

Instrumentation for Remote and Continuous Monitoring of Structure Conditions

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Long-term continuous monitoring of structures may be helpful in many aspects of structural engineering when parameters of interest can be affected significantly over time. Such monitoring systems require high-speed data acquisition systems, highly sensitive sensors, efficient operating software, and remote control and transfer mechanisms for data collection. Such remote monitoring systems are now possible. To test the idea of continuous monitoring for bridge structures and to examine the sensitivity of vibration properties to structural damage or deterioration, specifications for remote bridge-monitoring systems were developed. They were implemented on two bridges for experimental monitoring of conditions. Their capabilities are described and experience in their design, installation, and operation is summarized. Although intended for use in monitoring bridge structures, they may also be used where remote monitoring is appropriate for such civil engineering structures as dams, retaining walls, buildings, pavements, drainage structures, and traffic signal and sign structures.

Long-term continuous monitoring may be helpful for periodically evaluating structures, making decisions for preventive maintenance, and examining new design techniques. Such monitoring systems require high-speed data acquisition systems, highly sensitive sensors, efficient operating software, and remote control and transfer mechanisms for data collection. As a result of the advent of sensors with built-in electronics, high-speed digital boards, and fast computers, the development of such remote monitoring systems has become realistic.

Remote and continuous monitoring systems have been proposed as supplements to current inspection procedures for evaluating the conditions of structures. In general, such monitoring systems are required to identify damage or deterioration and then issue warning signals for necessary actions such as repair, rehabilitation, or operation control until the structure's condition is improved and satisfies current standards for operation. To meet these requirements, structure conditions must first be correlated with stable and measurable indexes (such as natural frequencies, mode shapes, and their derivatives). Criteria need to be developed to correlate changes in these indexes with structural damage or deterioration. A baseline should be established for these indexes. Data can then be collected continuously or periodically to determine these indexes at various times and to compare them with their baseline values for the detection of damage or deterioration by using the established criteria. It is important that these criteria take into account such field conditions as environmental effects (due to moisture, rain, snow, heat, etc.), variable loadings, and

electromagnetic disturbances to the data acquisition process. Moreover, the required instrumentation should be designed so that it can be sustained under these conditions for continuous data collection and processing with the needed precision.

A study was undertaken to examine the feasibility of using continuous monitoring for the detection of bridge damage or deterioration. The study identified feasible structural indexes for detecting such damage or deterioration by laboratory testing and theoretical analysis and examined the applicability of these indexes in the field. This paper focuses on experience with field instrumentation for remote bridge-monitoring systems (RBMSs) with the results of laboratory tests briefly summarized first. Construction specifications for RBMSs were developed for two bridges in Rochester, N.Y., and were included in their rehabilitation requirements. Data are being collected from a remote office to establish and study a baseline of structural indexes for consideration of the service environment and to examine the sensitivities of these indexes to structural damage or deterioration.

MODAL PROPERTIES AS STRUCTURAL INDEXES FOR DAMAGE DETECTION

In the present study, modal properties (natural frequencies, damping ratios, and mode shapes) and their derivatives [modal assurance criterion (MAC) and coordinate modal assurance criterion (COMAC)] were selected as the major structural indexes for condition assessment and monitoring because of their theoretical inherence to structures (1,2). Experimental modal analysis techniques were used to identify these indexes and study their variation as a result of the test environment. The impact test (3) was chosen to obtain these indexes because of its recognized reliability. In impact tests, several points on the structure are excited with an impact hammer. During each impact, excitation and structural responses at a measurement point are simultaneously recorded with a load cell and an accelerometer, respectively. Frequency response functions (FRFs) are calculated from these data by the Fourier transform theory (3). These structural indexes are estimated by using the FRFs. It is well known that because of various environmental noises, indexes based on measured data vary, even though the structure is unchanged.

Modal tests were first conducted on a $1/6$ -scale steel bridge model in the laboratory and a full-scale steel bridge in the field with portable instrumentation. The impact test was repeated 18 times over 6 months on the model to examine the repeatability of the measured structural indexes. These results were also used as a reference to evaluate another test method by using ambient traf-

fic as the vibration excitation for field application without affecting traffic (4,5). The impact test was also repeated 10 times over 2 months on a full-scale steel bridge to estimate variations in the measured structural indexes in the field. These tests led to the following conclusions (4-6).

1. Natural frequencies, mode shapes, and their derivatives may be considered for the detection of damage or deterioration on highway bridges. Criteria for warning triggers obtained by using these indexes need to be established to account for random variation in these indexes as a result of environmental conditions and the data collection process.

2. With consistency comparable to that of the impact test method, the ambient traffic excitation method can be used for remote and continuous monitoring without affecting traffic.

