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Procedia Engineering 199 (2017) 1683–1688

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

A decentralized strategy of structural reconfiguration in mitigation of vibrations

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Abstract

This contribution proposes a decentralized closed-loop control algorithm for semi-active mitigation of free vibrations in frame structures. The control uses dedicated dissipative devices, which consist of two controllable structural nodes placed pairwise in both ends of selected structural beams. The nodes are capable of a controlled transition between the standard frame mode of operation (full moment-bearing ability) and the truss mode in which they do not bear any moments and constitute in fact structural hinges. Syncronous switching is equivalent to reconfiguration of the global structure by (dis)allowing the involved beams to transmit moments and to accumulate vibration energy in the form of their bending strain. Upon switching to the truss mode, the accumulated energy is released into high-frequency local vibrations, which undergo quick dissipation by standard mechanisms of material damping. The approach is illustrated in a numerical example and verified in a preliminary experimental test.

Keywords: Mitigation of vibrations; Semi-active control; Decentralized control; Structural reconfiguration

1. Introduction

Semi-active control techniques and their applications for damping of structural vibrations attract more and more research effort [1,2]. There are two basic approaches to control in structural mechanics: passive systems and active control systems. Passive systems amount to structural optimization and involve in fact no control at all: they cannot adapt to varying excitation and response patterns, which limits their effectiveness. Their advantage is the passivity: they require neither complex controllers, nor actuating or sensing systems, nor power supply. The active control systems rely on specialized actuators that exert external and often significant forces. They are extremely effective, well-researched and widely applied [3], but the high control forces constitute their disadvantage in structural control due to the related high energy consumption and susceptibility to instabilities in case of power or actuator failure.

There is thus a surge in interest in control approaches that would be more effective than the passive optimum design and more cost-effective and failure-safe than the active systems. The intermediate approach of the semi-active control

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Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.363

systems is based on the fundamental idea of structural adaptivity [4], which is a concept ubiquitous in nature and clearly different from active counteraction to stimuli on one hand and passive dissipation of energy on the other hand. Instead of introducing external forces, actuators in a semi-active control system modify local structural properties such as viscous damping, mass moment of inertia or local structural topology including kinematic constraints. In this way, the semi-active control amounts to structural self-adaptation or reconfiguration. An obvious advantage is the significant reduction of the power demand, while the disadvantage is the increased theoretical difficulty in deriving the optimum control laws. Available studies include already a large number of various areas of application including seismic isolation [5], vehicle absorbers [6] and airbags [7], roadside barriers [8], landing gears [9], damping of torsional vibrations in electro-mechanical machine drivetrain systems [10–12], vehicle-track/span systems [13,14], pneumatic maritime fenders [15], protection against ice in arctic conditions [16], protection of turbine blades against sudden wind gusts [17], damping of transient vibrations in flexible space structures [18,19], etc.

The semi-active control can be implemented either using actuators with continuous control, such as pneumatic systems with controllable pressure release [20], or using bang–bang type control. In the latter class, besides stiffness-switched bars investigated, e.g., in [21,22] or systems aiming at maximization of instantaneous local dissipation of energy [23,24], there is a number of publications on on/off control strategies based on structural reconfiguration, which involve imposing or removing selected structural constraints. In case of vibrating mechanical systems, removing a constraint at the moment of a high local strain can lead to strong, high-frequency vibrations, which are effectively damped by means of standard mechanisms of material damping. In this way, a part of the energy accumulated in the form of strain in the low-frequency low-order vibration modes can be periodically released into high-order, high-frequency vibration modes, which leads to very quick decay of vibration amplitudes. In [25], such a damping strategy has been named the "prestress–accumulation release" (PAR) strategy. Even if there is a large variety of the applied control techniques (truss–frame nodes with controllable moment-bearing ability [19,26], controllable delamination [25], magnetorheological elastomers [27], jammed granular material [28], etc.), almost all available researches are systemically restricted in that they essentially

1. study the same basic example, which is the fundamental vibration mode of a sandwich cantilever beam with two detachable layers, and
2. apply the same global, centralized control strategy that enforces energy transfer to the high-frequency highly-damped longitudinal mode by detaching the layers in the maxima of tip displacement.

