Int. J. Engng Ed. Vol. 19, No. 3, pp. 503–511, 2003
Printed in Great Britain.
0949-149X/91 $3.00+0.00
© 2003 TEMPUS Publications.

Mechatronic Experiment on Remote Vibration Monitoring and Fault Diagnosis via the Internet*

K. K. TAN, K. N. WANG and K. Z. TANG
Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576. E-mail: kktan@nus.edu.sg

This paper presents the development of a 'mechatronic' experiment on the development of an intelligent vibration monitoring system for remote vibration signature analysis via the Internet. It will highlight the operational principles of the system, and the hardware and software requirements for the implementation of the system on the Internet to enable remote monitoring and fault diagnosis. Specific outcomes and screen snapshots at key stages of the experiment will also be provided.

INTRODUCTION

THE TERM 'mechatronics' was first introduced and registered in 1969 by an engineer called Tesuro Mori of Yaskawa Electric [1] to provide a semantic reference to the phenomenon of increasing interaction between the mechanical and electronics engineering disciplines. Mechatronics was mainly coined to refer to simplified mechanisms with sophisticated functions in electronics. The importance of a mechatronic approach in the design of new products and processes, through a seamless synergy of associated technological disciplines, is becoming increasingly recognized worldwide as a mean towards effective manufacturing to maximize economic gains [2–5]. As the benefits associated with applications of mechatronics become more evident, the education systems in many countries also evolve to reflect the need for a cross-disciplinary curriculum. At the National University of Singapore, a new program leading to the award of a Master of Science in Mechatronics was recently introduced. A specific focus of the mechatronic program is on real hands-on laboratory practice. Experiments of specially designed themes are to be systematically carried out by the students enrolled in the program as a core part of the program.

This paper will report on a specific experiment in the mechatronic program which is set up to provide hands-on experience in the application of a mechatronic device (accelerometer) and digital signal processing techniques to vibration monitoring and fault diagnosis of machines [6]. The accelerometer will provide directly vibration measurements, and an intelligent algorithm (to be programmed by the students) will carry out the fault inferencing procedures. The approach adopted in the experiment is based on capturing machine-specific vibration signatures and comparing these signatures to real-time vibration patterns to determine if possible faults have occurred.

In addition, students are introduced to how the Internet may further shape the operations of mechatronic systems. The Internet is the world's largest, most powerful computer network connecting personal computers, sophisticated mainframes, and supercomputers around the globe. 'World Wide Web' (WWW) as the fastest growing Internet service, is seen as an effective tool for distant operations. The WWW project, started by Tim Berners-Lee while at CERN (the European Laboratory for Particle Physics) [7] seeks to build a 'distributed hypermedia system'. In essence, the Web is a vast collection of interconnected document files, spanning the world. The WWW provides Internet users with a uniform and convenient means of accessing the wide variety of resources (pictures, text, data, sound, video) available on the Internet. Popular software interfaces, such as IE and Netscape, facilitate navigation and use of the WWW. In effect, the web is a distributed multimedia environment, which potentially can provide a truly integrated environment for information exchange. In the experiment, via remote laboratory access approaches, the students will implement remote monitoring and diagnosis of a single axis shaker to which they have earlier instrumented with the accelerometer. Thus, from a remote site, using only a regular web browser, they will be able to characterize the vibration signatures of machine, monitor their health, tune their thresholds and initiate alerts when abnormal conditions are encountered. This will be achieved using only existing extensible TCP/IP infrastructure.

* Accepted 19 February 2003.

VIBRATION MONITORING AND FAULT DIAGNOSIS

Mechanical vibration in machines and equipment can occur due to many factors, such as unbalanced inertia; bearing failures in rotating systems such as turbines, motors, generators, pumps, drives and turbofans; poor kinematic design resulting in a non-rigid and non-isolating support structure; component failure and/or operations outside prescribed load ratings [8]. The machine vibration signal can be typically characterized as a narrow-band interference signal anywhere in the range from 1 Hz to 500 Hz. To minimize the maintenance costs and production shutdown time resulting from damages induced from severe resonant vibration, a monitoring system with affordable installation cost and little reconfiguration requirement will be useful to provide suitable signals reflecting the health of the machine.

One approach towards achieving this objective can be based on an analysis of the vibration signal forthcoming from the mechanical system. This approach is very intuitive to the way an experienced operator will detect a fault from the abnormal machinery sound/noise generated. It uses an accelerometer mounted on the machine to yield an electrical signal measurement which is representative of the mechanical vibration, and a soft monitoring system which can trigger an alarm if a fault is detected according to certain criteria.