3. A limited number of lower modes may not be adequate for the detection of damage or deterioration, because certain types of damage or deterioration may affect only higher modes, and additional indexes of other modes may increase the confidence of diagnosis.

4. Temperature may change modal properties significantly, especially when support conditions are altered as a result. Thus, monitoring of temperature should be considered in a remote continuous monitoring system so that thermal effects can be included in the analysis and interpretation of the data obtained.

5. Care should be exercised in choosing the locations for transducers on the structure so that critical elements can be monitored effectively.

6. Cross-diagnosis (using multiple indexes or techniques) is warranted for the detection of damage or deterioration in real-world applications, since a single index cannot be conclusive because of the inevitable variation in the measured data.

REQUIREMENTS, SPECIFICATIONS, AND CAPABILITIES OF INSTRUMENTATION

On the basis of these conclusions and the experience gained in the laboratory test (4-6), specifications (7) for two experimental RBMSs were developed to satisfy the following requirements:

1. Structures should be monitored for at least one four-season cycle to study the influence of environmental conditions (such as temperature) to be covered by a baseline of structural indexes (natural frequencies, mode shapes, etc.). For the same purpose, the temperature at the site should be recorded.

2. Natural frequencies, mode shapes, and critical strains and inclinations should be obtained for cross-diagnosis. This requires simultaneous data collection from multiple locations.

3. Capabilities for remote control and transfer mechanisms for data collection are required.

Figures 1 through 5 show the bridge structures, specified sensors and their locations, and the configuration of the RBMS. The main features of the RBMS will now be discussed.

Weatherproofing

The system was designed for use under severe weather conditions in the field to protect its electronic and electrical components. Stainless steel enclosures were provided to avoid corrosion. All cables are enclosed in weatherproof conduits fastened to the bridge structure.

Sensors: Accelerometers

Eleven accelerometers, manufactured by ICS Sensors, were included; they had a sensitivity of about 1 V/g, frequency ranges of from direct current to greater than 300 Hz, and a transverse sensitivity of less than 5 percent. One accelerator channel can be chosen as a reference channel to trigger simultaneous data collection from all accelerometer channels. When the reference channel signal exceeds a user-specified value, data collection commences. Similarly, data collection will be aborted if the reference channel signal exceeds another user-defined value during operation. Each time trace of an accelerometer contains 16,384 points. Its fast Fourier transform (FFT) has 8,192 points in a frequency range of 0 to 256 Hz, giving a frequency resolution of 0.03125 Hz. If data collection is successfully completed, FFT of the time traces will be performed for all channels. Modal frequencies are then identified using FFT and are compared with corresponding baseline values to identify changes. If such changes exceed user-defined criteria, a warning alarm is triggered. Trigger parameters can be changed remotely by the user. The system stores up to five time traces in its memory to be downloaded to a remote office.

Sensors: Strain Gauges and Inclometers

Five channels of strain and inclination data are collected by the strain gauges and inclinometers shown in Figures 1 through 5. The hermetic-weldable type manufactured by HITEC Products, Inc., with a 5,000 microstrain range. The inclinometers were made by the Fredericks Company and had a resolution of less than 1 arc-

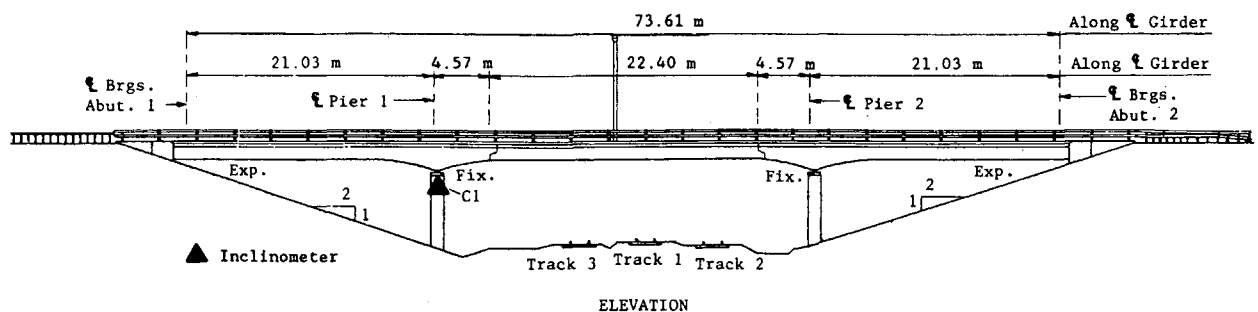


FIGURE 1 Elevation of the I-490 eastbound bridge over the Conrail main line showing instrumentation.

