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Monitoring of Bridges to Detect Changes in Structural Health

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ABSTRACT

This paper discusses the development and implementation of a relatively low-cost health monitoring system via telemetry. The subject of the studies is the Hormiguero bridge spanning the Cauca River in Colombia. This system is being implemented for real-time monitoring of accelerations of the bridge using the Colombian Southwest Earthquake Observatory telemetry system. This two-span metallic bridge, located along a critical road between the cities of Puerto Tejada and Cali in the Cauca Valley, was constructed approximately 50 years ago. Experiences with this system demonstrate how effective low cost systems can be used to remotely monitor the structural integrity of deteriorating structures that are continuously subjected to high loading conditions. This paper will discuss the health monitoring system and provide some results based on the data acquired from this system.

1. INTRODUCTION

Our aging infrastructure is a global concern. In all parts of the world highways are a key component in the transportation network. Risks associated with the damage or collapse of these bridges include not only the loss of human life, but a potential for extreme economic implications. In the U.S. alone, over 900-billion ton-miles of commercial traffic are traversing highways and highway bridges each year. Fifteen percent of bridges in the U.S. are classified as structurally deficient by the Federal Highway Administration [6] (see also: *http://www.fhwa.dot.gov*).

Deterioration and destruction of bridges may be sustained due to continued use and misuse (overloading) of the bridges, as well as catastrophic events such as earthquakes. Bridge damage has been sustained during nearly every major recent seismic event in the US [15]. Failures, such as the collapse of the Nimitz Freeway and Oakland Bay Bridge during the 1989 Loma Prieta earthquake and the numerous highway bridge failures in the Los Angeles area during the 1994 Northridge earthquake, remind us that continued research to minimize such damage must be pursued. The maintenance of highway bridges is essential to safeguard lives and maintain a high level of service. Failure of a bridge will most likely result in the loss of property or, more importantly, of human life. Additionally, during an earthquake, unsafe bridges may compromise emergency response and repair crews. Furthermore, traffic may be disrupted or completely stopped for days, weeks and even months following a seismic event. When all of these consequences are taken into consideration, the potential financial loss will far exceed that of rebuilding the bridges, or of repairing or retrofitting them before such an event if the damage can be detected early.

The focus of this paper is the development and implementation of a health monitoring system for bridges. The bridge selected for this study is the Hormiguero bridge in Colombia, South America. The bridge spans the Cauca river, and is a primary route between the cities of Puerto Tejada and Cali. The bridge is often overloaded with heavy trucks carrying sand and sugar cane. Over the years the bridge has obvious signs of deterioration from such use. Additionally, the bridge is in a seismically active region, and the bridge has periodically experienced earthquakes.

This paper will provide a description of the health monitoring system for the bridge and discuss the implementation of a strategy to identify the natural frequencies of the bridge. The bridge has been instrumented with accelerometers, and the responses are measured and recorded at the Colombian Southwest Earthquake Observatory. Traffic loads are used to excite the bridge, and the responses are measured. In this initial study, the Natural Excitation Technique [17–19] is used in conjunction with the Eigensystem Realization Algorithm [20] to identify the natural frequencies of the bridge and the associated directions of motion.

2. THE HORMIGUERO BRIDGE

The Hormiguero bridge spans the Cauca River on the road between Cali and Puerto Tejada and is located approximately 10 kilometers from the Universidad del Valle Campus in Cali. Cali is the capital city of the Department of Valle del Cauca and the third most important city in Colombia. The extraction of sand from the Cauca River and the cultivation of sugar cane are two of the main industries in Puerto Tejada, located in the northern part of the neighboring Department of Cauca. The two-lane road between Cali and Puerto Tejada is of vital importance for the local economy as the sand used in the construction industry in Cali and well as sugar cane needed in the sugar factories near Cali must be delivered across the bridge by truck (Figure 1).

