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Research Paper

On/off Nodal Reconfiguration for Global Structural Control of Smart 2D Frames

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Abstract. This paper proposes an on/off semi-active control approach for mitigation of free structural vibrations, designed for application in 2D smart frame structures. The approach is rooted in the Prestress–Accumulation Release (PAR) control strategies. The feedback signal is the global strain energy of the structure, or its approximation in the experimental setup. The actuators take the form of on/off nodes with a controllable ability to transfer moments (blockable hinges). Effectiveness of the approach is confirmed in a numerical simulation, as well as using a laboratory experimental test stand.

Keywords: Structural reconfiguration, Structural control, Semi-active control, Frame structures, Controllable nodes.

1. Introduction

Years of development in the field of engineering and science have led to the emergence of many types of the so-called intelligent or smart structures and systems for their maintenance. Their intelligence manifests itself in many different aspects, often imitates evolutionary developed natural design principles [1,2] and mechanisms of self-adaptation [3,4], and it is focused on the enhancement of structural properties in the sense of durability, safety, ergonomy, resistance to unexpected external loads, etc.

Performance improvement can be achieved in many ways. Their diversity is dictated by the different characteristics of the structures in question. An example is the modification of a cable internal structure with shape memory alloys in order to increase the damping behavior [5]. Shape memory alloys are also incorporated in systems of base isolation for buildings in earthquakes zones [6, 7]. One can distinguish between passive systems which utilize shape memory alloys for the enhancement of structural properties [8–10], and the active, semi-active and hybrid systems [11–12]. Another prominent example of adding smartness to a designed structure is a tuned mass damper, which applications can be subdivided, similarly to the case of shape memory alloys, into passive, active and semi-active solutions [13–15]. Systems consisting of multiple tuned mass dampers are also considered in the literature as a more robust alternative to single damper systems [16].

One of the numerous challenges associated with intelligent structures in mitigation of vibrations and improvement of their safety and endurance is the optimal placement of sensors for a data acquisition system [17–20], which may include the development of wireless acquisition systems [21,22]. The problem of sensor placement is directly related to another very broad research field of structural health monitoring (SHM). It can be described superficially as the strategies and systems developed for detection and identification of structural damages in various types of engineering structures. On a high level of abstraction, any structural health monitoring problem is an instance of a statistical pattern recognition problem [23, 24]. The solution techniques can adopt global [25], local [26] or a combined approach [27], and it can be focused on assessing the current (real time) state of the monitored structure [28] or on estimating its remaining service life [29].

A relatively large proportion of research related to smart structures is devoted to structural control and especially to vibration control. The field is very broad and an exhaustive overview of the control methods and applications can be found for example in the review reference [30]. To name only a few application examples and techniques, one can point out the control of seismically excited vibrations in earthquake engineering [31], energy harvesting and power management [32,33], fuzzy logic control [34] or control utilizing neural networks [31].

This paper presents a work devoted to the enhancement of dynamic response characteristics of slender, planar frame structures. In certain applications, such as space systems, high technical requirements regarding the system weight and/or maximum span are associated with a high level of slenderness of such structures. This feature is intrinsically linked to susceptibility to any external excitation, such as impacts, which excite the entire spectrum of eigenmodes and eventually end up as the free vibration case with the dynamic response of the structure consisting of only one or a few natural modes, or a harmonic force excitation corresponding to a single frequency (in particular one of structural resonant natural frequencies). The resulting vibrations, under the conditions of a high slenderness of the structure and its low natural vibration damping capacity, may lead to large deformations and long decay times which are both dangerous and uncomfortable for the users, and detrimental to many intended high-precision applications.

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In response to these problems, a vibration damping system has been designed and developed. It consists of i) dedicated semi-actively controlled nodes which can change their state of operation from the frame node (full transfer of moments between the adjacent elements) to the truss node (a hinge with no moment transfer ability) in a matter of milliseconds and ii) the control unit which implements the intended control strategy. The truss-like state of operation is activated only temporarily for very short time periods, so that the structure retains globally its default high stiffness associated with the frame-like state of operation. In contrast to earlier research based on local bending of elements [35], the proposed control strategy uses (an approximation of) the global strain energy of the structure as the feedback signal, which simplifies required instrumentation and constitutes thus an advantage in practical applications. It is shown here, both numerically and experimentally, that the investigated control approach works with a satisfactory effectiveness for mitigation of free structural vibration in the low natural frequencies of the investigated frame structure. The tested control strategy is well-suited for mitigation of vibrations in relatively complex structures and potentially also for higher vibration modes, which is a considerable extension when compared to other studies devoted to simple cantilever [36] beams, simply supported beams [37] or beam-like structures in their first, fundamental vibration mode [38].

