Application of MCLC Method for Estimating the Parameters of MEMS Sensors

E. Colinet[*], J. Juillard[*] and L. Nicu[**]

[*]Département SSE, SUPELEC, France, eric.colinet@supelec.fr
[**]LAAS, CNRS, Toulouse, France

ABSTRACT

This paper presents an extension of a novel identification method for MEMS parameters, known as MCLC. It is well suited for MEMS applications since it is quite easy to integrate with the sensor. Basically the method is based on the measurement of a limit cycle that appears when inserting the unknown system in a non-linear closed loop. This limit cycle can be used to estimate the parameters of the unknown system. In order to be efficient, the closed loop system is brought in a chaotic regime so that the limit cycle is infinitely long, which improves the accuracy of the MCLC method. Some results obtained by simulation are reported throughout the paper to illustrate the approach. Finally, an experimental setup is presented in order to validate this approach.

Keywords: MEMS sensors, chaos, system identification, nonlinear systems, limit cycles.

1 INTRODUCTION

In many MEMS sensor applications, the parameters which describe the entire system are usually not well defined. Possible reasons for this are mostly:

- dispersion due to the manufacturing process (residual stress, varying deposit thickness, etc.),
- environmental variations (temperature, ageing, pressure).

This lack of knowledge typically leads to a decrease in the sensor performances. For example, consider a closed-loop sensor for which a feedback control loop has been designed for its nominal characteristics. Even if one has taken into account possible fluctuations of the sensing cell characteristics to ensure the system's stability, it is impossible to guarantee the optimal sensor performance. To overcome this problem, the parameters of the sensing cell could be identified occasionally in order to adjust the feedback loop in consequence. Of course, the integration of this functionality together with the sensor represents a major challenge in the field of MEMS. This is even more crucial since classical identification methods [1-2] based on numerical computations require very high resolution analogical to digital converters that are difficult/costly to integrate.

The MCLC method [3-4] -for Measurement of Complex Limit Cycles- has been developed to take care of this problem. It basically requires only a one-bit ADC (comparator) and a set of digital filters. As its name suggests, it is based on the "measurement" of limit cycles, in our case "complex" binary discrete-time oscillations which appear at the comparator's output of a sigma-delta loop (fig. 1). The shape of these oscillations results from a synchronization phenomenon between the natural frequency of the sensing cell and the clock frequency of the discrete-time components. There are many advantages to this method:

- it is quite easy to implement since in it requires only one critical analog component i.e. the comparator which acts as a one bit ADC,
- the identification itself - meaning the post-measurement computations - can be implemented with ease in a DSP processor,
- it requires only the measurement of discrete switching times. Thus the method is purely digital.

In the first part of this paper, the MCLC approach is briefly presented. Further details can be found in previous papers [3-4]. Then, we focus on the choice of the discrete feedback filters and show that driving the system into a chaotic regime thanks to an appropriate choice can greatly reduce the number of experiments. Some simulations that illustrate this approach are given. In the last section, the experimental setup used for validating our approach is presented.

2 PRINCIPLE OF MCLC METHOD

Let us consider a system that can be modeled by a transfer function of the form:

$$H(s) = \frac{\sum_{i=0}^{n_b} b_i s^i}{\sum_{i=0}^{n_a} a_i s^i} \quad (1)$$

where coefficients $\theta=[b_0,\ldots,b_{nb}, a_0, \ldots, a_{na}]$ are unknown parameters that must be estimated.

In order to realize a parametric identification of those coefficients using the MCLC approach, the system is inserted in a non-linear closed loop. This feedback loop is composed of a one bit ADC followed by a programmable discrete time filter *G(z)* (fig. 1).

