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Decentralized algorithm for semi-active damping of forced vibrations using controllable truss-frame nodes

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Abstract

Semi-active systems for mitigation of vibrations proved to be effective in many applications. Their prominent advantage is that they combine strong points of passive and active damping systems. Proper design can ensure their reliability, which is what passive systems are praised for. A high effectiveness in vibration damping links them with active systems. At the same time they do not have many deficiencies of active systems. They are adaptive, so they can stay effective in different environmental conditions, which is the factor that eliminates passive systems from many implementations. Their mass and energy consumption is very low, and the controlled structure can stay in the safe configuration even in case of power supply failure, which puts them in contrast to many active systems. The mentioned attributes make them a good choice for many structures subjected to vibrations, especially when there is a strong emphasis on maximization of the efficiency/mass ratio of the damping system.

This contribution presents a decentralized closed-loop control strategy and applies it in a frame structure equipped with controllable truss-frame nodes. Such nodes can be switched between frame-like and truss-like states in a controllable manner. In the frame-like state the node transmits all forces and moments, while in the truss-like state only axial and shearing forces are transmitted. These nodes allow for structural reconfiguration, which can be utilized by semi-active control strategies for the purpose of vibration damping. The implemented control algorithm applies the Prestress-Accumulation Release (PAR) strategy based on the transmission of the accumulated potential energy to high modes of vibration, which are highly dissipative. Strain measurements are conducted locally on selected elements. A similar strategy proved its effectiveness in mitigation of free structural vibrations. This research studies the concept of its application to mitigation of forced structural vibrations, caused by variable external conditions.

Keywords: Semi-active damping, Truss-frame nodes, Prestress–Accumulation Release (PAR), Decentralized control.

1 Introduction

Negative effects of vibration are one of the most common problems in many fields of engineering. Vibrations that occur during operation of machines or structures may cause inconveniencies for their users, dangerous malfunctioning, fatigue damage or, in extreme cases, their complete destruction. Most often it concerns machines with elements rotating at high speed, such as car engines or turbomachinery, but it can affect other types of objects subjected to external excitation, e.g. windmills, buildings, bridges, etc.

The prevalence of vibrations motivate engineers and scientists to develop systems which would mitigate their effects or prevent their emergence. These systems can be grouped into three main categories, based on the way they affect a structure: passive, active and semi-active ones. The order in which they are listed is also related to the course of evolution of vibration damping strategies.

The earliest developed method – passive, is also the simplest one. It works on the principle of passive energy dissipation. Operational conditions of the structure are specified at the design stage and, based on them, the constructor may choose appropriate passive damping devices. This strategy works well when external conditions are stable, but even their slight modification can lead to strong reduction of the effectiveness of the applied dampers.

The need to increase the efficiency and to broaden the range of correct operation in conjunction with technological development has led to the emergence of active vibration damping systems [1]. They actively produce forces counteracting the motion caused by vibrations, which makes them very effective, however the actuators which are necessary in such systems are usually relatively heavy. They also require the development of the algorithms responsible for controlling the actuators. This makes them much more complex than passive ones. Active force application could be the cause of the injection of high amounts of the energy to the moving structure when the control algorithm is not properly designed. Such behavior can be very dangerous because it can magnify vibrations instead of mitigating them. This introduces some uncertainty in terms of the control system.

As if in response, in some measure, to the drawbacks associated with the use of both passive and active systems, scientists proposed a new concept of vibration mitigation systems – semi-active ones. These are the most technologically and theoretically advanced damping systems among others. Principle of operation of these systems is based on the instantaneous structural reconfiguration of the controlled structure, what entails local or global changes in its basic engineering properties, e.g., stiffness or damping. Well designed, they can be as efficient as active systems and as reliable as passive ones.

Despite the great complexity in development of this type of vibration damping systems, recognition of their advantages causes that an increasing number of scientists are inclined to conduct research on such solutions. A relatively large number of articles examine systems that consist of only a damping device or a single degree of freedom (SDOF), which can be represented as a mass-spring-damper system, e.g. [2, 3, 4]. A frequently described case is a damper with its damping capabilities modulated by the use of a piezoelectric material [5], magnetorheological fluid [6, 7] or, less often, magnetorheological elastomer [8]. A lot of attention is attracted to the problem of damping of vibrations in vehicles suspensions [9, 10, 11] and to seismic shocks protection [12, 13]. Semi-active control algorithms are also utilized in energy harvesting strategies [14] and rotating machinery [15].

