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Parameter identification strategy for online detection of faults in smart structures for energy harvesting and sensing

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Abstract

In this work, we propose a simple computational method to detect faults in smart piezoelectric structures based on a synchronization strategy. The flexible smart structures are in general described as distributed systems governed by partial differential equations. Numerical discetization is employed to derive a reduced order model such as his dynamic response is simulated solving only ordinary differential equations. Then, the parameter identification strategy is formalized as a dynamic optimization and evolution problem through a further proper set of ordinary differential equations. Lyapunov' theorems are employed to derive an integral type identification algorithm and to ensure the convergence of the procedure. The method is suitable to assess and model nonlinearities in the response of a flexible piezoelectric smart device due to material degradation or local failure. These features are very important to detect faults in the structure and to assess the system reconfiguration properties in real time.

Keywords: Fault detection; Lyapunov theory; Nonlinear Dynamics; Smart Structures

1. Introduction

Energy harvesting is the process by which energy is derived from external sources available in surrounding environment and stored for small autonomous devices [2]. Miniaturization of electronics parts and of power consumption today makes self-powered devices a reality [4]. In particular, vibration based energy harvesting devices [10] may represent a valuable method to charge miniaturized electronic sensors for the internet of things community [1]. The direct and indirect market in these sectors is huge (26 billion dollars for IoT devices and 3 billion dollars for energy harvesting devices by 2020). Indeed the possibility to have electronic devices without batteries represents today a challenge in several engineering fields and can boost the development and implementation of smart grids for monitoring

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applications [3]. In this framework, energy harvesting technologies from vibrations and for charging small electronic circuits present many advantages with respect to conventional solutions [6]. This is particularly evident for sensing and smart grid implementation in harsh environment. Furthermore, recent collapses of several engineering structures have increased the attention of scientific community on the importance of developing consistent fault detection and isolation methods to guarantee the increasing safety demand of real systems due to variations of material properties, load conditions etc. Fault-tolerant control techniques are necessary to avoid the need to stop the usability of an engineering infrastructure when a local problem appears. Usually a fault results in a deviation from the linear behavior assumed during the design stage. In this context, a fault detection strategy for linear time-invariant systems based on a gradient flow approach is proposed by [12]. The convergence is achieved minimizing the spectral condition number of the observer eigenvector matrix. The possibility to apply a filter design method for linear parameter varying systems to approximate the behavior of nonlinear systems using a bilinear matrix inequality techniques is discussed by [14]. For a class of nonlinear networked control systems with Markov transfer delays, an observer-based fault detection method is presented by [18]. Incomplete measurements due to random delay and stochastic dropout are common for network-based robust fault detection. A convex optimization problem to deal with this situation is discussed by [17]. Kalman filter techniques have been used for wind turbines applications in the framework of sensor fault detection and isolation [19], while a packet-based periodic communication strategy is proposed for fault detection of networked control systems by [16]. Furthermore, to handle systems with invariant parameters, a zonotope-based fault detection algorithm is presented by [15]. Finally, an effective scheme for detecting incipient faults in post-fault systems subject to adaptive fault-tolerant control is developed by [13]. In this paper, we propose a simple computational strategy based on a synchronization approach to detect faults in smart piezoelectric structures for energy harvesting and sensing applications. Generally, system identification techniques can be classified in two main categories, including parametric and non–parametric methods [9]. Both frequency-domain (FD) and time-domain (TD) approaches can be employed [7]. The flexible smart structures [5] are described as distributed systems governed by partial differential equations [8]. The parameter identification problem is formalized as a dynamic optimization and evolution problem through a proper set of ordinary differential equations. A suitable quadratic performance index of the Lyapunov type is used to derive an integral type identification algorithm. An application of the proposed approach is finally discussed.

