Active Vibration Control of Viscoelastic Core Sandwich Using PID, LQR and LQG Controllers

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Abstract

Vibration control is a fast-evolving topic, with research being conducted on various strategies to reduce dangerous vibration levels. Composite materials have the advantage of improved material qualities compared to metallic alloys while being low in weight. The current work primarily focuses on the design of the Linear Quadratic Gaussian (LQG) controller, Linear Quadratic Regulator (LQR) controller, and Proportional Integral Derivative (PID) controller used for the active vibration control of Carbon/Glass epoxy reinforced composite beams, using various control techniques upon composite sandwich beams with viscoelastic material core. The implementation of LQG, LQR and PID controller is done using the displacement-time data obtained from the finite element analysis to obtain transfer function, state space representation. From transfer function, controllers are implemented to check the change within amplitude and settling time using MATLAB-Simulink. Composite sandwich beams with a viscoelastic material core implanted between composite face plates have been designed, and active vibration control study has been conducted. The percentage reduction in settling time as well as vibrational amplitude has been discovered to be significant.

Keywords
PID, LQR, LQG, Composite materials, Viscoelastic material (VEM)

1.Introduction
Vibration control of structures has been an intense field of research since many years. The reason such importance is given to the field is because unwanted vibration causes structural failures and reduced lifetime, accuracy loss in precision equipment, and performance degradation in machines. Thus, vibrational control has been established as a significant field in the scientific world. Material science advanced during the industrial revolution, and several new materials were developed that not only have greater damping qualities, but also have more strength and toughness, and are better in certain ways than their popular predecessors-steel, iron, and aluminium. Fibre Reinforced Composites are one sort of material that fits this description. When compared to traditional structural metals, these composite materials have superior mechanical properties such as strength-to-weight ratio and stiffness-to-weight ratio. As a result, these materials are widely used in the aerospace and wind turbine blade sectors. Glass Epoxy Composite and Carbon Epoxy Composite are two examples of common fibre Reinforced Composites.

The mathematical equations for the flexible beam is developed using modal theory and implemented the LQR control (Zhang et al. 2008). Experimental study is conducted on the cantilever beam using PID controller and validated with the simulation results obtained (Alam and Rahman 2012). Active control scheme is implemented on the passive constrained beam and find out the optimum parameters to get the maximum damping in the structure (Lam et al. 1997). Integrated the active control methods into the finite element solutions in ANSYS. Both the numerical and experimental studies have done on the smart composite laminate structures under free and forced vibration conditons (Malgaca 2010). Active vibration control strategies for the vibration suppression in beam applications have been discussed, and effectiveness in implementing the controller numerically have been presented (Heganna and Joglekar 2016; Rimašauskienė et al. 2019; Kusagur et al. 2020; Tian et al. 2020; Reddy et al. 2021) The bending deformation and failure criteria in the sandwich beams composed of aluminium foam core and metallic face layer materials by using FEM was presented in the paper (Sha et al. 2011).

An active vibration control on a smart cantilever beam made from aluminium with bonded piezoelectric materials was conducted. The control signal for the actuator was generated by using a PID controller (Khot et al. 2013)(Khot et al. 2012). Rahman and Naushad. (2015) conducted study on active vibration suppression of smart beam and showed that the actuator and sensor-based control method is effective and the LabView control plots for various beams were used as a benchmark for analytical work. Active vibration control system has demonstrated the validity and efficiency of PID controller.
Based on the literature available it is found that there is no particular study done on active control of hybrid composite sandwich beams with different controllers. So, the present study is concentrated to develop the LQG, PID and LQR controllers for composite sandwich beam with viscoelastic core material. As a part of the study, first attempt is made to find out the transfer function of the composite for the viscoelastic sandwich beam from the transient response. Then, active control techniques are implemented on the sandwich beam transfer function to get the good reduction in settling time and vibration amplitude.

2.Material Data

These material properties are used as engineering data for the ANSYS analysis done in this study. The material properties (Table 1, 2, 3, 4, 5 and 6) have been obtained from Kutz (2015).

