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Continuous Monitoring of Bridge Structures

Surveillance continue des structures de ponts

Kontinuierliche Überwachung von Brückentragwerken

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SUMMARY

This paper reports on continued efforts to develop a global monitoring approach applicable to bridges. A fully operational, remote vibrational system is used. Evaluation is based on using normal traffic loading to develop a signature which will change when significant changes occur in the structural integrity. The vibrational signature has changed in this bridge due to lack of movement in the support bearings. The goal of this long term research has been to develop a bridge monitoring system which can prevent catastrophic consequences.

RÉSUMÉ

L'article rapporte les développements d'une approche globale de surveillance applicable aux ponts. Un système totalement opérationnel de mesures d'oscillations à distance est utilisé. L'évaluation est basée sur les vibrations provoquées par les charges de trafic normal et qui se modifient lorsque des changements significatifs apparaissent dans la structure. Dans le cas du pont étudié, la modification du signal était due à l'absence de déplacement des appuis. Le but de cette recherche à long terme a été de développer un système de surveillance pouvant prévenir des conséquences catastrophiques.

ZUSAMMENFASSUNG

Der Beitrag berichtet von Fortschritten bei der Entwicklung eines globalen Ueberwachungskonzeptes für Brücken. Dazu wird ein voll funktionsfähiges System der Schwingungsmessung aus der Ferne verwendet. Die Auswertung beruht auf Schwingungen durch normale Verkehrslast, die sich bei bedeutenden Schäden an der Tragsubstanz ändern. Beispielsweise ändert sich die Schwingungscharakteristik infolge mangelnder Bewegungsmöglichkeit in Brückenlagern. Das Ziel dieses langfristigen Forschungsvorhabens ist ein Brückenüberwachungssystem, das katastrophale Folgen verhindern kann.

1. Introduction

Approximately 20% of the bridges in the United States are structurally deficient or inadequate for current loading conditions. Many of these bridges are nearing their life expectancy, and others were designed for lighter loads and/or lower traffic volume. Economics dictates that not all problem bridges can be renovated or replaced when they achieve their life expectancy. Thus, inspection becomes critical.

Present practice in the United States, using available manpower, is to inspect bridges visually on approximately a two year cycle. This is not always adequate to prevent catastrophic consequences. In 1983, a section of a bridge on the interstate in Connecticut collapsed. Routine inspection of the bridge 10 months earlier was not able to provide indication that one of the pins holding up the span had developed fatigue cracks due to corrosion. In 1988, another bridge in Rhode Island was closed after discovery of a long crack in one of the girders. This crack would have resulted in collapse, had a passing motorist not contacted authorities. The bridge had been inspected 5 months earlier. Scour of bridge piers resulted in a collapse in New York in 1988, which also had recently been inspected.

These collapses, or near collapses, indicate the desirability of developing equipment to supplement the visual inspections. The general report from the 1992 Conference on Nondestructive Evaluations of Civil Structures and Materials in Colorado [see Reference 4], states that 'the present practice of visual inspections at long intervals must be replaced by frequent, automated condition monitoring" and that this should "provide an early warning of distress, support aggressive maintenance programs and promote the timely remedy of emerging deterioration." What is needed is a continuous system which can send an alarm when there is a serious structural problem. The system can't rely on manpower alone or special inspection techniques, since these are not always available when needed. Further, the system must act as a global monitoring technique. It must be able to detect a variety structural problems, including those which are not expected. Monitoring systems should link sensors placed at different locations on a bridge and should utilize recent advances in computer techniques and hardware.

Many techniques have been proposed for use of different kinds of sensors to assist in the evaluation of bridges. Most are limited to localized evaluations. Examples include evaluation of the strains in specific bridge components, acoustic emission techniques to follow a fatigue crack and tilt meters to evaluate support movements. Some researchers have proposed use of vibrational information, which is capable of providing a global assessment of the bridges. Presently vibrations are used in many monitoring applications, including manufacturing plants, power plants and aircraft.

