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Application of Thau Observer for Fault Detection of Micro Parallel Plate Capacitor Subjected to Nonlinear Electrostatic Force

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ABSTRACT

This paper investigates the fault detection of a micro parallel plate capacitor subjected tononlinear electrostatic force. For this purpose, Thau observer, which has demonstrated good performance in fault detection of nonlinear systems,as well asgoverning nonlinear dynamic equation of the capacitor,is presented. Upper and lower threshold for fault detection have been obtained. The robustness of the observer to noise, uncertainty as well as sensitivity to faults wasinvestigated. Finally, simulation results for fault detection of the capacitor are obtained and the ability of the observer in the vicinity of dynamic pull-in voltage has been checked.

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1. INTRODUCTION

In recent decades, micro electro mechanical (MEM) systems have gained popularity on engineering and industry for their remarkable advantages such as small size in order of magnitudes, high performance, possibilities for batch manufacturing, cost effective integration with electronic systems, and low (virtually zero) DC power consumption [1].

MEM tunable capacitors are the main parts of RF integrated circuits such as tunable filters and resonators [2].Furthermore, these devices with electrostatic actuation have been widely designed, fabricated, used and analyzed in micro actuators [3, 4] micro-phone [5-7], sensors [8, 9], capacitive micro-plate [10, 11] and micro capacitors [12, 13]. Despite the extensive effort accomplished on MEMS, there are not yet sufficient studies concentrating on fault detection of such systems. In the development of MEM systems, fabrication failure and fault analysis play a major role in evolution reliability.

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Choice of suitable method for fault detection of a system depends on the knowledge of physical laws and parameters of the system. For the system with the defined physical laws and parameters, white box analysis (kalman filter, extended kalman filter, Thau observer [14-17]) can be applied for fault detection. In this case, a residual signal can be obtained by comparing estimated output (state) with process output (state).

For the defined physical laws and unknown system parameters, gray box analysis (parameter identification, geometric approach [18-21]) can be implemented for fault detection. Using this analysis, system parameters can be extracted and residual signal can be obtained by comparing estimated parameter with nominal one.

In these analyses, violation of residual from threshold indicates the occurrence of fault in system.

If both physical laws and parameters of the system are undefined, fault detection process may be performed using black box analysis. This method can be used for fault detection, if only change of measured signal is related to system fault [17].

Most of the MEM systems are nonlinear in nature. Some studies regarding fault detection of these structures have been conducted. Asgary et al. [22]

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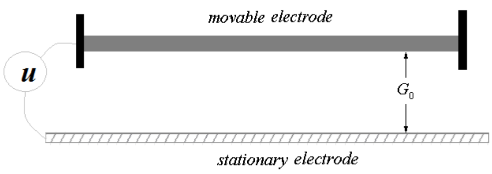
studied fault detection of nonlinear MEM devices using neural network. Reppa and Tzes [23] applied set membership identification for micro electrostatic actuators. They assumed that the system is linearly parameterizable, and the parameter vector contains quantities thatare susceptible to faults. Another study [24] on fault detection of MEM using frequency response was done by Zahidul Islam et al. Izadian and Famouri [25] studied fault diagnosis of micro lateral comb resonators. Their remarkable work is based on using multiple model adaptive estimators, but the electrostatic force term that is applied in this study is linearly proportion to state space.

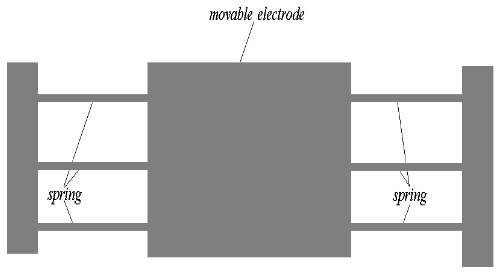
The aim of this paper is to develop diagnostic observer applied for the fault detection of a capacitive MEM switch in the presence of nonlinear electrostatic force. This is accomplished using "Thau" observer [26]. For this case, governing dynamic equation and parameters of systems are known. Thau's condition is a very useful analysis tool for state estimation and fault detection of nonlinear systems that ensures the asymptotic stability of the observer [27-30]. Atwo-parallel plate capacitor was applied to show the efficiency of the Thau observer for the fracture detection of a supporter beam of the capacitor. The stability condition for application of this observer in various circumstances was obtained and is presented. Furthermore, the ability of the observer in the vicinity of the unstable condition was analyzed.

