Proceedings of the 2009 Spanish Conference on Electron Devices - Feb 11-13, 2009. Santiago de Compostela, Spain.

Digital Resonance for MEMS

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***Abstract*—This work shows the application of Pulsed Digital Oscillators to the detection of physical changes in MEMS devices that cause small shifts in their resonance frequencies. Such devices can be used as resonators in several sensor applications. According to this, a case study using a PDO structure to measure small concentrations of volatile organic gas compounds (VOCs) is introduced here. The MEMS devices used are cantilevers with a thin layer of polymer sensitive to the VOC concentration. Such devices have been simulated with the Coventor software to see the influence of the polymer layers on their mechanical responses. Finally, experimental measurements with various VOCs have been done, and results extracted from two PDO system sources, digital and analog, have been analyzed and compared.**

I. INTRODUCTION

Pulsed Digital Oscillators (PDOs) are simple circuits initially designed to overcome some of the usual non linearity problems of MEMS actuation and sensing [1,2]. PDOs are sampled structures which, at each sampling time, detect if a MEMS device (i.e. a two-parallel plate resonator) is above or below its rest position and, through a 1-bit quantifier followed by a digital feedback loop, they generate series of short force pulses that actuate the MEMS resonator. So, in order to work properly, PDO structures only need to sense the sign of the position of the MEMS device.

Apart from their simplicity, another key feature of PDO structures is that the oscillation frequency can be extracted from the bit stream that actuates the MEMS device (digital output in Figure 1). Therefore working in the digital domain is straightforward when using PDOs, thus all digital facilities for data storing, data processing, etc. become easily available. On the other hand, one can also sense the MEMS position behavior in PDOs (i.e. analog output in Figure 1) and use it as an additional way to obtain the oscillation frequency, but the prize to pay is that the sensing requirements may increase and that some extra complex equipment for analog measurements must be used. Anyway and only for comparison purposes both ways, digital and analog, to extract the oscillation frequency have been used in this work.

On the other hand, a type of application where PDO systems can be rather advantageous is the sensing of phenomena that cause changes in resonance frequency. It is well known that the mechanical frequency of MEMS devices depends on the mass of their moveable parts. In example, if we take the usual 1D mass-spring model for a two parallel plate MEMS device, then we have

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m_{MEMS}}} \quad (1),$$

being f_O the mechanical resonant frequency, k the spring constant and m_{MEMS} the total mass of the moveable plate. Therefore, in a PDO system with such device the resonance frequency will inversely vary with the mass of the MEMS device. This principle can be applied to the sensing of dangerous compounds, such as VOCs, if we had MEMS devices where a change of the compound concentration would lead to a mass variation. For VOCs like toluene or benzene, polymers like PDMS or PECH can be used for this purpose.

Finally, let us note that the use of layers of polymers sensitive to VOCs is widely known and extensive bibliography on the subject [3, 5, 6] is available.

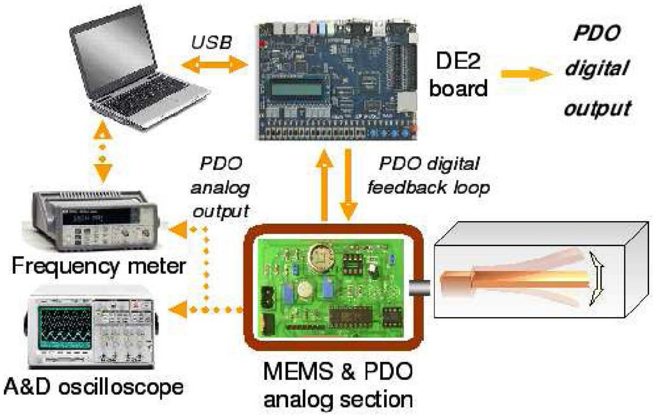


Figure 1. PDO-based experimental setup. Two simultaneous frequency measurements can be done, one extracted from the MEMS position sensing (analog output), and a second one extracted from the PDO bit stream (digital output).

