

Introducing Micro-Positioning Experimental Setup in Mechanical Engineering Curriculum

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Introducing Micro-Positioning Experiments in Mechanical Engineering Curriculum

Abstract

The objective of this paper is to introduce an experimental setup to control vibration for educational purposes in undergraduate mechanical engineering program. The experimental set up presented in this paper is designed to allow the instructors to tailor and customize the experiments per the requirements of various mechanical courses. This vibration control is structured to study and control the vibration of a piezoelectric tube actuator, which is controlled by applying voltage difference across x and y axis. The piezoelectric tube was selected to be at the center of the experimental setup due to its importance in micro-positioning systems such as the Atomic Force Microscope (AFM). Due to the negative effect of high vibrations on the performance of AFM and other micro-positioning systems, vibration reduction of piezoelectric actuators is a very active research topic. Therefore, the introduction of piezoelectric actuators vibrations control experiment offers an excellent opportunity for students to learn more about the engineering problems and challenges associated with micro-positioning systems, which are not typically covered in classic mechanical engineering curriculum. The experimental setup introduced in this paper was used in a project in advanced dynamic systems and controls course. In this project, the students applied input shaping feedforward techniques to control the vibrations of piezoelectric tube when subjected to input step excitation. The success of the vibration reduction controllers was verified using the data acquired from two fiber optic displacement sensors. In addition, the experiment exposed the students to essential experimental principles such as calibration, data acquisition and sensor limitations.

Introduction

In this paper, we introduce a vibration control experimental setup for educational purposes. This experimental setup is designed to be useful in several mechanical engineering courses, as it provides the instructors with the ability to select the aspects that suit the needs of their courses. In general, the experimental setup allows the students to have a hands-on experience with a real-world problem while achieving a number of educational objectives.

This experimental setup can be used in a number of courses such as controls, vibrations and dynamics, introduction to mechanical measurements, and design of experiments. Depending on their courses' needs, the instructors will be able to select the aspects to focus on. Basic educational engineering elements and skills such as sensor noise, calibration, and programming are iterated upon in addition to advanced theoretical concepts, which are implemented according to the needs of the instructors. For example, the experimental setup was used to introduce and apply feedforward control scheme, in particular, input shaping. The setup also allows the students to expand their skills by working on system identification, modeling, designing and implementation of different controllers.

Piezoelectric materials are a popular class of solid smart materials that exhibit mechanical strain when subjected to electrical voltage. Conversely, when the piezoelectric materials are subjected to mechanical strain, electrical charges accumulate, inducing a voltage difference. By utilizing the phenomena of piezoelectricity, piezoelectric materials are commonly implemented in micro and nano actuators and sensors. Piezoelectric materials, in particular lead zirconate titanate ceramics, are used in applications that require control of displacement within a small range of motion with high precision and high resolution. Therefore, the piezoelectric materials are commonly used in micro-positioning systems such as in Atomic Force Microscope (AFM) [1]. They are used in numerous fields such as biomedical, automotive, aerospace and optical engineering [2]. Piezoelectric materials are used as flexible structures to replace the bulky classic mechanical, thus occupying less space in the micro-positioning systems. In addition, the piezoelectric actuators are efficient in terms of energy consumption.

Despite the several advantages of piezoelectric actuators, there are a number of limitations that must be taken into account and are an active topic for researchers and developers. In addition to nonlinearities that affect the precision of the micro-positioning output such as creep and hysteresis, the high vibrations reduce the precision and quality of actuation. Working with multi-axis actuation, as in this experimental setup, adds to the complexity of the control requirements. Therefore, this experimental setup presents an excellent opportunity for the students to be exposed to a fundamental research problem that engineers and developers encounter.

In the following sections, we will present a description of the experimental setup used to control the vibrations in a multi-axis piezoelectric tube. We will also discuss our experience with using the setup for one course, and suggest a few approaches to utilize the setup in a number of courses in undergraduate mechanical engineering.

