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To cite this version:

Kouider Bendine, Zouaoui Satla, Farouk Benallel Boukhoulda, Mohammed Nouari. Active Vibration damping of Smart composite beams based on system identification technique. Curved and Layered Structures, 2018, 5 (1), pp.43-48. 10.1515/cls-2018-0004 . hal-03325698

HAL Id: hal-03325698

https://hal.univ-lorraine.fr/hal-03325698v1

Submitted on 25 Aug 2021

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Research Article

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Active Vibration damping of Smart composite beams based on system identification technique

https://doi.org/10.1515/cls-2018-0004
Received Nov 30, 2017; accepted Feb 14, 2018

Abstract: In the present paper, the active vibration control of a composite beam using piezoelectric actuator is investigated. The space state equation is determined using system identification technique based on the structure input output response provided by ANSYS APDL finite element package. The Linear Quadratic (LQG) control law is designed and integrated into ANSYS APDL to perform closed loop simulations. Numerical examples for different types of excitation loads are presented to test the efficiency and the accuracy of the proposed model.

Keywords: composite, smart structures, identification system, piezoelectric

1 Introduction

Composite structures offer a combination of low-density, high-strength and lightweight which make them extensively merged in many industrial sectors such as aerospace and automotive. The working environments of the composite structures are subjected to ambient vibration that commonly goes unused unwanted and can lead to catastrophic failure. To reduce the risk of the composite structures damaged [8], active vibration damping technique is gradually becoming a reality in different areas. Inspired by the phenomena of piezoelectricity in certain materials the active vibration technique requires bonding piezoelectric patches in a conventional structures to create a kind of smart structure that has the ability of self-control [1, 3, 7].

The last few decades have witnessed a huge amount of research reports dedicated to analyse the active vibration control of composite structures with distributed piezoelectric sensors and actuators. The investigation is mainly performed either analytical or by using finite element method, for the analytical approaches reader can be refer to [5, 15–17], however in this paper will focus on the works done using finite elements methods [14] developed a finite element model based on third order laminate theory for the active vibration control of composite beams with distributed piezoelectric sensors and actuators [6] developed a finite element formulation for modelling and analysis of isotropic as well as orthotropic composite beams with distributed piezoelectric actuators subjected to both mechanical and electrical loads [2] suggested a finite element method (FEM) to study the active vibration control smart FGM beam based on higher-order shear deformation theory. The piezoelectric sensors and actuators positions have a great influence on the control system efficiency and reliability. Hence, many research papers were focused on finding the most appropriate location that lead to cost and weight reduction [16] presented an approach based on the Rayleigh–Ritz (RR) assumed mode shape method to predict the behavior of a thin plate with piezoelectric patches bonded to its surface. [21] proposed optimization technique of the placement and size and the feedback control gains of the control system for vibration damping of beam structures. [22] studied the optimization of the size and location of piezoelectric actuators/sensors, and the controller parameters of composite beam by using the particle swarm optimization algorithm.

Moreover, extra research papers are used commercially software such APDL which has the ability to model piezoelectric materials and perform the investigation of the active vibration control. [13] proposed a performance criterion for the optimization of piezoelectric patch actuator locations on flexible plate structures using APDL and genetic algorithm. [11] dealt with the active control of a smart laminate composite structure (SLCS) by using type of controllers direct velocity feedback (DVF) and displace-

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ment feedback (DF) controls with constant gain are used. [18] proposed a prototype developed in APDL for the active vibration control of lightly damped cantilever aluminium using a linear quadratic controller (LQ). [9] coupled APDL and Matlab to study the active vibration control of a cantilever beam by means piezoelectric patch and PID controller. Unfortunately, the use of certain control algorithm such as LQR requires a state space mathematical model of the smart structure. Several work dealt with the extraction of state space model using the system identification technique. [12] used known Observer/Kalman filter Identification (OKID) to obtain an explicit state space model for control law based on the output of a commercial finite element code APDL. [20] introduced an experimental device for the identification and validation of active vibration control of lightly damped cantilever aluminium beam with piezoelectric patch. [4] presented a methodology to use the software APDL in modelling and active vibration control of a functionally graded (FGM) plate with upper and lower surface bonded piezoelectric layers.

