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Real Time Mechatronic Design Process for Research and Education

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Abstract

This paper presents the design methodology used in various real time mechatronics projects that involve data acquisition, real time control and embedded processing. As a design philosophy, mechatronics serves as an integrating approach to engineering design. A mechatronically designed product relies heavily on system sensing and component modeling and simulation to establish the optimal design tradeoffs between electronic and mechanical disciplines when subject to specific cost and performance constraints. The mechatronic method followed by us incorporates a language-neutral approach for real time modeling using graphics based visual simulation programs.

The projects discussed in the paper are Mechatronics Technology Demonstrator using damped oscillator system, Thrust Control for Rocket Propulsion, Fuel Flow Metering and Control System, Active Noise Control, Time Delay Heat Blowers. Also discussed is an example of Rapid Prototyping of Vibration Monitoring System. The ideas and techniques developed during the interdisciplinary simulation process provide the ideal conditions to raise synergy and provide a catalytic effect for discovering new and simpler solutions to traditionally complex problems. Mechatronic products exhibit performance characteristics that were previously difficult to achieve without this synergistic combination.

1. Introduction to Mechatronics

Mechatronics is a methodology used to achieve an optimal design of an electromechanical product. The ideas and techniques developed during the interdisciplinary simulation process provide the ideal conditions to raise synergy and provide a catalytic effect for discovering new and simpler solutions to traditionally complex problems. There is a synergy in the integration of mechanical, electrical, and computer systems with information systems for the design and manufacture of products and processes. The synergy can be generated by the right combination of parameters, that is, the final product can be better than just the sum of its parts.

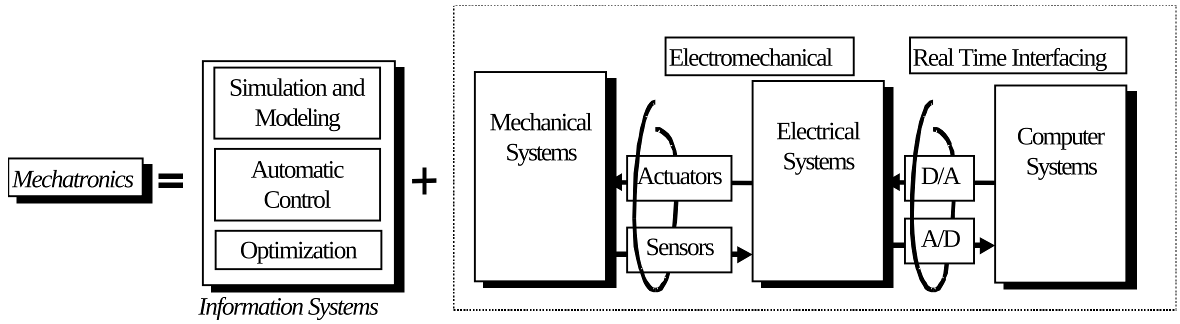

Fig. 1. - Key Mechatronic Elements

Mechatronic products exhibit performance characteristics that were previously difficult to achieve without this synergistic combination. The key elements of the mechatronics approach[1] are presented in Figure 1. Mechatronics is the result of applying information systems to physical systems. The physical system, the rightmost dotted block, consists of mechanical, electrical, and computer (electronic) systems as well as actuators, sensors, and real time interfacing. Sensors and actuators are used to transduce energy from high power, usually the mechanical side, to low power, the electrical and computer or electronic side. The block labeled mechanical systems frequently consists of more than just mechanical components and may include fluid, pneumatic, thermal, acoustic, chemical, and other disciplines as well.

1.2 Special Features of Mechatronic System

Starting with the basic system design phase and progressing through the manufacturing phase, the mechatronic process optimizes the system parameters at each phase to produce a high quality multi-disciplinary[2] integrated product in a short cycle time. The Mechatronics design process is shown in Figure 2. Mechatronics employs control systems to provide a coherent framework for component interactions and their analysis. Integration within a mechatronic system is performed through the combination of hardware components and software, including information processing. This is known as Hardware-In-The-Loop simulation. Hardware integration results from designing the mechatronic system as an overall system which includes the sensors, actuators and embedded computer as well. Software integration is based on control functions and algorithms to be performed.

The benefits of the mechatronic design approach are greater productivity (shorter development cycles and faster time to market), higher quality, and lower cost products. They also provide additional influence through the acquisition of knowledge information from the process. A mechatronic product can achieve impressive results if it is effectively integrated with the concurrent engineering management strategy.

In this paper the following ideas are discussed:

- Overview and explanation of mechatronics from a model based perspective.
- Modified Analogy Approach for creating dynamical models of physical systems.
- Modeling as well as selection principles of sensors and actuators

Case studies complete with parts list suitable for laboratory exercises.