2. Control System

The designed vibration damping system incorporates a heuristically derived control strategy. It aims at transferring the vibration energy accumulated in the form of the elastic strain energy between the eigenmodes of the involved structure. In particular, it strives to shift the energy from the mode of vibration that actually prevails in the dynamic response of the structure into higher vibration modes (of orders of hundreds of hertz), where the potential for mitigation of vibrations of the structure is presumably enhanced by a significant increase in material damping capabilities. The control strategy is inspired by an earlier research in the strategy of accumulation of the strain energy of the structure and its immediate release through a momentary, local reconfiguration of some of its elements [38–40], which was called by the authors a Prestress–Accumulation Release control strategy (PAR). The applied criterion of energy accumulation, and the technique of a temporary reconfiguration of the structure in order to release the energy, allows to directly assign the proposed control strategy to the family of PAR approaches.

2.1 Semi-active Node

An inherent part of the vibration mitigation system are the dedicated, controllable semi-active nodes. These are special structural nodes which can connect three beam elements in a planar structure. Connection to one of these beams can be switched between the frame-like mode of operation (when the maximum bending moment is transmitted) and the truss-like or hinge mode (when the bending moment is not transmitted). This change is conducted in a matter of milliseconds thanks to the utilization of very fast piezoelectric stacks. These features result in an exceptional ability to locally reconfigure the structure, changing for a very short time its mechanical characteristics by imposing/removing kinematic constraints of an appropriate form. The design of the nodes is subject to fail-safe design principles, which means that in the case of a power failure the node remains in its default frame-like mode of operation.

A simplified mechanical model of the node is presented in Fig. 1 as embedded in the global configuration of the physical lab structure used in the experimental verification. The classical finite element of a two-dimensional beam has six degrees of freedom (DOFs): two translational DOFs and one rotational DOF per each of its ends (for example x_1, y_1, θ_1 and x_2, y_2, θ_2 for the beam B_1 in Fig. 1). In a typical aggregation process, the beams B_1 and B_2 would share the DOFs x_2, y_2, θ_2 in their common node. However, the considered semi-active node allows an additional rotational DOF φ_2 to be introduced. The rotation angle of the beam B_1 in the common node is denoted by θ_2 and that of the beam B_2 by φ_2. Thanks to this idea, the beams B_1 and B_2 are connected only through two DOFs (x_2 and y_2), as if they were truss elements. The described case corresponds to the very short moment of operation when the semi-active node ability to separate the rotational DOFs is activated. In the normal course of operation (the default state), the nodes remain in the frame-like state, which eliminates the relative motion of θ_2 and φ_2 by imposing the kinematic constraint on the rotational velocities:

$$\dot{\theta}_2 = \dot{\varphi}_2 \tag{1}$$

If the beam B_2 is equipped with such nodes at both its ends, its structural behavior can be switched on demand between the frame-like and the truss-like modes. This extraordinary property is extensively employed in the proposed control strategy.

The physical model of the node implements the described reconfiguration behavior by means of the dry friction between two interfacing conical surfaces which are pressed against each other with a high force generated by stiff springs and temporarily relieved by the piezoelectric stack. The numerical implementation necessary for the purpose of simulations and fast prototyping uses a controllable rotational damper and is described in Section 3.1.

2.2 Control Strategy

The equation of motion for a system equipped with a set of semi-active nodes (with the controllable reconfiguration ability modelled by dampers, as described in detail in Section 3.1) can be described in the following form:

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + \left(\boldsymbol{C} + \sum_{i=1}^{N} \alpha_i(t)\boldsymbol{C}_i\right)\dot{\boldsymbol{u}}(t) + \boldsymbol{K}\boldsymbol{u}(t) = \boldsymbol{f}(t) \tag{2}$$

with the initial conditions

$$\begin{aligned} \boldsymbol{u}(t_0) &= \boldsymbol{u}_0 \\ \dot{\boldsymbol{u}}(t_0) &= \boldsymbol{v}_0 \end{aligned} \tag{3}$$

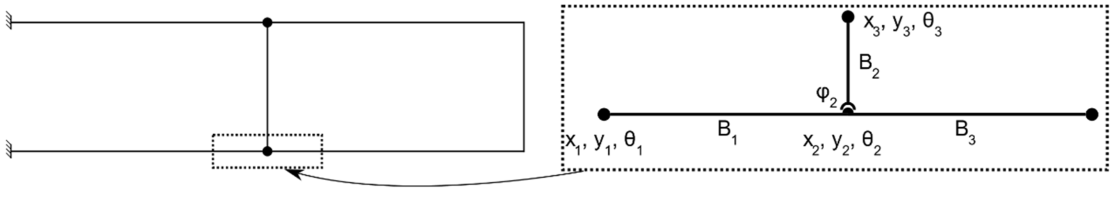

Fig. 1. Scheme of the semi-active node. The involved degrees of freedom are explicitly denoted.

