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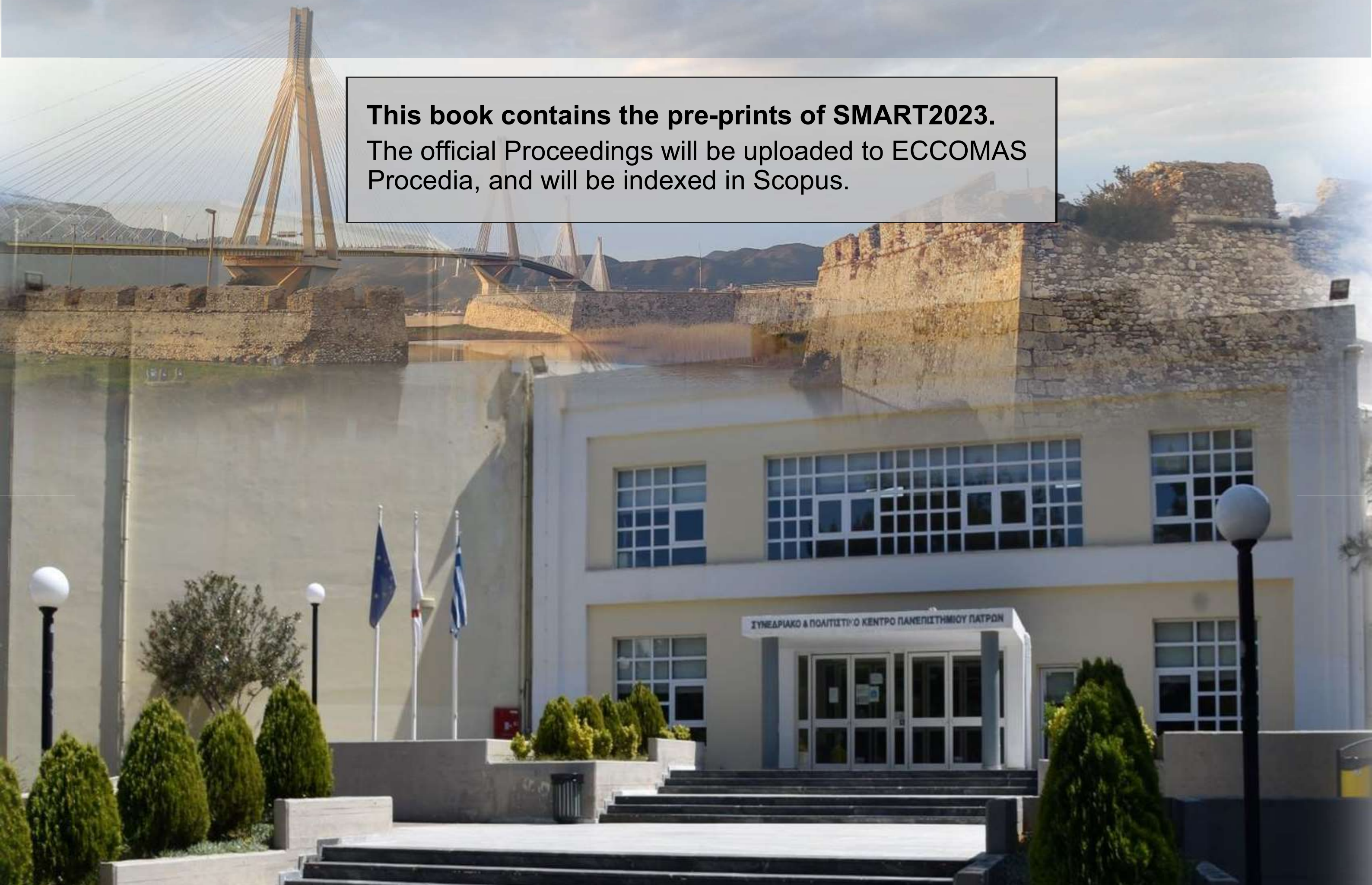