Some authors consider more complicated structures such as, e.g., the Smart-Spring concept [16], a bag filled with granular material placed between two beams [17] or an analogous double-beam structure connected by one or many damping elements [18, 19].

We considered the system described first in [20] and proposed a semi-active, decentralized damping strategy which performed very well in suppressing free structural vibrations [21, 22]. Here we present its high efficiency in reduction of externally induced vibrations caused by harmonic excitation.

2 Damping devices

Proposed control strategy is made possible by the use of special truss-frame nodes, which are able to change their state of operation. When the control signal is in its low state the node behaves in a frame-like manner – its moment transmission ability is set to the highest level. Operation of a control algorithm might result in setting the signal controlling the behavior of the semi-active node to the high state and switching it to a truss-like state, in which the moment transmission ability of the node is set to its lowest possible level. The use of piezoelectric stacks allowed to obtain high frequency of changes between the states of nodes.

A beam incorporated into a frame structure via the described nodes can significantly influence its stiffness by switching between truss- and frame-like states of semi-active nodes. Local, instantaneous change of stiffness at the right moment may lead to modification of the motion resulting in an immediate reduction of the vibration amplitude. Furthermore, decentralization of the control strategy allows for the extraction of such a beam as an independent energy-dissipating device.

A theoretical model of the considered semi-active node was proposed, which allows for conducting numerical simulations in a straightforward manner while maintaining satisfactory compliance with reality. The model of choice was the viscous rotational damper which connects two coincidental rotational degrees of freedom, with the damping factor changing on demand during the simulation between its maximum ($\gamma = \gamma^{\max}$) and minimum values ($\gamma = 0$). Such a model of the connection makes it possible to simulate the switching between the states in a reliable and efficient way.

General equation of motion of a sample structure with such damping devices can be written as:

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \left(\boldsymbol{C} + \sum_{i=1}^{N} \gamma_i(t)\boldsymbol{C_i}\right)\dot{\boldsymbol{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{F}(t) \tag{1}$$

where M and K stand for the structural mass and stiffness matrices, C is the damping matrix of the structure in the truss-like state, and γ_i defines the damping factor of each semi-active node, which can be considered as a control function. C_i is the classical coefficient matrix of rotational damper which is the same as of a spring element stiffness matrix in two dimensional FEM analysis and F is the external force.

It should be remembered that this modelling method is suitable only for transient simulations. In static analyses, the damping factor of the equation of motion is removed and therefore the structure behaves as if the semi-active nodes were in the truss-like state.

3 Control algorithm

Presented control strategy is based on the concept called Prestress Accumulation-Release, originally described in [20, 23]. It utilizes the idea of transferring the energy from lower to higher vibration modes characterized by shapes of a higher spatial frequency and a higher modal stiffness. As a result, the strain energy is distributed over a larger number of smaller deformations, which results in a reduction of the displacements of the structure. The most important in the application of this control algorithm is that higher-order modes of vibration tend to be better attenuated by means of material damping, which means that the energy dissipation is significantly increased.

Global optimal control problem can be formulated as the minimization of the functional specified as the energy integral of the structure:

$$F = \int_{T_s}^{T_f} \left(E_{kinetic} + E_{potential}\right) dt = \frac{1}{2}\int_{T_s}^{T_f} \left(\dot{\boldsymbol{x}}^T(t)\boldsymbol{M}\dot{\boldsymbol{x}}(t) + \boldsymbol{x}^T(t)\boldsymbol{K}\boldsymbol{x}(t)\right) dt \tag{2}$$

State space formulation of such a problem, utilized in the Pontryagin minimum principle, gives the bang-bang form of the control strategy [24]. However it is impossible to determine its form directly using this principle, because it requires the integration of a system of differential equations describing the motion of the structure, some of which include members with positive and others with negative damping factor. This feature makes it numerically unstable.

