Structural Monitoring and Evaluation Tools at Caltech: Instrumentation and Real-Time Data Analysis

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ABSTRACT

This paper presents a summary of the structural monitoring tools available at the California Institute of Technology (Caltech) and selected research using these tools.

The Caltech Online Monitoring and Evaluation Testbeds (COMET) site is an educational and research tool that archives real-time data from the Southern California Earthquake Data Center (SCEDC) stations MIK (Millikan Library) and CBC (Broad Center). The COMET site allows users to view and download real-time data, as well as perform dynamic analysis using Caltech's MODE-ID software.

Ambient analysis of data from Millikan Library has revealed a change in dynamic properties based on weather conditions, especially rainfall and windstorms. During heavy rains, the fundamental E-W and Torsional frequencies of Millikan Library can increase by 3-5%. Strong winds can decrease all fundamental frequencies by 2-4%. Results such as these have important implications in the development of structural health monitoring methods that use changes in modal parameters to infer damage.

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INTRODUCTION

In this paper a summary is given of selected structural monitoring and evaluation tools available at the California Institute of Technology (Caltech). Examples are provided of research currently being performed using data from instrumented buildings on the Caltech campus.

CALTECH ONLINE MONITORING AND EVALUATION TESTBEDS: COMET

The Caltech Online Monitoring and Evaluation Testbeds (COMET) site, `comet.caltech.edu`, was developed as an educational tool as well as a testbed for the development of structural health monitoring techniques.

The COMET site acts as an interface between the Southern California Earthquake Data Center (SCEDC) database and a web-browser, using an implementation of the Earthworm Processing System. Real-time data from two campus buildings, Millikan Library (SCEDC station MIK) and the Broad Center (SCEDC station CBC) is archived from the SCEDC at 80sps and 100sps respectively and stored on a local hard drive. COMET users can log onto the site and download selected data, display these data, and perform modal analysis using Caltech's MODE-ID modal analysis software. The COMET interface was implemented by Dr. H. F. Lam, City University of Hong Kong, during a postdoctoral scholarship at Caltech.

Online Tools

MODE-ID: Analysis of real-time or archived data

MODE-ID is a modal analysis package that identifies the dynamic characteristics of a system based on time-domain information. The MODE-ID program can be used on strong motion input, as in the case of an earthquake ground motion, as well as on ambient data. The COMET website allows for ambient analysis of real-time and archived data. The following description is adapted from the COMET: Theory section, which was developed by M. M. Muto, a graduate student in Civil Engineering at Caltech.

Modal decomposition allows for the response of a structure to be expressed as a superposition of the responses of several single-degree-of-freedom (SDOF) oscillators, each corresponding to a mode of vibration. A modal model of the structure can be constructed as follows (Beck et al., 1994). Consider a building where N measurements are available for N_{in} channels of input (e.g. base accelerations) and N_{out} channels of output (e.g. floor accelerations). If R modes are considered for the model, then the predicted time history for the ith output channel can be expressed as:

$$\ddot{x}_i = \sum_{r=0}^{R} \ddot{x}_{ir}(t) \qquad i = 1, 2, \ldots, N_{out}$$

(1)

where x_{ir} is the contribution of the r_{th} mode to the i_{th} output channel, and for $r = 1, \ldots, R$ is governed by the differential equation:

$$\ddot{x}_{ir} + 2\zeta_r\omega_r\dot{x}_{ir} + \omega_r^2 x_{ir} = \phi_{ir}\sum_{k=1}^{N_{in}} P_{rk}f_k(t)$$

$$x_{ir}(0) = \phi_{ir}c_r$$
$$\dot{x}_{ir}(0) = \phi_{ir}d_r \tag{2}$$

where:

ω_r : natural frequency of rth mode

ζ_r : damping ratio of rth mode

ϕ_{ir} : modeshape component of rth mode at the ith location

P_{rk} : participation factor of the kth input channel for the rth mode

f_r : input vector for kth channel

c_r : initial modal displacement of rth mode

d_r : initial modal velocity of rth mode

In some cases, such as during shaking by an earthquake, the response also includes a pseudo-static component:

$$\ddot{x}_{i0} = \sum_{k=1}^{N_{in}} r_{ik}f_k(t) \qquad i = 1, 2, \ldots, N_{out} \tag{3}$$

where the pseudo-static matrix r_{ik} directly relates the input and output channels.

Let $\underline{\theta}$ denote a vector of all the unknown modal parameters. Having selected a general form for the model, a solution can be obtained by determining the combination of parameters that gives the "best" possible model. This will require some quantitative measure of the model's performance. MODE-ID uses the mean-squared error:

$$J(\underline{\theta}) = \sum_{i=1}^{N_{out}} \sum_{n=1}^{N} [\hat{y}_i(n) - \ddot{x}_i(n; \underline{\theta})]^2 \tag{4}$$

This is in some sense the distance between the model output, x, and the measured response y. The error is normalized by the mean-squared value of the measurements, giving a measure of fit J, which could be interpreted as the mean-squared fractional error. The optimal model is the one that minimizes J; this is equivalent to finding the projection of the data onto the space of modal responses. The program MODE-ID performs the optimization by using an iterative scheme called modal minimization.

