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WORKSHOP NOTES

Session (3-7)
"Dev. of a Prototype Remote Vibration
Monitoring System for Bridges",
John T. DeWolf, PhD. Univ. of Ct.

DEVELOPMENT OF A PROTOTYPE REMOTE VIBRATIONAL MONITORING SYSTEM FOR BRIDGES

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INTRODUCTION

There are currently more than 230,000 deficient bridges on public roads in the United States, according to Federal Highway Administration studies. Many of these spans were built in the 1950s and 1960s. Some have referred to the situation as a time bomb ticking (1). Connecticut, which has one of the most far reaching bridge rehabilitation and replacement programs in the country, is currently undergoing a 10 year program involving 1600 bridges. This involves less than half of the 3600 bridges in the state system. It is obvious that resources (construction manpower, equipment and materials) do not exist to work on all bridges which are nearing the life expectancy or deficient, even if sufficient funds were available.

This paper reports on work underway at the University of Connecticut on the development of a permanently installed, continuously operating field monitoring system. The system will allow for the continued use of bridges which are nearing their life expectancy and provide for additional evaluation. The goal is to extend life expectancies, provide for better data on when repair or renovation work must begin, and to prevent catastrophic consequences when major problems develop.

GENERAL APPROACH TO MONITORING

The present approach to monitoring is based on visual inspection, often at approximately 2 year intervals. While many problems can be determined in this procedure, limitations exist. It is not always possible to see all parts of the bridge, and some failures have been known to occur over small time periods. As an example, a multiple steel girder Rhode Island bridge in the interstate system developed cracks across the tension flange of one of the outside girders followed by cracking of the web. This then led to the beginning of a crack in the next interior girder. One estimate was that this potentially catastrophic condition occurred in a 72 hour period (2).

Potential non-visual monitoring approaches include monitoring deformations, such as deflections or strains, or vibrations, which normally involves collecting acceleration data. Various techniques are available for monitoring deformations. However, they are not useful for most bridge applications. Deflections do not become significant until the bridge is in the process of collapsing. Strains can be successfully used for localized problems, such as the determination of cracks in a part of a connection. However, they are not useful where overall monitoring is needed to evaluate the bridge's continued usefulness.

Vibrational monitoring based on acceleration data has been widely used in other industries for both localized and overall behavior. Certification that a bridge is safe for continued use must be based on information gained from the overall performance.

Acceleration data can be processed in many different ways, and the data does not fully depend on the loading applied to the structure. Thus, it is possible to use moving vehicle loading as a basis of evaluation. The information can be interpreted to yield both an overall picture, or signature, for the bridge, as well as localized information on cracking and deformations.

BACKGROUND WORK AT THE UNIVERSITY OF CONNECTICUT

Researchers at the University of Connecticut have been involved in the development of a full-scale field bridge monitoring system. This development was started after experience with actual vibrational monitoring, including a major literature survey (3) and a field study of a 4 span, continuous girder bridge in Connecticut (4-6). Vibra-Metrics, Hamden, Connecticut, consulted on this study, and the results indicated the feasibility of long term vibrational monitoring as a means of evaluation. The study also demonstrated that modifications were needed to equipment (accelerometers and processing equipment) for bridge use.

Research continued at the University of Connecticut to develop monitoring techniques. The goal was the study how major defects in a bridge would alter the bridge vibrational signature. Two studies (7-12) have involved single and double span bridge models, with the second comprising multiple girders and a deck. The loading consisted of a moving vehicle at different speeds, with variable mass and variable roadway roughness. The failure mechanisms investigated were cracking in the girders, connections problems and support movements.

A cooperative research investigation between the University of Connecticut and Vibra-Metrics began in 1988 to develop a prototype bridge monitoring system. The initial portion involved both model work and actual tests on a Connecticut bridge to establish equipment specifications for the monitoring system. Testing of the full-scale prototype system began in the summer of 1990 and installation on a Connecticut bridge is scheduled for early fall 1990.

