On the use of thermomechanical couplings for the design of adaptive structures

Morvan Ouisse, Pauline Butaud, Emmanuel Foltête, and Gaël Chevallier

Univ. Bourgogne Franche-Comté, FEMTO-ST Department of Applied Mechanics, 24 rue de l'épitaphe, 25000 Besançon, France

ABSTRACT

Thermomechanical couplings are responsible for the smart behavior of Shape Memory Polymers (SMPs). Additionally to the shape memory effect, the strong and fast glass transition in this kind of material is directly related to radical changes in the storage modulus and loss factor of the material. When integrated into composite structures, these materials can be used to change in real time the global stiffness and structural damping. This type of strategy opens new ways for vibration control which are currently investigated at FEMTO-ST institute. Several applications of this concept are described, corresponding to various scales and frequency ranges. For each of them, the design strategy based on finite element analysis is shown, taking advantage of thermomechanical couplings to describe the various behaviors of the composite. Then, the prototypes are manufactured and tested. Various complexity levels in the thermal fields are obtained through regulation, from homogeneous to gradient or even heterogeneous so that many structural behaviors can be obtained and changed in real time. Illustrations are shown on sandwich panels, phononic crystals and acoustic black holes. Open challenges are finally discussed.

Keywords: Thermal control, vibration control, damping, shape memory polymers

1. INTRODUCTION

Shape Memory Polymers (SMPs) have been widely investigated in the past years as they possess interesting properties for smart applications. Due to their fast glass transition between the glassy and the rubbery state, they exhibit a radical change in the storage modulus when the temperature is crossing this transition. This provides the so-called memory effect which makes possible for the material to recover its initial shape when the material is heated above the glass transition. This transition is well known in the context of viscoelastic materials.[1,2] Another effect which is much less investigated for SMPs is the very large loss factor which is resulting from this fast glass transition.[3,4] In the works presented here, it is proposed to take advantage of these strong temperature dependency so that these materials can be used as part of composite structures for vibration control. However, since the viscoelastic properties are dependent on both frequency and temperature,[1,5,6] it is of first importance to take into account the temperature effects for the design of composite structures whose damping properties are provided by polymer materials,[7–11] and the materials have to be chosen in adequacy with the operating temperature ranges in order to guarantee the robustness of the design.[12]

The composite structures proposed in this article fall in the adaptive structures family, that comes from active control strategies.[13,14] Here the concepts may rather be qualified as semi-active[15,16] or simply adaptive, since the characteristic time required to pass from one configuration to another (a few seconds) is much larger than the periods associated to the dynamical effects to be controlled. Damping control is an important question which can be addressed by smart structures[17,18] with several strategies, among which magneto-elastic couplings,[17,19] or smart honeycomb composite cores based on shape memory polymers.[20] Thermal tuning is also a promising way to control the mechanical properties,[21] in particular with shape memory polymers or alloys[22,23] .

2. MATERIAL

All structures presented in this paper are based on tBA-PEGDMA[24], a shape memory polymer whose storage modulus is around 2 GPa in the glassy state and below 1 MPa in the rubbery state, with a loss factor around 2.5 at the glass transition (close to 70°C at 1 Hz). An analytical thermomechanical viscoelastic model has been identified, which provides all required relationships between the temperature and the mechanical properties of the material.[24] The complex temperature- and frequency-dependent modulus writes

$$E^*(\omega) = E_0 + \frac{E_\infty - E_0}{1 + \gamma(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + \gamma(i\omega\beta\tau)^{-1}}. \tag{1}$$

Here $k = 0.17$, $h = 0.79$, $\gamma = 1.43$, $\beta = 3.1 \times 10^4$, $i = \sqrt{-1}$, ω is the angular frequency, E_0 is the rubber modulus when $\omega \to 0$ and E_∞ is the glassy modulus when $\omega \to +\infty$. τ is the characteristic time, computed according to the Time-Temperature Superposition principle by $\tau(T) = a_T(T)\tau_0$ with $\tau_0 = 2.13 \times 10^{17}$ s. The shift factor a_T is expressed by a Williams–Landel–Ferry (WLF) law:

$$\log(a_T) = \frac{-C_1(T - T_0)}{-C_2 + (T - T_0)}, \tag{2}$$

with $C_1 = 28.28$, $C_2 = 12.5$°C and $T_0 = 20$°C.

This model has been implemented in a finite element code for the simulations.