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EXPERIMENTAL VERIFICATION OF A SEMI-ACTIVE MODAL CONTROL ALGORITHM FOR STRUCTURES WITH LOCKABLE JOINTS

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Abstract. In this study an experimental program for verification of modal control algorithm for semi-active structures is proposed. The considered control approach assumes redirecting of mechanical energy between vibrational modes. The presented research is focused on development of an investigation method that would allow for demonstrating the control concept. Moreover, a suitable flexible structure equipped with semi-active elements is introduced. The proposed laboratory structure is a flat slender frame equipped with a set of six joints. A deliberate design of the joints provides a feasibility for a controllable transfer of the bending moments between chosen adjacent elements of the frame.

Such a structure delivers a possibility of real-time modification of its local bending stiffness and therefore can be categorised as semi-active. The investigation covers identification of the modal parameters of the laboratory model, implementation of the control algorithm on an FPGA processor, providing a testing program that exemplifies the process of energy management between the eigenfrequencies. The results reveal that the response of the semi-active structure reflects the derived control algorithm assumptions.

To sum up, the modal control algorithm based on real-time monitoring of the structure's modal parameters is experimentally implemented and verified in a laboratory environment.

Key words: vibration control, semi-active, modal control, experimental verification, lockable joints

1 INTRODUCTION

Vibration mitigation and control is an important and still valid issue in engineering structures even if it is being considered for decades now. Contemporary progress in the material sciences and new configurations of slender structures provide new challenges in this field. One of promising and intensively developed methods for the vibration control is semi-active approach. The approach is characterized by adaptable modification of the inherent mechanical properties of the structures (i.e. stiffness, damping or inertia) in order to withstand the current operational conditions. The semi-active techniques are considered as comparably effective to active methods but operating exclusively in a dissipative mode, which provides an unconditional stability. Moreover, the semi-active systems require minimized amount of energy for operation, which make them more feasible and more attractive for wide class of implementations [1].

Semi-active devices controlled by suitable algorithms proved their efficiency both in researchers' studies and practical applications. One of examples is a switching oil damper developed along with dedicated control law by Kurino et al. [2]. Strategy devoted to light-weight frame structures was proposed by Gaul et al. [3]. In this case friction-based semi-active joints were employed. They were controlled with two algorithms: local feedback and global clipped-optimal feedback.

Despite the efficiency of semi-active control strategies usually they are based mainly on local energy dissipation mechanisms inside the controlled devices. Recently developed control strategies based on the transfer of the mechanical energy from the lower-order to the higher-order vibration modes allow to avoid this limitation. The low-frequency vibration modes usually are weakly damped. Hence, switching of the structural vibration into the high-frequency vibration modes allows to take advantage of the associated material damping. It results in quick dissipation of the energy in the entire volume of the structure due to natural mechanisms of dissipation. A semi-active control strategy allowing "switching" between vibration modes was proposed by Holnicki-Szulc and called "prestress-accumulation release" (PAR) [4]. Later, this strategy was developed to be realized with semi-actively lockable joints that depending on the control signal can transmit the bending moment between connected structural members or can be unlocked and work as a hinge [5]. This strategy is based on the fact that the vibrating structure accumulates strain energy during its deformation. When this energy achieves maximum level the joints are unlocked for very short time interval and later immediately locked again. This causes releasing of the accumulated strain energy into vibration in high-frequency oscillations resulting effective energy dissipation in the inherent material damping. Despite its effectiveness PAR control utilizes only the information from the strain gauges in the vicinity of the lockable joints. It can cause sensitivity to local maximums of the strain energy resulting in redundant joint unlocks. Recently, Ostrowski et al. proposed modal approach that employs information about global state of the system carried by the estimates of the modal velocities [6, 7]. In this approach, at the expense of additional sensors required for modal filtering, better performance is achieved along with lower number of joint unlocks, which causes their lower operational wear. Due to additional information in the modal approach it is also possible to pursue the priority on vibration modes to be mitigated first. Moreover, the transfer of the mechanical energy from currently excited modes to the preselected one is possible that has application in energy harvesting.

