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Title: Neural Network Based System for Damage Identification and Location in Structural and Mechanical Systems

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Neural Network Based System for Damage Identification and Location in Structural and Mechanical Systems

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Abstract

This is the final report of a three-year. Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Recent advances in wireless, remotely monitored data acquisition systems coupled with the development of vibration-based damage detection algorithms make the possibility of self- or remotely-monitored structures and mechanical systems appear to be within the capabilities of current technology. However, before such a system can be relied upon to perform this monitoring, the variability of the vibration properties that are the basis for the damage detection algorithm must be understood and quantified. This understanding is necessary so that the artificial intelligence/expert system that is employed to discriminate when changes in modal properties are indicative of damage will not yield false indications of damage. To this end, this project has focused on developing statistical methods for quantifying variability in identified vibration properties of structural and mechanical systems

Background and Research Objectives

If accurate vibration-based damage detection is to be applied to *in situ* structures, sensitivity of vibration test results to environmental conditions and test procedures such as changes in temperature, traffic loading, wind, excitation method, etc. should be quantified to the extent possible. To date the vibration testing community has not developed methods to quantify the test-to-test variability in identified modal parameters such as resonant frequencies and mode shapes. Therefore, as a prerequisite to the development of sophisticated vibration-based damage detection algorithms, this project focused on developing methods to statistically quantify variability in modal parameters. These

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methods were applied to data from bridge structures where a considerable amount of environment variability was observed primarily as a result of changing thermal expansion during the course of a day. Data from test taken at various times during a day then had to be run through the damage detection algorithms to verify that they did not give false-positive indications of damage.

Although the number of papers reporting experimental modal analyses results from structures and mechanical systems has greatly increased in recent years, very few of the articles examine the variability in the modal properties that can arise from changes in environmental conditions or from random and systematic errors inherent in the data acquisition/data reduction process. A thorough study of the variability of the modal parameters must be conducted before vibration-based damage identification algorithms can be applied with any confidence.

Importance to LANL's Science and Technology Base and National R&D Needs

Vibration-based damage detection algorithms are being developed for stockpile surveillance as well as for detection of damage on a wide variety of mechanical and structural systems. However, for the results of these analyses to be meaningful one must be able to distinguish changes in vibration characteristics resulting from damage from those resulting from test-to-test variability. This project extends the state of the art in experimental vibration data analysis such that statistical analysis procedures are incorporate01d into the parameter estimation process. Such procedures can now be used with all vibration testing conducted at LANL and this unique capability sets our test methods apart from those of other vibration testing facilities.

Scientific Approach and Accomplishments

The statistical significance of vibration-based damage identification parameters is studied via application to the data from the tests performed on the Interstate 40 highway bridge in Albuquerque, New Mexico and to the data obtained from the Alamosa Canyon Bridge in southern New Mexico. Two analysis techniques were used to estimate the statistical confidence intervals on modal parameters identified from measured vibration data. The first technique is Monte Carlo simulation, which involves the repeated simulation of random data sets based on the statistics of the measured data and an assumed distribution of the variability in the measured data. A standard modal identification procedure is repeatedly applied to the randomly perturbed data sets to form a statistical distribution on the identified modal parameters. The second technique is the Bootstrap approach, where individual frequency response function (FRF) measurements are randomly selected with replacement to form an ensemble average. This procedure, in effect, randomly weights the various FRF measurements. These weighted averages of the FRFs are then put through the modal identification procedure. The modal parameters identified from each randomly weighted data set are then used to define a statistical distribution for these parameters. The basic difference in the two techniques is that the Monte Carlo technique requires the assumption on the form of the distribution of the variability in the measured data, while the bootstrap technique does not. Also, the Monte Carlo technique can only estimate random errors, while the bootstrap statistics represent both random and bias (systematic) errors. However, the bootstrap technique requires that every frequency response function is saved for each average during the data acquisition process.

Next, a test of statistical significance is applied to the mean and confidence interval estimates of the modal properties and the corresponding damage indicators. The damage indicator used in this study is the change in the measured flexibility matrix. Previously presented deterministic results from the I-40 bridge data indicate that damage is detectable in all of the damage cases from these data sets. The results of this study indicate that the changes in both the modal properties and the damage indicators are statistically significant for all of the damage cases. However, these changes are distributed spatially for the first three damage cases and do not localize the damage until the fourth and final damage case.

Figure 1 shows the first mode frequencies measured on the Alamosa Canyon Bridge in southern New Mexico along with their 95% confidence limits plotted as a function of the measurement completion time. Also plotted on Figure 1 is the change in temperature between the two thermometer readings made on the concrete deck (east - west). This figure clearly shows that the changes in modal frequencies are related to the temperature differentials across the deck. The first mode frequency varies approximately 5% during this 24-hr time period. Similar variations and correlation with deck temperature differentials were observed for the other modes of the structure. Figure 1 motivates the need for performing a statistical analysis of the identified modal properties before a damage identification algorithm is applied to these quantities.

