Active damping of high modal density of bladed structures with piezoelectric patches

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Abstract

In this study, active vibration control of high modal density in the bladed rail structures, with piezoelectric patches utilizing decentralized controller evaluated numerically and experimentally. Because of higher number of modes of bladed rails in a very short frequency range, mitigating these modes (called as family mode) is quite challenging task. A bladed rail is considered with 5 blades which create 5 modes in family mode. An integral force feedback controller is designed for the numerical model. The numerical results show an acceptable performance of the proposed controller on high modal density vibration reduction. For validating these results, a bladed rail had been manufactured and piezoelectric patches are designed and produced specially for this experiment. These patches are glued to the structure with high precision method. The controller can easily mitigate acceptable amount of the family mode vibration. This shows the applicability of proposed configuration and controller on mitigating high modal density modes.

1 Introduction

Nowadays, bladed structures are widely used in aerospace applications and in particular turbomachinery structures such as fan, compressor stages and turbine stages. To improve the performance of these systems in terms of the energy consumption, new technologies have been developed to use low-density structures. However, these structures possess a very low internal damping which as a consequence may lead to high level of vibration and also high-cycle fatigue problems. This issue can lead to malfunctioning of the structure in the system which can be a dangerous and catastrophic. Suppressing their undesired vibration is of interest for many researchers and engineers in this field around the world. For this purpose, two common methods are developed which are passive and active methods.

Previously, several passive techniques have been used for the vibration reduction 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.

On the other hand, to overcome the performance limitations of the passive methods, active methods were introduced since they are less sensitive to the system's parameters. Numerous amounts of research have been carried out for active vibration control with piezoelectric patches embedded on various structures. Jamshidi et al [10-15] studied active vibration control of conical shells using piezoelectric patches to sense and mitigate the vibration using various types of controllers. In bladed structures, since the vibration level is very high in the family mode and usually, they are located at higher frequencies, a robust and powerful controller should be used to mitigate them. There are many conventional controllers which previously had been applied for the active vibration control of structures like beam, plate and shells. However, because of intensive number of modes in a short frequency range in bladed structures, those conventional controllers cannot damp these modes significantly. Therefore, a powerful controller with a specially designed piezoelectric patches should be considered for this case which can reduce the displacement of the blades.

In this study, active vibration control of the bladed rail structure which has 5 blades, with 5 pairs of piezoelectric patches are evaluated numerically and experimentally. For this purpose, five pairs of piezoelectric patches are considered to sense the displacement of each blade and actively apply a momentum in a reverse direction to reduce the vibration of each blade separately. 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, a controller is designed for the numerical model, based on. 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 shown that the unified decentralized NDF controller can mitigate the first family mode easily and it has a high performance. To validate these results, a bladed rail is 3D printed by aluminum material. For mounting on the optical table, a fixture is designed and manufactured using CNC machines. For damping the family mode, 5 pairs of trapezoidal piezoelectric patches are specially designed and produced to enhance controllability of actuator. Afterwards, these patches are glued on the bladed rail to carry out the experiment. The controller is updated based on the extracted experimental open loops and applied on the structure in decentralized manner. The displacement of the middle blade is measured by laser vibrometer during the experiment and the transfer function between acoustic excitation and middle blade's displacement is considered as performance index of system. The performance index of system is extracted in the controlled and uncontrolled condition to evaluate the performance of proposed active vibration control method. The results show a very satisfactory amount of vibration mitigation on the first family mode of the bladed rail. This proves the proposed method applicability on damping the high modal density of bladed structures.

2 The bladed-rail structure

In this section, for evaluating the high modal density problem, a bladed structure which can be representative of any circular bladed structures is considered. Typically, any structure which 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 at higher frequencies called as high modal density. 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. Therefore, a powerful controller should be designed in a way to mitigate all of the modes existing in a band of frequency.

In this study, for evaluating high modal density vibration mitigation, a simple bladed rail structure with 5 blades is considered (Fig.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. 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 performance any designed controller for the system. To avoid disturbing the air flow around the blades the piezoelectric patches are placed on the below section of blades. The patches are considered to be located exactly beneath each blade. Since the blades are inclined, the geometry of patches is designed to be trapezoidal. By this way, the sensor can measure the displacement of bended surface inclusively. Moreover, the actuator can apply higher amount of momentum on structure to decrease the vibration (Fig.1).

