NOVEL ELECTRICALLY TUNABLE MECHANICAL RESONATOR FOR ENERGY HARVESTING

Christian Peters[1], Dominic Maurath[1], Wolfram Schock[1] and Yiannos Manoli[1,2]
[1]Chair of Microelectronics, Department of Microsystems Engineering (IMTEK),
University of Freiburg, Germany
[2]HSG-IMIT – Institute for Micromachining and Information Technology, Villingen-Schwenningen, Germany

Abstract: This paper presents a novel electrically tunable resonator which can be used as a resonator structure for vibration based energy harvesters. The adjustment of the resonant frequency is provided by mechanical stiffening of the structure using piezoelectric actuators. The geometrical design parameters are optimized with ANSYS. The prototype resonator is fabricated by laser cutting of steel stripes and afterwards gluing to commercially available piezoelectric actuators. The tuning voltage is chosen to be ±5 V leading to a measured resonant shift of ±15 % around the inertial resonant frequency of 78 Hz.

Key words: tunable resonator, tunable harvester, electrically tunable

1. INTRODUCTION

Progress in low-power microelectronic devices allows wireless sensor networks to operate over a certain time on battery power without maintenance. However, batteries are sensitive to high and low temperatures and deplete over time. Energy harvesting generators can solve this problem by transforming ambient energy like vibration into electrical energy. Thus, sensor networks can be placed at locations which are difficult to access, since no battery replacement is required.

The focus in this paper is on resonant electromechanical resonators which convert vibration energy into electrical energy. Transformation principles could be based on: (i) inductive, (ii) piezoelectric or (iii) capacitive techniques. These harvesters are able to generate electrical energy while being driven from a vibration containing a frequency very close to the natural frequency of the resonator. Even a small difference between excitation and resonant frequency leads to a poor power generation and the harvester is not able to supply even small low-power systems. The excitation frequencies are commonly defined by the excitation source and can hardly be influenced. Thus, a typical design flow starts with the analysis of the excitation frequencies and amplitudes. An overview of the dependence of power on excitation frequency and amplitude can be found in [1]. A frequency with a large amplitude is chosen and the harvester is designed to this frequency. However, this frequency could change due to temperature variations, deterioration or if the vibration source, e.g. an engine, is driven in different operation ranges. Therefore a generator with a fixed resonant frequency is a strong restriction and adjustability becomes very important.

Different tunable concepts can be found in literature. Wu et al. presented a piezoelectric generator which can be tuned between 91.5 Hz to 94.5 Hz [2]. The spring stiffness of this piezoelectric cantilever is influenced by connecting capacitors to the piezoelectric electrodes. This reduces the electromechanical counterforce and thus, the spring stiffness. Leland et al. used axial preload applied to a piezoelectric bimorph generator. A decrease of the resonant frequency of around 24 % is reported. But the preload is applied using a large differential micrometer [3]. In [4] a tunable electromagnetically harvester is shown. A rotary suspended magnet moves between two fixed magnets having the opposite polarity to the moving magnet. Thus a non-linear spring constant results. Both fixed magnets could be adjusted by screws resulting in a frequency tuning range from 30 to 60 Hz.

These concepts have some drawbacks like small tuning range, no practicable tuning concept or electrical tuning is hard to implement or not very energy efficient.

This paper is organized as follows. Section 2 introduces the tunable resonator. The fabrication is described in Section 3 and the measurement results are given in Section 4. This paper finishes with a conclusion.

2. TUNABLE RESONATOR

The approach presented in this paper is to increase the stiffness of a cantilever beam by increasing its geometrical moment of inertia. This is realized using piezoelectric actuators. Piezoelectric materials can generate large forces and have low power consumption. Furthermore they are commercially available with different dimensions and properties. Customized micro fabrication of piezoelectric layers is also possible.

