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Active vibration control of a smart beam by a tuner-based PID controller

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Abstract

In this study, a tuner-based Proportional-Integral-Derivative controller is proposed to actively control a smart beam. In numerical simulation environment, the performance of the tuner-based PID and a positive position feedback controller in damping the forced vibrations of a smart beam using a piezoelectric actuator are investigated. The finite element method is used to numerically model the smart beam by exporting the state-space matrices that are characterized with regard to the active vibration control loop. Two types of vibration data with sine tones are comprised in order to stimulate behavior of the proposed system. The first one is the composition of the first and second natural frequencies of smart beam. The second one is the composition of the first to the third natural frequencies of smart beam. In the tuner-based PID, controller design tuner toolbox is used to obtain suitable PID coefficients. In this simulation environment active vibration control based on the proposed tuner-based PID and on positive position feedback controllers is studied and compared. Additionally, the controller power consumption levels are determined for the proposed controller design. Numerical results show that the overall tuner-based PID control performance of flexible smart beam system is more effective than the positive position feedback controlled system for forced vibration control. Also, the tuner-based PID controller provides more energy savings than the positive position feedback controller.

Keywords

Active vibration control, positive position feedback controller, tuner-based PID controller, piezoelectric actuator

Introduction

With numerous applications, smart structures are among the most studied areas of mechanical engineering. Smart structures offer innovative solutions to several important problems of mechanical systems such as vibration and noise reduction. For example, piezoelectric material-based structures are used as sensors for measuring amplitudes and frequencies of vibrations and used as actuators to suppress vibrations.[1] Due to their importance, significant amounts of research effort are currently being put into the manufacturing, analyzing, and modeling of smart materials like the piezoelectric materials, the shape memory alloys, the magnetorheological and the electrorheological fluids, etc.[2] The novel structures equipped with these materials are proposed as solutions to many applications such as vibration control, shape control, damage detection, passenger comfort in vehicles, manufacturing, micro robots, etc.[3,4] Among these, vibration control, with its essential applications in several industries, is of utmost importance. To achieve vibration isolation or reduction, several active and passive vibration control methods are presented in the literature.[5] Passive methods are implemented by using damping components and isolators. On the other hand, active vibration control methods are realized in different ways such as shifting natural frequencies of the structure with structural changes or reducing the amplitude of the natural frequency on the system.[6]

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Mechanical vibrations are studied in order to reduce the harmful effects of structural fatigue or to reduce the disturbing noises of the system.[7] To this end, there are two important aspects in active vibration control that need to be studied. First, the structure which is subjected to vibrations must be well studied by using numerical methods such as the finite element analysis (FEA) and by experimental tests like modal test, signal analysis, operational test, etc.[8–12] The other aspect is the design procedure of the robust active controller. In active vibration control literature, classical, modern, and robust controller design techniques are generally applied to the selected systems. Then, the control performances of these methods are tested by using different evaluation methods.[13–18]

Piezoelectric patch transducers are the materials which are used as the sensor and the actuator characteristics by means of generating and storing electrical charges. The piezoelectric patch consists of piezoceramic, electrodes, and polymer materials which are all electrically isolated and mechanically strengthened.[19,20] Hence, piezoelectric patch transducer is used only as an actuator to suppress vibration according to the control loop within the scope of this paper. The smart structures are comprised of pairs of the sensors and actuators placed on the main structure.[21] With the aforementioned information, a smart beam is created using a beam, a piezoelectric patch (as actuator), strain gauge (as sensor), and an investigated controller. The aluminum beam is used as the main structure of the smart beam which will be studied by numerical modeling. A piezoelectric patch actuator is attached to the cantilever beam at the root in order to provide maximum control force. Linear strain data are obtained at the opposite side of the piezoelectric patch to measure amplitude of the vibrations. Tip displacement data on the end of the smart beam are then obtained to measure the vibrations at the beam tip. The smart beam configuration is used to achieve active vibration control. Numerical and experimental modal analyses are carried out in order to characterize the dynamics of the structure. "*Spmwrite*" command in ANSYS/Workbench is used for numerical model of the beam in the form of state-space matrices.[22] As the vibration data actuating the proposed system, two types of sine tones are used: the combination of the first and the second natural frequencies with different amplitudes and the combination of the first to the third natural frequencies with different amplitudes. The actuation data are in the form of accelerations and have different root mean square (RMS) values.