The matrices $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ correspond to the mass, damping and stiffness matrices of the structure equipped with the semi-active nodes, which means that the number of the DOFs is appropriately adjusted and accounts for the additional rotational DOFs. The matrices $\boldsymbol{C}_i$ represent rotational dampers utilized for coupling the rotational DOFs in semi-active nodes, see Section 3.1. Time-dependent parameters α_i can be considered as damping parameters of each damper. The control strategy is implemented by means of switching their values between off (small) and on (large) states. The vector $\boldsymbol{f}$ represents the time-dependent external excitations, which vanishes in the considered here case of free vibrations, and x_0 and v_0 are vectors of the initial conditions.

It should be noted that, due to the adoption of such a mathematical description, the analysis of any system equipped with semi-active nodes modeled in such a way must concern dynamic phenomena. In the static case, the rotational dampers do not properly model the blocking of the relative movement.

The proposed control algorithm is based on the Pontryagin's maximum/minimum principle. Derivation of the globally optimum control strategy, for the mechanical system described by eq. (1), leads to the bang-bang type of control. Due to numerical stability issues it is however impossible to determine the exact form of the control function [35]. Despite this disappointing fact, the general result obtained through the analysis is considered very useful as it can serve as a basis for developing heuristic closed-loop control algorithms.

The control strategy is implemented into frame structures by equipping selected beams of the frame with the described semi-active nodes at their both ends. This makes effectively such a beam a special device that can influence the dynamics of the entire structure by having its behavior briefly switched from that of a beam element (with full transmission of moments) into a rod-like element (with transmission of axial forces only), which affects temporarily the effective global stiffness of the entire structure and can result in local high-frequency vibrations.

Drawing on the PAR methodology and the bang-bang optimal control approach, a heuristic vibration damping algorithm has been designed that aims at transferring the strain energy of the vibration mode into higher modes by nodal structural reconfiguration. Notice that the higher vibration modes are high-frequency and thus expected to be effectively damped by means of natural material damping mechanisms. The control approach attempts, in each local vibration cycle, to transfer as much of strain energy as possible. Intuitively, it can be expected that the most of the energy can be transferred into higher vibration modes when the structure is at its maximum strain level. In the light of such observations, a control algorithm was designed in which the state of the semi-active nodes is switched in a synchronized manner between frame-like and truss-like modes using the global strain energy of the structure as the feedback signal. Initially, the nodes remain in the frame-like mode of operation. The algorithm tracks the energy signal and sends a state switching signal to the semi-active nodes at the moment when it attains its locally maximum value. Controlled nodes are then switched to the truss-like (hinge) mode for a very short time t_0, so that the structure remains only temporarily in the state of reduced global stiffness, but such a release of the kinematic constraint allows a part of the accumulated bending strain energy to be released into high frequency local vibrations. These local vibrations should be allowed to decay and dissipate the energy, and consequently the time t_0 should be within their timescale, but short in comparison to the global low-frequency vibrations that are subject to mitigation. In practice, the exact value of t_0 is not crucial, as the algorithm tends to stay similarly effective for a wide range of its values. The switching law for the nodal parameters α_i (control functions) can be presented as:

$$\alpha_i = \begin{cases} 0 & \text{at } \max(E_{\text{strain}}) \\ \alpha^{\max} & \text{otherwise} \end{cases} \tag{4}$$

Since the control strategy is fundamentally global, all nodes are controlled synchronously, so that all parameters α_i switch their mode of operation in the same moment.

3. Numerical Example

The control strategy was examined numerically with a frame model prepared using the Finite Element (FE) method. Such a model can be used in order to accelerate and facilitate, compared to the experimental method, the effectiveness of analysis at the initial design stages of the proposed system. The model was implemented using typical six DOF beam elements and rotational damper elements with damping coefficient treated as the control function and adjusted on demand. A proportional Rayleigh damping model was adopted with only the stiffness matrix taken into account. The proportionality coefficient was set to a typical level that ensures damping at 1% of the critical damping ratio for the first vibration mode.

In this work, the case of free vibrations is considered. The initial displacement conditions are used. They are set to either the first or the second natural mode. These low-order modes have the lowest natural (material) damping, and they are thus the most prone to prolonged vibrations and the most difficult to mitigate.