Modal approach for the transfer the energy to the higher-order vibration modes was evaluated only numerically in works [6, 7]. Thus, the present study describes the experimental validation of the proposed control strategy and focuses on the issues of the hardware and signal-processing limitations as well as assessment of the control performance under laboratory conditions.

2 INVESTIGATION CONCEPT

The investigation concept assumes utilization of a laboratory stand for purpose of the modal control approach demonstration. In general the stand is a slender frame, supported in a cantilever configuration, equipped with six lockable joints that enable a controllable transfer of bending moments between adjacent beam members (Fig. 1). The investigation's primary objective is to assess the modal control approach feasibility. The features of the concept are the sensors' arrangement, modal parameters determination, data conditioning and the algorithm feasibility under forced vibrations excited with a modal shaker.

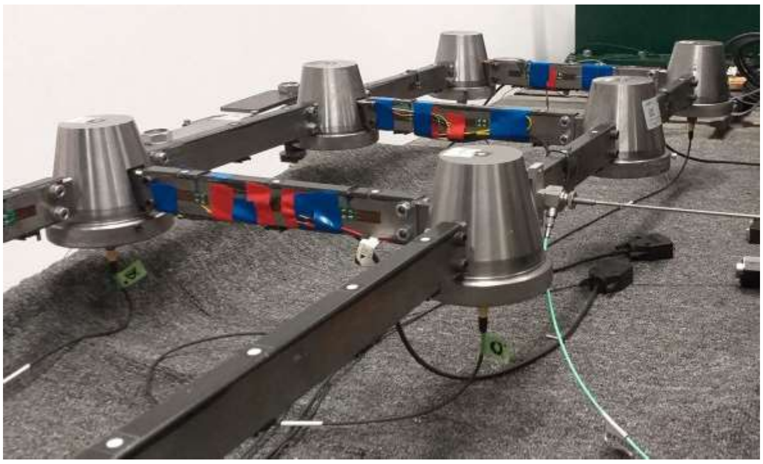


Figure 1: Demonstration stand with six lockable joints

2.1 Sensors location on the frame.

The proposed control strategy employs modal velocities of first several vibration modes. It requires, at least, as many sensors to monitor structural velocities at specified points, as vibration modes to be monitored. Selection of the sensor locations is crucial for the quality of the modal velocities estimation. Proper selection of the sensor locations allows for reduction of the measurement spillover effect that can result in destabilization of the system in purely active control approaches, whereas in semi-active control it can degrade control performance [8].

The widely accepted criterion of the optimal sensor placement is maximization of the determinant of the Fisher information matrix (FIM) [9]. This criterion provides a trade-off between the biggest values of mode shapes at sensor locations and the linear independence of the resulting vectors. This requires known mode shapes, e.g. from finite element (FE) model. Selection of the sensor locations among candidate sensor locations is usually discrete combinatorial problem. Moreover, the number of candiate sensor locations usually is large due to sophisticated FE models currently used. Hence, dedicated approach to select optimal locations is required to reduce the computational effort. In this work a method based on the convex relaxation of the discrete combinatorial problem into its countinous counterpart is adopted [10].

In the present study the first three vibration modes of the structure are to be monitored. Thus, three sensor locations for monitoring of the structural velocities are to be selected. To this end, the first three vibration modes calculated from the FE model for the joints in the unlocked state are considered (see: Figures 2a-c). Sensor locations optimal with respect to the determinant of FIM are very close to these shown in Figure 2d. These sensor locations are finally selected due to practical reasons such as the fact that circular surfaces of the joints are normal to the measurement direction. It is visible that vectors that could be formed from mode shapes at sensor locations represent biggest structural displacements and are linearly independent.