Despite the occurrence of this problem, the result in the form of a bang-bang control is very important, because it indicates the nature of the control strategy to be sought.

Semi-active nodes installed at the ends of selected beams allow to temporarily change the way the beam works from frame to truss mode. Such a change causes immediate release of any flexural deformation to which the beam has been subjected which results in excitation of high-frequency local, quickly damped vibrations. The second way of energy dissipation is associated with the PAR strategy. A brief local reconfiguration of the structure may result in excitation of higher order modes of vibration without increasing the total energy of the structure. Energy transferred to this modes, as mentioned earlier, tends to be dissipated faster than in fundamental ones. The combination of the two described energy dissipation mechanisms makes the proposed system very effective.

The control strategy using the mechanisms described above was originally presented in [21] and [22]. This heuristic algorithm can be presented in the form of the following block diagram:

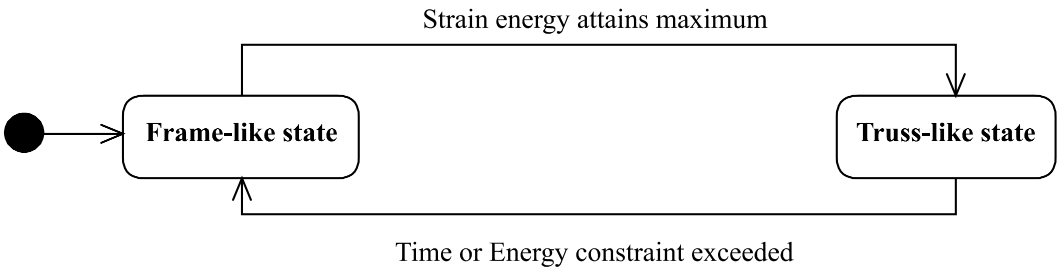

Figure 1. Block diagram of the proposed semi-active control algorithm

When the structure does not oscillate, the semi active nodes remain in the frame state. When vibrations occur and a certain level of their amplitude or elastic energy is attained, the algorithm can start its operation. The nodes remain in the frame state during the build-up of the strain energy, which is referred to as the Prestress–Accumulation phase. When the maximum of this energy is detected by the controller, the semi-active nodes are temporarily switched to the truss state. This action is called the Release phase. When the strain energy of the selected beam falls to a given level, or when that beam stays in the truss state for a certain time, the nodes are switched back to the frame state. This sequence is repeated iteratively until the vibrations reach the desired level.

This control strategy is applied locally, for each selected beam in the structure equipped with semi-active nodes.

4 Numerical example

It was shown that the structure containing the described semi-active nodes in their frame state is in conformity with the pure frame model of the same topology [21].

This numerical analysis demonstrates the effectiveness of the created algorithm in reducing the amplitude of vibrations of frame structures subjected to a harmonic external loading. The considered structure is presented in Figure 2.

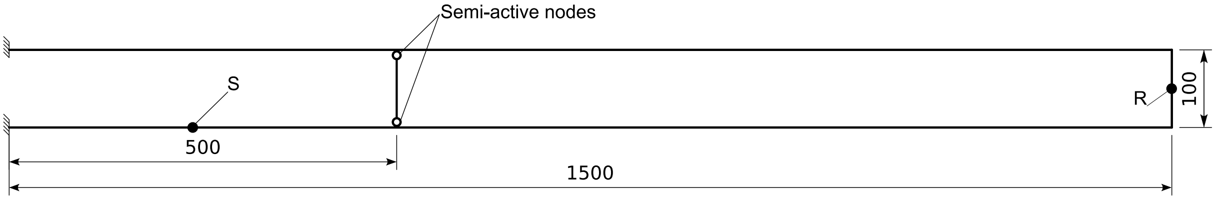

Figure 2. Frame structure considered in the numerical example

It is a 2D frame with the dimensions marked in the figure, made of steel with Young's modulus E = 200 [GPa] and density ρ = 7850 [kg/m^3]. The cross-section of the beams is a square with a side dimension of 5 [mm]. One vertical beam is equipped with semi-active nodes at both ends, which makes it a damping device of the described type. The external harmonic force is applied to the structure at a selected point, in particular at the point S. The harmonic excitation frequencies have been chosen to correspond to the first two natural frequencies of the structure under consideration – 5.1 [Hz] and 15.9 [Hz].