2. MODEL DESCRIPTION

Figure 1a shows schematic view of a parallel plate capacitor, which consists of a movable electrode suspended over a stationary conductor plate. The primary gap between two electrodes is G_o. Attractive electrostatic force due to the applied bias voltage u pulls movable electrode down towards the stationary plate. Figure 1b shows top view of the movable electrode, which is suspended by six supporting beams (three at each side). The area and thickness of movable electrode are S and h, respectively. Width, thickness and length of beams are b, h, and L, respectively. The equivalent stiffness of each beam is $k = 12EI/L^3$, where E and I are Young's modulus and cross section moment of inertia, respectively. The movable electrode is considered isotropic with density of ρ.



a. Front view of capacitor



b. top view of capacitor

Figure 1. Parallel plate tunable capacitor

3. MATHEMATICAL MODELING

The governing dynamic equation of an electro-mechanical tunable capacitor such as the one in Figure 1.a can be described as:

$$m\frac{d^2z}{dt^2}+c\frac{dz}{dt}+k_{eq}z=q_{elec} \tag{1}$$

where z, m, c, and k_{eq}, are the deflection, mass, damping coefficient, and equivalent stiffness ($k_{eq}=6k$) of the movable electrode, respectively. Also, q_{elec}represents electrostatic force.

When the actuating voltage u is applied between the movable and stationary electrodes, the electrostatic force is computed using a standard parallel capacitance model, which yields [31]:

$$q_{elec}=\frac{\varepsilon_0 S u^2}{2(G_0-z)^2} \tag{2}$$

where $\varepsilon_0 = 8.854\times10^{-12}C^2N^{-1}m^{-2}$ is the permittivity of the vacuum within the gap.

For convenience, Equation (1) may be rewritten in a non-dimensional form by defining the following parameters [32]:

$$w=\frac{z}{G_0}\ ,\ \tau=\frac{t}{t^*} \tag{3}$$

where τ is the dimensionless time, and $t^*=\sqrt{\frac{m}{k_{eq}}}$.

Therefore, Equation (1) may be written as:

$$\frac{d^2w}{d\tau^2}+c'\frac{dw}{d\tau}+w=\frac{\alpha u^2}{(1-w)^2} \tag{4}$$

where c' and α are dimensionless damping and electrostatic coefficients, respectively, defined as:

$$c':=\frac{c}{t^*k_{eq}}\ ,\ \alpha:=\frac{\varepsilon_0 S}{2k_{eq}G_0^3} \tag{5}$$

Residual is the index of an observer-based fault detection, which takes the information of faults. It is generated by comparing the outputs of the system and their estimates obtained by an observer. For safe (fault-free) system, without any disturbances and modeling uncertainties, the outputs are equal with their estimations. In this condition, residual equals to zero. Any deviation of residual from zero will announce thepresence of a fault. Existence of the disturbances and uncertainties are unavoidable, and the residual signal is not completely decoupled from their effect; so, even for fault-free system, residual deviates from zero. Therefore, a threshold is needed to handle the effect of disturbances and uncertainties. Selection of threshold plays an important role in the performance of the fault detection system. If it is selected too high, some faults would not be detected. Conversely, if it is selected too low, disturbances and uncertainties will result in false alarms [33]. In this paper, the Thau observer is applied for residual generation and the threshold is obtained based on the asymptotic results of residual with extreme magnitude of the uncertainty.

