ME 256

Comparative analysis of several design methods for compliant mechanisms

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Models for analysis

- Empirical modeling of elastic pairs
- Elastica analysis of beam segments
- Pseudo Rigid-Body (PRB) modeling
- **Finite element analysis**
- Spring-Lever (SL) and Spring-Mass-Lever (SML) modeling
- Compliant ellipsoid modeling
- Non-dimensional maps

Synthesis methods

- Kinetostatic synthesis using PRB modeling
- **Topology and shape optimization**
- Selection and re-design
- Instant-centre method
- Design using building blocks
- Pragmatic design with non-dimensional maps
- Intuitive design using a kit

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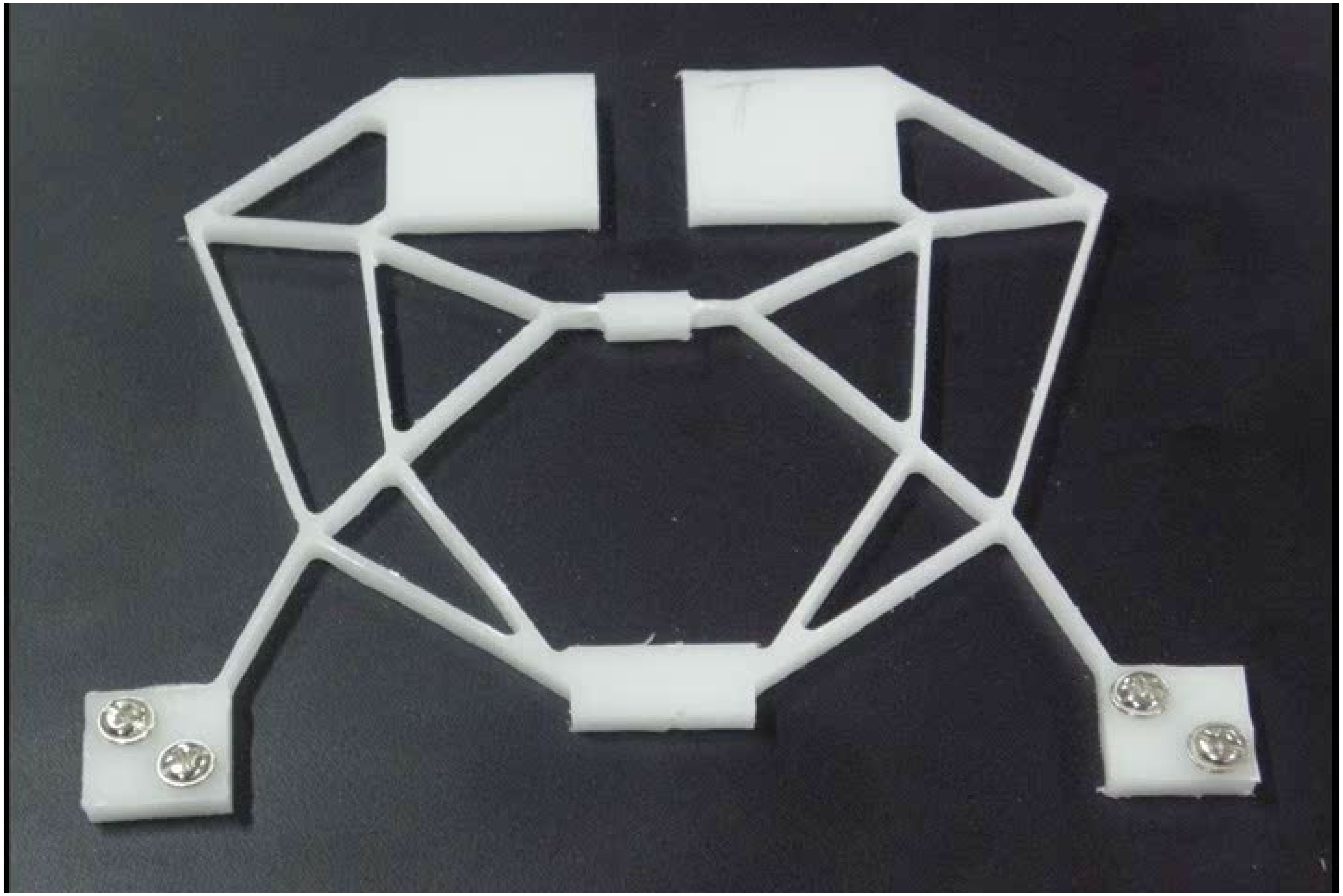
Compliant Mechanism kit



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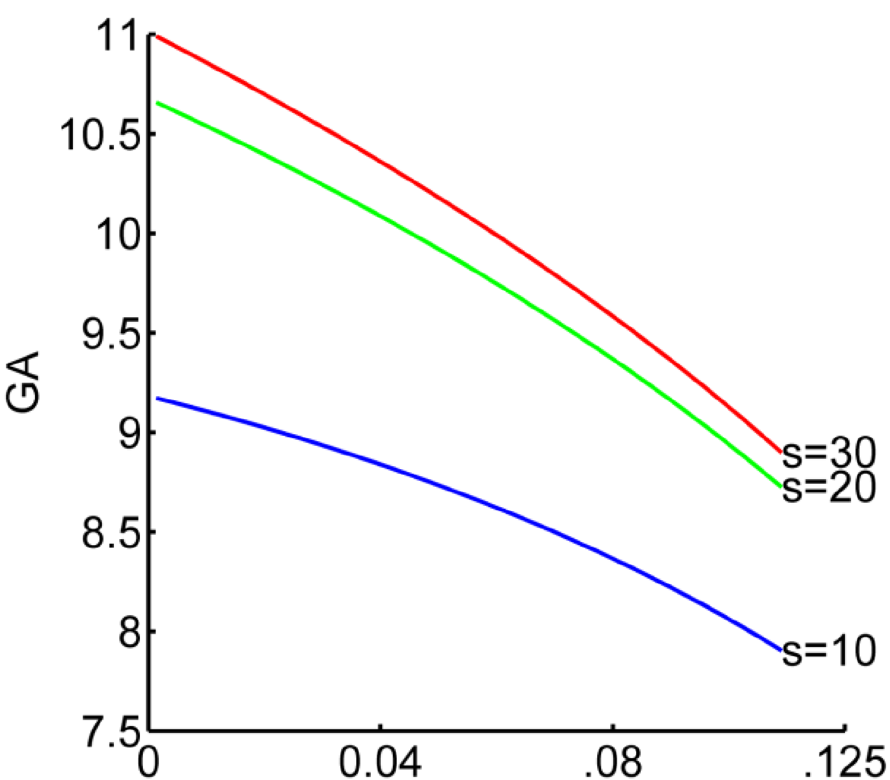
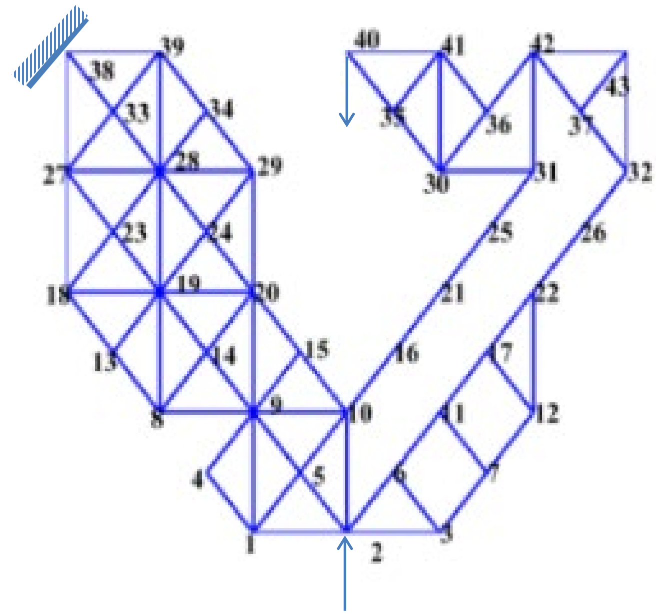
Kinetoelastic maps