Due to its critical location, the bridge is often loaded with heavy trucks exceeding the weight limit of the bridge. For instance, the trucks that transport sugarcane are 25 meters long and have a gross weight of 80 metric tons distributed over five axes. Furthermore, the bridge is located in one of the more seismically active zones of Colombia and is periodically subject to earthquakes.

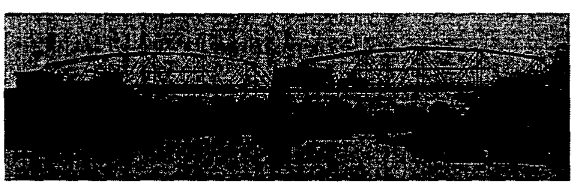

Figure 1. The Hormiguero Bridge.

2.1 Description of the structure

The Hormiguero Bridge was constructed approximately 50 years ago and has a total length of 124 meters [23]. It is a two-span metallic bridge, and each span consists of two superior metallic frame arches joined by laced and riveted members. The concrete deck slab is supported on a series of seven longitudinal steel girders connected to transverse I-beams, which in turn are riveted to the inferior longitudinal members of the arches (Fig. 2). The superior members of the each arch are riveted box sections interconnected by riveted steel plates on each face (Fig. 3). The inferior members are inverted U-sections and are connected to the superior members by vertical and diagonal I-beam members by means of riveted gusset plates.

Both spans rest on seat-type abutments and a central rectangular concrete column. Seventy-eight wooden piles support each abutment, the Puerto Tejada side abutment having a height of 7.8 meters and the Cali side abutment having a height of 11.3 meters. The central bent is a monolithic concrete column 11 meters high, an average rectangular cross section of 7.6m x 2.2m and the footing is supported by 50 wooden piles.

Although precise information is unavailable, the bridge was constructed in the 1950's. Routine maintenance of the bridge was neglected until 1996 [16]. Due to the loading demands and lack of maintenance the bridge has greatly deteriorated. Most of the connections present some type of damage ranging from advanced stages of corrosion to complete fractures and loss of rivets. Corrosion is aggravated by the decomposing sugar cane that accumulates on the bridge deck. Some of the superior bracing elements have been struck by vehicles that exceed the height limit of the bridge and have disconnected. The concrete deck has numerous potholes and cracks that result in high levels of vibration in the structure when vehicle pass over the bridge. The footing of the central column is scoured to such an extent that many of the wooden piles are exposed and greatly deteriorated and the upstream end of the footing is badly fractured and completely detached from the remainder of the footing (see Fig. 4).

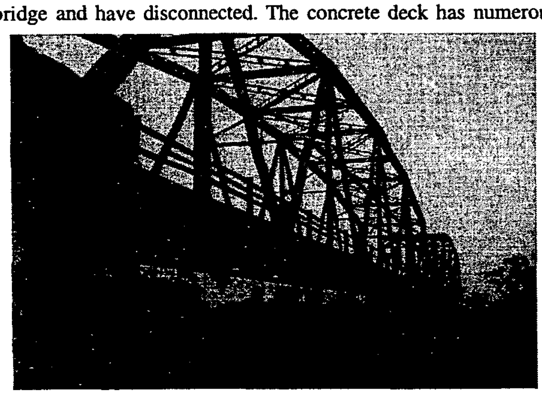

Figure 2. Steel Superstructure.

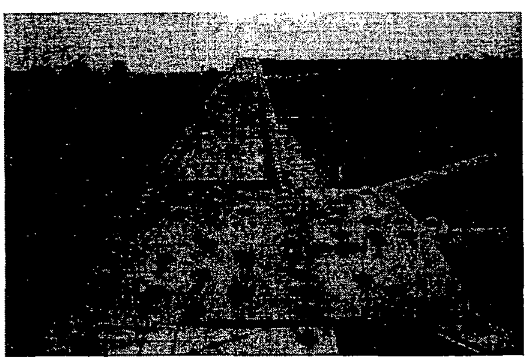

Figure 3. Riveted Connections.

