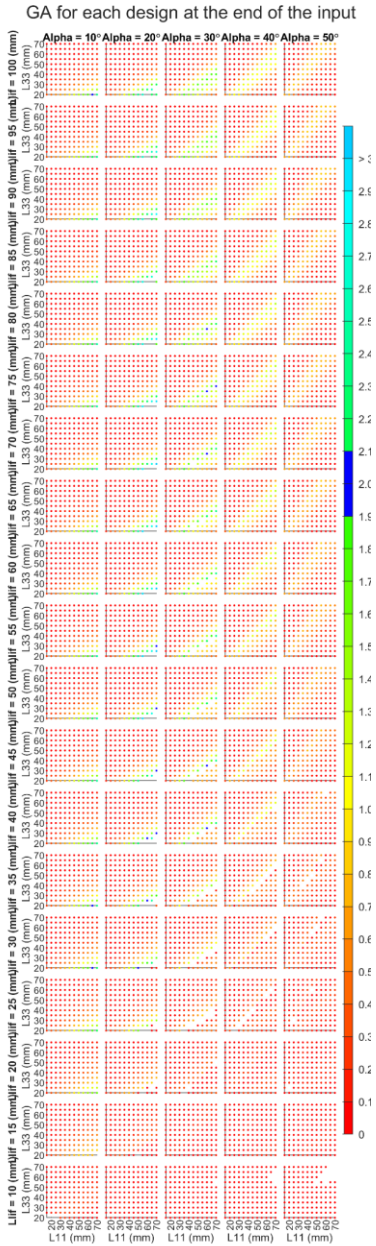
68733 points analysed



Tile plots







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Results and discussion

1. Introduce mechanism and capabilities Schematic of design with parameters + design with deformation
2. Showing how different parameters alter the results qualitatively and quantitively Displacement relation
3. What behaviour is desired? Setup of criteria..
4. First investigation to decrease design space Parameter plots of GA, Sin, Force capacity
5. Full investigation into decreased design space, and iterate while: Resulting criteria plot
    1. Narrowing search space
    2. Tightening constraints
6. Validate the results with tested prototype DD and FD graph with FEM and Test
7. Mention best result

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Plots

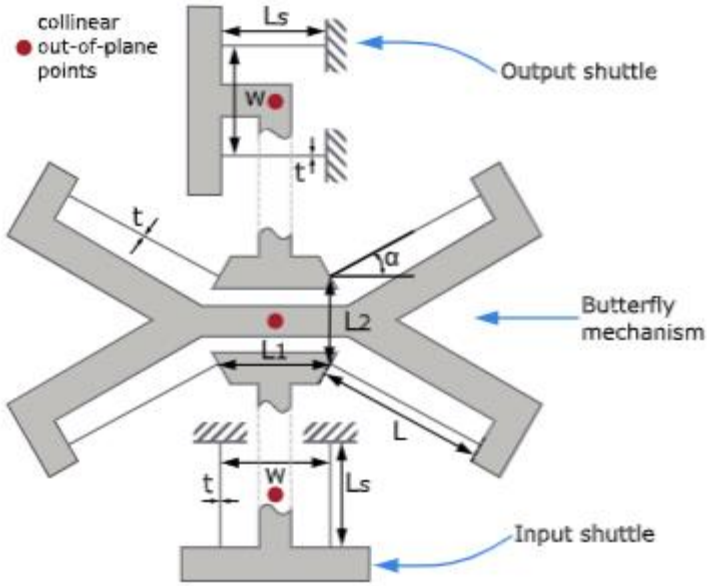


Figure 1: Schematic of the eight-bar mechanism based frequency doubler building block

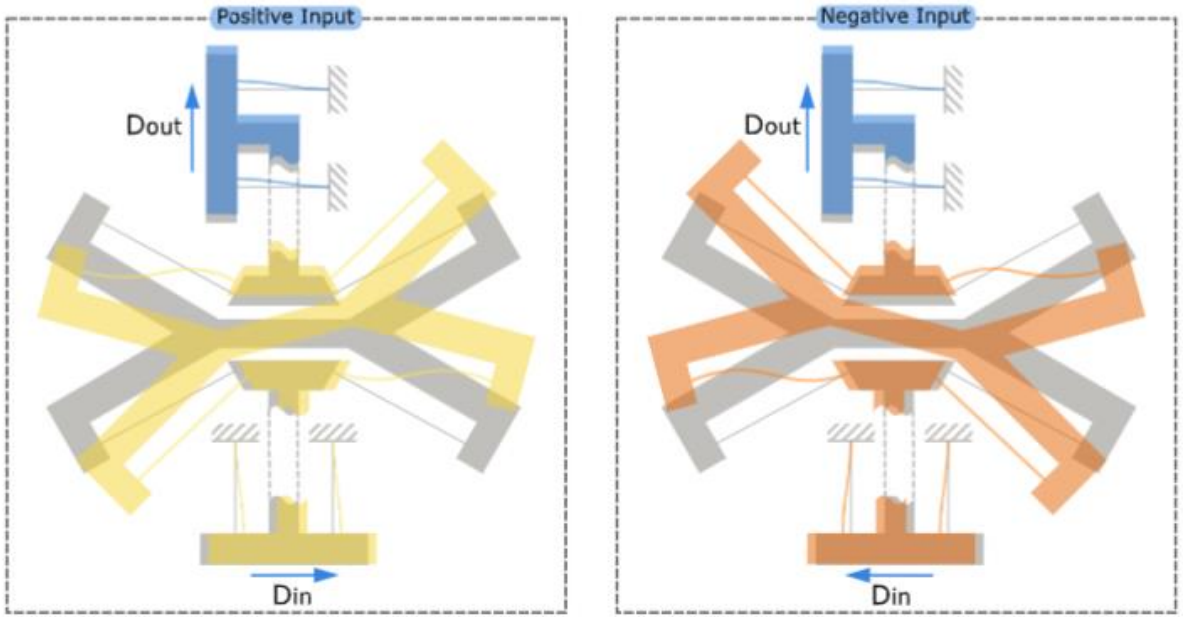
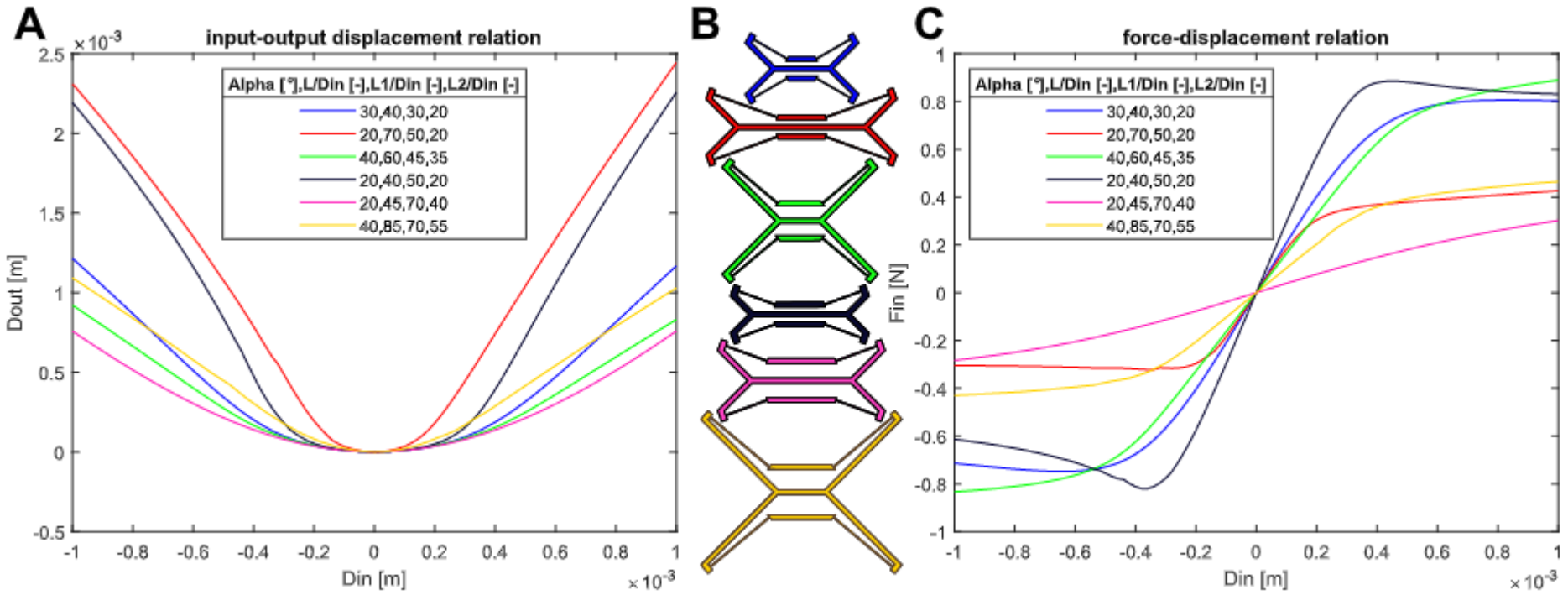
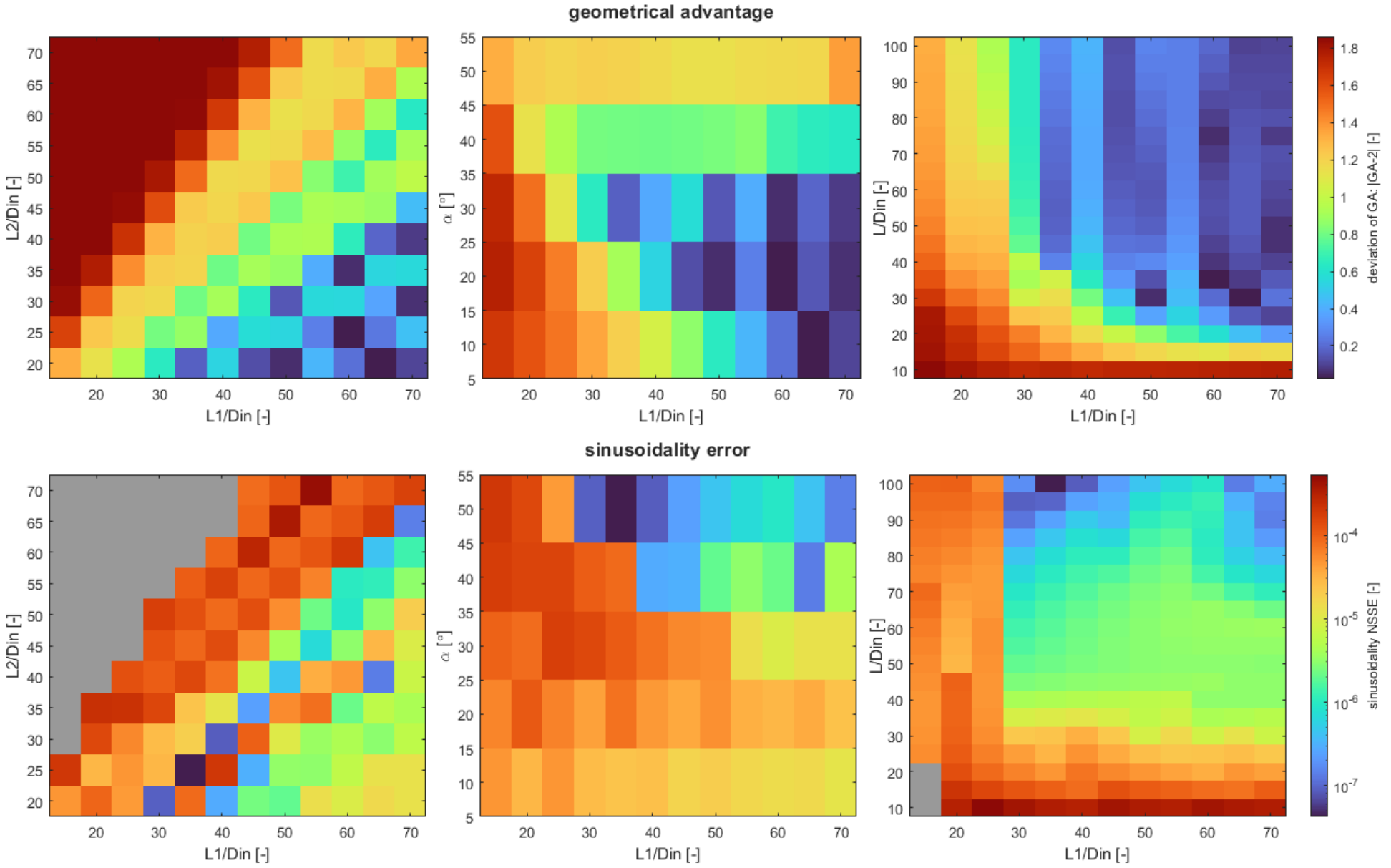


Figure 3: Input-output displacement characteristics for a positive input displacement (left) and a negative input displacement (right).

