AC 2007-2861: PRECISION POSITIONING AND VIBRATION MEASUREMENT USING INTELLIGENT INSTRUMENTATION AND SIMULATION TOOLS

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PRECISION POSITIONING AND VIBRATION MEASUREMENT USING INTELLIGENT INSTRUMENTATION AND SIMULATION TOOLS

Abstract:

The objective of this research is to detail the development of a simple and unique instrumentation for precise micro-measurement as well as vibration measurement in an integrated manufacturing set up that can be demonstrated in a student laboratory. Based on this we propose new research for a smaller embedded measurement unit. All machines have some amount of forced vibration. However, in some cases, this vibration may cause damage to the machinery. Understanding vibration in aerospace applications is critical for any system that will be exposed to vibrating motion. Previously, strain gauges and piezoelectric accelerometers have been adequate for measuring vibration. However due to the increased requirements in performance, these methods are slowly being replaced by laser-based precision instruments. One of the main reasons for this transition is the fact that the equipment in these methods must be mounted on the surface of the object being measured which can result in increasing the mass and altering the frequency, mode shape of the vibrating object. Laser technology is a non-contact measuring method and provides the resolution needed to satisfy the changing requirements.

In order to demonstrate precise positioning and motion control for creating and detecting vibrational movements, an experimental test bed was constructed. Software based simulation tools were used to control the positioning system. For vibration monitoring, the vibrating surface was discretely sampled by individual laser pulses and recorded by the position sensitive detector by the generation of pulses whose magnitudes are proportional to the instantaneous surface displacements. With a sufficiently high sampling rate, reconstruction of the vibration wave form is achieved by conducting peak detection of the resultant series of pulses. Vibration sensing by position sensing detector and vibration sensing by interferometry were the two techniques that were experimented with the new micro-positioning system. Three methods of micro-positioning and measurement were experimented; a precision encoder, an optical interferometer and an integrated vision system. Data was collected at successive points along the translation stages. The results showed that the optical interferometer and the encoder produced the most accurate results. It was also observed that significantly higher peak optical power levels of the probe laser pulses lead to proportional enhancement in the position sensitive detector response and remarkable improvement in detection sensitivity. This paper also outlines the results of the new approach in micro-positioning, displacement creation and vibration sampling in high precision machine tools. Additional results with the prediction of break-through detection in laser drilling manufacturing process has also been documented.

Introduction

Positioning systems are widely used in many industrial applications such as actuators, CNC machines, automated testing, calibration, inspection as well as processes such as laser welding and cutting. Micro-positioning refers to mechanical movement where the positioning accuracy is in the micron or sub-micron range. Nano-positioning refers to positioning accuracy in the nanometer or sub-nanometer range[6].

Design rules normally used for millimeter or sub-millimeter accuracy do not always apply in the micro- and nano-ranges. Performance in these realms cannot be achieved by simply reducing the pitch of a lead screw or increasing the gear ratio of a motor/gear head unit. Further, friction, play, backlash, tilt, windup and, temperature effects play an increasing role in limiting accuracy and resolution. To be successful, a great deal of attention must be paid in design, manufacturing and material selection[4].

There are generally two situations in which vibration measurements are taken. One is in a surveillance mode to check the performance of the machinery on a routine basis. The second situation is during an analysis process where the ultimate goal is to fix a problem. In either situation, there are several types of instruments available to take measurements, and acquire data. Vibration measurements plays vital role in solving vibration problems. Vibration research supports a variety of industries and essential governmental functions, often leading to standards and to testing and measurement methods that improve industrial and scientific capabilities. Vibration measurements underpin a broad spectrum of activities, including noise control and abatement, health and safety programs, product development, acceptance testing, condition monitoring, and object detection.

Vibration monitoring is of extreme importance in several areas such as power generation, automotive applications, aerospace applications. Examples in power generation include turbo-machinery compression systems vibration, parts monitoring, nuclear reactors vibrations, industrial testing of motors. Examples in automotive vibrations include engines, pumps, gearboxes, chassis windshields. Examples in aerospace applications include aircraft wings and engines vibration, helicopters, large space structures, rocket engines.