A novel controller named tuner-based PID (TBPID) controller is proposed. Then, TBPID and a positive position feedback (PPF) controller design are utilized in order to actively damp the forced vibrations at the target level. In the TBPID design, controller design tuner toolbox in MATLAB is used to obtain suitable Proportional-İntegral-Derivative (PID) coefficients according to basic optimization rules. Finally, the linear strain value is obtained from the nodal point close to the beam anchoring. Both linear strain value and the tip displacement of the beam are investigated by means of RMS values to interpret the controller performance. Also, RMS values of the control signal for the proposed controller are used to evaluate controller power consumption.

Numerical modeling of the smart beam

The FEA is used as the numerical modeling tool to simulate the dynamic characteristics of structures. In our system, a smart beam of size 450 mm × 35 mm × 1.7 mm with a commercially existing piezoelectric patch actuator

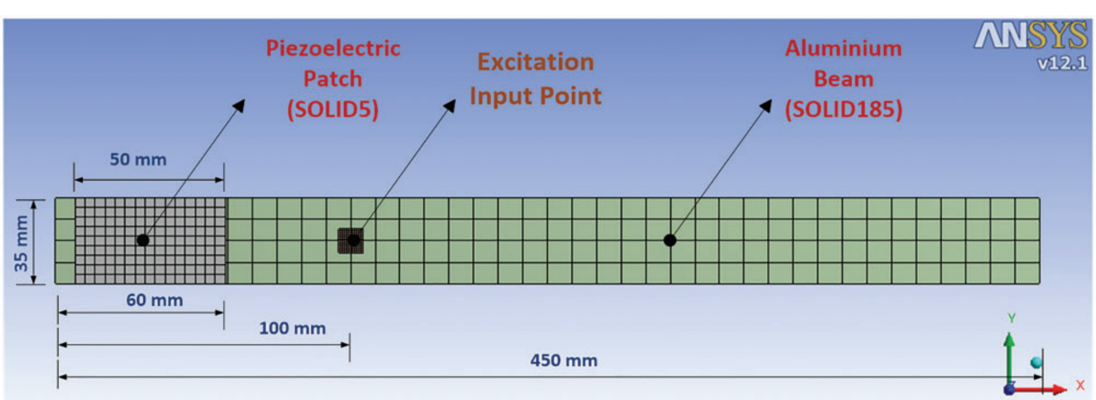

Figure 1. Model of the smart beam in ANSYS.

(PI Dura-act 876.A12) of size 50 mm × 35 mm × 0.7 mm is modeled using the ANSYS/Workbench software. The designed model is shown in Figure 1.

Numerical modal analysis method is implemented in the ANSYS/Workbench software platform according to the material properties listed in Table 1. The piezoelectric material properties are defined using the utilities of the ANSYS/Workbench software package. The reduced piezoelectric strain matrix (e) and the elastic stiffness matrix (c^E) under constant electrical field are also defined.

To provide a successful modeling and to simulate a realistic system behavior, modal analysis is applied numerically and experimentally. The results of modal analysis are presented in Table 2. The mode shapes direction of the first three modes of structure is vertical to the XY plane. The fourth mode shape of smart beam is lateral movement. Presented smart structure design, the first three natural frequencies of the structure can be controlled due to the mode shapes directions. Upon examining Table 2, it can be said that the numerical and experimental results agree well. Additionally, to provide control loop, the system has two inputs (piezoelectric patch (V) and excitation (g)) and two outputs (the linear strain (mm/mm) and the tip displacement (mm)). Realistic numerical model of the system is obtained by considering these input/output parameters. "*Spmwrite*" command is used for defining the state-space matrices in ANSYS/Workbench. The state-space matrices of the smart beam system are extracted from the results of the modal analysis following the method given in Lüleci.[22] It is observed from the results that there is no need to deploy a complete modal analysis for the smart beam. Instead, first four modes of the smart beam are investigated within the specified boundary conditions.

