Design, Analysis and Testing of Flexurally Amplified Piezoactuator Based Active Vibration Isolation System For Micromilling

Divijesh P†, Muralidhara‡, Rathnamala Rao‡, Rehna Mueen Ahmed†, & Sushith K†

†Department of Mechanical Engineering, NMAMIT, Nitte-574110, VTU, Belgaum
‡Department of Electronics and Communication Engineering, NITK, Surathkal-575014

Email: divijesh@nitte.edu.in

ABSTRACT: Vibration is considered to be one of the limiting factors which affects precise measurements and surface finish of various mechanical components. Active Vibration Isolation is one such effective method which reduces the unwanted vibrations in any mechanical systems in a wide range of frequencies. This paper presents the design, analysis and testing of an active vibration isolation system based on Flexurally Amplified Piezo actuators (FAP1 and FAP2). The proposed set up aims at obtaining 180° out of phase displacement signal to the generated displacement signal using FAPs thereby minimising vibrations at the isolation platform. The maximum displacements of FAP1 and FAP2 obtained for 0-150V sinusoidal peak to peak amplitude at 1Hz frequency was found to be 810µm and 780µm respectively. The experimental displacements obtained were compared with simulated displacements using Forward Bouc-Wen hysteresis model and found very well agreed with each other within 1% error. An attempt has been made to estimate the voltage required for obtaining any desired displacement of FAPs using Inverse Bouc-Wen model through Simulink. The experimental displacements for the corresponding estimated voltages were obtained for FAPs. Finally, the proposed set up was tested by actuating both FAP1 and FAP2 separately and simultaneously for 0-150V at 1Hz frequency and was found that the displacements obtained were 180° out of phase thereby minimizing vibrations at the isolation platform.

KEYWORDS: Vibration, Flexurally Amplified Piezo actuator, Voltage, Displacement.

INTRODUCTION

Vibration of any mechanical component or structure leads to less accuracy in productivity and results in poor quality and surface finish of the machined products. By proper machine design with stiffness the vibration can be reduced to a considerable amount. Generally, the vibrations between vibratory source and receiving structure are controlled using passive and active techniques. Passive vibration isolation techniques include isolation using elastomers, rubber pads, mechanical springs etc. However, they are limited to low frequency applications and they do not provide damping at lower frequencies. Active Vibration Isolation systems form a substitute to passive systems in wide variety of applications for varying frequencies. A typical active vibration isolation system makes use of sensors, actuators and signal processing unit which are controlled using either internal or external controller using various types of control algorithms. The sensors detect the incoming vibration signals in the form of displacement, velocity and acceleration and these data are sent to controller which in turn sends a counter vibration signal to the actuators thereby reducing the sensed vibrations. The signal processing systems acquire data from the sensors using data acquisition system. Actuators play an important role in nullifying the sensed vibration signals. Depending upon the type of actuation, the actuators may be electromechanical, electromagnetic or piezoelectric devices. Piezoelectric devices work on the principle that when voltage is applied the materials undergo mechanical strain. Piezoelectric materials such as piezo stack actuators are widely used for active vibration control applications since they offer high static and dynamic forces, high stiffness, allow high frequency dynamic applications and contain no moving parts. However piezo actuators exhibit nonlinear hysteresis behaviour between applied voltage and resulting displacement. In the present work flexurally amplified piezo actuators are used for active vibration isolation since they produce a displacement amplification up to 20 and have a good mechanical efficiency.
Piezoelectric actuators have found a variety of applications out of which active vibration isolation is one such application. Researchers have carried out sufficient work on active vibration isolation using piezoelectric materials through different control algorithms. An active vibration isolation system was designed and developed for controlling the plate vibrations using strain gauges as sensor element and piezo ceramic patch as actuation element using PID control algorithm [1]. A phase lock loop based active vibration isolation system has been developed using shaker and actuator for attenuating vibrations affecting a structure. A shaker was used to generate vibrations and a piezoelectric actuator was used as force transducer to suppress these vibrations. For generating a counter vibration signal the phase and gain of suppressing signal should be out of phase to generated vibration signal. This was accomplished using automatic phase and gain compensation built in phase lock control system [2]. Multiple error least mean square (LMS) algorithm and clear box algorithm have been implemented for active vibration isolation on spacecraft using Stewart platform [3]. Based on experimental results it was concluded that LMS algorithm was preferred over clear box algorithm for vibration isolation. A dynamic virtual nonlinear magnetostrictive actuator active vibration isolation model was established based on neural network sliding mode control algorithm [4]. The algorithm was proposed as active control controller thereby reducing the force transmission to the base and broadening vibration isolation bandwidth. Piezoelectric patches have been used as actuators [5] for active vibration control of a structure. The modal parameters and frequency response of the structure was obtained using analytical model of the structure. A controller was designed and was implemented to the analytical model and the analytical results were compared with experimental results using Raspberry Pi 3 microprocessor. Active vibration control of machine tool has been carried out using two piezoelectric stacks along z-axis caused due to floor vibration. Vibration signal was continuously acquired using accelerometer in real time and PID control scheme was used to minimise the error [6]. A vibration isolation set up has been designed [7] using elastomeric vibration isolators to generate the vibrations and a force actuator to cancel the vibrations of a plate like structure.

