AN AUTOMATED DAMAGE DETECTION SYSTEM FOR ARMORED VEHICLE LAUNCHED BRIDGE

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Abstract. This paper presents an overview of an automated damage detection system for the Armored Vehicle Launched Bridge (AVLB). The system utilizes a non-contact laser vibrometer mounted on a computer-controlled robotic gantry as the measurement sensor. Acquired data is automatically processed to obtain strain energy mode shapes, which are used as the damage indicator. The analysis of the strain energy mode shapes is performed by a fuzzy expert system. This system was successfully tested on a full-scale AVLB with different damage scenarios.

INTRODUCTION

Constructed Facilities Center at West Virginia University has developed an automated damage detection system for AVLB [1]. The goal of the design is to detect structural damage in AVLB that might be threatening to the normal operation of the bridge. Another goal is to replace periodical assessment of the bridge condition using subjective visual inspection with a reliable automated system based on dynamic characterization methods.

Distinct features of the system include: full automation of every step in the damage detection procedure; application of a non-contact laser vibrometer as primary measurement sensor; utilization of the modal strain energy method as the core of the damage detection capabilities of the system; employment of methods of computational intelligence and soft computing (such as fuzzy logic) for “smart” processing of the signals within the system.

IMPLEMENTATION

The implementation of the automated damage detection system demands special attention to the automation of the data acquisition, processing of the acquired data by the damage detection method and analysis of the damage indicators. Automation of the system requires that these operations have to be seamlessly integrated within the system. These major issues are considered in the following sections.

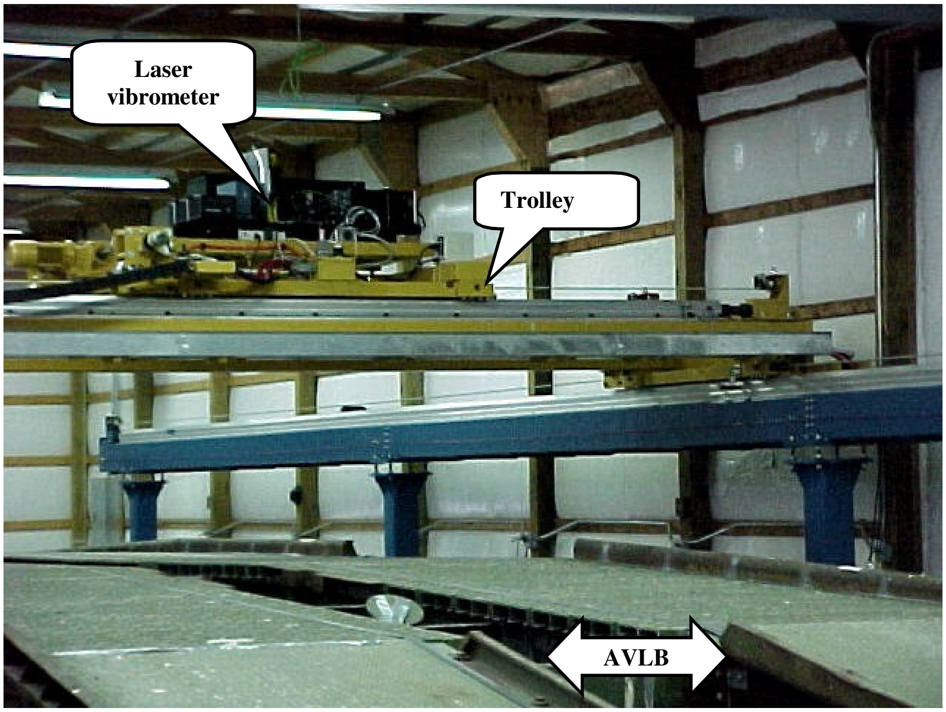

FIGURE 1. Robotic gantry crane.

System Setup

The main backbone of this stationary installation is a robotic gantry crane (Figure 1). The gantry crane allows two-dimensional motion of the mobile trolley within the field of approximately 900 x 250 inches (22.86 m x 6.35 m) with the accuracy of positioning about one tenth of an inch (2.5 mm). Combined with programmable control, such high positioning accuracy allows acquisition of vibration data from literally any point on the bridge surface.

The Ometron VS100 laser vibrometer is mounted on a platform on the top of the trolley. It can acquire vibration data only from one point at a time. The gantry crane has to position the vibrometer over the measurement spot before data acquisition can begin. Visual observation over the positioning process is performed using a wireless camera whose output is connected to a monitor on the operator's workplace.