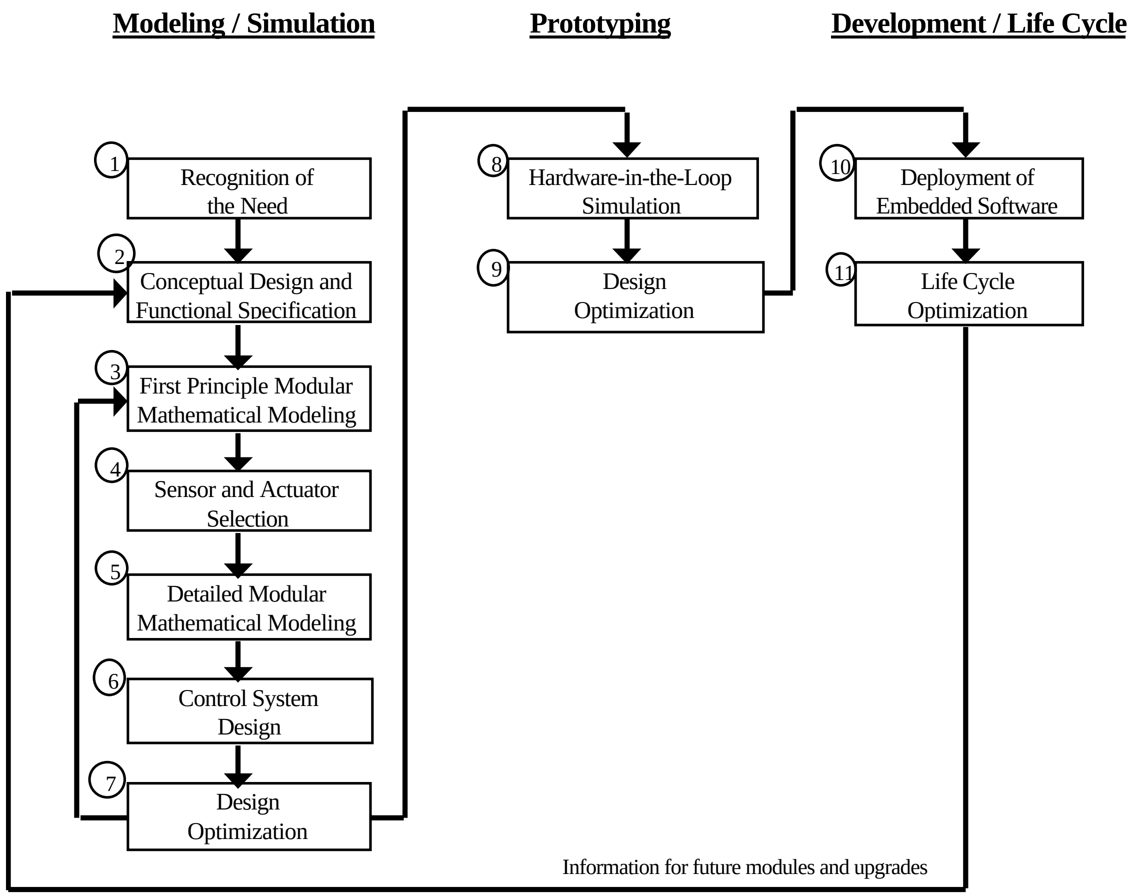

Fig. 2. - Mechatronic Design Process

2. Language-Neutral Approach in Mechatronics

Today, a mechanical engineer with training in mechatronics offers three new benefits. First, a mechatronics engineer is familiar with the benefits and limitations of cross-discipline technologies in software and electronic hardware. Second, a mechatronics engineer has been trained on how to apply this knowledge to optimize a mechanical design. Third, a mechatronics engineer understands how to rapidly prototype and test various embedded solutions to develop a final solution. One of the major challenges of any mechatronics sequence is the process for software design, implementation, and test. Basically there are two teaching approaches; (1) focus on the embedded software programming and embedded hardware aspects which include language, computer architecture, and development tools or (2) focus on visual language-neutral programming applications, such as Simulink, Labview, VisSim, and others, which generate less efficient software but do not require the time needed to gain an intimate knowledge of a language and its development environment. The authors have used the second approach successfully applied for many years. It is the author's belief that embedded software development cannot and should not be a focus area for mechanical engineers.