The problematic of using controllers as LQR and LQG in active vibration control is that they required a good knowledge of the structures behaviour which means the necessity of a mathematical model of the structures such as state space representation. In the present paper, a methodology is presented using system identification technique based on the input-output of the structure to derive a space state model for the structure under consideration. The aim is to carry out a numerical investigation of the active vibration control of composite beam using LQG. First the smart structure is modelled in the commercial finite element software APDL, after the system identification toolbox in Matlab is used to get the state space model based on the input/output time histories of the structure. Final the LQG control law is designed and integrated into APDL to perform closed loop simulations.

2 Modeling of smart composite beam

Consider a smart composite beam bonded with piezoelectric actuators. By means of finite element method, the system equation of motion of the smart composite beam can be expressed as:

$$\begin{cases} [M]\left\{\ddot{U}\right\} + [Cd]\left\{\dot{U}\right\} + [K]\{U\} + \{K_{me}\}\{\varphi\} = \{F_m\} \\ \{K_{me}\}^T\{U\} - [K_e]\{\varphi\}_a = -[K_e]\{\varphi\} \end{cases} \tag{1}$$

Where $\{U\}$ denotes structural displacement vector, $\{\varphi\}$ indicates electric potential. $[M]$, $[K]$, $[Cd]$, $\{K_{me}\}$, $[K_e]$ and $\{F_m\}$ are respectively the mass, the elastic stiffness, the damping, the piezoelectric, the dielectric stiffness matrices and the vector of external nodal mechanical forces.

It must be noted, that the damping matrix is assumed to be constructed as the weighted sum of structural mass and stiffness matrices:

$$[Cd] = \alpha[M] + \beta[K] \tag{2}$$

where α and β are damping constants.

The basis of simulation of the smart composite beam has been carried out by using APDL APDL finite element package. The following section describes in detail the steps involved in using the software for analysis of the smart structure. First the geometric solids of the composite beam and the actuator are created using the block command, then the mechanical properties needed for the composite part are inserted using MP command, while the piezoelectric matrices are specified using TB and TBDATA commands. The meshing is performed using two types of three dimensional structural element, (SOLID45) for the composite beam and (SOLID5) for the piezoelectric patch, after that the degrees of freedom, VOLT, are coupled for the nodes at the top and bottom surfaces of the parch by CP command. Finally the appropriate boundary conditions were applied at the fixed end.

3 Identification of the state space equation

Many control algorithms require a mathematical model of the controlled structure in a state-space form. Many works used mathematical formulation based on analytical or numerical models to obtain such a space state form of the structure under control. Unfortunately this processes become unpractical in complexes structures. This work evaluates the possibility of

Using system identification technique to retrieve a space state form based on the input-output extracted data from ANSYS. The process is begun by preparing the smart beam under ANSYS as discussed in section 2. Then, a pseudo random binary sequence (PRBS) signal was applied to the piezoelectric actuator and used to excite the composite beam in the bandwidth of interest. The code used is discussed as following:

At starting points we define create a vector using *DIM command and then fill it with random voltage amplitude of –100 and 100 values by means do loop as:

```
DIM=1000
Dt=0.01
 *DIM, force,ARRAY,DIM          ¡ Creat force vector
*DO, i, 1, DIM, 1               ¡ loop starting
*VFILL, force (i),RAND,-1,1     ! Fill vector with random number
*IF, force (i),LT,0,THEN        ! If case force < 0
        force(i)=-100
*ELSEIF, force (i),GT,0         ! Elseif case force > 0
                force(i)=100
        *ENDIF
*enddo                          ¡ loop end
```