Main principles

The main idea behind the approach is to construct a vibration signature based on pattern recognition of 'acceptable' or 'healthy' vibration patterns, against which the actual vibration pattern is compared. Figure 1 highlights the key steps involved. An accelerometer, mounted on the machine being monitored, is used to provide measurements of the vibration signals in an electrical form. These signals can subsequently be digitized and acquired into a microprocessor-based system in which resides the intelligent vibration analysis program. The vibration analysis program can work in two modes: the learning and monitoring mode. The learning mode is to be initiated to identify the normal vibration characteristics of the machine, i.e., the vibration signature. The mode can be re-initiated at any time when the operator feels a relearning/retraining is necessary (for example, after the machine has undergone modifications/retrofitting). Thus, normal vibration signatures can be extracted in this way automatically through only a pushbutton on the software interface. Thereafter, the monitoring system can enter a continuous monitoring mode. In the monitoring mode, the vibration signals are continuously acquired and compared to the pre-acquired 'normal' signatures. If the deviation from the signature exceeds a certain specified threshold, an alarm can be raised to alert the operator of possible machine malfunction.

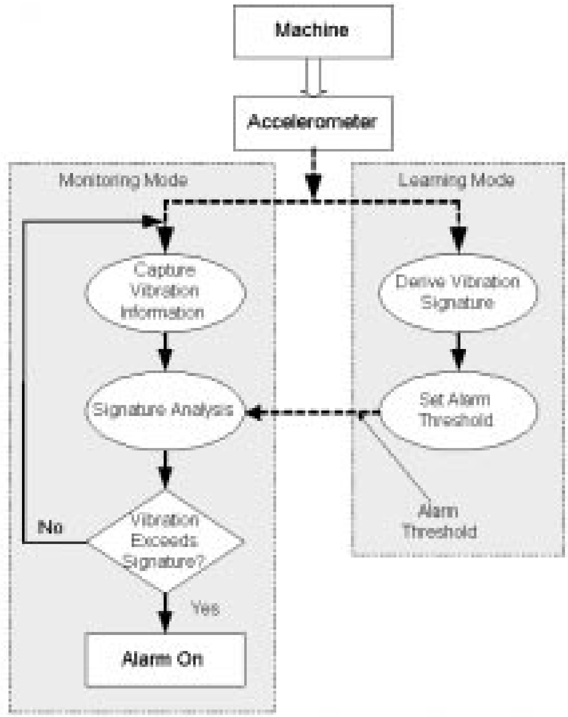

Fig. 1. Key operational steps of the intelligent vibration monitoring system.

Vibration measurements

Vibration measurements are collected by mounting an accelerometer (one example is shown in Fig. 2), on the machine to be monitored. It acts as an interface between the motor (or machine) and the data acquisition card, by converting mechanical vibrations into electrical signals. Accelerometers are available in a large variety of sizes, shapes and styles to suit a broad range of test and control applications. Each accelerometer series is designed with a particular group of measurement and control applications in mind.

The construction of the real-time vibration measurement system is inexpensive and requires only commercially available, low-cost components. The accelerometer and a data acquisition card residing on a personal computer (PC) (or alternatively, a DSP standalone device) are the only hardware required. The installation can be hassle-free, as the accelerometer can be mounted directly, independent of the machine's own control system. Thus, there is no need to retrofit the machine to implement the monitoring system.

Vibration signature

In the learning mode, the vibration signals, with the machine operating under normal conditions, are acquired by the accelerometer and buffered in the data acquisition card. A suitable vibration signature is then extracted from the vibration signals. There are many types of vibration signatures that can be adequate

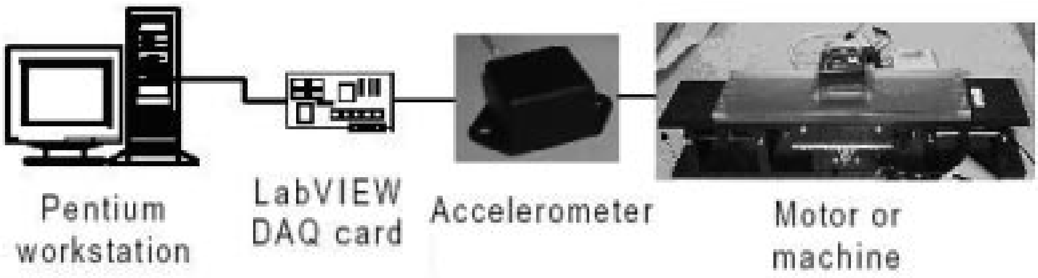

Fig. 2. Vibration signal acquisition system.

for the purpose of machine monitoring. One possible signature can relate to the spectrum of the vibration signal which can be efficiently obtained using the Fast Fourier Transform (FFT) algorithm [9]. This is the form of the signature which will be used in the paper. Other forms of vibration signature can be used as well. For example, another form of vibration signature may be based directly on the amplitude of the vibration; yet another form may use a time series analysis of the vibration.