$$\eta = \frac{\overline{F}\;\overline{s}^{2}}{\overline{E}\;\overline{b}\;\overline{d}}$$

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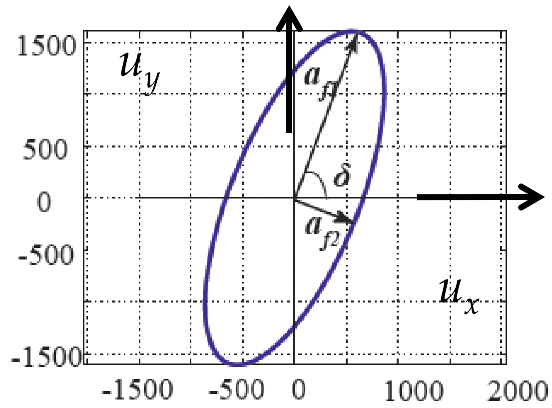
A Geometric Representation

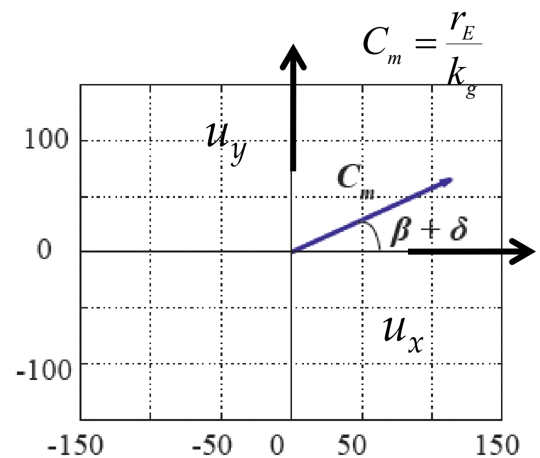
$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{12} & C_{22} & C_{23} \\ C_{13} & C_{23} & C_{33} \end{bmatrix}$$

Series Combination: Compliance ellipses add, coupling vectors add with modifications

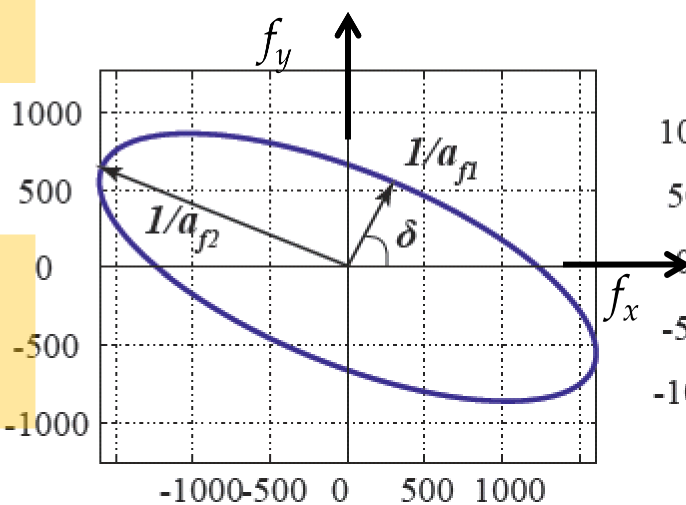
Parallel Combination: Stiffness ellipses add, coupling vectors add