After defining the random force, a transient analysis is performed; this process can be implemented in ANSYS using this code:

```
Tstep=0.01                      ! Specifies the time step sizes
Tstop=10                        ! Sets time to Tstop second
Tres=0.01
/SOLU
ANTYPE,4                        ! Set the transient analysis
TRNOPT,FULL,,DAMP               ! Specifies transient analysis
                                  options
LUMPM,0                         ! Lumped mass set to zero
OUTRES,ALL,ALL                  ! Controls the solution data
                                  written to the database
DELTIM,Tres                     ! Specifies the time step sizes to
                                  be used for load steps
TINTP,,0.25,0.5,0.5             ! Integration parameters, by
                                  default
counter=0
```

The final step is applying the random voltage; this can be done by selecting a value from the vector force that has been already created for each time step as:

```
*DO,t,2*Tstep,Tstop,Tstep
        TIME,t
counter=counter+1
d,p1,VOLT,force(counter)        ! Input voltage of magnitude of
                                  force
SOLVE                           ! Solve
 *ENDDO
FINISH
```

This excitation signal was chosen to guarantee all the resonance modes are captured. Input/output time histories data is then loaded into Matlab System Identification Toolbox for the extraction of the state space equation which can be derived as:

$$\begin{aligned} x(k\dot{}+1) &= [A]\,x(k) + [B]\,u(k) \\ Y(k) &= [\hat{C}]x(k) \end{aligned} \tag{3}$$

Where $\{\boldsymbol{x}\}$ is the state vector, $\{\boldsymbol{Y}\}$is the output vector, [A] is the system matrix, [B] is the control matrix, and $[\hat{C}]$ is the output matrix.

4 Optimal Controller Design

In order to actively attenuate vibrations, optimal linear Quadratic Gaussian (LQG) control algorithm which is based on the minimization of the performance index J [19] given as:

$$\begin{aligned} J = E\Bigg[& x^T(T)\,[F]x(T) \sum_0^T \Big(\{x(k)\}^T\,[Q]\,\{x(k)\} \\ & + \{u(k)\}^T\,[R]\,\{u(k)\}\Big)\Bigg] \end{aligned} \tag{4}$$

where E denotes the expected value the matrices $[F]$ $[Q]$ and $[R]$ are weighting matrices. The discrete-time LQG controller is

$$\begin{aligned} X(k\dot{}+1) &= [A]\,\overline{x}\,(k) + [B]\,u\,(k) + K(k+1)(y\,(k+1) \\ &\quad - C(k+1)\,\{A\overline{x}\,(k) + Bu(k)\} \\ u\,(k) &= -L\overline{x}(k) \end{aligned} \tag{5}$$

where $\overline{x}$ denotes the estimated state, and $[Kb]$ is the gain matrix given by

$$Kb = (C^T PC)^{-1} C^T P$$

[P] is the unique and solution of the reduced Riccati equation which given by:

$$[P]\,[A] + [A]^T\,[P] + [Q] - [P]\,[B]\,[R]^{-1}[B]^T\,[P] = 0 \tag{6}$$

The feedback gain matrix equals

$$L = (B^T SB + R)^{-1} B^T SA$$

where S satisfies the following algebraic Riccati equation

$$\begin{aligned} & A^T \Big(S - SB\Big(B^T SB + R\Big)^{-1} B^T S)A \\ & +Q - [P]\,[B]\,[R]^{-1}[B]^T\,[P] = 0\Big) \end{aligned}$$

The implementation of the control algorithm in APDL is performed as is presented in the previous study of the authors [4].

5 Results and discussion

Considering a composite beam (550 × 40 × 3 mm^3) with cantilever boundary condition and one bounded piezoelectric actuator (44 × 40 × 0.25 mm^3). The host beam is made of 4 graphite–epoxy (carbon-fiber reinforced) layers. Each layer is of thickness 3/4 mm, while the orientations are taken as (0/45/−45/90), the piezoelectric actuator is made of PZT5. The material properties of the considered structure are given in Table 1. The first four frequencies are obtained using APDL and they are plotted as frequency response function in Figure 1. While the corresponding mode shapes are shown in Figure 2.

