Active Vibration Control of MR Fluid Core Sandwich Beam 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 having improved material qualities that are comparable to metallic alloys while being low in weight. This work primarily focuses on the design of various combinations of Carbon/Glass epoxy reinforced composite beams, as well as vibration control using various control techniques (Semi-active and Active) of various combinations of hybrid composite sandwich beams with Magneto- Rheological fluid core, as well as the implementation of LQG, LQR, and PID controllers using ANSYS and MATLAB Simulink. It is designed with mainly two different combinations (Carbon Fibre - MR Fluid Core - Carbon Fibre, and (Glass Fibre - MR Fluid Core - Glass Fibre) and vibration response has been taken based on the literature studies that have been carried out on the Composites beams (Glass + Carbon reinforced in epoxy matrix composite separately). Composite sandwich beams with a magneto-rheological fluid core implanted between composite face plates have been created, and a semi-active and active vibration control study has been conducted. The study then moves on to designing a Linear Quadratic Gaussian (LQG) controller, Linear Quadratic Regulator (LQR) controller, and Proportional Integral Derivative (PID) controller for Active vibration control of hybrid composite sandwich beams. These controls were used to minimize the settling time and vibrational peak amplitudes on the created composite sandwich beam. The percentage reduction in settling time as well as vibrational amplitude was discovered to be significant.

Keywords

PID, LQR, LQG, Free Vibration, ANSYS, Magneto Rheological Fluid

1. Introduction

For millennia, vibration control has been a debated subject. According to records, the Roman civilization investigated the natural frequencies of its bridges. Uncontrolled vibration produces a variety of severe damages to various engineering structures, which is why the concept of vibration reduction is given such weight. Unwanted vibration leads to structural problems and shorter lifespans, as well as a loss of accuracy in precision equipment and machine performance. As a result, vibrational control has gained prominence in the scientific community. Because knowledge of damping qualities was limited at the time, damping capabilities of a material were not considered a significant issue when choosing materials for engineering applications. 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. Magnetorheological fluids are a suspension of tiny, low-coercivity, non-colloidal ferromagnetic particles in a carrier fluid (usually carbonyl iron 20%-40% by volume). They are controlled fluids with the ability to transition from a liquid to a semi-solid (quasi-solid) kind of behaviour in the presence of external magnetic fields. These modifications are both quick and reversible. This is the magnetic resonance fluid effect. The ferromagnetic particles typically range in size from 1 to 10 m. (Weiss et al. (1994)). To minimize gravitational settling and promote particle suspension, change viscosity, and inhibit wear, several additives comparable to those found in commercial lubricants are often used (Kciuk.and Turczyn (2012)).

MR fluids can be operated at temperatures ranging from -40°C to +150°C. The particles of MR fluid magnetize in a magnetic field and form chains in the direction of the field lines. The apparent yield stress rises as a result of this reorganisation. MR fluids display increased resistance to flow (apparent viscosity) or increasing stiffness (elastic modulus) with increasing field strength, depending on the deformation (Premalatha.et al. (2012), López-López et al. (2006), Iglesias et al. (2012), Genc and Phule (2002), Muddebihal and Patil (2020), Zhu. W. (2019)). When compared to electro rheological fluids, MR fluids have a higher stiffness and can attain a higher yield stress. As a result, structural vibrations can be more easily controlled. By partially activating a region of the MR fluid filled sandwich beam, the first natural frequency of vibration is reduced significantly. This is accomplished by altering the magnitude of the magnetic field (Genç.and Phulé. (2007)).

MR fluid fulfils the critical performance criteria such as low initial viscosity, high shear upon the application of the magnetic field, low hysteresis, low power consumption, temperature stability, and fast response. With optimized control of external magnetic field strength, the fatigue failure can be reduced and undesirable resonance can be eliminated. Their unique nature has made MR fluids suitable for semi – active energy – dissipating applications. Vibration suppression capabilities of MR fluid in sandwich beams were presented with both experimental and using finite element formulations and the Ritz method. The presented results show the significant vibration suppression capabilities of the MR sandwich beams with a magnetic field (Vasudevan et al. (2010)). 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 conditions (Malgaca (2010)).