3.1 Semi-active Node Model

A dedicated approach is required in order to model the proposed semi-active nodes and integrate them within the finite element model of the larger controlled frame structures. The employed physical semi-active nodes work by means of the dry friction between two conical surfaces pressed against each other. The greatest convergence with the physical device would be achieved if the mathematical model took into account the interaction of friction surfaces by utilizing a dry friction model. However, this would significantly increase the level of the complexity of the model. The nonlinearity introduced with the dry friction would result in the increased analysis times and difficulties in applying the control algorithm. These inconveniences have led to an alternative solution, thanks to which the system remains linear during the entire analysis. Switching between the two opposite operation modes of the semi-active nodes is implemented with the on/off rotational damper with a variable damping coefficient. When the nodes are supposed to operate in their default frame-like state, the damping coefficients of the dampers are set to their large maximum value, which effectively results in an almost immediate blocking of the relative movement of the rotational DOF in these nodes, as required by eq. (1). If there is a need to change the mode into the truss-like one, the damping coefficients of the dampers are set to zero, which results in unblocking the relative movement of the involved rotational DOF. The exemplary frame model with the semi-active nodes represented in the proposed way proved to be a very good approximation of the pure frame numerical model [40].

The exemplary part of the structure presented in Fig. 1 can be represented as a FEM model in a way shown in Fig. 2.

Two beam elements (B_1 and B_2) with six DOFs each are connected in the semi-active node (middle) which consists of four, instead of the classical three, DOFs: two translational and two rotational. The DOF numbering is as follows:

- Translational DOFs: 1, 2 (left node), 4, 5 (center node), 7, 8 (top node).
- Rotational DOFs: 3 (left node), 10, 6 (center node), 9 (top node).

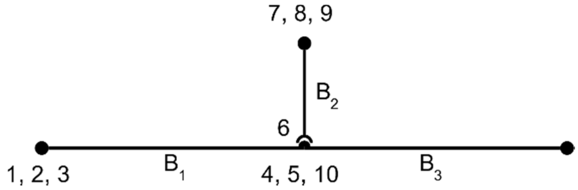

Fig. 2. FEM model of an exemplary beam system equipped with the semi-active node.
The numbers represent the numbering of the degrees of freedom (DOFs) and correspond to these shown in Fig. 1.

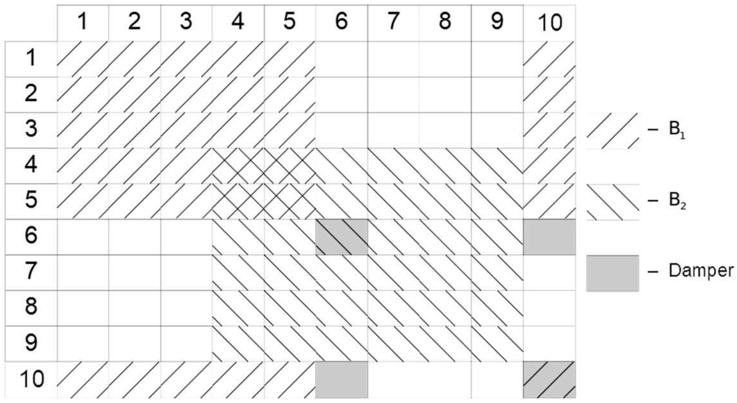

Fig. 3. DOF matrix of the two-beam system equipped with a semi-active node.

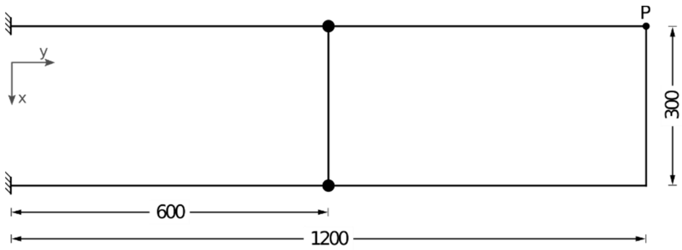

Fig. 4. Investigated frame structure with two semi-active nodes.

Introduction of the additional unaggregated rotational DOFs in the center node allows a truss-like type of connection (a hinge without the moment transfer ability) to be obtained, despite the fact that the finite elements used are of the beam type. Coupling of rotational DOFs 10 and 6 in the center node is achieved with a rotational damper, modeled with a simple damping matrix

$$\boldsymbol{C}_i = \boldsymbol{L}_i^{\mathrm{T}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \boldsymbol{L}_i \tag{5}$$

where $\boldsymbol{L}_i$ is the global-to-local coordinate transformation matrix of the ith damper, and which corresponds to the respective damping matrices in eq. (2). The coefficient α_i should be large enough to reliably model the kinematic constraint eq. (1) in transient simulations, but not too high so that the numerical stability is not undermined. In practice, any value from a wide range of at least 10^4 – 10^6 has been found to be appropriate. Finally, the DOFs of the beam B_3 shown in Fig. 3 are aggregated in the standard way with the DOFs 4, 5 and 10 of the beam B_1.

A graphical representation of the global matrix of DOFs for the beams B_1 and B_2 is presented in Fig. 3. The DOFs of beam B_1 are aggregated into the global DOF matrix in blocks which correspond to DOFs numbered 1–5 and 10, while the DOFs of beam B_2 are aggregated in blocks numbered 4–9. The additional damper matrix elements are arranged in the global matrix in positions corresponding to DOFs 10 and 6.

