AMBIENT VIBRATION ANALYSIS OF A HIGHWAY BRIDGE WITH SUBSPACE METHOD AND FREQUENCY DOMAIN DECOMPOSITION

Shutao Xing[1], Marvin W. Halling[2], Paul J. Barr[3], Qingli Meng[4]

[1] *PhD Student, Dept of Civil and Environmental Engineering, Utah State University, Logan, Utah, USA*
Email: Shutao.Xing@aggiemail.usu.edu, ShutaoXing@yahoo.com

[2] *Associate Professor, Dept of Civil and Environmental Engineering, Utah State University, Logan, Utah, USA*
Email: marv.halling@usu.edu

[3] *Assistant Professor, Dept of Civil and Environmental Engineering, Utah State University, Logan, Utah, USA*

[4] *Associate Professor, Dept. of Structural Engineering, Institute of Engineering Mechanics, Harbin, China*

ABSTRACT:
This paper presents the structural identification of a highway bridge using the vibration measurements from existed structural seismic instrumentation that for long term monitoring of a highway bridge at Utah. As for the damage detection algorithms, one of the subspace identification methods, N4SID is used together with classical frequency domain decomposition method (FDD). These two approaches are found to be able to get frequencies quite satisfactorily. The influence of the temperature on the modal frequencies has been investigated with 13 months' monitoring data. The results showed that daily fluctuations as well as seasonal fluctuations of frequencies can be identified by the methods utilized in this study. It can be seen that the extreme temperatures can cause the natural frequencies to shift. Computed through the identification algorithms of this paper, the distributions of the modes at different temperatures are presented.

KEYWORDS:
Highway Bridge, Health Monitoring, Ambient Vibration, Subspace Identification, Frequencies Change

1. INTRODUCTION

This study investigates the natural frequencies of an in-service highway bridge that is subjected to ambient vibration excitation. For structural health monitoring, the system identification methods are vital as well as challenging and still under developing. System identification is basically to describe algorithms that build dynamical models from measured data. For structures of civil engineering, this is usually to obtain the stiffness, modal parameters from acceleration, velocity, displacement etc. There are many existed identification algorithms that deal with input-output identification. While it is rarely possible to conduct forced-vibration experiments in in-service structures, and it is not practical to measure ambient input either. These limitations led to the algorithms using the ambient vibration measurements. We apply a stochastic subspace algorithm N4SID in identification of modal properties of a real-time monitoring bridge, N4SID has been implemented in MATLAB 2004. The identification process and results by N4SID are studied to evaluate its performance.

Dynamic properties of a structure can provide a direct correlation between the physical properties of a structure and its structural integrity. It has been shown that a structure's physical properties such as stiffness can change due to surrounding environmental changes Researchers have found that temperature, heavy rains, diurnal variations, and strong winds can change a structure's natural frequency by up to 3 percent (Bradford et al., 2004). In this paper, we have analyzed the ambient vibration data of more than one year to get the correlation of the frequency change and temperature, the frequency domain decomposition are used to extract the natural frequencies from these data. Dynamic response is unique to each structure and will remain nearly constant unless otherwise affected by experimental changes or damage to the structure, so it is beneficial to establish a baseline mode. These changes could lead to shifts in the modal parameters such as natural frequency, mode shapes, and damping. However, localized damage may not always shift or change the modal parameters on a global response spectrum. Localized damage may have a significant effect on higher modes of response (Farrar and Cone, 1995). The data from multiple sensors are more meaningful than single sensor. Thus, this correlation between the dynamic properties and the actual physical properties of a specific structure are essential in detecting structural changes and damage.

2. LONG TERM MONITORING OF AN IN-SERVICE BRIDGE

A long-term structural health monitoring project funded by the Utah Department of Transportation (UDOT) and the Federal Highway Administration (FHWA) is being performed on an overpass bridge at the 2100 South Interchange of I-15 in Salt Lake City, Utah. This bridge is referred to as the I-80 Flyover Bridge. The goal of this research project was to install long-term instrumentation that could monitor changes in dynamic behavior of the bridge on a daily basis and to function as a recording station in the event of an earthquake.

