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DECENTRALIZED DAMPING OF VIBRATIONS IN 2D FRAME STRUCTURES USING CONTROLLABLE NODES

B. Poplawski[a*], G. Mikułowski[a], A. Mróz[b] and Ł. Jankowski[a]

[a] Institute of Fundamental Technological Research, Polish Academy of Sciences
Pawińskiego 5B, 02-106 Warsaw, Poland
e-mail: bpop@ippt.pan.pl, gmikulow@ippt.pan.pl, ljank@ippt.pan.pl

[b] ADAPTRONICA Sp. z o.o.
Szpitalna 32, 05-092 Łomianki, Poland
e-mail: amroz@adaptronica.pl

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Abstract. Extensive research efforts have been recently devoted to semi-active structural control [1, 2] with its paradigms of smart self-adaptivity and low consumption of energy, which is used for local adaptation rather than to generate external control forces. Considered application areas include adaptive landing gears, seismic isolation systems, vehicle-track/span systems, power train electro-mechanical systems, damping of flexible space structures, vehicle crashworthiness, arctic engineering, wind turbines, etc. A part of the research concerns semi-active management of strain energy for damping of structural vibrations. Early works considered truss structures with stiffness-switched bars [3]. They later evolved into either standalone one degree of freedom stiffness-switched dampers and isolators [4] or investigations in triggering modal energy transfer to highly-damped high-order modes, see, e.g., [5, 6]. The latter researches seem all to study the fundamental vibration mode of a cantilever beam with two detachable layers and differ mainly in the actuator technologies; the main idea is to employ actuators for a quick release of the vibration-related strain energy. This research extends the problem to general 2D frames. Controllable truss-frame nodes are incorporated into the structure. Thanks to their controllable ability to transmit moments, they allow for a quick transition between truss and frame modes. We propose a new, decentralized, closed-loop control strategy based on local energy measures. Vibration damping is more effective than in the previously studied control scheme based on a global energy measure, especially for higher vibration modes. Mitigation of vibrations will be presented in representative numerical examples, including a comparison to the global energy-based control strategy. Finally, results of experimental study, conducted on a structure analogous to the one from numerical simulations, will be demonstrated.

1 INTRODUCTION

Semi-active control techniques, utilized in damping of structural vibrations, proved to be very effective in numerous applications. Research areas of semi active systems are extensive and contain such fields as earthquakes protection [7], mitigation of vehicles suspension vibrations [8], adaptive landing gears [9], widely understood shock and vibration protection [10] or space structures vibrations damping [5]. The advantages of semi-active systems, compared to passive or active methodologies, can be treated as an explanation for the growing number of scientists conducting research in this area.

Passive vibration damping systems are used in engineering for many years because of their simplicity of operation. They passively produce reaction forces, in response to excited movement of the structure, which cause vibrations to decay. Their advantage is the passivity, which determines the aforementioned plainness of design and application. Passive damping systems can be optimized for a specific structure in a relatively easy way. They do not require any sensors, controllers or external power supply. The basic flaw of passive systems arises from their inability of adjustment to different excitation conditions. This is often the reason why these methods of vibrations damping cannot be effectively applied in demanding applications.

Active control systems are the subject of research in not much less extent than passive systems. Their popularity is associated with the great efficiency of vibrations damping, with which they are identified. Most often they consist of large hydraulic actuators attached to crucial structural elements, system of sensors and a controller, which, thanks to appropriate control algorithm, can cause satisfactory energy absorption [11]. They are very effective, but a significant shortcoming, which is the possible instability of the structure associated with high control forces, or in case of power failure, can make them dangerous in applications where high reliability is required. Another drawback is high energy demand resulting from the use of servomotors.

Semi-active vibration damping systems can be located between passive and active ones. They can achieve comparable efficacy to active systems while avoiding their disadvantages. Their energy consumption is very low because of negligible control forces introduced to the system. This also eliminates the susceptibility to instabilities related with high control loads. Well-designed semi-active system has a comparable trustworthiness to passive solutions, which is frequently essential. Combination of the advantages of both, passive and active damping systems results in very good performance in terms of reliability as well as damping effectiveness.

