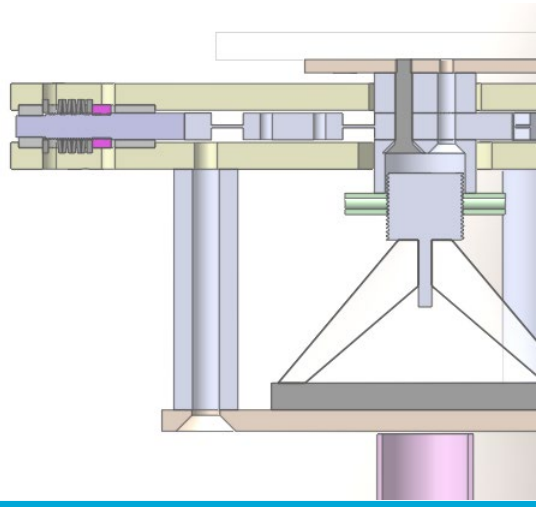
Attenuating Vibrations with Negative Stiffness

Improving Active Vibration Isolation by Reducing Suspension Stiffness with a Negative Stiffness Mechanism

Jan Los



3ME Lecture Room C

Final Thesis Presentation

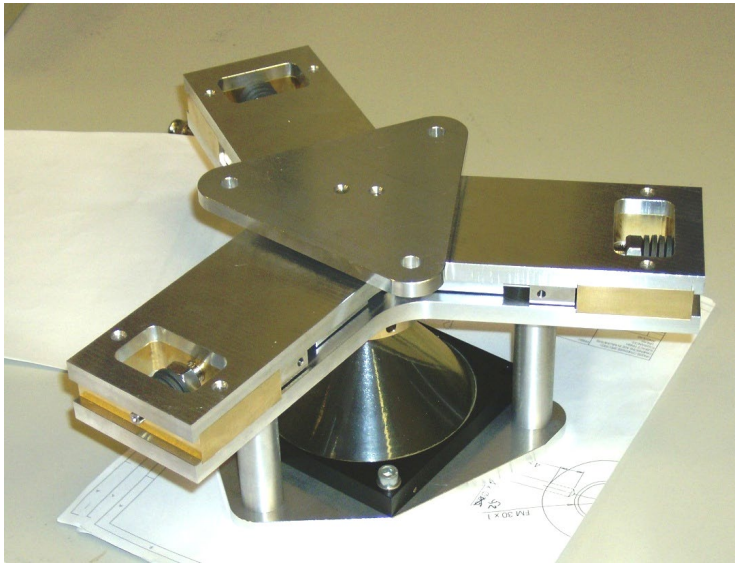
Exam Comitee:

Prof.ir. R.H. Munnig Schmidt
Ir. J.W. Spronck
Ir. N. Rijnveld
Dr.ir. J.L. Herder

November 14, 2023

Improving Active Vibration Isolation by Reducing Suspension Stiffness with a Negative Stiffness Mechanism

disturbing vibrations



suspension for vibration isolation

Presentation Contents

PART 1 Introduction to Vibration Isolation

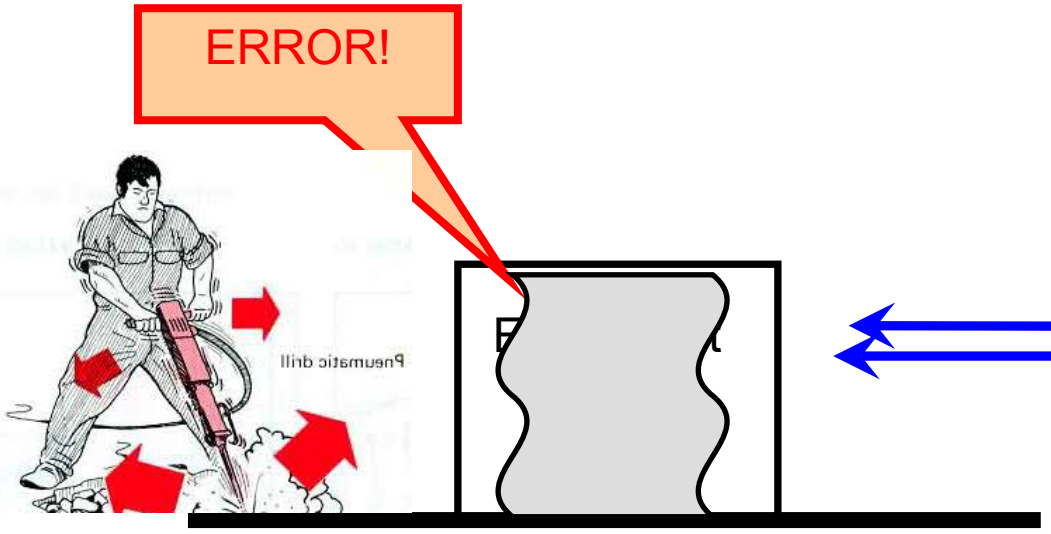
PART 2 The Kolibri System Vibration Isolation System

PART 3 Design of the Negative Stiffness Mechanism

PART 4 Results

PART 5 Conclusions and Recommendations

Vibrations and Vibration Isolation



Equipment and Instruments can not vibrate

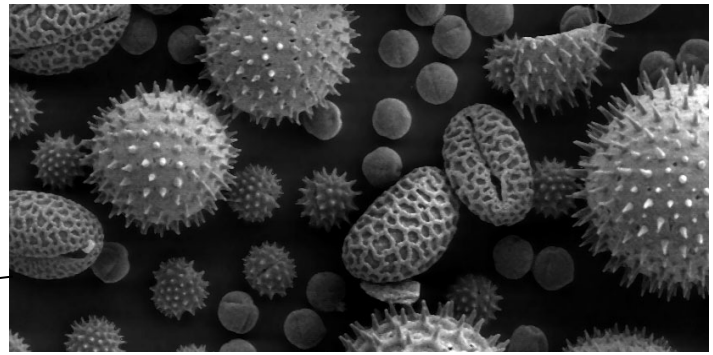
Suspension for vibration isolation

The ground is vibrating

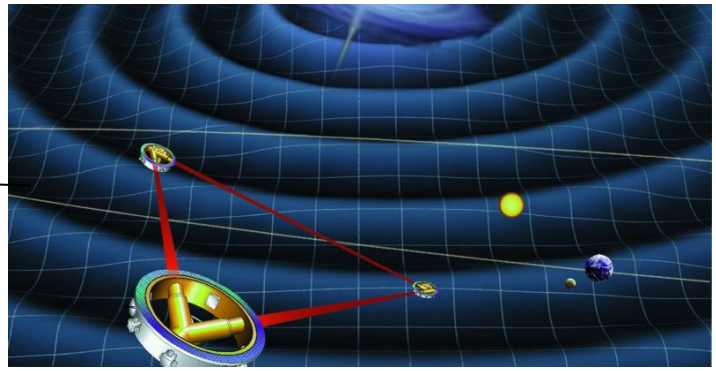
Sensitive Equipment and Instruments

which need a high level of vibration isolation

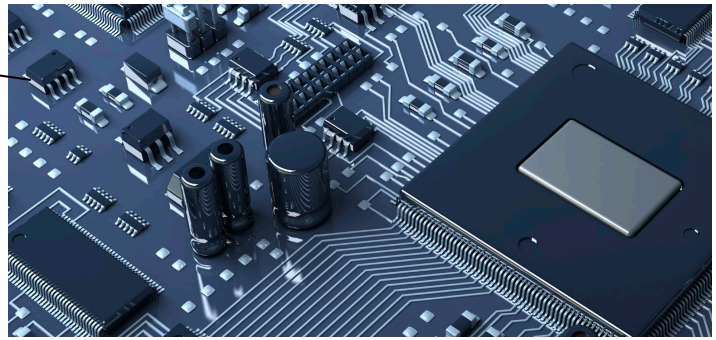
- Microscopy



- Interferometry



- Lithography



PART 1 Introduction to Vibration Isolation

PART 2 The Kolibri System Vibration Isolation System

PART 3 Design of the Negative Stiffness Mechanism

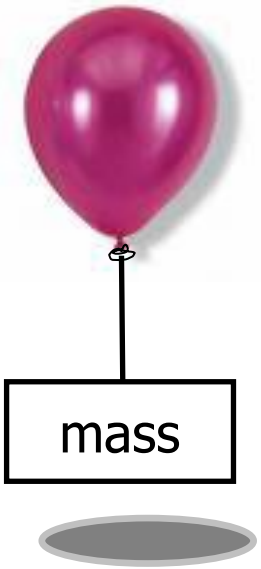
PART 4 Test Results

PART 5 Conclusions and Recommendations

The Kolibri Project at TNO Science and Industry

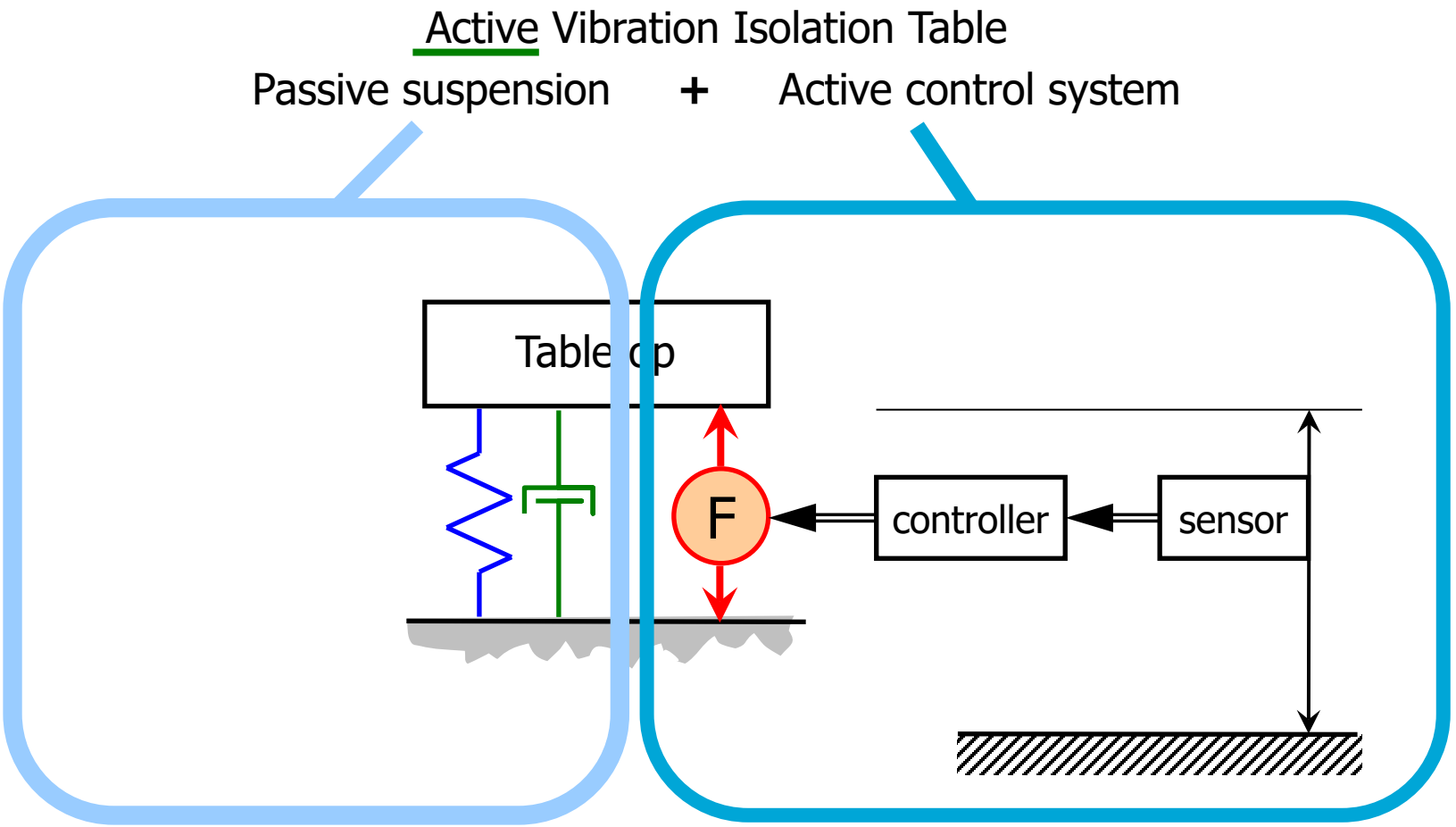
Vibration Isolation System

The Kolibri bird

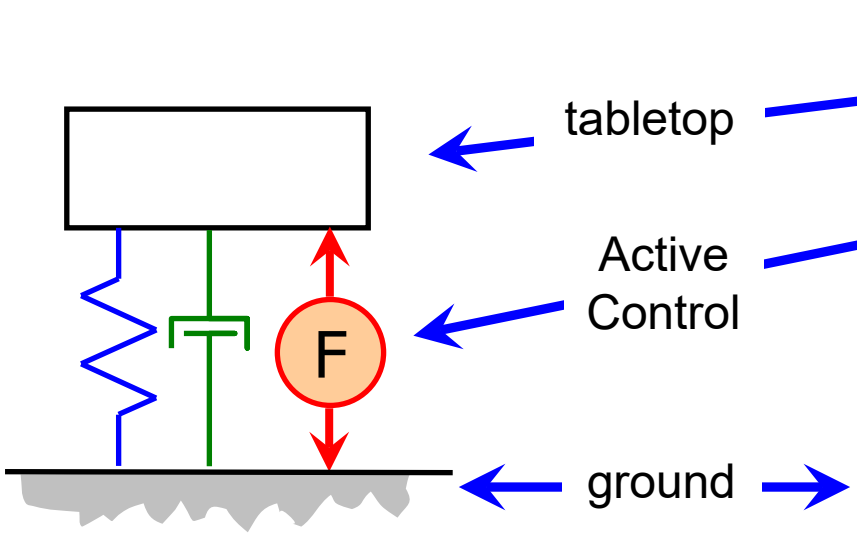


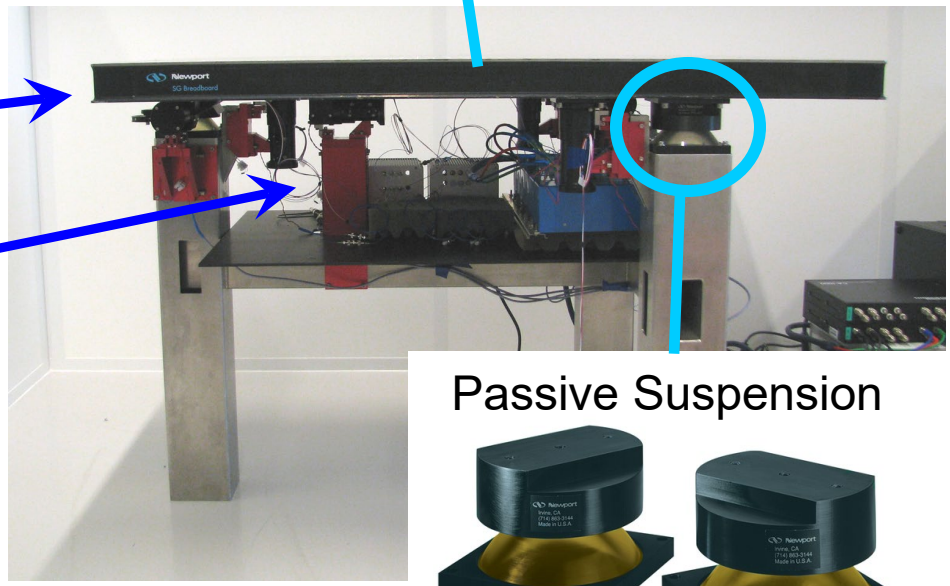
The Kolibri Table

The Kolibri Table at TNO (2)