The I-80 Flyover serves as a connector from westbound I-80 to westbound SR-201. The bridge comprises four individual structures, containing a total of 25 spans, with an overall length of 1.14 kilometers. The superstructure consists of a reinforced concrete deck supported by 3 steel I girders. The selected test structure is a long, multi-span bridge with relatively tall columns, and contains several expansion joints. Other characteristics which factored into the selection of this bridge are that it is located only 6 kilometers away from the Wasatch Fault, a large normal fault capable of up to a Magnitude 7.5 event, and that it is founded on very soft deep Lake Bonneville sediments. It is the first bridge instrumented with strong motion instrumentation within the state of Utah. Figure 1 shows an aerial view of the I-80 Flyover.

Figure 1 Aerial Photograph of I-80 SR-201 Bridge.

3. IDENTIFICATION OF MODAL FREQUENCIES USING N4SID

While frequencies are studied currently, mode shapes and damping ratios can also be obtained using N4SID.

3.1 The Vibration Data

13 months ambient vibration data from the real-time bridge monitoring system for the I-80 flyover are used for this study using the frequency domain decomposition. Each dataset has duration of 200 seconds, and sampled frequency is 200HZ. On February 31, 2008, a magnitude of 6.0 struck wells, Nevada, it arrived at Salt Lake City around 7:15PM (local time), and we pick 300 seconds' data from this time for the identification study by the subspace method, N4SID. All the selected vibration data has been detrended to remove the mean shift from

zero due to sensor inaccuracies before modal analysis.

3.2 Basic Formulations for Modal Analysis Using N4SID

In the case of ambient noise, the input is implicitly accounted for by unknown noise w; a linear time-invariant structural model can be described by the discrete 1st order difference equation

$$x(k+1) = Ax(k) + w(k) \tag{3.1}$$
$$y(k) = Cx(k) + v(k) \tag{3.2}$$

where k is the sampling instant ($t = k\Delta t$), x is state vector, A is the state matrix, it is assumed to be zero mean and stationary, C is the output matrix., w is the process noise and v is the measurement noise, w and v are assumed as uncorrelated zero-mean stationary white noise vector sequences(Ljung 1999).

The complex eigenvalues (λ) and eigenvectors (ψ) of the damped system can be calculated from the system matrix A. The natural frequency f_k and the damping ratio are given as ς_k

$$\omega_k = \frac{|\ln(\lambda_k)|}{\Delta t} \qquad f_k = \frac{\omega_k}{2\pi} \qquad \varsigma_k = \frac{-\mathrm{Re}[\ln(\lambda_k)]}{\omega_k \Delta t} \tag{3.3}$$

The kth complex mode shape ϕ_k sampled at sensor locations can be evaluated using the following expression:

$$\phi_k = C\psi_k \tag{3.4}$$

If the damping is assumed to be small and nearly classical, then the modal properties of the undamped structure can be approximated as (Alvin 1994)

$$f_k = \frac{|\lambda_k|}{2\pi} \qquad \varsigma_k = \frac{\mathrm{Re}(\lambda_k)}{2\pi f_k} \qquad \phi_k = |C\psi_k| \cdot \mathrm{sign}[\mathrm{Re}(C\psi_k)] \tag{3.5}$$

To determine the order of the state-space model, i.e., dimension of the state vector x(k), is an important step for implementation of the subspace method. Theoretically, an N-degree-of-freedom system will have an order of 2N. But our studies show that we need a much bigger order number to get reasonable results and extract information for sufficient modes that are wanted.

3.3 Analysis of Frequencies Identified Using N4SID

Table 3.1 shows the identified modal frequencies using N4SID (order = 540), which is compared with the previous results identified from forced vibration data using classical frequency response function. They are matched pretty well for estimation purpose. The difference between them is due to many factors besides the modal analysis methods, the previous results are from forced vibration data from all the 18 channels, and the N4SID results at this paper only processed the data from 1 channel only. Also they are identified in 2002 and 2008 respectively; the bridge's frequencies may have changed a little bit, this is not the main source of the difference though. But the subspace methods produce many spurious modes, which are not listed here, and they missed some modes as shown in Table I. It need more study on the stabilization of this method.