3. Examples of Real Time Mechatronics Design

Mechatronic principles and design methodology are explained with the help of several case examples. These projects demonstrate the characteristics of visual simulation, model building, data acquisition and control. The projects are:

1. Mechatronic Technology Demonstrator
2. Thrust Control of Rocket Propulsion
3. Alternate Fuel Flow Metering and Control
4. Active Noise Control of Exhaust System
5. Time-Delay Blower
6. Rapid Prototyping of Vibration Monitoring System

3.1 Mechatronics Technology Demonstrator[3]

The Mechatronics Technology Demonstrator (MTD) is an experimental system developed by the authors. It is a damped oscillator system with an electromagnetic force actuator and a non-contact position sensor. It is built from low cost components available at most electronic, hardware, and home supply stores. It is suitable for studying the key elements of mechatronic systems including; mechanical system dynamics, sensors, actuators, computer interfacing, and application development. The MTD can be constructed in two configurations, vertical (Figure 3) and horizontal (Figure 4).

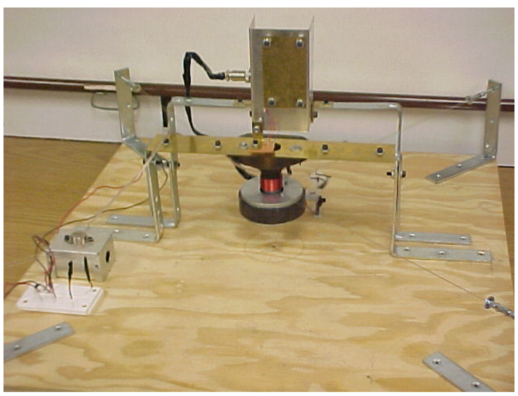

Fig. 3 - Vertical MTD Configuration

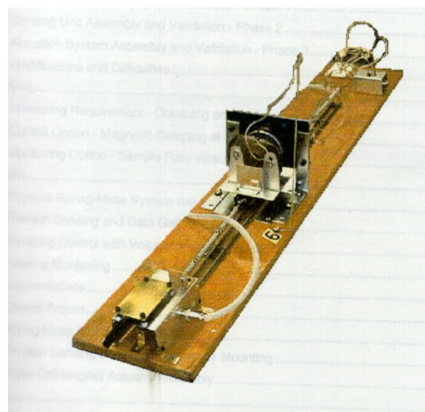

Fig. 4. - Horizontal MTD Configuration

The vertical configuration offers greater motion control over shorter distances while the horizontal configuration provides just the opposite. Regardless of the configuration, position of the mass in the MTD is measured using a position sensing detector (PSD) device. The PSD outputs a voltage proportional to the intensity of the light cast upon it. The light source, a laser similar to the type used for overhead presentations, is fastened to the base of the MTD and aimed at a mirror attached to the mass. The laser is adjusted until the reflected beam just hits the center of the PSD when the mass is motionless and in its normal position. As the mass moves around its normal position the reflection angle changes which, in turn, changes the area (intensity) of the light hitting the PSD and hence its voltage. Aside from the initial "tuning" of the laser beam angle, the motion sensing method is extremely accurate, non-contact, and extremely easy to implement. To provide force inputs to the mass for motion and/or active damping a voice-coil/magnetic actuator is used.

Both the sensor and the voice coil actuator are connected to the PC based visual modeling and real time simulation application using a general purpose I/O card. The voltage output by the PSD is amplified for direct connection without the need for additional amplification. The current used to drive the voice coil, however, does need amplification. Modeling of the damped oscillator system represented by the following equation in transfer function form:

$X / F = 1 / (Ms^2 + K)$ where,
X = displacement of the cart.
F = force exerted on the cart.
M = mass of the cart.
s = the derivative function.
K = the equivalent spring constant.

(i)Real-Time Modeling Simulation

- The physical model of the damped oscillator system is constructed using the block diagram. The model will provide prediction from a force input to the mass displacement (and velocity). To verify the performance of the model, the experiment is conducted in parallel with actual data obtained along with a plot of comparison displacement outputs. Model parameters are adjusted until good performance correlation exists. An example of a block diagram model is shown in Figure 5.

