

Automated Laser Sensor System

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ABSTRACT

This paper presents an automated laser sensor system developed for damage detection of an Armored Vehicle Launched Bridge (AVLB) used by the US Army. The paper recounts the five-year effort aimed at developing a condition assessment system for AVLBs. A prototype automated laser sensor system built and tested by CFC-WVU consists of: 1) automated robotic gantry, 2) laser vibrometer, 3) data acquisition system, 4) excitation mechanism and 5) a master control program. The laser is mounted on the roving platform of the gantry, enabling it to scan structures upto dimensions of 76 ft by 18ft, the input signal for the excitation mechanism and the velocity output are generated and acquired using the master control program and data acquisition hardware.

The sensor system is ideal for testing large structures such as full-scale aircraft wings, automotive panels, bridge decks, and AVLBs. The high spatial density provided by this system enables the use of the strain energy based damage detection algorithm. Proof-of-concept tests were conducted on an AVLB using the automated laser sensor system and a strain energy damage detection algorithm. Test results and system description are presented in this paper.

INTRODUCTION

The U.S. Army developed an Armored Vehicle Launched Bridge (AVLB), as a mobile assault bridge that can be launched by an armored vehicle¹, and has about 900 AVLBs in its inventory. Figure 1 shows the AVLB in the launching position. Typically an AVLB is composed of four main girders, pairs of girders are braced with cross bracings and a deck to form two treadways.

The current criteria developed for inspecting these bridges are presented in the Preventive Maintenance Checks and Services (PMCS) manual for AVLB class 60 and 70. The method of inspection relies entirely on visual inspection of primary structural members. A reliable and global non-destructive testing (NDT) method was needed to complement the mostly qualitative visual inspection technique. Therefore remote laser vibration sensing technology was developed to achieve the high degree of damage detection. The

Constructed Facilities Center (CFC) at West Virginia University (WVU) teamed with the University of California at San Diego (UCSD), and Litton Laser System Inc., under contract from the US Army, to develop a laser based damage detection system for AVLB.



Figure 1 AVLB in the launching position

DEVELOPMENT OF A LASER SENSOR SYSTEM

The Phase I of this research program began in 1995, and initially the CFC focused on the development of the structural models required to determine the structural integrity of bridge members such as hinges, angles, or connectors. The CFC examined vibration signature data in terms of frequency and mode shape shifts in lower- and higher-order ranges for the purpose of damage detection.

CFC researchers demonstrated that modal strain energy is more sensitive to damage than frequency shifts and mode shape variations². Numerous vibration tests were conducted on simple structural components including aluminum rods, and plates to establish their vibration responses due to artificially made cuts³. The CFC also established the dynamic characteristics of an AVLB 60 upgrade given to WVU by the US Army. The field test constituted the first modal test conducted on an AVLB. From the testing, four distinct bending modes were identified. The results also indicated that the AVLB behaves as four loosely coupled girders, which helped in system design, namely a decision was made that the girders be tested on individual basis. The test also provided information on the frequency range for the first three bending modes and the necessary excitation levels⁴.

On the other hand, the Litton Laser Systems researchers extended existing laser vibration sensor performance and demonstrated that the laser vibration data can be used interchangeably with contact sensors in the development of damage detection algorithms.

In addition, critical areas such as the man-machine interface, data presentation and storage, system size and weight were investigated. Furthermore, a strain energy based damage detection algorithm was developed and automated using virtual instrumentation software, LabVIEW⁶. This automation considerably simplifies the process of damage detection.

Ramamurthy⁷ has developed a prototype Decision Support System (DSS) for the condition assessment of the Armored Vehicle Launched Bridge (AVLB). The DSS relies on an expert system for bridge condition assessment, which includes the vibration inspection procedures and refined visual inspection procedure. Sazonov⁸ studied the various different methods that can be used to improve the sensitivity of the damage detection algorithm and also explored the feasibility of applying computational intelligence for sensitivity improvement.

