



EURODINAME III - An International Symposium on Dynamic
Problems of Mechanics
June 8-11, 2026 - Giens Peninsula, FR



EURODINAME-2026-13457

NUMERICAL PROOF OF CONCEPT OF A SELF-ADAPTIVE MECHANICAL SYSTEM USING A MULTI-AGENT APPROACH

Camila da Silva Almeida

Rafael Teloli

Emmanuel Foltête

Université Marie et Louis Pasteur, SUPMICROTECH, CNRS, institut FEMTO-ST, F-25000 Besançon, France

e-mails: camila.almeida@femto-st.fr, rafael.teloli@femto-st.fr, emmanuel.foltete@femto-st.fr

Abstract. Natural systems such as bird flocks, fish schools, and insect swarms exhibit self-organization emerging from simple local interactions, giving origin to complex collective behavior. Inspired by these mechanisms, this work proposes a self-adaptive structure composed of interconnected cells capable of locally tuning their viscoelastic properties according to temperature and excitation frequency. The structure is formulated as a distributed multi-agent system, where each cell operates as an autonomous agent governed by local sensing and interaction rules. Agents interact only with their nearest neighbors by exchanging local frequency response information that describes their dynamic behavior, no centralized controller is employed. Each agent has internal states and update laws that govern the adjustment of its viscoelastic parameters. Through these decentralized interactions, the agents aim to reach consensus, meaning that neighboring converge to compatible dynamic responses. In contrast to approaches based on centralized control combined with global thermal mapping, the mapping in the proposed framework is used exclusively to initialize local parameters. Adaptation and consensus remain fully distributed, providing a scalable and robust strategy for intelligent structures operating in complex environments.

Keywords: Multi-consensus, Multi-agent, Self-adaptiveness, Vibrations, Viscoelasticity

1. INTRODUCTION

Due to their low mass and limited structural damping, flexible structures are susceptible to persistent vibrations that are difficult to suppress during operation (Qiu *et al.*, 2023). Since structural vibrations can cause fatigue and potential damage, several vibration control strategies have been developed (Qiu *et al.*, 2022). Active vibration control is extensively used in industry due to its advantages, such as reduced structural weight and overall system costs. Among the most commonly used strategies are proportional (P), proportional derivative (PD), and proportional integral derivative (PID) controllers, which act on a specific system input based on the error between the reference and the measured output (Mohit *et al.*, 2015). In their conventional implementation, controllers are typically employed within centralized control architectures, where a single control unit processes the system error and generates the control action. As the dimensionality of the system increases, the computational complexity associated with centralized control grows significantly, requiring an increasingly greater amount of calculations and processing resources (Soto and Adeli, 2017). To overcome this, decentralized control techniques have been used to replace the global control system with multiple local control systems.

Nagata *et al.* (2012) present a control strategy for mechanical systems with a large number of degrees of freedom inspired by the concept of emergence observed in living organisms. The approach relies on simple local rules between neighboring subsystems to generate a desired global behavior without requiring a centralized control architecture. Emergence refers to the phenomenon in which complex collective functions arise from decentralized local interactions, where each element operates autonomously based solely on information from its neighbors. Despite the absence of global coordination, coherent patterns and adaptive responses to environmental variations naturally arise from these interactions. In a related approach, Soto and Adeli (2017) propose an active vibration control strategy for smart structures based on agents and replicator dynamics derived from evolutionary game theory. Two schemes are developed, a Centralized Replicator Controller (CRC) with a single agent, and a Multi-Agent Replicator Controller (MARC) with a decentralized structure, both aimed at minimizing structural energy. The decentralized approach seeks to enhance the robustness of the system



and the tolerance of failures. The method is applied to the suppression of seismic vibrations in multi-story buildings and compared with the classical Linear Quadratic Regulator (LQR) controller. From a reinforcement learning perspective, Qiu *et al.* (2023) propose an active vibration control method based on multi-agent reinforcement learning to suppress vibrations in a flexible beam system with piezoelectric actuators. The controller was trained using an algorithm that significantly reduces vibrations during and after motion, outperforming conventional PD Control. Additionally, Lei *et al.* (2012) introduce a control strategy based on the distributed model obtained by Hamilton's principle, explicitly considering the coupling between displacement, angle, and vibration. In this case, vibration suppression is achieved through a distributed controller that ensures consensus among agents and guarantees the tracking of reference trajectories, promoting stability and dynamic coherence of the system.

