proceedings

MDPI

Abstract

Platform for Weakly Coupled Electro-Mechanical Resonators with Arbitrary Tunability †

Ruopeng Chen [1,*], Bernardo Pereira [2], Chen Wang [2], Michael Kraft [2] and Georges Gielen [1]

[1] ESAT-MICAS, KU Leuven, 3000 Leuven, Belgium; georges.gielen@kuleuven.be
[2] ESAT-MNS, KU Leuven, 3000 Leuven, Belgium; bernardo.pereiramadeira@kuleuven.be (B.P.); chen.wang@esat.kuleuven.be (C.W.); michael.kraft@kuleuven.be (M.K.)
* Correspondence: ruopeng.chen@esat.kuleuven.be
† Presented at the XXXV EUROSENSORS Conference, Lecce, Italy, 10–13 September 2023.

Abstract: This paper presents a platform for weakly coupled mechanical and electrical resonators with arbitrary tunability. Two- and three-degree-of-freedom (DoF) weakly coupled resonator systems are demonstrated experimentally with this platform, showing excellent tuning and matching flexibility. Fully electrical coupling logic circuitry gives the proposed system better adjustability and lower susceptibility to fabrication tolerances compared to purely mechanical weakly coupled resonators. Due to its mother/daughter board structure and the simplicity of the coupling logic, the proposed system can easily be extended to any-DoF systems.

Keywords: weakly coupled resonators; electro-mechanical resonators; multi-degree-of-freedom weakly coupled system; tunable weakly coupled system

Citation: Chen, R.; Pereira, B.; Wang, C.; Kraft, M.; Gielen, G. Platform for Weakly Coupled Electro-Mechanical Resonators with Arbitrary Tunability. *Proceedings* **2024**, *97*, 138. https://doi.org/10.3390/proceedings2024097138

Academic Editors: Pietro Siciliano and Luca Francioso

Published: 1 April 2024

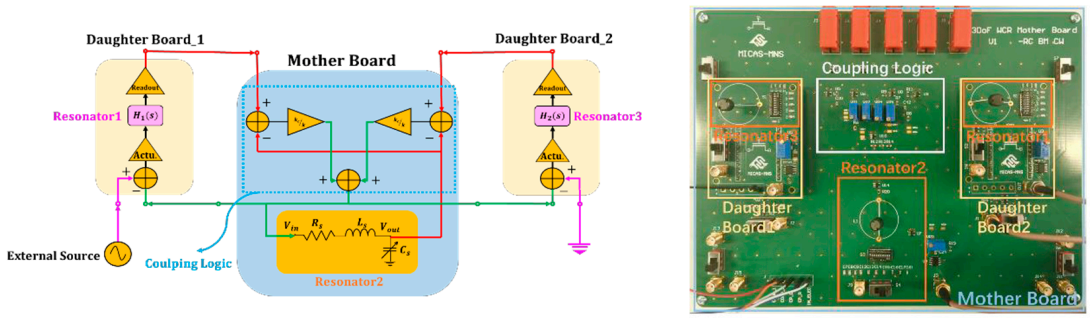
1. Introduction

In recent years, there has been a growing interest in weakly coupled resonators due to their enhanced sensitivity and common-mode resilience in contrast to single resonators [1–3]. However, conventional coupled resonators are limited in their adjustability after fabrication as they are purely mechanical resonators. The pre-mode localization effect resulting from micro-fabrication tolerance, such as mass, spring, and damping mismatch, can cause coupling system issues.

This work presents a fully tunable platform for coupling mechanical and electrical resonators with an arbitrary coupling factor, rather than relying solely on mechanical resonators. The electrical resonators can easily be tuned and matched to the mechanical resonators after fabrication. By adding more electrical/mechanical resonators and extending the coupling logic circuitry, the proposed structure can be extended to any type and any-degree-of-freedom (DoF) weakly coupled resonators. Compared to existing solutions for tunability, which require computational hardware [4], the proposed system reduces the complexity of setup and avoids data conversion and processing at runtime.

2. System Structure and Working Mechanism

A 2-DoF and 3-DoF coupled resonator system is demonstrated to show the effectiveness and flexibility of the proposed platform, which is derived from the serial RLC electrical equivalent. The platform is shown in Figure 1 [5]. Electrical or mechanical resonators R_1 and R_3 are connected on the daughter boards. Each resonator has an independent actuation circuit and readout circuits. To demonstrate the functionality, R_1 and R_3 are the equivalent circuit of the mechanical resonators. In future work, R_1 and R_3 will be replaced with actual mechanical resonators. All resonators are connected through the tunable coupling circuit on the mother board. Resonator R_2 is a tunable RLC electrical resonator made up of lumped components. The coupling logic is built with analog operation circuits [6], which realizes fully electrical coupling. It has a coupling factor k_c/k ranging from 0 to 1.