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 (S.M. Khot et al. (2013), S.M.Khot (2012)). Active vibration control strategies for the vibration suppression in beam applications have been discussed, and effectiveness in implementing the controller numerically have been presented (Rimašauskienė et al. (2019), Tian et al. (2020), Kusagur. (2020), Reddy et al. (2021)). 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.

As the literature review shows Kalman filters, which are used as another form of statistical interpolation, to have less settling time and also, the Background error covariance matrices also evolve with the flow in KF implementations. Based on the literature available it is found that there is no particular study done on active control of MR fluid based composite sandwich beams with different controllers. So, the present study is concentrated to develop the LQG, LQR, and PID controllers for composite sandwich beam with MR fluid core material. As a part of the study, first attempt is made to find out the transfer function 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 have been obtained from Kutz (2015) (Table 1, 2, 3, 4, 5 and 6).

2.1 E-Glass Epoxy Composite

Table 1. Physical property

Density	1850 kg/m^3

Table 2. Orthotropic elastic parameters

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 elastic parameters

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 Magnetorheological Fluid

Table 5. Physical property

Density	3500 Kg/m^3

Table 6. Orthotropic elastic parameters

Storage Modulus (Pa)	**Poisson's Ratio**	**Operating Temperature**	**Loss Modulus (Pa)**
$1.09*10^6 + 2.41*10^6$(B)	0.3	-40°C – 150°C	$80.51*10^3$ – $159.35*10^3$(B)

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. The composite beams were modelled and analyzed to obtain their free vibration response so as to study and compare their inherent damping behaviour.

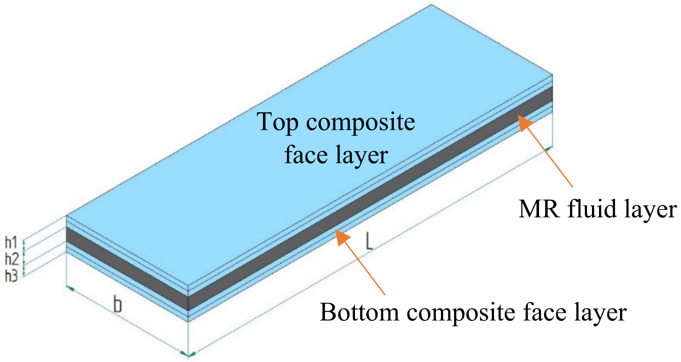

Figure 1. Design of composite sandwich beam with MR fluid and composite face layers

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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. Active vibration control 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-MRF-CF (with 0.08T magnetic field).

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 [22-25]. 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 – MRF – 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 = FO Sin(ωt)). The time domain graph obtained for 4 different cases of vibration control is shown below, namely:

1. i. Without implementation of controller.
2. ii. With Implementation of PID controller.
3. iii. With implementation of LQR controller.
4. iv. Implementation of LQG controller.

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.