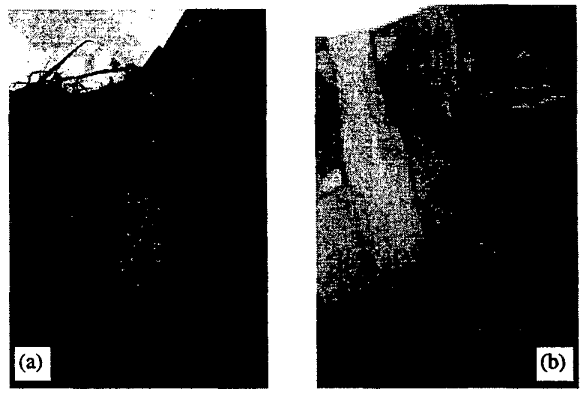

Figure 4. Components of bridge: (a) fractured pier footing, and (b) exposed and deteriorated piles.

Preliminary measurements of the vibrations in this structure have been obtained with a portable data acquisition system. This system consists of eight seismic accelerometers (Wilcoxon Research Model 731A) with corresponding amplifier and filter units and a laptop computer with National Instruments DAQCard 700 and Labview. These tests indicate that the vertical peak accelerations of the deck of the bridge hit 0.15g with traffic loads, and displacements of more than 0.5 centimeters have been recorded. These measurements indicate that the bridge has existing vibration problems that should be investigated with more detail.

2.2 Finite element model of the structure

A FEM model of the bridge including the abutments and central bent has been developed using program SAP2000 Non Linear [26]. The model consists of 896 frame elements, 10 shell elements and 57 solid elements. Existing damage in the bridge from the last 50 years of service is being identified and incorporated into this model. Care has been taken to account for different types of connections between elements, damaged connections, modifications made to the structure, damage to scour of the footing of the central pier, and soil-structure interaction.

The baseline model of the existing bridge is being used for comparative studies to detect any further damage in the bridge due to traffic loading and correlation of these changes with the model of the existing bridge allows these changes to be quantified. The model will also allow the effectiveness of future repairs of the bridge to be evaluated by comparison with experimental data. Work presently under way will take into account temperature effects in the model and allow changes in structural response due to temperature and those due to damage to be distinguished. The results of the finite element analysis will be provided in future papers.

3. INSTRUMENTATION/MONITORING SYSTEM

Before we begin monitoring this bridge it is necessary to develop and identify a model of the current state of the bridge. The Universidad del Valle has instrumented the bridge with a set of accelerometers and is in process of implementing an online structural health monitoring strategy. Data is transmitted to the School of Civil Engineering using a telemetry system that is currently used for the Colombian South West Earthquake Observatory (OSSO *http://osso.univalle.edu.co*) for seismic monitoring in the southwest part of the country [5].

The set of WR-731A accelerometers with corresponding amplifiers and filters, an FM radio transmitter Monitron TT-2A and system SA-01 are installed under the bridge deck. The system SA-01 consists of a mixer board MLC-05, power calibration board PC1, VCO board VFC-05, and a voltage surge protection unit USS8. The instrumentation is installed in a steel case of dimensions 55 cm x 60 cm x 35 cm (Fig. 5) that is welded between two of the girders. Initially only one channel is being transmitted due to limitations in the telemetry system (which is presently being expanded). The signal is received by a radio receiver Monitron TR-2 at the Colombian South West Earthquake Observatory, where after being demodulated is digitized by a 16 bit A-D converter at a 200 Hz sample rate.

The digital signal is then sent via intranet to the Earthquake Engineering and Structural Dynamics Laboratory at the School of Civil Engineering and Geomatics, where the online structural health monitoring strategy is being implemented in MATLAB® [29]. An on-line level III structural health monitoring algorithm is being developed to make it possible to detect damage in the structure, the approximate location of the damage, and the extent of damage. A diagram of the monitoring system is provided in Fig. 6.