VIBRATIONAL MONITORING

Vibrational monitoring has been used for many different kinds of structures, including machinery, power plants, and aircraft. Most existing equipment has been designed for these applications. It is not directly applicable to bridges, however, since natural frequency levels in bridges are lower and since long time records must be gathered. Much of the work at the University of Connecticut has been directed at the determination of the necessary specifications for bridge applications. This section contains a general description of what is needed for bridges, whether for long term monitoring or short term evaluations.

Changes in flexibility which result from problems in the structure which lead to deterioration in load capacity are not readily determined from deformation monitoring. However modal analysis, based on the relationships between applied forces and resulting vibrations, offers the opportunity to lump the combined effects of the decks, girders, diaphragms and supports to determine a 'signature' and then use this to evaluate the changes in flexibility due to different problems. It is not limited to a specific dynamic load, and instead, it can work under highly variable loading.

A structure subject to moving, or dynamic, loads oscillates about a reference position. A one-degree-of-freedom system spring vibrates in one mode at its fundamental frequency. More complicated structures, such a bridges, oscillate in a combination of modes and frequencies. The modes refer to a set of unique shapes. The fundamental mode for a simple beam has a shape similar to the deflection of a simply supported beam, i.e. a half sine wave. Higher modes involves multiples of the single sine wave.

A bridge vibrates in many components, all simultaneously. The separate components, each with a specific natural frequency and mode shape, are often shown in plots known as frequency spectra showing the variance of the vibrational amplitude versus frequency. These plots are taken over a specific time period. A spectrum is in the form shown in Fig. 1. This shows amplitude, which is related to the accelerations versus natural frequency. The natural frequencies are those associated with the peaks (f1 and f2), and each natural frequency is associated with a mode shape. The peak values shown on the plots do not necessarily occur simultaneously. Bridges usually only exhibit a small number of dominant frequency components or modes and corresponding natural frequencies. The deflections which are associated with the higher modes are related to the inverse of the frequencies so that the deflections and resulting stresses for these modes are very small. These spectra form the basis of the bridge's signature.

The stages involved in vibrational monitoring are: (1) Use of sensors, typically accelerometers which measure the accelerations, for data acquisition; (2) Signal processing to transform the data into a signature, such as a series of frequency spectra; (3) Condition assessment based on comparison of the vibrational signature to a reference signature.

Piezoelectric accelerometers are universally used. They are based on using a piezoelectric material which generates an electrical charge when it is mechanically stressed; as the bridge oscillates, an inertial force is induced in the sensor. Important accelerometer characteristics include sensitivity, mass, dynamic range and frequency range. It is the last that is most important in bridge monitoring; it is necessary to measure vibrations as low as 1 or 2 Hz (cycles per second). Sensitivity refers to the signal level; a large signal is required so that the signal-to-noise level is high (noise is electrical noise or interference which arises from various interference effects). High sensitivity requires a relatively large assembly. The mass used in the accelerometer should be much smaller than that of the vibrating object, which is not a problem for bridges. The dynamic range refers to accelerations levels, and it is important to match this to the bridge's acceleration levels.

Prior to choosing an accelerometer for bridge monitoring, it is necessary to estimate the natural frequencies through some type of numerical analysis. This can be a free vibrational analysis, as opposed to a forced vibrational analysis which is considerable more difficult and generally not feasible. It is desirable to have the minimum accelerometer frequency level an order of magnitude below that for the bridge, i.e. the accelerometer should be effective at a value of 0.2 Hz for a bridge with a fundamental natural frequency of 2.0 Hz. The accelerometer should also have constant phase information over the required frequency range. Temperature effects are important at the lower frequencies. As an example wind can create temperature problems.

Accelerometers are normally placed near the center of the spans, in locations where significant movement/accelerations might be critical. It is important that they not be attached at nodes, i.e. where mode shapes have zero displacements. Otherwise, the corresponding natural frequency and mode shape will not be part of the signature. Reference points are also needed, i.e. one or more accelerometers should be placed at a support.