Design Methodology for Precise Positioning

- Software System Tools
- Positioning and Motion Control

Software System Tools

VisSim is a Windows-based program for the modeling and simulation of complex nonlinear dynamic systems. VisSim combines an intuitive drag & drop block diagram interface with a powerful simulation engine. The visual block diagram interface offers a simple method for constructing, modifying and maintaining system models. The simulation engine provides fast and accurate solutions for linear, nonlinear, continuous time, discrete time, time varying and hybrid system designs[7]. With VisSim/Real-Time, users can connect a VisSim model directly to the outside world via digital and analog input/output blocks. VisSim/Real-Time supports analog and digital input/output boards from National Instruments. No code generation or programming is required to configure and use VisSim/Real-Time. Applications can perform real-time simulation, data acquisition and control directly from Windows 9x/NT/2000/XP. There is no difference between running a regular VisSim simulation and a real-time HIL system.

MATLAB is a popular tool for use in data analysis, visualization, image processing, algorithm prototyping, modeling and simulation and is widely used in scientific and engineering circles. It consists of a highly integrated set of tools for mathematical computing, data visualization and extensible programming interfaces. It can be used in the command line mode or a customized user interface can be developed. Key MATLAB features are:

- Discipline specific toolboxes
- Tools for custom user interface development
- External interfaces for C/C++, Java, Fortran and LabVIEW
- Compiler for speed and ease of program dissemination

SIMULINK is a software application used for modeling, simulation and analysis of dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sample time or a hybrid of the two. Systems can also be multi-rate, i.e., contain different rates for various sampling or updating functions. It contains a user interface to build block diagram models via simple drag and drop mouse operations.

SIMULINK includes a comprehensive library of sinks, sources, linear and nonlinear components and connectors. Users can design a customized system then simulate it. The results can be imported into the MATLAB workspace for further processing and visualization.

LabVIEW is a feature-rich application that relies primarily on a user interface to construct a model. It uses a diagrammatic approach versus text-based coding to simplify development and troubleshooting. LabVIEW programs use “virtual instruments” or VIs that are displayed as screen icons. Each VI consists of a front panel view and a block diagram view. The front panel view shows the user interface (e.g. knobs, sliders, switches, graphical displays). The block diagram view shows how specific inputs, outputs, internal components (or sub-VIs) are connected including the “wires” that pass data between them[3].

Positioning and Motion Control

Motion controllers are used to direct the actuation process by issuing commands to motors based on measured feedback of actual position[1]. Various forms of intelligent processing are also incorporated to maximize the real-time performance of the system. Today, motion controllers are mostly based on digital devices that calculate trajectories and then compare them to actual motor or actuator positions[5]. Motion control systems consist of three main elements (Figure 1)

- Motion controller
- Motion driver (motor or amplifier)
- Motion device (encoder)

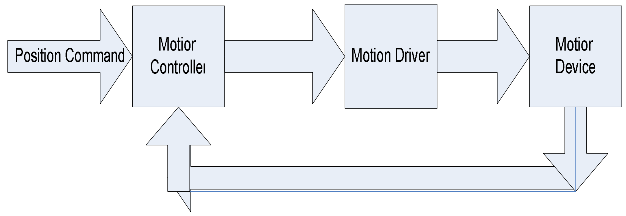


Figure 1 - Motion Control System

The motion controller is used to control motion devices such as stages or actuators. The motion controller acts as the brains of the system by computing desired positions, motion profiles and time trajectories for the motors. It is common to use some type of application software to perform these functions. Amplifiers (i.e. motion drivers) receive commands from the controller and generate the electrical signal(s) to drive the motors. Motors provide the necessary torque to the mechanical system, e.g. linear slides, robotic arms or some other actuator design. Motor selection and mechanical design is a critical part of a motion control system, and most manufacturers provide a wealth of data and assistance in this process.

The motion sensor is a device that captures actual movement and closes the feedback loop to the motion controller. A motion sensor is not always required for such as with stepper motors, but is essential for servo motor control. For this project, a widely used motion sensor called a quadrature encoder was used. It senses the shaft position of the motor and feeds the result to the motion controller. Other feedback devices include potentiometers for analog position, tachometers for velocity feedback, absolute encoders for absolute position measurement. Input/output devices important in motion control include limit switches, home switches, position triggers, and position capture inputs. Limit switches provide information about the end of travel to avoid damage to the mechanical system. When a motion system hits a limit switch, it typically stops moving. Home switches indicate the home position for use as a reference point for use in such applications as pick-and-place systems where a series of measurements are required at prescribed positions.

