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High modal density active vibration attenuation of bladed structure with a decentralized optimal negative derivative feedback controller

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Summary

In this study, an active vibration mitigation of bladed structures with piezoelectric patches utilizing decentralized negative derivative feedback (NDF) controllers is evaluated numerically and experimentally. Such structures have protruding identical blades, which create numerous modes in a short interval of frequency named as high modal density or mode family. Therefore, mitigating these modes is quite challenging. As a case study, a bladed rail is considered with 5 blades, which subsequently has 5 modes in a family of mode in a very short frequency range. A numerical model of the bladed rail including 5 pairs of piezoelectric patches (sensors and actuators) is extracted. Afterwards, a decentralized NDF controller is designed based on maximum damping and H_2 method for this model, which is desirable for reducing vibration corresponding to the first family mode. The numerical results show a perfect performance of the proposed controller on high modal density vibration attenuations. For validating these results, two separate bladed rails have been manufactured, and different piezoelectric patches have been attached to them. The same procedure for designing NDF controller has been done for both of the structures. Experimental results show that the family mode of the bladed rail is completely damped using decentralized NDF controller. Even though the pole-zero patterns change from the first structure to the second one, the controller can easily mitigate the family mode vibration flawlessly. This shows high applicability of proposed controller on mitigating high modal density modes.

KEYWORDS

bladed rail, decentralized controller, family mode, high modal density, negative derivative feedback (NDF), piezoelectric sensor/actuators

1 | INTRODUCTION

Bladed structures are very common in various industries like aviation and turbomachinery industry. The new modernized industry is focusing on the development of energy-efficient structures to reduce the fuel consumption, currently. Therefore, lightweight structures with materials such as aluminum are extensively used, in these applications. While this can effectively decrease the fuel consumption, due to the very low structural damping, it can easily increase the vibration level enormously and lead to high cycle fatigue problem. Therefore, a careful consideration should be taken to damp the vibration of bladed structures.

In recent decades, vibration control has acknowledged more and more importance owing to the significant development of light and low damped structures. The main problem for these structures is related to the amplification of vibration near their natural frequencies, mainly due to the low damping ratio associated with structure's modes. A high vibration level can lead to a degradation of system performance in terms both of positioning error and structure's health and lifetime.

One of the main issues of the bladed structures is the modes related to their blades' displacement, which is called as family of mode. Each bladed structure has a number of blades, and the displacement of these blades (while the structure's body is approximately is static) creates enormous numbers of vibrational modes. The quantity of these modes is the same as the number of blades in the structure, which is always a high value. Furthermore, this high number of modes has a very close natural frequency, and this means that in a very short range of frequency, these structures have high numbers of vibrational modes, which is called as high modal density. Because of high number of modes in the family of mode, it is strongly recommended to consider a very wise method to damp these modes to avoid catastrophic failures caused by high cycle fatigue induced by higher levels of vibration.

Recently, piezoelectric materials are being used to reduce the vibration of structures actively and passively. While passive methods are useful for fail safe applications, they do not reduce vibration levels effectively. In active vibration control applications, piezoelectric patches can be used to sense the structure displacement and also to apply moment on the structure in a reverse direction to reduce the vibration effectively. A powerful controller can amplify the piezoelectric sensor output signal and apply it on the piezoelectric actuator to mitigate the vibration. Due to high number of modes in the frequency range of a high modal density, designing and applying an appropriate controller can be a challenging task.

Previously, several techniques have been used for the vibration control of the bladed disks such as friction-based damping,[1,2] viscoelastic damping,[3] hard coating on the blade surface,[4] contactless eddy current damper,[5] electromagnetic damping using actively controlled magnets,[6] using self-tuning impact dampers,[7] and integrating the damping materials into the hollow blades.[8] Mokrani[9] demonstrated an interesting experimental approach using piezoelectric patches on the bladed rail structure to damp family of modes passively by optimal shunt damping techniques. However, there is no available research on active vibration mitigation of bladed rail structures with piezoelectric patches, which can reduce more the vibration level.

Previously, numerous amounts of research have been carried out for active vibration control with piezoelectric patches on various structures. Jamshidi and Jafari[10–15] studied using piezoelectric patches to sense and mitigate the vibration of conical shells using various controllers. Since the vibration level is very high in the family mode and in higher frequencies, for mitigating them, a robust and powerful controller should be used. There are many conventional controllers that previously had been applied for the active vibration control of structures like beam. However, because of intensive amount of mode of the structure at a frequency range, those conventional controllers cannot mitigate enough vibration. Therefore, a powerful controller should be considered for this case that can reduce the displacement of the blades.

In the past, numerous types of controllers had been designed and implemented on the various structures with piezoelectric patches. Some of these controllers are Positive Position Feedback (PPF), Resonant Controller (RC), Integral Resonant Controller (IRC), Positive Position Feedback with Feed-through (PPFFT), and so on. While some of these controllers have an acceptable performance on the vibration reduction of a single mode, they do not have the ability to mitigation high modal density modes. Therefore, a more powerful controller should be considered for this application. Recently, based on a resonant control technique, a negative derivative feedback controller (NDF) had been presented by Cazzulani et al.[16]

The NDF compensator is designed to work as a band-pass filter, cutting off the control action far from the natural frequencies associated with the controlled modes and reducing the so-called spillover effect. NDF has better performance with respect performance with respect to all the other techniques analyzed, both in terms of achieved damping and robustness to low-and high-frequency problems. Syed[17] did a comparative study between PPF and NDF for vibration control of a flexible arm featuring piezoelectric actuator. Based on evaluated performance measures, NDF controller was more effective than PPF controller. Syed[17] did a comparative study between PPF and NDF for vibration control of a flexible arm featuring piezoelectric actuator. Based on evaluated performance measures, NDF controller was more effective than PPF controller. Cola et al.[18] claimed that NDF proves particularly robust against spillover since modal velocity is fed back through a band-pass filter so that undesired effects can be limited both at high and low frequencies.

There are many articles for damping the bladed structures; however, most of them are using passive methods,[19–23] which do not provide higher amount of vibration reductions. Therefore, in this study, an active method is utilized. For tunning NDF controller, a new method based on maximum damping method and H_2 optimization method is utilized. In a multi-input multi-output (MIMO) system, for simplification, a decentralized controller can be considered. In this configuration, a unified controller is designed, which can be applied to all the loops independently.

In this study, active vibration control of the bladed rail structure that has 5 blades, with 5 pairs of piezoelectric patches, is evaluated numerically and experimentally. In the first step, a numerical model of the bladed rail structure with 5 pairs of piezoelectric patches using SDT tool software is extracted. The numerical model has 5 piezoelectric sensor outputs and 5 piezoelectric actuator inputs for closing the controlling loops and one blade's displacement output and the same blade's force input for evaluating the performance index of the system. Afterwards, an NDF controller is designed for the first open loop of numerical model, based on maximum damping and H_2 method. Then, the designed controller is applied to all of the loops in a decentralized way to mitigate the first family mode of the bladed rail. The results showed that the unified decentralized NDF controller can mitigate the first family mode easily, and it has a high performance. To validate these results, two separate bladed rails with different piezoelectric patches are manufactured and assembled in the laboratory. The open loops of the first bladed rail extracted and an optimal NDF controller are designed for the first open loop in a same way. Then, the unified controller is applied to all loops of the first bladed rail structure in a decentralized way. The magnitude of vibration reduction using this controller is outstanding, and the family mode is damped totally using this method. Afterwards, for evaluating the robustness of the proposed method, the same procedure has been carried out again and applied to the second bladed rail structure, which has different material for the structure and also piezoelectric patches. The result of this experiment was also outstanding and satisfactory, and all of modes in the family are totally damped. This shows the robustness and applicability of the proposed controller for mitigating high modal density vibration applications.

2 | THE BLADED RAIL STRUCTURE

In this section, for evaluating the high modal density problem, a bladed structure that can be representative of any circular bladed structures is considered and explained. Typically, any structure that has several blades can be considered as a bladed structure. The substantial challenge of these structures is that they have many families of mode, and each family mode is located in a short interval of frequency with high frequency values. The quantity of modes in each family is the same as the number of structure's blades. Since these modes are very close to each other in the frequency domain, if they are excited, they can create enormous amount of vibration. Therefore, a careful consideration should be taken to reduce high amount of vibration in this frequency range. Reducing high modal density vibration is quiet challenging task, which is the main focus of present article.