2. Method

In general, the dynamic response of a piezoelectric structure can be determined after a numerical discretization of the partial differential equations describing the domain considered. The FE equations are:

$$\begin{bmatrix} \mathbf{M} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{pmatrix} \ddot{\mathbf{u}}_d \\ \ddot{\boldsymbol{\phi}} \end{pmatrix} + \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{pmatrix} \dot{\mathbf{u}}_d \\ \dot{\boldsymbol{\phi}} \end{pmatrix} + \begin{bmatrix} \mathbf{K}_{uu} & \mathbf{K}_{\mathrm{u}\phi} \\ \mathbf{K}_{\phi\mathrm{u}} & -\mathbf{K}_{\phi\phi} \end{bmatrix} \begin{pmatrix} \mathbf{u}_d \\ \boldsymbol{\phi} \end{pmatrix} = \begin{pmatrix} \mathbf{f}_u \\ \mathbf{f}_\phi \end{pmatrix} \tag{1}$$

where the matrices $\mathbf{K}_{uu}$ and $\mathbf{K}_{\phi\phi}$ are the mechanical and electrical stiffness matrices, $\mathbf{K}_{\mathrm{u}\phi}$ and $\mathbf{K}_{\phi\mathrm{u}}$ are coupling matrices due to the electromechanical solid behaviour, $\mathbf{M}$ and $\mathbf{C}$ are the structural mass and the damping matrices. $\mathbf{f}_u$ and $\mathbf{f}_\phi$ are the force vectors due to mechanical and electrical fields, $\mathbf{u}_d$ and $\boldsymbol{\phi}$ are nodal displacement and electric potential vectors. After projection in the modal space, a set of ordinary differential equation is obtained such as the system of governing equations in terms of a modal displacement vector $\mathbf{Y}(t)$ and electrical potential $\mathbf{V}(t)$ is:

$$\mathbf{M}_m\ddot{\mathbf{Y}}(t) + \mathbf{C}_m\dot{\mathbf{Y}}(t) + \mathbf{K}_m\mathbf{Y}(t) + \mathbf{e}_m\mathbf{V}(t) = \mathbf{M}_m\mathbf{F}(t), \tag{2}$$

$$-\mathbf{C}_r\dot{\mathbf{V}}(t) + \mathbf{e}_m^T\dot{\mathbf{Y}}(t) = \mathbf{I}(t) = \mathbf{R}_r^{-1}\mathbf{V}(t), \tag{3}$$

where $\mathbf{M}_m$, $\mathbf{C}_m$ and $\mathbf{K}_m$ are diagonal modal mass, damping and stiffness matrices, $\mathbf{C}_r$ and $\mathbf{R}_r$ are the capacitance and resistance matrices, $\mathbf{e}_m$ is the piezoelectric coupling matrix, $\mathbf{F}(t)$ represents the mechanical modal forces and $\mathbf{I}(t)$ is a current vector. The upper dot indicates a time derivative.

With some algebra, according to [9], system equations 2 and 3 can be written in state variable form as follows: $\dot{\mathbf{z}} = \mathbf{Az} + \mathbf{Bu}$ and after introducing an output vector $\mathbf{y} = \mathbf{Cz} + \mathbf{Du}$, the set of equations:

$$\begin{cases} \dot{\mathbf{z}} = \mathbf{Az} + \mathbf{Bu} \\ \mathbf{y} = \mathbf{Cz} + \mathbf{Du} \end{cases} \tag{4}$$

