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PHYSICS-BASED WIRELESS STRUCTURAL HEALTH MONITORING AND CONTROL USING TEMPORAL FINITE ELEMENTS

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Abstract

Integrating structural control into wireless structural health monitoring systems typically entails implementing control algorithms that predict counteracting forces for keeping the structural response within acceptable bounds. Control algorithms usually involve data-driven analysis, implemented in wireless sensor networks as feedback-loop systems. Although effective, data-driven analysis for structural control hardly accounts for the physics underlying the structural behavior. In an attempt to implement structural control in an intuitive manner for engineers, this work suggests an embedded structural control method that builds upon physics-based modeling, using the finite element method for analysis. In particular, the proposed physics-based wireless structural health monitoring and control (SHMC) method bases the prediction of control forces on temporal finite elements (TFE), which integrate the time dimension into the well-known FE spatial shape functions. Prior to embedment, the TFE models are reduced to (i) decrease the computational burden on the sensor nodes and (ii) match the discretization of the TFE models with the degrees of freedom measured by the SHMC system. The proposed SHMC method is implemented in a prototype wireless SHMC system and validated in laboratory tests on a model frame structure mounted on a shake table. The results showcase the capability of the physics-based wireless SHMC method to retain the structural response within previously defined bounds.

Keywords: Structural control; structural health monitoring; wireless sensor networks; finite element modeling; temporal finite elements; embedded computing.

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1 INTRODUCTION

In recent decades, structural control (SC) has been gaining traction in civil engineering [1], aiming to suppress structural response potentially harmful to the stability and functionality of civil engineering structures. SC systems encompass devices ("controllers") installed in civil engineering structures that are capable of exerting forces counteracting the structural response, thus keeping the response within acceptable bounds.

Traditional SC systems are typically centralized, i.e. a single controller is used for managing the structural response. While effective to some extent, centralized SC systems frequently fail to meet the complex requirements of large-scale structures due to the reliance on a single point of control, which can lead to ineffective control as well as to scalability issues. The increasing complexity and scale of modern infrastructure has paved the way for distributing SC methods, by allocating control tasks to wireless sensor nodes, serving as local controllers, to enhance the efficiency and responsiveness of SC systems [2]. Referred to as "decentralized SC", distributing SC methods facilitates exerting counteracting forces to dynamic loads in a localized manner, allowing each controller to address the structural responses in its immediate surroundings while avoiding communication "bottlenecks" [3]. In addition, wireless sensor nodes enable quick and easy modification of the decentralized SC systems without requiring cumbersome installations for every new controller added to the systems. Decentralized SC systems are often integrated into wireless structural health monitoring system (SHM) systems, whereby each wireless sensor node is responsible for collecting and locally analyzing structural response data, and for applying control forces in its vicinity.

Most research approaches on SC (including decentralized SC) have been focusing on defining effective control algorithms. Broadly speaking, control algorithms can be categorized into *open-loop*, *feedback*, *feedforward*, or a combination of feedback and feedforward [4]. Open-loop control is based on predefined control forces without requiring real-time feedback from the structure. An example of open-loop control is the "instantaneous control" approach [5], which is effective in structures with predictable structural response but can hardly adapt to disturbances. The bulk of research on SC involves feedback control algorithms that base control forces on real-time data ("feedback"), thus achieving the structural response prescribed by the control strategy. Typical examples of feedback control algorithms include the modal space control algorithm [6], which decomposes the dynamics of the structure into eigenmodes to which the control forces are individually targeted, and the linear quadratic regulator (LQR), which optimizes a quadratic cost function to ensure stability and structural response within bounds in structures exhibiting linear behavior [7]. Further examples include the bounded state control approach [8], the sliding mode control [9], proportional-integral-derivative algorithms [10], and adaptive control [11]. Feedforward control foresees disturbances or changes in the structural behavior and adjusts the control forces accordingly, optimizing SC in real time [12], which is particularly useful in environments where prior knowledge of disturbances is available. Combinations of feedback and feedforward strategies include the H2 and H^{∞} approaches [13, 14].

