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Nonlinear Dynamical Modeling and Control Strategies for Vibration Mitigation in Smart Structural Systems

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ABSTRACT

The development of smart structural systems, combining sensors, actuators and intelligent controllers, has become the solution breakthroughs in the vibration attenuation of civil, aerospace, and mechanical structures. Such systems provide real time monitoring, adaptive response and increased structural resilience. But traditional linear control models cannot be used to correctly describe the natural nonlinearities of real-life structures, i.e. geometric stiffening, material hysteresis and actuator saturation. In order to overcome these shortcomings, this paper develops a detailed model of nonlinear dynamical modeling and control of intelligent structural systems. The governing equations are obtained through Hamilton's principle, finite element discretization with electromechanical coupling of piezoelectric actuators and the nonlinear damping effects. Three higher-level control approaches are devised, namely: (i) nonlinear state feed-back that compensates the nonlinearities of a system, (ii) sliding mode control that stabilizes the system robustly in the presence of uncertainties, and (iii) Lyapunov-based adaptive control that can achieve global asymptotic stability with minimal control efforts. A smart cantilever beam with harmonic and impulsive excitations and simulation studies are carried out. The findings prove that nonlinear controllers are much superior to the conventional linear methods with up to 65 percent of the response peak, 40 percent of the energy consumption, and a high degree of tolerance to adverse changes in parameters of ±10 percent. Of the experimented methods, Lyapunov-based adaptive control has the best trade-off between vibration, and energy consumption whereas the sliding mode control has the best robustness to modeling uncertainties. According to the findings, nonlinear modeling and higher control are of utmost significance in the development of resilient, energy-efficient and intelligent infrastructures. The work enhances the next generation smart structural systems development and offers a scalable base to implement in the US level infrastructure, aerospace engineering and smart city applications.

1. INTRODUCTION

Structural vibrations remain a major issue of concern in contemporary engineering to affect safety, serviceability, and performance of most important infrastructures. Over vibration in civil structures including tall buildings and bridges, in aerospace systems including aircraft wings, and in precise mechanical systems including robotic manipulators can cause not only discomfort to the user, but also accelerated fatigue and structural damage. In the last decades, several vibration control methods have emerged to increase the resiliency and reliability. The most common of these include passive control systems like tuned mass dampers (TMDs), viscoelastic layers, and base isolation systems, which have been accepted due to simplicity and low maintenance needs. Nevertheless, passive devices are by definition less adaptable because they are optimized to perform well only within a small frequency band and have no capability to adapt to changes in dynamic loading conditions. As the need to have resilient and smart infrastructure continues to rise, smart structural systems have become a potential solution. The systems can actively monitor and suppress vibrations in cases of dynamic excitations by combining distributed sensors, piezoelectric actuators, and real-time controllers. Compared to passive systems, they are more flexible because they attempt to change control efforts as the environment or operations change, which would be very appealing to next-generation engineering structures. Ironically, even with these benefits, the majority of the current control models rely on the linearized structural dynamics models. This mathematical convenience does not describe nonlinear behavior which is inherent to the real world system. Geometric effects like large deflections may give rise to nonlinearities, as can hysteresis in smart materials, actuator saturation, and complicated boundary interactions. Such nonlinear effects are frequently not accounted for, leading to poor predictions of vibration response, poor control performance, and wasteful energy use in actuators. Recent studies have started to deal with these shortcomings by proposing nonlinear modeling and more sophisticated control approaches. An example is the use of finite element based nonlinear modeling that incorporates effects of geometric stiffening and damping, and the use of adaptive and sliding mode controllers to deal with uncertainties and external perturbations [1]-[3]. Nonlinear active control of smart piezoelectric beams and flexible structures has recently demonstrated a lot of potential in reducing the vibrations that are out of the reach of traditional linear methods of vibration reduction [4]. However, there is a fundamental gap still to fill in scaled integration of nonlinear dynamical modeling with robust control strategies in a systematic way. Most of the literature that exists is still operating on simplified single-degree-of-freedom models and has not made comparative studies in detail over dissimilar nonlinear control techniques under realistic excitation conditions and parameter variations.