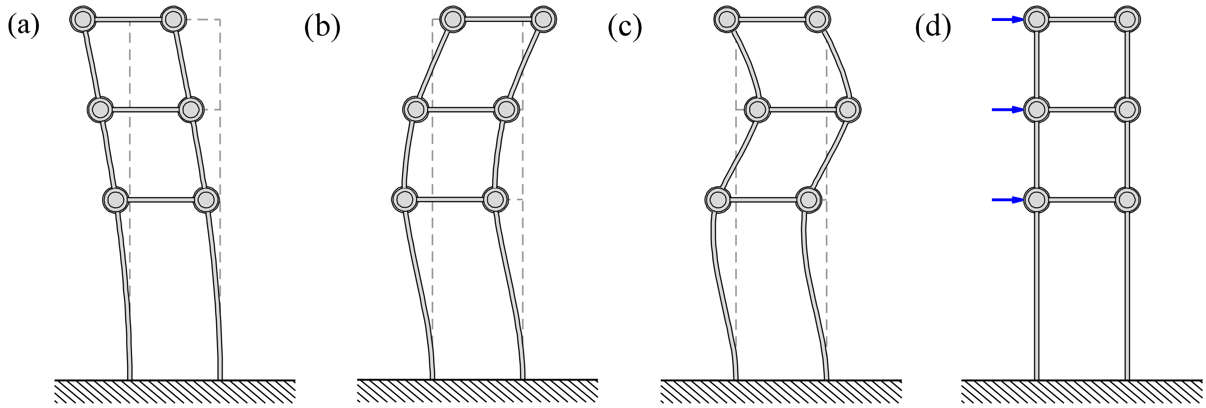


Figure 2: (a-c) first three vibration modes calculated form the FE model for the unlocked state of the joints and (d) indicated sensor locations for modal filtering

2.2 Modal velocities determination

A suitable technique of structural velocities measurement at the selected locations (Fig. 2d) are adopted. The measured structural velocities are consequently transformed to the modal velocities as described in [6, 7]. Two types of sensors have been taken under consideration for this purpose: piezoelectric accelerometers and laser triangular sensors. Each of them is characterized by advantages and limitations when considered for this particular application.

The advantage the accelerometers is that they provide an absolute measure and they require no fixed reference location. Therefore, they can be mounted directly on the structure. Moreover, obtaining the velocity from acceleration signal requires its integration. In this case, the signal to noise ratio parameter of the integrated signal is kept high, which is an important advantage. However, the time integration process requires an initial condition, which is difficult to determine in real-life operating conditions.

On the other hand, laser sensors provide a displacement signal that is referenced against an external fixed position. Such an adequate fixed position is not always available. The most important advantage of the optical technique is its non-contact nature, which consequently adds no mass to the tested structure. The displacement signal requires differentiation in order to receive a velocity at the point. The differentiation operation demands no initial condition to be calculated but the procedure amplifies disturbances in the resulting signals, which often is a profound problem when using them as inputs for digital controllers.

In the presented setup the laser displacement sensors are utilized since in the laboratory conditions the reference position is obtainable and a specific signal conditioning operation can be applied in order to adopt the signal as the input for the digital modal controller.

2.3 Experimental modal parameters identification

The experimental modal identification procedure is essential in order to determine the control parameters for the modal controller. The identification process has been conducted with a classical modal analysis methods with modal hammer and modal shaker excitation. Nine in-plane modal forms and corresponding modal parameters are identified. With their use a numerical model of the frame is fitted and its parameters identified. The identified numerical model served as a basis for determination of a set of control algorithm parameters dedicated to the particular case of the experimental demonstrator. The identification method has been introduced in publication [11].