Table 3.1 Comparison of frequencies identified by N4SID with those identified by FDD (Dye,2002)

Mode	1	3	4	5	9	10	12	13	14	15
FDD: Mean Natural Frequency (Dye, 2002)	1.114	1.482	1.58	1.76	2.7	3.07	3.49	3.76	4.24	4.73
N4SID: Order =540	1.25	1.495	1.59	1.85	2.64	3.03	3.47	3.68	4.16	4.86
Mode	17	18	19	20	21	22	23	24	25	26
FDD: Mean Natural Frequency (Dye, 2002)	5.571	6.165	7.33	9.04	10.7	11.8	13	14.3	15.6	17.2
N4SID: Order =540	5.5	6.163	7.3	9.28	10.8	11.7	13	14.3	16.2	17.4

The determination of the order plays an important role in implementation of N4SID, it is a challenging problem. The N4SID has been conducted with order number from 40 to 540, and the results are shown in Figure 2. From figure 2, most mode frequencies could be identified, the bigger the order, the more modal frequencies can be identified, but also more spurious modes. For this chosen dataset, order = 180 is an optimized number. With the order number increased, the computation time increased very quickly, and this makes the N4SID not a competitive method. More study on this method is going on, e.g., the stabilization diagram for the N4SID is being processed, and could be presented in the future to improve the way of using N4SID.

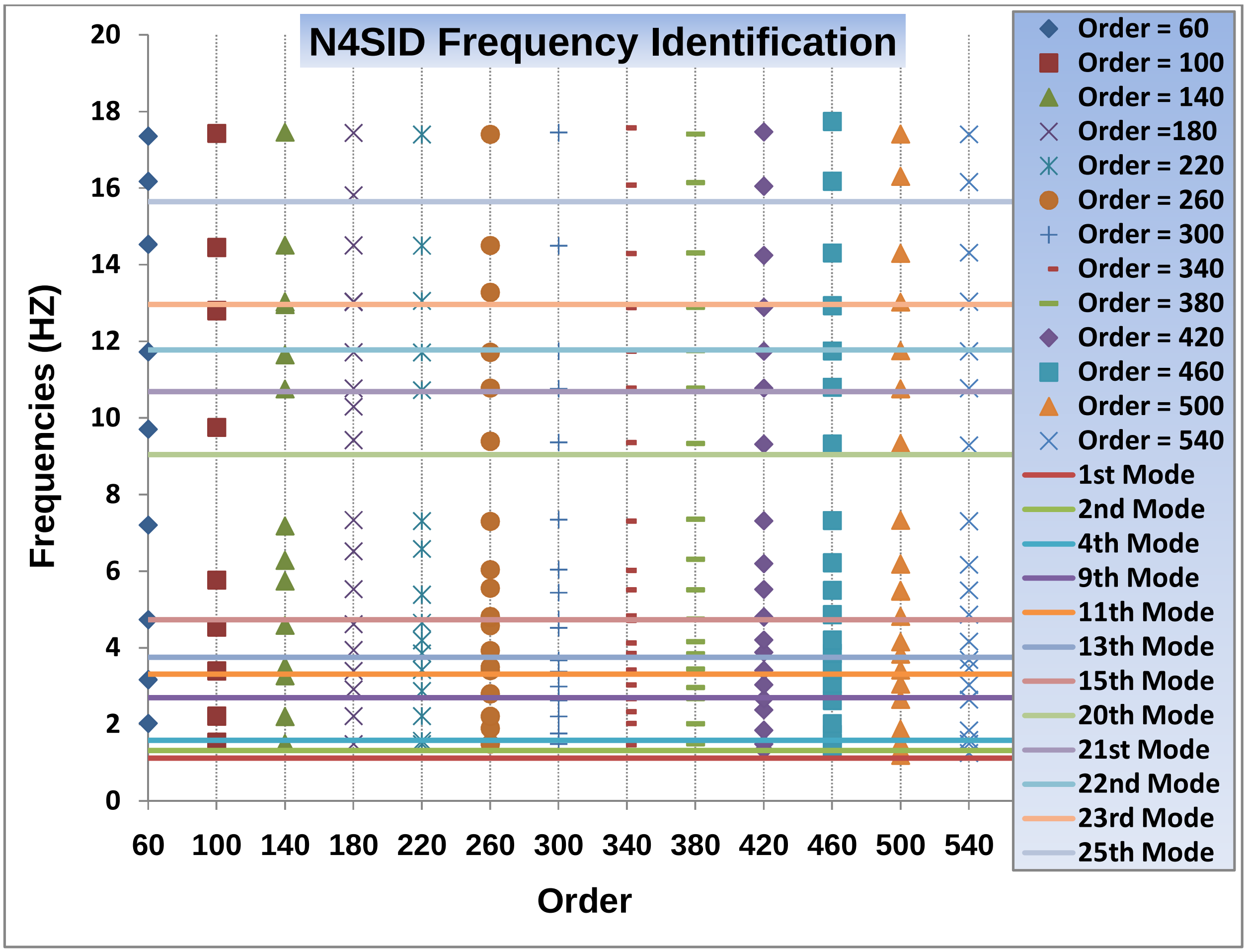

Figure 2 Comparison of Frequencies Identified by N4SID of Different Orders and FDD

