Design and Optimization of a Quasi Zero-Stiffness System for Low-Frequency Vibration Isolation in Magneto Cryo-Nanoscope

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Introduction

Scanning Near-Field Optical Microscopy (SNOM) allows researchers to visualize and characterize nanostructures and nanoscale phenomena with exceptional detail, reaching a spatial resolution down to tens of nanometers or even below. This fine level of resolution has unraveled hidden intricacies in materials, leading to breakthroughs in various scientific disciplines since traditional optical microscopes are limited by the diffraction of light.

An AFM probe is used to scan the sample's surface with subwavelength precision. This tip is brought into close proximity to the sample surface. At such close distances, the interaction between the light, tip, and sample significantly modifies the optical scattering from the tip, leading to the generation of near-field evanescent waves. Usually, a commercial SNOM is operated at room temperature without cryogen. A perfect vibration isolation is not needed in most cases.

Low-temperature measurements are crucial for studying phase transitions and correlated states in 2D materials. To conduct SNOM at low temperatures for material characterization is, however, a daunting task, especially with a close-cycle cryostat. For example, a closed-cycle dilution refrigerator usually requires frequency isolation to prevent the transmission of low-frequency noise from the pulse tube into the scanning probe system. We recently built a room-temperature SNOM and two cryo-SNOMs in Liu's lab. Our task is to improve the performance of those systems.

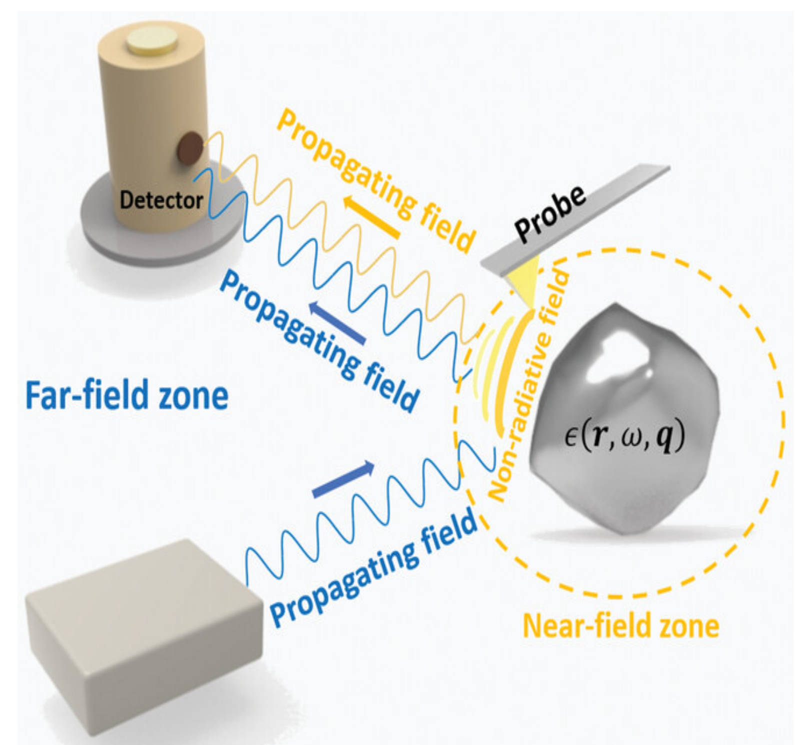

Figure 1. Far-field (blue) and near-field (yellow) measurements, accessing the propagating and evanescent fields, respectively. [1]

Room-Temperature SNOM

- Supports a faster, more **cost-effective**, **environmentally friendly,** and **sustainable** approach by acting as a playground for preliminary studies
- **Thermal noise** and **drift** become more pronounced, requiring sophisticated noise reduction and signal processing techniques.