Active vibration control of a cantilever beam has been carried out by designing and implementing a controller based on PID theory with output feedback [8]. Structural vibrations of flexible beam have been controlled using piezoelectric actuators where the optimal locations, control gains and excitation voltage which is to be given to piezo actuators were identified using modified independent model space control method [9]. The dynamic response of a Functionally Graded Material plates has been controlled using piezoelectric sensors and actuators based on constant velocity feedback control algorithm through closed loop control [10]. A linear Quadratic Gaussian algorithm based controller has been designed and implemented on ANSYS finite element model for active vibration control of piezoelectric smart structures. Experimental investigations have been carried out for the same based on Kalman filter Identification technique. A controller has been designed using proportional-integral-derivative theory with output feedback in Simulink for active vibration control of cantilever beam. The control law was then incorporated into the ANSYS finite element model to perform closed loop simulations and experimental investigations [11]. Strain gauge sensors and fiber reinforced piezoelectric actuator have been used for active vibration control of a smart cantilever composite beam when subjected to periodic excitation. A PID controller has been used for controlling the vibrations [12].

Based on the literature survey carried out, none of the researchers have used flexurally amplified piezo actuator for generating and nullifying the vibration signals. In addition, researchers have used different control systems for phase and gain compensation and also to generate 180° out of phase voltage signal to be given to the actuators for suppressing the vibration signals. In the present work an attempt has been made in overcoming the issue of generating 180° out of phase voltage signal through the proposed design itself. The setup is designed with the goal that actuating FAP1 and FAP2 separately when mounted in the proposed set up should result in displacement of FAP2 to be 180° out of phase to the displacement of FAP1 resulting in minimizing vibrations at the isolation platform. The objectives of the present work include design and development of active vibration isolation set up using flexurally amplified piezo actuators where FAP1 is used to generate vibrations and FAP2 for nullifying the generated vibrations due to FAP1. The analysis of FAPs are carried out using ANSYS software to determine stiffness along X and Z direction and amplification factor. The hysteresis identification of FAPs are carried out using experimental voltage displacement plots. The simulated displacement of FAPs with hysteresis are compared with experimental displacements using Forward Bouc-Wen hysteresis model. Normally in any machining operations, tool or work piece will be subjected to vibrations in terms of displacement or accelerations. Hence for controlling the vibrations of tool or work piece from failure it is required to estimate the voltage which causes these vibrations so that this voltage could be given as an input to piezo actuators. In the present work the Forward Bouc-Wen hysteresis model is rearranged to obtain Inverse Bouc-Wen hysteresis model for estimating the required voltage which causes these vibrations and also to compensate hysteresis. Further the proposed set up is
tested by actuating FAP1 and FAP2 individually and also simultaneously at a particular voltage and frequency so as to obtain minimum vibrations at the isolation platform.

The proposed active vibration isolation set up design is explained in Section 2. The stiffness and amplification factors of both FAPs were determined using ANSYS analysis software as described in Section 3. Section 4 includes experimental set up for displacement measurement of the FAPs along with hysteresis identification and hysteresis modelling of FAPs. In Section 5, Forward Bouc-Wen model simulation and validation through experimental results have been carried out. Inverse Bouc-Wen model simulation and validation has been carried out as described in Section 6. The testing of the proposed set up was described in Section 7. Results and Discussions have been described in Section 8. Conclusions are presented in Section 9.