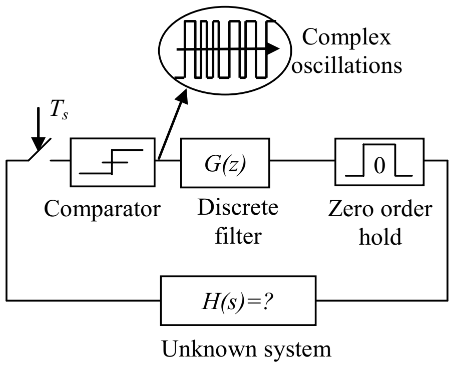

fig. 1: the unknown system is placed in nonlinear closed loop. Given an appropriate discrete filter, complex oscillations depending on *H(s)* can be observed at the comparator's output.

Using an appropriate filter *G(z)*, this closed-loop system can exhibit oscillations, the so-called "limit cycles". These limit cycles are completely characterized by the ADC switching moments, which depend on the values of the system parameters. Therefore by collecting many different cycles using different discrete filters *G(z)* to avoid redundancy, one may extract the parameters of interest by minimizing a cost function.

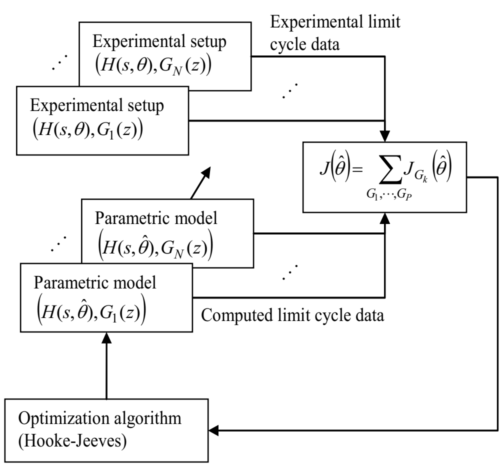

fig. 2: proposed parameter identification scheme using limit cycle information.

An almost natural choice for the cost function is:

$$J_G(\theta) = \frac{1}{N}\sum_{k=0}^{N-1}\left[\hat{u}(k) - u(k)\right]^2 \tag{2}$$

where N is the length of the measured limit cycle u and $\hat{u}$ is the binary response of the parametric model of the system to u. Since $\left|\hat{u}(k) - u(k)\right|$ takes only two values, it is clear that N must be as large as possible for criterion (2) to be "smooth". Therefore, the ideal feedback filter *G(z)* is a filter that produces the longest limit cycles. However it is difficult to guarantee *a priori* the length of the limit cycles since it is dependent on *H(s)* which is by definition not known. Using different feedback filters is another way to obtain a smoother cost function. This method, which is represented in fig. 2 is used with success in [3-4]. However, this method may be difficult to apply in some circumstances: for example, it may be difficult to bring a very stable system[1] to oscillate with a long cycle.

We propose in the following section a way of obtaining very long limit cycles in most practical cases.

3 CHAOTIC MCLC

Consider a discrete integrator filter *G(z)* of the form:

$$G(z) = \pm\frac{z^{-1}}{1 - pz^{-1}} \tag{3}$$

where $0<p$ represents a leak in the integrator.

For values of p smaller than 1, *G(z)* is stable (it has only one pole inside the unit circle): inserting this filter in a nonlinear feedback loop will usually result in a limit cycle of finite length. The limiting case of p=1 corresponds to a perfect integrator: treating this case from a theoretical point of view is very delicate, see for example [5-6]. Practically, a perfect integrator still outputs limit cycles with finite lengths.

We now propose to use values of p larger than 1 in order to drive the whole system into a chaotic regime. Although *G(z)* now has a pole outside the unit circle, the comparator forces the whole system to be confined to a finite region of its phase space, as long as the pole stays "close enough" to the unit circle. Moreover, the trajectory in the phase space of the system never goes through the same point twice: this means that the system has a nearly periodic behavior. Thus, it is possible to generate indefinitely long limit cycles, provided the system is "chaotic enough": a compromise must therefore be found between chaos and global system stability.

A typical choice for *G(z)* is :

$$G(z) = \frac{z^{-1}}{1 - pz^{-1}} G_1(z) \tag{4}$$

where $1<p<1.01$ and $G_1(z)$ a stable discrete filter.

