

# A Remote Demonstration System to Enhance Engineering Classroom Instruction and Student Learning\*

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*This paper describes the development of a unique remote laboratory instructional aid for illustrating advanced concepts in structural dynamics using smart actuators and sensors and wireless communication technology. Specifically, a remotely operated laboratory demonstration system is developed using spread spectrum wireless modems, data communication software, and an experimental cantilever/cantilever beam structure with integrated piezoelectric sensors and actuators. This system can be used to excite a structure located in a laboratory setting far removed (approximately 1 mile) from the classroom environment to obtain vibration data. Commands are issued from a notebook personal computer to instruct the system to either excite the structure or acquire data from sensors mounted externally to the structure. Data from measurements made on the structure are then transmitted wirelessly back to a notebook computer for processing and analysis in the classroom environment. Advanced concepts such as modal analysis, damping, and nonlinear phenomena can be illustrated to students using data from an experimental structure without ever leaving the classroom setting.*

## INTRODUCTION

CLASSROOM INSTRUCTION can at times be difficult when there is a need to demonstrate a particular concept experimentally such as the various analysis tools used in the field of structural dynamics to process vibration data. It is common to have students either perform experiments in the laboratory or to hold classroom instruction in the laboratory setting to demonstrate important concepts. However, because of student safety, insufficient laboratory space, and the operation of intricate equipment, it is not always possible to have students enter research environments to demonstrate important concepts. Thus, there is a need to expose students in the classroom environment to experimental research testbeds to enhance their understanding of advanced concepts of a particular subject matter. This can be accomplished using wireless communication technology, a personal computer and the use of data communication software.

This paper describes the components of a remote wireless laboratory demonstration system for measuring static and vibratory loads on an experimental aluminum beam structure with a bolted-lap joint located at its mid-span. The uniqueness about this system is that it is portable, self-contained, and inexpensive. It can be programmed to actively excite the structure to retrieve sensor data, or to passively retrieve

sensor data generated from ambient excitations. The system can be used as a valuable instructional aid to illustrate important concepts in structural dynamics such as, modal analysis, damping, nonlinear phenomena, and the effects of boundary conditions on the vibration response. In addition, the system has a dual-use capability, which permits it to double as a research system for monitoring the health of structures remotely. This is an important attribute considering the fact that there has been a considerable amount of activity in the field of structural health monitoring and damage detection [1-11] with the majority of publications appearing in the literature in the last 5 years.

Nevertheless as an aid for classroom instruction, the system must be capable of performing two functions: (1) first acquire the data from externally mounted or embedded sensors on a structure and (2) deliver this data back to the classroom environment for processing, analysis and interpretation. Acquisition of the embedded sensor data by traditional methods does not pose a difficult task, however, transferring this data from one location to another effectively and economically is indeed a challenge. Since many classrooms in engineering schools are not equipped with local area networks (LANs) or phone jacks, a wired connection is not always a viable option. A more economical and practical approach is to avoid the dependency on a wired connection by exploiting wireless communication technology. Data from sensors located on the structure can then be transferred through the air to either a laptop or personal computer located in the classroom environment.

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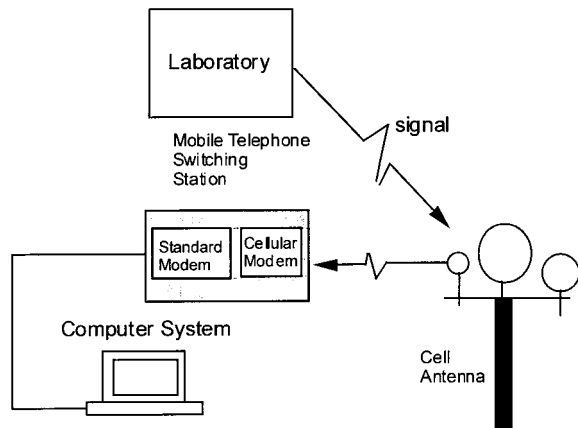


Fig. 1. Pictorial of a wireless cellular dial-up data transfer system.

