19th Symposium IMEKO TC 4 Symposium and 17th IWADC Workshop
Advances in Instrumentation and Sensors Interoperability
July 18-19, 2013, Barcelona, Spain

Electromechanical characterizations of MEMS based energy harvesters by harmonic sampling analysis method

Alexandre Bounouh and Denis Bélières

LNE – 29 avenue Roger Hennequin, 78197 Trappes, France - alexandre.bounouh@lne.fr

Abstract- This paper presents a new and accurate experimental method based on electrical harmonic distortion analysis to determine mechanical characteristics (resonant frequency) of MEMS devices used in widespread applications as in energy scavenging, cantilever-based microsystems for gas sensing and atomic force microscopy or in any kind of MEMS resonators. Resonant frequencies ranging from 0.8 kHz to 5 kHz of electrostatic actuated MEMS-based harvesters have been measured by this technique with an uncertainty as low as a few parts in 10^3 constituting an outstanding result compared to the other methods.

I. Introduction

Micro-Electro-Mechanical Systems (MEMS) are microscopic systems that combine mechanical, optical, electromagnetic, thermal and also fluidic components with electronics on semiconductor substrates. The advantages of MEMS technologies lie in the improvement of the product performance, the new functionalities, the reduction of energy consumption, the mass production, the miniaturization and the increased reliability and integration. They are also compatible with CMOS IC so that electronics could be integrated in the same process [1]. This makes today MEMS technology in a mass production phase for many applications with a huge future prospect as can be seen from the market of inkjet heads, pressure sensors and MEMS based µ-displays. The same trends are foreseen for MEMS-based applications, related to RF-MEMS, Optical MEMS, µ-Fluidics, inertial MEMS (gyroscopes and accelerometers) and silicon-based microphones. To go with their successful deployment, MEMS sensors in general will definitely require a source of energy of reduced dimensions as MEMS-based vibrations powered energy harvesters having a power rating from few nano to milli watts range. Whatever the type of mechanically powered energy scavengers, electrostatic, electromagnetic or piezoelectric [2], the maximum electrical power generation from mechanical vibrations of MEMS transducers is given at resonant frequency, especially when the source amplitude is small compared to the possible proof mass displacement and has only a narrow frequency bandwidth. Hence, the knowledge of the resonant frequency and the damping factor of MEMS-based generators is crucial for matching them to the vibrational sources specifications.

I. Measurement principle and modelisation

The electrical power generation from mechanical vibrations in almost all energy harvesters is achieved through a mechanical resonator made of a proof mass m coupled with the environmental vibrations by an elastic spring having a stiffness k (Fig.1). Thanks to this coupling, the mass oscillates in the reference system and accumulates a mechanical energy, which is converted into electric energy through an electromechanical transducer. The damping factor α has two components: one related to the inertia of the mass, which corresponds to the energy losses and the second is related to the force induced by the electromechanical transduction.

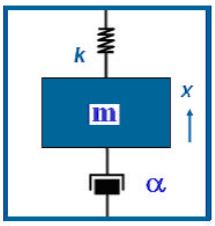

Figure 1. Schematic representation of a vibrational energy harvester.

The electrostatic resonant energy harvester includes a mechanical resonator associated with a capacitive transducer. The capacitive transducer is a device with two electrodes. The first one is attached to the proof mass, the second electrode is being fixed to the frame and submitted to the external vibrations. However, an electrical voltage could be applied to the MEMS variable capacitor, which allows us to characterize its dynamical mode motion. The capacitance varies with the displacement *x* as:

$$C(x)=\frac{C_0}{1-x} \tag{1}$$

where C_0 is the capacitance at rest. If the frequency of the applied voltage is very low, the displacement can be considered as being instantaneous. If it is very high, the dynamic displacement can be neglected and the RMS voltage is only taken into account, which also causes a static displacement. Hence, in the dynamic mode, the overall system mass + spring + damper is equivalent to a low-pass filter which will be characterised by its cut-off frequency and its damping factor. It will be modellized by an electrical LC filter damped by a resistor. Starting from the applied voltage $v(t)$, the electrical force $f(t)$, the displacement $x(t)$, the capacitance $c(t)$ and at last the current $i(t)$ are determined. The relation between $i(t)$ and $v(t)$ completely defines the electrical characteristics of the dipole.
Using *Genesys*TM software, we built an electrical model of this non linear-capacitance $C(x)$ allowing the definition of the relationship between current and voltage at any times. The equations defining the current as a function of voltage and time are represented by the flowchart of figure 2, where V_{pi} is the pull-in voltage of the MEMS.

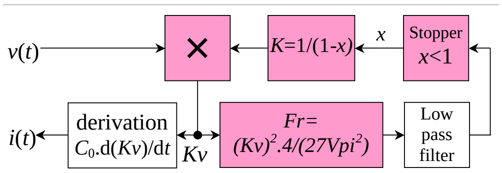

Figure 2. Flowchart of fundamental equations of the MEMS

To perform the calculations, the MEMS variable capacitor is wired as a feedback element on an inverting operational amplifier and driven by a sine current. Figure 3 shows the RMS voltages of harmonics. One can see that before the stopper, only the 3rd harmonic is present.

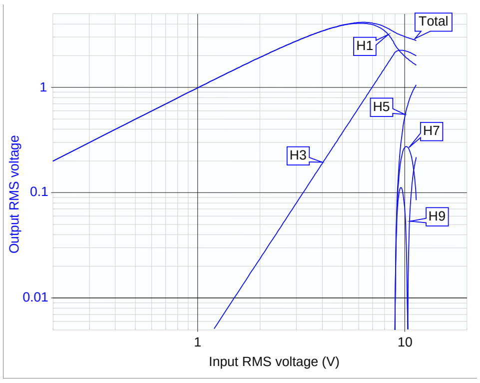

Figure 3. Calculations of RMS voltages of harmonics of a MEMS variable capacitor

When varying the frequency, the displacement *x* is filtered by the mechanical low-pass filter, and the distortion follows the response curve of this filter. The frequency of the mechanical vibration is twice the electrical signal frequency. Figure 4 gives for a MEMS device having a resonant frequency of 10 kHz the RMS voltage of the 3rd harmonic (0 dB is the *V*pi reference). Seven curves are plotted for each input voltage, with a varying from 1/8 up to 1 with v2 ratios. In all cases, the cut-off frequency is at 5 kHz. This shows that in theory it is possible to determine the mechanical parameters (cut-off or resonance frequency and damping) by the measurements of this 3rd harmonic distortion.

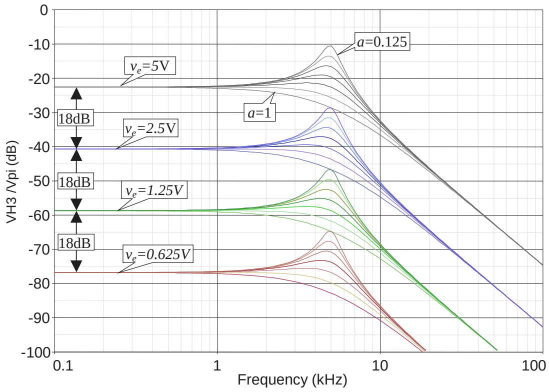

Figure 4. Absolute level of the 3rd harmonic with sine current input

III. Experimental results

Several variable capacitor MEMS, named B1, B2 and B3, have been designed and fabricated with a SOI (silicon On Insulator) wafer surface micromachining process [3]. The MEMS structures were designed by using CoventorWare software [4]. The structures are made of fixed and movable electrodes fitted with split-fingers. Spring dimensions (length and width) are calculated to have a stress below 1 GPa with a displacement equal to one third of the gap. Table 1 gives an example of the various dimensions of a typical MEMS structure designed to have a resonant frequencies ranging from 0.8 kHz to 4 kHz.