4. SYSTEM IDENTIFICATION

The technique used herein to identify the natural frequencies of the Hormiguero bridge employs the Natural Excitation Technique [17–19] and the Eigensystem Realization Algorithm [20]. To identify the natural frequencies of the bridge we first obtain cross-correlation functions from the system from forced vibration data. The cross-correlation functions are used to identify modal characteristics from free vibration data. Measurement of the excitation is not required to apply this methodology, although the disturbance should be random and broadband. In this experiment, the excitation is traffic (usually large, fully-loaded trucks) crossing the bridge periodically. Details on the methodology are discussed in the following sections.

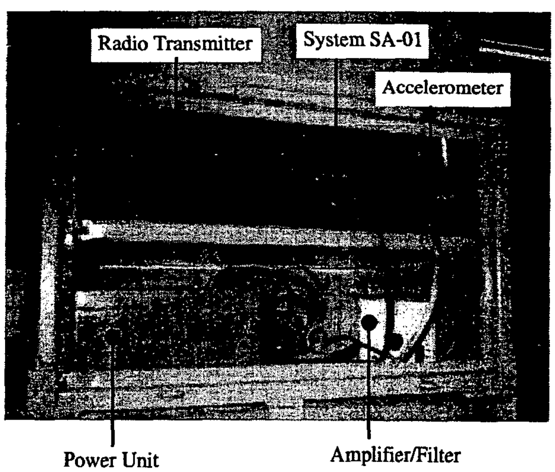

Figure 5. Instrumentation and Transmission Equipment.

4.1 Natural Excitation Technique

We are often interested in monitoring the health of a structure when the disturbance to the system cannot be measured. The development of the Natural Excitation Technique (NExT) provided a estimating parameters when this is the case [17–19]. James et al. recognized that the cross-correlation function for between two displacement or two acceleration measurements on a structure satisfies the homogeneous differential equation governing the motion of the system. This result can be used to obtain modal parameters for the system from the correlation functions.

The effectiveness of the NExT technique has been demonstrated through the identification of structural modal parameters in different types of civil structures using ambient vibration. Researchers have employed this technique for the identification of modal properties in both analytical and experimental studies. For example, Beck et al. [2,3] applied the NExT method to identify modal parameters for the Robert A. Millikan Library located at the California Institute of Technology. In this study two lateral frequencies and one rotational frequency were found for this nine story building using a total of six accelerometers. Farrar and James [13] also used the NExT method to determine natural frequencies and mode shapes of a portion of a highway bridge spanning the Rio Grande along the former I-40 highway.

Consider the differential equation for a multi-degree-of-freedom system

$$\mathbf{M}\ddot{x}(t) + \mathbf{C}\dot{x}(t) + \mathbf{K}x(t) = y(t) \tag{1}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, and $\mathbf{K}$ is the stiffness matrix, $x(t)$, $\dot{x}(t)$ and $\ddot{x}(t)$ are vectors of displacement, velocity and acceleration, and $y(t)$ is a vector describing the forces applied to the structure.

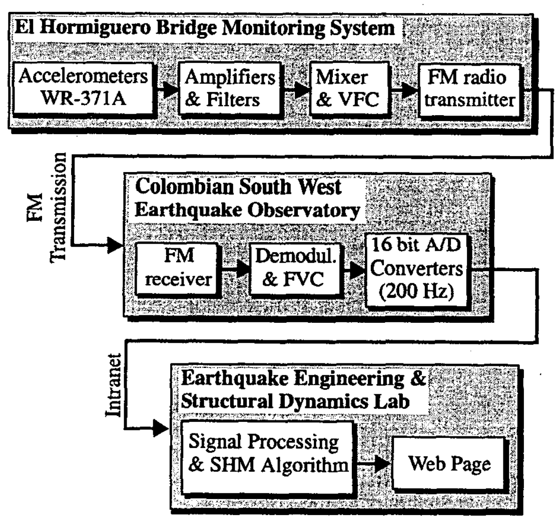

Figure 6. Diagram of the Monitoring System.

