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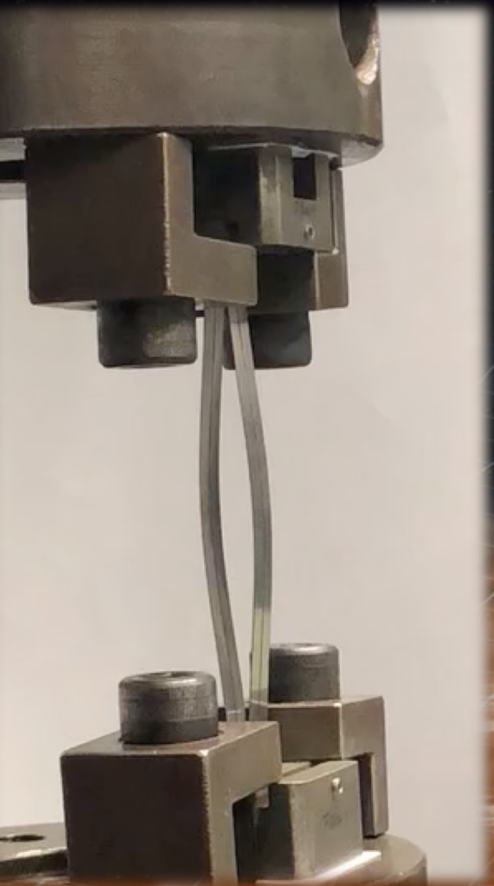
Geometric contoured Euler spring for vertical vibration isolation in future gravitational wave detectors



J.V. van Heijningen, J. Winterflood, W. Zheng, L. Ju

University of Western Australia

Sala dei Notari, Perugia | 16.02.2019

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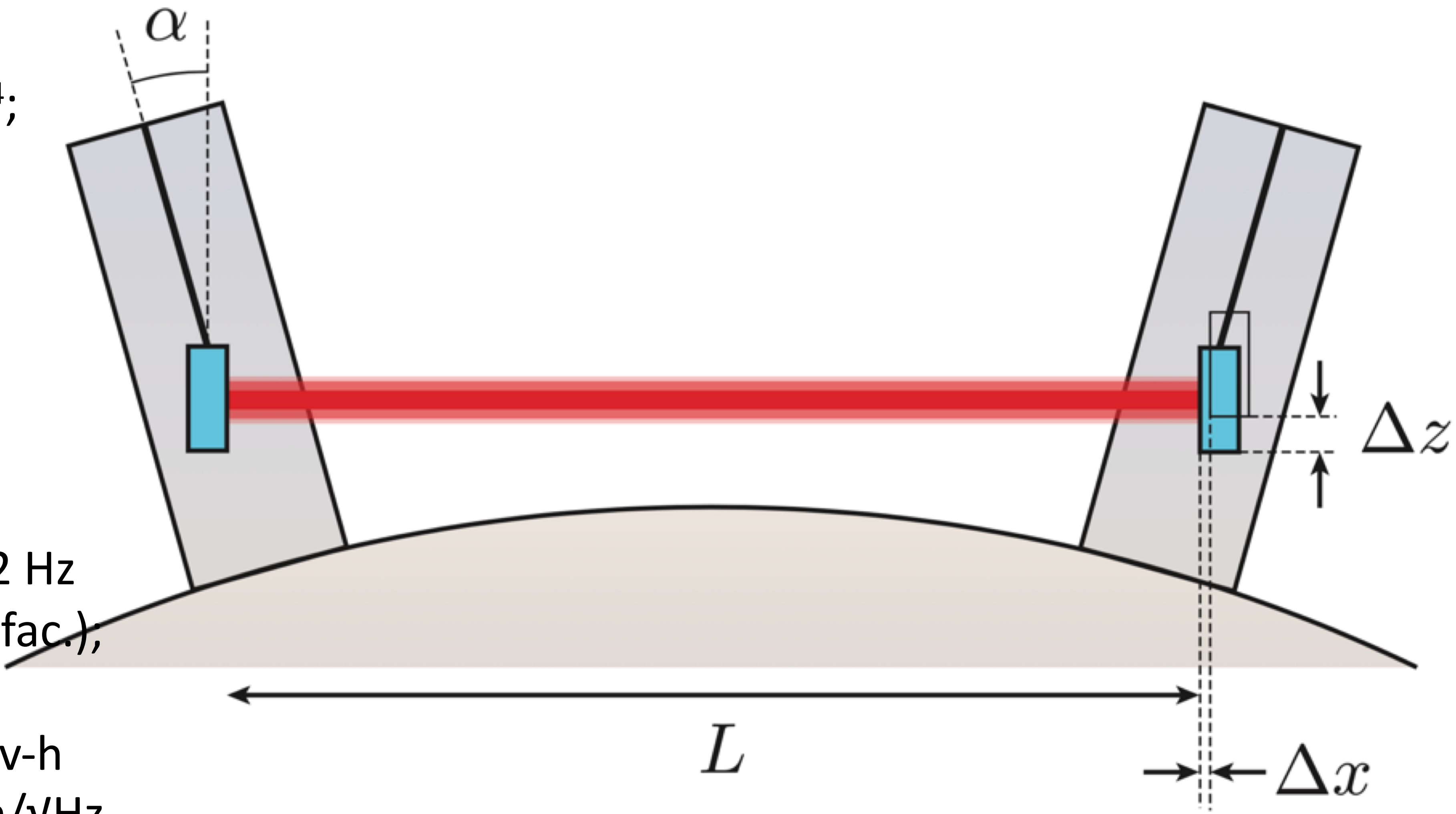
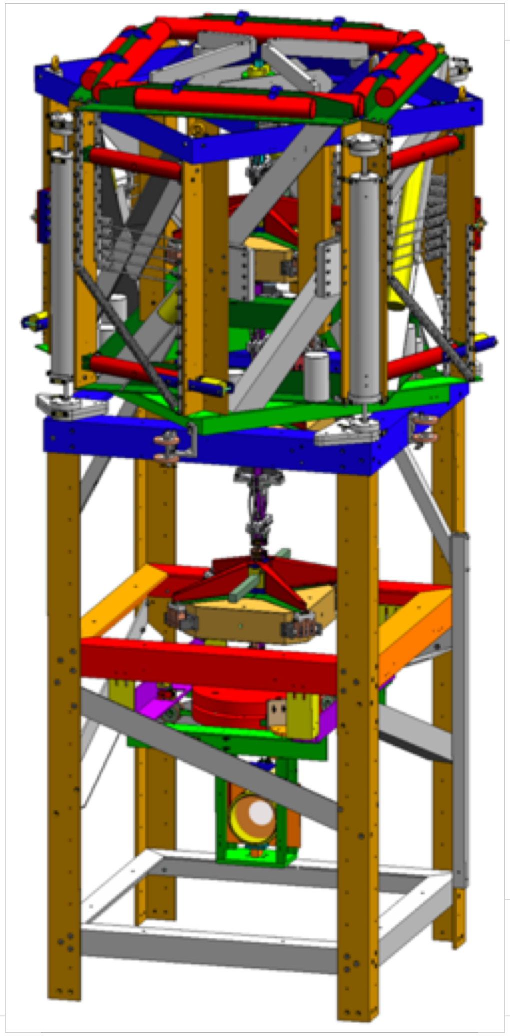
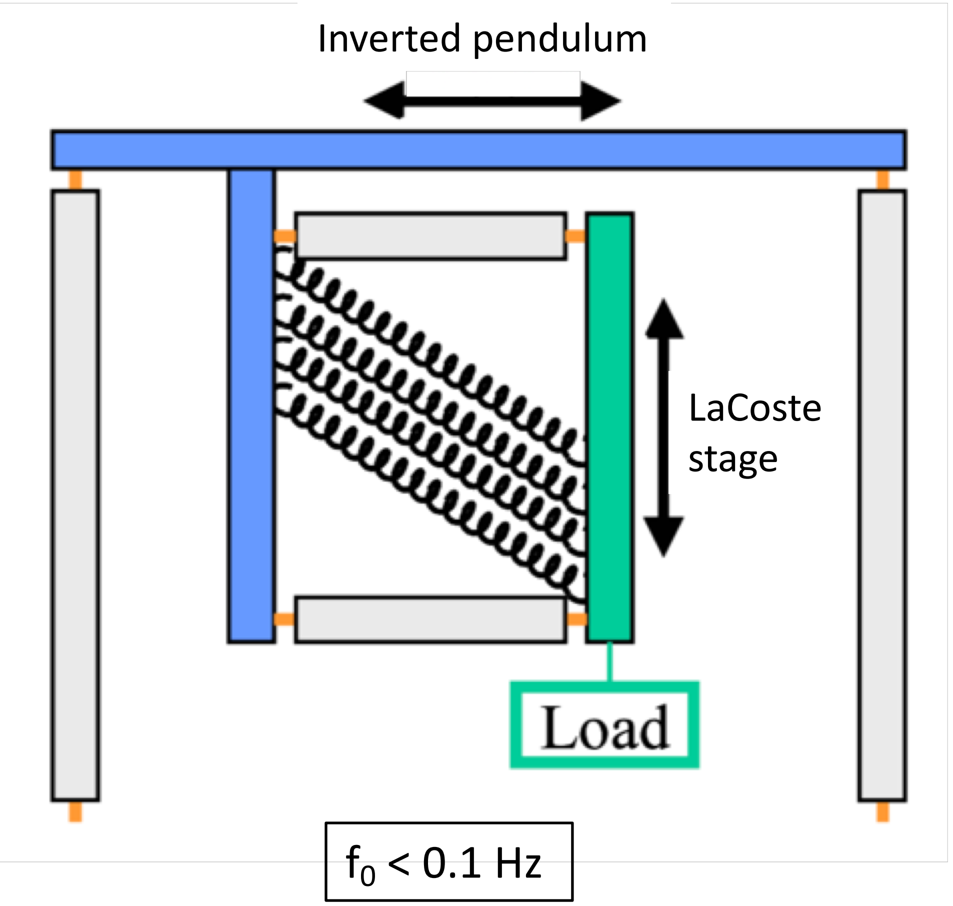
Why do we need vertical vibration isolation?

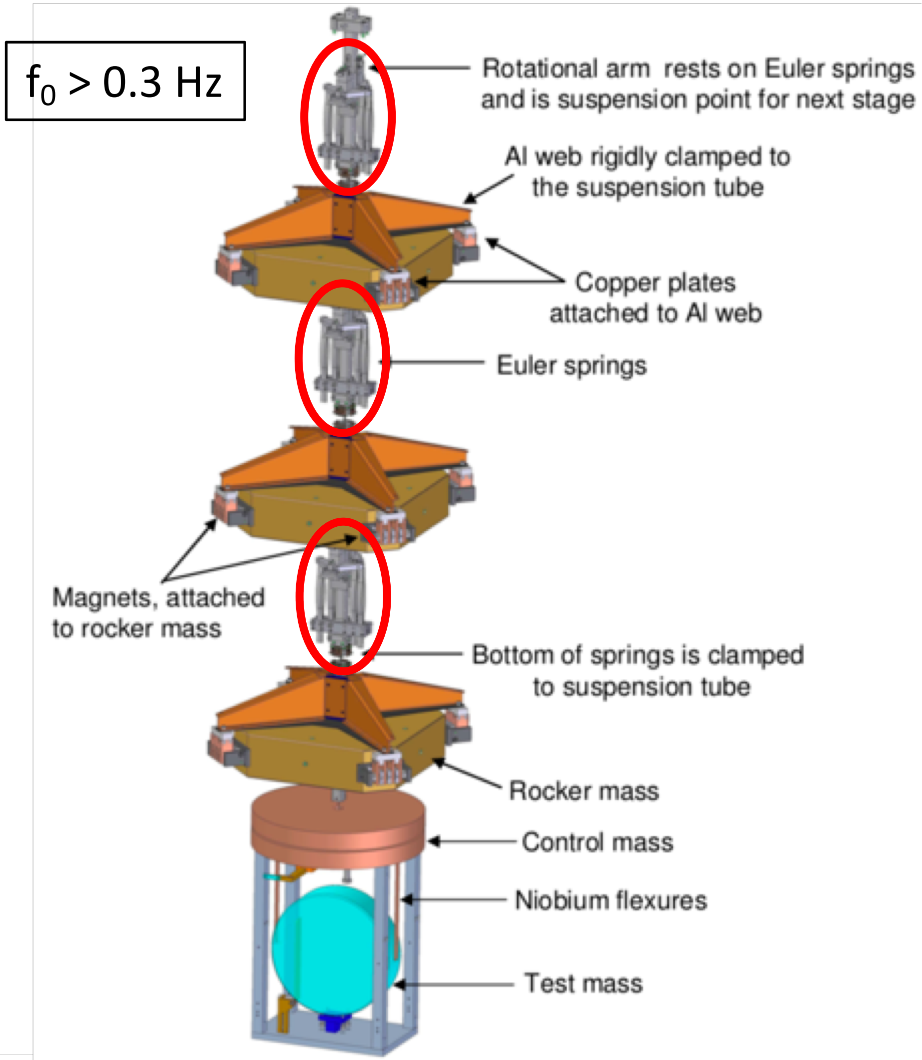
- For 3 km, $\alpha \backsim 2.4 \times 10^{-4}$;
- For 10 km, $\alpha \backsim 8 \times 10^{-4}$ (we can keep 0.1%);
- ET design requires at 2 Hz $h = 10^{-23}\ 1/\sqrt{\text{Hz}}$ (10 sft.fac.);
- 10 km arms and 0.1% v-h coupling yields 10^{-16} m/√Hz.