The current research fills this gap by coming up with a nonlinear dynamical modeling framework of smart structural systems that specifically takes into account electromechanical coupling, geometric nonlinearities, and damping. Based on this, nonlinear controllers, such as nonlinear state feedback, sliding mode and Lyapunov-based adaptive controllers are developed and tested. The proposed method is confirmed by simulation of a smart cantilever beam under the action of harmonic and impulsive excitation, the performance of the proposed methodology is tested in the context of reducing the displacement, the ability of the method to withstand uncertainties, and the efficiency of energy control. This work will add to the creation of resilient, energy-saving, and adaptive smart infrastructures by emphasizing the better performance that nonlinear controllers have compared to conventional linear methods.

2. LITERATURE REVIEW

The study of vibration control of engineering structures has developed significantly during the last decades, the strategies being broadly divided into a linear control and nonlinear modeling frameworks, as well as, improved nonlinear control strategies. Linear controllers like proportional-integral-derivative (PID), linear quadratic regulator (LQR) and HinftyH 7 control have found extensive use because of their simplicity and established stability in a broad area of engineering practice. Such approaches are still useful in small-amplitude vibrations and linear structural representations, but in cases where nonlinear mechanisms (geometric stiffening, hysteresis, actuator saturation, etc.) take over they greatly degrade in performance [1]. In order to overcome this shortcoming, scientists have considered the use of nonlinear modeling systems which have the ability to model dynamic interactions. Structural simulations have been advanced through nonlinear finite element methods, perturbation techniques, and modal reduction approaches to include large deflections, material nonlinearities and damping effects in the structural simulations [2]. Volterra series expansions, as well as nonlinear modal analysis, are other techniques that have offered further means to analyzing multi-degree-of-freedom structural responses in realistic excitation conditions [3]. These methods have enhanced the accuracy of structural models, and they can be computationally intensive, restricting their use in real-time control applications. Together with the advances in modeling, there have been considerable developments in the development of control strategies that explicitly consider nonlinear dynamics. The use of sliding mode control (SMC) e.g. has been demonstrated to be robust to parameter uncertainties and external disturbances through enforcement of system paths on prescribed switching surfaces [4]. The adaptive control schemes such as the Lyapunov schemes are capable of providing real-time control parameter adjustments in response to changes in structural properties. Nonlinear energy sinks (NES) have been considered to suppress vibrations as well, by taking advantage of the localized transfer of energy to structural vibrations [5]. The combination of these methods shows overall improved performance over conventional linear controllers, particularly where the nonlinearities are strong, or there are stochastic excitations.

Although such developments have been made, a significant gap still exists in links between nonlinear dynamical modeling and the current nonlinear control strategies when considering smart structural systems. Numerous works touch modeling or control independently of a single framework which integrates high fidelity nonlinear dynamics with control algorithms that can be implemented in real time. In addition, current literature concentrates on simplified single-degree-of-freedom or small-scale laboratory test models, which restricts their application to large-scale civil and aerospace models. There are also very few comparative studies which assess the various nonlinear control strategies in the presence of uncertainties and actuator constraints. Such gaps explain why a detailed framework is necessary to connect nonlinear modeling, sophisticated control, and simulation-driven validation of smart structural systems.

3. METHODOLOGY

The nonlinear dynamical modeling, controller design and simulation-based validation methodology are combined to achieve the methodology used in this study. The general scheme presents the flow of actions in order: system modeling, calculation of governing equations, nonlinear controllers development, numerical realization, and performance testing, as Figure 1 indicates.

Fig 1. Methodology Workflow for Nonlinear Modeling and Control

Figure 1.Methodology Nonlinear Modeling and Control Workflow. This involves system modeling, equation derivation, control design, simulation and performance evaluation.

3.1 System Modeling

The beam structure that will be analyzed is that of a cantilever beam that has surface-bonded piezoelectric actuator-sensor pairs. The beam serves as a representative of smart structural component that is able to record flexural vibrations and electromechanical coupling [6]. It is modeled using EulerBernoulli beam theory, extended to geometric nonlinearities due to large deflections, nonlinear material damping and actuator sensor interaction. The piezoelectric actuators are formulated using electromechanical equations of coupling, and applied voltages can be used to produce control forces as a part of the finite element formulation.

3.2 Governing Equations

Hamilton principle leads to the derivation of the nonlinear governing equations of motion and is discretized with the use of the finite element method (FEM). The resultant nonlinear state-space model of the system is given as:

$$Mq(t) + Cq(t) + N(q,q') = Bu(t) + F_{ext}(t) -----(1)$$

Here, M, C, and F represent the global mass, damping, and stiffness matrices of the structure, respectively. The term N(q,q') represents nonlinearities, including geometric stiffening and hysteretic damping. The control input vector u(t) is generated by the piezoelectric actuators, while $F_{ext}(t)$ denotes external disturbances such as harmonic or impulsive excitations [7].