The fundamental idea, which is the genesis of semi-active control, is the structural adaptivity [12]. These control systems do not introduce external forces to the structure. They are modifying its structural properties, such as local stiffness, moment of inertia or local structural topology. Thanks to these techniques, controlled structure is adapting to existing conditions in a way such that its vibrations damping capabilities are significantly enhanced. Nevertheless theoretical difficulty in derivation of optimal control laws is a disadvantage. Topology reconfiguration makes it very difficult to apply the theory of optimal control for these systems.

Semi-active control algorithms can be implemented as continuous control techniques, i.e. making use of pneumatic systems [13] for smooth adjustments of the structure, or as a bang-bang type of control [3, 14]. On/off strategies are based on structural reconfiguration, which involve reformulation of selected structural constraints. One of the concepts for vibrations suppression in frame or truss structures is to excite high-frequency local vibrations by short-term reduction of local stiffness. A part of the strain energy of the structure, accumulated in the low-frequency vibration modes, is transmitted into high-frequency modes. Energy of these vibrations is generally dissipated very effectively by means of standard material damping mechanism. This leads to quick attenuation of vibration amplitudes. The described damping technique is called prestress-accumulation release (PAR) strategy [15].

Almost all preceding researches investigate the same basic example of the first, fundamental vibration mode of a cantilevered beam [5, 6, 15, 16]. This contribution focuses on 2D frame structure, which is a much more complex system. Selected beam is equipped with blockable hinges at its end nodes. These semi-active nodes can change their state between frame-like mode and truss-like mode (coupled/uncoupled rotational degrees of freedom between neighboring beams). Exemplary frame with described nodes is presented in Figure 1.

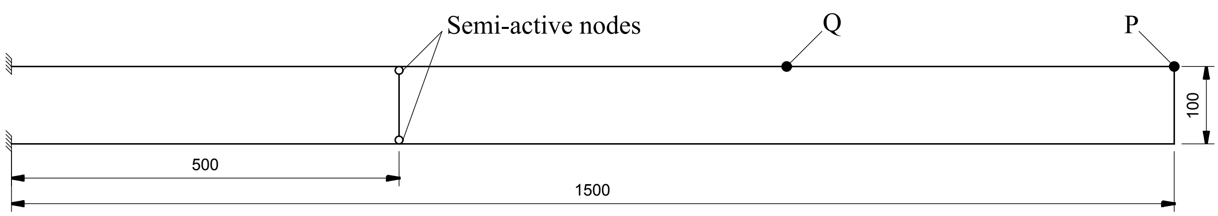

Figure 1: Considered 2D frame structure equipped with semi-active nodes (dimensions in [mm])

Technique of vibrations mitigation presented here, utilizes the PAR concept. Strain energy accumulated in the beam equipped with semi-active nodes is released into its high-frequency local vibrations in the moment of uncoupling rotational degrees of freedom. In this contribution we propose a closed-loop decentralized control strategy, which is based on local strain energy measures. The advantage of this approach over global energy measures, presented in recent paper [17], can be noticed both in vibrations mitigation efficiency and in implementation complexity in real structures.

2 MODEL OF THE SEMI-ACTIVE NODE

There are two main approaches to formulation of the mathematical model of controllable nodes considered herein:

1. *Dry friction modeling.* This model is the most consistent with reality among any others and has been successfully used in earlier researches [14, 18]. Physical realization of nodes with the ability to switch from truss to frame mode of operation is done by varying the normal force between frictional surfaces of the node, which is clamping them together. The actual moment transfer mechanism in this case is based on dry friction, so this model is best suited to reality. However, the resulting mathematical model is nonlinear, which makes it difficult to use with optimal control theory.

2. *Switching between different models.* In this approach mathematical model of the structure is switched between different implementations during the simulation. The system remains linear in-between the switchings and models the ideal truss-frame nodes with zero or

infinite moment-bearing ability. This technique involves changes in the effective number of DOFs of the structure, which, as in case of the dry friction model, provoke theoretical difficulties in view of optimal control theory.

