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ON-OFF DAMPING OF FREE VIBRATIONS AND OPTIMUM ACTUATOR PLACEMENT

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1. Introduction

Damping of free vibrations is important, e.g., in flexible space structures, which are subject to shocks (pyrotechnic activators, appendage deployments, thermal shocks, etc.) that often result in prolonged vibrations due to low natural damping [1]. The two extremes in mitigation of vibrations are passive damping systems and actively controlled absorption systems. Passive systems can be optimized for a specific shock, but they can adapt neither in time nor to varying shocks, which limits their effectiveness. Active systems rely on dedicated actuators that introduce external control forces. They are extremely effective and well-researched [2], but in applications to structural damping they have important disadvantages, such as high control forces and the related high energy consumption, as well as susceptibility to instabilities in case of a power loss or actuator failure. There is thus an interest in semi-active approaches [3] based on the fundamental idea of adaptivity: a concept ubiquitous in nature and clearly different from passive dissipation and active counteraction. Instead of exerting external control forces, actuators in a semi-active system modify local mechanical properties of the structure: the control amounts to self-adaptation, and the energy consumption and failure risk are low.

Semi-active damping of structural vibrations includes strategies of strain energy management [4–7]. However, most publications consider the same example of a cantilever beam with detachable layers and the same control concept (energy transfer from the fundamental to the highly-damped longitudinal vibration mode), and differ only in technology (truss-frame nodes [4], magnetorheological elastomers [5], jammed granules [6], delamination [7]). We consider truss-frame nodes with controllable moment-bearing ability. The concept of such a node was introduced in [8], where they acted as dissipaters: the control maximized their force–displacement hysteresis loop due to dry friction. In contrast, we follow the approach of [4] and aim at dynamic structural reconfiguration and releasing local strain energy into high-order dissipative modes. The strategies in [4–7] are limited to the first vibration mode of a cantilever beam. During the presentation, we will propose a partial-state feedback semi-active control algorithm that is applicable to arbitrary structures and arbitrary vibration patterns. Namely, we will (1) state the model of controllable nodes and (2) the control objective, (3) derive basic properties of the optimum control, (4) propose the control algorithm with a quantitative criterion for optimum actuator placement, and (5) demonstrate the effectiveness in numerical examples.

2. Optimum control

Structural dynamics is described by the following equation:

$$(1)\qquad \mathbf{M}\ddot{\mathbf{x}} + \left(\mathbf{C} + \sum\nolimits_i c_i \Delta\mathbf{C}_i\right)\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{0}, \quad \mathbf{x}(0) = \mathbf{x}_0, \quad \dot{\mathbf{x}}(0) = \mathbf{0},$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ denote structural matrices, $c_i \in [0, c_{\mathrm{max}}]$ is the control signal, and $\Delta\mathbf{C}_i$ couples the rotational degrees of freedom (DOFs) in the ith controllable node. Define the control objective as

$$(2)\qquad F := \int_0^T \left(\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{K}\mathbf{x} + \frac{1}{2}\dot{\mathbf{x}}^{\mathrm{T}}\mathbf{M}\dot{\mathbf{x}}\right) \mathrm{d}t.$$

Using the adjoint variable method (or the Pontryagin minimum principle), it can be shown that the optimum control switches between 0 and c_{max}. The control algorithm to be proposed traces the local strain energy, while the actuator placement criterion quantifies the potential for its accumulation.

3. Numerical example

Consider a 2D frame with 5 mm $\times$ 5 mm elements made of steel (7850 kg/m^3, 200 GPa). A finite element model of 16 Euler-Bernoulli beam elements was used with the Newmark integration scheme. Two example responses are shown in Fig. 1. With respect to the optimum scheduled passive control, the proposed semi-active control reduced the objective function respectively by 20% and 36%. With respect to the uncontrolled system, the reduction was 93% and 72%.

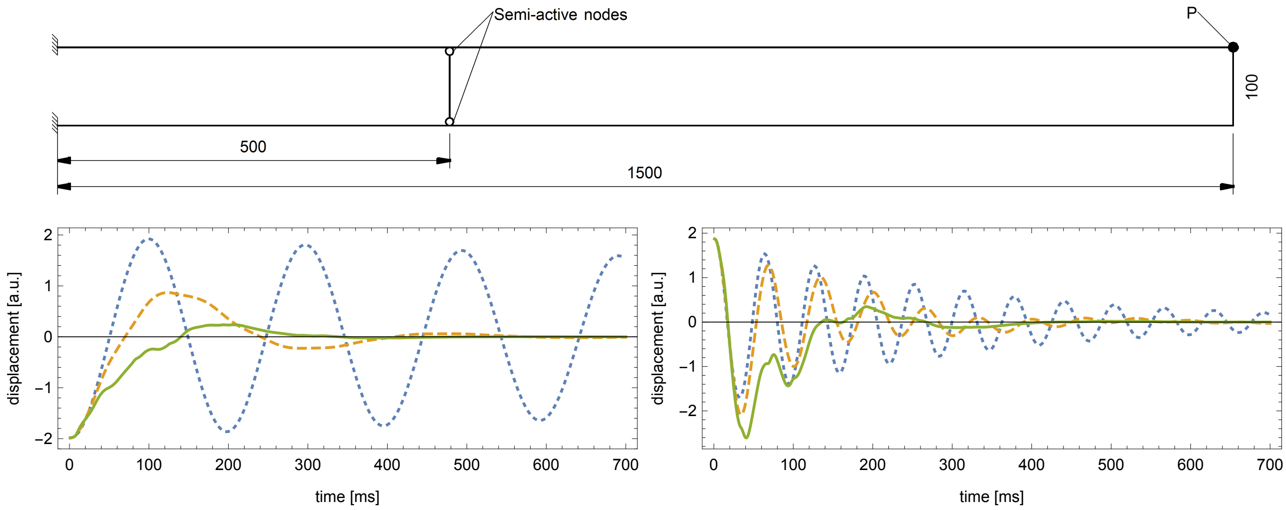

Figure 1. (top) 2D frame model, dimensions in mm; (bottom) Vertical displacements of point P for $\mathbf{x}_0$ being the first (left) and the second (right) vibration mode shape: uncontrolled structure (dotted blue), optimum scheduled passive control (dashed yellow), the proposed semi-active control algorithm (solid green).

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5. References

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