The described simplified model illustrates well the methodology used to simulate the behavior of the utilized semi-active node. Although it is an approximate solution, in the case of a dynamic analysis, it is a reasonable, effective and accurate representation of the transient behavior of the actual system.

3.2 Investigated Structure

The structure used for the analysis is presented in Fig. 4. It is a planar frame, fixed at the left end, with two vertical beams. One of the vertical beams is equipped with the discussed semi-active nodes at both of its ends, which is marked with black circles.

The beams have been divided into a total of 60 finite elements, grouped into various sections of distinct geometrical and material characteristics. These characteristics of the individual components have been selected in such a way that the numerical model best reflects the actual physical structure utilized for the experimental study in Section 4. The model includes the masses of the semi-active nodes and passive joints, mounting and sensing equipment, etc. Technical details are readily available upon request from the corresponding author.

A good fit between the numerical model and the experimental structure is confirmed by the closely matching values of the first three natural frequencies listed in Table 1. The third natural frequency is already comparable to the maximum operational frequency of the physical semi-active nodes (about 170 Hz). Therefore, the first two vibration modes are selected as the target modes to be mitigated and serve as the initial displacements conditions. Their shapes are presented in Fig. 5.

Table 1. Natural frequencies of the numerical model and the experimental structure.

	1st mode	2nd mode	3rd mode
Numerical frequency [Hz]	13.6	38.8	122.4
Experimental frequency [Hz]	13.6	38.8	125.4

3.3 Results

The application of the proposed vibration damping strategy in simulation of free vibrations has resulted in a significant reduction of the lateral displacements of the investigated frame for the first and the second natural modes. This result has been presented in Fig. 6 and 7 in the form of the displacements of frame tip (the representative point P) in the direction x, see Fig. 4.

In the case of the first natural mode, the frame displacements are mitigated almost completely within the first switching cycle of the semi-active nodes. Only a certain small residual displacement remains in the dynamic response until the end of the simulation, which is related to the fact that the nodes, after being unblocked, might be blocked again in a geometric configuration that is slightly different from the initial configuration. In the case of the second natural mode, the vertical displacements are mitigated in a less spectacular manner, but still very significantly, which confirms the effectiveness of the proposed approach.

Figures 6 and 7 confirm the effectiveness of the approach by comparison to the passive frame structure. Such a structure corresponds to the nodes fully blocked, which is represented by $\alpha_i = \alpha^{max}$ in eq. (4). A further natural baseline for comparison and assessment of the proposed approach is provided by operating the nodes at constant moderate levels of viscous damping, in-between the upper and lower bounds of 0 and α^{max} exploited in the PAR approach. The overall effectiveness can be globally quantified in terms of the total mechanical energy of the structure. Figure 8 plots the root mean square (rms) value of the total mechanical energy (computed in the considered time interval of 0 s to 1 s) in dependence on the constant damping coefficient α_i of the nodes. The corresponding rms values obtained for the semi-actively controlled structure are represented by the dashed horizontal lines of the respective colors.

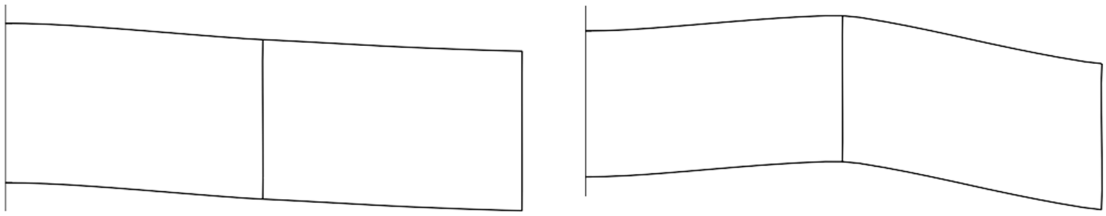

Fig. 5. First (left) and second (right) vibration modes of the structure.