2.1 E-Glass Epoxy Composite

Table 1. Physical property

Density	1850 Kg/m^3

Table 2. Orthotropic elasticity properties

E_X (MPa)	E_Y (MPa)	E_Z (MPa)	ν_{XY}	ν_{YZ}	ν_{ZX}	G_X (MPa)	G_Y (MPa)	G_Z (MPa)
35000	35000	900	0.28	0.4	0.4	351.56	12500	12500

2.2 Carbon Epoxy Composite

Table 3. Physical property

Density	1450 Kg/m^3

Table 4. Orthotropic elasticity properties

E_X (MPa)	E_Y (MPa)	E_Z (MPa)	ν_{XY}	ν_{YZ}	ν_{ZX}	G_X (MPa)	G_Y (MPa)	G_Z (MPa)
59160	59160	7500	0.04	0.3	0.3	3605.77	22753.8	22753.8

2.3 Viscoelastic Material (VEM): DYAD 606

Table 5. Physical property

Density	1850 Kg/m^3

Table 6. Orthotropic elasticity properties

Storage Shear Modulus	**Poisson's Ratio**	**Operating Temperature**	**Loss Shear Modulus**
20 MPa	0.49	10°C – 80°C	1.05 at 40°C

3. Methodology

3.1 Designing of Hybrid Sandwich beam

Engineers who are building and analyzing multi-layer composites use Ansys Composite Pre-Post. We can generate complicated shell and solid composite models in ACP PRE with the proper fibre orientation and lay-up definition. Create parametric design analyses to assess the influence of specific parameters such as number of layers, fibre orientation, and so on the design and behaviour of the structure by performing FE analysis on composite models and post-processing results specific to composites (such as failure criteria). The Hybrid composite beam utilized in the modelling is 200mm x 20mm x 3mm in size (thickness of each layer being 1mm). To build the composite beams, ASTM E- 756 standards were used (Figure 1). The composite beams were modelled and analyzed to obtain their free vibration response so as to study and compare their inherent damping behaviour.

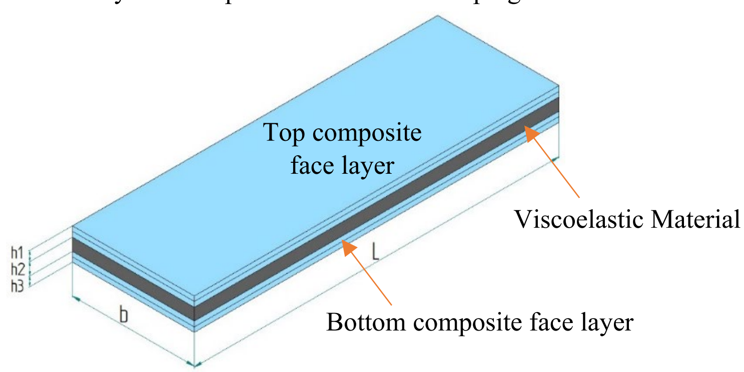


Figure 1. Design of viscoelastic composite sandwich beam

3.2 Active Vibration Control

Active vibration control is the active application of force in an equal and opposite fashion to counter or cancel the forces imposed by external vibration. For this purpose, Linear Quadratic Regulator (LQR) controller & Proportional Integral Derivative (PID) controller and Linear Quadratic Gaussian (LQG) controller were implemented. It is applied to different combinations of beams, by choosing the optimal models of beams obtained, based on best maximum amplitude & natural frequencies among other beams, in previous sections – Namely – CF, CF-VEM.

3.2.1 Transfer Function

Using a ratio of polynomials, transfer function models describe the link between a system's outputs and inputs. The order of the denominator polynomial is the same as the model order. The model poles of the denominator polynomial are the roots of the denominator polynomial. The numerator polynomial's roots are referred to as the model zeros. The MATLAB application System Identification was used to find the transfer function. First, open the System Identification app and import time domain data. As visible in the MATLAB workspace, the input and output names must be provided. For the ANSYS models, the start time is set to 0 and the Sample time is set to 0.01. After the data has been imported, double-check the time domain and frequency domain graphs by checking the appropriate boxes. Then, Select Estimate in the Transfer Function Models from the System Identification app. For the transfer function, a continuous model is chosen. To obtain the best fit to estimation, the number of poles and zeros are increased. For the transfer function, the model with the best fit is chosen.