A signal conditioner is connected to the accelerometers. The signal conditioner should have filters which do not cut off any portion of the frequency range of interest. The signal from the accelerometers will be in analog form. Before any data processing can occur, the signal must be converted to digital form. It is important that digitizing be done at a high rate. If it is necessary to record 100 Hz frequency components, digitizing at 100 points per second would provide for only one point for the 100 Hz vibrational component.

The frequency spectra can be obtained from either a FFT analyzer, which performs Fast Fourier analysis, or a computer with software. FFT analyzers generally do not have adequate time ranges for bridge data. Most analyzers have 400 to 800 useful points. For a 400 point machine and a desired frequency range up to 20 Hz, the maximum record length would be 400/20 which is equal to 20 seconds. Bridge monitoring should normally treat frequencies well above 20 Hz. It is also useful to have a little time prior to the entrance of the vehicle and then after it leaves to get the free vibrations. Thus most analyzers will not work for longer bridges.

Modal analysis of the data involves the determination of mode shapes and subsequent analysis. The mode shapes show how a bridge deforms and stiffness properties can be inferred from them. The determination of mode shapes involves looking at the data from two accelerometers simultaneously and making phase comparisons. Phase comparisons show whether the two channels are deforming in the same direction at the same time. Additional analysis can include integration of the acceleration data to determine the velocities and deflections. It is important that the data be sufficient to have both the number of points and resolution to perform this integration. Otherwise numerical problems occur.

EXPERIMENTAL DATA FROM UNIVERSITY OF CONNECTICUT STUDIES

Examples of both field and model data are presented to demonstrate both the feasibility of using vibrational analysis to develop a signature for a bridge and possible monitoring techniques.

Fig. 2 shows a cross section and longitudinal section on one side of the centerline for the four span bridge studied by University of Connecticut researchers. The overhang from the main supporting girders shown in the cross section plays a major influence on the vibrational behavior, and there are thus substantial torsional modes. A response spectrum for this bridge is shown in Fig. 3. The two plots represent the behavior on the opposite sides of the interior span. The lowest, or fundamental, natural frequency is at 2.0 Hz, and this represents a torsional mode shape. The spectrum was determined for a truck crossing the bridge, and the tests involved different speeds and travel lanes. The experience from this investigation was invaluable in determining needs for the subsequent model study.

A diagram for the setup for the model study is shown in Fig. 4. Fig. 5 shows the cross section and the position of the supports for this study. The bridge was tested in both a single and double span configuration. Different vehicles, speeds and variable roadway roughness were used to determine the initial signature. Tests then involved cracks, support displacements and loosening of connectors. As an example, the spectra for both the baseline (uncracked) condition and the single span bridge with a crack located near the center of the span in Fig. 6. Note that the amplitudes have increased and some of the peaks have shifted horizontally. Table 1 shows the changes to the lower natural frequencies for the crack for the three lowest bending modes. The third crack increment decreased the section moment of inertia by 33 percent. This resulted in a change in natural frequencies up to 10 percent, demonstrating that one possible sign of structural degradation is the change that occurs in some of the natural frequencies.

Similar results occurred for the model bridge in the two span configuration. Changes in the mode shapes also occur due to cracking. Fig. 7 shows the change in the fundamental mode shape for the two span model when a crack occurred near the center of one span. Fig. 8 shows the influence of cracking on the first bending mode in this model.

The model shown in Fig. 5 is essentially one-dimensional. As noted with the results of the four span field study, torsional deformations can play a significant roll on the vibrational behavior. Also, many bridges have multiple girders. Thus a second model study was conducted to evaluate the influence of deterioration on a multiple girder bridge. The cross section with 4 girders is shown in Fig. 9. The overall results were similar, with changes in natural frequencies up to 10 percent for development of a crack.