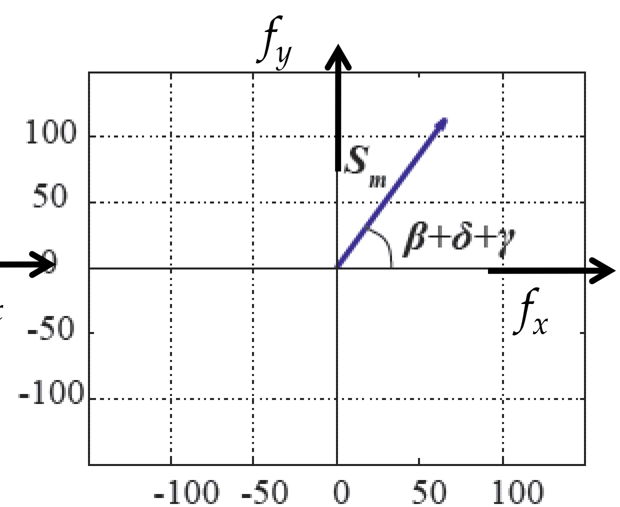
Compliance ellipse



Coupling vector



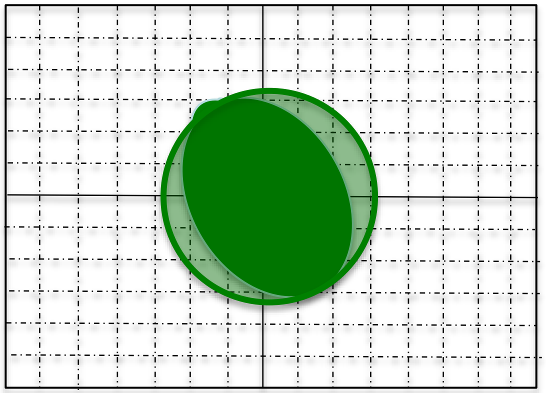
Stiffness ellipse

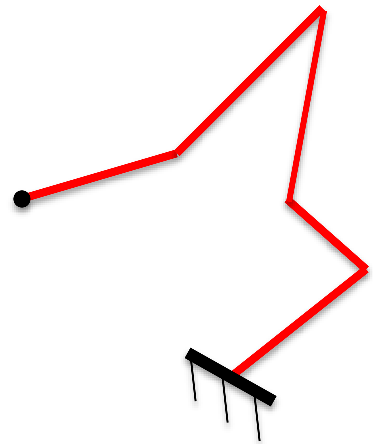


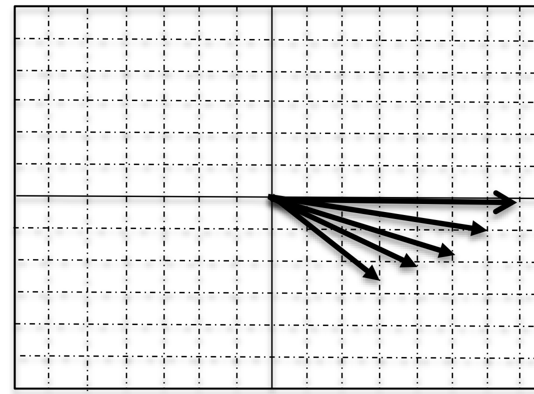
Stiffness coupling vector

Problem Decomposition

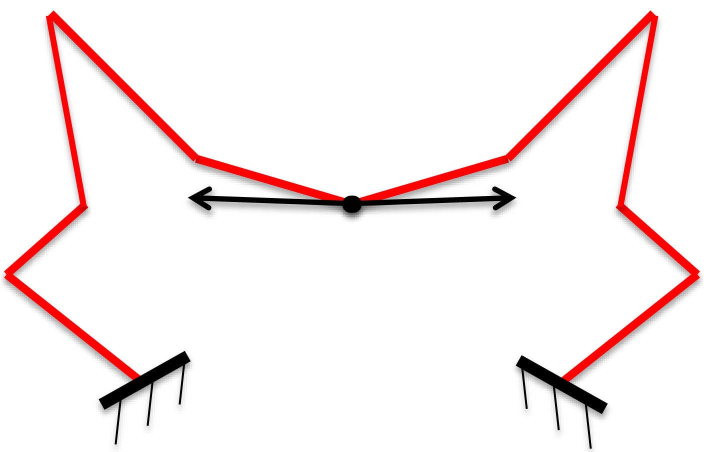
Symmetric half design by series decomposition