If there are different operational modes of the machines, then there can be multiple vibration signatures each corresponding to one operational mode. Based on the signature, an alarm threshold can be set which encompasses the vibration signature with spare tolerance to cater for inevitable deviations which should not be diagnosed as faults, an example of which is given in Fig. 3. The setting of the threshold can be based on specific information available, or it can be set as the 'worst-case' envelope of the multiple signatures obtained over a longer period of time.

Fault diagnosis

Possible faults can be diagnosed by comparing the actual vibration pattern acquired continuously against the vibration signature and the alarm threshold obtained during the learning mode. When the comparison shows a violation of the threshold, an alarm can be set. A more sophisticated fault inference scheme can be formulated based on more than one evaluation criterion using a fuzzy inferencing scheme. Interested readers can refer to [10]. Different levels of alarm can be set corresponding to the extent of violation of the threshold, and therefore providing an indication of the urgency of attention needed.

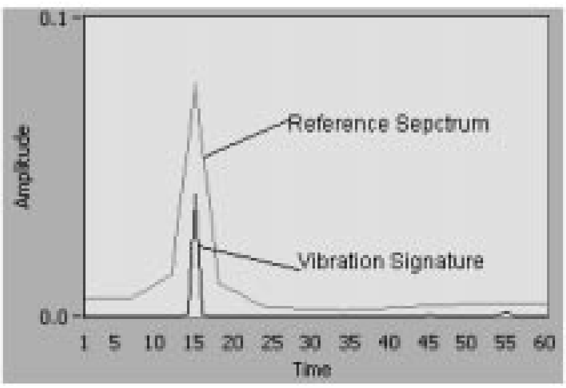

Fig. 3. Alarm threshold setting based on the vibration signature.

REMOTE OPERATIONS

Many manufacturing processes are now widely distributed geometrically, due to economy-related strategies in spreading the manufacturing and distribution processes. The layout of an entire plant can now be rather extensive, spreading across continents in certain cases. Therefore, it has become an important challenge to be able to optimize any synergy opportunities in the operations of these distributed systems. In many cases, the same set of processes to manufacture the same product (or to monitor the same process) can be cloned over different plants. This requires close coordination and synchronization of the distributed operations, as well as an efficient remote monitoring and control facility in place. Thus, an extensive and 'borderless' approach towards the monitoring of machines and process is crucial to enhance overall efficiency and operational costs. In this section, the hardware and software requirements to enable remote operations of the earlier described monitoring system will be highlighted.

Hardware configuration

The hardware that is necessary and used in the development of the remote monitoring at the server's end, is the server itself, consisting of a data acquisition (DAQ) card installed in a PC. The PC which is linked to the Internet, is used primarily for data acquisition and control of the remote machine. The accelerometer acts as an interface between the motor (or machine) and the data acquisition card. It converts mechanical acceleration into electrical signals. The analog electrical signals from the accelerometer are then acquired by the DAQ card as raw data and stored in the PC for further conditioning and analysis. The hardware connection is depicted in Fig. 4.

Software configuration

The recommended software development platform for this miniproject is *Laboratory Virtual Instrument Engineering Workbench* (LabVIEW) [11]. It is a graphical programming language. The

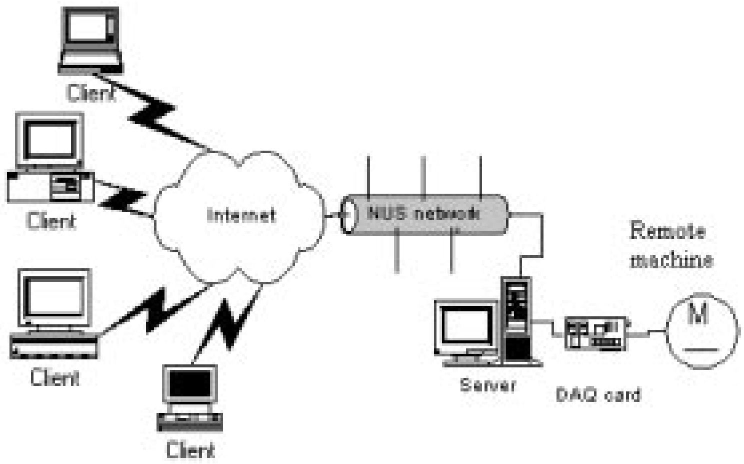

Fig. 4. Hardware connections of the remote monitoring system.

software is windows-driven, and various functions can be performed simply by placing icons and carrying out the soft-wiring connections. LabVIEW is integrated fully for communication using standards such as GPIB, RS232, RS485, and it facilitates interfacing to plug-in data acquisition cards.