Quadrature encoders are used in this application as the motion device sensor. A quadrature encoder is connected directly to the shaft of the motor and has two outputs, commonly called Channel A and Channel B. Channel B output is shifted by 90 degrees from channel A which enables direction of rotation information to be obtained. The ability to detect direction is critical if encoder rotation stops near a pulse edge. The quadrature scheme can effectively “multiply” the number of counts or pulses during each revolution of the shaft. In the times-one mode, counts are generated only on the rising edges of Channel A. In the times-two mode, both the rising and falling edges of Channel A generate counts increasing the resolution by a factor of two. In the times-four mode, the rising and falling edges of Channel A and Channel B generate counts increasing resolution by a factor of four.

An encoder is a device that converts linear or rotary displacement into digital or pulse signals. The most popular type of encoder is the optical encoder, which consists of a rotating disk, a light source, and a photo detector (light sensor). The disk, which is mounted on the rotating shaft, has patterns of opaque and transparent sectors coded into the disk (). As the disk rotates, these patterns interrupt the light emitted onto the photo detector, generating a digital or pulse signal output.

The most common type of incremental encoder uses two output channels (A and B) to sense position. Using two code tracks with sectors positioned 90° out of phase (Figure 2), the two output channels of the quadrature encoder indicate both position and direction of rotation. If A leads B, for example, the disk is rotating in a clockwise direction. If B leads A, then the disk is rotating in a counter-clockwise direction. Therefore, by monitoring both the number of pulses and the relative phase of signals A and B, you can track both the position and direction of rotation.

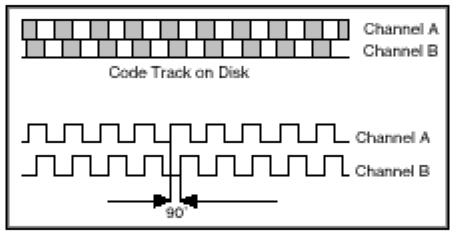


Figure 2 Quadrature Encoder Output Channels A and B

In addition, some quadrature detectors include a third output channel—called a zero or reference signal—which supplies a single pulse per revolution. This single pulse can be used for precise determination of a reference position.

Positioning Using Encoder and Software Tools

Encoder
The first method of position control was based on a quadrature encoder. A linear motion experiment was set up using an 80 turns per inch lead screw with a gear head ratio of 16:1. The encoder generated 40 counts per revolution. *Table 1* show the resolution per count and maximum travel rate for the experimental setup.

Gearhead Ratio	**Resolution**		**Maximum Travel Rate**	
	µinch/count	µm/count	inch/sec	mm/sec
16:1	19.53	0.496	0.26	6.60

Table 1 – Encoder resolution calculation

VisSIM was used to control the motorized stage and a LabVIEW VI was developed to count the encoder output pulses. Four different linear positions were run, and the pulse count from the quadrature encoder was captured and converted to displacement.

Positioning using Interferometry and Software Tools

Interferometer

An interferometer is a device that uses interference between two beams of collimated light to obtain measurements. In theory, measurements based on this method could be made with great precision since optical wavelength can be sub-micron. For this experiment, one of the mirrors constituting one of two arms of the interferometer was attached to the motorized stage. As the mirror was moved, changes in the interference pattern were measured and counted. Figure 3 shows the fringe pattern that was developed. Each fringe corresponded to a motion of one-half of one wavelength.

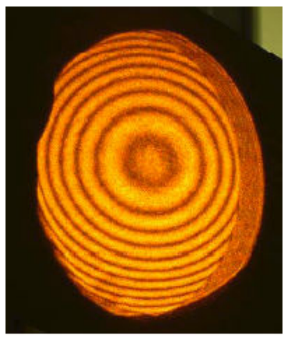


Figure 3 – Interferometer fringe pattern

A phototransistor was located in the center of the fringe pattern and converted the optical signal to an electrical one. As the stage was moved, the optical signal went from light-to-dark then dark-to-light. The movement of one fringe pattern corresponded to a distance of $\lambda/2$ or 0.316µm. The phototransistor signal was fed to a LabView for counting and display.