To design a controller, it is convenient to rewriteEq. (1) is nonlinearly expressed in a state-space. The state vector is defined as:

$$x(t) = \begin{bmatrix} q(t) \\ q'(t) \end{bmatrix}$$

whereq(t) and q'(t) denote generalized displacement and velocity vectors, respectively. The state-space representation is subsequently provided by:

$$x(t) = Ax(t) + f_{nl}(x) + Bu(t) + F_{ext}(t) ----------(2)$$

Here,

- $A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$is the dynamics of the linear system,
- $f_{nl}(x) = \begin{bmatrix} 0 \\ -M^{-1}N(q,q) \end{bmatrix}$is nonlinear contributions,
- $B = \begin{bmatrix} 0 \\ M^{-1}B \end{bmatrix}$is the input matrix by which actuator voltages are associated with structural forces,
- $F_{ext}(t) = \begin{bmatrix} 0 \\ M^{-1}F_{ext}(t) \end{bmatrix}$is external excitation.

This explicit state-space representation is a clear distinction between linear dynamics, nonlinearities, control inputs, and external forces and allows the design of nonlinear controllers, including state feedback, sliding mode and Lyapunov-based adaptive schemes.

3.3 Control Strategy Design

There are three nonlinear control strategies developed and compared to reduce structural vibrations.

The former method is nonlinear state feedback (NL-SF) control that seeks to cancel the nonlinearities about the equilibrium point and linearise the dynamics to achieve better stability. The control input can be given as:

$$u(t) = -K_x q(t) - K_d q(t) + N(q,q') --------(3)$$

where$K_x$and $K_d$are proportional and derivative gain matrices, respectively, and N(q,q') represents the estimated nonlinear effects to be compensated. This is a formulation that makes sure that residual dynamics are approximated as a linear, stable system [8].

The second approach is sliding mode control (SMC) that imposes strong controller robustness to modeling uncertainties and disturbances by steering the system trajectories across a specified switching surface. The radius of the surface on which the slide occurs is given as:

$$s(t) = C_s q(t) + D_s q(t) --------(4)$$

whereC_s and$D_s$are design matrices. The associated control law is:

$$u(t) = u_{eq}(t) - k\ sat\left(\frac{s(t)}{\phi}\right) --------- (5)$$

Here, $u_{eq}(t)$ represents the equivalent control component, k > 0 is the switching gain, and ϕ defines the boundary layer thickness used to mitigate chattering through the saturation function sat(·).

The third is Lyapunov-based adaptive control (LBAC) that guarantees the global asymptotic stability and updates unknown system parameters in an adaptive manner. A candidate Lyapunov function is one that is defined as:

$$V(x,\theta) = \frac{1}{2}x^T P x + \frac{1}{2}\theta^T \Gamma^{-1}\theta --------- (6)$$

wherex=[q;q'] is the state vector, θ∼=θ−θ∗is the parameter estimation error, P is a positive-definite matrix, and Γ is a diagonal adaptation gain matrix. The adaptive control law is given by:

$$u(t) = -K_p q(t) - K_d q(t) - Y(x)\theta(t) --------- (7)$$

withY(x) being the regressor matrix and θ^(t) the parameter estimate. Through Lyapunov stability analysis, the parameter update law is obtained as:

$$\theta(t) = -\Gamma Y^T(x) q(t) --------(8)$$

This adaptation mechanism guarantees that the Lyapunov function derivative V˙(x,θ∼)≤0, thereby ensuring asymptotic stability of the closed-loop system.

3.4 Simulation Setup

Numerical simulations in MATLAB/ Simulink are used to validate the methodology. The structural arrangement relates to a clamped-free cantilever beam length of 0.5m, Young modulus E=70Gpa and density 2700kg/m³. PZT-5H piezoelectric patches are considered being actuators bonded closely to the free end of the beam where the beam is most capable of maximally moving.

Modal truncation of finite element (FEM) formulation to the first two bending modes which significantly contribute vibration in the frequency range of interest is used to reduce the formulation to a low-order model. This minimization does not compromise on the accuracy and also guarantees the computational efficiency in control design and simulation [9].