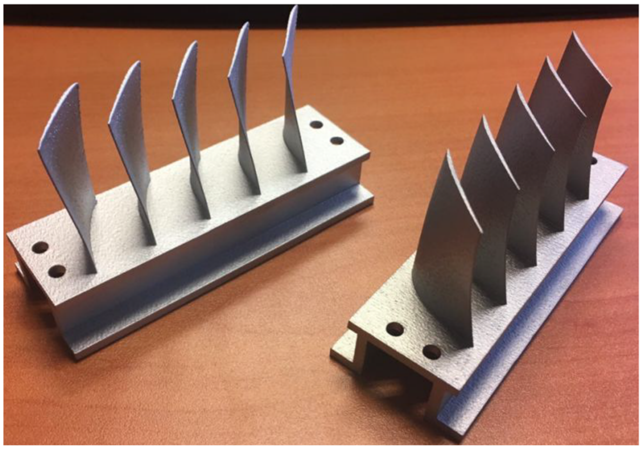


FIGURE 1 The bladed rail structure with five blades

In this study, for evaluating high modal density vibration mitigation, a simple bladed rail structure with 5 blades is considered (Figure 1). The blades are placed in a linear rail close to each other for simplification. Since the structure has five blades, it will have a family of mode with 5 modes in a very short range of frequency called as high modal density.

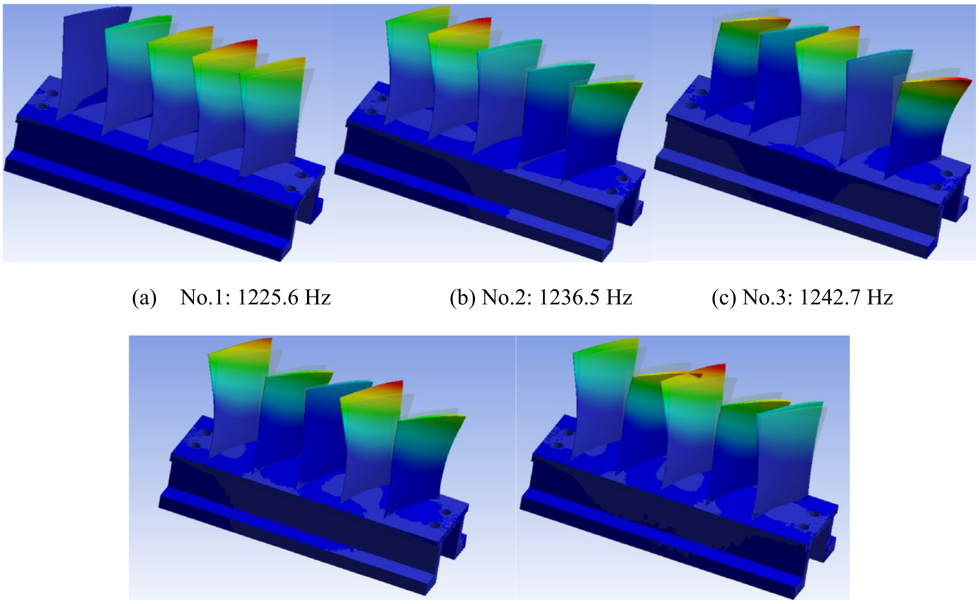
The mode shapes of the first family mode for the bladed rail are extracted using FEM analysis, and they are presented in Figure 2. Obviously, in the frequency interval between 1225 and 1250 Hz, five modes exist, which is called the first family mode. The natural frequencies related to these modes are very close to each other, which creates a high modal density. Clearly, in all of these modes, only the blades have displacements, and other sections of the structure are approximately motionless and static. This means that, in these modes, the blades undergo a flexural deformation without significant displacement in the structure's base. Therefore, these modes are mostly related to the blades' displacements, and for controlling these modes, it is recommended to consider a logical solution, which decreases the displacement of the blades.

For controlling each blade's displacement effectively, a pair of piezoelectric patches (one as a sensor and the other one as an actuator) is considered, for each blade. In overall, 5 pairs of piezoelectric patches are used as sensors and actuators. The location of the patches plays an important role on the plant's control authority. However, due to the complexity of the structure and also existing air flow around the blades, there is not high flexibility for choosing the optimal location for the piezoelectric patches. Therefore, the patches are considered to be located exactly beneath each blade, in the structure's base, where there is no interaction with the air flow around the blades (Figure 3).

For mitigating the vibration of family mode, first a numerical model of the bladed rail with considered piezoelectric patches is extracted, and a controller is designed for the model. After evaluating the attained results, experiments carried out to evaluate the proposed method. In the next steps, first the procedure of reduced order model extraction is explained. Then, an optimal NDF is designed for the model. In the end, experiments are carried out to validate the obtained numerical results.

3 | REDUCED ORDER MODEL

In this section, a reduced order model based on the first family mode is extracted for the considered configuration in Figure 3, using Structural Dynamics Toolbox (SDT software), which has a capability to model the piezoelectric patches. The numerical model should have the capability to evaluate the structure's response using various control strategies.



(a) No.1: 1225.6 Hz (b) No.2: 1236.5 Hz (c) No.3: 1242.7 Hz

(d) No.4: 1245.4 Hz (e) No.5: 1246.7 Hz

FIGURE 2 The first family mode of the bladed rail: (a) first mode, (b) second mode, (c) third mode, (d) fourth mode, (e) fifth mode

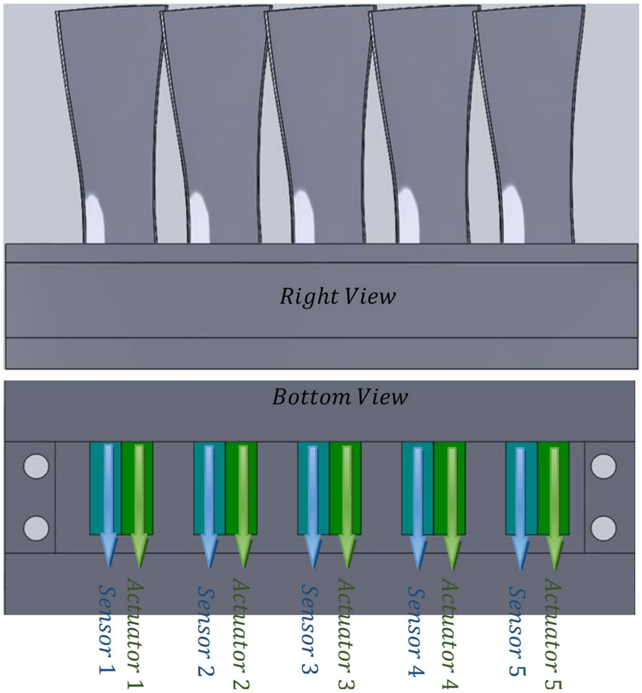


FIGURE 3 Configuration of the piezoelectric patches and location for active vibration control implementation of bladed rail

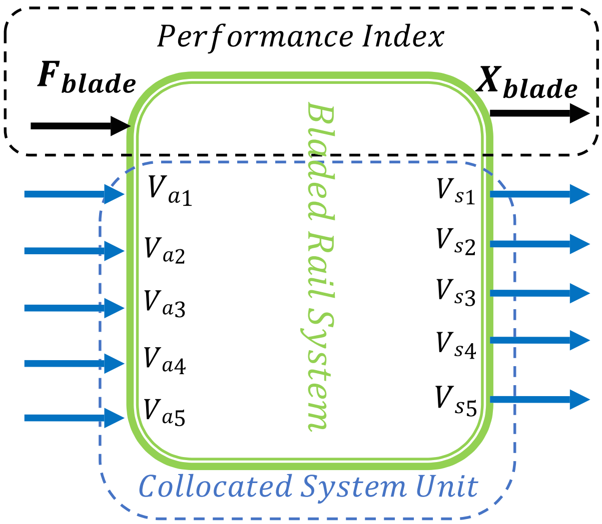


FIGURE 4 The extracted numerical model schematic

Also, for evaluating the performance of the system, when any controller is applied, the middle blade's displacement is considered as an output, and the middle blade's force is also considered as an excitation input of the system. The frequency response between the middle blade's force to the displacement is used as a performance index of system. Therefore, the final model consists of 5 controlling outputs/inputs (piezoelectric sensor/actuator patches) and the performance index output/input (the middle blade's displacement/force) (Figure 4). By closing the controlling loops, the performance index of the system can be evaluated.