A schematic of the proposed tunable resonator is shown in Fig. 1a. Two actuators, a clamped and a free one, are connected together with three hinges. The free actuator can swing around the axis of rotation if a suitable excitation is applied to the clamp. For an electromagnetic solution a magnet could be located at the free moving actuator and induce a voltage into a fixed coil placed under the actuator. The resonant frequency of this rotational mass spring system can be described by:

$$f_{res} = \frac{\sqrt{\frac{k}{l^2 m}}}{2\pi}, \tag{1}$$

where k, m and l are the spring stiffness, the mass, and the distance between the pivot and the mass, respectively. With no voltage applied to the actuators the cross section is shown in Fig. 1b. The stiffness of the structure is increased by applying an electrical potential to the actuators resulting in a structure shape schematically depicted in Fig. 1c. Both outer hinges move up by Δy, depending on the applied potential. There is no common axis of rotation anymore. The hinges get slightly compressed and stretched during a swing of the free actuator. The forces needed for this deformation and the distance between the axes cause an additional hinge moment and thus, a stiffer structure results. The natural frequency increases.

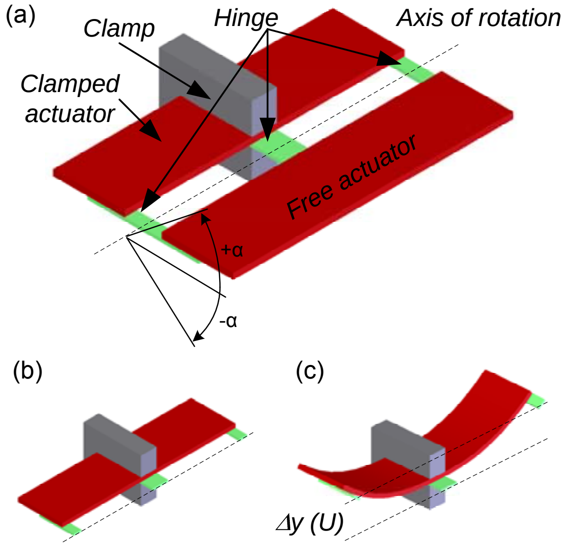

Fig. 1: a) schematic of the resonator. b) cross section without applied voltage and c) with applied voltage.

The structure has been simulated and optimized using ANSYS™. Fig. 2 shows the simulated moment of torque of a resonator versus the deflection angle α with and without applied tuning voltage. The tuning voltage is 30 V resulting in a Δy of 240 µm (see Fig.1c).

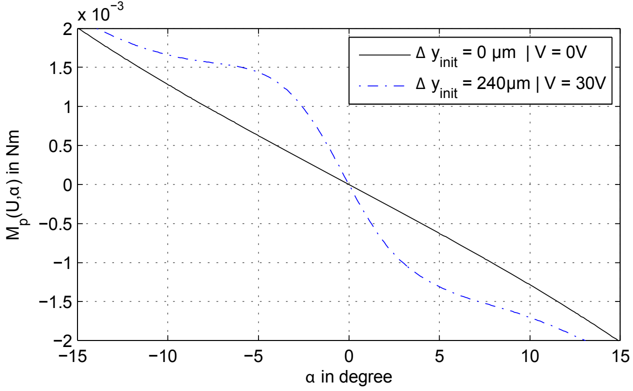

Fig. 2: Simulated moment of torque of the resonator versus the deflection angle α with and without an applied tuning voltage of 30 V.

Without applied voltage a nearly linear curve results. With applied tuning voltage a strongly non-linear behavior occurs. At low deflection angles a very stiff structure is observed. At around 5° the moment of torque flattens and at high deflections it approaches the initial curve. Nevertheless, the moment of torque with applied voltage is always larger compared to the structure without applied voltage. The simulated torsional stiffness of the resonator is shown in Fig. 3.

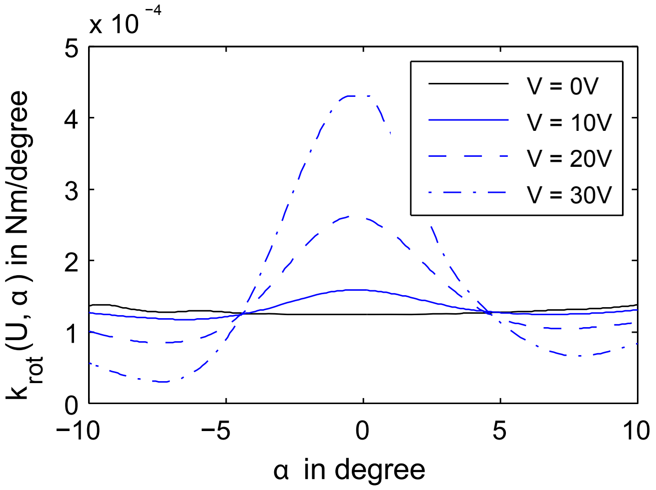

Fig. 3: Simulated stiffness of the resonator versus deflection angle α for different applied voltages.