Description of the experimental setup

The piezoelectric tube actuator is the main component in the experimental setup. Therefore, the setup was designed to conform to the specifications and operating requirements of this piezoelectric tube. The piezoelectric tube is actuated on the x or/ and the y axis by applying a voltage difference across the electrodes. When subjected to voltage difference, the accumulated stress causes the piezoelectric tube to bend. Fixing one end makes the tube act as a cantilever beam, as shown in Figure 1. The piezoelectric actuator model used was the commercially available *TB6309 80um* from PiezoDrive.

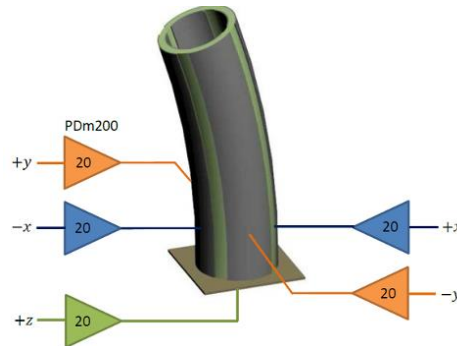


Figure 1. Piezoelectric tube electrodes and axes.

The piezoelectric tube is mounted on a static stage bolted to an aluminum frame. Figure 2 shows the CAD drawing and the actual model of the experimental setup, featuring the piezoelectric tube actuator, the linear stages, the heating elements and the fiber optic displacement sensors. Two fiber optic displacement *D20-Philtech* sensors are used to measure the displacement of the tip along the x and y axes of the piezoelectric tube. Since the fiber optic sensor can accurately read the position only off flat surfaces, a guide cube was placed on the top of the tube. The natural frequency of the piezoelectric tube can be changed by adjusting the mass of the guide cube. This is achieved by adding screws to pre-made holes in the guide cube. In addition to the natural frequency, the temperature can be controlled via a nichrome alloy heating element, which is mounted around the piezoelectric tube. An IR temperature sensor is mounted on the aluminum frame and directed to read the temperature of the piezoelectric tube.

Figure 3 shows all the components used in the experiment. The piezoelectric tube's electrodes are connected to the PDm 200 PiezoDrive power amplifiers. The amplifiers require a steady voltage of ± 16 V which is supplied by the NI virtual bench's programmable power supply. The input signal for actuating the piezoelectric tube through the PDm 200 amplifiers are provided by the Quanser DAQ board's analog output channels. The position measurement from the fiber-optic sensors fixed to the linear stage is processed by the fiber-optic signal conditioners. The conditioned signals are then relayed to the computer through the analog input channels of the Quanser DAQ board. The heating element constructed around the piezoelectric tube is connected to the UPM power amplifier. The power to the heating element is modulated using the analog output channel from the Quanser DAQ Board. The readings from the IR temperature sensor are acquired via an Arduino UNO board. Both the Arduino UNO and the Quanser DAQ boards are connected to the computer via USB cables (Not shown in the figure).