For this purpose, SDT tool software that is developed in the MATLAB environment is used. This software has the ability to model piezoelectric patches as sensor and actuators. The boundary condition for the bladed rail is assumed to be clamped from the holes in the structure, which is located on the horizontal rail (Figure 1).

The bladed rail and piezoelectric patches' material are considered as aluminum and PIC255, respectively. The material properties of piezoelectric patches are presentenced in Table 1. For extracting the model, the structural damping is

TABLE 1 The material properties of piezoelectric patches-PIC255

Property	Symbol	Value	Unit
Piezoelectric strain constants	d_{31}	−180	10^{-12} m/V
	d_{33}	400	10^{-12} m/V
	d_{15}	550	10^{-12} m/V
Compliance coefficients	S_{11}	16.1	10^{-12} m^2/N
	S_{33}	20.7	10^{-12} m^2/N
	S_{12}	−5.22	10^{-12} m^2/N
	S_{13}	6.27	10^{-12} m^2/N
	S_{44}	47.5	10^{-12} m^2/N
Permittivity coefficients	$e_{11}{}^{\sigma}$	14,609.1	10^{-12} F/m
	$e_{33}{}^{\sigma}$	15,494.5	10^{-12} F/m
Density	ρ	7800	kg/m^3

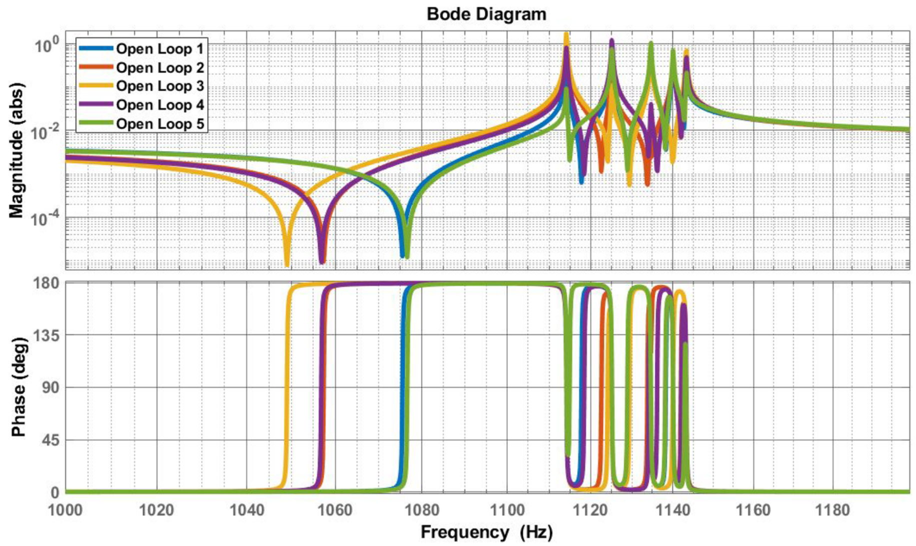


FIGURE 5 Open loops of extracted bladed rail's numerical model

assumed to be very low. The Abaqus software is used to mesh the structure, and afterwards it is imported to the SDT software. By using this software, the reduced order state-space model, considering the first family of mode, is extracted.

The reduced order model has been extracted based on the first mode family. The controlling inputs and outputs are related to the piezoelectric actuator and sensor, respectively. By closing the controller loops, the vibration level of the structure should decrease in the considered modes. So, the final aim is to close the controlling inputs and outputs and evaluate the system response by performance index input and output with controller and compare it when there is no control.

It has been shown that the use of collocated actuator and sensor always leads to alternating poles and zeros near the imaginary axis. This property guarantees the asymptotic stability, even if the system parameters are subject to large perturbations.[24] After extracting the numerical model from SDT, it should be checked if the response of piezoelectric sensor and actuator pairs is collocated in terms of pole-zero pattern. Therefore, the open loop frequency response of each pair is extracted and presented in Figure 5. Interestingly, alternating poles and zeros in the frequency response of all of the open loops assure that all of the sensor/actuator pairs have a collocated response in the numerical model.

The frequency response between the middle blade's applied tip force and its displacement (the performance index) is presented in Figure 6. Obviously, in a short band of frequency (50 Hz), there are 5 modes that are considered as a high modal density. The ideal controller should damp this high model density.

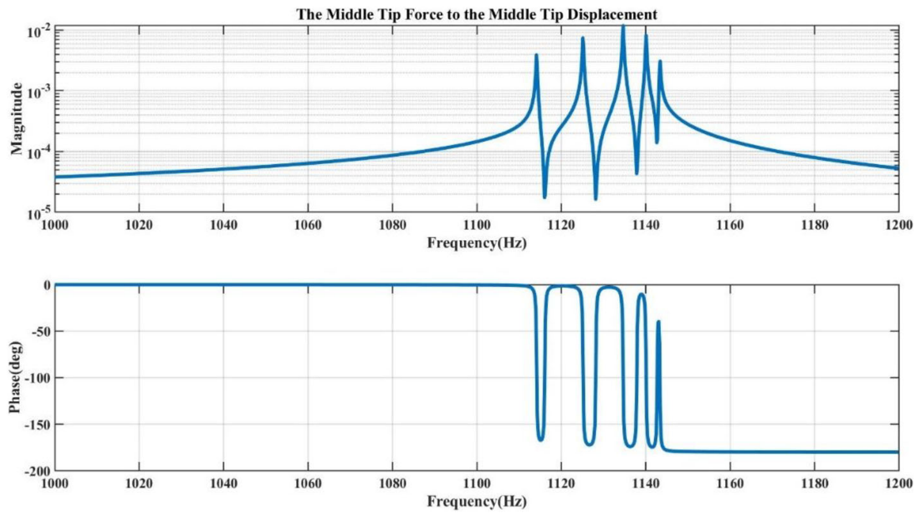


FIGURE 6 Frequency response between the middle blade's applied tip force and its displacement (performance index)

After extracting the model of the bladed rail, the biggest challenge is designing and implementing a controller that can mitigate the vibration of the considered family mode. In the next section, a decentralized controller is designed to mitigate the vibration of caused by the first mode family.

4 | CONTROLLER DESIGN

In this section, a controller is designed for implementing to the bladed rail structure's model. Vibration mitigation of high modal density modes is a challenging task that cannot be done with a simple conventional controller. Considering the fact that high signal amplitudes (voltages) cannot be applied on piezoelectric actuators makes this task even more complicated. Usually, the family modes of bladed structures are located in the high frequency bandwidth, which makes mitigating them a more demanding problem. Therefore, a careful consideration should be taken to design an appropriate controller with robust performance.

In this study, the controller is considered to be feedbacked identically in a decentralized way (Figure 7). In this arrangement, each sensor signal is feedbacked only to corresponding actuator pair, using an identical controller. Therefore, in this arrangement, five loops are closed with identical controller in a decentralized way (Figure 7). The identical controller should be designed in a way that each loop can reduce a considerable amount of vibration of the family mode. In this way, when all of the loops are closed, the level of vibration reduction will be magnificent.