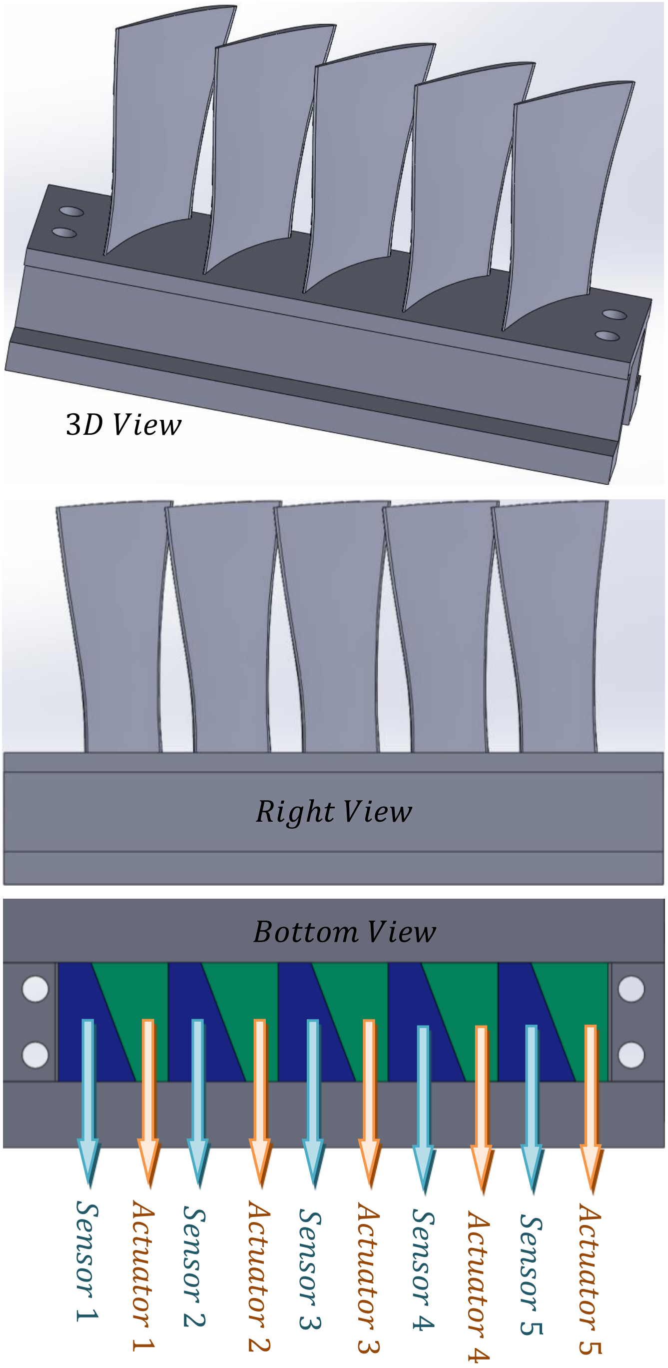

Figure 1: The bladed rail structure with five blades

In this study, the controller is considered to be feedbacked identically in a decentralized way (Fig.2). 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 (Fig.2). 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.

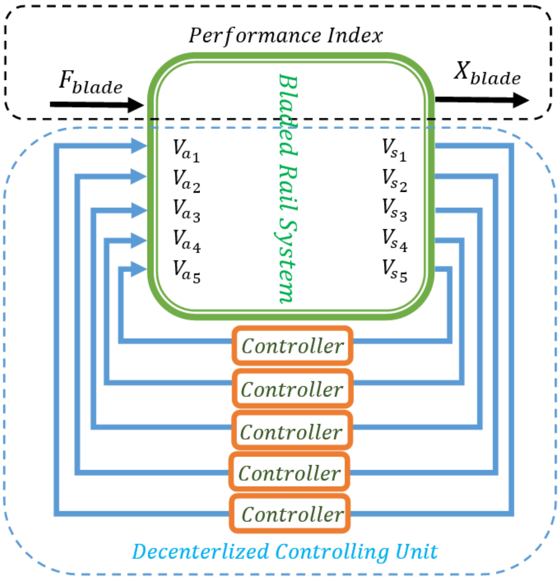

Figure 2: The configuration of decentralized controller

3 Numerical results

In this section, a reliable numerical model, which is reduced ordered based on the first family mode, is extracted for the considered configuration in the Fig.2, 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. The frequency response between the middle blade's force to its displacement is used for determining the performance index of system. Therefore, a model with 5 controlling outputs/inputs (piezoelectric sensor/actuator patches) and a performance index output/input (the middle blade's displacement/force) is extracted. By closing the controlling loops, the performance index of the system can be evaluated (Fig.2).

