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ENVIRONMENTAL VARIABILITY OF MODAL PROPERTIES

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Interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil, mechanical and aerospace engineering communities. Significant work has been done in the formulation of vibration-based damage detection algorithms, but unfortunately, investigations studying the variability of dynamic properties caused by changing environmental and operational conditions have been lacking. A thorough understanding of this variability is necessary so that changes in vibration response resulting from damage can be discriminated from changes resulting from such variability. In this paper the variability in modal properties of the Alamosa Canyon Bridge in southern New Mexico will be discussed.

INTRODUCTION

Current damage-detection methods are either visual[1] or localized experimental methods such as acoustic or ultrasonic methods, magnet field methods, radiographs, eddy-current methods and thermal field methods[2]. All of these experimental techniques require that the vicinity of the damage is known *a priori* and that the portion of the structure being inspected is readily accessible. Subject to these limitations, these experimental methods can detect damage on or near the surface of the structure. The need for additional global damage detection methods that can be applied to complex structures has led to the development of methods that examine changes in the global dynamic characteristics of the structure.

The basic concept in linear, vibration-based damage detection is that global modal parameters (notably resonant frequencies, mode shapes, and modal damping) are functions of the

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physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties will cause changes in the modal properties and the measured response of the structure. Recent research has focused on developing methods to measure and analyze changes in these global dynamic properties in an effort to detect and locate damage on a local level.

Recent advances in wireless, remotely monitored data acquisition systems coupled with the development of vibration-based damage detection algorithms make the possibility of remotely monitoring a bridge appear to be within the capabilities of current or near-future technology. However, before such a system can be relied upon to perform this monitoring, the variability of the dynamic properties that are the basis for the damage detection algorithm must be understood and quantified so that changes in vibration response resulting from damage can be discriminated from changes resulting from such variability. This variability could be the result of both changing environmental and operational conditions as well as the testing and data reduction procedures.

Several field tests of the Alamosa Canyon Bridge have been performed to study various aspects of applying vibration–based damage detection methods to a real world *in situ* structure. This bridge is aligned primarily in the north-south direction and is located adjacent to Interstate 25 (I-25) approximately 16 km (10 miles) north of Truth or Consequences, New Mexico. The bridge, as seen from the arroyo it crosses, is shown in Figure 1.

Initially, it was the investigators' intent to introduce various types of damage into this bridge and study several damage detection methods along with the feasibility of continuously monitoring such a structure. However, restrictions that the damage to the Alamosa Canyon Bridge be relatively benign or repairable made it difficult to take the damage identification portion of the study to completion, as realistic damage scenarios could not be introduced with the equipment on hand during these tests. Subsequently, this study focused on quantifying the variability in identified modal parameters caused by sources other than damage. During various tests of the Alamosa Canyon Bridge, variability caused by environmental effects, vehicles on the bridge, the excitation source (ambient or impact) and the data reduction processes were studied.[3] A summary of these various effects presented in Ref. 3 shows that the most significant source of variability was thermal gradients across the bridge deck. In this paper the variability caused by environmental effects will be discussed. The reader is referred to References 4-8 for additional studies that discuss the influence of environmental variability on bridge modal properties.

RESULTS FROM THE ALAMOSA CANYON BRIDGE TESTS

Two preliminary tests of the Alamosa Canyon Bridge performed in August and December of 1995 resulted in slightly different frequencies being obtained for the modes identified. For this reason, subsequent tests were performed that were specifically designed to examine the variability in modal parameters of the first span of the bridge caused by environmental effects. In August of 1996 modal tests were performed on the bridge at two-hour increments over a 24-hour time period. The bridge was instrumented with 30 accelerometers, five indoor-outdoor digital-readout thermometers and was excited by an instrumented hammer. Accelerometer and temperature measurement locations are shown in Figure 2. Thirty averages were used for all the FRFs. The thirty averages of a typical driving point (pt 2 in Fig. 2) FRF measurement are shown in Fig. 3. The data acquisition took approximately 30 to 45 minutes. Complete details of the testing can be found in Farrar, et. al.[3] The changes in frequencies were assumed to be primarily caused by the changes in temperature affecting the material properties and boundary conditions of the structure. The expansion joints located at either end of the spans were filled with dirt thereby limiting the expansion of the bridge caused by temperature.

