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Self-adaptive piezoelectric vibration absorber with semi-passive tunable resonant shunts

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Abstract

This paper proposes a novel self-adaptive strategy to control piezoelectric vibration absorbers (PVA) using a semi-passive resonant shunt with tunable inductance for vibration attenuation of harmonically excited structures. The tunable inductor is realized using ferrite cores and its inductance is controlled by means of the air gap effect between the cores using piezoelectric stack actuators. This device allows the control of the resonance frequency of the shunt circuit. The adaptive resonant shunt leverages the effect of antiresonance resulting from the electromechanical coupling of the structure with a resonant shunt with low electrical damping to attenuate the vibration of the harmonically excited structure. A machine learning control method based on a Gaussian process regression model is used to drive the tunable inductance based on minimizing the time-averaged RMS response of the structure. The experimental application of the proposed strategy is illustrated in an application to attenuate a single-mode of a simplified aircraft fuselage structure. A reduction of about 30% in the maximum vibration amplitude is observed by comparing the self-adaptive resonant circuit and a traditional resonant circuit designed based on the equal-peaks method.

Keywords: Adaptive shunt, Semi-passive resonant shunt, Piezoelectric vibration absorber, Tunable inductor, Machine learning control

1. Introduction

The growing demand for more efficient and environmentally friendly structures has led to a current trend toward lightweight structures, often more flexible and making them more susceptible to vibrations. This brings new challenges for current vibration control technologies, which must operate with increasing efficiency and contribute a minimum of mass to the structures on which they are installed [1]. In this context, one such technology that is gaining increasing interest are piezoelectric vibration absorbers (PVA). These devices, invented by Forward [2], employ piezoelectric transducers mounted on or even embedded in a primary

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30 structure to convert mechanical energy into electrical energy, which can be dissipated in
31 an appropriate electrical circuit, called a shunt. The first shunt introduced by Forward [2]
32 and one of the most famous is the so-called resonant shunt composed of a resistor and an
33 inductor connected in series or parallel. Since then, different types of passive and active
34 shunt circuits have been developed for single and multi-mode damping of vibrations [1].

35 The theoretical foundations for the design of resonant PVA shunts were laid by Hagood
36 and Flotow [3] based on the equal-peak design method developed for dynamic vibration
37 dampers (DVA), which is considered to be an equivalent mechanical system. This method
38 provides an approximate solution of values for resistance and inductance to the optimization
39 problem defined by minimizing the H_∞ -norm of the system's frequency response function
40 (FRF) considering a single mode. Recently, an analytic closed-form solution to this opti-
41 mization problem was proposed by Soltani et al. [4]. Several other methods for designing
42 resonant circuits have been investigated and proposed in the literature, including more
43 complex shunts and multiple modes of vibration [5, 6]. Most of these methods focus on
44 broadband frequency excitation, with the objective of attenuating single or multiple vibra-
45 tion modes as much as possible. Fundamentally, they rely on tuning the electrical resonance
46 frequency to the desired mechanical resonance frequency, in order to maximize the transfer
47 of vibration energy from the primary structure to the shunt circuit, where it is dissipated
48 through electrical damping. Although PVA with resonant shunts can provide an important
49 vibration attenuation for low frequency modes, small variations in the resonance frequency
50 of the shunt or the primary structure cause substantial performance degradation [7, 8].

51 In view of this problem many studies have investigated PVAs with adaptive resonant
52 shunts, which are circuits capable of performing on-line adaptation of their impedance [1].
53 This type of device is commonly used to improve the robustness of piezoelectric absorbers
54 in operation, which are very sensitive to uncertainties due to operational and environmental
55 conditions. The adaptive shunt circuit is able to change its properties to compensate for
56 possible effects of variation in its resonance frequency or of the structure, improving the
57 robustness of the vibration attenuation performance. For the design of an adaptive shunt
58 two elements are essential: a mechanism to drive its natural frequency and a strategy of
59 control. Hollkamp and Starchville [9] were the pioneers to propose a PVA with an adaptive
60 shunt, capable of automatically adjusting to the resonance frequency of a defined vibration
61 mode using a motorized potentiometer and a synthetic inductor. They proposed a control
62 strategy based on the minimization of the root mean squared value of the time-vibration
63 signal by gradient-search algorithm. Fleming et al. [10] applied a control strategy for the
64 single-mode shunt damping in a cantilevered beam structure using a synthetic impedance
65 controlled by adjusting the relative phase difference between the velocity and the electrical
66 current flowing in the shunt, which was later extended to multi-mode shunt damping by
67 Niederberger et al. [11]. Gripp et al. [12] explored the use of a negative capacitance with
68 an adaptive resonant shunt, controlled by the relative phase difference between velocity and
69 electrical current, to improve the attenuation robustness of the PVA in the face of variations
70 in the natural frequency of the host structure. They demonstrated a significant gain in
71 attenuation performance of this circuit in a shell structure compared to a purely adaptive
72 resonant shunt. More recently, Gardonio et al. [13] demonstrated that minimizing the time-

73 averaged vibration response of a mechanical system with a PVA when the system is excited
74 by a stochastic force is equivalent to maximizing the time-averaged electric power dissipated
75 by the resonant shunt, which is characterized by a bell-type non-convex surface with a single
76 maximum. From this result they developed an adaptive shunt using a controller based on
77 the extremum seeking algorithm capable of adjusting online the resistance and inductance
78 emulated by an synthetic impedance to maximize the time-averaged electric power dissipated
79 by the PVA [14]. In addition to adaptive shunts, which are usually based on active circuits,
80 switching shunts based on semi-active circuits such as state switching and synchronized
81 switch damping have also been explored in the literature to improve the PVA robustness
82 [15–18]. The major drawbacks of switching shunts are the high order frequency signals
83 required to control the switching circuits and the acoustic disturbances during operation [1].

84 The adaptive PVA shunts proposed in the literature are mostly oriented to structures
85 excited in a broad frequency band, aiming to ensure near-optimal attenuation independent
86 of variations in the natural frequencies of the structure’s modes, which usually leads to a fre-
87 quency response function with two equal-peaks. On the other hand, in harmonically excited
88 structures, minimizing the vibration amplitude at each frequency leads to an even more
89 efficient solution by tuning the electrical resonance frequency to the excitation frequency
90 and decreasing the electrical damping as much as possible, creating an anti-resonance [19].
91 For very low damping, this anti-resonance can practically cancel the steady state vibra-
92 tion amplitude of the structure. This effect can be exploited with adaptive shunt circuits
93 capable of tuning their electrical resonance frequencies by changing their parameters to
94 attenuate structures excited with time-varying harmonic signals. This strategy, known as
95 antiresonance locus, was recently exploited by Audeley et al. [19, 20] in an electromag-
96 netic vibration absorber with adaptive resonant shunt controlled by an electronic chopper
97 with pulse-width modulation. Despite being a well established strategy in the literature
98 and already explored for electromagnetic vibration absorbers, the experimental application
99 of the antiresonance locus strategy to absorbers based on piezoelectric transducers has not
100 yet been investigated and proves to be challenging because the required reduction in the
101 electrical damping reduces the robustness and stability margin of the structure, hindering
102 the design of a suitable controller, and it also increases the energy flowing through the
103 shunt circuit. This latter issue hampers the application of active circuits commonly used
104 in adaptive shunts, such as virtual inductors realized for example using Antoniou’s circuit
105 [21] or Riordan’s gyrators [22], or synthetic impedance circuits [23]. Although these active
106 circuits provide a remarkable electrical frequency adaptability, they suffer from saturation
107 limits often related to their operational amplifiers. Details of the saturation issues faced by
108 virtual inductors and synthetic impedances, as well as the delay-induced instabilities of the
109 latter, are discussed in Dekemele et al. [24] and Raze [25] respectively. In this context, a
110 novel semi-passive resonant shunt is proposed in this work to enable the application of the
111 antiresonance locus strategy using piezoelectric transducers for vibration attenuation, which
112 has the potential to substantially reduce the mass added to the primary structure compared
113 to electromagnetic transducers, since they are lighter and the resonant circuit that presents
114 more weight can be positioned outside the structure through the electrical connection.