The bladed rail and piezoelectric patches' material are considered as aluminum and PIC255, respectively. The material properties of piezoelectric patches are presentenced in Table No.1. For extracting the model, the structural damping is assumed to be very low. The Abaqus software is used to mesh the structure and afterwards it is imported to the Structural Dynamics Toolbox (SDT software). By using this software, the reduced order state-space model, considering the first family of mode, from the finite element model is extracted.

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}^{σ}	14609.1	10^{-12} F/m
	e_{33}^{σ}	15494.5	10^{-12} F/m
Density	ρ	7800	kg/m^3

After extracting the numerical model from SDT, the open loop frequency response of each pair is extracted and presented in Fig.5. Obviously, alternating poles and zeros in the frequency response of all of the open loops assure that all of the sensor/actuator pairs are collocated.

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 gains of all plants of the system considering the designed NDF controller are shown in Fig.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 displacement) in the controlled condition is calculated and compared with uncontrolled response (Fig.6). The result is presented in Fig.12. Obviously, the controller can mitigate all of the five modes in the family mode impeccably.

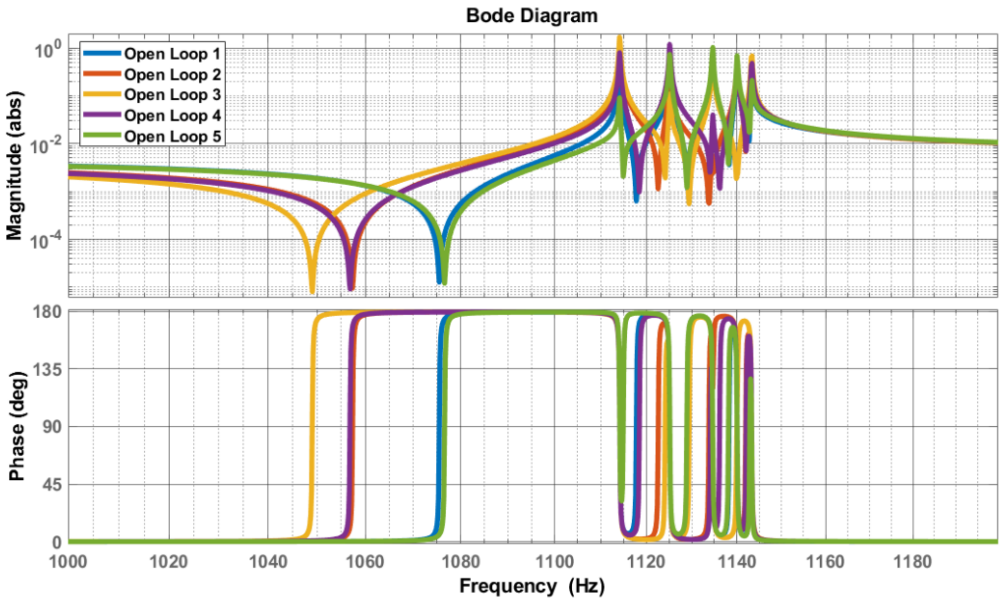

Figure 3: Numerical open loops

For these open loops, an IFF controller is designed in order to damp the family mode. In order to have higher values of damping in the family mode, the IFF controller optimized based on methods presented in []. The controller's transfer function is presented in Eq.1.

$$C(s) = -\frac{15.0666*10^4\, s}{(s+290.9)(s+32.79)} \tag{1}$$

Considering the designed controller, the loop gains (plant multiplied by controller) are calculated and presented in Fig.4. The controller has a performance in the frequencies which the magnitude of loop gain is higher than one. So, each loop is responsible to increase the damping of the family mode a portion.