A correlation analysis was performed between the resonant frequencies and the individual temperature measurements, the average temperature on the top of the deck, the average temperature on the bottom side of the deck and the temperature differentials between the east and west sides of the bridge on both the top and bottom sides of the deck. The resonant frequencies were found to have the highest correlation coefficient, 0.94, with the temperature differentials across the top of the deck. Figure 4 shows the frequencies of the first mode and the temperature differential between the east and west sides of the bridge on the top side of the deck plotted as a function of the measurement completion time. The frequency of the first mode varied by approximately 5% during this 24-hour time period. Similar variations and correlation with deck temperature differentials were observed for the other modes of the structure.

To confirm the observation that the changes in modal frequency of this structure are related to the temperature differential across the deck, a second set of 24-hour data was taken in July, 1997. Data were again taken every two hours over an approximate 24-hour period. Note that it rained heavily before the second 24-hour test was started and this moisture could change the effective mass of the deck as well as equilibrate the temperature distribution. The results from this test for the first mode are shown in Figure 6. Once again there was a clear correlation between the temperature differential across the deck and the modal frequencies. Similar variations and correlation with deck temperature differentials were observed for the other modes of the structure. The frequencies of the first, second and third modes varied by approximately 4.7%, 6.6% and 5.0% respectively over the 24-hour period.

The authors speculate that the sensitivity of modal frequencies to temperature differential across the deck is the result of the bridge being oriented in a north-south direction and the corresponding thermal expansion of its deck. In the morning the sun heats the bridge on the east side producing the temperature differential across the deck. The expansion joints were filled with debris as shown in Figure 5 and the structure was not free to expand. Therefore, the temperature differential and corresponding thermal expansion altered the boundary conditions of the structure, which then altered the resonant frequencies exhibited by the bridge.

Although the temperature differentials were found to be correlated to the resonant frequencies, the uncertainty bounds are still relatively large in the relationship between these quantities. To illustrate this, the frequencies of the first mode, a linear regression curve fit and the 95% prediction intervals were plotted versus the temperature differential for the first 24-hour test as shown in Figure 7. Data from the second 24-hour test are also included in this figure to see if they fall within the 95% prediction intervals determined from the first test. In general, the data from the second test falls within the 95% prediction intervals except for the largest differential temperature of over 30°F. This temperature differential was outside of the range of those found from the first test. Therefore, adequate quantification of environmental and operational variability of the modal properties of a bridge may require measurements to be made over several years, at different times of the year, during different weather conditions, and when the bridge is experiencing a range of operational conditions.

It is important to note that the correlation discussed thus far in this paper, that is, between the modal frequencies and the temperature differentials across the deck is in no way unique. A similar quality correlation can be obtained by comparing the modal frequencies to time-shifted temperature data. This type of correlation is reasonable because the mass of the bridge will cause the modal parameters to lag behind the temperature, that is, the bridge takes some time to warm up and cool down. One way to account for this temporal dependence is the use of a linear adaptive filter. In order to consider both the time and spatial variation of temperature the temperature readings at the current time and the previous times can be used as inputs. This approach has been applied to these data sets and details of this study can be found in Sohn[9]. Basically, Sohn used the data from the first 24-hour test to train a linear filter and then used data from the second test to check to see if the data fell within the 95% confidence intervals predicted by the model. This comparison is shown in Figure 8 . From this figure it can be seen that the 95% confidence interval is significantly tighter than that found using the simple linear regression between the frequencies of the first mode and the temperature differentials across the deck. The comparison of the prediction intervals obtained from the first data set and the measured frequencies from the second data set revealed that the bridge experienced a statistically significant decrease in the modal frequencies as shown in Figure 8. Considering the severe rain prior to testing it is very possible that this decrease of the frequency was mainly caused by the increase of the bridge mass as the bridge absorbed significant amounts of moisture. This study clearly indicates that more than just temperature measurements are required to adequately characterize changes in modal properties because of environmental variability.