3. SANDWICH PANEL WITH TUNABLE CORE

The first illustration is a sandwich panel made from aluminium skins and SMP core[25]. This panel exhibits a highly resonant behavior at ambient temperature, while homogeneous heating around 80°C leads to very flat frequency responses in a wide frequency range (10 Hz to 10 kHz covering 10 modes). The measurements correlate very well with the 3D finite element model, for the various temperature states investigated (see Fig. 1).

This was possible thanks to deep investigations on the thermomechanical properties of the material and the identification of the associate model. 3D modelling of the multilayer composite was required as existing zig-zag[26, 27] models fail for very high damping levels as this is the case for the material used here.

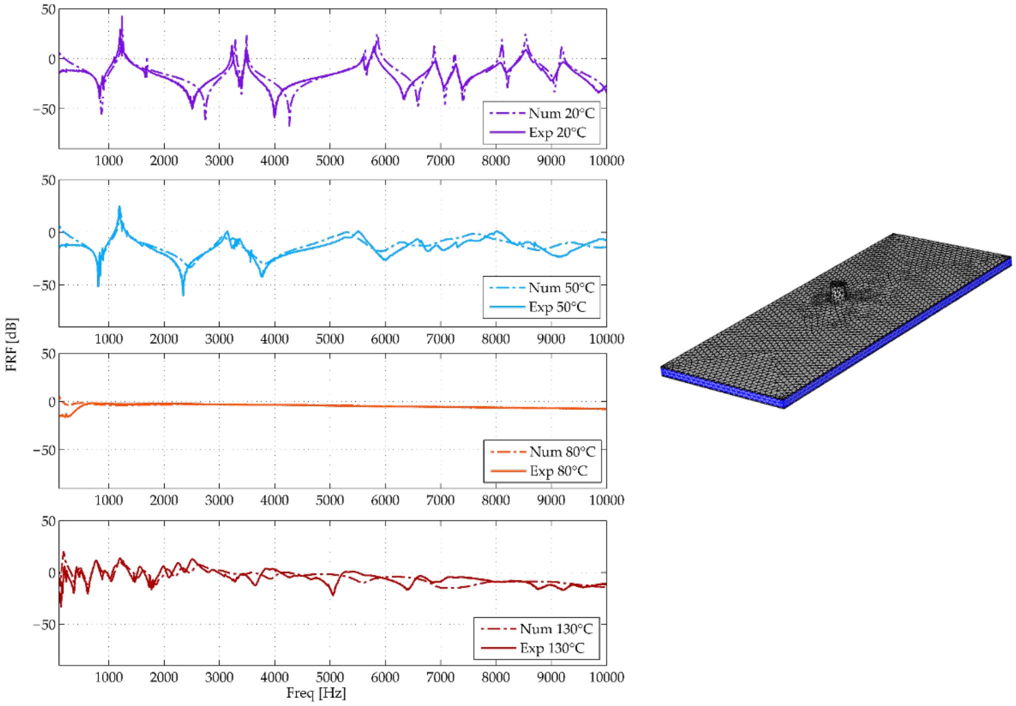

Figure 1. Temperature tuning of the core of a sandwich panel: frequency response functions (test/model correlation, left) and 3D finite element model (right)

4. TWO-STATES ADAPTIVE PHONONIC CRYSTAL

As the storage modulus of the SMP is radically changed between the glassy and the rubbery states, it becomes possible to design two-states systems. This has been recently applied for the tuning of the stiffness of a phononic crystal built with composite slots, made from aluminium cylinders with SMP interface to the host plate[28] (see Fig.2). This structure hence possesses two radically different states: at ambient temperature, a classical stop-band behavior is obtained, while when heated above the glass transition, a bare plate behaviour is measured, allowing all waves to travel freely in the host plate.

