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Optimal control-based methodology for active vibration control of pedestrian structures

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ABSTRACT

Civil structures such as floor systems with open-plan layouts or lightweight footbridges can be susceptible to excessive levels of vibrations caused by human activities. Active vibration control (AVC) via inertial-mass actuators has been shown to be a viable technique to mitigate vibrations, allowing structures to satisfy vibration serviceability limits. It is generally considered that the determination of the optimal placement of sensors and actuators together with the output feedback gains leads to a tradeoff between the regulation performance and the control effort. However, the "optimal" settings may not have the desired effect when implemented because simplifications assumed in the control scheme components may not be valid and/or the actuator/sensor limitations are not considered. This work proposes a design methodology for multi-input multi-output vibration control of pedestrian structures to simultaneously obtain the sensor/actuator placement and the control law. This novel methodology consists of minimising a performance index that includes all the significant practical issues involved when inertial-mass actuators and accelerometers are used to implement a direct velocity feedback in practice. Experimental results obtained on an in-service indoor walkway confirm the viability of the proposed methodology.

1. Introduction

Improvements in design and construction methods have led to light and slender floor structures which have increased susceptibility to vibration. This is exacerbated by the current trend towards design of more open-plan structures. Examples of significant vibrations due to human-induced excitations have been found in open-plan floors and footbridges, as well as other structures [1,2]. These structures satisfy ultimate limit state criteria but have the potential of attracting complaints due to excessive human-induced vibrations [3]. Active vibration control (AVC) via inertial-mass actuators has been shown to significantly reduce the level of response, allowing otherwise excessively lively structures to satisfy vibration serviceability limits. However, AVC is a relatively new area of research in the civil engineering community and, as such, there are a number of obstacles that must be overcome before the field can mature fully [4]. One of these obstacles is the limitations of inertial-mass actuators, such as force and stroke saturations and low-frequency response. Single-input single-output (SISO) control strategies dealing with these problems have been proposed [5–7]. Here, the stability of the overall system is guaranteed and the sensitivity to stroke saturation, which can damage the inertial-mass actuator hardware, is alleviated.

It has been shown that the use of only one inertial-mass actuator may limit the number of controlled vibration modes since the mode shape of a mode to be controlled should have sufficiently large amplitude at the control location. In addition, the dynamics of inertial-mass actuators also limit the maximum damping imparted to a structure. One obvious solution is to use multiple SISO control schemes, which are designed independently for each location (this strategy is commonly denoted as multi-SISO control). Although multi-SISO control can be a viable solution [8], it may be of limited efficiency since the structural system does not act independently at each control location (i.e., a force applied at one location will influence the structural response at another location for every mode shape that is non-zero at both locations).

A better performance can be achieved if a multi-input multi-output (MIMO) control strategy is used. This was shown in [9], where an optimal direct output velocity feedback (DVF) MIMO

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controller was presented. This DVF MIMO control strategy finds the optimal gain matrix and the optimal location for a predefined number of actuators and sensors. The optimal sensor/actuator placement and the gain matrix is obtained by minimising a performance index (PI) that considers the amplitude and duration of the vibration and the maximum force imparted for each actuator. Simulation results were presented in [9], demonstrating the advantages of using MIMO control as opposed to SISO control. However, the controller proposed in [9] considers an ideal DVF limited only by the maximum actuator force. To implement DVF using inertial-mass actuators, the following additional issues have to be carefully considered:

- the actuator bandwidth (i.e., frequency response) significantly affects the stability of the overall control scheme and limits the maximum damping imparted to the structure,
- the actuator stroke saturation, which also limits the maximum damping imparted, could result in dramatic adverse effects on the actuator performance and its hardware,
- the velocity is obtained by integrating the output signal of an accelerometer, necessitating the use of a lossy integrator, which affects the stability of the control scheme,
- a low-pass filter may be required to guarantee the finite gain property of the control loop at high frequencies, avoiding spillover problems [10], and
- the frequency bandwidth where humans perceive the vibration [11] may be considered to focus the control effort on the most important vibration modes.

These issues were not considered in [9] and hence the method presented there is not implementable as such. The work presented here builds on the idea presented in [9] and considers the aforementioned practical issues to propose a novel control design methodology. This methodology is illustrated by designing and testing an AVC for an in-service indoor walkway.

This paper is organised as follows. Section 2 explains the control scheme elements paying special attention to the inclusion of the practical issues into the closed-loop and to the definition of a weighted state vector that takes into account the human vibration perception. Section 3 details the design methodology. Section 4 provides the description of the in-service indoor walkway and the experimental implementation of the design methodology on the structure. Section 5 concludes the paper.