Therefore, the structure has the lowest stiffness if no voltage is applied. Dependent on the applied voltage stiffening occurs at low deflection angles. Thus, if tuning in both directions is desired two solutions exist: (i) defining the middle point by an offset voltage (e.g. 10 V) or (ii) adding a mechanical spacer (some 10 µm) to pre-deflect the structure. Both approaches have been tested. The advantage of the first concept is that the middle point is not fixed and can be electrically adjusted. In the second solution the middle frequency is fixed, but in this state the power consumption is zero because no voltage must be applied to the very high ohmic piezoelectric actuator. The spacer could be placed at the inner hinge as shown in Fig. 4 or at both outer hinges.

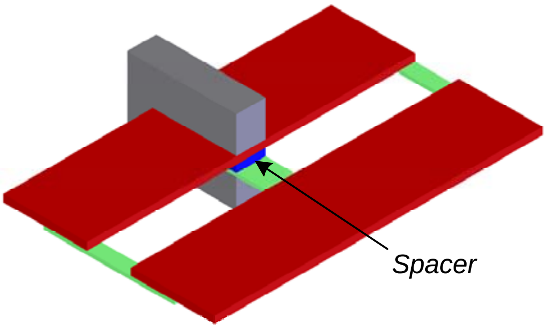

Fig. 4: Pre-deflection of the resonator using a thin (80 µm) spacer placed at the inner hinge.

3. FABRICATION

The hinges are made of steel stripes with a thickness of 50 µm and fabricated using laser cutting. The stripes are fixed on a vacuum chuck to avoid buckling of the thin metal during laser cutting. Commercially available piezoelectric actuators [5] are glued to the hinges using instant adhesive. Electric contact is done by soldering very thin wires to the piezoelectric actuators. These wires must be very soft to avoid an influence on the resonator. Since the electric current is very low, the resistance is not important. One actuator is clamped in a metal support. Fig. 5 shows a photograph of the assembled harvester.

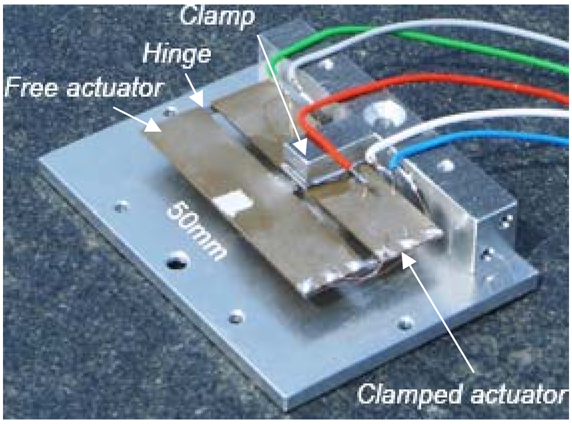

Fig. 5: Photograph of the electrically tunable resonator with the wires for the electrically tuning and the clamp support.

4. MEASUREMENT RESULTS

The fabricated resonator is mounted on a mechanical shaker and driven at different frequencies. The amplitude of the free actuator, and thus the deflection angle α is measured using a laser interferometer. The reference beam of the laser interferometer is focused on the clamp.

Fig. 6 shows the measured change of the resonant frequency versus the applied tuning voltage. The structure is pre-deflected using a mechanical spacer with a height of 80 µm at the inner hinge. The initial resonant frequency is 78 Hz, the maximum frequency change in positive direction is 14.2 % and in negative 15.8 % using a tuning voltage of only ±5 V. The main parameters are summarized in Tab. 1. A tuning range of around 15 % at an initial frequency of 78 Hz using only ±5 V is far beyond the state-of-the-art. This tuning range could be further increased by simply increasing the tuning voltage.

Table 1: Parameters of the tunable resonator with a maximum applied tuning voltage of ±5 V.