4.1 | Optimal NDF

In this section, in order to achieve highest amount of vibration reduction possible in the family of mode, an NDF is designed optimally. NDF is a band-pass filter, cutting off the control action far from the natural frequencies associated with the controlled modes, which reduces the spillover effect. As a bandpass filter, it can effectively control the lower and higher frequency disturbances. Besides, it is a very efficient controller for applying on higher frequencies modes with low damping. Therefore, it is one of the most appropriate controllers that can be used to damp high modal density, and it is chosen to damp the first mode of family. NDF controller's equation is presented in Equation 1.

$$C(s) = -\frac{K_c \omega_c s}{s^2 + 2\xi_c \omega_c s + \omega_c^2} \tag{1}$$

where K_c, ω_c, and ξ_c are gain, cutoff frequency, and damping ratio of the NDF controller, respectively. For designing NDF controller, these parameters should be determined optimally. Based on the previous researches, NDF can be

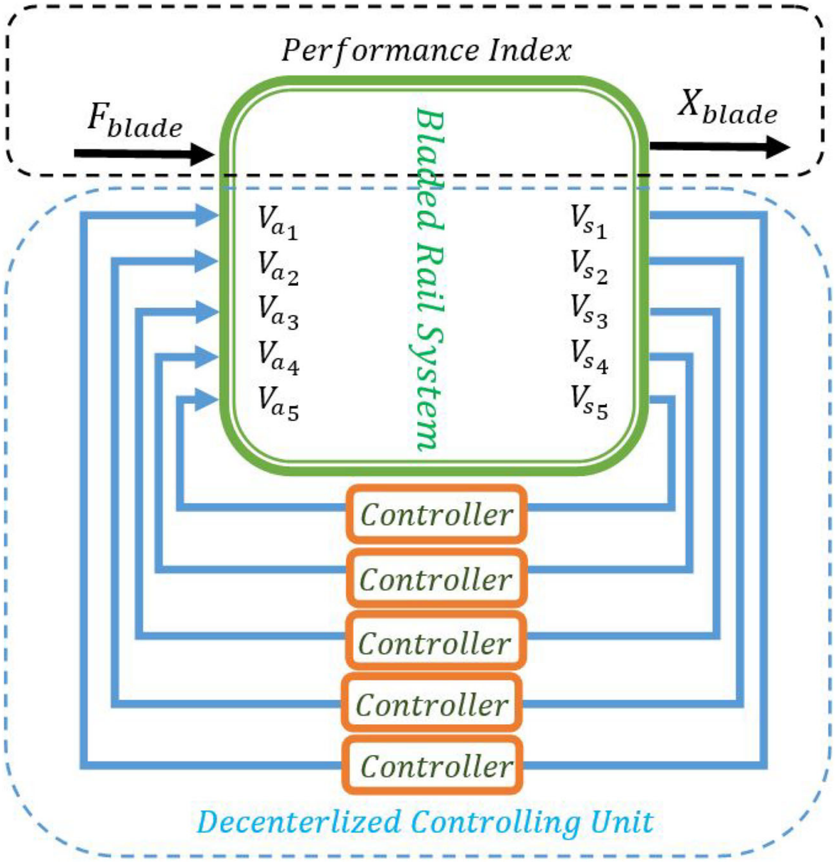


FIGURE 7 Schematic diagram of bladed rail system with decentralized controller unit and performance index section

designed to damp one mode. In this way, it can easily damp the targeted mode. If the cutoff frequency of the controller is lower than targeted mode, then not only NDF will damp the targeted mode but also it can attenuate vibration of the modes after the targeted mode, as well. Specially, if the modes are in the vicinity and close to the target mode, they will be affected even more. This is one of the biggest benefits of NDF controller, which is very useful in this application. Since the modes in the family mode are very close to each other, if the first mode of family is targeted to damp by NDF, then definitely, the next modes will also be damped as well.

Another important factor is that the distance between zero and pole, in the family mode of bladed rail, decreases from the first mode to the fifth mode. This is vividly shown in the open loop frequency response of all the loops in Figure 5. This means that in the first mode of family, the distance between the zero and pole is the highest in comparison with other modes. As mode number increases in the family mode, this distance decreases. For further clarification, this phenomenon is also shown in the root locus plot of the first loop (Figure 8). In collocated systems, if the distance between the zero and pole is higher, then higher value for closed loop damping can be achieved as well. As the distance between zero and pole increases, it would be easier to increase the closed loop damping to higher levels, regardless of controller's type. Therefore, the NDF is designed based on the first mode of the family mode, which has higher distance between zero and pole. For this purpose, a collocated model (with one zero and pole) is fitted on the first mode (Figure 9), and this model is utilized in the designing process of NDF filter.

For determining the parameters of the controller optimally, a straightforward method is used. First, maximum damping method is used to find candidates of the controller's pole location, which can create maximum possible closed loop damping. Afterwards, H_2 method is utilized to choose the optimal choice between the candidates proposed by maximum damping method. The designed NDF controller's parameters are presented in Table 2.

After designing the NDF for the fitted model, it is enhanced and applied on the first open loop plant. By this method, maximum damping possible considering this controller is extracted. The root locus of first loop's plant with designed NDF is shown in the Figure 10. Comparing Figure 8 with Figure 10 shows that the plant's damping has been increased from 0.0001 to 0.021, which is a very high increase.

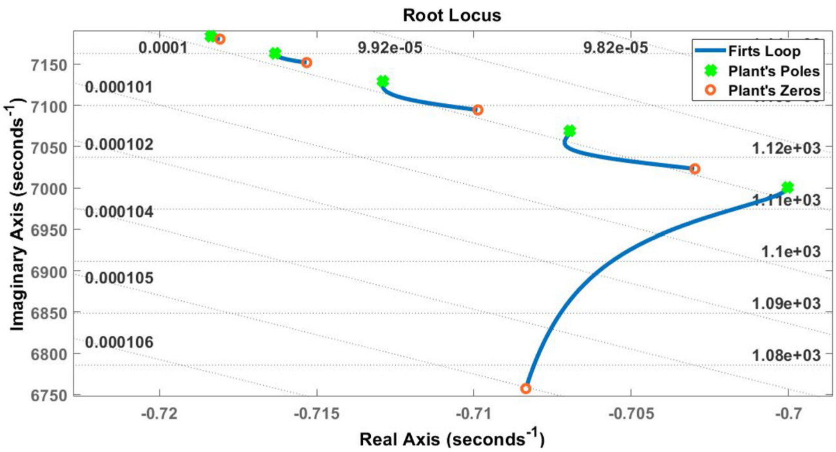


FIGURE 8 Root locus plant of first loop

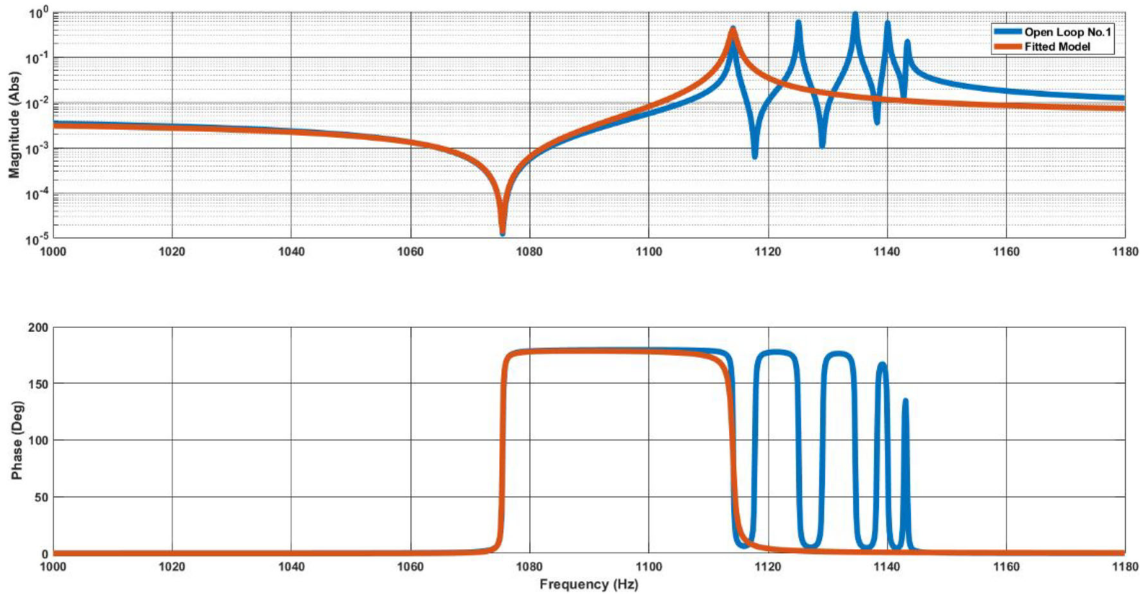


FIGURE 9 Open loop no. 1 and the fitted model for designing NDF

TABLE 2 Designed NDF controller parameters

NDF parameters	K_c	ξ_c	ω_c
Value	8.2013	0.0227	1076.7 (Hz)

4.2 | Decentralized NDF

Since the designed NDF controller works for a band of frequency in which the first mode of family exists, it can be applied to all of the loops. After designing an optimal NDF controller, it is applied for all of loops of model in a decentralized way. The loop gain of all plants of the system considering the designed NDF controller is shown in Figure 11. As shown in the figure, clearly the loop gain has higher values than one, in a band of frequency. The controller works only in this band of frequency in which first family mode exists. On the other hand, in other frequencies, it has no significant effect which is completely desired.