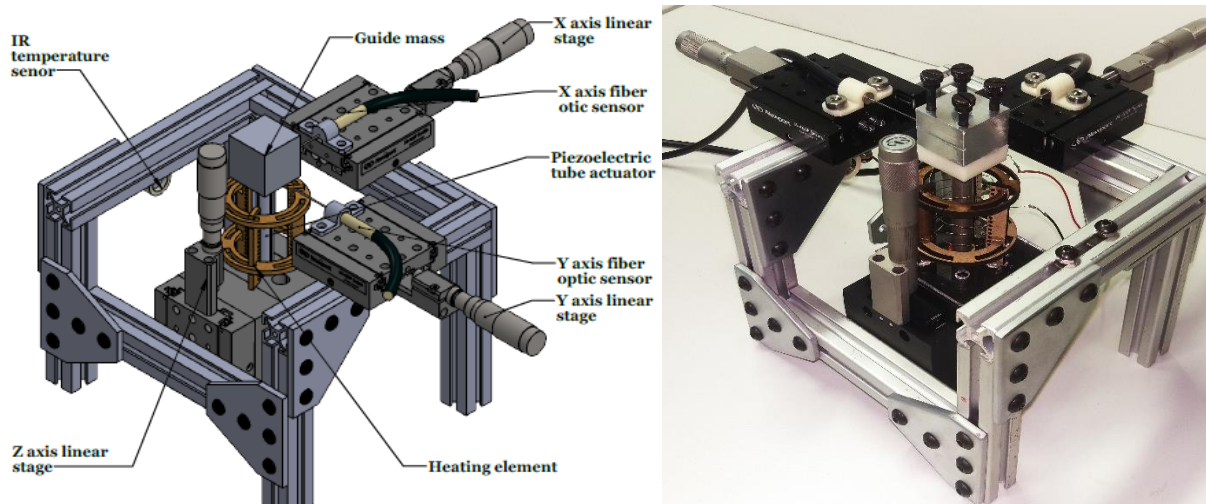


Figure 2. Piezoelectric vibrations experimental setup, featuring the piezoelectric tube actuator, the linear stages, the heating elements and fiber optic sensors. On the left, the CAD drawing, on the right, the actual model with four bolts to add mass to the guide.

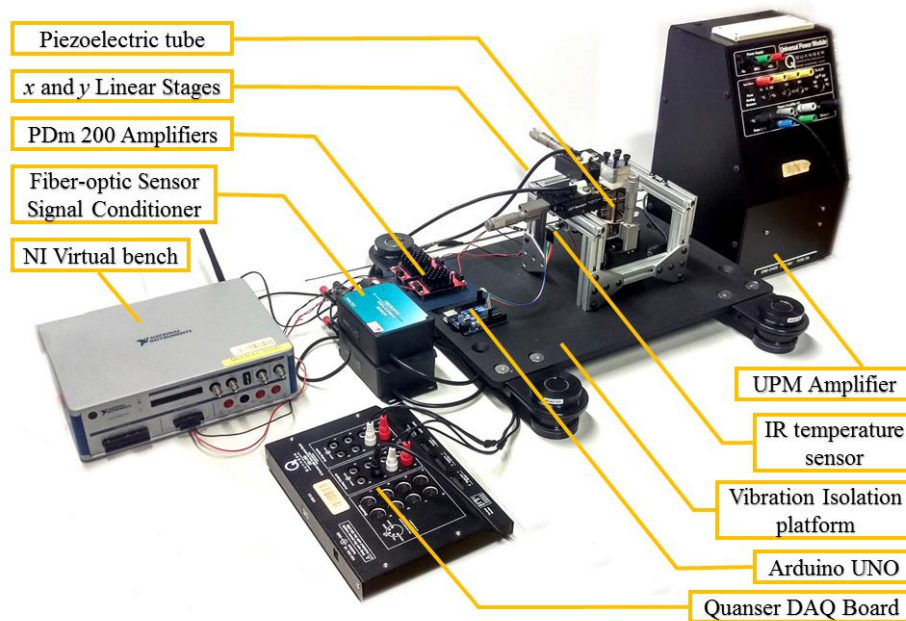


Figure 3. All the components used in the experimental setup are shown.

The complete schematic of the process is shown below in Figure 4. The temperature of the piezoelectric tube was controlled by using the heating element and the IR temperature sensor. The piezoelectric tube's actuation and vibration measurement was done through the Quanser DAQ board.