Positioning using Vision System

A vision system can be classified in a broad sense as a non-contact optical sensor system that obtains geometric information about a part such as position, orientation, size, shape, or surface contour. Vision systems are often used for mapping the shape of a tool. In this experiment, it was used to measure stage translation.

The machine vision process was divided into four steps: image formation, image preprocessing, image analysis, and image interpretation. IMAQ Vision Builder is a tool for prototyping and testing image processing applications. IMAQ Vision Builder uses the IMAQ Vision Library and is a standalone executable that can be used independent of other programs.
The first step was to set up the camera over the translation stage. Using the pixel diameter from the certificate of accuracy and the dot diameter of the target grid, a conversion factor is computed and applied to a LabVIEW so the stage translation measurement is displayed.

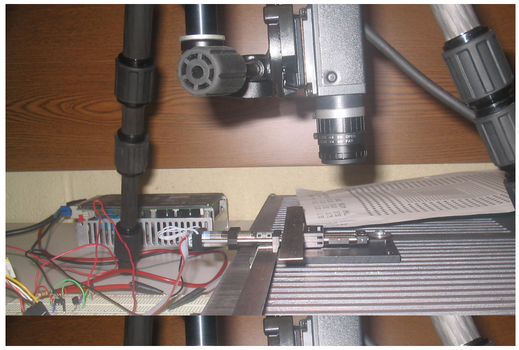
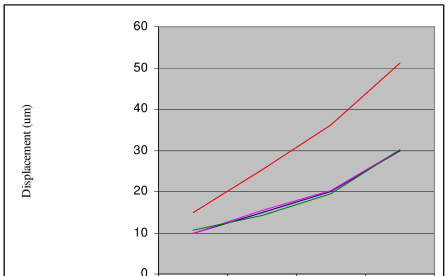


Figure 4 Setup of the camera and its connection with the computer

Measurement data was acquired for each of the three methods: quadrature encoder, interferometer and vision system. For baseline purposes, micrometer measurements were recorded. Data was collected at four successive points along the translation stage. The results are shown in Figure 4 for all three methods as well as for the micrometer. Two methods produced excellent agreement with the micrometer baseline. The root mean square (rms) error for the interferometer was 0.278µm while the encoder produced an rms error of 0.572µm. The vision system performed the least favorably with an rms error of 14.5µm.



	1	2	3	4
Micrometer	10	15	20	30
Encoder	10	15.37	20.33	30.25
Interferometer	10.75	14.23	19.61	30.05
Vision System	15	25.25	36.22	51.2

Translation Point

Figure 4– Stage translation results

Interferometry for Measuring Vibrations in Machine Tools

Vibration monitoring in precision machine tools is extremely important if the machine tools are used for the creation of miniaturized components. Monitoring of vibration in turning and milling machines is possible with non contact laser vibration sensors. The milling operation is a cutting process using a rotating cutter with one or more teeth. An important feature is that the action of each cutting edge is intermittent and cuts less than half of the cutter revolution, producing varying but periodic chip thickness and an impact when the edge touches the workpiece. The tooth is heated and stressed during the cutting part of the cycle, followed by a period when it is unstressed and allowed to cool. The consequences are thermal and mechanical fatigue of the material and vibrations, which are of two kinds: forced vibrations, caused by the periodic cutting forces acting in the machine structure and chatter vibrations, which may be explained by two distinct mechanisms, called "mode coupling" and "regeneration waviness", explained in Tobias[8] Koenigsberger & Tlusty[9] and Budak & Altintas[10]. The mode coupling chatter occurs when forced vibrations are present in two directions in the plane of cut.

The regenerative chatter is a self excitation mechanism associated with the phase shift between vibrations waves left on both sides of the chip and happens earlier than the mode coupling chatter in most machining cases. In milling, one of the machine tool workpiece system structural modes is initially excited by cutting forces. The waved surface left by a previous tooth is removed during the succeeding revolution, which also leaves a wavy surface due to structural vibrations. The cutting forces become oscillatory whose magnitude depends on the instantaneous chip dynamic thickness, which is a function of the phase shift between inner and outer chip surface. The cutting forces can grow until the system becomes unstable and the chatter vibrations increase to a point when the cutter jumps out of the cut or cracks due the excessive forces involved. These vibrations produce poor surface finishing, noise and reduce the life of the cutter. In order to avoid these undesirable effects, the feed rate and the depth of cut are chosen at conservative values, reducing the productivity.