Controller design and results

Vibration excitation

In vibration damping, dynamic loadings including natural frequencies of the system are generally applied to the system.[23] In this case, the system is best excited by the forced vibrations. Thus, the two excitation data with sine tones are derived from the first two and the first three natural frequencies of the smart beam in order to actuate the proposed system. The data are obtained by adding sinus tones to a signal with a frequency of 8 Hz and amplitude of 2.5 g with time duration of 10 s. Sine-two excitation signal consists of two sinusoidal functions which have frequencies of 8 and 45 Hz with amplitudes of 2.5 and 1.2 g, respectively. Similarly, sine-three excitation signal

Table 1. Patch properties of the beam and the piezoelectric patch.

Aluminum beam			
P	2770 kg/m^3		
E	69 GPa		
υ	0.34		
Piezoelectric patch			
c_{11}^E	123 GPa	e_{31}	−7.15 N/V m
c_{12}^E	76.7 GPa	e_{33}	13.7 N/V m
c_{13}^E	70.3 GPa	e_{15}	11.9 N/V m
c_{33}^E	97.1 GPa	$\varepsilon_{11}^s/\varepsilon_0$	930
c_{44}^E	22.3 GPa	$\varepsilon_{33}^s/\varepsilon_0$	857
c_{66}^E	23.2 GPa	ρ	2800 kg/m^3

Table 2. Numerical and experimental natural frequencies of the smart beam.

	Frequency (Hz)	
Modes	Numerical	Experimental
1	7,81	7.79
2	45,37	47.12
3	119,33	122.24
4	145,61	149.57

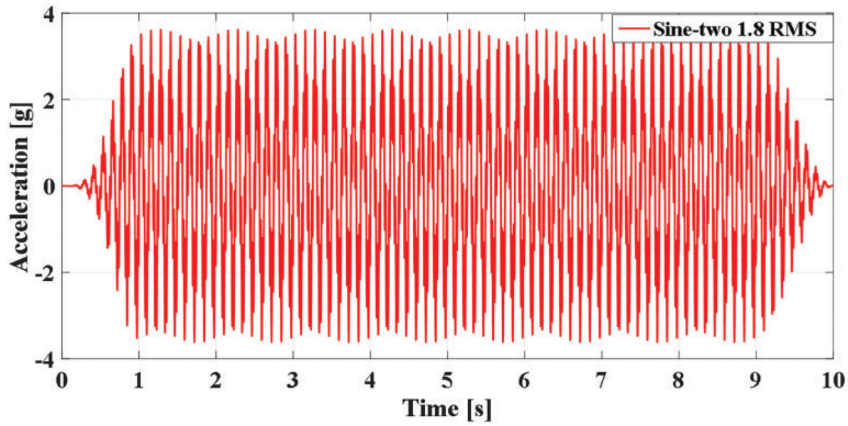

Figure 2. Sine-two excitation signal (1.8 RMS).
RMS: root mean square.