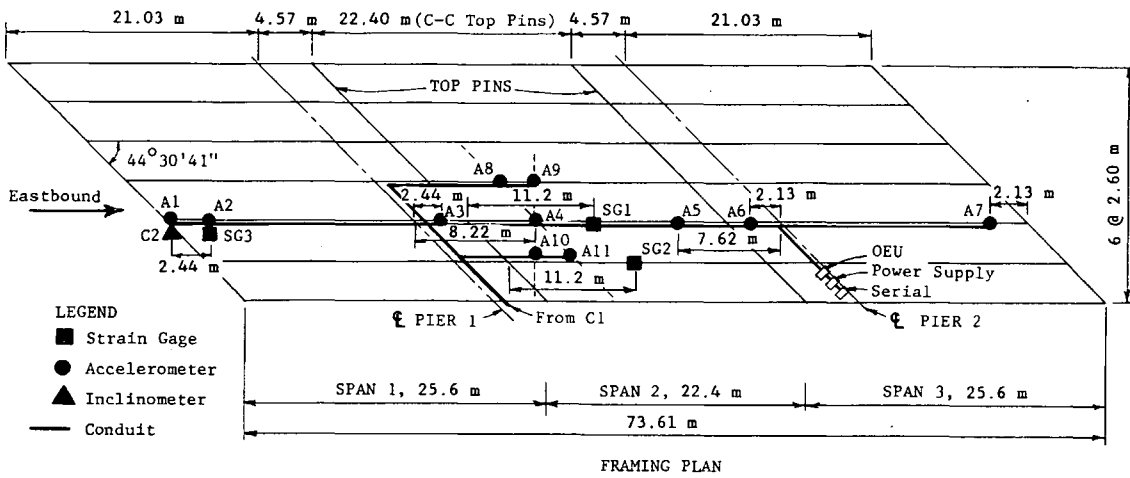


FIGURE 2 Plan of the I-490 eastbound bridge over the Conrail main line showing instrumentation.

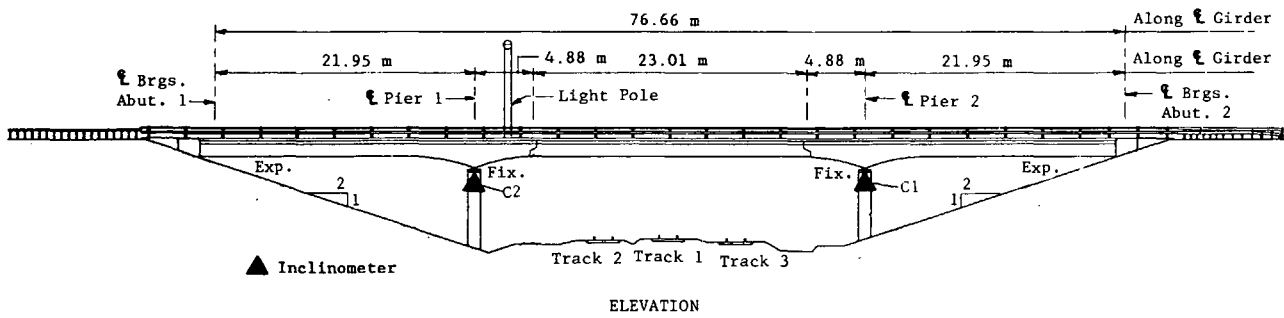


FIGURE 3 Elevation of the I-490 westbound bridge over the Conrail main line showing instrumentation.