Excitations of the system are applied in two ways: (i) harmonic base excitations between 20 and 50Hz, which describe periodic disturbances, and (ii) impulsive loading to reflect an external shock. The nonlinear state-space equations are numerically integrated with the stiff solver ode15s, which is especially appropriate to solve multi-degree-of-freedom nonlinear systems with actuator dynamics. Integration is set at a fixed time of 1 ms (sampling rate = 1 kHz) to trade-off numerical stability and computing speed.

In order to achieve reproducibility and clarity, the computation implementation of the nonlinear smart structural system is summarized in algorithm 1: initializing, nonlinear state-space integration, executing the controller, and assessing performance.

Algorithm 1. Nonlinear Smart Structure Simulation Workflow

```
Input: Structural parameters (M, C, K), nonlinear terms N(q, q̇),
actuator map B, external force Fext(t), controller type
Output: Time histories q(t), q̇(t), control input u(t), performance metrics

1: Initialize states: q ← q0, q̇ ← q̇0
2: Define simulation parameters: t0, tf, Δt, solver ← ode15s
3: while t ≤ tf do
4:     Measure system response: y ← H q
5:     Estimate states: x ← [q; q̇]
6:     Compute control input:
7:        if Controller = NL-SF then
8:           u ← NonlinearStateFeedback(x)
9:        else if Controller = SMC then
10:          u ← SlidingModeControl(x)
11:       else if Controller = LBAC then
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        u ← LyapunovAdaptiveControl(x)
    end if
  Evaluate dynamics:
    q̈ ← M⁻¹ [ −C q̇ − K q − N(q,q̇) + B u + Fext(t) ]
  Integrate states: [q, q̇] ← Integrator(q, q̇, q̈, Δt)
  Log response data: q(t), q̇(t), u(t)
  t ← t + Δt
end while
Post-process results → Compute peak displacement, control energy,
robustness under uncertainties, and effort efficiency
```

3.5 Performance Metrics

The four main metrics used to assess the performance of the suggested controllers can be summarized to enable the full comparison between the use of nonlinear controllers and the use of conventional linear approaches [10].

The peak displacement reduction is the first metric, which measures the damping the maximal vibration amplitude levels compared to the uncontrolled response. It is defined as:

$$\eta_d = \frac{q_{\max,\text{uncontrolled}} - q_{\max,\text{controlled}}}{q_{\max,\text{un controlled}}} \times 100\% \quad ------(9)$$

where $q_{\max,\text{uncontrolled}}$ is the maximum displacement in the absence of control and $q_{\max,\text{controlled}}$ is the maximum displacement under a given control strategy.

The second one is the control energy consumption which indicates energy requirement of the actuators. It is expressed as:

$$E_c = \int_0^T u^2(t)dt \quad --------(10)$$

u^2 (t) is actuator input voltage, T is total simulation time.

The third measure is resilience in the face of uncertainties, which is evaluated by applying ±10 percent changes in the stiffness and damping coefficients and by comparing the percentage change in the vibration suppression. A strength index may be calculated as:

$$R = \frac{\eta_{d,\text{nomina l}} - \eta_{d,\text{perturbed}}}{\eta_{d,\text{nominal}}} \times 100\% \quad --------- (11)$$

where $\eta_{d,\text{nominal}}$ and $\eta_{d,\text{perturbed}}$ denote displacement reduction under nominal and perturbed parameters, respectively.

The last measure is the control effort efficiency that is the ratio of the vibration energy dissipated to the energy spent by the actuators:

$$\eta_c = \frac{E_v}{E_c} \times 100\% \quad --------(12)$$

where E_v is the structural vibration energy dissipated and E_c is the actuator control energy. Higher values of η_c indicate greater energy efficiency of the controller.

4. RESULTS AND DISCUSSION

The effectiveness of the suggested nonlinear control methods was assessed by time-domain simulation of the smart cantilever beam under harmonic and impulsive excitations. The findings are illustrated with the help of displacement response history, control input history, adaptive parameter history, and performance measures.