4. CHANGE IN MODAL FREQUENCIES WITH TEMPERATURE

In this section, the variation of modal frequencies with respect to the temperature change is investigated. Frequency domain decomposition method is hired as the structural identification method, which is more computational efficient compared with the N4SID.It performs well for the identification of undamaged structures. Twelve modal frequencies were selected for monitoring. These modes are in the set of lower 26 modes identified from modal analysis. Modal frequency data for these twelve modes is presented in Table 4.1.

In an effort to show the correlation between frequency and temperature, scatter plots for the 12 selected modes were constructed and a linear regression trend line was fit to each data set. The data gathered from February 2007 to February 2008 were used to construct the plots. While the correlation coefficients are not large, modes

1, 4, 13 exhibited a downward trend in frequency as the temperature rises, whereas modes 11, and 23 exhibit an upward trend. A representative sample of these plots is shown in Figure 3. Although a downward trend in frequency as temperature increases may be anticipated due to decreases in material stiffness at higher temperatures, an upward trend could be the result of the structure expanding due to temperature increases, causing expansion joints and other connections to tighten. The fact that some modes increase and other decrease is a subject for further investigation. These plots also help to visualize graphically how the data is distributed for these tests. Tight groupings such as those seen for mode 1 (and to a lesser degree, mode 2) reflect that the standard deviations for those modes are smaller than the modes with wider spread data sets such as modes 13 and 23. There are outlying points in each graph, but there have been enough data points taken that these points do not have a significant adverse influence on the results.

Table 4.1 Mean modal frequencies chosen for monitoring

	Jun-2001	Feb-2007	Mar-2007	Jan-2008	Jul-2007
Mean Temperature(^{0}C)	21.3305	4.2143	8.1529	-2.1829	29.9474
Mode 1 (Hz)	1.1090	1.1417	1.1435	1.1415	1.1309
Mode 2 (Hz)	1.3800	1.3713	1.3709	1.3272	1.3310
Mode 4 (Hz)	1.5860	1.5901	1.5876	1.5845	1.5812
Mode 9 (Hz)	2.6700	2.6981	2.7070	2.7106	2.7048
Mode 11 (Hz)	3.3030	3.2957	3.3196	3.3054	3.2928
Mode 13 (Hz)	3.7350	3.8692	3.8265	3.8289	3.8001
Mode 15 (Hz)	4.7770	4.8490	4.8587	4.7695	4.6849
Mode 20 (Hz)	9.1520	9.5933	9.5686	9.5364	9.4472
Mode 21 (Hz)	10.6620	10.7783	10.7474	10.7010	10.6732
Mode 22 (Hz)	11.8350	11.4850	11.5512	11.5264	11.8330
Mode 23 (Hz)	12.9980	12.8871	12.8371	13.2078	13.0839
Mode 25 (Hz)	16.0130	15.7960	15.5852	15.6009	15.6977

