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Active isolation of electronic micro-components with piezoelectrically transduced silicon MEMS devices

Y Meyer¹, T Verdot¹, M Collet¹, J Baborowski² and P Muralt²

¹FEMTO ST département LMARC, UMR 6174, 25 000 Besançon, France

²Ceramics Laboratory, Materials Institute, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Thin PZT films have a major interest for active control of mechanical structures. Precisely, it is an open field for the isolation of micro-components sensitive to dynamic effects. Indeed, the electronic components used, for example, in aircraft endure intense vibrations due to acceleration. These vibrations have some disturbing effects on the frequency stability and on the usable life of the electronic elements. The isolation of these elements becomes crucial to protect them from the vibrating environment. In order to manage this problem, it is advisable to isolate the electronic card either at the case level or at the card level or at the sensitive element level. The latter solution was chosen. Thus, we have direct access to the control electronics and the energy sources and the control energy is lower. An active suspension system is developed between the support and the sensitive element to be isolated. An original active suspension system is designed. Some modeling difficulties arise due to the existence of the inevitable bottom electrode common to the actuating layers and to the sensing layer.

1. Introduction

The constant miniaturization of electronic components essential with electronic cards such as frequency generators, vibrating gyroscopes and certain accelerometers generates two major difficulties. On the one hand, the size of the soldered connection points has been reduced considerably, approaching a material's yield. On the other hand, the reduction in dimensions of these elements involves fatally that of their useful mass. Then, these electronic components become very sensitive to the external noise and become inefficient and inaccurate. Consequently, the accuracy of measurements is lost in the noise level of the signal. These two problems are solved if the device can be stabilized.

There are various methods likely to solve these limitations. Indeed, it is possible to stabilize the sensitive components at the level of the cases containing the carrying electronic cards. Generally, this solution is obtained by using passive isolation strategies [9, 1–3]. A second solution involves stabilizing at

the level of the cards. It is possible to apply some active isolation strategies by using piezoelectric patches [4–7]. The last solution is at the level of the electronic components themselves. This paper examines this method. The principal idea is to create 'small isolation islands' to isolate each sensitive component individually. The control electronics already present on the cards and the traditional design methods of these cards are exploited to machine a carrying structure. So, the stabilization structure will integrate into the design phase of the electronic circuits. Thus, it becomes necessary to use a machining technology compatible with those of the printed circuits. The control law is founded on the classical collocated 'sky-hook' strategy [8, 9] with an internal sensor.

The objective of this research program is to create, manufacture and test a piezoelectric system micromachined and integrated on silicon substrate for the active isolation of micro-components sensitive to environmental vibrations. In this paper, the concept of 'small isolation islands' is validated.

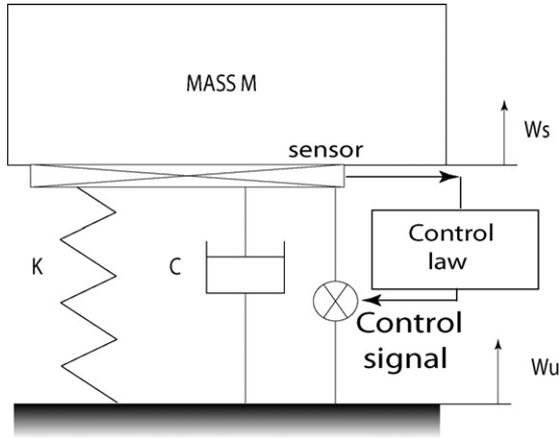


Figure 1. Principle scheme of a 'local' active isolator.

In the first part of this paper, the 'small isolation island' that we study is described as well as its manufacturing process. Moreover, a multiphysics finite element model of the structure is developed with the bottom electrode common to the actuating and sensing layers. This model predicts the motion of the coupled structure and the output voltage across the sensor in response to an external random impulse applied to the boundaries of the suspension.

In the second part of this paper, the structure is characterized experimentally in order to validate the numerical model. The restrictions of this model are analyzed. Experimental control of the device is achieved. An integral force feedback (IFF) strategy [9] is applied. The resultant closed-loop system's robustness and stability are analyzed.