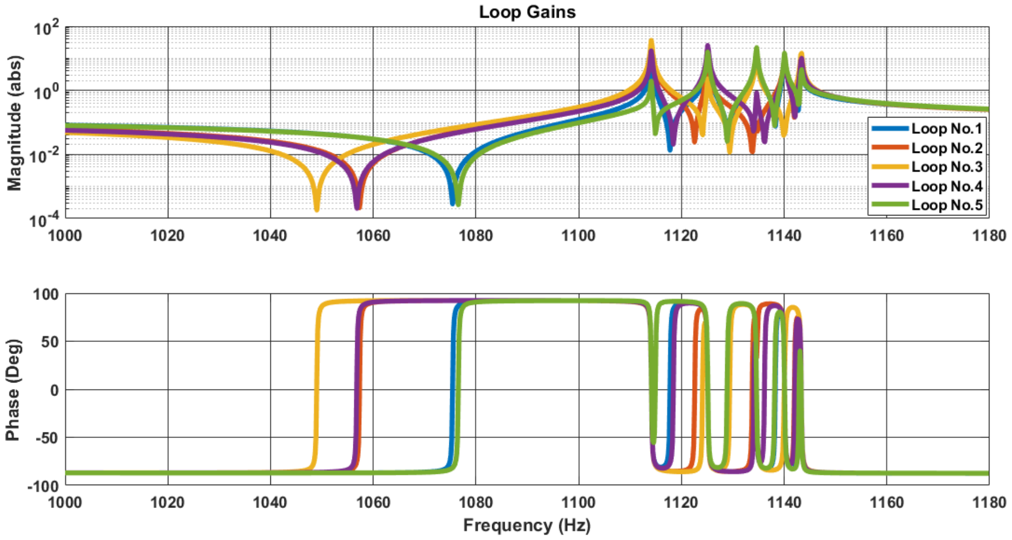

Figure 4: Loop gains considering the designed IFF controller

The designed controller is used the all the loops of the bladed rail in a decentralized manner (Fig. 2). The performance index of the bladed rail which considered as the transfer function between the middle blade's force to the middle blade's tip displacement is calculated in the open loop condition and compared with the condition that the loops are closed. These results are presented in Fig. 5.

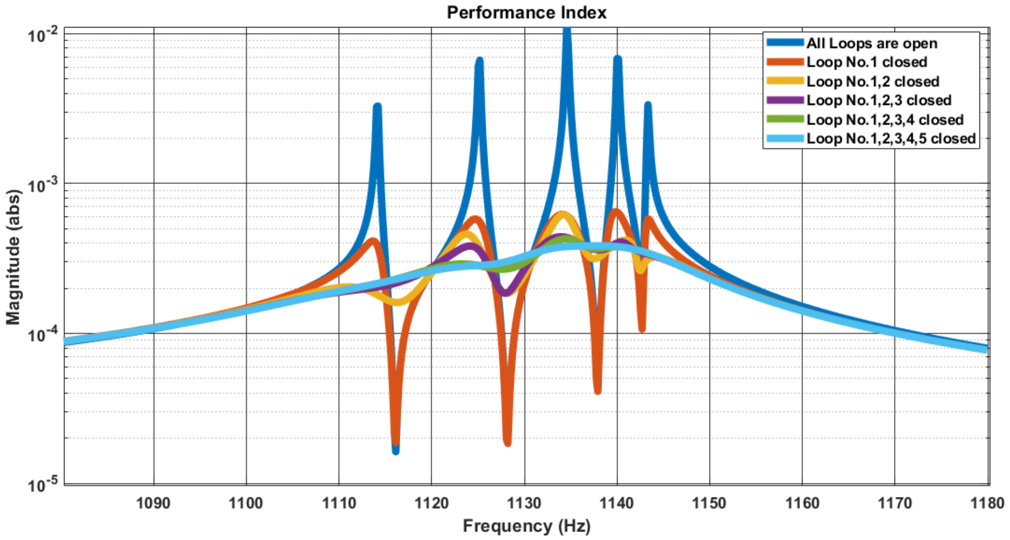

Figure 5: Performance index of the bladed rail in controlled and uncontrolled condition

The above figure, shows vividly the effectiveness of the designed controller on the first family of mode of the bladed rail. As it is obvious, all of the modes of the family, is damped effectively by the proposed decentralized controller. Therefore, this decentralized IFF controller is recommended for vibration mitigation of the high modal density.