Table 1. Dimension of the MEMS structures (µm)

Gap		4
Movable mass	Length	1292
	Width	150
Fingers	Number	150
	Length	350
	Width	6
Spring	Number	4
	Length	265
	Width	4

Figure 5 shows SEM photography of a MEMS device realized by this SOI surface micromachining process.

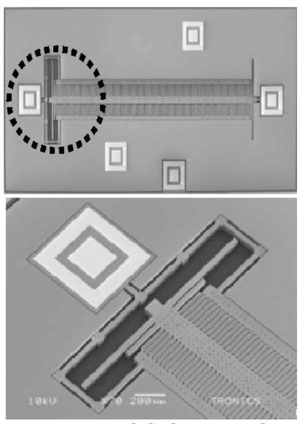

Figure 5. SEM photography of a MEMS structure: a global view and a zoom around the left side of the structure.

Deep Level Transient Spectroscopy (DLTS) measurement system has been used to measure the capacitance change with time when an impulse dc voltage is applied to the MEMS. Even if this system is intended to be used for semiconductors characterizations, it allows us to estimate the MEMS resonant frequency. On the other hand, we have implemented a measuring system of the harmonic distortion of the MEMS driven by a sine current. The input signal is provided by a SRS Stanford D360 having an ultra low distortion level and the output signal is sampled by using a digital voltmeter Agilent 3458A put in its subsampling mode. The spectrum of the signal is constructed through a FFT treatment (typically 1024 points and 16 points per period). The ratio H3/H1 is then measured over a wide range of frequency (Fig.6), which allows us to determine both the cut-off frequency (resonant frequency) and the damping factor.

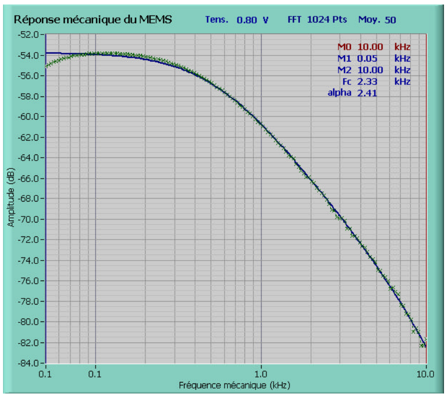

Figure 6. Experimental curve showing the 3rd harmonic behavior versus the input current frequency and a theoretical fit allowing to determine the cut-off frequency and the damping factor

For all MEMS devices, the mechanical resonant frequencies are measured with a relative uncertainty of a few parts in 10^3 (1σ) and are in a very good agreement with the values estimated with DLTS measurements (Tab. 2). This result and the uncertainty budget will be refined by implementing a Monte-Carlo method.

Table 2. Resonant frequencies of several comb-drive MEMS devices (B1 to B3) measured both by DLTS measurement system and the distortion technique

MEMS	**Resonant frequency (kHz)**	
	DLTS (s=0.01)	*Distortion (s=0.002)*
B1	0.80	0.792
B2	2.27	2.334
B3	4.70	4.754

References

[1] F. Lochon, I. Dufour and D. Rebière, Sensors and Actuators B, 118, 292-296, 2006.

[2] P. Beeby *et al*., "*Energy Harvesting Vibration Sources for Microsystems Applications* ", Review Article Proc. of Measurement Science and Technology, R175-R195, 2006.

[3] J. Collet, "*MEMSOI Multi project wafers service - SOI High Aspect ratio Micromachining*", MEMS and System Package Workshop, IMEC Belgium, November 2007.

[4] A. Bounouh, H. Camon and D. Bélières, "*Wideband high stability MEMS based AC voltage references*", IEEE Trans. Inst. Meas., 99, 2013. DOI: 10.1109/TIM.2012.2225963.