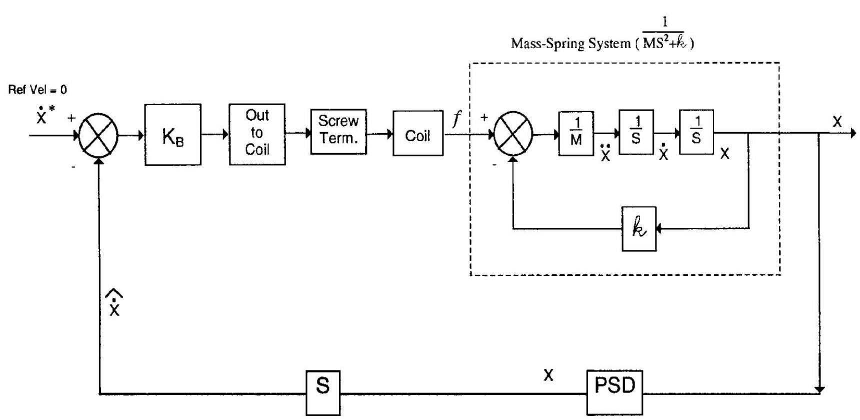

Fig. 5. - Physical system block diagram for MTD

- A Least Square model of the damped oscillator system is developed using a step force input to the mass and recording the resulting displacement. The parameters in the second order model are computed using the least square method with gradient adjustment. To verify the performance of the model, it is run in parallel with additional data records.

(ii) Real-Time Control Studies

- Closed loop control is used to provide additional electronic damping to the MTD in order to smooth the time response. Two control options are considered; rate feedback control design and validation and on/off control design and evaluation.
- A model based control algorithm of the "rate feedback" type is designed to electronically increase the damping applied to the mass. This will require installation and calibration of the magnetic actuator and design of the rate feedback control algorithm. The mass displacement response using rate feedback algorithm is shown in Figure 6.

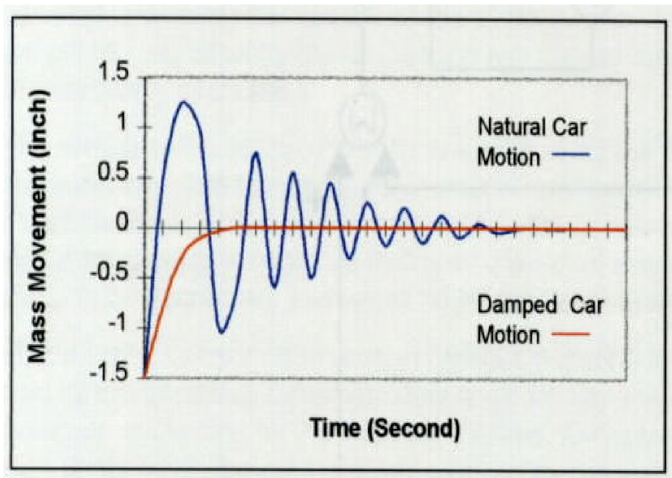

Fig. 6. - Mass displacement response with rate feedback control

- On/off control can be designed which increases the damping applied to the mass. This will require installation and calibration of the magnetic actuator and design of the rate feedback control algorithm. The algorithm will sense peak points of mass acceleration, negate them and send the information back to the actuator.

3.2 Thrust Control of Rocket Propulsion[5]

The objective of this research is to simulate rocket thrust control in the laboratory. Controlling the nozzle pressure to within a set tolerance of a given set point by modulating the water flow into the nozzle using a valve controlled by a rotary motor. A pressure sensor in the nozzle provides feedback for the proportional, integral (PI) control system. The experimental test setup is shown below in Figure 7.

The Thrust Control Group employed a four-step approach to solving the problem of controlling the nozzle exhaust pressure as follows:

- Collect experimental data using real system for data collection.
- Generate transfer function from unit step response graph.
- Put transfer function into PI controller model adjusting K_i and K_p for best response.
- Replace the system model with the real system and test it.

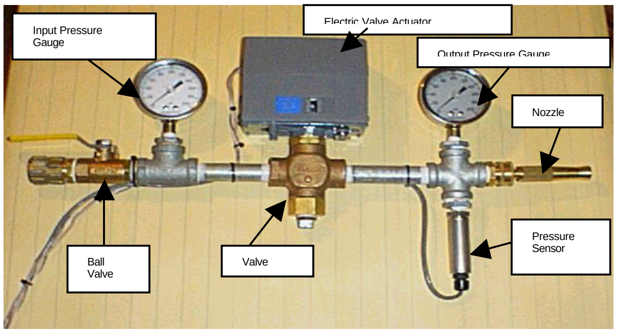

Fig. 7. - Thrust Control Setup

Thrust control block diagram programming environment simulation and thrust profile test results are shown in Figure 8.

