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A DAMAGE-TOLERANT MODAL OBSERVER APPLIED TO THE STRUCTURAL HEALTH MONITORING OF A CLOSED-LOOP STRUCTURE SUBJECTED TO SEISMIC EVENTS

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Abstract. *This paper investigates a technique for structural health monitoring (SHM) applied to a closed-loop structure subjected to damage. SHM-vibration-based techniques are typically designed for open-loop systems to avoid damage effect attenuation in structural vibrations due to the controller action. However, aiming to make the structure more secure against ambient agents and the consequences of their actions such as damage, a new damage-tolerant active controller generation has been developed and applied to smart structures. In this context, an adequate structural monitoring module is necessary to signal to the control system the damage occurrence. For this reason, this paper investigates a new SHM technique based on a damage-tolerant modal observer and on a reference model. The residue obtained by the state-vector difference between the reference model and the modal observer is used to determine the damage occurrence. A vertical flexible building model is used as a case study structure, including health and damage conditions, to examine the SHM strategy. Results show that the proposed methodology for SHM purpose is effective for damage detection in closed-loop structures.*

Keywords: *Damage-tolerant modal observer, structural health monitoring, active vibration control, damage-tolerant active control*

1. INTRODUCTION

The development of new materials has led to the construction of larger, lightweight, and more flexible structures. Consequently, the structures are subjected to environment disturbances such as wind, earthquake, ocean forces, among others. Theses agents may conduct to structural performance worsening due to damage caused by impact or excessive vibrations that may lead to damage or damage severity increase. Thereby, an appropriate control system is often recommended to mitigate structural vibrations (Pereira and Serpa, 2015; Khan and Kim, 2019; Bendine *et al.*, 2019). However, regular active vibration control (AVC) techniques do not take into account the possibility of damage occurrence and its consequence such as vibration increase and control system instability.

Damage-tolerant active control (DTAC) is an area that arose from the need to make the structure operation more secure with an appropriate performance. This research field was proposed by Mechbal and Nóbrega (2012), merging the concepts of vibration control and fault-tolerant control. The DTAC system needs to be able to solve the traditional problems of regular active vibration control as well as to prevent or retard damage occurrence. Moreover, in the case of structural damage, the DTAC system must work to mitigate the damage effects and to reduce damage propagation. For these purposes, structural health monitoring (SHM) techniques are used to signal to the DTAC controllers the damage occurrence, aiming for the control system to adapt itself to maintain an adequate performance (Genari *et al.*, 2017a).

Recently, Genari *et al.* (2017b) proposed a framework for DTAC that uses two controllers working in collaboration. The first controller is used to solve the regular challenges in the active vibration control. The second controller is designed to actuate in the case of damage, in which the controller parameters are adapted online using a SHM module. The framework was tested using finite element models of a case study structure, considering health and increasing damage conditions. In this paper, the objective is to investigate the SHM module effectiveness proposed by Genari *et al.* (2017b), considering a closed-loop structure model subjected to damage with different damage effects such as natural frequency shift and vibration increase. The SHM module is tested in a case study simulation of a smart tall building equipped with an active mass driver. The aluminum structure, representing the building, is assembled over a mobile basis to simulate seismic events and a piezoelectric element on a column is used to generate the vibration signal. A pole-placement-based controller is designed to solve the regular AVC problem and a damage-tolerant modal observer is designed to estimate the real modal state vector, which is used in the control law. The SHM module is constructed by comparing the state vector of a reference model with the estimated vector, in which the difference between these two vectors indicates damage. A damage scenario is induced in the structure, showing that the SHM module is an effective technique for damage detection in closed-loop structures.

2. STATE-SPACE MODEL OF FLEXIBLE STRUCTURES

The flexible structures are usually modeled by the matrix differential equations, which may be easily converted into a state-space model, a representation often used in control system design. The movement equations of a generic flexible structure are given by

$$\mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{D}\dot{\mathbf{q}}(t) + \mathbf{K}\mathbf{q}(t) = \mathbf{B_w}\mathbf{w}(t) + \mathbf{B_u}\mathbf{u}(t) \tag{1}$$

$$\mathbf{y}(t) = \mathbf{C_d}\mathbf{q}(t) + \mathbf{C_v}\dot{\mathbf{q}}(t) + \mathbf{D_w}\mathbf{w}(t), \tag{2}$$

in which $\mathbf{q}(t)$ denotes the displacements, $\mathbf{y}(t)$ represents the output vector, $\mathbf{M}$ is the mass matrix, $\mathbf{D}$ is the damping matrix, and $\mathbf{K}$ is the stiffness matrix. The input matrices are $\mathbf{B_w}$ and $\mathbf{B_u}$, $\mathbf{w}(t)$ represents the disturbance forces acting in the structure, $\mathbf{u}(t)$ denotes the control forces, and the output matrices are $\mathbf{C_d}$ and $\mathbf{C_v}$. Furthermore, the vectors and matrices have appropriate dimensions in relation to the model order and the numbers of outputs and inputs.