that fully describes the dynamic response, is obtained. If $\boldsymbol{\lambda}$ is the vector of unknown parameters, the aim is to find the set $\boldsymbol{\lambda}^*$ that minimizes the difference: $\mathbf{E}(\boldsymbol{\lambda}^*(t)) = \hat{\mathbf{y}}_{out}(\boldsymbol{\lambda}^*(t), t) - \mathbf{y}_{exp}(t)$ between the real system and the system model response, see Figure 1. Therefore, a quadratic minimization function ψ such as: $\psi(\boldsymbol{\lambda}, t) = \mathbf{E}(\boldsymbol{\lambda}^*(t))^T \mathbf{E}(\boldsymbol{\lambda}^*(t))$ is introduced and the variation in time of the unknown vector parameters $\dot{\boldsymbol{\lambda}}(t)$ is assumed to change according to the directional derivative of ψ with respect to $\boldsymbol{\lambda}$: $\dot{\boldsymbol{\lambda}}(t) = -\boldsymbol{\kappa}\left(\frac{\mathcal{D}\psi(\boldsymbol{\lambda},t)}{\mathcal{D}\boldsymbol{\lambda}(t)}\right)^T$ where $\boldsymbol{\kappa}$ is a diagonal matrix and $\mathcal{D}$ indicates a directional derivative. Consequently, $\dot{\psi}(\boldsymbol{\lambda}, t) = -\boldsymbol{\kappa}\left[\mathbf{e}(\boldsymbol{\lambda}, t)^T \frac{\mathcal{D}\mathbf{e}(\boldsymbol{\lambda},t)}{\mathcal{D}\boldsymbol{\lambda}(t)} \left(\frac{\mathcal{D}\mathbf{e}(\boldsymbol{\lambda},t)}{\mathcal{D}\boldsymbol{\lambda}(t)}\right)^T \mathbf{e}(\boldsymbol{\lambda}, t)\right]$ and Lyapunov' theorems guarantee the convergence of the procedure.

3. Results and discussion

The configuration considered for the device under investigation is also given in Figure 1. In place of the experimental data, we use a predefined set of target parameters for generating a target solution and benchmarking the proposed method. Furthermore, to exploit the effectiveness of the proposed numerical procedure, a time varying stiffness is considered for the reference case with the aim to simulate the appearance of damage in the structure due to a local fault or distributed material degradation. With the aim to validate the proposed procedure, we here report the simultaneous estimation of parameters K_1 and e_1. Figure 2 reports the relative trajectories. It can be seen that the target values are identified after a time of less of 1 second. This is in agreement with the error trajectory. It is worth to underline that the convergence speed is function of the employed gain coefficients matrix $\boldsymbol{\kappa}$. Figure 3 highlights the effectiviness of the proposed online identification strategy. Infact, it can be observed how the model output chases the reference system response when the zero error condition is achieved.