In general, the consensus problem in multi-agent systems is characterized as the process through which all agents in a system converge to a common agreement regarding certain states of interest (Hu *et al.*, 2024). Despite these approaches, important challenges remain in integrating consensus based control within multiphysics environments. In this article, we develop a distributed multi-agent system structured through a graph-based topology, in which each agent communicates with its nearest neighbors. Based on the local information exchanged within the network, the agents dynamically adjust their internal properties, such as stiffness and damping, by changing their local temperature to achieve consensus among neighboring states and reduce vibrations in the system. An equivalent physical model, based on a mass-spring-damper system, is adopted to represent the dynamic behavior of the system. In this model, each mass represents an agent. The springs model the equivalent stiffness of the system, mainly related to the storage modulus of the material, while the dampers represent the energy dissipation mechanisms associated with viscoelastic losses. The main contribution of this study lies in the integration of consensus-based multi-agent control within a dynamic multiphysics environment, coupling thermal and mechanical domains for vibration reduction. This framework enables adaptive and coordinated behavior under varying operating conditions, distinguishing it from conventional methodologies. Although there are existing studies on consensus in multi-agent systems, none have explored the concept from the perspective proposed in this work.

Towards this background, this paper is organized as follows: Section 2 introduces the concept of viscoelastic materials, as well as the notions of stiffness and damping from a thermo mechanical perspective. Section 3 presents the problem formulation and introduces an illustrative example. Section 4 discusses the results obtained, validating the approach proposed in this study. Section 5 presents the conclusions reached.

2. VISCOELASTIC MATERIAL

Viscoelastic polymeric materials exhibit mechanical behavior that is strongly influenced by temperature due to their microstructure composed of interconnected molecular chains. The mobility of these chains varies with thermal level, leading to significant changes in mechanical properties. At temperatures below the glass transition, the material displays high stiffness characteristic of the glassy state. Above this range, increased molecular mobility results in a pronounced reduction in stiffness. Variations in excitation frequency produce a similar effect, highlighting the dependence of the mechanical response on both temperature and frequency (Moreira *et al.*, 2010).

The viscoelastic material considered in this study is the tBA/PEGDMA polymer, whose mechanical properties depend on both temperature and frequency. Due to the complexity of the underlying physical mechanisms governing, a phenomenological model is adopted to describe their viscoelastic behavior. The complete mathematical formulation used to generate these curves is presented by Butaud (2015). This modeling approach provides sufficient accuracy for the purposes of the present study.

The mechanical properties dependent on temperature and frequency are illustrated in Fig. 1. The results highlight the possibility of tuning the stiffness and damping characteristics of the tBA/PEGDMA polymer through temperature control, depending on the frequency range of interest.

3. PROBLEM STATEMENT AND FORMULATION

The viscoelastic behavior of the material is described using an equivalent mass-spring-damper model of four degree of freedom (DOF), illustrated in Fig. 2. Within this mechanical analogy, the spring accounts for elastic energy storage, while the damper represents viscous energy dissipation mechanisms. This lumped-parameter representation allows viscoelastic effects to be incorporated into the equations of motion in a straightforward and physically consistent manner (da Silva (2003)). Although simplified, the model adequately captures the essential dynamic characteristics of the material within the frequency range of interest. In this formulation, each mass represents an agent.