Using LabVIEW, 32-bit compiled programs that provide fast execution speeds needed for custom data acquisition, test and measurement solutions can be created. As LabVIEW is a true 32-bit compiler, standalone executables can also be created easily. It contains comprehensive libraries for data collection, analysis, presentation and storage. Traditional program tools are also included in LabVIEW. Breakpoints and single-stepping through the program can be done in the LabVIEW environment. These make debugging and program development easier. LabVIEW provides numerous mechanisms for connecting to external code or software through DLLs, shared libraries, ActiveX and more. In addition, many add-on toolkits (for example, the Internet toolkit and DSP toolkit) are available for a variety of application needs.

Essentially, the distant remote monitoring application, as with other network applications, consists mainly of two parts: the client and the server. The main idea behind the implementation of the remote monitoring session is to deliver the raw vibration data as well as the analysis results to the client as real-time as possible. The client runs a web browser to view the remote front panel and uses the LabVIEW run-time engine to control the remote program. The run-time engine can be freely downloaded from the website of National Instruments Pte Ltd [12]. The software requirements and interaction are depicted in Fig. 5.

HTTP server

A Hypertext Transfer Protocol (HTTP) *server* is a computer program (housed in a host computer) that serves HTML pages or files and run applications on the host when requested by client machines over the Internet. The *Internet Developers Toolkit* package [12], an add-on component

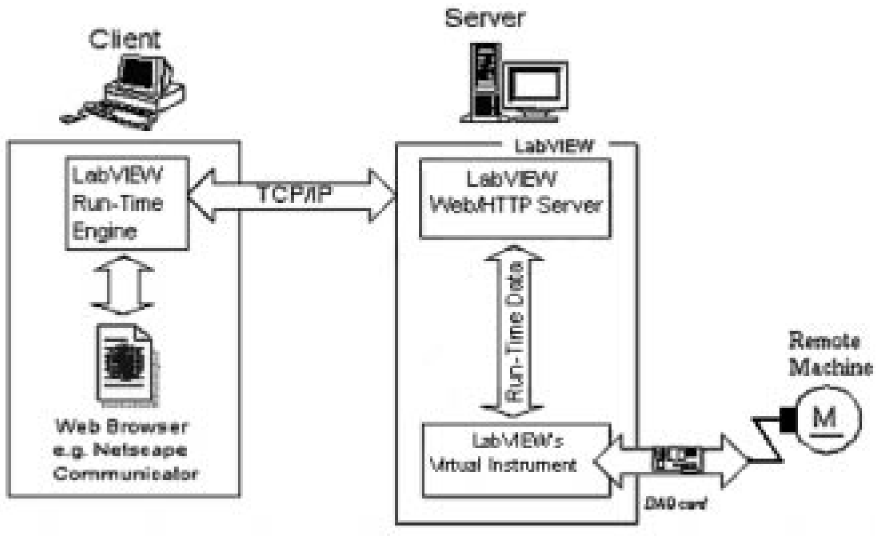

Fig. 5. Software requirements and interactions.

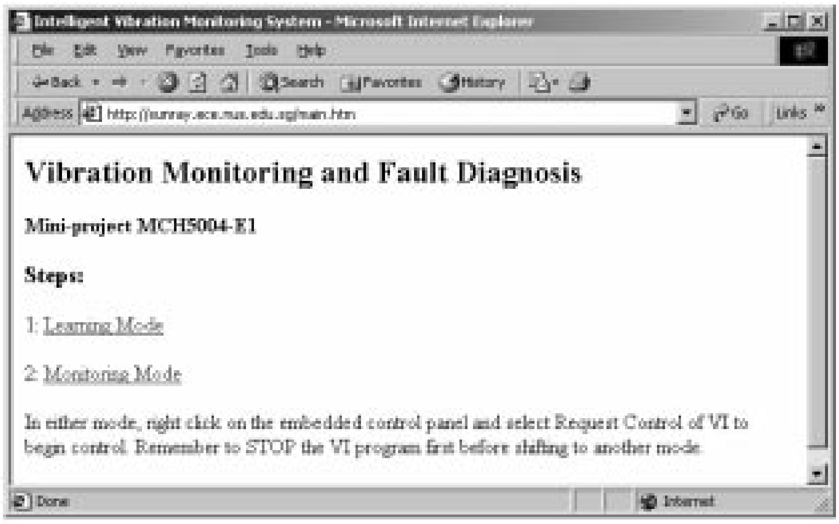

Fig. 6. User interface of the remote vibration monitoring system.