2. Design concept of the active suspension

2.1. Functioning principle

The basis of an active isolator is the addition of an 'active' function to the traditional suspension. The objective is the diminution of the mechanical overpressure without degradation of the high frequency decay rate. The passive isolator constitutes the framework of the device. A network of sensors and actuators is added to the suspension, as shown in figure 1. The sensors monitor the vibratory state of the suspended mass. This strategy is efficient with absolute information: acceleration, reaction force and, eventually, absolute displacement or absolute speed. The different variants are based on the measurement type which is executed. In [10], a study of the features of the 'sky-hook' strategy with different measurement types is detailed. Then, this makes it possible to create the input signal of the actuators via a controller. Of course, this will be a function of the nature of the transmitted information but also of the reaction type produced by the actuators.

The example of the one single degree of freedom system is taken again; its equation of motion is written

$$M\ddot{W}_s + C\dot{W}_s + KW_s = F_{\text{ext}} + u_{\text{control}} \quad (1)$$

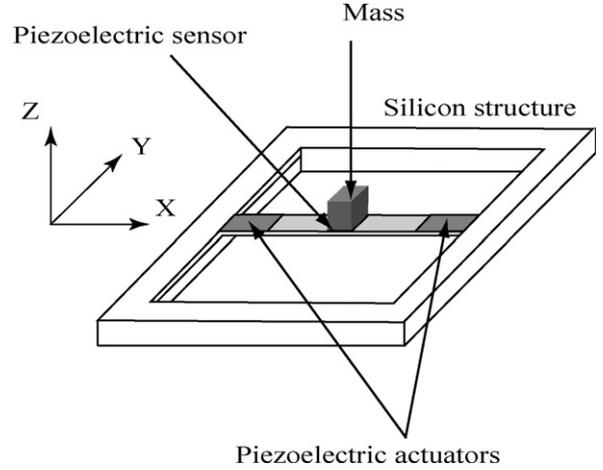


Figure 2. Structure of the suspension.

where

$$F_{\text{ext}} = C\dot{W}_u + KW_u: \quad \text{the external impulse (in N)} \quad (2)$$

$$u_{\text{control}}: \quad \text{the control force (in N).}$$

The aim of the control is to attenuate the resonance peak. The signal of the chosen sensor is proportional to acceleration. Thus, it is integrated to achieve the desired effect. The control law is related to the 'proportional-integral' method [11]. Within the framework of active control, the strategy is called a 'sky-hook' damper [9], where G is a strictly positive proportionality factor.

$$u_{\text{control}} = -G \int y dt = -G \int \alpha \ddot{W}_s dt = -G\alpha \dot{W}_s. \quad (3)$$

The 'sky hook' has two major advantages. It is robust. In other words, even if the structure changes due to ageing in the shocks or the system drift, the control will remain powerful. In addition, no matter what the structure is simple or complex, the 'sky hook' is stable under conditions exposed in [9]. The disadvantage of the 'sky hook' is the non-optimality of the control law. Thus, it becomes imperative to optimize the placement of the sensors and the actuators on the system in order to achieve good control results.

2.2. Experimental device

A silicon clamped-clamped beam, as shown in figure 2, is used as a basic passive structure on which the element to be isolated is placed [12]. The active function is conferred to the structure by two piezoelectric actuators and one piezoelectric sensor deposited on the top face of the beam. These active parts of the system are founded on thin layers of PZT type [13].

Thus, the direct and opposite piezoelectric effects are used. In order to simultaneously allow detection and activation, a multielectrode system was conceived. The actuators are placed near to the boundaries of the beam and their length is optimized in order to obtain the maximum action force on the first natural mode [14, 15]. The sensor is located in the middle of the suspension. It constitutes the support of the sensitive element, in our case a small mass made of steel. It obtains an