Theoretical difficulties associated with both described solutions, led to the emergence of the third concept proposed in [17]. Finite element model of semi-active node is build as a hinge with two unaggregated rotational DOFs with rotational damper, which can couple them at any time and block relative rotations. In truss-like mode of the node, damping coefficient of the damper is set to zero, so these DOFs remain uncoupled and moment is not transmitted between neighboring beams. Switching to frame-like mode is performed by changing damping coefficient to a large value, which effectively couples DOFs and blocks the reciprocal movement. In this state the semi-active node imitates the behavior of frame node. Damping coefficient of the semi-active nodes needs to be properly chosen in order to ensure good agreement with purely frame model. Such definition of the model determines its application only to transient analyses.

Equation of motion of the system without any external excitation forces reads:

$$M\ddot{x}(t) + \left(C + \sum_{i=1}^{N} \gamma_i(t) C_i\right)\dot{x}(t) + Kx(t) = 0, \quad x(t_0) = x_0, \quad \dot{x}(t_0) = 0 \tag{1}$$

where M is the mass matrix, K stands for the stiffness matrix, C is the damping matrix of the structure in the truss-like state with all hinges unblocked. Control function $\gamma_i \in [0, \gamma_{max}]$ can be interpreted as damping coefficient in the ith semi-active node. C_i represents rotational DOFs coupling matrix, which for two and three coupled DOFs are:

$$L_i^T \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} L_i, \qquad L_i^T \begin{bmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{bmatrix} L_i \tag{2}$$

where L_i is the transformation matrix from global coordinate system to local coordinate system of the element.

3 CONTROL ALGORITHM

The objective function F to be minimized in the global optimum control problem, can be defined as the integral of the total energy of the construction:

$$F = \int_{t_0}^{t_f} \left(\frac{1}{2}\dot{x}^T(t)M\dot{x}(t) + \frac{1}{2}x^T(t)Kx(t)\right) dt \tag{3}$$

for the system defined by the differential equation of motion (1), with constraint defined by boundary values of control functions γ_i.

Reformulation of the problem, utilizing state-space approach, allows for the employment of the Pontryagin minimum principle [19]. It leads to the conclusion that globally optimal control functions $\gamma_i^{opt}(t)$ are of the bang-bang type:

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

where $w(t)$ is called the switching function. It depends on the displacement vector $x(t)$ and a co-state vector $u(t)$ which satisfies the co-state equation that is the original equation of motion of the system with negative structural damping and a pseudo load vector. Negative structural damping in the co-state equation excludes the possibility of its integration forward in time. This is the reason why it cannot be used for the computation of optimal control (4) in real time. Nevertheless, control strategy (4) is of great relevance, as it shows that optimal control strategy has a bang-bang nature.

Structural energy dissipation occurs by excitation of high-frequency local oscillations in beams equipped with semi-active nodes. Strain energy of the beam, which is related to bending, is transmitted into its quickly damped, higher modes of vibrations when controllable nodes are simultaneously switched to truss-like state. After sufficient part of the energy is dissipated, nodes can be switched to frame-like state, thereby allowing once again for strain energy accumulation. This approach allows to consider such beam as an independent dissipative device. Control loop needs to be fed back with strain energy of the controlled beam signal, which can be easily measured locally using strain gauges. Most of this energy could be released into high-frequency local vibrations.

Theoretical difficulties associated with derivation of the formal optimal control strategy, resulted in creation of heuristic control algorithm described by the following steps:

1. Beam stays in the frame-like state until its strain energy reaches maximum.
2. At the moment of maximum energy semi-active nodes switch to the truss-like state.
3. After time t_0 or when elastic energy falls below the threshold, semi-active nodes switch back to the initial, frame-like state.
4. Repeat from step 1.

Above control algorithm is presented clearly in Figure 2.

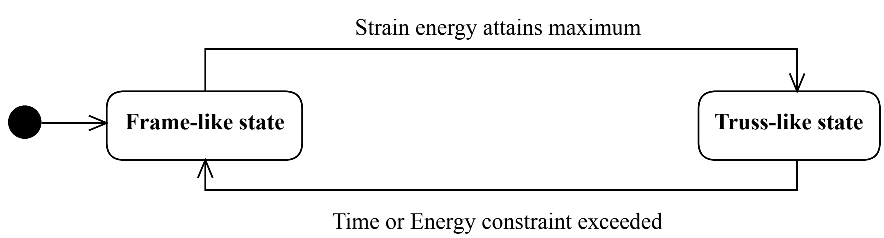

Figure 2: Heuristic control algorithm

Time t_0 should be established as some very small value, so the global stiffness of the structure would be not compromised. It could be set to one period of the bending vibrations (S-type) of the controlled beam.