The Kolibri Table at TNO (3)



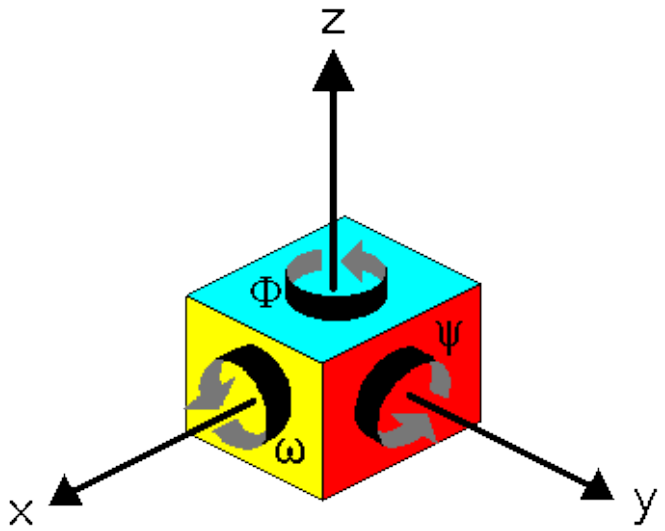


Passive Suspension

The Kolibri Table at TNO (4)

Vibration Isolation in 6 Degrees Of Freedom (DOFs):

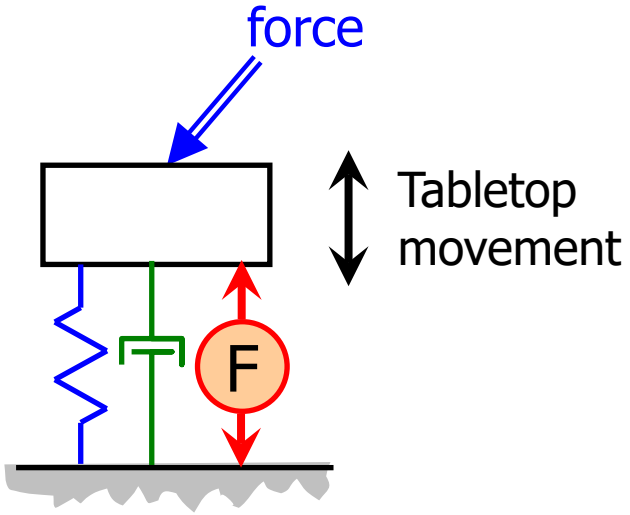
3 translations
3 rotations



Isolation Performance Indicators

- **Compliance**

Sensitivity to direct disturbance forces

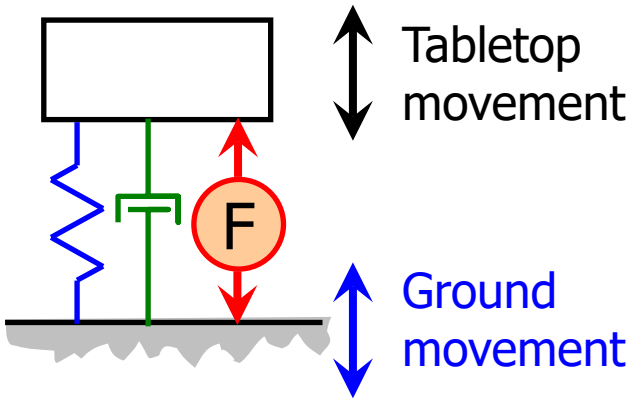


- **Transmissibility**

Sensitivity to ground vibrations

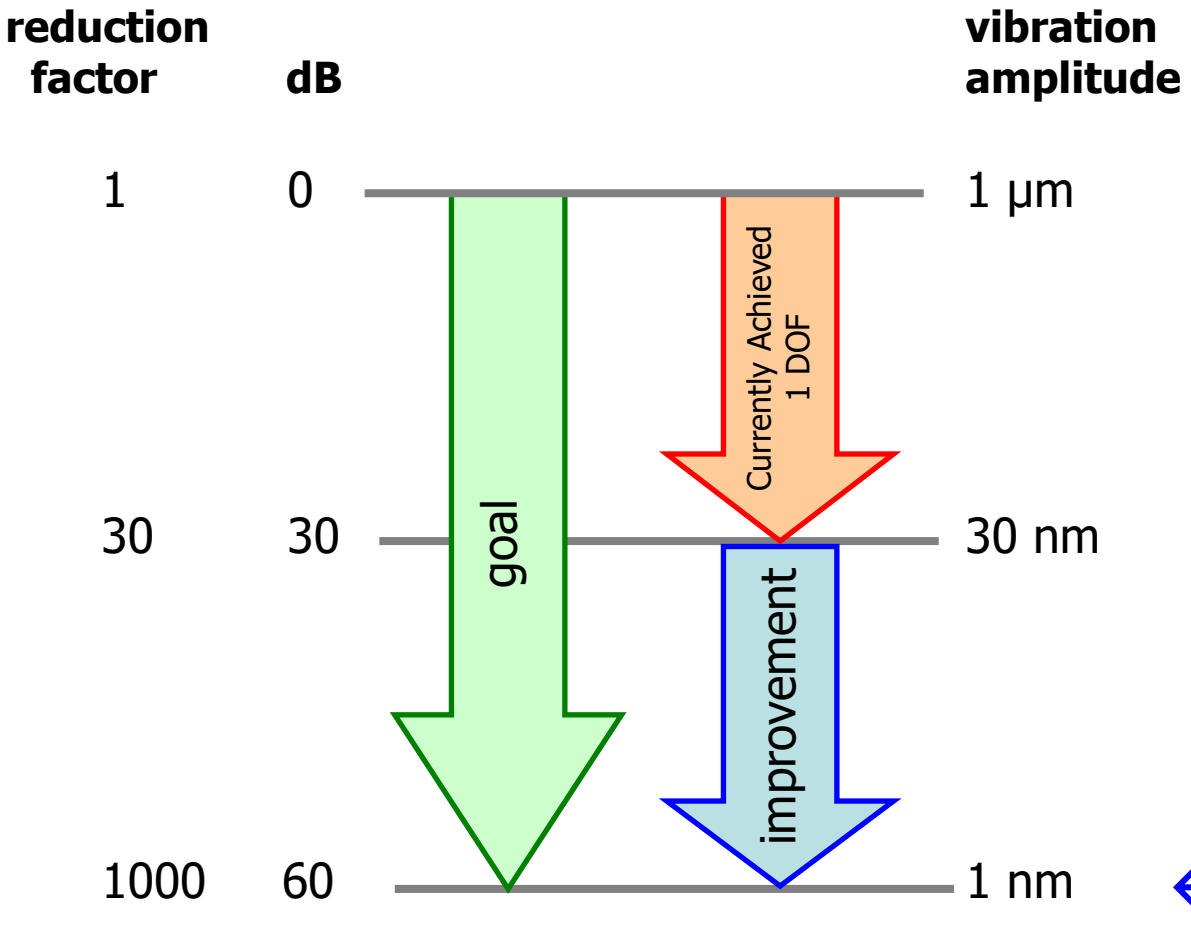
Kolibri Table goal:

Reduction of ground vibrations
at 1 Hz
with a factor 1000



The Research Problem

Kolibri Isolation Performance (at 1 Hz)



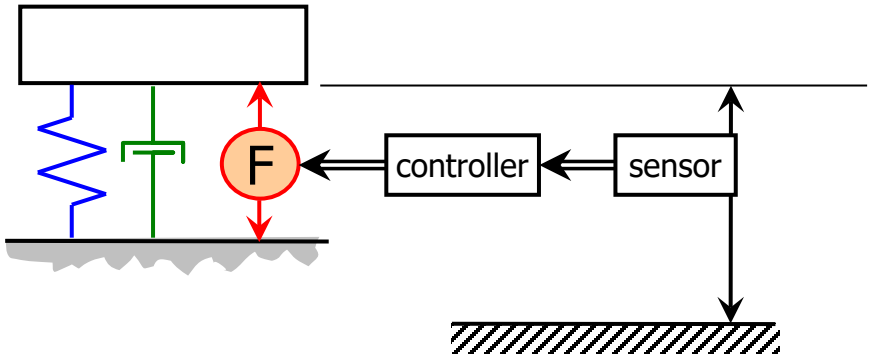
My Research Goal

- Find most limiting factor for the isolation performance.

  System Analysis

- Develop a solution for this limitation.

  Design



Total System Analysis - Results

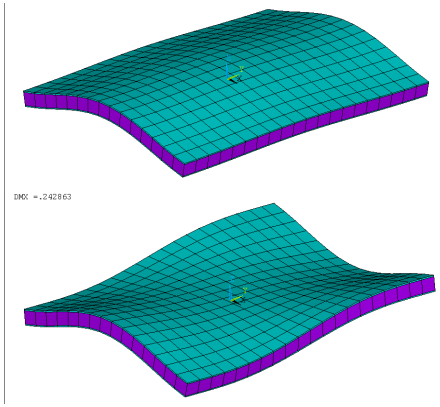
3 main groups of limitations:

- Internal Resonances
- Cross Coupling between the 6 degrees of freedom
- Passive Suspension

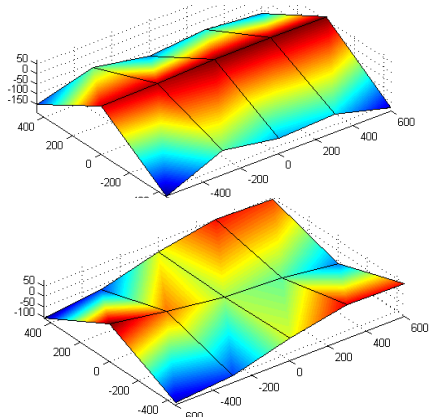
Limitation 1

Internal Resonance modes

fifth resonance mode – 520 Hz
(vibrations are exaggerated)



Model



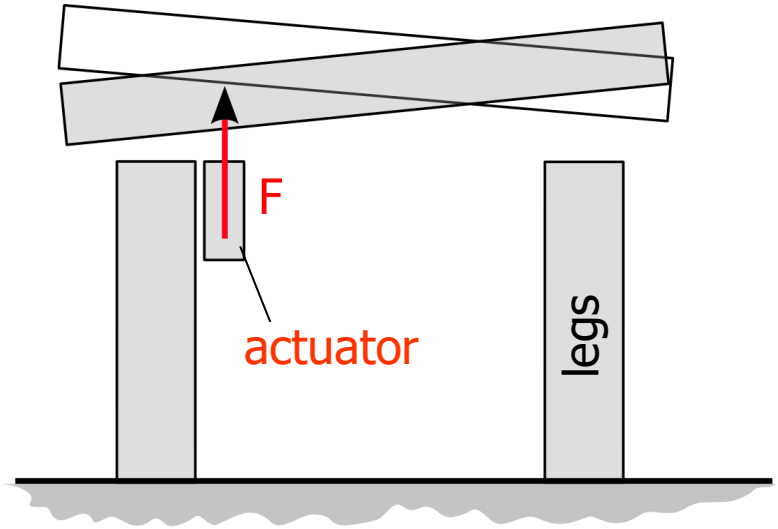
Measurements

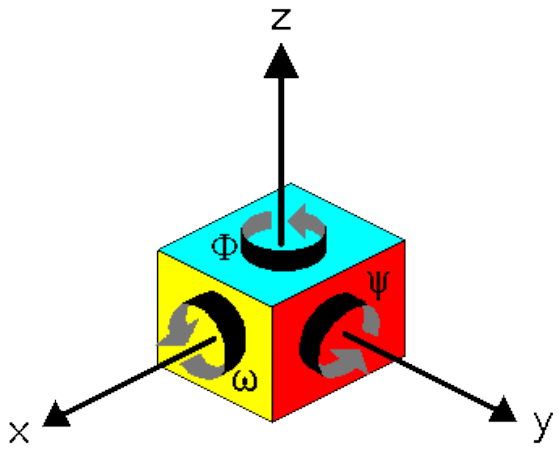
Conclusion:

Tabletop stiffness is too low and therefore limits control performance

Limitation 2

Cross-coupling behavior between the 6 DOFs



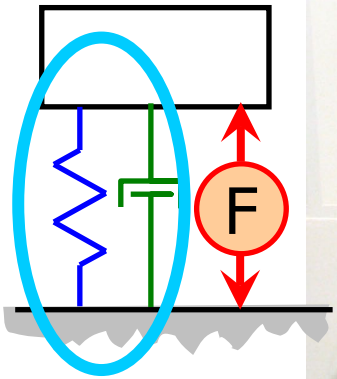


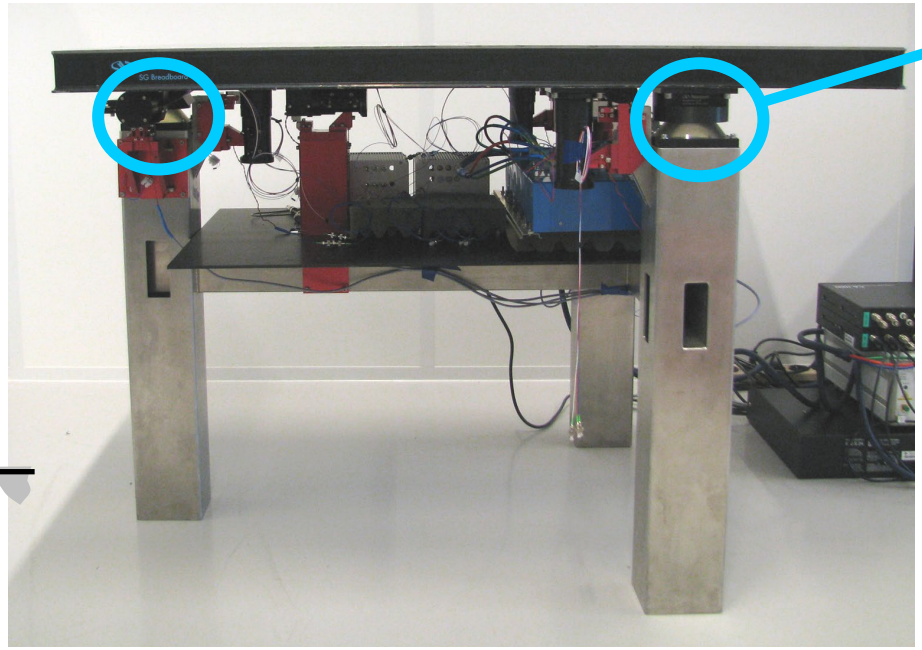
Conclusion:

Isolation Performance
6 DOF < 1 DOF

Limitation 3

The Passive Suspension



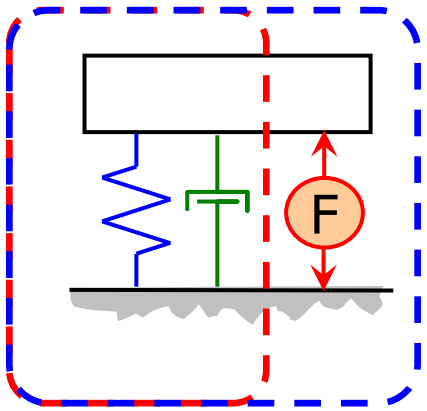


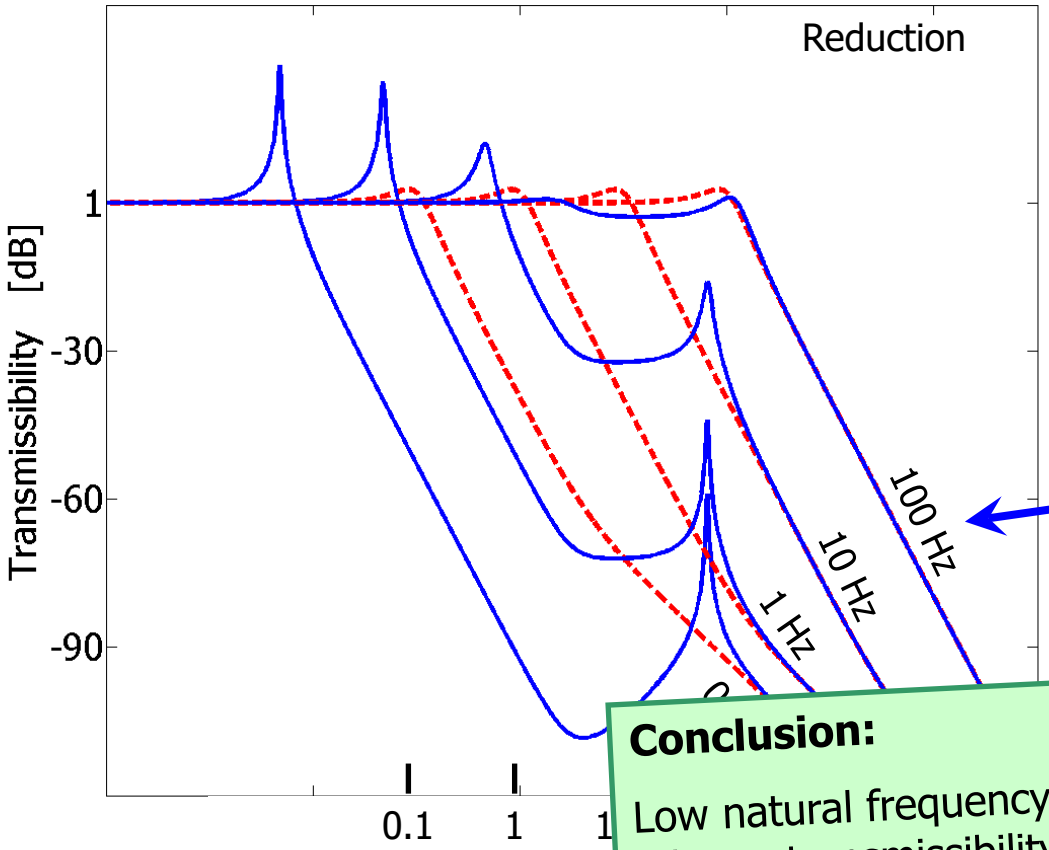
Natural frequency

- tabletop mass
- suspension stiffness

Limitation 3: The Passive Suspension

The effect of natural frequency





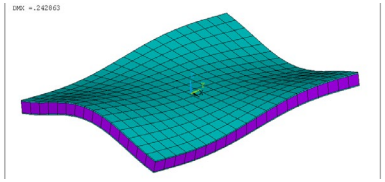
Conclusion:

Low natural frequency results in a lower transmissibility

→ Extra reduction with control

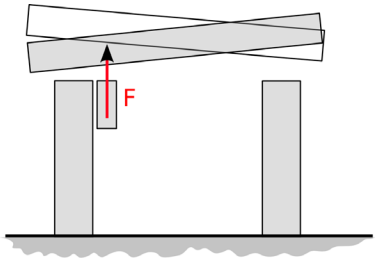
Limitations Analysis: Summary

1 ~~Internal resonances~~



- Use a stiffer breadboard
- Solutions are limited
- Limitation is not most challenging to solve
- Separate research project started

2 ~~Cross coupling behavior~~



- Typical controller design problem
- Separate research project started

3 Passive Suspension

- High performance improving potential
- Universal design solution

PART 1 Introduction to Vibration Isolation

PART 2 The Kolibri System Vibration Isolation System

PART 3 Design of the Negative Stiffness Mechanism

PART 4 Test Results

PART 5 Conclusions and Recommendations

Passive suspension design - Goal

Design a passive suspension with a

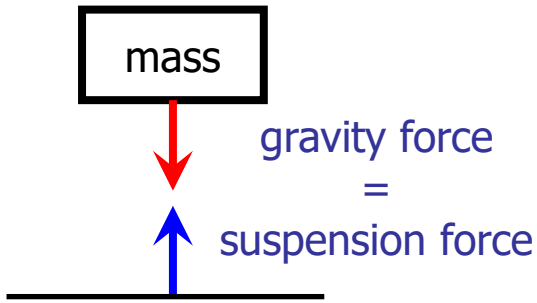
Low natural frequency of 0.5 Hz in vertical degree of freedom.