Figure 2. View of the phononic crystal with the adaptive SMP interface

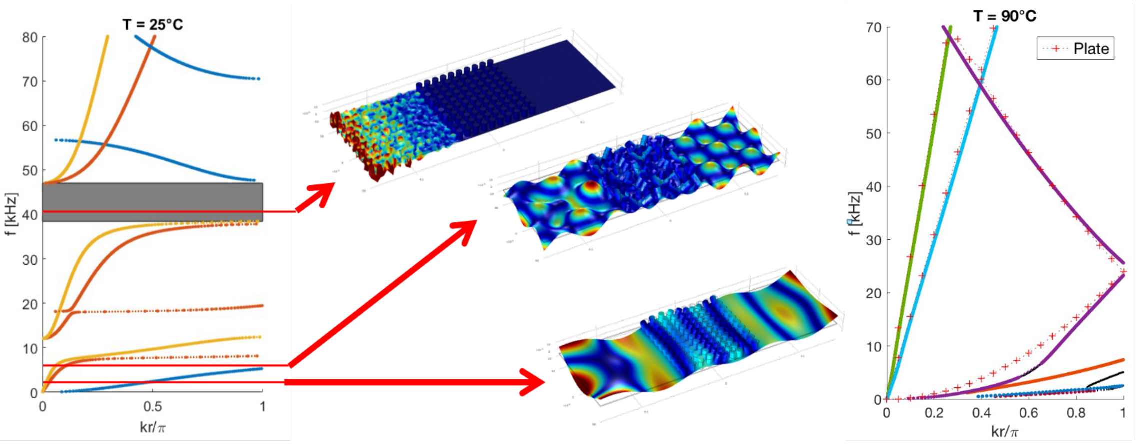

Figure 3. Ilustration of the principle of the two-states phononic crystal (dispersion diagrams and vibration response of the finite structure). At 25°C, the structures is a phononic crystal with a classical stop-band band, while the phononic aspect is removed at 90°C with a behavior very close to a bare plate.

The model-based design of such a metamaterial requires the ability to compute dispersion diagrams for structures with dissipative and frequency-dependent properties, which is only possible with very specific techniques.[29] As for the previous case, the experimental validation was performed with uniform heating of the material. To this end, a thermal chamber is used and the measured behaviours are in accordance with the simulation results shown in Figure 3.

5. ACOUSTIC BLACK HOLES WITH TUNABLE PROPERTIES

The last example associated to homogeneous temperature field is a beam with an Acoustic Black Hole (ABH) termination. This termination has a varying thickness so that the bending waves velocity decreases when approaching the end of the beam. Their energy can hence be dissipated with a damping layer. The corresponding damping level plays a major role in the efficiency of the ABH. The heating of the SMP layer provides an easy way to reach the optimal configuration[30], so that incoming waves can be efficiently absorbed by the ABH (see Figure 4). In this case, analytical models were used both for the beam and the material using RKU[31] model combined with the material model described above in the paper.

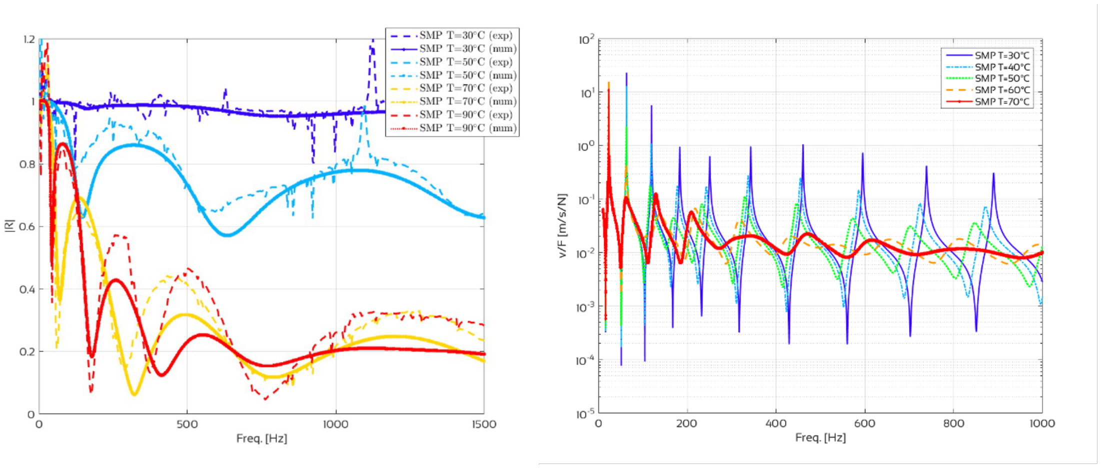

Figure 4. Reflection coefficient of an acoustic black hole termination on a beam (left) and input mobility of the beam. The model correlates well with the experiments, and the frequencies of the minimum of the reflection coefficient (ie. the location of the maximum absorption) can be tuned with the temperature.

