www.czasopisma.pan.pl www.journals.pan.pl
ARCHIVES OF ACOUSTICS
Vol. **43**, No. 3, pp. 397–402 (2018)

DOI: 10.24425/123911

Nonlinear Structural Acoustic Control with Shunt Circuit Governed by a Soft-Computing Algorithm

Sebastian KURCZYK, Marek PAWEŁCZYK

Institute of Automatic Control
Silesian University of Technology
Akademicka 16, 44-100 Gliwice, Poland; e-mail: Sebastian.Kurczyk@polsl.pl

(*received August 10, 2018; accepted May 30, 2018*)

Noise control has gained a lot of attention recently. However, presence of nonlinearities in signal paths for some applications can cause significant difficulties in the operation of control algorithms. In particular, this problem is common in structural noise control, which uses a piezoelectric shunt circuit. Not only vibrating structures may exhibit nonlinear characteristics, but also piezoelectric actuators.

In this paper, active device casing is addressed. The objective is to minimize the noise coming out of the casing, by controlling vibration of its walls. The shunt technology is applied. The proposed control algorithm is based on algorithms from a group of soft computing. It is verified by means of simulations using data acquired from a real object.

Keywords: Active Noise Control; adaptive control; neural network; vibrating plate.

1. Introduction

Active Structural Acoustic Control (ASAC) uses forced vibration of a structure to reduce unwanted noise passing through the structure (Pawełczyk, 2014). For some applications the noise source can be enclosed in a casing. Vibration of the casing wall can be then controlled and thus reduce the noise. Classical control approaches to noise reduction are well described in the literature (Elliott, Nelson, 1993; Sibielak *et al.*, 2015; Bismor, 2015). However, semi active approach, namely the shunt technique is particularly interesting due to small power supply requirements and simplicity of the hardware (Mao, Pietrzko, 2013; Kurczyk, Pawełczyk, 2013). It uses a piezoelectric material firmly bounded to the vibrating structure to transform mechanical energy to the electric current, and then disperse that energy (Qiu, Ma, 2014).

Macro-Fibre Composite (MFC) can be used as the piezoelectric element in the shunt system. The MFC is made of piezo-ceramic fibres, connected to electrodes and sandwiched between a protective film. The arrangement of the fibres affects the patch property. The advantage of using MFCs over classical PZTs is that MFCs introduce small mass and stiffness to the entire structure with a larger efficiency. Unfortunately, they exhibit a nonlinear behaviour.

Considering the advantages of semi-active shunt technique, researchers have paid a lot of attention to this approach. Shen *et al.* (1998) considered the use of a soft computing algorithm to control a vibrating plate with PZT actuators. They used genetic algorithm and fuzzy based controller (Shen *et al.*, 2000). Their ideas were further investigated by using type-II fuzzy logic (Homaifar *et al.*, 2001; Shen, Homaifar, 2001). Lin and Hao (2001) used robust fuzzy based control to a thin vibrating plate. Darus and Tokhi (2005) proposed both fuzzy logic and neural network based controllers. Sharma and Singh employed fuzzy modal control and fuzzy sliding model to control a vibrating plate (Sharma *et al.*, 2007; Sharma, Singh, 2010). Shirazi *et al.* (2011) focused on fuzzy control with a functionally graded material and a rectangular plate. Mazur and Pawełczyk (2013) used a single nonlinear filter for a vibrating plate. Lin and Chiang (2014) considered a multiple degrees-of-freedom flexible structure with genetic based control algorithm. The use of MFC actuators and sensors for circular plates were investigated by Leniowska and Mazan (2015). Muradova and Stavroulakis (2015) proposed a fuzzy based hybrid control of von Kármán plate. Yang and

Chen (2015) performed an experimental study of the vibrating, rectangular plate, with adaptive fuzzy sliding mode controller. Gampa and Das (2016) proposed an optimisation of the shunt patch placement, based on the fuzzy-GA algorithm. Morzyński *et al.* (2016) considered an active window panel, that can reduce the sound passing through. In the earlier work, Górski and Morzyński (2013) also proposed an GA based approach to adaptive notch filter noise reduction.

