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MITIGATION OF DYNAMIC RESPONSE IN FRAME STRUCTURES BY MEANS OF SMART JOINTS

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Abstract. This paper discusses passive and semi-active techniques of structural control by means of smart joints, and then it proposes a specific smart joints system for frame structures and tests its capability in mitigation of free vibrations. Basically, the proposed solution modifies frame beams by addition of truss-type hinges, and its effectiveness relies on the softening effect that occurs in compression due to geometric nonlinearities and which triggers the highly-damped high-frequency response modes of the structure. First, the finite element (FE) model of the specific frame structure with geometrical nonlinearities is derived, and the proposed passive joints are described and incorporated into the model. Then, their principle of operation and effectiveness is examined numerically for the first two natural modes of vibrations with various initial displacement amplitudes. An objective function is proposed to assess joints placement, based on the efficiency in mitigation of the excited vibrations.

1. INTRODUCTION

Mitigation of structure response is still an important and current research topic. Most papers are focused on vibration damping problems, both free [1-5] and forced [6, 15]. Nevertheless, absorption of impact loads is also the subject of an ongoing research [1,7]. Vibration damping techniques are generally divided into three groups: passive, active and semi-active. Passive solutions, which are the simplest and the most reliable, usually incorporate frictional, viscous or pneumatic dampers. For some applications, mainly in civil engineering, systems of tuned-mass-dampers (TMD) [16] and tuned-inerter-dampers (TID) [8] are applied. Also combination of both systems, TMD and inerters, are analyzed [9]. Another passive technique for suppression of structural vibrations relies on the introduction of initial stresses in the structure [10], which influence its natural frequencies and amplitudes. Active vibration suppression is often considered in the context of counteracting the effects of earthquakes or strong winds, which can be very dangerous for high-rise buildings [11]. Common practice in such cases is to use large hydraulic actuators for which the application of an appropriate control algorithm can lead to satisfactory results of energy absorption [12]. The best possible solution is often associated with active control and significant control forces, despite potential dangers appearing in case of the control system failure. In recent years a growing interest in semi-active vibration damping techniques can be noticed. Semi-active approach combines the advantages of passive and active systems. Well designed, they can be very reliable, even in case of power failure, and as efficient as active systems. They have been used in seismic tremors protection for many years [13] as a more trustworthy alternative to active strategies. They can also be applied to mitigate vibrations of vehicles suspension [14], frames and trusses [1-4] and other engineering structures.

The solution proposed here is based on the use of specific joints, selectively activated for identified excitation conditions in order to improve vibration damping effect. An important advantage of the proposed joints is that the mechanism of free vibration damping is purely passive. After activation of the joints, energy is dissipated passively but as soon as vibrations are suppressed, joints are deactivated and the structure turns again into its basic frame configuration.

2. DAMPING OF FRAME FREE VIBRATIONS WITH SMART JOINTS

The discussed novel technique of free vibration damping was developed in the Institute of Fundamental Technological Research, Polish Academy of Sciences, and it is discussed here using an exemplary case study. The main advantage of such solution is its passive operation and the ability of adaptation to the excitation conditions. Moreover, dissipation in the excited structure, both in case of activated and blocked joints, is realized by the mechanism of structural material damping without additional dampers. The proposed smart joints in the activated mode do not transfer any moment between the neighboring elements. In the inactive mode, they do not modify the typical frame connection between the frame elements.

The subject of analysis is the frame structure presented in Fig. 1. The structure is equipped with proposed joints that enable modification of the effective global stiffness of the structure. In case of free vibrations, joints are activated and additional rotational degrees of freedom are added to the nodes, which turn in this way into hinges (no transmission of moments). The effect is the nonlinearly decreasing effective bending stiffness in the involved part of the frame and excitation of higher modes which are efficiently mitigated by structural material damping. An important issue to be considered during the placement of the smart joints is not to change the structure into a mechanism. Moreover, the temporary effect of weakening of the structure should be taken into account, too.