#### Options for wireless data transfer to a remote location

Wireless communication technology in the United States has evolved over the last two decades to a point where there presently exists a wireless communication infrastructure for transmitting voice and electronic data. Auctioning of the frequency spectrum over the last 20 years by the Federal Communication Commission (FCC) has spawned new industries in analog cellular telephony, digital radio and now more recently digital cellular telephony in the form of the personal communication system (PCS). In addition, the FCC has recently set aside a frequency band allotted strictly for use by educational institutions for the transfer of data. Therefore, data gathered remotely can be easily transferred to any location where cellular telephony and digital radio is supported (See Fig. 1). These systems exist in most metropolitan communities.

Current firms offering wireless services in either digital radio or digital cellular are listed in Table 1. Digital radio is primarily a low throughput system set up for one-way and two-way paging services.

Digital cellular, however, provides considerable throughput with a direct wireless link to a potentially mobile processing center for data retrieval. Cellular voice channels, however, throw a number of obstacles in the path of dial-up data. The first and probably most important being cellular modems. Because of frequent data errors these modems must be equipped with special protocols to handle pure data streams. Nevertheless, cellular carriers are taking steps to ensure reliable high-speed performance over their networks.

One approach which attempts to circumvent the cellular infrastructure involves combining the infrastructure of the information superhighway, the Internet, with wireless telemetry. This scheme exploits the radio frequency part of the spectrum to transfer data from a remote location over short distances to a local Internet provider. This data is then sent over wire via the Internet to a central location for evaluation. A recently formed corporation called Tetherless Access Ltd (TAL) specializes in such systems. TAL's technology allows personal computers, workstations, and local area networks to be networked wirelessly, with single-link distances of up to 30 kilometers and the ability to cover greater distances with multiple wireless hops. TAL's advanced technology delivers raw data throughput of 160 kilobits per second (Kbps), or an average end-user rate in a loaded network of 64 Kbps. TAL networks make use of low-cost, scalable technology and license-free part of the radio spectrum over short distances. This system, however, is still under development and does not exist in most metropolitan areas.

#### A REMOTE WIRELESS LABORATORY DEMONSTRATION SYSTEM

A more economical approach to wireless data transfer for in-class laboratory demonstrations has evolved from a recent FCC ruling to allocate a significant portion of the 900 MHz frequency band license-free to digital data transfer over short

Table 1. Companies offering digital wireless services

Wireless services	Type	Coverage	Speed	Availability	Internet access
Ardis	Packet radio	Nationwide, urban	1 Kbps	All major cities	E-mail
RAM mobile data	Packet radio	Nationwide, urban	2 Kbps	All major cities	E-mail
Destiner	Two-way paging	Nationwide, urban	< 1 Kbps	Est 1995	E-mail
Circuit switched cellular (Cellular One, Bell Atlantic, etc.)	Dial-up and cell phone	Nationwide, urban and some rural	4.8 Kbps and higher	All major cities	Full dial-up capability
Cellular digital packet DAT	Packet cellular	Nationwide, urban and some rural	4.8 Kbps	19 cities	Full dial-up capability
Metricom	Unlicensed packet radio	University and corporate	19.2 Kbps	3 cities	Full dial-up capability
Tetherless Access Ltd	Unlicensed packet radio	Selected locations	56 Kbps	In beta test phase	High-speed backbone
Teldesic	Low earth orbit	World-wide	2 Mbps	Year 2001	High-speed backbone

distances. This ruling has resulted in the development of a number of new products including digital home telephones, security systems and wireless modems. The digital home telephones and security systems typically operate at 900 MHz frequencies with ranges up to 500 ft. Similarly, the wireless modems operate in the 902 to 928 MHz frequency range using spread spectrum technology and are made by several manufacturers with data throughputs greater than 28.8 Kbps. The advantages of spread spectrum technology used in wireless modems include system flexibility, interference immunity, error-free communication and real-time data throughput. In addition, these wireless modems can be configured to have two-way capability along with the ability to transfer voice data. However, the most unique feature about the wireless modems is that the FCC has permitted them to be operated over greater distances (approximately 3 to 5 miles) with minor modifications in the transmitting antenna. Even greater distances are possible by using them as transceivers involving multiple wireless hops before arriving back at a some central or mobile processing

center. Customizing the communication software of the modems which handles error detection, packet sequencing and flow control can minimize interference from other similar wireless modems. Therefore, the existing communications infrastructure for cellular telephony can be avoided altogether by effectively using spread spectrum wireless modems to transfer data obtained from sensors mounted on experimental testbeds.