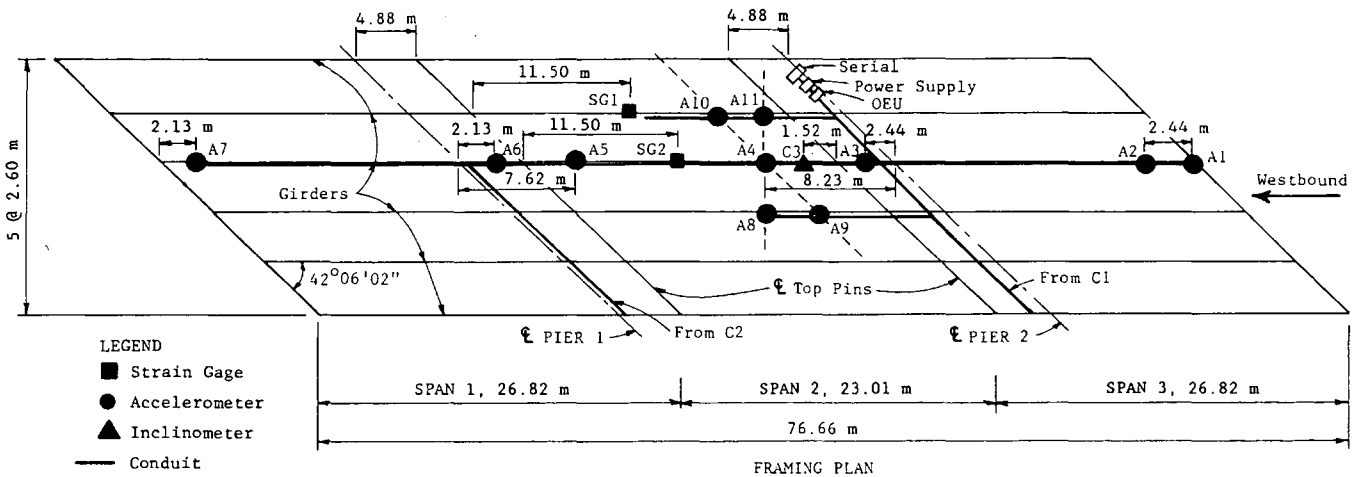


FIGURE 4 Plan of the I-490 westbound bridge over the Conrail main line showing instrumentation.

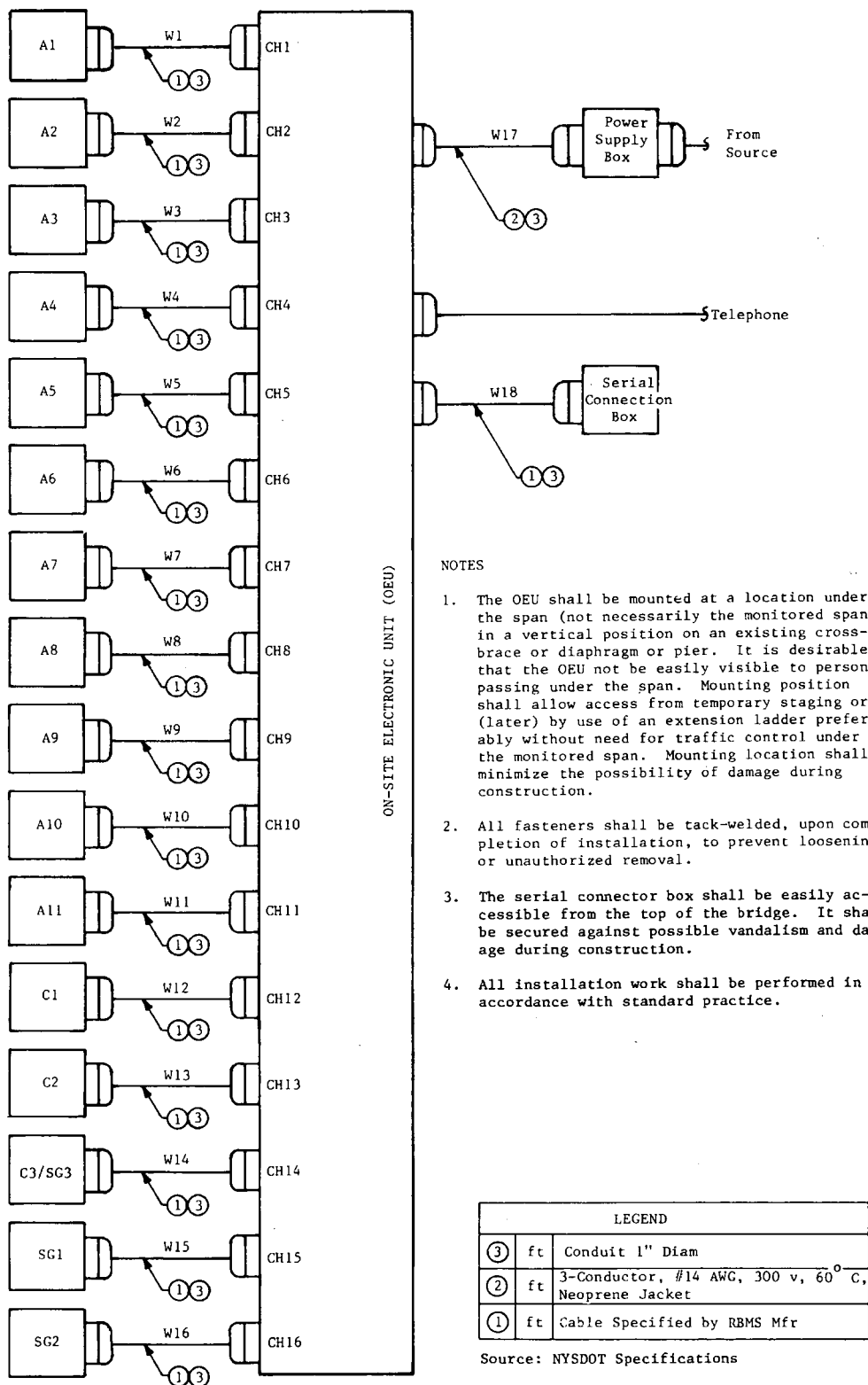


FIGURE 5 RBMS configuration for bridges over the Conrail main line.

