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COMPUTATION OF STRUCTURAL FLEXIBILITY FOR BRIDGE HEALTH MONITORING USING AMBIENT MODAL DATA

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ABSTRACT

The issues surrounding the use of ambient vibration modes for the location of structural damage via dynamically measured flexibility are examined. Several methods for obtaining the required mass-normalized dynamic mode shapes from ambient modal data are implemented and compared. The methods are applied to data from a series of ambient modal tests on an actual highway bridge. The results indicate that the mass-normalization procedures considered all gave comparable results. The results also indicate that for the damage case examined, the flexibility from the ambient mode shapes gave a better indication of damage than the flexibility from the forced-vibration mode shapes. This improved performance is attributed to the higher excitation load levels that occur during the ambient test.

INTRODUCTION

The measured flexibility matrix has been shown to be useful for the indication of structural damage from measured modal data (see, for example, Aktan, et. al. (1994), Pandey and Biswas (1994), Toksoy and Aktan (1994), Doebling (1995), and Robinson, et. al. (1996)). A drawback to using the measured flexibility matrix is the necessity of having mass-normalized mode shapes. For a forced vibration test, the mass-normalization can be implemented from the driving-point inertance measurement. However, for a modal test which uses ambient measurements, the normalization is not as straightforward.

The difficulty of obtaining mass-normalized modes from ambient modal tests is relevant because of the practical issues surrounding the testing of large civil-engineering structures such as highway bridges. During a bridge test, it is often impractical to eliminate automobile traffic from the bridge, making the controlled conditions required for a forced vibration test difficult, if not impossible. Also, it is difficult to provide a significant level of input force for very large bridges. Thus, ambient modal tests are often the only practical source of modal data for large civil-engineering structure.

In this paper, three methods for mass-normalizing ambient modes are compared, and the resulting flexibility matrices are used to attempt to locate damage imposed in a known location on the structure. The methods are applied to modal data obtained from an actual highway bridge.

THEORETICAL BACKGROUND

The structural flexibility matrix $[G]$ can be estimated from the measured mass-normalized mode shape matrix $[\Phi]$ and the diagonal matrix of measured structural eigenvalues $[\Lambda]$ (where the entries in the eigenvalue matrix are the squares of the circular modal frequencies) as

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$$[G] \approx [\Phi][\Lambda]^{-1}[\Phi]^T \qquad (1)$$

The equivalence is approximate because the structure is a continuum and contains a theoretically infinite number of modes which are all required to fully define the static load-displacement relationship represented by $[G]$, but in practical applications only a small subset of these modes are measured. However, these modes are typically those that are lowest in frequency and therefore contribute the most to the flexibility matrix. The measured flexibility matrix is used to detect damage in a structure by first computing the pre-damage flexibility $[G_u]$ using the pre-damage mode shapes and frequencies, then computing the post-damage flexibility $[G_d]$ using the post-damage mode shapes and frequencies. The difference between these two matrices

$$[\Delta G] = [G_d] - [G_u] \qquad (2)$$

can then be used to hypothesize where the stiffness of the structure has decreased, as would be expected when damage occurs. One way to examine the flexibility change graphically is to take the diagonal entries in $[\Delta G]$, which represent the point flexibilities at the measurement degrees of freedom (DOF). These point flexibilities are the response at each DOF caused by an applied static unit load at that DOF. The point flexibilities are used as the indicator of damage in this paper. Other methods of using the change in flexibility to locate damage have been proposed by Toksoy and Aktan (1995) and Pandey and Biswas (1994).

As discussed above, the measured mode shapes used to compute the flexibility matrix must be mass-normalized (see, for example, Doebling (1995)). For a mass matrix $[M]$, this condition can be expressed

$$[\Phi]^T[M][\Phi] = [I] \qquad (3)$$

The mode shapes obtained from a modal extraction procedure generally have arbitrary magnitude. Therefore, a procedure is needed to normalize the modes with respect to the mass matrix, so that the flexibility matrix will have the proper magnitude. The four mode normalization schemes used in this paper are described as follows:

1. Guyan-Reduced Mass Normalization (GRM)

   This method uses a finite element model (FEM) mass matrix, reduced to the measurement DOF, to normalize the mode shapes such that Eq. (3) is satisfied. The reduction is done according to Guyan (1965), and assumes that the inertial forces in the structure are negligible. This assumption typically makes the GRM method valid for only the lowest frequency modes.