115 The control of PVA with adaptive shunts mostly relies on traditional control approaches

116 based on system identification to design a controller, and then depend on accurate model de-
117 scriptions to enable safe and high performance control. This process can be time-consuming
118 and a complex endeavor in the presence of nonlinearities. Machine learning methods can
119 circumvent this process by learning the system’s input-output characteristics directly from
120 data, offering a significant potential for control, which although have been extensively ex-
121 plored in the past years in robotic applications [26, 27], to the author’s best knowledge has
122 not been yet explored in PVA. A machine learning control approach using a Gaussian Process
123 Regression model (GPR) is investigated in this work in the development of a self-adaptive
124 PVA based on the anti-resonance locus strategy for vibration attenuation of harmonically
125 excited structures. It is important to note that the self-adaptive capability is fundamentally
126 different from that applied in PVA with traditional adaptive shunts, as the system learns
127 how to adapt to changes in excitation frequency by itself through the machine learning
128 model. This type of self-adaptive or self-learning strategy has recently been explored in the
129 literature for other vibration control techniques. Wang et al. [28] proposed a self-learning
130 tuning method based on neural networks for an electromagnetic vibration absorber with
131 negative stiffness under variable frequency excitation. Song et al. [29] investigated the use
132 of a nonlinear autoregressive with exogenous input model for vibration identification and
133 control of a flexural beam with piezoelectric actuators. A similar approach using a GPR
134 model was recently explored by Maiworm et al. [30, 31] in a control framework for scanning
135 quantum dot microscopy.

136 In this paper, we propose a self-adaptive PVA with semi-passive resonant shunt for vi-
137 bration attenuation of structures subjected to time-varying harmonic excitations. The main
138 objective of this paper is to circumvent the above-mentioned challenges in developing this
139 type of device and to demonstrate the experimental application for vibration attenuation
140 in a demonstrator. We present the development of a tunable resonant shunt composed of a
141 passive inductor with movable ferrite cores and low internal resistance. A simple mechanism
142 to control its inductance and consequently the electrical resonance frequency of the shunt is
143 proposed based on the use of voltage-driven piezoelectric stack actuators to control the air
144 gap between its ferrite cores. A machine learning approach to control this device based on
145 GPR model is investigated. This model is used in an offline step for supervised learning of
146 the control signal applied to the resonant shunt to minimize the vibration of the main struc-
147 ture as a function of the excitation frequency, thus providing the self-adaptive capability of
148 its electrical resonance frequency to the time-varying tonal excitation for real-time control.
149 Therefore, the self-adaptive PVA proposed in this work, which seeks to attenuate vibration
150 based on the anti-resonance locus strategy using the ML control algorithm, requires, in addi-
151 tion to the piezoelectric patch connected to the tunable semi-passive shunt circuit, a second
152 piezoelectric sensor patch on the structure used as a sensor and a digital processing unit to
153 execute the control algorithm. The potential range of applications of the self-adaptive PVA
154 investigated here, which is limited to harmonically excited structures, targets propulsion
155 systems, such as propellers or turbofan engines, and rotating machinery in general.

156 This paper is organized as follows: in Section 2 a lumped mass model of a single-degree-
157 of-freedom structure connected to a resonant shunt is reviewed and is used to present the
158 theoretical foundations of the strategy for vibration attenuation of harmonically excited

159 structures based on antiresonance locus. A brief description of the semi-passive tunable res-
 160 onant shunt development and the theoretical concept behind the inductance tuning device
 161 based on the air gap between the movable ferrite cores is presented. Then, the self-adaptive
 162 control strategy based on the GPR model for the implementation of closed-loop system is
 163 presented. The experimental setup for applying the proposed methodology on the demon-
 164 strator and the results obtained are presented and discussed in Section 3. Finally, the
 165 conclusions are summarized in Section 4.

166 2. Piezoelectric vibration absorbers

167 In this section a lumped mass model of a structure connected to a PVA with resonant
 168 shunt is presented. This simplified model is sufficient to show the fundamentals of the
 169 operation and design of a PVA, as well as the adaptive strategy for vibration attenuation of
 170 harmonically excited structures. The fundamentals for the design of the tunable inductance
 171 are presented and discussed. Finally, the complete self-adaptive strategy for online control
 172 of the system is proposed.

173 2.1. Lumped parameter model of structure with piezoelectric vibration absorber

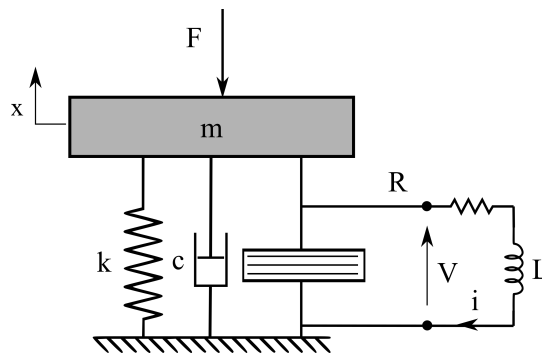


Figure 1: Lumped mass model of the structure with the piezoelectric vibration absorber.

174 The lumped mass model of a structure coupled to a piezoelectric transducer connected
 175 to a resonant shunt composed of an inductor and a resistor in series is schematically repre-
 176 sented in Figure 1. An external force F is applied to the structure, causing a mechanical
 177 displacement x and a voltage V across the electrodes of the transducer. The governing
 178 equations of the coupled mechanical and electrical systems are given by [25]:

$$\begin{cases} m\ddot{x} + c\dot{x} + k_{oc}x - \theta q = F \\ L\ddot{q} + R\dot{q} + \frac{1}{C^\epsilon}q - \theta x = 0, \end{cases} \quad (1)$$

179 where m , c , k_{oc} represent the mass, damping and stiffness of the structure when the trans-
 180 ducer is open-circuited (including the mechanical stiffness of the piezoelectric component),
 181 q is the electric charge displacement, θ is the piezoelectric coupling coefficient and C^ϵ is the
 182 piezoelectric capacitance at constant strain.

183 The electromechanical coupling factor of this system is defined based on the mechanical
 184 behavior considering open-circuit ($q = 0$) and short-circuit ($V = 0$) electrical boundary
 185 conditions, and it is given by:

$$k_c = \sqrt{\frac{\omega_{oc}^2 - \omega_{sc}^2}{\omega_{sc}^2}} \quad (2)$$

186 where ω_{oc} and ω_{sc} are the resonance frequencies of the structure with the transducer in
 187 open-circuit and short-circuit configurations respectively, and are defined by:

$$\omega_{oc} = \sqrt{\frac{k_{oc}}{m}} \quad \text{and} \quad \omega_{sc} = \sqrt{\frac{k_{sc}}{m}} = \sqrt{\frac{k_{oc} - \theta^2 C^\varepsilon}{m}} \quad (3)$$

188 where k_{sc} is the structural stiffness when the transducer is short-circuited.

189 The electromechanical coupling defined by Equation 2 is an important factor consid-
 190 ered for shunt circuit design because it represents the efficiency of strain energy conversion
 191 into electrical energy. Furthermore, it can be easily identified experimentally through the
 192 frequencies of the structure in open and short-circuit, which allows to mitigate modeling
 193 uncertainties [25].

194 The dynamic behavior of the electric circuit RL can be characterized by the resonance
 195 frequency (ω_e) and the electrical damping (ξ_e), which are obtained by:

$$\omega_e = \frac{1}{\sqrt{LC^\varepsilon}}, \quad \xi_e = \frac{R}{2} \sqrt{\frac{C^\varepsilon}{L}} \quad (4)$$

196 The frequency response function of this model can be computed from the Fourier trans-
 197 form of the Equation 1 and results in:

$$H(\omega) = \frac{X(\omega)}{F(\omega)} = \frac{-\omega^2 L + i\omega R + \frac{1}{C_p^\varepsilon}}{(-\omega^2 m + i\omega c + K_{oc}) \left(-\omega^2 L + i\omega R + \frac{1}{C^\varepsilon} \right) - \theta^2} \quad (5)$$

198 where $X(\omega)$ is the Fourier transform of x , $F(\omega)$ is the Fourier transform of F and $i = \sqrt{-1}$.

199 Based on the FRF, the problem of vibration attenuation considering a broadband ex-
 200 citation can be described as an optimization problem, where one wants to minimize the
 201 H_∞ -norm, for example the FRF maximum amplitude. The solution of this optimization
 202 problem considering the FRF displacement/force leads to an approximation for the optimal
 203 inductance and resistance values [6]:

$$L_{ep} = \frac{1}{C^\varepsilon \omega_{oc}^2} \quad \text{and} \quad R_{ep} = \sqrt{\frac{3}{2}} \frac{k_c}{C^\varepsilon \omega_{oc}} \quad (6)$$

204 This solution shows no significant difference for systems with low structural damping
 205 (below 10%) as demonstrated by Thomas et al. [6]. It leads to a FRF with two peaks of
 206 equal amplitudes around the resonance frequency of the mechanical system with a substantial
 207 amplitude attenuation compared to the system with an open-circuit transducer (or without
 208 PVA) as presented in Figure 2. However, small variations in the properties of the shunt

209 or the structure can cause an important increase in the maximum amplitude. It should be
 210 remarked that this solution considers a broadband frequency excitation near the mode and
 211 constant properties of the shunt.