4 NUMERICAL EXAMPLE

Structure considered in this contribution is presented in Figure 1. It is a 2D frame built of steel beams with 5x5 [mm] cross-section. The left end nodes are fixed and the middlemost vertical beam is equipped with the semi-active nodes which makes it a dissipative device. This model was presented earlier with global energy measure control algorithm [17]. Herein results obtained with this algorithm are compared to local energy measure control strategy. Three different cases are considered, where each of the first three vibration modes of the structure is set as the initial displacement condition.

The time course of vertical displacement of point P (marked in Figure 1) for the first vibration mode is presented in Figure 3. Frame model, without any semi-active nodes, is used as a reference case, where only material damping is included. Two semi-active control strategies: with global energy measure (SAGEM) and with local energy measure (SALEM), are compared to optimal passive damping. Optimal passive damping was found by inserting rotational dampers in place of semi-active nodes and adjusting their damping coefficient to provide the best oscillations mitigation performance. Vertical black line indicates the moment of the first control action described in previous paragraph and shown in Figure 2.

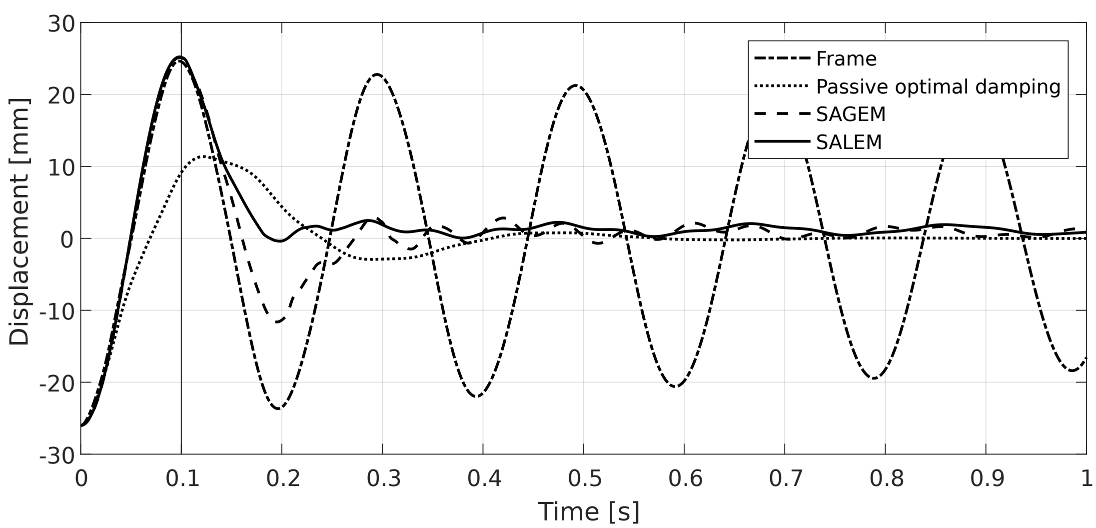

Figure 3: Vertical displacement of point P for the first mode shape

Local energy measure control strategy (solid line) is characterized by excellent vibrations mitigation capabilities. Despite the delay in the start of the control action, in comparison to the passive strategy, oscillations are damped after just 0.2 [s] and a quarter of a vibrations cycle. After that time only residual displacements remain. It is certainly the best result of all three considered options. This demonstrates the effectiveness of the semi-active control strategy based on local energy measure.

For the case of second mode shape, global energy measure control strategy does not perform satisfactorily. It does not mitigate vibrations, but introduced disorder causes a change in structure's dynamic response resulting in fading of the 2nd mode and the 1st mode appearing after a couple of vibration cycles. This procedure can bring oscillations suppression, because 1st mode is efficiently damped using this control scheme, however the duration of the control action may be unacceptable. Control strategy based on local energy measurement is much more efficient.