4.1.2 Free Vibration

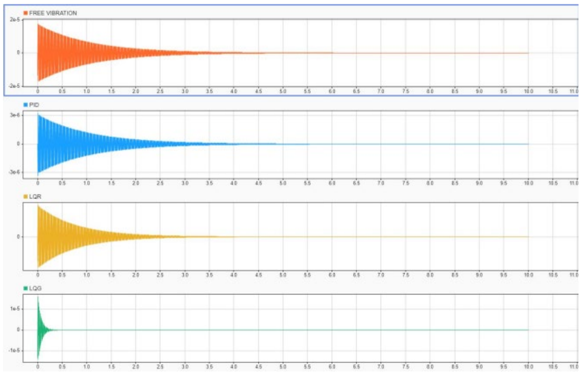

Figure 2. Active Control of GF-MRF-GF Beam – Free vibration

4.1.3 Free vibration response at different time intervals:

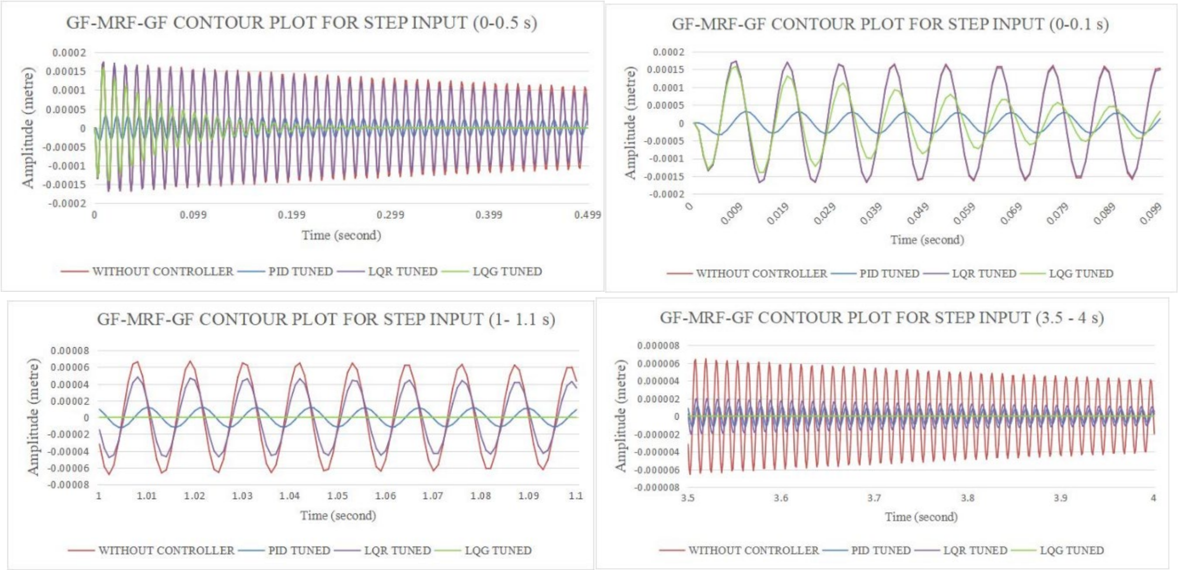

Figure 3. Active Control of GF-MRF-GF Beam – Free vibration

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

GF-MRF-GF	Settling Time (In seconds)	Peak/Max Amplitude (in mm)	t1/2 (In seconds)
Without Controller	8	0.173	0.707
With PID Controller	6	0.032	0.663
With LQR Controller	5	0.172	0.6
With LQG Controller	0.5	0.159	0.1
% Reduction (With PID controller vs. Without controller)	25.00	81.50	-
% Reduction (With LQR controller vs. Without controller)	37.50	0.58	-
% Reduction (With LQG controller vs. Without controller)	93.75	8.09	-

For GF-MRF-GF sandwich beam in free vibration, on observing Figure 2 &3, and Table 7, we can infer that PID, LQR and LQG controllers are comparable which are reducing the vibrational amplitudes by 81.50% and 0.58% and 8.09% respectively and they are also reducing settling time for 0.173mm by 25% and 37.5% and 93.75% respectively as shown. So PID is working better in reducing the amplitude and LQG is better in reducing the time to settle significantly.

4.1.4 Forced Vibration

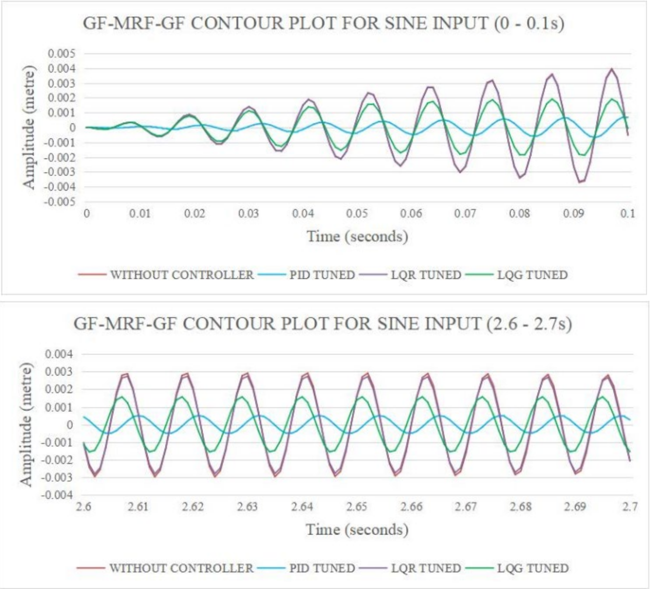

Figure 4. Active Control of GF-MRF-GF Beam-Forced vibration

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

GF-MRF-GF	Max. Amplitude
Without Controller	0.2758
With PID Controller	0.0465
With LQR Controller	0.2713
With LQG Controller	0.156
% Reduction (With PID Controller vs. Without Controller)	83.14
% Reduction (With LQR Controller vs. Without Controller)	1.63
% Reduction (With LQG Controller vs. Without Controller)	43.44