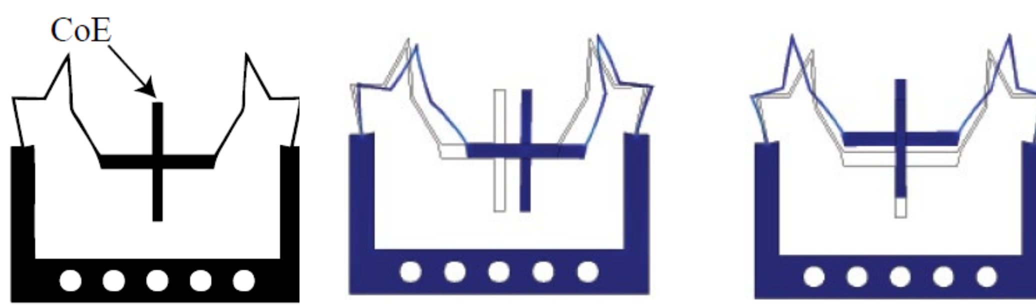




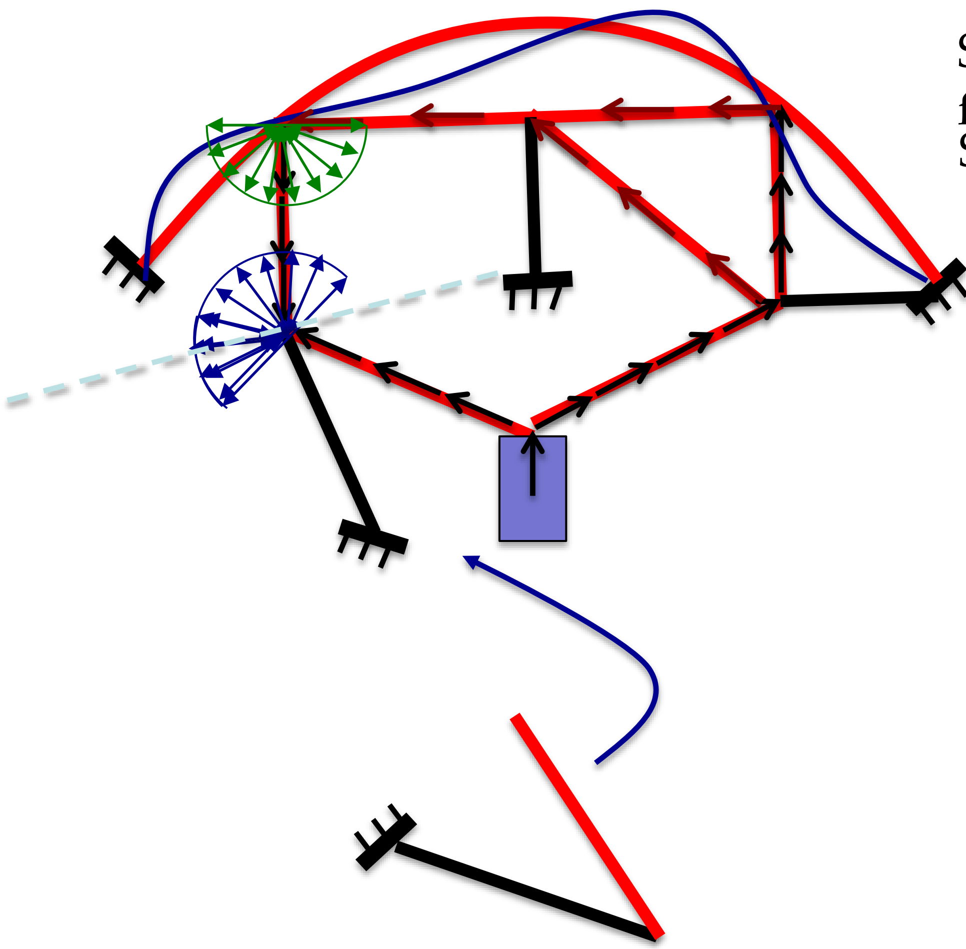


Final Mechanism Assembly





Guidelines for Synthesis



Step 1: Visualize load flow

Step 2: Analyze feasibility

Step 3: Replace load paths with building blocks

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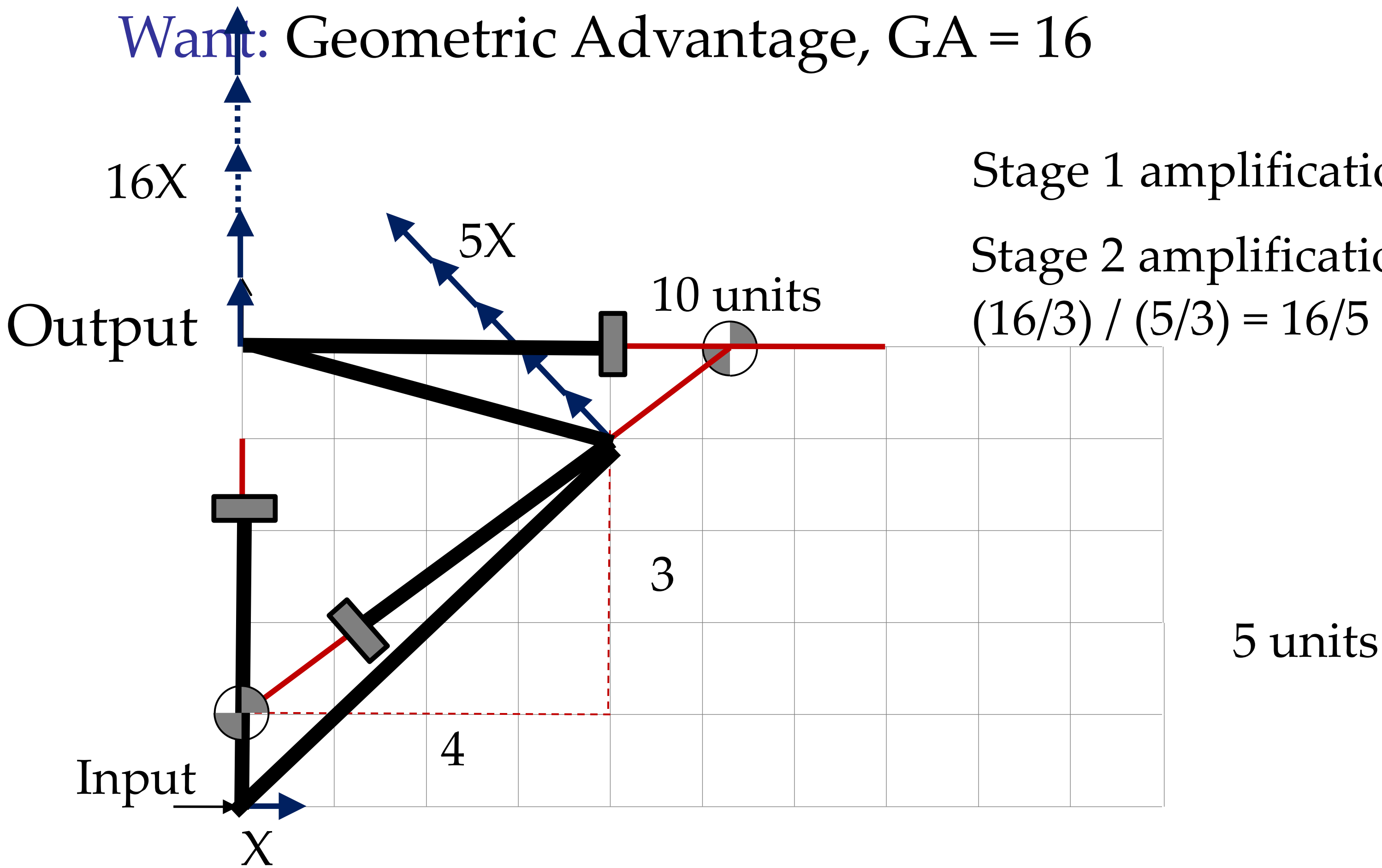
Instant centre method