To further improve the strain energy based algorithm, Chen et al.,⁹ developed a damage detection technique using non-contact laser vibration measurements coupled with two dimensional (2-D) strain energy approach. The experimental study was conducted on aluminum and composite plates, for different damage scenarios. 2-D strain energy distribution shapes were constructed and damage was identified. To investigate the sensitivity of the algorithm at critical locations, Venkatappa et al.,¹⁰ studied the modal behavior of a hinged aluminum girder model using a laser vibrometer. It was concluded that using the data collected at the tapered ends in any curvature based damage detection algorithm could lead to erroneous results, because there is no angle correction applied to the velocity output from vibrometer for the tapered section.

Kosmatka (UCSD) et al.,¹¹ developed a damage detection algorithm that was based on data obtained from analytical models of the structure in addition to vibration test data. Utilizing the data obtained from vibration tests conducted on the AVLB at WVU by SDRC¹², damage location, damage estimation and damage assessment were conducted. The algorithm was able to determine damage location. Aluri¹³, and Sazonov¹⁴, completed the final design, development, and installation of the laser sensor system in 2000. Aluri used the laser sensor system to conduct modal tests on AVLB and detect damage using the strain energy approach. Sazanov¹⁴, also conducted modal tests on AVLB, and used the modal data to validate the non-baseline (i.e., undamaged state data not required) damage detection algorithm. A theory for determining the optimal spatial resolution for damage detection for the strain energy approach was established.

AUTOMATED LASER SENSOR SYSTEM

As mentioned earlier, the prototype automated laser system was a culmination of several years of extensive research and development. The design of the laser system evolved through a collaboration with Litton Laser System, and input from US Army. As a result, an automated laser sensor system was designed and built for testing the AVLB. The system consists of five parts: 1) Automated robotic gantry, 2) Laser vibrometer, 3) data acquisition/signal generation hardware, 4) excitation mechanism, and 5) a control program written in LabVIEW.

A high precision robotic gantry consisting of a roving platform, supported on 10 columns was designed to carry the laser vibrometer and other accessories (upto 500 lb. load), and move in both X and Y directions with varying speeds covering an area of 916" X 217". A Ometron VS100 laser vibrometer was mounted on top of the platform, which is used to collect the velocity data of the AVLB. It consists of a visible red Helium Neon laser and works on the principle of Doppler interferometry. The vibrometer can measure the velocities at distances up to 200 m having 80 dB dynamic range, the frequency range of measurement is between 0.01 Hz to 300 kHz.

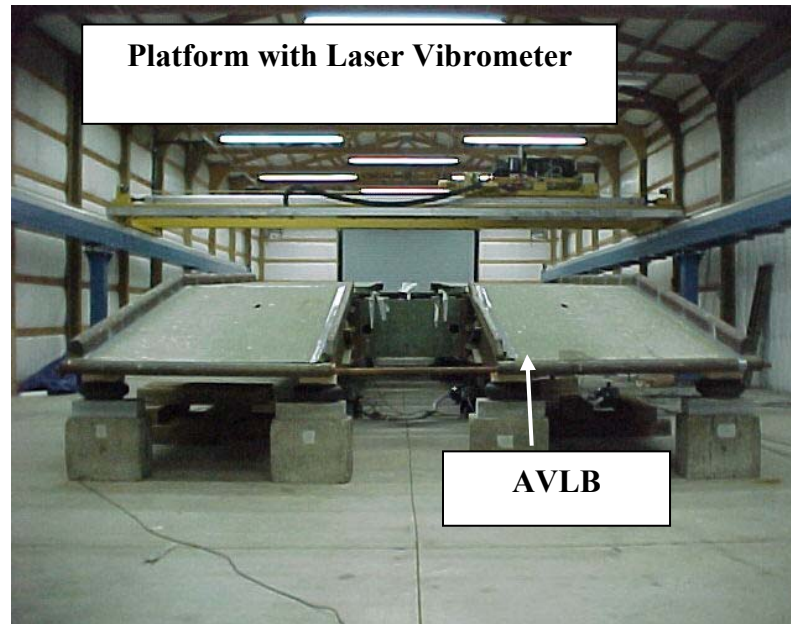


Figure 2. Automated Laser Sensor System.

A data acquisition system, consisting a 16-channel A/D card with a maximum sampling of 100 kHz and 16-bit resolution, and a 2-channel function generator was built to acquire laser output signal and generate a driving signal for the excitation mechanism. A wireless camera is also mounted on the gantry platform and is connected to a television; this set-up helps to adjust the position of the laser platform with reference to the AVLB. Four electrodynamic shakers were utilized to excite the AVLB. Each shaker can apply 110-pound peak (pk) force with a maximum of 1 inch peak to peak stroke.

