Modal Testing for Nondestructive Evaluation of Bridges: Issues

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Currently, global bridge inspection relies primarily on visual inspection with its well-known limitations. Among the promising global nondestructive methods is modal testing on which research has been conducted for two decades. The concept of the method is that modal characteristics (frequencies and mode shapes) of the structure are directly related to its stiffness properties which change as the structure deteriorates. At Iowa State University, a research program has been initiated to study modal testing using ambient excitation with the objective to determine the ability of the method to detect, locate, and determine the measurable size of defects in steel plate girder bridges. Effects of several factors on modal signatures are examined either experimentally or theoretically: environmental conditions, excitation trucks, pseudo-structural defects, deck rehabilitation, and structural cracks. The experimental portion consisted of modal tests on a bridge (Boone River Bridge in Hamilton County, Iowa) that was made available for the current investigation by the Iowa DOT. This paper presents the experimental investigation: motive, investigated parameters, and test program. Since the research is still in progress, only some preliminary results are given. Considering these results, the modal testing procedure presented proved to be an efficient method to monitor the health of bridge structures. Key words: modal testing, nondestructive bridge testing, environmental conditions, excitation methods.

INTRODUCTION

Current bridge evaluation is based almost entirely on the use of visual inspection with its many limitations. Other localized experimental techniques such as ultrasonic methods are used only if a segment of a bridge is suspected to be defective by visual inspection. The inspection cycle time is another facet to the problem. Inspection cycles set by federal regulations vary according to the bridge classification (use and essentiality) with a regular interval of two years. Often, such a period is sufficient for defects to grow and to cause major problems. As such, there is a great need for improving bridge evaluation techniques. Primarily, the desired technique should be (1) global in nature and (2) automated. Modal testing appears to fulfill both requirements. The objective of modal testing is to obtain a signature of the dynamic or vibration behavior of a structure in the form of mode shapes and frequencies. The frequencies of vibration of the structure are directly related to the stiffness and the mass of the structure. If the structure deteriorates, the stiffness will decrease and, hence, so will the frequencies of vibration. Further, changes in mode shapes are also expected to relate to the defect location. The first use of modal testing dates back to the 1950's. Since then, it has been used extensively in testing aerospace and offshore structures.

Several researchers have conducted modal tests on bridges to monitor changes in the modal properties due to changes in the structural condition (repair or induced defects). For example, Salawu and Williams (*1,2*) investigated the effects of deck repair and bearing replacement on the modal characteristics of a voided slab bridge. Aktan et al. (*3*) monitored the modal characteristics of two truss bridges while the bridge was loaded to failure. In other investigations, Aktan et al. (*4,5*) gave a strong argument supporting modal testing and stated that it is the only nondestructive method capable of determining the global condition of civil infrastructures (including bridges). Further, Aktan et al. presented (*6*) a conceptual system, that incorporates modal testing as well as strain monitoring, to accurately assess the structural condition of bridge structures. They commented that adopting similar systems would eliminate the subjectivity encountered in current bridge-management programs.

Recently, Alampalli et al. (*7,8*) addressed an essential question of what the minimum flaw size that can be detected using modal testing. The authors predicted that a 6 cm crack length would be the minimum size detectable at the most critical section of the bridge. However, this was based on tests conducted in the laboratory remote from inevitable environmental conditions encountered in the field. Further, in almost all previous investigations, bridges were excited by an impact hammer and the response was measured at closely spaced points. If a modal test were to be automated which is a basic requirement for a successful bridge evaluation program, the ambient traffic, not an impact hammer, would be the perfect source of excitation.

Research was initiated at Iowa State University with a primary objective to determine the discrimination limits of modal testing by field testing of a typical steel plate girder bridge using ambient or controlled traffic as an excitation source. Sensitivity of the modal signatures to several condition changes of an actual bridge was evaluated both experimentally and theoretically. Experimentally, the effects of four parameters are investigated: (1) environmental conditions (temperature and wind), (2) pseudo change in the structural stiffness (i.e., change in the bridge mass), (3) excitation methods, and (4) deck rehabilitation. This paper presents the research methods for the experimental phase of the research. The tested bridge is briefly described and the instrumentation is presented. The test program is introduced with a description of the modal test procedure. Further, the method utilized to extract the modal data is described. Finally, some preliminary results are presented.