10 Hz → 0.5 Hz

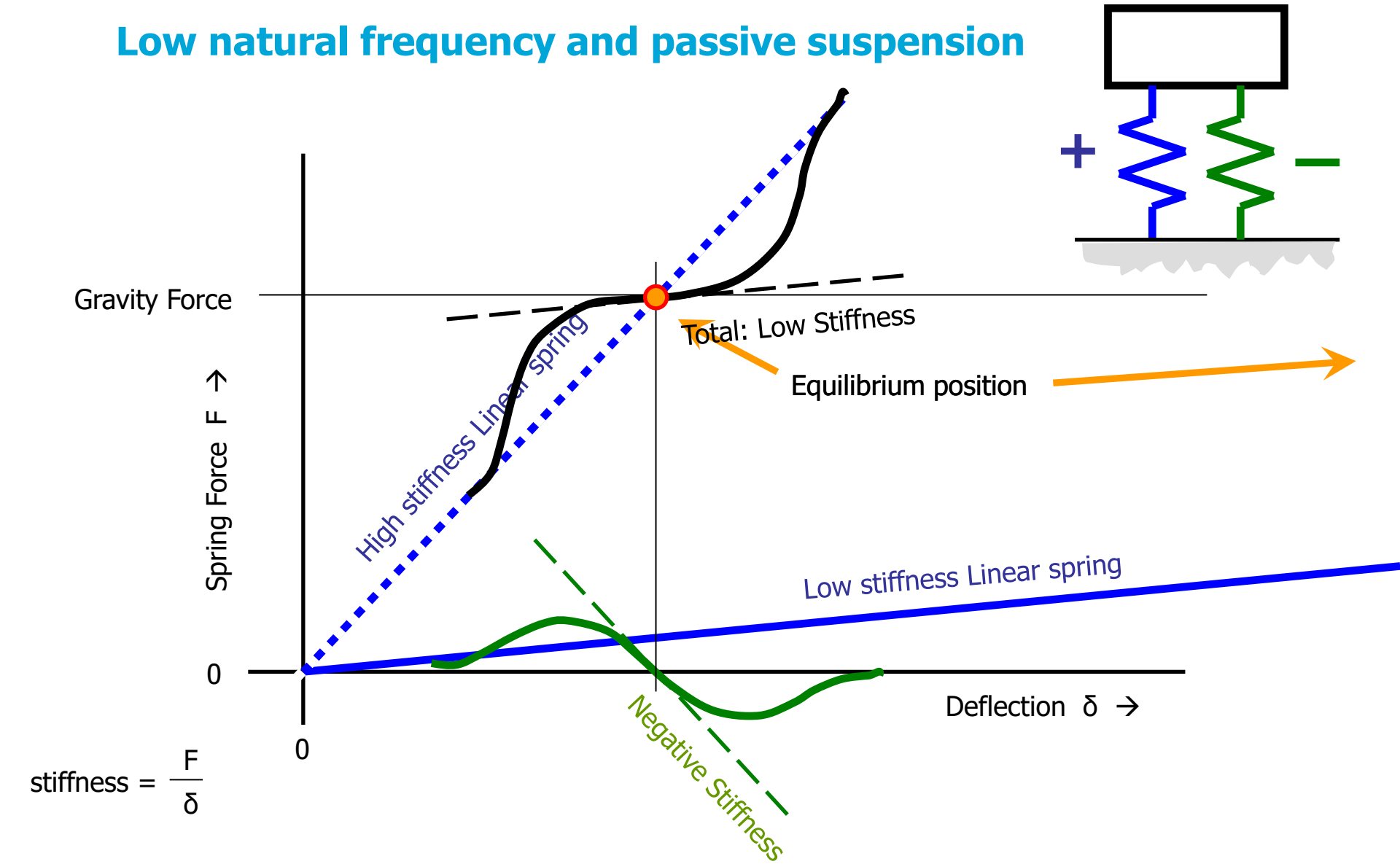
Needed for Kolibri specifications

Most challenging direction

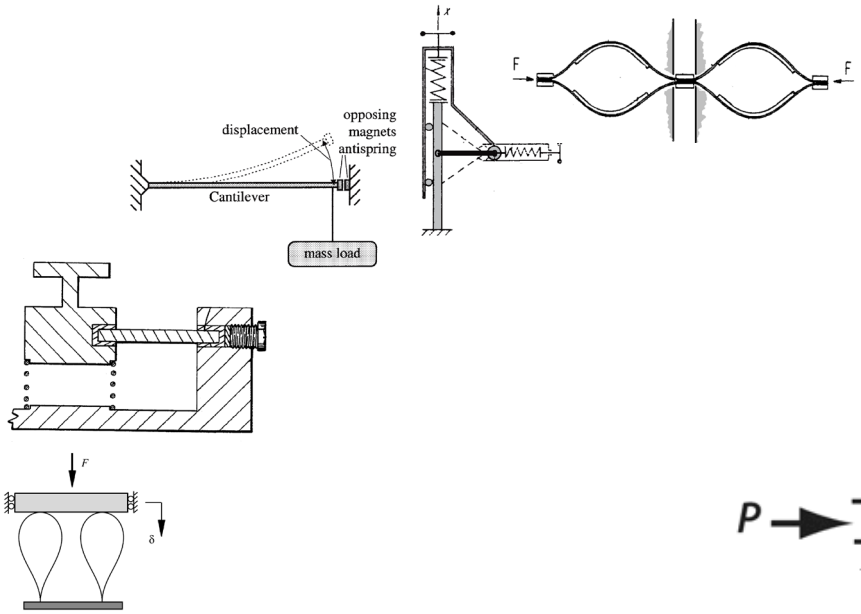
because: gravity compensation

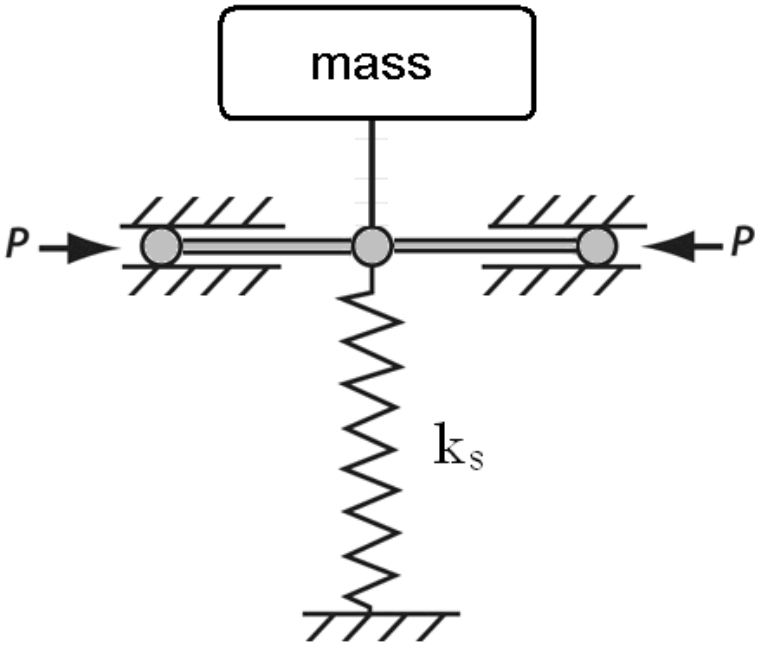


Low natural frequency and passive suspension

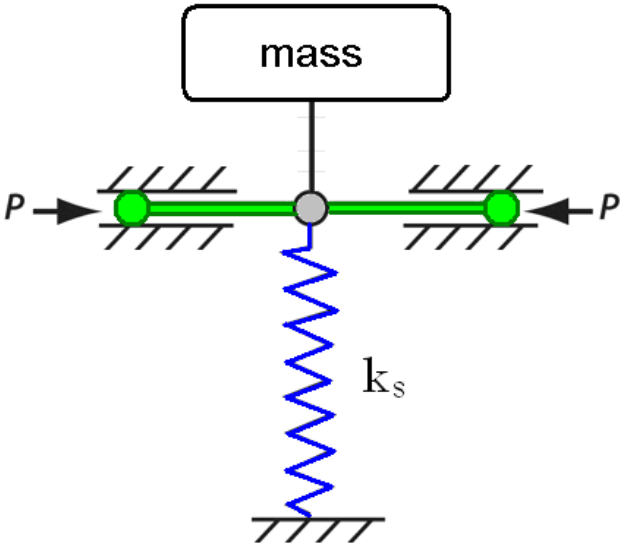


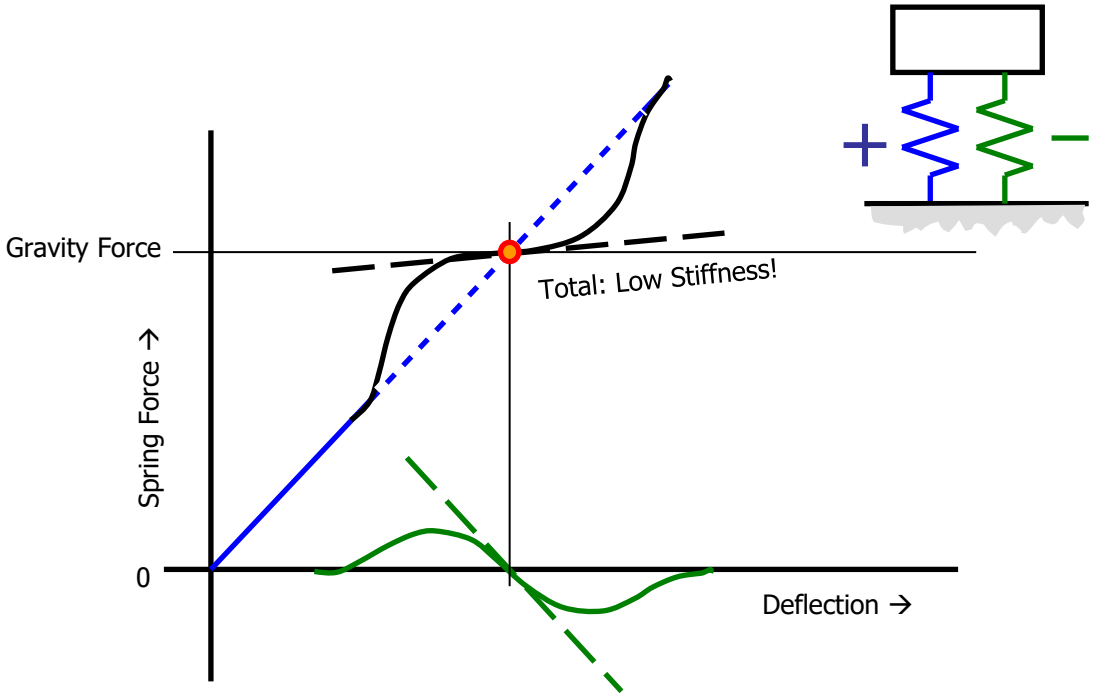
Negative Stiffness Mechanism – Working Principle (1)





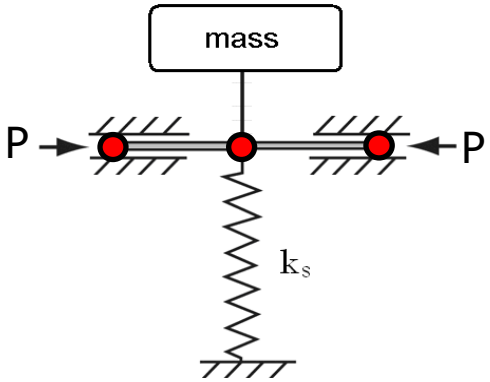
Negative Stiffness Mechanism – Working Principle (2)

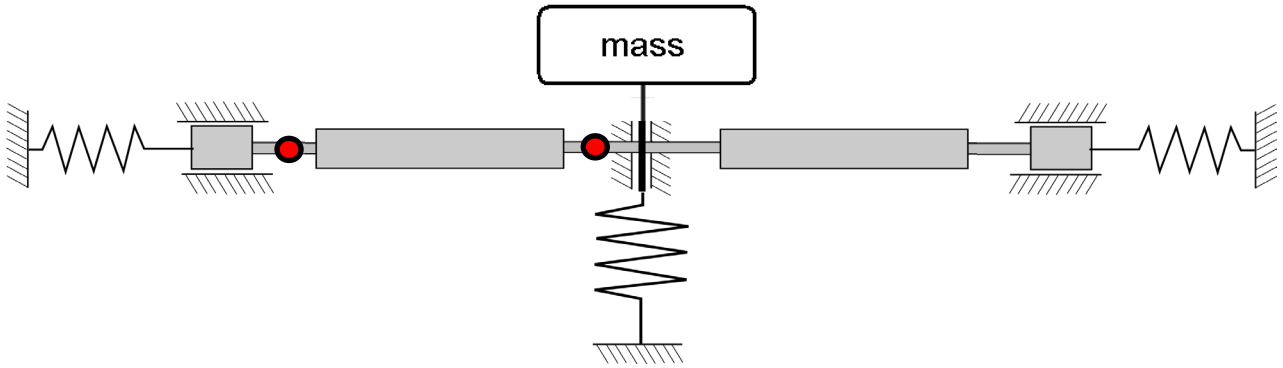


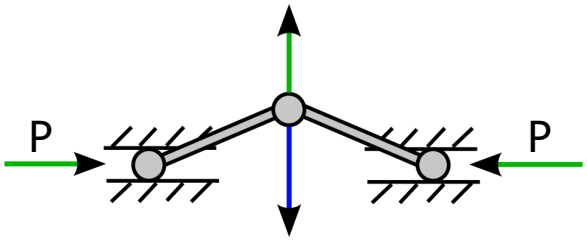


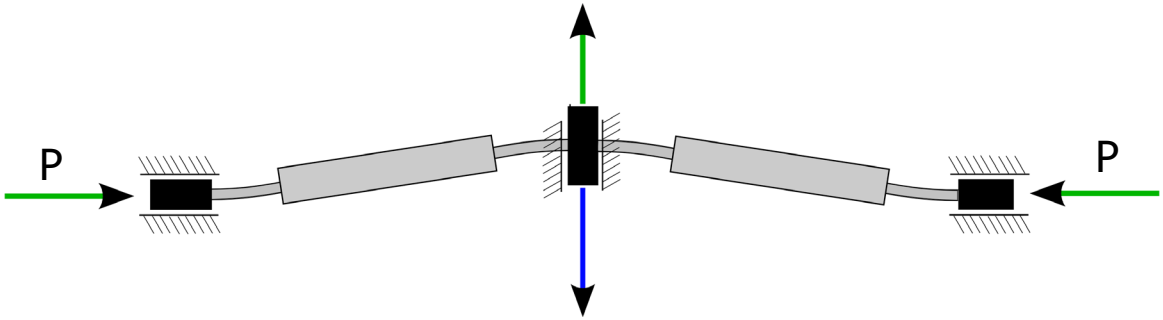
Radial pretensioning members

- flexural hinges



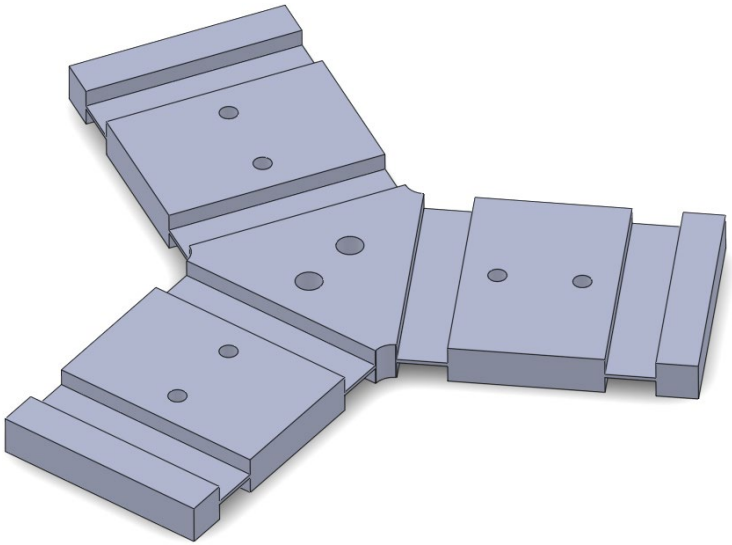


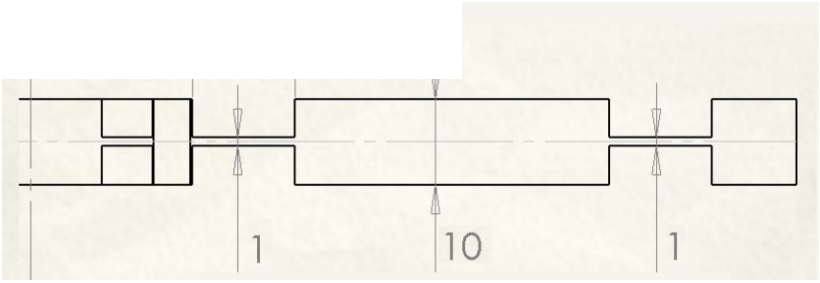


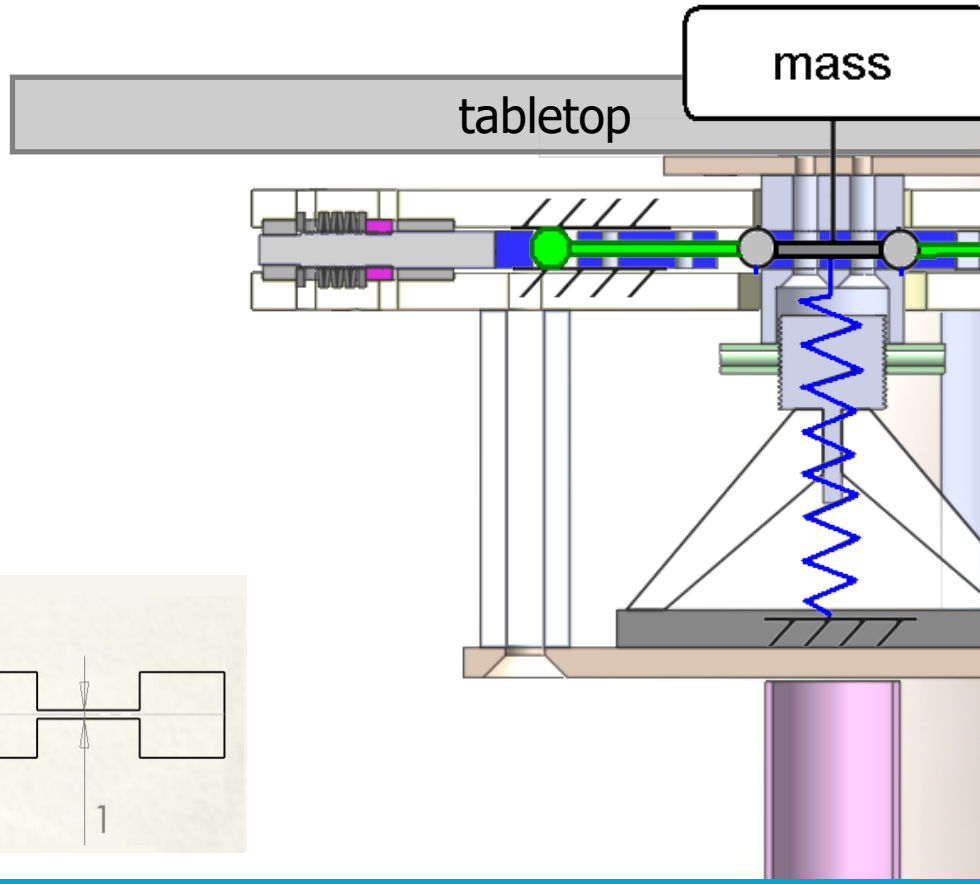


Final radial flexure design

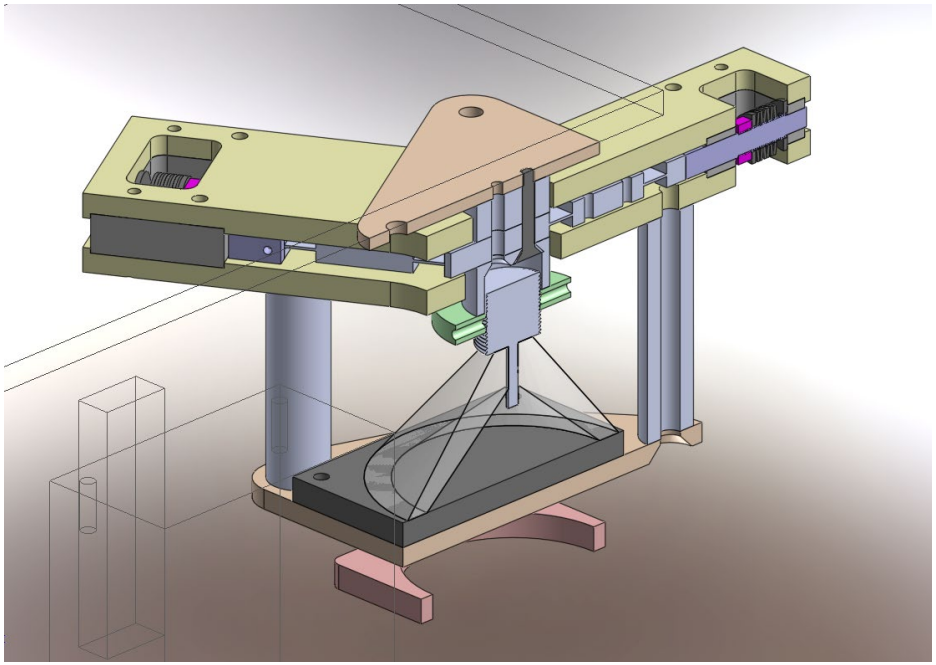
- 3 axi-symmetric members
- minimal vertical stiffness; maximal horizontal stiffness