This contribution focuses on 2D frame structures. Selected structural beams are turned into dissipative devices by replacing their two end nodes with a pair of synchronously controlled truss–frame nodes (blockable hinges). Such nodes are capable of a controlled transition between the truss and the frame mode (zero to full moment-bearing ability), and so they can be used to enable or block the transmission of moments between different parts of the structure through the involved beam, which is equivalent to local structural reconfiguration. As in the PAR strategy, upon unblocking the hinges, the bending strain energy accumulated in the beam is released into its high-frequency quickly-damped local oscillations. We address both of the deficiencies mentioned above, and as the main novelty factor, we propose a new closed-loop decentralized control strategy, which is based on a local energy measure and does not need any global structural model. Potential applications are light and inherently flexible structures of various types: space structures [18], deployable structures [19,29], modular structures [30], etc.

In the following sections, we will describe the model of the proposed dissipative device and the involved truss–frame nodes, formally define the control problem, propose the decentralized control algorithm and demonstrate its effectiveness in a numerical example involving a number of low-frequency vibration modes. Finally, we include preliminary experimental results obtained in a laboratory stand and actual piezo-driven truss–frame nodes.

2. Dissipative devices and the formal model of the semi-active node

2.1. Dissipative devices

This contribution uses the controllable truss–frame nodes pairwise on both ends of selected beam elements of the structure, which are in this way turned into specific dissipative devices without impeding their basic role as the structural members. The nodes are controlled synchronously, and switching them to the truss-like mode (unblocking the hinges) allows any locally accumulated bending strain of the involved beam and the related potential energy to be quickly released into high frequency local bending vibrations that are quickly dissipated by the standard mechanisms of material damping. Conversely, switching the nodes to the frame-like mode (blocking the hinges) couples the distinct parts of the structure by the moments that are transmitted through the involved beam and allows the potential energy of the bending strain to be accumulated again in the device.

2.2. Semi-active node

Formal investigations into optimum control by means of the dissipative devices described above require a theoretical model of the truss–frame nodes with controllable moment-bearing ability. In general, two possibilities exist:

1. *Dry friction modeling.* Such an approach has been used in earlier researches [18,19,23], which study nodes with an actuator placed in the axis. The actuator presses dedicated frictional surfaces against each other with a controllable force and controls in this way the moment-bearing level of the node. This approach is physically the most accurate and suitable for numerical simulations in commercial finite element (FE) software. However, the resulting model is highly nonlinear, which impedes theoretical analysis of the optimum control strategies.
2. *Model switching* between truss and frame modes of operation, which places the problem in the realm of switched systems control theory [31] and involves changing the effective number of DOFs during simulation. The system is linear between the switchings, which properly model the operation of an ideal truss–frame node with zero/infinite moment-bearing ability. However, optimum control of switched systems involves marked theoretical difficulties.

Both approaches involve significant theoretical difficulties, which has stipulated a third approach first proposed in [26]. The semi-active nodes are hinges with two rotational DOFs that remain unaggregated. In the basic, truss-like mode, these DOFs are not coupled, so that no moment is transmitted between the corresponding beams. Switching to the frame-like mode is simulated by introducing a large viscous damping of the relative rotational motion, which couples the respective DOFs. Such a modeling is approximate and suitable only for transient analysis, but it allows the structural response to remain linear. Effectively, the control takes the bilinear form [32] with the equation of motion:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \left(\mathbf{C} + \sum_{i=1}^{N} \gamma_i(t)\mathbf{C}_i\right)\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{0}, \qquad \mathbf{x}(0) = \mathbf{x}_0, \qquad \dot{\mathbf{x}}(0) = \mathbf{0}, \tag{1}$$

where $\mathbf{M}$ and $\mathbf{K}$ denote the structural mass and stiffness matrices, $\mathbf{C}$ is the damping matrix of the structure in its basic truss-like mode (all hinges unblocked), and $0 \le \gamma_i(t) \le \gamma^{\max}$ is the control function of the ith controllable node. When $\gamma_i(t) = \gamma^{\max}$, the node is in the frame-like mode and DOF coupling is enforced by the matrix $\mathbf{C}_i$, which for two and three coupled rotational DOFs takes respectively the following forms:

$$\mathbf{L}_i^{\mathrm{T}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \mathbf{L}_i, \qquad \mathbf{L}_i^{\mathrm{T}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{bmatrix} \mathbf{L}_i, \tag{2}$$

where $\mathbf{L}_i$ is the global-to-local DOF transformation matrix.