*Components of a remote demonstration system*

Figure 2 displays a schematic of a simple and inexpensive remote demonstration system for retrieving data from an experimental fixed/fixed cantilever test structure. The system consist of two wireless modems, a notebook computer, a data acquisition system and data communication software for uplinking commands and downloading sensor data. It is assumed that sensors, mounted either internally or externally to the structure, are monitored by a data acquisition system in close proximity to the experimental test structure. The system can be powered by battery in case of loss of electrical power. Commands from a notebook

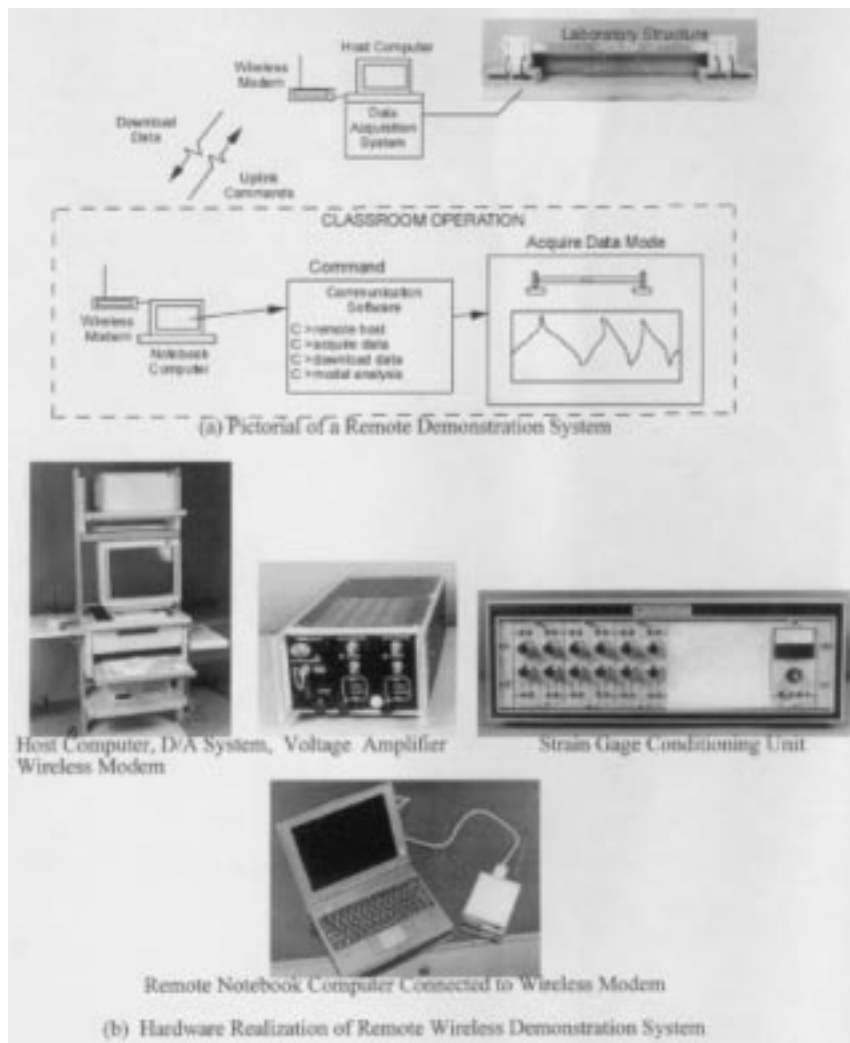


Fig. 2. Schematic of a remote wireless demonstration system.