212 *2.2. Adaptive shunt based on antiresonance locus*

213 In considering a harmonic excitation of the structure of known frequency Ω and an
 214 adaptive resonant shunt in which the inductance and resistance can be varied, a more efficient
 215 attenuation can be obtained using a different strategy, the antiresonance locus [20]. This
 216 strategy can be inferred from the FRF presented in Equation 5. The electromechanical
 217 coupling of the transducer induces a term in the numerator of the equation. For a given
 218 excitation frequency (Ω) and assuming null electrical resistance, one can show from Equation
 219 5 that the FRF is zero for :

$$L_{adaptive} = \frac{1}{C\epsilon\Omega^2} \quad (7)$$

220 This occurs due to the existence of an antiresonance, in which the excitation force coun-
 221 teracts the force generated by the electromechanical coupling, making the structure remain
 222 at rest [20]. It should be noted, however, that this case of complete vibration attenuation
 223 of the structure at rest is purely theoretical as it would imply an infinite current in the
 224 circuit. In practice, although significant vibration attenuation can be achieved, it is lim-
 225 ited. By increasing the electrical resistance in the circuit, some of the energy is dissipated
 226 as heat, reducing the attenuation effect on the antiresonance. If the electrical resistance
 227 remains small, the maximum attenuation is obtained for the inductance given by Equation
 228 7, for which $\Omega = \omega_e$. Therefore, by applying this strategy for a harmonic excitation vary-
 229 ing within a frequency range one can drastically attenuate the vibration amplitude of the
 230 structure as presented in Figure 2.

231 The application of this strategy depends on controlling of the resonance frequency of
 232 the electrical circuit through the inductance and a circuit with low electrical resistance. Al-
 233 though these two issues can be solved using a synthetic impedance to emulate the resistance
 234 and the inductance, this type of active circuit has instability problems along with other
 235 limitations already discussed previously. To circumvent these limitations, we propose the
 236 use of a semi-passive device that will be discussed in the next subsection.

237 *2.3. Semi-passive tunable inductor*

238 A passive inductor is a simple device, typically consisting of a coil of wire, which can be
 239 wound around a core made of different materials such as iron, ferrite, or air. This electrical
 240 component stores energy in a magnetic field when a current flows through the coil. The
 241 great difficulty in using passive inductors in PVA is related to the high values of inductance
 242 required for attenuation of low frequency modes - usually in the order of tens of H - which are
 243 difficult to find commercially or present impractical dimensions [32]. Nevertheless, Lossouarn
 244 et al. [32] recently demonstrated the feasibility of more compact high-value passive inductors
 245 using ferrite cores with high magnetic permeability. Although this allows the fabrication of
 246 the inductors necessary for the resonant circuit, these devices have constant inductance. In

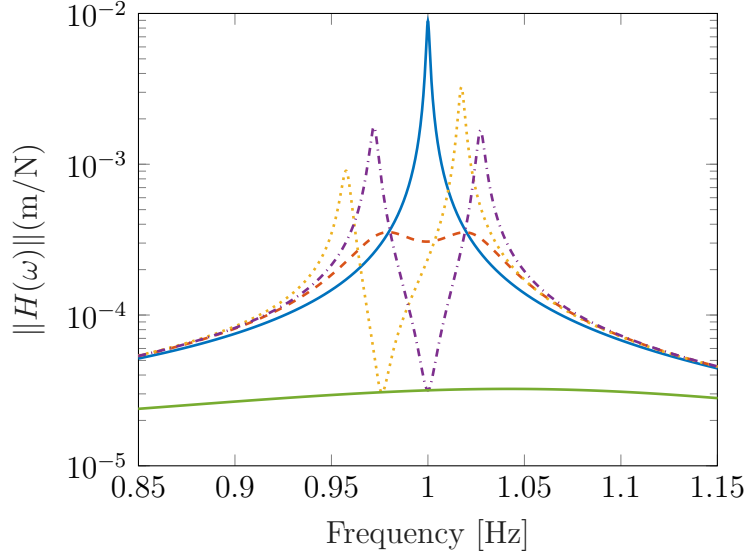


Figure 2: Frequency response function of primary system with an open-circuit transducer (—) and with resonant shunt circuit : $L = L_{ep}$ and $R = R_{ep}$ (- -); $L = L_{ep}$ and $R = 0.1R_{ep}$ (- · -); $L = 0.9L_{ep}$ and $R = 0.1R_{ep}$ (· · ·); $L = \frac{1}{C\epsilon\Omega^2}$ and $R = 0.1R_{ep}$ (—). A mechanical damping ratio of 0.08 % is considered for the system with open-circuit shunt.

247 order to realize a device with tunable inductance, necessary to implement the antiresonance
 248 locus strategy, we will investigate the effect caused by the air gap between the ferrite cores.

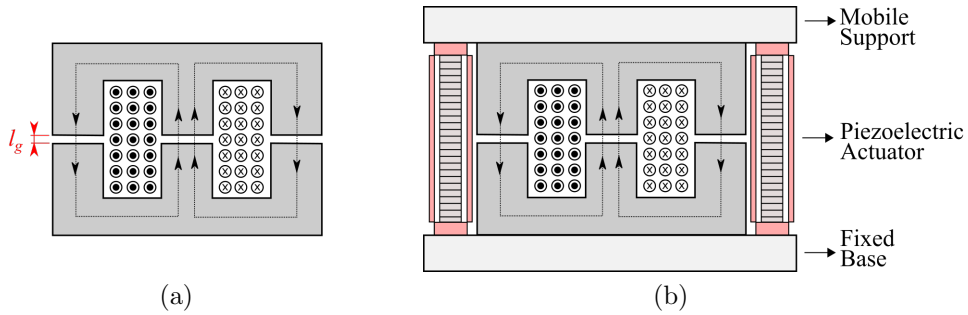


Figure 3: Inductance with air gap scheme.

249 The effects of the presence of an air gap between the cores of the inductors have been well
 250 studied in the literature. It is commonly exploited to improve the design of these devices,
 251 since it increases the saturation current, allows the storage of more energy, and decreases
 252 the sensitivity of the inductor to variations in the magnetic properties of the cores [33]. For
 253 the inductor illustrated in Figure 3(a), under assumption of a homogeneous flux density
 254 distribution, the inductance and air gap l_g are related by $L = C_1/(C_2 + C_3l_g)N^2$, where N
 255 is the number of turns in the coil, and C_1 , C_2 and C_3 constants are related to inductor's
 256 dimensions and physical properties as discussed Darleux [34]. Indeed, the inductance can
 257 be controlled by the air gap between the cores. It is important to note that this linear

258 relationship is valid under the assumption of a homogeneous flux density distribution, which
 259 is reasonable for a small air gap. However, as the gap increases, the magnetic flux lines
 260 begin to bulge, causing the effective reluctance of the air gap to decrease and the inductance
 261 to increase in a non-linear relationship, a phenomenon known as the fringe effect. For more
 262 details on the fringe effect, the interested reader may refer to [33, 35].

263 Small variations in the air gap can cause significant variations in inductance, thus re-
 264 quiring a precise control mechanism. For this purpose, we propose the use of the system
 265 illustrated in Figure 3(b) composed of two piezoelectric stack actuators capable of control-
 266 ling the air gap between the cores with micrometer precision and two mechanical supports
 267 attached to the cores. The piezoelectric stack actuators allow the upper core to be dis-
 268 placed by the force transmitted through the mobile support. The displacement is imposed
 269 by applying a constant voltage on the piezoelectric stacked actuators.

270 2.4. Self-adaptive PVA based on machine learning control

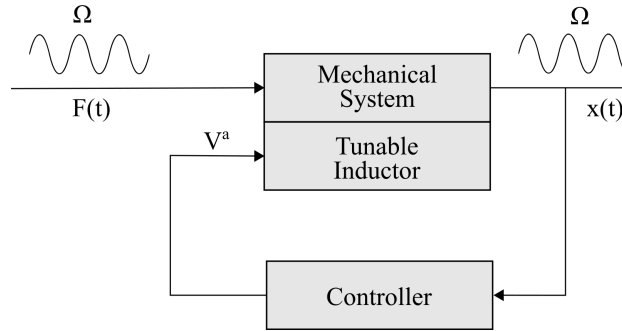


Figure 4: General schematic representation of the closed-loop control structure.