For evaluating the proposed method experimentally, in the next section an experiment is carried out to verify the performance of the proposed controller on damping high modal density of the bladed rail.

4 Experimental verificaton

In this section, an experiment is carried out to validate the proposed controller's performance experimentally. The bladed rail structure is 3D printed by aluminum material and the clamp is produced by a CNC machine with aluminum material as well. For increasing the performance of vibration mitigation, trapezoidal piezoelectric patches are especially designed and ordered to produce by smart material company. Since the blades of structure are inclined, the surface of sensor and actuator should be following this inclination. Therefore, these patches are especially designed and produced with a trapezoidal geometry to increase the performance of vibration reduction (Fig. 6). These patches are glued with a precise method using a specific fixture pressuring the patches uniformly on the bladed rail.

For exciting precisely, two acoustic speakers are used to excite the structure (Fig. 7) in the interested band of frequency by a chirp signal. Two speakers are placed in perpendicular directions in order to excite all of the modes in the first family. For measuring the displacement of structure, a laser vibrometer (Fig. 7) 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 is 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 are 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.

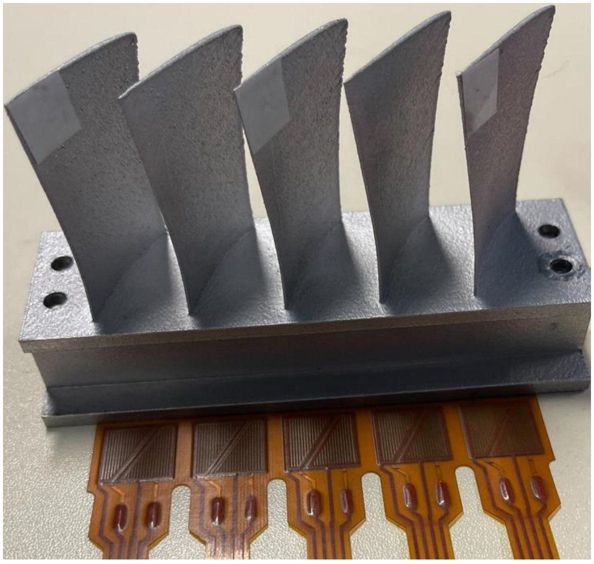

Figure 6: The 3D printed bladed rail with especially trapezoidal piezoelectric patches

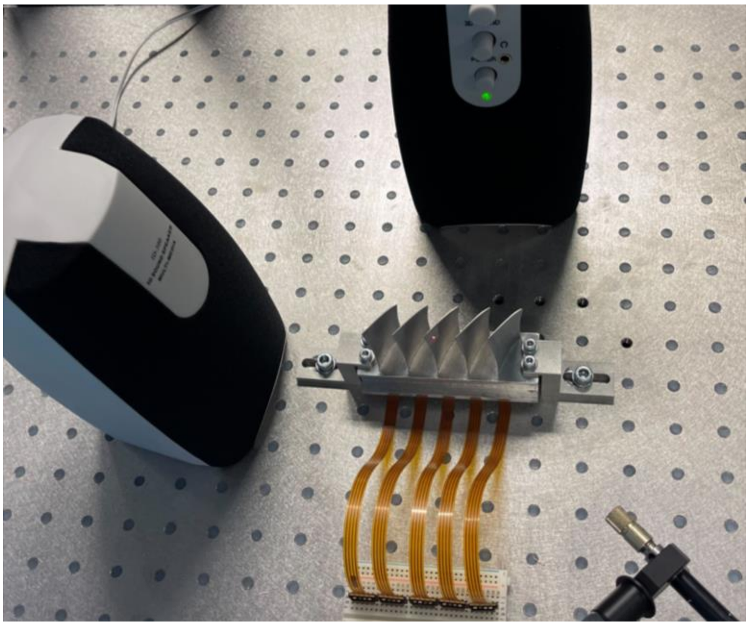

Figure 7: Experimental setup of bladed rail with glued patches on below.