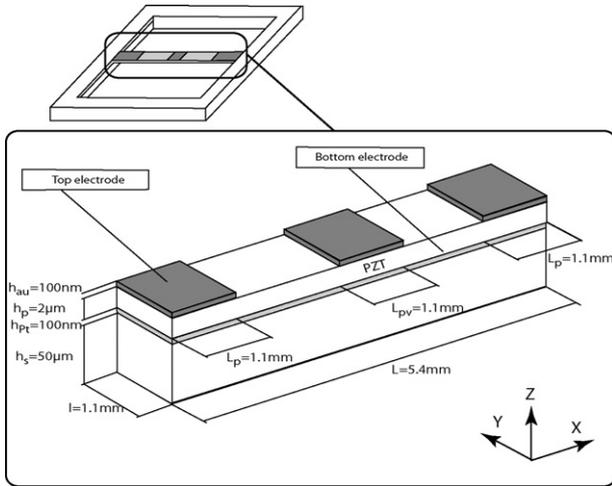


Figure 3. The dimensions of the suspension.

output signal mainly proportional to the acceleration endured by the component.

2.3. Manufacturing of the active suspension

The system's dimensions and machining conditions were designed to duplicate actual electrical components and these values were also used to validate experiments numerically. These elements were replaced mechanically by a cubic mass of 1 mm side made of steel weighing 7.8 mg. It should be noted that this value is representative of the masses of a real component to be controlled. As indicated in figure 3, the suspension systems are laminated piezoceramic clamped-clamped beams made of 50 μm thick silicon, 2 μm thick silicon oxide (SOI), one electrode a few nanometers thick, one layer of 2 μm thick PZT and one top electrode located where the layer is used (like an actuator or sensor). The beams used were 5.4 mm long and 1.1 mm wide.

The piezoelectric (PZT) MEMS micro-manufacturing was conducted in the laboratory. The integration of the piezoelectric layers (PZT by sol-gel) directly on SOI (silicon

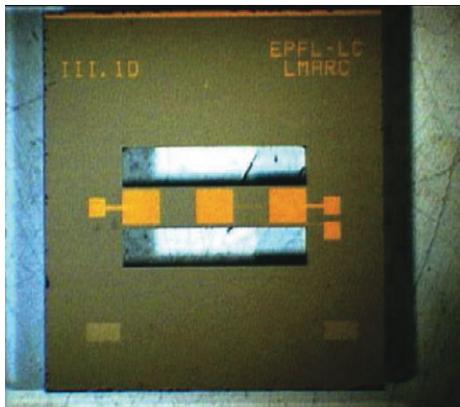
on insulator) substrates was conducted according to the literature [16, 17]. The mechanical and piezoelectric properties of the layers obtained at the end of the micro-manufacturing process were excellent and sufficient for the application concerned. The machined batches showed a yield higher than 95% on a silicon substrate 10 cm in diameter. No later deterioration of the system (tiredness, delamination) was observed. The individual devices could be relatively easily 'packaged' on electronic media of PCB type and thereafter integrated in a complete system. The electronic component to be protected was glued on the central part of the microsystem constituting the sensor of the system. In figure 4, we can observe the one single degree of freedom isolation structures employed for the numerical and experimental tests.

3. Modeling the active suspension

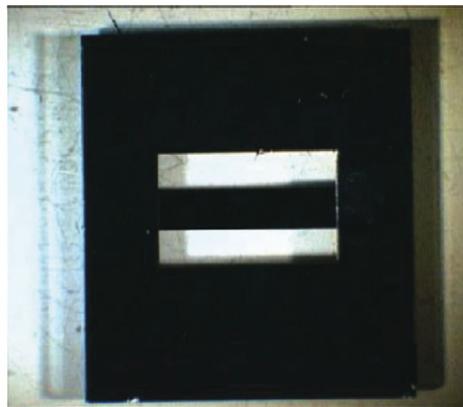
It is necessary to validate the principle of the 'small isolation island' on a numerical model. Initially, the naked suspension was studied, i.e. without the mass to be isolated. Thus, we were able to validate the model compared to the experimental results that were obtained. Then, the sensitive element was placed on the suspension in order to evaluate the performance of the suspension. These results were compared with those of the real structure.