the Fredericks Company and had a resolution of less than 1 arc-sec. The user can choose 1 of 16 options for the length of the strain or inclination time trace, ranging from 30 sec (at 10-msec intervals) to 32 days (at 178.2-sec intervals). Hence, each data record consists of 3,000 to 16,000 datum points depending on the time trace length. Data collection is triggered manually for individual channels from a remote office. Data collection is discontinued when five available records are filled with data. If the signal exceeds a user-defined magnitude, a warning alarm is turned on for the corresponding channel.

Communication Control

An RBMS is equipped with an internal 9,600-baud modem supporting the V32 protocol. Data are collected and the sensors are calibrated by a computer equipped with a compatible modem at a remote office through a regular telephone line. This can also be done with a portable IBM-compatible computer by using a serial port connection at the site. This provides flexible accessibility for on-site examination, repair, and calibration.

Data Storage

RBMS supports 16 channels of sensors (accelerometers, strain gauges, thermocouples, and inclinometers). Time domain data are obtained at various sampling speeds, with a storage capability of 16,384 datum points per record and five records per channel. These data can be retrieved by a remote host computer and can be stored in its hard drive or on floppy disks.

Data Collection Hardware

The RBMS consists of a central monitoring unit (CMU) with a 485 Data Bus architecture and supports 16 smart-sensor units (SSUs). The on-board memory contains a program supplied by the RBMS manufacturer to control data communication, memory management, and signal traffic direction for each SSU. Each SSU and CMU has its own address for efficient data access. Each SSU contains a minicontroller for data sampling and digitization and memory to store up to five records of data. The sensor instrumentation is provided with a selectable fixed-gain preamplifier.

Data Collection Software

Instrumentation operation is controlled by a proprietary program for remote calibration, data acquisition, and display of time traces for strain gauges and inclinometers and FFT of time traces for accelerometers. It also allows the operating parameters for each sensor channel to be changed (such as sampling frequency and sampling time for strain gauges and inclinometers, and triggering conditions for accelerometers). Time traces can be downloaded and only their FFT displayed. Thus, additional software was provided to perform FFTs of time traces after they are downloaded to a remote office, with several options of windowing (3). The behaviors of sensor amplifiers (such as offset, coupling, and gain) can also be monitored and adjusted with this software. It also allows the user to view real-time data from the sensors.

Power

The RBMS power supply consists of batteries charged by alternating current (ac) power with a low-voltage cutoff switch for protection from operation at freezing temperatures, and it can provide power for up to 48 hr in case of ac power failure. By transforming the 110-V line voltage, this power supply provides the dc voltage required by the various sensors, isolating them from the noise associated with an ac power supply. The system also contains a lithium battery with a 10-year service life to save the system configuration in case of power failure.

BRIDGE STRUCTURES FOR EXPERIMENTAL RBMS APPLICATION

Two bridges located in Rochester, N.Y., over Consolidated Rail Corporation (Conrail) tracks and carrying I-490 east (BIN 1048642) and I-490 west (BIN 1048641) were selected for experimental RBMS application. Both bridges were built in 1963, are about 76 m in length, and have three spans of steel girders (Figures 1 and 3). The horizontal solid lines in Figures 2 and 4 indicate steel girders. The end spans were supported by steel rocker bearings and were continuous over the reinforced concrete piers; the middle span was connected to the end spans by pin-and-hanger. Both bridges carry three lanes of traffic in opposing directions and are skewed as shown. Some secondary members suffered from severe section loss as a result of flaking rust (8,9). Delamination and deterioration of the upper portion of the concrete deck were also suspected. Some steel bearings were rusted and frozen. These bridges thus were recommended for rehabilitation, including (a) replacement of the corroded diaphragms, (b) repair of the concrete decks with a concrete overlay (after chipping off the top surface to the top rebars), (c) installation of new joint systems at the approaches, (d) replacement of the steel rocker bearings with elastomeric bearings with load plates, and (e) provision of continuity between the spans by splicing with steel plates. The last two items were done to meet a recently adopted rehabilitation policy for seismic hazards (10,11). These bridges were selected to be experimentally monitored by the RBMS, for examining the consistencies of the measured structural indexes, and for further understanding the sensitivity of the RBMS in detecting damage or deterioration. RBMS specifications were included in the rehabilitation contracts for the bridges. Their designed sensor locations, system configurations and cabling details are shown in Figures 1 through 5. Sensor locations, numbering, and wiring were slightly modified as appropriate during installation, before rehabilitation. The accelerometers were located such that the primary members, which are expected to be more severely loaded, can be monitored. The inclinometers and strain gauges were located to monitor the integrity of piers and the behaviors of elastomeric bearings and to record maximum strains resulting from traffic loads.