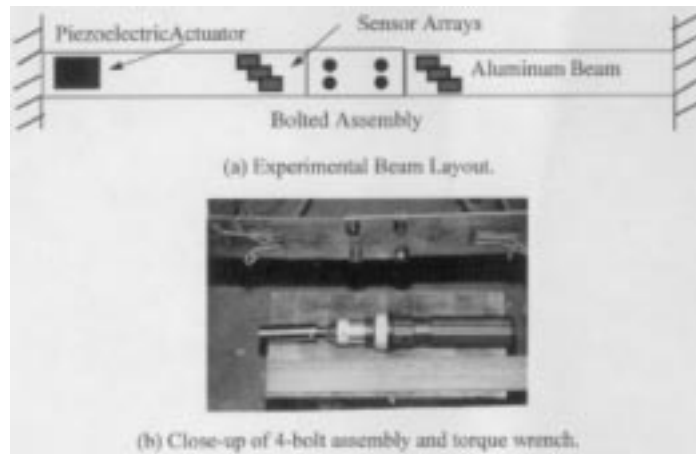


Fig. 3. Layout of laboratory beam.

computer are uplinked via the wireless modems to instruct the data acquisition system to record sensor measurements. Upon retrieving this data, additional commands are issued to download the data back to a remote notebook computer for analysis and interpretation in the classroom. The use of the notebook computer permits the operator to be mobile or stationary.

### VALIDATION OF REMOTE DEMONSTRATION SYSTEM

#### *Description of system*

To test and validate the approach described in section 3.0 and displayed in Fig. 2, a simple laboratory fixed/fixed aluminum beam structure was constructed with a bolted joint located in the center of the beam (See Fig. 3 and Table 2). Strain sensor arrays were placed on both sides of the bolted joint to detect changes in mechanical impedance due to loss of torque load. A host personal computer (PC) was used to instruct a Data Acquisition System to excite the structure in bending. Measurements were then recorded from all six strain sensors.

Commands to excite the structure and take data were up-linked from a notebook computer through a spread spectrum wireless modem located approximately 500 ft away from the data acquisition system in a remote classroom environment. Commands from the remote notebook computer were received through a second wireless modem connected to the host PC used to drive the data acquisition system near the site of the experimental

structure in the laboratory. The wireless modems use the standard RS-232 serial data interface at rates up to 38.4 Kbps in the frequency range from 902 to 928 MHz. A batch file was created on the host computer to generate steady-state and transient excitation commands to a piezoelectric actuator placed near the left fixed-end of the beam. Strain sensor data was then recorded on the hard drive of the host PC used to drive the data acquisition system. Once the sensor data was acquired, it could be retrieved across the same wireless modem link back to the notebook computer for assessment of damage in the bolted joint. Communication between the two computers and the two wireless modems was established using off-the-shelf communication software. This communication software enables the user to make the remote notebook emulate the host PC. Thus, commands issued in either the Windows or DOS environment of the remote notebook computer become the commands issued on the host PC. However, the communication software is more than just an emulation tool, it also enables the operator to view commands being carried out on the host computer.

Table 3 summarizes components used to create this remote wireless demonstration system. The system was validated at ranges up to 1 mile for approximately 1-hour without loss of communication link. However, communication link is strongly dependent on direct line-of-sight between the two wireless modems. Fortunately, a direct line of sight signal from the wireless modems was impaired as it passed through masonry building structures.

Table 2. Properties of Aluminum beam

Physical properties	Values/units
Stiffness, EA	29 MN-m <sup>2</sup>
Mass per unit length, $\rho A$	1.13 kg/m
Length	1.524 m
Torque capacity of bolts	100 oz-in

#### *Operation of remote demonstration system*

Using the *Communication* software, a communication link was established via the wireless modems to make the remote notebook PC emulate the windows environment of the host computer used to drive the data acquisition system. Upon emulating the windows environment of the host

Table 3. Components of remote wireless demonstration system

Item	Manufacturer
Wireless modem	Aerotelemetry Inc., model: Gina
Data acquisition system	Aerotelemetry Inc., model: Gina
Remote notebook personal computer	Hewlett Packard, model: 35655A (16-channel, 16-bit A/D)
Host personal computer	Pentium 100 AST
Communication software	NOW 486-DX50
Custom system identification/damage detection software	PC Anywhere, Symantec MATLAB, Mathworks Corp.

computer, the data acquisition software could be initiated to drive the actuator with one of three output signals; white noise, swept sine or a single transient pulse. Transfer function responses for all six strain sensors were obtained using either the white noise or swept sine output modes. Strain sensor transfer function response data was then temporarily stored on the hard drive of the host computer. A download command was then issued from the *Communication* software to transfer data to the remote notebook computer. Upon receiving the downloaded strain sensor response data, the software Matlab was initiated on the remote notebook computer to run system identification and modal analysis algorithms. Results for the undamaged and damaged system were plotted to the screen of the remote notebook computer and later stored as image files.