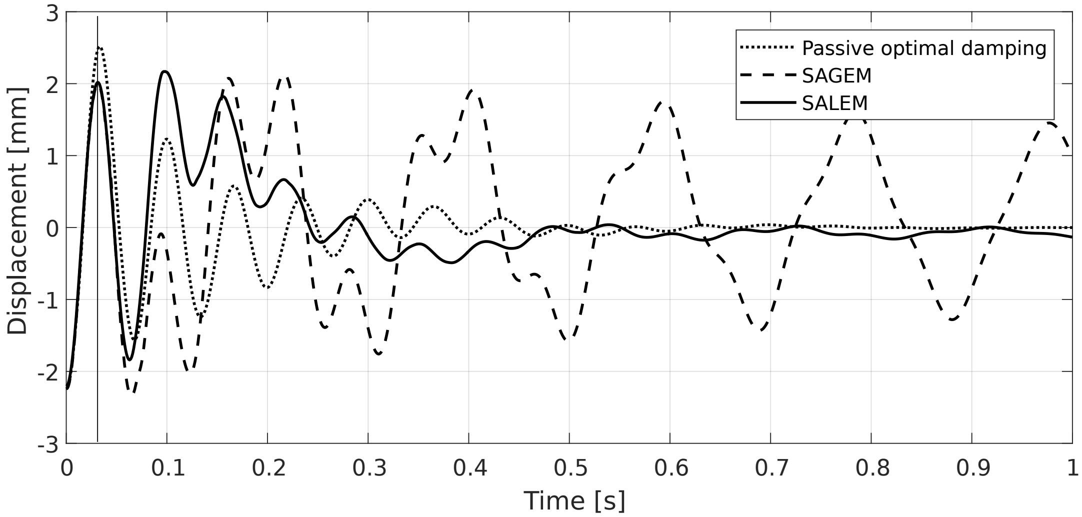

Figure 4: Vertical displacement of point P for the second mode shape

Oscillations damping rate is comparable with the passive optimal case. This is a significant qualitative change over the SAGEM control.

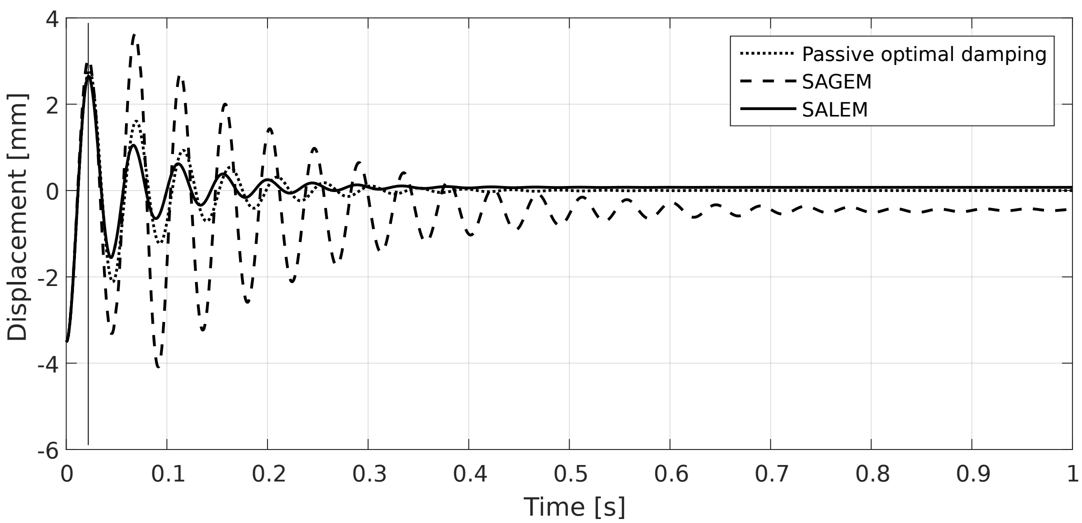

Figure 5: Vertical displacement of point Q for the third mode shape

Superiority of the SALEM control strategy over SAGEM and optimally adjusted passive dampers is seen for the third mode shape. Time courses of vertical displacement for this mode shape are presented in Figure 5. Performance of the SAGEM control is poor, this algorithm should not be used in this case. SALEM control, in opposition to SAGEM, performs very well. Oscillations are damped even quicker than in optimal passive case. This result is achieved by changing the way of energy dissipation, which was described in paragraph 3.