Vibration isolation systems at the Gingin facility

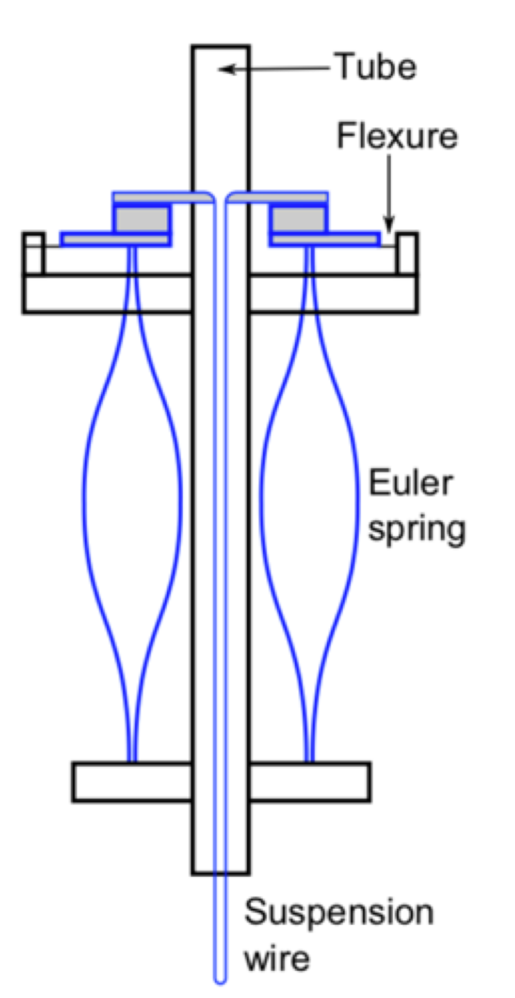


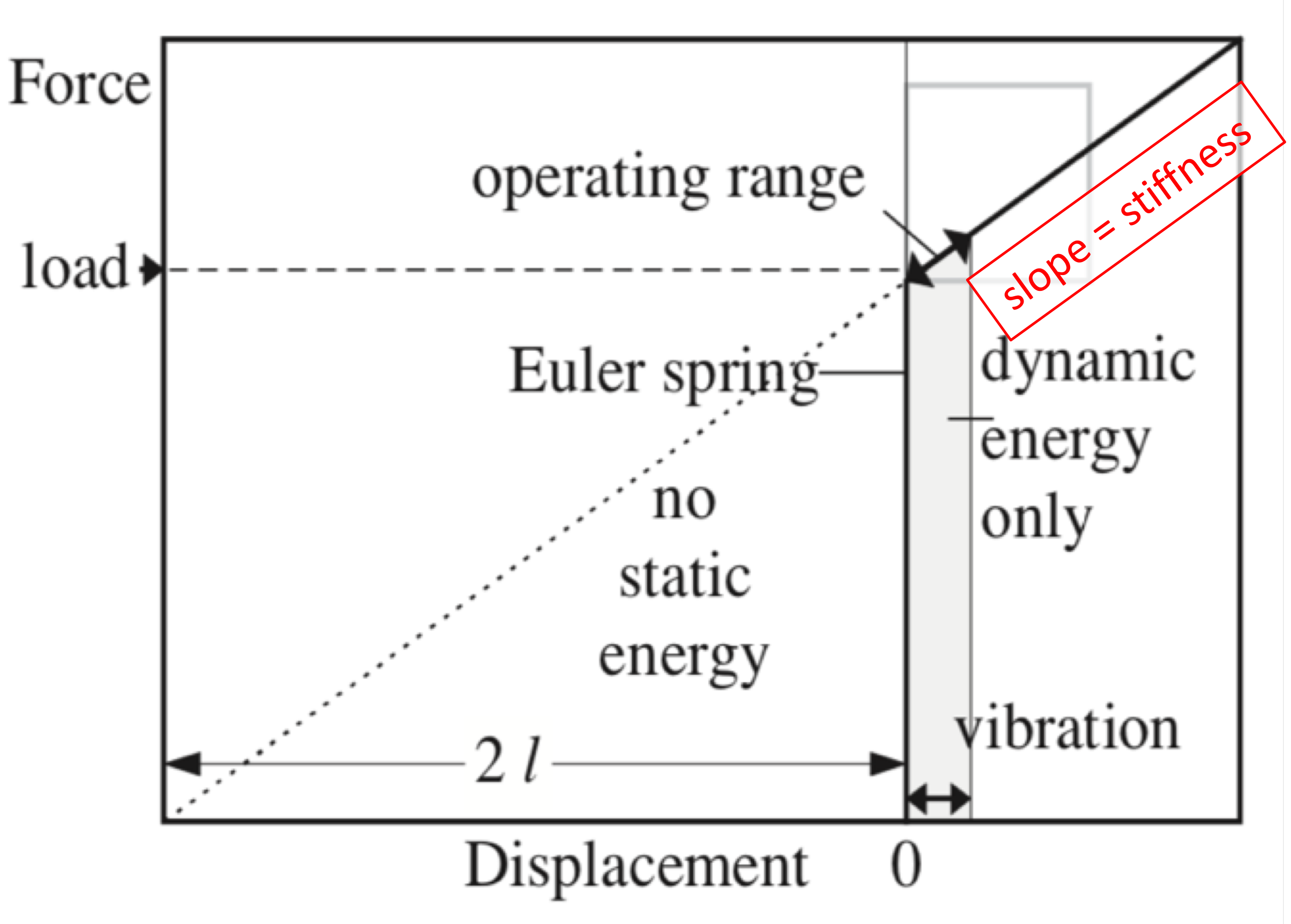


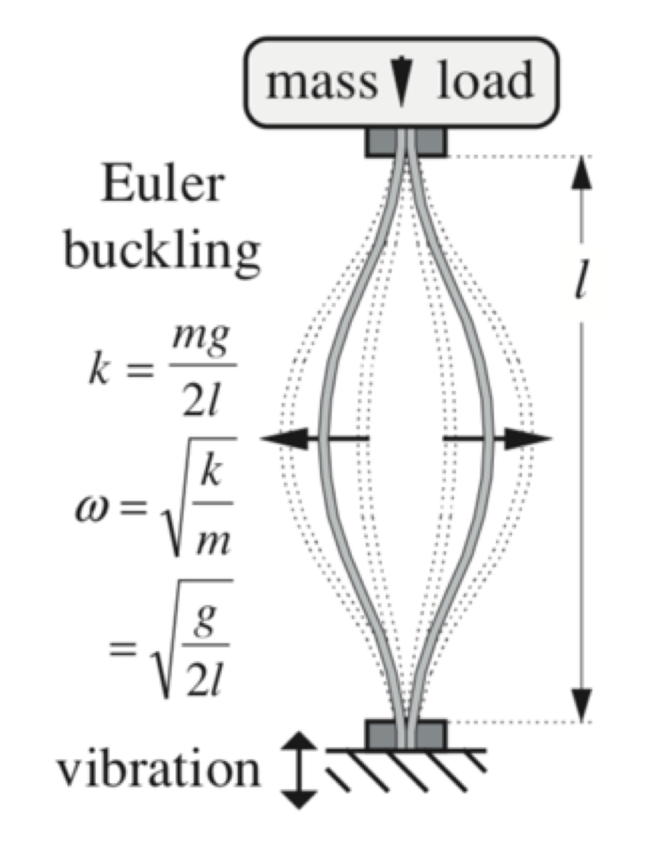


joris.vanheijningen@uwa.edu.au

Euler springs for vertical vibration isolation

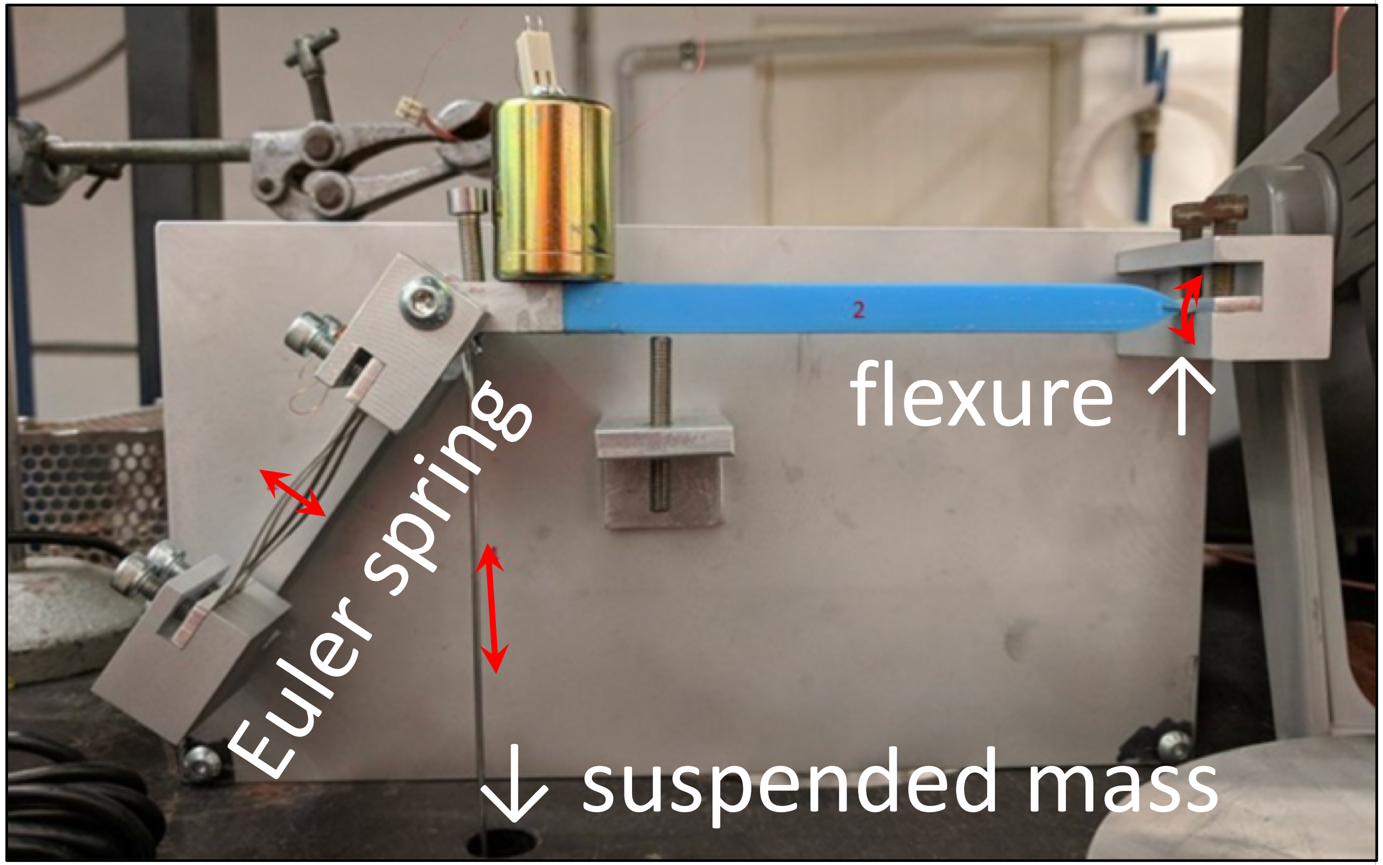


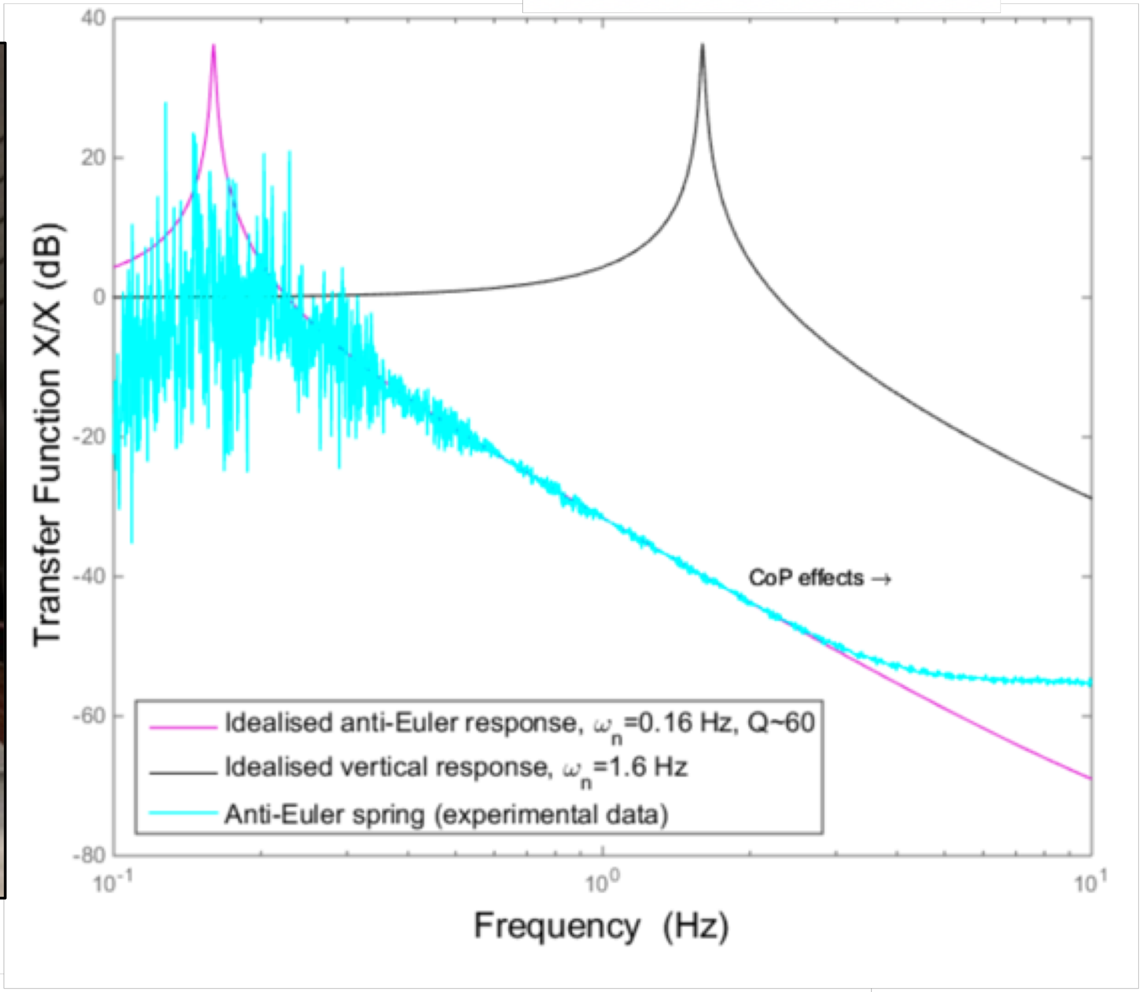




J. Winterflood *et al.*, "Using Euler buckling springs for vibration isolation", Classical and Quantum Gravity 19(7), 1639–1645 (2002)

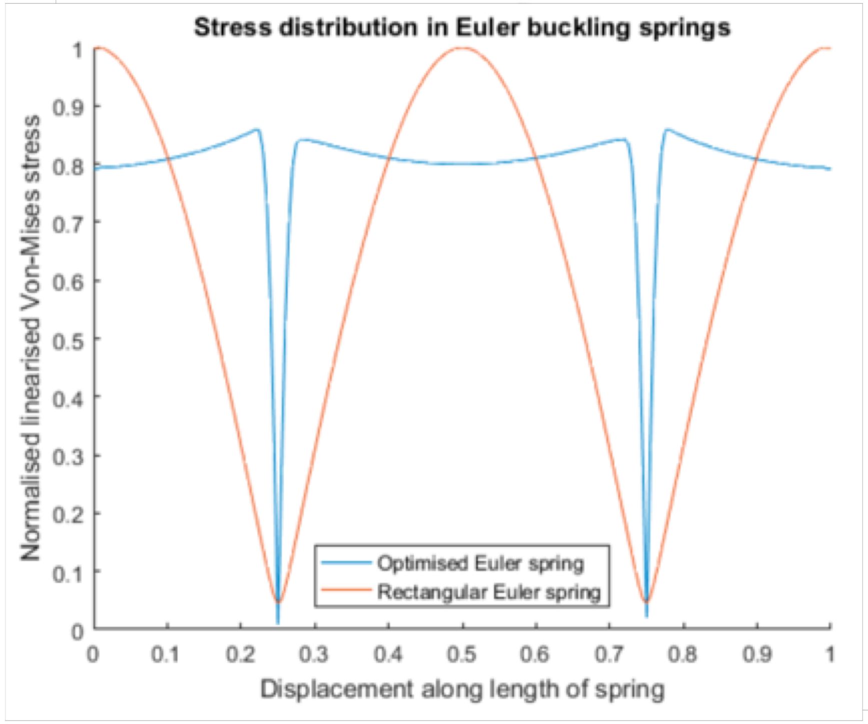
Blade under angle lowers resonance frequency