3.1. Modeling the mechanical part of the suspension

The numerical model employed is a multiphysics finite element model developed under the Femlab software. For the FE discretization of the model, the automatic mesher of Femlab[®] was used. In the 2D space (plan ZX), the finite elements of Argyris were used [18]. The 2D space was used in order to account for the shear effect in the piezoelectric film [19, 20]. The modeling of the system was based on the piezoelectric theory, that is to say on a linear theory [21–26]. Once the model had been developed, the different transfer functions of the coupled structure were used. The inherent damping factor is considered small ($\xi = 0.1\%$) because the materials used are brittle (silicon and PZT).



(a)



(b)

Figure 4. Close-up of the silicon structure: (a) the front face; (b) the back face.

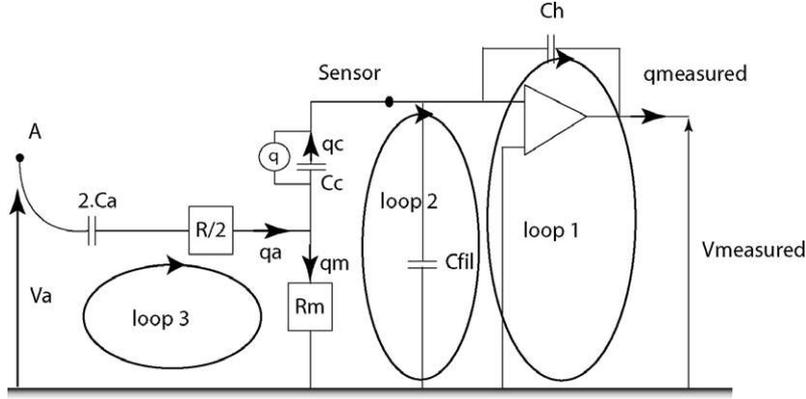


Figure 5. Equivalent electric scheme of the active suspension connected to the conditioning amplifier.

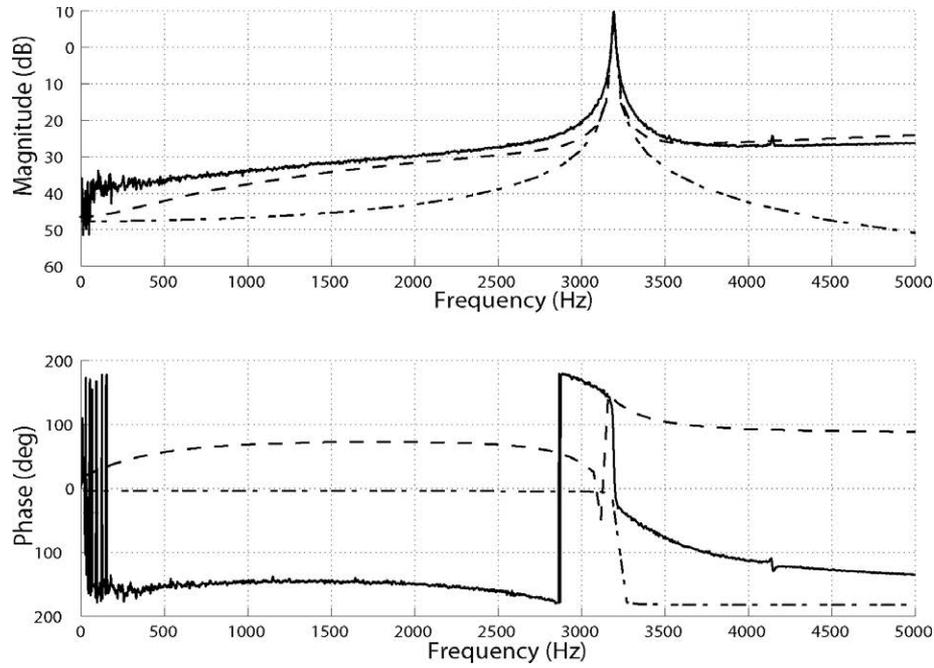


Figure 6. Bode diagrams between the output signal from the sensor and the signal applied to the actuators of the beam: measured (solid line), theoretical with the electric coupling (dotted line) and theoretical without the electric coupling (dash-dot line).