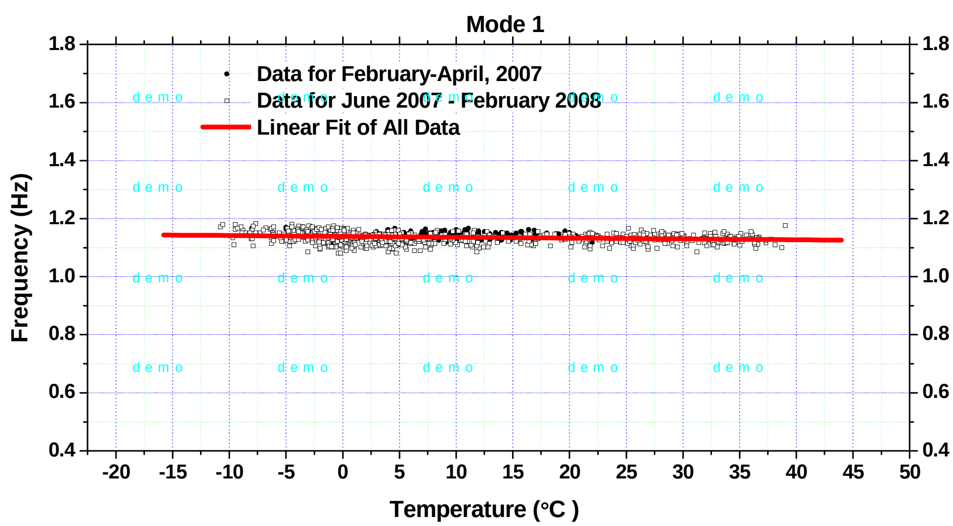

Figure 3 Correlation Plots of Temperature and Natural Frequency

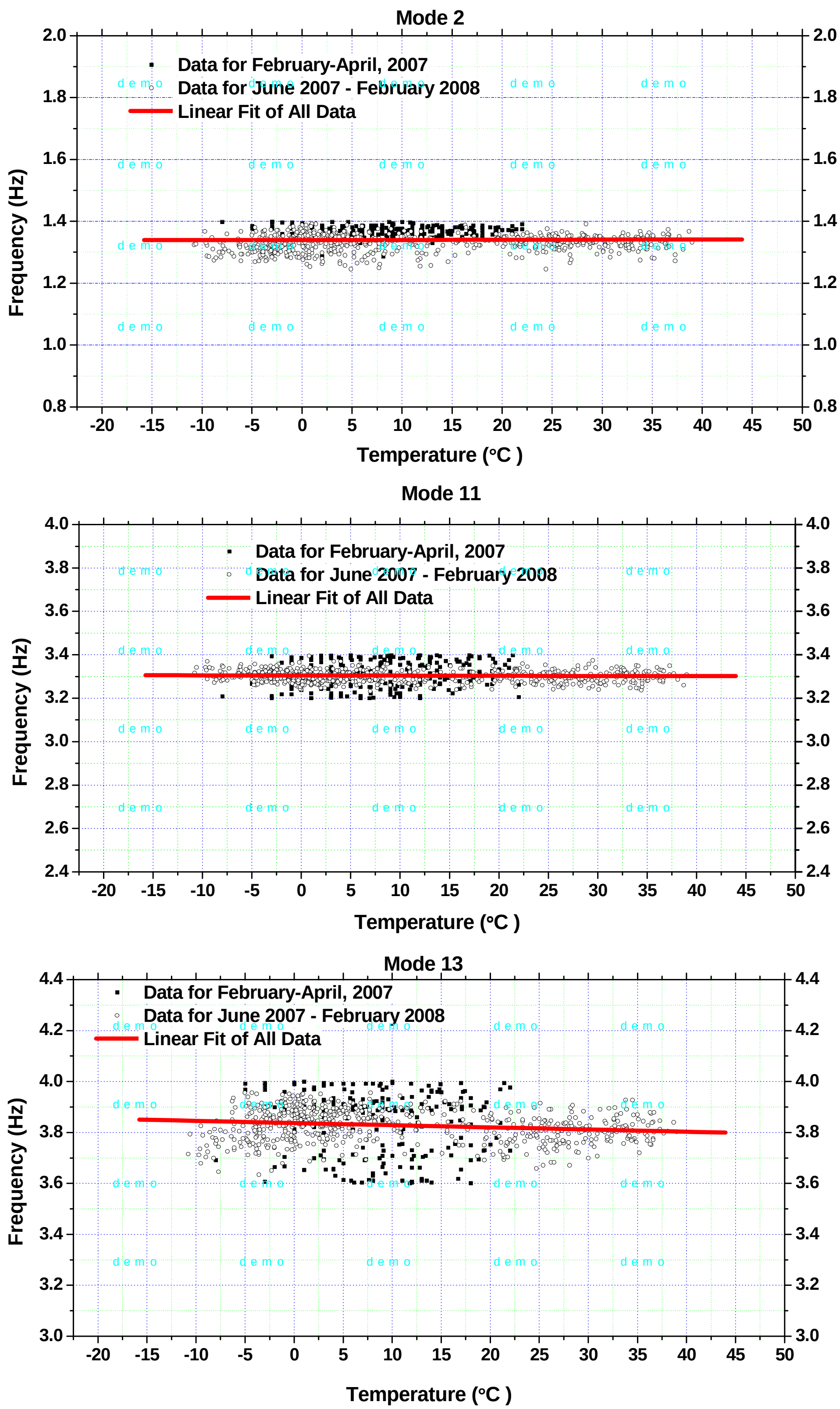

Figure 3 Correlation Plots of Temperature and Natural Frequency (contd)