II. MECHANICAL SIMULATIONS

The MEMS devices used are similar to those used in some previous works [1-3]: silicon cantilevers with thermoelectric actuation and piezoresistive position sensing through a Wheatstone bridge. Each cantilever is a moveable squared plate held by three arms of 100 μm long. Plate dimensions are 300 μm long and 300 μm wide, while thickness is 15 μm. In order to allow VOC sensing, a micropipette was used to deposit small polymer layers on top of the moveable plates.

978-1-4244-2839-7/09/$25.00 (C)2009 IEEE

The first objective was to analyze, through simulations, the mechanical properties (including vibration modes and the main resonance frequency) of the devices before and after the deposition of the polymer layer.

To a priori characterize such mechanical properties of our MEMS resonators the Coventor software environment was used. According to equation 1, the expected result is a decrease of the MEMS resonance frequency, since by adding a polymer layer the total mass of the device increases.

The detailed description of the making of the MEMS resonator, a bulk micromachining process from a SOI wafer, was introduced into the Coventor environment. From this information we obtained the 3D models that allowed us to perform mechanical and thermal simulations. As an example, Figure 2.a illustrates the first vibration mode of a specific MEMS cantilever, which exhibits a mechanical resonance frequency of 100.44 kHz.

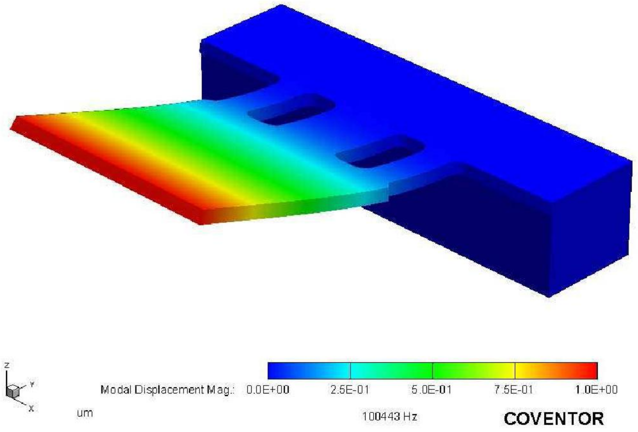


Figure 2a. Coventor mechanical simulation of the first vibration mode of a MEMS resonator without polymer layer.

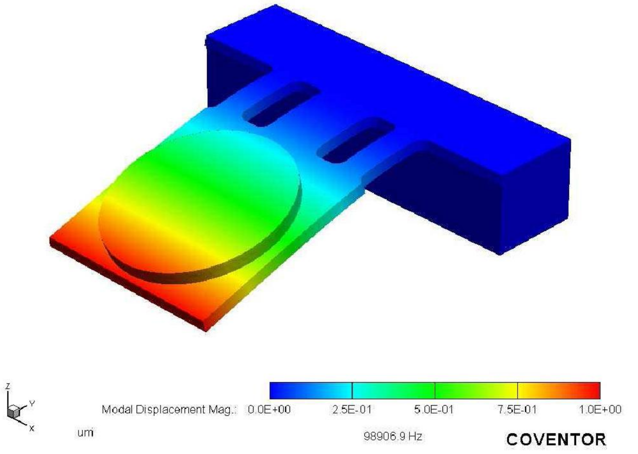


Figure 2b. Coventor mechanical simulation of the first vibration mode of a MEMS resonator with a PDMS layer deposited on top of the plate.

In our case, PDMS Sylgard 184 polymer layers have been deposited on the surface of the MEMS cantilevers. Then, an additional stage was included in the virtual description of the fabrication process mentioned above. In the specific case of the device of Figure 2a, a 20 μm thick layer of PDMS with a density of 9.7×10^{-17} kg/μm^2 was added at this stage, resulting in a new device with the structure and behavior shown in Figure 2b. Obviously, this new device exhibits a lower resonance frequency, as its mass has been increased by the PDMS layer. In particular, the value of the mechanical resonance frequency decreases to 98.906 kHz.