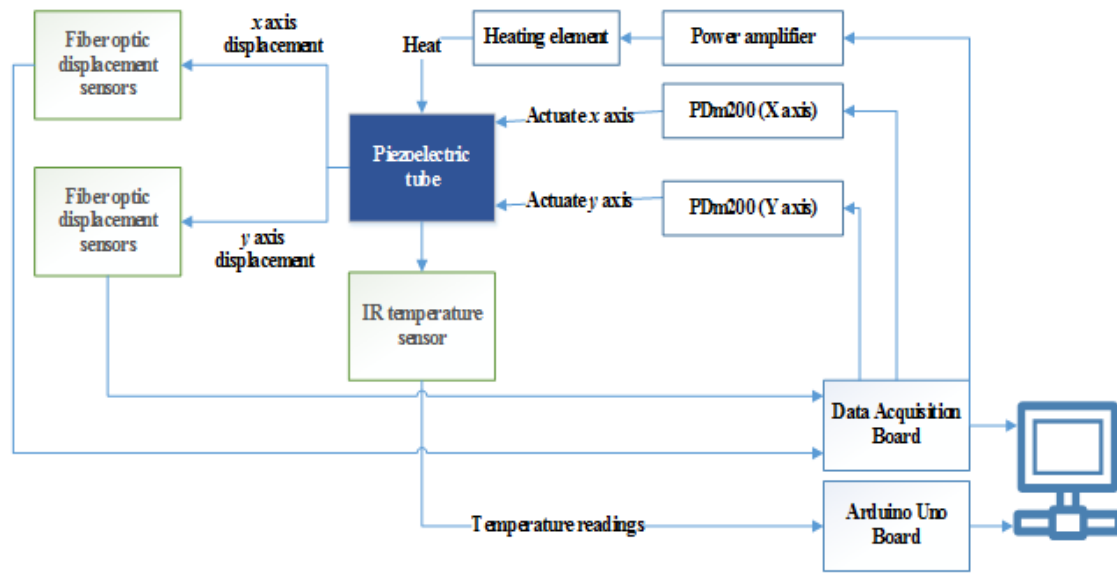


Figure 4. Schematic of the experimental set up working flow

In order to verify the functionality of the setup. The piezoelectric tube was excited using step input. The residual vibrations from the step input were compared with the residual vibrations of a step input after applying an input shape controller, as shown in Figure 5. The input shaping controller was tested on the setup before assigni to students and was successful in reducing the magnitude of vibrations immensely. Later, the students in the *advanced system dynamics and controls* course were successful in obtaining similar results with their own designed input shaping controllers, as explained in the Discussion section.

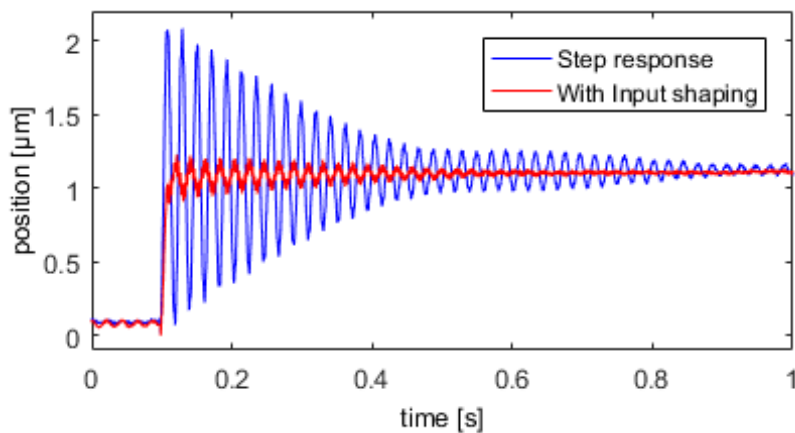


Figure 5. Residual vibrations of the piezoelectric tube with a step input with and without input shaping controller

Discussion

Since the experimental setup was designed to be modular, changes can be made easily. Additionally, the setup was designed to have a light weight and to fit in limited space. Furthermore, the setup is inherently safe and just requires basic electronics safety guidelines for operation.

In the following, we describe our experience in using the setup to fulfill learning objectives of the *advanced system dynamics and controls* course. Furthermore, we suggest a few approaches to use this setup in other courses.