For evaluating the designed controller in a decentralized way, all of loops are closed with designed controller, and the performance index of the system (frequency response between the middle blade's applied force tip and its

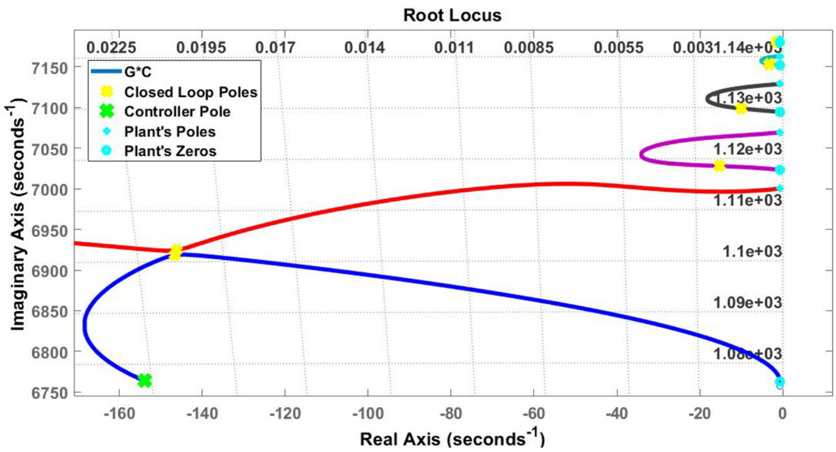


FIGURE 10 Root locus closed loop system for the first loop

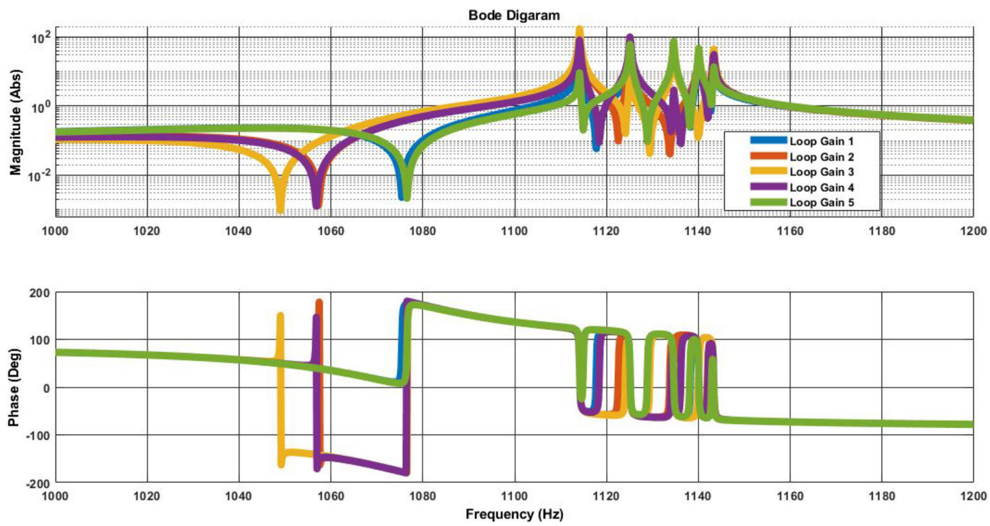


FIGURE 11 Loop gains considering the designed NDF controller

displacement) in the controlled condition is calculated and compared with uncontrolled response (Figure 6). The result is presented in Figure 12. Obviously, the controller can mitigate all of the five modes in the family mode impeccably.

The proposed method is utilized to damp the family of mode in the bladed rail in two experimental setups for evaluating its performance. The proposed controller works for both zero after pole and zero before pole pattern in the open loop of collocated patches.

5 | EXPERIMENTAL EVALUATION

In this section, in order to apply the decentralized NDF controller on the two bladed rails with different types of piezoelectric patches, two experiments are done. For this purpose, two bladed rails had been manufactured using a precise 3D printer by Aluminum material. Also, a clamp fixture, which is especially designed to clamp the structure on the table, is produced by a CNC machine. In each bladed rail, five pairs of piezoelectric patches are glued below the structure, in order to use them as sensors and actuators. The picture of the experimental setup of the bladed rail No.1 is presented in the Figure 13.

In order to calculate the performance index accurately, in the experiment, a very precise way should be used to excite the structure, and also another very high accurate device should be utilized to measure the displacement of one of the blade's tips.

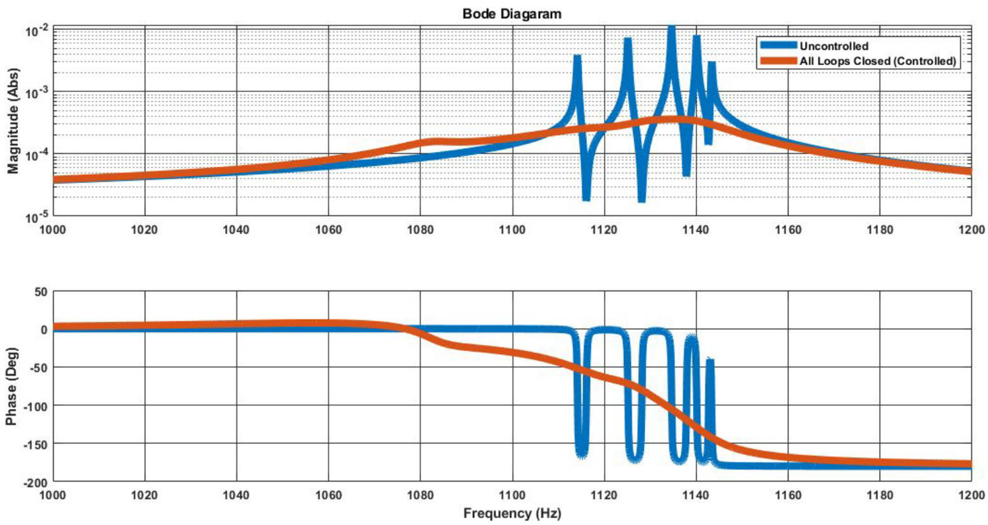


FIGURE 12 Performance index of system (frequency response between the middle blade's applied tip force and its displacement) in controlled condition comparing with uncontrolled response

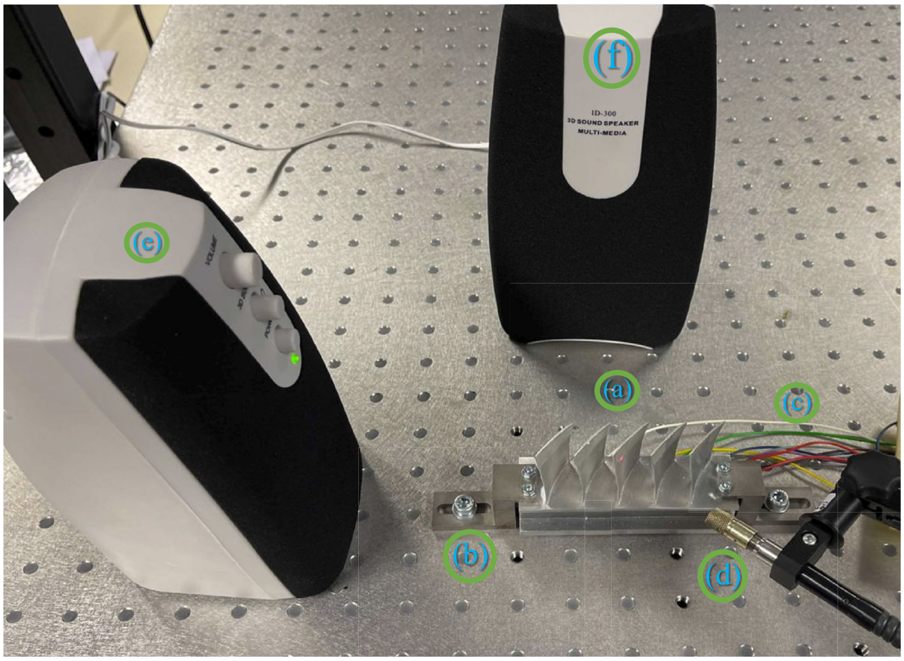


FIGURE 13 Experimental setup of bladed rail no.1 with detail components: (a) bladed rail, (b) clamped support, (c) piezoelectric patches' cables, (d) laser vibrometer (measuring the middle blades displacement), (e) acoustic exciter no. 1, (f) acoustic exciter no.2

For exciting precisely, two acoustic speakers are used to excite the structure (Figure 13e,f) in the band of frequency by a chirp signal, which the family mode exists. Two speakers are placed in two directions that are perpendicular to each other, and by this method, all of the modes in the first family are excited.