Assuming that the forces applied to the structure as well as the displacements, velocities and accelerations are each stationary random processes, Eq. (1) is written

$$\mathbf{M}\ddot{X}(t) + \mathbf{C}\dot{X}(t) + \mathbf{K}X(t) = Y(t) \tag{2}$$

where $X(t)$, $\dot{X}(t)$ and $\ddot{X}(t)$ are vectors of stochastic processes for the displacements, velocities and accelerations of the structure, and $Y(t)$ is the vector of stochastic processes describing the forces applied to the structure. Postmultiplying Eq. (2) by a scalar process $X_i(s)$, referred to as the reference response (one of the measured responses), and taking the expected value of each side yields

$$\mathbf{M}R_{\ddot{X}X_i}(t,s) + \mathbf{C}R_{\dot{X}X_i}(t,s) + \mathbf{K}R_{XX_i}(t,s) = R_{YX_i}(t,s) \tag{3}$$

where $R(\bullet)$ denotes a vector of correlation functions. Recognizing that the responses of the system are uncorrelated to the disturbance, we obtain

$$\mathbf{M}R_{\ddot{X}X_i}(t,s) + \mathbf{C}R_{\dot{X}X_i}(t,s) + \mathbf{K}R_{XX_i}(t,s) = 0. \tag{4}$$

For two weakly stationary random processes, $A(t)$ and $B(t)$, we can show [27, 8]

$$R_{A^{(n)}B}(\tau) = R_{AB}^{(n)}(\tau) \tag{5}$$

where $A^{(n)}$ denotes the nth derivative with respect to time of the random process $A(t)$, and $R_{AB}^{(n)}$ denotes the nth derivative of the correlation function $R_{AB}(\tau)$ with respect to τ.

Applying Eq. (5) to Eq. (4), and assuming that the random processes contained in the vectors $X(t)$, $\dot{X}(t)$ and $\ddot{X}(t)$ are weakly stationary, we can write Eq. (4) as

$$\mathbf{M}\ddot{R}_{XX_i}(\tau) + \mathbf{C}\dot{R}_{XX_i}(\tau) + \mathbf{K}R_{XX_i}(\tau) = 0. \tag{6}$$

Thus, the matrix of correlation functions satisfies the homogeneous differential equation of motion.

The NExT technique is implemented in MATLAB® [29]. Because the cross-correlation function and the cross-spectral density function are a Fourier transform pair, the cross-spectral density is computed directly from the data. For implementation, averaging and windowing are employed to increase the accuracy of the cross-spectral density function computations [4, 24].

For effective implementation, the reference signal should be selected to be a response that is not located at any node of the structure. Once the correlation function is obtained, a variety of methods may be applied to identify the modal parameters. Herein the eigensystem realization algorithm (ERA) is used, as discussed in the following section.

4.2 Eigensystem Realization Algorithm

Numerous techniques available for identifying the modal parameters from the free response data. Here the ERA [20] is adopted because it is quite effective for identification of lightly damped structures and is applicable to multi-input/multi-output systems. In the ERA, the Hankel matrix is formed

$$H(j-1) = \begin{bmatrix} x(j) & x(j+1) & \dots & x(j+p) \\ x(j+1) & \dots & & \\ \dots & & & \\ x(j+r) & \dots & & x(j+p+r) \end{bmatrix} \tag{7}$$

where $x(j)$ is the $m \times n$ response matrix at the j-th time step. The parameters p and r correspond to the number of columns and rows in the Hankel matrix. For good results, p should be selected to be approximately 10 times the number of modes to be identified, and r should be selected to be 2–3 times r. The Hankel matrix is evaluated for $H(0)$ and a singular value decomposition is performed as