Other studies involved test vehicles on an actual bridge. Some of the conclusions pertaining to potential monitoring applications are:

1. Natural frequencies and mode shapes are not influenced by vehicle velocity, roadway roughness or mass variations for the mass range expected on an actual bridge.

2. Crack propagation can cause substantial shifts in certain natural frequencies and mode shapes.

3. Support failures result in large changes to both the natural frequencies and mode shapes.

PROTOTYPE MONITORING SYSTEM

The prototype monitoring system for installation on a Connecticut Bridge this fall is diagramed in Fig. 10. Included in this system are 16 accelerometers for sensing the vibration, cluster modules with signal conditioning equipment, and a sentry unit to provide for A to D conversion, FFT analysis, and a computer with storage features to run the monitoring system. The computer provides for longer time lengths and the ability to tailor the system to a particular bridge. The data is then transmitted via a modem to a control center at the University of Connecticut for further processing and study.

Development of this system, along with definition of specifications for field bridge studies, should provide University of Connecticut researches with the capabilities for continued opportunities for the evaluation of Connecticut's bridges. The applications of the system also include conventional monitoring and shorter term studies to evaluate whether a particular bridge is behaving as expected.

ACKNOWLEDGEMENTS

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High Technology Research and Development Grant.

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TABLE 1 Resonant Frequencies for Cracked Double Span Bridge

Mode No.	Test*	Natural Frequency (Hz)	Percent Change
B1	A	32.33	-
	B	32.02	0.9
	C	30.96	4.2
	D	29.01	10.2
B2	A	46.58	-
	B	45.98	1.3
	C	45.38	2.6
	D	45.07	3.2
B3	A	118.1	-
	B	116.1	1.7
	C	115.7	2.0
	D	115.5	2.2

* A: Baseline bridge
B: First crack increment
C: Second crack increment
D: Third crack increment

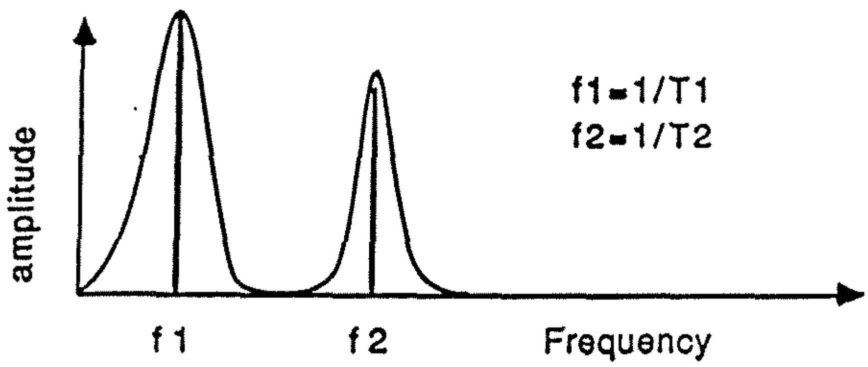
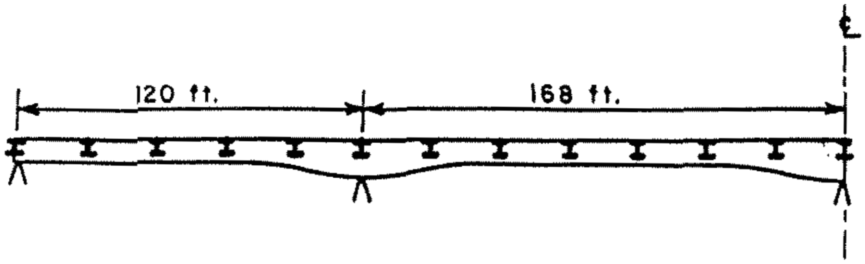
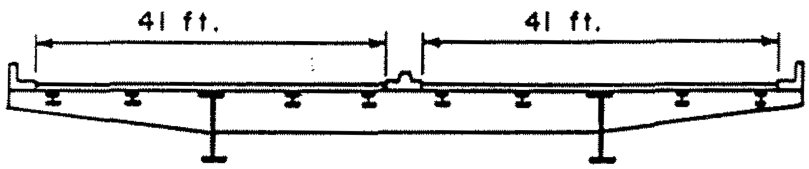