271 Having designed the semi-passive tunable inductor presented in the previous subsection,
 272 it can be used in a closed-loop system to implement the vibration attenuation based on
 273 the antiresonance locus approach. A diagram with all of the components of this system is
 274 illustrated in Figure 4. Recall that the main goal of the self-adaptive strategy proposed here
 275 is to minimize the vibration of the mechanical structure for a given harmonic excitation by
 276 controlling the tunable inductance through the applied voltage on the piezoelectric stack
 277 actuators.

278 As discussed for the simplified lumped mass model, the solution of this optimization
 279 problem is based on the strategy of an antiresonance locus considering a small resistance
 280 and adaptive inductance, leading to Equation 7, where the optimal inductance depends on
 281 the excitation frequency and represents the condition in which the frequency of the electrical
 282 circuit coincides with the excitation frequency. Although this solution can be directly related
 283 to the mechanism of inductance tuning through the air gap between the ferrite cores, it is
 284 important to note that this variable is driven by the voltage applied to the piezoelectric
 285 actuators, which has an unknown relationship with the air gap. To address this problem,
 286 we propose an approach based on machine learning control.

287 Machine learning control has recently been formalized by Duriez et al. [36] as a generic
 288 model-free strategy for controlling nonlinear systems, although one of the first works using
 289 this type of technique was reported by Fleming and Purshouse [37] in the past. In this
 290 approach, the control problem is formulated as an optimization with respect to a cost func-
 291 tion that can be evaluated using the system’s measured outputs. The control objective is
 292 to minimize the defined cost function within the space of the control laws. The controller is
 293 formulated based on a machine learning algorithm that is trained on an off-line learning loop
 294 using data from simulations or experiments. It is then used to minimize the objective in the
 295 online closed-loop control system [38]. Different machine learning algorithms have been used
 296 with this approach, including: genetic algorithms, reinforcement learning, artificial neural
 297 networks, and support vector machines [36, 39].

298 In this paper we propose to use the Gaussian process regression (GPR) model, a machine
 299 learning algorithm that has attracted attention due to its stochastic formulation and ability
 300 to describe nonlinear functions. We propose to use the GPR model in an off-line loop for the
 301 supervised learning, where a training data set under operational conditions is provided and
 302 the model learns by itself the relationship between the observed variables, which is a priori
 303 unknown. This model is then used in the closed-loop system using a controller, based on the
 304 machine learning approach to determine the applied voltage for each excitation frequency,
 305 in order to minimize the vibration amplitude of the structure. This novel self-adaptive
 306 strategy to control the resonant shunt is illustrated in Figure 5 and presented in detail in
 307 what follows.

308 In the problem presented in this paper, the cost function is the time-averaged RMS of
 309 the vibration of the mechanical system, which is assumed to depend only on the excitation
 310 frequency (Ω) and the applied voltage of the piezoelectric actuators (V^a) of the tunable
 311 inductance, and is expressed as $J(\Omega, V^a)$. This hypothesis is supported by the linear vibra-
 312 tion behavior of the structure for the applied excitation level. Additionally, environmental
 313 uncertainties, such as temperature variation, which can also impact this cost function, are
 314 not considered. This type of cost function was already explored with adaptive resonant
 315 shunts and is justified by its smooth behavior, less susceptible to noise than the maximum
 316 vibration amplitude, and the existence of a global minimum point as reported by Fleming
 317 and Moheimani [10].

318 Consider a data set available for training with noisy observations of the time-averaged
 319 RMS response $\mathbf{J} = [J_1, \dots, J_N]^T$ of the mechanical system for a set of applied actuator
 320 voltage $\mathbf{V}^a = [V_1^a, \dots, V_N^a]^T$ and excitation frequencies $\mathbf{\Omega} = [\Omega_1, \dots, \Omega_N]^T$. Adopting the
 321 notation of Rasmussen[40], let $\mathbf{x} = [\mathbf{V}^a, \mathbf{\Omega}]^T$ denote a matrix of multivariate training inputs,
 322 and $\mathbf{y} = [\mathbf{J}]$ denote the corresponding vector of training outputs. Assuming that these
 323 observations can be expressed following regression model :

$$y_i = f(x_i) + \varepsilon, \quad \varepsilon \sim \mathcal{N}(0, \sigma_n^2) \quad (8)$$

324 where f is a unknown function and ε is a Gaussian distributed noise with zero mean and
 325 variance σ_n^2 . Various methods can be used to solve this classic regression problem. We pro-
 326 pose in this work to apply the Gaussian Process regression (GPR) model, a non-parametric

327 stochastic model that has been recently explored for control problems of this type. Thus,
 328 the function f can be written as:

$$f(\mathbf{x}) \sim \mathcal{GP}(m(\mathbf{x}), k(\mathbf{x}, \mathbf{x}')) \quad (9)$$

329 where $m(\mathbf{x})$ and $k(\mathbf{x}, \mathbf{x}')$ are respectively the mean and covariance functions of the distri-
 330 bution over functions described by the Gaussian process.

331 The main aim of the GPR model is to make predictions for new input data that are not
 332 in the training data. Given a new input vector, \mathbf{x}_* , one can estimate the distribution over
 333 functions of a new point y_* given the previous observations as :

$$f_*(\mathbf{x}_*) \sim \mathcal{N}(m_*(\mathbf{x}_*), k_*(\mathbf{x}_*, \mathbf{x}_*)) \quad (10)$$

334 where

$$\begin{aligned} m_*(\mathbf{x}_*) &= k_*^T(\mathbf{x}^*, \mathbf{x}) [K(\mathbf{x}, \mathbf{x}) + \sigma_n^2 \mathbf{I}]^{-1} \mathbf{y}, \\ k_*(\mathbf{x}_*, \mathbf{x}'_*) &= k(\mathbf{x}_*, \mathbf{x}'_*) - k(\mathbf{x}_*, \mathbf{x})^\top (K + \sigma_n^2 \mathbf{I})^{-1} k(\mathbf{x}, \mathbf{x}_*). \end{aligned} \quad (11)$$

335 are the posterior mean and variance of the GPR model, \mathbf{I} is the identity matrix, σ_n^2 is
 336 the variance of the noise and K is a matrix whose i, j -th element is given by the covari-
 337 ance function $k(x_i, x_j)$. An effective and common choice for the covariance function is the
 338 squared-exponential function which is adopted in this paper. The hyperparameters of the
 339 GPR model comprising the noise signal (σ_n^2) and length-scale of the squared-exponential
 340 covariance function are obtained through the maximization of the marginal likelihood func-
 341 tion using a gradient-based optimizer based on the Sequential Least Squares Programming
 342 method. This traditional procedure for training the GPR model is not detailed here for
 343 the sake of clarity. The interested reader is invited to consult [40, 41] for more details. In
 344 addition, the code used for implementation is available on the github repository¹.

345 Assuming that the posterior mean of GPR model adequately represents the cost function
 346 $J(\Omega, V^a)$, it can be used to control the voltage applied to the piezoelectric actuators in order
 347 to minimize the vibration of the structure by solving the following minimization problem:

$$\bar{V}^a(\Omega) = \underset{V^a}{\operatorname{argmin}} m_*(\Omega, \mathbf{V}^a) \quad (12)$$

348 This problem can be solved for a given excitation frequency by interpolating the GPR
 349 model within the training domain and selecting the voltage to be applied to the piezoelectric
 350 actuators that provides the lowest value for the cost function. The complete closed-loop
 351 system based on the machine learning control approach is presented in the diagram of
 352 Figure 5. In the training step of the GPR model, which is carried out offline, the excitation
 353 frequency and the applied voltage are varied throughout the training domain and the cost
 354 function is obtained experimentally by calculating the RMS value of the system response for
 355 each operational condition. The excitation frequency is estimated from the system response

¹<https://github.com/jessepaixao/SPARTA>

356 signal using the fast Fourier transform based on the parabolic interpolation approach, which
 357 provides improved frequency resolution for harmonic signals [42]. It is important to note
 358 that in the closed-loop operation of the control system, only the excitation frequency is used
 359 as the input variable of the trained GPR model, which is used to estimate the voltage value
 360 that minimizes the cost function. Additionally, it should be emphasized that the trained
 361 GPR model provides an approximation of the cost function within the training domain and
 362 is only valid for closed-loop operation under the training conditions.