3.2. Modeling the common bottom electrode

As observed in figure 3, the actuators and sensor have the same bottom electrode. Experimentally, a resistance was measured with a value of 0.6 between the common bottom electrode and the electric ground. The measurements contain the output signal of the sensor but also a parasitic signal due to the resistance of the common electrode. The device connected to the conditioning amplifier can be electrically modeled as shown in figure 5. The sensor is equivalent to an electric capacity and a generator of electric charges in parallel.

By using loops 1, 2 and 3, the following relationship is obtained in the Laplace domain:

$$V_a = - \left(\frac{1 + 2C_a \left(\frac{R}{2} + R_m \right) s}{2C_a R_m C_c s} \right) q + \frac{1 + (R_m C_c + 2C_a \left(\frac{R}{2} + R_m \right) s) + 2C_a \frac{R}{2} R_m C_c s^2}{2C_a R_m C_c s} \times q_{\text{measured}} \quad (4)$$

The contribution of the mechanical part must be included in equation (4). The equivalent charge of the sensitive piezoelectric layer is related to the input voltage V_a as

$$q = H_{\text{sys}} V_a \quad (5)$$

The relationship between the feedback voltage and the measurement can be written by considering that the electric resistance between the grounds of the transducers is neglected ($R = 0$), such that

$$\frac{C_h V_{\text{measured}}}{V_a} = \underbrace{\frac{2C_a R_m C_c s}{1 + (R_m C_c + 2C_a R_m) s}}_A + \underbrace{\frac{(1 + 2C_a R_m s) H_{\text{sys}}}{1 + (R_m C_c + 2C_a R_m) s}}_B \quad (6)$$

Part A is related to the contribution of the electric coupling and part B to the contribution of the mechanical system.

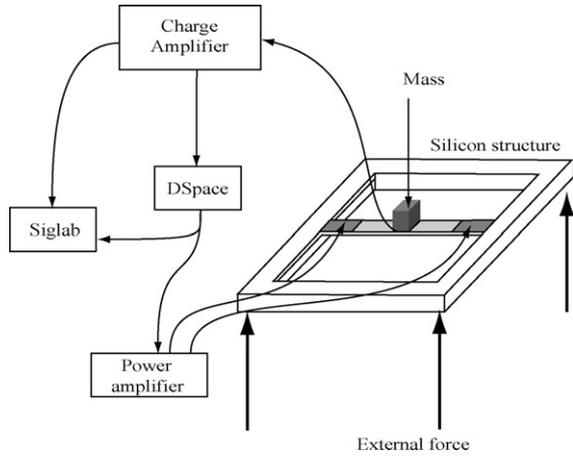


Figure 7. Control architecture.

3.3. Experimental characterization of the suspension

The objective is to validate the multiphysics model of this system with an internal measurement provided by the sensor located under the mass to be isolated. For this, a random input voltage is applied to the actuators of the suspension through a power amplifier and the output signal from the sensor is measured with a conditioning amplifier. A data acquisition process is used to obtain the experimental diagrams. In figure 6, the multiphysics model is verified with the simplified model of the electric coupling. The correlation between the magnitude diagrams is good. Nevertheless, an offset is observed with a value of 180° in the phase diagram. In fact, this offset is caused by the power amplifier.

4. Active control of the structure

4.1. Control architecture

The control strategy is based on the use of a piezoelectric layer directly forced by the acceleration of the sensitive system to

be isolated. The diagram of the control strategy is described in figure 7. The input of the controller is acceleration measurements. Then, the control signal is amplified and applied to the two piezoelectric activation layers, making it possible to apply the mechanical control force to the system. Moreover, a data acquisition process is placed in parallel to the controller for measurement purposes. Then, the system induces an active isolation along one single degree of freedom (the Z-axis) of the electronic system to be stabilized.

4.2. Experimental active control

Before using a controller algorithm, the feedback loop was simulated in order to evaluate the theoretical performances of the suspension. This makes it possible to evaluate the capabilities of the isolation strategy. The damping value was found to be 3.14% for an external excitation with a value of $11g_{rms}$ ($g_{rms} = 9.81 \text{ m s}^{-2}_{rms}$).