to LabVIEW, allows VIs to be converted into Internet-enabled applications.

User interface

The system uses a new feature of LabVIEW 6.1 to emulate a remote front panel. Compared to earlier versions of LabVIEW, this new feature greatly reduces the requirements in terms of network programming and bandwidth, as only crucial information will be transmitted. On the client's side, all the data transfer, in either direction, is realized using the LabVIEW run-time engine. The user can thus monitor and control the virtual instruments (VIs which are the programs) just as though they are running on the local PC. The home page serves as the gateway to the operational modes of the system is shown in Fig. 6.

Access security

Publishing the front panel on the Web will inevitably present security concerns, since anyone who can gain control of the VI can also manipulate it. So adequate access security must be put in place to prevent the system from being modified in any form by unauthorized users. In the experiment, access security is incorporated into the LabVIEW Web Server. It is achieved via the Basic Access Authentication scheme as specified in HTTP/1.0. It is a simple challenge-response authentication mechanism that is used by a server to challenge a client request and by a client to provide authentication information. It is based on the model that the client must authenticate itself with a user-ID and a password for each realm. The server will service the request only if it can validate the user-ID and password for the protection space of the Request-URL. It is also possible to control the access based on user name, password and user's IP address.

THE EXPERIMENT

A shaker table (Fig. 7) is used as the test platform representing the machine to be monitored. It is driven by a high torque direct drive motor (which has a maximum torque of 1.11 Nm, a maximum design load of 11 kg and generates a maximum force of 175 N). The maximum linear travel of the table is ±2 cm. An accelerometer mounted on the shaker table, as shown in Fig. 6, provides the vibration measurements. The specifications of the accelerometer used in the experiment are provided in Table 1. Normal operating conditions are emulated as corresponding to the shaker table receiving a sinusoidal input sequence at a frequency of 15 Hz.

The acquisition card, used in the experiment to acquire the measurements from the accelerometer, is one from National Instruments (model: *PCI-MIO-16E-4)*. The acquisition card supplies two channels of analog output and up to eight channels of analog input. The main specifications of the card are given in Table 2.

After a series of exercises on the essentials of LabVIEW through the tutorials provided on the

Table 1. Specifications of the accelerometer used in the experiment

Description	Value	
RemarkSpan (G)	±4	±5%
Sensitivity (mV/G)	500	±5%
Bandwidth (Hz)	DC-100	±5%
Noise (mg rms)	5	Typical
Zero G output (V)	+2.5 ± 0.1	@25 deg C
Zero G Drift (mV)	±60	0–70 deg C
Span output (V)	±2.0 ± 0.1	@25 deg C
Nonlinearity (%FS)	±0.2	Typical
Temperature range(deg C)	-40 to +85	
Alignment (degrees)	±2	Typical
Shock (G)	1000	
Output loading	>10KO < 1 nF	Max
Supply voltage (V)	+5 ± 0.25	
Supply current (mA)	8	Typical

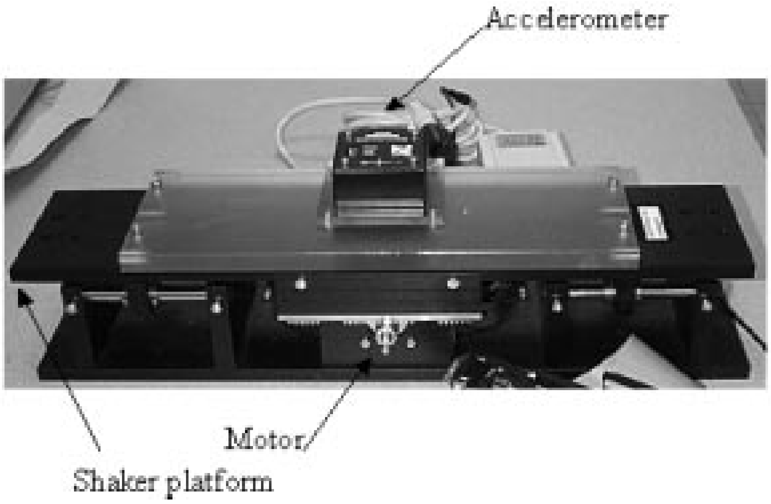

Fig. 7. Shaker table test-bed.