Figure 1 Example Frequency Spectrum



Bridge Longitudinal View



Bridge Cross Section

Figure 2 Continuous Four Span Bridge

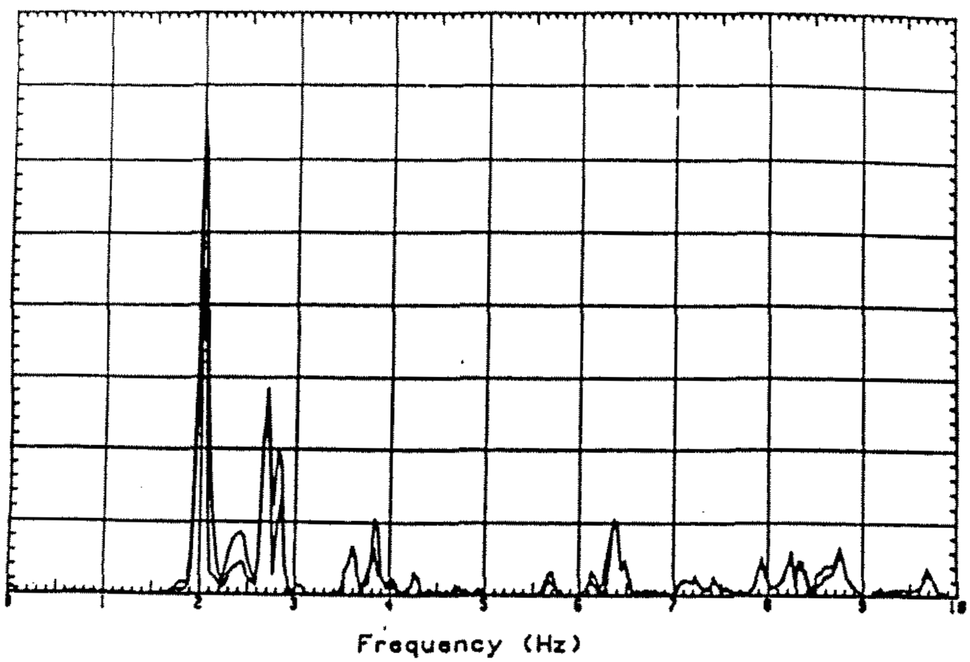


Figure 3 Frequency Spectrum for Four Span Bridge

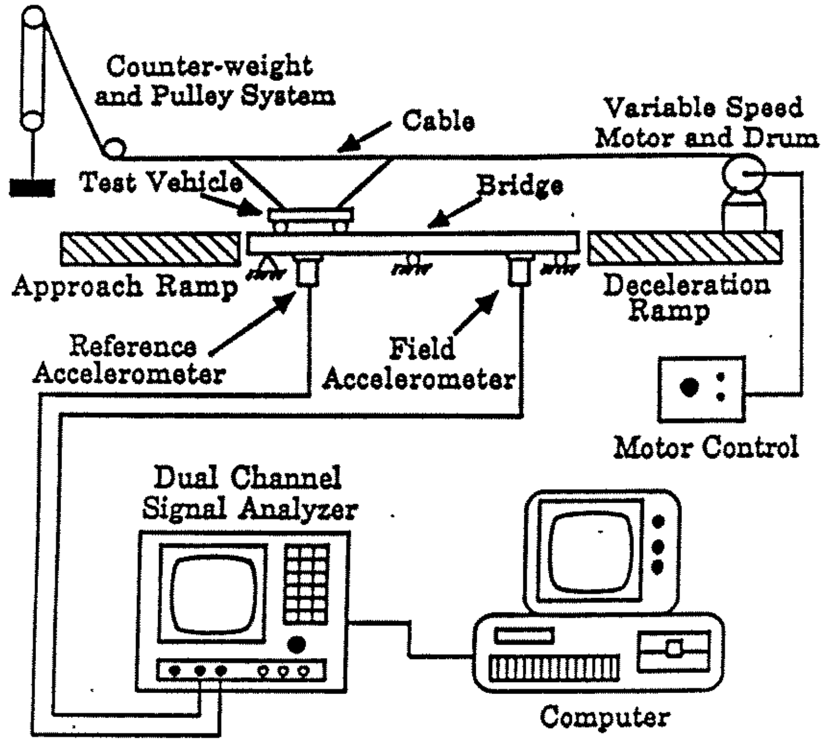
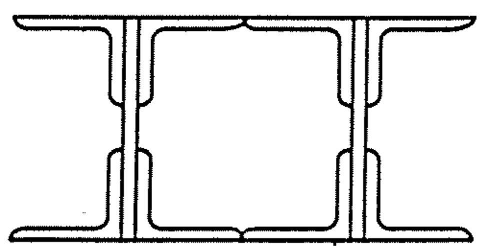
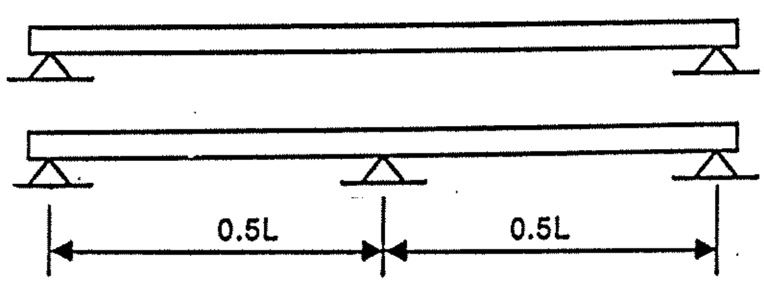