Want: Geometric Advantage, GA = 16

Stage 1 amplification = 5

Stage 2 amplification = (16/3) / (5/3) = 16/5



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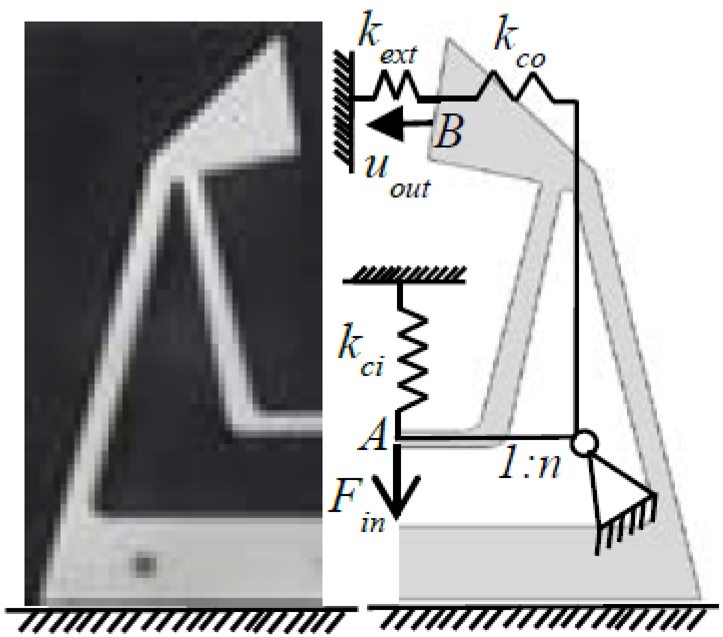
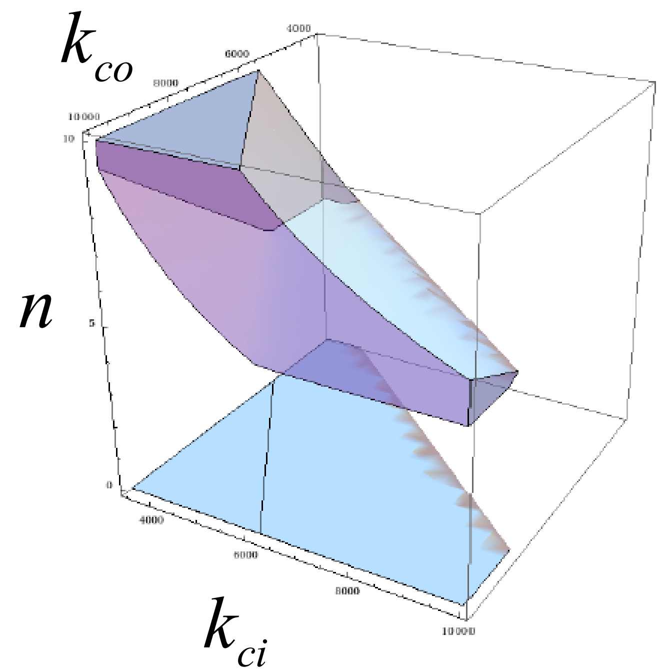
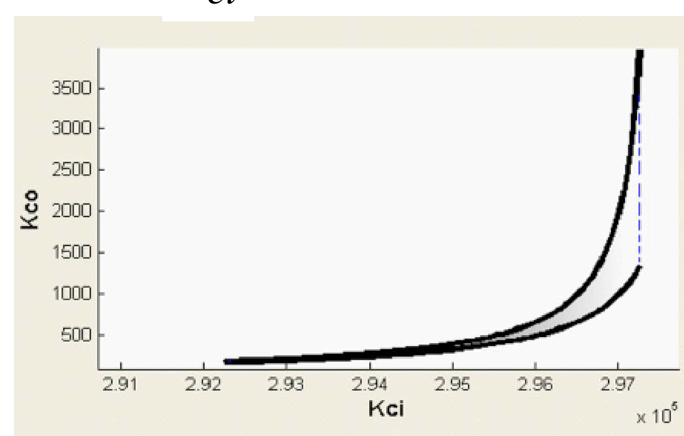
SL and SML models; feasibility maps; stiffness and inertia maps



SL model

Feasibility map





Modified design of the accelerometer by Abdolvand et al. 2007 using a DaCM

$190\,\mu\text{N} \le F_{in} \le 210\,\mu\text{N}$

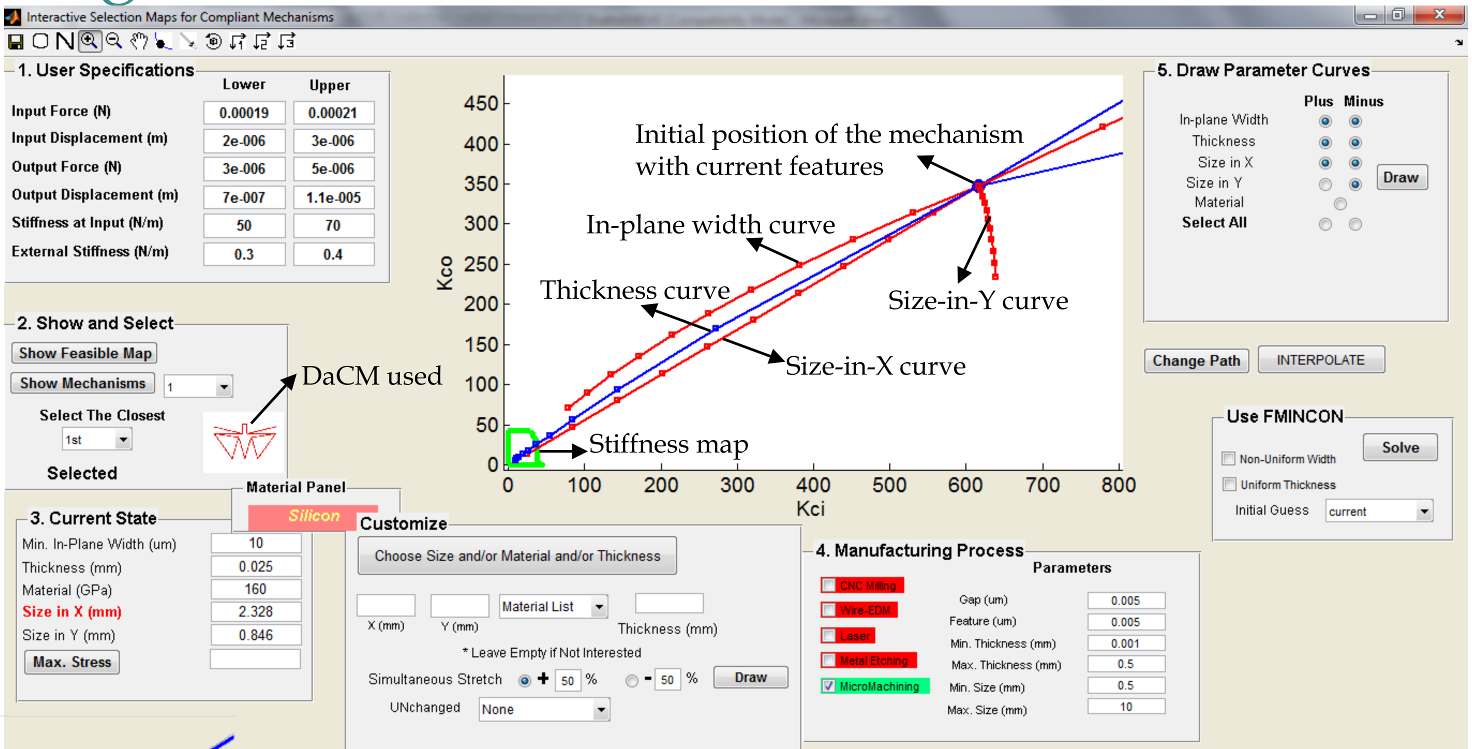
$2\,\mu\text{m} \le u_{in} \le 3\,\mu\text{m}$