6. LOCAL CONTROL OF DAMPING AND STIFFNESS IN MULTILAYERED COMPOSITES

Much more complex configurations can be obtained by performing local heating of the SMP: very heterogeneous temperature fields can easily be used to provide very heterogeneous mechanical properties, in terms of stiffness and damping. This has been used to obtain unusual compromises between stiffness and damping in composite panels with SMP cores[32].

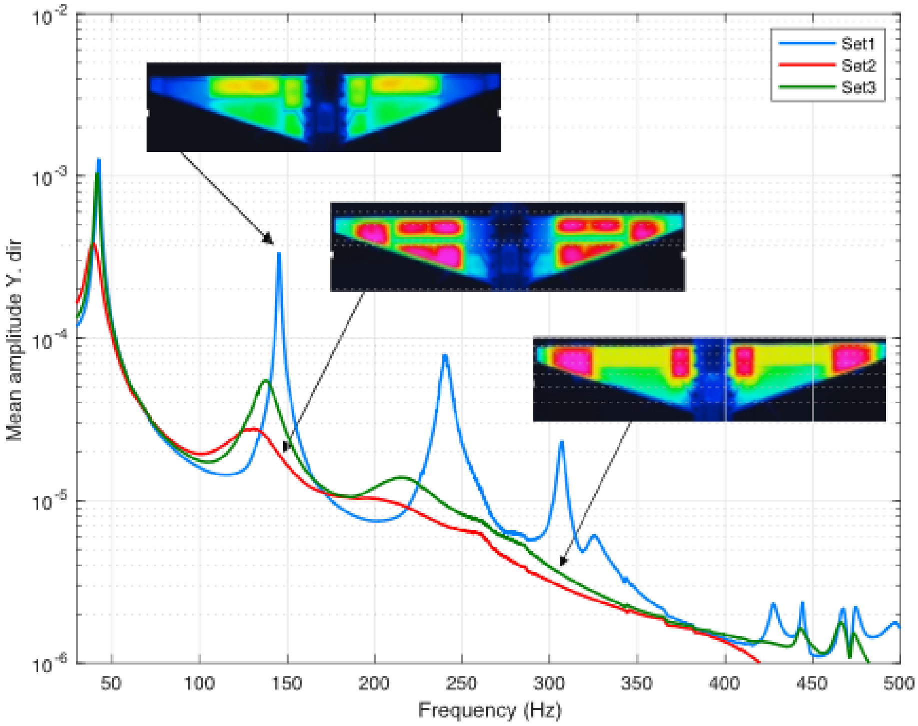

Figure 5. View of the thermal fields obtained on a multilayered composite structure, providing heterogeneous mechanical properties, and associated measurements of the averaged FRF over the structure. The colors on the mapping correspond to the temperature fields measured by infrared thermography, for temperature sets 1, 2 and 3 from top to bottom, respectively.

This kind of structure includes heating devices in the composite structure. They are made of copper tracks printed on one of the layer. Joule effect is used to heat the core, and PID-based temperature regulation provides the heterogeneous mechanical properties field with the embedded temperature sensors. The design of such structures requires the precise knowledge of the temperature field in the core: copper tracks size is defined according to thermal simulation, from which the mechanical properties of the SMP are defined and used in a 3D finite element of the composite structure. Then, optimization procedures are required to find optimal configurations corresponding either to best static (set 1) or dynamic properties (set 2), or a compromise between the two (set 3).

7. LOCAL CONTROL OF DAMPING AND STIFFNESS IN MULTILAYERED COMPOSITES

The concept has been recently extended to the ABH[33] (see Fig.6), providing a clear illustration of the concept of critical coupling thanks to the gradient of the mechanical properties, obtained with the ABH termination equipped with a thermal controler layer and a SMP patch.