Samman and Biswas [1] recommended using pattern recognition with vibrational measurements as a means of evaluating bridge problems. Lauzon and DeWolf [2] have reported on testing, conducted by Lauzon, of a bridge near collapse. Vibrations were used to obtain bridge signatures as the crack developed. This test demonstrated that changes to the structural integrity are discernable from vibrational information. The Lauzon test was part of a long term effort in Connecticut to develop a field monitoring techniques, involving both strains and vibrations, for application to bridges.

This paper reports on the recent efforts to use a fully operational remote vibrational monitoring system on an older continuous bridge. The bridge's performance has been evaluated in both summer and winter. The vibrational signature has changed due to changes in the supports.

2. Vibrational Monitoring Approach

Based on a laboratory study with a bridge model subject to moving loads, Mazurek and DeWolf [3] concluded that the ambient vibrational approach could provide a feasible bridge monitoring technique. They found that major deterioration is detectable by comparisons of natural frequencies and mode shapes. This information was correlated to finite element analyses.

Lauzon [2] applied the results of the laboratory study to a portion of a bridge with three girders. A crack was introduced in the outer girder, and a moving truck was used as test vehicle. Extension of the crack into the web resulted in the development of additional frequencies and changes to existing ones. Acceleration levels changed dramatically, depending on the location of the sensor. The conclusion was that a statistical analysis of the frequencies and the relative acceleration levels could provide a global sign of loss of structural integrity.

3. Prototype Monitoring System

The vibrational monitoring system was built by Vibra-Metrics of Hamden, Connecticut, in conjunction with researchers at the University of Connecticut. The system has 16 accelerometers, two cluster boxes and a sentry unit. The accelerometer placement is based on a finite element analysis which identifies the appropriate mode shapes. The sentry unit contains a computer with software for processing the data from the accelerometers. It also provides for communication with a remote monitoring site.

The monitoring system was first placed on a newer single span bridge consisting of a composite steel plate girder deck [4]. The results demonstrated that traffic induced vibrational data is stable and provides adequate information to develop a signature. Modifications were made to the system before installation on the bridge reported in this study. These consisted of refinements to the system resolution and communication capability.

4. Bridge Description

The bridge studied has two equal length spans, with continuity at the center support. The superstructure consists of a composite concrete slab on seven non-prismatic welded steel plate girders. The cross-section is shown in Figure 1. The bridge was built in 1954 and the bituminous deck was replaced in 1976. There are plans to replace splice connections in the future.

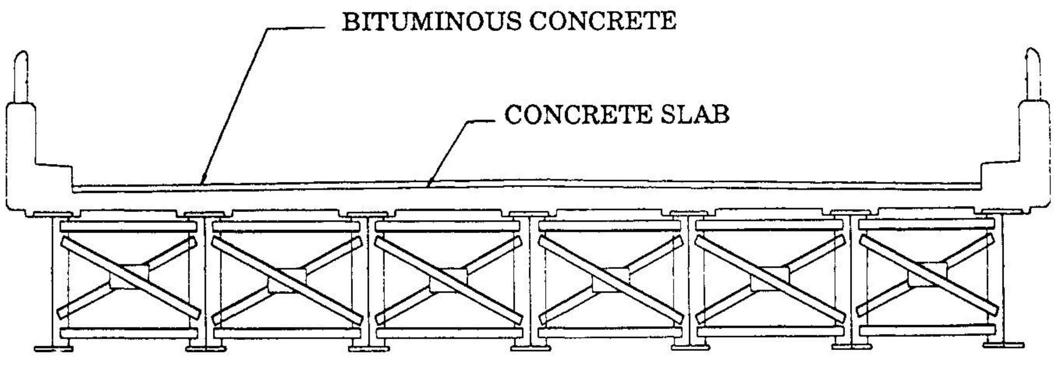

Figure 1: Bridge Cross-Section

The 16 accelerometers were located in both spans, distributed in both the longitudinal and transverse directions.