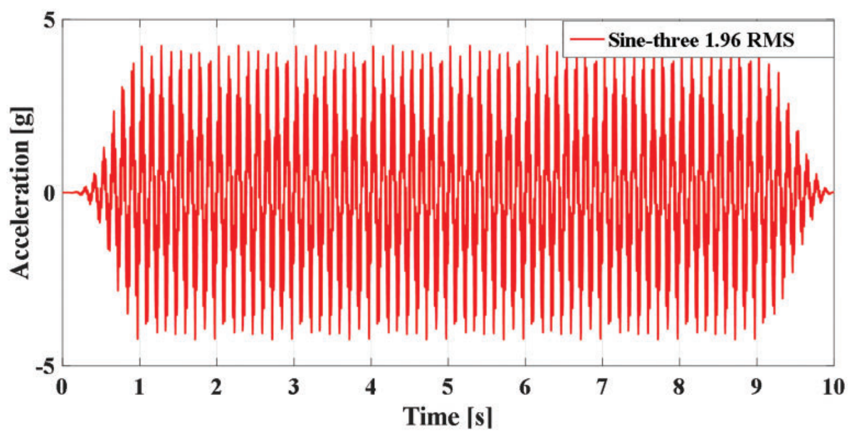

Figure 3. Sine-three excitation signal (1.96 RMS).
RMS: root mean square.

consists of three sinusoidal functions which have frequencies of 8, 45, and 119 Hz with amplitudes of 2.5, 1.7, and 0.4 g, respectively. For the first two and three modes, sine-two and sine-three have 1.8 RMS and 1.96 RMS values, respectively. The obtained acceleration is shown in Figures 2 and 3.

PPF controller design

PPF controller design is one of the useful controller design methods in terms of stability, robustness, and easy installation.[22] This controller design is effectively used in vibration damping or suppression studies. The PPF controller acts as a compensator and is an auxiliary system such as a mechanical vibration damper. If there is only one compensator in the controller design, a single target mode is damped in the narrow frequency range. If there are an appropriate number of parallel compensators, the multimodal control is achieved in the wide frequency range.[24] In the PPF controller designing, the second-order transfer functions (the compensators) for the PPF are created with the help of relating dynamic characteristics of the system. The compensator of the single PPF method is given in equation (1), where ξ_n, ω_n, and K are the damping ratio, the natural frequency, and the gain parameters, respectively. The first three modes of the smart beam are used to create the second-order transfer functions of the PPF controller for the multimodal control. The damping ratio and the gain factor for first three modes of the smart beam are chosen as $\xi_n = 0.02$ and $K = 10^7$, respectively.