website of National Instruments [11], the students will first design the program which runs on the server side to implement the intelligent vibration monitor system. It comprises the main steps, as shown in Fig. 1, necessary to implement the two modes of the system. The monitoring system is test-run locally first, on test data files as well as on the actual shaker table, to ensure that the system works in the two modes accordingly. Thereafter, the system is tested from a remote client connected to the Internet using a regular web-browser, to verify that the two modes can be operated remotely. In what follows, snapshots of the system at the client's side will be presented in order.

Table 2. Specifications of the DAQ card PCI-MIO-16E-4

Specifications	
Input characteristics	
1. Number of channels	16 single-ended
2.	
3. Type of ADC	Successive approximation
4.	
5. Resolution	12 bits, 1 in 4096
6.	
7. Max sampling rate	500 KS/s (KS: kilo samples)
8.	
9. Input coupling	DC
10.	
11. Input range	± 5 V
Bandwidth	600 kHz
Digital I/O	
1. Number of channels	8 input/output
2.	
3. Compatibility	TTL/CMOS
4.	
5. Power-on state	Input (High-Z)
6.	
7. Input Low voltage	0.0 to 0.8 V
8.	
9. Input High voltage	2.0 to 5.0 V
Slew rate	20 V/μs
Power requirement	+5VDC (0.9 A)

Initiating a session

At the client's side, the user will initiate a new session from a web browser, by specifying the *URL* of the server. The access authentication security scheme will be used to enable access to authorized users. The front panel (Fig. 1), serving as the user interface, will then be served from which the user can initiate either of the modes.

Learning mode

In the learning mode, the shaker table is set to receive the 'normal' sinusoidal input at a fixed frequency (15 Hz) which emulates the 'normal' working conditions of the machine. An example of the user-interface, as presented to the user in this mode, is shown in Fig. 8. The vibration signature, in the form of the vibration spectrum [9], is derived from the vibration signals with the machine running under these 'normal' conditions. The exact alarm threshold settings can be easily adjusted through the reference spectrum equalizers, thus producing the reference spectrum which can be displayed together with the spectrum of the actual vibration signals as shown in Fig. 8. By clicking on the Reference Spectrum Reset switch, the reference information thus derived will be stored in a data file residing in the server. This reference information can be later loaded for analysis purposes when running the monitoring mode of the program.

Monitoring mode

Following the learning mode, the user should put the program to run continuously in the monitoring mode. If the vibration spectrum computed is within the reference envelope, no alarm will be generated since the machine is deemed to be operating normally, as shown in Fig. 9. When the spectrum changes (for example, as a result of using a new input sequence emulating the occurrence of an abnormal event), the resultant vibration spectrum computed exceeds the acceptable threshold, thus triggering the alarm signal, as