Figure 4 illustrates this complete system in operation during a typical data run where a swept sine signal is being sent to the piezoelectric actuator to obtain transfer function data from the six strain sensors. Notice that in Fig. 4 the screen of the remote notebook computer displays exactly

the same data that is being recorded and displayed on the host PC across the wireless link in near real-time (approximately a 3 s delay).

For classroom instruction the laptop computer can be conveniently connected to an overhead projector display panel so that students will be able to follow the command sequence while the system is in operation. A summary of the command sequence for a typical data collection is given below:

- *Setup mode: wireless modems*  
Step 1: Configure modem parameters for data transfer.
- *Setup mode: host computer*  
Step 1: Boot-up the host PC (Windows environment).  
Step 2: Enable communication software to accept calls from the remote computer.
- *Setup mode: remote notebook computer*  
Step 1: Boot-up remote PC (Windows environment).  
Step 2: Enable communication software
- *On-line mode: command sequence for a remote operator with remote notebook computer*  
Step 1: From the communication software click on the call button to access the host computer. The remote computer should emulate the host computer's screen.  
Step 2: Once connection has been established, click on the data acquisition icon to initialize its system software and begin taking data.  
Step 3: After collecting the data, the user could request the file transfer command from the on-line menu to transfer data files from the host computer to the remote computer via wireless modem.  
Step 4: Initiate Matlab program software.  
Step 5: Load data from sensors and run custom system identification and modal analysis software.



Fig. 4. Remote wireless demonstration system in operation. In real-time, remote computer emulates host computer's screen during a data collection session.

Once the communication link is established during the setup mode, sensor data can be retrieved within seconds.

#### Demonstration on a sloppy bolted joint

Using this remote demonstration system, the laboratory fixed/fixed aluminum beam specimen with a bolted joint was excited in bending to obtain transfer function and transient response data from moment to strain sensor. This data was retrieved across the wireless link for various uniform torque loads. The maximum torque that the bolted assembly could support prior to yield was 100 in-oz. System identification was used to identify the transfer function model for the maximum torque load case. A graduate student with aid of a torque wrench varied the torque load on the bolted assembly from 30 in-oz to 100 in-oz at increments of 10 in-oz. Experimental results indicate that as the torque load is reduced, initially the beam gets softer. However, as the torque is reduced below 60 in-oz the bolt takes more of the dynamic load and the structure appears to get stiffer.

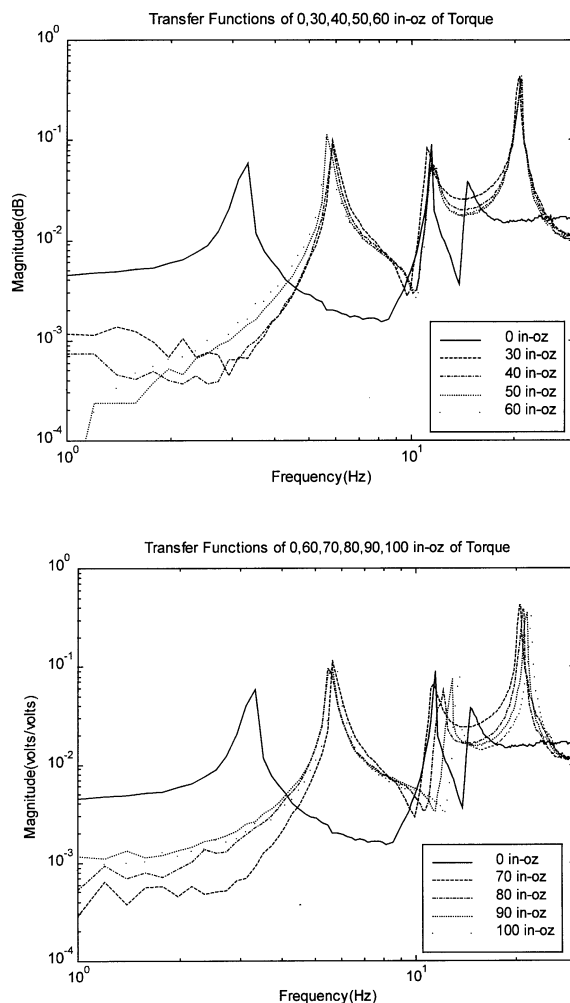


Fig. 5. Transfer function response from moment actuator to middle strain sensor on left side of bolt assembly for various bolt torque loads.