DISCUSSION

The variability of modal frequencies with temperature of a single span of a bridge has been presented. For the structure tested, the modal frequencies were found to vary by up to 6% over a 24-hour period. This variation was found to be correlated to the temperature differential across the deck. Bootstrap analyses of the 30 FRF samples that were analyzed to estimate a resonant frequency value revealed that variability associated with the measurement process and data reduction process was not as significant as the variability produced by the temperature differentials across the deck[3]. It is the authors' opinion that a required prerequisite for a remote bridge health monitoring system is a thorough study of the variability of dynamic properties caused by the changing environmental and operational conditions. Based on the results of these variability studies, it is conceivable that bounds can be developed for the dynamic parameters that could be monitored by a damage identification system. Damage must cause changes in the dynamic characteristics that are outside these bounds for a definitive statement to be made regarding the onset of damage in the bridge.

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Figure Captions

Figure 1 Alamosa Canyon Bridge Near Truth or Consequences, New Mexico

Figure 2 Accelerometer, impact and thermometer locations

Figure 3 Thirty driving point FRFs measured during a typical modal test.

Figure 4 Change in the first modal frequency during a 24-hour time period

Figure 5 Debris in expansion joint.

Figure 6 Change in the first modal frequency during the second 24-hour test

Figure 7 Relationship between the first modal frequency and the bridge deck temperature differential for both 24-hour tests

Figure 8 Prediction of the first modal frequency using a linear filter

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Figure 1 Alamosa Canyon Bridge Near Truth or Consequences, New Mexico