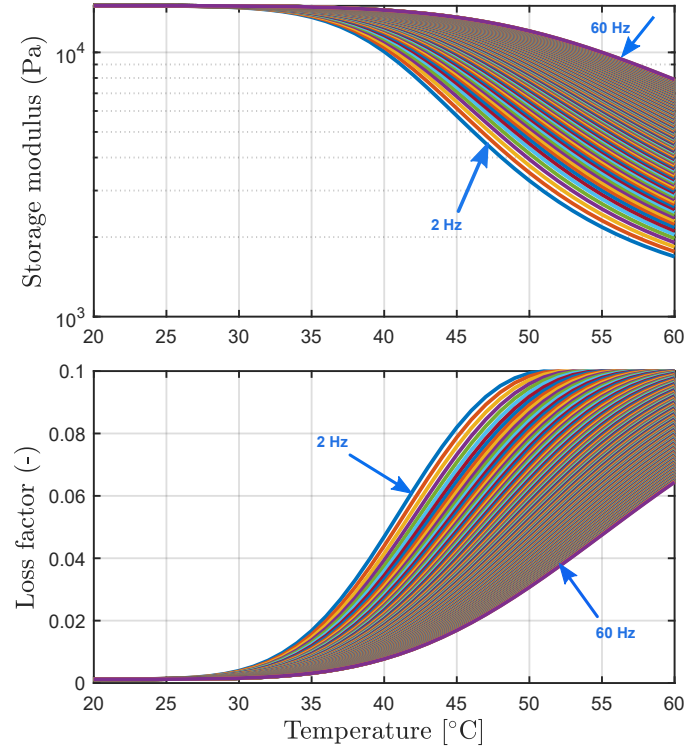


Figure 1. Storage modulus and loss factor of tBA/PEGDMA over a range of temperature and frequency.

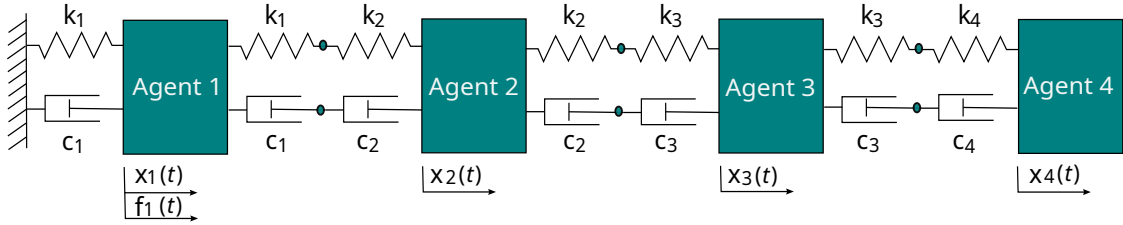


Figure 2. physical model of a mass-spring-damper system with 4 degrees of freedom.

Agent 1

The frequency response function can be expressed as:

$$\mathbf{H}(\omega, T) = \frac{\mathbf{X}(\omega, T)}{\mathbf{F}(\omega)} = (\mathbf{K}^*(\omega, T) - \omega^2 \mathbf{M})^{-1}, \quad (1)$$

where $\mathbf{M}$ denotes the mass matrix and $\mathbf{K}^*(\omega, T)$ represents the complex stiffness matrix of the system, which accounts for the viscoelastic behavior dependent on the frequency and temperature of the material, while $\mathbf{F}(\omega)$ denotes the external force vector and $\mathbf{X}(\omega, T)$ denotes the displacement vector in the frequency domain. The complex stiffness matrix is obtained from the adopted phenomenological model describing the viscoelastic response, in which the material properties are formulated as functions of excitation frequency and temperature. The parameters are extracted from the curves presented in Fig. 1, where the material behavior is characterized over the investigated operating range. An external excitation is applied at DOF 1, and the corresponding set of four frequency response functions (FRFs) is computed over the frequency range of interest. Subsequently, the squared magnitude of the FRFs is used to evaluate the adopted consensus metric, which provides a global measure of the dynamic response of the system.

The central research question addressed in this study is whether consensus in the dynamic frequency-domain response can emerge from purely local interactions among agents, in the absence of global system information. The analysis

evaluates whether local minimization of response discrepancies is sufficient to induce coordinated behavior at the system level.