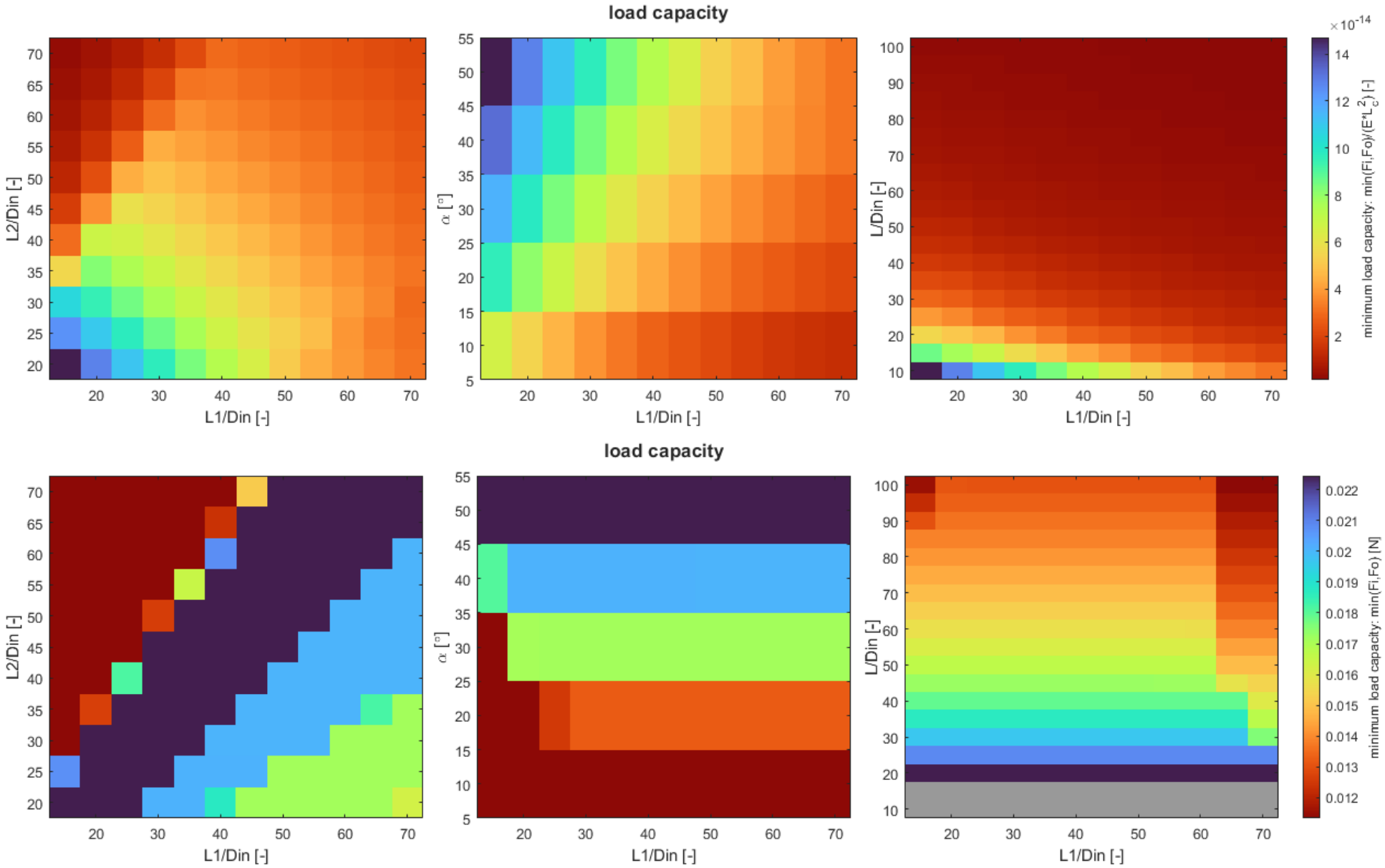
Frequency doubling capabilities and changing parameters



Plots


geometrical advantage
L2/Din [-]
L1/Din [-]
α [°]
L1/Din [-]
L/Din [-]
L1/Din [-]
deviation of GA: |GA-2| [-]
sinusoidality error
L2/Din [-]
L1/Din [-]
α [°]
L1/Din [-]
L/Din [-]
L1/Din [-]
sinusoidality NSSE [-]

Dimensionless Force? F/(E*[m^2])



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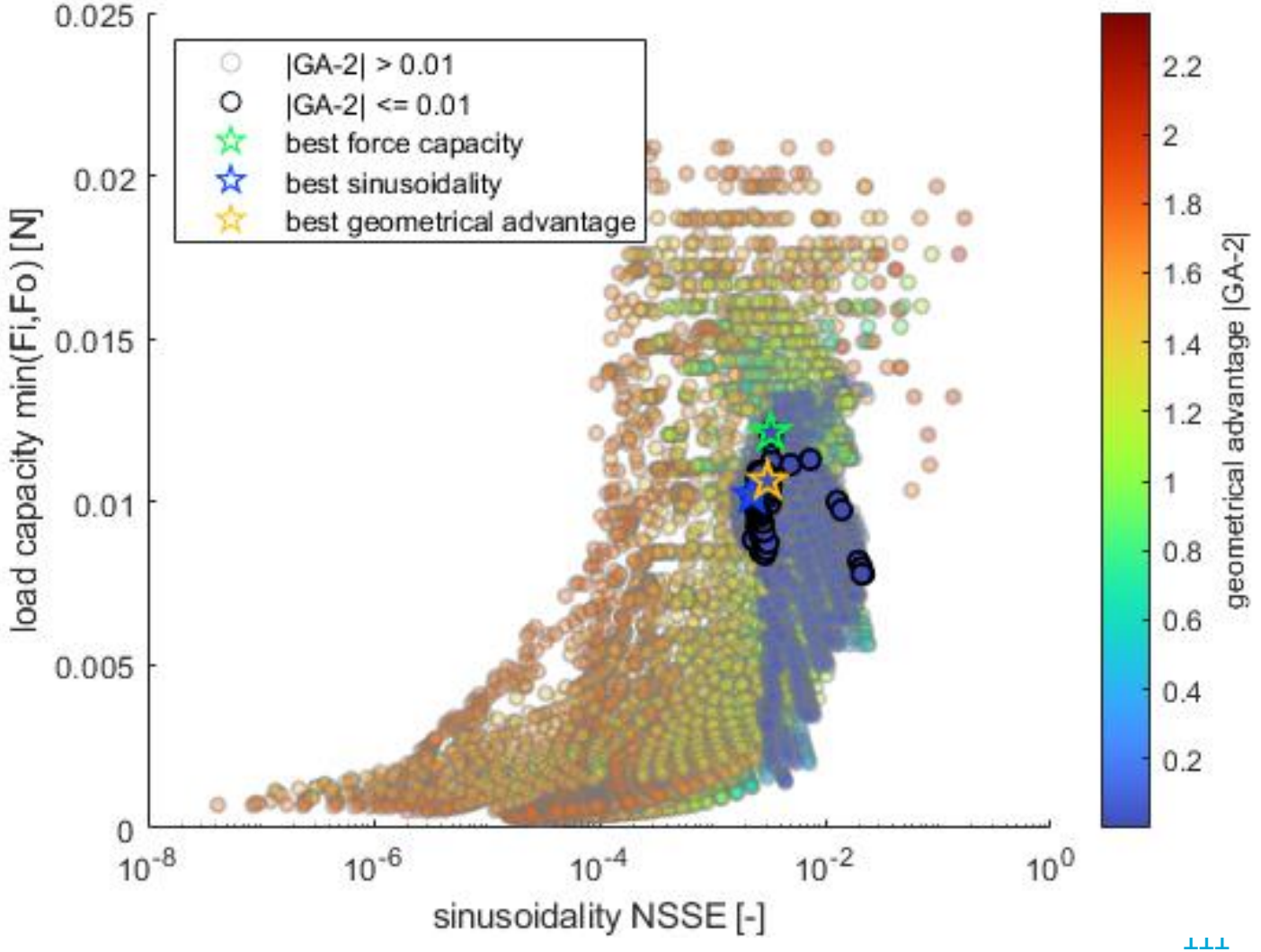
Criteria plot

Alpha: 26.1000
Llif: 40.2000
L11: 72.6000
L33: 37.7000

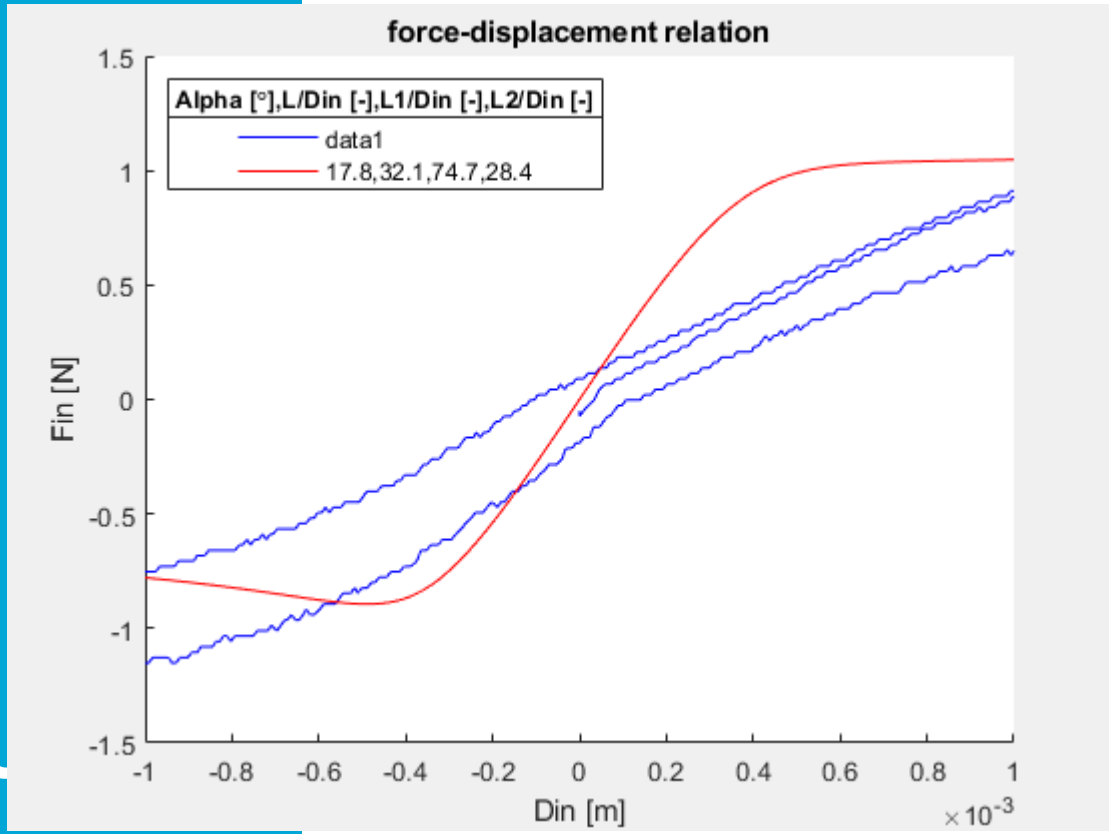
Alpha: 18.7000
Llif: 31.8000
L11: 71.9000
L33: 28.1000