3.2.2 Simulink

SIMULINK is a MATLAB based software package for modelling, simulating and analysing dynamical systems in continuous time. The transfer function obtained is then used to simulate the PID controller in Simulink [17-20]. The control algorithm is tuned to get the gains. Simulink allows us to safely tune the system without causing any damage. The output of the LQR controlled beam is then compared to the output of the normal beam.

4. Results and Discussion

4.1 Active Vibration Control of the Sandwich Beams

4.1.1 GF – VEM – GF

The transient analysis of the beam is conducted after giving – (i) impulse input of 5N for 0.01s & (ii) Forced input 5N at 10rad/sec frequency (in the form of $F = F_O \sin(\omega t)$). The time domain graph obtained for 4 different cases of vibration control is shown below, namely:

i. Without implementation of controller.
ii. With Implementation of PID controller.
iii. With implementation of LQR controller.
iv. Implementation of LQG controller.

And the respective values of Peak amplitudes & settling times are listed in the table below. Also, included is the reduction percentage of peak amplitude & settling time for 0.758mm (Table 7) (Figure 2).

4.1.2 Free Vibration

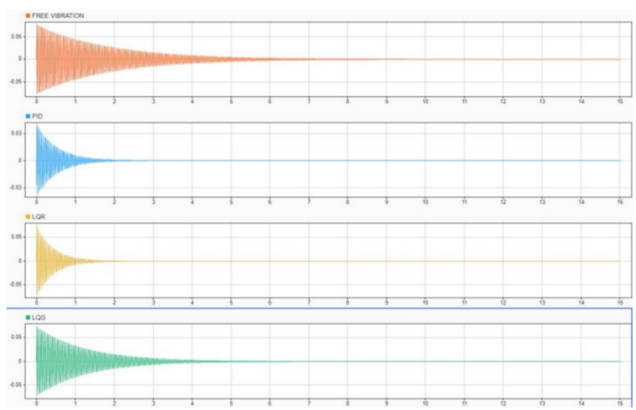
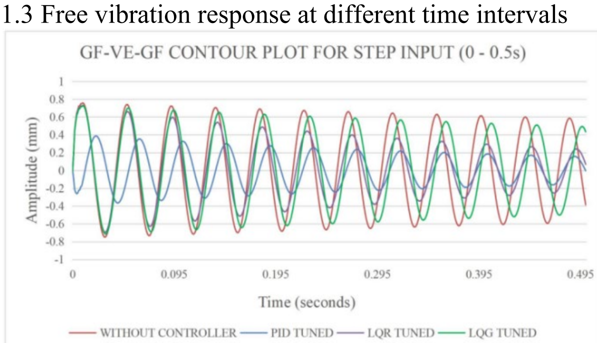
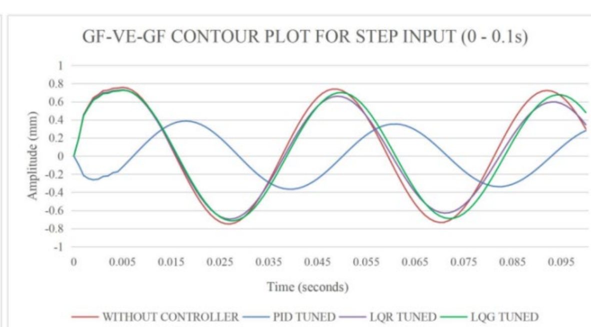