Considering the matrix $\mathbf{M}$ is nonsingular, Eq. (1) and Eq. (2) can be written as

$$\ddot{\mathbf{q}}(t) + \mathbf{M}^{-1}\mathbf{D}\dot{\mathbf{q}}(t) + \mathbf{M}^{-1}\mathbf{K}\mathbf{q}(t) = \mathbf{M}^{-1}\mathbf{B_w}\mathbf{w}(t) + \mathbf{M}^{-1}\mathbf{B_u}\mathbf{u}(t) \tag{3}$$

$$\mathbf{y}(t) = \mathbf{C_d}\mathbf{q}(t) + \mathbf{C_v}\dot{\mathbf{q}}(t) + \mathbf{D_w}\mathbf{w}(t). \tag{4}$$

Defining the state vector $\mathbf{x}(t)$ as a composition between the displacement vector $\mathbf{q}(t)$ and the velocity vector $\dot{\mathbf{q}}(t)$, i.e.,

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{x_1}(t) \\ \mathbf{x_2}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{q}(t) \\ \dot{\mathbf{q}}(t) \end{bmatrix},$$

Eq. (3) and Eq. (4) can be rewritten as

$$\dot{\mathbf{x}}_\mathbf{1}(t) = \mathbf{x_2}(t) \tag{5}$$

$$\dot{\mathbf{x}}_\mathbf{2}(t) = -\mathbf{M}^{-1}\mathbf{K}\mathbf{x_1}(t) - \mathbf{M}^{-1}\mathbf{D}\mathbf{x_2}(t) + \mathbf{M}^{-1}\mathbf{B_w}\mathbf{w}(t) + \mathbf{M}^{-1}\mathbf{B_u}\mathbf{u}(t) \tag{6}$$

$$\mathbf{y}(t) = \mathbf{C_d}\mathbf{x_1}(t) + \mathbf{C_v}\mathbf{x_2}(t) + \mathbf{D_w}\mathbf{w}(t). \tag{7}$$

The state-space model is obtained from Eq (5), Eq. (6), and Eq. (7) as

$$\dot{\mathbf{x}}(t) = \bar{\mathbf{A}}\mathbf{x}(t) + \bar{\mathbf{B}}_\mathbf{1}\mathbf{w}(t) + \bar{\mathbf{B}}_\mathbf{2}\mathbf{u}(t) \tag{8}$$

$$\mathbf{y}(t) = \bar{\mathbf{C}}_\mathbf{2}\mathbf{x}(t) + \mathbf{D_{21}}\mathbf{w}(t), \tag{9}$$

in which $\bar{\mathbf{C}}_\mathbf{2} = [\mathbf{C_d}\ \mathbf{C_v}]$ and $\mathbf{D_{21}} = \mathbf{D_w}$ and the matrices $\bar{\mathbf{A}}$, $\bar{\mathbf{B}}_\mathbf{1}$, and $\bar{\mathbf{B}}_\mathbf{2}$ are given by

$$\bar{\mathbf{A}} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{D} \end{bmatrix},\ \bar{\mathbf{B}}_\mathbf{1} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{B_w} \end{bmatrix} \text{ e } \bar{\mathbf{B}}_\mathbf{2} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{B_u} \end{bmatrix}.$$

The state-space model described by Eq. (8) and by Eq. (9) can be easily transformed into the modal canonical form, using a specific transformation matrix (Gawronski, 2004). For the approach of this paper, the following state-space model structure is adopted:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A_1} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{A_2} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{A_m} \end{bmatrix},\ \mathbf{B_1} = \begin{bmatrix} \mathbf{B_{11}} \\ \mathbf{B_{12}} \\ \vdots \\ \mathbf{B_{1m}} \end{bmatrix},\ \mathbf{B_2} = \begin{bmatrix} \mathbf{B_{21}} \\ \mathbf{B_{22}} \\ \vdots \\ \mathbf{B_{2m}} \end{bmatrix},\ \text{and } \mathbf{C_2} = \begin{bmatrix} \mathbf{C_{21}} & \mathbf{C_{22}} & \ldots & \mathbf{C_{2m}} \end{bmatrix},$$

in which m is the vibration mode number and the system matrix has a block diagonal structure, isolating each vibration mode.