Figure 4 Model Bridge Test Setup



Cross Section



Longitudinal Configurations for Tests

Figure 5 First Model Study

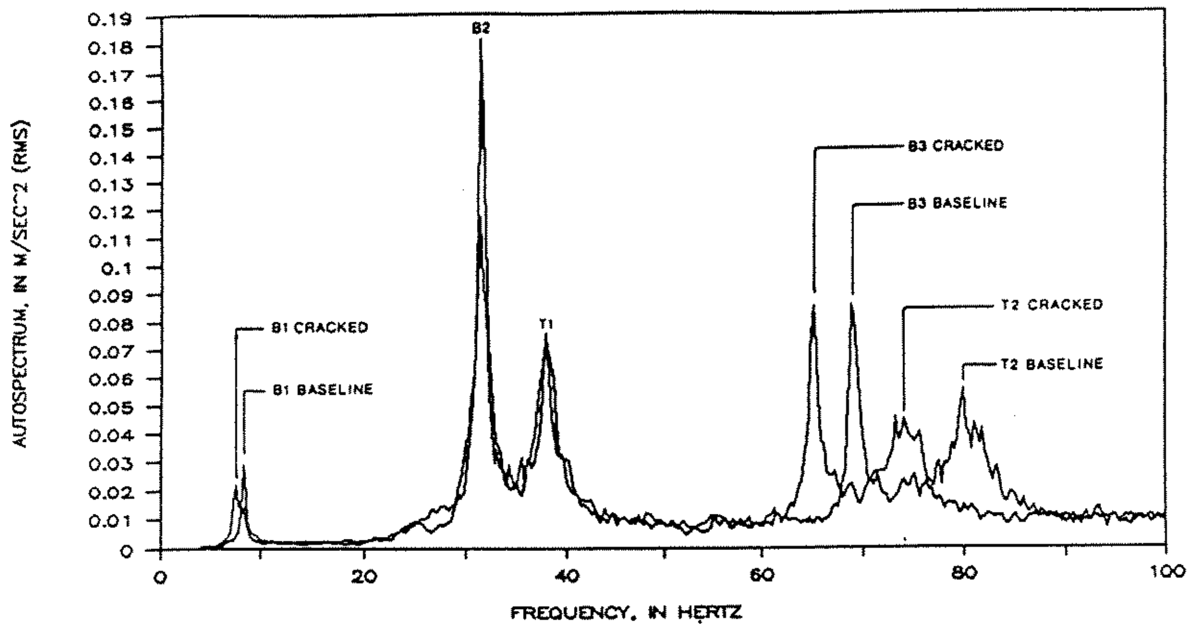


Figure 6 Spectra for Baseline and Cracked Conditions

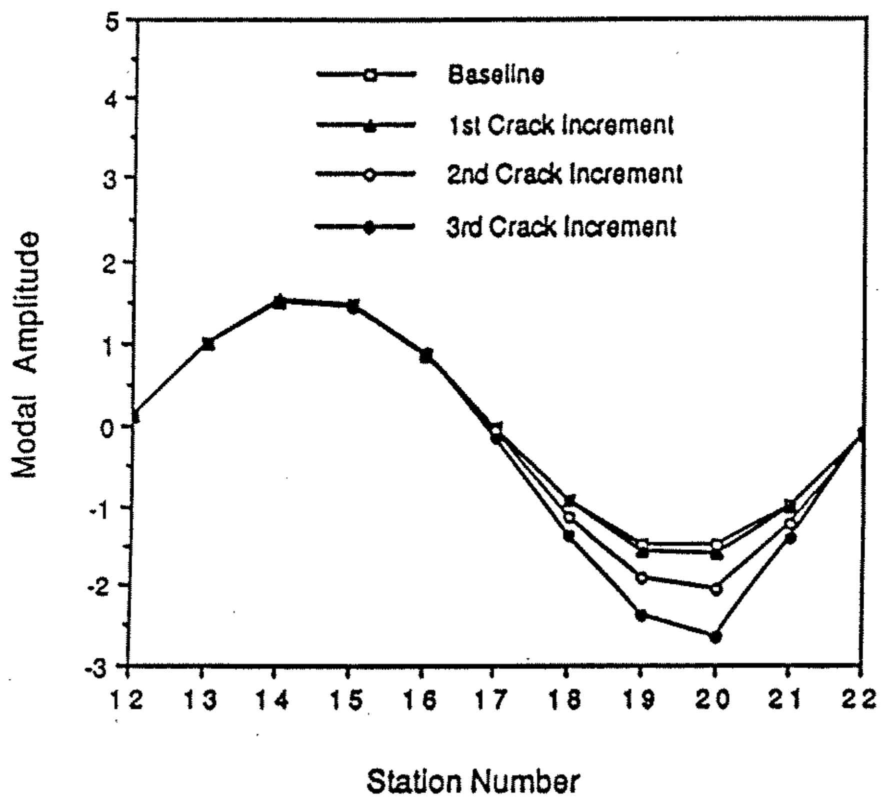