TYPICAL DATA FROM RBMS

Data Organization

Each sensor data record has a header that includes the control parameters to facilitate data management and processing. The header of a typical strain gauge data record is shown below.

PROFILE DATA

CMU NOTE: BIN 108642 Rochester
 CMU ID# 30
 SENSOR ID# 11
 SENSOR TYPE: PROFILE SENSOR
 START DATE: 11-19-1993
 START TIME: 15:02:47
 STOP DATE: 11-19-1993
 STOP TIME: 15:32:47
 THIS RECORD IS COMPLETE
 TOTAL PROFILE TIME: 30 Min
 TIME BETWEEN SAMPLES: 112 msec
 RAW PROFILE SAMPLES:
 [data]

It records data type, RBMS location, CMU identification number, sensor identification number, sensor type, data collection starting and ending dates and times, time length covered, and the time intervals in the data. The header is followed by raw data, which can be downloaded into a spreadsheet environment for further processing to obtain such physical parameters as strain, stress, acceleration, and inclination.

Accelerometer Data

Figure 6 shows a typical FFT record between 0.1 and 1.9 Hz (obtained from Accelerometer A9 on BIN 1048642 in Figure 2). It was recorded immediately after passage of a two-axle truck (with a gross weight of about 21.1 tonnes and axle spacing of 4.55 m) in the left lane at a speed of 8 km/hr. The first three identified modal frequencies were less than 1 Hz and are marked in Figure 6 at the peaks; the frequency resolution was 0.03125 Hz. Further detailed analysis is under way to identify the higher modal frequencies and mode shapes by using all accelerometer channels. These structural indexes will be recorded over forthcoming seasons to determine their variations with environmental conditions and sensitivities to structural damage or deterioration. The results may also be used to calibrate analytical models.

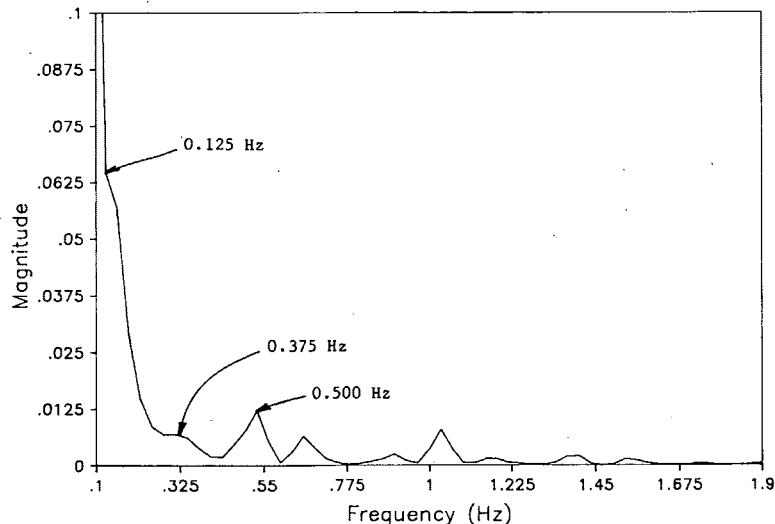


FIGURE 6 Typical FFT from Accelerometer A9 on the I-490 eastbound bridge.

Strain Gauge Data

Strain gauge data were also recorded during several passages of the same truck. A typical time trace (from Strain Gauge SG2 in Figure 2) is shown in Figure 7(a). This gauge was located on the bottom flange of the second girder from the right at the middle section of BIN 1048642. With no truck on the bridge, Figure 7(a) shows the initial zero response. When the truck entered the bridge and traveled on Span 1, the girder experienced negative moment at the strain gauge location, showing negative strains between 19.5 and 19.7 min. As the truck approached Span 2, this moment changed sign, showing a positive strain. The strain reached a maximum when the truck was at a critical position near 19.8 min, inducing maximum positive strain. The two peaks in Figure 7(a) were due to passage of the two axles. As the truck moved away from the critical location, the strain decreased and became negative when it was on Span 3 at 19.85 min and returned to the initial zero value when the truck left the bridge.

Similar behavior was observed whenever a truck crossed the bridge. Figure 7(b) shows seven consecutive time traces resulting from seven passages of the same truck. Note that Figure 7(a) is an expansion of the fifth truck passage in Figure 7(b). The first two peak responses in Figure 7(b) correspond to passages in the left lane, the third and fourth correspond to passages in the middle lane, and the last three correspond to passages in the right lane, beneath which the gauge was located, showing maximum responses. Note that RBMS allows display of such time traces in a remote office at the moment that vehicles cross the bridge. These strain data will be used to count traffic, determine service load spectra, and estimate the level and number of stress cycles for girder fatigue evaluation.