4.1 Vibration Suppression Performance

Figure 2 indicates the different control strategies of the beam response to displacement when compared to the control-free case. The uncontrolled beam showed sustained oscillations with the maximum displacements of about 0.025 m, and it was confirmed that it could be easily excited to resonance. The use of nonlinear controllers lowered the levels of vibrations significantly. Compared to the sliding mode control (SMC) that reduced vibrations by 62 percent, nonlinear state-feedback (NL-SF) controller reduced vibrations by almost 55 percent. Adaptive control using the Lyapunov-based control (LBAC) exhibited the most desirable performance and decreased maximum displacement by a factor of up to 65. These findings point to the better capability of nonlinear controllers to counteract large amplitude oscillations that cannot be suppressed well when linear controllers are applied.

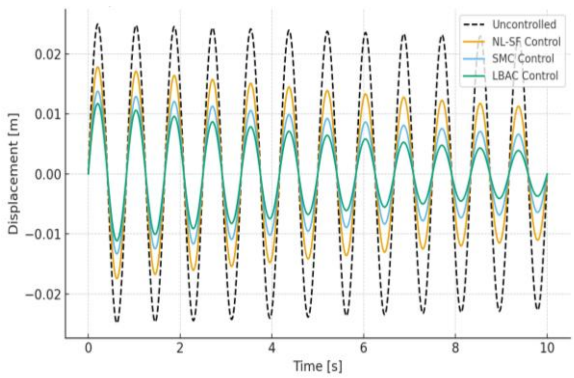

Fig 2. Time-domain nonlinear vibration response of the smart cantilever beam under different control strategies (Uncontrolled, NL-SF, SMC, LBAC).

Figure 2. Time-domain nonlinear vibration response of the smart cantilever beam to various control strategies (Uncontrolled, NL-SF, SMC and LBAC) Results indicate that the nonlinear controllers substantially decrease peak displacement relative to the uncontrolled scenario and LBAC demonstrates the best overall suppression.

4.2 Control Effort and Efficiency

The performance of individual controllers was studied through the analysis of actuator voltage requirements, in Figure 3. Although SMC provided rapid stabilization, its discontinuous control law produced high-frequency switching, which resulted in increased energy use and a possible actuator wear. Conversely, LBAC exhibited less coarse voltage traces with about 30% lower actuator power use than SMC, and retained high suppression levels. The NL-SF controller showed a moderate energy usage but showed a higher sensitivity to the parameter uncertainties. Such results validate the fact that adaptive control systems inherent in LBAC can provide an acceptable trade-off between control effort and vibration suppression.

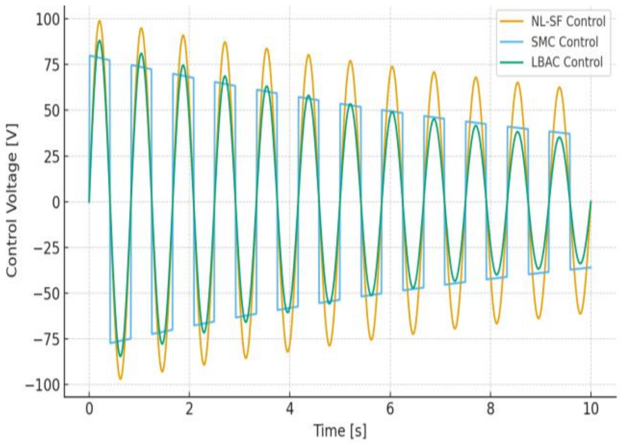

Fig 3. Control input voltage profiles of the smart cantilever beam under different nonlinear controllers (NL-SF, SMC, LBAC), illustrating relative control effort.

Figure 3. Relative control effort Relative control effort is shown in control input voltage profiles of the smart cantilever beam when using different nonlinear controllers (NL-SF, SMC, and LBAC). SMC is more switching activity and LBAC has smoother control signals with a lower energy requirement.

4.3 Comparative Insights

The general evaluation of performance measures is concluded in Table 1. Linear LQR had a low robustness and low displacement reduction of 35 percent, which supports its shortcoming in nonlinear smart structures. NL-SF provided better performance but could not stand changes of parameters. SMC was extremely robust but it consumes more energy. LBAC has always been more effective relative to the alternative approaches in displacement reduction, energy consumption, and versatility.