3.1 IMPACT OF THERMAL FREQUENCY DEPENDENCE ON DYNAMIC RESPONSE

As described in Section 2, the mechanical behavior of viscoelastic materials is strongly influenced by temperature and excitation frequency. Therefore, when the material is exposed to low temperatures, it tends to exhibit higher rigidity (higher storage modulus) and lower molecular mobility. Under these conditions, energy dissipation is generally reduced, except in the vicinity of the transition regions (Moreira *et al.*, 2010). Consequently, in frequency ranges where the response is dominated by stiffness, a colder configuration can provide better performance due to increased rigidity and reduced deformation amplitudes. However, at high temperatures, the material tends to behave more like an elastomer. In this condition, the molecular chains are more mobile, intensifying the internal friction mechanisms and increasing the loss factor in certain frequency ranges (Naresh *et al.* (2020)). Thus, in frequency bands close to resonance regions, damping becomes more decisive than stiffness for vibration attenuation. In such cases, a warmer configuration may provide better performance by promoting mechanical energy dissipation.

This means that an ideal configuration in a given frequency band under cold conditions may correspond to a different effective range under hot conditions. Therefore, depending on the frequency range analyzed, both a configuration with a response predominantly dominated by stiffness (cold condition) and one with a response predominantly dominated by damping (hot condition) can provide better results. The ideal condition arises from the balance between maintaining adequate structural stiffness and maximizing energy dissipation.

Figure 3 shows the magnituded squared frequency response of the system under two different temperature conditions, 30°C and 60°C, illustrating the explanation presented above. Note that the increase in temperature causes the natural frequencies to shift to lower values, reflecting the reduction in effective stiffness associated with the increase in molecular mobility of the viscoelastic material. On the contrary, the lower peak amplitudes observed at 60°C indicate greater energy dissipation, resulting in a reduction in the maximum amplitudes associated with the analyzed modes. However, the reduction in stiffness associated with the increase in temperature can make the structure too flexible, compromising its performance in certain frequency ranges.

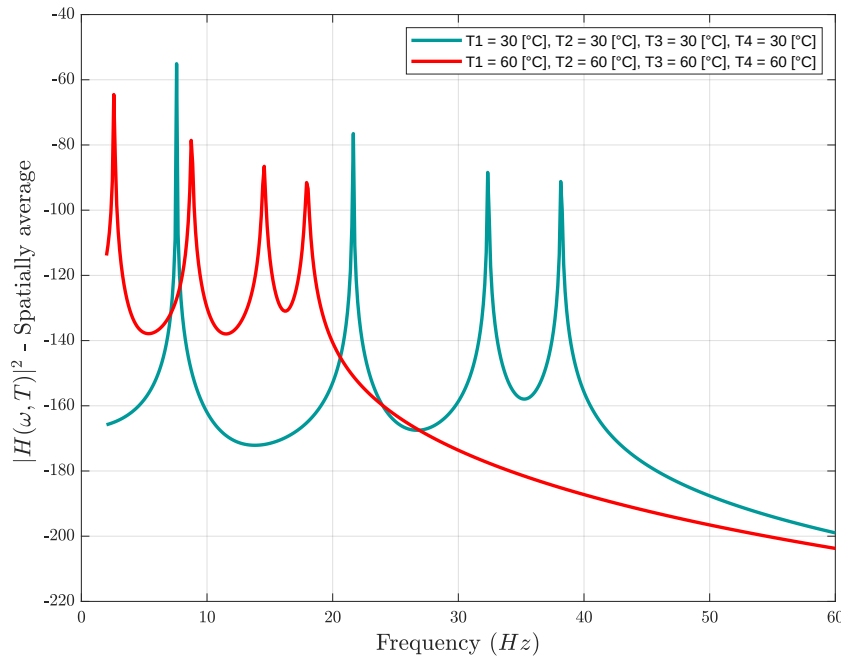


Figure 3. Compared frequency response function for 30°C and 60°C degrees.