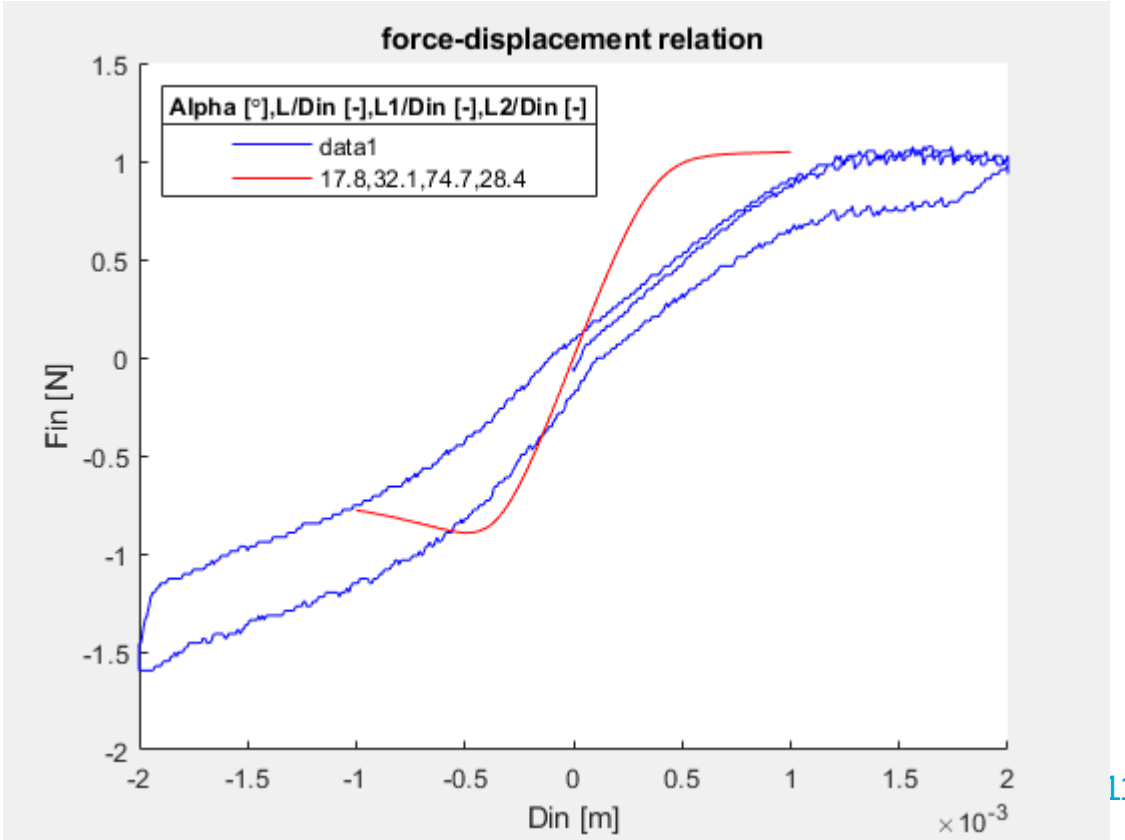
Alpha: 20.5000
Llif: 34.6000
L11: 63.2000
L33: 26.6000



Testing

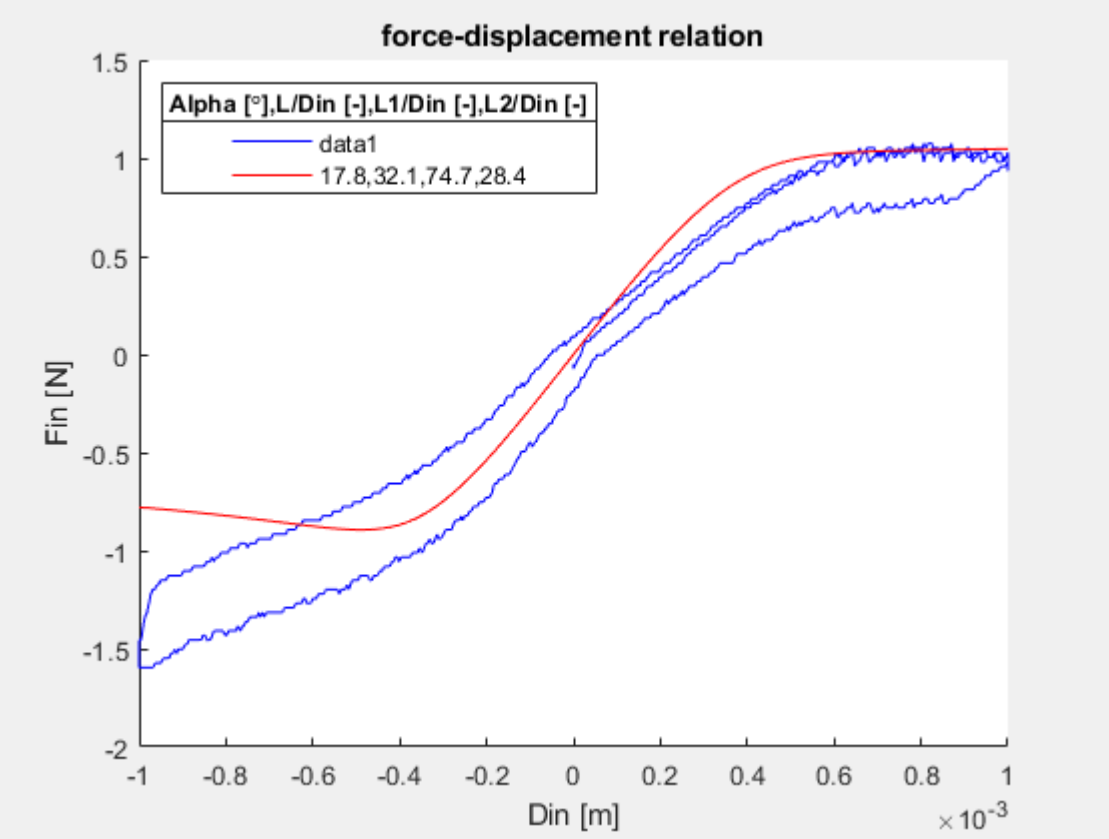
- Hysteresis
- Backlash
- Innacuracy of 3d printer
- Innacuracy in assembly