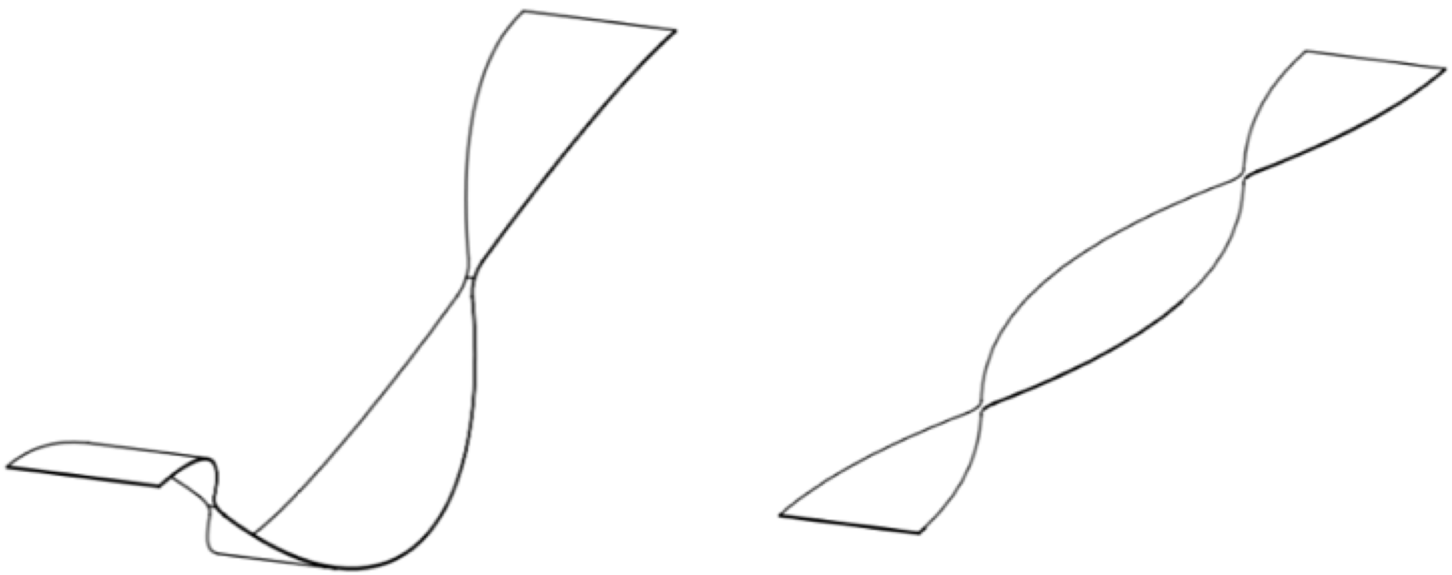




L. Wood, "Euler Buckling Springs for Isolation in Gravitational Wave Detectors", Master's thesis, University of Western Australia, 2018

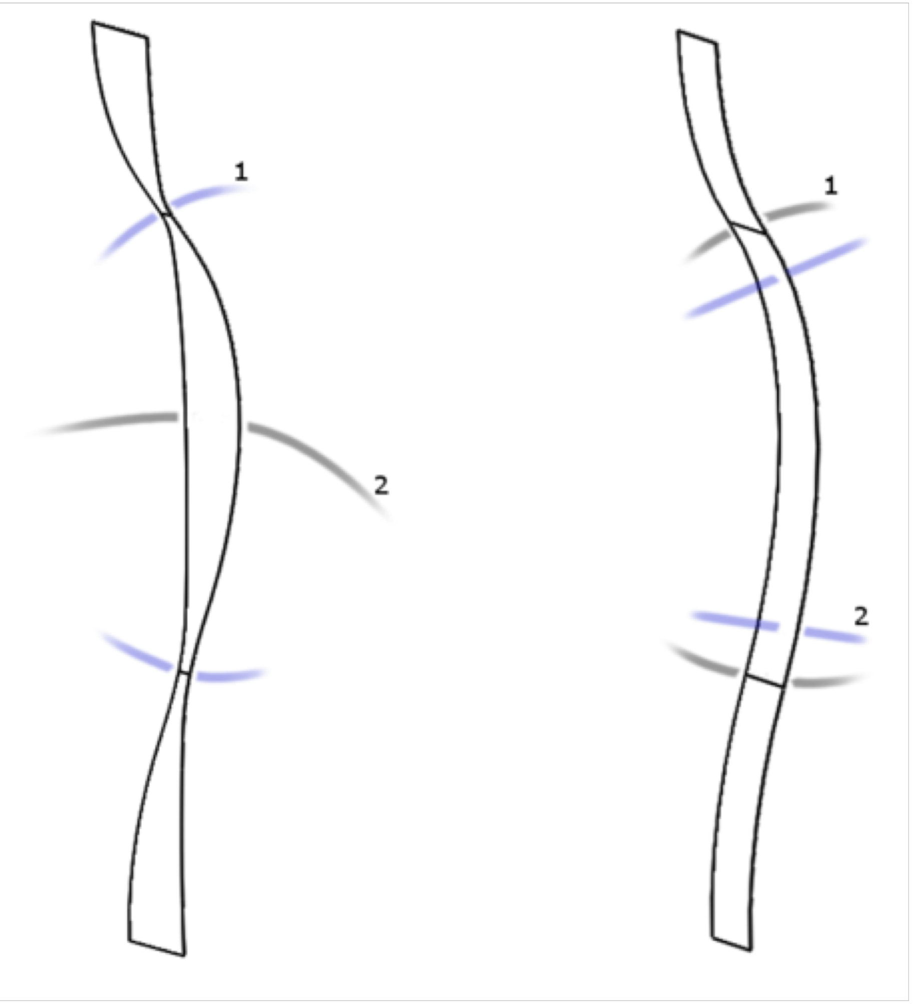
Cutting away mass from low stress areas…

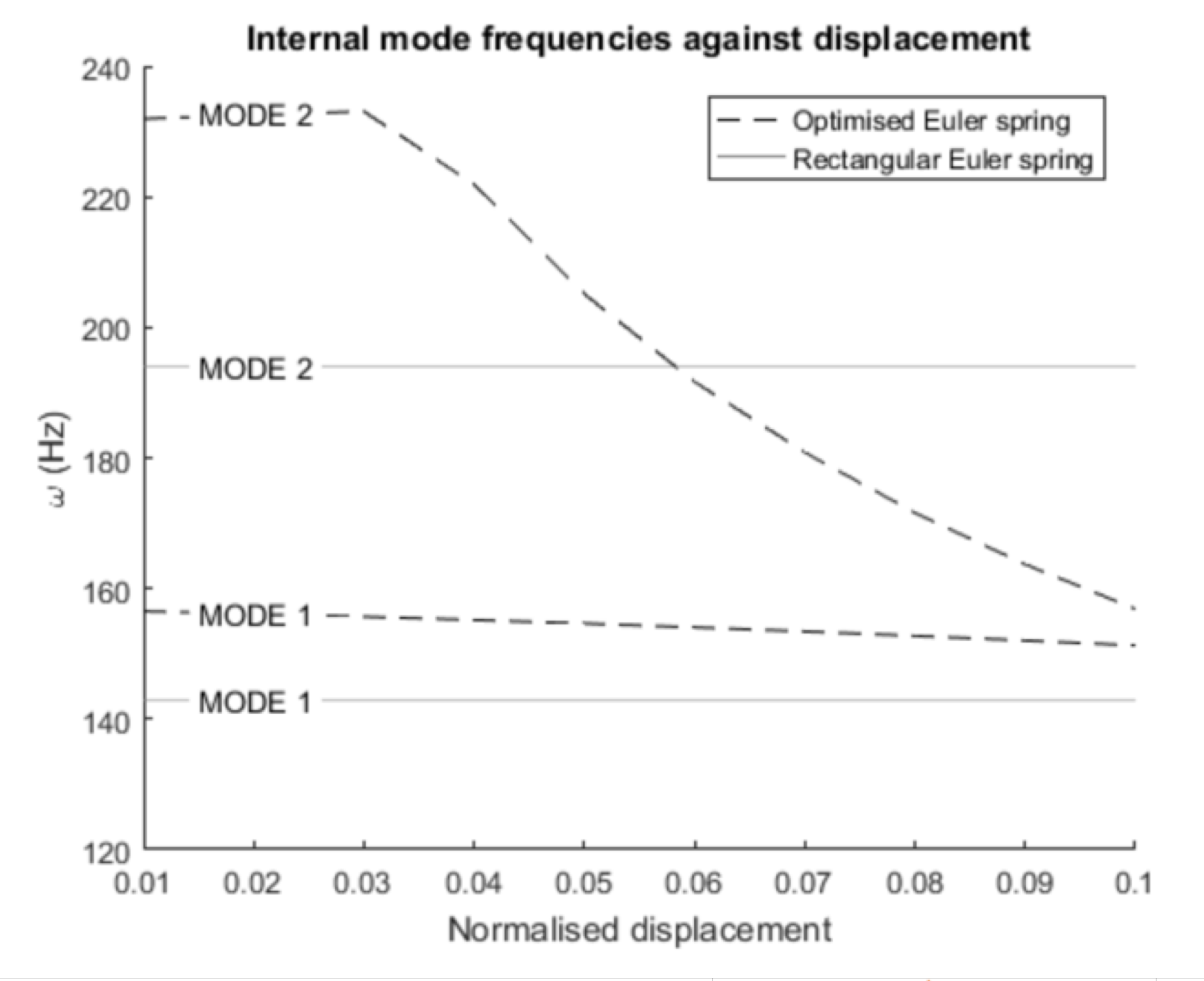




Natural shape of an rectangular Euler spring is an *elastica*, and has an uneven stress distribution

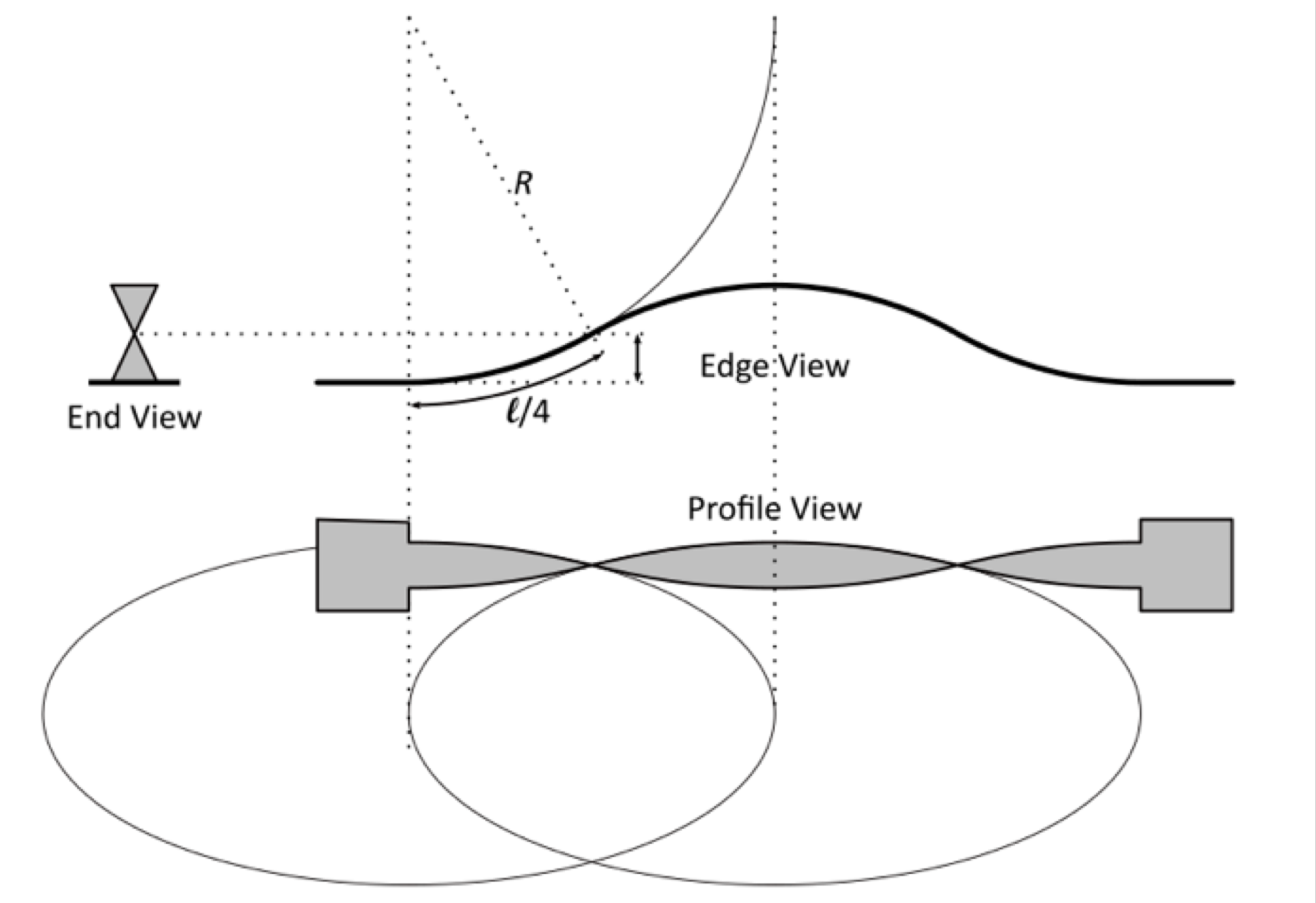
… increases the internal mode frequencies



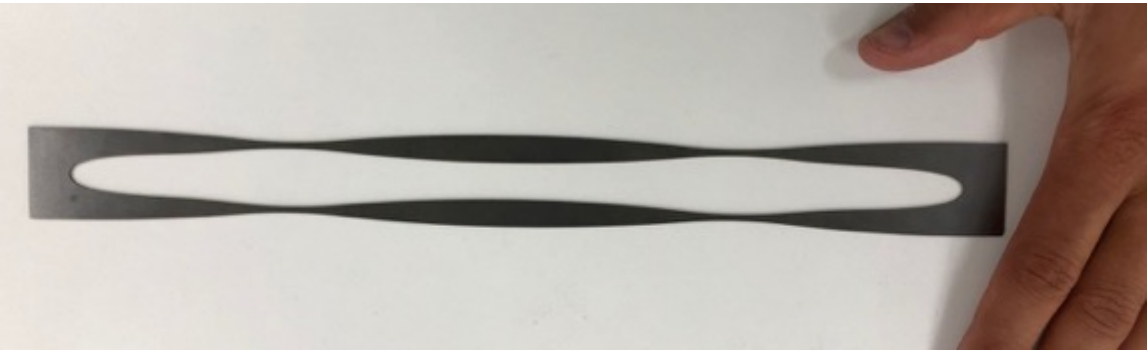


L. Wood, “Euler Buckling Springs for Isolation in Gravitational Wave Detectors”, Master’s thesis, University of Western Australia, 2018

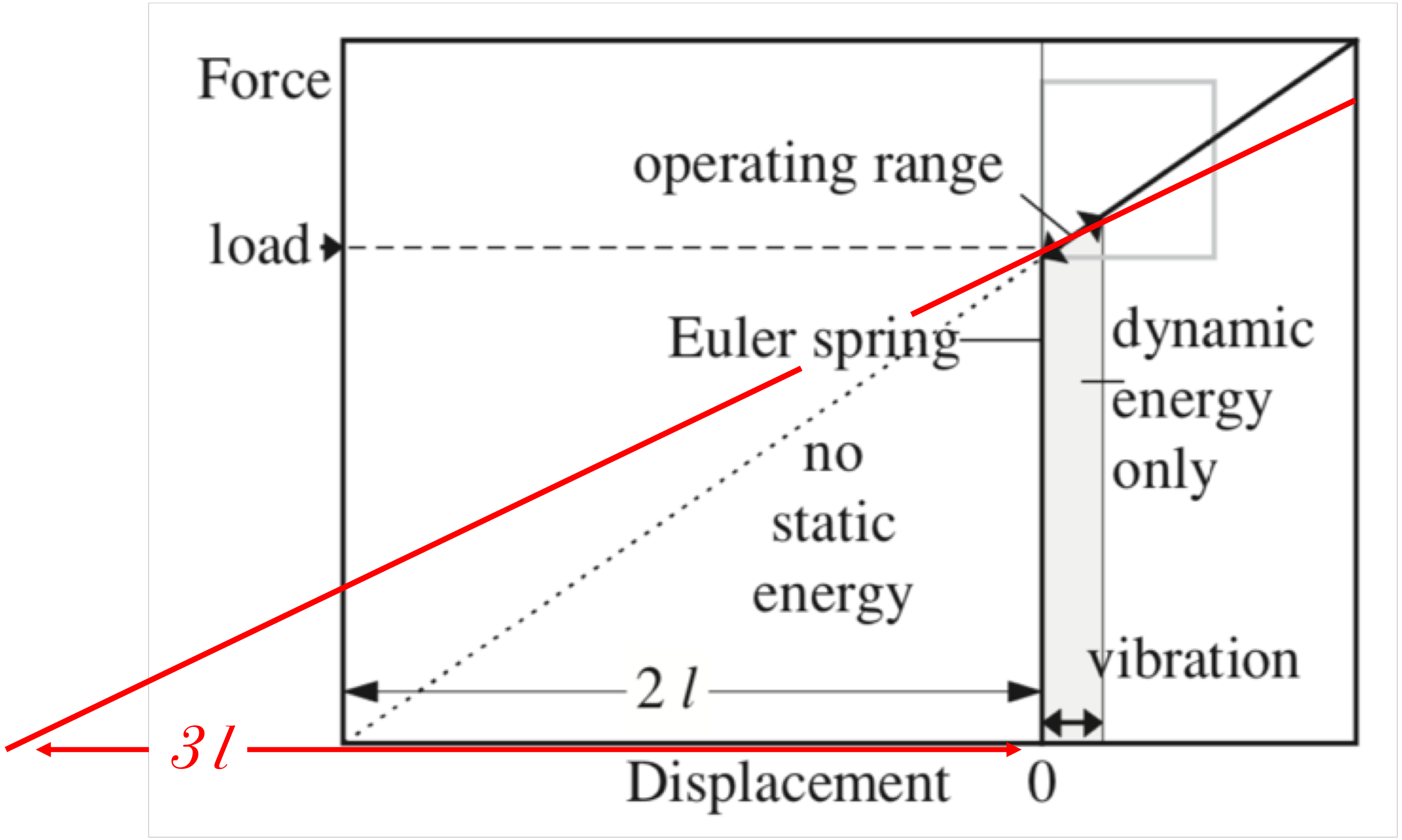
Where do we cut away material?