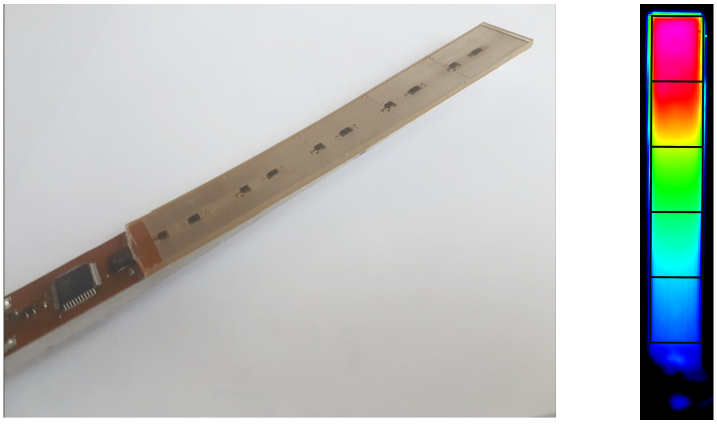

Figure 6. View of an ABH termination equipped with a thermal controler layer and an SMP patch (left) and example of gradient that can be obtained (right)

8. CONCLUSION

This paper reviews several recent applications of model-based concepts involving thermal control for structural dynamics applications. The key element is the SMP wich renders possible to obtain highly rigid or soft, highly damped or not configurations. Frequency and temperature-dependent material models are required, before being used in 3D models combining thermal and mechanical simulations. Experimental validation requires local heating strategies, that can be obtained with printed copper tracks and Joule effect. When fast changes are required, this technique is however limited to heating and has a poor efficiency for cooling, which currently constitutes a limitation in terms of time response for real-time applications.

ACKNOWLEDGMENTS

This work has been supported by EUR EIPHI (ANR-17-EURE-0002) and by eTNAA (ANR-17-CE08-0035-01).

REFERENCES

[1] Ferry, J. D. and Ferry, J. D., [*Viscoelastic properties of polymers*], John Wiley & Sons (1980).

[2] Rao, M. D., "Recent applications of viscoelastic damping for noise control in automobiles and commercial airplanes," *Journal of Sound and Vibration* **262**(3), 457 – 474 (2003).

[3] Tsai, Y., Tai, C.-h., Tsai, S.-J., and Tsai, F.-J., "Shape memory effects of poly (ethylene terephthalate-co-ethylene succinate) random copolymers," *European Polymer Journal* **44**(2), 550–554 (2008).

[4] Barwood, M. J., Breen, C., Clegg, F., and Hammond, C. L., "The effect of organoclay addition on the properties of an acrylate based, thermally activated shape memory polymer," *Applied Clay Science* **102**, 41–50 (2014).

[5] Caputo, M. and Mainardi, F., "Linear models of dissipation in anelastic solids," *La Rivista del Nuovo Cimento (1971-1977)* **1**(2), 161–198 (1971).

[6] Lakes, R. S., [*Viscoelastic solids*], vol. 9, CRC press (1998).

[7] Chang, K.-C., Soong, T., Oh, S.-T., and Lai, M., "Effect of ambient temperature on viscoelastically damped structure," *Journal of Structural Engineering* **118**(7), 1955–1973 (1992).

[8] Sefrani, Y. and Berthelot, J.-M., "Temperature effect on the damping properties of unidirectional glass fibre composites," *Composites Part B: Engineering* **37**(4-5), 346–355 (2006).

[9] Lesieutre, G. A. and Govindswamy, K., "Finite element modeling of frequency dependent and temperature-dependent dynamic behavior of viscoelastic materials in simple shear," *International Journal of Solids and Structures* **33**(3), 419–432 (1996).

[10] Millithaler, P., Dupont, J.-B., Ouisse, M., Sadoulet-Reboul, E., and Bouhaddi, N., "Viscoelastic property tuning for reducing noise radiated by switched-reluctance machines," *Journal of Sound and Vibration* **407**, 191–208 (2017).

[11] Bai, Y., Yu, K., Zhao, J., and Zhao, R., "Experimental and simulation investigation of temperature effects on modal characteristics of composite honeycomb structure," *Composite Structures* **201**, 816–827 (2018).

[12] Jaboviste, K., Sadoulet-Reboul, E., Peyret, N., Arnould, C., Collard, E., and Chevallier, G., "On the compromise between performance and robustness for viscoelastic damped structures," *Mechanical Systems and Signal Processing* **119**, 65–80 (2019).

[13] Fuller, C. C., Elliott, S., and Nelson, P. A., [*Active control of vibration*], Academic Press (1996).

[14] Inman, D. J., [*Vibration with control*], John Wiley & Sons (2017).

[15] Collet, M., Ouisse, M., and Tateo, F., "Adaptive metacomposites for vibroacoustic control applications," *IEEE Sensors Journal* **14**(6) (2014).

[16] Ouisse, M., Collet, M., and Scarpa, F., "A piezo-shunted kirigami auxetic lattice for adaptive elastic wave filtering," *Smart Materials and Structures* **25**, 115016 (2016).