3. CONTROLLER AND SHM FRAMEWORK

Figure 1 describes the controller block diagram, the damage-tolerant modal observer, and the SHM module. The controller generates the control signal $\mathbf{u}(t)$, created from the estimated state vector $\hat{\mathbf{x}}(t)$. The SHM module contains a state observer and a reference model block, whose output vector $\mathbf{x_r}(t)$ is compared to the observed state vector $\hat{\mathbf{x}}(t)$ to create the residue $\mathbf{r}(t)$, i.e., $r(t) = \mathbf{C_2}(\hat{\mathbf{x}}(t) - \mathbf{x_r}(t)) = \mathbf{C_2 e_x}(t)$. This residue is used to determine the damage occurrence, represented by the vector $\varphi(t)$. These modules are detailed in the next subsections.

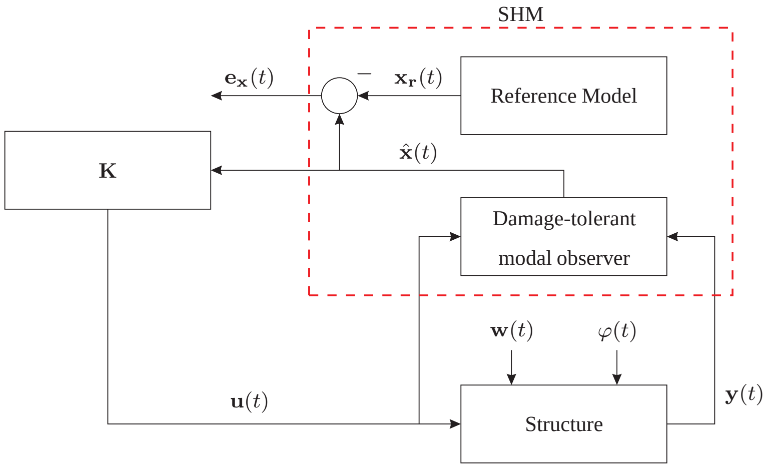


Figure 1: Detailed block diagram of the controller and the SHM framework.

3.1 Controller design

A flexible structure is described by the following modal state-space representation obtained in the previous section:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B_1}\mathbf{w}(t) + \mathbf{B_2}\mathbf{u}(t) \\ \mathbf{y}(t) &= \mathbf{C_2}\mathbf{x}(t) + \mathbf{D_{21}}\mathbf{w}(t), \end{aligned} \tag{10}$$

in which the pair $(\mathbf{A}, \mathbf{B_2})$ is considered controllable.

Considering the control law defined as $\mathbf{u}(t) = -\mathbf{K}\mathbf{x}(t)$, it is possible to rewrite Eq. (10) as

$$\dot{\mathbf{x}}(t) = (\mathbf{A} - \mathbf{B_2}\mathbf{K})\mathbf{x}(t) + \mathbf{B_1}\mathbf{w}(t),$$

in which the gain $\mathbf{K}$ leads the closed-loop poles to the desired locations. This control law requires that the state vector is available. However, sometimes, it is not possible to measure all the states, therefore, an observer is required.

3.2 Damage-tolerant modal observer

The damage-tolerant modal observer has two objectives in this paper. The first one is to provide the state-vector estimation to compose the control law. The second objective is to provide the state vector to be used in the SHM module, aiming to create the residue vector. To achieve these two objectives simultaneously, the observer has to be damage tolerant. Thus, a vector that describes the damage effects in the structural dynamics is added into the model represented by Eq. (10) to design the observer. The following representation is adopted to include damage effects in the state-space model (Genari *et al.*, 2017b):

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B_1}\mathbf{w}(t) + \mathbf{B_2}\mathbf{u}(t) + \mathbf{B_2}\varphi(t) \\ \mathbf{y}(t) &= \mathbf{C_2}\mathbf{x}(t) + \mathbf{D_{21}}\mathbf{w}(t), \end{aligned}$$

where the pair $(\mathbf{A}, \mathbf{C_2})$ is considered observable and $\varphi \in \mathcal{L}_2$ represents the unknown damage signal.