- Rectangular shape is not evenly stressed, so we change the shape to allow for circular bending
- For symmetry reasons, a monolithic double blade was fabricated



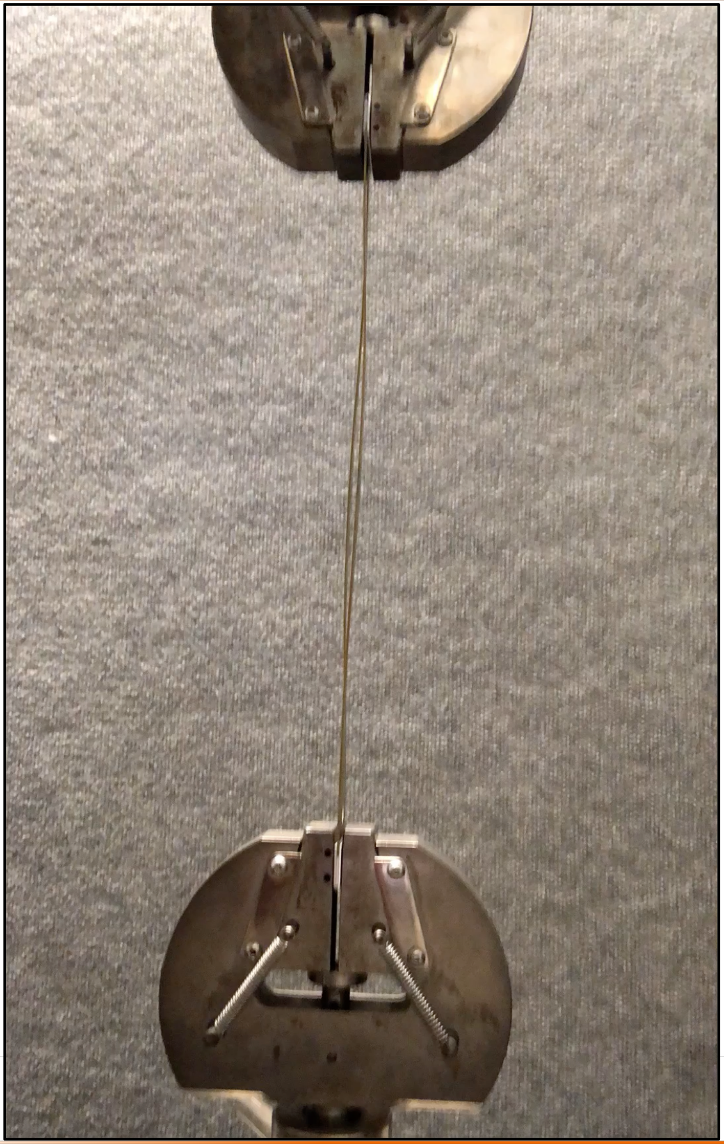
Theoretical stiffness $F_{load}/2L$ slope now $F_{load}/3L$

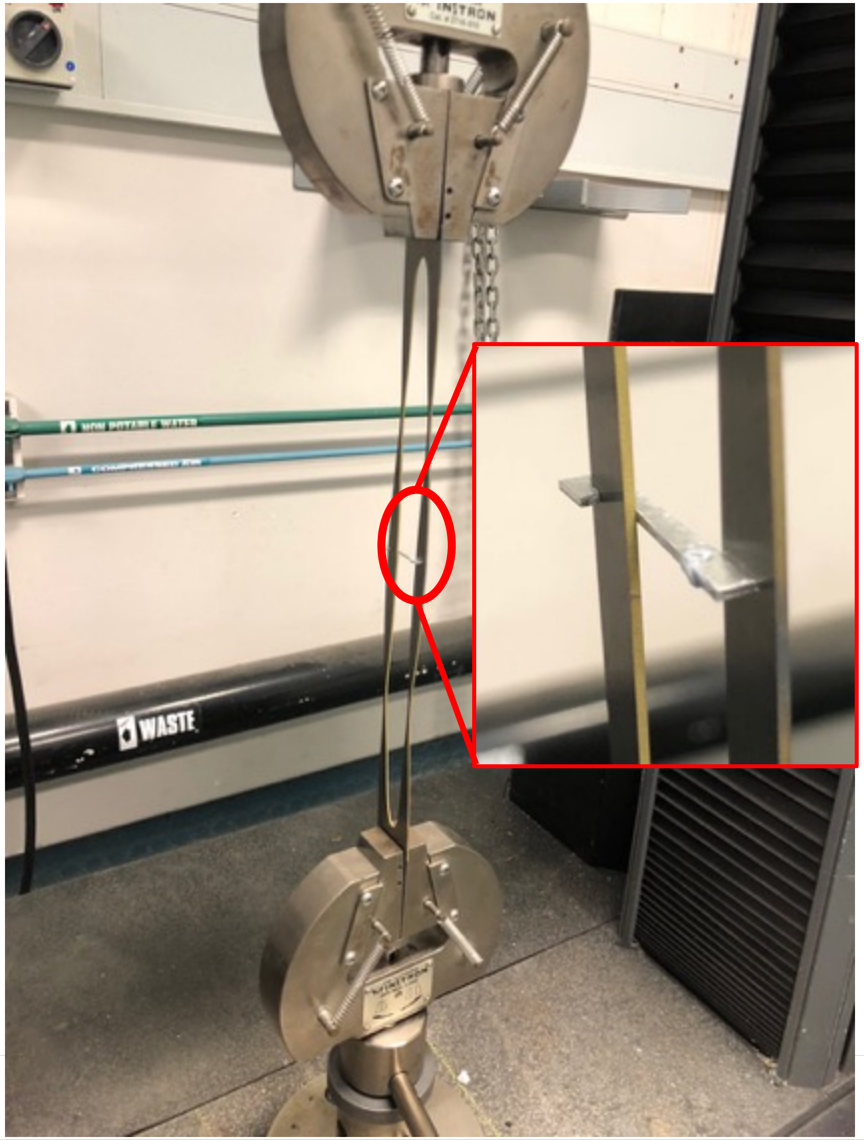


- Curvature is known, so we know energy stored as function of buckling distance;
- Differentiate this to obtain the force as a function of buckling distance as

$$F = \frac{dE_{stored}}{dx}.$$

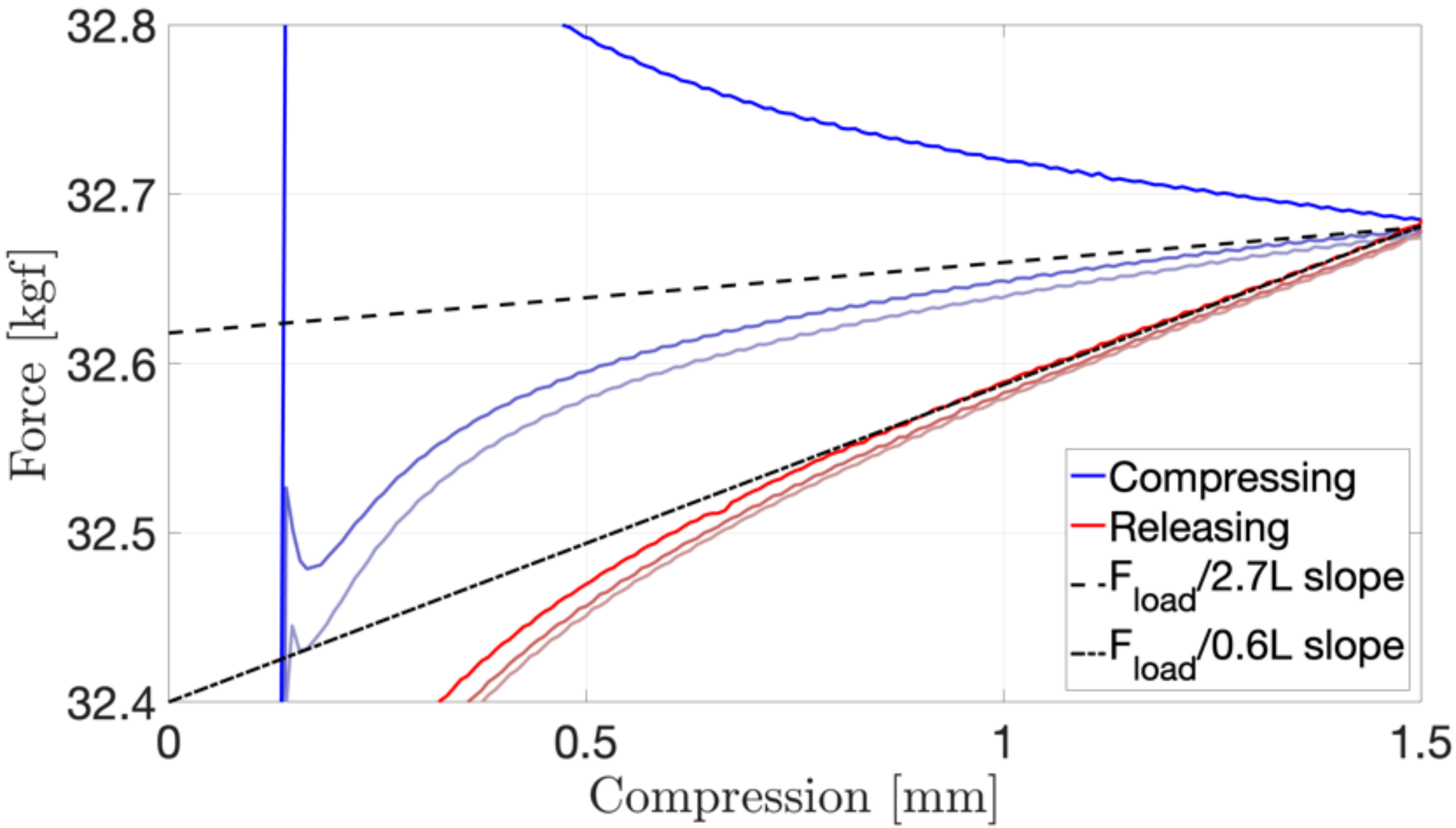
Contoured Euler springs in compression tester



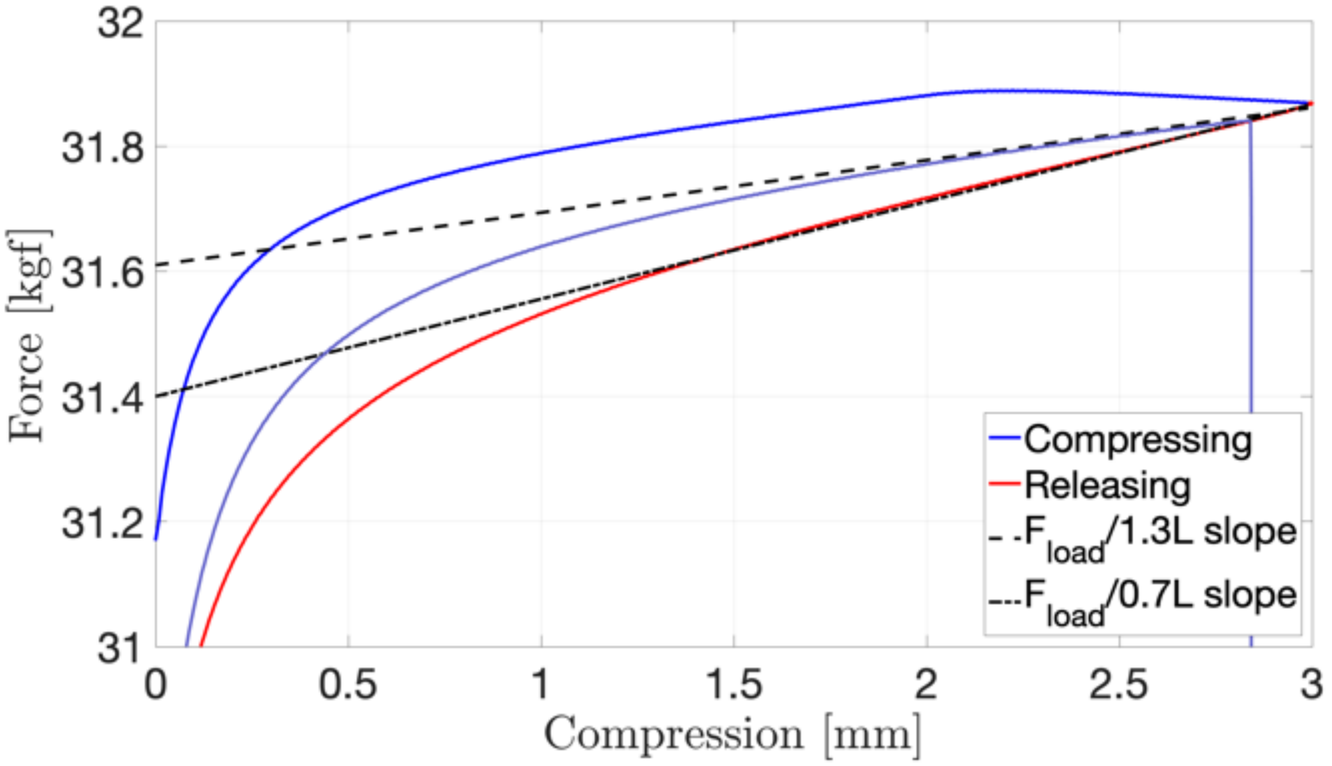


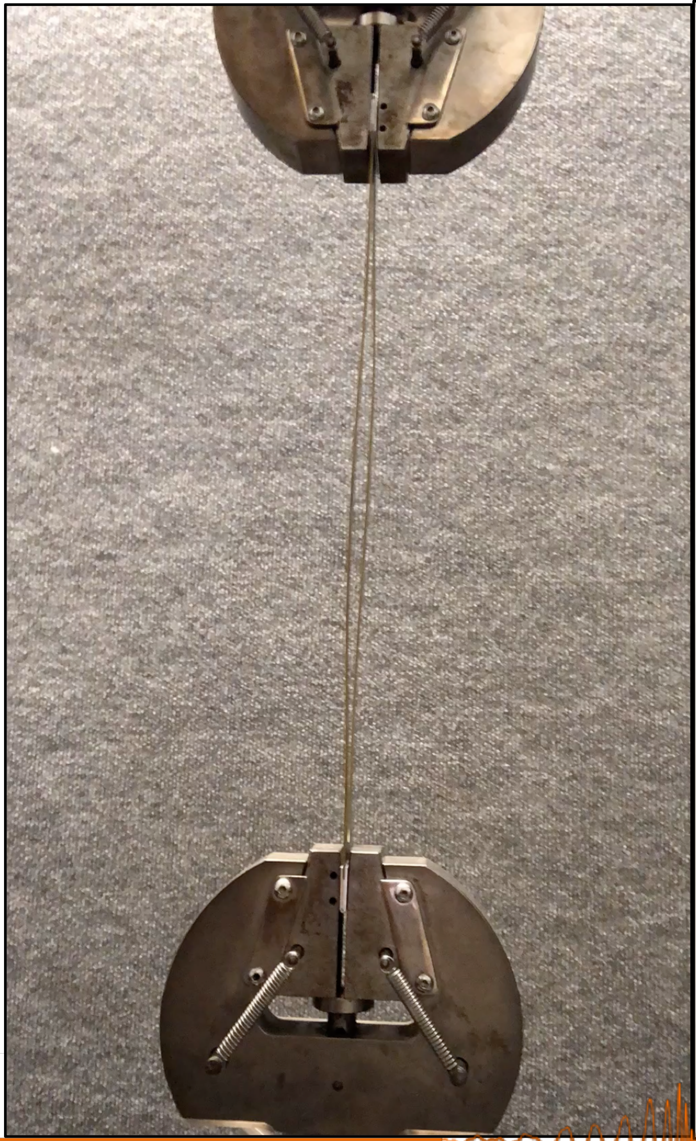
- We need a material that would snap rather then deform;
- We chose Tungsten Carbide to try first.