$$H(0) = PDQ^T. \tag{8}$$

where P and Q^T are the matrices of left and right eigenvectors of $H(0)$, respectively, and D is the diagonal matrix of singular values. Relatively small singular values along the diagonal of D correspond to computational modes. The rows and columns associated with computational modes are eliminated to form the condensed version of these matrices D_N, P_N, and Q_N. The state space matrices for the resulting discrete-time system are found using [20]

$$\hat{\mathbf{A}} = D_N^{-\frac{1}{2}} P_N^T H(1) Q_N D_N^{-\frac{1}{2}}, \quad \hat{\mathbf{B}} = D_N^{-1/2} Q_N^T E_m,$$
$$\hat{\mathbf{C}} = E_n^T P_N D_N^{-\frac{1}{2}} \tag{9}$$

where $E_n^T = [I \;\; 0]$ and $E_m = [I \;\; 0]$.

The $\hat{\mathbf{C}}$ matrix may be used to transform the computed eigenvectors of the state matrix (corresponding to the non-physical states in the identified model), to displacement output shapes at the floors of the structure using

$$\Upsilon = \hat{\mathbf{C}}\hat{\Phi} \tag{10}$$

where Υ is the matrix of ouput shapes and $\hat{\Phi}$ is a matrix of eigenvectors of the state matrix $\hat{\mathbf{A}}$. $\hat{\mathbf{B}}$ is not required for this analysis. The ERA method was implemented in MATLAB® [29].

5. EXPERIMENTAL RESULTS

Preliminary data was recorded on-site (not using the telemetry system) with the data acquisition system described previously. This traffic-induced vibration data is used herein to determine the natural frequencies and associated motions of the Hormiguero bridge. It will also be used to update the finite element model of the bridge in it's current state. The quality of the data obtained with the telemetry system will also be compared to that obtained on-site. The data for this experiment was recorded at 200 Hz. A 100 Hz lowpass filter was used to minimize aliasing in the signal. Note that the data obtained in these tests is not stationary, but the results indicate that the method is applicable.

A series of twelve tests were conducted on the Hormiguero bridge. The four sensor locations are shown in Fig. 7. In each test, a sensor was placed in location B in either the vertical or horizontal direction. In each test 120 seconds of response data was recorded and two channels of data were obtained. This time length allowed

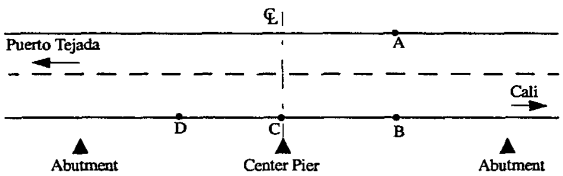

Figure 7. Sensor Locations for Various Tests.

for between one and eight trucks to pass over the bridge in the various tests.

The presence of large moving vehicles on the bridge may effect the natural frequencies of the bridge. This shift is due to the fact that the combined system, consisting of the truck(s) and the bridge, will have different natural frequencies than the bridge alone. Additionally, as the vehicle moves across the bridge, these system frequencies will fluctuate [12]. If these effects are significant, it is necessary to determine when the truck leaves the bridge, and use only free response data. To determine if this effect was significant, a spectrogram was computed as shown in Fig. 8. The natural frequencies remained fairly constant when the trucks were crossing the bridge, indicating the trucks have little influence on the natural frequencies of this bridge.

To compute the cross-spectral density functions, 2048 points were used in each frame and averaging was used. The correlation function was obtained by performing in inverse Fourier transform. Figure 9 shows a typical cross spectral density function and cross correlation function for the acquired data.

To implement the ERA, 250 rows and 50 columns were used to form the Hankel matrix. A representative distribution of singular values obtained within the ERA is shown in Fig. 10. For automated implementation, a criterion was selected for choosing the singular value cutoff (to eliminate numerical modes). The singular value cutoff was selected to be 80% of the RMS value of all of the singular values, as shown in Fig. 10.