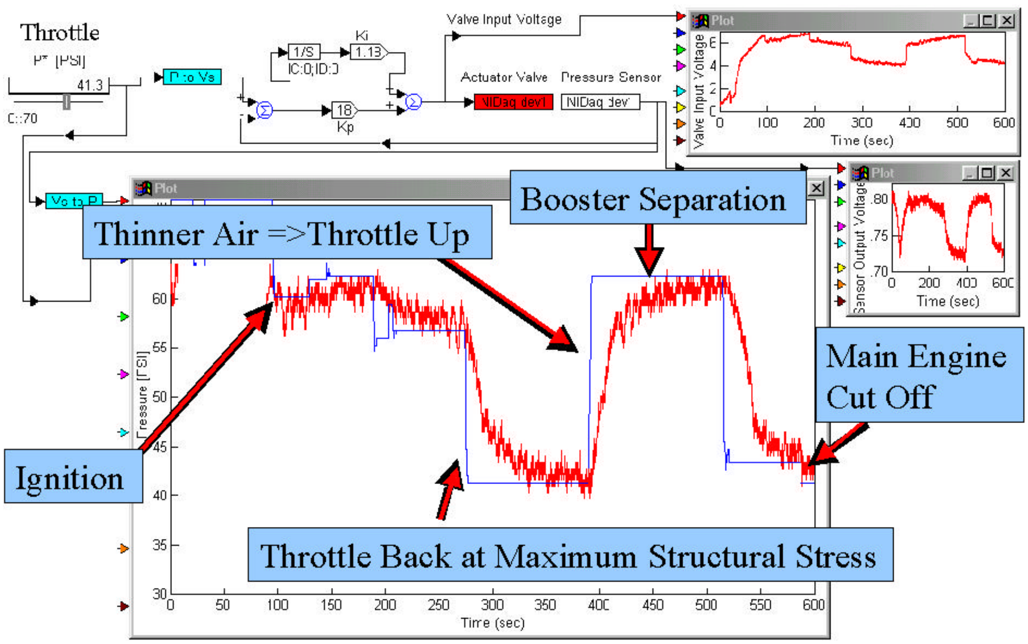

Fig. 8. - Thrust control block diagram simulation and test results

This project shows that the pressure at which exhaust leaves a nozzle can be controlled by an actuator valve up stream of the nozzle using proportional, integral control with a pressure sensor in the nozzle chamber providing feedback. Furthermore, this project has shown that the methodology followed here provides a clear path for controlling a system for which the exact physics and governing equations are not known. The process of taking unit step response data, generating a model from it, using that model to simulate and design a control system and then applying that control system to the mechanical hardware worked well.

3.3 Fuel Flow Metering and Control System using Differential Pressure Sensor[6]

Designing the control system was the focus of the project and any mechanical hardware problems that caused undue delays were undesirable. This project focused on measuring fuel flow to a jet turbine engine using a differential pressure measurement. Figure 9 shows a schematic of the flow metering project hardware.