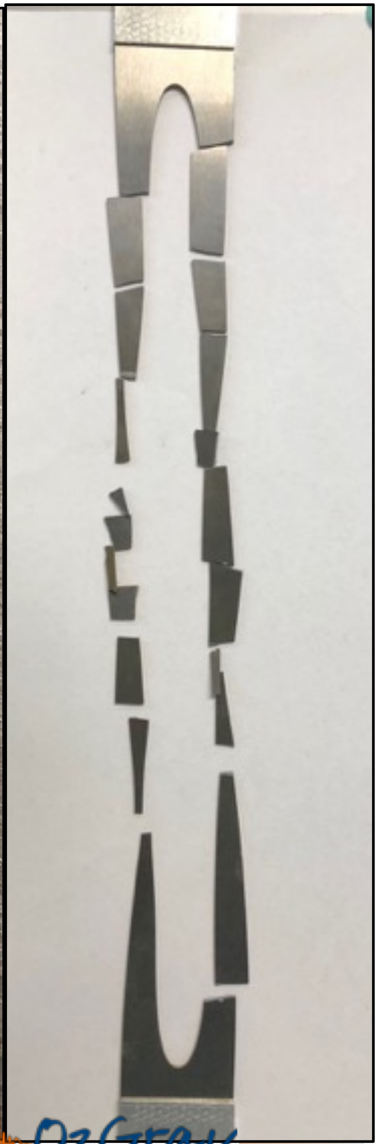
First results look promising for this geometry…



… but Tungsten Carbide is not good enough







joris.vanheijningen@uwa.edu.au

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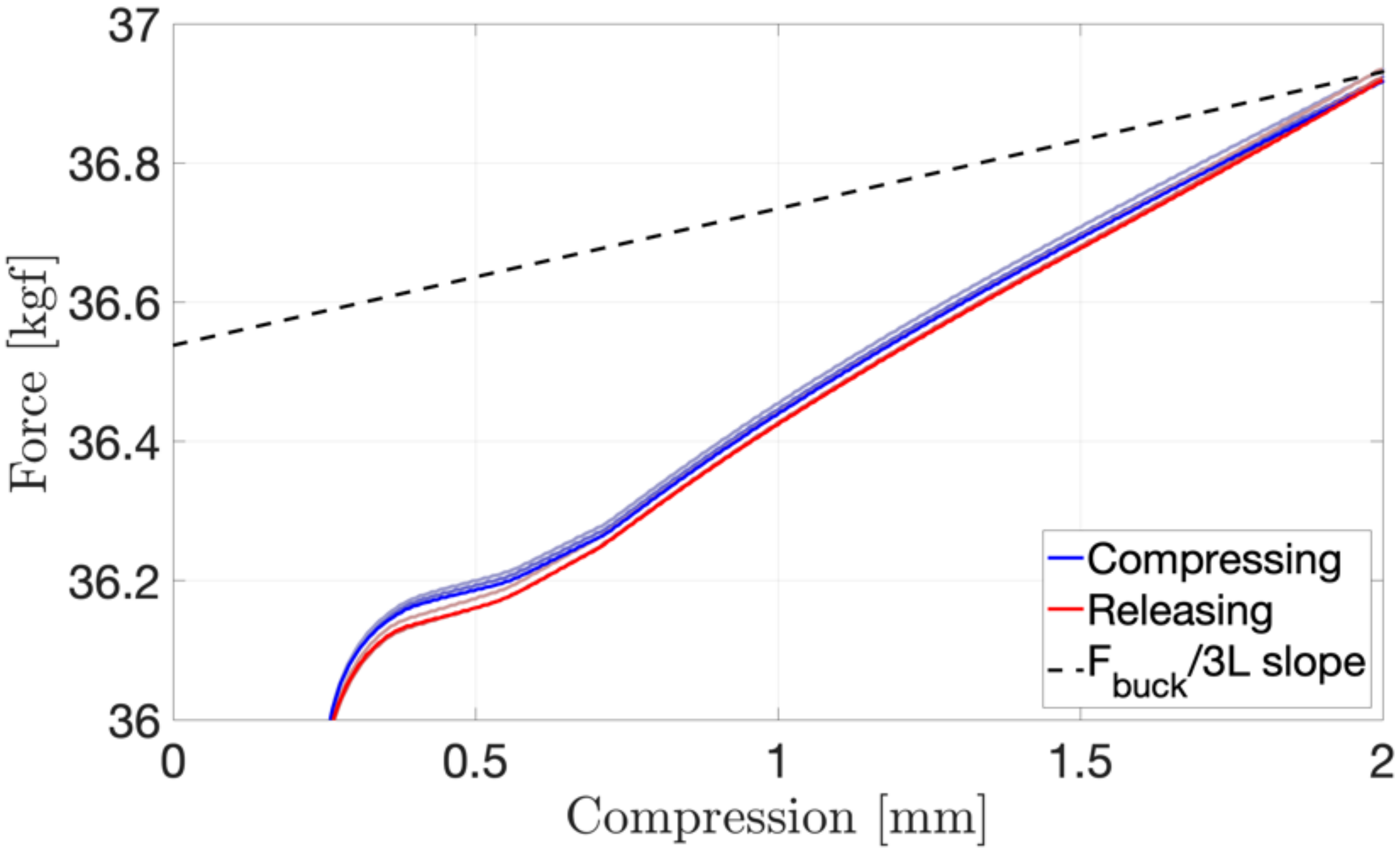
We changed to glassy metal blades

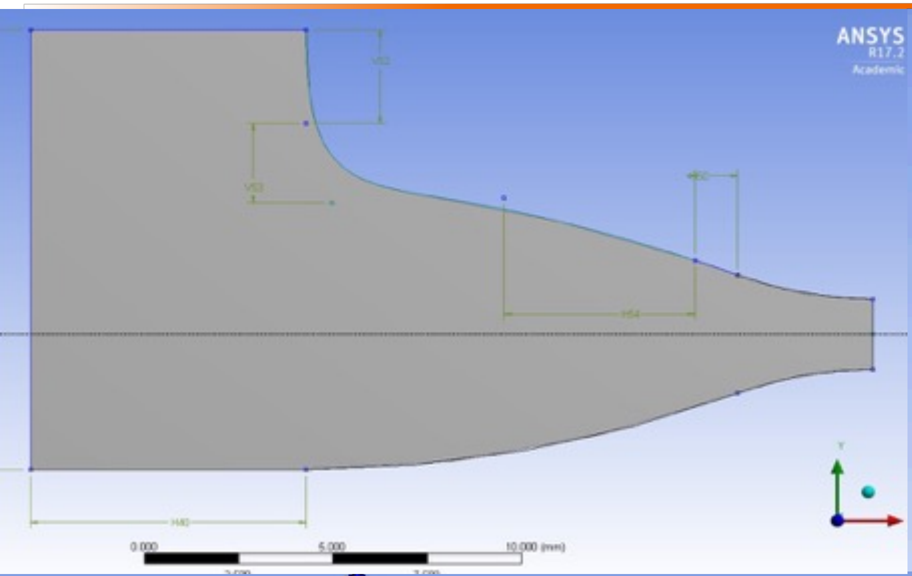
- Zirconium based alloy;
- Amorphous atomic structure;
- High yield strength (2GPa) and elasticity (2%).

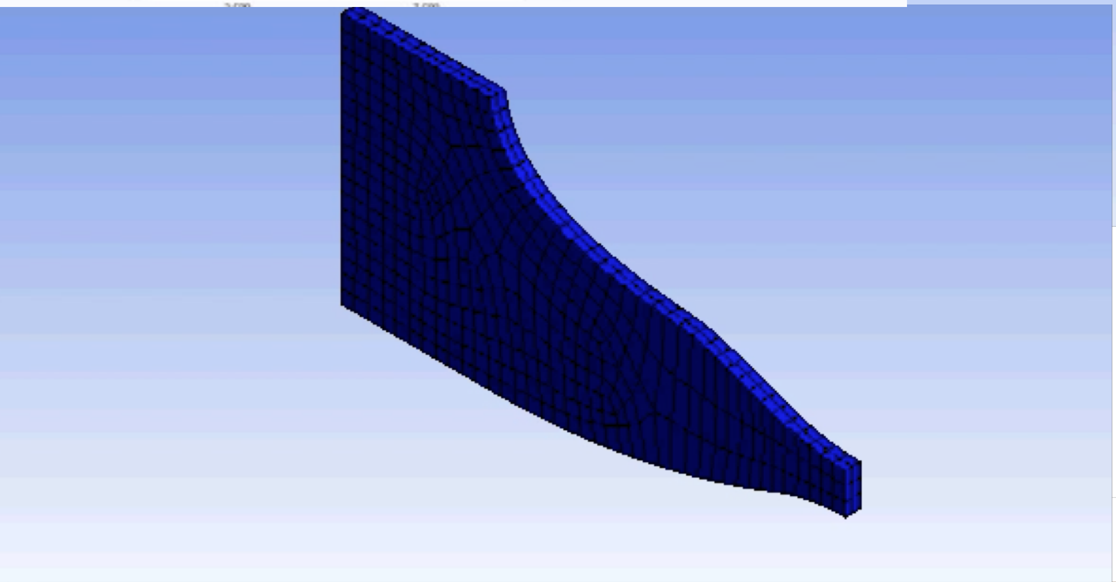
LIQUIDMETAL

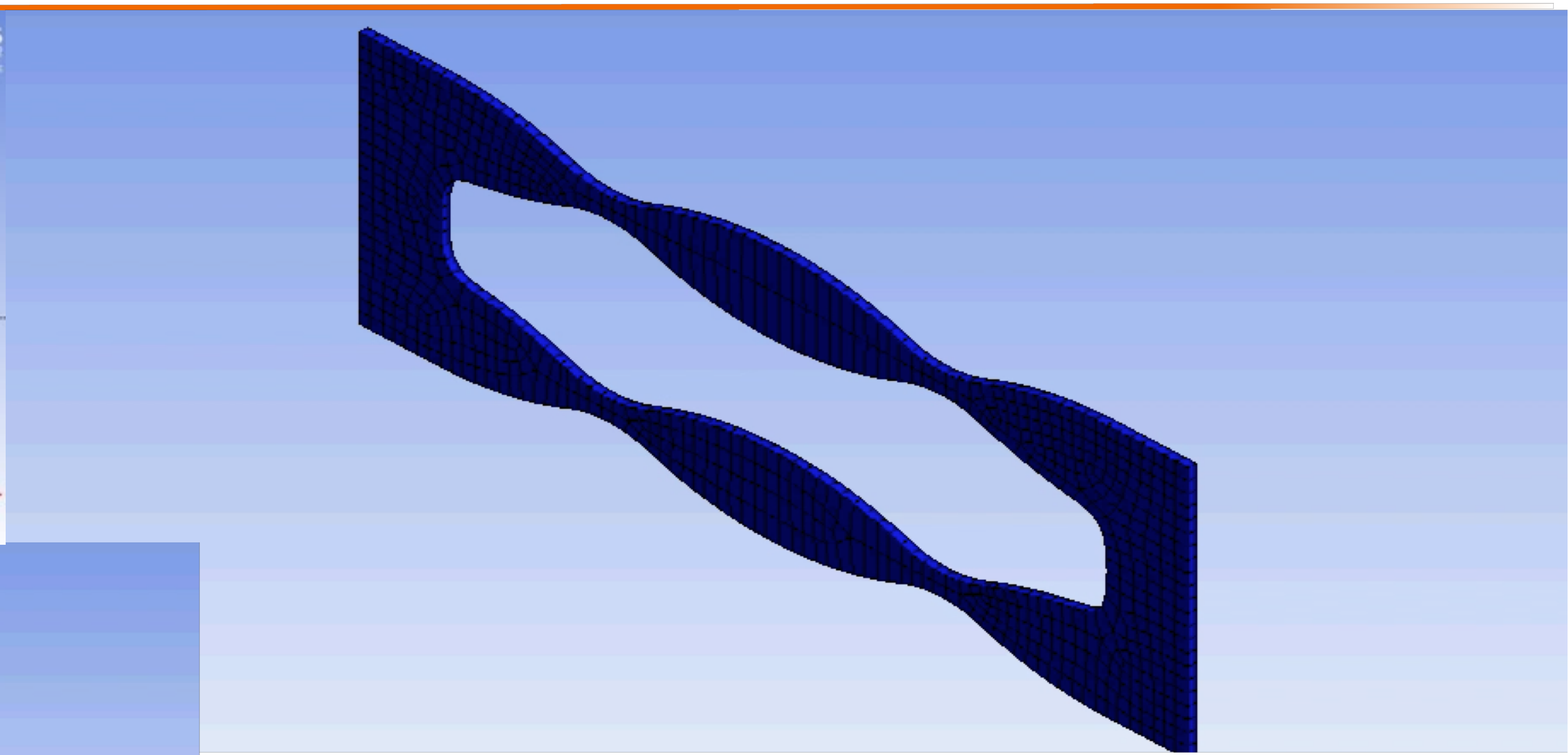
Preliminary results for LM105 glassy metal