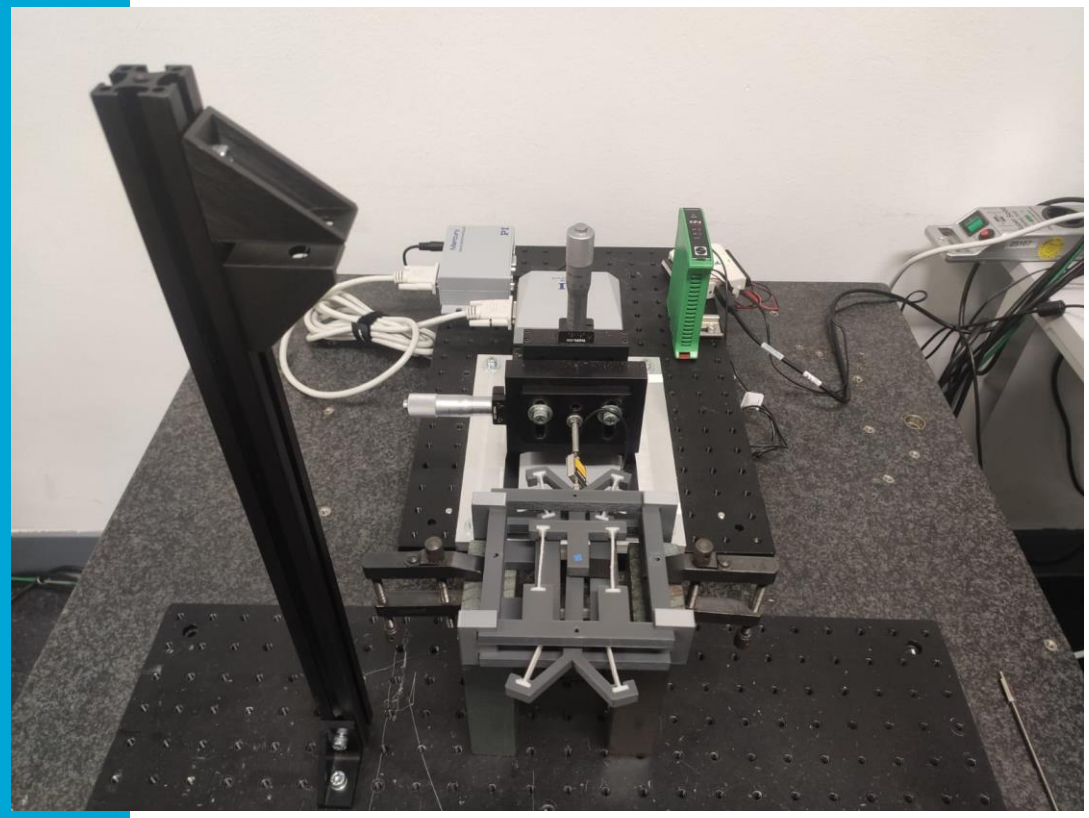


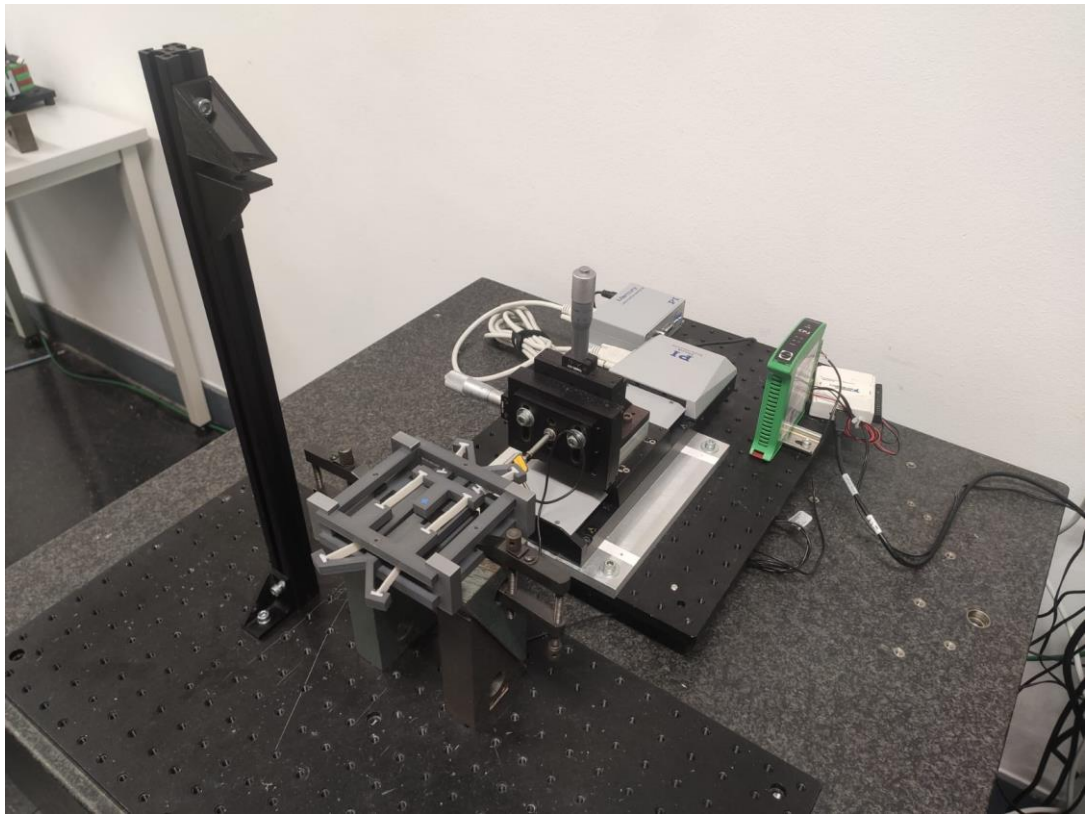
Testing

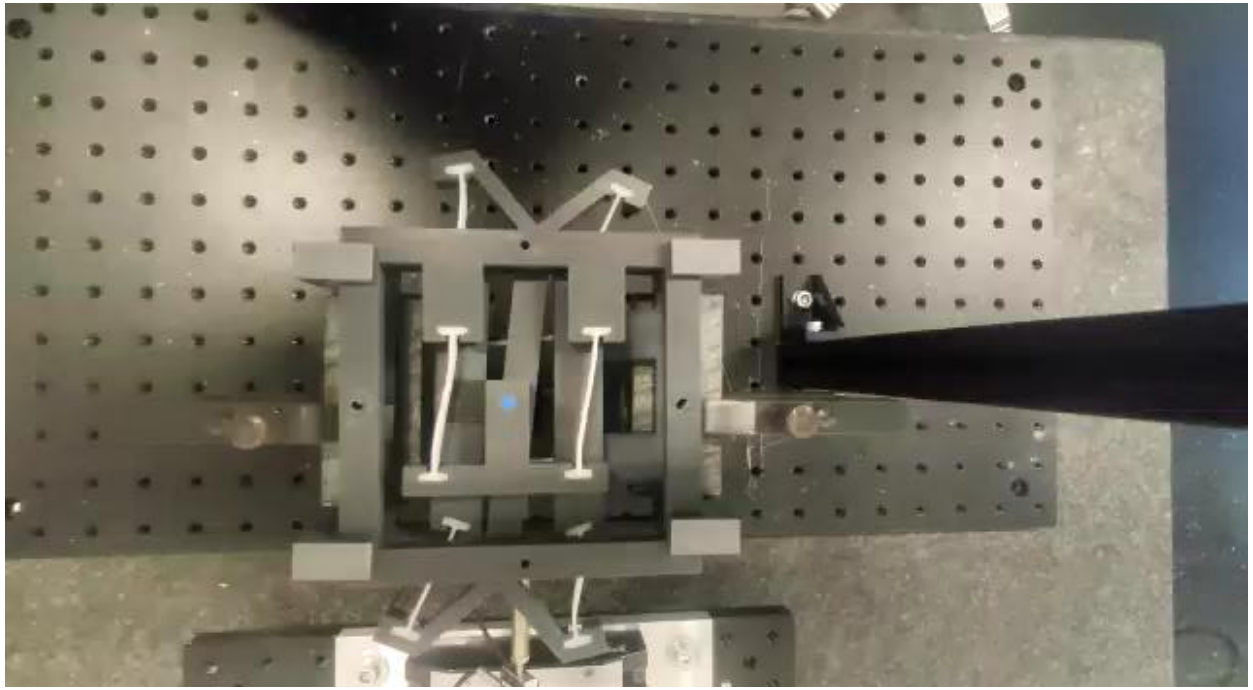
- If input displacement/2



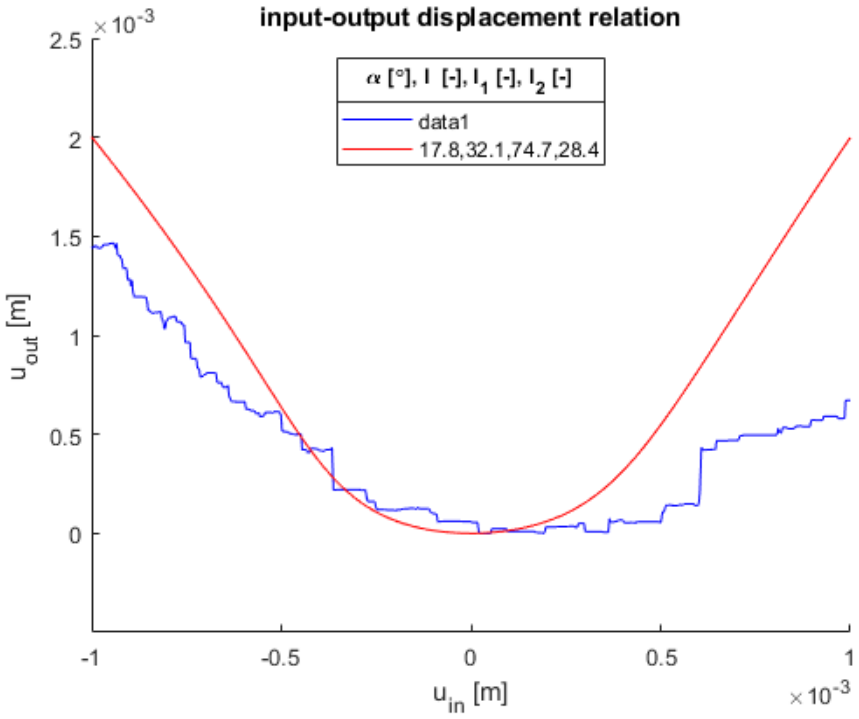
Mechanism with TPU flexures was tested, but did not work good enough