Inclinometer Data

A typical time trace of a girder's end inclination (C2 in Figure 2) resulting from passage of the same truck in the left lane is shown in Figure 8. In essence, this gives influence lines of girder inclination at a bearing. The inclination increased (downward or neg-

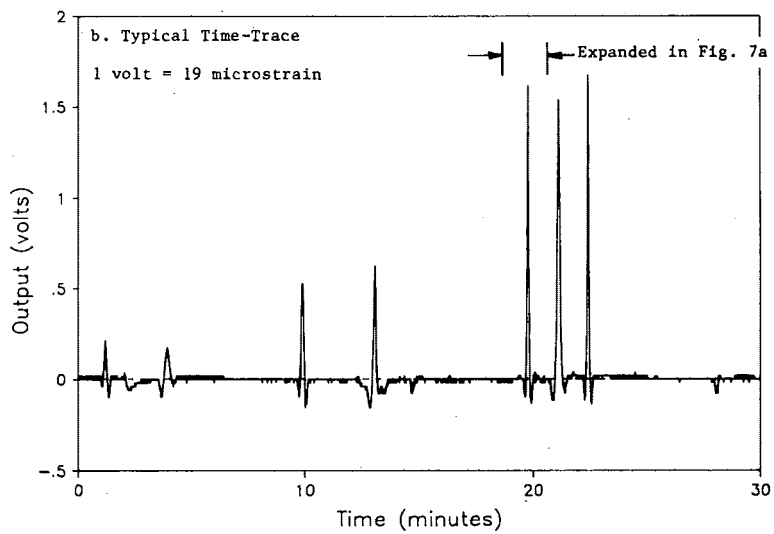
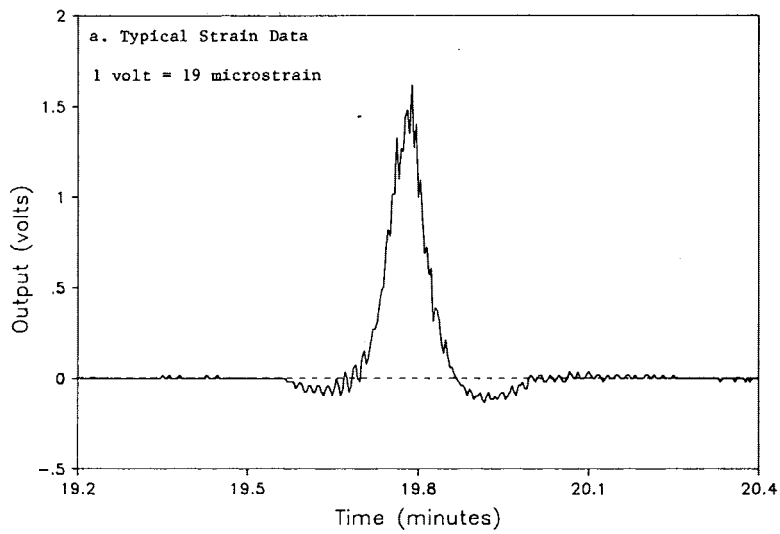


FIGURE 7 Typical strain data from Gauge SG2 on the I-490 eastbound bridge.

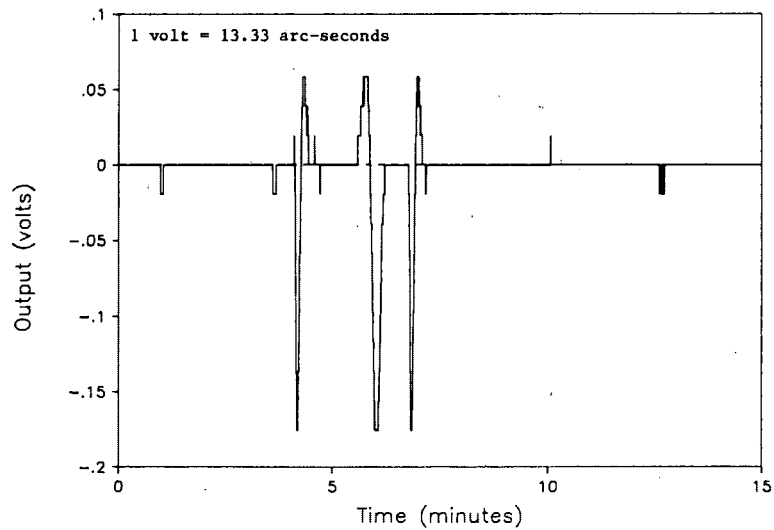


FIGURE 8 Typical time trace of inclination (Inclinometer C2) on the I-490 eastbound bridge.