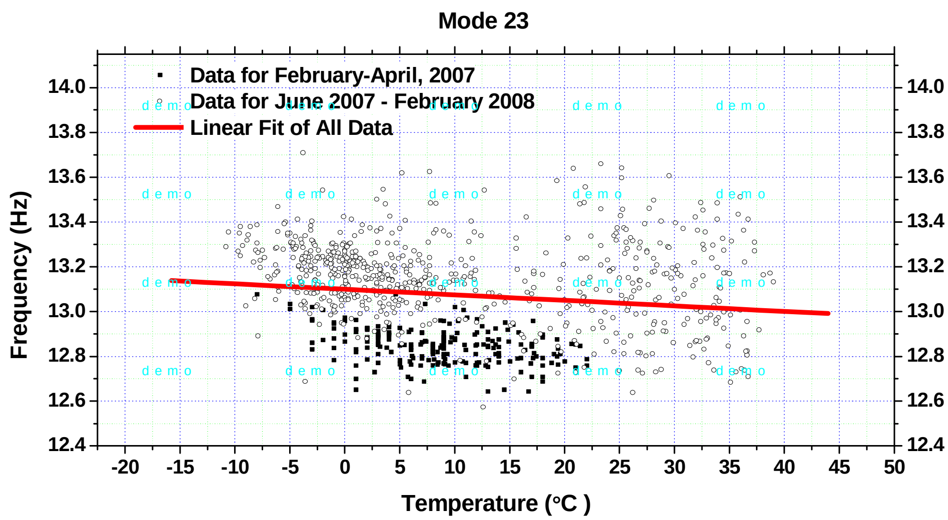

Figure 3 Correlation Plots of Temperature and Natural Frequency (contd)

Studies have shown that extreme temperatures can cause a structure's natural frequencies to shift by up to 3 percent (Bradford et al., 2004). To help verify these findings, an additional test was completed in which separate samples were taken from data recorded between February 13, 2007 and March 26, 2007. The times the samples were taken were solely dependent upon the temperature at the time of the sample. It was decided that data samples would be taken at any time of day if the temperatures were either -1˚ C (30˚ F), 4.5˚ C (40˚ F), or 10˚ C (50˚ F). Not only did the temperature need to be in one of those ranges for the time of sampling, but the temperatures had to be within that same range for at least two hours prior to the time of sampling. It was hoped this would allow the structure more time to become acclimated to that ambient temperature. Table 4.2 shows the statistical information for the data sets of the three described temperature ranges. There exists a slight shift in frequencies from -1˚ C to the higher temperatures, while the standard deviations and normalized variations are relatively unaffected for the three different temperature ranges.

Table 4.2 Natural frequencies for samples taken based on temperature

	Ambient Test (-1˚ C)			Ambient Test (4.5˚ C)			Ambient Test (10˚ C)		
Mode	Mean Natural Frequency	Standard Deviation	Norm. Variation	Mean Natural Frequency	Standard Deviation	Norm. Variation	Mean Natural Frequency	Standard Deviation	Norm. Variation
1	1.146	0.01	0.99%	1.139	0.01	1.26%	1.140	0.01	1.02%
2	1.380	0.01	0.89%	1.370	0.01	0.95%	1.367	0.02	1.17%
4	1.588	0.03	1.85%	1.584	0.03	1.70%	1.581	0.02	1.30%
9	2.670	0.12	4.42%	2.701	0.10	3.58%	2.688	0.09	3.22%
10	3.034	0.07	2.37%	3.037	0.08	2.76%	3.045	0.08	2.56%
11	3.320	0.06	1.93%	3.329	0.06	1.85%	3.326	0.06	1.77%
13	3.829	0.12	3.26%	3.820	0.13	3.48%	3.809	0.14	3.76%
15	4.865	0.05	1.06%	4.843	0.06	1.28%	4.847	0.04	0.80%
20	9.606	0.02	0.20%	9.590	0.02	0.18%	9.552	0.07	0.75%
21	10.782	0.06	0.52%	10.785	0.16	1.50%	10.744	0.11	1.02%
22	11.499	0.38	3.31%	11.618	0.45	3.85%	11.653	0.46	3.97%
23	12.925	0.05	0.35%	12.872	0.06	0.44%	12.845	0.10	0.75%
25	15.588	0.50	3.21%	15.583	0.49	3.14%	15.735	0.47	2.98%