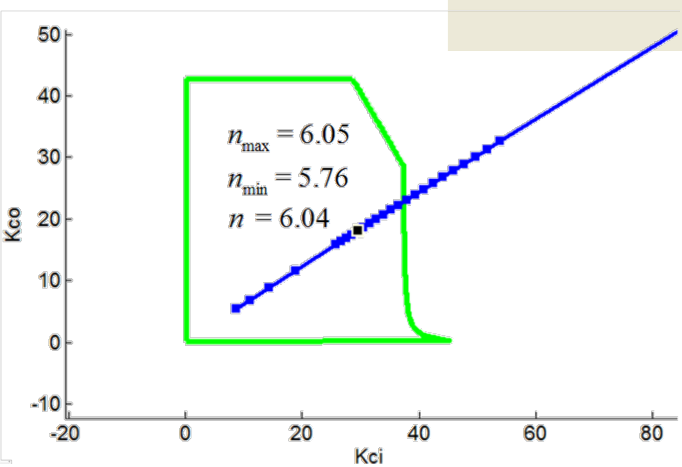
$3\,\mu\text{N} \le F_{out} \le 4\,\mu\text{N}$

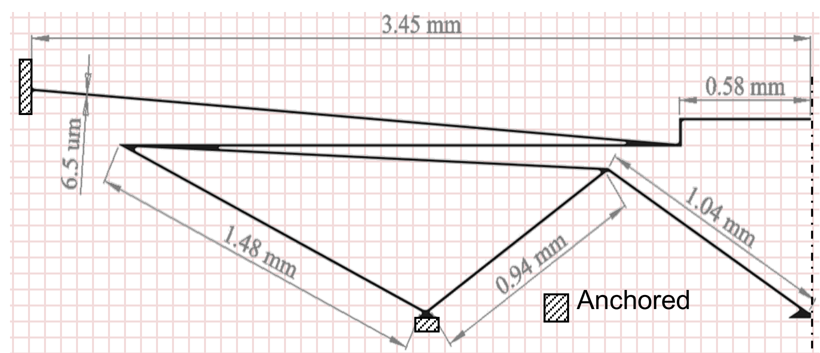
$7\,\mu\text{m} \le u_{out} \le 11\,\mu\text{m}$

$50\,\text{N/m} \le k_s \le 70\,\text{N/m}$

$0.3\,\text{N/m} \le k_{ext} \le 0.4\,\text{N/m}$







Re-designed and optimized DaCM

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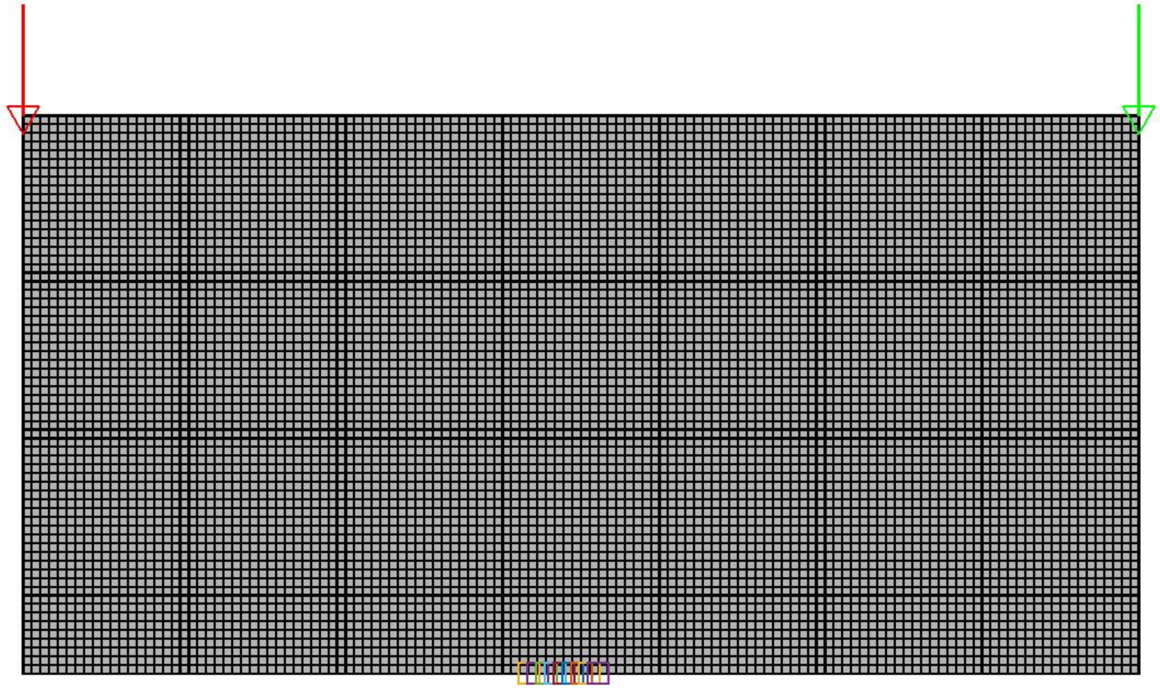
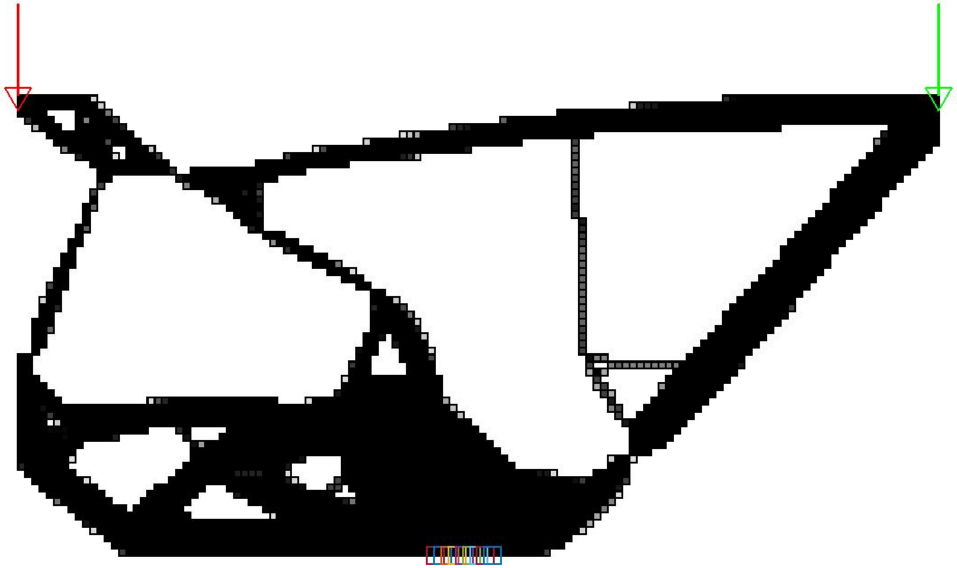
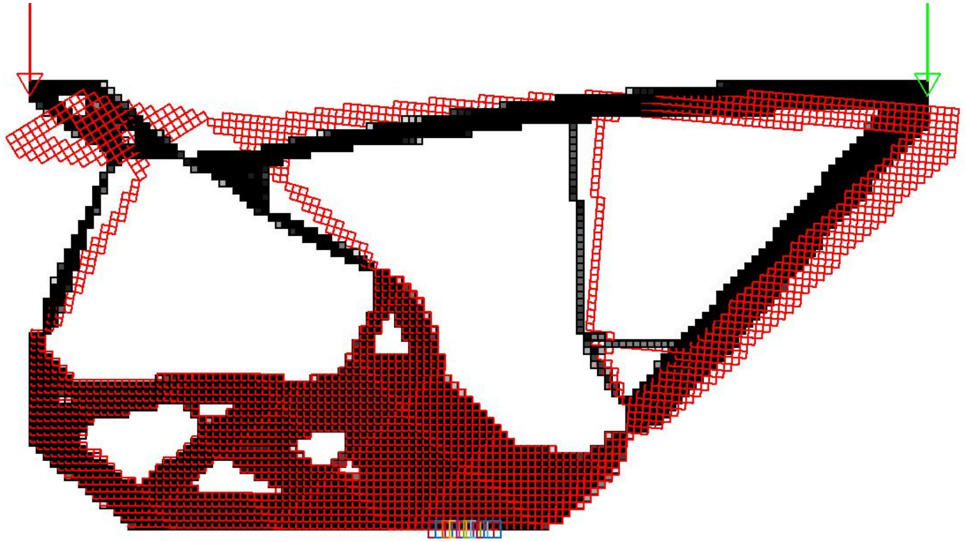
Problem specification for YinSyn