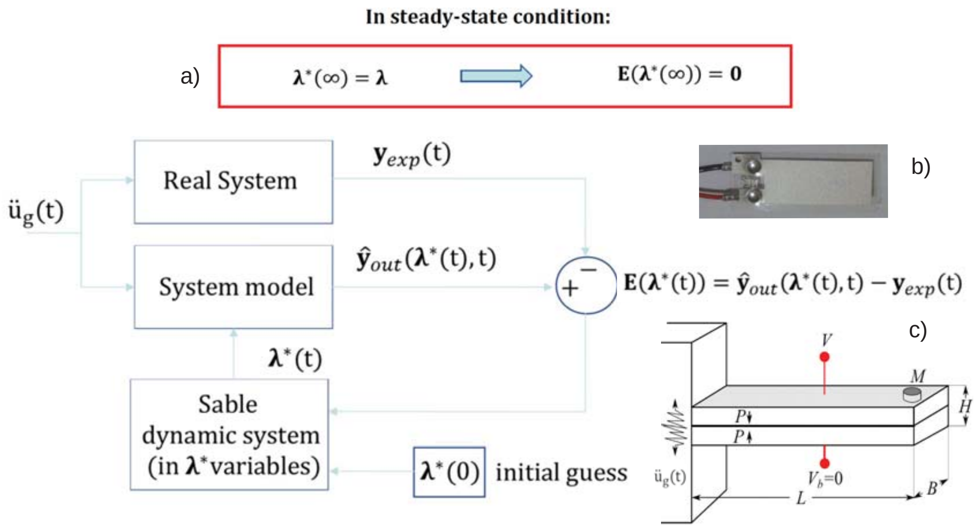

Fig. 1. Real system and system model, numerical strategy

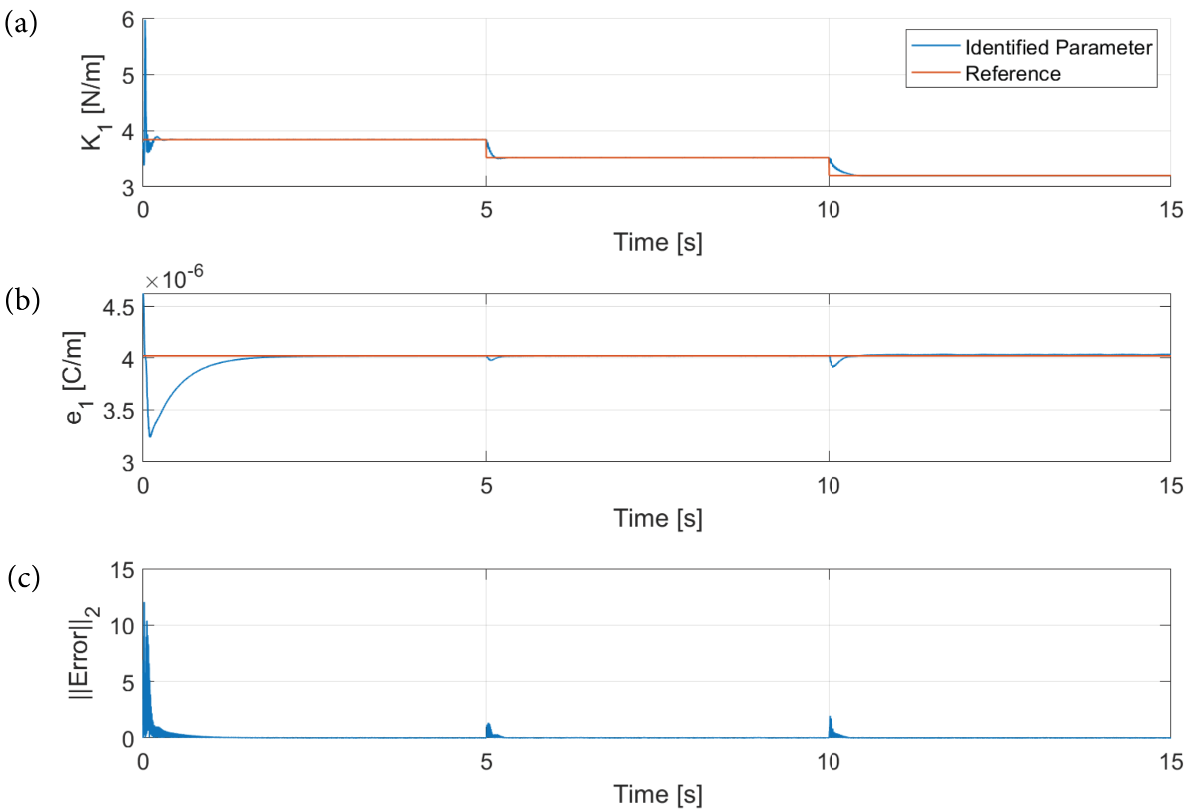

Fig. 2. Reference system presenting a time-varying stiffness coefficient, a) evolution in time of the identified stiffness coefficient (blue curve) vs the reference parameter (red curve); b) evolution in time of the identified coupling coefficient (blue curve) vs the reference target value (red curve); c) evolution in time of the error $\mathbf{E}(\lambda^*(t))$ 2-norm: $||Error||_2 = \sqrt{\mathbf{E}^T\mathbf{E}}$.