The AVLB is supported on 8 airbags providing mechanical decoupling of the bridge from its support. Four 100 lb. shakers provide excitation to each of the bridge's girders. Each shaker is connected to the bridge surface in the following manner (Figure 2): an aluminum plate is glued to the bridge surface using a fast-hardening epoxy. A force transducer is attached the aluminum plate by a stud; the signal from the force transducer will provide reference signal during vibration testing. The shaker's plate is connected to the force transducer by a stinger of adjustable length. A forced air ventilation unit accomplishes the proper cooling of the shaker's core.

A Pentium 500MHz computer performs tasks of controlling the gantry, supplying excitation signals to the bridge exciters, acquiring and processing the data. It is equipped with a 16-channel 12-bit data acquisition (DAQ) system and two 2-channel 16-bit digital-

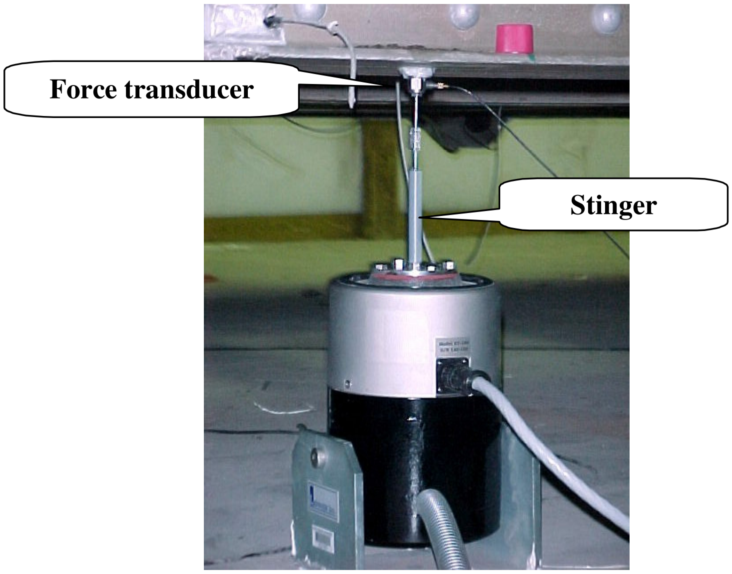

FIGURE 2. Shaker setup.

to-analog cards for excitation output. The gantry control interface is connected to a standard serial port. The signal output of the laser vibrometer is directly connected to one of the input channels of the DAQ card. Four input channels are used to acquire data from the accelerometers mounted on the bridge at the shaker locations. Accelerometer signals are used as reference during the testing. Another four input channels acquire signals from the force transducers, registering the force input from each of the shakers.

Automation of the Data Acquisition

Acquisition of the vibration data by a laser vibrometer has its specifics. Reliable operation of the laser vibrometer depends on many characteristics of the test setup, such as reflective properties of the surface, distance to the object, focusing, etc. Experiments conducted during the design of the system revealed a need for special signal processing solutions to provide reliable data acquisition from the surface of the AVLB due to the negative effect of signal dropouts [2]. Detailed information about these solutions can be found elsewhere [1, 3].

The damage detection system provides two modes of operation: sinusoidal dwell testing and random excitation testing. During the sinusoidal dwell testing, the bridge is excited by a sinusoidal signal source at one of its natural frequencies. Then, the mode shapes for that natural frequency may be acquired by reading the amplitude and phase of the sinusoidal vibration at each point of the bridge. Thus, the mode shapes are acquired directly from the structure without intermediate processing steps. Another significant advantage of the sinusoidal dwell testing is that all of the excitation energy is concentrated in one frequency only (for example, in random testing the excitation energy is spread among a band of frequencies) which makes the data acquisition process more reliable. The data acquisition process during sinusoidal dwell testing consists of two major tasks: identification of modal frequencies (modal identification) and modal scanning.