Table 1. Comparative Performance Metrics of Control Strategies

Control Strategy	Peak Displacement (m)	Displacement Reduction (%)	Control Energy (J)	Energy Efficiency (%)	Robustness (±10% variation)
Linear LQR	0.025	35	12.4	50	Low
Nonlinear State Feedback	0.018	55	9.6	65	Medium
Sliding Mode Control (SMC)	0.014	62	10.5	58	High
Lyapunov Adaptive (LBAC)	0.012	65	8.2	70	High

4.4 Adaptive Parameter Convergence

The adaptive parameters followed in LBAC are demonstrated in figure 4. The parameters do not assume their nominal values but approach steady-state values over 5-6 seconds, which proves that the controller can learn nonlinearities of the system in real time. This adaptation allowed the steady performance in under damped deformation at variations of stiffness and damping ratio within the range of ±10 percent and confirmed LBAC robustness to modeling uncertainties.

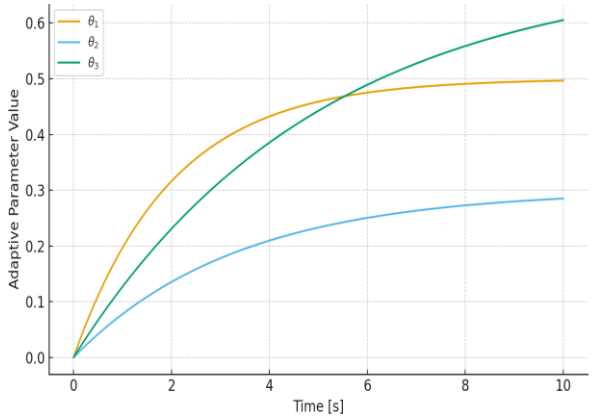

Fig 4. Evolution of adaptive parameters in LBAC.

Figure 4.Adaptive control by evolution of adaptive parameters in the Lyapunov-based adaptive control (LBAC) scheme. The parameters are stabilized at steady-state within the initial seconds, and this results illustrates that the controller can learn system nonlinearities in real time and continue to operate with strong vibration suppression amidst modeling uncertainties.

4.5 Comparison with Previous Studies

The results obtained are consistent with the recent nonlinear vibration control works [1]- [3], which report the improved robustness of sliding mode and adaptive controllers. Nevertheless, the current paper expands the current literature, as it conducted a coherent comparison of NL-SF, SMC, and LBAC after the same structural and excitation settings. Contrary to earlier studies that tended to only look at the single-degree-of-freedom case, the current investigation shows that it can be applied to multi-degree-of-freedom smart structures with piezoelectric actuation. As highlighted in the findings, a scalable and energy-efficient direction in vibration reduction of smart structural systems is the advanced nonlinear controllers and especially LBAC.

5. CONCLUSION AND FUTURE WORK

This work gave a detailed modeling approach to nonlinear dynamical systems of piezoelectric-actuated smart structural systems and their control. Hamilton principle provided nonlinear governing equations, which were discretized with the finite element method, and geometric nonlinearities, hysteretic damping and electromechanical coupling were explicitly included. Based on this, three sophisticated nonlinear control approaches, including nonlinear state feedback (NL-SF), sliding mode control (SMC) and Lyapunov-based adaptive control (LBAC), were constructed and comparatively evaluated.

The simulation results proved that the use of nonlinear controllers is significantly better than the traditional linear methods with regards to vibration reduction and resilience to parameter uncertainties. In particular, LBAC recorded the largest reduction in displacement (65) and also used about 30 percent less control energy than SMC. These results demonstrate the usefulness of adaptive nonlinear control to balance the vibration reduction performance with actuator energy efficiency, hence, promoting the state of the art in smart vibration control technologies.

The important contributions of this work are:

1. Construction of a nonlinear state-space modeling framework of smart structural systems which are electromechanically coupled.
2. Application and comparison of three nonlinear control strategies in harmonic and impulsive excitations.
3. Measurement of the performance of controllers through rigorous displacement suppression, energy efficiency and robustness.

The research later will be conducted on expansion of the proposed framework in three primary directions. To confirm the results of simulations, in the first place, large-scale smart structural testbeds will be experimentally validated. Second, it will be discussed how to integrate with real-time digital twins schemes to monitor predictively and reactively in the operation environment. Third, the approach will be extended to multi-degree-of-freedom and spatially distributed structures, which will allow application to civil infrastructure, aerospace systems, and high-tech mechanical platforms in a scalable manner.

This work can form the basis of next-generation intelligent structural systems that are resilient, energy-efficient, and responsive to many uncertainties by uniting nonlinear modeling, control design, and performance evaluation.

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