Solution given by YinSyn





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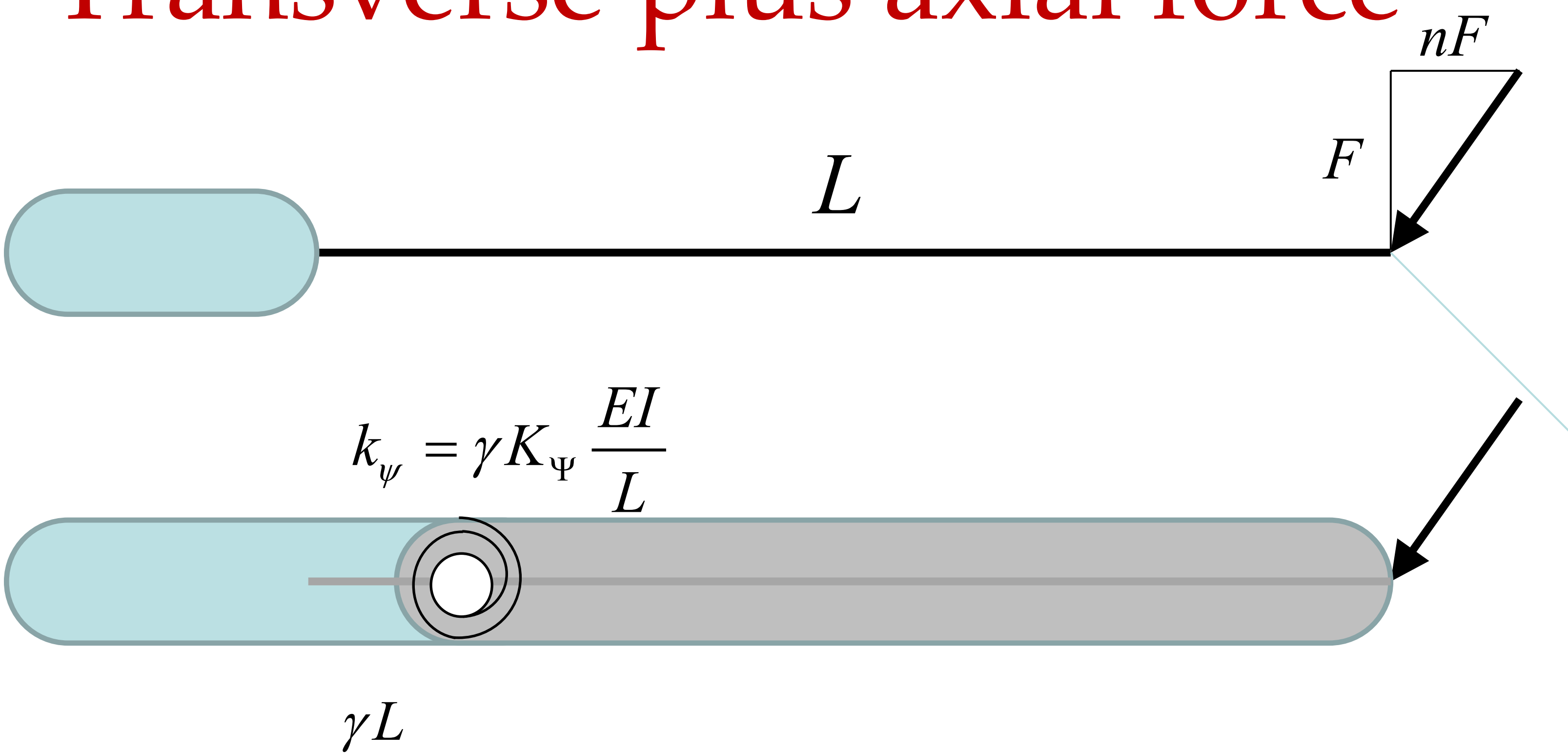
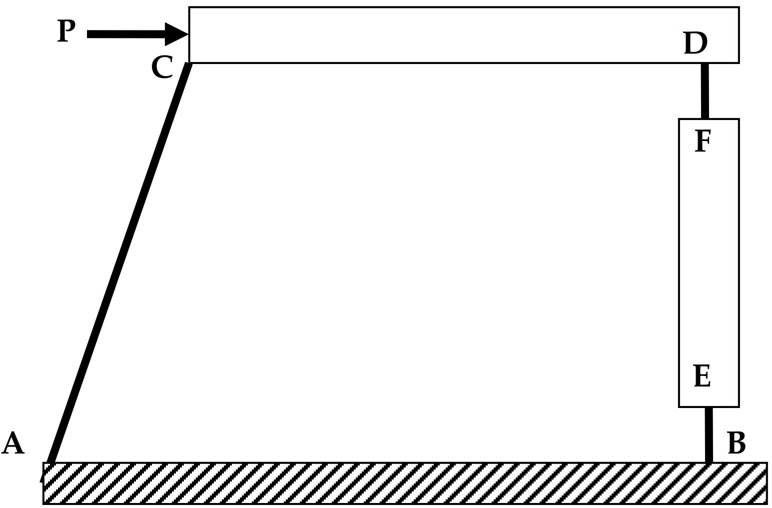
Transverse plus axial force