3. Optimum control problem

The concept of a node with controllable ability to transmit moments, based on dry friction, has been already studied in [18,23]. However, unlike [19,26] and this contribution, the controllable nodes acted there as local friction-based energy dissipaters, and the considered control objective focused on instantaneous energy dissipation by maximizing the local force–displacement hysteresis loops. In contrast, a global optimum control problem can be defined as the task of minimizing the objective function F defined as the integral of the total structural energy,

$$F = \int_0^T \left(\frac{1}{2}\dot{\mathbf{x}}^{\mathrm{T}}(t)\mathbf{M}\dot{\mathbf{x}}(t) + \frac{1}{2}\mathbf{x}^{\mathrm{T}}(t)\mathbf{K}\mathbf{x}(t)\right) \mathrm{d}t, \tag{3}$$

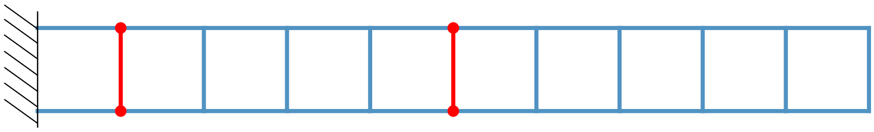

Fig. 1. The 2D frame structure model considered in the numerical example. Vertical beams no. 1 and 5 are equipped with controllable nodes.

with respect to the control functions $0 \le \gamma_i(t) \le \gamma^{\max}$ and subject to the equation of motion (1). Using the state-space formulation and the Pontryagin minimum principle [33], it is relatively easy to show that the corresponding globally optimum control functions $\gamma_i^\star(t)$ have the following bang–bang form:

$$\gamma_i^\star(t) = \begin{cases} 0 & \text{if } w(t) < 0, \\ \gamma^{\max} & \text{if } w(t) > 0, \end{cases} \tag{4}$$

where $w(t)$ is called the switching function and depends on the response $\mathbf{x}(t)$ and a certain co-state vector $\mathbf{u}(t)$. The co-state vector satisfies the co-state equation, which is the equation of motion of the original structure with negative structural damping and a certain pseudo load. Due to the negative damping, the co-state equation can be numerically integrated only backward in time, so that it cannot be used to compute online the optimum control (4) during forward simulation of the equation of motion (1). In other words, the optimum control function (4) is given in an implicit form. Even though, (4) is an important result, as it assures that the optimum control has a bang–bang character.

4. Decentralized control algorithm

The controllable nodes are used pairwise in both ends of selected structural elements. The nodes are controlled synchronously, so that switching them to the truss-like state releases any bending distortion of the element into its high-frequency and quickly vanishing local oscillations. In this way, each such element is turned into a dissipative device, which is controlled independently of other such devices. The control feedback signal is the strain energy of the involved element associated with its bending distortion, that is the energy that can be released into its high-frequency local oscillations. Such a signal is intrinsically local and can be measured locally by using, e.g., a few strain gauges. The following intuitive decentralized control law is used: the element starts the operation in the frame-like mode and

1. stays in the frame-like mode (hinges blocked) as long as its local bending strain energy increases,
2. switches to the truss-like mode (hinges unblocked), when its local bending strain energy stops increasing,
3. switches back to the frame-like mode (hinges blocked again) after being t_0 ms in the truss-like mode.

Finally, the element waits for the next maximum of the local energy, so that the above control sequence is repeated iteratively. The element stays in the truss-like mode for a relatively short time t_0, and the global stiffness of the structure is not compromised. To ensure that the released bending strain energy is dissipated, the time t_0 is set in numerical simulations to one period of the natural bending vibrations (S-type) of the involved beam. In the experiment, the time t_0 is set arbitrarily and it is limited by the maximum operation frequency of the controllable nodes. In practice, the choice of t_0 is not crucial, as the above control algorithm tends to stay effective for a wide range of its values.

5. Numerical example

The modeled structure (Fig. 1) is a 2D frame, 1 m long and 0.1 m high, of steel beams 1 mm × 1 mm in cross-section. The DOFs in the two leftmost nodes are blocked. Vertical beams no. 1 and 5 are turned into dissipative devices. The controllable nodes in their ends decouple the rotational DOFs of the vertical and horizontal beams. The first three global vibration modes (6.1 Hz, 18.7 Hz and 32.3 Hz) are used as the initial displacement. The free responses are compared for the passive and semi-actively controlled frames. There is thus a total of 6 cases (3 modes × passive/semi-active). Fig. 2 shows the time evolution of the total structural energy (logarithmic scale) and of the tip vertical displacement. Note that larger displacement is possible at lower overall structural energy, which confirms that the objective function (3) is not universal.