Table 1: Material proprieties

Proprieties	Graphite/epoxy	PZT G-1195
Poison's ratio	0.31	0.3
Density ρ (kg/m^3)	1550	7600
Elastic stiffness matrix (GPa)		
E11	119	63.0
E22	8.67	63.0
E33	8.67	63.0
G12	5.18	24.2
G13	3.29	24.2
G23	3.29	24.2
Piezoelectric strain matrix		
e31	-	12.5
e33	-	12.5
e15	-	12.5
Dielectric matrix (F/m)		
g11		1.53×10^{-8}
g22		1.53×10^{-8}
g33		1.53×10^{-8}

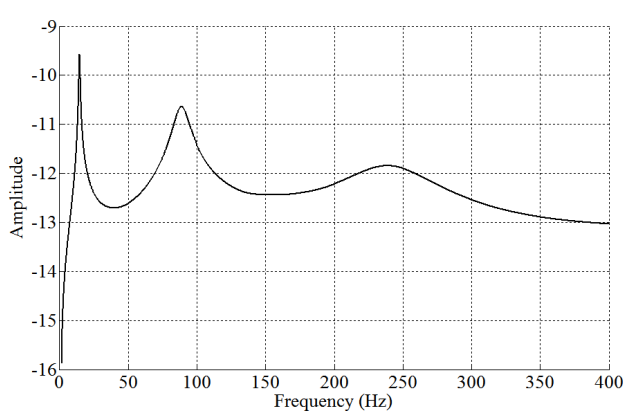

Figure 1: Frequency response

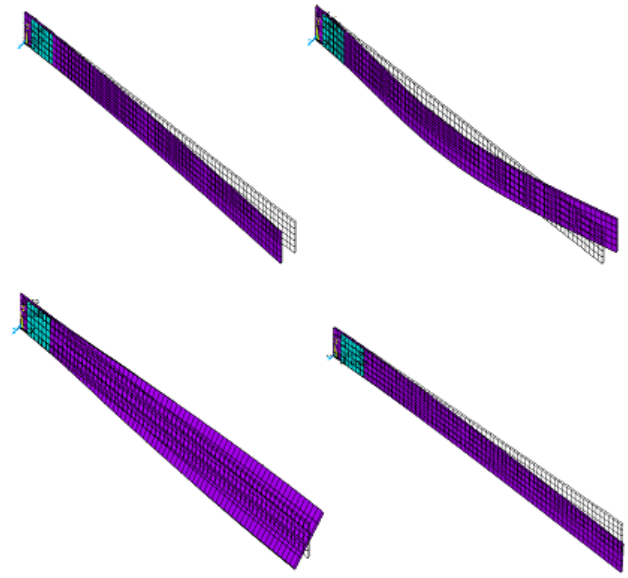

Figure 2: First four mode shapes

To obtain the state space equation, the model is subjected to a random chirp voltage with repeatable value