2. Orthogonal Procrustes Expansion (OPE)

   The OPE technique was developed as a mode shape expansion method, but can also be used to mass-normalize a set of measured modes if the corresponding mass-normalized FEM modes are available. The derivation of this method can be found in Zimmerman and Smith (1992).

3. Diagonal Mass Matrix (DM)

   This method uses a diagonal mass matrix to simulate the actual mass matrix of the structure. The diagonal entries in the mass matrix are assigned to be the maximum singular value of the Guyan-reduced mass matrix, so that it has the approximately correct overall magnitude. The normalization is then implemented in the same manner as the GRM.

4. Driving Point Normalization (DP)

   This method uses the measurement from the driving-point accelerometer to select the normalization factors for the mode shapes. This method requires a collocated input force and response acceleration measurement, so it is only relevant for forced-vibration testing techniques.

DESCRIPTION OF EXPERIMENT

A series of modal tests was performed in December, 1995, on a decommissioned highway bridge near Truth or Consequences, New Mexico. The bridge consists of seven spans, each 15 m (50 ft) long and 7.2 m (24 ft) wide. Each span is each supported by rollers at one end and by half-rollers at the other end. The rollers rest on concrete piers, and because there is no load-carrying structure between the spans they can be modeled and tested independently.

Modal tests were performed on several of the bridge spans. Excitation was provided for the forced-vibration portion of the test using a modal impact hammer. Ambient vibration data was also acquired, using excitation provided by traffic on an adjacent bridge and by an automobile driven across the span. For one span of the bridge, a cross-member was unbolted to simulate damage, and both impact hammer and ambient data were

acquired before and after the unbolting. The modes were extracted from the ambient modal data by measuring the cross-power spectral magnitudes and phases at the modal frequencies relative to a reference accelerometer measurement.

ANALYSIS OF RESULTS

The modes that were extracted from the ambient and hammer test data were normalized using methods 1-3 described in the theory section (in the case of the hammer data, method 4 was also applied). The second transverse bending mode (around 20.5 Hz) was selected as the mode of interest, because it was predicted to be the most sensitive to the structural damage. The displacements of this mode shape determined from the ambient data set are plotted in Figure 1, demonstrating the scaling of methods 1-3. Also plotted in Figure 1
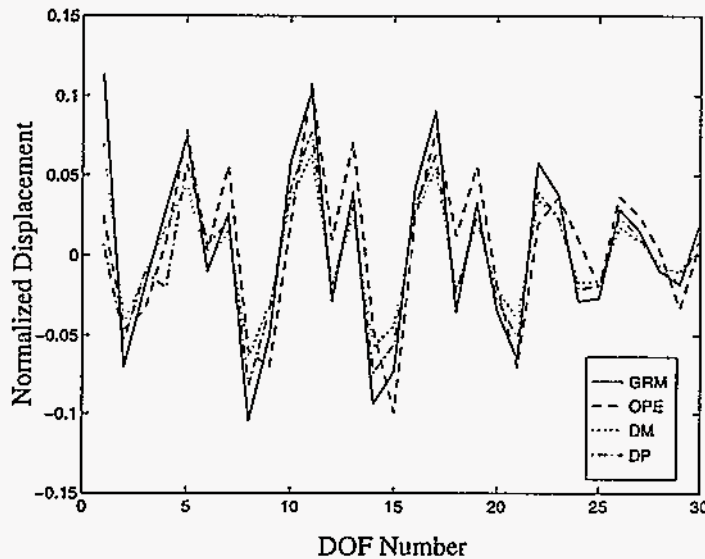

Figure 1: Ambient Mode at 20.5 Hz using 3 Different Normalization Procedures

Table 1 :RMS Difference and MAC for Ambient Mode Normalization Procedures (Relative to DP)

Method	RMS Difference	MAC
GRM	65%	85%
OPE	61%	77%
DM	40%	85%

are the displacements of this mode shape extracted from the impact hammer test and normalized using the method 4 (the DP technique). The root-mean-square (RMS) differences and modal assurance criteria (MAC) between the DP normalized impact-hammer mode and the ambient modes normalized using methods 1-3 are shown in Table 1. As shown in Table 1, using the DM method seems to produce a mode which is the closest to the driving-point-normalized mode. However, the driving point sensor used in this test was not very well collocated with the location of the impact hammer, so the accuracy of the mass normalization using the DP method is itself suspect.