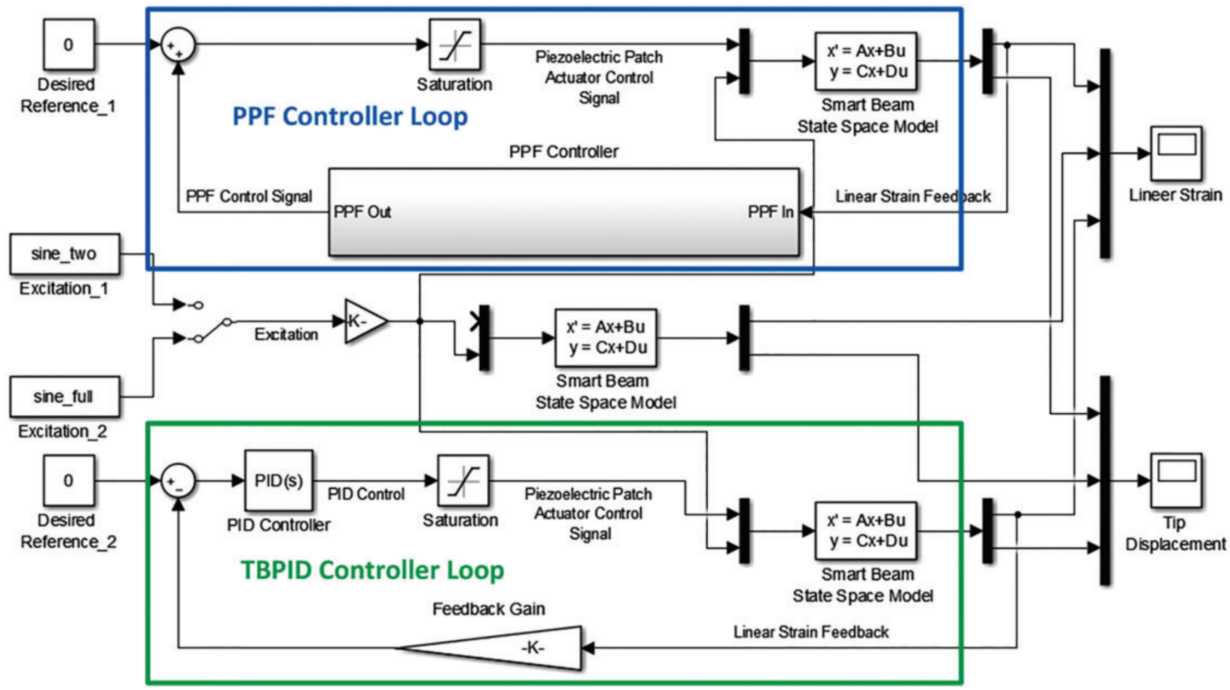

Figure 4. Block diagram of system.
TBPID: tuner-based Proportional-Integral-Derivative; PPF: positive position feedback.

$$H(s)_n = \frac{K}{s^2 + 2\xi_n\omega_n s + \omega_n{}^2} \tag{1}$$

The transfer functions for the three modes are derived from equation (1). Then, they are applied parallel to the control loop as a positive feedback with the help of the determined coefficients that can be tuned.

TBPID controller design

The PID controller design is the simplest controller in terms of easy installation and robust performance.[17] To provide better closed-loop performance of the controller, three parameters of the PID should be tuned according to the boundary conditions. To obtain suitable PID parameters, a tuner-based PID (TBPID) controller design is presented using MATLAB/Simulink/Control System Tuner toolbox. First, in the toolbox, two blocks (PID, feedback gain) are selected in order to tune the parameters. The transient goal method that includes the impulse signal is also used to achieve better controller performance. The reference model is selected as a second-order transfer function. The tuning parameters of the PID controller are optimized as $K_p = -3664.08$, $K_i = $ 4.7e-06, and $K_d = 8.03$. The filter coefficient (N) is obtained as $N = 988.55$. A feedback gain ($FG = 275.27$) is used from the output of the system. These parameters provide the best controller performance demonstrated by the results of a series of closed-loop tests.

Controller performance of proposed designs

The block diagram of proposed controller designs is shown in Figure 4. TBPID and PPF controllers are designed for active vibration control in MATLAB/Simulink. In order to achieve a collocated control, strain responses are used as the feedback in these controller designs instead of the tip displacement due to the signal source location. Additionally, tip displacements and strain responses are investigated in order to understand the controller performance. Proposed controller designs are investigated in two aforementioned excitations as sine-two and sine-three. Controller performances are examined in simulations to investigate the system performances numerically. The RMS values of results are evaluated to clearly understand the control level reduction. The RMS value is the most effective measurement of amplitude because it both takes the time history of the wave into account and

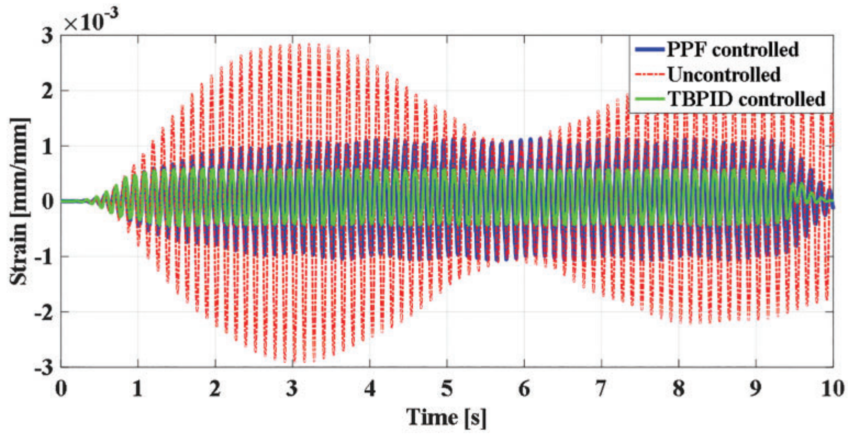

Figure 5. Strain response under the sine-two excitation.
PPF: positive position feedback; TBPID: tuner-based PID.

