Application of Set Membership Identification for Fault Detection of MEMS

Vasso Reppa

University of Patras
Electrical and Computer Engineering Department
Rio, Achia 26500, GREECE
Email: freppa/tzes@ee.upatras.gr

Abstract - In this article, a set membership (SM) identification technique is tailored to detect faults in micro-electromechanical systems. The SM-identifier estimates an orthotope which contains the system’s parameter vector. Based on this orthotope, the system’s output interval is predicted. If the actual output is outside of this interval, then a fault is detected. Utilization of this scheme can discriminate mechanical-component faults from electronic component variations frequently encountered in MEMS. For testing the suggested algorithm’s performance in simulation studies, an interface between classical control-software (MATLAB) and circuit emulation (HSPICE) is developed.

Index Terms – MEMS, Fault Detection, Set Membership Identification

I. INTRODUCTION

MicroElectroMechanical Systems (MEMS) have been applied in diverse areas [1]. Amongst the reasons for their explosive growth is the coupling of different field components such as mechanical, electric, thermal, optical, fluidic etc.[2]. Simulation of MEMS is quite demanding since various certain modeling aspects need to be considered. Their dynamic behavior can be analyzed via simplified compact models and the corresponding associations, leading to a system description known as the (simplified) "Generalized Kirchhoffian Network" [3].

Computer-aided design (CAD) for MEMS is primarily constituted of electronic design automation (EDA) and mechanical design automation (MDA) [4]. Typical MDA-based system level simulators generating reduced-order macromodels [5] can be used for further analysis using hardware description languages (HDL) [6]. Popular simulators like Coventor ARCHITECT [7] and NODAS [8] use VHDL-AMS and AHDL. Departing from the HDL-based MEMS simulators, a cluster of software relying on Matlab has emerged [9,10]. From the EDA-industry, SPICE and its spinoffs (HSPICE, PSPICE, etc) are the most widely accepted simulators [11,12]. In recent years, there is trend to implement simulators, which are characterized of multi language capability, such as SMASH [13], Synopsys SABER [14, 15], which are compatible with SPICE and HDL.

The formation of an integrated simulation kernel, capable of modeling MEMS’ mechatronic elements is of paramount importance. This kernel can be used in Fault Detection (FD) of MEMS [16-21]. FD in MEMS is quite difficult, since faults can originate from various sources such as the electronic and the “mechanical” sections. Furthermore, FD must distinguish cases corresponding to faulty components from those that are related to aging components. Electronic components exhibit different aging attributes compared to the mechanical ones (micro-springs and dashpots). Mechanical components, after significant wear tend to break down in a catastrophic manner; electronic elements (micro-resistors, etc.) have a rather gradual decay in their characteristics (i.e., resistance variations). Therefore, a scheme is needed to distinguish these two cases, and assign a fault to the sudden change in the system’s parameters.

Inhere, the development of a FD-scheme for MEMS systems with sudden changing dynamics (jump-systems) is addressed. The system’s parameter vector is identified through a sliding-window orthotopic SM-identification scheme. A recursive algorithm predicts the interval of the system’s output based on the identified parameter bounds. The fault is detected when the actual system output is not within the predicted ‘worst case’ interval output, or when the actual parameter vector is not within the identified interval.

In the remaining of this article, a suggested FD-scheme is coupled to an integrated MEMS simulation kernel composed of HSpice and Matlab [22]. Extensive simulation cases are examined for classical MEMS (microactuator system in [23]). Worst cases scenarios are developed for handling variations of the electronic components. These responses are compared to the ones corresponding to sudden microspring cracks. The FD-scheme can distinguish with a certain degree these sudden cracks (jumps).

II. PROBLEM STATEMENT – CASE STUDY

The development of a FD-mechanism for sudden changes in MEMS is the primary scope of this article. The MEMS is composed of certain electronic components coupled to a set of micro mechanical elements. Major faults similar to those attributed to mechanical component failures need to be distinguished from the errors attributed to the perturbations of the electronic components from their nominal values.

From a system’s point of view, the MEMS is considered as a MIMO-nonlinear system. In the generic case, the system’s description is
where \( u \) is the excitation vector, \( y \) is the system’s outputs, \( x \) is the internal state vector, \( \theta \in \mathbb{R}^P \) corresponds to the component (resistor, capacitor, etc.) vector, and \( e \) is the noise corrupting the measurements. Under the assumption, that:

a) the aforementioned nonlinear system can be approximated as a linear one [24], whose discrete dynamics is

\[
\dot{x} = f(x, \theta, u), \quad y = g(x, \theta) + e \quad (1)
\]

b) \( \dot{\theta}(k) \) remains constant over a sliding window with length \( L' \), or \( \dot{\theta}(k) = \dot{\theta}(k-1), \ldots, \dot{\theta}(k-L') \). The window’s minimum length, \( L^* \) is assumed to be known, whereas the time instants–jump \( \theta(k_i) \neq \theta(k_i - 1) \) are unknown. This jump–parameter configuration is typical of systems prone to failure or abrupt structural changes.

c) The noise sequence is point-to-point restricted, or \( |e(k)| \leq M(k) \), with the \( M(k) \)–bound known a priori.