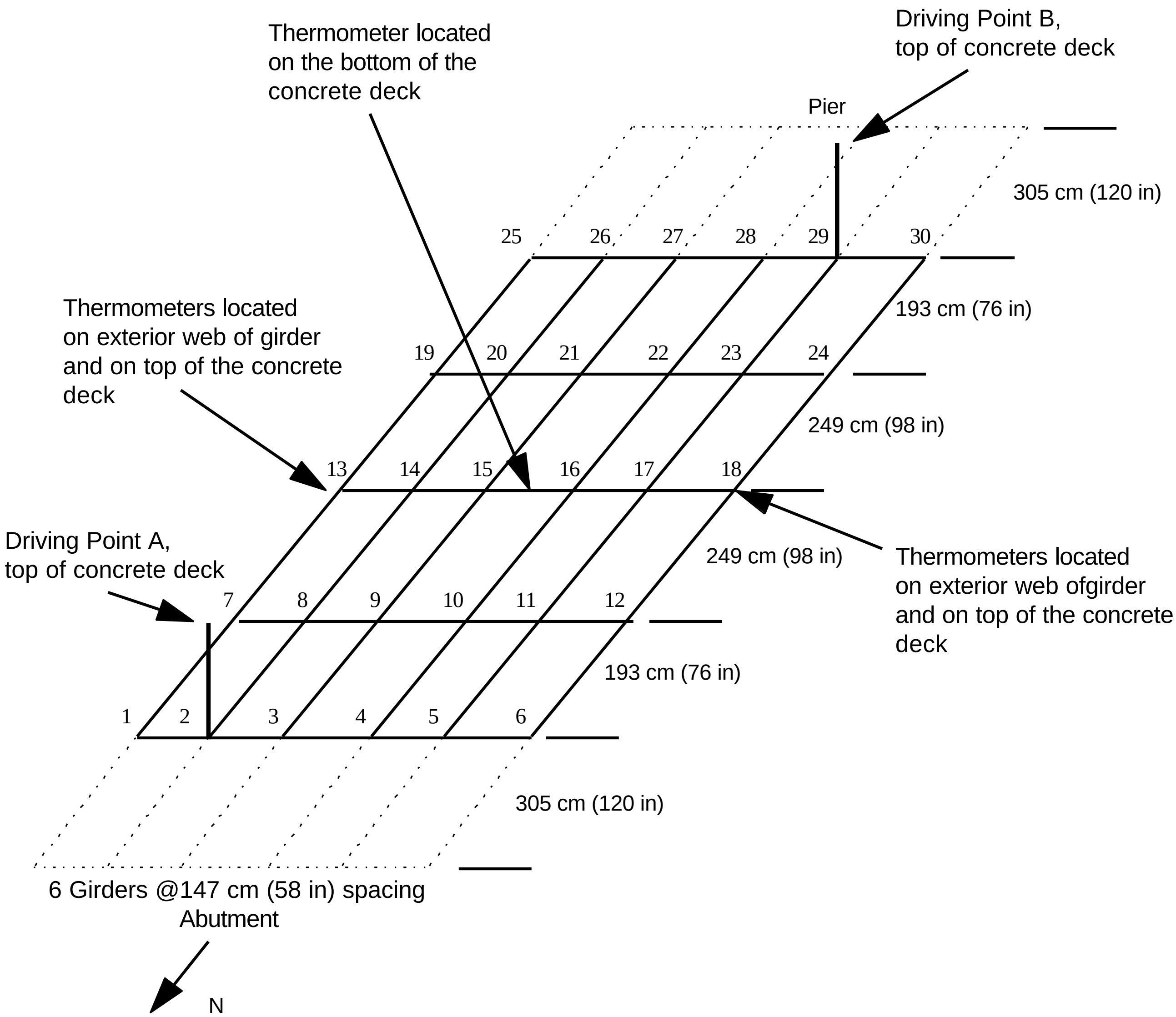
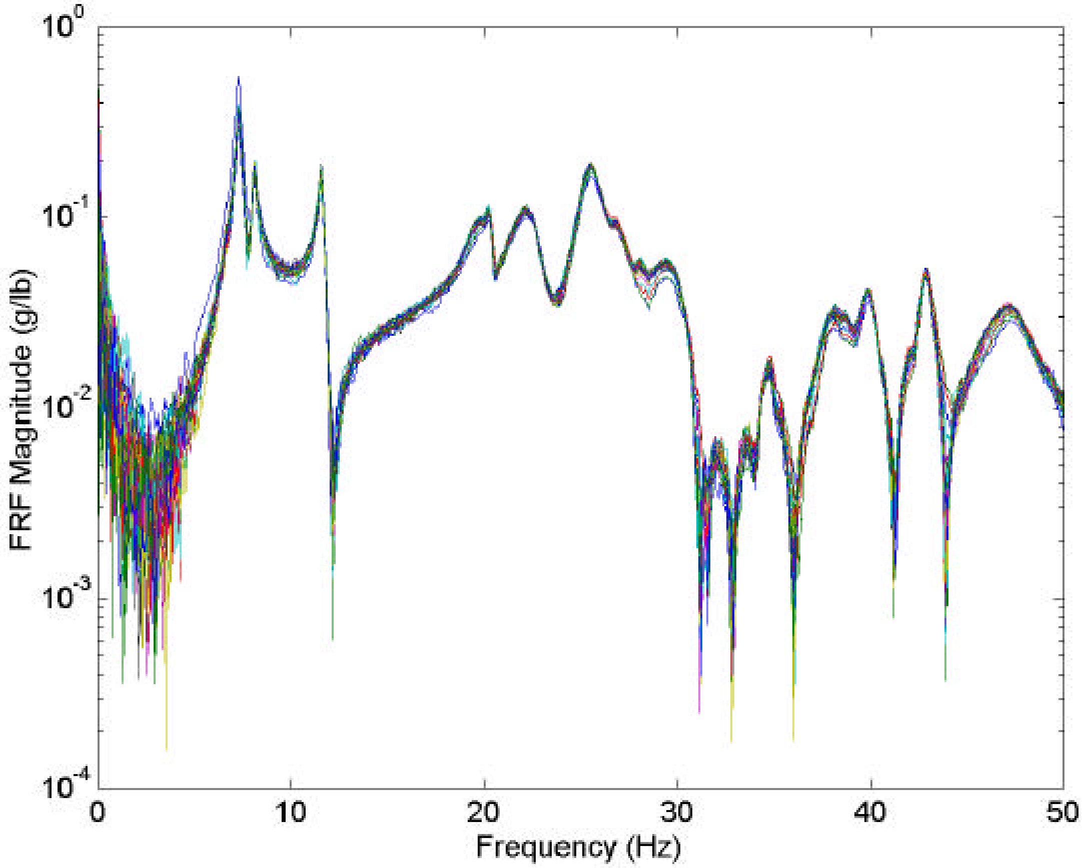