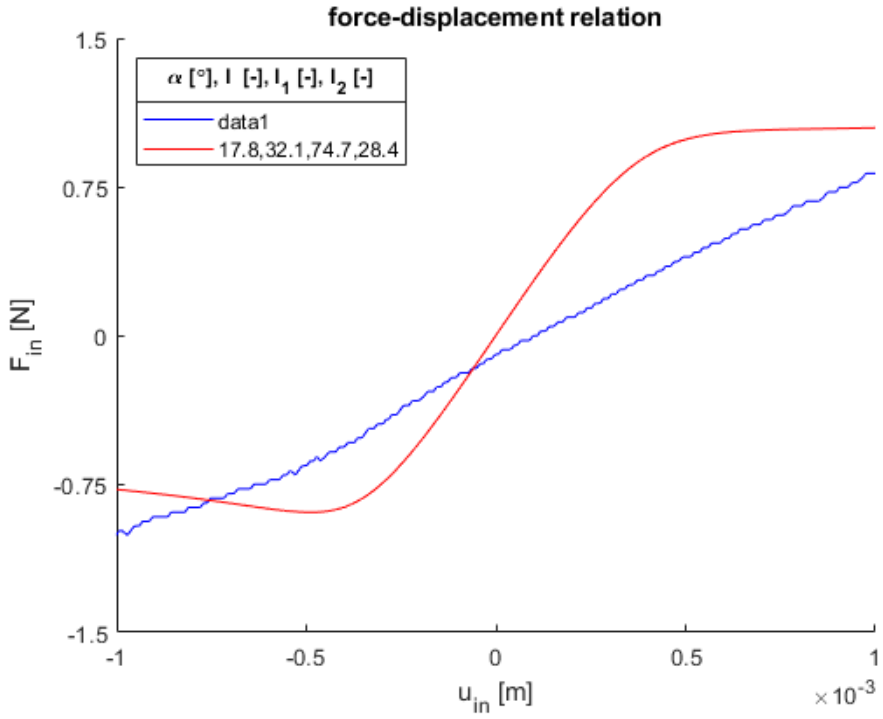




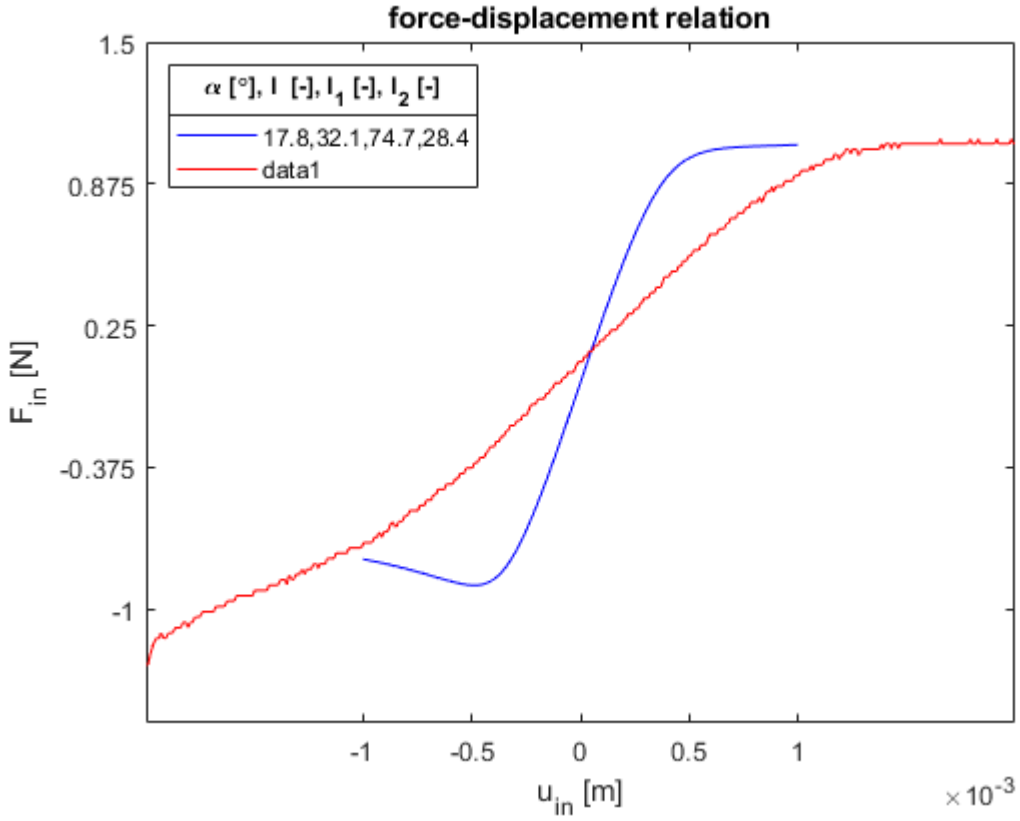


Testresults with TPU

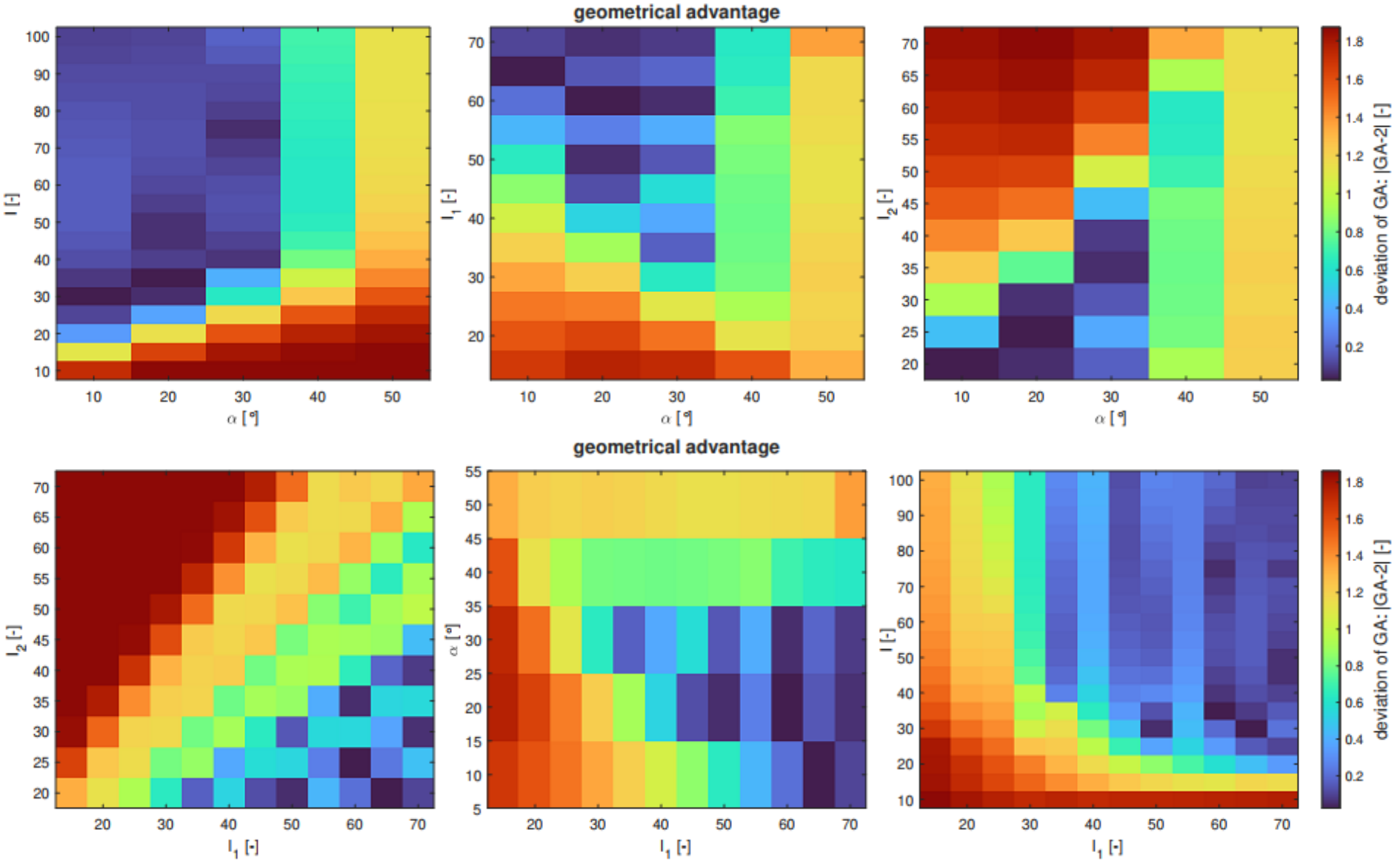


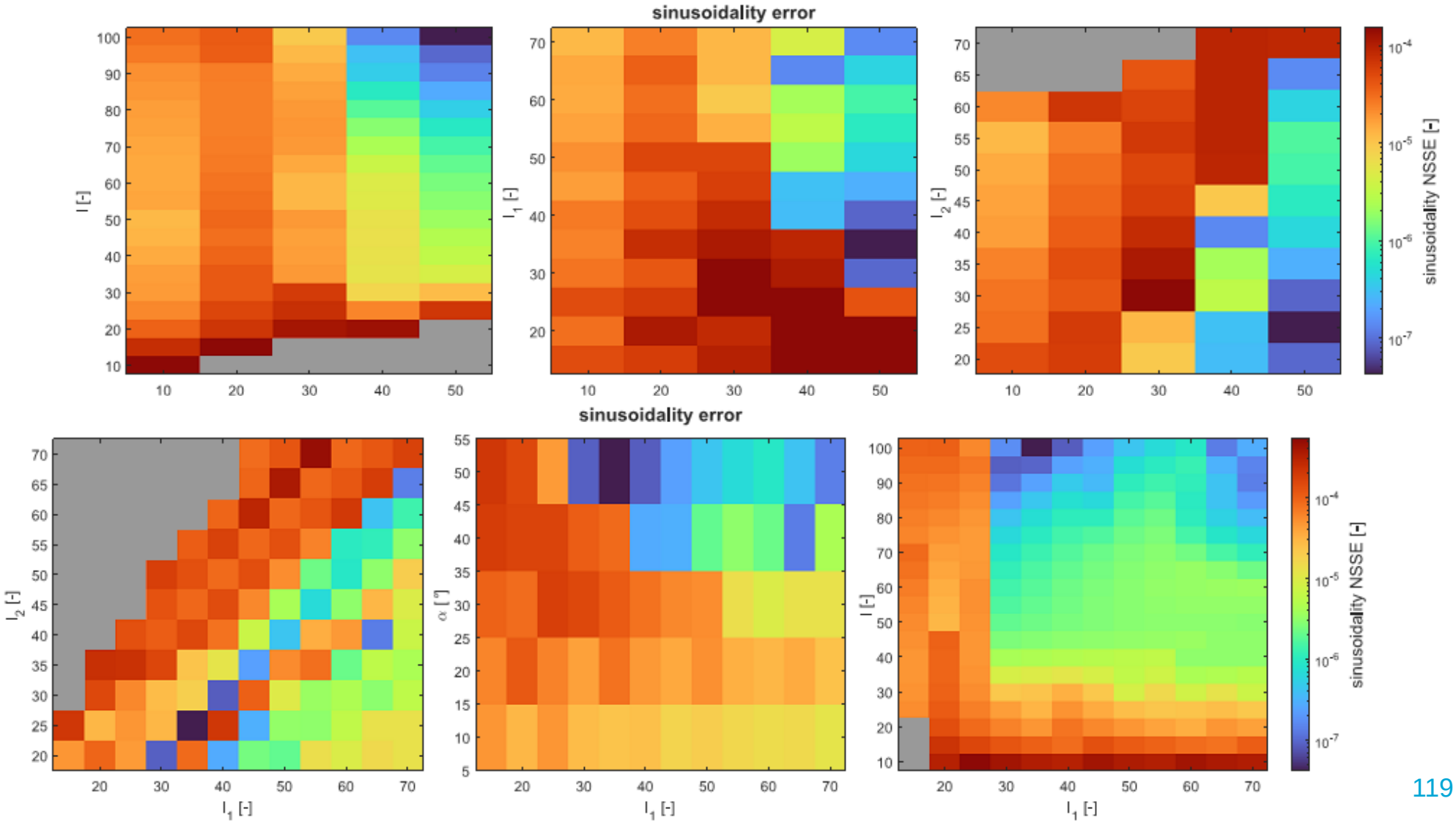


Behavior for larger domain



Updated contour plots (Alpha vs l1)

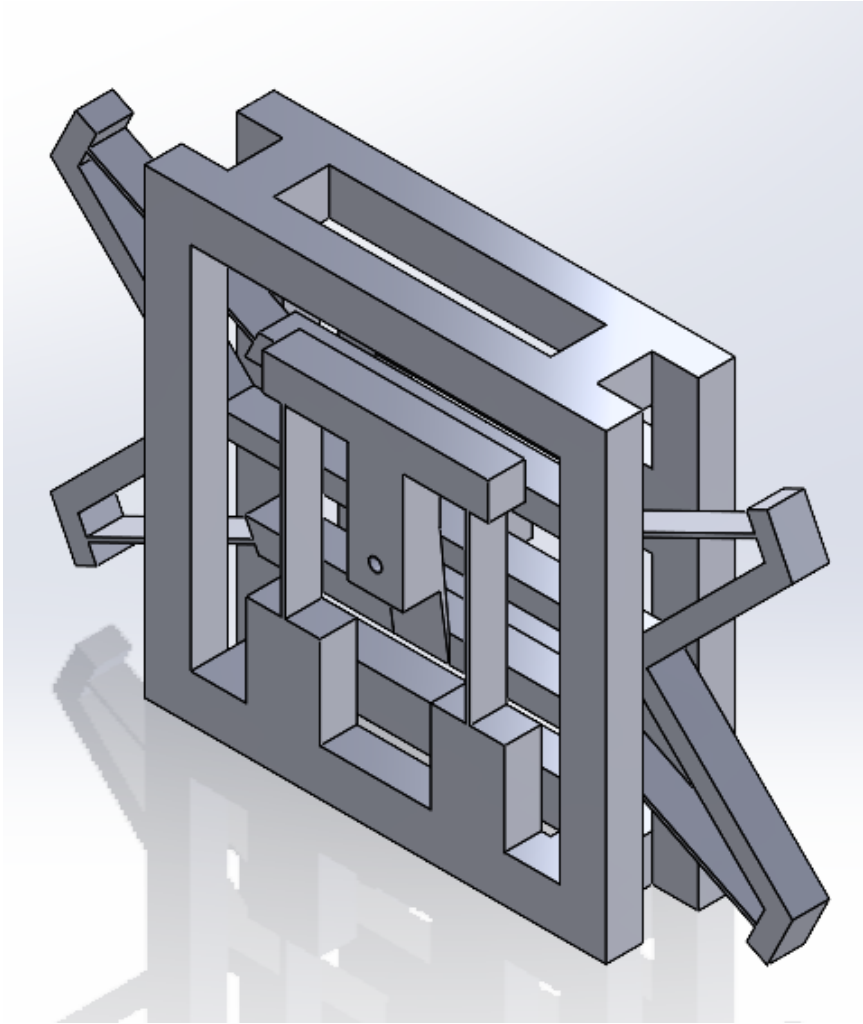



sinusoidality error
l [-]
l1 [-]
l2 [-]
sinusoidality NSSE [-]
sinusoidality error
l2 [-]
α [°]
l [-]
l1 [-]
sinusoidality NSSE [-]

Problem with materialize

- Connection piece way too flexible
- Overall structure way too flexible

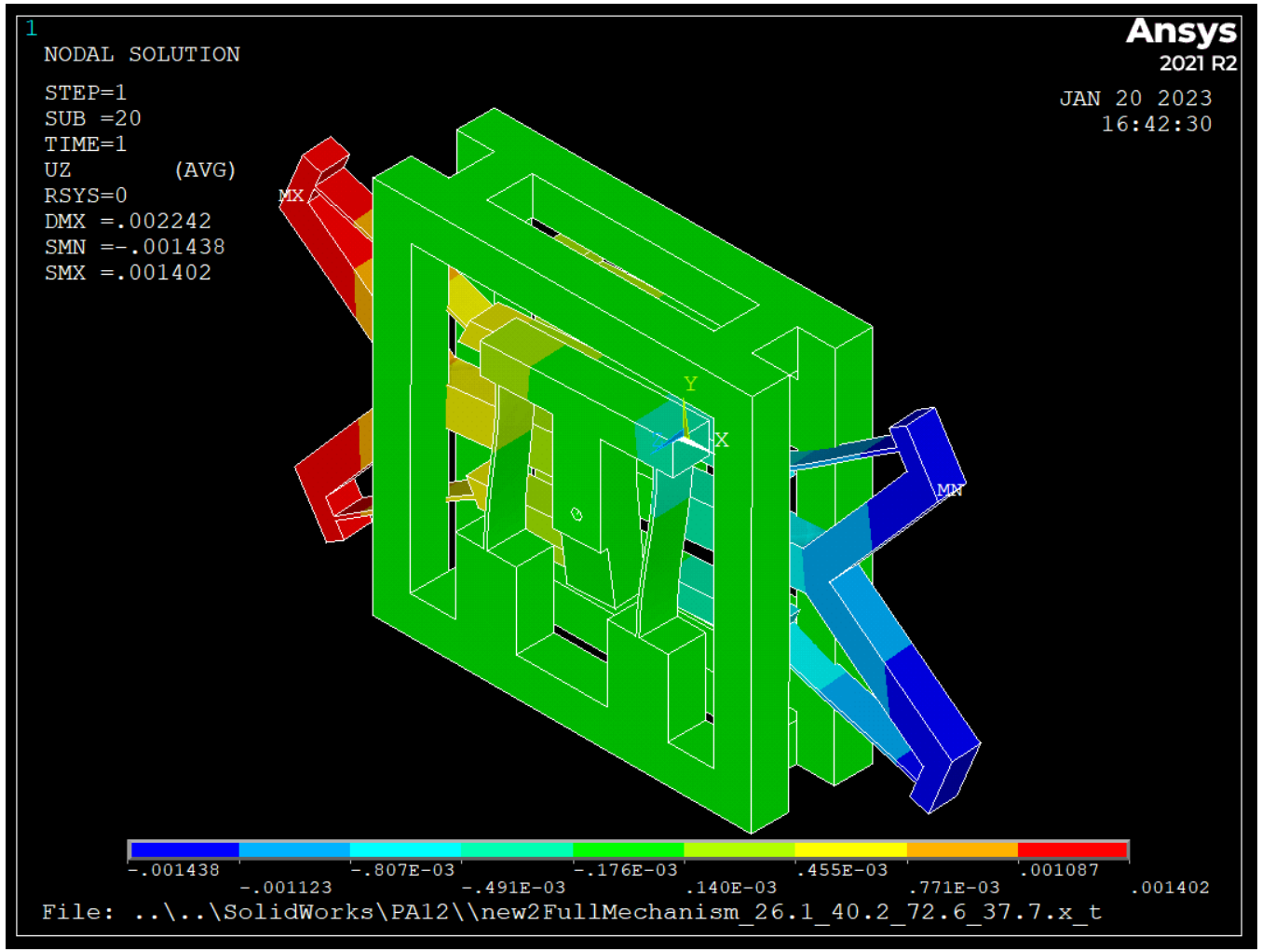
- Found out that using this part in FEM analysis, did not lead to frequency doubling