Finite element modeling to find optimal shape



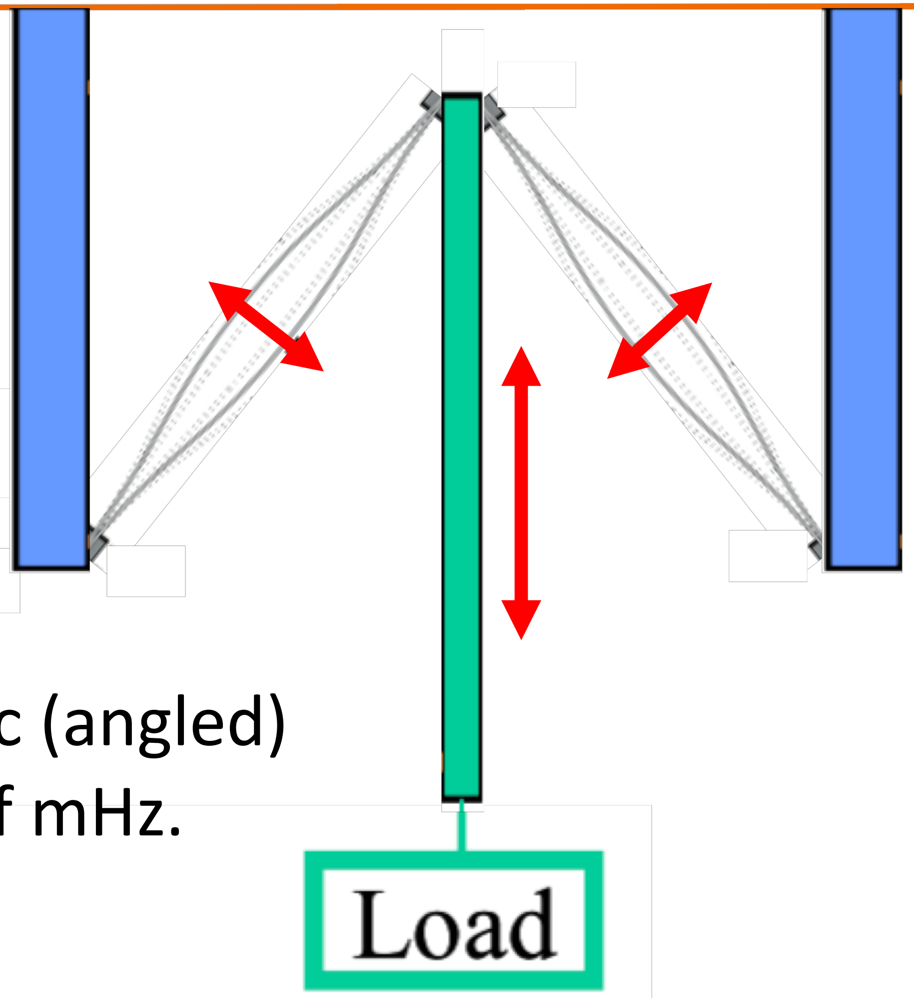




Optimising the shape of monolithic blade for:

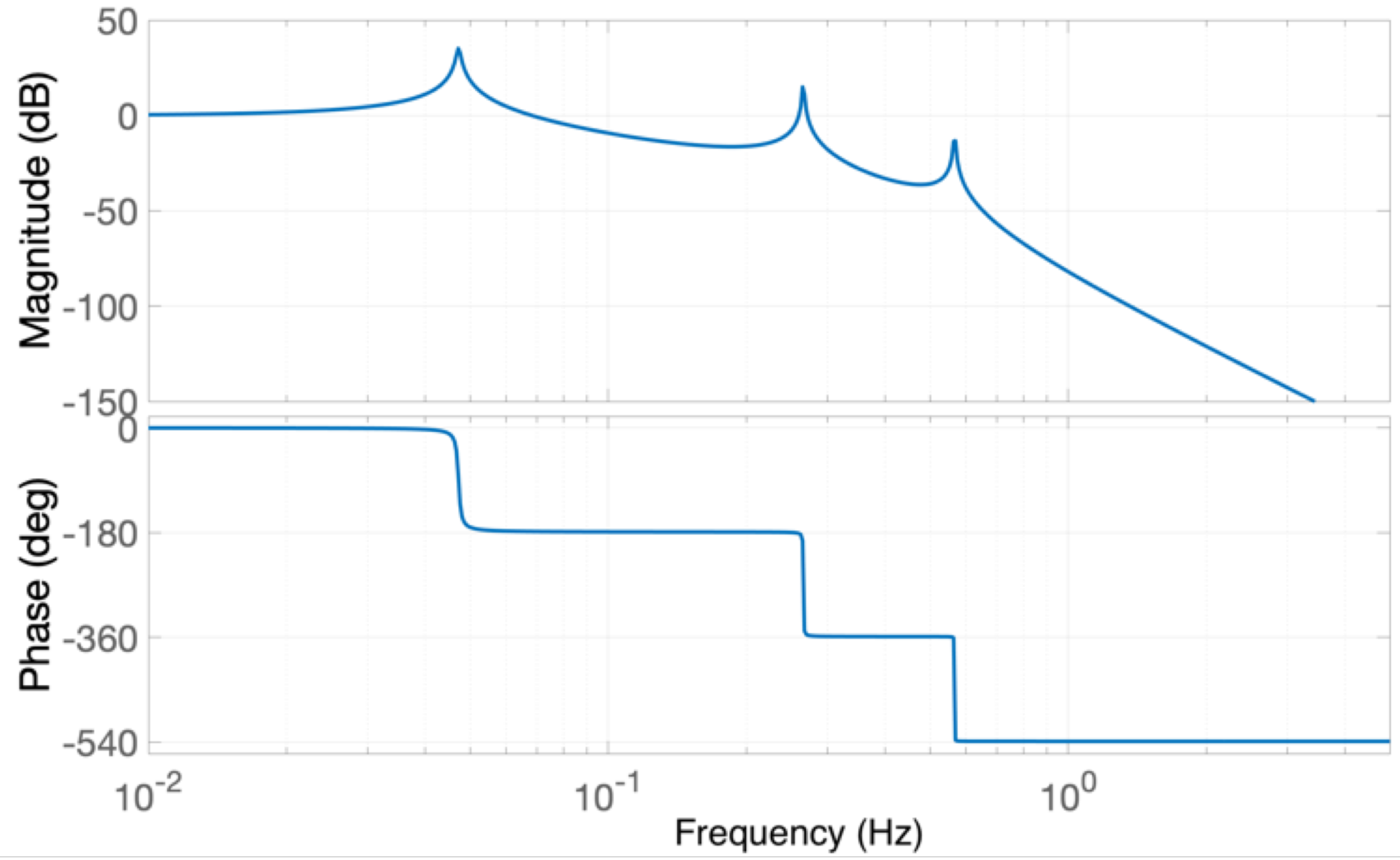
- a homogeneous stress distribution;
- no added stiffness at the base.

Combining two ideas into a pre-isolation stage



- Using contoured and geometric (angled) blades, we aim to reach tens of mHz.

Vertical pre-isolation makes life easier



- 10^{-16} m/√Hz at 2 Hz requires < 10^{-6} isolation;
- With a 50 mHz pre-isolator and two 0.4 Hz stages this is within reach;
- A Virgo SA has 1.5 x 10^{-6} at 2.25 Hz (source: ET-025-09)

Summary

- Putting the blade under an angle and changing its shape lowers the stiffness and increases the internal mode frequencies;
- Tungsten carbide blade measurements have shown us the promise of the contouring;
- Glassy metals results are not fully understood, but are not lossy and constant slope;
- We propose combining the two improvements in Euler spring design to conceive a vertical pre-isolator for future detectors.

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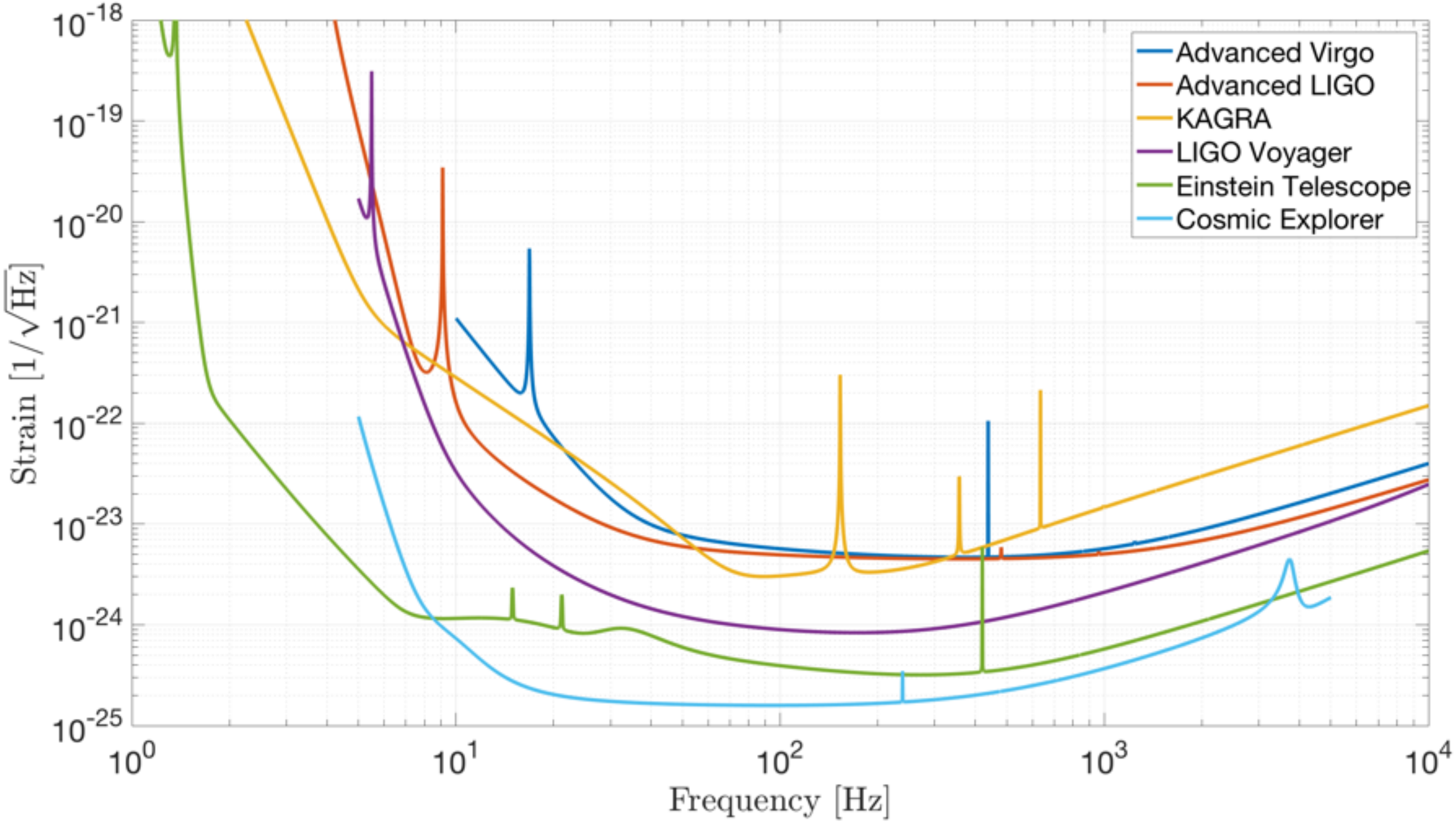
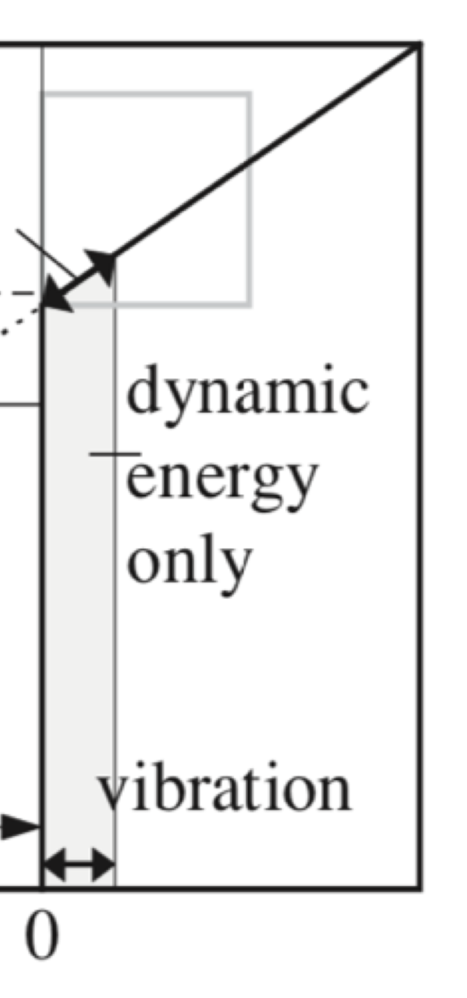
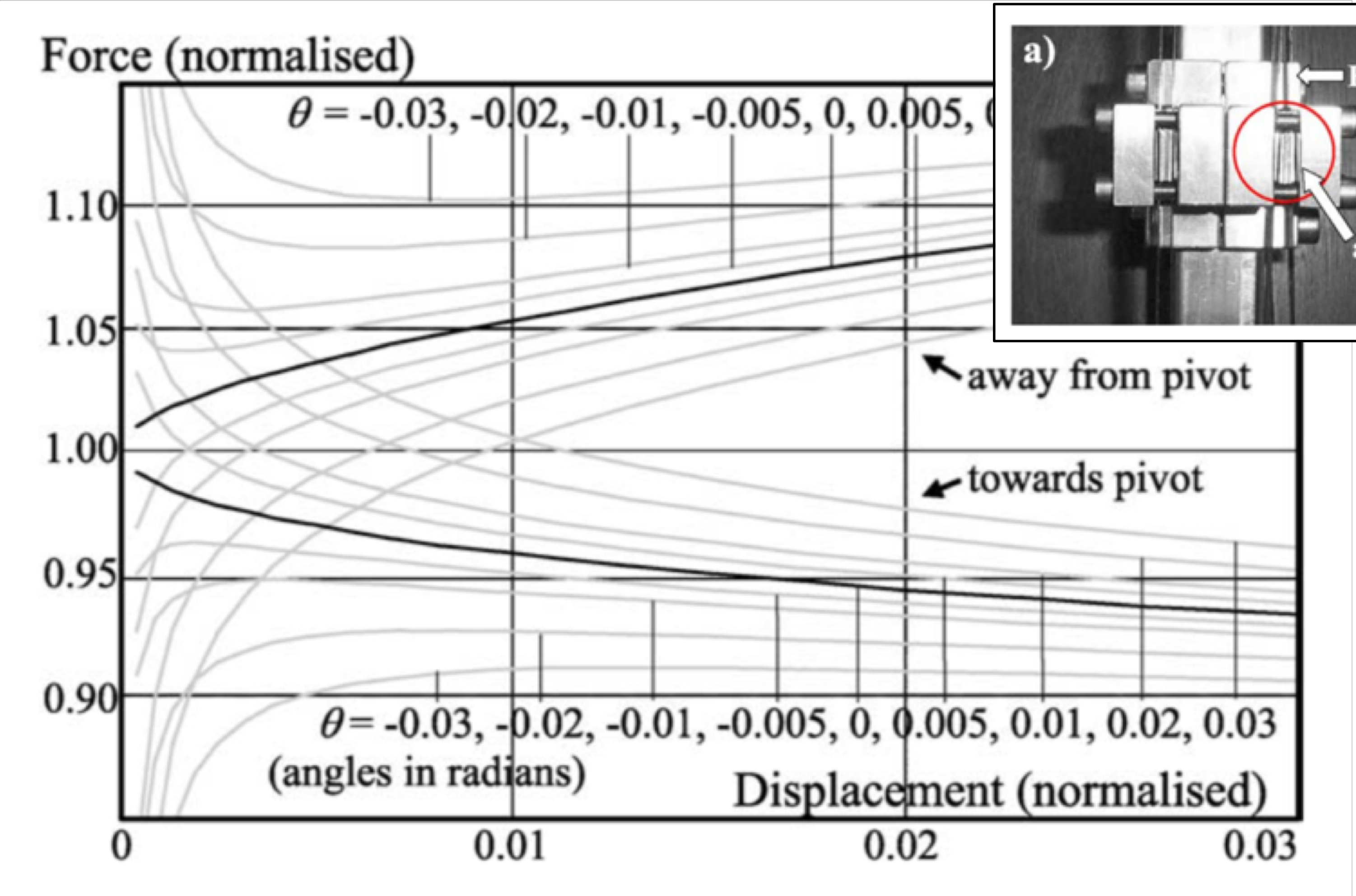
2G and 3G detector sensitivities