2. Control scheme

This section explains the general scheme shown in Fig. 1 used to define an optimal DVF MIMO control from the proposed optimisation design process, which is also included in this section. The dynamics included in Fig. 1 are grouped into the following blocks:

1. The flexible structure, such as a floor or lightweight footbridge, which is modelled by n vibration modes. The inputs are the force generated by p actuators ($\mathbf{u}_s$) and r perturbations ($\mathbf{w}_s$). The accelerations measured by a set of accelerometers at q different locations ($\mathbf{y}_a$) are considered as control outputs.
2. The additional dynamics needed to obtain the velocity from the accelerometers are denoted as lossy integrators. The lossy integrators are considered as ideal integrators plus high-pass filters [12]. Thus, each lossy integrator carries out the magnitude and phase shift of an ideal integrator at frequencies above the cut-off frequency of the high-pass filter whilst removing any DC component and avoiding unnecessary high sensitivity to stroke saturation at low frequencies.
3. The control gain matrix and the required low-pass filters, which are required to guarantee the finite gain property of the control loop at high frequencies, avoiding spillover problems [10].
4. The saturation nonlinearity models the actuator force limitation, which is limited by the maximum power amplifier input. This maximum value can be decreased to reduce the risk of stroke saturation but also reducing the actuator performance.
5. The dynamics of the inertial-mass actuators.

2.1. Description of the control scheme components

For the sake of simplicity, the flexible structure and the integrators are grouped so that the output of the resulting system is $\mathbf{y}_s$, which is the velocity at q locations. Thus, the standard state-space representation of the model for this flexible structure is represented as follows:

$$\begin{aligned}\dot{\mathbf{x}}_s &= \mathbf{A}_s\mathbf{x}_s + \mathbf{B}_{s_1}\mathbf{u}_s + \mathbf{B}_{s_2}\mathbf{w}_s,\\ \mathbf{y}_s &= \mathbf{C}_s\mathbf{x}_s.\end{aligned} \tag{1}$$

If model (1) is defined in modal coordinates, the state-space matrices are as follows [13]:

$$\mathbf{A}_s = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{\Omega}^2 & -2\mathbf{Z}\mathbf{\Omega} \end{bmatrix}, \quad \mathbf{B}_{s_1} = \begin{bmatrix} \mathbf{0} \\ \mathbf{\Phi}_u \end{bmatrix}, \quad \mathbf{B}_{s_2} = \begin{bmatrix} \mathbf{0} \\ \mathbf{\Phi}_w \end{bmatrix}, \quad \mathbf{C}_s = [\,\mathbf{\Phi}_y \quad \mathbf{0}\,], \tag{2}$$

where $\mathbf{\Omega}$ is a $n \times n$ diagonal matrix formed by the natural frequencies ($[\omega_1, \ldots, \omega_n]$), $\mathbf{Z}$ is a $n \times n$ diagonal matrix formed by the damping ratios ($[\zeta_1, \ldots, \zeta_n]$) and $\mathbf{\Phi_u}$, $\mathbf{\Phi_y}$ and $\mathbf{\Phi_w}$ are matrices with dimensions $n \times p$, $q \times n$ and $n \times r$, respectively. Each kth column of $\mathbf{\Phi_u}$ and $\mathbf{\Phi_w}$ and each row of $\mathbf{\Phi_y}$ is formed by the kth vibration mode values at the positions of the actuators ($\mathbf{\Phi_u}$), perturbations ($\mathbf{\Phi_w}$) and sensors ($\mathbf{\Phi_y}$).

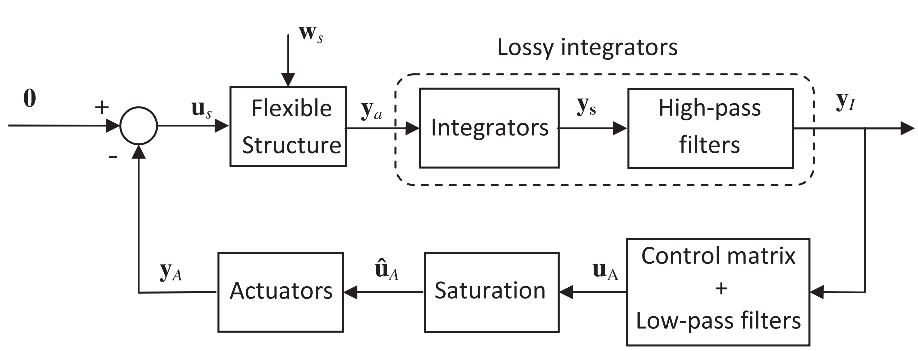

Fig. 1. General control scheme.