Figure 7 Change in Mode Shape for Crack Development in Double Span Model

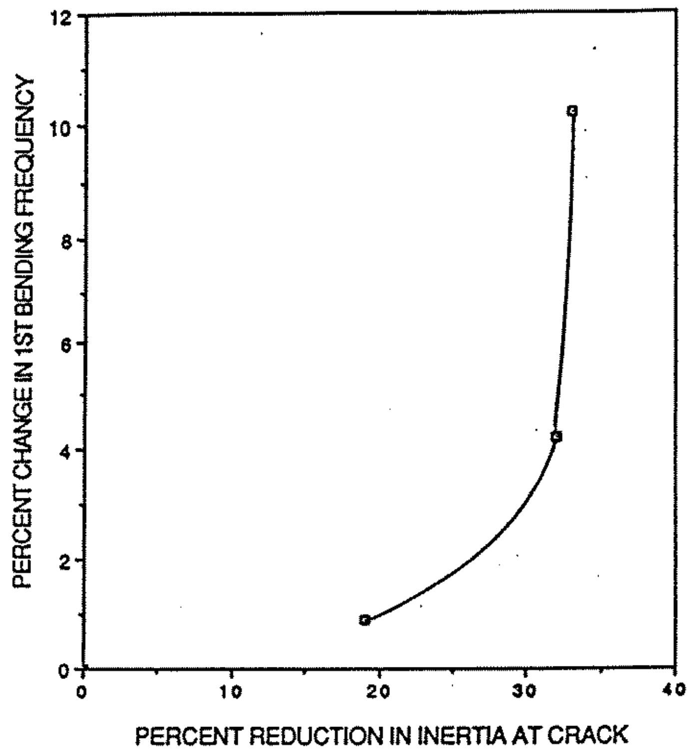
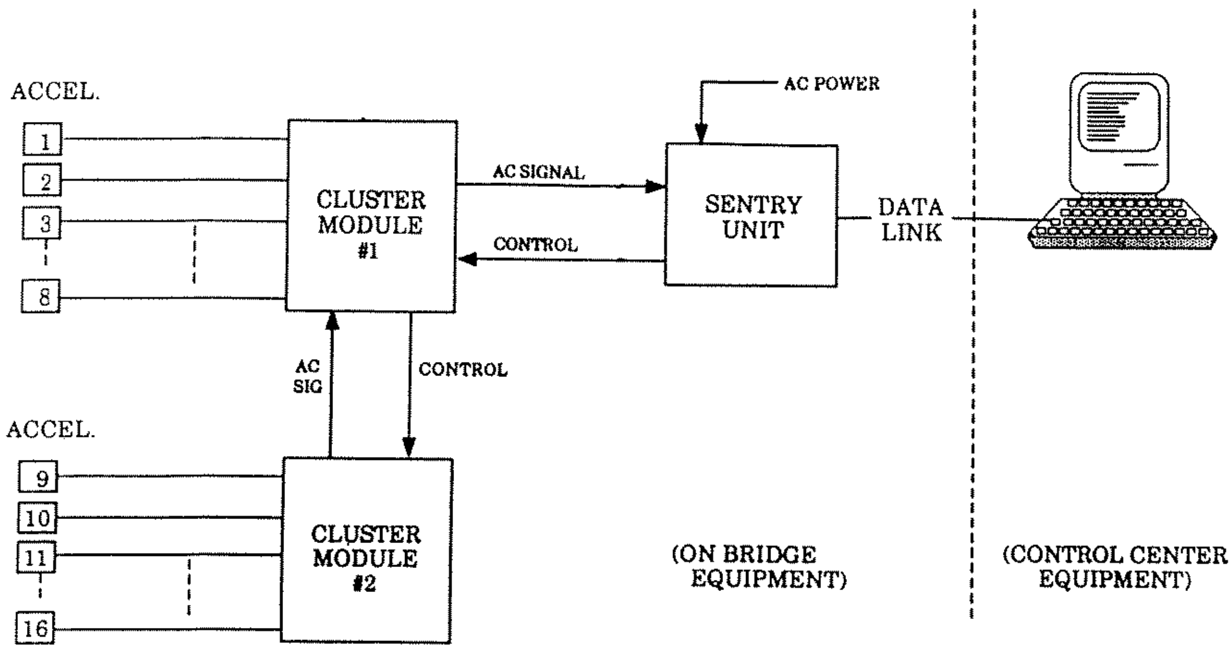


Figure 8 Change in Natural Frequency Versus Reduction in Moment of Inertia for First Bending Mode for Double Span Model with Crack

Figure 9 Cross Section for Second Model



FUNCTION	SENSES VIBRATION	FILTER POWER CONVERT MULTIPLEX INTERFACE/BUSS CONTROL	BUFFER FFT COMPARE TO PRESET LEVELS ALARM INTERFACE/BUSS CONTROL

Figure 10 Prototype Monitoring System