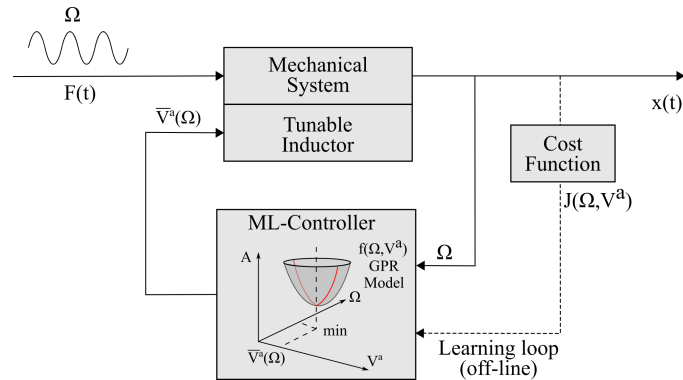


Figure 5: Proposed self-adaptive strategy for the the closed-loop operation of the PVA with semi-passive tunable inductor based on the machine learning control approach using GPR model for vibration attenuation of a harmonically excited structure.

363 3. Experimental validation of the self-adaptive vibration absorber

364 In this section the experimental application of the proposed strategy is presented for a
 365 simplified aircraft prototype. This mechanical structure is used only as a demonstrator for
 366 the validation of the methodology for vibration reduction. The design and realization of
 367 the resonant shunt and the passive tunable inductor are discussed. Then, the self-adaptive
 368 strategy is utilized for the vibration attenuation of the airplane prototype considering a
 369 swept harmonic excitation and the results obtained are discussed.

370 3.1. Experimental Setup

371 A photograph of the experimental apparatus is provided in Figure 6(a). The simplified
 372 aircraft mockup was suspended on a test rig by flexible cables to simulate free-free boundary
 373 conditions. Two piezoelectric patches were glued to the airplane wings, the first used for
 374 vibration attenuation connected to the shunt circuit, denoted PZT2, and another employed
 375 as a collocated sensor to measure the voltage, denoted as PZT1. A schematic representation
 376 detailing all components and the integration of the experimental setup is shown in Figure
 377 6(b), where three subsystems can be identified: the so-called testing subsystem highlighted
 378 in red, responsible for the excitation and vibration measurement of the structure to perform
 379 the tests; the named control subsystem highlighted in blue, an active circuit responsible for
 380 controlling the shunt circuit; and lastly the resonant shunt subsystem highlighted in green,
 381 a passive circuit.

382 The testing subsystem is managed by a computer dedicated to signal analysis and inte-
 383 grated with the Polytec controller. The structure is excited using an electrodynamic shaker
 384 positioned close to PZT 1 and the applied excitation force is measured using a load cell PCB
 385 type 208C01. The transverse velocity is measured at the point shown in Figure 6(b), the
 386 tip of the other wing to which the excitation is applied, using the Polytec Laser Doppler
 387 vibrometer PSV-500 Xtra 1D. The control subsystem is managed by the Raspberry Pi with
 388 the add-on boards MCC 128 and MCC 152 manufactured by Measurement Computing, ded-
 389 icated respectively for acquisition and analog signal generation. A voltage divider is used
 390 to adjust the voltage measurement at PZT2 to the acquisition card limits of plus or minus
 391 10V. The piezoelectric actuators in charge of the inductance variation are controlled by the
 392 signal generated in the MCC-152 card, which is amplified with a gain of 20 in the Cedrat XX
 393 power amplifier. The resonant circuit consisting only of the tunable inductor is connected
 394 to PZT2 and mounted right next to the aircraft prototype. The machine learning control
 395 algorithm for closed-loop operation in the experimental tests performed are implemented on
 396 the Raspberry Pi.

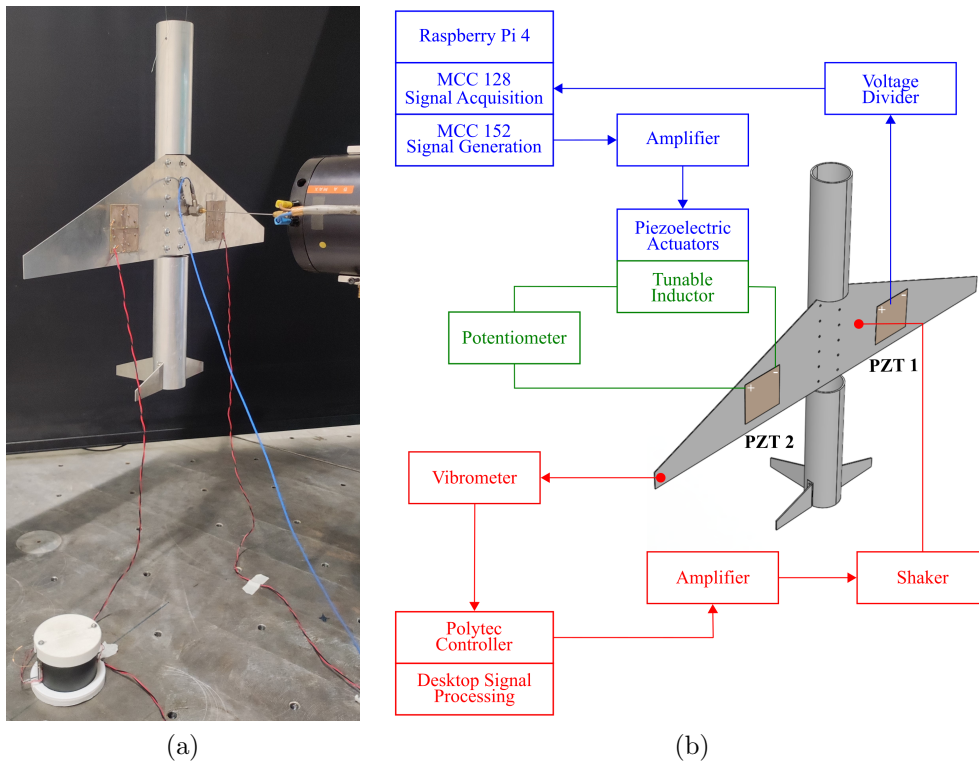


Figure 6: Photograph of the experimental setup (a) and its schematic representation (b).

397 3.2. Design and manufacturing of tunable passive inductor

398 The position and dimensions of the piezoelectric patches shown in Figure 6 were chosen
 399 based on a parametric study of the finite element model of the aircraft prototype coupled

400 with the piezoelectric patches. This model of the prototype aircraft was recently explored in
 401 the study presented by Bachy et al. [43] with a different type of absorber, where more details
 402 about its formulation, material properties and dimensions are presented. The parametric
 403 study using this model was carried out by varying the position of the piezoelectric patches
 404 along the wings of the prototype. The position providing the maximum electromechanical
 405 coupling factor with respect to the third bending mode of the aircraft was chosen. The choice
 406 of this symmetric mode was based on a compromise between its frequency and the inductance
 407 required to tune the PVA. Note that a mode with a lower resonance frequency would be
 408 possible, but would require a higher inductance (see Equation 4) and would consequently
 409 increase the number of turns required for the same type of ferrite core, thus increasing the
 410 dimensions of the inductor. The width and length dimensions of the patches were chosen
 411 to maximize the piezoelectric capacitance, aiming to reduce the inductance required that,
 412 according to Equation 6, is inversely proportional to the piezoelectric capacitance.

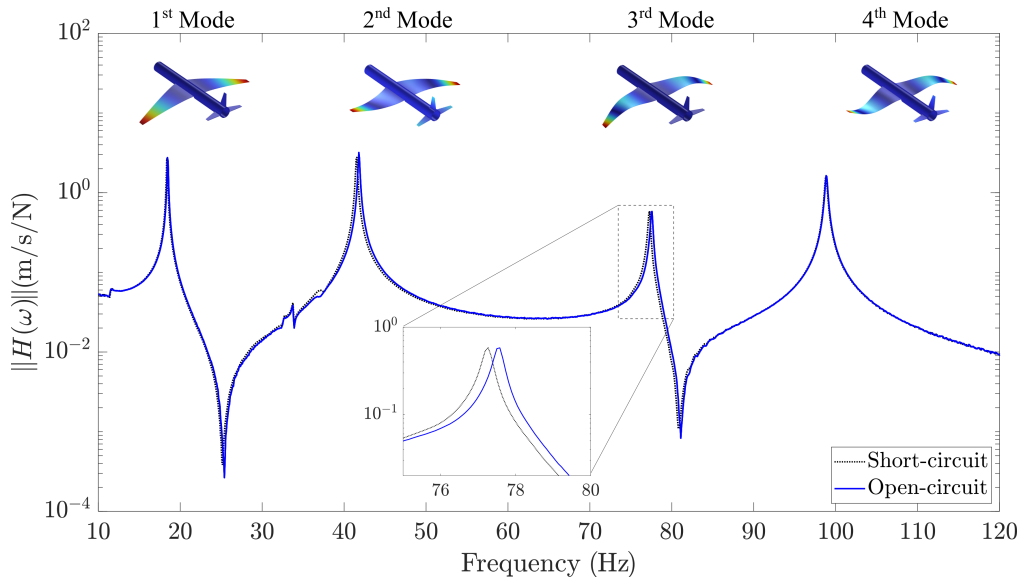


Figure 7: Mobility frequency response function and corresponding mode shapes for short-circuit and open-circuit patch configurations.