Figure 2. Active Control of GF-VEM-GF Beam – Free vibration

4.1.3 Free vibration response at different time intervals





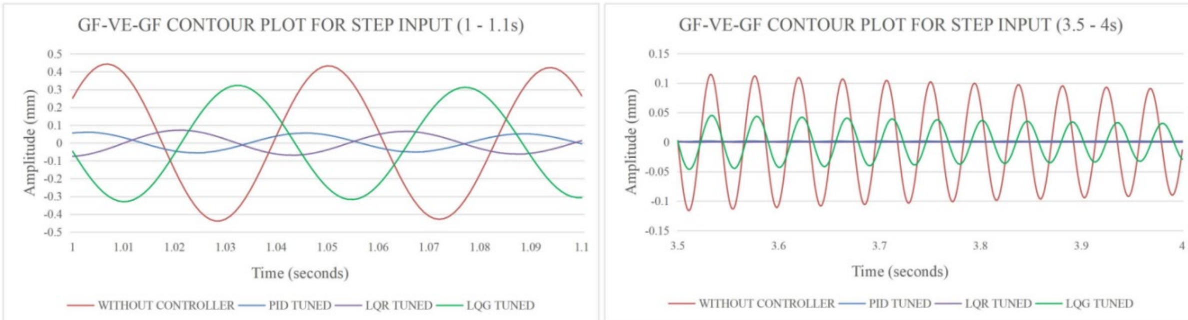


Figure 3. Active Control of GF-VEM-GF Beam–Free vibration

Table 7. Comparing PID, LQR & LQG controller – GF-VEM-GF beam (free vibration)

GF-VEM-GF	Settling Time (In seconds)	Peak/Max Amplitude (in mm)	t1/2 (In seconds)
Without Controller	9.8	0.7586	1.3
With PID Controller	3.3	0.3877	0.4
With LQR Controller	2.9	0.7313	0.31
With LQG Controller	6.4	0.7266	0.9
% Reduction (With PID controller vs. Without controller)	66.33	48.89	-
% Reduction (With LQR controller vs. Without controller)	70.40	3.60	-
% Reduction (With LQG controller vs. Without controller)	34.70	4.21	-

For GF-VE-GF sandwich beam in free vibration, on observing Figure 2 and 3, and Table 8, we can infer that there have been significant active control of the beam by PID and LQR and LQG controllers which are reducing the vibrational amplitudes by 48.89% and 3.60% and 4.21% respectively and They are also reducing settling time for 75.86 mm by 66.33% and 70.40% and 34.70% respectively as shown. PID is well reducing vibrational amplitude and settling time.

4.1.4 Forced Vibration

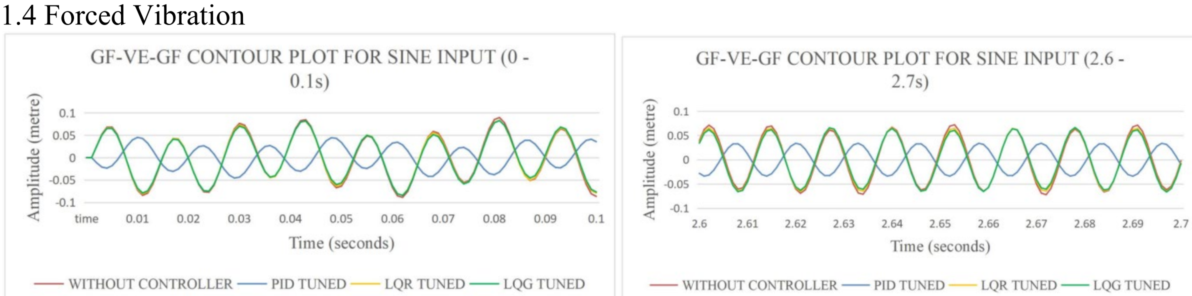


Figure 4. Active Control of GF-VEM-GF Beam-Forced input

Table 8. Comparing PID, LQR & LQG controller – GF-VEM-GF beam (forced vibration)

GF-MRF-GF	Max. Amplitude
Without Controller	72.16
With PID Controller	33.94
With LQR Controller	65.5
With LQG Controller	66.37
% Reduction (With PID Controller vs. Without Controller)	52.97
% Reduction (With LQR Controller vs. Without Controller)	9.23
% Reduction (With LQG Controller vs. Without Controller)	8.02

For GF-VE-GF sandwich beam in forced vibration, on careful observation of Figure 4 and Table 8, we can see that the settling time for the beam is lowest in case of LQR controller and the max amplitude is also very low in case of PID controller. PID controller offers a significantly huge reduction of 52.97% in forced and 48.89% in free vibration. While LQR reduce amplitude up to 9.23% in forced and 3.60% in free vibration and LQG reduces amplitude up to 8.02% in forced and 4.21% in free vibration as shown. So, it is observed that PID controller is reducing the vibration noticeably and it can be stated that PID is working better than LQR and LQG in terms of settling time and vibrational reduction in case of modelled GF-VEC-GF beam.