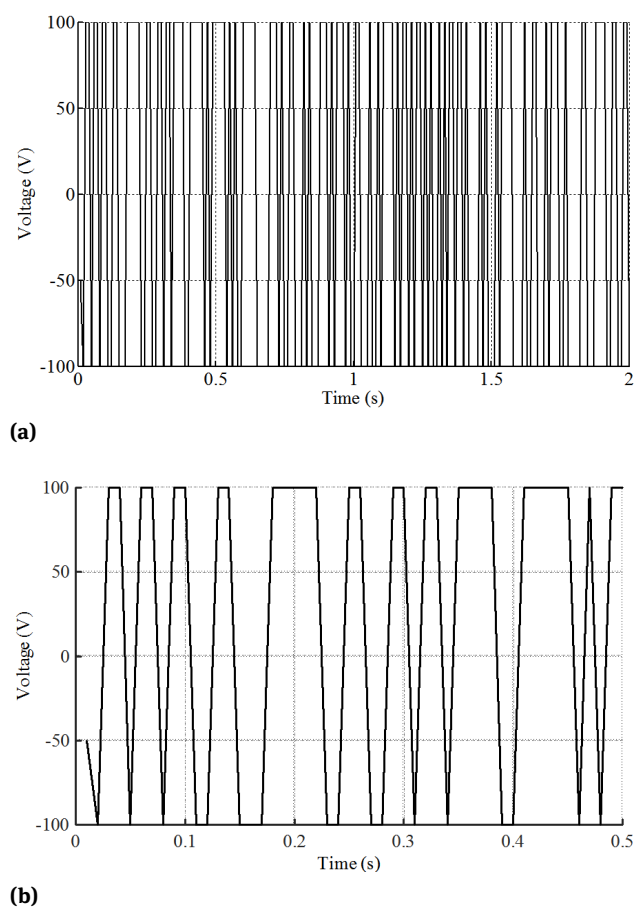

Figure 3: The applied voltage (a) full range (b) Detail view

(−100v and 100v) with a sampling time of T=0.01 seconds (the whole process has been discussed in section 3). The applied random voltage is shown in Figure 3, while the beam response is presented in Figure 4. The input-output time history obtained from Ansys is now used to obtain the final state-space model using system identification toolbox in Matlab [10]. Using the space state model, an LQG control algorithm is designed and implemented in APDL for the closed loop simulation,

The deflection of the beam due to the applied PRBS voltage is plotted in Figure 4. As can be seen from Figure 4, the amplitude of the deflection beam is unpredictable which help to test a large number of resonance frequencies. As an example, the enlarged view of deflections for the time interval [2.4, 3.4] is displayed.

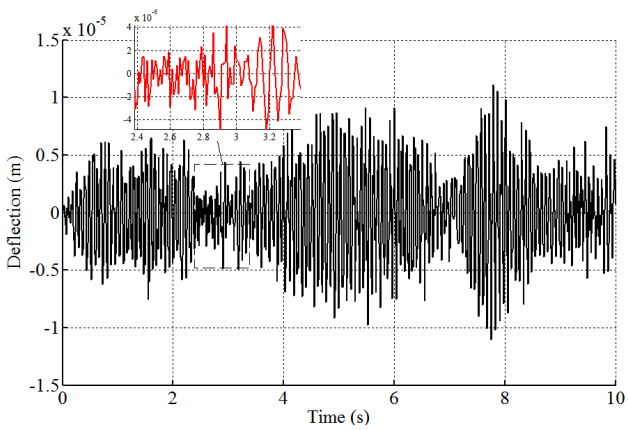

Figure 4: The tip deflection of the beam under random voltage excitation

To test the effectiveness of the present methodology, first the free end of the beam is subjected to a transverse load of 1N magnitude for 0.01s. Figure 5 presents the tip

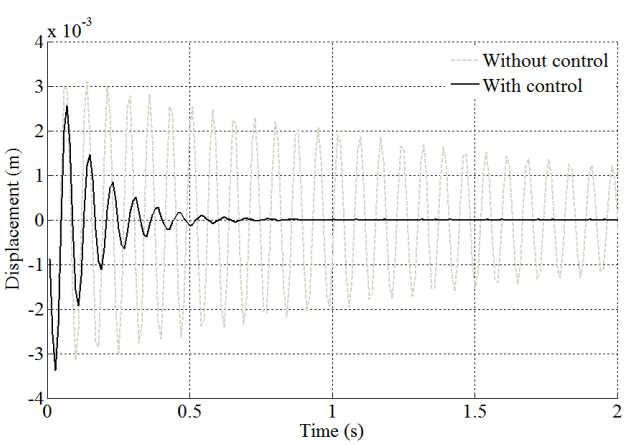

Figure 5: The tip deflection of the beam under transient excitation

deflection of the beam with and without control; the results show clearly that the vibration is efficiently reduced in matter of amplitude and time. The corresponding control voltage is given in Figure 6.