Figure 3 presents the comparison between the time courses of vertical displacements of the point R (see Figure 2) when the control algorithm is turned off and the semi-active nodes remain in the frame state throughout the simulation (Passive case) and when it is switched on (Semi-active case).

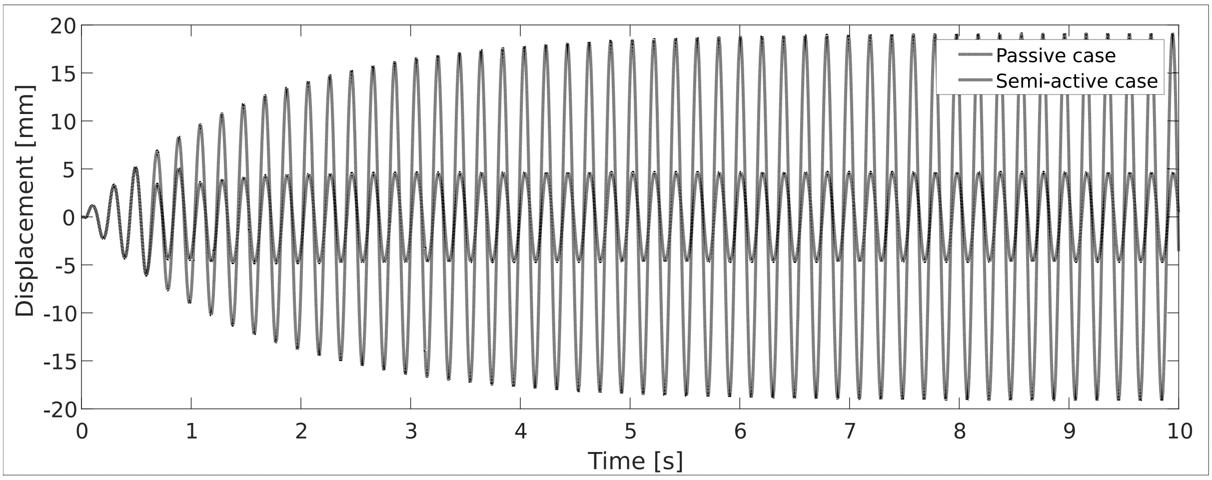

Figure 3. Comparison of vertical displacements of point R for the first natural frequency

Initially the vibrations increase, but when the appropriate displacement amplitude is achieved, the control algorithm starts and reduces them very efficiently. The displacement amplitude of the tip of the structure is reduced by about four times in relation to the passive case.

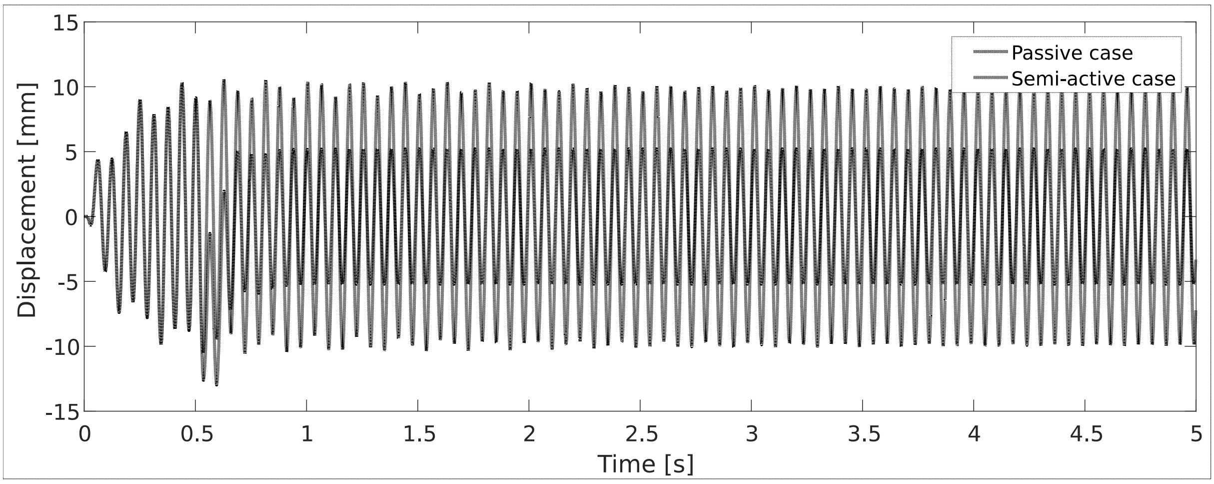

Figure 4. Comparison of vertical displacements of point R for the second natural frequency