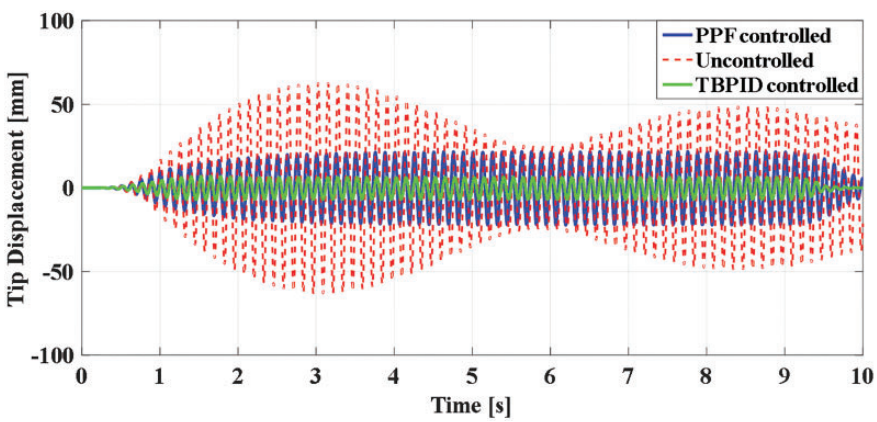

Figure 6. Tip displacement response under the sine-two excitation.
PPF: positive position feedback; TBPID: tuner-based PID.

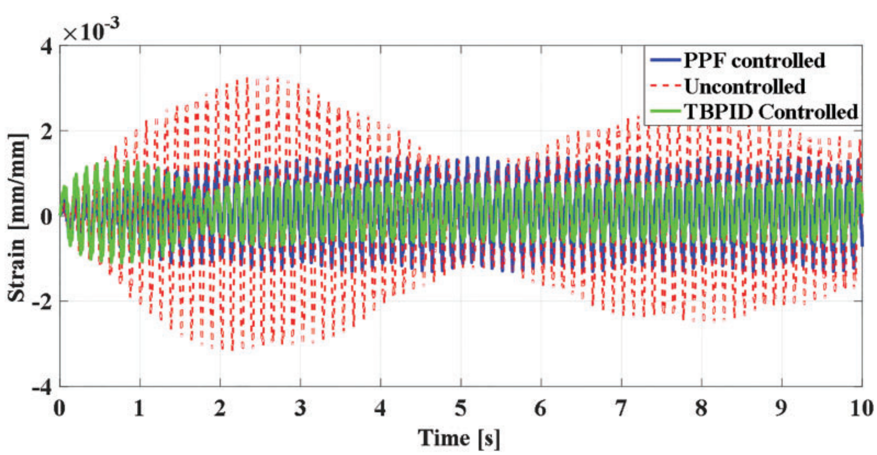

Figure 7. Strain response under the sine-three excitation.
PPF: positive position feedback; TBPID: tuner-based PID.

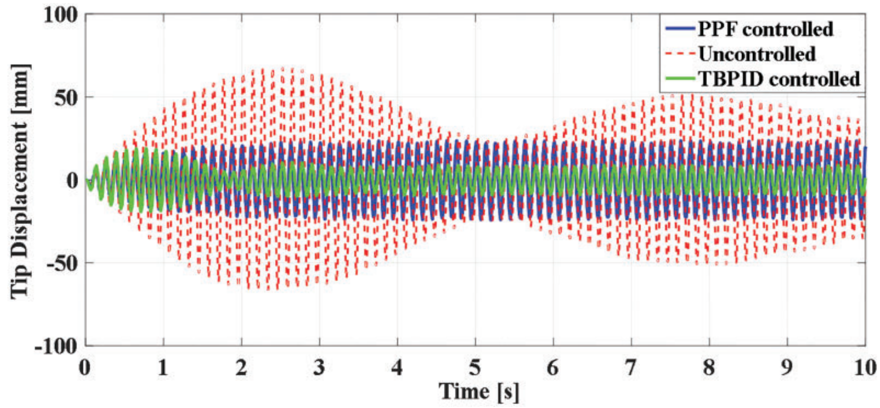

Figure 8. Tip displacement response under the sine-three excitation.
PPF: positive position feedback; TBPID: tuner-based PID.