4. THAU OBSERVER

The Thau observer was designed for the state estimation of a nonlinear dynamical system [26]. It has already been applied for fault detection of non-linear dynamic systems [27]. Consider the nonlinear system with form of:

$$\begin{aligned} \dot{x} &= Ax + Bu + g(x,u) + \eta(x,u) \\ y &= Cx \end{aligned} \tag{6}$$

where $x \in R^n$, $u \in R^r$ and $y \in R^p$ are state, input and output vectors, respectively; A, B, and C are known system matrices, $g(x,u)$ represents the nonlinear function and $\eta(x,u)$ represents unknown nonlinear function which contains noises and uncertainties. It must be noted that $\eta(x,u)$ is a bounded function.

For implementation of Thau observer, the following conditions must be satisfied:

1. matrices A and C are observable, i.e. $\begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{pmatrix}$ is full rank.
2. the nonlinear function $g(x,u)$ is continuously differentiable and satisfies the Lipschitz condition locally with constant γ , i.e:

$$\| g(x,u) - g(\hat{x},u) \| \le \gamma \| x - \hat{x} \| \tag{7}$$

If the above conditions are satisfied, the structure of the Thau observer for Eq. 6 is given by:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + g(\hat{x},u) + K(y - \hat{y}) \\ r &= y - C\hat{x} \end{aligned} \tag{8}$$

where $\hat{x}$ and $\hat{y}$ represent estimated state and output, r is residual and $K = P^{-1}C^T$ is the gain of observer and the matrix P is the solution of the Lyapunov equation

$$A^T P + PA - C^T C + \theta P = 0 \tag{9}$$

where θ is a positive parameter which is chosen in such a way that Eq. 9 has a positive definite solution[33].

4. 1. Mathematical Model in State Space Form

Consider $x_1 = w$ and $x_2 = \frac{dw}{d\tau}$; so, Eq. 4 rewritten in the state space form as:

$$\begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -c' \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{\alpha u^2}{(1-x_1)^2} \end{bmatrix} \\ y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{cases} \tag{10}$$

Matrix $\begin{bmatrix} C \\ CA \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ is full rank; therefore, system is observable. As it is stated in [12], $0 \le x \le 0.66$, so, term $\frac{\alpha u^2}{(1-x)^2}$ is locally Lipschitz and terms 1 and 2 for observer design is fulfilled. In this paper, output is considered as the non-dimensional deflection *w.* Pursuing the same procedure, the structure of the Thau observer may be rewritten as:

$$\begin{cases} \begin{bmatrix} \dot{\hat{x}}_1 \\ \dot{\hat{x}}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -c' \end{bmatrix} \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{\alpha u^2}{(1-\hat{x}_1)^2} \end{bmatrix} \\ + K(y - \hat{y}) \\ r = y - \hat{y} \end{cases} \tag{11}$$

5. SIMULATION RESULTS

In this section, fault detection of parallel plate capacitor with nonlinear electrostatic term has been developed. Spatial properties of the capacitor are shown in Table 1. The system output is position of the movable electrode with respect to the stationary electrode. Residual is obtained using Thau observer as the difference of system output and the estimated one.It is assumed that the applied voltage is contaminated by noise with 26dB. SNR[2], and also 5% uncertainty in determination of S/G_0 .

[2]Signal-to-Noise Ratio

TABLE 1. Spatial properties of the micro parallel plate capacitor

Properties	Value
Area of movable electrode (S)	$400\mu m \times 400\mu m$
Thickness of movable electrode	$1\mu m$
Thickness of beam	$1\mu m$
Length of beams	$100\mu m$
young's modulus of beams	$169GPa$
G_O	$4\mu m$
density	$2300\frac{Kg}{m^3}$

The simulated fault is the fracture of one of the six supporter beams, being an abrupt fault. As a result, the beam fracture decreases the stiffness and damping of the system to $\frac{5}{6}k_{eq}$ and $\frac{5}{6}c$, respectively. It is considered that magnitudes of mass for faulty and fault free cases are the same.As mentioned before, for application of Thau observer, the P matrix, depending on the parameter θ, must be positive definite. Figures 2 and 3 show the variation of the first and second eigenvalues of the matrix P with respect to θ. As it is seen, for $\theta \geq 0.04$ the eigenvalues are positive, making the matrix P positive definite.