413 The initial design of the resonant circuit was performed considering constant induc-
 414 tance, given by Equation 6. The electromechanical coupling was estimated using Equation
 415 3 and the natural frequencies obtained from the experimental FRFs shown in Figure 7
 416 for the piezoelectric transducers in open-circuit and short-circuit conditions. The value
 417 of the piezoelectric capacitance at constant strain was measured experimentally using an
 418 impedance analyzer. From the estimated experimental parameters and using Equation 6,
 419 an inductance of 28.64 H and a resistance of 1533.18 Ω were obtained for the equal-peak
 420 design solution. All the numerical values are summarized in Table 1.

421 The inductance and resistance estimates for the solution based on the equal-peaks
 422 method was used as a starting point for the tunable inductor design. Among the various
 423 commercially available ferrite cores, the T26 ferrite was chosen because it offers a suitable

Table 1: Numerical values for the experimental estimated parameters.

ω_{oc} (Hz)	ω_{sc} (Hz)	k_c	C^ε (nF)	L_{ep} (H)	R_{ep} (Ω)	A_l ($\mu\text{H}/\text{tr}^2$)
77.56	77.25	0.0897	147	28.64	1533.18	10

424 compromise between inductance factor and maximum saturation current. Based on the
 425 initial values of inductance an resistance and the inductance factor supplied by the manu-
 426 facturer of the T26 ferrite cores it is possible to calculate the number of windings required
 427 to make the coil, which was 1692 turns. However, since the tunable inductance is controlled
 428 by the air gap between the cores, which decreases the inductance as the air gap increases,
 429 the coil is made with a higher number of turns to allow the inductance to vary within a
 430 margin of plus or minus 10% of the calculated initial value. Thus, the coil was manufactured
 431 using an automatic winding machine with 1900 turns of 0.35 mm diameter copper wire. The
 432 inductor was assembled using the coil and the T26 ferrite cores along with piezoelectric stack
 433 actuators. The overall dimensions of the ferrite core are 70 mm in diameter and 42 mm in
 434 height. The inductance measured using a LCR meter for the assembled inductor without
 435 air gap between the cores was 35.5 H with a quality factor of 181.3, which is equivalent to a
 436 DC resistance of 95 Ω . A photograph of the tunable inductor including the fixed base and
 437 movable support additively fabricated using PLA and the piezoelectric actuators is shown
 438 in Figure 8(a).

439 The characterization of the relationship between the inductance and the applied voltage
 440 in the piezoelectric actuators was performed using the experimental setup schematized in
 441 Figure 8(b). A voltage generator was used to apply a constant signal varying from 0 to 5
 442 V with a step of 0.5 V, while an LCR meter was used to measure the inductance at each
 443 level. This test was repeated three times and the results obtained are shown in Figure 8(c).
 444 Note in this curve that with increasing applied voltage, raising the space between the ferrite
 445 core proportionally, initially induces a linear variation in inductance. However, as the gap
 446 increases, the magnetic flux lines start to bulge out around the gap, causing a reduction
 447 in effective air gap reluctance and consequently an increase in inductance, a phenomenon
 448 known as the fringing effect, which explains the change in trend of the curve. For more
 449 details on fringing effect the interested reader can refer to [33, 35].

450 3.3. Self-adaptive control based on Gaussian Process Regression

451 The application of the proposed self-adaptive strategy requires an initial supervised learn-
 452 ing step performed off-line. The aircraft prototype is submitted to an automated data
 453 collection process for training the GPR model. Using the test and control subsystem simul-
 454 taneously, a constant amplitude harmonic excitation signal is applied to the shaker and the
 455 excitation frequency is varied from 70 to 85 Hz with a step of 0.5 Hz. For each frequency
 456 the voltage applied to the piezoelectric stack actuators is varied from 0 to 5 V with a step of
 457 0.25 V, for a total of 651 test configurations. For each configuration the structure is excited
 458 for 2 seconds followed by 1s of rest, and the synchronized acquisition of the time signals of
 459 velocity measured by the vibrometer and voltage at the PZT1 is performed. This process,

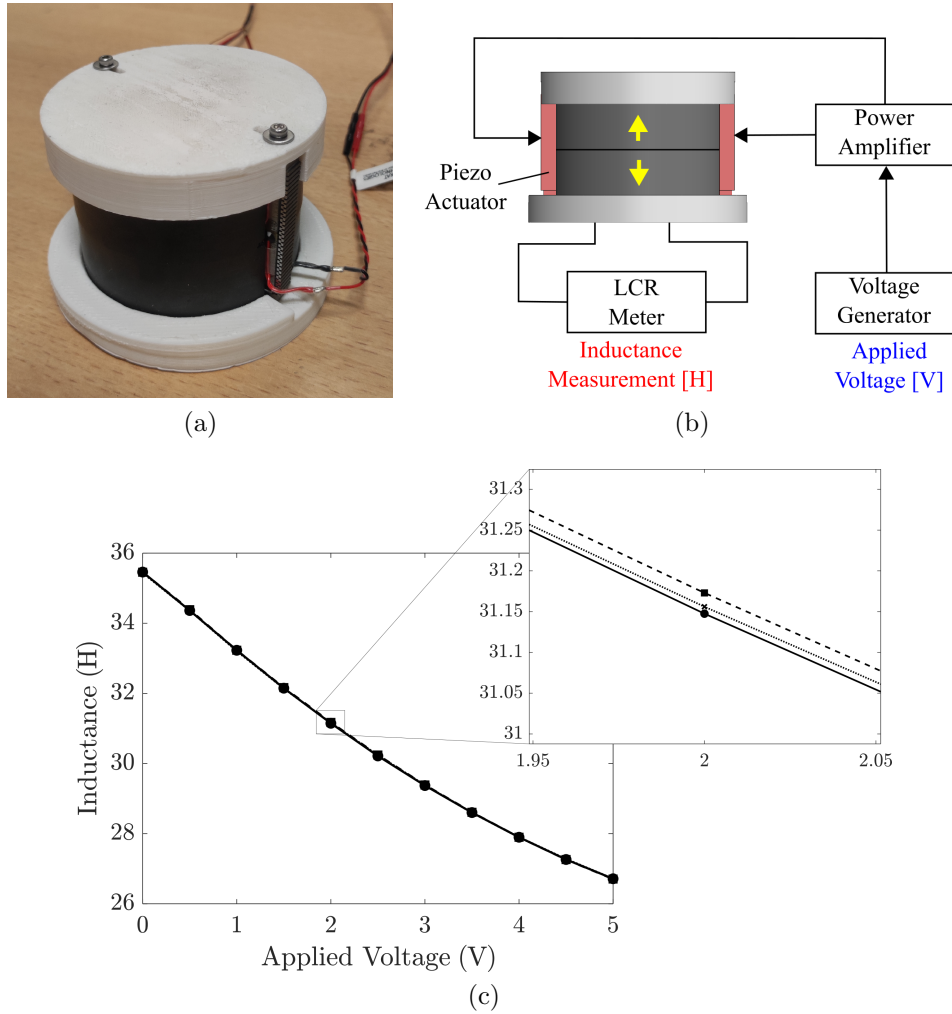


Figure 8: Experimental characterization of the semi-passive tunable inductor. Photograph of the (a) fabricated device, (b) schematic of the experimental setup used for the characterization, and (c) results of the experimental characterization of the variable inductance as a function of the voltage applied to the stack for the three tests performed: test 1 (---), test 2 (—) and test 3 (⋯).

460 which is fully automated, takes approximately 32 minutes.