This paper focuses on a neural network control of the shunt circuit mounted on a rectangular plate. Nonlinear MFC based shunt circuit is considered. First, a vibrating plate model, followed from the literature, is presented. Then, the nonlinear MFC model is proposed. Next, a neural network based shunt switching algorithm is introduced and justified. In the end, simulation results are presented and summarised.

2. Vibrating plate model

According to the Kirchhoff-Love plate theory, the fundamental equation of motion in Cartesian coordinates is (Mao, Pietrzko, 2013):

$$\frac{h_s^3 E}{12(1-\nu^2)}\nabla^4 w(x,y,t) + \rho h_s \frac{\partial^2 w(x,y,t)}{\partial t^2} = F, \qquad (1)$$

where h_s is the plate thickness; E and ν are the Young's modulus and Poisson's ratios; $w(x,y,t)$ is the transverse displacement; ρ is the plate's density; F is the force applied to the plate; Nabla symbol is interpreted as:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}. \qquad (2)$$

Applying the modal analysis theory, the transverse displacement, $w(x,y,t)$ can be expressed as the superposition of an infinite number of mode shape functions $\varphi_{mn}(\cdot)$ (Mao, Pietrzko, 2013). Here, the Rayleigh-Ritz mode shape is assumed. Therefore, the mode shape function can be considered to be the product of the one-dimensional beam eigenfunctions:

$$w(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \phi_m(x)\phi_n(y)\eta_{mn}(t), \qquad (3)$$

where $\eta_{mn}(t)$ is the modal amplitude of the (m, n)-th mode of the plate.

Considering only the transverse motion of the plate, the kinetic, and strain, energy can be obtained as suggested in (Wrona, Pawełczyk, 2013; 2016a; 2016b). Based on the works described in (Wrona, Pawełczyk, 2013; 2016a; 2016b) the generalised equation of plate vibration can be formulated as:

$$\mathbf{M}\ddot{\boldsymbol{\eta}} + \mathbf{B}\dot{\boldsymbol{\eta}} + \mathbf{K}\boldsymbol{\eta} = \mathbf{F}_s, \qquad (4)$$

where:

$$M_{mn} = \int\limits_{L_x}\int\limits_{L_y} \rho h_s \phi_m \phi_n \,\mathrm{d}x\,\mathrm{d}y, \qquad (5)$$

$\mathbf{B}$ is assumed to be proportional to $\mathbf{K}$ (Mao, Pietrzko, 2013). The proportion is found experimentally;

$$K_{mn} = D\int\limits_{L_x}\int\limits_{L_y}\left[\frac{\partial^2\phi_m}{\partial x^2}\frac{\partial^2\phi_n}{\partial x^2} + \frac{\partial^2\phi_m}{\partial y^2}\frac{\partial^2\phi_n}{\partial y^2} + 2\nu\frac{\partial^2\phi_m}{\partial x^2}\frac{\partial^2\phi_n}{\partial y^2} + 2(1-\nu)\frac{\partial^2\phi_m}{\partial x\partial y}\frac{\partial^2\phi_n}{\partial x\partial y}\right]\mathrm{d}x\,\mathrm{d}y, \qquad (6)$$

$$F_s = \int\limits_{L_x}\int\limits_{L_y} F\phi_m\phi_n\,\mathrm{d}x\,\mathrm{d}y, \qquad (7)$$

and $\mathbf{F}_s$ represents a modal force.

3. MFC nonlinear model

Properties of the Macro-Fibre Composite element vary based on the fibres alignment (Smart Material Corp., 2016). Different MFC compositions results in specific MFC features. Based on the data published by the MFC supplier, three types of MFCs can be discussed; see Table 1.

Table 1. Chosen MCF properties, based on the data published in (Yang, Chen, 2015).

Property/type	Piezoelectric effect	Piezoelectric coefficient (low-field) [pC/N]	Directional characteristic
P1	d33	4.0E+2	anisotropic
P2	d31	−1.7E+2	anisotropic
P3	d31	−1.7E+2	orthotropic

Depending on the demands, different MFC types give better results, when considered as a sensor, or an actuator. This paper focuses on the semi-active shunting technique, and therefore the P1 type MFC is selected. The P1 type MFC has a higher piezoelectric coefficient than the P2 type, but unfortunately it exhibits a nonlinear property.