3.2 GRAPH LAPLACIAN POTENTIAL

A graph is denoted by $G = (V, E)$, where V represents the set of vertices (or nodes) and $E \subseteq \{\{i, j\} \subset V : i, j \in V, i \neq j\}$ represents the set of edges. Thus, each edge $\{i, j\} \in E$ indicates an undirected connection between the vertices

i and j . The set of vertex is defined as $V := \{1, 2, \dots, N\}$, where N denotes the total number of vertices in the graph. Graphs may also be classified according to the direction of their edges. In directed graphs, edges are ordered pairs (i, j) , and it is possible that $(i, j) \in E$ while $(j, i) \notin E$ Bapat (1996), Buciualea Vlas (2024). Throughout this work, we consider simple undirected graphs as shown in Fig. 4.



Figure 4. Communication topology of the multi-agent system.

The adjacency matrix of G , denoted by $A(G) \in R^{N \times N}$, is defined by Bapat (1996) as:

$$a_{ij} = \begin{cases} 1, & \text{if } \{i, j\} \in E, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Since G is undirected, $A(G)$ is symmetric. The degree of vertex $i \in V$ is defined as:

$$d_i = |\{j \in V : \{i, j\} \in E\}|. \quad (3)$$

$$D(G) = \text{diag}(d_1, d_2, \dots, d_N). \quad (4)$$

The Laplacian matrix is defined as follows:

$$L(G) = D(G) - A(G). \quad (5)$$

Based on the graph topology illustrated in Fig. 2, the Lagrangian matrix of the system can be expressed as follows:

$$L(G) = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix}.$$

Finally, for a general undirected graph, the Laplacian potential of the graph is defined by Zhang *et al.* (2011):

$$V_L(G) = \sum_{i,j=1}^N a_{ij}(x_j - x_i)^2 = 2x^T Lx, \quad (6)$$

where a scalar vibrational response metric associated with agent i is defined as

$$x_i = \int_{\omega_1}^{\omega_2} |H_i(\omega, T)|^2 d\omega, \quad (7)$$

being $H_i(\omega, T)$ the local magnituded squared frequency response of agent i , evaluated over the frequency interval $[\omega_1, \omega_2]$. Then the global response vector is defined as

$$x = [x_1, x_2, \dots, x_N]^T \in R^N. \quad (8)$$

The Equation (6) is adopted as a cost function to adjust the parameters of each agent, with the aim of attenuating the overall dynamic response of the system. The performance of the system is evaluated based on the frequency band integrated response. For each band, the parameters of the agents are dynamically adjusted to minimize the response discrepancy between neighboring agents, as defined by the communication topology (see Fig. 3). In this formulation, $V_L(G)$ quantifies the vibrational disagreement among neighboring agents. It satisfies $V_L(G) \geq 0$, and $V_L(G) = 0$ if and only if $x_1 = x_2 = \dots = x_N$, which characterizes the consensus in the vibrational response.

This decentralized formulation ensures that each agent relies exclusively on the information of its nearest neighbors when evaluating the cost function. As a result, the optimization process remains fully distributed, while the collective interaction among agents leads to a global attenuation of the system response.

4. RESULTS

Table 1 presents the temperature combinations considered optimal for reaching consensus among agents in different frequency bands of the vibrational response. It can be observed that in bands $2 - 10Hz$, $10 - 17Hz$, $17 - 28Hz$ and $28 - 40Hz$, associated bands where the vibratory response is increased, the optimal configurations involve different temperatures for the agents. This behavior is directly related to the influence of structural dynamics on the consensus process. Close to natural frequencies, the vibrational response increases, making the system more sensitive to variations in stiffness and damping. For certain agents, increasing the temperature favors consensus, increasing energy dissipation and reducing resonance amplitudes. For others, maintaining higher structural stiffness is more relevant to limit excessive displacements and preserve local dynamic stability. Thus, global consensus arises from the balance between the effects of stiffness and dissipation, which vary according to the modal participation of each agent. The bands $40 - 50Hz$ and $50 - 60Hz$, located immediately after the last modal peak, are in a region where the dynamic response is already significantly reduced and less sensitive to stiffness variations. In this range, the behavior of the system becomes progressively less dependent on the dominant modal contribution, which explains the persistence of the same optimal combinations observed for both bands.