In figures 8 and 9, the controlled and uncontrolled transfer functions between the force applied to a seismic mini-table (especially manufactured for this application) are presented as well as the internal acceleration measurement used for the control of the device. An attenuation of about 20 dB was observed from the resonance peak of the first suspension mode of the system on a silicon substrate for an external force with a value of $11g_{rms}$. The value of the damping ratio of the controlled system was close to 1.7%. The difference with the modeling was due to the non-linearities of the ferroelectrics within the piezoelectric thin film. So, the control is conditioned to the anti-resonance frequency of the global system.

The correct operation of the actuators is shown. The internal sensor that was used presents strong capacitive couplings with the actuators. This electric coupling was evaluated and included in the model. However, the robustness and the efficiency of this strategy were shown with the use of the transducers made of piezoelectric thin layers. The results that were obtained are compiled to conceive a new control strategy, allowing better performances.

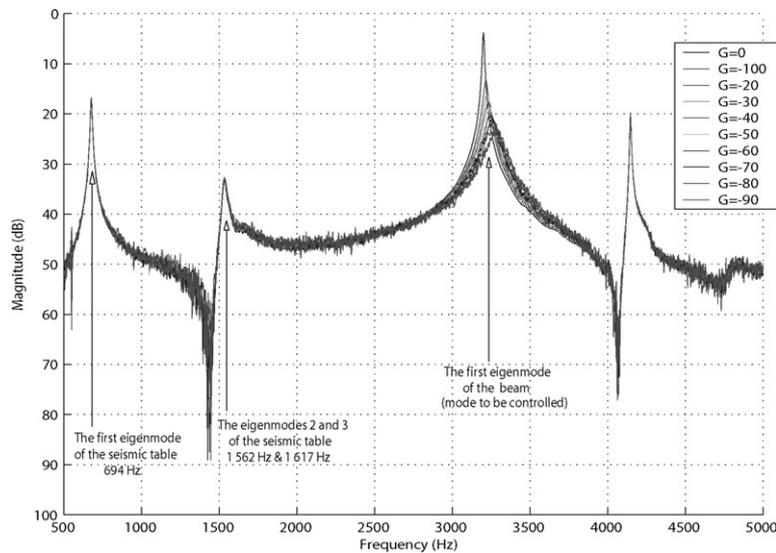


Figure 8. Active control of the suspension mode for different control gains.

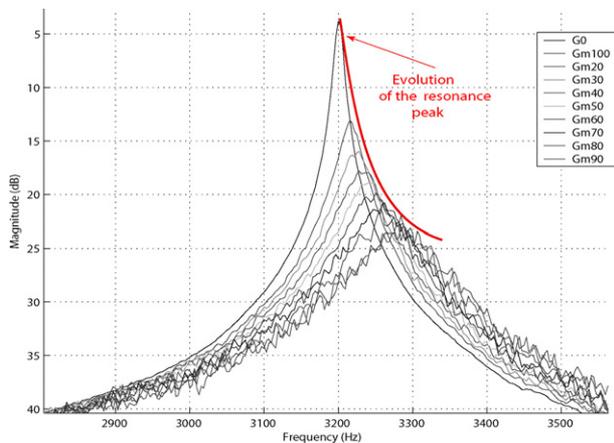


Figure 9. Close-up on the suspension mode for different control gains.

5. Concluding remarks

The experimental results show an attenuation of the resonance peak of the first suspension mode of the system on silicon. The correct functioning of all the piezoelectric layers is shown. However, technical difficulties limit the isolation performance of the structure. New control strategies are under development to manage these difficulties. Moreover, the ferroelectric modeling [27–30] is developed to improve the obtained results beyond the coercive field. New devices are under development to eliminate the physical problems of the system. This research theme has a very strong scientific potential. Currently, the systems presented in this paper are the subject of an industrial patent. Thus, the prospects are very varied at the technological level as well as the conceptual one.

Future developments will make it possible to approach the concept of the ‘small isolation islands’ in particular by the use of the AlN material for the piezoelectric layers. The integration of the suspension system will be done directly in the substrate containing the components to be protected and the electronics dedicated to their use. The two great advantages of the AlN layers compared to those of PZT are

- the possibility of targeting the deposition zones and
- the non-utility of the poling phase of the piezoelectric material.

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