These observations are illustrated in Fig. 5 which plots the transfer function for the middle strain sensor on the left side of the beam. The sloppy bolted joint case (0 in-oz case) is plotted in both graphs to illustrate the loss of energy and nonlinear effects introduced by the joint dynamics.

In the classroom environment, a lumped-parameter model of the nonlinear bolted joint dynamics can be introduced as:

$$m\ddot{x} + c\dot{x} + k_{NL}x = F - \mu N \text{sign}(x) \quad (1)$$

where  $m$  is the mass of the bolted assembly,  $c$  is the viscous damping,  $k$  is the nonlinear spring stiffness and  $\mu$  is the static or dynamic friction coefficient between the bolt, nut and structural members. Dividing equation (1) through by  $m$  leads to:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2x = F/m - \mu \text{sign}(x)/m \quad (2)$$

where  $\zeta$  is the damping ratio and  $\omega_n$  is the natural frequency of vibration.  $N$  is the normal force created by the meshing on the bolt, nut and members. Using the vibration data, the various terms of this lumped-parameter model can be identified to illustrate the nonlinear effects of a bolted joint on the modal vibration response. Results from system identification of the first three modes are listed in Tables 4 and 5 for the various torque loads. Notice that viscous damping,  $\zeta$ , increases with loss of torque load. However, natural frequency values for the first three modes shows an initial joint softening followed by joint stiffening as the torque load is reduced. This corresponds to a redistribution of the preload from the members to the bolt. As the members begin to separate, the bolts are carrying more of the dynamic load. This is an important result that is difficult to convey to students without such an apparatus to develop and test nonlinear models of bolted joints in the classroom.

## SUMMARY AND CONCLUSIONS

This paper has presented a simple and inexpensive approach for a remote laboratory demonstration system involving spread spectrum wireless modems, a PC-based data acquisition system, off-the shelf communication software, conventional sensors, and custom vibration analysis software. The total cost of the components used to set up the remote wireless demonstration system was less than \$10 000, not including the cost of the data acquisition system. The system has been validated on a laboratory test structure with a bolted joint over ranges of up to approximately 1 mile with no loss of communication signal. Data rates achieved on transferring data files are

Table 4. Tabulation of modal natural frequencies (Hz)

Natural Freq.	30 in-oz	40 in-oz	50 in-oz	60 in-oz	70 in-oz	80 in-oz	90 in-oz	100 in-oz
Mode 1	5.8953	5.8051	5.6870	5.6237	5.7169	5.5004	5.5199	5.7187
Mode 2	11.1166	11.4789	11.4895	11.6174	11.2594	11.9579	12.7416	13.4211
Mode 3	20.4378	20.6762	20.7143	20.7580	20.4412	20.9161	21.4379	22.2407

Table 5. Tabulation of damping ratios ( $\zeta$ )

Damping ratios	30 in-oz	40 in-oz	50 in-oz	60 in-oz	70 in-oz	80 in-oz	90 in-oz	100 in-oz
Mode 1	0.0176	0.0150	0.0148	0.0142	0.0164	0.0124	0.0083	0.0072
Mode 2	0.0128	0.0154	0.0074	0.0074	0.0074	0.0066	0.0098	0.0076
Mode 3	0.0078	0.0078	0.0150	0.0160	0.0147	0.0148	0.0065	0.0066

in the order of 38.4 kbps which are faster than conventional modems. The system will find great use as an instructional aid to help illustrate modeling concepts and advanced principles of structural dynamics when compared with real experimental test data. Such a system may find use in courses where there are either limited laboratory resources,

intricate equipment, large class sizes or safety issues that prevent students from entering the laboratory setting.

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