Figure 2 Accelerometer, impact and thermometer locations



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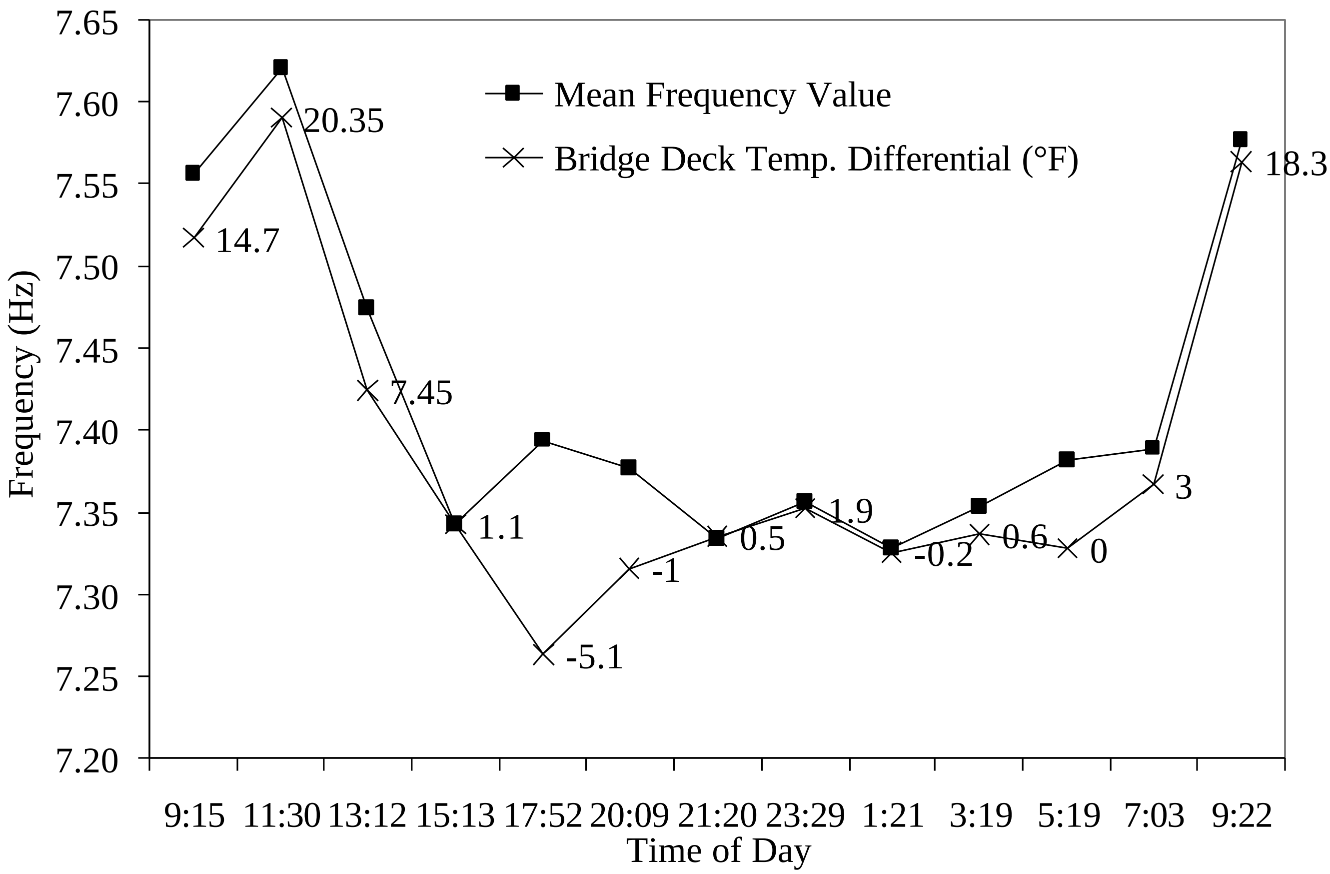