5 PRELIMINARY EXPERIMENTAL RESULTS

A laboratory stand was build in order to verify the results obtained in numerical analyses. Tested frame structure is visualized in Figure 6. It is geometrically similar to the one considered in the numerical example. The frame is build in a modular manner, which allows for its simple expansion with additional segments.

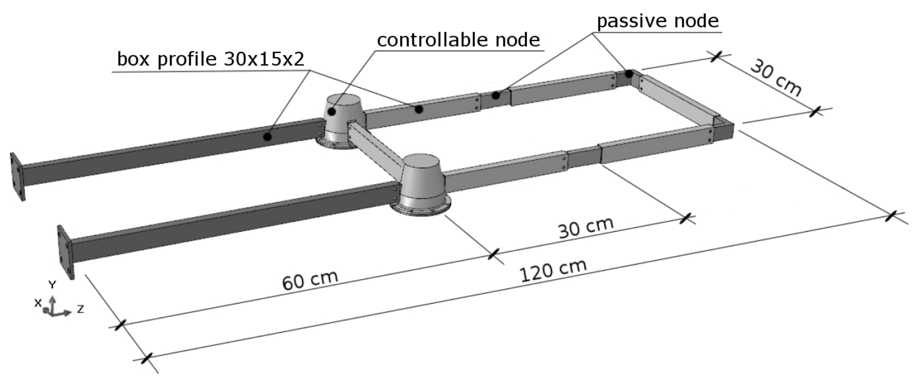

Figure 6: Frame structure used in experiment

Initial displacement conditions were set as a small in-plane displacement of the tip which excited mainly the first two global vibration modes. Comparison of the tip displacement between uncontrolled and controlled structure is presented in Figure 7. The displacements were not obtained by direct measurements, but on the way of double integration of the accelerations by the data acquisition system.

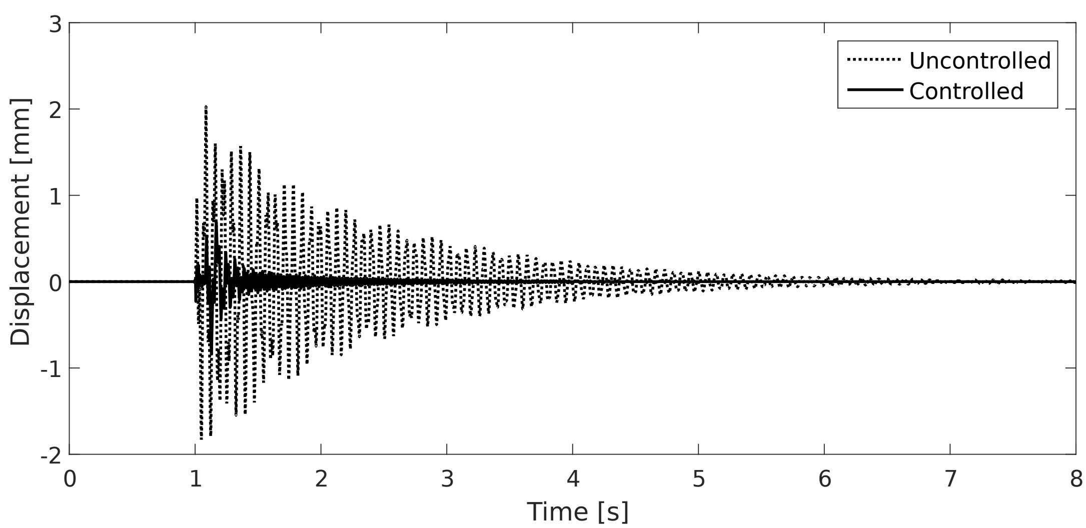

Figure 7: Comparison of tip displacements

It is easily noticeable that utilization of the control system results in significant attenuation of oscillations. Excited oscillations are damped after a couple of vibration cycles.

6 CONCLUSIONS

A semi-active decentralized control technique based on structural reconfiguration was proposed in this contribution. Numerical results obtained for exemplary frame structure are very promising and a preliminary experiment confirms the effectiveness of the developed control strategy.

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