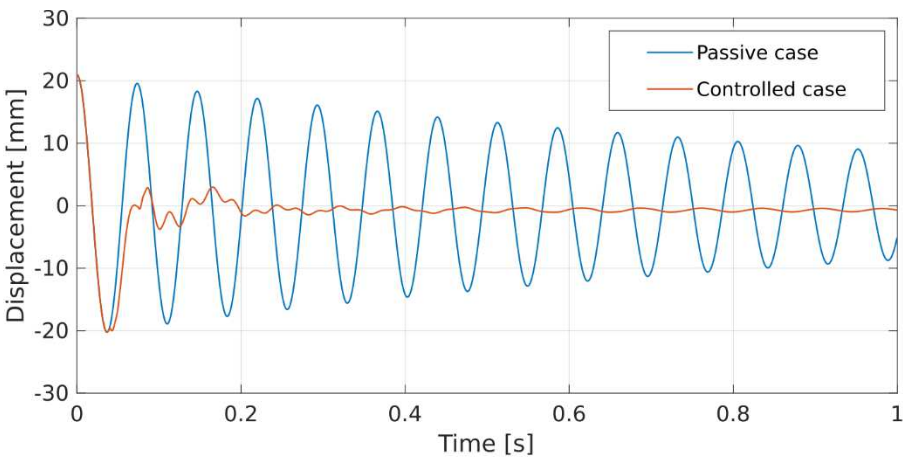

Fig. 6. Displacements of the frame tip (point P) along the x axis for the first vibration mode of the structure.

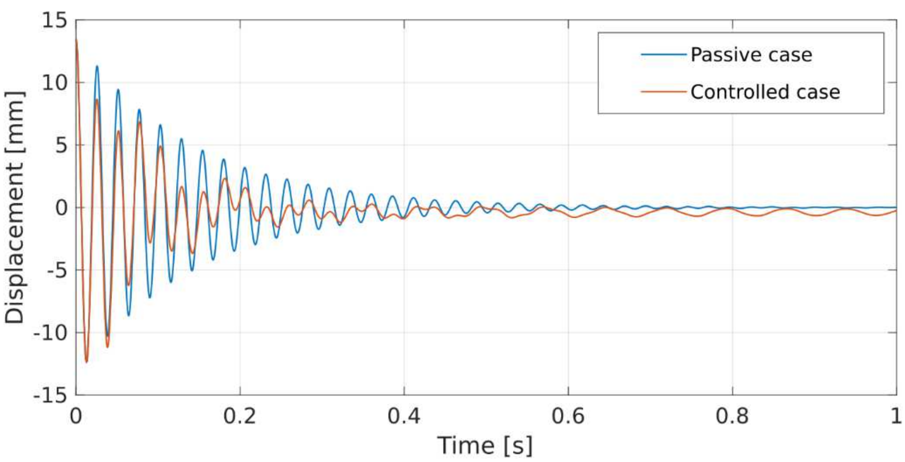

Fig. 7. Displacements of the frame tip (point P) along the x axis for the second vibration mode of the structure.

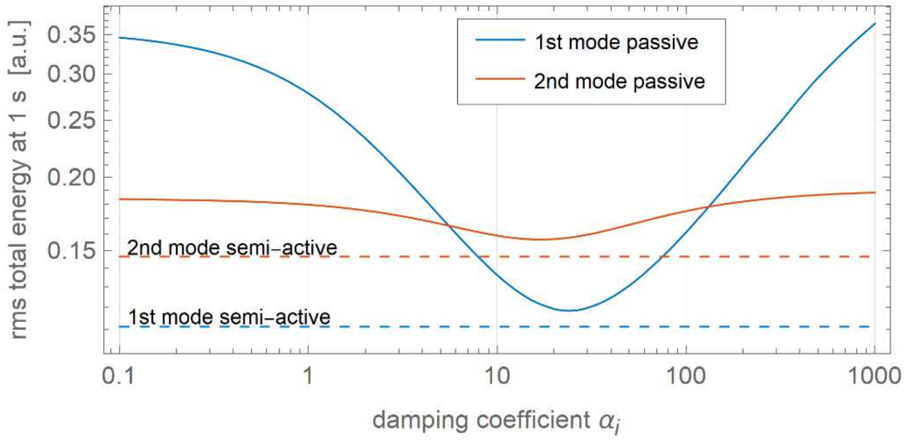

Fig. 8. Rms of the total mechanical energy of the passive structure.

Fig. 9. Ten segment frame structure. The location of the semi-active nodes is marked with bold dots.

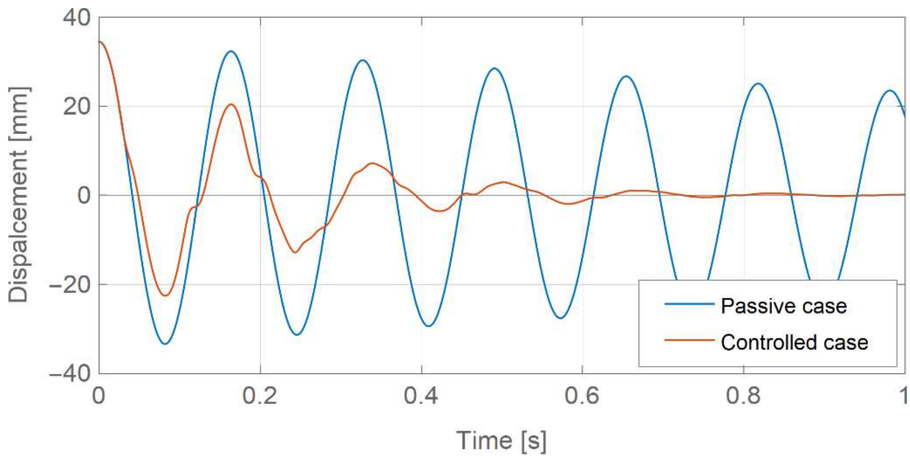

Fig. 10. Tip displacements of the 10-segment frame (point P) along the x axis for the first vibration mode.