The purpose of modal identification is to isolate and determine approximate modal frequencies of the bending modes of vibration. The test setup for both modal identification and modal scanning is illustrated in Figure 3. The bridge is simultaneously excited by 4

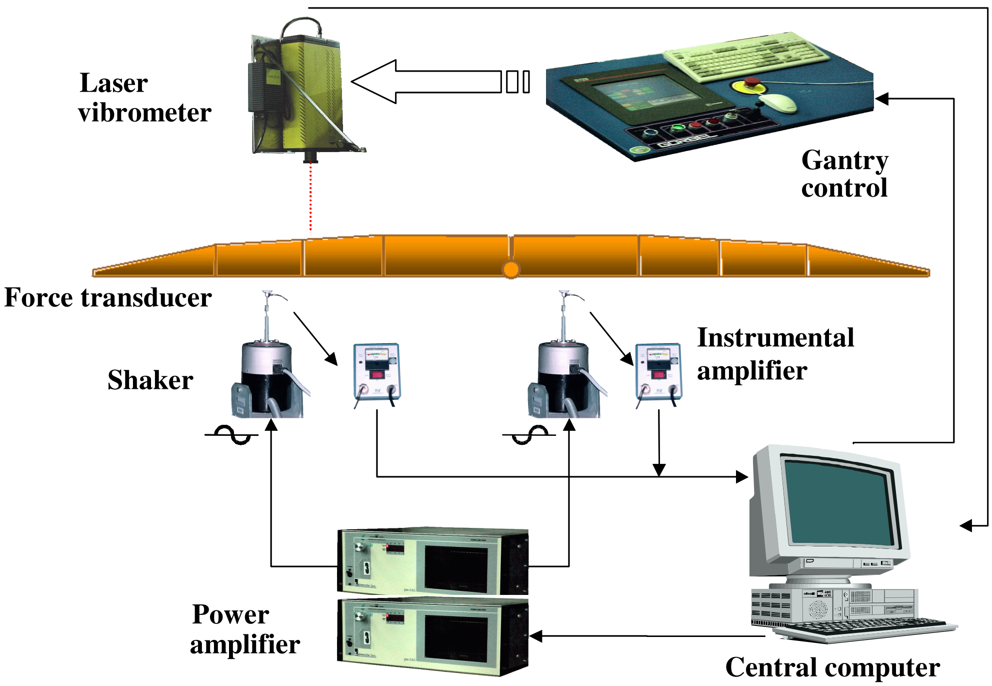

FIGURE 3. Test setup for sinusoidal dwell testing.

shakers (2 shakers on each side of the bridge) for any vibration mode other than first bending mode. The first bending mode is excited only by the 2 shakers located at the center. The sinusoidal excitation for the shakers at the center has 180° shift relative to the excitation supplied to the off-center shaker.

Combined with the analytically determined shaker positions, this excitation pattern is able to excite second, third and fourth bending modes of AVLB. The shakers positions are such that they do not fall onto the node lines of the first four bending modes. The modal identification is performed using a slow sinusoidal sweep procedure, where excitation frequency varies over time in small discreet increments. The modal frequencies are identified by observing the amplitude and phase of bridge response relative to the amplitude and phase of the excitation signal.

After the modal frequencies have been identified, the mode shapes should be acquired by the modal scanning procedure. The robotic gantry crane positions the laser vibrometer at several locations along each girder while the laser vibrometer acquires vibration parameters [1]. Obtained mode shapes can later be processed by strain energy software to analyze them for the presence of damage.

Advantages of the sinusoidal dwell testing include: ease of obtaining the mode shapes (no complicated signal processing is necessary); high accuracy of the mode shapes due to high relative energy at which a mode is excited (at a single frequency vs. a frequency band) and comparatively accurate control over the quality of the data acquisition; precise control over excited mode of vibration (only bending modes are of interest); relatively high sensitivity to damage (due to high mode shape accuracy); the requirements for measurement equipment are not very demanding due to the high energy of an excited mode.

The disadvantages, however, include the following: only one mode shape can be acquired during a single scan (the time to conduct a multi-mode test is proportional to the number of modes to be acquired); trial-and-error identification of modal frequencies (modal identification procedure locates some modes that are not purely bending; there is no way to tell whether a mode is bending until a full scan is conducted, thus some scans will take time but produce no result); harder to automate test procedure; the sine dwell testing cannot reliably identify changes in modal frequencies of individual components (for example, if three out of four girders of the bridge are undamaged and have first bending frequency about 9Hz and the fourth girder is damaged and has its first bending frequency at about 7Hz, then sinusoidal excitation at 9Hz will excite only three undamaged girders and will not excite the damaged girder).