Despite the effectiveness of the SC algorithms previously mentioned, the existing SC algorithms hardly account for the physics of structural behavior, rendering the control strategies counter-intuitive to engineering practitioners. This study introduces an embedded structural health monitoring and control (SHMC) method that bases the computation of control forces on the temporal finite element (TFE) method. The proposed method combines TFE analysis for granting physical meaning to control forces with model-order reduction (MOR) for computational efficiency, which is crucial for embedment in wireless sensor nodes. The embedded SHMC method is implemented in a prototype wireless sensor network, which consists of wireless sensor nodes with embedded software for data collection and for prescribing velocities proportional to viscous forces via TFE analysis that can be applied for keeping the displacements within predefined bounds. The feasibility of the embedded SHMC method is demonstrated in laboratory tests on a frame structure. The remainder of the paper includes a brief presentation of the embedded SHMC method in Section 2, including TFE analysis and model-order reduction, followed by the implementation and validation, presented in Section 3. In Section 4, the study is summarized and key conclusions are drawn, while future work is also discussed.

2 EMBEDDED SHMC BASED ON TEMPORAL FINITE ELEMENT ANALYSIS AND MODEL-ORDER REDUCTION

In this section, the embedded SHMC method is presented. First, the model-order reduction and TFE aspects are illuminated, followed by an overview of the method.

2.1 Model-order reduction

Finite elements hold a central role in the proposed method, which fosters the computation of control forces based on the outcome of finite element analysis. However, coupling finite element models with SHMC systems frequently results in a discretization mismatch between the – typically – finely meshed finite element models and the sparse degrees of freedom measured by the SHMC systems [15]. To address this mismatch, this study employs model-order reduction of finite element models to the degrees of freedom actually measured by the SHMC systems. MOR builds upon the component mode synthesis rationale, proposed by Craig and Bampton [16], according to which a finite element model of a structure with N degrees of freedom can be reduced to b (measured) degrees of freedom. The $a = N - b$ degrees of freedom are substituted by the generalized degrees of freedom, corresponding to the eigenvalue analysis of the a degrees of freedom, while considering the b degrees of freedom fixed. The equation of motion of the N-degree-of-freedom (DOF) model is shown below:

$$\mathbf{M}^{N\times N}\ddot{\mathbf{x}}^{N\times 1}(t)+\mathbf{C}^{N\times N}\dot{\mathbf{x}}^{N\times 1}(t)+\mathbf{K}^{N\times N}\mathbf{x}^{N\times 1}(t)=\mathbf{p}^{N\times 1}(t), \tag{1}$$

where the matrices $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ contain masses, damping factors and stiffnesses, respectively, and the vectors $\mathbf{x}$, $\dot{\mathbf{x}}$ and $\ddot{\mathbf{x}}$, represent the displacements, velocities and accelerations, respectively, as functions of time t. Finally, the vector $\mathbf{p}$ holds the loads applied on the structure. By rearranging the degrees of freedom in the matrices and vectors, the equation of motion is converted into:

$$\left[\begin{array}{c|c}\mathbf{M}_{aa} & \mathbf{M}_{ab}\\ \hline \mathbf{M}_{ba} & \mathbf{M}_{bb}\end{array}\right]\left\{\begin{array}{c}\ddot{\mathbf{x}}_a\\ \hline \ddot{\mathbf{x}}_b\end{array}\right\}+\left[\begin{array}{c|c}\mathbf{C}_{aa} & \mathbf{C}_{ab}\\ \hline \mathbf{C}_{ba} & \mathbf{C}_{bb}\end{array}\right]\left\{\begin{array}{c}\dot{\mathbf{x}}_a\\ \hline \dot{\mathbf{x}}_b\end{array}\right\}+\left[\begin{array}{c|c}\mathbf{K}_{aa} & \mathbf{K}_{ab}\\ \hline \mathbf{K}_{ba} & \mathbf{K}_{bb}\end{array}\right]\left\{\begin{array}{c}\mathbf{x}_a\\ \hline \mathbf{x}_b\end{array}\right\}=\left\{\begin{array}{c}\mathbf{p}_a\\ \hline \mathbf{p}_b\end{array}\right\}. \tag{2}$$