For GF-MRF-GF sandwich beam in forced vibration, upon checking Figure 4 and Table 8, we can observe that the max amplitude is also very low in case of PID controller. PID controller offers a significantly huge reduction of 83.16%. While LQG reduce amplitude to 43.44% and LQR reduce amplitude to 1.63% as illustrated. So, it is clearly evident that both PID and LQG controllers are reducing the vibration significantly and LQG is reducing the vibration very less compared to others. PID is slightly working better in case of GF sandwich beam with MR fluid.

4.2 CF – MRF – 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 = $F_0\sin(\omega t)$). 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

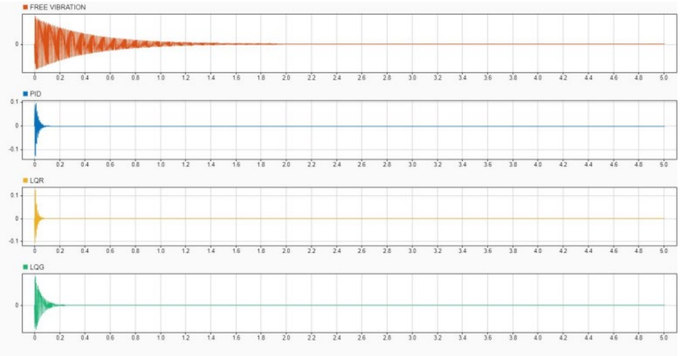

Figure 5. Active Control of CF-MRF-CF Beam – Free vibration

4.2.2 Free vibration response at different time intervals:

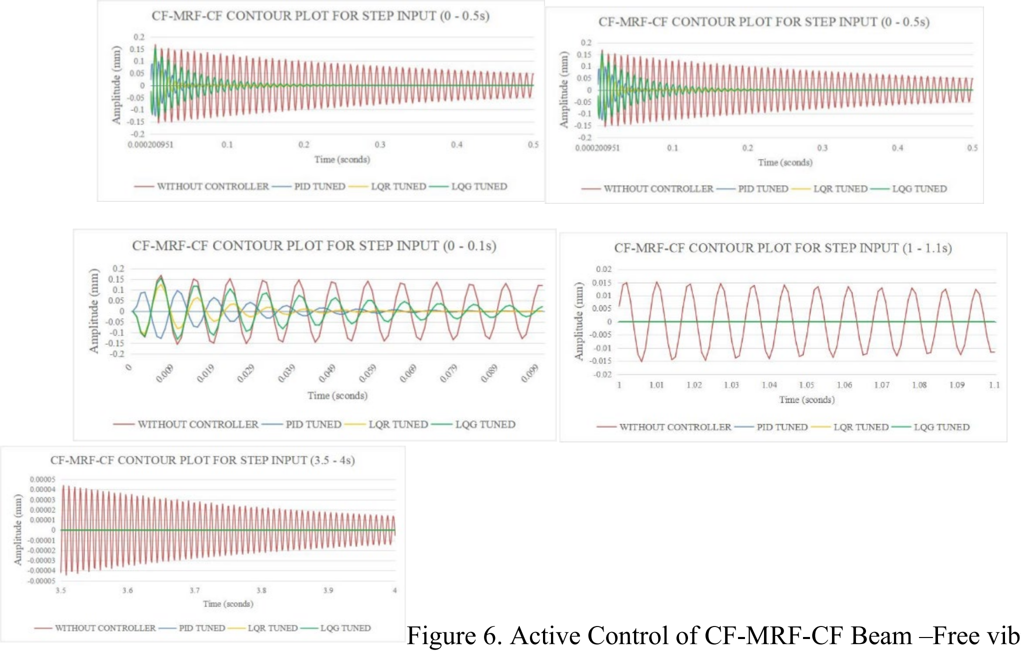

Figure 6. Active Control of CF-MRF-CF Beam –Free vibration

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

CF-MRF-CF	Settling Time (In seconds)	Peak/Max Amplitude (in mm)	t1/2 (In seconds)
Without Controller	2.2	0.168	0.27
With PID Controller	0.2	0.097	0.023
With LQR Controller	0.12	0.125	0.015
With LQG Controller	0.3	0.155	0.04
% Reduction (With PID controller vs. Without controller)	90.90	42.26	-
% Reduction (With LQR controller vs. Without controller)	94.54	25.60	-
% Reduction (With LQG controller vs. Without controller)	86,36	7.74	-

For CF-MRF-CF sandwich beam in free vibration, on observing Figure 5 and 6, and Table 9, we can see that there has been significant active control of the beam by all PID and LQR and LQG controllers and the controller's effects are comparable which are reducing the vibrational amplitudes by 42.26% and 25.60% and 7.74% respectively and they are also reducing settling time for 0.168mm by 90.90% and 94.54% and 86.36% respectively as illustrated. So PID is working better in reducing the amplitude and LQR is working better in reducing the time to settle significantly.