Random excitation testing is another way to extract mode shapes from a structure. In this particular case a true random, burst signal was selected to excite the structure. The general outline of the method is as follows: the bridge is excited by a short burst of random signal containing non-zero amplitudes for all harmonics within a frequency band of interest (white noise). This burst should excite all natural frequencies of the bridge at once. Since both excitation input and vibration response are acquired, the Frequency Response Function (FRF) can be computed, identifying the bridge characteristics between the point of excitation and point of measurement; the mode shapes for any natural frequency can be extracted from the set of FRFs obtained during scanning procedure (fixed excitation point, variable measurement point) by a curve-fitting procedure. Thus, a single scan collects information about all mode shapes within the frequency band of the excitation signal. However, the energy content per frequency is significantly lower than in sinusoidal dwell testing.

Random excitation testing setup is illustrated in Figure 4. Under computer control vibration data is acquired at several locations along each girder. At each scan location, the computer calculates the averaged autopower and crosspower spectra, which are used to compute FRFs:

$$H(w) = \frac{\frac{1}{N}\sum_{m=1}^{N} S_{io}^{m}(w)}{\frac{1}{N}\sum_{m=1}^{N} S_{i}^{m}(w)} \tag{1}$$

where H(w) – frequency response function;

$S_i(w)$ – input (excitation) average autopower spectrum;

$S_{io}(w)$ – average crosspower spectrum (excitation – vibration response).

After the FRFs have been obtained, they are used to produce mode shapes. There are four tasks accomplished during this stage of processing:

1. Save FRFs for long-term storage.
2. Detect modal frequencies.
3. Extract mode shapes
4. Save mode shapes for long-term storage.

All these tasks are completely automated.

To identify actual modal frequencies, the average power spectrum is computed from the acquired set of FRFs. Modal frequencies are indicated by peaks in the average power spectrum. The search algorithm starts from the value of a target frequency (determined experimentally or through a finite element model) and looks for a peak in the neighborhood of that value. Once a peak is found, the frequency of its highest point is taken as the sought modal frequency.

After all modal frequencies of interest have been detected, the mode shapes are extracted from the FRFs. The method used to extract mode shapes is single-mode curve fitting [4]. A single FRF is a vector of complex numbers. If imaginary part of the same

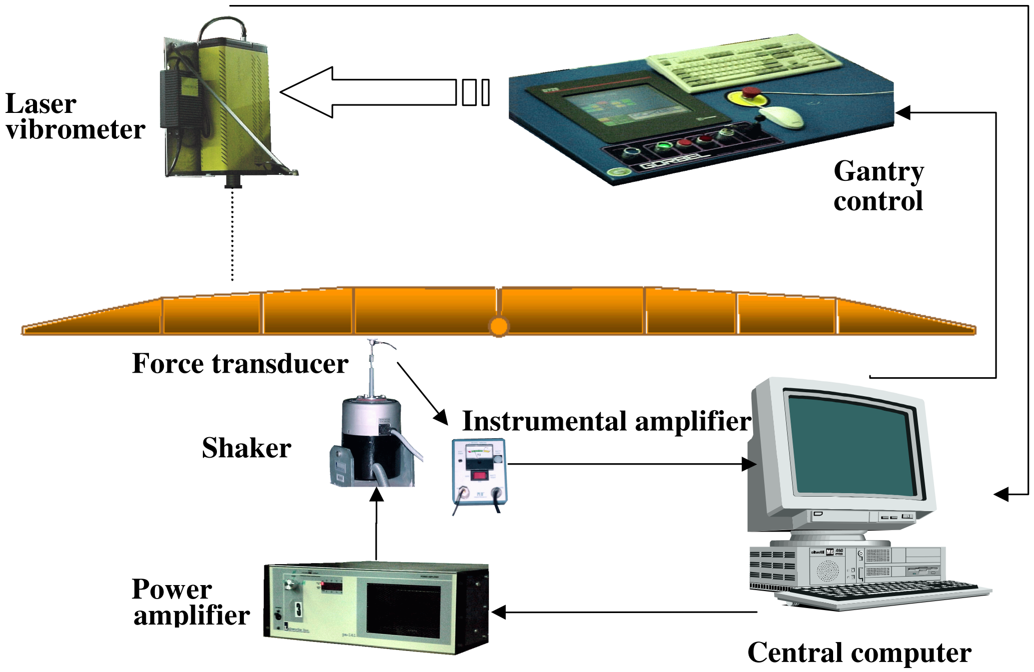

FIGURE 4. Test setup for random excitation testing.

element of different FRFs computed for different locations along the length is plotted vs. location, it will chart the mode shape at given frequency.