Accelerometers is one of the contact type vibration measuring instruments. An accelerometer is an instrument for measuring accelerations, detecting and measuring vibrations, or for measuring acceleration due to gravity (inclination). Accelerometers can be used to measure vibration on vehicles, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. One of the most common uses for micro electro-mechanical system (MEMS) accelerometers is in airbag deployment systems for modern automobiles. In this case the accelerometers are used to detect the rapid negative acceleration of the vehicle to determine when a collision has occurred and the severity of the collision.

Interferometer for Vibration Measurement

An interferometer is constructed from a beam splitter and two mirrors. This device uses the principles of Twyman-Green interferometer when it is used with a monochromatic source, such as a laser, to test optical components. The beamsplitter is a partially reflecting mirror that separates the light incident upon it into two beams of equal strength. After reflecting off the mirrors, the two beams are recombined so that they both travel in the same direction when they reach the screen. The condition of constructive and destructive interference depends on the difference between the paths traveled by the two beams. Since each beam must travel the distance from the beamsplitter to its respective mirror and back, the distance traveled by the beam is 2L as shown in the Figure. If the path-length difference, $2L_1$-$2L_2$, is equal to an integral number of wavelengths, m λ, where m is an integer, then the two waves are in phase and the interference at the screen will be constructive.

$$L_1-L_2= m \lambda /2 \quad (m = \ldots,-1, 0, 1, 2 \ldots)$$

If the path-length difference is an integral number of wavelengths plus a half wavelength, the interference on the screen will be destructive. This can be expressed as

L_1-L_2= m λ /4 (m = odd integers)

In most cases the wavefronts of the two beams when they are recombined are not planar, but are spherical wavefronts with long radii of curvature. The interference pattern for two wavefronts of different curvature is a series of bright and dark rings. The above discussion still holds for any point on the screen. Usually, the center of the pattern is the point used for calculations. In the above discussion, it was assumed that the medium between the beamsplitter and the mirrors is undisturbed air. If allowed for the possibility that the refractive index in those regions could be different, then the equation for the bright fringes should be as

n_1L_1- n_2L_2= m λ /2 (m = ….,-1, 0, 1, 2 ...)

Thus, any change in the refractive index in the regions can also contribute to the interference pattern. In optical system design, interferometers such as the Michelson interferometer can be used to measure very small distances. For example, a movement of one of the mirrors by only one quarter wavelength (corresponding to a path-length change of one half wavelength) changes the detected irradiance at the screen from a maximum to a minimum .Thus, devices containing interferometers can be used to measure movements of a fraction of a wavelength. For this experiment, one of the mirrors constituting one of two arms of the interferometer was attached to the motorized stage. As the mirror was moved, changes in the interference pattern were measured and counted.

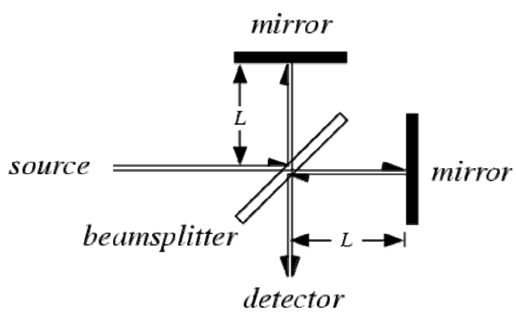


Figure 5 Principle of Interferometric Measurement

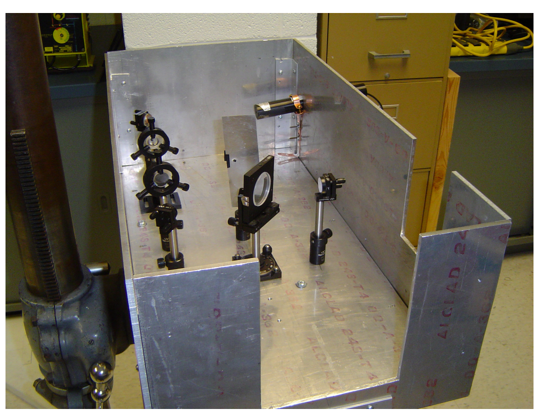


Figure 6: Interferometer Prototype for Precision Measurement

A motorized stage is set with known value of frequency and amplitude. Visual simulation is run to find out the frequency response characteristics curve. The frequency domain curve and the maximum vibration of the motorized stage is shown by the peak frequency in the Figure 7