ACTIVE VIBRATION ISOLATION SET UP DESIGN

A Flexurally Amplified Piezo actuator makes use of six multi-layer piezoelectric stack actuators (10x10x20 mm³) as primary actuator shown in Figure 1, with each stack actuator producing a maximum displacement of 20µm for an input voltage of 150V.

![Figure 1. Flexurally Amplified Piezo actuator (FAP)](image)

The main block of the proposed set up houses the two FAPs, the support block, the bracket, linear guide ways and the isolation platform as shown in Figure 2. One end of FAP1 is supported by the support block which is fixed and the other end is connected to the bracket which moves vertically via the linear guide ways. FAP2 is supported by the bracket and the isolated platform and its free movement is possible via another set of linear guide ways. The setup is designed in such a way that when voltage is supplied to FAP1 alone, the bracket along with FAP2 and isolation platform moves in the upward direction and when the voltage is supplied to FAP2 alone, the isolation platform moves in the downward direction thereby producing a net displacement at the isolation platform.

ANALYSIS OF FLEXURAL AMPLIFIERS
The analysis of flexural amplifiers was carried out in ANSYS Mechanical APDL software to obtain their displacements and stiffness along Z-direction and X-direction respectively. X-axis of the amplifier is the axis along which the piezoelectric stacks are placed and Z-axis is the axis perpendicular to X-axis along which the displacements get amplified. The analysis of FAPs along Z-direction were carried out by fixing the bottom end of the flexural amplifier and by applying a series of load ranging from 10N to 100N at the top end of the amplifier. Similarly, the analysis of FAPs along X-direction were carried out by fixing the left end of the amplifier and by applying a series of load ranging from 10N to 100N to the right end of the amplifier. Figure 3 and Figure 4 shows the displacement of FAP1 obtained along Z-direction and X-direction for a load of 100N.

From the above plots, it can be observed that the Z-direction displacement and X-direction displacement of FAP1 for a load of 100N was 1016µm and 48.8µm. The stiffness of FAPs along Z-direction was found for a series of load ranging from 10N to 100N as shown in Figure 5 and 6. Since Flexural Amplifiers are used to amplify the displacement of piezo stacks it is required to calculate the amplification factor which is the ratio of maximum Z-direction displacement versus maximum X-direction displacement for a given load.
From the above plots it is evident that for a load of 100N the Z-direction displacement for FAP1 was found to be 1020µm and 1449µm respectively and also the load vs displacement plots for FAP1 and FAP2 was found to be linear. Table 1 shows the X-direction and Z-direction stiffness and amplification factor values for FAP1 and FAP2.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>FAP1</th>
<th>FAP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness along Z-direction</td>
<td>0.098N/µm</td>
<td>0.069N/µm</td>
</tr>
<tr>
<td>Stiffness along X-direction</td>
<td>20.57N/µm</td>
<td>19.92N/µm</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>19.52</td>
<td>18.92</td>
</tr>
</tbody>
</table>

HYSTERESIS IDENTIFICATION AND MODELLING OF FLEXURALLY AMPLIFIED PIEZO ACTUATORS

The response of a piezo actuator to an applied input voltage becomes unpredictable due to hysteresis behaviour. Hence it is required to accurately model the voltage-displacement relationship of the FAPs including hysteresis behaviour to improve their positioning accuracy. Experiments have been conducted to measure the displacements of FAPs as shown in Figure 7.

![Figure 7. Experimental set up for displacement measurement of FAP](image)

A sinusoidal voltage signal of 0-7.5V is generated at 1Hz frequency through NI PXIe-6363 Data Acquisition System in LabVIEW. The voltage signal is amplified using LA75 Voltage Amplifier having a gain of 20 times the input voltage signal. The voltage supplied to FAP after amplification is 0-150 peak to peak amplitude. The displacement of FAP is measured using ILD 2220 Laser Displacement sensor. Figure 8 represents the Simulink block diagram of Bouc-Wen hysteresis model.
The parameters of the Bouc-Wen model namely Alpha, Beta, Gamma and d for both FAP1 and FAP2 were estimated by the simplex search method in Control and Estimation Tools Manager of MATLAB/Simulink. The parameters were estimated using known parameter values of FAP1 and FAP2 along with their experimental voltage displacement plots at 150V for 1Hz frequency. Table 2 shows the known parameter values of FAP1 and FAP2 along with Bouc-Wen parameter values.