(Doebling, et al., 1997) shows the results of similar analyses applied to the estimation of modal damping, mode shapes and mode shape curvature. Figure 2 shows the first mode of the I-40 bridge in its undamaged state and after the first level of damage. Damage was located at position 20. Error bounds for the modal amplitudes have been calculated by Monte Carlo statistical procedures. From this figure it is clear that there is a statistically significant change in the mode shape at this first level of damage. However, the results shown in this plot cannot be used to definitively state that the change in the mode shape resulted from damage as opposed to changing environmental conditions.

For the I-40 bridge test, several conditions occurred that were beyond our control and that could have significantly influenced the experimental modal analyses results and, in turn, damage identification results. Inevitably, tests of any *in situ* structure will have unavoidable conditions arise that are beyond the control of the experimentalist and that can potentially influence the outcome of the study. The only thing that can be done is to note the condition and perform additional tests in an attempt to quantify the influence of the changing condition. Examples of some of these unplanned changing conditions on the I-40 bridge are listed below.

1. The load cell located between the actuator and reaction mass showed that the vibration from traffic on the adjacent bridges, transferred through the ground to the piers and abutment of the bridge being tested, caused the bridge deck to put a peak force of 150 pounds into the reaction mass. Coherence functions can be used to determine if sources of excitation other than the Sandia shaker are significantly contributing to the measured response. For an ideal linear system the coherence function will yield a value of one. If the response is completely unrelated to the input, this function will yield a value of zero. Values between zero and one result when there is extraneous noise in the measurements, the structure is responding in a nonlinear manner, or sources of input other than the one being monitored are causing the response. For lightly damped structures, low coherence can also occur around resonances when the system response is calculated from a series of time windows as was done in these tests. The response in a particular window is strongly dependent on energy input during the previous window, particularly at resonance, and this response will be uncorrelated with input measured during the current window. A plot of the area under the coherence function for the various measurement locations as a function of their distance from the shaker is shown in Figure 3. The reduction in coherence that can be observed in this plot is caused by the inputs that result from extraneous sources of noise (traffic on the adjacent spans) causing a greater portion of the measured response at locations further from the excitation source. With the exception of measurement points directly above the support locations where the signal-to-noise ratio is inherently low, there is a distinct trend of poorer coherence as a function of distance from the shaker. The effects of the extraneous inputs are minimized by the averaging process used to calculate the FRFs.

2. Demolition of the concrete deck at the west end of the bridge was started before the forced vibration tests and continued while they were underway proceeding to the third span in from the west end. Portions of the foundation around the north side of the east abutment were removed to build an access ramp for construction work. Both the demolition and the construction of the access ramp can be viewed as changing the boundary conditions of the test structure. Forced vibration measurements taken before and after the access ramp was constructed showed no changes in the resonant frequencies of the structure. Because forced vibration measurements were not made before the demolition of the west end began, the extent of this change on the measured modal properties could not be easily quantified.

This study also investigated procedures to perform damage assessment given that only a an initial measurement of the structure had been taken. This process involved extensive numerical modeling of the bridge using the finite-element method. Once a finite-element analysis has been benchmarked or correlated against the measure modal properties, simulated damage scenarios can be introduced into the model and either an eignevalue analysis can be performed or, to better simulate an actual modal test, a time-history analysis can be performed. Mode shape data can then be obtained from either type of analysis and the various damage identification methods can be applied to the observed changes in the modal properties. If a statistical analysis has been applied to the measured modal parameters of the baseline or undamaged structure, then it can be established that the changes in the monitored modal properties such as mode shape curvature resulting from the simulated damage are greater than the variations that can be attributed to experimental repeatability. In addition, the statistical variations calculated for the measured modal properties on the undamaged structure can be assumed to apply to the numerical results from the damaged structure. The use of statistical variations measured on the undamaged structure and assumed for the numerical simulation of the damaged structure can then be used to establish the threshold damage level that can be reliably detected.

The statistical analysis procedures outlined in this summary have been implemented in a general purpose MATLAB-based computer code for experimental modal analysis and finite-element model refinement that is available at:

http://esaea-www.esa.lanl.gov/damage_id.

To the authors knowledge there are no other computer routines designed to analyze experimental modal data that have statistical analysis procedures embedded in them.