The traditional Luenberger observer configuration is used to estimate the modal state vector (Ogata, 2009):

$$\begin{aligned} \dot{\hat{\mathbf{x}}}(t) &= \mathbf{A}\hat{\mathbf{x}}(t) + \mathbf{B_2}\mathbf{u}(t) + \mathbf{L}(\mathbf{y}(t) - \hat{\mathbf{y}}(t)) \\ \hat{\mathbf{y}}(t) &= \mathbf{C_2}\hat{\mathbf{x}}(t), \end{aligned}$$

in which $\hat{\mathbf{x}}(t)$ and $\hat{\mathbf{y}}(t)$ are the estimations of the state and the output vectors. The gain $\mathbf{L}$ is chosen so that $\hat{\mathbf{x}}(t)$ converges to $\mathbf{x}(t)$ asymptotically.

The estimation error dynamics $\dot{\mathbf{e}}(t)$ is given by

$$\begin{aligned} \dot{\mathbf{e}}(t) &= \dot{\mathbf{x}}(t) - \dot{\hat{\mathbf{x}}}(t) \\ &= \mathbf{A}\mathbf{x}(t) + \mathbf{B_1}\mathbf{w}(t) + \mathbf{B_2}\mathbf{u}(t) - \mathbf{A}\hat{\mathbf{x}}(t) - \mathbf{B_2}\mathbf{u}(t) - \mathbf{L}(\mathbf{y}(t) - \mathbf{C_2}\hat{\mathbf{x}}(t)) + \mathbf{B_2}\varphi(\mathbf{t}) \\ &= \mathbf{N}\mathbf{e}(t) + \mathbf{E}\mathbf{w}(t) + \mathbf{B_2}\varphi(t), \end{aligned} \tag{11}$$

in which $\mathbf{N} = \mathbf{A} - \mathbf{LC_2}$ and $\mathbf{E} = \mathbf{B_1} - \mathbf{LD_{21}}$.

The observer gain $\mathbf{L}$ is computed in order to minimize the estimation error and to attenuate the influence of damage and disturbance in the state estimation. The following theorem shows the modal observer design process.

Theorem 1. *The estimation error dynamics given in Eq. (11) is globally stable in relation to the H_∞ performance if there exist matrices $\bar{\mathbf{P}} = \bar{\mathbf{P}}^T \geq 0$, Θ, and scalars γ, ν, $\alpha > 0$ that satisfy $\|\mathbf{e}(t)\|_2 \leq \gamma\|\varphi(t)\|_2$, $\|\mathbf{w}(t)\|_2 \leq \nu$, and the following linear matrix inequality (LMI) (Genari* et al.*, 2017b):*

$$\begin{bmatrix} \mathbf{A}^T\bar{\mathbf{P}} - \mathbf{C_2}^T\mathbf{\Theta}^T + \bar{\mathbf{P}}\mathbf{A} - \mathbf{\Theta}\mathbf{C_2} + I + \alpha\mathbf{I} & \bar{\mathbf{P}}\mathbf{B_2} & \bar{\mathbf{P}}\mathbf{B_1} - \mathbf{\Theta}\mathbf{D_{21}} \\ \mathbf{B_2}^T\bar{\mathbf{P}} & -\mu\mathbf{I} & \mathbf{0} \\ \mathbf{B_1}^T\bar{\mathbf{P}} - \mathbf{D_{21}}^T\mathbf{\Theta}^T & \mathbf{0} & -\frac{1}{\beta}\mathbf{I} \end{bmatrix} < 0, \tag{12}$$

in which $\mu = \gamma^2$, $\beta = \alpha^{-1}\nu^2$, and the observer gain is computed as $\mathbf{L} = \bar{\mathbf{P}}^{-1}\mathbf{\Theta}$.