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FIGURE 1 Boone River bridge on IA-17.

BRIDGE DESCRIPTION

The bridge tested in this study is located approximately 2 km south of U.S. 20 on Iowa Highway 17 (IA-17). The bridge was constructed in 1972, and as shown in Figure 1, it is a three-span, steel welded plate girder bridge. A 200 mm thick reinforced concrete deck slab is supported on five plate girders of spans 29.70, 38.10, and 29.70 m, respectively. Composite action is provided between the deck slab and the steel girders using shear studs. At intermediate locations, X-type cross frame diaphragms brace girder webs at approximately 6.70 m intervals. Deck rehabilitation was conducted in the spring of 1997 during which 40 mm of concrete overlay was added to the existing deck.

RESEARCH METHODS

Vibration Measurement

The acceleration dynamic response of the bridge was measured and recorded using a data acquisition system (DAS). The recorded data was transferred, on site, to a notebook computer where it was stored and later transferred to the structural engineering laboratory at Iowa State University for analysis. Accelerometers were connected to the DAS using special coaxial cables, some as long as 100 m. Data were sampled at 100 points per second giving a Nyquist (cut-off) frequency of 50 Hertz. The total sampling time per test was varied as it depended on the response of the bridge to the passing vehicles. At least thirty seconds of data were collected per test with few tests exceeding a sixty-second recording time. Therefore, a frequency resolution of at least 0.033 Hertz was attainable.

Modal Test Procedure

A three-dimensional finite element model was constructed for the Boone River Bridge to help in understanding the modal behavior of the bridge, determining the response frequency range of interest, and choosing the sensor locations. Accelerometer stations were along the bridge shoulders with distances between consecutive stations varying between 3.90 and 7.00 m. The acceleration response was measured at 42 points (21 on each side of the bridge) with four of these points on the pier sections. Steel plates were affixed to the deck using moisture resistant epoxy and the accelerometers (with magnetic bases) were attached to these plates. As the number of DAS channels was limited, it was necessary to acquire data at reference locations to obtain mode shape information. Consequently, two accelerometers were attached to a reference station for all tests to provide a common database for all test results. The modal test started with the six other accelerometers attached to the steel plates (on the deck) at six locations. With the traffic restricted on the bridge, a test truck (excitation source), provided by the Iowa DOT, traveled in the West Lane at a speed of 50 km/h (in several cases the speed was approximately 80 km/h). The traffic was then allowed on the bridge and the accelerometers, other than those at the reference stations, were moved to new locations. The same procedure was repeated until data at all the 40 stations was acquired. This accounted for seven test truck runs for each test.

Test Program

A summary of the tests is presented in Table 1. Tests were categorized in five groups: A, B, C, D, and E. Within each group, two digits designate each test: the one to the right refers to the test order, and the other represents the year in which the test was conducted. Tests with the letter d after the two digits were conducted after artificially changing the pseudo stiffness of the bridge (i.e., adding a vehicle on the bridge deck) to simulate damage. The test duration varied from one test to another but was generally performed well within 90 minutes.

TABLE 1 Summary of Conducted Modal Tests

Group	Test	Parameter investigated	Induced or apparent condition change from that in October 1997
A	71-74,76-78	Environmental effects	No change
B	71d	Simulated-structural defects	232 kN (mid span of Intermediate Span)
	72d		232 kN (mid span of South Span)
	73d		232 kN (quarter point of Intermediate Span)
	74d		14 kN (mid span of Intermediate Span)
	76d		76 kN (mid span of Intermediate Span)
	77d		36 kN (mid span of Intermediate Span)
	78d		147 kn (mid span of Intermediate Span)
C	61,75	Excitation method	Ambient traffic for excitation
D	61	Deck repair	Before deck rehabilitation, ambient traffic excitation
E	81,82		No apparent change