$l_{actuator}$ [mm]	$w_{actuator}$ [mm]	$h_{actuator}$ [µm]	l_{hinge} [mm]	w_{hinge} [mm]	h_{hinge} [µm]	$f_{res,0}$ [Hz]	$f_{res,max}$ [Hz]	$f_{res,min}$ [Hz]
45	11	600	2	2	50	78	89	66

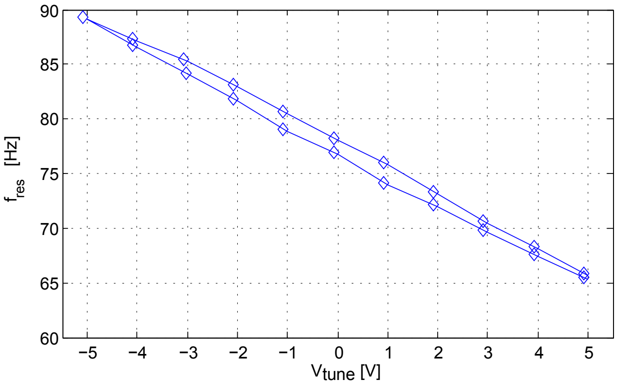

Fig. 6: Measured resonant frequency f_{res} versus applied tuning voltage V_{tune}.
$f_{res,0}$=78 Hz, $f_{res,max}$=89 Hz, $f_{res,min}$=66 Hz.

The difference of the deflection angle α with and without tuning is measured and shown in Fig. 7. Applying a suitable tuning voltage to the actuators leads to a wide plateau over the excitation frequency. Because of the non-linear behavior, the uncontrolled resonator possesses practical amplitudes only in a narrow frequency range. The largest amplitude only occurs if the excitation frequency is decreased from a frequency higher than 47 Hz. However, such a frequency sweep can not be assumed in a real world application. Thus only the maximum deflection angle (2.65°) for increasing f_{exc} can be used reliably. The controlled resonator avoids this complication. Hence, a high and nearly constant amplitude over a wide frequency range results.

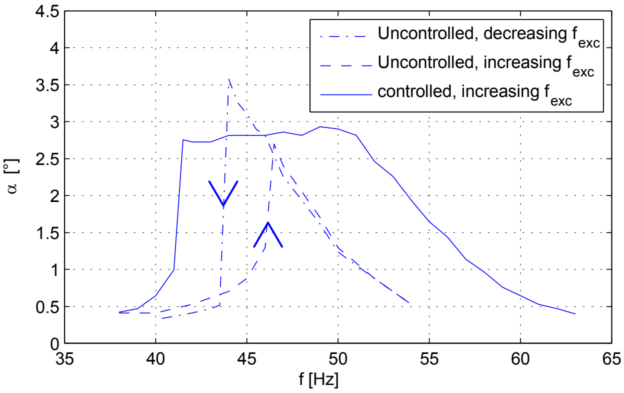

Fig. 7: Measured deflection angle α versus excitation frequency without tuning (uncontrolled) and with applied tuning (controlled).

5. CONCLUSION

The proposed resonator allows a very power efficient electrical tuning in a wide range. Low resonant frequencies (some tens of Hz), which are important for energy harvesting applications, are easily reached. With only ±5 V tuning voltage the resonant frequencies is tuned ±15 %. Larger tuning ranges could easily be reached by increasing the tuning voltage.

The resonator is suitable for nearly every kind of conversion principle which generates electrical power out of an alternating amplitude.

Acknowledgements

The authors would like to thank Mr. Dietmar Schuhmacher from the HSG-IMIT for the laser cutting of the hinges and Mr. Chris Steinert for his help during the measurements with the laser vibrometer.

REFERENCES

[1] Williams C B and Yates R B 1995 Analysis of a micro-electric generator for microsystems *Proc. Transducers/Eurosensors Stockhol, Sweden* **1** 369-72

[2] Wu W-J, Chen Y-Y, Lee B-S, He J-J, Peng Y-T 2006 Tunable resonant frequency power harvesting devices *Proc. of SPIE* **6169** 55-62

[3] Leland E S, Wright P K 2006 Resonance tuning of piezoelectric vibration energy scavenging generators using compressive axial preload *Smart Mater. Struct.* **15** 1413 20

[4] Spreemann D, Folkmer B, Maurath D Manoli Y, 2006 Tunable transducer for low frequency vibrational energy harvesting *Proc. Eurosensors XX Göteborg Sweden*

[5] *Pi-Ceramic GmbH PL112 - PL140 PICMATM* *http://www.piceramic.de/site/bender_002.html*