The first step in experiment is to extract the open loops of piezoelectric patches. For this purpose, a sine chirp signal is injected to each actuator piezoelectric patch and measured the collocated sensor piezoelectric patch. This procedure has been done for each pair of piezoelectric patches and the 5 open loops are extracted and shown in Fig. 8.

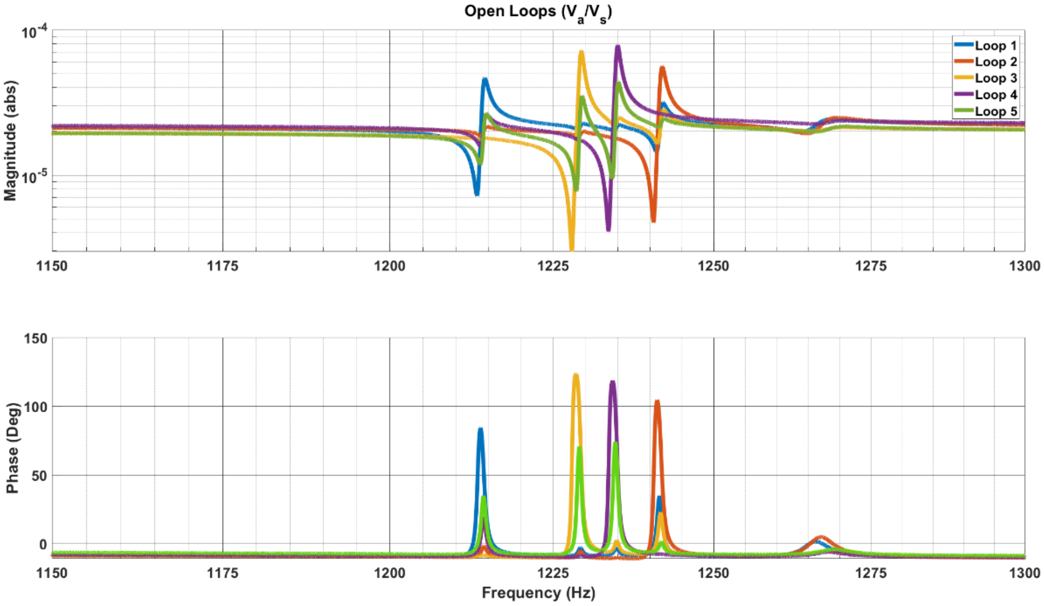

Figure 8: Experimental setup's open loop

Firs a model is fitted for each of extracted open loops to design a controller. Using fitted plants, the designed IFF controller in numerical section is updated in order to damp the family mode impactfully. The new controller's transfer function is presented in Eq.2.

$$C(s) = -\frac{5.0222*10^8\, s}{(s+290.9)(s+32.79)} \tag{2}$$

Considering the designed controller, the loop gains (each plant multiplied by controller) are calculated and presented in Fig. 9. The designed controller has a performance in frequencies which the magnitude of loop gain is higher than zero decibel.