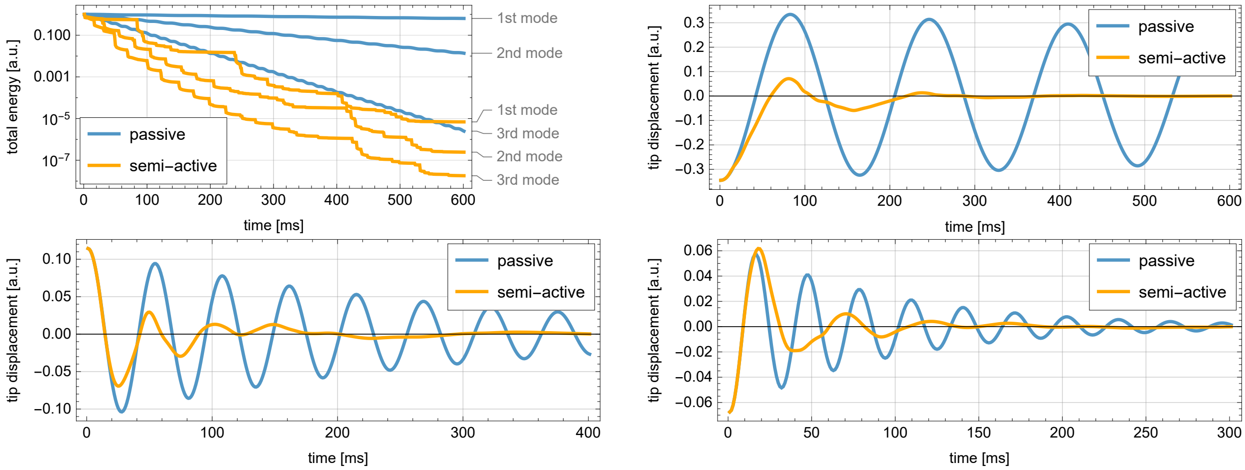

Fig. 2. Numerical example: total structural energy and tip vertical displacements for modes 1, 2 and 3.

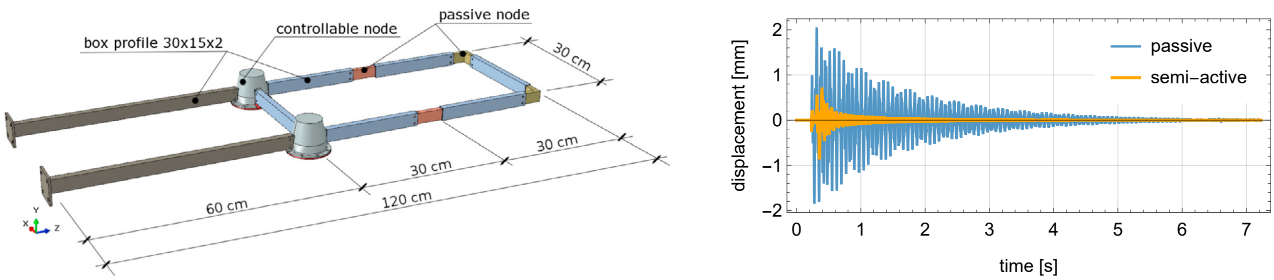

Fig. 3. Experimental example: (left) The 2D frame structure. (right) Tip displacements for the passive and semi-actively controlled structure (double integrated accelerations with enforced periodic zero conditions).

6. Preliminary experimental results

A scheme of the experimental structure is shown in Fig. 3(left). The structure included two semi-actively controlled nodes. The initial displacement conditions corresponded to a few mm forced tip displacement, which involved mainly the first two global bending modes of natural vibrations (14.8 Hz and 40.4 Hz). Fig. 3(right) compares the tip displacement of the passive structure and of the semi-actively controlled structure. The displacements have been obtained by automatic double integration of the accelerations by the data acquisition system. Even though the automatized integration procedure included periodic setting the signal to zero to avoid divergence, the much quicker vanishing amplitudes in the semi-active case are easily noticeable.

7. Conclusions

This contribution has proposed a semi-actve decentralized control strategy based on structural reconfiguration and truss–frame nodes with a controlable moment-bearing ability. The control has a bang–bang character and it has been tested in a numerical example and in a preliminary experiment.

Acknowledgements

Support of the National Science Centre, Poland, granted through the projects Ad-DAMP (DEC-2014/15/B/ST8/04363) and AIA (DEC-2012/05/B/ST8/02971), is gratefully acknowledged.

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