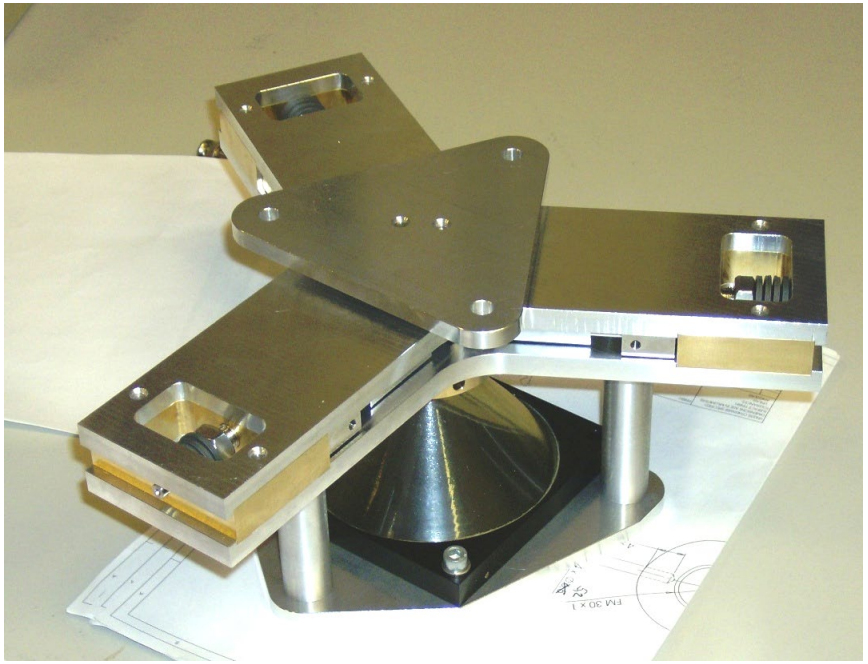


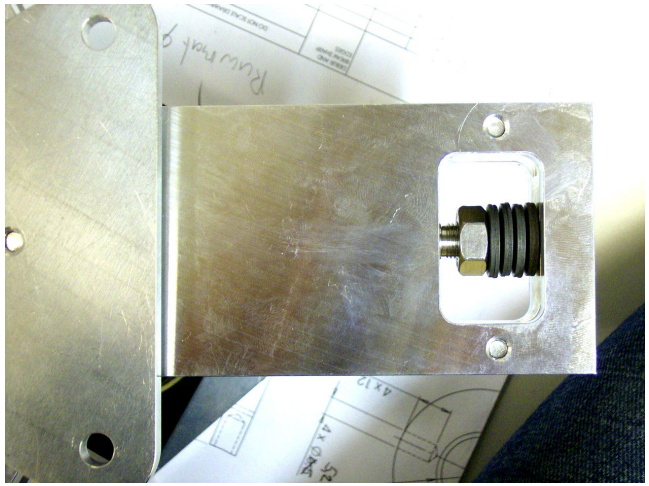




Completed Suspension

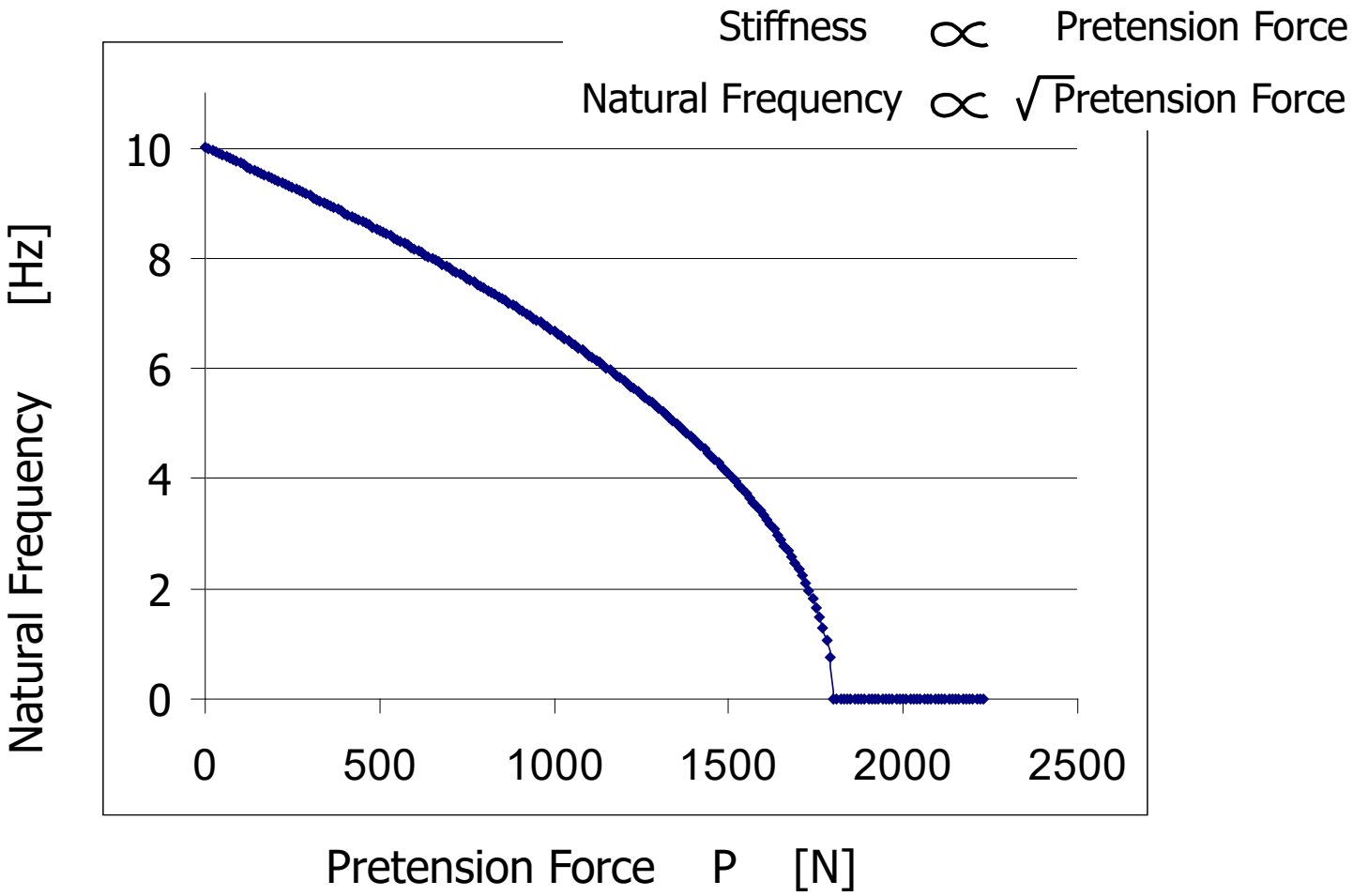






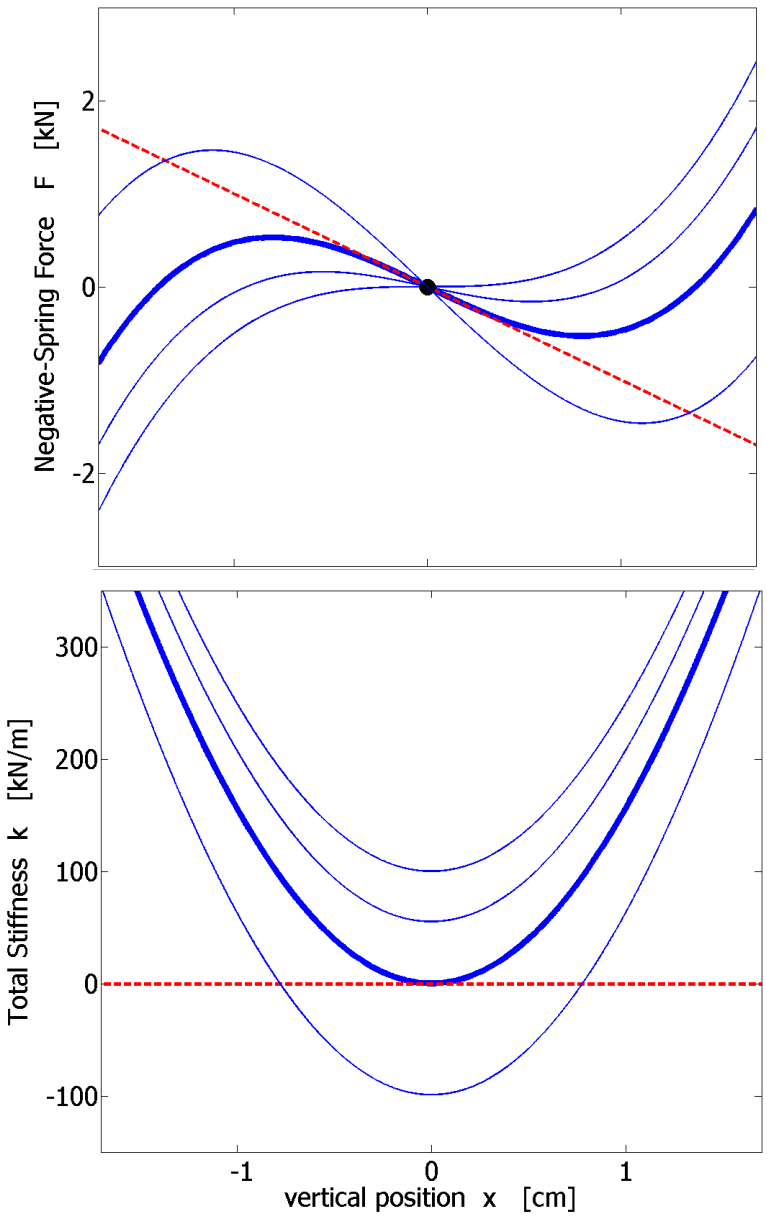
Expected behavior (1)

Vertical Natural Frequency reduction **in** equilibrium position



Expected behavior (2)

Stiffness **around** equilibrium position



Pretension Force P

0 N

500 N

1800 N ← Critical Pretension Force

3000 N

PART 1 Introduction to Vibration Isolation

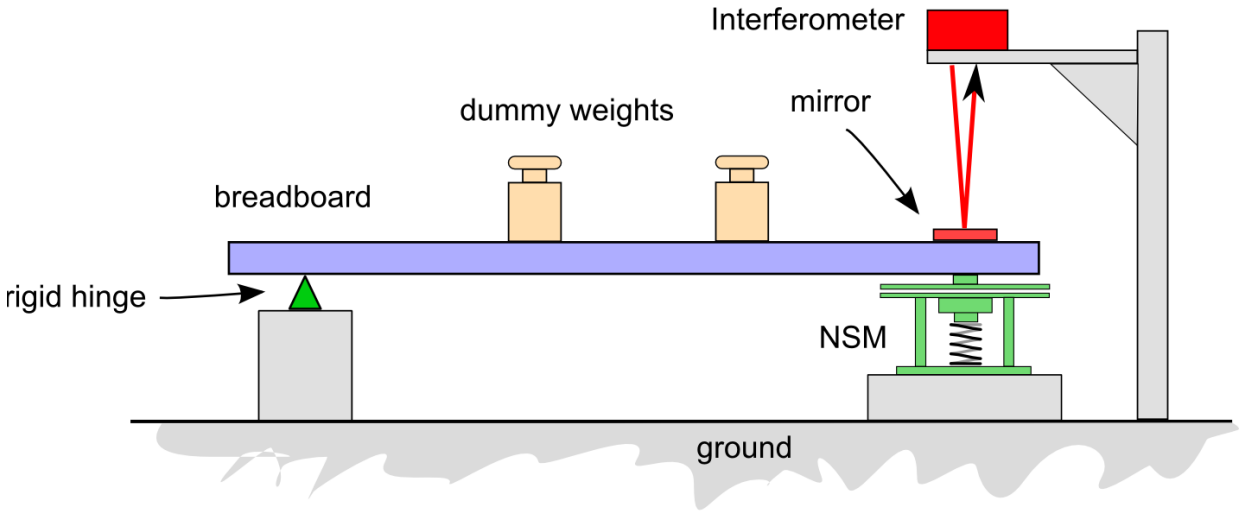
PART 2 The Kolibri System Vibration Isolation System

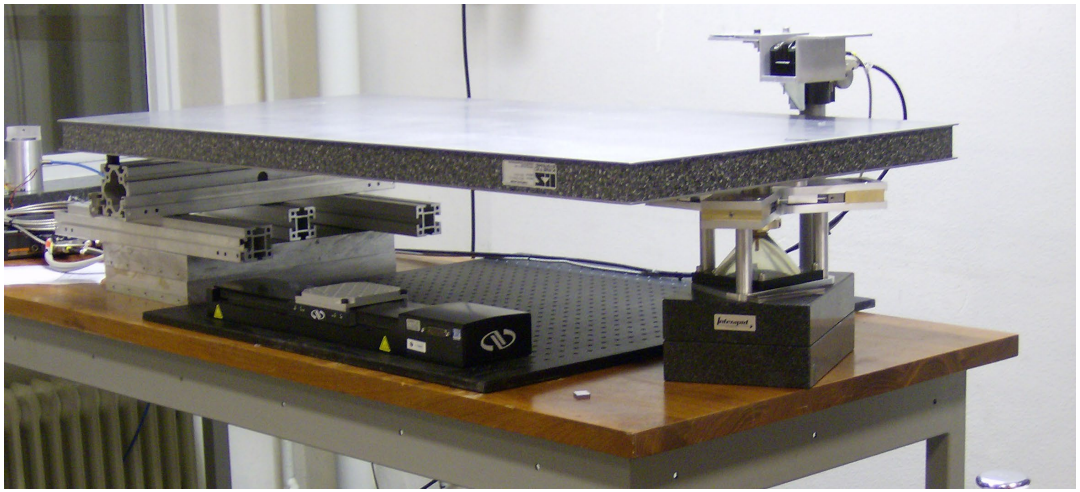
PART 3 Design of the Negative Stiffness Mechanism