4.2 CF – VEM – CF

The transient analysis of the beam is conducted after giving – (i) impulse input of 5N for 0.01s & (ii) Forced input 5N at 10rad/sec frequency (in the form of F = FO Sin(ωt)). The time domain graph obtained for 4 different cases of vibration control is shown below, namely:

v. Without implementation of controller.
vi. With Implementation of PID controller.
vii. With implementation of LQR controller.
viii. Implementation of LQG controller.

And the respective values of Peak amplitudes & settling times are listed in the table below. Also, included is the reduction percentage of peak amplitude & settling time for 0.01mm.

4.2.1 Free Vibration

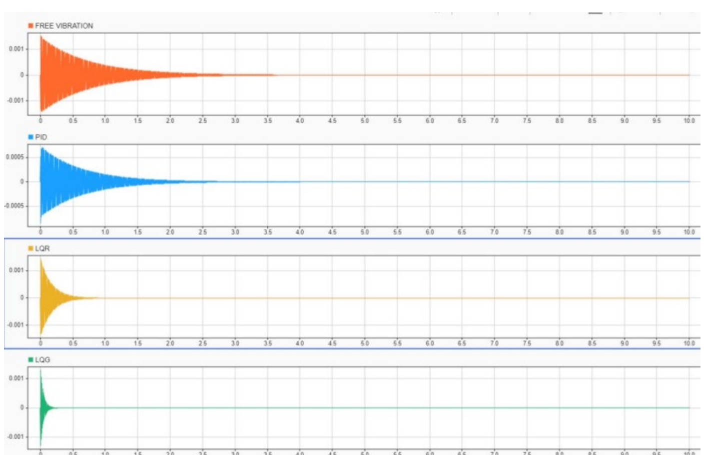


Figure 5. Active Control of CF-VEM-CF Beam – Free vibration

4.2.2 Plotting the same for different time intervals

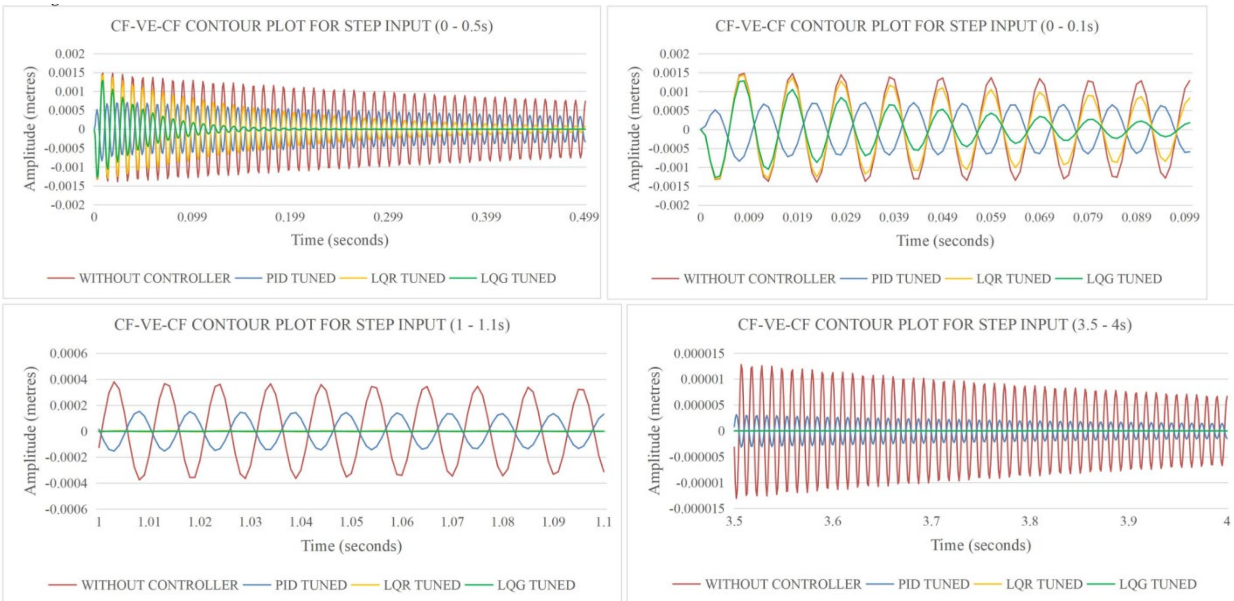


Figure 6. Active Control of CF-VEM-CF Beam –Free vibration

Table 9. Comparing PID, LQR & LQG controller – CF-VEM-CF beam (free vibration)

CF-VEM-CF	Settling Time (In seconds)	Peak/Max Amplitude (in mm)	t1/2 (In seconds)
Without Controller	5.8	1.482	0.52
With PID Controller	4.2	0.706	0.47
With LQR Controller	1.4	1.435	0.12
With LQG Controller	0.35	1.285	0.03
% Reduction (With PID controller vs. Without controller)	27.59	52.36	-
% Reduction (With LQR controller vs. Without controller)	75.86	3.17	-
% Reduction (With LQG controller vs. Without controller)	93.97	13.29	-