TGQ Testing Gradient Measurements using RT SNOM

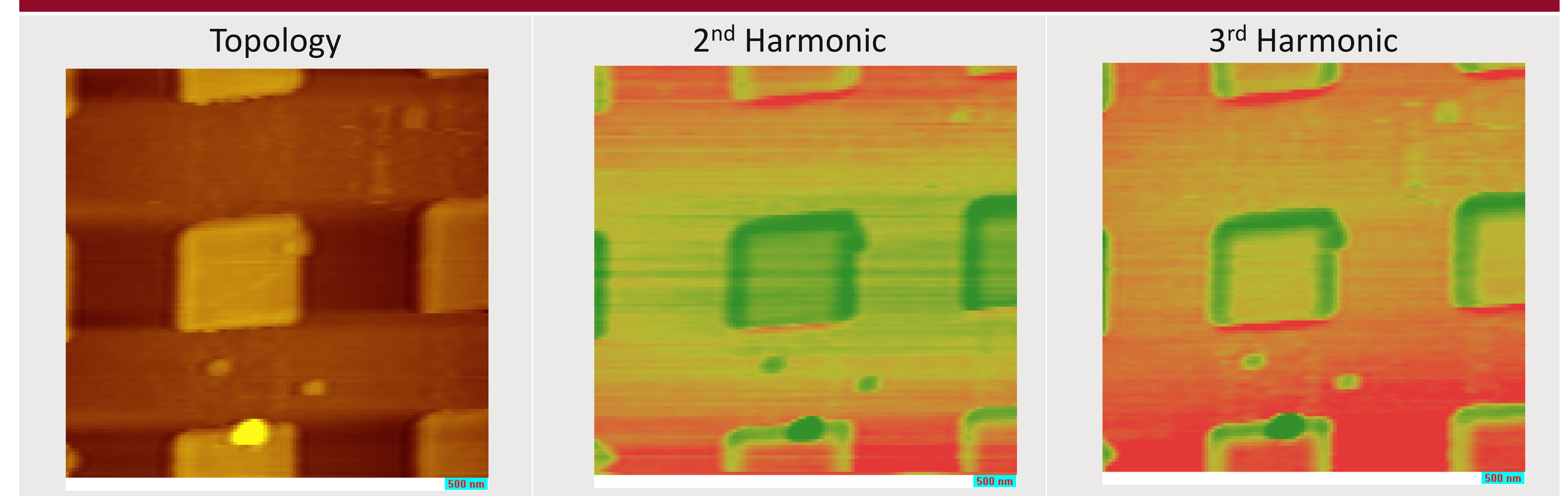

Table 1. Maximum noise-to-signal ratio for the first three harmonics in TGQ. The first image reveals the topographic information of the sample surface with subwavelength resolution, while the second and third harmonics offer deeper insights into the sample's local optical properties and material composition. Images via room-temperature measurements in SNOM 3 in Liu's Lab.