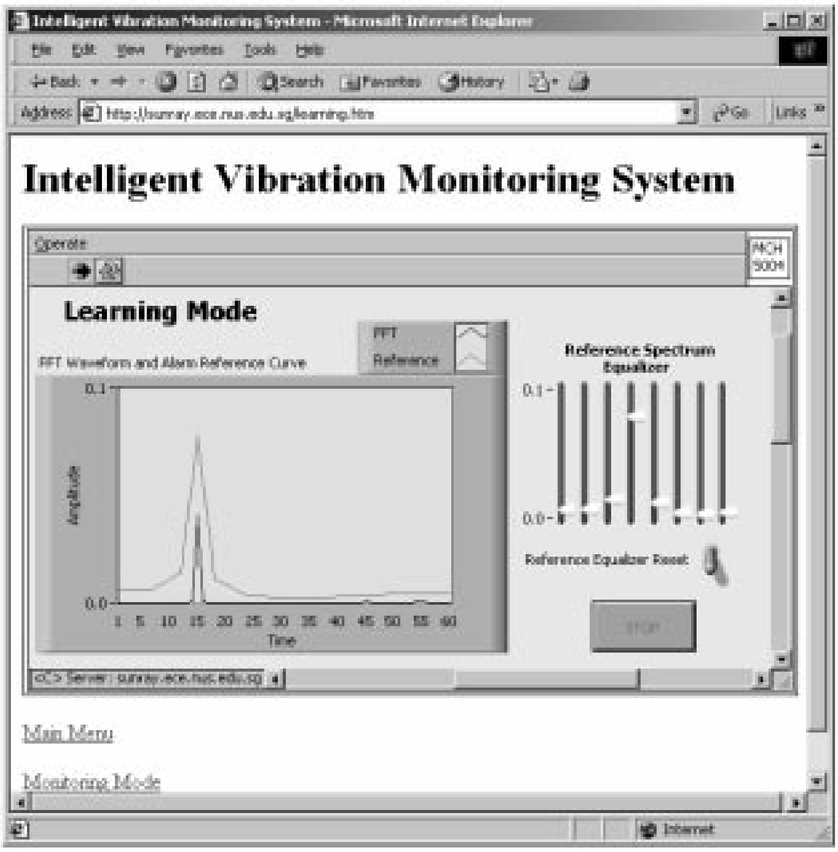

Fig. 8. Snapshot of the interface when the system is in the learning mode with the shaker receiving a 15 Hz sinusoidal signal.

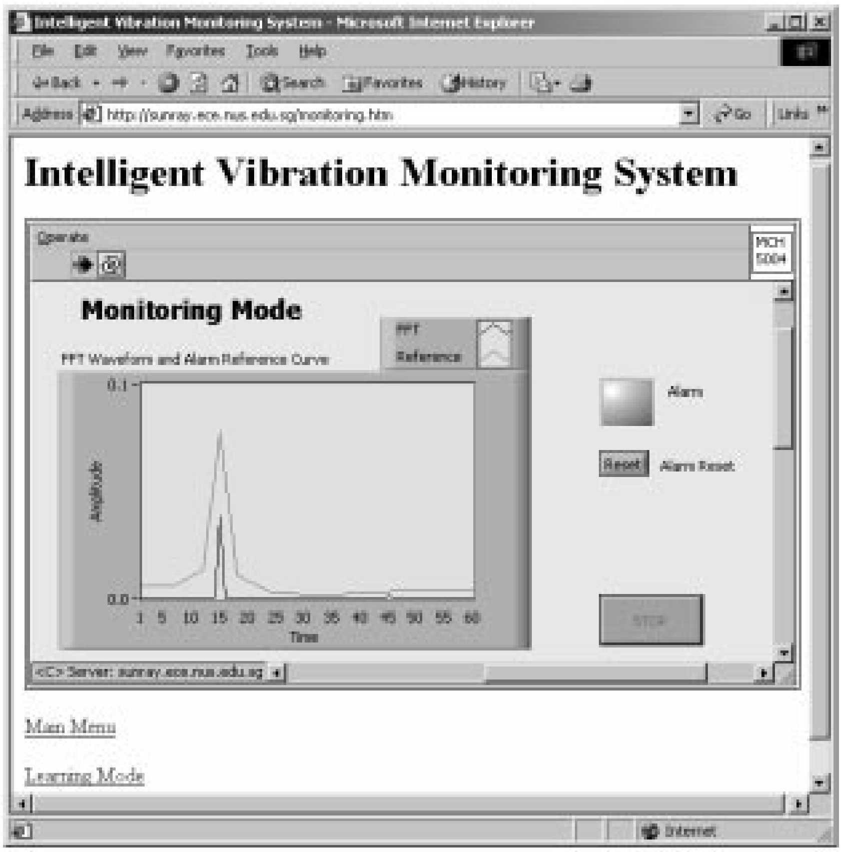

Fig. 9. Snapshot of the interface when the system is in the monitoring mode with the shaker receiving a 15 Hz sinusoidal signal.

Fig. 10. Snapshot of the interface when the system is in the monitoring mode with the shaker receiving a 15 Hz square wave signal.