Vibration amplitude mitigation for the second mode of vibration (Figure 4) is not as spectacular as for the first mode, however, it is still a reduction of the displacement at the tip of the structure by about 50%. Here, the algorithm starts after half a second from the start of the simulation.

5 Experimental verification

The proposed control strategy was verified experimentally at the laboratory stand. The frame structure, analogous to the numerical model, is equipped with two semi-active nodes. The topology of the considered frame is presented in Figure 5.

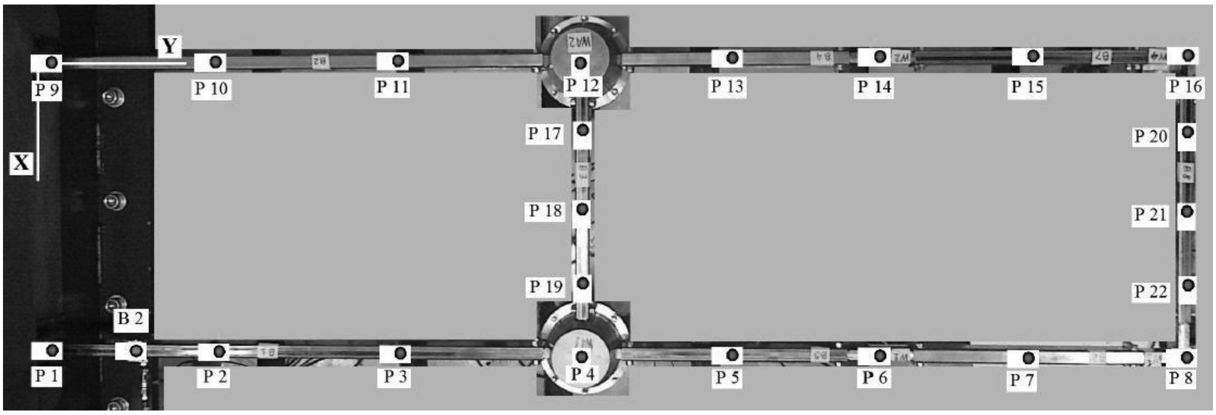

Figure 5. Laboratory model of the frame structure.

It is built of steel beams with a 15×30 [mm] box profile cross-section. Its length is 1200 [mm] and width is 300 [mm]. As in the numerical example – it is fixed at the left end side. The control system used allows for effective operation within the scope of the first two natural modes of the structure – 14 [Hz] and 39 [Hz]. The harmonic external excitation is applied at the point B2 (see Figure 5).

Figures 6 and 7 show the time courses analogous to those in Figures 3 and 4 – compare the time courses of strains in passive and semi-active cases. The point at which the strains are measured is P15 (see Figure 5).