The MOR is achieved by solving the eigenvalue problem ($\mathbf{K}_{aa}\boldsymbol{\varphi}_k = \lambda_k\mathbf{M}_{aa}\boldsymbol{\varphi}_k$) and by retaining the m most significant eigenvalue analysis outcomes, which are integrated with the static constraint modes ($\boldsymbol{\Psi}_{ab} = -(\mathbf{K}_{aa})^{-1}\mathbf{K}_{ab}\mathbf{I}_{bb}$) into the transformation matrix:

$$\boldsymbol{\Psi}_b = \begin{bmatrix}\boldsymbol{\Phi}_{am} & \boldsymbol{\Psi}_{ab}\\ \mathbf{0}_{bm} & \mathbf{I}_{bb}\end{bmatrix}. \tag{3}$$

The transformation matrix is used for calculating the reduced-order matrices $\tilde{\mathbf{K}} = \boldsymbol{\Psi}^T\mathbf{K}\boldsymbol{\Psi}$ and $\tilde{\mathbf{M}} = \boldsymbol{\Psi}^T\mathbf{M}\boldsymbol{\Psi}$, whose layout is formed as follows:

$$\tilde{\mathbf{K}} = \left[\begin{array}{c|c} \tilde{\mathbf{K}}_{bb} & \mathbf{0}_{bm} \\ \hline \mathbf{0}_{mb} & \mathbf{\Lambda}_{mm} \end{array}\right], \qquad \tilde{\mathbf{M}} = \left[\begin{array}{c|c} \tilde{\mathbf{M}}_{bb} & \tilde{\mathbf{M}}_{bm} \\ \hline \tilde{\mathbf{M}}_{mb} & \mathbf{I}_{mm} \end{array}\right], \qquad \mathbf{\Lambda}_{mm} = diag\left(\lambda_1, ..., \lambda_m\right). \tag{4}$$

With respect to damping, an assumption typically adopted in structural engineering is followed, according to which damping factors are proportional to stiffnesses, following the Rayleigh paradigm ($\tilde{\mathbf{C}} = \beta\mathbf{K}$), with $\beta = \xi/(\pi f)$ being the Rayleigh coefficient, and f being an eigenfrequency of the structure.

2.2 Temporal finite element analysis for structural control

The computation of control forces builds upon the temporal finite element analysis concept proposed in [17]. In general, TFE analysis represents an improvement over the traditional finite element analysis, owing to the incorporation of temporal discretization, in addition to the spatial discretization of traditional FE analysis. In this context, temporal finite elements employ principles of classical mechanics, such as Hamilton's law of varying action, to simulate the evolution of structural response trajectories in response to dynamic loads [18]. TFE analysis is used in SC primarily to predict how structures are expected to respond under dynamic and transient loads. In the context of SC, TFE analysis enables modeling dynamic responses in complex structures under variable external loads, which is crucial for designing and optimizing control systems that mitigate vibrations and enhance structural resilience and stability against dynamic loads. The equation serving as a basis for TFE-enabled SC, using the reduced-order matrices previously mentioned, is shown below:

$$\begin{bmatrix} \frac{\tau}{6}\tilde{\mathbf{K}} + \frac{1}{\tau}\tilde{\mathbf{M}} + \frac{1}{2}\tilde{\mathbf{C}} & \mathbf{0} \\ \frac{\tau}{3}\tilde{\mathbf{K}} - \frac{1}{\tau}\tilde{\mathbf{M}} + \frac{1}{2}\tilde{\mathbf{C}} & \tilde{\mathbf{M}} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{b,n+1} \\ \dot{\mathbf{x}}_{b,n+1} \end{bmatrix} = - \begin{bmatrix} \frac{\tau}{3}\tilde{\mathbf{K}} - \frac{1}{\tau}\tilde{\mathbf{M}} - \frac{1}{2}\tilde{\mathbf{C}} & \tilde{\mathbf{M}} \\ \frac{\tau}{6}\tilde{\mathbf{K}} + \frac{1}{\tau}\tilde{\mathbf{M}} + \frac{1}{2}\tilde{\mathbf{C}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{b,n} \\ \dot{\mathbf{x}}_{b,n} \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{p}}_{b,n} \\ \tilde{\mathbf{q}}_{b,n} \end{bmatrix}. \tag{4}$$

In Equation 4, τ denotes the time step duration, $\tilde{\mathbf{p}}_b$ the reduced-order load vector, and $\tilde{\mathbf{q}}_b$ the impulse vector. For each time step n+1, Equation 4 yields a prediction of the displacement $\mathbf{x}_{b,n+1}$. If the prediction exceeds a predefined threshold δ, the displacement $\underset{\sim}{\mathbf{x}}_{b,n+1}$ is set equal to the threshold, and the velocity $\dot{\underset{\sim}{\mathbf{x}}}_{b,n+1}$ necessary for maintaining the below-threshold-level displacement is back-calculated from Equation 4. The velocity difference $\dot{\mathbf{x}}_{b,n+1} - \dot{\underset{\sim}{\mathbf{x}}}_{b,n+1}$ is used as a basis for computing control forces due to the proportionality between velocities and viscous forces exerted from damping devices typically installed on structures to reduce oscillations. Considering a structure equipped with a SHMC system, the rationale of the proposed embedded SHMC method applied within a single wireless sensor node for n_o structural response data points is illustrated in Figure 1.

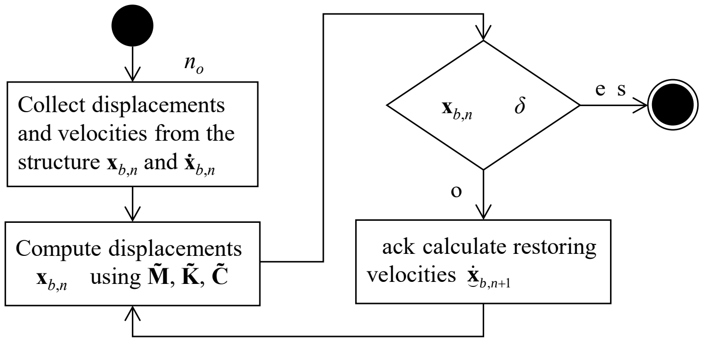

Figure 1: Overview of the embedded SHMC method.

3 IMPELEMENTATION AND VALIDATION

The proposed embedded SHMC method is prototypically implemented into a wireless SHMC system and validated in laboratory tests, as described in this section. First, the hardware and software implementation are illustrated, followed by the presentation of the tests and the discussion of the results.

3.1 Implementation into a prototype wireless SHMC system

The prototype wireless SHMC system consists of wireless sensor nodes, equipped with embedded computing capabilities. Each wireless sensor node features a programmable microcontroller, into which software can be embedded, and an actuator interface, on which damping devices can be installed to apply the control forces, computed by the embedded software. Furthermore, each wireless sensor node communicates via a wireless transceiver with a base station, through which remote coordination of the wireless SHMC system is enabled.

With respect to embedded software, the goal of the implementation is to keep the computational burden as low as possible in an attempt to preserve the inherently limited computational resources of the wireless sensor nodes. In this regard, the SC algorithm is implemented in the single class `Controller`, written in the Java programming language, with the tasks of computing displacements and control ("restoring") forces organized in separate methods. Managing the peripherals of the wireless sensor node for sampling and for actuating are organized in dedicated classes `Sampler` and `Actuator`, respectively. A unified-modeling-language (UML) diagram of an extract of the embedded software is shown in Figure 2. The validation tests are presented in the next subsection.