	Displacement (mm)			
Translation point →	1	2	3	4
Encoder	10	15.376	20.336	30.256
Micrometer	10	15	20	30
Vision system	15	25.25	36.22	51.2
Interferometer	10.757	14.238	19.616	30.058

Table 2: Comparison of Measurement

Displacement measurement:

Table 3 shows the experimental results for regular intervals of micrometer displacement in positive direction(μm).

Number of fringes	Distance=n x ג /2(μm)	micrometer(μm)
97	30.55	30
109	34.18	35
126	39.78	40
143	44.89	45

Table 3 Displacement measurement

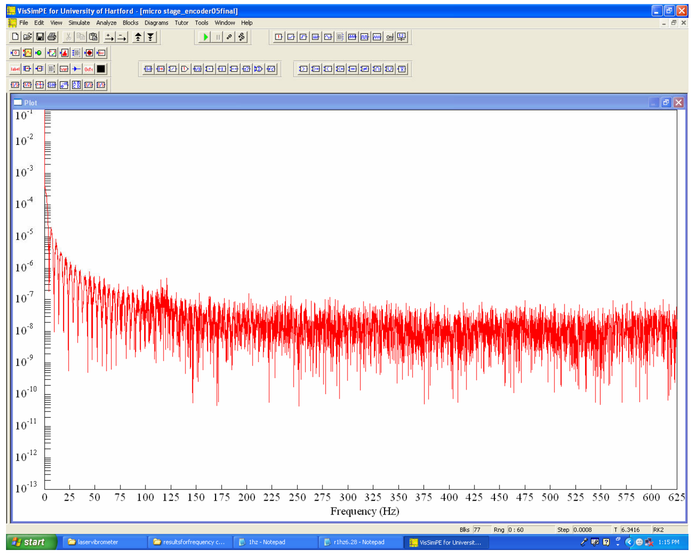


Figure 7: Graph plotted for frequency domain curve

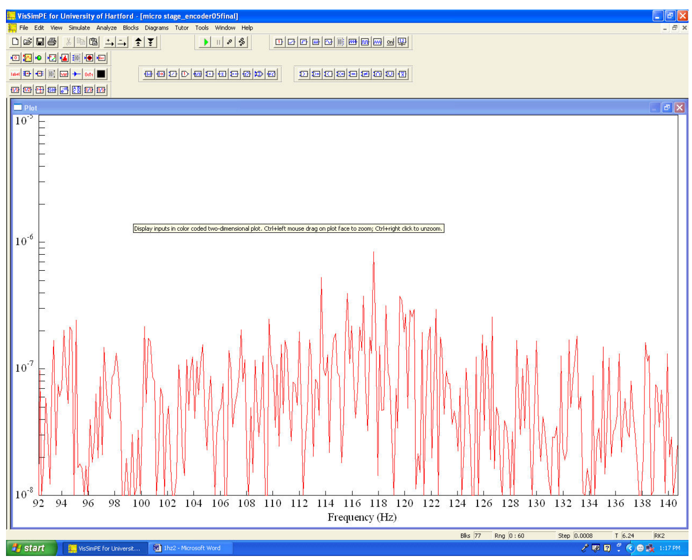


Figure 8. Peak dominant frequency graph

Figures 9 and 10 show the experimental prototype in the University of Hartford to test vibrations of a machine tool.