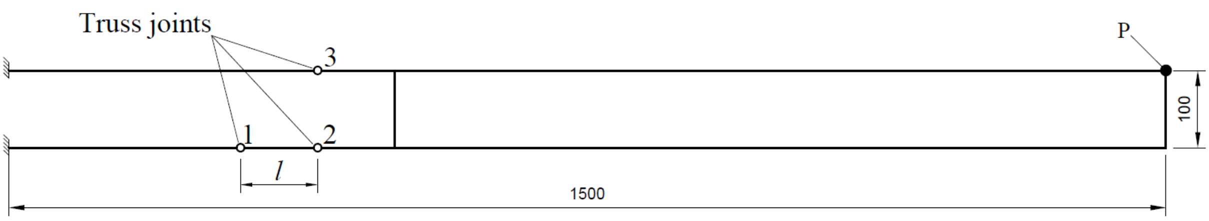

Figure 1. Scheme of the analyzed structure (dimensions in [mm])

The effectiveness of free vibration damping in frame structures is assessed by means of the assumed goal function, which in the present case study was defined as the time integral of the global potential structural energy:

$$I = \int_{t=0}^{t=1s} \left(\frac{1}{2} \boldsymbol{x}^{\mathrm{T}} \boldsymbol{K} \boldsymbol{x} \right) dt \tag{1}$$

Additionally, other quality indices or constraints can also be considered. For instance, an important factor is the amplitude of displacements of the point in the structure with the highest vibration amplitude. Optimal values of the selected goal function (1) not always go together with the mentioned criterion.

3. NUMERICAL ANALYSES

The free vibration dynamics of the frame structure presented in the previous section is described by the typical equation of motion:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{0} \tag{2}$$

The structure was divided into 128 beam finite elements of the same length. The smart joints were modeled by uncoupling the rotational degrees of freedom between the neighboring elements. The damping matrix $\boldsymbol{C}$ was composed of the coefficients described by the Rayleigh model of damping. Because of the geometric nonlinearity introduced by the smart joints, nonlinear analyses were performed for all simulations. The differential equations of motion were integrated using the Newmark method combined with the iterative Newton scheme for update of the stiffness matrix.

A number of numerical analyses was performed to examine the effectiveness of the proposed solution (in terms of the assumed goal function) and to find the optimal placement of the smart joints in the structure. Placement of the joints was considered only in the left section of the frame because of the longitudinal deformations that occur in this area and which are needed to achieve a better vibration damping by implementation of proposed joints system. Simulations included initial displacements corresponding to the first and the second mode of structural vibrations, each of three different amplitudes (small, medium and large). Tab. 1 compares the values of the goal function for the structure without the smart joints and the structure with selectively placed joints.

Table1. Goal function values [$\cdot 10^{-3}$] for the original frame structure and the structure enhanced with the proposed smart joints: (1) original frame structure, (2) best joints placement, (3) worst joints placement

No of mode	**Small initial displacement**			**Medium initial displacement**			**Large initial displacement**		
	1	**2**	**3**	**1**	**2**	**1**	**1**	**2**	**3**
1	1.3	0.35	1.2	8.2	2.6	7.8	49.6	30.8	48.2
2	1.5	0.71	1.2	11.4	8.4	10.4	428.8	412.3	512.4

Optimization of joints placement in the structure in relation to the goal function was defined as a search for the optimal position of the first joint and the distance to the second joint (length *l* of the truss element). In Fig. 2. and Fig. 3., the values of the goal function normalized with respect to the value obtained for the original structure without any joints are presented. The graphs shown in Fig. 2. present maps of the normalized goal function for different amplitudes of the initial displacement conditions in the case of the first vibration mode. The optimal position and length of the truss rod can be specified based on these maps. The advantageous effect of the smart joints related to the introduced geometrical nonlinearity in the structure is easily seen. Effectiveness of the solution decreases with the increase of the initial displacements amplitude but even then the values of the goal function are considerably lower than the values obtained for the original structure.