Advanced system dynamics and controls

The experimental setup described in this paper was used for a project in the *advanced system dynamics and controls* course. The course aims at introducing the students to some advanced control techniques while emphasizing on mechanical modelling techniques. The experiment was used to fulfill the course requirements by challenging the students to work on an input shaping feedforward problem. Input shaping is a feedforward control technique that does not need any sensor and only relies on the system characteristics to suppress vibrations. However, the sensors in this context are being used to verify and validate the implemented controller. Since the scope of the course was to only cover Single Input Single Output (SISO) systems, the experiment was performed using only one axis. The heating element described in the previous section was not also not used.

At the first phase of the project, the students learnt about the introductory concepts and mathematical formulation of input shaping control, sensitivity and piezoelectricity, as well as the necessary mathematical formulations for their future work. Later, the students experimentally determined the mathematical modeling of the piezoelectric actuator, and identified the vibration system characteristics, such as the natural frequency and damping ratio. The characterization and modelling process was done via Matlab's system identification toolbox.

Based on the theoretical knowledge presented in the classroom, the students designed a number of input shaping controllers, such as ZV Shaper, ZVD Shaper and ZVDD Shaper [5]. This phase also required the correct vibration characterization of the system from the earlier stages, and the simulation of the system's vibrational behavior. Afterwards, the students tested their controllers against a number of vibrations induced by step inputs. Furthermore, the controllers were tested for robustness by examining the vibration reduction under changes in the mass of the vibrating beam, which subsequently changed the parameters characterizing the system. Across the different student teams, the results were satisfactory and confirmed the robustness of their controllers.

The project was successful as the students, divided into groups of four, had the opportunity to work on a real-world vibration control problem. The project's educational process reinforced the students' theory-based knowledge with skills acquired from experimental work, such as programming and data analysis. By the end of the course, the students were successful in delivering the planned objectives of this advanced level experiment. In addition, the controllers were implemented using Matlab and Simulink, which helped the students hone their programming skills.

The experiment can be fine-tuned to address the needs of other courses in the classic mechanical and industrial curricula. Working with this experiment affords the students to work with a wide range of aspects and issues, which allow the instructors to select and tailor and customize the experiment according to the desired level of the difficulty and allotted time. Here, we propose a few courses in which this experimental setup can be useful.

1- Introduction to mechanical measurements

The *introduction to mechanical measurements* is a course typically offered to mechanical engineering students in their second year. The course introduces basic concepts essential for experimental work such as sensor calibration, the concept of natural and damped frequencies and data acquisition principles.

One suggested approach is to use the piezoelectric tube as a cantilever beam and use step input to acquire information about the vibrational characteristics of system. In addition, the students can expand the experiment by using different added masses in order to understand the effect of mass on the various vibrational parameters of the systems.

2- Dynamics and Vibrations/ Introduction to Control Systems

The *dynamics and vibrations* course is offered during the third year of a mechanical engineering degree. The course focuses on the modelling of mechanical systems, characteristics and deriving the constitutive equations. The experiment is a hands-on experience for the students to model the tube as a cantilever beam, derive the constitutive equations via data acquisition and programming. In the next course, *dynamic systems and controls*, the basic feedback controllers can be applied to control the vibrations.

3- Design of Experiment

The modularity of the design of the setup provides an opportunity for the students to modify and enhance the setup for their use in the *design of experiment* course. Different set of sensors or actuators can be embedded into the setup to afford the investigation of different parameters. For example, the setup can be modified to investigate feedback control techniques. The students can investigate the effect of different step input excitations or different temperatures on the characteristics of the model. The results can be compared used statistical analysis methods for validation.

Conclusion

As the world hurls towards manufacturing in the nano-scale, the demand for studying and understanding tools such as piezoelectric tube actuators and sensors have increased. Exposure to the piezoelectric experimental setup detailed in this paper will aid students in pursuing further studies in this exciting field. The experimental setup presented in this paper is also meant to be modular and customizable such that it can meet the requirements of other courses that involve study of vibration, material properties, and control schemes. It was successfully deployed as a project for the *advanced system dynamics and controls*. In the future, it will be utilized for other courses as described above.

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