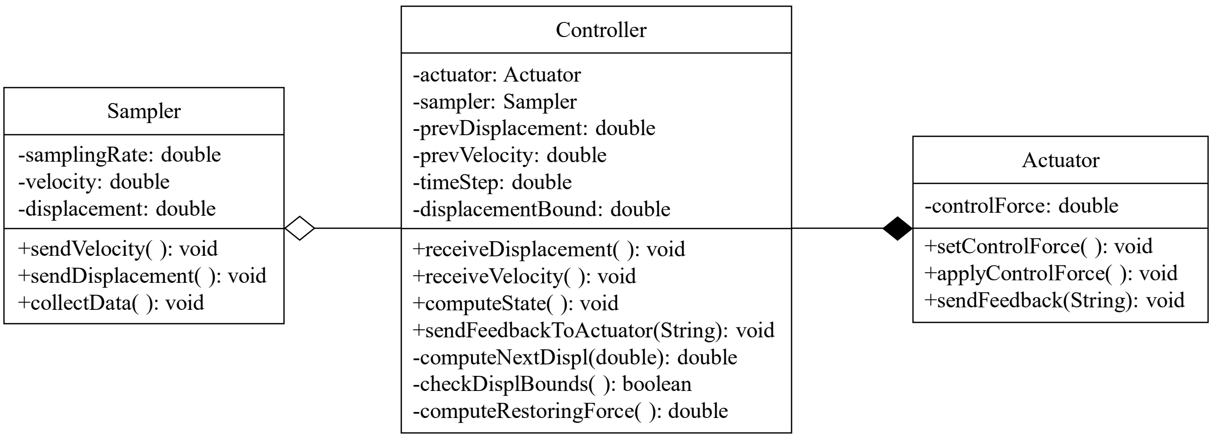

Figure 2: UML diagram of an extract of the embedded software.

3.2 Validation tests

The embedded SHMC method is validated through tests conducted on a laboratory frame structure. The experimental setup consists of the structure equipped with a wireless SHM system comprising two wireless sensor nodes, labeled SN1 and SN2. The structure encompasses 12 stories with rectangular plates of dimensions 17.70 cm × 13.20 cm (length × width). The total height of the structure is 60.60 cm, and all structural elements have a uniform thickness of 0.4 mm. The geometrical details of the structure are illustrated in Figure 3.

