INTRODUCTION

Precision engineering and metrology play a vital role in modern manufacturing, from nanotechnology to aerospace applications. Since mechanical engineers are major players in manufacturing, it is very important to introduce them to basic principles involved in precision engineering and metrology. Not only must the theory be presented, but it is crucially important that students gain hands-on experience in the laboratory in order to truly understand the fundamental concepts.

We are in the process of developing a system for instructional purposes (shown in Figure 1 below) that is capable of demonstrating some basic principles and measurement techniques involved in precision engineering and metrology.

The system consists of a monolithic single degree of freedom flexure stage that is mounted on top of a linear air bearing stage. The compound stage system serves as a combined example of the use of bearing elements that are often employed in precision engineering applications.

The system is instrumented with several kinds of displacement measurement devices, vibration, and temperature sensors.

Targets for a laser triangulation sensor and a capacitance gage are mounted on the flexure stage. Laser triangulation and capacitance probes are mounted on one side of the target. A retro-reflector for a laser interferometer is mounted on the other side of the target. The laser triangulation and capacitance sensors serve as examples of distance measuring sensors using laser triangulation and capacitance principles. The interferometer serves as an example of distance measuring technology using interferometric principles. The configuration of the triangulation sensor, capacitance sensor and the laser interferometer is used to demonstrate Abbe’s principle and what will result when there is an offset distance between the axis of measurement and the axis of translation of the stage. There are also two accelerometers, one on the flexure stage and the other on the air bearing stage. These measure relative vibration between the flexure stage and the air bearing stage. Several thermocouples are attached in different locations on the system to measure temperature. This data is used in turn to show how temperature variation affects precision measurements. The entire system is automated using a program written in LabVIEW. The system as a whole can be used to demonstrate the steps involved in the calibration of the sensor technologies. Also the system can be used for the demonstration of angular errors in a staging system.

FIGURE 1. Precision engineering and metrology demonstration system. The system consists of a compound single degree of freedom flexure and linear air bearing stage. Metrology elements include a laser triangulation sensor, capacitive displacement gauge, distance measuring laser interferometer, laser vibrometer, and thermocouples for measuring ambient and system temperatures.
SYSTEM DETAILS

Stages & Motion Control

**Flexure Stage**
We adapted the classic single degree-of-freedom micro-positioning stage described by Scire and Teague for the flexure [1]. This was done in part for historical reasons and in part for its use of levers for magnifying the input motion provided by a piezoelectric actuator. In our experience, most mechanical engineering students have little to no exposure to flexures prior to taking our graduate level Precision Machine Design course. The use of an oft-quoted and well documented design affords students an opportunity to interact with a practical example of a monolithic flexure using circular notch hinges that they encounter in their textbook and readings for the course.

As shown in Figure 2, the flexure stage consists of circular notch hinges with an average radius of 3.36 mm and notch thickness of .64 mm and a single lever arrangement to amplify actuator input. Originally we tried to construct the cascading two-lever design described by Scire and Teague, which had an amplification factor of 28, but limitations in the output force of our piezo actuator and errors in fabrication resulted in our using only a single lever arrangement. The two lever arms measure approximately 60.0 mm and 8.3 mm, which provides an amplification of the piezo displacement of approximately 7.2:1.

The actuator is a Burleigh model PZS-050. The piezoelectric element is specified to give an output of 50µm for an input of 150 VDC. We were limited to a variable DC voltage supply that was capable of supplying 0-50V, so the effective maximum travel of the tip of the actuator was approximately 17 µm unblocked.

**Air bearing Stage**
The flexure is mounted on top of an Aerotech ABL 1000 linear air bearing stage, which provides both coarse and fine positioning for the entire system. Instead of the regular house air supply we used dry nitrogen at 80 psi. The encoders with the ABL 1000 allow the stage to be positioned to a resolution of 10 nm. The stages are driven using linear brushless servo motors and are controlled by Aerotech’s BAI controller. The BAI controller is controlled by the system computer through LabVIEW drivers and a LabVIEW virtual instrument that we wrote.

**Sensors for position measurement**

**Laser Triangulation sensor**
The system uses a Keyence LB70 laser triangulation sensor, which has a measurement resolution of 10 microns. The measurement range for this sensor is +/- 40 mm. The manufacturer’s specified linearity is 1.6% of FS (80 mm)

**Capacitance sensor**
The system uses an ADE 3500 capacitance displacement gauge to measure the displacement of the retroreflector as the flexure is actuated. Using a 12-bit data acquisition unit, we found the resolution of the capacitance gauge to be approximately 0.1 micron. The total range of the capacitance gage is about 250 micron. The capacitance gauge is mounted on the air bearing stage, and its target is mounted on the back of the laser retroreflector, which is mounted on the flexure.