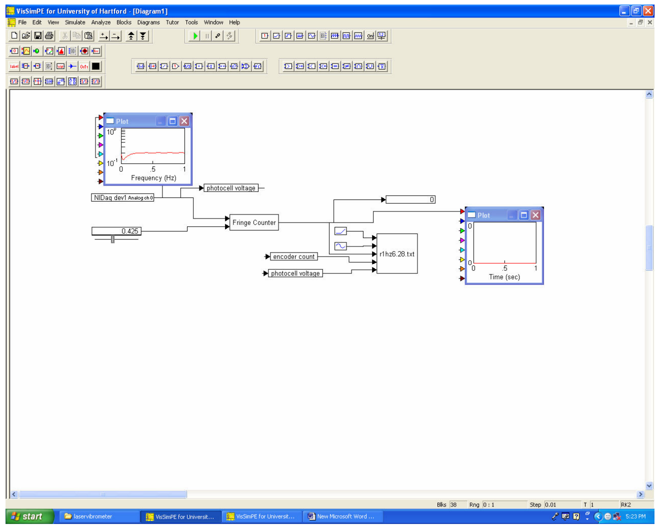


Figure 9 Vissim program for fringe counting

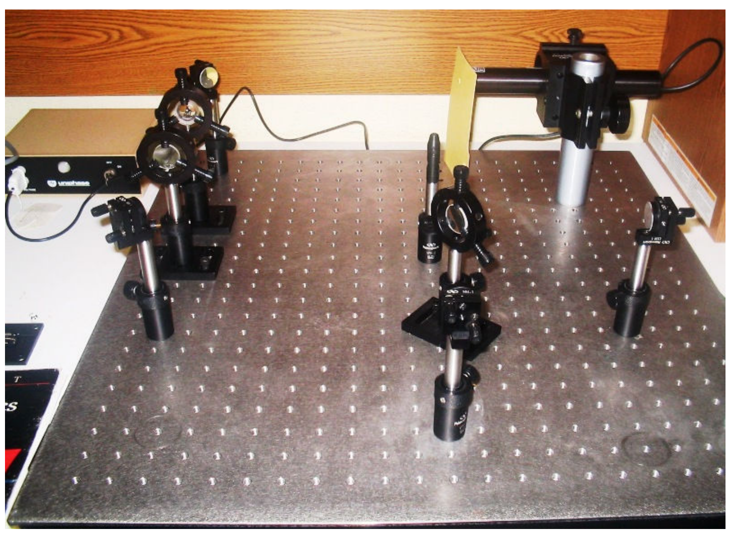


Figure 10: Optical components on the testing bed.

Further Research and Conclusion

Based on our current research and experience, the prototype interferometer provides an effective means to measure vibration in a student laboratory. The personal computer based software system used to process and interpret the results is useful for demonstrating the principles in a classroom or laboratory setting. Based on our results we have introduced additional research activity that will produce a much smaller processor system, based on the use of a field programmable gate array (FPGA). The use of a single FPGA to construct an entire intelligent instrumentation system, uniquely tailored to the application is a new computer engineering paradigm. Apart from the FPGA itself, the concept is based on classical computer engineering principles, where a processor uses a bus to access peripherals. In this case an optical photo sensor or charge-coupled imaging device (CCD) is selected to serve as such a peripheral. Such a system allows the optical test bench to be used without requiring the use of a PC and accompanying commercial software.

The elements of the FPGA based system approach are as follows. First, software tools are used to implement an entire microprocessor system using an FPGA along with an analog adapter board. Next, the operating system is selected and required libraries and device driver software are written. Finally, the application software is written and tested. While such a processor system is described using a hardware description language such as VHDL, the resulting description is not considered software but rather is used to configure the hardware. Once configured, writing the libraries, drivers, and application involves conventional software development tools.

In conclusion, this research demonstrates how software based simulation tools can be successfully used monitor and control precise positioning and how it can be used in creating and detecting vibrations especially in machine tools, and demonstrated in a student laboratory. Precise positioning and motion control was achieved by an experimental test bed with a micro-positioning stage. With a sufficiently high sampling rate, reconstruction of the vibration wave form was achieved by conducting peak detection of the resultant series of pulses. Two techniques were experimentally investigated using the same micro-positioning platform. They were, vibration sensing by position sensing detector and vibration sensing by interferometry. This paper also outlines the results of our approach in micro-positioning, displacement creation and vibration sampling in high precision machine tools. Additional results with the prediction of break-through detection in laser drilling manufacturing process has also been documented.

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