For measuring the displacement of structure, a laser vibrometer (Figure 13d) is utilized, which has a high precision capability for displacement measurement, and it is used for measuring the structure's middle tip's displacement. The transfer function between middle blade's tip displacement to the acoustic excitation signal (applied chirp signal) is calculated in the experiment and considered as a performance index of the structure.

For evaluating the controller effect on the family mode vibration mitigation, the performance index of structure in the controlled and uncontrolled conditions is calculated and compared with each other. During the experimental evaluation, a *dSpace MicroLabBox* system has been used both for data acquisition and for control purposes. The whole control scheme is implemented in the *Matlab Simulink* environment and then downloaded to the processor unit of the *MicroLabBox* system. The control scheme and data measurements are updated at a sampling frequency of 40 kHz, in order to have accurate measurement in higher frequencies. In the next sections, the results attained from the first bladed rail are described in detail.

5.1 | First bladed rail

In this section, the proposed decentralized NDF controller is applied on the first bladed rail structure, and the results are extracted and evaluated in detail. The experimental setup of first bladed rail is presented previously in Figure 13.

The first step for carrying out an experiment is extracting each loop's frequency response. To extract the open loops, a chirp signal with altering frequency from 1 to 1.5 KHz is applied to each piezoelectric actuator patch, and simultaneously, the signal of collocated piezoelectric sensor patch is measured. The frequency response between the measured sensor signal and applied actuator signal represents the open loop transfer function of considered loop. This procedure has been done for all of the piezoelectric pairs, and all of 5 open loops of first bladed rail are extracted and presented in Figure 14.

The experimental open loops show that all of them have an altering pole and zero pattern, which means that all of the sensor/actuator pairs are collocated, which is exactly the same as the numerical model. The pattern for all of them is zero before pole and the magnitude level of open loops are approximately the same, which is ideal for designing a unified decentralized controller.

The next step is designing an optimal NDF controller for extracted open loops. As mentioned in Section 4, in the procedure of NDF controller design, it is better to consider the cutoff frequency of NDF controller to be located before the targeted modes. So, it is better to consider the cutoff frequency before the targeted family mode.

Another important point is the distance between the zero and pole in the family of mode. Like numerical model, in experimental open loops, as the mode number increases in the family of mode, the distance between the zero and pole decreases. Therefore, in the family mode, the first mode has highest distance between pole and zero. As a consequence, in overall, for designing NDF controller, it is better to consider to damp the first mode in the family mode. For this reason, an acceptable one ordered collocated model is fitted to the first mode of family mode in the first open loop (Figure 15).

Considering this fitted model, an optimal NDF based on maximum damping and H_2 method has been designed,[25,26] and after a minor enhancement, it has been applied on the first open loop. The designed controller parameters are presented in Table 3.

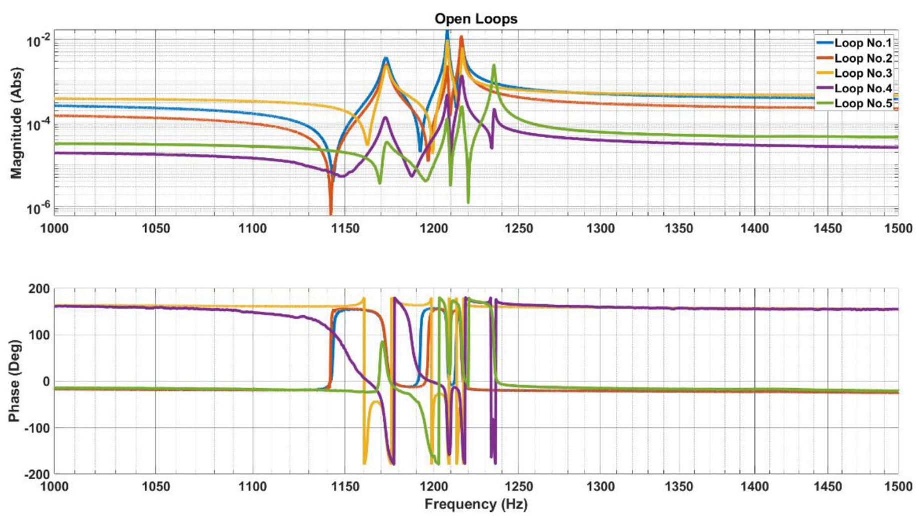


FIGURE 14 Experimental open loops of the first bladed rail

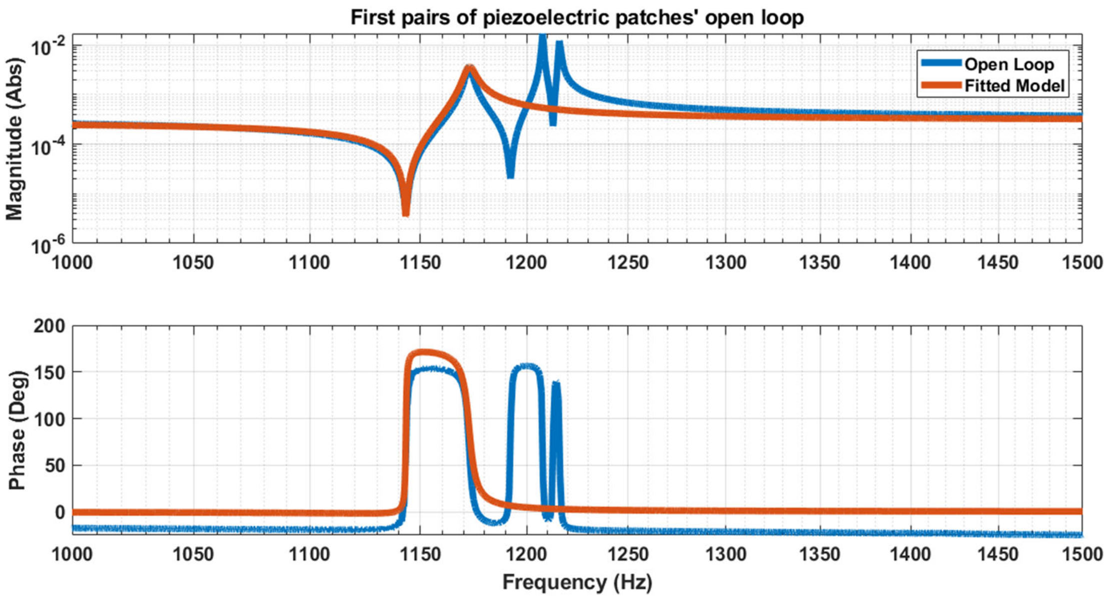


FIGURE 15 First open loop with fitted model on the first mode

TABLE 3 Designed NDF controller parameters for the first bladed rail

Parameters of NDF	K_c	ξ_c	ω_c
Value	215.4905	0.0140	1128.5 (Hz)