4 SIMULATION

It is a common enough situation to have a MEMS sensor for which the first resonant mode is dominant. Thus, we illustrate the chaotic MCLC method by identifying atransfer function of the following form:

[1] as a sensor with a built-in analog control loop, e.g. a ΣΔ sensor.

$$H(s) = \frac{G}{s^2 + 2\xi\omega_0 s + \omega_0^2} \tag{5}$$

ω_0 is the natural pulsation and ξ the quality factor. Both coefficients are unknown and must be identified.

In the following figures, the nominal values for ω_0 and ξ are, respectively, 1rad.s^{-1} and 0.1 and the value for the sampling period is T_s=1s. The cost function is plotted in fig. 3 for different values of N. As expected, when N increases, the accuracy of the method increases too. Thus, as opposed to the case when stable discrete filters are used, it is possible to identify a second-order system with only one experiment, the accuracy depending mostly on the number of points N that can be handled.

5 IMPLEMENTATION

An experiment has been set up in order to validate this approach. It is composed of two different parts (fig. 4-5): the first one is a reusable digital circuit, consisting of a relay, an FPGA and a fast switching DAC. The design of the digital part is aimed at universality: it is easily reprogrammable and can be plugged into virtually any physical system with a moderate bandwidth (smaller than 20kHz). The second part of the experiment is an optical setup that uses white light in order to detect the vibration of a set of micro-machined cantilever beams. The principle of the measurement is that the intensity of the reflected light is modulated as the beam's tip moves in and out of focus. This light modulation can then be converted into an electrical signal, sent into the digital world and then processed. The chip on which the micro-beams have been etched is fixed on a piezo-electric membrane with a very flat frequency response. The vibrations of this membrane are controlled by the reprogrammable digital circuit, thus closing the loop.

Unfortunately at that point because of a poor detection signal quality, we were not able to test our method on this particular case. We are now looking into a detection system using a phase-locked loop amplifier. Meanwhile, a resonant active filter with adjustable quality factor has been used to demonstrate the feasibility of our method. As expected, we were able to identity with good precision the filters parameters [3].

6 CONCLUSION

We have presented in the present paper an extension of the MCLC method for estimating the parameters of MEMS sensors. This method of identification fits perfectly the constraint of MEMS design. Indeed it requires only one critical analog circuit (a comparator) which doesn't cover a large area of silicon. An improvement of the method was demonstrated: by driving the system into a chaotic regime, it is possible to produce an indefinitely long limit cycle. Thus the accuracy of the chaotic MCLC method, with only one feedback filter, is as good as that of the deterministic MCLC, using a large number of feedback filters. Some simulation results were then shown and the experimental setup on which the method will be tested was presented.

REFERENCES

[1] Ljung L., "System identification - theory for the user", Prentice Hall, 1987

[2] Voda A., Landau I.D., "The auto-calibration of P.I. controllers based on two frequency measurements", International Journal of Adaptive Control and Signal Processing, vol. 9, no. 5, pp. 395-422

[3] Juillard J., Colinet E., Nicu L., Bergaud C., "Digital self-calibration method for MEMS sensors", IEEE Transactions on Instrumentation and Measurement. Submitted

[4] Colinet E., Juillard J., Kielbasa R., "Self-calibration method for a sigma-delta micro-accelerometer", IEEE Instrumentation and Measurement Technology Conference, vol 2, pp. 1170-1174, 2004

[5] Feely O., Chua L.O., "The effect of integrator leak in ΣΔ modulation", IEEE Transactions on Circuits and Systems, vol. 38, 11, pp. 1293-1305, 1991

[6] Strogatz S., "Nonlinear dynamics and chaos", Westview press, December 2000.