5. 1. Determination of the Static Threshold In this part, the static thresholds are determined. Upper and lower thresholds are obtained based on the asymptotic results of the residual for fault-free capacitor (ARRFFC), considering maximum amount of noise for the upper threshold and minimum amount of noise for the lower threshold. The level of uncertainty was maximum (5%) for both cases. Figures 4 and 5 show the convergence of ARRFFC and determination of upper and lower threshold for $\theta = 1$ and $u = 5.2V$. As shown in these figures, upper and lower threshold equal to 9.7×10^{-3} and -8.2×10^{-3}, respectively.

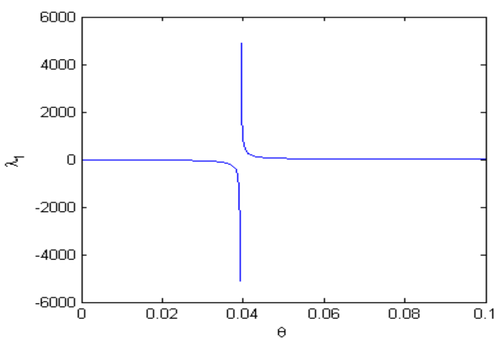


Figure 2. First eigenvalue λ_1 versus θ parameter

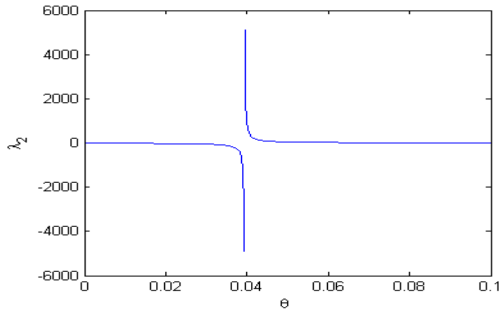


Figure 3. Second eigenvalue λ_2 versus θ parameter

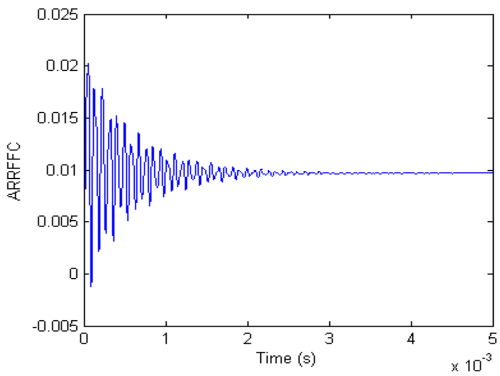


Figure 4. ARRFFC considering maximum magnitude of noise and maximum amount of uncertainty versus time for $\theta = 1$

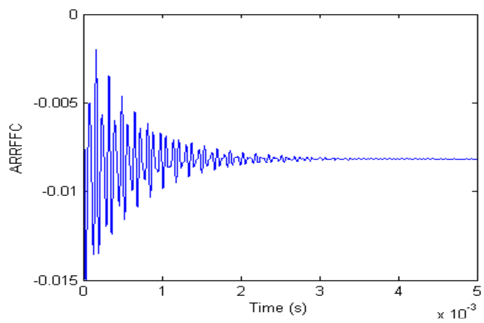


Figure 5. ARRFFC considering minimum magnitude of noise and maximum amount of uncertainty versus time for $\theta = 1$

In continuation, sensitivity of observer for different amount of θ has been discussed. As mentioned before, selection of threshold plays an important role in the performance of fault detection scheme. If it is selected too high, sensitivity of observer to fault may be decreased, and if it is selected too low, disturbance and uncertainty will result in existence of fault alarm.