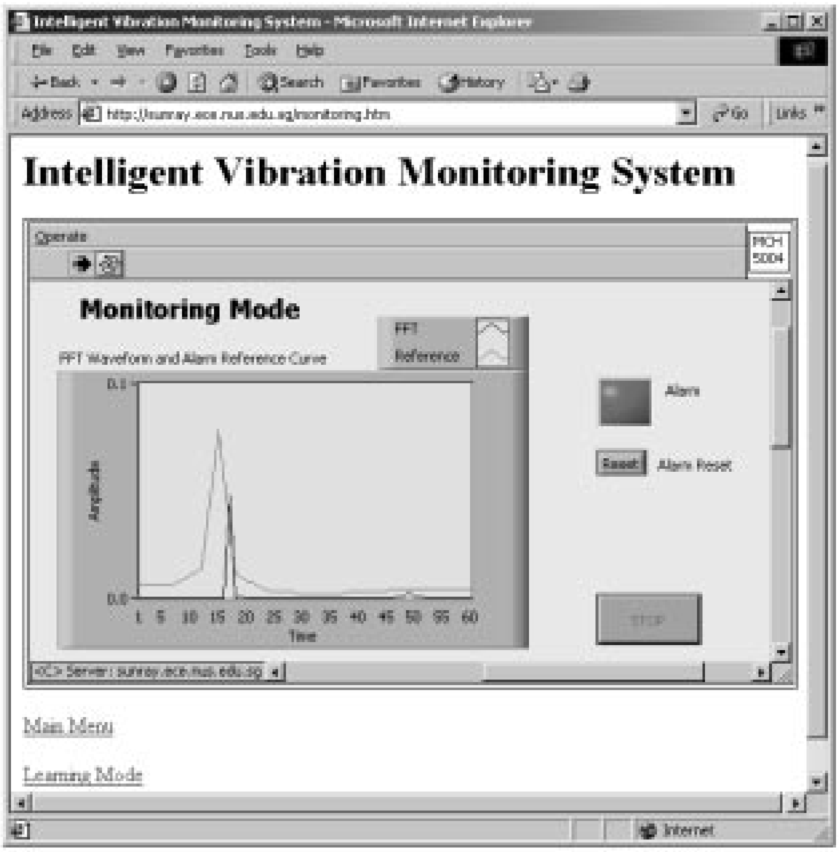

Fig. 11. Snapshot of the interface when the system is in the monitoring mode with the shaker receiving a 17 Hz sinusoidal signal.

shown in Figs 10 and 11 when a change in signal type and frequency is made respectively.

CONCLUSIONS

The development of a mechatronic experiment on the development of an intelligent vibration monitoring system for remote vibration signature analysis via the Internet has been presented in the paper. It uses a vibration signature analysis approach in the frequency domain to determine the health of the machine, based on only the vibration signals. Using only off-the-shelf components, the entire system can be operated from anywhere with an access to the Internet.

REFERENCES

1. N. Kyura and H. Oho, Mechatronics—an industrial perspective. *IEEE/ASME Transactions on Mechatronics* **1**(1), 1996, pp. 10–15.
2. R. W. Daniel, and J. R. Hewit, Editorial, *Mechatronics*, **1**(1), 1991, pp. i–ii.
3. V. A. Job and J. Wim, Mechatronics in the Netherlands, *IEEE/ASME Trans. Mechatronics* **1**(2), 1996, pp. 106–110
4. S. Vesa, Ten years of mechatronic research and industrial applications in Finland, *IEEE/ASME Trans. Mechatronics,* **1**(2), 1996, pp. 103–105.
5. K. K. Tan, T. H. Lee, H. F. Dou and S. Y. Lim, Various developments in mechatronics in Asia, Mechatronics, **8**, 1998, pp. 777–791.
6. Clarence W. de Silva, *Vibration, Fundamentals and Practice, CRC* Press LLC: Washington DC, (1999).
7. Tim Berners-Lee Biography, http://www.decus.org/decus/people/berners-lee.html
8. Robert K. Vierck, *Vibration Analysis*, Crowell, New York, (1979).
9. Robert W. Ramirez, *The FFT Fundamentals and Concepts,* Prentice-Hall Inc., Englewood Cliffs, (1985).
10. K. Z. Tang, K. K. Tan and C. W. de Silva, Monitoring and Suppression of Vibration in Precision Machines, *J. Intelligent and Fuzzy Systems*, under review, (2002).
11. Application notes and other references on National Instruments LabView webpage, http://www.natinst.com/labview.
12. National Instruments LabVIEW Internet Developers Toolkit Webpage http://www.natinst.com/labview/internet/

Kok Kiong, Tan received his Ph.D. in 1995 from the National University of Singapore (NUS). Prior to joining the university, he was a research fellow at SIMTech, a national R&D institute spearheading the promotion of R&D in local manufacturing industries, where he has been involved in managing industrial projects. He is currently an associate professor with NUS and his current research interests are in precision motion control and instrumentation, advanced process control and autotuning, control and monitoring via the Internet, and general industrial automation.

Kangning, Wang is currently a Master of Engineering student with the National University of Singapore working on his thesis on remote monitoring and virtual experiments.

Kok Zuea Tang is currently a Ph. D. student with the National University of Singapore. He obtained his M.Eng. in 2000 and his current research interests are in precision motion control and remote monitoring.