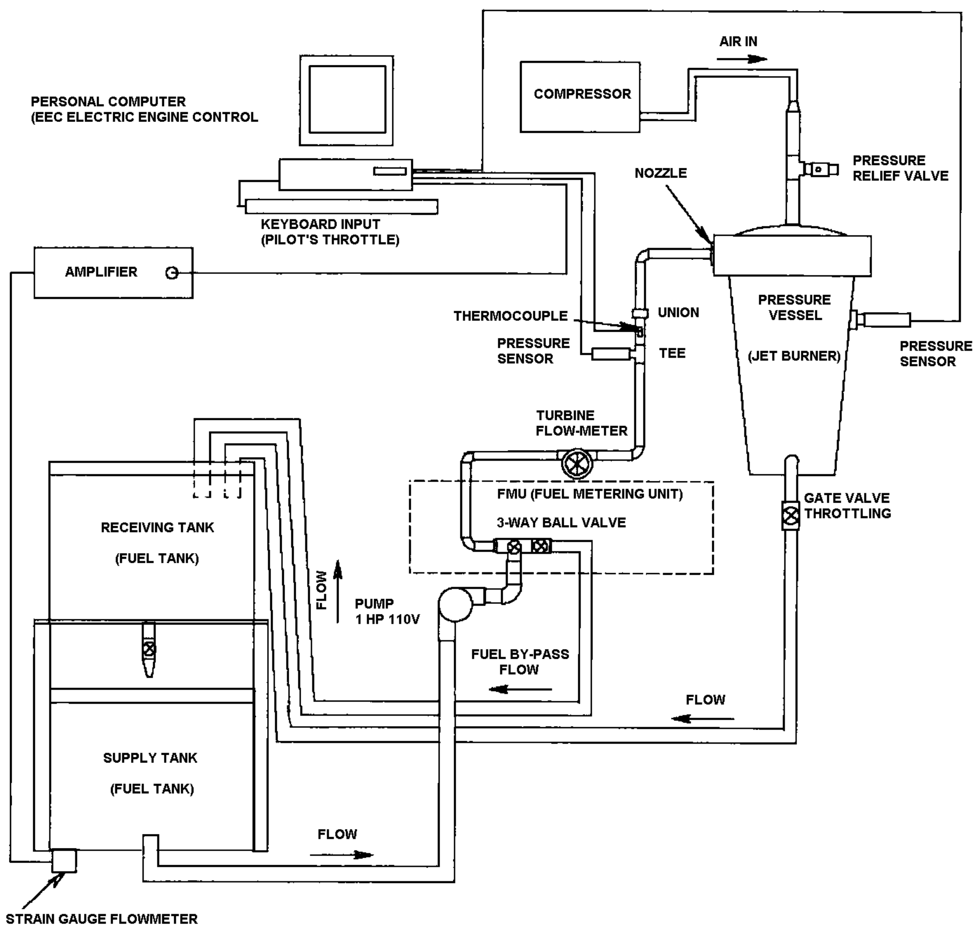

Fig. 9. - Flow Metering System Setup

This case study is of use to the aerospace industry. An aerospace engine control company sought an alternative method of measuring fuel flow to a jet engine. The present method used a Linear Variable Displacement Transformer (LVDT) valve position sensor to determine the amount of fuel flowing to the jet engine. The position of the fuel control valve was correlated to the volume per time passing through to the engine. This method required in-system calibration -- an unwanted requirement. The challenge was to relieve the company of this requirement without adding any undesirable side effect such as cost, size, weight, complexity, inaccuracy or fuel flow drag. It was concluded that differential pressure sensing can accurately measure fuel flow in this application while reducing the size, weight and complexity of the design and could reduce the total system cost when factors such as the savings of a simplified control valve and the elimination of in-system calibration costs are considered.

3.4 Active Noise Control Exhaust System

A control system for an active noise control exhaust was designed and implemented for application on the formula Society of Automotive Engineering racecar. The design incorporated a single microphone, speaker, and a Digital Signal Processing (DSP) Controller. Testing was made on both an open loop and closed-loop system. The open loop, reflecting the theory, produced good results. Figure 10 shows the test setup components for this project.

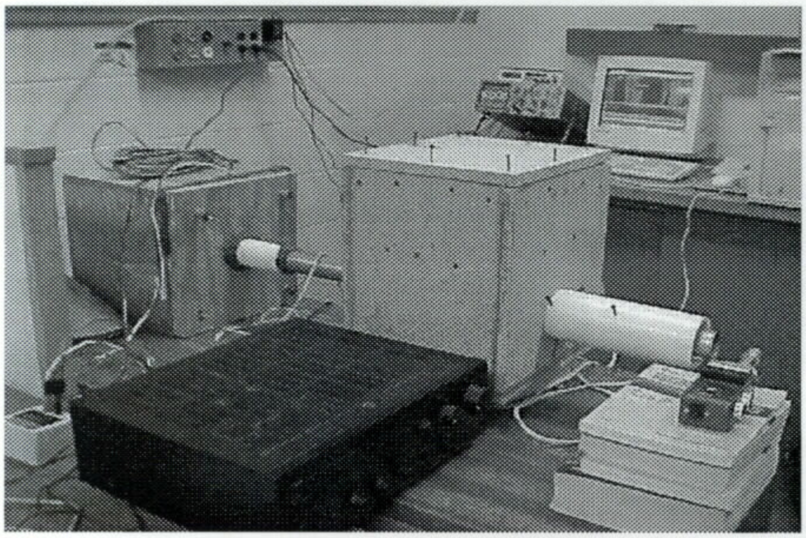

Fig. 10. - Active Noise Control experimental setup

The general design of the system consists of a passive muffler to filter out upper mid to high frequencies and an active system to reduce the low to lower mid frequencies. The active system is positioned downstream of the passive system. The prototype system incorporates a single speaker and microphone in a band pass box and the DSP processor used as the adaptive controller.

3.5 Time Delay Heat Blower

The project consists of 10-foot long pipe, a heat blower placed on one end of the pipe, a temperature measurement probe placed on the opposite end of the pipe, and a computer interfacing the heat blower and temperature probe. Figure 11 shows the hardware components and test setup. The systematic design of the project was constructed in Vissim (Visual Simulation) software. The system was designed to enable a user to put in a desired temperature, and maintain the output temperature taking into consideration changes on the ambient temperature. The objective of this project was to steadily control a temperature based system of hot air through the 10' tube using Vissim and data acquisition board to acquire temperature readings and control the heat blower. Using heat transfer analysis the system was modelled using conduction and convection relations. Time lag was identified that occurs from the time the heat blower is activated to the time the temperature probe detects temperature change on the other end. A time-delay transfer function was inserted in the simulation model in order to eliminate the lag. With this transfer function, the output temperature was controlled to within 1 degree of the desired output temperature.