Figures 6, 7, and 8 show the residuals for fault free case with θ=*0.1*, θ=*1*, and θ=*2*, respectively. By comparing these figures, it may be seen that by increasing θ, the sensitivity of the observer to noise and uncertainty is increased, resulting in decrease of robustness. As shown in Figure 8 for $\theta=2$, the sensitivity is so high that the observer residuals surpass the threshold levels, for the fault-free case. On the other hand, with $\theta=0.1$ the sensitivity is too low to detect faults. In this paper, for fault detection, θ is selected as one which has a suitable level of sensitivity to fault detection in the presence of noise and uncertainty.

5. 2. Fault Detection Results for $\theta = 1$ Figures 9-12 show residual versus time for various amounts of applied voltages. Fracture of the beam occurred in this time interval. These figures show that Thau observer with $\theta = 1$ has good ability in quick detection of fault. Dynamic pull-in voltage for fault-free capacitor is *5.82V*, and for faulty capacitor is about *5.35V*. Dynamic pull-in phenomenon is an unstable condition which can occur in MEMS capacitor subjected to nonlinear electrostatic force [1], [10, 11], and [34]. In this condition, movable electrode knocks up to the stationary electrode and loses its stability. As shown in Figure 12, this observer can detect fault of capacitor in the vicinity of dynamic pull-in voltage (unstable condition).