PART 4 Test Results

PART 5 Conclusions and Recommendations

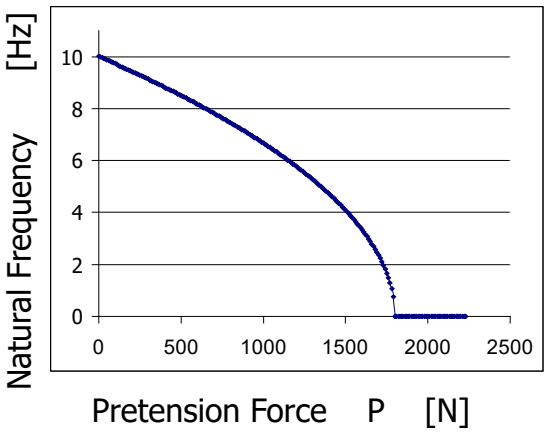
Testing the NSM – Test set-up

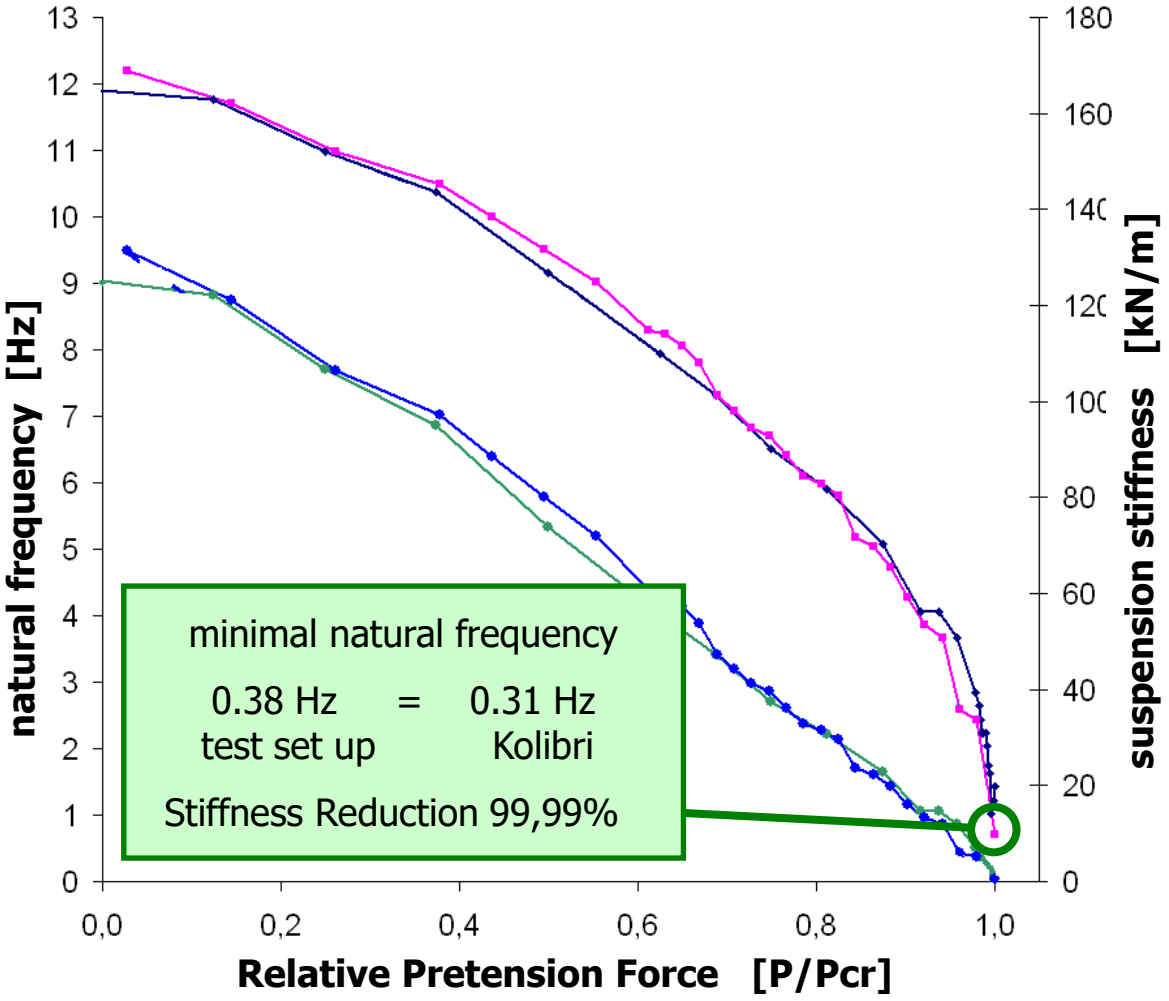




Testing the NSM – Pretensioning behavior

Natural frequency **in** equilibrium position





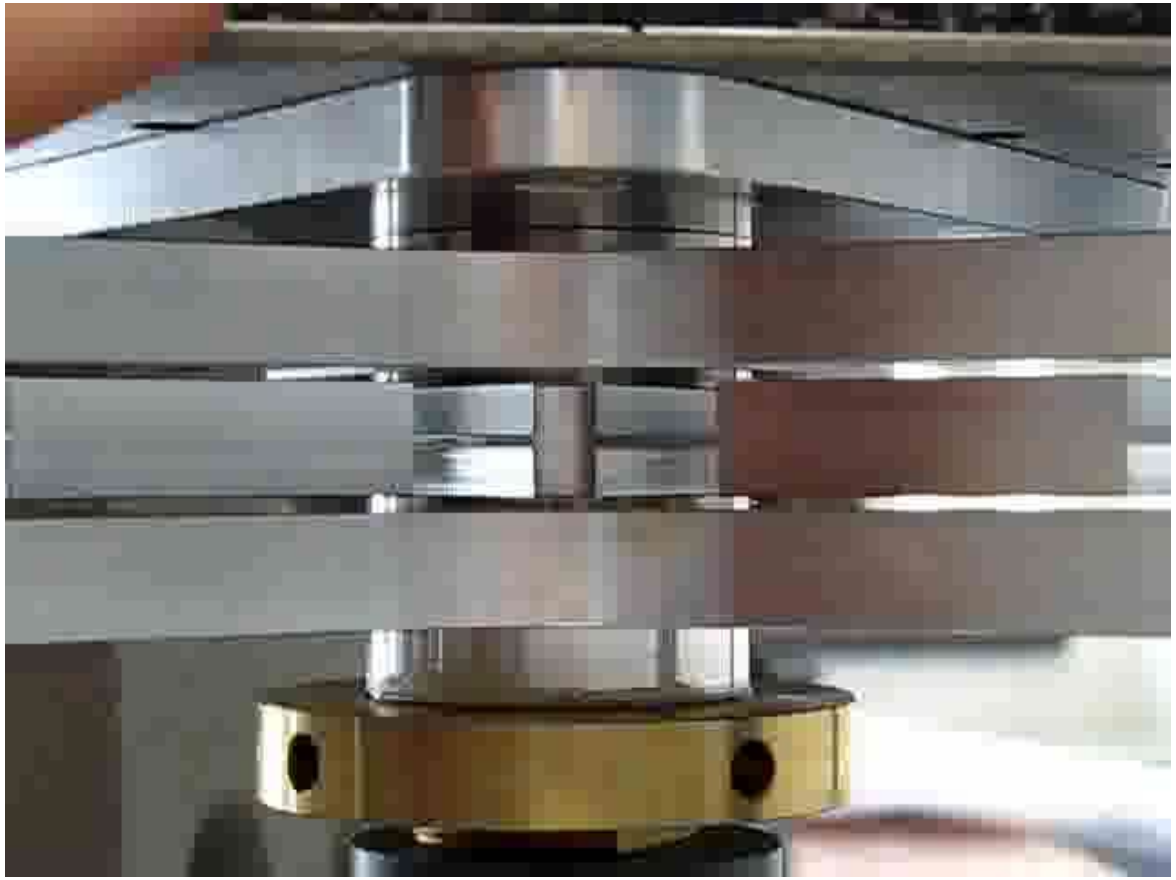
Demo of Tabletop Motion

Frequency approx. 1 Hz

Tabletop

Suspension

Ground



PART 1 Introduction to Vibration Isolation

PART 2 The Kolibri System Vibration Isolation System

PART 3 Design of the Negative Stiffness Mechanism

PART 4 Test Results

PART 5 Conclusions and Recommendations

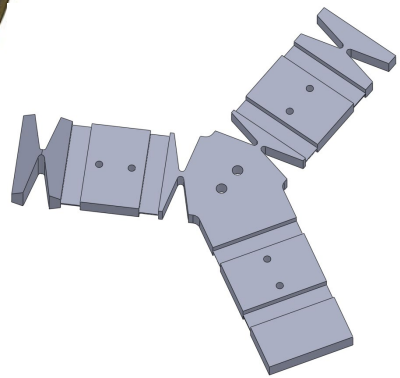
Conclusions

- Vertical natural frequency is within the design specifications → 0.31 Hz

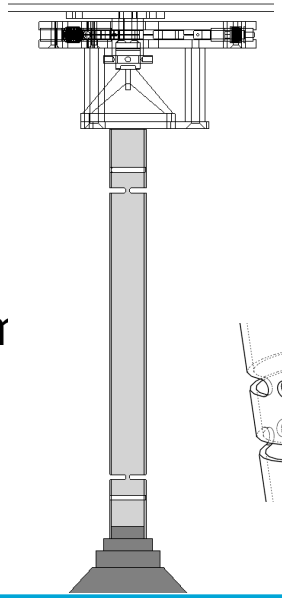
  If the passive suspension is the only limitation,
  this will result in a vibration isolation of 60 dB

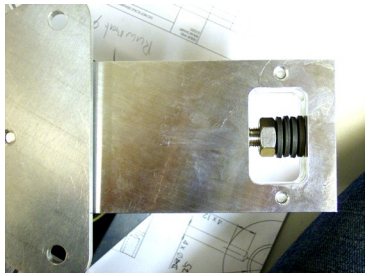
- Pretension Force Accuracy is not sufficient and should be improved

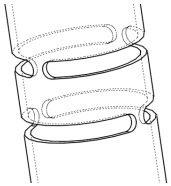
Recommendations



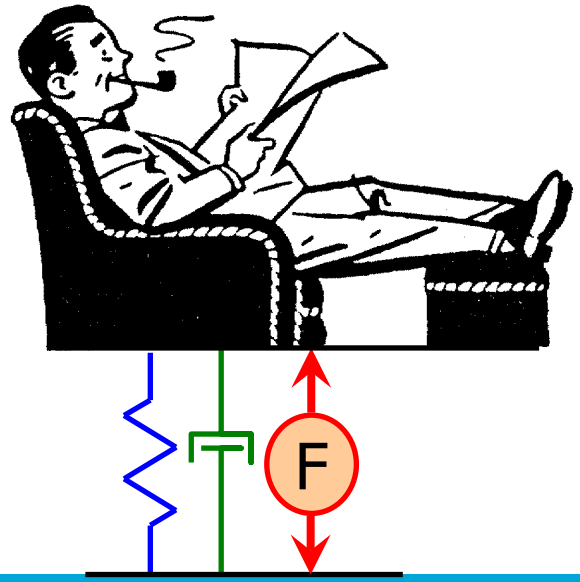
- Use other gravity compensating spring
- Improve flexure design
- Improve pretensioning force resolution
- Extend isolation for other degrees of freedom

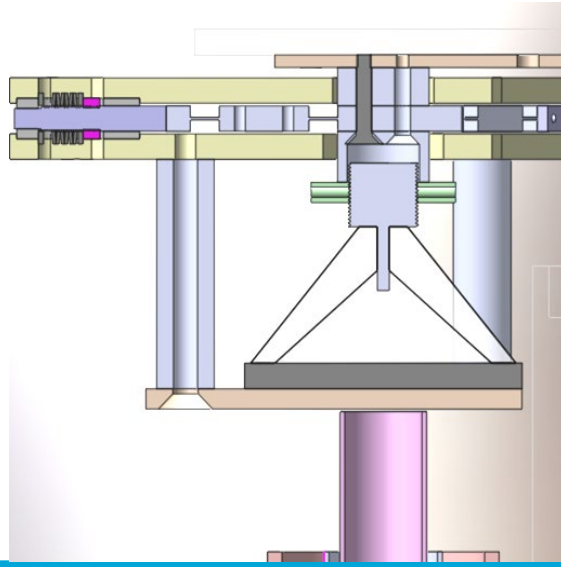






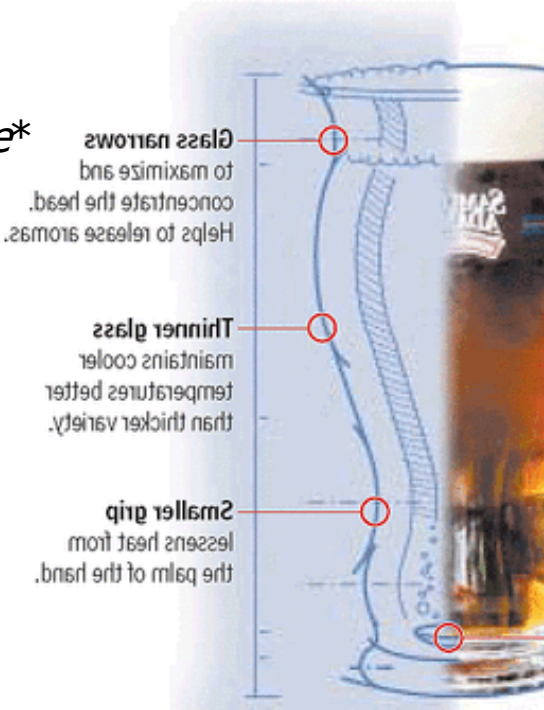
Attenuating Vibrations with Negative Stiffness





Life after the presentation….