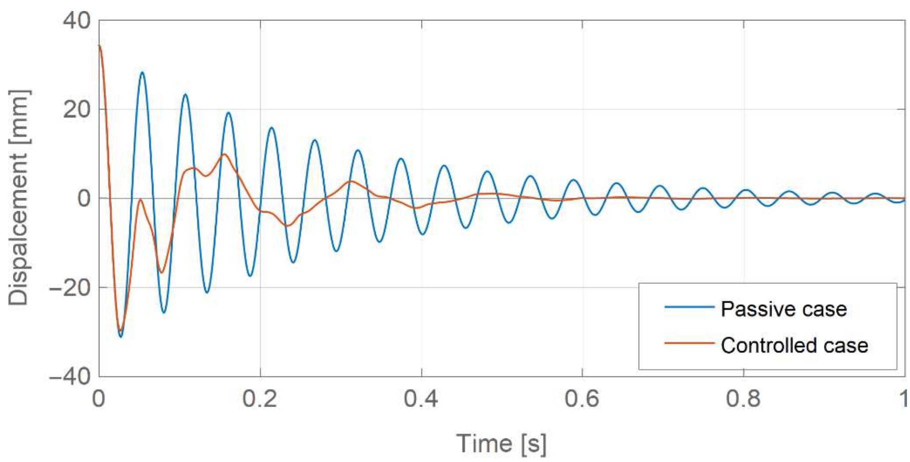

Fig. 11. Tip displacements of the 10-segment frame (point P) along the x axis for the second vibration mode.

The semi-active approach is more effective in the entire range of the damping coefficients and for both modes of vibration. The worst-case improvement in terms of the total energy rms is over 6%. Moreover, moderate levels of viscous damping in the nodes compromise the overall high effective stiffness of the frame-like structure (which is preserved by the semi-active approach), while being difficult to be precisely designed and maintained during the operation.

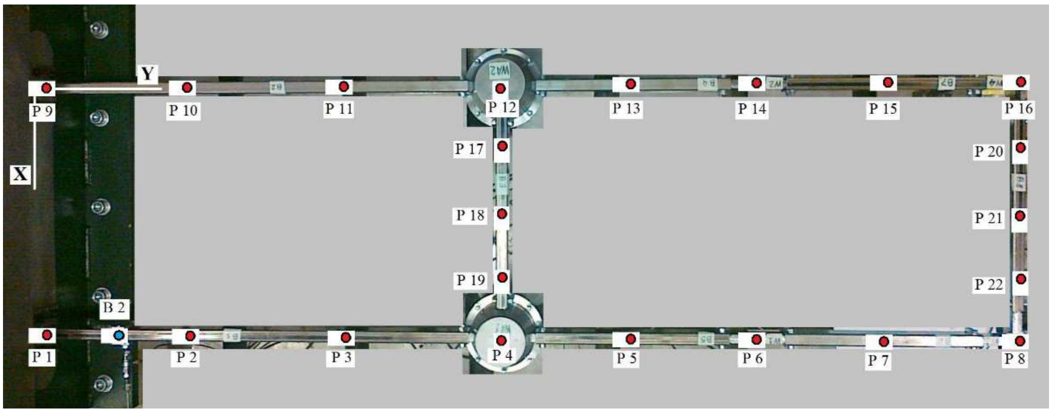

Fig. 12. Experimental frame structure equipped with two semi-active nodes.

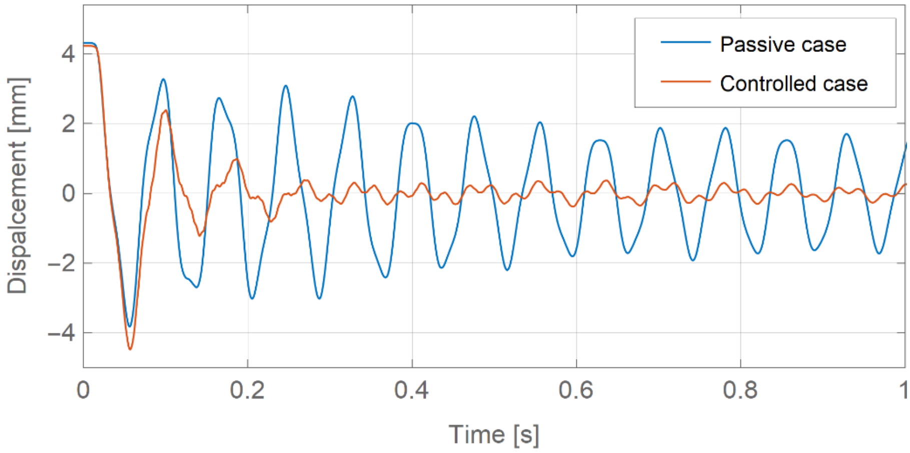

Fig. 13. Experimental displacements of the frame tip (point P16) along the x axis, see Fig. 12.