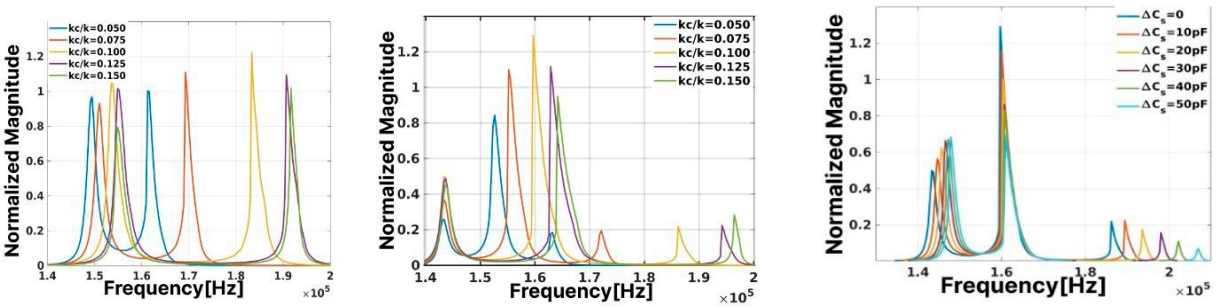


(**a**) (**b**)

Figure 1. Proposed tunable platform for weakly coupled electro-mechanical resonator systems: (**a**) simplified schematic of the proposed system; (**b**) PCB implementation of the proposed system.

3. Measurement Results and Discussion

Figure 2 shows the measurement results of a 2-DoF and 3-DoF weakly coupled resonator system. Figure 2a,b show the frequency responses of resonator R_1 with different coupling factors. The plots show that the distances in frequency between different modes widen when the coupling factor increases. Figure 2c shows the frequency responses of resonator R_1 when keeping the coupling factor at 0.1 and reducing the capacitance value in the RLC resonator R_2. Due to the perturbation in stiffness, corresponding frequency shifts and magnitude changes are observed.



(**a**) (**b**) (**c**)

Figure 2. Measurement results of the proposed tunable weakly coupled resonator system: (**a**) frequency response of Resonator R_1 with different coupling factors in the 2-DoF coupled resonator system; (**b**) frequency response of Resonator R_1 with different coupling factors in the 3-DoF coupled resonator system; (**c**) frequency response of Resonator R_1 with capacitance value perturbation in electrical resonator R_2 in the 3-DoF coupled resonator system.

The results show that the proposed platform system can couple individual resonators together with an arbitrary coupling factor, demonstrating excellent flexibility and tunability. Also, since the coupling logic is a combination of identical analog operation circuits, it is easy to extend to higher-dimensional DoF systems.

Author Contributions: Conceptualization, R.C.; methodology, R.C.; Validation, R.C. and B.P.; investigation, R.C.; writing—original draft preparation, R.C.; writing—review and editing, C.W., M.K. and G.G.; supervision, C.W. and G.G.; funding acquisition, G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by KU Leuven and "HEMCORES PROJECT(G0B4421N)" grant from the Flemish FWO, from 5 September 2022 to 27 September 2026.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Only data figures are provided in the proceeding paper. If original measurement data is required, please contact the author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wang, Y.; Zhao, C.; Wang, C.; Cerica, D.; Baijot, M.; Xiao, Q.; Stoukatch, S.; Kraft, M. A mass sensor based on 3-DOF mode localized coupled resonator under atmospheric pressure. *Sens. Actuators A Phys.* **2018**, *279*, 254–262. [CrossRef]
2. Wang, L.; Wang, C.; Wang, Y.; Quan, A.; Keshavarz, M.; Madeira, B.P.; Zhang, H.; Wang, C.; Kraft, M. A review on coupled bulk acoustic wave MEMS resonators. *Sensors* **2022**, *22*, 3857. [CrossRef] [PubMed]
3. Wang, Y.; Liu, H.; Wang, C.; Zhao, C.; Redoute, J.; Stoukatch, S.; Xiao, Q.; Tu, L.; Kraft, M. Towards a Hybrid Mass Sensing System by Combining a QCM Mass Sensor With a 3-DOF Mode Localized Coupled Resonator Stiffness Sensor. *IEEE Sens. J.* **2021**, *21*, 8988–8997. [CrossRef]
4. Humbert, C.; Walter, V.; Leblois, T. A mass sensor based on digitally couple and balanced quartz resonators using mode localization. *Sens. Actuators A Phys.* **2022**, *335*, 113378. [CrossRef]
5. Baijot, M. *Three Degrees of Freedom Weakly Coupled Resonators Used for Mass Measurement*; Université de Liège: Liège, Belgium, 2016.
6. Kasai, Y.; Yabuno, H.; Yamamoto, Y.; Matsumoto, S. Ultra-sensitive minute mass sensing using a microcantilever virtually coupled with a virtual cantilever. *Sens. J.* **2020**, *20*, 1823. [CrossRef] [PubMed]