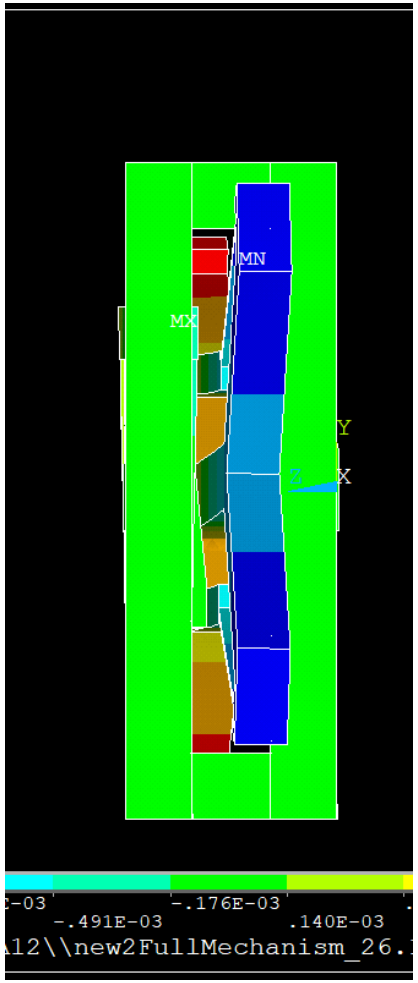


Summary of FEM attempts

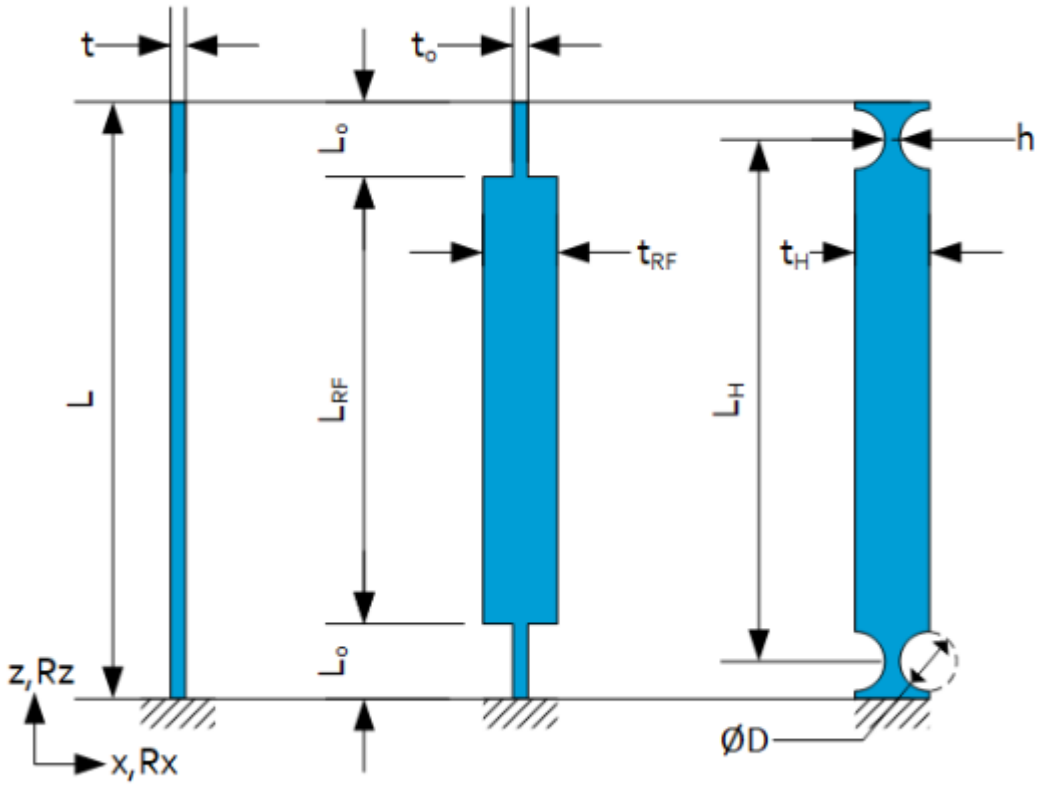
- Make connection piece thicker
- Widen the distance between input flexures from 40 – 60 mm such that connection piece can be made super thick
- Made in/output shuttle thicker

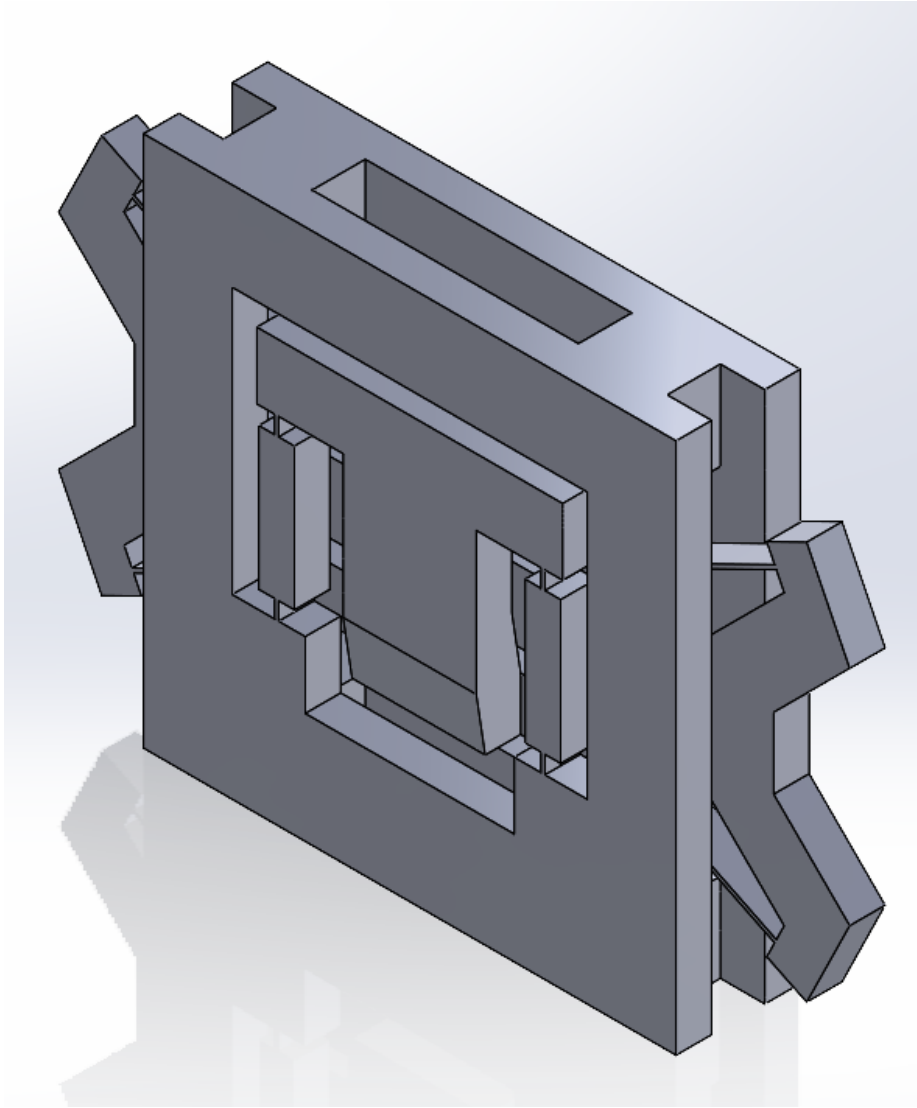
Parasitic rotation??