3 EXPERIMENTAL STAND AND METHODS

3.1 Test stand details

The test stand is a slender frame mounted in a cantilever configuration to a stiff foundation presented in Fig. 3. The dimensions of the frame are 1200 mm in length and 300 mm in width. The longitudinal elements of the frame are connected perpendicularly with three transverse elements – connecting beams. The cross section of the utilized beam elements are 15 x 30 mm rectangles with the 2 mm wall thickness. The lockable joints allow for controlling the transfer of local moments between the longitudinal and connecting beams. The transfer of the moments along the longitudinal members is continuous and uncontrolled by the lockable joints. The lockable joints allow for obtaining two states of operation: locked when the moments' transfer is increased and unlocked when the transfer is significantly reduced.

Figure 3: Test stand layout

At the present stage of the research only one pair of the lockable joints is controlled, whereas the remaining ones are continuously locked. The pair of the lockable joints, placed at the end of the structure, is selected to be controlled due to the fact that all first three monitored vibration modes are well-controllable by these joints. In other words this beam transmits significant bending moments in all three vibration modes.

3.2 Experimental system instrumentation

The demonstration frame has been prepared in order to conduct tests of the control algorithm in the presence of harmonic excitation. The harmonic excitation is chosen as a basic testing excitation type that is demanded for verification of the proposed algorithm.

The frame is instrumented with the following set of equipment:

- three displacement laser sensors Baumer OADM-2016 characterized with 10 μm linear resolution. The sensors are configured to monitor displacements of three joints in transversal direction (Fig. 2d),
- two pairs of strain sensors mounted on the third connecting beam measuring local bending,
- force sensor fixed in the driving point and collocated with the modal shaker stinger (Fig. 3).

3.3 Experimental modal identification

The experimental structure chosen for the tests has been identified via a classical modal analysis. The analysis is conducted in spacial resolution 150 mm along the beam members of the frame, which results in 41 measurement locations for three-directional accelerometers. The structure is analyzed in the frequency range from 1 Hz up to 800 Hz. The modal parameters are determined in 3D (in-plane, out-of-plane and tortional modes) but in the consequent step nine in-plane modes are extracted for further analysis. The nine mode shapes are further utilized for the numerical model parameters identification. Figure 4 depicts the identified in-plane mode shapes with the corresponding frequencies. Although the proposed control algorithm is aimed at monitoring of the three mode shapes characterized with the lowest frequencies, the nine modes are necessary to be determined for a correct numerical model parameters identification.

4 RESULTS AND DISCUSSION

The presented control algorithm is designed for transferring vibrational energy from the low-frequency vibration modes to the higher ones. The objective of the control operation is to mitigate the vibration in the lower frequency range, which is the most difficult in damping by classical means. The algorithm assumes transfer of the vibration energy to the higher-frequency range and utilization of natural damping mechanisms in the structural material.

The tested algorithm is configured to monitor the dynamic state of the complete frame by the displacement signals acquired at the three joints connected to the beams and monitoring of the bending moment transmitted by the controlled lockable joints by means of two pairs of strain gauges located on the third beam.

The laboratory tests are aimed at determination of the demonstrator response to a continuous harmonic excitation in passive and controlled modes of operation. The frequencies of the excitation are 9,5 Hz and 9,8 Hz. The first value corresponds to the first eigenfrequency of the frame with the controlled joints in the unlocked state. The second value is the first eigenfrequency of the frame in a state when all the joints are locked. The unlocking of the