3.3 Reference model and SHM module

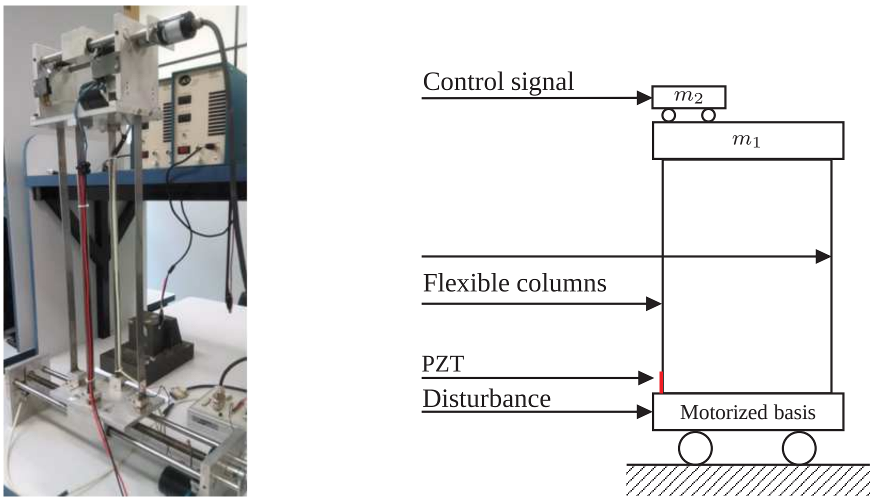
The reference model is built with the closed loop of the healthy structure with the controller and modal observer. The reference model module continuously generates the reference state vector $\mathbf{x_r}(t)$ without damage influence. To generate the residue, the estimated state vector is compared with the reference vector, i.e., $r(t) = \mathbf{C_2}\mathbf{e_x}(t)$, where it is possible to analyze the damage effects in the structural dynamics.

4. RESULTS

This section presents a case study application of the damage-tolerant modal observer to monitor the structural health of a flexible vertical structure. Initially, the vertical structure that simulates a tall building is introduced. Then, the control law and modal observer are designed for lateral vibration control. After that, a damage case and the respective vibration effects are presented. Finally, damage is provoked and the SHM technique is investigated for damage detection in the controlled structure.

5. Flexible structure description

The vertical flexible structure is presented in Fig. 2a and can be divided into three main parts: basis, flexible system that simulates a tall building and active mass driver. The basis comprises a lead screw mechanism coupled to the mechanical structure. Thus, the rotational movements of a DC motor is converted into linear movements of the basis. The structure comprises the mass m_1 supported by four aluminum columns attached to the basis and there is a piezoelectric element glued onto one column to measure lateral vibration. The active mass m_2 is moved linearly by another DC motor using a similar lead screw mechanism and the control system is designed to minimize the lateral vibration due to disturbance caused by the basis movement. For this purpose, a control signal is used to create a specific movement of the active mass driver to compensate the perturbation. Figure 2b shows the block diagram that describes the experiment.



(a) Structure. (b) Block diagram.

Figure 2: Structure setup.

The vertical structure model was experimentally identified in (Genari *et al.*, 2015) for the frequency band between 0 Hz and 6 Hz, a bandwidth that concentrates the most energy of real earthquakes (Spencer *et al.*, 1994; Abreu *et al.*, 2009; Abreu and Lopes Jr., 2010). The structure model is given by

$$\dot{x}(t) = \begin{bmatrix} -0.4282 & 15.6400 & 0 \\ -15.640 & -0.4282 & 0 \\ 0 & 0 & -20.5940 \end{bmatrix} x(t) + \begin{bmatrix} 0.0942 \\ 0.2234 \\ 0.1334 \end{bmatrix} w(t) + \begin{bmatrix} -0.0157 \\ -0.0214 \\ -0.0175 \end{bmatrix} u(t) \quad (13)$$

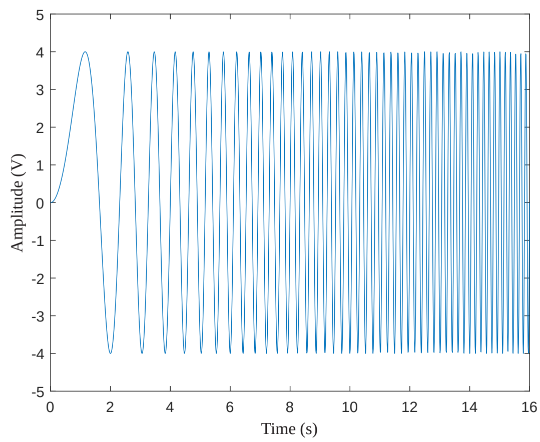
$$y(t) = \begin{bmatrix} -2.1785 & 2.0789 & 6.8361 \end{bmatrix} x(t). \quad (14)$$