4.2.3 Forced Vibration

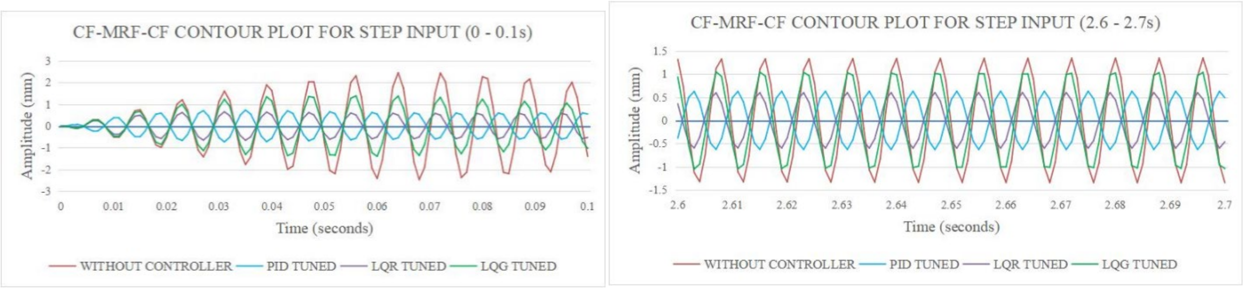

Figure 7. Active Control of CF-MRF-CF Beam-Forced vibration

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

CF-MRF-CF	**Max. Amplitude**
Without Controller	1.351
With PID Controller	0.632
With LQR Controller	0.603
With LQG Controller	1.09
% Reduction (With PID Controller vs. Without Controller)	53.21
% Reduction (With LQR Controller vs. Without Controller)	55.36
% Reduction (With LQG Controller vs. Without Controller)	19.31

For CF-MRF-CF sandwich beam in forced vibration, on observing Figure 7 and Table 10, we can infer that the amplitude reduction is more in the casoe of LQR (55.36%) than PID (53.21%) controller and LQG (19.31). So, it is clearly evident that both the PID and LQR controllers are reducing the vibration significantly by noticeable degree and the settling time for the beam is lowest in case of LQR controller and the max amplitude is also very low in case of LQR controller. LQR controller offers a significantly huge amplitude reduction of 25.6% (free vibration) and 55.36% (forced vibration) as shown.

5. Conclusion

In the case of composite beams having Magnetorheological Fluid Core, when it comes to the material having low stiffness, such as Glass Fibre, PID can be used to reduce the max amplitude, whereas LQG can be used to reduce the settling time. In the case of high stiff materials, such as Carbon fibre, again PID can be used to reduce the max amplitude, in the free vibration application, although for forced vibration, LQR performs better. When it comes to reducing the settling time, LQR performs the best. These are the important observations which can be seen to be potentially applied on the Aerospace and Automobile applications, the sports car, and aero plane wings in particular.