To locate the "damage" imposed by the loosening of the cross-member, the flexibility for the mode of interest (20.5 Hz) was computed for both the undamaged and damaged cases from both the ambient and forced-vibration data. The change in the point flexibilities for this mode from the ambient test data is shown in Figure 2(a). A peak is clearly visible 7.5 m (300 in.) from the end of the span. The sensor at 4.5 m (180 in.) from the end, which is closest to the actual damage, does not show as much of a flexibility change. Thus, one of the sensors adjacent to the damage location has the largest flexibility change, but it is not the sensor which is closest to the damage. It is hypothesized that this discrepancy is due to the fact that the flexibility is composed of only one mode, so that the flexibility shape is biased in favor of the locations where that mode shape has the largest magnitude.

The flexibility change for the corresponding mode from the hammer data set is shown in Figure 2(b). This plot also shows a large flexibility change near the damage location, but has several peaks which are just as large at locations symmetrically opposed on the structure. Comparison of the overall magnitude of Figure 2(a) and Figure 2(b) also shows that the peak flexibility change is much larger in the ambient case. A possible reason for this is that the damage causes a load-dependent nonlinearity to manifest in this mode, and so the excitation provided by the automobile (which has a mass in excess of 2000 kg (4400 lb)) causes this mode shape to change more than the excitation from the hammer.
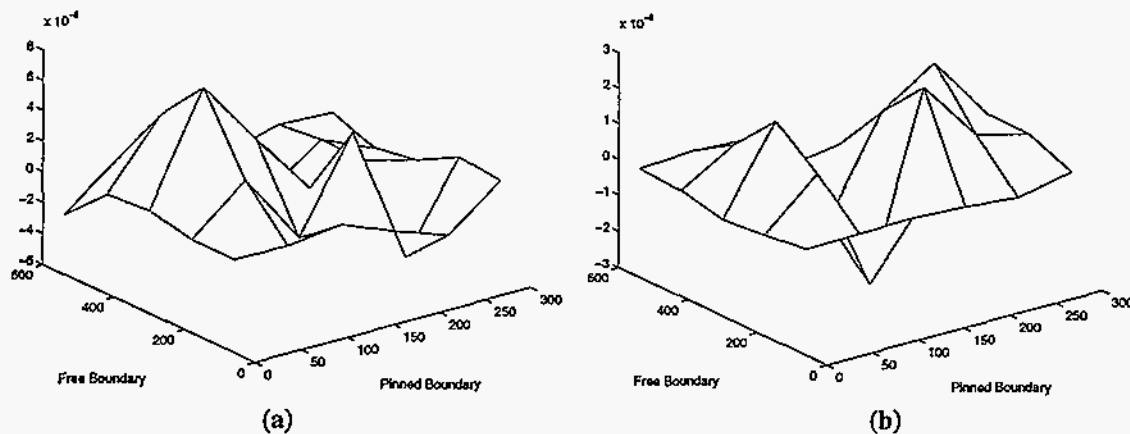
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Figure 2: Point Flexibility Change for (a) Ambient Mode and (b) Hammer Mode

CONCLUSION

Several mass-normalization procedures were applied to mode shapes obtained using ambient modal test techniques. Overall, the methods produced similar results when compared to the driving-point mass-normalized mode from the forced-vibration test. The results also demonstrate that modes obtained from ambient vibration data can give flexibility-based damage detection results which are as just as accurate as modes from a forced-vibration test. In the case of this damage analysis, better results were obtained from the ambient data, presumably because of the higher load levels involved.

ACKNOWLEDGMENTS

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