6. Controller and observer design

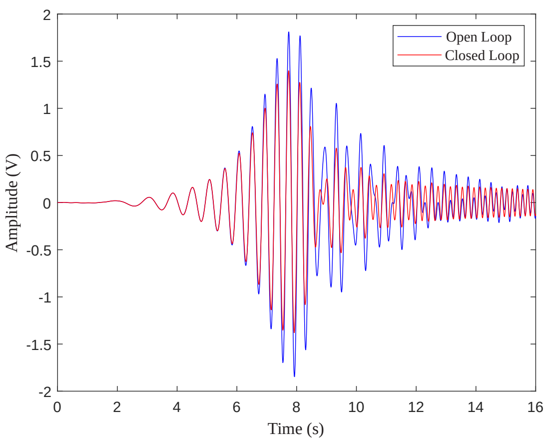
The control law is designed to attenuate the lateral vibrations of the flexible structure, taking into account that the control signal needs to remain inside of ± 15 V due to the bench-scale structure characteristic. For this purpose, the poles are allocated in $-0.85 \pm 15.6401j$ and -24.5 and the observer is designed from the solution of LMI in 12 with $\mu = \beta = 0.5$. The gains generated to the controller and the observer designs are

$$K = \begin{bmatrix} -23.8490 & -26.6409 & -217.4318 \end{bmatrix} \text{ and } L = \begin{bmatrix} -6587.5171 \\ 1688.7572 \\ -769.2018 \end{bmatrix}.$$

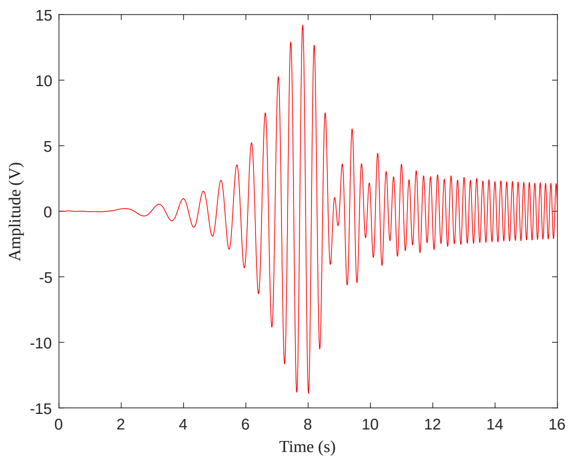
To analyze the control performance for the healthy structure, the disturbance shown in Fig. 3a is built as a chirp signal with amplitude of 4 V, 16 seconds of period, sampled at 100 Hz, and frequency band between 0 Hz and 6 Hz. The structure responses in open loop and closed loop are compared in Fig. 3b, where the state vector is estimated using the damage-tolerant modal observer and, then, it is used to create the control law. The controller reduces the lateral vibrations $y(t)$ by almost 28%, generating the control signal presented in Fig. 3c with values between 15 V and -15 V. This result is similar to the performance obtained with the H_∞ controller in (Genari *et al.*, 2015).



(a) Disturbance signal $w(t)$.



(b) Lateral vibrations.



(c) Control signal.

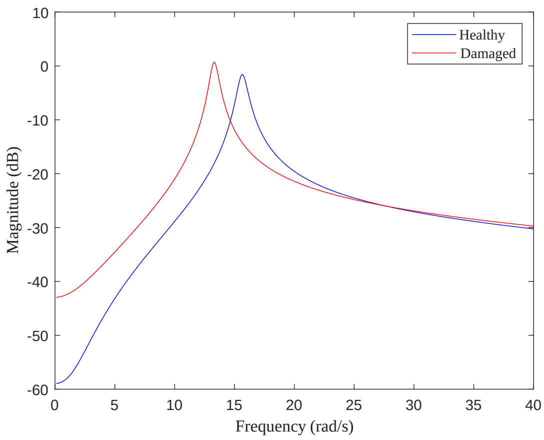
Figure 3: Healthy structure vibration control.