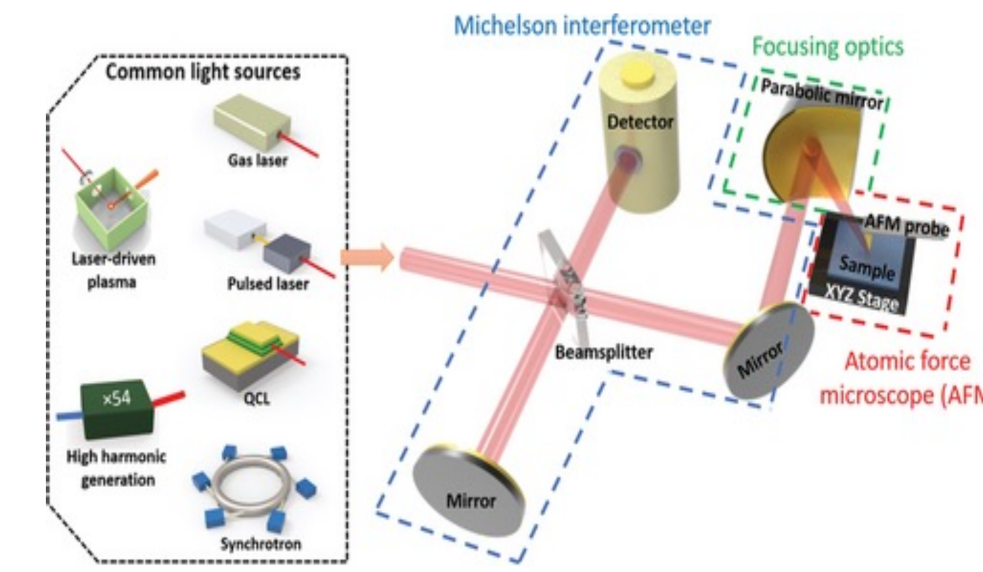

Figure 2. SNOM Schematic. [1]

Conclusions

The room temperature SNOM setup has the potential as a versatile playground for samples and lasers, paving the way for future s-SNOM measurements. By providing a platform to explore and optimize various experimental parameters, this system becomes a crucial steppingstone toward enhanced sensitivity and resolution in nanoscale imaging and spectroscopy.

Once the QZS activity of the flexure is fine-tuned, we will optimize the structure's natural frequency to less than 1 Hz, allowing low-frequency noise from the cooling system to be mitigated.

A quasi-zero stiffness flexure acts as a soft, long spring with a **spring constant close to zero**, allowing for low resonance frequency with **higher stability** in a **compact package**, allowing depression of low-frequency noise.

- Closed-cycle dilution refrigerators introduce **low-frequency noise** directly to the SNOM. Attenuating such frequencies requires a passive damper with a resonance frequency of **less than 1 Hz.**
- In traditional linear isolators, reducing stiffness requires long, soft springs and results in larger static deflections. Nonlinear isolators achieve a balance between **high static stiffness** and **low dynamic stiffness**.
- Quasi-zero stiffness can be achieved with linear isolators and a buckling component, but this reduces the stability of the system. A single flexure introduces higher stability.

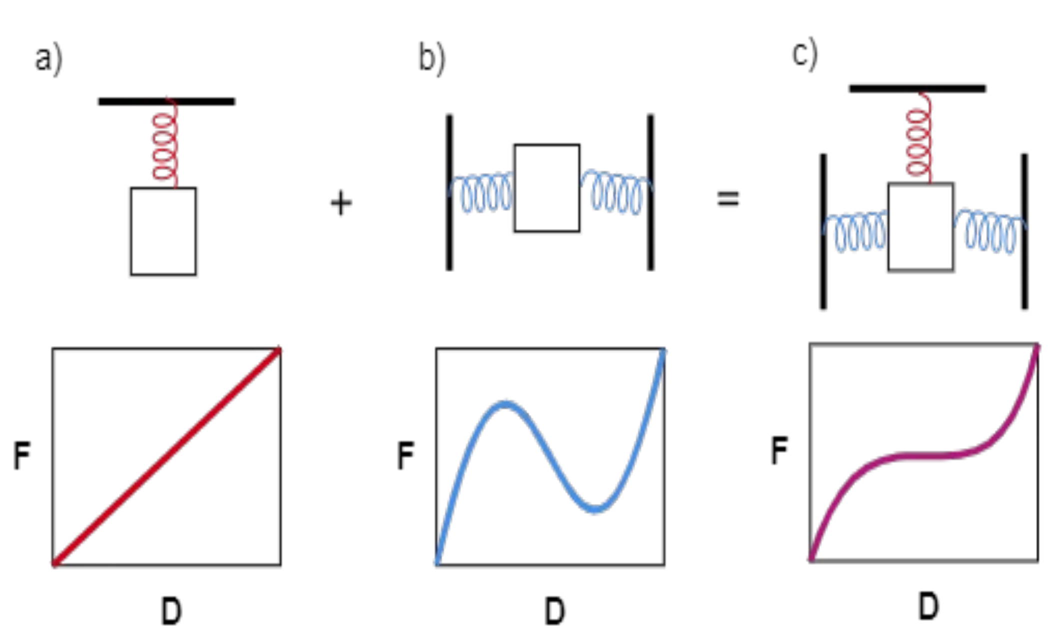

Figure 4. Positive Stiffness (a) can be combined with negative stiffness (b) to create quasi-zero stiffness (c).