A control program was written in LabVIEW by Sazanov¹⁴, while a small part of the program was developed by Litton Laser Systems. The purpose of this program is to automate the gantry control, data acquisition and the signal generation. The control program essentially has four modules: 1) Sine Mode Testing module, 2) 2-Ch Generate Sinusoid module, 3) Observation Panel module, and 4) Modal Scanner module. Each module automates a specific task involved in the dynamic testing of the AVLB.

CASE STUDY: DYNAMIC TESTING AND DAMAGE DETECTION ON AVLB

The primary input for the damage detection is the mode shape information. Resonant sine dwell tests were conducted on the AVLB to determine the vibration signatures. The AVLB was placed on eight airbags, four on each end of the bridge, to simulate the free-free boundary condition. Swept sinusoidal testing was done to identify the natural frequencies of the AVLB. The first three bending mode frequencies of the AVLB were identified as 8.7 Hz, 18.2 Hz, and 37.2 Hz respectively. The vibration data of the AVLB collected using the laser sensor system correlated well with previously conducted field-tests at WVU.

Electrodynamic shakers were used to excite the AVLB at each resonant bending frequency. The AVLB was maintained in the resonant state, the laser mounted on the movable platform of the gantry was used to collect the output response of all the four girders of the AVLB. The whole process of exciting the AVLB, roving of the laser platform over the girders of AVLB, collection of the laser velocity output was accomplished using the Sine Mode testing module and 2-Ch Generate Sinusoid module of the master control program, built for this purpose. Additional information regarding the test setup and test procedure can be found in reference 13.

The first bending mode of the undamaged AVLB extracted using the resonant sine dwell testing is shown in figure 3. Artificial damage was induced by removing the bottom center hinge of one of the girders of the AVLB. The AVLB deflected considerably due to the induced damage indicating a significant reduction in stiffness. Figure 4 shows the first bending mode shape of the damaged AVLB. It can be observed from Figures 3 and 4 that there is a significant difference in the mode shape characteristics of the damaged and undamaged AVLB.

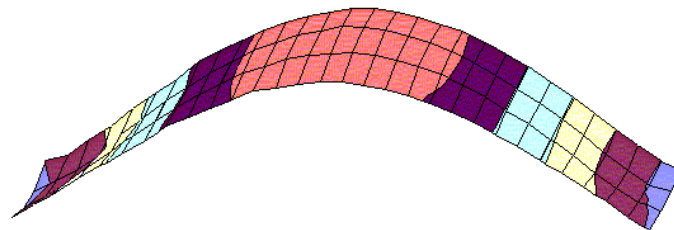


Figure 3. First Bending Mode of AVLB – 8.7 Hz, Undamaged Case

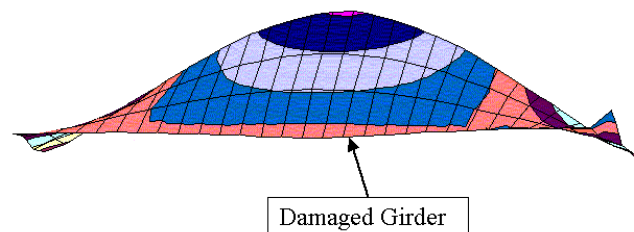


Figure 4. First Bending Mode of AVLB – 8.8 Hz, Central Pin Removed

Resonant tests were also conducted for four different damage scenarios simulated on the AVLB. The damage detection algorithm was applied to the first, second, and third bending modes data of the AVLB, damage was identified in either first, second, or third bending modes depending on the damage location.

STRAIN ENERGY BASED DAMAGE DETECTION

Damage can be characterized in terms of reduction in stiffness at a cross section of the structure. The Euler-Bernoulli equation clearly reveals that the beam bending curvature is inversely proportional to its stiffness. Damage at any section results in an increase in curvature at that section, which is local in nature. Hence curvature based methods can be used to identify damage. The strain energy distribution along a structure can be defined between any two arbitrary points a~b.