6.1 Damage detection in the closed-loop structure

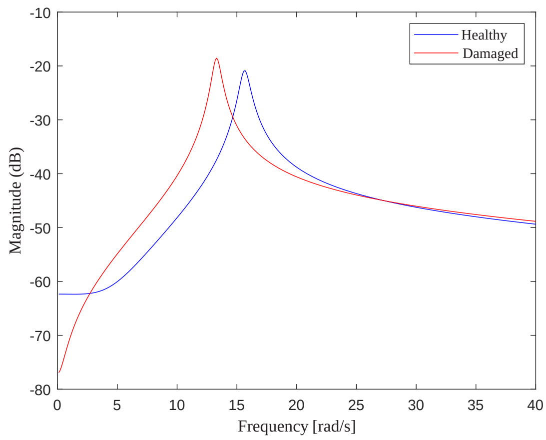
Structural damage may significantly alter the dynamic response due to changes in stiffness, mass, or energy dissipation (Sohn *et al.*, 2004). In this context, damage is here simulated in the structure to provoke vibration increase and natural frequency shift. For this purpose, the following model matrices that represent the damaged structure are used to produce the mentioned dynamics effects:

$$A_d = \begin{bmatrix} -0.4282 \times 0.85 & 15.6400 \times 0.85 & 0 \\ -15.640 \times 0.85 & -0.4282 \times 0.85 & 0 \\ 0 & 0 & -20.5940 \end{bmatrix} \text{ and } C_d \;\; = \begin{bmatrix} -2.1785 & 2.0789 & 6.8361 \end{bmatrix} \times 1.1.$$

Figure 4 compares the frequency responses of the damaged and the healthy structures, in which P_{yw} represents the transfer function of the output $y(t)$ in relation to the disturbance $w(t)$ and P_{yu} is the transfer function that relates the output $y(t)$ with the control signal $u(t)$. it is possible to note that there is a frequency shift between the damaged and the healthy structure models, where the peak response also increases due to the damage effect. The natural frequency shift and vibration increased may also be visualized in the time domain presented in Fig. 5, when the input is the disturbance signal $w(t)$ shown in Fig. 3a.



(a) P_{yw}.



(b) P_{yu}.

Figure 4: Frequency response comparison between damaged and healthy structures.

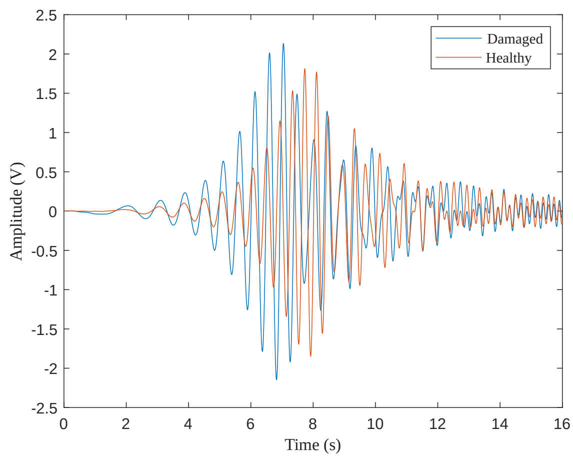
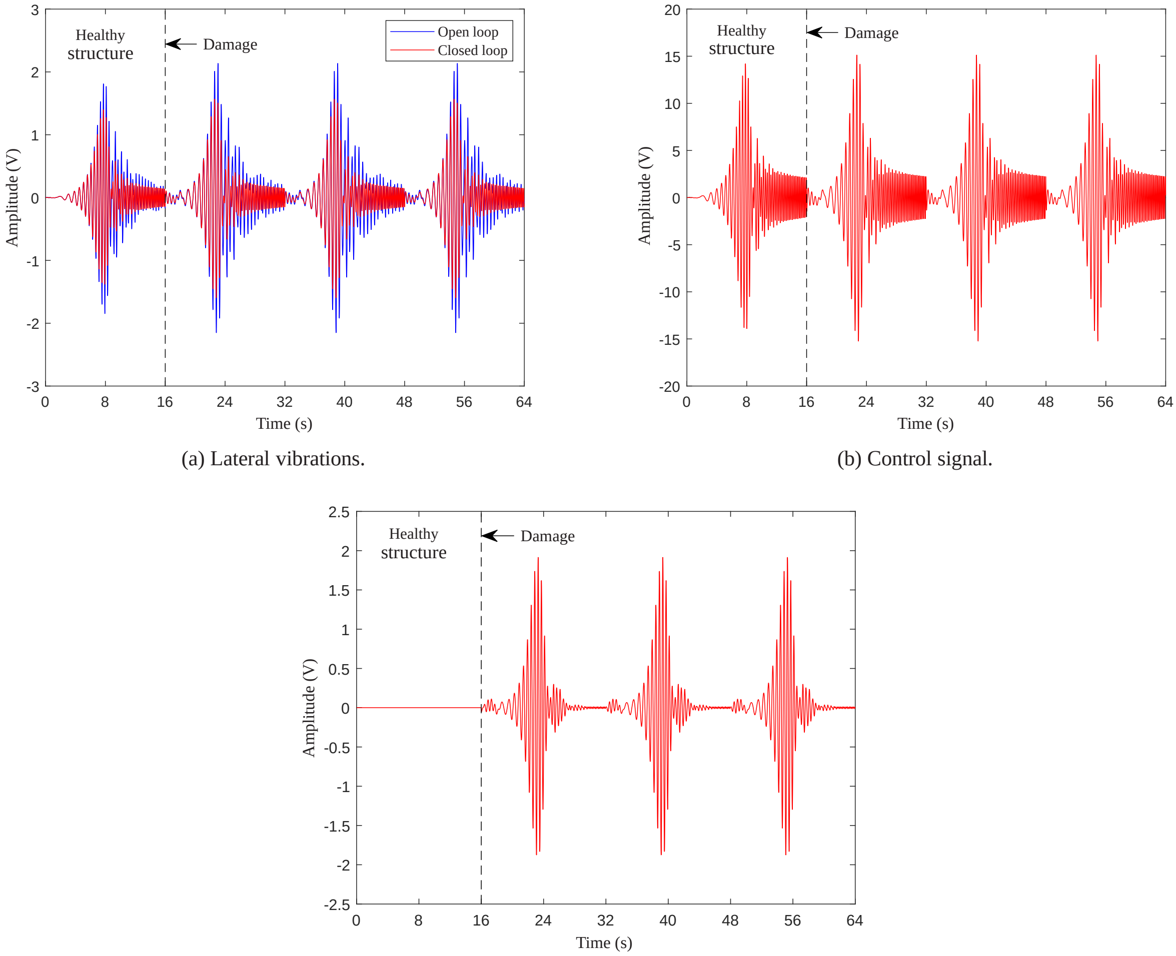