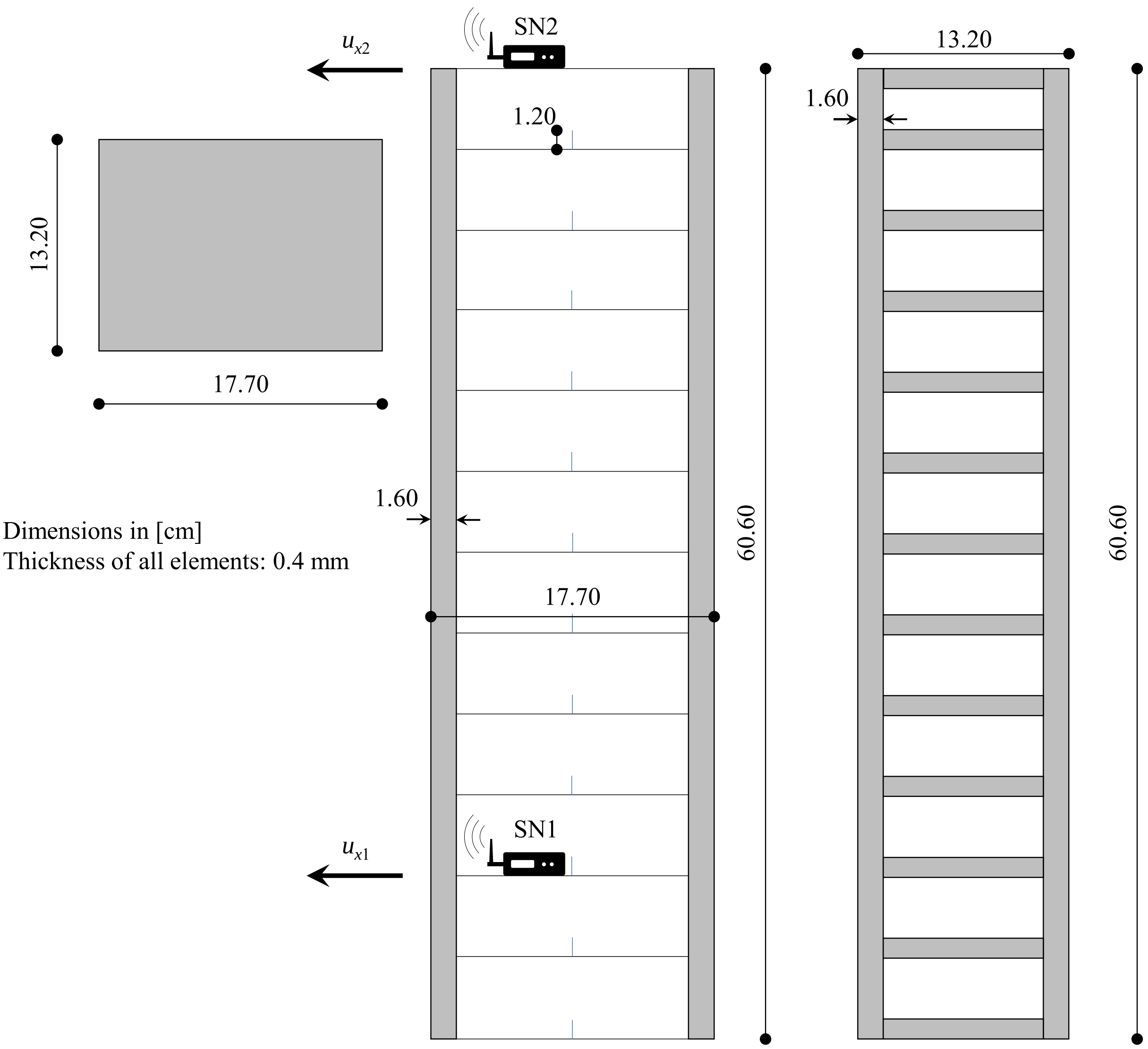

Figure 3: Geometrical details of the frame structural model.

The experimental setup is shown in Figure 4. The sensor nodes are installed on two stories of the structure: Sensor node SN1 is positioned close to the base of the structure, at a height of z = 0.11 m from the base, and sensor node SN2 is located at the top of the structure, at z =0.606 m. Both sensor nodes collect displacements and velocities along the x direction (ux1 and ux2, respectively), as marked in Figure 3, which is the most flexible direction of the structure and, thus, the direction in which the structure is prone to large oscillation amplitudes. The sampling rate on both sensor nodes is set equal to 100 Hz. Each sensor node features one microcontroller of type ESP32-S3-DevKitC-1 and one WiFi/Bluetooth transceiver. In terms of sensors, each sensor node is equipped with an Adafruit BNO085 inertial measurement unit, integrating accelerometer, gyroscope, and magnetometer functionalities [19]. The power supply consists of 5V and 3.3V regulators that support the ESP32-S3 microcontroller and sensors. The sensor nodes and the structure are mounted on a shake table, designed in previous work [20], for imparting forced vibrations. A finite element model of the structure is created and reduced to the two degrees of freedom actually measured. The elements of the reduced-order matrices corresponding to the degree of freedom measured by each sensor node are embedded into the microcontroller of the respective sensor node and used by the `Controller` classes for computing the displacements at each time step.