Figure 5 presents the magnituded squared frequency response corresponding to the configurations indicated in Table 1, evaluated over the entire frequency range. Temperature variation can be observed to significantly alter the dynamic behavior of the system, both in terms of the natural frequency positioning and the intensity of the resonance amplitude. In configurations associated with higher temperatures, the natural frequencies shift to lower values, reflecting the reduction in the effective stiffness of the viscoelastic material resulting from increased molecular mobility. In addition, a reduction in peak amplitudes is observed, indicating greater energy dissipation and, consequently, lower dynamic amplification in the close of resonance. These results reinforce that the effect of temperature on the vibrational response does not occur uniformly and that the balance between stiffness and damping plays an important role.

To confirm the convergence of the system and verify whether the agents reached consensus, the difference in the vibrational response was analyzed. Fig. 6 shows the evolution of this difference, which allows the collective behavior of the agents to be evaluated. It can be observed that, in all bands analyzed, the vibrational difference between the agents tends to zero, indicating that consensus was effectively reached. However, the frequency bands $17 - 28Hz$ and $28 - 40Hz$ show greater variation during the convergence process, suggesting a dynamic sensitivity in these frequency ranges.

These results demonstrate that the system was able to achieve consensus among agents, even in the absence of global information about structural dynamics. The convergence of the vibrational difference to values close to zero indicates that the local interaction mechanism was sufficient to promote collective coordination. In addition, it is observed that the agents were able to identify optimal temperature settings for different frequency bands, adapting to the dynamic behavior of each band analyzed. On the one hand, there is variation among the optimal temperatures obtained, which shows that the results are not trivial, nor are they the result of a single dominant configuration. On the other hand, the observed behavior reflects the complex interaction between stiffness, damping, and modal contribution in each frequency band.

Table 1. Temperature combinations for each agent that minimize the cost function

	2 - 10 [Hz]	10 - 17 [Hz]	17 - 28 [Hz]	28 - 40 [Hz]	40 - 50 [Hz]	50 - 60 [Hz]
T1 [°C]	20	20	44	60	60	60
T2 [°C]	60	52	29	60	60	60
T3 [°C]	52	20	60	51	60	60
T4 [°C]	60	20	29	43	60	60

5. CONCLUSIONS

In this work, a multi-consensus system for vibration reduction was implemented. A viscoelastic material with temperature and frequency dependent properties was used, and a cost function was employed to iteratively adjust the material properties until a configuration was found in which the disagreement between each agent and its closest neighbors tended toward zero. None of the agents had access to the system's global vibrational information. Thus, the proposed strategy is characterized as a decentralized approach, in which each agent makes decisions based exclusively on local information.

The analysis of the results demonstrated that, for each frequency band considered, a specific temperature configuration was identified as optimal. It was also observed that, depending on the analyzed band, one material response curve may exhibit superior performance compared to others. This occurs because viscoelastic behavior is intrinsically dependent on both frequency and temperature, directly influencing the storage modulus and, in particular, the loss factor of the material. In certain frequency ranges, the material may exhibit a greater capacity for mechanical energy dissipation, associated with the peak of the loss factor, resulting in increased damping and, consequently, improved vibration attenuation performance. However, in other bands, the same thermal configuration may not coincide with the region of maximum dissipation,