atively) as the truck approached Span 1 and reached a maximum when it was near the middle of Span 1. It returned to zero as the truck reached Pier 1. As it traveled on Span 2, the inclination deviated from zero in the opposite direction, as expected in the case of a continuous bridge. The inclination approached zero as the truck left the bridge, and the girder returned to its unloaded position. The first and third passages induced similar behaviors. The second passage showed a mirror symmetry in comparison with those of the other two, because the truck was driven in the opposite direction. These inclination data will supplement strain data in counting traffic and determining service load spectra. They will also help in monitoring bearing and pier performances in relation to environmental conditions for the evaluation of structural integrity.

PRELIMINARY EXPERIENCE

The main objectives of the RBMS field experiments are (a) to verify the conclusions obtained previously in laboratory and field testing by portable instrumentation and analytical studies (4-6), (b) to examine the repeatability of the structural indexes, and (c) to understand the sensitivity of this technique for the detection of damage or deterioration with the instrumentation subjected to the service environment. The data can also be used to meet the needs of research and planning in other areas (strain histograms, truck traffic counts, etc.). Since installation of the RBMS, data are being collected periodically, and data collection is planned to continue for 24 months. The experience with the system to date will now be discussed.

Power

The RBMS was supported by a 110-V ac power line in the current study, but this may not be economical for all applications. Alternative power supplies should be considered, if such an on-site power line is costly.

Automation of Data Collection and Processing

Currently, the system can store up to 80 records (16 channels \times 5 records per channel). It takes about 3 min to download a record from the RBMS to a host computer using a 9,600-baud V32 modem and thus requires about 4 to 5 hr to download all 80 records. This process also requires constant interaction between the user and RBMS, since for each record (every 3 min) the user must name the file in which the data are to be saved and specify the channel and record from which they are to be downloaded. The user also must continuously monitor the modem connection condition because the modem may sometimes hang up because of electrical disturbances on the telephone line. Further automation is needed for the data transfer process (including monitoring of the modem connection conditions).

Postprocessing of the data also seems to be tedious. Currently, collected time domain data are transferred to a spreadsheet environment for analysis. Many spreadsheet packages cannot take as many as 16,384 points and do not have a wraparound feature. Automation for these operations is needed for efficient data processing. In addition, data collection and processing for the struc-

tural indexes are now manual, including the identification of natural frequencies, mode shapes, and so on. Conceptually, artificial intelligence devices with high-speed computers may be used as cost-effective alternatives.

Sensor Calibration

After installing the RBMS (before rehabilitation of the bridge), some sensors were calibrated by using trucks of known weight. Recalibration was conducted after rehabilitation caused changes in the bridges' structural conditions.

Communication

Each RBMS is equipped with a conventional telephone line for data transfer using a host computer in a remote office. It has been observed that the on-site modem may hang up because of electrical disturbances on the telephone line, discontinuing data collection. A conditioned line may resolve this problem, but it could be relatively expensive. Thus, the feasibility of using wireless communication (such as a cellular telephone or satellite) may be worth investigating as an economical solution to this problem. A serial port connection was made available at the site for convenient operation, such as the downloading of data. On the other hand, measures against vandalism may be needed.

Data Storage

Each time trace record and FFT record occupies about 80 and 120 kilobytes of disk space, respectively. If all recorded data (time traces of all channels and FFTs of time traces of accelerometer channels) are to be saved, about 13 megabytes of disk space will be required. For weekly downloading, for example, about 650 megabytes of storage space per RBMS would be required annually. For long-term data collection with the RBMS, sufficient data storage devices and an effective filing system will be necessary to handle such large volumes of data.

POTENTIAL FURTHER APPLICATIONS

A wide variety of sensors can be attached to the remote monitoring system discussed here and thus can be used to monitor various civil engineering structures (including retaining walls, dams, buildings, and bridge piers) for various purposes (including traffic data collection, structural condition monitoring, and load data collection). For example, the strain data collected can be used to record vehicular loads on bridges or simply to count traffic. Wind response can be obtained continuously from a remote office. The effects of environmental parameters on structures can also be studied. These data will help in the examination of assumptions about design and evaluation and in making rational decisions for management.

CONCLUSIONS

Innovative data acquisition system technologies are available for use in the long-term monitoring of structures; these include smart

sensors, control systems, telecommunications devices, and fast computers. If adequate and efficient analysis procedures are available and are implemented by automatic processing devices, long-term data collection and condition monitoring can be accomplished as described here.

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