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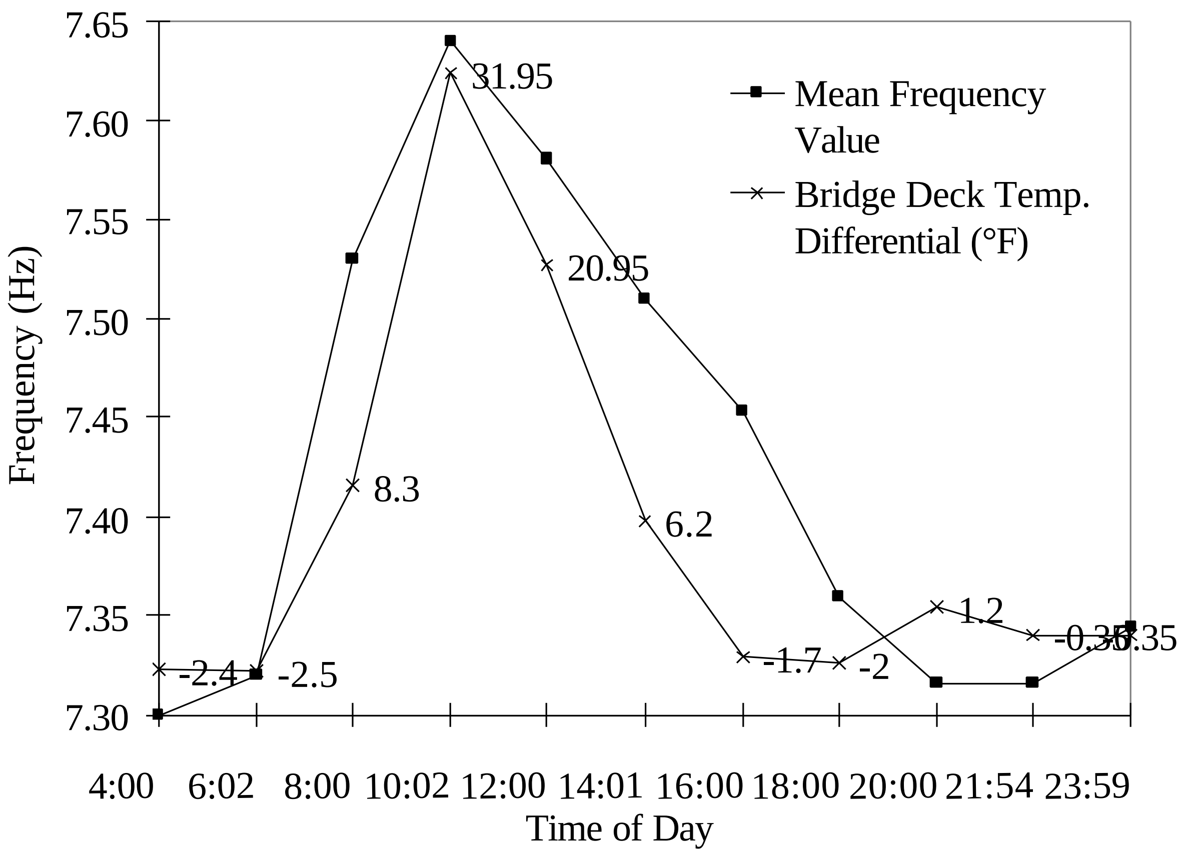