3.4 Verification Using a 10-Segment Frame

The approach was additionally verified numerically using a frame structure with a more complex, 10-segment geometry, see Fig. 9. The frame is modeled to be made of steel with the density 7850 kg/m^3 and Young's modulus 200 GPa. The beams are 1 mm x 1 mm in cross-section and each 0.1 m long, so that the dimensions of the entire frame is 1 m x 0.1 m. The semi-active nodes are placed pairwise on both ends of the leftmost vertical beam, as explicitly marked with bold dots in Fig. 9.

As in the preceding sections, the first two modes of vibration served as the initial displacement conditions. Due to the slenderness of the structure, these modes have the typical cantilever beam type shapes. The lateral displacements of the frame tip (point P) are plotted in Fig. 10 and 11 respectively for the first and the second mode. Each plot compares the displacements of the passive frame and the semi-actively controlled frame. Significant reduction of vibrations can be clearly observed.

4. Experimental Example

The control strategy was verified also experimentally, using a physical frame structure and a laboratory setup. The topology of the structure (top view) is presented in Fig. 12. It corresponds to the numerical model shown in Fig. 4. Main elements are steel box profiles with dimensions 15 mm x 30 mm x 2 mm.

In the physical laboratory structure, it is not possible to impose initial displacement according to the assumed mode of vibration. It was decided that a satisfactory approximation would be to impose a lateral initial displacement of the frame tip, that is point P16 (see Fig. 12), in the x direction, which corresponds to a mix of the first and the second natural mode. As a feedback control signal, an approximation of the total strain energy was used in the form of the data collected from a strain gauge located at point P15. It has been considered as a proxy for the potential energy of the frame.

The lateral displacements of point P16 were tracked with a fast camera and processed using Digital Image Correlation software. Such a procedure allowed very accurate results to be obtained, which are presented in Fig. 13. The participation of the first two eigenmodes can be observed in the passive response of the investigated structure. Despite the fact that the control system achieves the switching frequency of semi-active nodes below the third natural frequency of the structure, the high effectiveness of the proposed control approach is clearly visible. The vibrations are mitigated almost immediately after the first 2-3 switching cycles of the semi-active nodes.

The obtained experimental results are fully consistent with the results of the numerical calculations and confirm the high effectiveness the proposed control approach in damping of free vibrations in planar frame structures.

5. Conclusion

A two-phase energy management strategy has been developed for semi-active mitigation of structural vibration based on the principles of the Prestress–Accumulation Release (PAR) approach. The proposed strategy utilizes specially designed semi-actively controllable nodes. The global strain energy of the structure is considered as the feedback signal. In real life structures, obtaining an estimate of their total elastic energy is an onerous task, but the presented experimental research has shown that it is possible to use a certain proxy that yields very satisfactory results. Both the numerical and experimental analyses have proved a very high efficiency of the proposed approach in mitigation of the free vibrations in planar frame structures.

Author Contributions

B. Poplawski planned and executed the numerical investigations and prepared the original draft. G. Mikułowski planned, prepared and conducted the experiments. A. Orlowska consulted the numerical procedures and mathematical modeling, reviewed the original draft and examined the theory validation. Ł. Jankowski initiated and supervised the project and prepared the final manuscript. All authors discussed the results, reviewed and approved the final version of the manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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Nomenclature

x_i	Vertical displacement of the ith node (i=1,2,3)	α_i	Damping coefficient of the ith damper
y_i	Horizontal displacement of the ith node (i=1,2,3)	α^{max}	Maximum damping coefficient
θ_i, φ_i	Rotation at the ith node (i=1,2,3)	$\boldsymbol{u}(t)$	Structural displacement vector
$\boldsymbol{M}, \boldsymbol{C}, \boldsymbol{K}$	Mass, damping, stiffness matrices	$\boldsymbol{f}(t)$	Structural excitation vector
$\boldsymbol{C}_i$	Damping matrix of the ith rotational damper	$\boldsymbol{u}_0$	Initial displacement conditions
$\boldsymbol{L}_i$	Global-to-local coordinate transformation matrix for the ith damper	$\boldsymbol{v}_0$	Initial velocity conditions
		t	Time

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