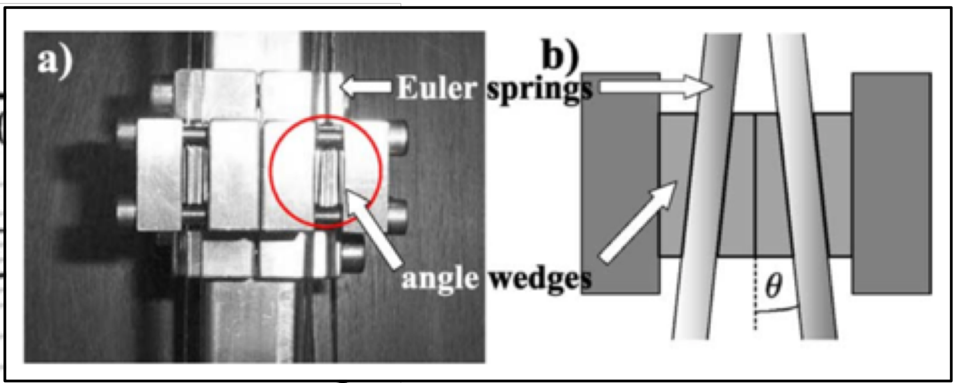


M. Evans, "Unofficial sensitivity curves (ASD) for aLIGO, Kagra, Virgo, Voyager, Cosmic Explorer and ET", DCC document T1500293-v11

Launching angle can cancel slopes

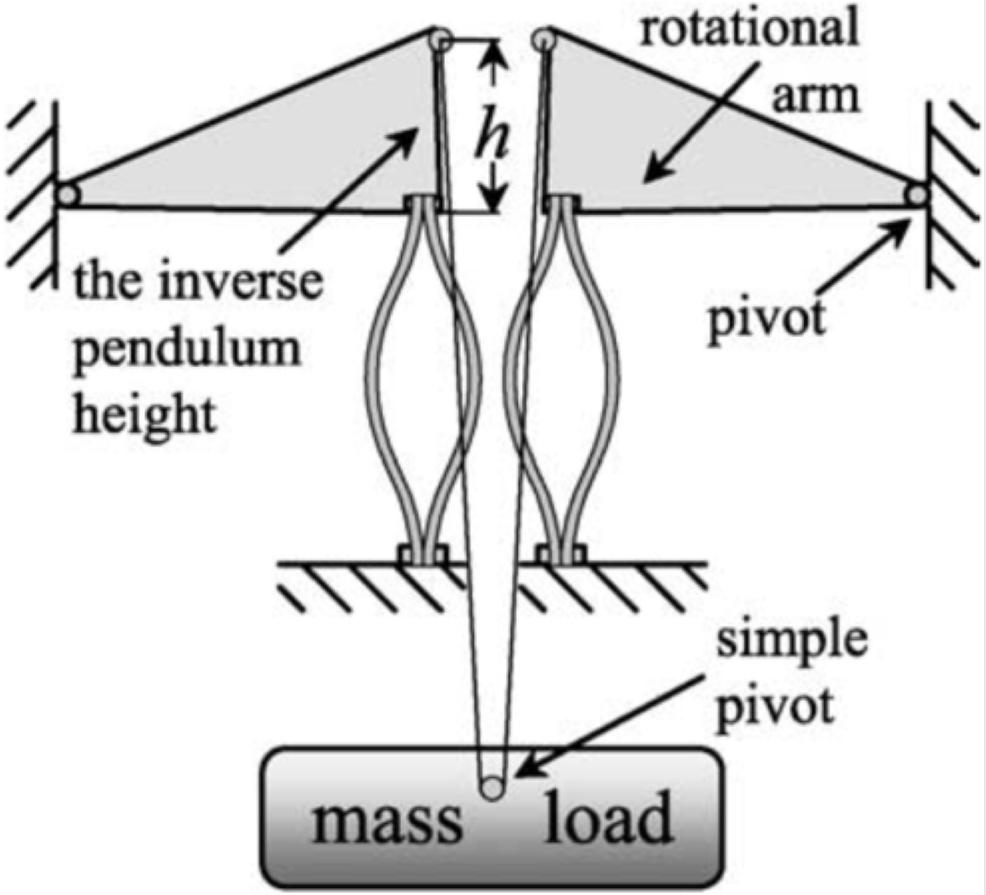


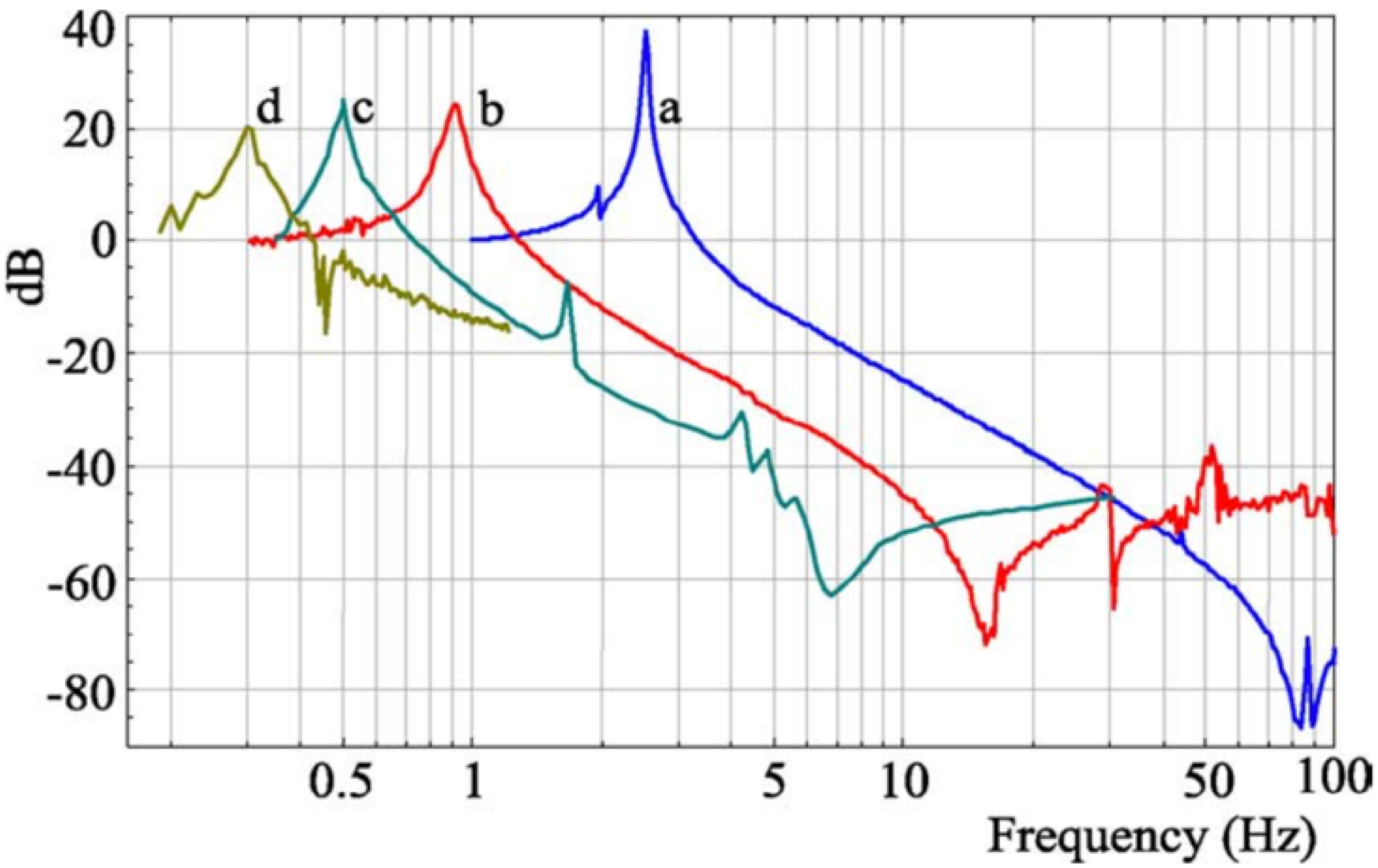




E.J. Chin, K.T. Lee, J. Winterflood, L. Ju & D.G. Blair, "Low frequency vertical geometric anti-spring vibration isolators", Physics Letters A 336 (2005) 97–105

An ideal versus a real Euler spring





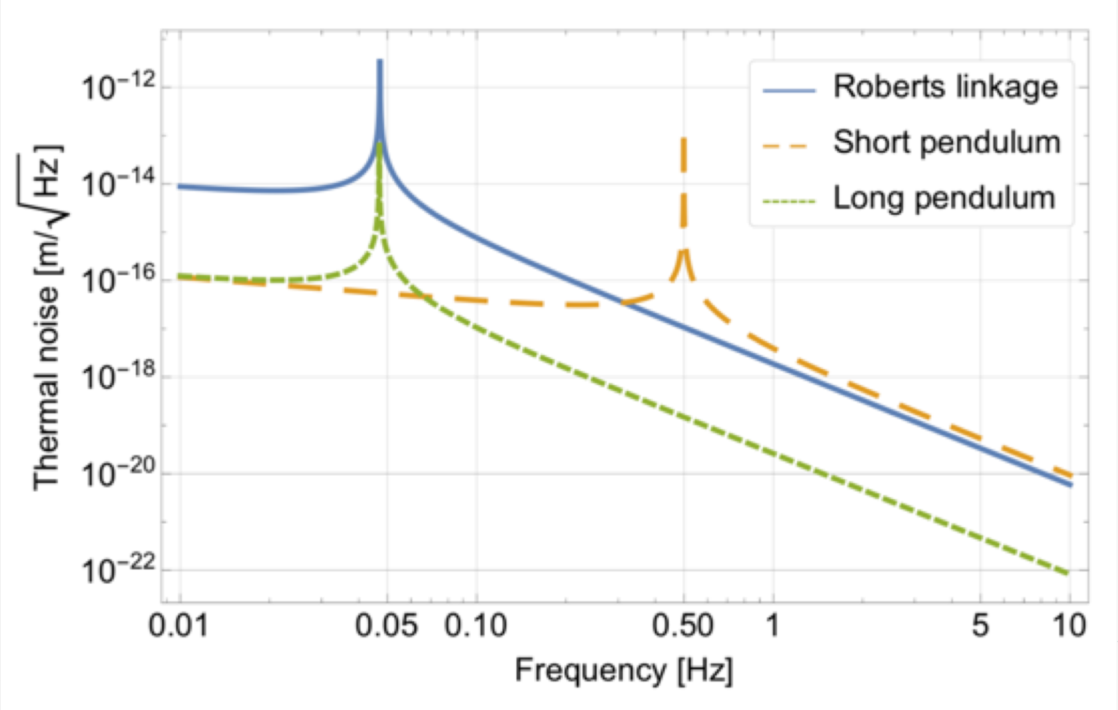
E.J. Chin, K.T. Lee, J. Winterflood, L. Ju & D.G. Blair, "Low frequency vertical geometric anti-spring vibration isolators", Physics Letters A 336 (2005) 97–105

What about thermal noise?

Suspension-thermal noise in spring-antispring systems for future gravitational-wave detectors

Jan Harms
Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy

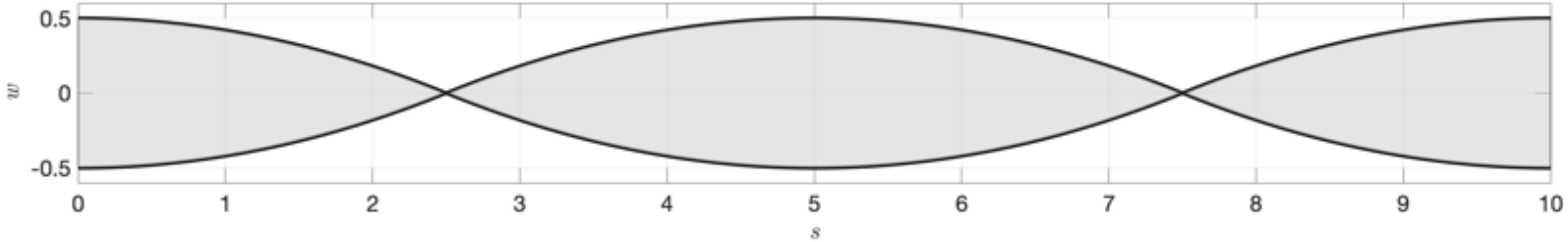
Conor M Mow-Lowry
Institute of Gravitational Wave Astronomy, School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK



- ➢ It seems 'cheating' with the resonance frequency does not give (much) in terms of thermal noise
- ➢ So we propose to do the same trick as is done in horizontal: a very high Q final stage in vertical

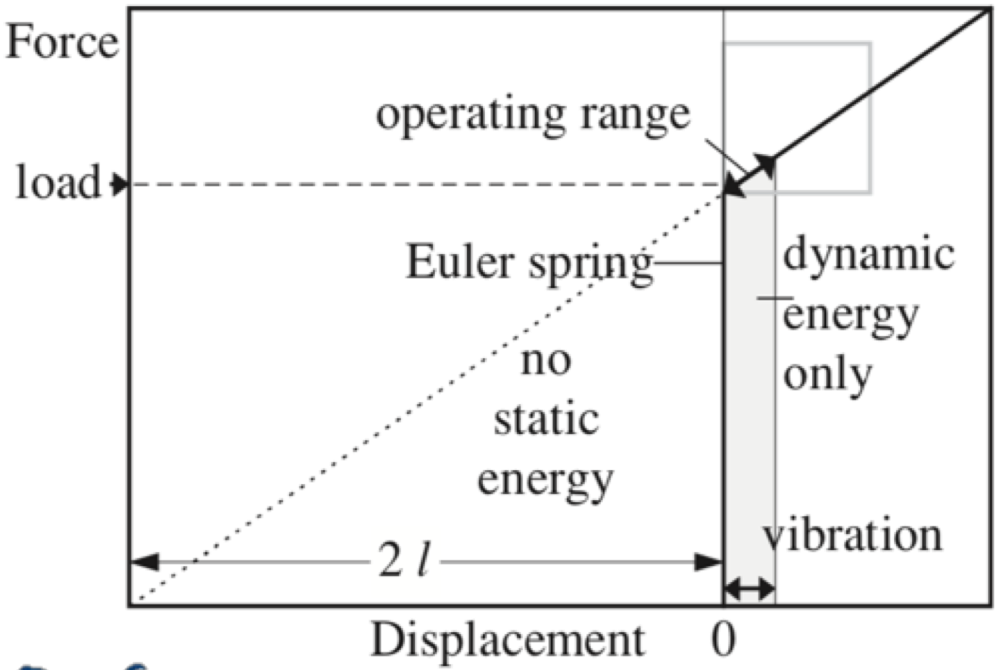
Optimised Euler Spring blade

$$w(s) = \frac{\pm w_0}{2 + 2\cos\left(\frac{\ell}{8\pi R}\right)}\left[\cos\left(\frac{s_{\mathrm{pw}}}{2\pi R}\right) - \cos\left(\frac{\ell}{8\pi R}\right)\right]$$
$$= \frac{\pm w_0}{4}\left[\cos\left(\frac{s_{\mathrm{pw}}}{2\pi R}\right) - \cos\left(\frac{\ell}{8\pi R}\right)\right]\csc^2\left(\frac{\ell}{16\pi R}\right)$$



$$F_{\mathrm{buck}} = \Bigg(- Y t^3 w_0 \csc^2\left[\frac{\arccos\left(\frac{\ell - x}{\ell}\right)}{4\pi}\right]\left[2\pi \arccos\left(1 - \frac{x}{\ell}\right)\left(1 + 2\cos\left[\frac{\arccos\left(1-\frac{x}{\ell}\right)}{2\pi}\right]\right)\right]$$
$$+ \arccos^2\left(1 - \frac{x}{\ell}\right)\cot\left[\frac{\arccos\left(1-\frac{x}{\ell}\right)}{4\pi}\right] + 4\pi^2 \sin\left[\frac{\arccos\left(1-\frac{x}{\ell}\right)}{2\pi}\right]\Bigg)\left(6\ell^2\pi\sqrt{\frac{(2\ell - x)x}{\ell^2}}\right)^{-1}$$

$$= 1 + \frac{(3 + 28\pi^2)x}{84\pi^2} + \frac{(3 + 60\pi^2 + 448\pi^4)x^2}{3360\pi^4}$$