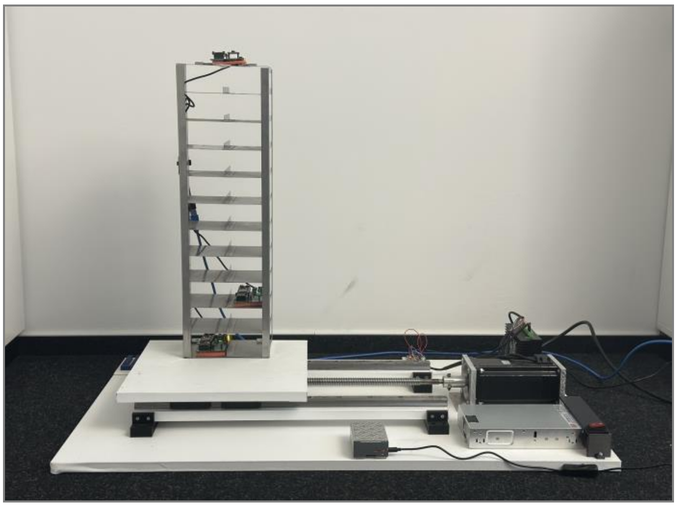

Figure 4: Experimental setup for the validation experiments.

Three tests are conducted under different excitation conditions. In the first test, the top of the structure is deflected and left to vibrate freely. The second test involves exerting a sine-wave excitation with 1 mm amplitude and 5 Hz frequency to the structure via the shake table, and the third test is conducted with hammer-induced excitation ("hammer test"). The purpose of conducting tests with different excitation conditions is to investigate the robustness of the embedded SHMC method under variable loading conditions that may manifest in real-world structures. Each test is conducted for an approximate duration of 60 s. For each time step in each test, the embedded algorithm computes the control forces to be applied by the actuator as well as the resulting displacements, assuming that the control forces have been applied. Since in real-world conditions, the external loads are rarely known, the contribution of the terms $\tilde{\mathbf{p}}_b$ and $\tilde{\mathbf{q}}_b$ is neglected in an attempt to investigate the real-world applicability of the proposed method. The results of the tests are shown in the following figures, focusing on time windows where the vibration reduction is evident.

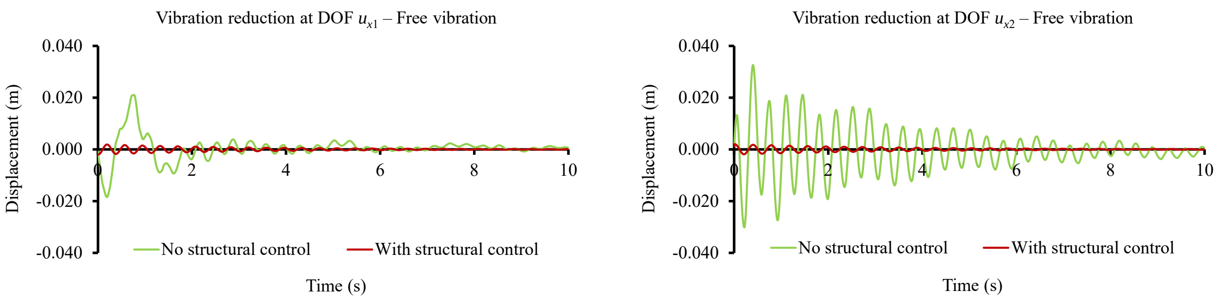

Figure 5: Vibration reduction under free vibration.