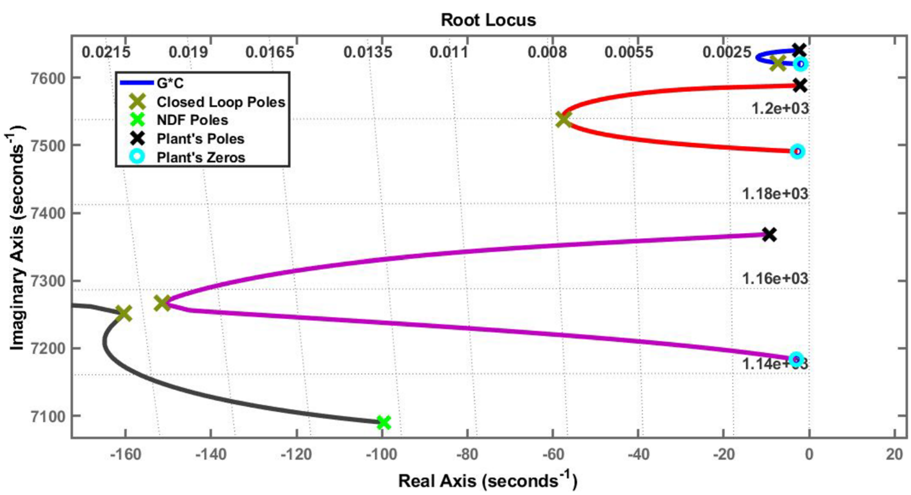


FIGURE 16 Root locus plot for the first open loop using the designed optimal NDF controller

Comparing the Table 3 with Table 2 shows that, except the gain, other parameters of NDF for the numerical model and the experiment are very close each other. The high difference between the gains of controller comes from the fact that in the experiment, a signal conditioner is utilized for the piezoelectric sensor output and also an amplifier is used to amplify the actuator signal. In the experiment, in order to reduce the sensor noise, a signal conditioner is advised to utilize. Both of signal conditioner and amplifier have a gain that changes the level of open loops (it is also clear by comparing the magnitude level of the numerical open loops [Figure 5] and experimental open loops [Figure 14]). For this reason, the gain of controller changed significantly from numerical model to the experimental setup.

The difference between the cutoff frequency (ω_c) of the NDF controller originates from the fact that the natural frequencies of the family mode in the numerical model and experimental setup are not the same, which is completely normal due to clamping boundary conditions. However, the damping coefficient (ξ_c) of NDF controllers is approximately the same. The root locus of first open loop model (full collocated model with 3 poles and zeros presented in Figure 15) with NDF controller is presented in Figure 16.

Evidently, the designed NDF controller can increase the closed loop damping of the system significantly. Moreover, the controller's pole is located in an optimal location, which magnifies the loop between all of zeros and poles of open loop, especially in the first loop. As a consequence, the damping of the system in the first mode increased from 0.0013 to 0.021, which is a huge improvement on damping enlargement. Similarly, the damping of the system in the second mode increased from 0.000289 to 0.008 and in the third mode increased from 0.000301 to 0.001. This high amount of damping enhancement led to apply the same controller for other loops of the system in a decentralized manner. After applying this optimal NDF controller, the loop gain of all the 5 loops is extracted and presented in Figure 17.

Obviously, the open loop graphs show that each loop is responsible to reduce the vibration of family of mode for a certain amount. This means that as the number of closed loops increases, the vibration reduction will increase as well. Therefore, when all of the loops are closed, the vibration reduction magnitude is the highest possible using this NDF controller. For this purpose, first all of the loops are closed by the designed controller and then the performance index of system (frequency response from acoustic excitation to the laser vibrometer measurement of the middle's blade displacement) is extracted and compared with the condition when there is no control on the structure. The result is presented in Figure 18.

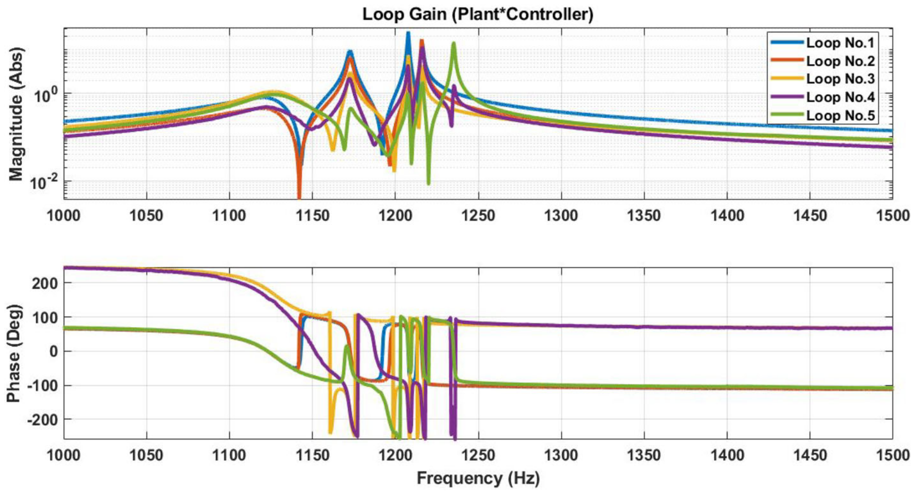


FIGURE 17 Experimental loop gains for all loops using the designed NDF controller

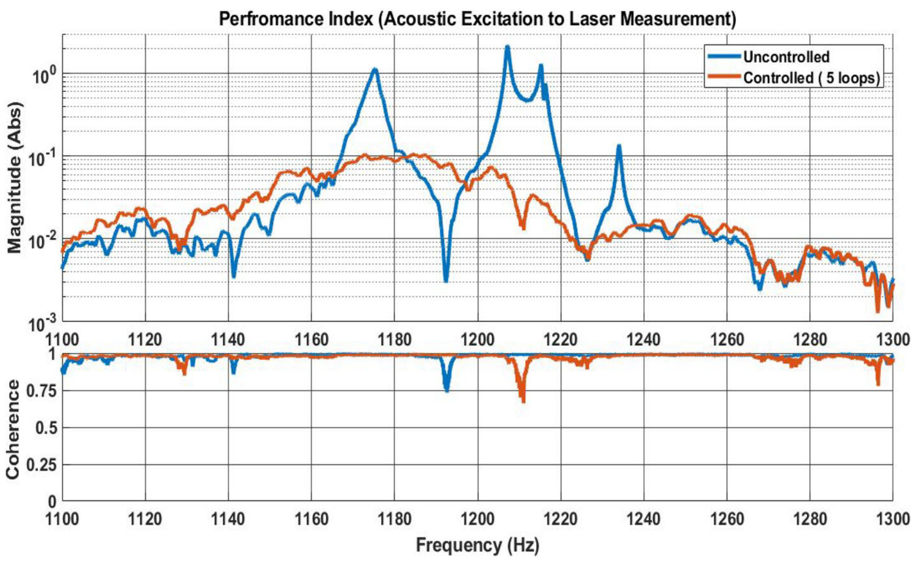


FIGURE 18 Performance index of first bladed rail in controlled (5 loops are closed) and uncontrolled condition

First of all, from Figure 18, it shows that in uncontrolled condition, the structure has five modes in a short band of frequency from 1160 Hz to 1240 Hz, which is considered as the first family mode. The second important point is that using decentralized optimal NDF controller, all of the modes in the family are damped magnificently. The level of vibration attention in all of the modes is admissible, and all of modes are totally damped. The only downside of this method is slightly vibration magnification before the family mode (from frequency of 1120 to 1160 Hz), which is neglectable. Therefore, in overall, this result shows that applying optimal NDF controller in a decentralized way can easily mitigate the vibration level of the first bladed rail. To make sure that this proposed method is applicable to any structure, the same procedure has been applied on the second bladed rail, which has a different structure material and piezoelectric patches.

5.2 | Second bladed rail

In this section, the same procedure of designing an optimal NDF control is done for another bladed rail. The experimental setup of the second bladed rail is shown in Figure 19. The second bladed rail structure is 3D printed with aluminum, and the clamp is produced by a CNC machine with aluminum material as well, which differs from the previous bladed rail setup. Also piezoelectric patches that are glued to this bladed rail have a different material, but their dimension and their location on the blow of the bladed rail are the same.

Similarly, the first step is extracting each loop's frequency response. To extract the open loops, a chirp signal with altering frequency from 1 to 1.5 KHz is applied to each piezoelectric actuator patch, and simultaneously, the signal of collocated piezoelectric sensor patch is measured. This procedure has been done for all of the piezoelectric pairs, and all of 5 open loops of first bladed rail are extracted and presented in Figure 20.

The experimental open loops show that all of them have an altering pole and zero pattern, which means that all of the sensor/actuator pairs are collocated, which is exactly the same as the numerical model. The pattern for all of them is zero after pole, and the magnitude level of open loops is approximately the same, which is ideal for designing a unified decentralized controller.