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

where,

U_{ab} = strain energy calculated over a zone ranging from 'a' to 'b'

(ϕ'') = modal curvature of an arbitrary (single) mode

EI = flexural rigidity of the cross-section

As mentioned earlier, damage in a structure, i.e. reduction in moment of inertia will result in an increase in the curvature, therefore leading to higher strain energy values at the damage location from experimental results. The difference between the strain energy distributions of undamaged and damaged structures can be used to indicate the severity of damage³

$$\Delta U_{abj} = U_{abj} - U_{abj}^*$$

U_{abj} = strain energy distribution (j^{th} mode) of undamaged structure

U_{abj}^* = strain energy distribution (j^{th} mode) of damaged structure

The above equation for the strain energy difference does not take into account the change in the moment of inertia at the damaged cross-section. Hence, the strain energy difference calculated at the damaged cross-section is not highly accurate value. The entire process of normalizing the mode shapes, calculating strain energy distributions for undamaged and the damaged structures and also calculating the difference in strain energy distribution had been automated using LabVIEW⁶.

The damage detection sensitivity is enhanced by using the dynamic strain energy function definition given by, Weaver¹⁵.

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

where ϕ = mode shape vector

The product of the squares of the curvature and the mode shape vector results in reducing the strain energy values at near zero locations (nodal points) while affecting values occurring at the peaks. This process has also been incorporated into the damaged detection algorithm. It can be observed from Figure 5 that the damage location (i.e., at the center of the girder) can be clearly identified.

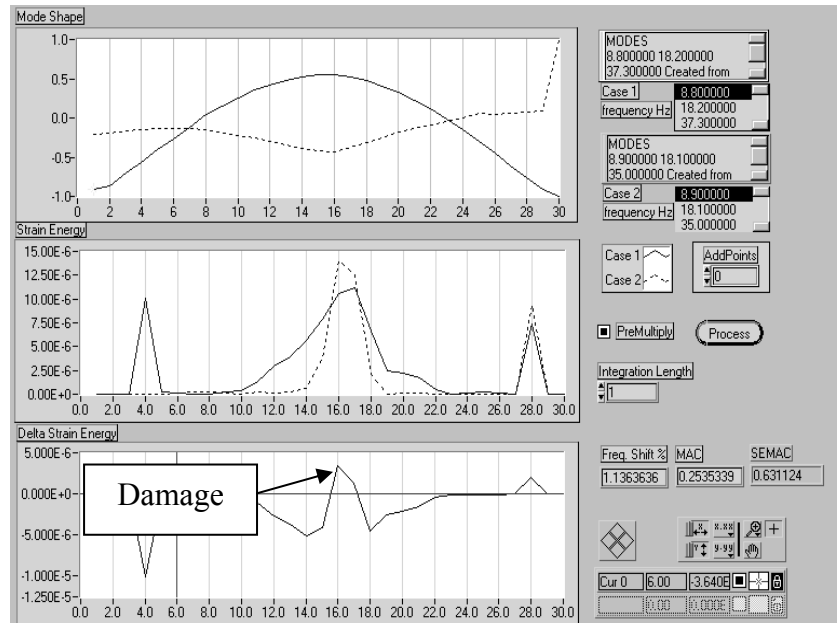


Figure 5 Comparison of Strain Energy Distribution of Undamaged and Damaged (Central Pin Removed) AVL B Girders - First Mode

Conclusions

This paper reports the design, development and validation of an automated laser sensor system. The accomplishments of the five-year research program include: 1) development of a prototype automated laser-based sensor system. The system includes a laser vibrometer, automated robotic gantry, data acquisition system and a control program. 2) modal testing was done on the AVL B using the automated sensor system to study the modal characteristics of the AVL B and establish the validity/accuracy of the automated system, and 3) development of a strain energy based damage detection algorithm which was applied to the AVL B test data and damage was clearly located in 2 out of the 4 simulated damage cases.

Acknowledgements

The authors would like to acknowledge the financial support provided by the US Army (contract # DAAE07-96-C-X226), and the contributions of Shen-En Chen, Suhas Venkatappa, John Moody, Vikram Ramamurthy, Rajesh Kalluri of CFC-WVU, Andy Culkin, and Brian Hornbeck of the US Army.

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