The resulting natural frequencies of the system are provided in Table 1. Note that transverse, vertical, and torsional modes were identified, as well as modes that appear to be combinations of these motions. Several of the modes appear to correspond to coupled motions. This is most likely due to the fact that the center of inertia and the center of stiffness are far apart in this bridge. Using the system identification methodology described here, the modes were detected successfully (see Table 1 for results).

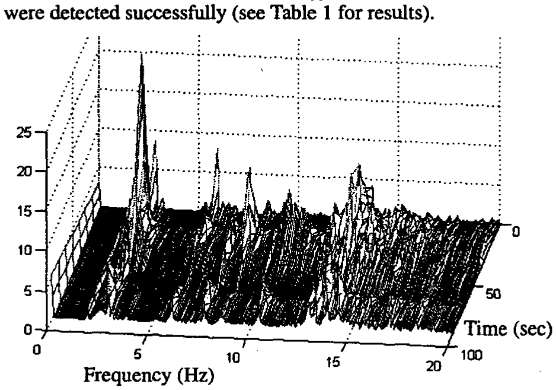

Figure 8. Representative Spectrogram.

Table 1: Identified Natural Frequencies and Modes.

Frequency (Hz)	*Associated Mode*
1.9	1^{st} Transverse
2.8	1^{st} Vertical
3.2	1^{st} Transverse/Torsional
5.8	2^{nd} Vertical
7.5	2^{nd} Transverse/Torsional
8.6	3^{rd} Vertical
13.6	3^{rd} Transverse/Torsional

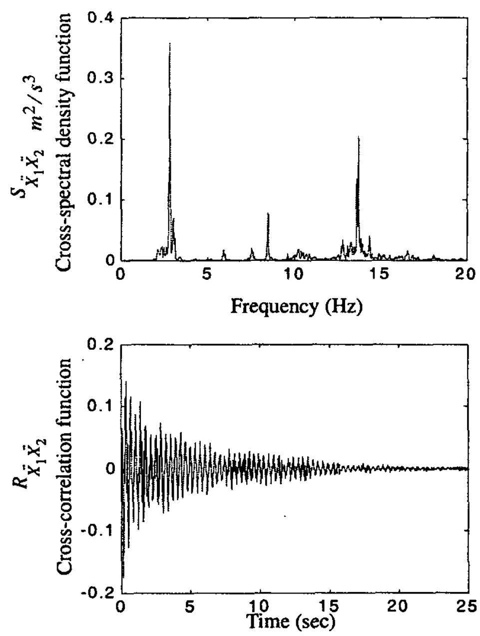

Figure 9. Representative Cross-Spectral Density and Correlation Functions.

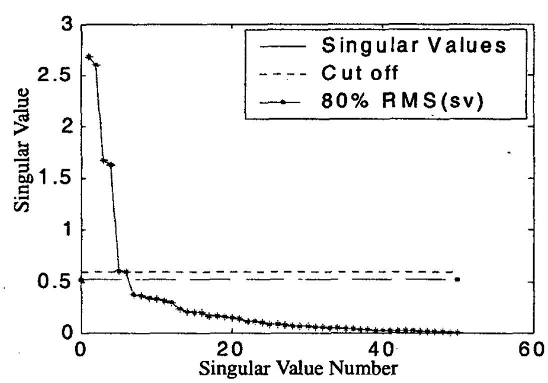

Figure 10. Representative Singular Values of Hankel Matrix

6. SUMMARY

Recent experiences with a simple health monitoring system on the Hormiguero bridge demonstrate how effective low-cost equipment can effectively be used to remotely monitor the integrity of structures. A series of tests were conducted and acceleration responses of the bridge to traffic loading were recorded. The Natural Excitation Technique was applied in conjunction with the Eigensystem Realization Algorithm to identify natural frequencies of the bridge as well as the associated directions of motion.

Further information on this project can be found on the following web sites:
http://solidos.univalle.edu.co, http://wusceel.cive.wustl.edu/quake

7. ACKNOWLEDGMENT

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