Table 3. The evaluation of the presented controller designs.

	Under the sine-two excitation RMS values		Under the sine-three excitation RMS values	
	Strain (mm/mm)	Tip displacement (mm)	Strain (mm/mm)	Tip displacement (mm)
Uncontrolled	1.47×10^{-3}	32.28	1.47×10^{-3}	31.02
PPF	0.6×10^{-3}	13.76	0.7×10^{-3}	16.19
TBPID	0.35×10^{-3}	3.79	0.49×10^{-3}	5.8
	Power consumption RMS values (V)			
PPF	481.1		540.3	
TBPID	363.2		503.7	

PPF: positive position feedback; RMS: root mean square; TBPID: tuner-based PID.

gives an amplitude value that is directly related to the energy content, and therefore the destructive capabilities of the vibration environment.[25]

The simulation results of the strain and the tip displacement with PPF controlled, TBPID controlled and uncontrolled are shown under the sine-two excitation in Figures 5 and 6.

Similarly, under the sine-three excitation, the simulation results of the strain and the tip displacements with both PPF controlled, TBPID controlled and uncontrolled are shown in Figures 7 and 8. It is clear that the sine-three excitation including the first three modes is a more complex structure than the sine-two excitation. Consequently, there are some differences in control responses. At the beginning of the simulation, the TBPID controller has a lagged response compared to the PPF controller. However, the TBPID controller shows better damping performance as the simulation runs.

The effects of the presented controller designs on the system are given in Figures 5 to 8 and by the RMS values that are shown in Table 3. As can be seen from the results, it is noted that the active forced vibration control of the system using PPF and TBPID is realized successfully for both control techniques. Under the sine-two excitation, forced vibrations of controlled systems are suppressed by about 60 and 76.2% with reference to the uncontrolled strain response for the PPF and the TBPID controllers, respectively. Similarly, the forced vibration of the proposed system is also suppressed by about 57.3% (PPF) and 88.25% (TBPID) with respect to the tip uncontrolled displacement response. For the case of the sine-three excitation, the forced vibrations of the controlled systems are suppressed by about 53 and 66.7% with reference to the uncontrolled strain response for the PPF and the TBPID cases, respectively. Likewise, the forced vibrations of the proposed system are suppressed about 47.8% (PPF) and 81.3% (TBPID) with reference to the uncontrolled tip displacement response. RMS values of control signals for the proposed controller are also examined to evaluate the controller power consumption. Power consumptions in terms of voltage are assumed to carry unit current such that watts are represented by voltages. The TBPID controller provides 24.5 and 6.7% more energy savings than the PPF controller for sine-two and sine-three stimulation types, respectively.

Conclusions

TBPID controller and a PPF controller are numerically investigated to damp the force vibrations of a smart beam using a piezoelectric actuator. Numerical results show that the overall TBPID control performance of flexible smart beam system is more effective than the PPF controlled system for forced vibration control. However, it should be emphasized that the PPF controller for free vibration control is better than the PID-based controllers. Also, RMS values of the control signal for the proposed controller are investigated to evaluate the controller power consumption. As a result of this evaluation, the TBPID controller provides more energy savings than the PPF controller for all presented controllers.

As a future work, TBPID controller design can be used and implemented for vibration control of a helicopter fuselage system in the flight tests in order to decrease the interior noise level of the vehicle.

Declaration of conflicting interests

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