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References

Weiss, K. D., Carlson, J. D., & Nixon, D. A. Viscoelastic properties of magneto-and electro-rheological fluids. Journal of Intelligent Material Systems and Structures, 5(6), 772-775, 1994.

Kciuk, M., & Turczyn, R. Properties and application of magnetorheological fluids. Journal of Achievements in Materials and Manufacturing Engineering, 18(1-2), 127-130, 2006.

Premalatha, S. E., Chokkalingam, R., & Mahendran, M. Magneto mechanical properties of iron based MR fluids. Am. J. Polym. Sci, 2(4), 50-55, 2012.

López-López, M. T., Kuzhir, P., Lacis, S., Bossis, G., González-Caballero, F., & Durán, J. D. Magnetorheology for suspensions of solid particles dispersed in ferrofluids. Journal of Physics: Condensed Matter, 18(38), S2803, 2006.

Iglesias, G. R., López-López, M. T., Duran, J. D. G., González-Caballero, F., & Delgado, A. V. Dynamic characterization of extremely bidisperse magnetorheological fluids. Journal of colloid and interface science, 377(1), 153-159, 2012.

Genç, S., & Phulé, P. P. Rheological properties of magnetorheological fluids. *Smart Materials and Structures*, *11*(1), 140, 2002.

Muddebihal, A. B., & Patil, S. F. Preparation and study of characteristics of iron based MR fluids. Materials Today: Proceedings, 24, 1132-1137, 2020.

Zhu, W., Dong, X., Huang, H., & Qi, M. Iron nanoparticles-based magnetorheological fluids: A balance between MR effect and sedimentation stability. Journal of Magnetism and Magnetic Materials, 491, 165556, 2019.

Genç, S., & Phulé, P. P., Rheological properties of magnetorheological fluids. Smart Materials and Structures, 11(1), 140, 2002.

Rajamohan, V., Sedaghati, R., & Rakheja, S. Vibration analysis of a multi-layer beam containing magnetorheological fluid. Smart Materials and Structures, 19(1), 015013, 2009.

Lam, M. J., Inman, D. J., & Saunders, W. R. Vibration control through passive constrained layer damping and active control. Journal of Intelligent Material Systems and Structures, 8(8), 663-677, 2009.

Malgaca, L. Integration of active vibration control methods with finite element models of smart laminated composite structures. Composite Structures, 92(7), 1651-1663, 2010.

Khot, S. M., Yelve, N. P., & Shaik, S. Experimental study of active vibration control of a cantilever beam. In 2013 6th International Conference on Emerging Trends in Engineering and Technology (pp. 1-6). IEEE, 2013.

Khot, S. M., Yelve, N. P., Tomar, R., Desai, S., & Vittal, S. Active vibration control of cantilever beam by using PID based output feedback controller. Journal of Vibration and Control, 18(3), 366-372, 2012.

Khot, S. M., Nitesh P. Yelve, and Shoaib Shaik. "Experimental study of active vibration control of a cantilever beam." 2013 6th International Conference on Emerging Trends in Engineering and Technology. IEEE, 2013.

R. Rimašauskienė, V. Jūrėnas, M. Radzienski, M. Rimašauskas, and W. Ostachowicz, "Experimental analysis of active–passive vibration control on thin-walled composite beam," Compos. Struct., vol. 223, p. 110975, 2019.

J. Tian, Q. Guo, and G. Shi, "Laminated piezoelectric beam element for dynamic analysis of piezolaminated smart beams and GA-based LQR active vibration control," Compos. Struct., vol. 252, p. 112480, 2020.

S. M. Kusagur, G. Arunkumar, and T. C. Manjunath, "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., vol. 37, no. Part 2, pp. 2075–2082, 2020.

R. S. Reddy, S. Panda, and A. Gupta, "Nonlinear dynamics and active control of smart beams using shear/extensional mode piezoelectric actuators," Int. J. Mech. Sci., vol. 204, no. January, p. 106495, 2021.

Rahman, N. U., & Alam, M. N. Structural control of piezoelectric laminated beams under thermal load. Journal of Thermal Stresses, 38(1), 69-95, 2015.

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

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