5. Field Results

Previous work at the University of Connecticut has defined the baseline signature of a bridge in terms of the natural frequencies and mode shapes. The acceleration patterns also form a part of this signature. The monitoring system was used to collect accelerations and process the data to develop the modal information. A typical frequency spectrum, taken during one collection period, is shown in Fig. 2.

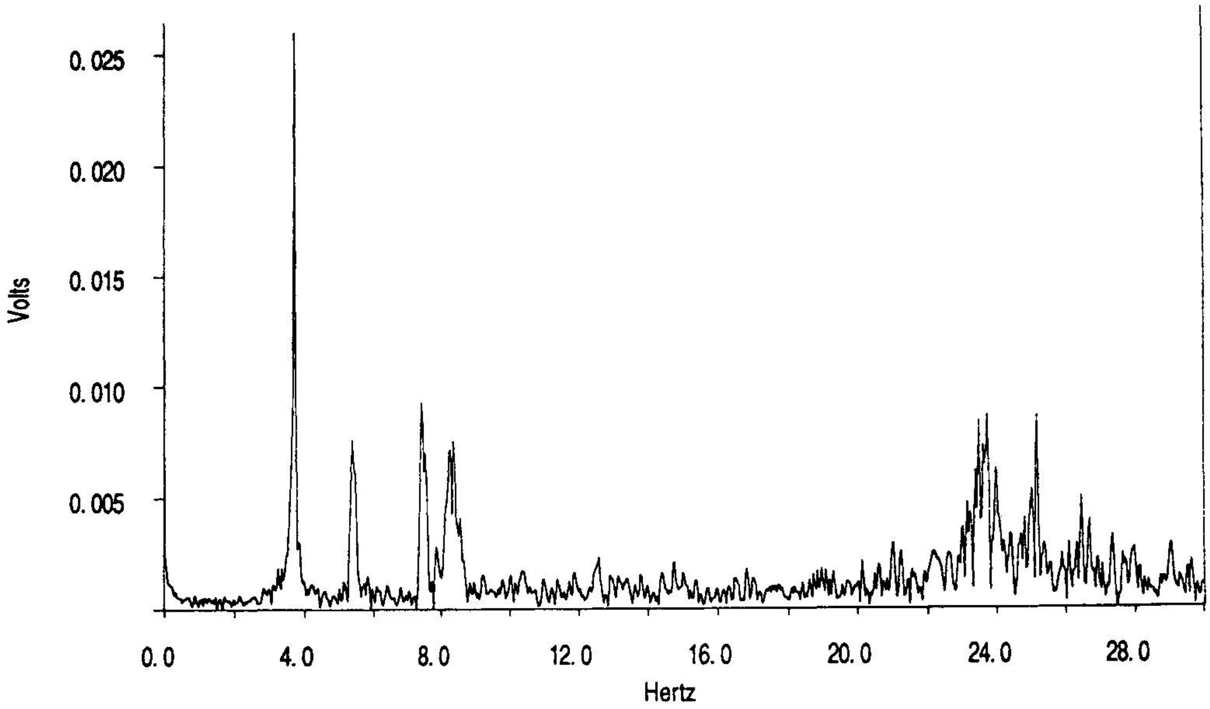

Figure 2 Typical Frequency Spectrum

This figure is a plot of volts (proportional to acceleration) versus frequency. Natural frequencies are associated with peaks in this diagram. However, not all peaks correspond to natural frequencies. It is necessary to compare spectra using modal analysis to determine which peaks correspond to natural frequencies.

The natural frequencies for the first bending (displacements vary in longitudinal direction), first torsional (displacements vary in the transverse and longitudinal directions), and second bending modes were identified using the monitoring system. In November prior to the onset of colder weather, these values were 3.6, 4.15, and 5.3 Hz respectively.