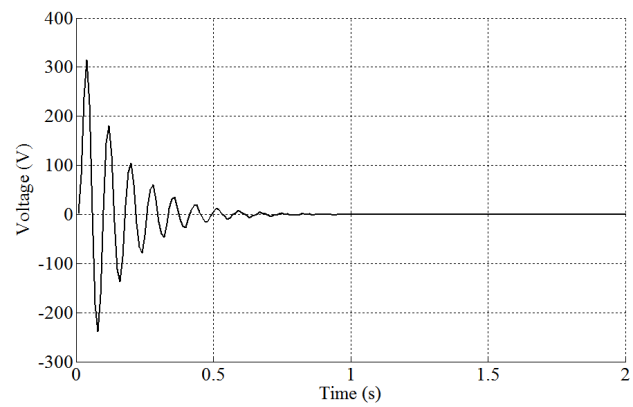

Figure 6: Control voltage variation under transient excitation

In the second case, the beam is subjected to external random load with range of [-1,1] N at the free end. Results for the displacement of the beam with control off and on are shown in the same Figure (Figure 7) for comparison reason. The corresponding voltage is presented in Figure 8. It can be noticed that the controller successfully reduce the vibrations amplitude.

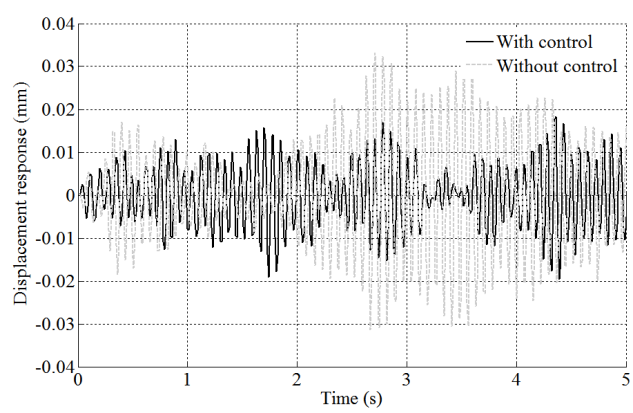

Figure 7: The tip deflection of the beam under random excitation

6 Conclusions

A methodology to reduce actively the vibrations of composite beam based on APDL has been introduced in this paper. The input-output time histories provide by APDL is

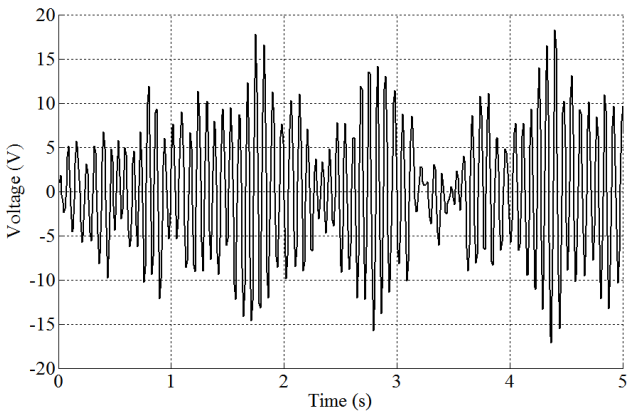

Figure 8: Control voltage variation under random excitation

coupled with system identification technique to obtain the state space equation. LQG control law is designed and implemented into APDL to calculate the voltage gain. Numerical results demonstrate that the control algorithm is efficient in reducing the vibration which encourages using the presented technique for more complex problems.

References

[1] Aridogan, U., Basdogan, I., 2015. A review of active vibration and noise suppression of plate-like structures with piezoelectric transducers. J. Intell. Mater. Syst. Struct. 26, 1455–1476.

[2] Bendine, K., Boukhoulda, B.F., Nouari, M., Satla, Z., 2016. Structural Modeling and Active Vibration Control of Smart FGM Plate through ANSYS. Int. J. Comput. Methods 1750042.