Flexure Design and Simulation

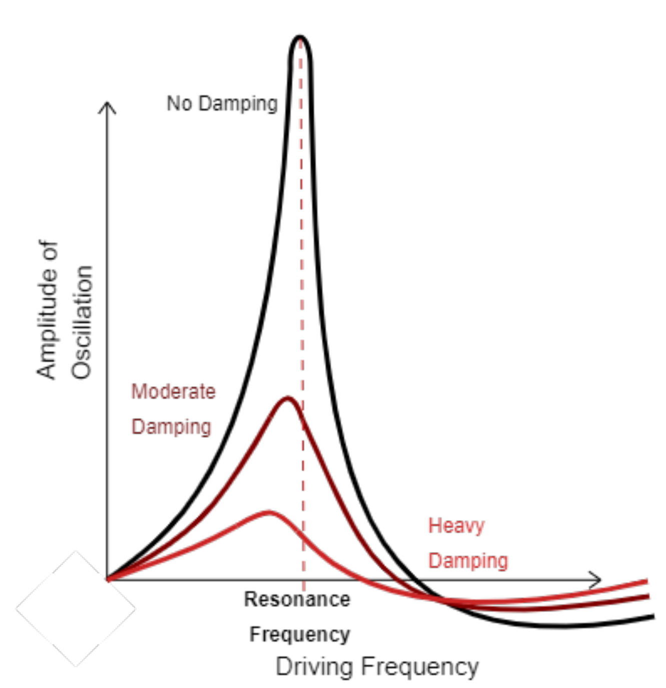

Figure 3. Steady-state variation of amplitude with frequency and damping of a driven simple harmonic oscillator. Vibration isolation occurs at frequencies higher than $\sqrt{2}f_{(resonance)}$

- We use COMSOL Multiphysics software for finite element analysis. We investigate the mechanical behavior and performance of the flexure under different loading conditions and fine-tune the geometry and material properties to achieve enhanced vibration isolation and expanded working ranges for the QZS system.
- Our design exclusively employs curved beams and excludes the use of springs. This configuration is specifically tailored to meet the stringent requirements of SNOM applications.