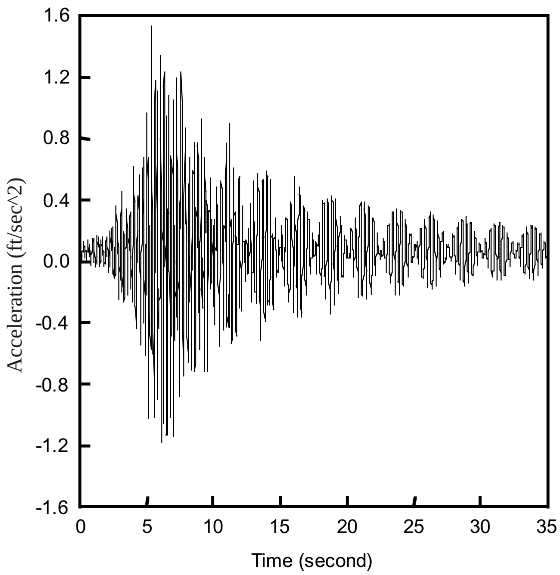

FIGURE 2 Time domain signal for the acceleration at Point RE during Test 72, Run 3.

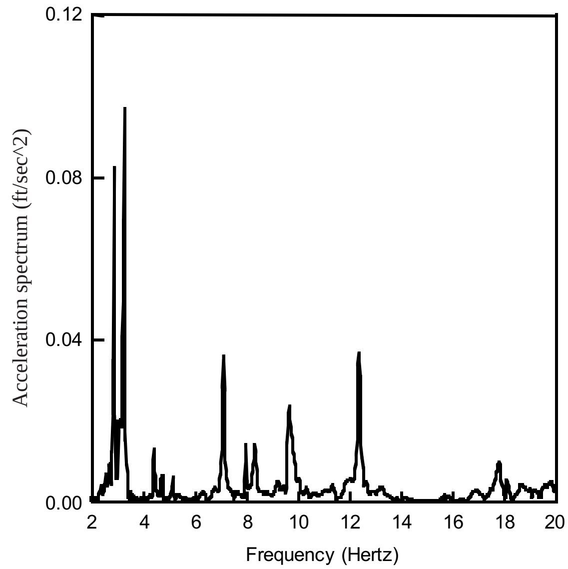

FIGURE 3 The acceleration spectrum at Point RE during Test 72, Run 3.

No change in the structural condition of the bridge was reported by the Iowa DOT or noticed by the test team while conducting Group A tests. Therefore, any changes in the modal parameters during these tests were attributed to environmental conditions and/or experimental noise. Effects of simulated structural defects were examined by conducting the Group B tests using different-weight vehicles placed on the bridge at different locations in the East Shoulder. This changed the mass distribution of the structure and, therefore, the frequencies and mode shapes as well. The same would have been true of a change in the stiffness were made to the bridge. Obviously, the former approach is simpler than the latter and was chosen for this research. Tests of Groups A and B were conducted in pairs, that is, tests having pseudo-structural defects (added mass-Group B) were conducted concurrently with tests with no condition alteration (Group A) to minimize possible environmental effects on the results.

To determine whether the exciting truck would have an effect on the extracted modal properties of the bridge, the bridge was excited by trucks from ambient traffic in Group C tests. While preparing the test program, there was no intention to study the effects of deck rehabilitation. However, after conducting Group A tests, it was obvious that the modal characteristic of the bridge differed significantly from those during Group D (conducted in 1996). After checking with the Iowa DOT, it was determined that deck rehabilitation had been performed in early 1997 (before Group A). This allowed an additional parameter (i.e. the effect of deck rehabilitation) to be investigated.

ANALYSIS METHOD

In the current investigation, the peak amplitude method (indirect frequency domain) is utilized. In this method, the natural frequencies correspond to amplitude peaks of the response in the frequency domain. The mode shapes are computed from the ratios of the peak amplitudes, taking into consideration the relative phase angle, at various points of the bridge. The method assumes that the modes are real and it provides good results if the modes are well separated. A fast Fourier transform (FFT), with a rectangular window, was applied to each acceleration time history to get the acceleration response in the frequency domain (the acceleration auto-spectrum or the acceleration spectrum). For example, in Figure 3, the acceleration spectrum that corresponds to the acceleration time history in Figure 2 is given. Natural frequencies appear as peaks in the response spectrum. It should be noted that not all peaks correspond to natural frequencies as some peaks in acceleration spectra simply corresponded to noise in the electrical measuring system. After preliminary investigations of all response spectra, it was possible to isolate ten modes of vibration and determine the corresponding natural frequencies. An interactive program written in C++ was used to extract the frequencies and mode shapes. Figure 4 illustrates the shape of the first six detected modes.