For CF-VE-CF sandwich beam in free vibration, we can observe from Figure 5 and 6, and Table 9, that there has been significant active control of the beam by all PID and LQR and LQG controllers which are reducing the vibrational amplitudes by 52.36% and 3.17% and 13.29% respectively. They are also reducing settling time for 75.86 mm by 27.59% and 1.482% and 93.97% respectively as illustrated. For reducing the vibration amplitude max for PID and reducing settling time LQR is better compared to others.

4.2.3 Forced Vibration

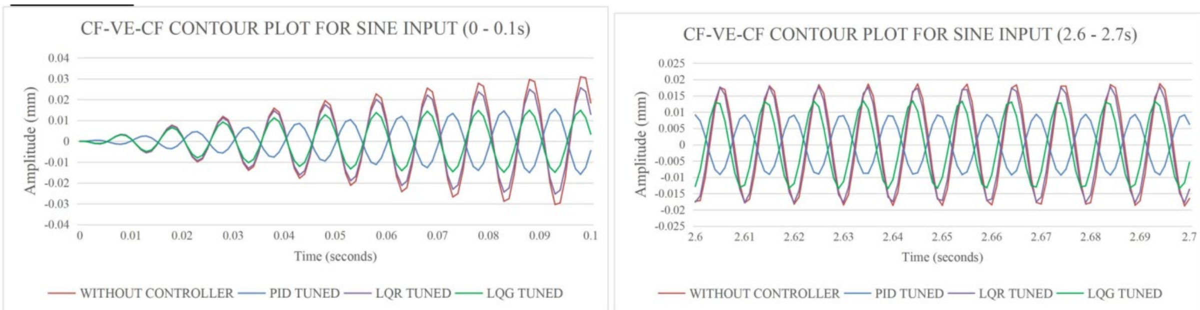


Figure 7. Active Control of CF-VEM-CF Beam-Forced vibration

Table 10. Comparing PID, LQR & LQG controller – CF-VEM-CF beam (forced vibration)

CF-VEM-CF	Max. Amplitude
Without Controller	18.39
With PID Controller	9.13
With LQR Controller	17.79
With LQG Controller	13.38
% Reduction (With PID Controller vs. Without Controller)	50.35
% Reduction (With LQR Controller vs. Without Controller)	3.26
% Reduction (With LQG Controller vs. Without Controller)	27.24

For CF-VE-CF sandwich beam in forced vibration, we can infer from Figure 7 and Table 10, that PID controller offers a significantly huge reduction of amplitude 50.35% in forced and 52.36% in free vibration. LQG controller offers a significantly huge reduction of 27.24% in forced and 13.29% in free vibration. The settling time is lowest in case of LQG controller and the max amplitude is very low in case of PID controller.