After the mode shapes have been extracted, they are saved in the work directory and control is transferred to the next software module that will process the mode shapes and perform automatic damage detection.

Advantages of the random excitation testing include: all mode shapes are acquired in a single scan (only the ones within the frequency band of random excitation); identification of modal frequencies is performed after the scan of a structure, thus significantly reducing the time required for this step (in sinusoidal dwell testing, the modal frequencies should be identified before the scan but if a frequency was identified incorrectly, a repeat scan will be necessary); test procedure is easy to automate, no operator intervention is necessary at any stage of the test; each part of the structure (for example, each girder) will display its own modal properties that are somewhat independent of the rest of the structure.

The disadvantages include the following: less precision of the mode shapes (this problem is not characteristic of the method but of the measurement equipment in use); the excitation energy is spread among a band of frequencies thus requiring more sensitive equipment; the mathematics involved is far more complicated than in sinusoidal dwell testing.

Automation of Damage Detection and Analysis of Damage Indicators

After the mode shapes have been obtained, the system must perform damage detection by computing strain energy mode shapes (SEMS). The displacement bending mode shapes extracted from FRFs or acquired by sinusoidal dwell testing are processed using numeric algorithms implementing the strain energy formula [5,6]:

$$U_{ab} = \frac{1}{2}\int EI(\phi'')^2 dx \qquad (2)$$

where, U_{ab} - strain energy calculated on interval a – b;
EI – flexural stiffness of the cross-section;
ϕ - mode shape vector (displacement mode shape);
ϕ'' - second derivate of ϕ with respect to x;

The locations on the structure that have abrupt changes in the stiffness (such as a crack) will show up on the strain energy mode shapes as peaks positioned at the damage location. Analysis of the damage indicators (peaks) is performed by a fuzzy expert system specifically designed for this task. Implementation of the damage analysis subsystem as a fuzzy expert system was stipulated by several factors:

1. A study of SEMS has shown that simple methods as thresholding perform very poorly in detecting damage and miss many cases of damage [7].
2. The nature of the strain energy formula makes it very sensitive to measurement noise and that, in turn, creates false peaks on SEMS.
3. The amplitude of a damage peak depends not only on the severity of damage but also on the peak's location. The damage may not show up in all but only in some mode shapes.

While a human expert does not have a problem recognizing damage peaks on the SEMS and distinguishing them from noise and artifacts of numerical computations, the computer does. A fuzzy expert system is a very good candidate to simulate the human approach to the damage detection problem: it can incorporate all the major components of the process – expert knowledge, pattern recognition and problem domain knowledge; it offers an explanation of how each decision was reached with all reasoning steps included; fuzziness of the system allows to easily deal with the ambiguities of the problem.

The tests of the fuzzy expert system have shown that it provides the quality of damage detection comparable with a human expert. It also demonstrated a high degree of noise-tolerance.

TESTING

Testing of the system was performed on six cases of simulated damage by removing some structural components of the bridge (such as hinge pins). The system was able to detect every case of single or multiple pin removal. Damages of less severity were harder to simulate due to the fact that no actual damage could be inflicted to the bridge. The less severe damage was modeled by removing some of the deck plates, which according to the bridge manual should not affect the structural integrity of the bridge [8]. Nevertheless, sinusoidal dwell testing was able to detect deck plate removal at some points of the bridge and could not detect it at other points. More experimental results from the real damage experiments are necessary to investigate sensitivity of the system to the lower-level damages.

Preliminary results showed that sinusoidal dwell testing had higher sensitivity to lower level damages but did not fare very well in pin removal experiments. Random excitation testing demonstrated superiority when higher level damage led to significant difference in modal frequencies of damaged and undamaged girders, and at the same time maintained decent sensitivity to lower level damages.

CONCLUSIONS

The automated damage detection system for AVLB performed reliably and accurately in the conducted experiments. The system supports two modes of operation: sinusoidal dwell testing and random excitation testing. Each of the modes of operations has its own advantages that may be used to accommodate the damage detection task at hand. Both sinusoidal dwell testing and random excitation testing may suffer from reduced accuracy due to signal dropouts.

Goals of the system's design were successfully achieved: the system performs reliable non-destructive testing and evaluation of AVLB without human intervention. Designed subsystems and methods can be utilized in non-destructive testing of various structures, where the method of strain energy mode shapes is applicable.

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