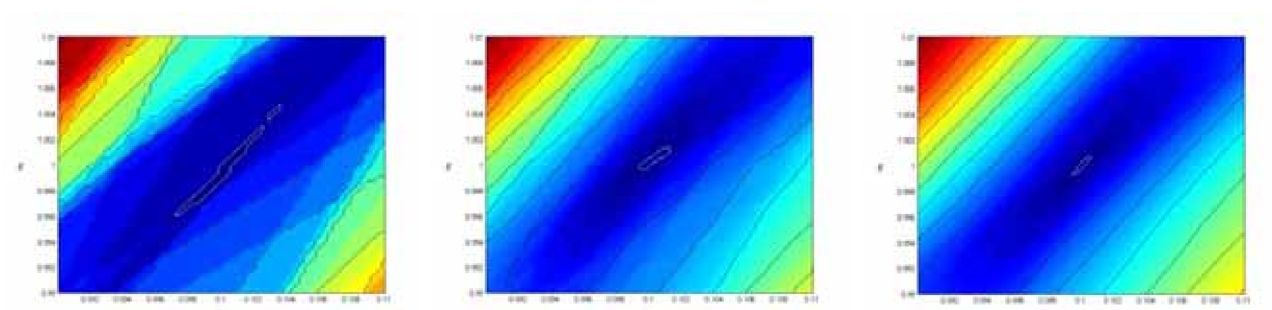

fig. 3: map and isolines of the cost function for system (5). The x-axis corresponds to ξ and the y-axis to ω_0. The white line corresponds to 1% of the maximum cost. From left to right, the number of points for each is simulation is 500, 5000 and 50000.

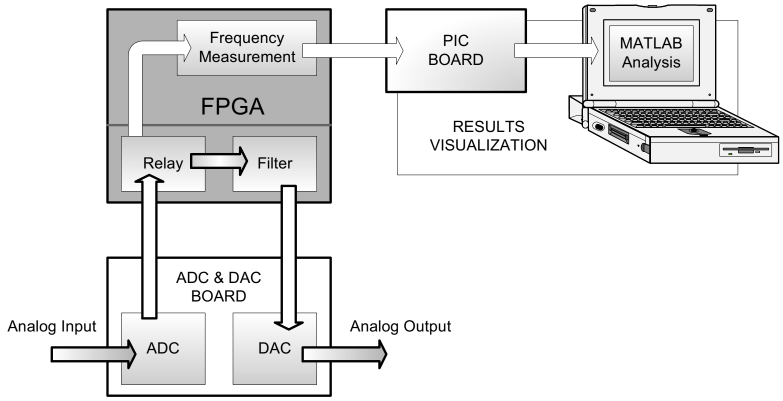

fig. 4: digital part of the experimental setup. An FPGA is used to implement the various feedback filters. The limit cycle data is then sent to a PC for the parameter extraction routine.

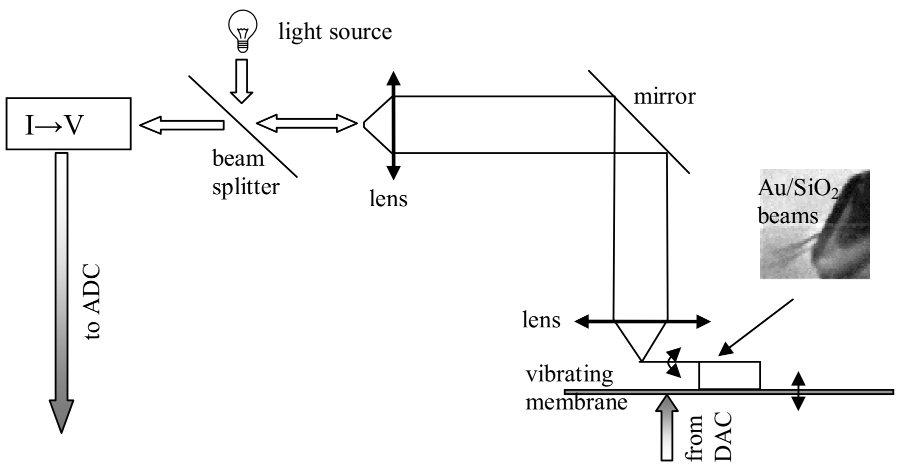

fig. 5: analog part of the experimental setup. SiO_2 beams with a thin layer of Au are brought to oscillate thanks to piezoelectric membrane. The displacement of the beam's tip is detected thanks to an optical setup: the reflected amplitude varies when the tip moves in and out of focus