Small peaks were found at frequency values near 7.5 and 8.5 Hz on a regular basis. However, when an attempt was made to identify the mode shapes for these frequencies, the phase information was unrecognizable. In the range of 12.0 to 16.0 Hz, there are many peaks which were consistently excited. Two peaks usually appeared at 14.1 and 15.0 Hz, but again, the phase information was unrecognizable. While, analytical and finite element beam models indicate that there is another bending mode in this range, the large number of peaks within this range did not allow determination of the frequencies from the test data. Previous studies at by researchers at both the University of Connecticut and at other institutions have demonstrated that there is only sufficient energy to excite the lowest natural frequencies, and thus that it is not possible to decipher the higher modes.

The bridge's mode shapes are directly related to acceleration levels. To plot a mode shape, the phase angle of each channel is determined with respect to a given reference channel. The lowest bending and torsional modes shapes are shown in Figs. 3 and 4, respectively.

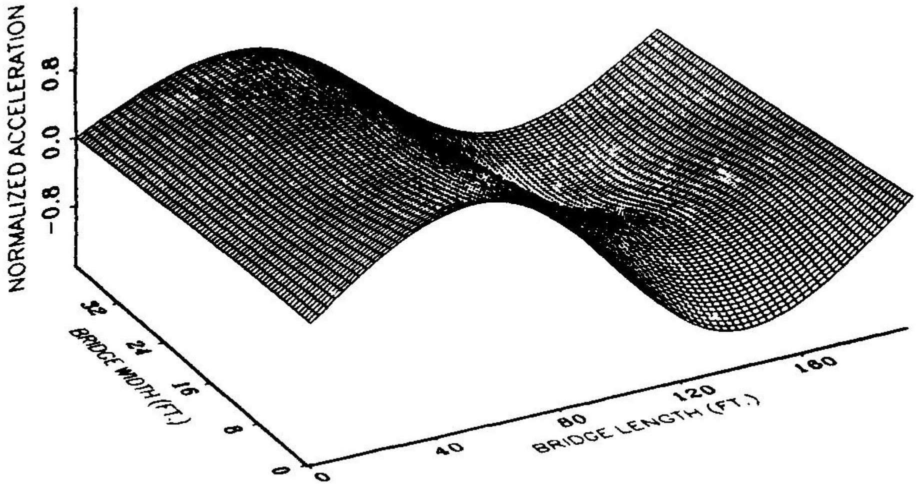

Figure 3 First Bending Mode Shape

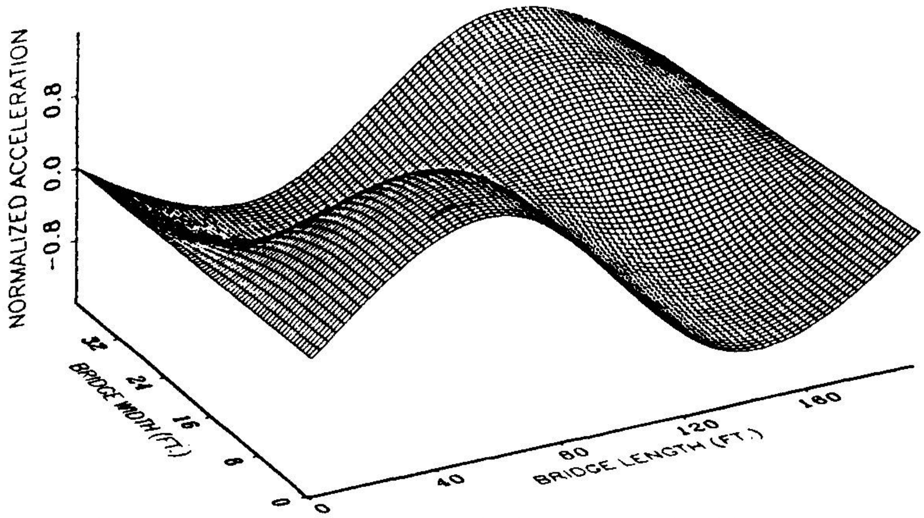

Figure 4 First Torsional Bending Mode Shape

The stability of the natural frequencies and mode shapes was determined by comparing data collected at different times. Lauzon and DeWolf have shown that structural damage affects relative acceleration levels, in addition to the frequencies and mode shapes. Thus other statistical efforts involved evaluation of accelerations. The results of these comparisons is reported in more detail by Conn and DeWolf [5,6].