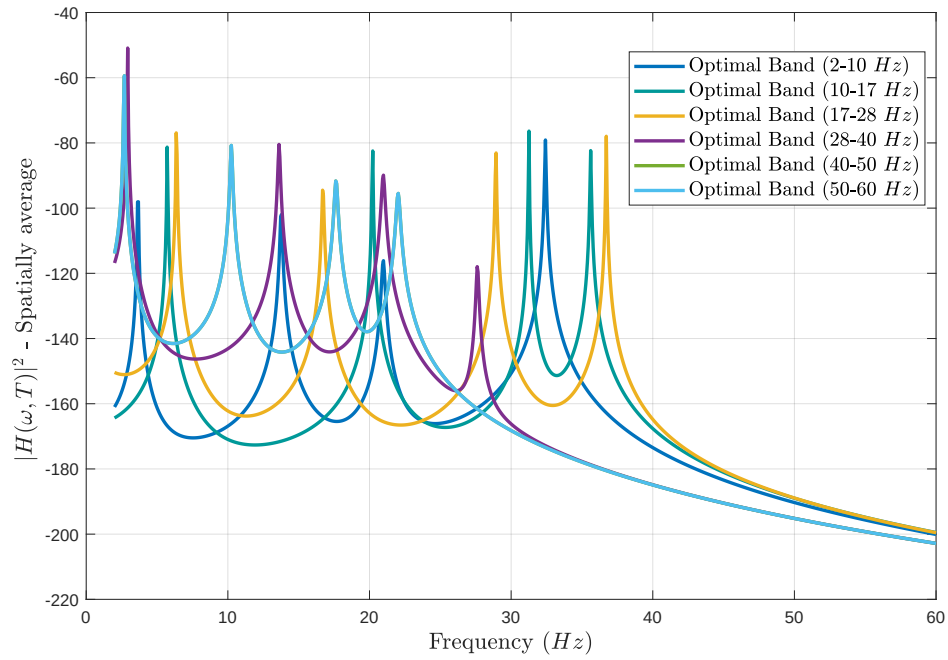


Figure 5. Compared frequency response function for optimal configurations per band.

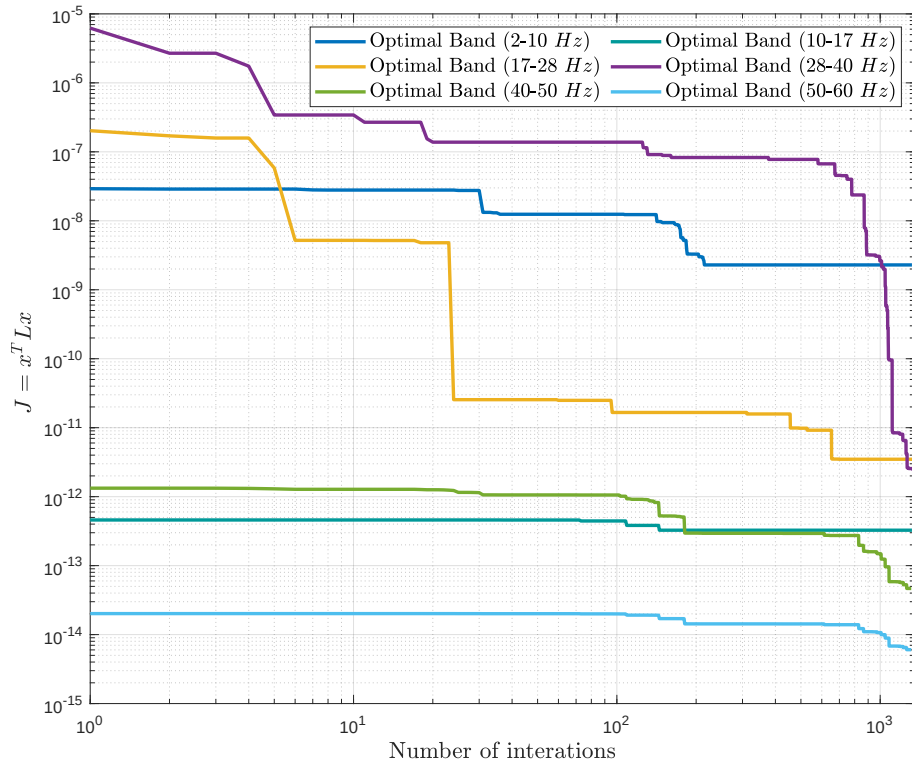


Figure 6. Convergence of the Laplacian potential, indicating consensus among agents.

making another curve, corresponding to a different thermal condition, more efficient.