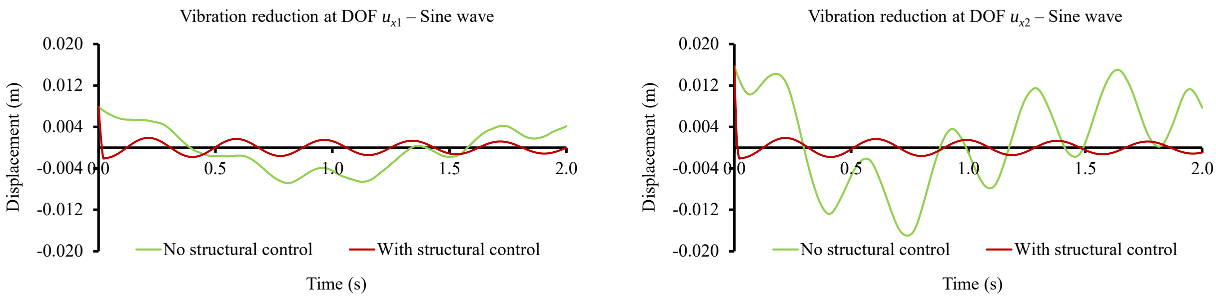

Figure 6: Vibration reduction under sine-wave excitation.

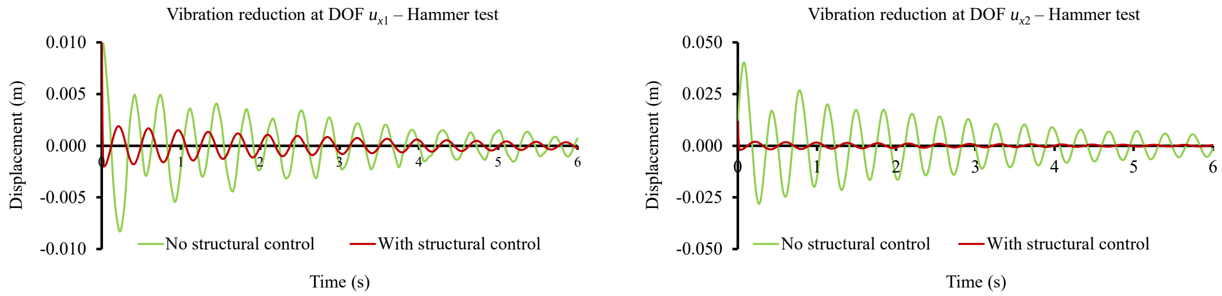

Figure 7: Vibration reduction under hammer-induced excitation.

The favorable effect that the control forces can impose on the vibration of the frame structure is evident in all the results. The strongest effect is observed in the free vibration test, in which the terms $\tilde{\mathbf{p}}_b$ and $\tilde{\mathbf{q}}_b$, which are neglected, are practically equal to zero. For the hammer test, the vibration reduction is also significant, regardless of the forced-vibration-driven part of the structural response at the beginning of the test. The performance of the embedded SHMC method may be suboptimal in some time windows of the sine-wave test, due to the structural response being dominated by harmonic excitation, i.e. the non-transient component of forced vibration. Nevertheless, as shown in Figure 6, the proposed method is still capable of keeping the displacement within predefined bounds even without accounting for the external harmonic load.

4 SUMMARY AND CONCLUSIONS

Structural control has frequently been combined with structural health monitoring for prescribing control forces to retain the structural response within acceptable bounds. Estimating the control forces typically relies on control algorithms, which use data collected from the structures (usually structural response data) to predict future "states" of the structures. However, most control algorithms are usually data-driven without explicitly accounting for the physics governing the structural response. This paper has proposed a structural control method, amenable to distribution in state-of-the-art wireless sensor networks, used for SHM. Specifically, the proposed embedded SHMC method combines model-order reduction, which allows local application at the sensor-node level, with temporal finite element analysis, which enables estimating the future displacements of a vibrating structure as well as prescribing velocities for keeping the displacement within predefined bounds. The proposed method has been implemented in a prototype wireless sensor network as an embedded algorithm and validated in laboratory tests on a multi-story frame structure. The results of the experiments demonstrate the effectiveness of the embedded algorithm in prescribing velocities for control forces that reduce the vibration of the shear frame in two locations (close to the base and at the top story of the frame). Furthermore, neglecting the external loads has exhibited minimal impact on the performance of the embedded SHMC method, which is relevant for real-world applications, since external loads are rarely known. Future work will include implementing the embedded SHMC method into a fully-fledged wireless SHMC system equipped with devices that can apply the control forces prescribed by the proposed method.

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