[3] Bendine, K., Boukhoulda, F.B., Haddag, B., Nouari, M., 2017. Active vibration control of composite plate with optimal placement of piezoelectric patches. Mech. Adv. Mater. Struct.

[4] Bendine, K., Boukhoulda, F.B., Nouari, M., Satla, Z., 2016. Active vibration control of functionally graded beams with piezoelectric layers based on higher order shear deformation theory. Earthq. Eng. Eng. Vib. 15, 611–620.

[5] Bruant, I., Gallimard, L., Nikoukar, S., 2010. Optimal piezoelectric actuator and sensor location for active vibration control, using genetic algorithm. J. Sound Vib. 329, 1615–1635.

[6] Elshafei, M.A., Alraiess, F., 2013. Modeling and analysis of smart piezoelectric beams using simple higher order shear deformation theory. Smart Mater. Struct. 22, 35006.

[7] Fuller, C.C., Elliott, S., Nelson, P.A., 1996. Active control of vibration. Academic Press.

[8] Gay, D., 2014. Composite materials: design and applications. CRC press.

[9] Khot, S.M., Yelve, N.P., Tomar, R., Desai, S., Vittal, S., 2012. Active vibration control of cantilever beam by using PID based output feedback controller. J. Vib. Control 18, 366–372.

[10] Ljung, L., 1998. System Identification, in: Signal Analysis and Prediction, Applied and Numerical Harmonic Analysis. Birkhäuser, Boston, MA, pp. 163–173.

[11] Malgaca, L., 2010. Integration of active vibration control methods with finite element models of smart laminated composite structures. Compos. Struct. 92, 1651–1663.

[12] Meng, G., Ye, L., Dong, X., Wei, K., 2006. Closed loop finite element modeling of piezoelectric smart structures. Shock Vib. 13, 1–12.

[13] Peng, F., Ng, A., Hu, Y.-R., 2005. Actuator placement optimization and adaptive vibration control of plate smart structures. J. Intell. Mater. Syst. Struct. 16, 263–271.

[14] Peng, X.Q., Lam, K.Y., Liu, G.R., 1998. Active vibration control of composite beams with piezoelectrics: a finite element model with third order theory. J. Sound Vib. 209, 635–650.

[15] Reddy, J.N., 1999. On laminated composite plates with integrated sensors and actuators. Eng. Struct. 21, 568–593.

[16] Sadri, A.M., Wright, J.R., Wynne, R.J., 1999. Modelling and optimal placement of piezoelectric actuators in isotropic plates using genetic algorithms. Smart Mater. Struct. 8, 490.

[17] Sun, B., Huang, D., 2000. Analytical vibration suppression analysis of composite beams with piezoelectric laminae. Smart Mater. Struct. 9, 751–760. https://doi.org/10.1088/0964-1726/9/6/303

[18] Takács, G., Rohaľ-Ilkiv, B., 2012. Direct closed-loop active vibration control system prototype in ANSYS, in: INTER-NOISE and NOISE-CON Congress and Conference Proceedings. Institute of Noise Control Engineering, pp. 1–12.

[19] Takács, G., Rohaľ-Ilkiv, B., 2012. Model Predictive Vibration Control: Efficient Constrained MPC Vibration Control for Lightly Damped Mechanical Structures. Springer Science & Business Media.

[20] Takács, G., Rohal'-Ilkiv, B., 2010. Piezoelectric wafer based feedback in vibration control of lightly damped beams, in: Proceedings of the 9th International Scientific—technical conference—Process Control.

[21] Yang, Y., Jin, Z., Soh, C.K., 2005. Integrated optimal design of vibration control system for smart beams using genetic algorithms. J. Sound Vib. 282, 1293–1307.

[22] Zorić, N.D., Simonović, A.M., Mitrović, Z.S., Stupar, S.N., 2012. Optimal vibration control of smart composite beams with optimal size and location of piezoelectric sensing and actuation. J. Intell. Mater. Syst. Struct. 1045389X12463465.