III. POLYMER LAYER CHARACTERIZATION

Figure 3 shows a 3D image, obtained with a Wyko NT9300 interferometric microscope, of a MEMS resonator. The image clearly shows the deposited PDMS. Since good values of height and perimeter of the PDMS layers are easy to obtain, one can estimate the PDMS volumes, and using the specific gravity provided by the manufacturer (1.03×10^3 kg/m^3), an approximated value of the deposited PDMS mass can be calculated. In the case of Figure 3, such extra mass is found to be 1.02×10^{-9} Kg.

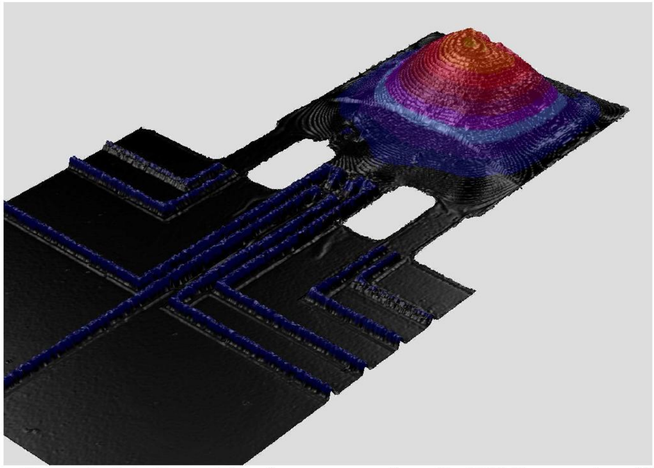


Figure 3. Interferometric microscope caption of a MEMS resonator with a PDMS layer deposited on its top.

Table I shows a comparison of some frequencies obtained from simulations and their corresponding experimental ones, before and after PDMS deposition. Table I also contains the estimation values of the mass of the polymer deposited and the effective spring constant k obtained by reversing equation 1.

TABLE I
COMPARISON BETWEEN SIMULATION AND EXPERIMENTAL RESULTS

Parameter	Coventor Simulation	Experimental Results
Initial f_0 (kHz)	100.443	96.278
f_0 with polymer (kHz)	98.906	87.331
Δf_0 (kHz)	1.537	9.397
m (kg)	1.03×10^{-10}	1.02×10^{-9}
k (N/m)	398.3	1548.5

IV. EXPERIMENTAL RESULTS

The setup described in Figure 1, formed by the MEMS resonator and two electronic boards that control the analog and digital parts of the PDO system, was used in the experimental measurements. Let us remember that one of the highlights of PDO systems is a built-in analog to digital conversion, but it is also possible to obtain data in analog format. As discussed above, the difference between these two available output formats is that the analog one requires a continuous position sensing mechanism and some extra equipment to monitor the frequency, while the digital option uses the same board to implement the digital feedback loop and to directly extract the digital data.

All digital parts of the measurement system have been written in VHDL and programmed on a Cyclone II FPGA from Altera contained in the digital board used, namely a DE2 development board from Terasic Technologies. Moreover, the SRAM available on the board was used to temporarily store the data, before sending them through an USB link to a personal computer for processing and visualization.