461 Samples of the time signals for the wing velocity measured by the vibrometer and voltage
 462 at PZT1 for an excitation frequency of 70 Hz and applied voltage on the piezoelectric
 463 actuators of 0 V are presented in Figure 9. The time-averaged RMS values of the signals
 464 for all experimentally tested conditions as a function of excitation frequency and applied
 465 voltage on the stack are represented through the surface plots presented in Figure 10. It can
 466 be observed by analyzing the surface presented in Figure 10(a) that the RMS value of the
 467 velocity has a smooth behavior in relation to the excitation frequency, with the existence
 468 of minimum operating points - highlighted by the blue dots - as a function of the voltage
 469 applied to the piezoelectric stack actuators, which controls the resonance frequency of the
 470 electric circuit. It is important to note that the minimum points for the velocity surface

471 coincide exactly with the minimum points for the voltage values in PZT 1. This is because
 472 the two surfaces have a remarkably similar shape. This fact can be quantitatively verified
 473 by calculating the distance between the two normalized surfaces, which have a maximum
 474 distance of 0.0028. Therefore, it allows the use of the voltage signal measured at PZT 1
 475 to evaluate the cost function, which is considerably more practical for the implementation
 476 in practice than the velocity measured by the vibrometer, since the transducer is already
 477 installed in the structure and can be readily measured. The voltage measured on PZT sensor,
 478 which is proportional to its strain, is therefore in this case proportional to the velocity of the
 479 structure at the measured point. Hence, hereafter the measured velocity by the vibrometer
 480 will only be used for validation of the implemented control system.

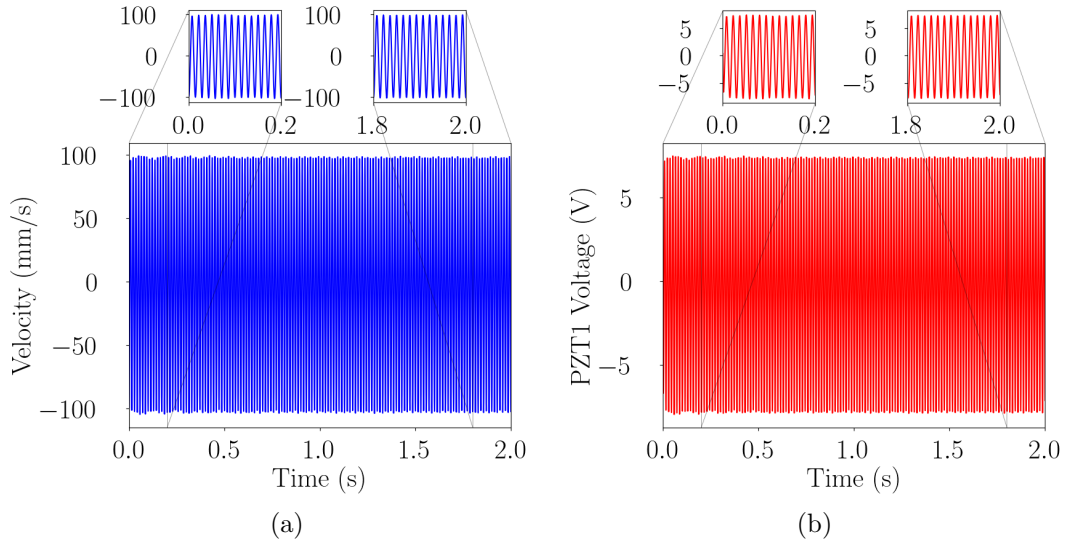


Figure 9: Time signals of (a) velocity at measured point by the vibrometer and (b) voltage in PZT 1 for 75 Hz excitation frequency and 0V applied to piezoelectric stack actuators.

481 A total of five tests were performed to collect experimental data with the 651 mentioned
 482 configurations. The data sets from four of these tests were used to train the GPR model,
 483 considering the excitation frequency and the applied voltage on the piezoelectric actuators
 484 as input variables and the RMS voltage value at PZT 1 as output. The experimental data
 485 used for training and the predicted mean of the trained model is presented in Figure 11. The
 486 model validation was performed using Root-Mean Squared Error (RMSE) criterion based
 487 on leave-one-out cross-validation method, for which the last data set from the five was used.
 488 The maximum RMSE between the RMS voltage of PZT 1 experimentally observed and
 489 predicted by the model obtained was of 0.038. This low RMSE value is a strong indicator
 490 of adequate prediction the trained GPR model.

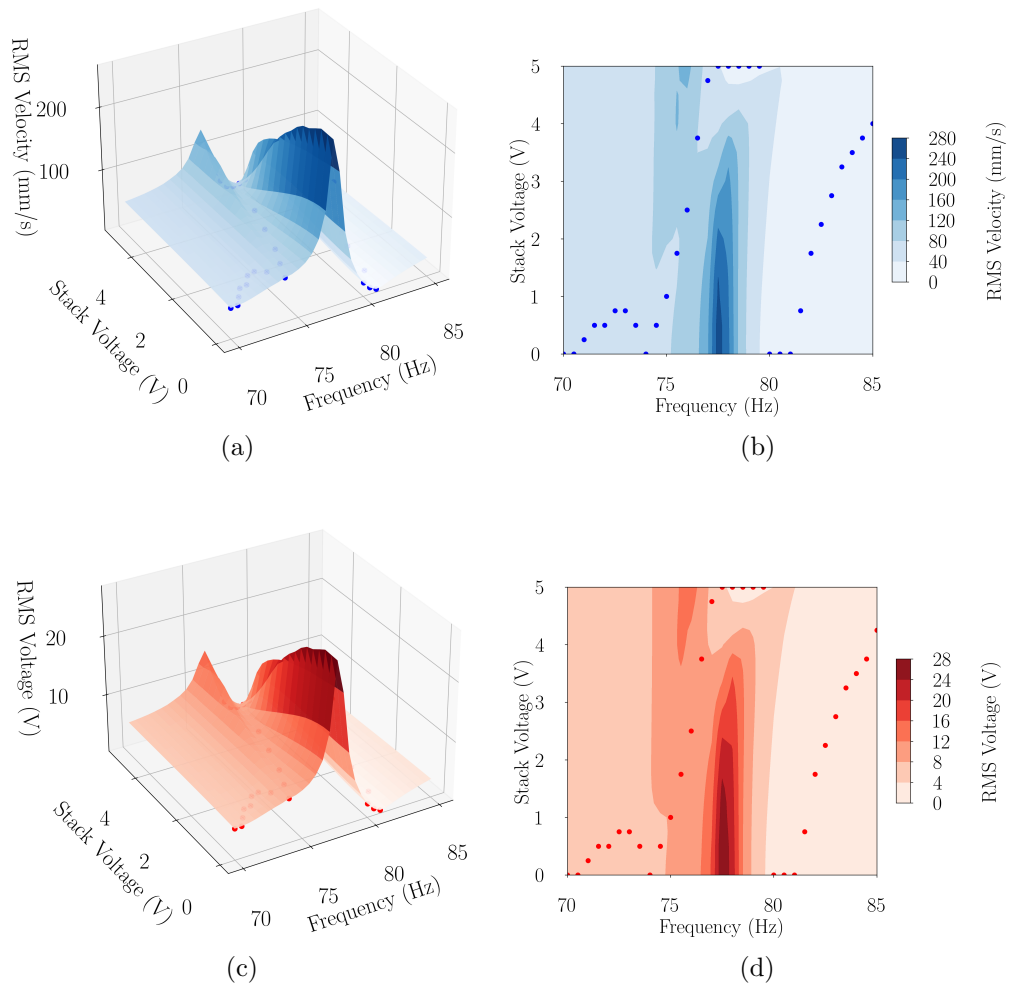


Figure 10: Experimental surfaces obtained for the RMS value of velocity (a)(b) and voltage at PZT 1 (c)(d) as a function of excitation frequency and applied voltage on the piezoelectric actuators for the first test performed.

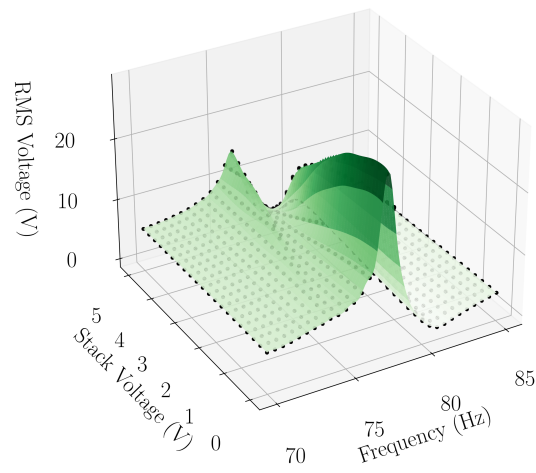


Figure 11: Predicted mean (■) by the GPR model trained with the experimental data (●) used for training from four of the five tests.