4. Conclusion

In this paper a novel approach for parameter identification and fault detection in smart piezoelectric systems has been presented. The design methodology is formulated as a constrained optimization problem where the objective function is the error between the model system response predicted at each time through numerical simulations and the real system output. A gradient based model has been derived and its convergence properties based on Lyapunov theory is proved. A numerical experiment demonstrates the effectiveness of the approach. The main advantage relies on the capability to assess system reconfiguration properties in real time.

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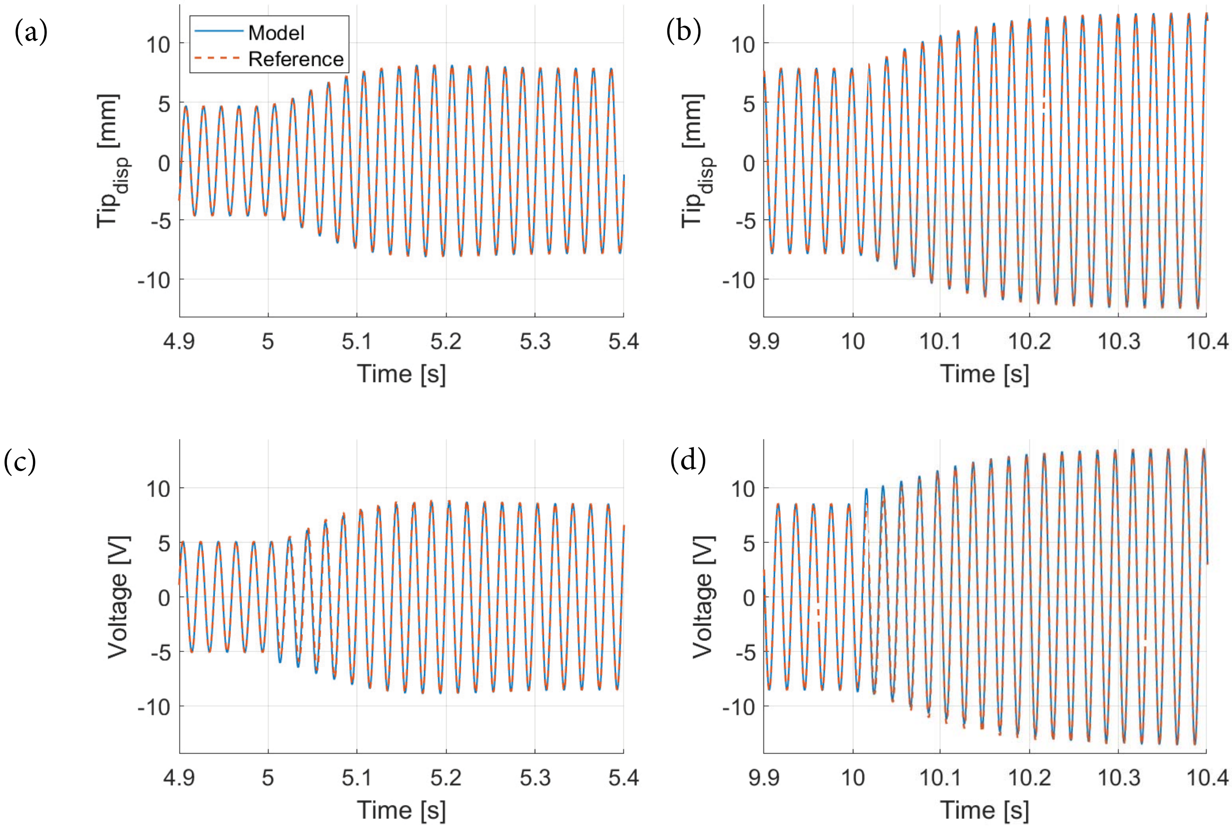

Fig. 3. Reference system presenting a time-varying stiffness coefficient due to local failure; a,b) time evolution, in transient and steady-state conditions, of the reference tip displacement (red dashed curves) vs the on-line identification solution (blue curves); c,d) reference output voltage (red dashed curves) vs the on-line identification solution (blue curves).

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