The next step is designing an optimal NDF controller for extracted open loops. For this purpose, the same algorithm that has been explained in the numerical model control design (Section 4) and for the first bladed rail

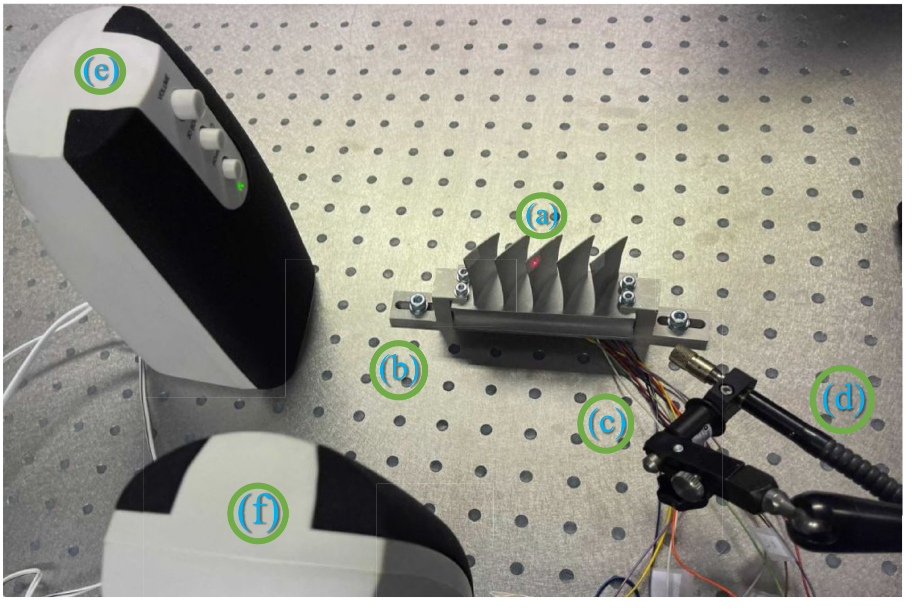


FIGURE 19 Experimental setup of bladed rail no. 2 with detail components: (a) bladed rail, (b) clamped support, (c) piezoelectric patches' cables, (d) laser vibrometer (measuring the middle blades displacement), (e) acoustic exciter no. 1, (f) acoustic exciter no. 2

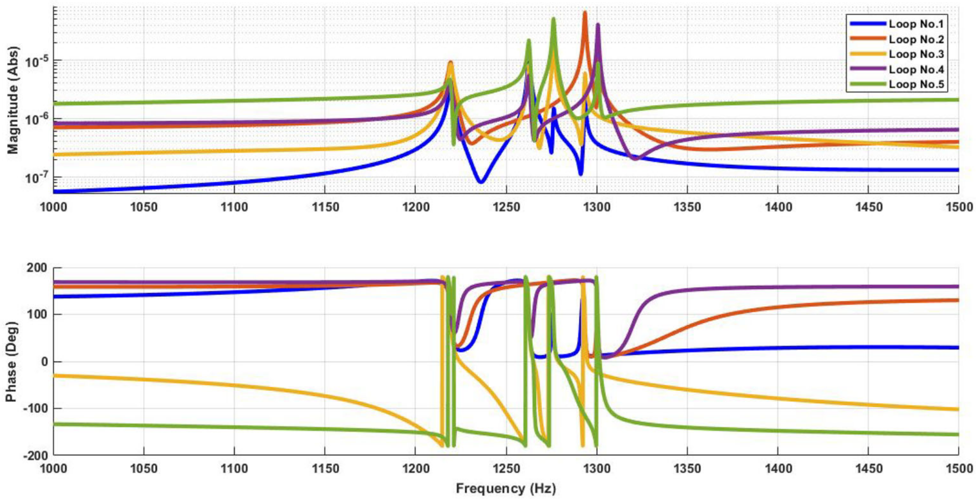


FIGURE 20 Experimental open loops extracted for the second bladed rail

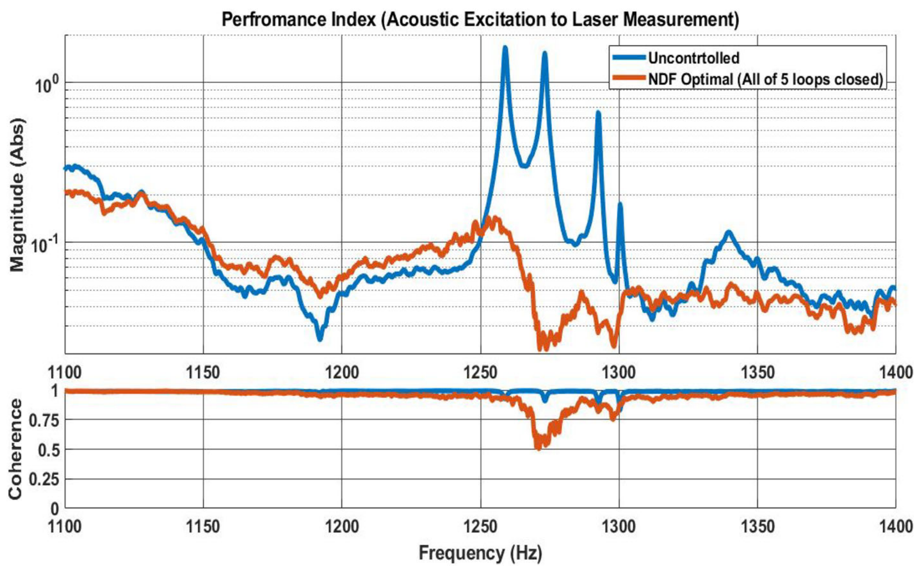


FIGURE 21 Performance index of second bladed rail in controlled (5 loops are closed) and uncontrolled condition

(Section 5.1) has been done for the second bladed rail as well. After designing the controller, it has used to close all of the loops of the second bladed rail. For evaluating the effect of the controller, first all of the loops are closed by the designed controller and then the performance index of system (frequency response from acoustic excitation to the laser vibrometer measurement of the middle's blade displacement) is extracted and then the performance index of system is compared with the condition when there is no control on the structure. The result is presented in Figure 21.

First of all, from Figure 21, it shows that in uncontrolled condition, the structure has a family mode in a short band of frequency from 1250 to 1300 Hz. The second important point is that using decentralized optimal NDF controller, all of the modes in the family are damped magnificently. The level of vibration attention in all of the modes is admissible, and all of modes are totally damped. The only downside of this method is slightly vibration magnification before the family mode (from frequency of 1150–1250 Hz), which is completely neglectable. Therefore, in overall, this result shows that applying optimal NDF controller in a decentralized way can easily mitigate the vibration level of the second bladed rail as well.

6 | CONCLUSION

In this study, active vibration control of bladed rail structure with piezoelectric sensors and actuators was studied numerically and experimentally. An optimal NDF controller is designed, and it has been applied in a decentralized way. Bladed rail structures have some blades that create the vibrational modes with close natural frequencies, which is called family modes. First a model of bladed rail with 5 blades has been extracted using SDT tool software. Afterwards, a decentralized optimal NDF controller is designed for the model, which is desirable for reducing vibration caused by family mode. The results showed an outstanding amount of vibration reduction in the family mode. For validating these results, two separate bladed rails had been 3D printed, and in each of them, 5 pairs of piezoelectric patches are glued underneath them. For the first bladed rail, the open loops of all of the piezoelectric pair are extracted, and the first loop is considered for designing the NDF. The first mode in the family mode is targeted in design procedure, and it has been shown that all of the modes in the family will have higher closed loop damping. Therefore, the controller is applied to all of the loops in a decentralized way. The results showed that by this method, all of the modes of family have been completely damped. The same procedure has been done on the second bladed rail, which has been made of different material. The results of the second bladed were also astonishing, and all of the modes were totally damped using the optimal NDF controller in a degenitalized way. In overall, these results demonstrate the high power and applicability of NDF controller on vibration attenuation of high modal density in the bladed structures at higher frequencies.

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AUTHOR CONTRIBUTIONS

Rasa Jamshidi: Conceptualization; methodology; software; visualization; writing–original draft. **Ahmad Paknejad:** Review & editing. **Christophe Collette:** Review & editing; funding acquisition, supervision.

DATA AVAILABILITY STATEMENT

No additional data available.

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