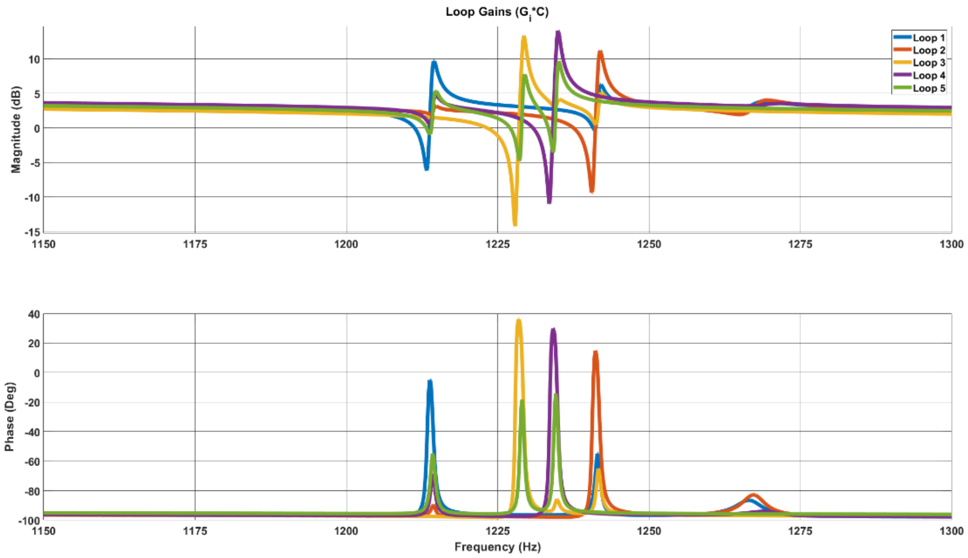

Figure 9: Loop gains

The designed controller is used to close all of the bladed rail’s loops in a decentralized manner as shown in Fig. 2. The transfer function between the acoustic excitation signal to laser vibrometer signal (performance index) is calculated in the open loop condition and compared to the condition when all of loops are closed. These results are presented in Fig.10.

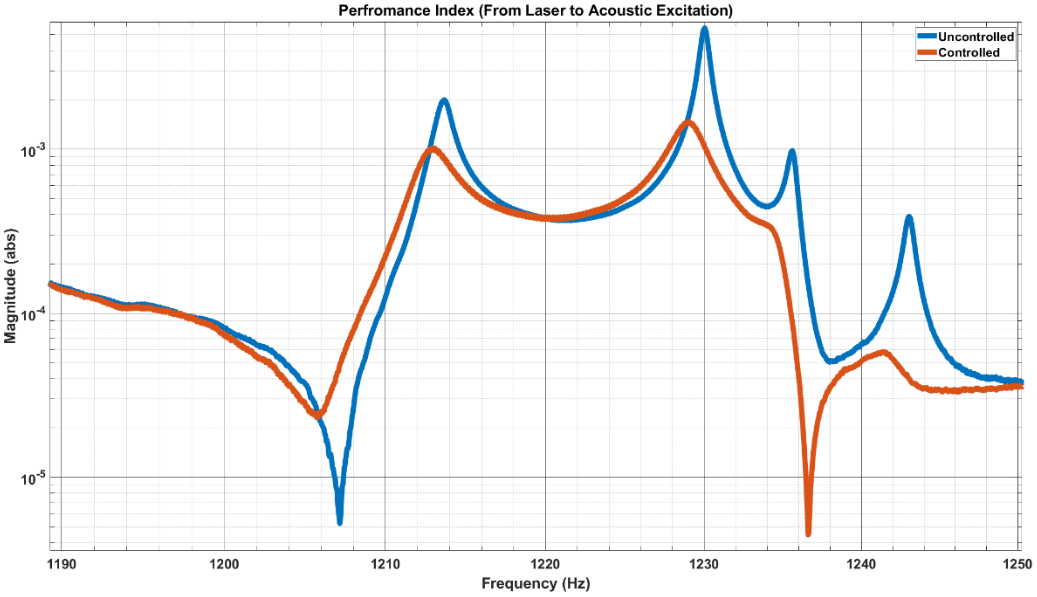

Figure 10: Performance index

Clearly, in the uncontrolled condition a family of mode exists which are located very close to each other called as family mode. These modes are damped in controlled condition significantly. This shows the power of active vibration control stagey to damp the family mode impactfully. Moreover, the design of piezoelectric patches increased the performance of controller significantly. Therefore, it is highly recommended to design a specific piezoelectric patch for each active vibration control of smart structures.

5 Conclusion

In this study, an active control method is proposed to reduce high modal density vibration of the bladed structures. Specific piezoelectric patches were designed and used for both sensing the motion and actuating on the structure. For obtaining maximum control authority, the shape of piezoelectric patches designed and produced with trapezoidal geometry. A numerical model of the system was extracted and a decentralized integral force feedback controller was designed to mitigate the vibration of the first family of mode. Numerical simulations were performed to assess the performance of the designed control system in terms of the closed-loop damping of the system. The results showed that the proposed controller can mitigate the first family of mode the structure significantly. To validate the numerical results, an experiment is carried out and the active vibration control of high modal density by using a decentralized IFF controller is evaluated experimentally. For this purpose, a bladed rail had been manufactured and piezoelectric patches designed and produced and glued to structure precisely. The same procedure for designing controller has been done for the structure. Experimental test showed high effectiveness of the proposed controller on vibration reduction of first family mode of the bladed rail and by this method, high modal density can be damped drastically.

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