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Glassy metals: amorphous non-crystalline structure

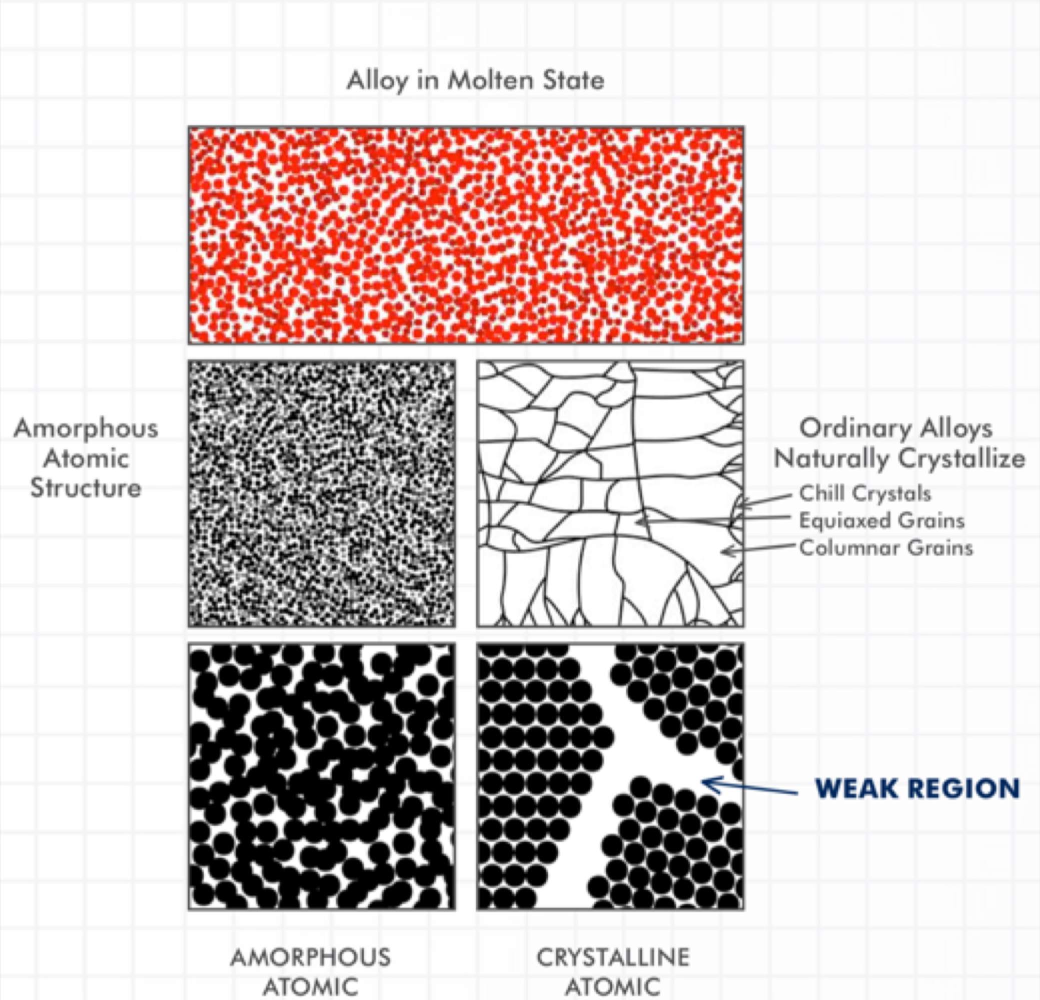
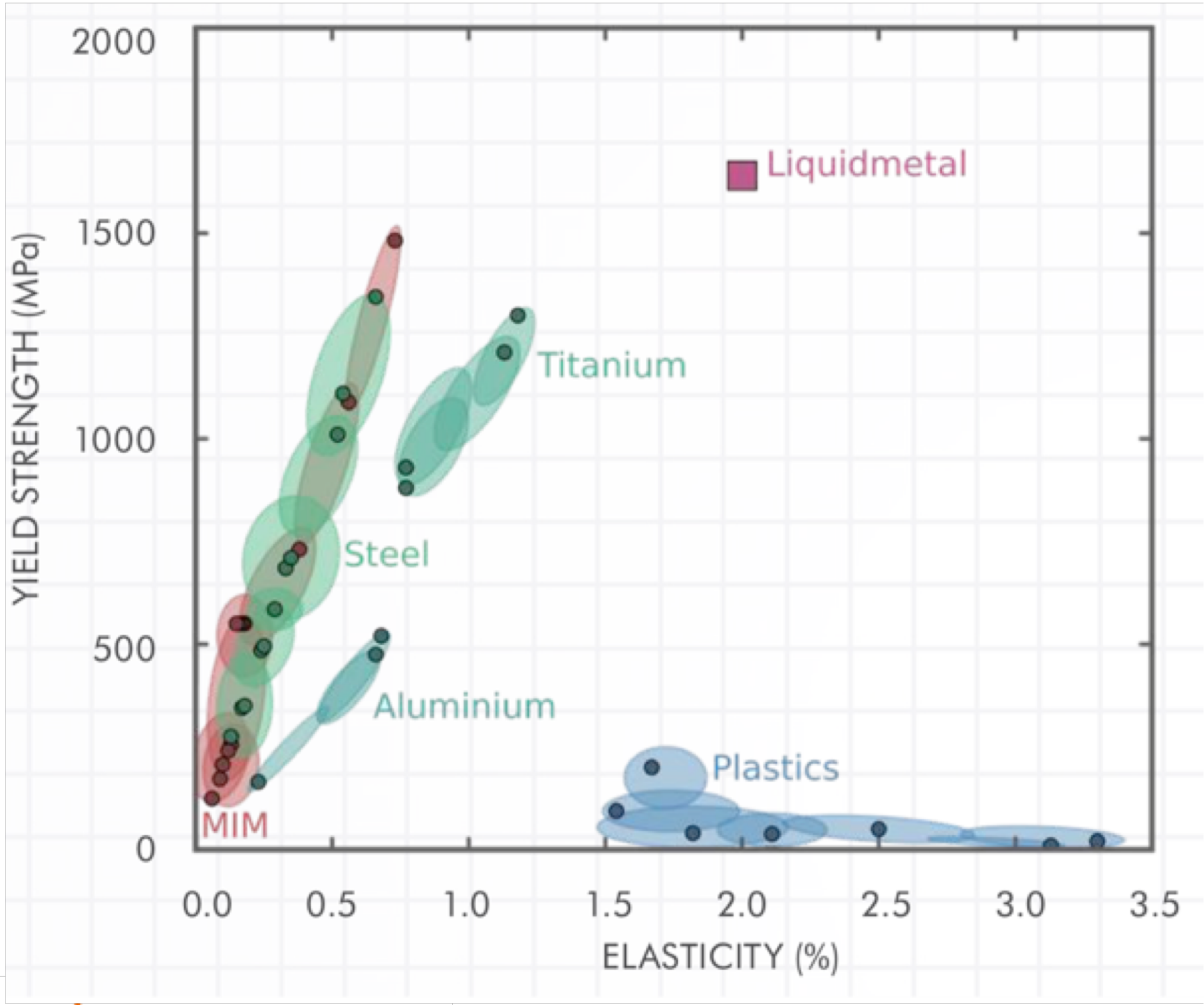
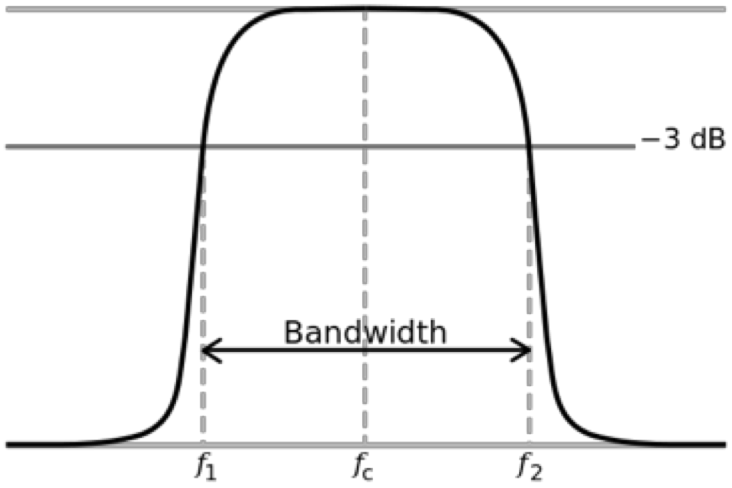
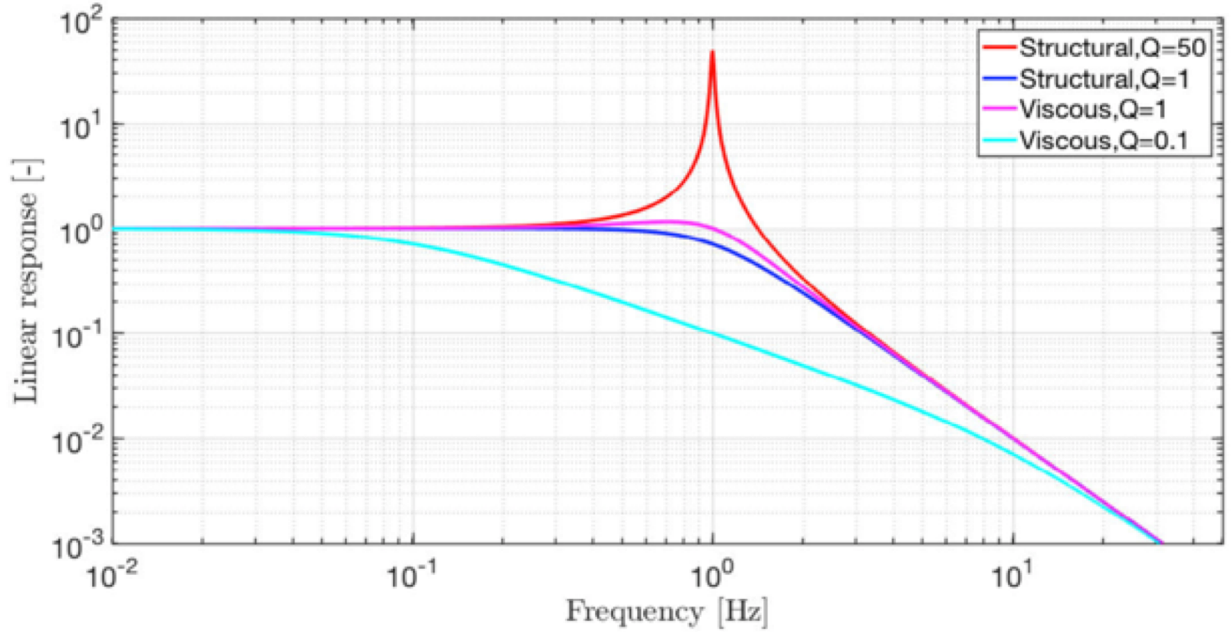


Figure 2.



Intermezzo: quality factor of a spring



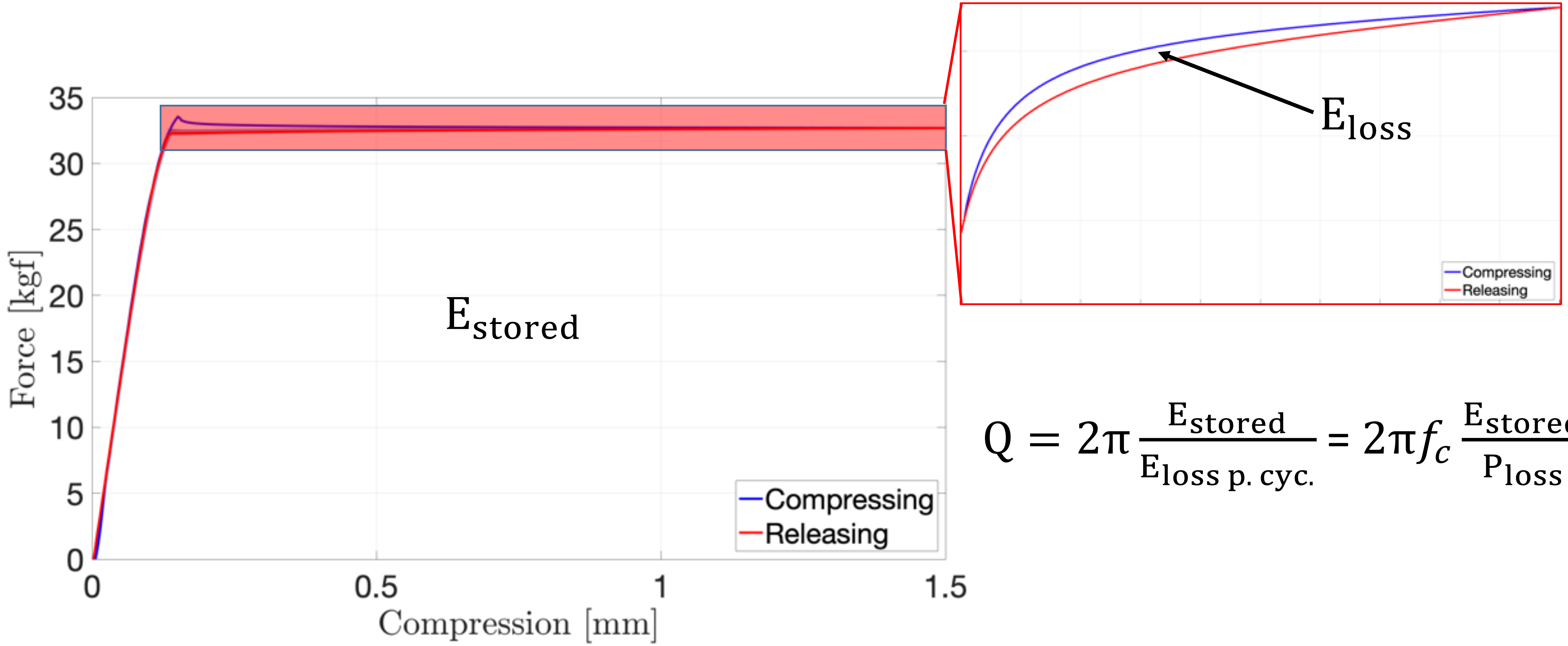


$$Q = \frac{f_c}{\Delta f} = \frac{f_c}{f_2 - f_1}$$

$$\mathcal{H}_v = \frac{\omega_0^2}{\omega_0^2 + i\frac{\omega_0\ \omega}{Q} - \omega^2}, \text{ where } Q_v = \frac{m\omega_0}{\gamma}$$

$$\mathcal{H}_s = \frac{\omega_0^2}{\omega_0^2(1 + i\phi) - \omega^2}, \text{ where } Q_s = \frac{1}{\phi}$$

Quality factor determined from areas



$$Q = 2\pi \frac{E_{stored}}{E_{loss\ p.\ cyc.}} = 2\pi f_c \frac{E_{stored}}{P_{loss}}$$