PRELIMINARY RESULTS

Utilizing Group A test results, a regression analysis was conducted to determine statistically the impact of ambient temperature and temperature differential between both sides of the deck slab on the measured frequencies. Figure 5 illustrates the results of the correlation analysis between the normalized frequencies and ambient temperature. A high correlation coefficient of approximately 85% was computed. As shown in the figure, the frequencies of vibration tend to decrease with temperature increase. On the other hand, it was found that the effect of temperature differential on measured frequencies was minimal.

The effect of the deck rehabilitation on the modal characteristics can be evaluated by comparing the results of Group D test to

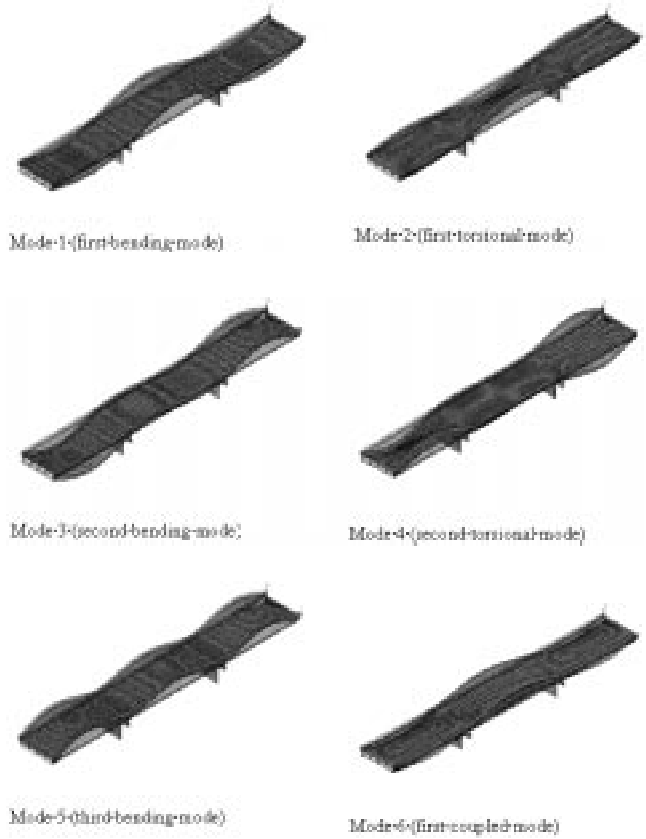

FIGURE 4 Description of the first six modes.

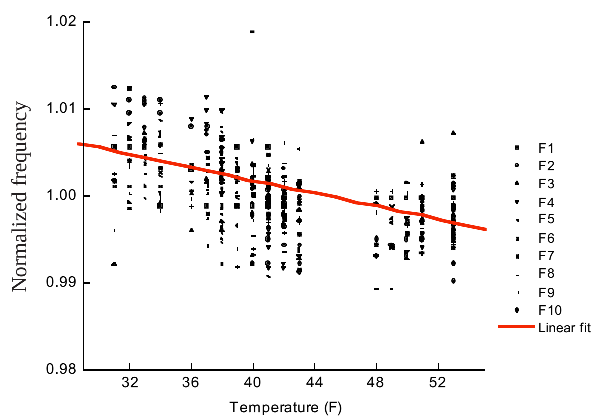

FIGURE 5 Regression results for the effect of ambient temperature on the natural frequencies.

TABLE 2 First Eight Natural Frequencies of Groups A and D Tests

Modal frequencies	Before Rehabilitation	After (Hertz)
F1	2.99	2.90
F2	3.29	3.28
F3	4.58	4.42
F4	4.81	4.76
F5	5.35	5.17
F6	6.72	7.16
F7	7.57	8.00
F8	8.02	8.38

those of Group A (a comparison is presented in Table 2). The added mass of the deck rehabilitation resulted in lowering the longitudinal bending frequencies (F1, F3, F5) significantly; however, it enhanced the transverse rigidity of the bridge resulting in minimal changes in the longitudinal torsional modes (F2, F4) and an increase in coupled longitudinal-transverse bending modes (F6, F7, F8).

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