Figure 6 Change in the first modal frequency during the second 24-hour test

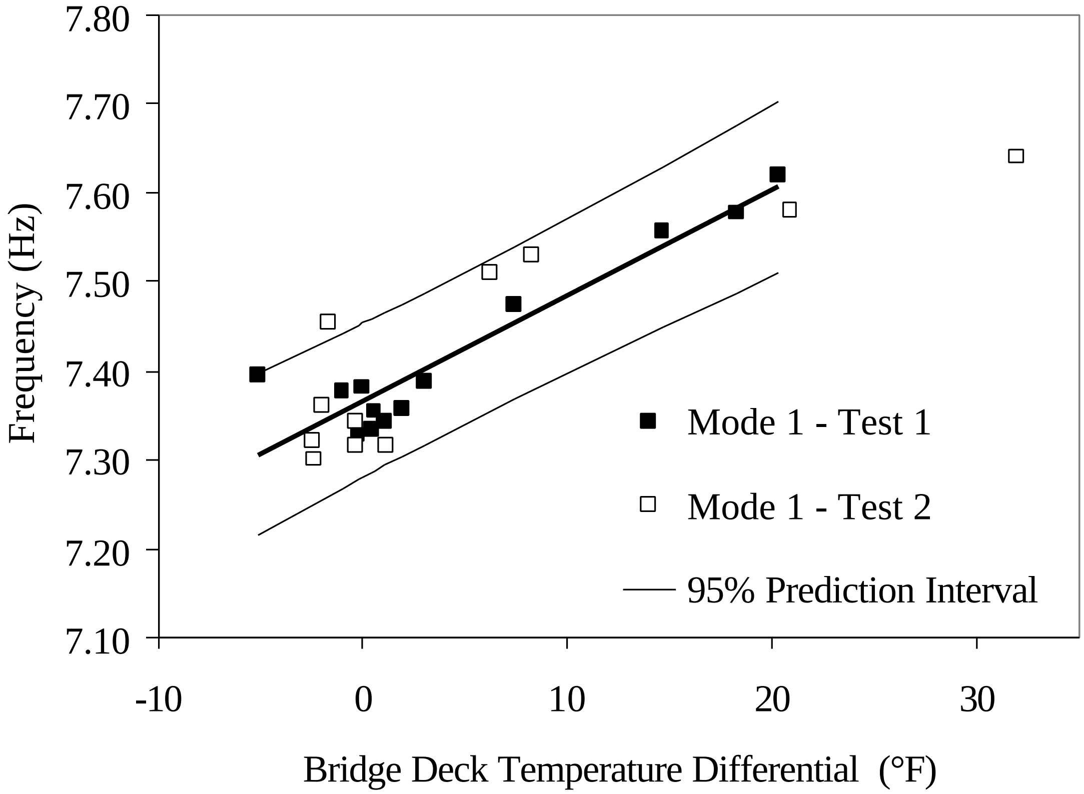

Figure 7 Relationship between the first modal frequency and the bridge deck temperature differential for both 24-hour tests

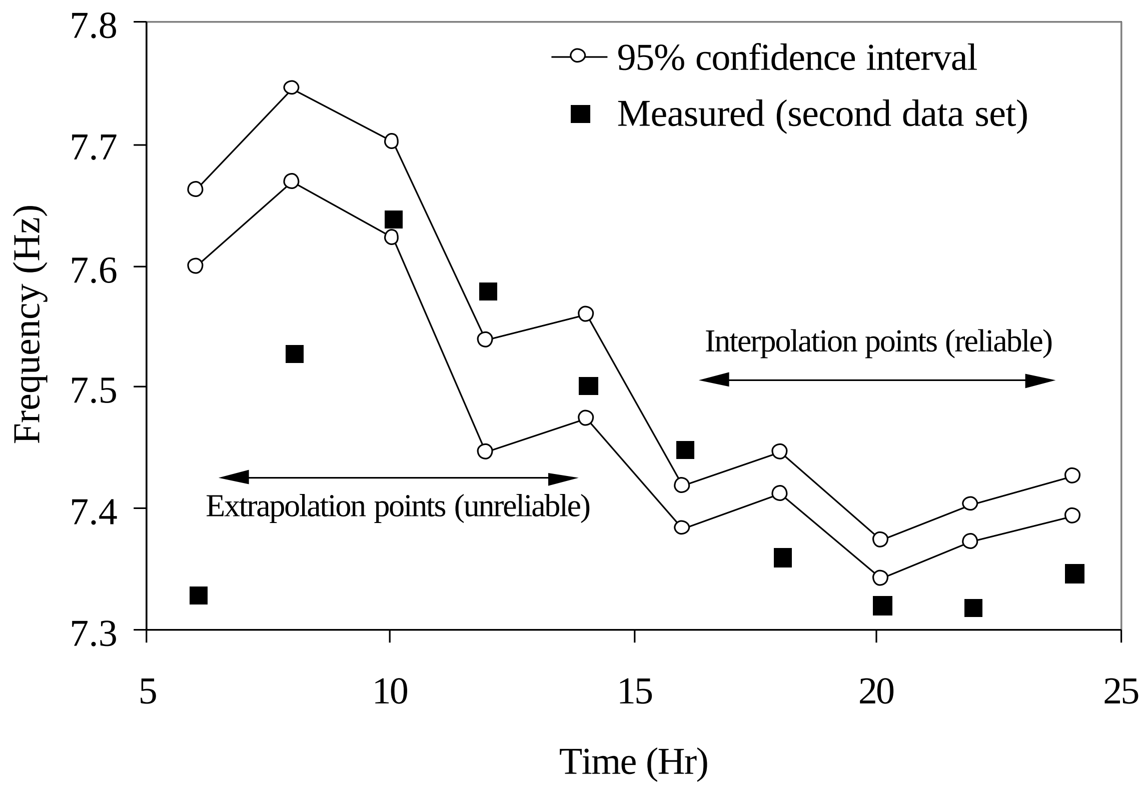

Figure 8 Prediction of the first modal frequency using a linear filter