The single MFC patch is bounded to the plate as an actuator in the shunt circuit, and the collocated second MFC is used as a reference sensor. The placement of the MFC is crucial for the system to produce optimal electric charge. The problem is well known in the literature (Mao, Pietrzko, 2013). The MFC patch is mounted in the centre of the rectangular plate, based on the modal analysis (Wrona, Pawełczyk, 2013) – see Fig. 1.

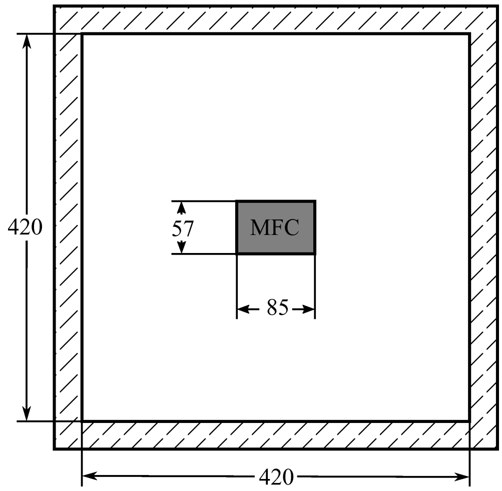


Fig. 1. Placement of the MFC shunt element on each wall.

The electric charge generated by the piezoelectric element, can be described as (Mao, Pietrzko, 2013):

$$Q = \mathbf{\Psi}^{\mathrm{T}}\boldsymbol{\eta} + C_p V, \tag{8}$$

where $\mathbf{\Psi}$ is a modal piezoelectric coupling matrix; C_p and V are the MFC capacitance and applied voltage, respectively. Elements of the piezoelectric coupling matrix are assumed to be explained by:

$$\Psi_{mn} = \int_{L_x}\int_{L_y}\int_{h_p} s(x,y)\left(e_x\frac{\partial^2\phi_{mn}(x,y)}{\partial x^2} + e_y\frac{\partial^2\phi_{mn}(x,y)}{\partial y^2}\right) z\frac{\partial\phi_\nu(z)}{\partial z}\,\mathrm{d}z\,\mathrm{d}y\,\mathrm{d}x, \tag{9}$$

where L_x, L_y, h_p are dimensions of the plate, and thickness of the MFC, respectively; $s(x,y)$ is a shape function; e_x and e_y are piezoelectric coefficients, dependant on X- and Y-directions of the plate; $\phi_\nu(z)$ is the thickness function. The shape function $s(x,y)$ is used to apply the piezoelectric effects only to the area of MFC placement. The nonlinear character of P1 type MFC is modelled by introducing a third power of the MFC electric charge:

$$Q_n = aQ + bQ^3, \tag{10}$$

where a and b are found experimentally.

4. Shunt switching algorithm

There are a few strategies of controlling the shunt switching circuit (Mao, Pietrzko, 2013). In one of them the state-switching technique uses only the switch, while the pulse-switching circuit introduces additional resonant elements, such as resistance and inductance. The effectiveness of the shunt structure depends on the MFC placement and the circuit Quality factor.

In this paper, a state-switching shunt structure is considered. The advantage of this structure is that it allows tuning the circuit-switching algorithm for every frequency.

Introducing additional mass and stiffness to the wall structure, requires updating Eq. (4) into:

$$(\mathbf{M}_s + \mathbf{M}_p)\,\ddot{\boldsymbol{\eta}} + \mathbf{B}\dot{\boldsymbol{\eta}} + (\mathbf{K}_s + \mathbf{K}_p) = \mathbf{F}_s + \mathbf{F}_p, \tag{11}$$

where subscripts 's' and 'p' stand for wall structure (plate) and piezoelectric element (MFC), respectively. Mass and stiffness matrices for the MFC element are found according to Eqs. (5) and (6). The modal force introduced by the MFC is formulated as:

$$\mathbf{F}_p = \mathbf{\Psi} V. \tag{12}$$

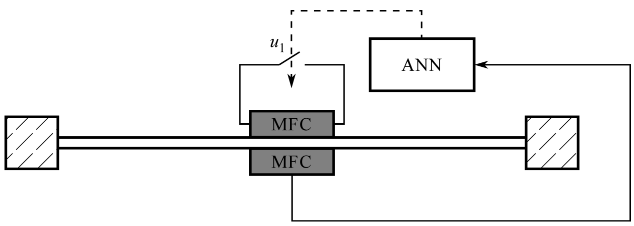
For the state-switching circuit without external power source, the charge produced by the MFC is obtained from Eqs. (8) and (10). It has been proven that no damping is added to the structure when the switch is on. The switching law should satisfy the condition (Mao, Pietrzko, 2013):

$$Q_o \mathrm{sign}(\dot{\eta}) \leq 0, \tag{13}$$

where Q_o is the MFC charge for the opened circuit.

A nonlinear MFC is chosen in place of a linear MFC because of their properties (see Table 1). The nonlinear MFC has a greater piezoelectric coefficient, meaning that it can generate a higher charge, and thus improving the signal-to-noise ration of the measurement. Since the charge generated on the MFC is governed by a nonlinear property, the classical control algorithm is converted into a neural network. The ANN is then trained by the switching law (13), as if in the linear case. This approach allows the ANN to include sensor nonlinearity. The proposed reasoning is presented in Fig. 2.

a)



b)

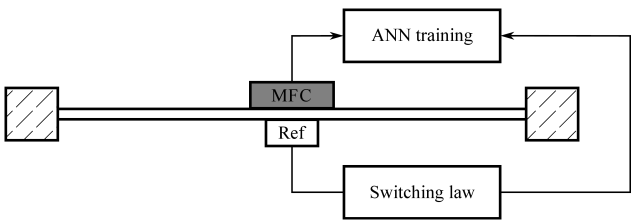


Fig. 2. Structure used for the learning process and control: a) offline training, b) online control.

The linear vibration sensor is used only for the process of learning the ANN when configuring the system. It is preferred if the reference sensor does not load the structure. In this research a laser vibrometer was used. In the operation stage (online control), the MFC sensor provides data to the ANN algorithm, which is used to control the switch.

The ANN used in this experiment has three layers: input, hidden, and output. Input and hidden layers use sigmoid activation function:

$$\mu(x) = \frac{1}{1 - \mathrm{e}^{x}}. \tag{14}$$

The output neuron uses the step function to determine the output state: shunt circuit ON or OFF.

The backpropagation algorithm is used during the learning process. The structure of the ANN is presented in Fig. 3.

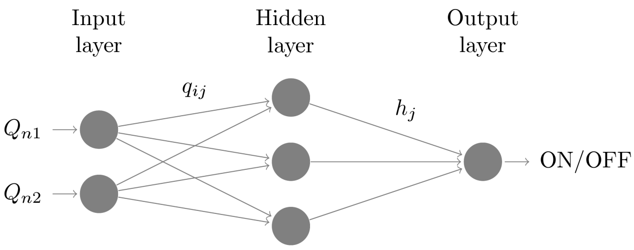


Fig. 3. Structure of the artificial neural network used as switching controller.

The Input layer consists of time delayed collocated sensor charge samples: Q_{n1}, Q_{n2}, ..., Q_{nN}. The data are used to conclude the moment of switching.

5. Simulation experiment

A simulation experiment was conducted based on experimental data acquired form a real active device casing. Namely, signals from plate velocity and displacement measurement (acquired with a laser vibrometer) were used as reference. The real device casing was excited by a loudspeaker with a tone of considered frequency. Parameters of the single wall plate are included in Table 2.

Table 2. Single plate material property used for the simulation experiment.

Plate property	Dimensions [mm]	Mass [kg]	Density [kg/m^3]	Young's modulus [GPa]	Poisson's ratio
Plate	420×420×3	1.428	2700	70	0.35

A tonal excitation was considered. The plate was excited at the frequency of the first mode, i.e. 87 Hz. The training was performed using a displacement and velocity of the centre point of the plate. The trained ANN was then tested using a nonlinear MFC sensor. Results of the experiment are presented in Fig. 4.