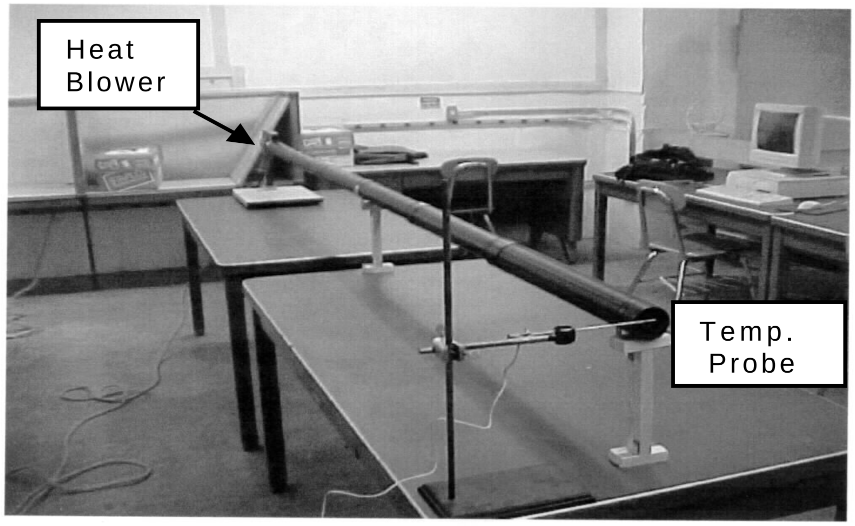

Fig. 11. - Time Delay Blower test setup

3.6 Rapid Prototyping of Vibration Monitoring System [4]

Using microcontrollers embedded in an application can be extended to educate more about Rapid Control Prototyping and Hardware-in-the-Loop simulation for instrumentation and smart sensor product development. This Hardware-in-the-Loop Simulation testing provides the designer reassurance that any assumptions made on the plant model were correct. If any assumptions were incorrect, however, the designer does have the opportunity to optimize the design before committing to the real target hardware platform. Microcontrollers embedded into sensor products add end-user value to products. Many new applications become cost effective when the cost of incorporating a microprocessor into a sensor compares to that of adding an op amp and several resistors.As an example, a system used for detecting unbalance in machinery is described in the next paragraphs. Figure 12 shows a schematic of such system being used at the University of Hartford, which incorporates Digital Signal Processing (DSP).

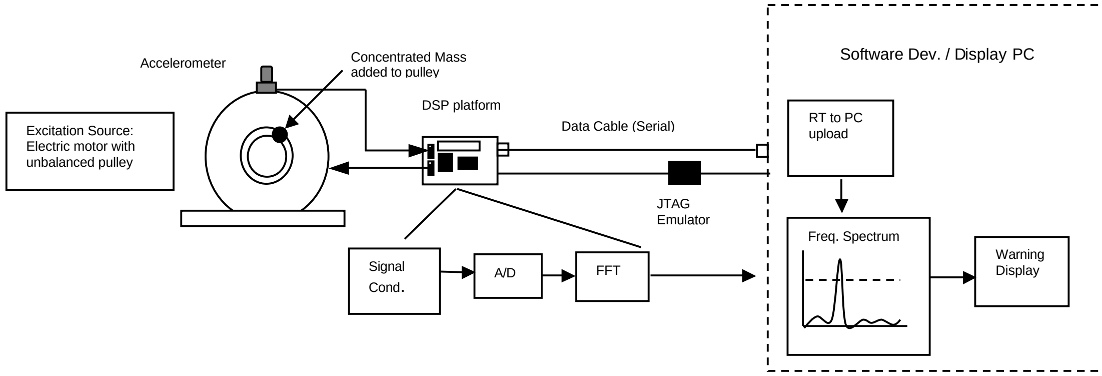

Fig. 12. - Embedded DSP based Hardware-in-the-Loop Setup for instrumentation sensor

In this case, the goal is to detect unbalance in an electric motor and give feedback in the form of a warning display or on/off control signal. The criteria for determining unbalance is obtained from Fast Fourier Transform (FFT) analysis. FFT allows us to determine the fundamental frequency of vibration produced by the unbalance. Due to the nature of the fault being detected the dominant amplitude of vibration is expected to be present in the lower frequencies that is in the range of a few hundred Hz. This embedded DSP based Hardware in the Loop setup consist of the following components: 1) Electric motor used as excitation source with balanced/unbalanced pulley placed on its shaft. 2) Uniaxial accelerometer to measure radial acceleration component. 3) DSP platform used for conditioning of signal from accelerometer, Analog to Digital conversion of signal, FFT and limit detect algorithm processing. 4) Software development and display PC for frequency spectrum display and warning display.