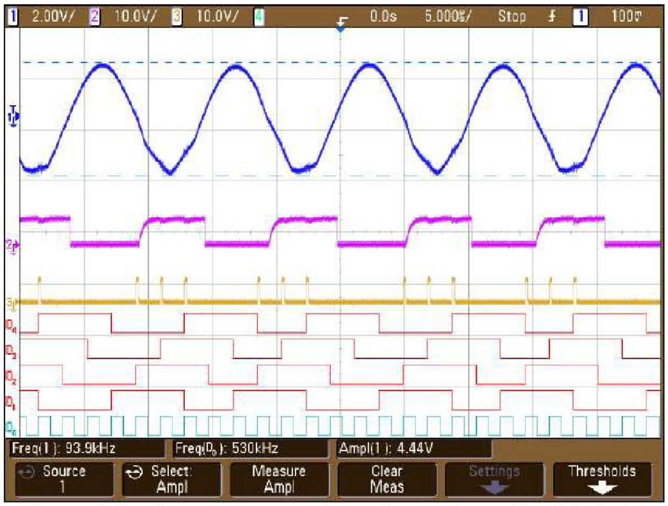
The measures have been done using MEMS resonators coated with PDMS introduced in a test chamber. Constant 100 ml flows of synthetic air alternating with flows of various concentrations of benzene and toluene were introduced into the chamber. In the specific examples described below the 100 ml of synthetic air alternated with 100 ml of benzene.

A. Analog Results

The analog output channel directly shows the PDO oscillation frequencies measured. It comes from an instrumentation amplifier located after the MEMS position sensor structure and before the transition to the digital domain done by a 1-bit quantifier. An Agilent 53131 universal counter, which periodically sends the data to the personal computer, has been used to monitor the oscillation frequencies.

In addition, a mixed analog & digital oscilloscope has been used to check the time behavior of the most relevant signals of the measurement system. Figure 4 shows an oscilloscope screenshot example of those analog and digital signals. Analog channel 1 (ch_A1) shows the position of the MEMS resonator, while ch_A2 is a signal which enables generating the pulses to drive the MEMS resonator (ch_A3).

Concerning the digital channels, ch_D0 is the sampling clock signal, while ch_D1 is the synchronized output of the 1-bit quantifier, and channels ch_D2 to ch_D4 correspond to the same signal, but after a chain of m delays. This m-delay chain is the digital feedback loop used in the specific PDO systems of this work. For the case shown in Figure 4, only one delay (m=1), which corresponds to the channel ch_D2, was used.



1 2.00V/ 2 10.0V/ 3 10.0V/ 4 0.0s 5.000$/ Stop 1 100?

Freq(1): 93.9kHz Freq(D0): 530kHz Ampl(1): 4.44V

Figure 4. Oscilloscope screen captures of resonator position (ch_A1), input pulses (ch_A3), quantifier-comparator output (ch_D1), delayed comparator output (ch_D2) and sample clock (ch_D0), for a PDO topology with $m = 1$ and a sampling frequency $f_S = 526$ kHz.

Figure 5 shows an example of temporal behavior of the PDO oscillation frequency after some changes on the concentration of benzene within the test chamber. At first the chamber contains only ambient air, but after 50 s, 400 ml of synthetic air are introduced. This changes the trend of the response curve due to the dehumidification of the PDMS layer: it means loss of mass, so the oscillation frequency increases. During the interval between 200 s and 400 s, 200 ml of benzene mixed with 200 ml of synthetic air have been introduced. We can see there that the polymer increases its mass due to the progressive absorption of benzene molecules, translating it as a decrease of the oscillation frequency. After that, both the dehumidification mechanism commented above and the temperature drift apply (there is no temperature control in the experiment), resulting on a frequency increase that leads to some saturation.

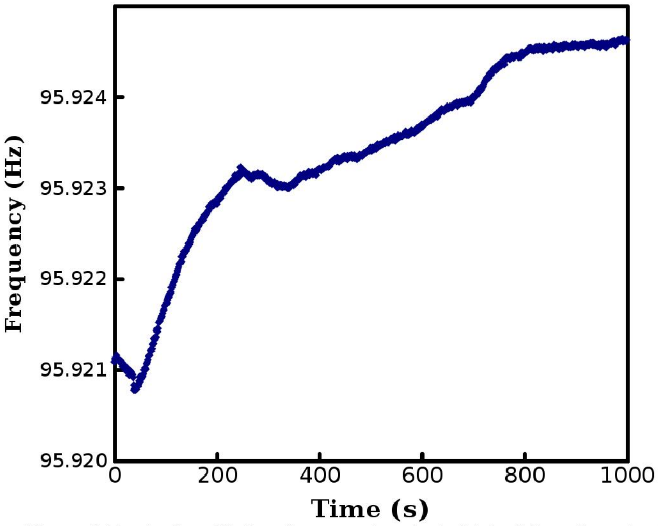


Figure 5 'Analog' oscillation frequency transient obtained from the output of the PDO instrumentation amplifier after a frequency meter.