The shifts in natural frequencies for each temperature range with respect to other ranges are calculated and can be seen in Table 3. The shifts in the natural frequency for -1˚ C vs 4.5˚ C and -1˚ C vs 10˚ C ranged from 0.03 – 1.35 percent while the shifts for 4.5˚ C vs 10˚ C had a smaller range of 0.00-0.98 percent. This was an interesting result because the difference in temperature ranges is 5.5˚ C, yet the natural frequencies did not shift proportionally with the change in temperature. One possible reason for this is that the samples taken for a temperature of -1˚ C were below freezing. This extreme temperature could have more adverse affects on the bridge than the range of more mild temperatures between 4.5˚ C and 10˚ C.

5. CONCLUSIONS

The subspace method N4SID has been implemented and investigated using the ambient vibration analysis from real-time bridge monitoring data, modal frequencies obtained are satisfactorily. The problems with this algorithm are expensive computation time and unstable results with the choice of different order numbers. More studies need to be spent on this algorithm for structural identification projects.

Classical frequency domain decomposition methods are utilized to get the frequencies from 13 months' ambient vibration data. This study includes correlations of modal natural frequencies with temperature over a pretty large range of temperatures.

The I-80 Flyover Bridge in Salt Lake City shows some distinct trends correlating changes in natural frequency with changes in temperature. The range in variations of the twelve monitored modes were as high as 3 percent, corresponding to changes in temperature of as much as 11˚C. The amount and direction (up or down) of the shifts were modal dependent. Three of the twelve monitored modes showed an increase in modal frequency as a result of an increase in temperature, while the other nine monitored modes showed a decrease in modal frequency as a result of an increase in temperature.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Federal Highway Administration (FHWA) and the Utah Department of Transportation (UDOT) for their generous support.

REFERENCES

Alvin, K.F., and Park, K.C., (1994), Second-order structural identificatioin procedure via state-space-based system identification, *AIAA, J.*, 32:2, 397-406.

Alicioglu, B., Lus, H., (2008), "Ambient Vibration Analysis Subspace Methods and Automated Mode Selection: Case Studies", *J. of Bridge Engineering* 134:6, 1016-1029

Ball, A.W. 2005. Modal analysis of a multi-span reverse curve steel girder bridge using computer modeling. M.S. thesis. Utah State University, Logan, Utah.

Bradford, S.C., Clinton, J.F., Favela, J., and Heaton, T.H. 2004. Results of Millikan Library forced vibration testing. Technical Report: EERL-2004-03.California Institute of Technology.

Cunha, A., Caetano, E., and Delgado, R. (2001). Dynamic tests on large cable-stayed bridge. *J. Bridge Engrg.*, 6:1, 54–62.

Skolnik, D., Lei, Y., Yu, E., Wallace, J.W., (2006). Identification, Model Updating and Response Prediction of an Instrumented 15-Story Steel-Frame Building, *Earthquake Spectra* 22:3, 781-802.

Farrar, C.R., and Cone. K.M. (1995). Vibration testing of the I-40 Bridge before and after the introduction of damage. Proc. of the 13th International Modal Analysis Conference, Nashville, Tennessee. 203-209.

Halling, M.W., Xing, S., Barr, J.B., Zach, H., (2008), Changes in Modal Frequencies of a Highway Bridge, Proc of 6th National Seismic Conference, Charleston, South Carolina, USA.

Kramer, C., De Smet, C. A. M., and Peeters, B. (1999). Comparison of ambient and forced vibration testing of civil engineering structures. Proc. 17th International Modal Analysis Conference, Kissimmee, FL.

Ljung, L. (1999). System Identification: Theory for the user, 2nd Ed., PTR Prentice-Hall, Upper Saddle River, N.J.