**Table 2.** Known parameter values and Bouc-Wen parameter values for FAP1 and FAP2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>FAP1</th>
<th>FAP2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (m)</td>
<td>0.015</td>
<td>0.015</td>
<td>kg</td>
</tr>
<tr>
<td>Damping coefficient (b)</td>
<td>150</td>
<td>150</td>
<td>Ns/m</td>
</tr>
<tr>
<td>Stack Actuator Stiffness (K_s)</td>
<td>2.5e8</td>
<td>2e8</td>
<td>N/m</td>
</tr>
<tr>
<td>Flexural Amplifier Stiffness (K)</td>
<td>98000</td>
<td>69000</td>
<td>N/m</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>13.52</td>
<td>12.9166</td>
<td>-</td>
</tr>
<tr>
<td>alpha</td>
<td>0.222</td>
<td>0.290</td>
<td>-</td>
</tr>
<tr>
<td>d</td>
<td>1.4310e-7</td>
<td>1.45e-7</td>
<td>m/V</td>
</tr>
<tr>
<td>beta</td>
<td>0.0150</td>
<td>0.0261</td>
<td>l/V</td>
</tr>
<tr>
<td>gamma</td>
<td>0.0045</td>
<td>0.00462</td>
<td>l/V</td>
</tr>
</tbody>
</table>

**FORWARD BOUC-WEN HYSTERESIS MODEL SIMULATION AND VALIDATION**

Forward Bouc-Wen simulation has been carried out in Simulink to obtain simulated displacement for a sinusoidal peak to peak voltage signal of 0-150V at 1Hz frequency as shown in Figure 9.
Here stiffness of both the stack actuators and the flexures were considered as the stack actuator exerted force when the voltage was applied with the flexure resisting it. Both FAP1 and FAP2 consisted of 6 stack actuators, 3 on each side. Hence a gain of 3 was also coupled and multiplying further with the amplification factor resulted in obtaining the displacement of the FAPs along Z-direction.

**INVERSE BOUC-WEN MODEL SIMULATION AND VALIDATION**

Generally during micro milling applications, the work piece will be subjected to vibrations. Hence in order to nullify these vibrations it is required to first estimate the voltage which generates these vibrations so that FAPs could be actuated with the same voltage to nullify the generated vibrations. In the present work, an attempt has been made to estimate the voltage that generates the vibrations due to FAPs using Inverse Bouc-Wen model in Simulink as shown in Figure 10.

**Figure 9.** Forward Bouc-Wen hysteresis model

A desired displacement is given as an input to Inverse Bouc-Wen model which estimates the voltage to be supplied to FAP1 and FAP2 to produce this displacement. Inverse Bouc-Wen model validation is carried out by comparing the desired displacement with the experimental displacement corresponding to the voltage estimated and also simulated displacements. The model estimates the voltage corresponding to these desired displacements and the displacements corresponding to the voltages are obtained experimentally.

**TESTING OF THE PROPOSED ACTIVE VIBRATION ISOLATION SET UP**

The proposed set up has been tested to obtain the displacements of FAP1 and FAP2 at the isolation platform. Figure 11 shows the block diagram for testing the proposed set up.
A sinusoidal voltage signal of 0-7.5V is generated at 1Hz frequency through NI PXIe 6363 DAQ and is amplified using voltage amplifier 20 times the input voltage signal. Thus both FAP1 and FAP2 are actuated with input voltage of 0-150 V peak to peak amplitude. Initially a sinusoidal voltage signal of 0-150V peak to peak amplitude is supplied only to FAP1 through Voltage amplifier 1 which represents the disturbing or generated vibrations and its displacement is measured at the isolation platform using ILD 2220 Laser Displacement sensor. The displacement of FAP2 is also measured at the isolation platform for the same range of voltage supply of 0-150V peak to peak amplitude through Voltage Amplifier 2. Finally both FAP1 and FAP2 were actuated simultaneously and the results were plotted.

RESULTS AND DISCUSSIONS

Figure 12(a) and (b) shows the experimental displacement plots obtained by actuating FAP1 and FAP2 with peak to peak amplitude of 0-150V at 1Hz frequency.