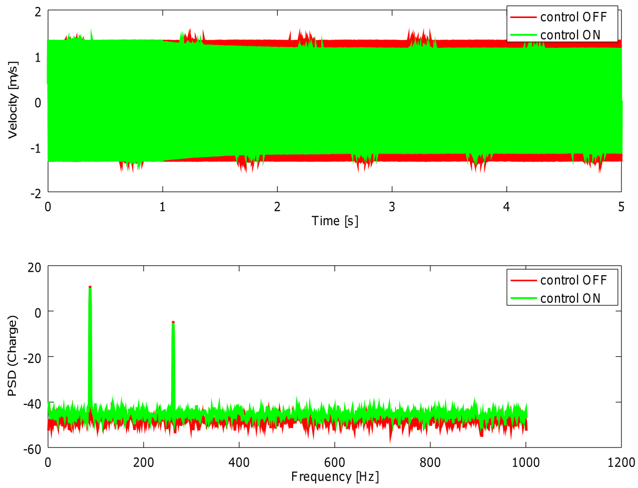


Fig. 4. Simulation experiment for state-switching shunt circuit, and a tonal excitation, with nonlinear MFC sensor. Control starts after 1 second.

As presented in Fig. 4, the use of ANN to control the shunt switch results in a slight, 2 dB on average (for a hundred simulations) performance improvement, in terms of vibration control. Considered ANN consisted of 128 neurons in each of input and hidden layers. This final structure is a result of implementing a growth method and training each candidate for 500 epochs. Such limited effectiveness was expected when considering a semi-active state-switching shunt circuit, what has been discussed in (Mao, Pietrzko, 2013). Much better results can be obtained with the pulse-switching shunt circuit, however, at the expense of versatility.

6. Summary

In this paper, an artificial neural network based shunt circuit controller is discussed to control vibration of a structure. In particular, a device casing has been considered as the structure in order to develop a technique for improving its acoustic isolation. The motivation for using ANN is the fact that some MFCs introduce nonlinearities to the control structure. The proposed approach uses the soft computing to obtain a nonlinear switching control, based on the linear switching law. The proposed algorithm has been tested in a simulation experiment, and discussed. The use of the state-switching shunt circuit has been motivated by an assumption not to make parameters of the circuit dependant on the noise frequency. If the pulse-switching technique with additional dynamics in the circuit were used, the results would be much better at the expense of necessity of retuning the circuit if the frequency changes.

Acknowledgments

The research reported in this paper has been supported by the National Science Centre, Poland, decision no. DEC-2017/25/B/ST7/02236.

Authors are grateful to two anonymous reviewers for their valuable comments, that improved this paper.