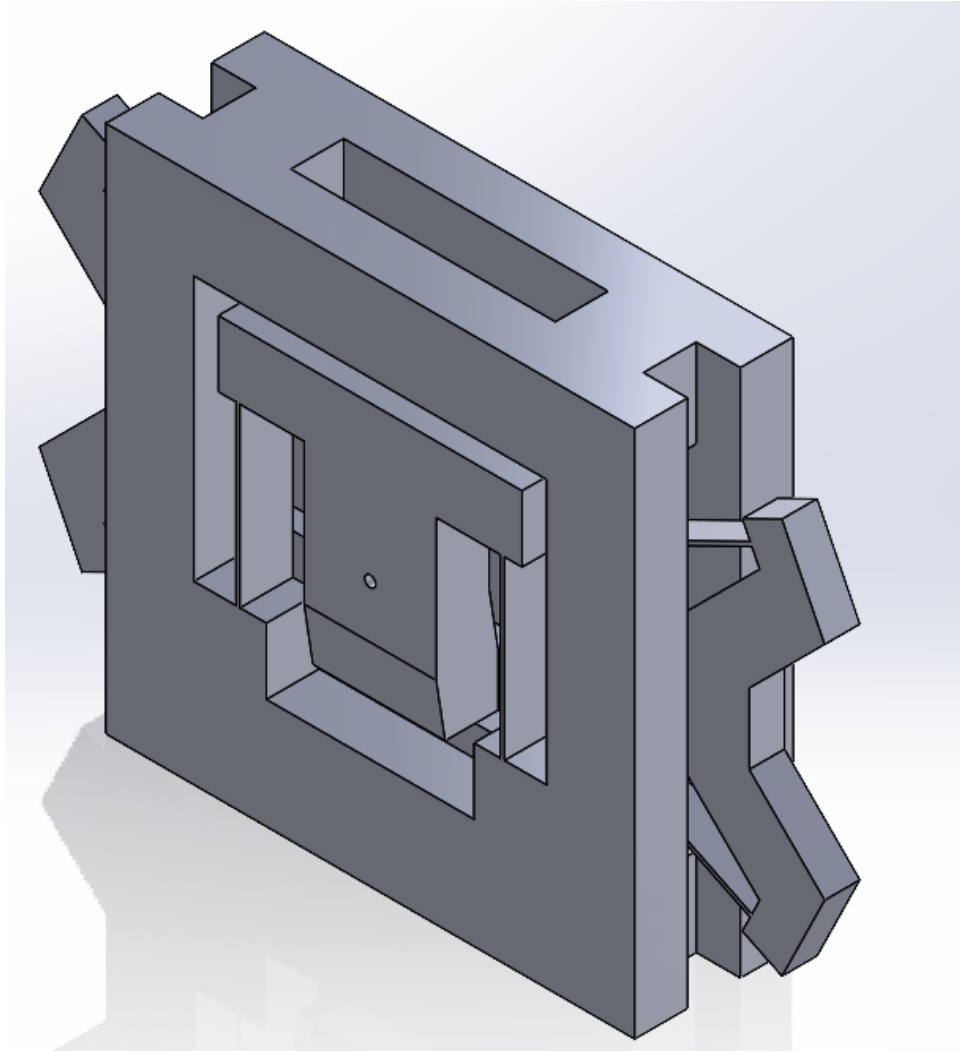




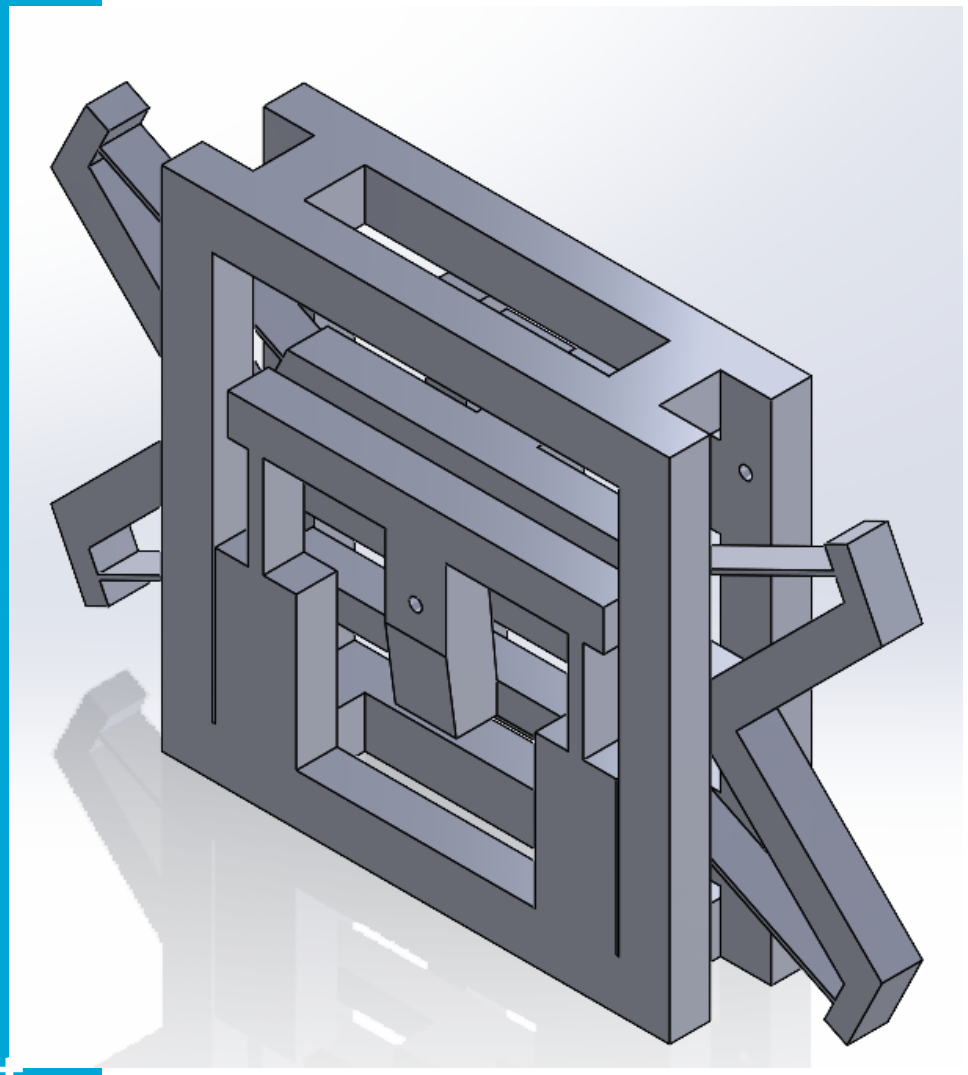
Tried Lumped flexures

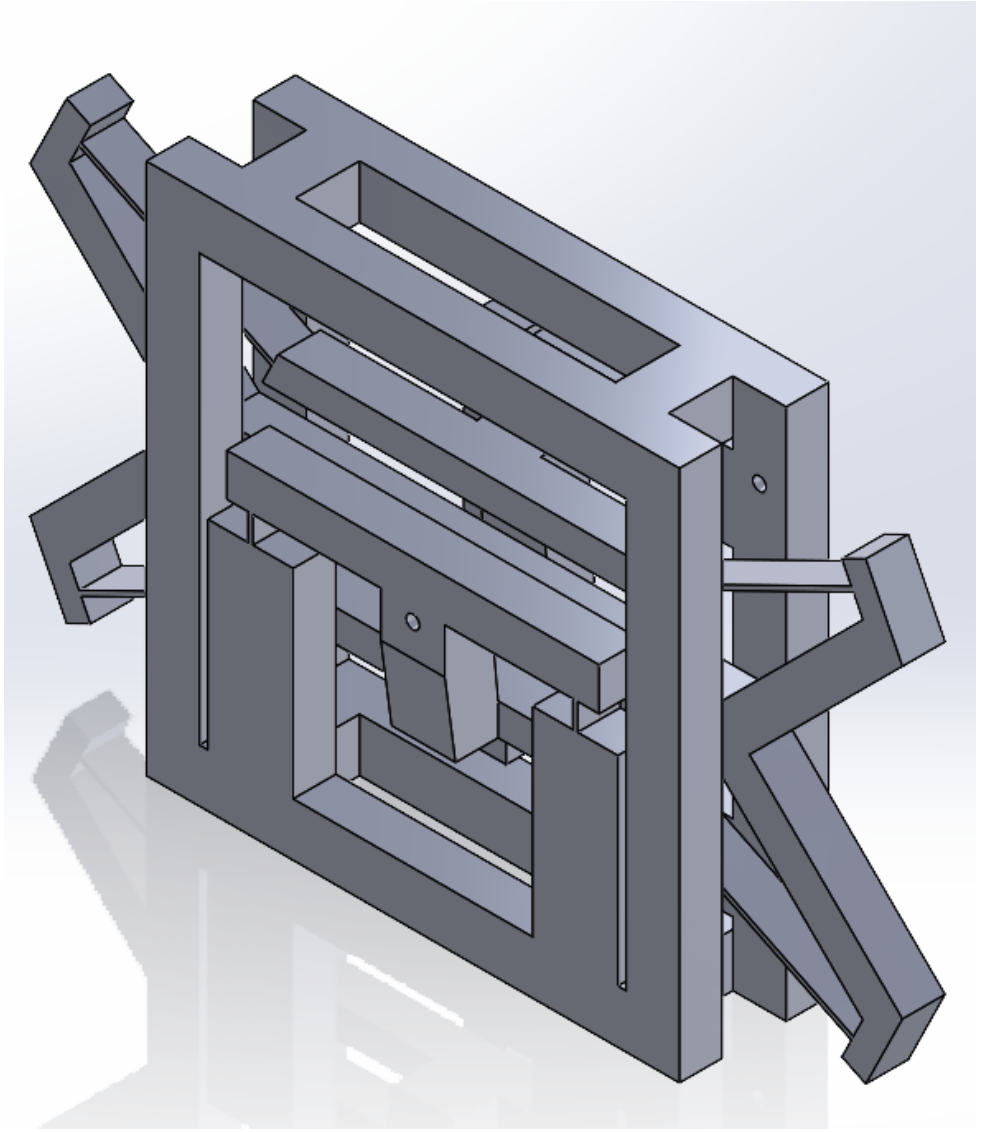






Some weird attempts

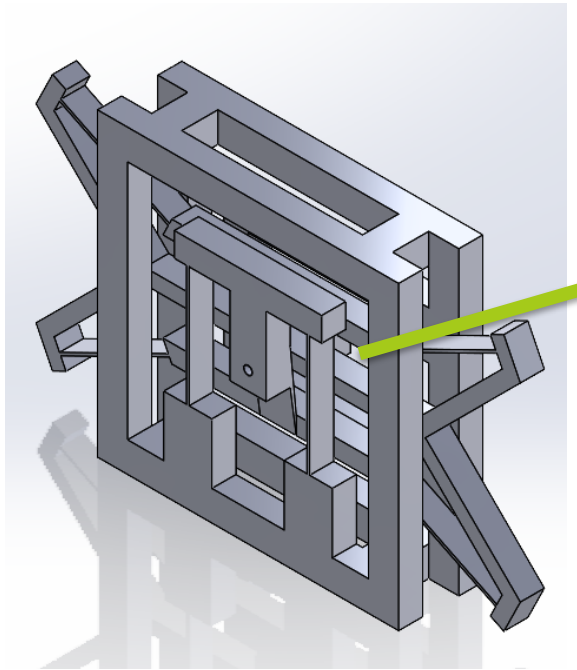


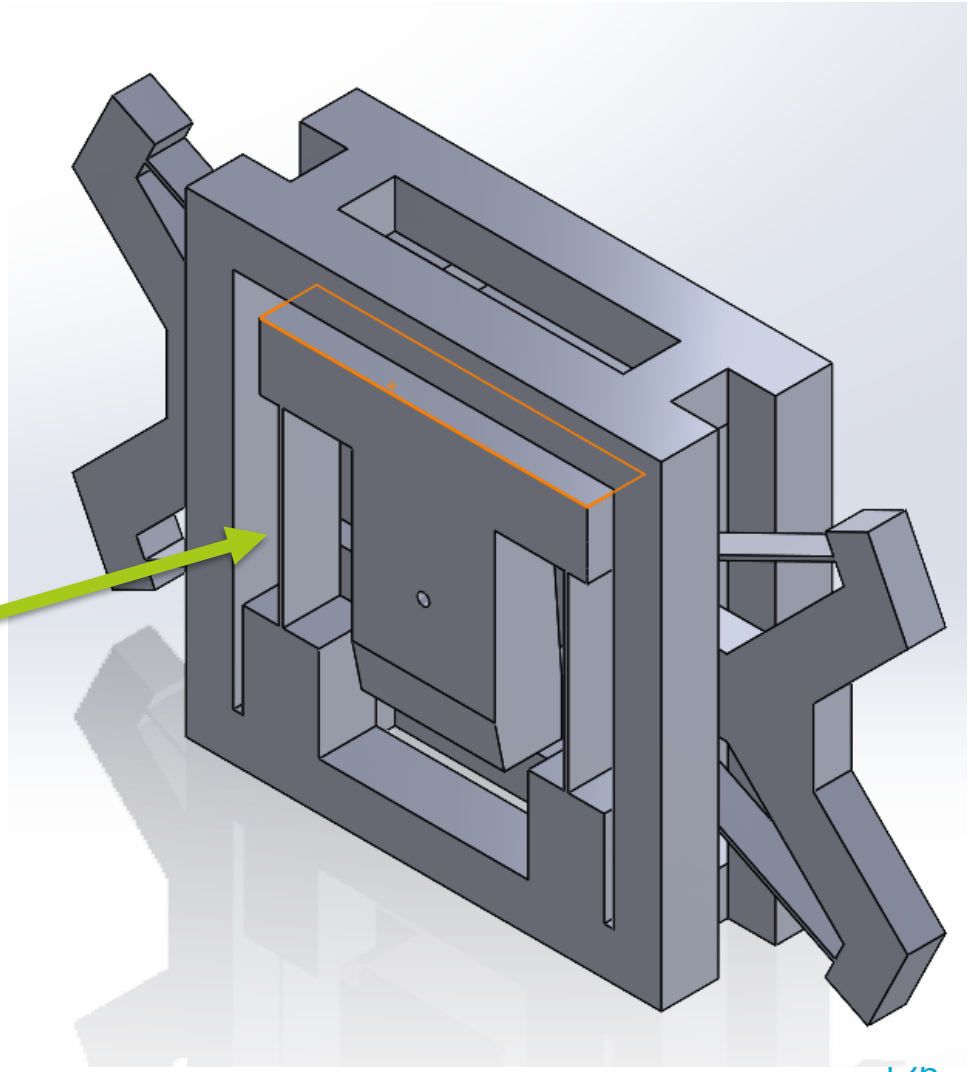


Final resulting prototype

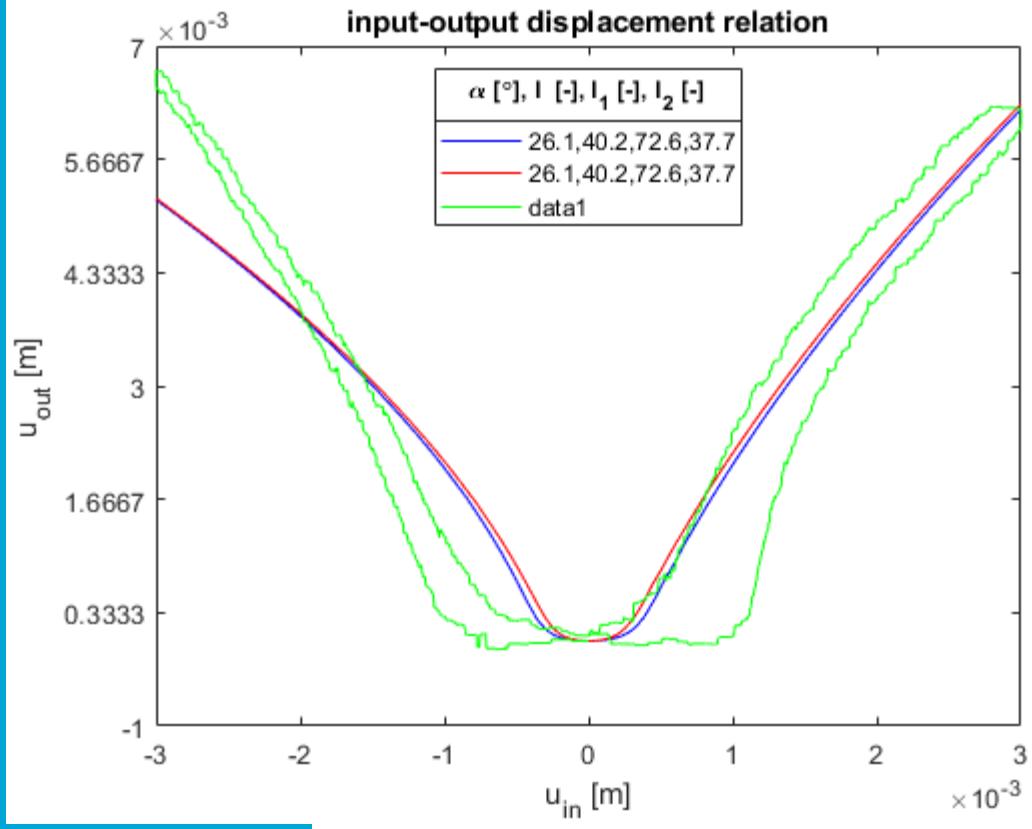
Changes

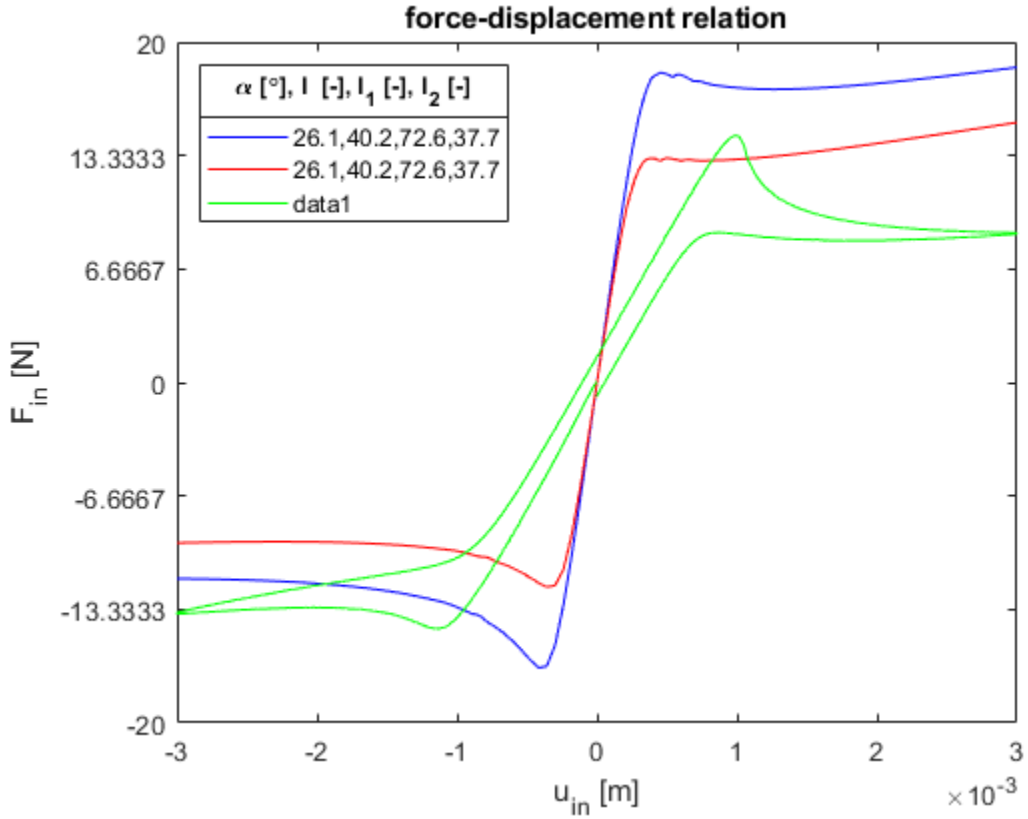
- Thicker in/output structure
- Made overall structure thicker wherever possible
- Old:

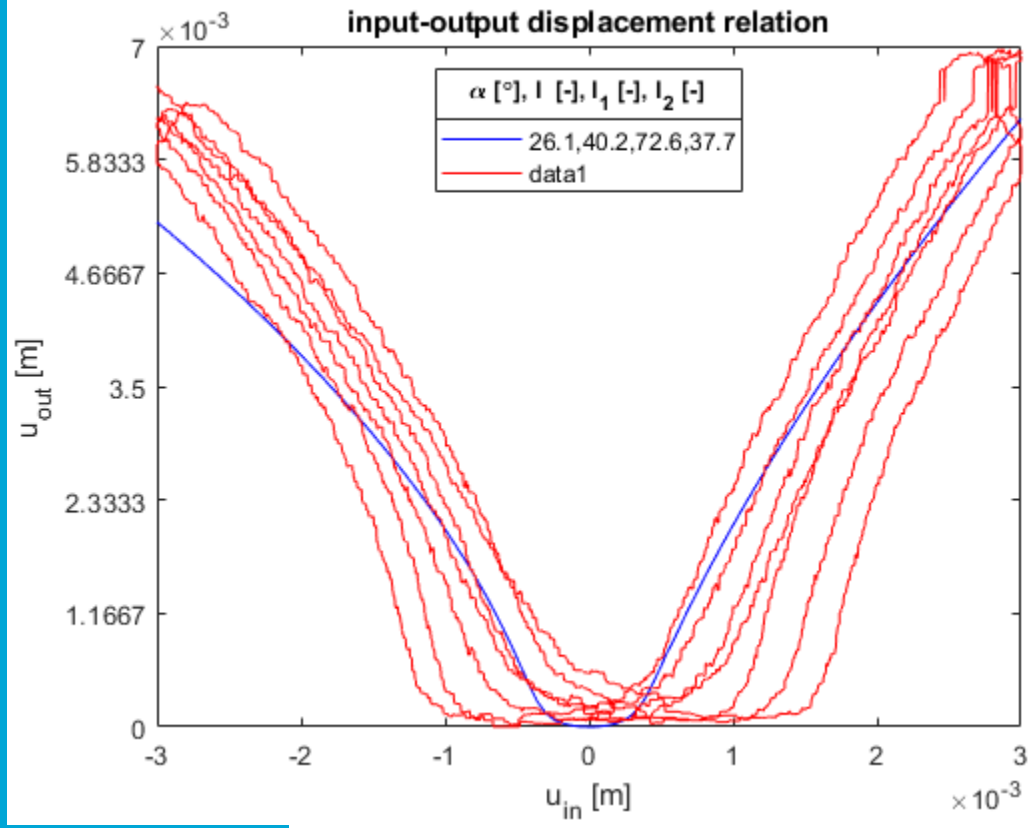


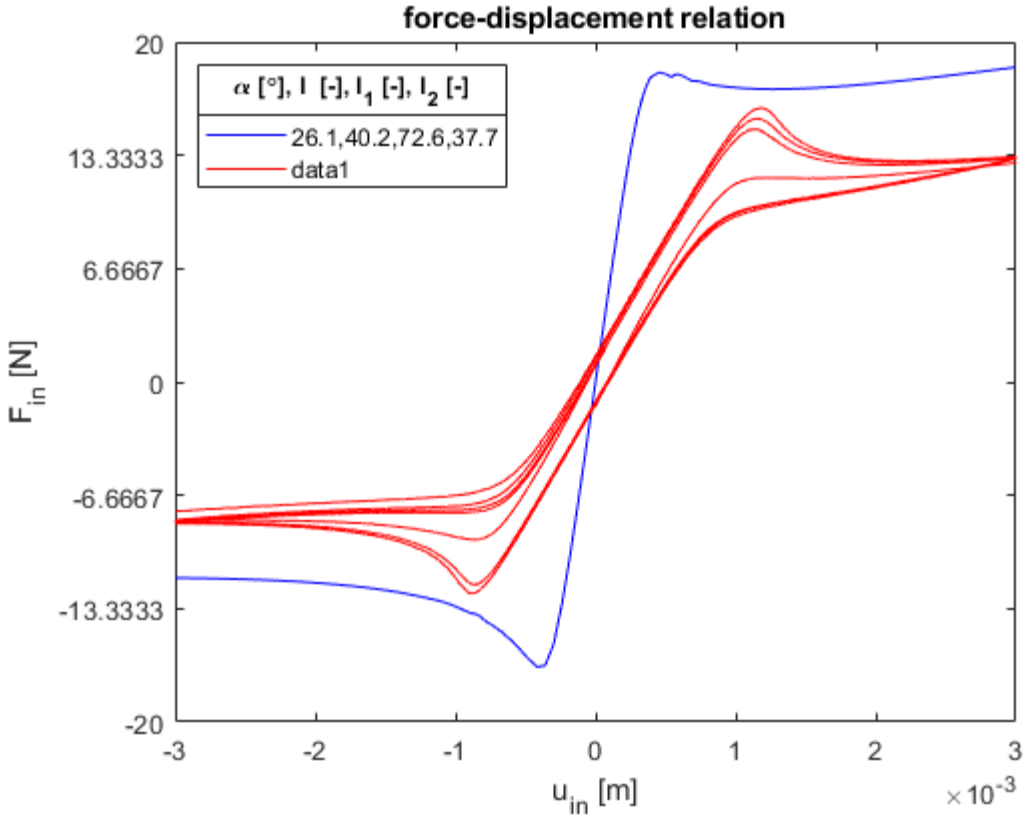


Testing


input-output displacement relation
α [°], l [-], l1 [-], l2 [-]
26.1,40.2,72.6,37.7
26.1,40.2,72.6,37.7
data1
×10^-3
7
5.6667
4.3333
3
1.6667
0.3333
-1
u_out [m]
-3
-2
-1
0
1
2
3
u_in [m]
×10^-3


force-displacement relation
α [°], l [-], l1 [-], l2 [-]
26.1,40.2,72.6,37.7
26.1,40.2,72.6,37.7
data1
20
13.3333
6.6667
0
-6.6667
-13.3333
-20
F_in [N]
-3
-2
-1
0
1
2
3
u_in [m]
×10^-3


input-output displacement relation
×10^-3
7
5.8333
4.6667
3.5
2.3333
1.1667
0
u_out [m]
α [°], l [-], l1 [-], l2 [-]
26.1,40.2,72.6,37.7
data1
-3
-2
-1
0
1
2
3
u_in [m]
×10^-3


force-displacement relation
20
13.3333
6.6667
0
-6.6667
-13.3333
-20
F_in [N]
α [°], l [-], l1 [-], l2 [-]
26.1,40.2,72.6,37.7
data1
-3
-2
-1
0
1
2
3
u_in [m]
×10^-3