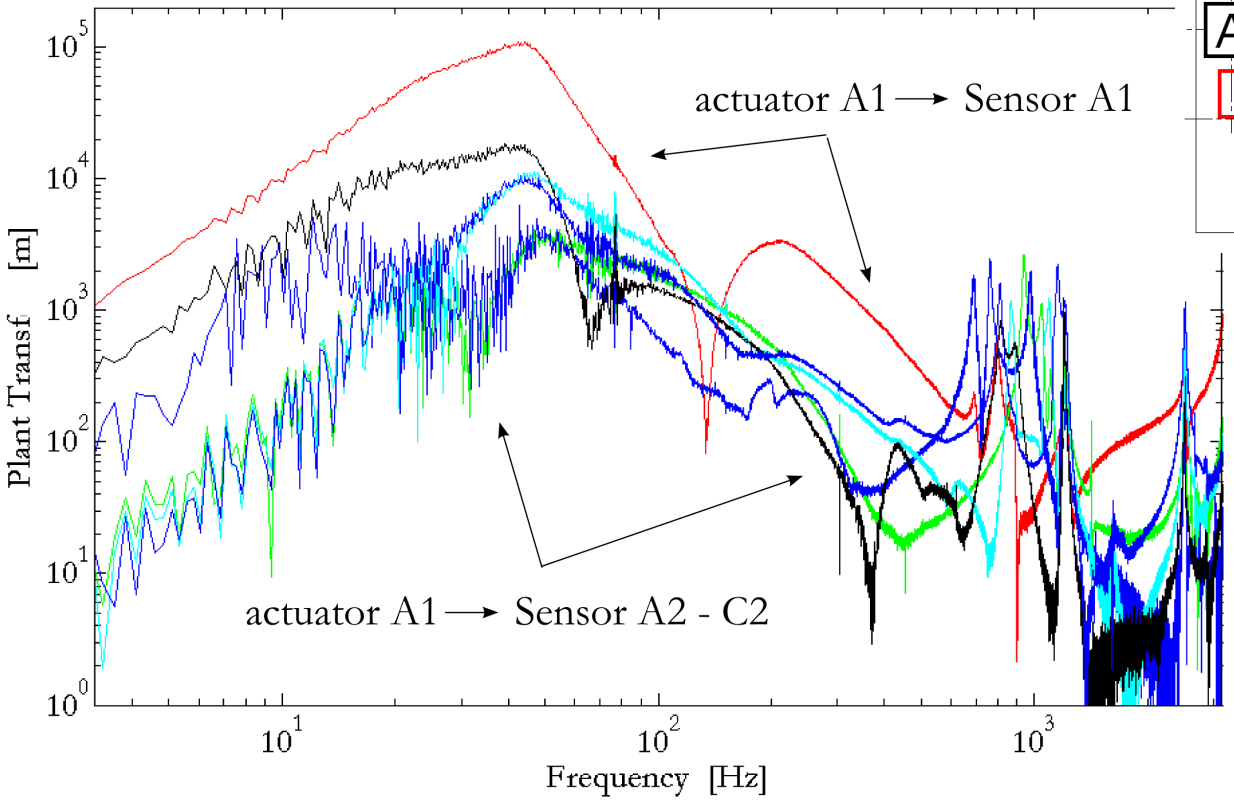
14:45 – 16:00	Coffee, thee and cake	Koffie, Thee en Koek
16:00 – 16:15	Announcement Grade	Examen Uitslag
20:00 – ?	Borrel in Confide*	Borrel in *Confide**

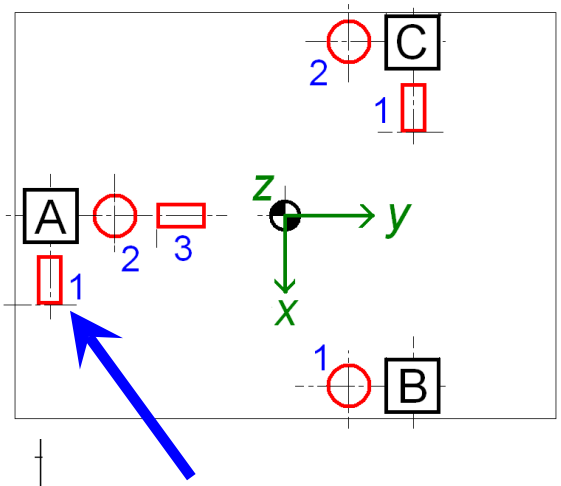


* Society Building of C.S.R., Oude Delft 9

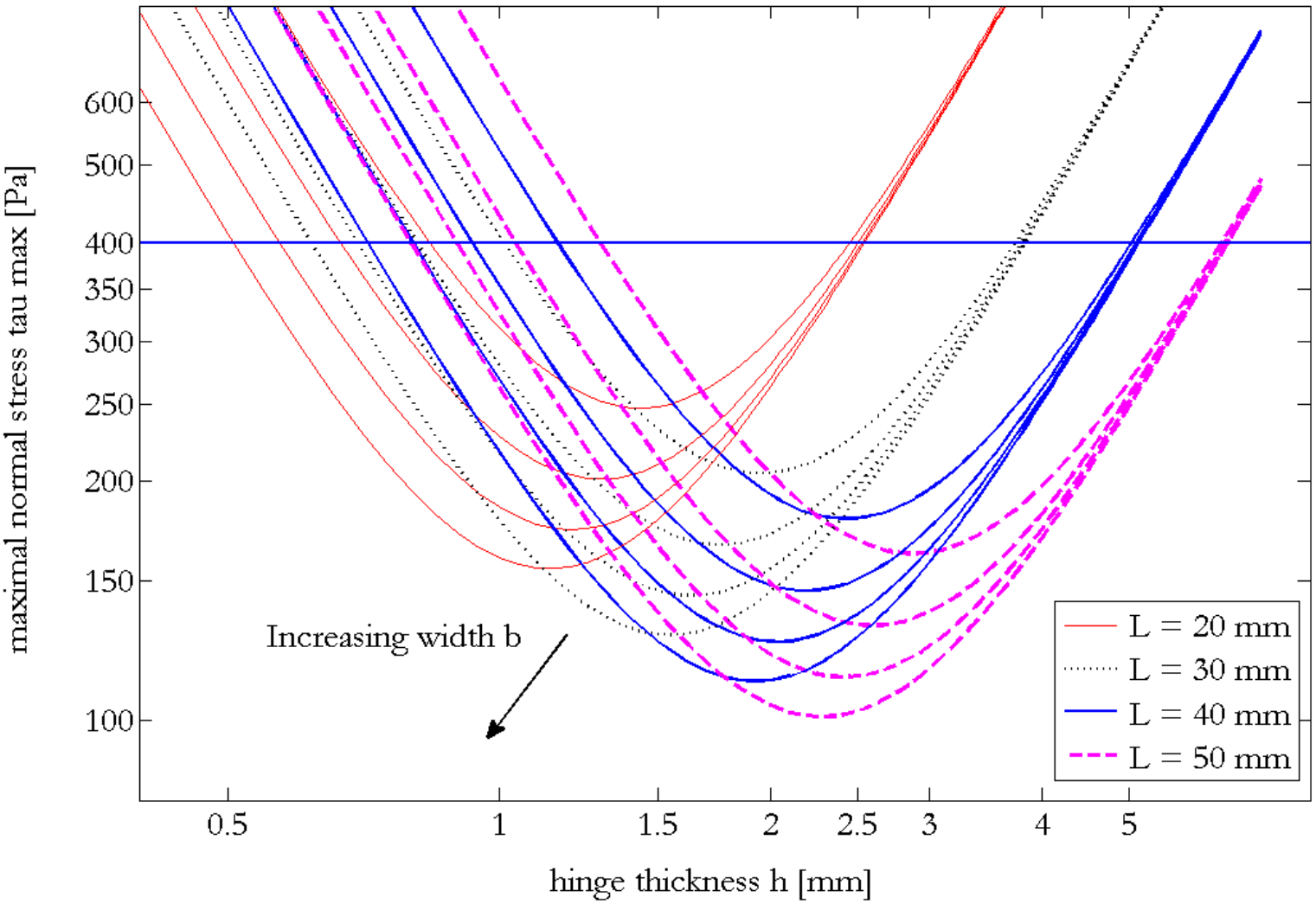
Breadboard Honeycomb

Limitation 2 - Cross coupling Behavior

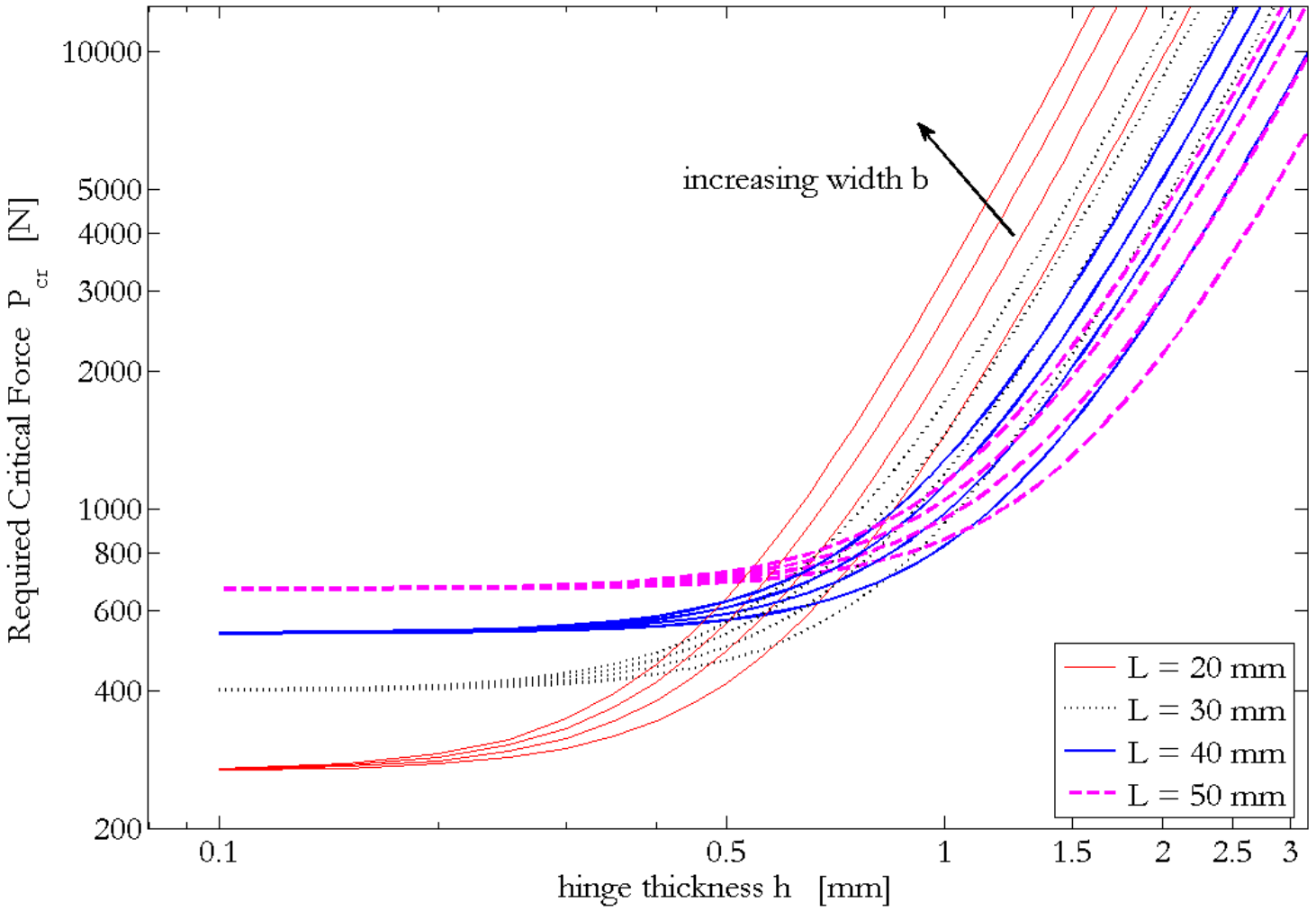




Parameter study for flexure hinges (1)

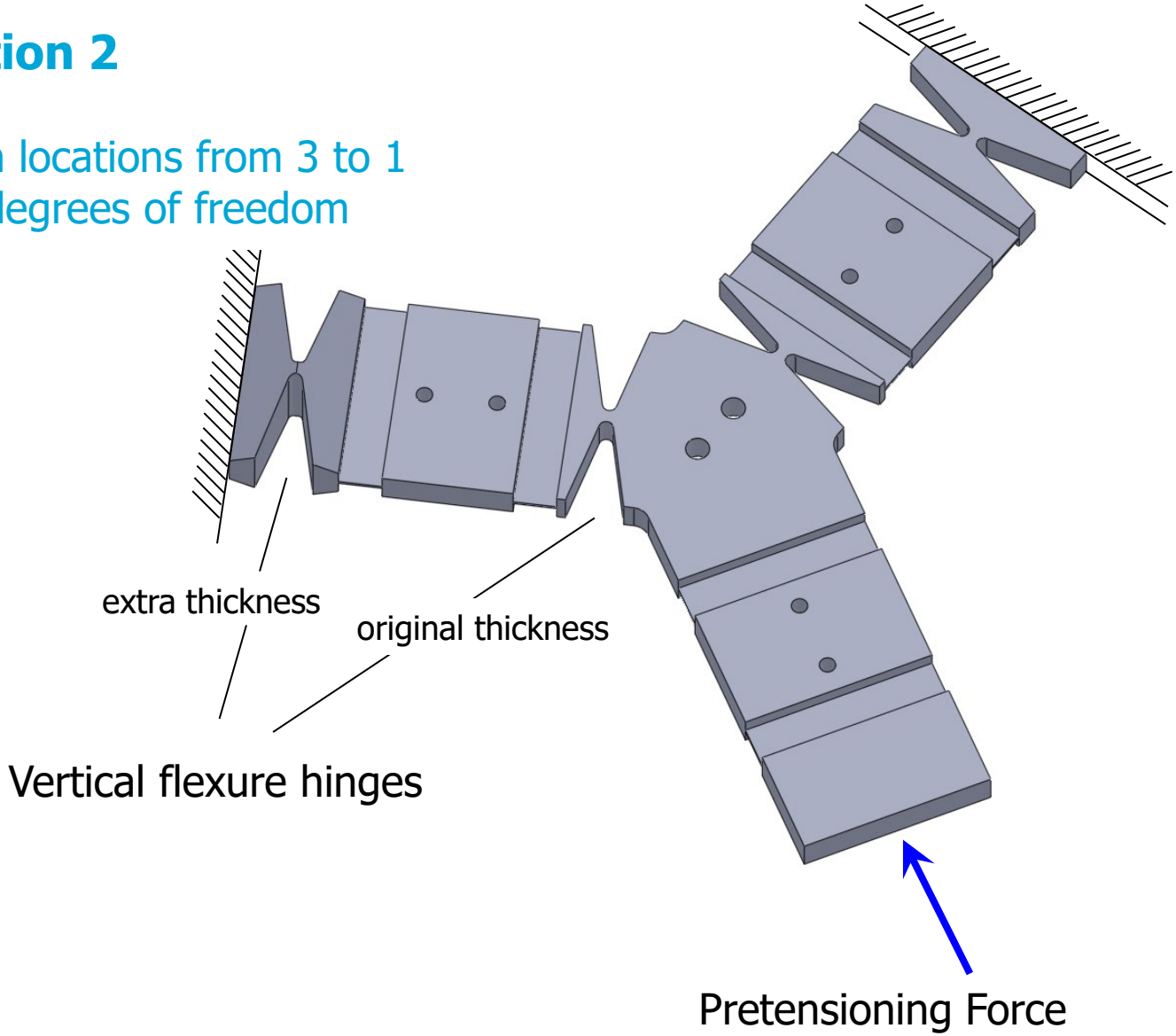


Parameter study for flexure hinges (2)