**Laser Interferometer**
The system uses an HP 5519 laser head and HP 10702A linear interferometer as the reference scale for the entire system. The retroreflector is mounted on the center line of both the air-bearing and flexure stages. The air temperature, pressure and relative humidity are monitored by an HP 10751A air sensor, which the HP software uses for environmental correction.
Environment Conditions
We are in the process of incorporating some monitoring of environmental conditions into the system. The effects of temperature gradients and external vibration are always of practical concern, and we would like the students to experience their effects.

Thermocouple
We used thermocouples to monitor the ambient temperature and the temperature of the stage system. We did not make use of this data in this phase of development.

Non-contact Vibrometer
We intended to also use a Polytech PDV-100 portable laser vibrometer to monitor vibration of the granite base, but we were not able to integrate this measurement into the system in the first phase of development.

SYSTEM INTEGRATION
Mechanical Hardware
The laser triangulation sensor and capacitance gauge are mounted on adjustable brackets. The capacitance gauge was purposely offset by 22 mm in the y direction (see Figure 1) from the centerline of travel of the flexure, so the effect of Abbe offset could be vividly demonstrated [2]. Figure 3 shows the difference in x-displacement measurement by the interferometer and the capacitance gage.

Electrical Hardware & System Software
The air bearing stage was controlled using the Aerotech’s BAI controller. The position commands were given by the program written in LabVIEW. A National Instruments USB 6008 data acquisition device was used for collecting data from the laser triangulation sensor and the capacitance gage. A LabVIEW program was written to collect this data automatically from the gages. The final goal is to integrate the motion and position feedback systems (triangulation sensor, cap gage and interferometer) using a single program to control and acquire the data automatically.

SYSTEM TESTING
It is important for students to understand that any measurement system that has been built needs to be tested for functionality and performance. Functionality tests include verifying that system components work as expected. Some examples include the working of the electrical hardware, the fit and function of the mechanical hardware, the correct configuration of software drivers and versions, etc. Our demonstration system was tested at the individual component level, which included the stages, sensors, and data acquisition hardware to make sure each component was operational.

The main performance tests for many precision systems include tests for resolution, repeatability, accuracy, linear positioning errors, angular errors, linearity, range, etc. Due to time constraints, we chose to measure just a few combined characteristics of the stages and sensors.

The first test involved moving the air bearing stage at intervals of 5 mm over a distance of 50 mm. At every 5 mm location, the interferometer and the Keyence sensors measurements were recorded. The data from the air-bearing stage encoders were compared with the interferometer and the Keyence sensor. This experiment helps us answer two important questions:

1. Are the stage errors within the specification provided by the manufacturer? (The interferometer is assumed as the reference.)
2. Does the linearity of the Keyence sensor meet the manufacturer’s specification? If not, why not? (Some reasons might include the type of the target, its location, the alignment of the sensor, etc.) Might there be other issues related to the operational characteristics of the sensor?

In our case, relating to the first question, the results in Figure 4 show that the stage errors are within the manufacturer provided specification of 0.6 micron (+/- 0.3 micron). However, the manufacturer’s testing condition is unknown (location of the interferometer optics etc.)

Relating to the second question, our results showed that there is a very large error (>10%) in the measurements of the laser triangulation sensor. Other studies have shown that such errors can be due to the alignment, type of target, interaction of the sensor with the target, calibration, etc. [3] The source of the errors we found needs further investigation.

The second test involved moving the flexure stage at intervals of 5 microns over a distance of 50 microns. At every 5 micron location the interferometer and the capacitance readings were noted. The data from the interferometer was compared with the capacitance sensor data. This experiment helps us answer two important questions:
1. Are the capacitance gauge errors within the specification provided by the manufacturer? (The interferometer is assumed as the reference.)
2. What is the effect of the capacitance gauge being offset in the y direction by 22 mm from the measurement axis of the interferometer based on the Abbe principle?

The typical linearity for capacitance gauges like the one we used is about 0.25% of the range of measurement. However, the data shows that these errors are of much high order, and hence the variation is due to the position of the capacitance gauge with respect to the measurement axis of the interferometer.

![Error due to Abbe Offset](image)

**FIGURE 3.** Difference in x-displacement measurement of the retroreflector as measured by the interferometer and capacitance gage. The capacitance gage axis was offset by 22 mm from the centerline of travel of the retroreflector to demonstrate the effect of Abbe offset.

**CONCLUSIONS**

We have created a system that can be used to demonstrate precision engineering concepts and sensor technologies and give mechanical engineering students hands-on experience with them. Specifically the system demonstrates:
- precision bearing technologies: air bearings and flexures
- the effect of Abbe offset in displacement measurement
- several displacement measurement techniques: laser interferometry, capacitive sensing, and laser triangulation

The system also allows us to demonstrate:
- concepts of range, resolution, and accuracy
- concepts of calibration
- practical aspects of data acquisition

**FUTURE WORK**

Future work involves making the whole system fully automated and making the fixtures so that the measurement setup can be assembled and disassembled in a very short period of time.

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**REFERENCES**