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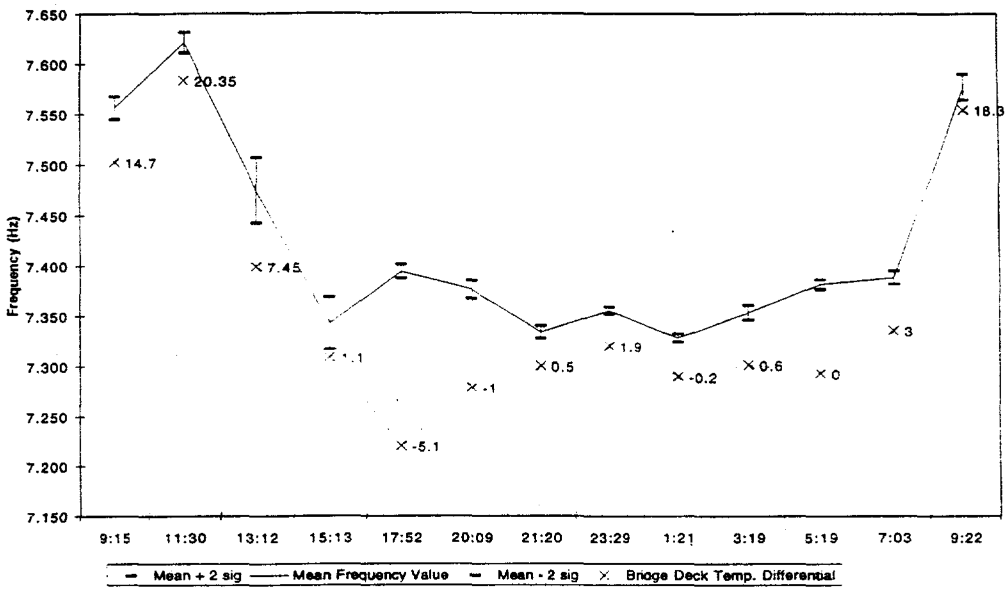

Fig. 1. Change in the first mode frequency during a 24 hr time period.

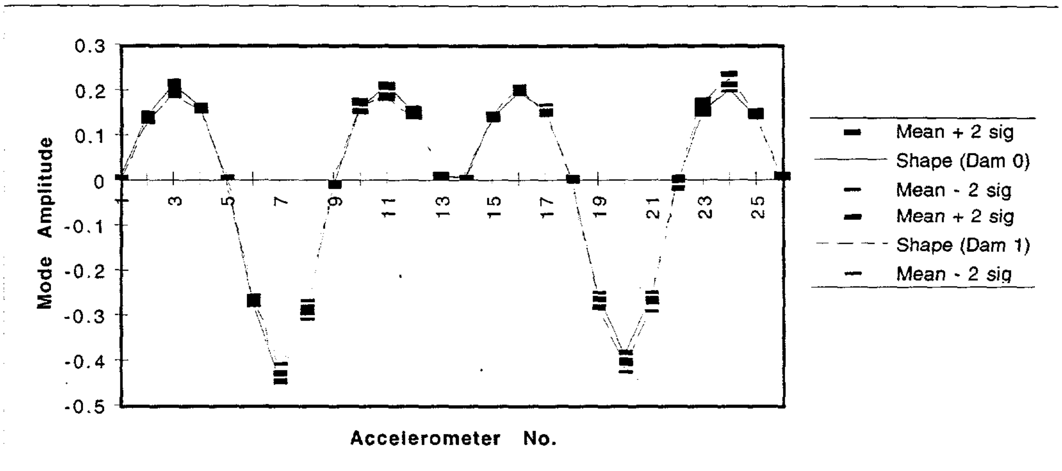

Figure 2. First mode shape amplitudes and their corresponding 95% confidence limits for the undamaged structure compared to similar quantities measured after the first damage case.

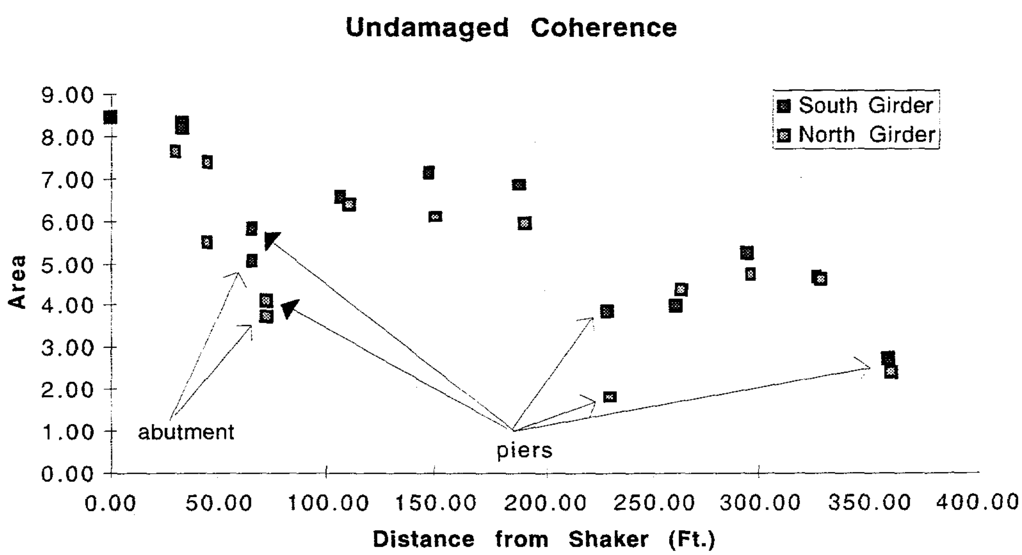

Figure 3. Area under the coherence function over the frequency range of 2 - 11 Hz plotted as a function of the sensor's distance from the shaker.