5. Conclusion

In the case of composite beams having viscoelastic material core, when it comes to the material having high stiffness, such as Carbon Fibre, PID can be used to reduce the max amplitude, whereas LQG can be used to reduce the settling time. In the case of low stiff materials, such as Glass fibre, again PID can be used to reduce the max amplitude, although for reducing the settling time, LQR needs to be used. These are the important observations which can be seen to be potentially applied on the Aerospace and Automobile applications, the sports car, and aeroplane wings in particular.

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References

Alam MN, Rahman NU, Active vibration control of a piezoelectric beam using PID controller: Experimental study. Lat Am J Solids Struct 9:657–673, 2012.

Drive B, Park D, Polymers EARVD, Complex Modulus of Typical Damping Treatments, 2003.

Heganna SS, Joglekar JJ, Active Vibration Control of Smart Structure Using PZT Patches. Procedia Comput Sci 89:710–715. https://doi.org/10.1016/j.procs.2016.06.040, 2016.

International A, Standard Test Method for Measuring Vibration-Damping Properties of Materials E756-9804. 05:1–18. https://doi.org/10.1520/E0756-05R17.2, 2017.

Khot SM, Yelve NP, Shaik S, Experimental study of active vibration control of a cantilever beam. Int Conf Emerg Trends Eng Technol ICETET 1–6. https://doi.org/10.1109/ICETET.2013.2, 2013.

Khot SM, Yelve NP, Tomar R, et al , Active vibration control of cantilever beam by using PID based output feedback controller. JVC/Journal Vib Control 18:366–372. https://doi.org/10.1177/1077546311406307, 2012.

Kusagur SM, Arunkumar G, Manjunath TC, Modelling of smart intelligent materials with PZT & PVDF sensors/actuators to control the active vibrations of flexible aluminum mechanical cantilever beams using proportional integral derivative (PID) techniques. Mater Today Proc 37:2075–2082. https://doi.org/10.1016/j.matpr.2020.07.507, 2020.

Kutz M (ed), Mechanical Engineers' Handbook. John Wiley & Sons, Inc., Hoboken, NJ, USA, 2014.

Lam MJ, Inman DJ, Saunders WR, Vibration control through passive constrained layer damping and active control. In: Davis LP (ed) Smart Structures and Materials 1997: Passive Damping and Isolation. pp 60–69, 1997.

Malgaca L, Integration of active vibration control methods with finite element models of smart laminated composite structures. Compos Struct 92:1651–1663. https://doi.org/10.1016/j.compstruct.2009.11.032, 2010.

Reddy RS, Panda S, Gupta A, Nonlinear dynamics and active control of smart beams using shear/extensional mode piezoelectric actuators. Int J Mech Sci 204:106495. https://doi.org/10.1016/j.ijmecsci.2021.106495, 2021.

Rimašauskienė R, Jūrėnas V, Radzienski M, et al, Experimental analysis of active–passive vibration control on thin-walled composite beam. Compos Struct 223:110975. https://doi.org/10.1016/j.compstruct.2019.110975, 2019.

Sha JB, Yip TH, Teo MH, FEM modelling of single-core sandwich and 2-core multilayer beams containing foam aluminum core and metallic face sheets under monolithic bending. Prog Nat Sci Mater Int 21:127–138. https://doi.org/10.1016/S1002-0071(12)60046-X, 2011.

Tian J, Guo Q, Shi G, Laminated piezoelectric beam element for dynamic analysis of piezolaminated smart beams and GA-based LQR active vibration control. Compos Struct 252:112480. https://doi.org/10.1016/j.compstruct.2020.112480, 2020.

Zhang J, He L, Wang E, Gao R, A LQR controller design for active vibration control of flexible structures. Proc - 2008 Pacific-Asia Work Comput Intell Ind Appl PACIIA 2008 1:127–132. https://doi.org/10.1109/PACIIA.2008.358, 2008.

Kutz, M. (Ed.). Mechanical engineers' handbook, volume 1: Materials and engineering mechanics. John Wiley & Sons, 2015.

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