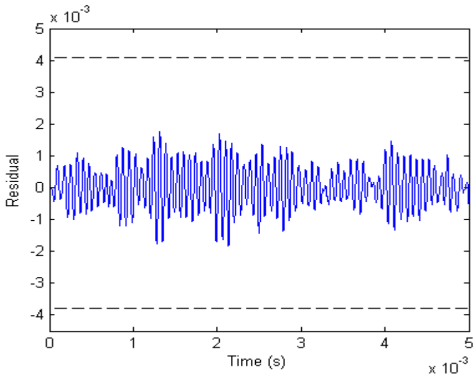


Figure 6. Residual versus time for $\theta = 0.1$

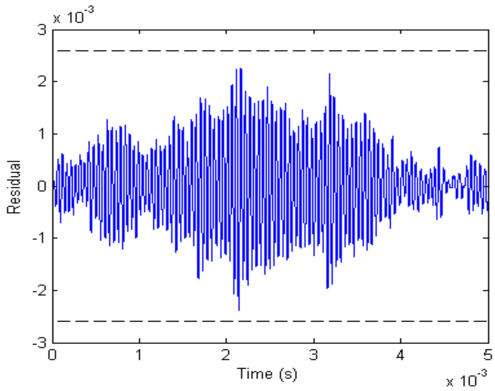


Figure 7. Residual versus time for $\theta = 1$

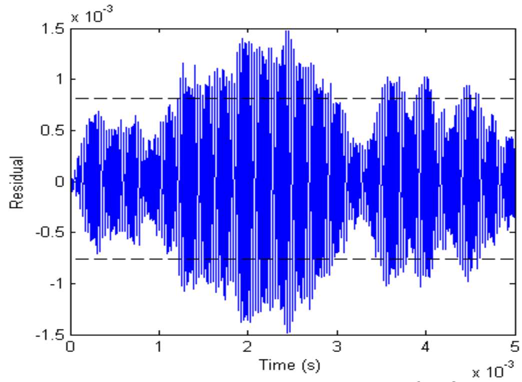


Figure 8. Residual versus time for $\theta = 2$

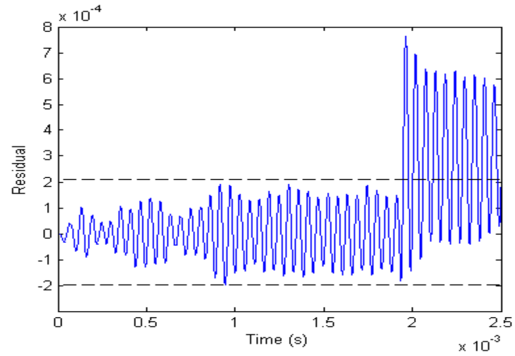


Figure 9. Residual versus time for $u=1V$ and $\theta = 1$

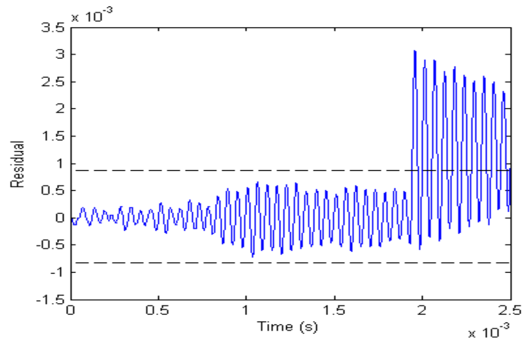


Figure 10. Residual versus time for $u=2V$ and $\theta = 1$

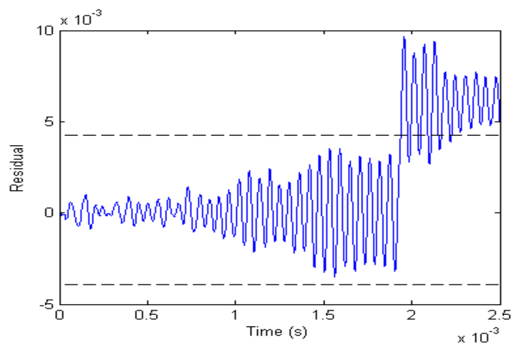


Figure 11. Residual versus time for $u=4V$ and $\theta = 1$

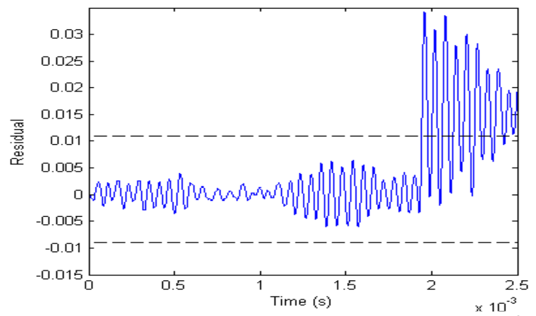


Figure 12. Residual versus time for $u=5.3V$ and $\theta=1$

6. CONCLUDING REMARKS

In this paper the problem of fault detection of a type of nonlinear system, which is a parallel plate capacitor, was studied. The approach is based upon designing a Thau-type observer sensitive to specific fault. The nonlinear dynamic model of the capacitor in two cases of healthy (no-fault) and cracked failure mode was obtained and the performance of the observer investigated.

Upper and lower threshold limits were obtained based on asymptotic results of the residuals for fault-free case. Moreover, the sensitivity of the observer to fault as well as robustness to the noise and uncertainty was examined. The results show that with increasing θ parameter higher than a limit has an adverse effect on fault detection in the presence of noise. Proper value of θ parameter, making the observer robust to noise and sensitive to fault, was selected. It was shown that Thau observer has good ability in fracture detection of the supporter beam of the capacitor, even in the vicinity of dynamic pull-in voltage.

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Noise And Uncertainty

چکیده

در این مقاله عیب‌یابی ریزخازن صفحه موازی که تحت تاثیر نیروی غیرخطی الکترواستاتیک قرار دارد، مورد بررسی قرار گرفته است. به این منظور روئیت‌گر تائوکه قابلیت خوبی برای عیب‌یابی سیستم‌های غیرخطی دارد، ارائه و معادلات غیرخطی دینامیکی خازن تعیین شده است. آستانه‌ی بالایی و پایینی عیب‌یابی تعیین شده و حساسیت روئیتگر به عیب و مقاومت آن در مقابل وجود اغتشاش و عدم قطعیت سنجیده شده است. در انتها نتایج شبیه سازی برای عیب‌یابی خازن تعیین و ارائه و توانایی روئیت‌گر در عیب‌یابی سیستم در نزدیکی ولتاژ ناپایداری سنجیده شده است.

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