3.3.1. Closed-loop control based on the trained GPR model

Once the GPR model has been trained in the off-line learning loop, the self-adaptive control strategy can be tested in closed-loop. The test subsystem is used to excite the structure with a swept-sine signal with frequency varying linearly from 70 Hz to 85 Hz and a duration of 120 seconds. The machine learning control algorithm based on the trained GPR model is implemented on the Raspberry Pi, responsible for the control subsystem that runs independently. The voltage acquisition at PZT 1 is performed at a sampling frequency of 2500 Hz and with a duration of 0.5 s. For each voltage time signal acquired the frequency is estimated using the fast Fourier transform based on the parabolic interpolation approach. The signal frequency is then used as input to the GPR model, which is used to estimate the voltage that must be applied to the piezoelectric actuators to minimize the stress on PZT 1 and consequently the vibration in the structure. This whole process takes place in a closed-loop online on the Raspberry Pi board.

The experimental results of the self-adaptive control strategy is compared to the solution provided by the equal-peak design, in which the inductance is kept constant regardless of the operating conditions. This solution is obtained experimentally by adjusting the tunable inductance to the condition where the experimental FRF of the system has two equal-peaks around the mode of interest. It is important to note that the resistance of the shunt circuit was kept unchanged at 95 Ohms. The results obtained for these two strategies are presented in Figure 12. An attenuation gain of 3.07 dB (equivalent to an amplitude reduction of approximately 30%) is obtained by comparing the maximum amplitudes can be observed for the self-adaptive strategy for frequencies around the third mode, which can be explained by the antiresonance locus at the excitation frequency. In particular, at the resonant frequency of the mode of interest, the two solutions perform similarly, which is to be expected, since in this case the excitation frequency coincides with the frequency of the mode for which equal-peak method solution is based and the resistance of the shunt has not modified. It should be emphasized here that the purpose of this comparison is only to highlight the strategic difference between the two methodologies, since better vibration attenuation is already expected for harmonically excited structures from the self-adaptive methodology, which is based on the antiresonance localization strategy, compared to the equal-peaks methodology. The peak in the velocity response at 80s is due to the drastic decrease in the voltage applied to the piezoelectric actuators, causing a sharp decrease in inductance. This causes a transient response of the system, which soon reaches the steady-state response, but that should be further investigated.

The voltage signal applied to the tunable inductor has a relationship with the electrical resonance frequency of the shunt whose trend can be inferred from its inductance. With the increase of the applied voltage, it is expected a decrease in inductance (see Figure 8) and consequently an increase in the electric resonance frequency of the shunt (see Equation 4). Thus, the analysis of the time signal of the voltage applied to the actuators indicates that there was an overall increase in resonance of the electrical circuit from 0 to approximately 60 s, following approximately the same trend of the excitation frequency. However, one can question the behavior of the sharp reduction of the applied voltage around 80 s which indicates a reduction of the electric resonance frequency as the excitation frequency increases.

534 Although this behavior cannot be explained regarding the antiresonance locus strategy pre-
535 sented in the previous section for the lumped mass model, it is important to note that this
536 experimental application involves a complex structure with multiple modes, some of which
537 are close to each other (see mode 3 and 4 in Figure 7). Moreover, the nonlinear effects of the
538 semi-passive tunable inductor as well as uncertainties, are difficult to take into account in
539 the traditional model-based control approach. This justifies and strengthens the advantages
540 of the model-free approach based on the machine learning control method presented here.

541 The machine learning control strategy proposed in this work is applicable for the op-
542 eration of the structure under operating conditions within the conditions used in training
543 of the GPR model, which limits its application in more challenging scenarios susceptible
544 to unforeseen variations in environmental and operating conditions. However, recent works
545 involving the use of GPR models has already shown the possibility of updating a trained
546 model with data obtained during operation in a way that allows the adaptation of the con-
547 troller in case of structural changes [44]. Alternatively, the application of gradient-based
548 optimization methods for the online controlling of the input variable of the closed-loop sys-
549 tem as applied in the past may be envisaged [10, 11]. This approach offers the advantages
550 of not requiring a training phase as is the case in the machine learning approach, and of
551 being adaptable in operation to the different sources of uncertainty affecting the system.
552 However, they require a longer convergence time to a control solution for the system, which
553 hinders their application in cases of time-varying harmonic signals such as those studied in
554 this work.

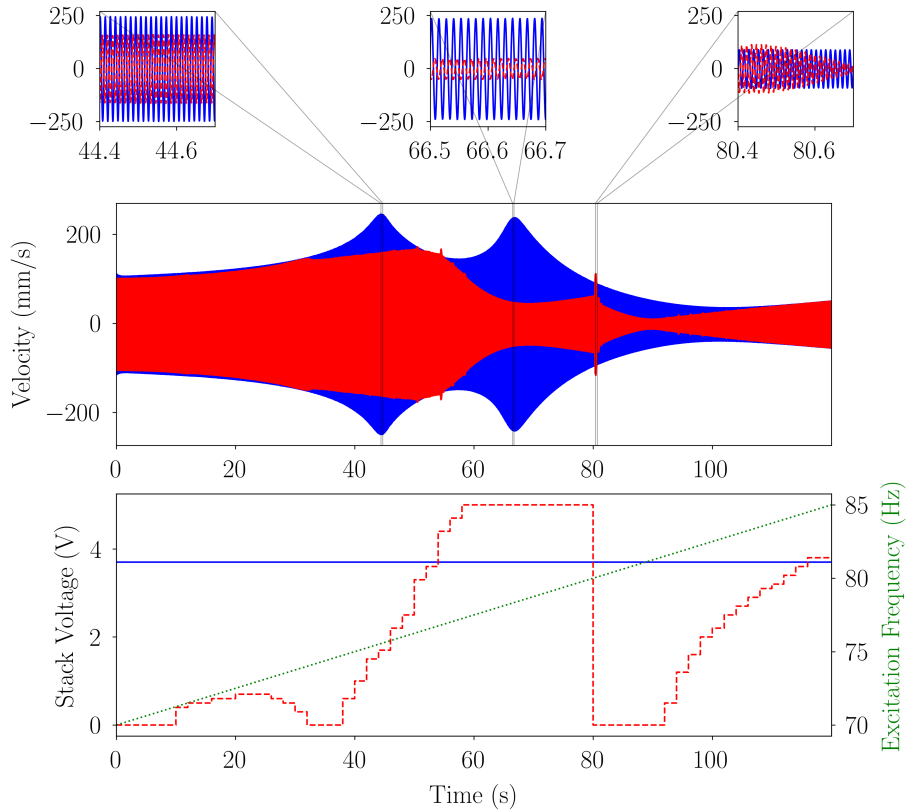


Figure 12: Closed-loop experimental application of the self-adaptive strategy based on the trained GPR model (- -) compared to the solution provided by the equal-peak method (—), in which inductance remains constant. The structure is excited with a swept-sine signal with frequency varying linearly (····) from 70 Hz to 85 Hz.

555 4. Conclusions

556 This paper proposed a self-adaptive PVA with semi-passive resonant shunt for used in
557 the vibration attenuation of harmonically excited structures. This technique has many ad-
558 vantages. A resonant shunt composed only of passive components circumvents the main
559 limitation of the widely used synthetic impedances, in particular the problem of instabil-
560 ity. In addition, the inductance of the novel high-Q tunable inductor can be controlled by
561 the application of a simple constant voltage signal, unlike the devices with similar capabili-
562 ties based on SSD and PWM techniques that require signals at high-switching frequencies.
563 Moreover, the proposed self-adaptive strategy based on machine learning control does not
564 require a physical model of the closed-loop system since it employs a supervised learning
565 approach via a GPR model to learn how to control the semi-passive tunable inductor to
566 achieve the maximum vibration attenuation as function of the excitation frequency. The ap-
567 plication of this strategy was demonstrated experimentally on a simplified airplane mockup.
568 The results show a significant improvement of approximately 3.07 dB (equivalent to an am-
569 plitude reduction of approximately 30%) in vibration attenuation for a swept sine excitation
570 compared to a traditional resonant shunt with fixed inductance. Future applications to the

571 attenuation of vibrations in rotating machinery are envisaged as well as an extension to the
572 case of broadband frequency excitations.

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576 **Declaration of interest**

577 The authors declare that they have no known competing financial interests or personal
578 relationships that could have appeared to influence the work reported in this paper.

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