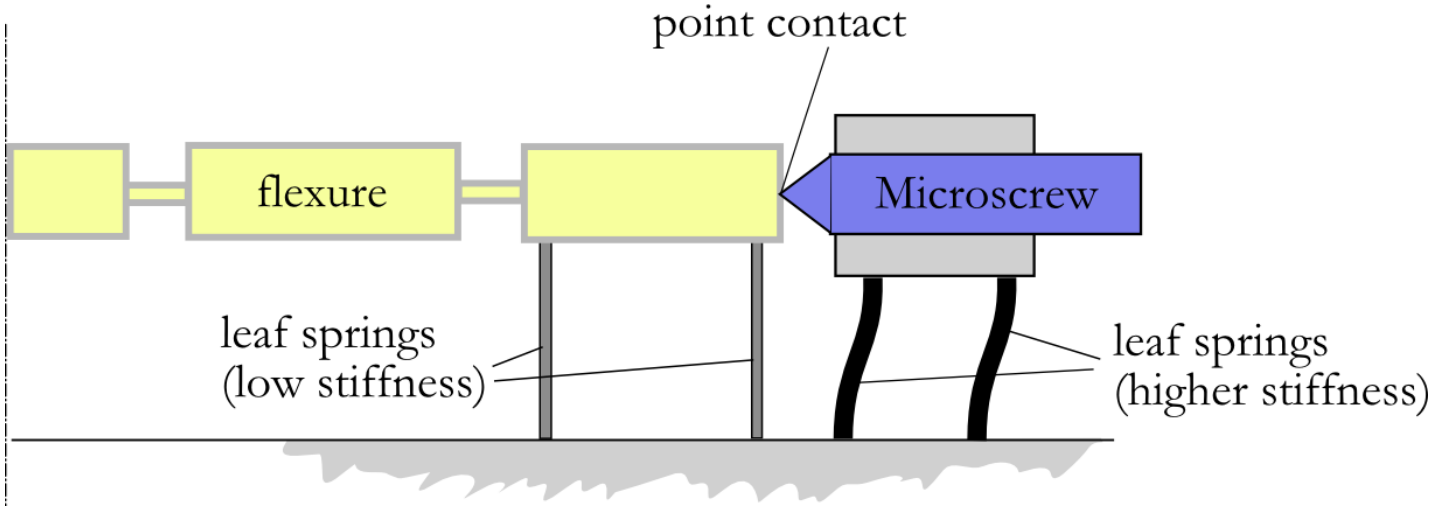
Recommendation 2

Reduce pretension locations from 3 to 1
Improve internal degrees of freedom

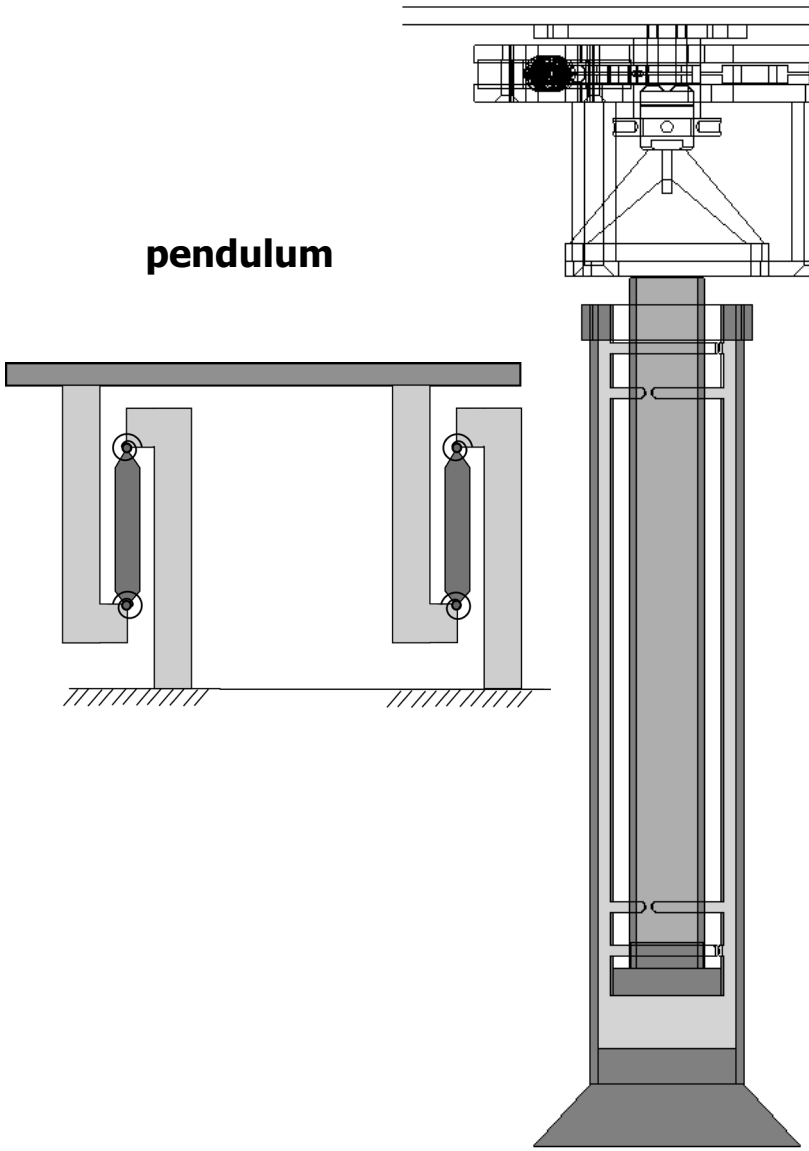


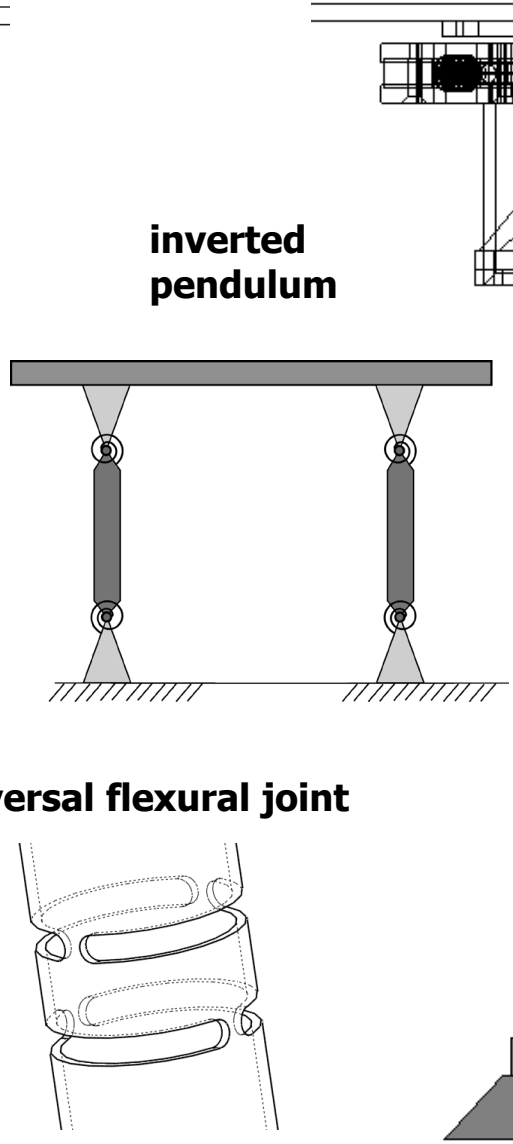
Recommendation 3

Increase Pretensioning accuracy
Eliminate play and friction



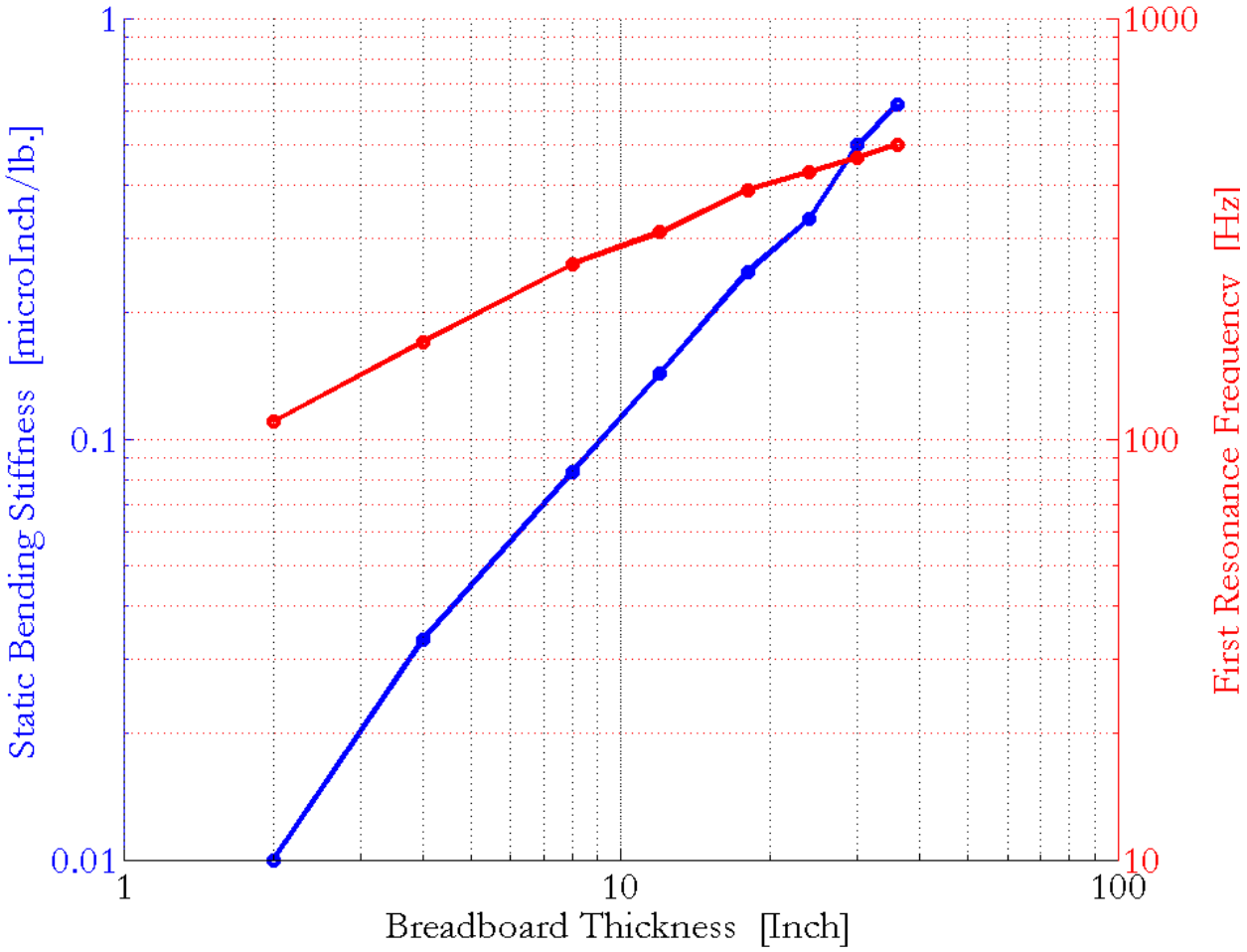
Recommendation 4: Extend the suspension with isolation in more DOFs



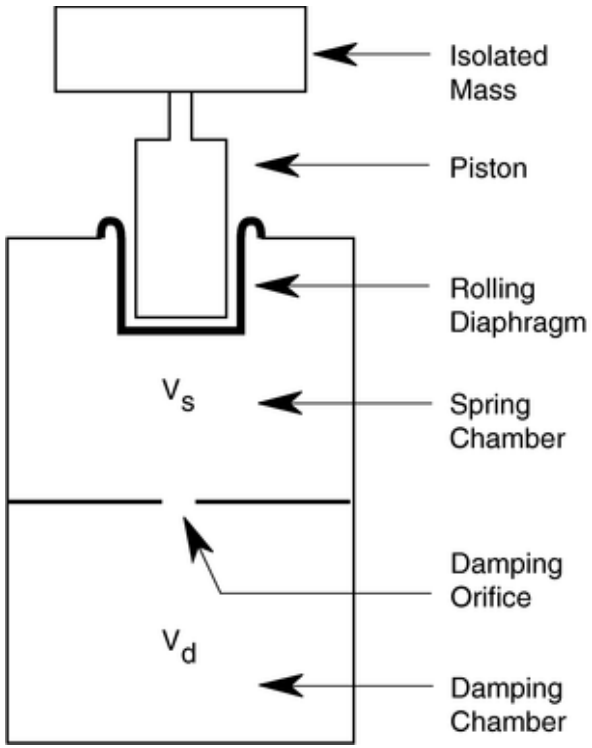


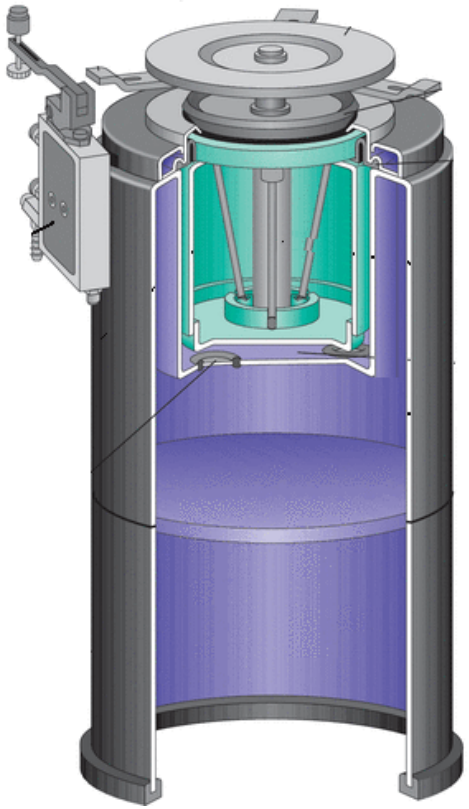
universal flexural joint

Breadboard thickness and natural frequency



Air mounts


Isolated Mass
Piston
Rolling Diaphragm
V_s
Spring Chamber
Damping Orifice
V_d
Damping Chamber



Measurement:

P > Pcr 2 equilibrium positions