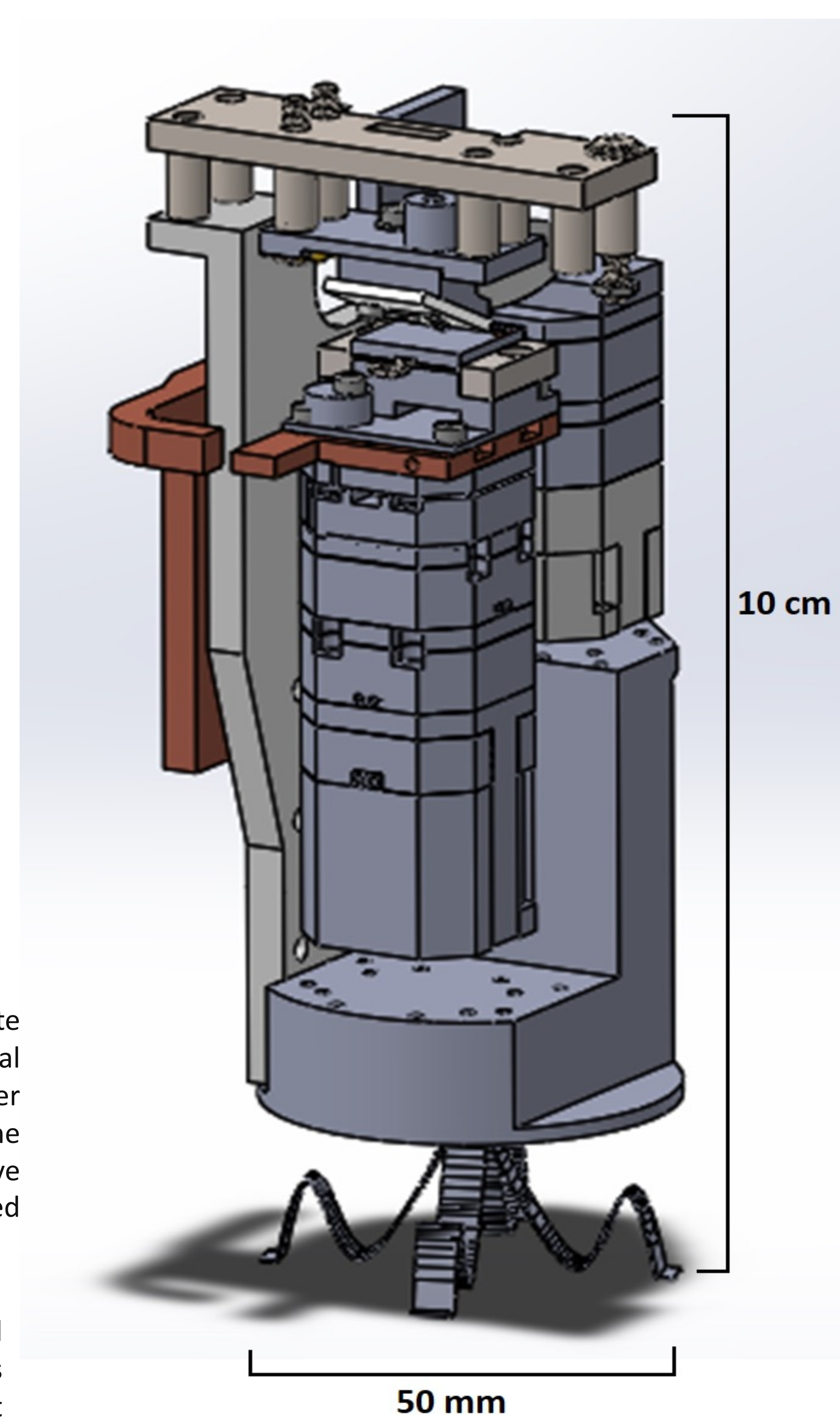

Figure 4. Schematic of QZS Flexure attached to s-SNOM stage.

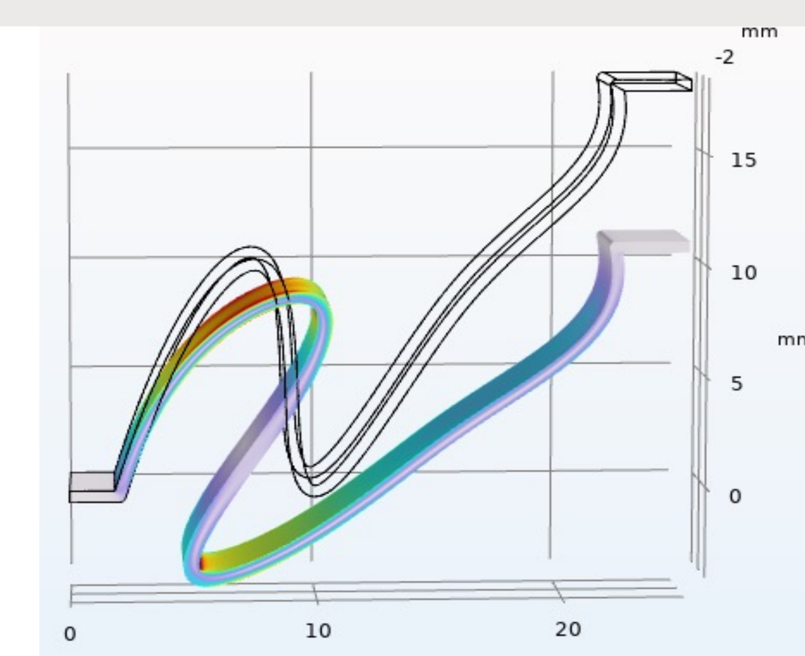

Figure 5. Deformation of QZS flexure under prescribed displacement.