This noise sequence indirectly induces an uncertainty in the utilized identified model, \( \hat{y}(k) = \hat{\theta}(k)\hat{\Phi}(k) \) and can be thought as the source of parametric uncertainty. Subsequently, interval bounds on the \( \hat{\theta}(k) \)–parameter vector can be defined by mapping the noise–contaminated observations into uncertainty in the model.

The objective of the suggested FD–scheme [25, 26], shown in Fig. 1, is to identify the time instants where certain ‘generic’ faults occur. These generic faults can be attributed to: a) large measurement errors, and/or b) significant system reconfigurations [27] which lead to inconsistent model descriptions. Typical sources for such faults are micromechanical component failures, exogenous disturbances, resulting in the system’s parameter-vector switchings.

### III. FAULT DETECTION METHODOLOGY

Consider the system (2), with its inherent description (3)-(4) and the assumptions stated earlier. The FD-scheme consists of a SM-identifier and an output predictor.

#### A. Orthotopic Set Membership Identification

The OSMI (Orthotopic Set Membership Identification) problem is stated as: Compute the uncertainty interval \( \hat{\theta}(k), j = 1, \ldots, p \) for the \( j \)-th component of \( \theta(K) \) over the current sliding window, so that:

\[
\hat{\theta}_j(K) - \hat{\theta}_j(K) = \left[ \theta_j^-(K), \theta_j^+(K) \right] \Rightarrow
\]

\[
\hat{\theta}_j(K) = \hat{\theta}_j(K) = \left[ \min \theta_j(K), \max \theta_j(K) \right], j = 1, \ldots, p
\]

with,

\[
\hat{\theta}_j^+(K) = \left\{ \theta(K) \in \mathbb{R}^P \left[ \Phi_{K,L} \right] \left[ \theta(K) \right] \right\}
\]

\[
i = \left\{ y \in \mathbb{R} : \hat{y}(i) - e^M(i) \leq y(i) \leq \hat{y}(i) + e^M(i), i = K-L+1, \ldots, K \right\}
\]
Let \( \Phi_p \) be a \( p \times p \) partition matrix of matrix \( \Phi_{K,L} \) with full rank; for notational simplicity assume that the first \( p \) rows of matrix \( \Phi_{K,L} \) form this submatrix \( \Phi_p \), as in the following,

\[
\begin{bmatrix}
\Phi_{L-p}((L-p)\times p) \\
\Phi_p(p\times p)
\end{bmatrix}
\]

and let \( C \) be its inverse \((C=[\phi^T])\). Then, the bounds \( \theta^+ \) and \( \theta^- \) can be found from the optimal solutions to the following \( 2p \) linear programming (LP) problems [28],

\[
\theta^+_i(K) = \max(-\omega), \quad \theta^-_i(K) = \min(-\omega)
\]

\[
\begin{bmatrix}
z'_j \quad z''_j \\
\end{bmatrix} \begin{bmatrix}
\omega_i \\
\end{bmatrix} = 0
\]

subject to

\[
z'_j - z''_j + s_j = y(j) + e(j)M, \quad j = 1, \ldots, p
\]

\[
-z'_j + z''_j + s_{j,p} = -y(j) + e(j)M, \quad j = 1, \ldots, p
\]

\[
\phi^T C z' - \phi^T C z'' + s_{j,p} = y(j) + e(j)^M, \quad j = p + 1, \ldots, L
\]

\[
-\phi^T C z' + \phi^T C z'' + s_{j,K} = -y(j) + e(j)^M, \quad j = p + 1, \ldots, L
\]

\[
\begin{bmatrix}
z'_i \quad \ldots \quad z'_j \quad \ldots \quad z'_p \\
z''_i \quad \ldots \quad z''_j \quad \ldots \quad z''_p
\end{bmatrix}
\]

\[
\begin{bmatrix}
z'_j \quad \ldots \quad z''_j
\end{bmatrix} \geq 0, \quad z''_j \geq 0, \quad j = 1, \ldots, p
\]

where \( \omega = \sum_{i=1}^n c^T_i(l)(z'_i - z''_i) \)

\[
(8)
\]

The generic expression for \( \bar{y}(k+\lambda|k), (1 \leq \lambda \leq p-m) \) is:

\[
\bar{y}(k+\lambda|k) = \sum_{i=0}^{\lambda-1} b_{i,k}^A (k+i) + A_1^\lambda + \bar{e}(k+\lambda) + \sum_{i=1}^{\lambda-1} \bar{a}_{mi}(k) \bar{e}(k+i)
\]

\[
(12)
\]

where \( A_1^\lambda, B_{i,k}^A, i = 0, \ldots, \lambda - 1 \) are computed using the following recursive scheme:

\[
B_{i,k}^A = \sum_{j=1}^{\lambda-1} \theta_{m+j}(k) B_{i,k}^{2-j} + \theta_{(k-1)-j}(k), i = 0, \ldots, \lambda - 1
\]

\[
A_1^\lambda = \sum_{j=m+1}^{\lambda-m} \theta_{j}(k) y(k-j+m+\lambda-1), \lambda \geq 2
\]

\[
A_1^\lambda = \sum_{j=m+1}^{m} \theta_{j}(k) y(k-j+1) + \sum_{j=m+1}^{\lambda} \theta_{j}(k) y(k-j+m)
\]

\[
(13)
\]

C. Fault Detection Identification

The FD-scheme recognizes a fault when the actual \( y(k) \) is not within the predicted intervals, \( y(k) \not\in \bar{y}(k+k-1) \).