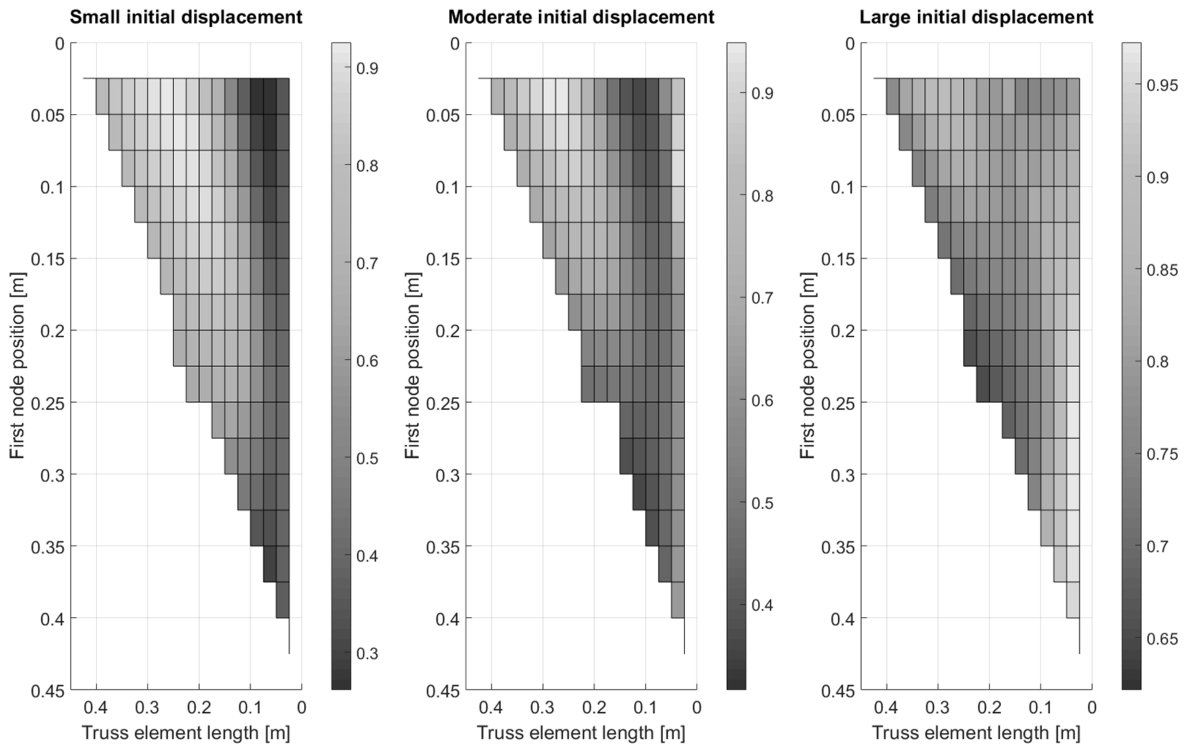

Figure 2. Values of the goal function depending on the position of the first joint and on the length of the truss element for different initial displacements of the entire structure (mode 1)

For small and moderate initial displacement of the structure, the smart joints should be placed in short distance to the fixed end or in the proximity of the vertical beam. For a large initial displacement, the first joint should be placed near the middle of the left section of the structure and the second joint in the proximity of the vertical beam.

Analogous graphs for the case of second mode excitation (initial displacement) were shown in Fig. 3. The effectiveness of the smart joints for the second mode of structural vibration is lower than for the first mode. However, for small and moderate initial amplitudes of the free vibrations, the proposed solution is definitely advantageous. The values of the goal function suggest that the beginning of the truss rod (the first joint) should be placed near the fixed end of the structure for all analyzed initial conditions.