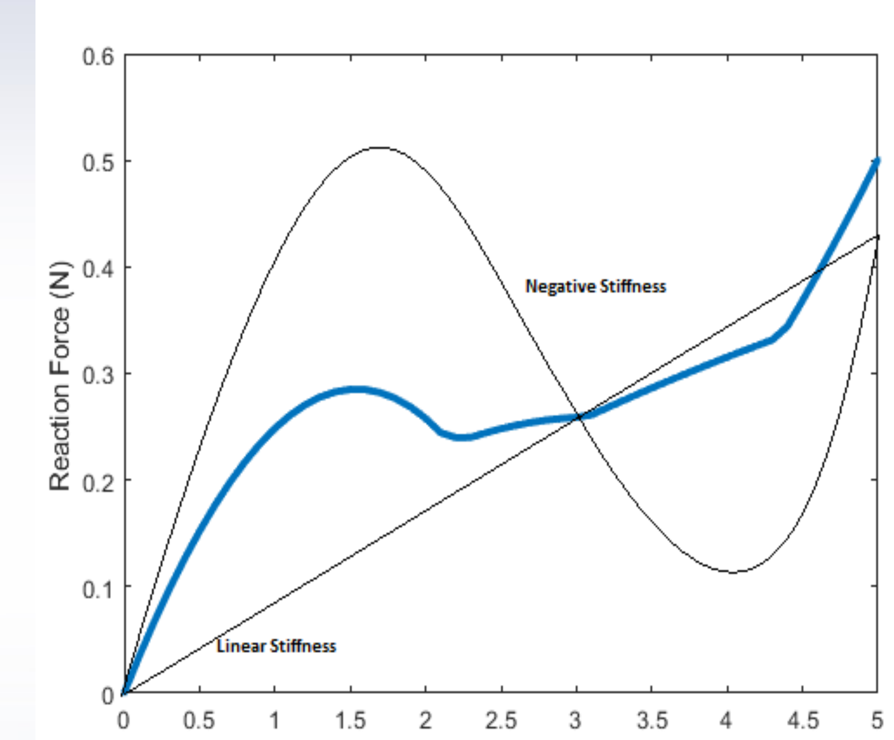

Figure 6. Displacement vs. Force Graph for Flexure. Linear Stiffness and Negative Stiffness examples added.

References

[1] Chen, X., Hu, D., Mescall, R., You, G., Basov, D. N., Dai, Q., Liu, M., Modern Scattering-Type Scanning Near-Field Optical Microscopy for Advanced Material Research. *Adv. Mater.* 2019, 31, 1804774. https://doi.org/10.1002/adma.201804774

[2] Changqi Cai, Jiaxi Zhou, Kai Wang, Hongbin Pan, Dongguo Tan, Daolin Xu, Guilin Wen, Flexural wave attenuation by metamaterial beam with compliant quasi-zero-stiffness resonators, Mechanical Systems and Signal Processing, Volume 174, 2022, 109119, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2022.109119.

[3] Qiang Wang, Jiaxi Zhou, Kai Wang, Qida Lin, Daolin Xu, Guilin Wen, A compact quasi-zero-stiffness device for vibration suppression and energy harvesting, International Journal of Mechanical Sciences, Volume 250 2023, 108284, ISSN 0020-7403, https://doi.org/10.1016/j.ijmecsci.2023.108284.

[4] Freeman, M., Brar, V., "A Quasi-Zero Stiffness Damper for Cryogen Free SPM"

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