IV. SIMULATION RESULTS

The suggested FD-algorithm is applied to the MEMS [23], which corresponds to a micromechanical moving plate (prismatic microactuator) suspended by four serpentine springs. The plate’s vertical position, \( z \), and angular rotation about lateral axes, \( \theta \) and \( \phi \), are controlled by four digital loops. Under each quadrant of the plate, there is a parallel-plate sense capacitor which creates a capacitive divider with a fixed reference capacitor. The voltage change, appearing in the capacitive divider, is observed by a driven shield electrode together with an integrated CMOS buffer amplifier. Finally, the digital feedback to electrostatic actuators at each corner is achieved by off-chip \( \Sigma \Delta \) electronics.

Equivalent compact models are used for describing the components of this microactuator, forming a generalized Kirchoffian network, as shown in Fig. 2.

The micromechanical plate with the four springs and the squeeze film damping are represented as a lumped parameter model (mass-spring-damper). Springs are the typical mechanical components in which a fault, such as the destruction of one of them, can be detected in the form of a sudden change in the overall stiffness-parameter. In this case-study, the FD-scheme is examined in detecting damages (cracks) in the “microsprings”. These cracks are detected despite any small perturbations from the nominal values of the electronic components (capacitors, inductors and resistors). These perturbations are considered as uncertainties, which are represented by bounded variables [22].
To investigate the FD-scheme’s efficiency, the microactuator-system’s is simulated subject to the following assumptions.

- Micromechanical component failures are simulated as cracks in the springs leading to the corresponding reduction in the stiffness (25% reduction).
- The electronic components can vary from their nominal values with a maximum 1% error.
- The exciting input (microactuator-position) corresponds to step responses, with amplitude varying between 20 mV to 90mV.

Several runs (100+) with randomly perturbed electronic component values were simulated and the transient characteristics were recorded. The observed parameters were: the vertical displacement of the plate, $z$, the vertical applied force, $f_z$, the modulated sensor output voltage $V_{\text{sense}}$ and the peak-to-peak sensor voltage. For simulation purposes, an interface was developed between HSpice and Matlab. HSpice is used primarily for the transient system characteristic, whereas Matlab implements the FD-algorithm from the data imported from HSpice. The interconnection between MATLAB and HSPICE facilitates the procedure of fault simulation.

A. Nominal system behavior

The system’s nominal response when excited by a reference voltage of 56 mV appears in Fig. 3. The plate’s displacement is presented in Fig. 4.

B. FD-behavior under mechanical faults and electrical component variations

From the simulation runs, it was observed that the system was quite sensitive to the amplitude of the exciting step inputs. Rather than applying the OSMI-algorithm for every input
value, eight (8) banks of fault detectors are used depending on the value of the input $20 \pm 10 \text{ mV}$, $i = 0, ..., 7$.

For input voltages between 20 mV and 50 mV, the FD-scheme could not distinguish the faulty response due the simulated microcracks and attributed it to possible electrical component perturbations. In contrast of this, for input voltages between 60mV and 90 mV, the FD-scheme could diagnose the cause of the fault as one that did not emanate from the electrical component-perturbations.

In the sequel, we present the system’s responses (displacement and vertical force) for excitations of 30mV and 80 mV, respectively.

In the first case, the simulation of the displacement (force) is shown in Fig. 7 (8). Several runs (100+) are presented in these figures, corresponding to perturbations in the electronic components.

In the second case, the simulation of the displacement (force) is presented in Fig. 9 (10).

C. Output envelope generation

The bounds [31] of the system response for all runs appear in the sequel. Fig. 11 (12) shows the “envelope” of the displacement (force), within which all responses are placed from possible perturbations in the electronic components and input voltages of 30 mV. Similar results for an 80 mV exciting input appear in Figs. 13 and 14, respectively. In these Figures, the system’s faulty predicted response because of a microcrack is presented (blue line). As shown in Figs. 13 and 14, this predicted response violates the recorded bounds and a fault is detected.
V. CONCLUSIONS

The development of a fault detection scheme, relying on orthotopic set membership identification tailored for MEMS is presented in this article. Accordingly, this scheme can be used to distinguish certain mechanical faults (microcracks) against perturbations of the electrical components. Simulation studies investigate the efficiency of the FD-scheme.

REFERENCES