From the above plots it can be observed that for 0-150V peak to peak amplitude the maximum displacement of FAP1 was found to be 810µm and 780µm for FAP2 respectively. It can be also observed that when the voltage plots reached to zero, the displacement plots have not reached zero because of the hysteresis behaviour exhibited by flexurally amplified piezo actuators. The hysteresis plots are obtained by plotting voltage displacement plots with voltage along x-axis and displacement along y-axis as shown in Figure 13a and b respectively.
From the above plots it can be observed that both FAP1 and FAP2 exhibited hysteresis of about 68µm and 30µm. However, for precise positioning and control of flexurally amplified piezo actuators it is required to compensate and model the hysteresis behaviour. The hysteresis behaviour of the FAPs have been described using Bouc-Wen hysteresis model. The experimental displacement plots have been simulated using Forward Bouc-Wen model. Forward Bouc-Wen model validation has been carried out by giving voltage as the input to the model to obtain displacement as the output. The experimental and simulated displacement plots using Forward Bouc-Wen hysteresis model for FAP1 and FAP2 are as shown in Figure 14 and 15.

From the above plots, it can be observed that Forward Bouc-Wen model resulted in an approximation of displacement of FAPs with hysteresis for a given input voltage applied to it. For a input voltage of 0-150V, the maximum simulated displacement for FAP1 was observed to be 800µm for 810µm experimental displacement and maximum simulated displacement for FAP2 was found to be 785µm for 790µm experimental displacement at 1Hz frequency. However, for estimating voltage corresponding to any reference displacement, Inverse Bouc-Wen model validation has been carried out by comparing the simulated displacement and experimental displacement corresponding to estimated voltage.

Figure 16 and 17 shows the plots of desired displacement, simulated displacement and experimental displacements corresponding to the voltage estimated using Inverse Bouc-Wen model.
From the above plots it can be observed that for a desired displacement signal of 810µm for FAP1 the voltage estimated has a peak amplitude of 150V with minimum negative voltage of -5V and for a desired displacement signal of 780µm for FAP2 the voltage estimated has a peak amplitude of 150V with a minimum negative voltage of -5V. The simulated and experimental displacements obtained for both FAP and FAP2 have been in very good agreement with each other. Further it is also observed that the hysteresis has been eliminated in displacement plots with voltage plot being negative.

The proposed flexurally amplified piezo actuator based active vibration isolation set up is tested to obtain source displacement (FAP1) and isolator displacement (FAP2) when actuated individually and also to obtain net displacement when both FAP1 and FAP2 are actuated simultaneously for 0-150V at 1Hz frequency and the graphs are plotted as shown in Figure 18.

Figure 18 shows the maximum displacement of FAP1, FAP2 and the net displacement measured at the isolation platform for 0-150V peak to peak amplitude at 1Hz frequency. It is observed that the maximum displacement of FAP1 was 810µm and the maximum displacement of FAP2 was 780µm respectively. It is also observed that when both FAP1 and FAP2 are actuated simultaneously the net displacement obtained at the isolation platform is minimum about 44µm thereby achieving minimum vibrations at the isolation platform.

CONCLUSIONS

In the present work, the design, analysis and development of flexurally amplified piezo actuator based active vibration isolation system has been carried out. The stiffness of the FAPs along X-direction and Z-direction and amplification factors of the FAPs were identified in ANSYS software. The maximum displacement of FAP1 and...
FAP2 were found experimentally for peak to peak amplitude voltage of 0-150V at 1Hz frequency. The simulation and validation of Forward Bouc-Wen model was carried out for flexurally amplified piezo actuators by comparing with experimental displacements to estimate displacement with hysteresis. It was found that the simulated displacements and experimental displacements agreed very well with each other with a maximum error of 1% for 0-150V voltage supply. Inverse Bouc-Wen simulation has been carried out to estimate the voltage required for a desired displacement and also to compensate hysteresis. For a reference or desired displacement, simulated displacement and experimental displacements obtained for voltage estimated using Inverse Bouc-Wen model were compared and found to be agreed very well with each other. Finally, experiments were conducted on the proposed set up by actuating FAP1 and FAP2 separately and simultaneously for 0-150V peak to peak amplitude at 1Hz frequency. From the experimental results it was observed that the displacement of FAP1 and FAP2 were 180º out of phase with each other when actuated simultaneously resulted in minimum vibrations of about 44µm at the isolation platform. Thereby it can be concluded that the proposed set up design resulted in achieving minimum vibrations at the isolation platform. From the results it can be observed that almost 95% of vibration isolation has been achieved at the isolation platform. The error in vibration isolation could be still minimized using closed loop control and also by considering hysteresis effect. The proposed set up has been designed for isolating the vibrations of the work piece mounted at the isolation platform using FAPs during micro milling applications.

REFERENCES