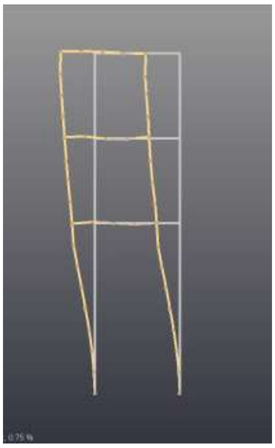
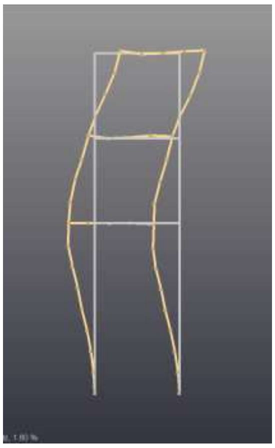
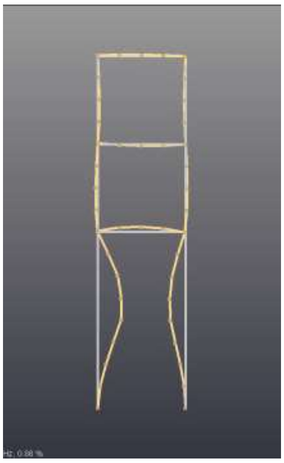
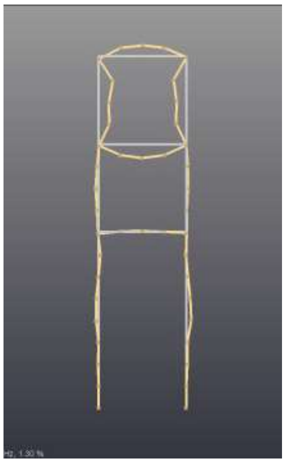
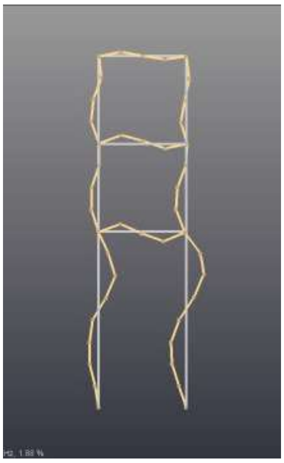
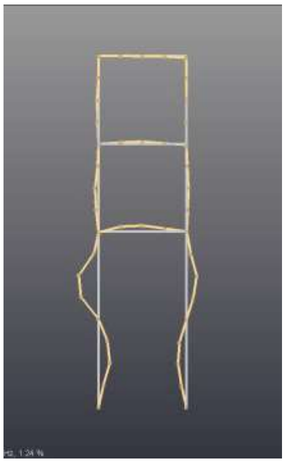
		
9.8 Hz	35.93 Hz	74.73 Hz
		
227.97 Hz	248.2 Hz	311.76 Hz
		
322.85 Hz	612.84 Hz	765.17 Hz

Figure 4: Identified in-plane mode shapes and eigenfrequencies joints results in decrement of the eigenfrequency of the frame due to the fact that effective stiffness of the structure is reduced within the process.

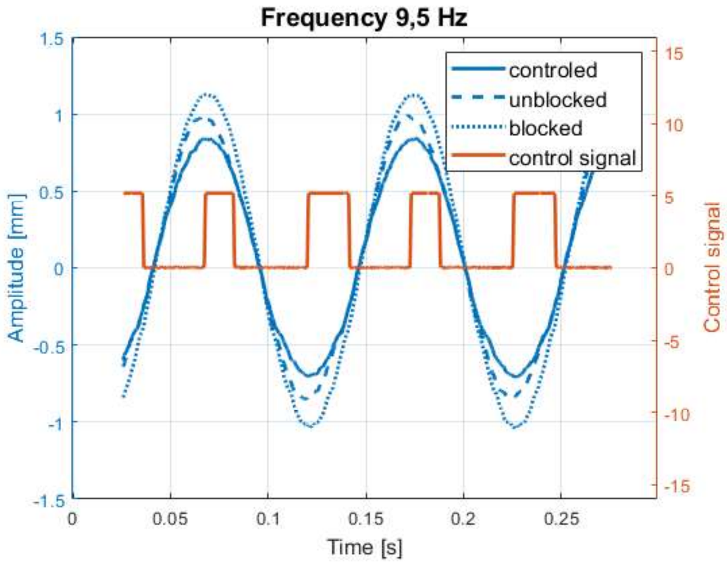


Figure 5: Time response of the demonstration frame at 9,5 Hz excitation frequency

