Robust semi-active control for energy transfer between structural vibration modes: methodology and experiments

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Vibration remains one of the key challenges across mechanical engineering, motivating ongoing advances in damping and control. Since dissipated energy is typically lost as heat, recent research increasingly explores the integration of vibration suppression with energy harvesting [1].

This work proposes a semi-active modal control strategy that enables precise energy transfer between selected vibration modes by locking or unlocking rotational joints (see: Fig. 1a), effectively switching the structural stiffness. This induces modal coupling and imposes directed energy flow. Such an approach can be employed for two functional objectives: **damping**, by shifting energy from low-frequency modes to higher, more strongly damped ones (see: Fig. 1b), and **energy harvesting**, by concentrating energy in a target mode tuned to a harvester. The approach shows excellent performance in simulations and experiments [2]. Here, the focus is placed on robustness with respect to modeling errors, demonstrating that the controller remains effective despite substantial stiffness deviations. Experimental results are compared with those obtained using a finely calibrated model with 17 adjusted stiffness parameters.

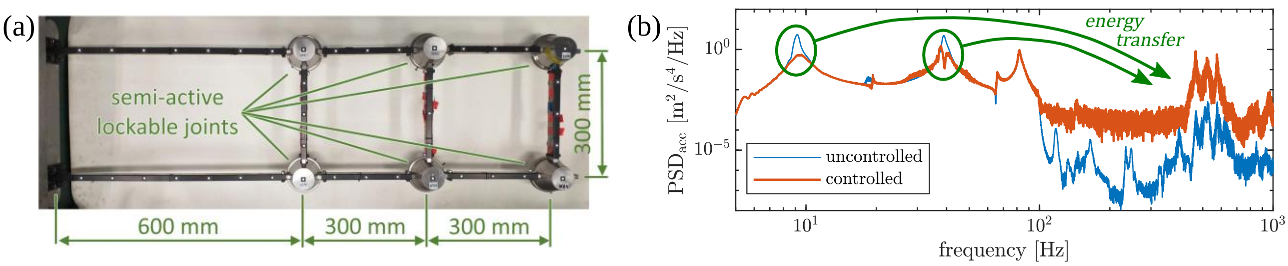

Figure 1. (a) photo of laboratory-scale frame structure equipped with six lockable joints and (b) experimentally obtained power spectral density (PSD) of the structural tip acceleration in log–log scale, demonstrating the transfer of energy from the monitored vibration modes into higher-order, unmonitored modes; the PSD associated with the first mode is reduced by 90%.

Results demonstrate that, despite substantial changes in natural frequencies (up to 80 %) due to stiffness errors in the model used by the controller, the control performance is nearly the same as for the controller based on the calibrated model. Due to these advantages and the high control performance, the proposed control strategy has broad applicability to real engineering structures and is robust to changes in structural properties caused by operational wear.

[1] T. Yang, S. Zhou, G. Litak, X Jing, Recent advances in correlation and integration between vibration control, energy harvesting and monitoring. Nonlinear Dyn. 111, 20525–20562, 2023. https://doi.org/10.1007/s11071-023-08999-2

[2] M. Ostrowski, Semi-Active Control of Energy Transfer Between Vibration Modes in Mechanical Structures, Institute of Fundamental Technological Research, Polish Academy of Sciences, 2025 https://doi.org/10.24423/9788365550644