At the onset of colder winter weather in December, the three lowest natural frequencies associated with the mode shapes began to shift (from 3.6 to 4.0 Hz, from 4.15 to 4.8 Hz, and from 5.2 to 6.0 Hz). A plot of temperature vs. frequency for the lowest natural frequency is shown in Figure 5. Further study indicated that the frequencies changed only for temperatures with values between 0°F to 60°F. There are no significant changes in natural frequencies for temperatures above 60°F.

Review of possible causes indicated that the bridge bearings were not completely free to translate. The bridge was thus not able to contract, and as a consequence axial tension forces were developed in the girders. Analytically, it has been shown that the lowest natural frequencies will change by approximately 5 percent with a 60°F temperature change, based on a prismatic single beam model [5,6]. Further study is now underway to evaluate and verify the changes in natural frequencies. The results establish that changes in the structural integrity do result in changes in the bridge vibrational signature.

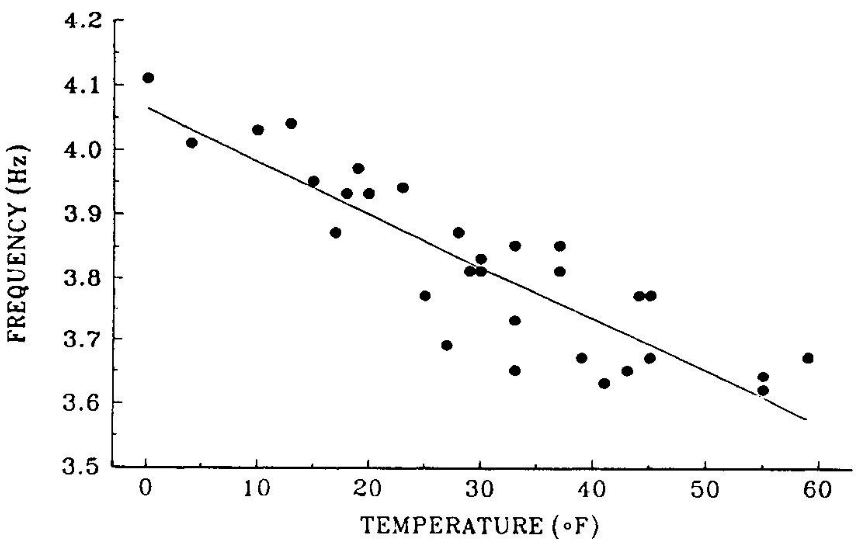

Figure 5 Frequency vs. Temperature for First Bending Mode

6. Conclusions

As shown in previous work with the vibrational monitoring system on a newer bridge, natural frequencies and mode shapes were relatively stable under varied traffic conditions. These form the bridge's baseline signature.

In this study, the monitoring system was placed on a continuous two span bridge. The data collected was relatively consistent during warmer weather. In the winter, the substantially lower temperatures caused the natural frequencies to increase. It was concluded that these are due to lack of full displacement at the bearings at the end of the bridge. These bearings should be free to rotate and allow longitudinal displacement. The changes to the natural frequencies demonstrate that the proposed approach, based on the vibrational monitoring, is able to detect changes in the structural performance.

This study has been a part of a continuing effort to establish that vibrational information can be used to evaluate the structural integrity of a bridge. Support from the State of Connecticut Department of Transportation and Vibra-Metrics, Hamden, Connecticut, a company which manufactures vibrational equipment, is gratefully acknowledged.

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