In this context, it is important to emphasize the need to establish a balance between vibration reduction and preservation of the stiffness of material, which prevents it from becoming excessively flexible. Thus, the relationship between stiffness and damping must be taken into account when defining the ideal operating conditions. This constitutes the next

step in this work.

Therefore, the proposed system demonstrates adaptive capability, being able to autonomously identify the best conditions for different vibrational environments by exploiting the thermal frequency dependence of the viscoelastic material to minimize disagreement among agents and, consequently, reduce the vibration levels of the system.

6. ACKNOWLEDGEMENTS

This work has been supported by the EIPHI Graduate School (contract ANR-17-EURE-0002) and the Region Bourgogne Franche-Comté and ANR JCJC project (ANR-25-CE51-5866)

7. REFERENCES

- Bapat, R.B., 1996. "The laplacian matrix of a graph". *Mathematics Student-India*, Vol. 65, No. 1, pp. 214–223.
- Buciulea Vlas, A., 2024. "Robust graph topology inference".
- Butaud, P., 2015. *Contribution à l'utilisation des polymères à mémoire de forme pour les structures à amortissement contrôlé*. Ph.D. thesis, Université de Franche-Comté.
- da Silva, L.A., 2003. *Internal variable and temperature modeling behavior of viscoelastic structures: A control analysis*. Ph.D. thesis, Virginia Polytechnic Institute and State University.
- Hu, X., Xiong, Y., Zhang, Z. and Li, C., 2024. "Consensus of a new multi-agent system via multi-task, multi-control mechanism and multi-consensus strategy". *Neurocomputing*, Vol. 584, p. 127586.
- Lei, Y., Wu, D. and Lin, Y., 2012. "A decentralized control algorithm for large-scale building structures". *Computer-Aided Civil and Infrastructure Engineering*, Vol. 27, No. 1, pp. 2–13.
- Mohit, Chhabra, D. and Kumar, S., 2015. "Active vibration control of the smart plate using artificial neural network controller". *Advances in Aerospace Engineering*, Vol. 2015, No. 1, p. 137068.
- Moreira, R., Corte-Real, J. and Rodrigues, J.D., 2010. "A generalized frequency-temperature viscoelastic model". *Shock and Vibration*, Vol. 17, No. 4-5, pp. 407–418.
- Nagata, T., Takemura, K., Sato, K. and Matsuoka, Y., 2012. "Emergent design of dynamical behavior". *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, Vol. 6, No. 2, pp. 274–286.
- Naresh, K., Khan, K.A., Umer, R. and Vasudevan, A., 2020. "Temperature-frequency-dependent viscoelastic properties of neat epoxy and fiber reinforced polymer composites: experimental characterization and theoretical predictions". *Polymers*, Vol. 12, No. 8, p. 1700.
- Qiu, Z.c., He, C.h. and Zhang, X.m., 2022. "Multi-agent cooperative structural vibration control of three coupled flexible beams based on value decomposition network". *Engineering Applications of Artificial Intelligence*, Vol. 114, p. 105002.
- Qiu, Z.c., Hu, J.f. and Zhang, X.m., 2023. "Multi-agent reinforcement learning vibration control and trajectory planning of a double flexible beam coupling system". *Mechanical Systems and Signal Processing*, Vol. 200, p. 110502.
- Soto, M.G. and Adeli, H., 2017. "Multi-agent replicator controller for sustainable vibration control of smart structures". *Journal of Vibroengineering*, Vol. 19, No. 6, pp. 4300–4322.
- Zhang, H., Lewis, F.L. and Qu, Z., 2011. "Lyapunov, adaptive, and optimal design techniques for cooperative systems on directed communication graphs". *IEEE transactions on industrial electronics*, Vol. 59, No. 7, pp. 3026–3041.

8. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.