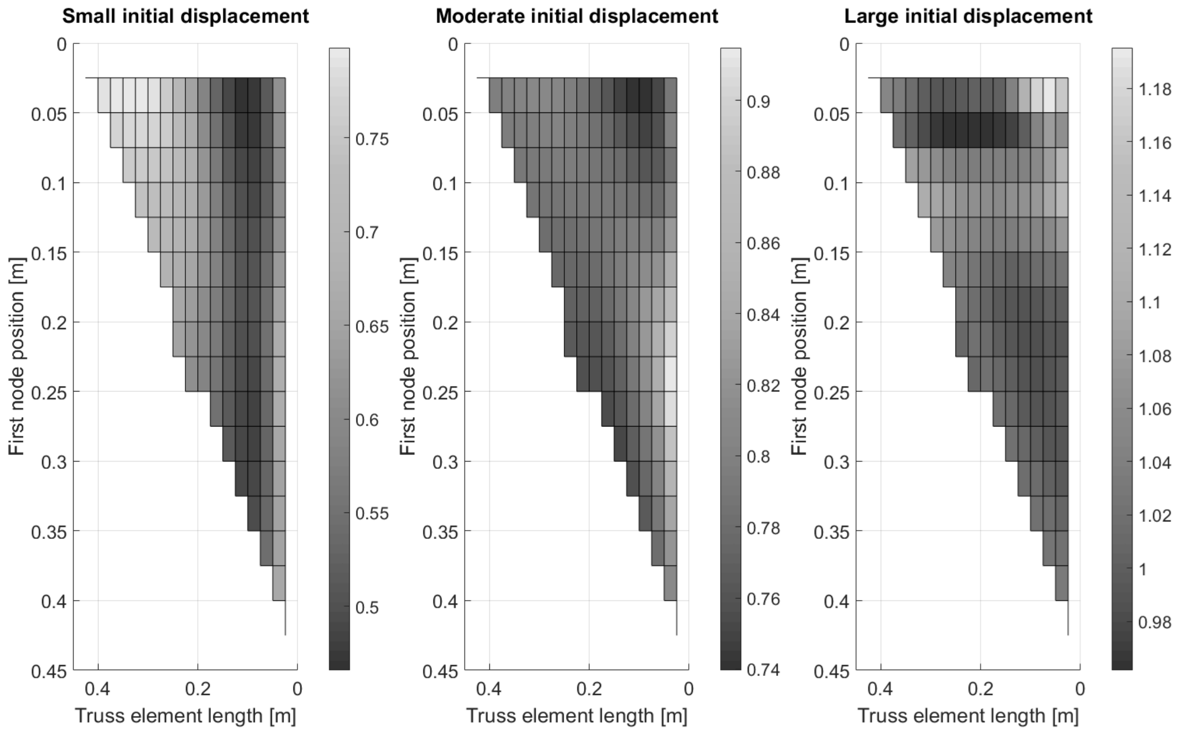

Figure 3. Values of the goal function depending on the position of the first joint and on the length of the truss element for different initial displacements of the entire structure (mode 2)

In Fig. 4, the time history of the vertical displacement of point P is shown (small initial displacement, mode 1). Despite the fact that the use of the smart joints is efficient in terms of the goal function (integral of the global potential energy) also for the worst placement of the smart joints, for the worst placement the vibration of point P is less damped than in original construction.

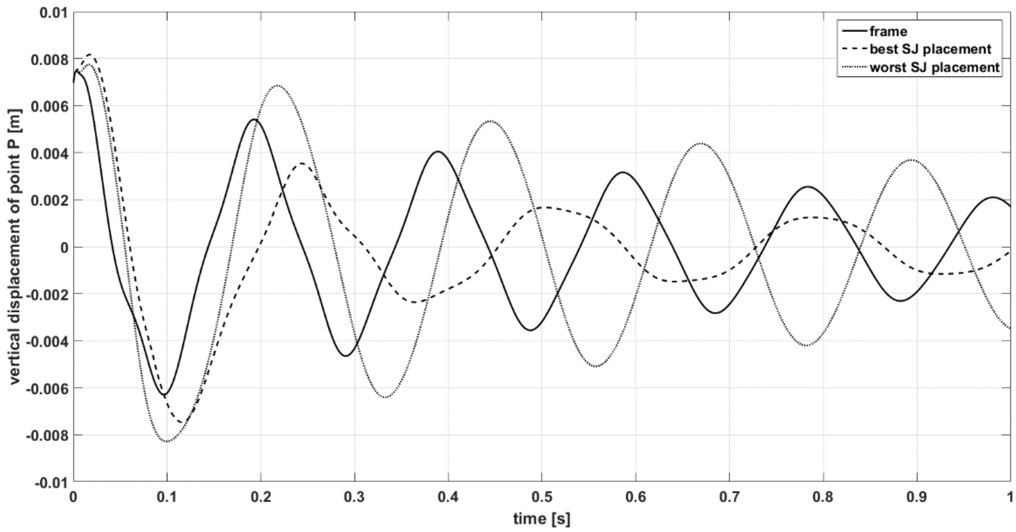

Figure 4. Vertical displacement of point P for small initial displacement of the structure (mode 1)

According to the numerical analyses, an adaptable scheme of smart joints usage can be proposed by activation of selected joints according to the identified load conditions. It allows to achieve an adaptable, passively operating system with enhanced damping capabilities. After suppression of vibrations, the smart joints should be deactivated so that the structure retrieves its original stiffness.

4. CONCLUSIONS

In this contribution, smart joints were proposed as a passive-like solution for free vibration damping. Nonlinear FEM analyses were conducted in a selected case study to present the potential of the proposed technical solution. Search of optimal placement of joints was performed based on the assumed goal function and an additional quality index was evaluated. Proposed solution ensures improvement of global damping capabilities of frame structure for variety of the initial structure displacement conditions. The advantageous effect is more significant for modes of structural vibration in which large longitudinal displacements appear. System of smart joints presented in the paper can be used in structures which are not subjected to the static lateral loads.

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