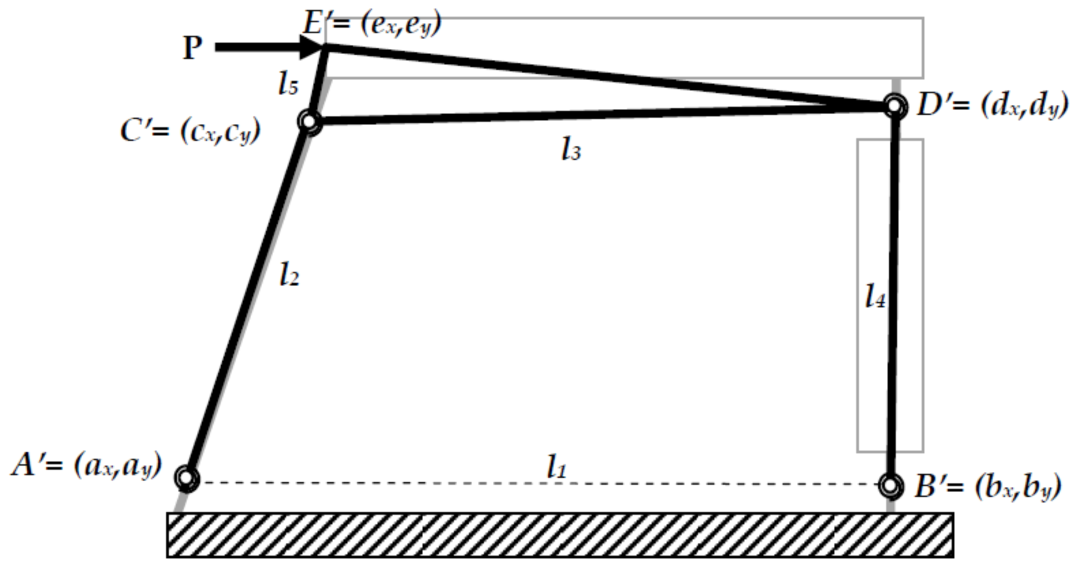


$$\gamma = \begin{cases} 0.84 - 0.007n + \cdots & 0.5 < n < 10 \\ 0.85 - 0.02n + \cdots & -1.83 < n \le 0.5 \\ 0.91 + 0.01n + \cdots & -5 < n \le 1.83 \end{cases} \qquad K_{\Psi} = \begin{cases} 3.02 + 0.12n \\ 1.97 - 2.62n + \cdots \\ 2.65 - 0.05n + \cdots \end{cases}$$

Different ranges for n

Kinetoelastostatic analysis





$$PE = \frac{1}{2}\left\{\begin{array}{l}\kappa_1\left(\phi_2-\phi_{20}\right)^2+\kappa_1\left(\phi_3-\phi_2-\left(\phi_{30}-\phi_{20}\right)\right)^2+\ldots \\ \kappa_2\left(\phi_4-\phi_3-\left(\phi_{40}-\phi_{30}\right)\right)^2+\kappa_2\left(\phi_4-\phi_{40}\right)^2\end{array}\right\}-P\left(e_x\big|_{\phi_2}-e_x\big|_{\phi_{20}}\right)$$

$$\frac{\partial PE}{\partial \phi_2}=0$$

Synthesis equations

$$\frac{\kappa_3\left\{(\psi_1-\psi_0)-(\beta_1-\beta_0)\right\}\left(\dfrac{l_2\sin(\beta_1-\theta_1)}{l_4\sin(\beta_1-\psi_1)}-\dfrac{l_2\sin(\psi_1-\theta_1)}{l_3\sin(\beta_1-\psi_1)}\right)}{(\theta_1-\theta_0)}=T_1$$

$$\frac{\kappa_3\left\{(\psi_2-\psi_0)-(\beta_2-\beta_0)\right\}\left(\dfrac{l_2\sin(\beta_2-\theta_2)}{l_4\sin(\beta_2-\psi_2)}-\dfrac{l_2\sin(\psi_2-\theta_2)}{l_3\sin(\beta_2-\psi_2)}\right)}{(\theta_2-\theta_0)}=T_2$$

$$\mathbf{Z}_2\left(e^{i(\theta_1-\theta_0)}-1\right)+\mathbf{Z}_3\left(e^{i(\beta_1-\beta_0)}-1\right)+\mathbf{Z}_4\left(e^{i(\psi_1-\psi_0)}-1\right)=\mathbf{0}$$

$$\mathbf{Z}_2\left(e^{i(\theta_2-\theta_0)}-1\right)+\mathbf{Z}_3\left(e^{i(\beta_2-\beta_0)}-1\right)+\mathbf{Z}_4\left(e^{i(\psi_2-\psi_0)}-1\right)=\mathbf{0}$$

Comparison of Synthesis methods

Method	Systematic	Intuitive	Computation	Easy/hard	Pragmatic	Maturity
Kinetostatic synthesis using PRB modeling	✓		↑	✗		✓
Topology and shape optimization	✓		↑	✗		✓
Selection and re-design	✓		↓	✓	✓	✓
Instant-centre method		✓	↓	✓		
Design using building blocks		✓	↑	✗	✓	
Pragmatic design with non-dimensional maps		✓	↓	✓	✓	
Intuitive design using a kit		✓	0	✓		✓

Main points

- We discussed seven methods for designing compliant mechanisms.
- There are some more.
- Different levels of maturity, effectiveness, and ease of use.
- The bottom line:
  – Designers have enough guidelines today.