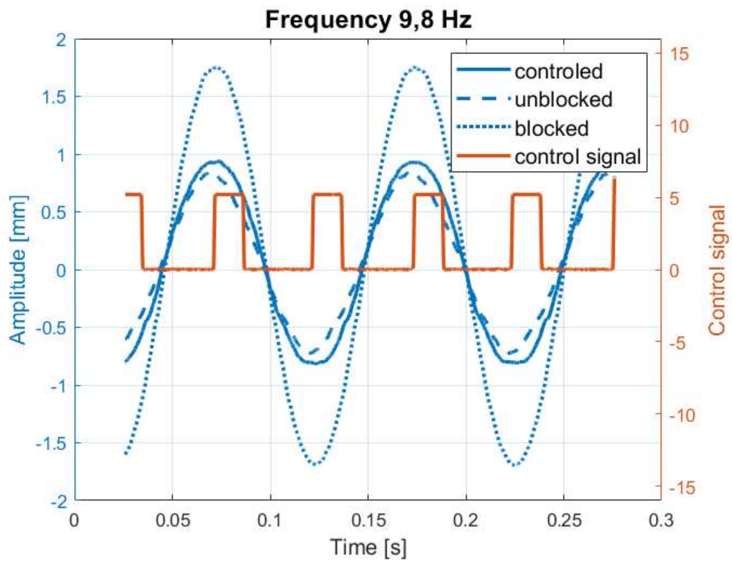


Figure 6: Time response of the demonstration frame at 9,8 Hz excitation frequency

The effectiveness measure applied to assess the algorithm is defined as the amplitude of transverse in-plane vibration of the third-level connection beam. The corresponding amplitude is measured with the laser displacement sensor as it is introduced in the instrumentation section.

Figures 5 and 6 present time histories of the frame at harmonic excitations 9,5 Hz and

9,8 Hz, respectively. The presented plots depict the displacements at the point of measurement in three modes of operation: 1. passive with locked joints, 2. passive with unlocked joints, 3. semi-active with joints controlled. Additionally, corresponding histories of the control signals are presented on the right axes. Low level of the signal means that the joints are in the locked state, whereas the high level means their unlocked state.

The results demonstrate that the introduction of the control strategy allows for obtaining reduction in the amplitude of vibrations. In the case of the 9,5 Hz excitation the reduction is 26 % whereas for the case of 9,8 Hz the reduction of the amplitude is 47 %. The difference between the control effectiveness for the two tested frequency variants might be related to differences in the dynamic response of the two analyzed cases. The results of the passive tests for both locked and unlocked modes of operation differ between each other due to modal characteristic of the frame. The switching between the modes of operation results in shifting of the dynamic characteristic of the frame (e.g. eigenfrequencies, dynamic stiffness).

An important observation can be drawn from the plots in Fig. 6. That is the passive unlocked mode of operation apparently exceeds the controlled mode result in the effectiveness aspect. The effect is related to the above mentioned dynamic characteristics shifting. In the unlocked mode of operation, the frame response is shifted out of the resonance what additionally reduces the amplitude. Therefore, it should be taken into consideration that the dynamic stiffness parameter of the locked and controlled frame is kept constant as revealed in [12] and those two results should be treated as meaningful in the analysis. Therefore, the measured 47 % in reduction might be considered as the respective effectiveness of the method in this example.

5 CONCLUSIONS

The presented work analyses effectiveness of modal control algorithm adopted to a planar frame equipped with lockable joints. The study reveals that the proposed method is able to reduce a forced harmonic vibrations in the range of low frequencies, which is the most demanding range from the point of view of vibration control. The tests revealed that the reduction efficiency might be up to 47% of the measured displacements in the considered case.

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