Algorithm development and debugging is done on the PC using block diagram simulation software capable of generating C code. This makes it a language neutral process and a resulting code that is portable. Several block diagram programming tools for DSP exist such as Matlab Simulink and Hypersignal Ride. These are programs capable of simulating algorithms in a graphical user interface (GUI) environment using a host of software building blocks. The program is then compiled, converted into assembly code and downloaded to the DSP platform for execution. With the DSP being used as the processor, the PC is then used only as a means of visual display for results.

For this setup, two test cases are considered: One with a balanced pulley added to the electric motor shaft and the other with an unbalanced pulley added to the shaft. The amplitude vs. frequency response was recorded for the balanced and unbalanced conditions and are shown in Figure 13 and 14 respectively. For the balanced case, a peak amplitude of 14.1 Db is observed at 30 Hz. Where as for the unbalanced case a peak amplitude of 37.6 Db is present at 30 Hz. Thus a threshold value can be set such that a limit detect algorithm can determine the unbalance condition and provide the appropriate feedback control signal.

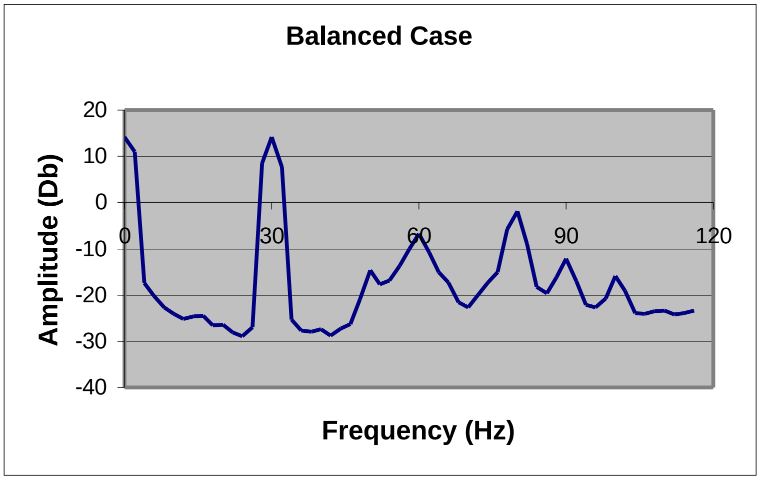

Fig. 13. - Amplitude vs. Frequency response for balanced motor

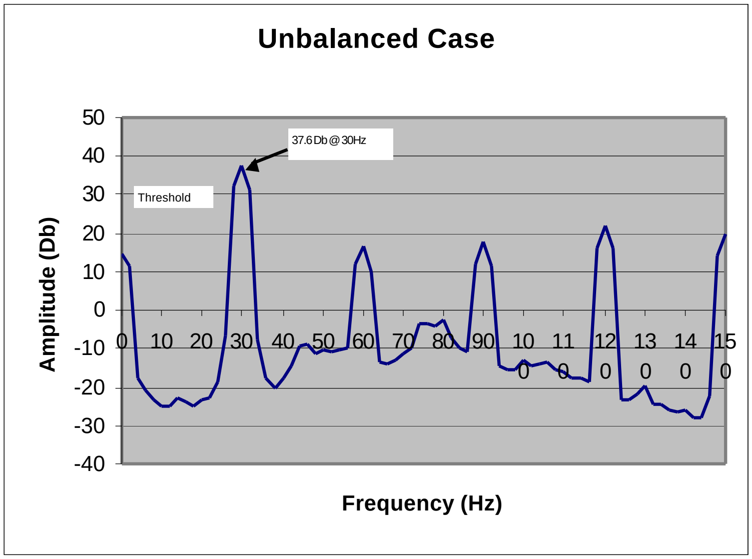

Fig. 14. - Amplitude vs. Frequency response for unbalanced motor

DSP based Hardware-in-the-Loop testing using block diagram simulation software can be made to provide real-time control with minimum expertise in embedded processors. Hardware-in-the-loop simulation is a cost-effective method to perform system tests in a virtual environment. Most of the environment components are replaced by mathematical models while the components to be tested are inserted into the closed loop. As such, rapid prototyping and hardware-in-the-loop simulation are an integral part of today's product development process. So the use PC based modeling simulation along with Rapid Control Prototyping and Hardware-in-the-Loop simulation demonstrates a level of interaction with the modeling of a system that is not possible when code is directly ported to the final target platform.

4. Conclusion

The design oriented mechatronics examples presented here incorporate a language-neutral teaching approach for mechatronics system design courses that links the educational experience more closely with the processes and projects found in industry. The paper presented here addressed the recent advances in Mechatronics education as well as several case studies.

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