[17] Irazu, L. and Elejabarrieta, M. J., "A novel hybrid sandwich structure: Viscoelastic and eddy current damping," *Materials & Design* **140**, 460–472 (2018).

[18] Ganguli, A., Deraemaeker, A., and Preumont, A., "Regenerative chatter reduction by active damping control," *Journal of Sound and Vibration* **300**, 847–862 (2007).

[19] Irazu, L. and Elejabarrieta, M., "Effect of magneto-elastic force on magneto-dynamic model of viscoelastic-magnetorheological sandwiches," *Smart Materials and Structures* **28**(7), 075022 (2019).

[20] Tao, R., Yang, Q.-S., Zhang, X.-J., Liu, X., He, X.-Q., and Liew, K.-M., "Numerical study of smart honeycomb core using shape memory polymers," *Journal of Applied Polymer Science* **135**(2), 45672 (2018).

[21] McCoul, D., Rosset, S., Besse, N., and Shea, H., "Multifunctional shape memory electrodes for dielectric elastomer actuators enabling high holding force and low-voltage multisegment addressing," *Smart Materials and Structures* **26**(2), 025015 (2016).

[22] Coppola, A. M., Griffin, A. S., Sottos, N. R., and White, S. R., "Retention of mechanical performance of polymer matrix composites above the glass transition temperature by vascular cooling," *Composites Part A* **78**, 412–423 (2015).

[23] Zhang, R.-X., Ni, Q.-Q., Masuda, A., Yamamura, T., and Iwamoto, M., "Vibration characteristics of laminated composite plates with embedded shape memory alloys," *Composite Structures* **74**, 389–398 (2006).

[24] Butaud, P., Ouisse, M., Placet, V., Renaud, F., Travaillot, T., Maynadier, A., Chevallier, G., Amiot, F., Delobelle, P., Foltête, E., and Rogueda-Berriet, C., "Identification of the viscoelastic properties of the tBA/PEGDMA polymer from multi-loading modes conducted over a wide frequency–temperature scale range," *Polymer Testing* **69**, 250–258 (2018).

[25] Butaud, P., Foltête, E., and Ouisse, M., "Sandwich structures with tunable damping properties: on the use of shape memory polymer as viscoelastic core," *Composite Structures* **153**, 401–408 (2016).

[26] Marchetti, F., Ege, K., Leclere, Q., and Roozen, N., "On the structural dynamics of laminated composite plates and sandwich structures; a new perspective on damping identification," *Journal of Sound and Vibration* **474**, 115256 (2020).

[27] Arasan, U., Marchetti, F., Chevillotte, F., Jaouen, L., Chronopoulos, D., and Gourdon, E., "A simple equivalent plate model for dynamic bending stiffness of three-layer sandwich panels with shearing core," *Journal of Sound and Vibration* **500**, 116025 (2021).

[28] Billon, K., Ouisse, M., Sadoulet-Reboul, E., Collet, M., Butaud, P., Chevallier, G., and Khelif, A., "Design and experimental validation of a temperature-driven adaptive phononic crystal slab," *Smart Materials and Structures* **28**, 035007 (2019).

[29] Collet, M., Ouisse, M., Ruzzene, M., and Ichchou, M., "Floquet–bloch decomposition for the computation of dispersion of two-dimensional periodic, damped mechanical systems," *International Journal of Solids and Structures* **48**(20), 2837–2848 (2011).

[30] Ouisse, M., Renault, D., Butaud, P., and Sadoulet-Reboul, E., "Damping control for improvement of acoustic black hole effect," *Journal of Sound and Vibration* **454**, 63–72 (2019).

[31] Ross, D., Ungar, E., and Jr., E. K., "Damping of plate flexural vibrations by means of viscoelastic laminae," *J.E.Ruzicka(Ed.), Structural Damping* , 49–87 (1960).

[32] Butaud, P., Renault, D., Verdin, B., Ouisse, M., and Chevallier, G., "In-core heat distribution control for adaptive damping and stiffness tuning of composite structures," *Smart Materials and Structures* **29**, 065002 (2020).

[33] Raybaud, G., Pelat, A., Ouisse, M., and Gautier, F., "Zero reflections by a 1d acoustic black hole termination using thermally controlled damping," *Journal of Sound and Vibration* **510**, 116282 (2021).