References

1. Bismor D. (2015), *Extension of LMS stability condition over a wide set of signals*, International Journal of Adaptive Control and Signal Processing, **29**, 653–670.
2. Darus I.Z.M., Tokhi M.O. (2005), *Soft computing-based active vibration control of a flexible structure*, Engineering Applications of Artificial Intelligence, **18**, 93–114.
3. Elliott S.J., Nelson P.A. (1993), *Active Noise Control*, IEEE Signal Processing Magazine, **10**, 12–35.
4. Gampa S.R., Das D. (2016), *Optimum placement of shunt capacitors in a radial distribution system for substation power factor improvement using fuzzy GA method*, Electrical Power and Energy Systems, **77**, 314–326.
5. Górski P., Morzyński, L. (2013), *Active noise reduction algorithm based on NOTCH filter and genetic algorithm*, Archives of Acoustics, **38**, 2, 185–190.
6. Homaifar A., Shen Y., Stack B.V. (2001), *Vibration control of plate structures using PZT actuators and type II fuzzy logic*, Proceedings of the 2001 American Control Conference, Vol. 2, pp. 1575–1580, Arlington, USA, June 25–27.
7. Kurczyk S., Pawełczyk M. (2013), *Fuzzy control for semi-active vehicle suspension*, Journal of Low Frequency Noise, Vibration and Active Control, **32**, 3, 217–225.
8. Leniowska L., Mazan D. (2015), *MFC sensors and actuators in active vibration control of the circular plate*, Archives of Acoustics, **40**, 2, 257–265.
9. Lin Ch.-L., Hao P.-S. (2001), *Robust fuzzy control of a vibrating thin plate*, JSME International Journal Series C: Mechanical Systems, Machine Elements and Manufacturing, **44**, 2, 315–326.
10. Lin J., Chiang C.B. (2014), *Positioning and vibration suppression for multiple degrees of freedom flexible structure by genetic algorithm and input shaping*, Smart Structures and Systems, **14**, 3, 347–365.
11. Mao Q., Pietrzko S. (2013), *Control of noise and structural vibration. A MATLAB-based approach*, Springer, London.
12. Mazur K., Pawełczyk M. (2013), *Active noise control with a single nonlinear control filter for a vibrating plate with multiple actuators*, Archives of Acoustics, **38**, 4, 537–545.
13. Morzyński L., Zawieska W., Krukowicz T. (2016), *The system for active control of sound transmission through a window panel – the concept and simulation results*, Solid State Phenomena, **248**, 35–40.
14. Muradova A.D., Stavroulakis G.E. (2015), *Hybrid control of vibrations of a smart von Kármán plate*, Acta Mechanica, **226**, 3463–3475.
15. Pawelczyk M. (2014), *Advances in active control of machinery and device noise*, Proceedings of the 6th International Conference on Modelling, Identification & Control (ICMIC), pp. 99–104.
16. Qiu Z., Ma B. (2014), *Adaptive resonant vibration control of a piezoelectric flexible plate implementing Filtered-X LMS algorithm*, International Journal of Acoustics and Vibration, **19,** 4, 224–239.
17. Sharma M., Singh S.P. (2010), *Fuzzy sliding mode control of plate vibrations*, Shock and Vibration, **17**, 71–92.
18. Sharma M., Singh, S.P., Sachdeva B.L. (2007), *Modal control of a plate using a fuzzy logic controller*, Smart Materials and Structures, **16**, 1331–1341.
19. Shen Y.X., Homaifar A. (2001), *Vibration control of flexible structures with PZT sensors and actuators*, Journal of Vibration and Control, **7**, 3, 417–451.
20. Shen Y., Homaifar A., Bikdash M., Chen D. (1998), *Genetic algorithms- and fuzzy-based vibration control of plate using PZT actuators*, Proceedings of the 37th IEEE Conference on Decision & Control Tampa, Vol. 3, pp. 2930–2933, Florida, USA, December 16–18.
21. Shen Y., Homaifar A., Chen D. (2000), *Vibration control of flexible structures using fuzzy logic and genetic algorithms*, Proceedings of the 2000 American Control Conference, Vol. 1, No. 6, pp. 448–452, Chicago, USA, June 28–30.
22. Shirazi A.H.N., Owji H.R., Rafeeyan M. (2011), *Active Vibration Control of an FGM rectangular plate using fuzzy logic controllers*, Procedia Engineering, **14**, 3019–3026.
23. Sibielak M., Raczka W., Konieczny J., Kowal J. (2015), *Optimal control based on a modified quadratic performance index for systems disturbed by sinusoidal signals*, Mechanical Systems and Signal Processing, **64**, 498–519.
24. Smart Material Corp. (2016), http://www.smart-material.com/, 10 March 2016.
25. Yang J.Y., Chen G.P. (2015), *Experimental study of adaptive fuzzy sliding mode control for vibration of a flexible rectangular plate*, Journal of Aerospace Engineering, **28**, 4, 04014098.

26. Wrona S., Pawełczyk M. (2013), *Controllability-oriented placement of actuators for active noise-vibration control of rectangular plates using a memetic algorithm*, Archives of Acoustics, **38**, 4, 529–536.

27. Wrona S., Pawełczyk M. (2016a), *Shaping frequency response of a vibrating plate for passive and active control applications by simultaneous optimization of arrangement of additional masses and ribs. Part I: Modeling*, Mechanical Systems and Signal Processing, **70–71**, 682–698.

28. Wrona S., Pawełczyk M. (2016b), *Shaping frequency response of a vibrating plate for passive and active control applications by simultaneous optimization of arrangement of additional masses and ribs. Part II: Optimization*, Mechanical Systems and Signal Processing, **70–71**, 699–713.