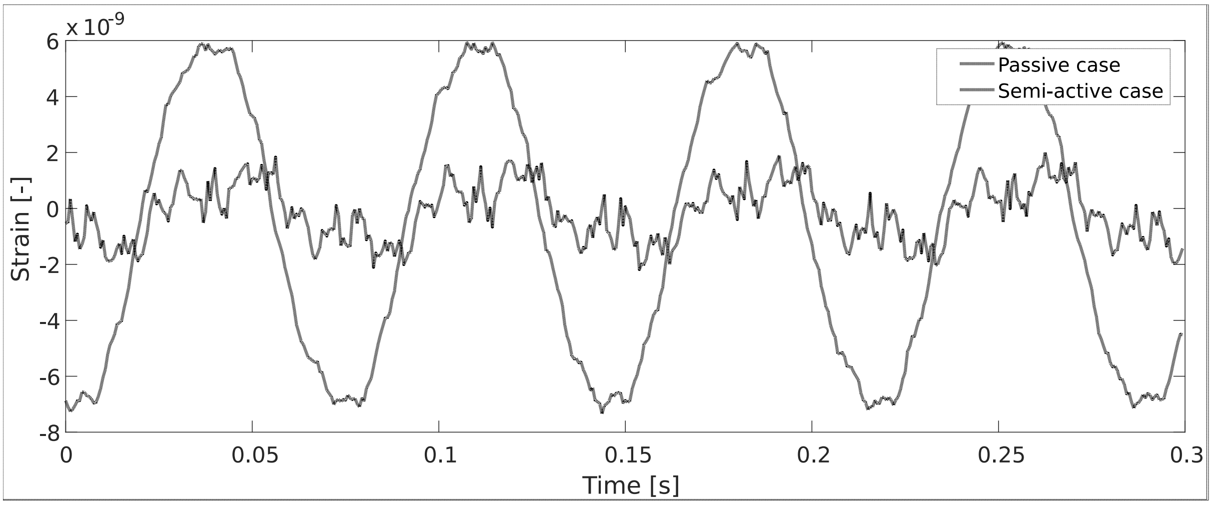

Figure 6. Comparison of strains at point P15 for the first natural frequency

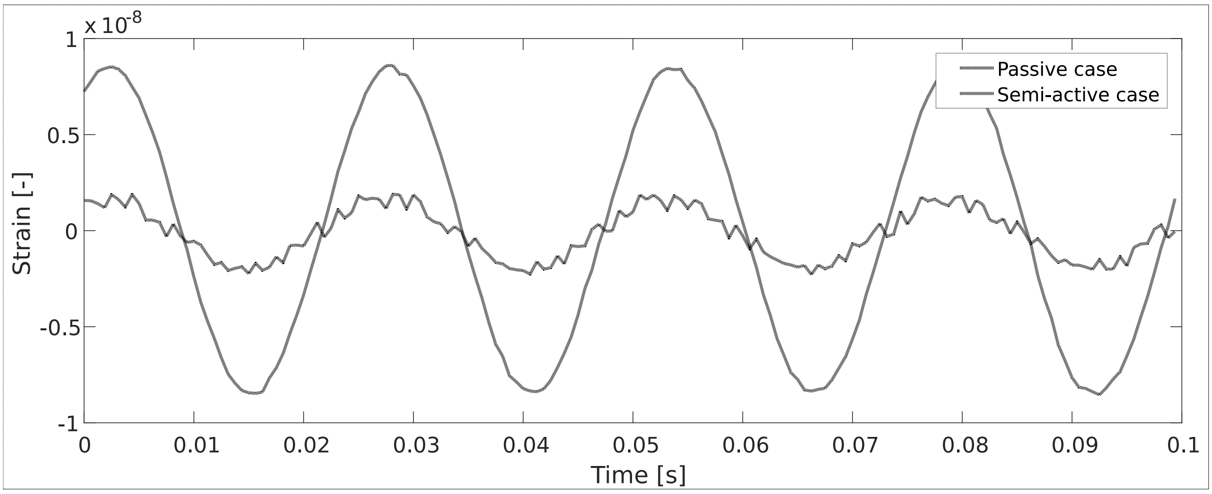

Figure 7. Comparison of strains at point P15 for the second natural frequency

Experimental results confirm the effectiveness of the developed semi-active vibration mitigation algorithm. For the first eigenform, the strain amplitude is reduced about three times, while for the second it is reduced about four times.

6 Conclusions

This paper presented the efficiency of the semi-active harmonic vibration reduction strategy based on the energy transfer (PAR). Proposed algorithm proved to be effective both in numerical simulations and in laboratory tests. The reduction in displacement or strain amplitudes was very high (at least 50% in each case). It is therefore advisable to use it for the reduction of cyclically induced vibrations of slender frame structures. The semi-active nodes are designed in such a way that the vibration reduction system is safe for the structure even in the event of power failure. Thus the system can also be used for applications requiring a high level of safety.

Further research work will include applications to more complex 3D structures such as wide-span skeletal roofs [25] and modular structures [26].

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