Figure 5: Time response comparison between damaged and healthy structures.

The control system and the SHM module are also tested for the damaged structure, where the same chirp disturbance presented in Fig. 3a is now used with four periods. In the first period, the structure is healthy and, in the remaining three periods, the structure is damaged. It is possible to verify, in Fig. 6, that damage causes a small structural vibration increase with the structure in closed loop and with the damage-tolerant modal observer providing the real state vector. In reaction to the vibration increase, the control signal also presents a small increase, with which the controller acts to minimize damage effects in the structural vibration, decreasing the damage signature in the structure vibration. Figure 6c shows the residue signal generated by the proposed SHM module. The residue is null for the healthy structure and increases with damage occurrence, showing that the proposed technique is effective in damage detection for closed-loop structures. Despite the reasonable results for the control performance, the control law design does not take into account the damage occurrence, i.e, the control system is not designed to guarantee stability in the case of damage. Thus, the damage-tolerance characteristic is provided by the correct structure state estimation using the damage-tolerant modal observer.



(a) Lateral vibrations.

(b) Control signal.

(c) Residue.

Figure 6: Structure vibration control.

7. CONCLUSION

A SHM methodology was presented in this paper for damage detection in controlled flexible structures, based on a modal observer that presents damage tolerance. The observer has the traditional Luenberger configuration, however, the respective observer gain is obtained by the solution of a LMI, formulated to minimize the damage and disturbance effects in the state estimation. The difference between state vectors of the reference model and the damaged structure is used to indicate the damage occurrence. A vertical flexible building model is used as a case study structure, including health and damage conditions, to examine the performance of the damage detection approach. Simulated results show that the vibration amplitude in the closed-loop configuration did not change significantly with damage, however, there was a shift in the structure natural frequency. In this context, the proposed SHM methodology was able to identify the damage occurrence in the structure in a closed-loop application, even with a small vibration amplitude change. As future objectives, the methodology will be experimentally validated in the vertical structure and an adaptive control law will be investigated to provide an adequate performance and robustness for the closed-loop system, using in the controller reconfiguration the damage information contained in the residue generated by the SHM module.

8. ACKNOWLEDGEMENTS

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