B. *Digital Results*

The PDO digital channel allows obtaining measurements directly from the control circuitry through the bit stream transmitted by the digital feedback loop. Figure 6 shows the results obtained from the output of the 1-bit quantifier for the same experimental case as in Figure 5. A sampling frequency of 526 kHz was used and 9000 samples were captured. As it can be seen, this ‘raw’ digital response exhibits a strong quantification noise, but its shape is rather similar to the analog transient in Figure 5.

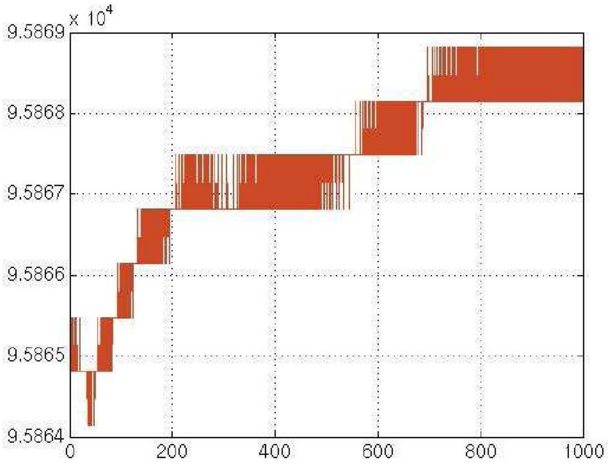


Figure 6. ‘Raw digital’ oscillation frequency transient obtained directly from the PDO feedback loop samples. Frequencies in Hz, time in s.

A well-known advantage of digital formats is the data post-processing facility. Thus, in order to reduce the quantification noise of the ‘raw’ digital data, a raised cosine filter was defined and applied using the Matlab environment. The new ‘filtered’ digital result is shown in Figure 7. Let us note that the improvement between Figures 6 and 7 is more than obvious. Moreover, it demonstrates the equivalence between results in PDOs obtained easily by digital means (Figure 7) and the real behavior of the system obtained by using sophisticated equipment from the analog channel (Figure 5).

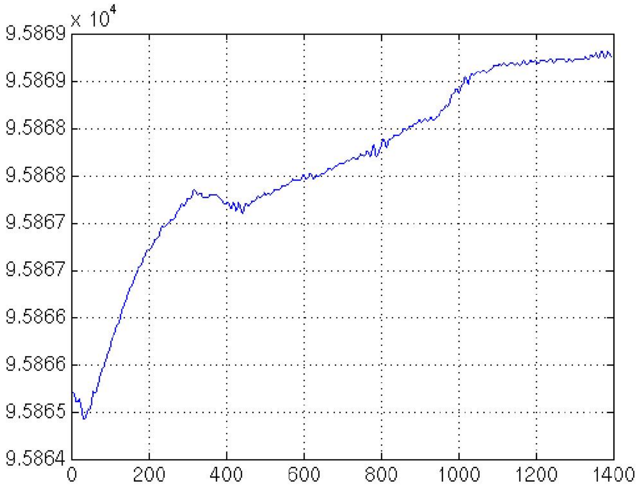


Figure 7. ‘Filtered digital’ oscillation frequency transient obtained from the PDO feedback loop samples. Frequencies in Hz, time in s.

ACKNOWLEDGMENTS

This work was supported by the Spanish government through a TEC2007-67951/MIC project.

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