Though modal identification from earthquake records is a useful tool, the long interval between events, as well as the considerable variation in the amplitude of the input excitation make it unsuitable for long-term monitoring of a building's dynamic characteristics. One might consider applying MODE-ID directly to ambient response measurements during the continually occurring low-level ambient vibrations. However, in the ambient case, measurements of the base motion of the building do not accurately capture the input excitation to the structure, as wind and other

vibration sources, which are negligible in comparison to excitation by earthquakes, can be significant in the absence of strong shaking. In this case the input excitation for the structure is effectively unknown.

MODE-ID takes advantage of the fact that the theoretical cross-correlation functions of the response satisfy the equations of motion for free vibrations (Beck, 1996), as follows. Consider the equations of motion for a structure:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = Bf(t)$$
$$x(0) = x_0$$
$$\dot{x}(0) = \dot{x}_0$$

(5)

Modeling the ambient forces as a weakly stationary stochastic process in which future input forces are uncorrelated with the current structural response, that is:

$$E\left[f(t+\tau)x^T(t)\right] = 0, \quad \tau > 0$$

(6)

One can then write:

$$M \cdot E\left[\ddot{x}(t+\tau)x^T(t)\right] + C \cdot E\left[\dot{x}(t+\tau)x^T(t)\right] + K \cdot E\left[x(t+\tau)x^T(t)\right] = 0$$

(7)

which leads to:

$$M \cdot \frac{\partial^2 R(\tau)}{\partial \tau^2} + C \cdot \frac{\partial R(\tau)}{\partial \tau} + K \cdot R(\tau) = 0$$
$$R(0) = E\left[x(t)x^T(t)\right]$$
$$\frac{\partial R(0)}{\partial \tau} = E\left[\dot{x}(t)x^T(t)\right]$$

(8)

where $R(\tau)$ is the cross-correlation matrix function of $x(\tau)$. In other words, each column of $R(\tau)$ is a solution of a free vibration problem with respect to the time lag, τ. It can be verified that the cross-correlation matrix for acceleration, $R^a(\tau)$, also satisfies the same equation. For ambient vibration measurements, one can estimate the cross-correlation function for each measurement channel with respect to a reference channel r from the acceleration measurements $y(t)$.

$$R_{ir}^a = E\left[y_i(t+\tau)y_r(t)\right] \approx \frac{1}{T}\sum_{t=1}^{T} y_i(t+\tau)y_r(t)$$

(9)

From this, one can construct a vector of these estimated cross-correlation functions,

$$y_{AV}(\tau) = \begin{bmatrix} R_{1r}^a(\tau) & R_{2r}^a(\tau) & \cdots & R_{qr}^a(\tau) \end{bmatrix}^T \quad \tau = 0, 1, \ldots$$

(10)

Finally, the modal parameters can be identified using $y_{AV}(\tau)$ as if it were a measured free-vibration response, a problem MODE-ID is well suited for. This analysis can be performed on real-

time data or archived data from the COMET site, using any of the channels from Millikan Library or the Broad Center.

Visualization of real-time or archived data

The COMET site contains a convenient visualization application that allows users to plot selected data from any of the COMET channels. The user can plot data from the COMET archives or generate a plot based on the near real-time data that is continuously streaming into the COMET site. A preliminary gallery of special events has been collected and is available on the website.

Data storage and retrieval of real-time or archived data

The COMET site, in addition to providing analysis and visualization tools, allows users to download stored data. The data from the SCEDC stations are digitized at 24bits, and recorded at 80sps from MIK and 100sps for CBC for one year. These archives allow for analysis of very high-frequency behavior of the library; the SCEDC itself permanently stores 20sps data and stores 80-100sps data for triggered events only.

INSTRUMENTATION

The Caltech campus has instruments in five buildings; the COMET site currently is acting as an interface only with the more densely instrumented Broad Center and the Millikan Library. SCEDC data from all five stations can be obtained from the SCEDC website:
`www.scedc.scec.org/stp.html`

Millikan Library: SCEDC Station MIK and the USGS Dense Array

SCEDC Station MIK

Station MIK, located on the 9th floor of Millikan Library, was the first station integrated into the COMET system. Three channels of data from a tri-axial Episensor and 24bit Quanterra datalogger are continuously telemetered to the SCEDC archives for permanent storage of 20sps data, and the COMET site stores the data at 80sps for one year.

USGS Dense Instrumentation Network

Thirty-six FBA-11 instruments are distributed throughout the Millikan Library: three uniaxial FBA-11 instruments on each floor and three vertical instruments in the basement, collectively referred to as the USGS Dense Instrumentation array. The data from this network is digitized and recorded by two parallel systems: the DIGITEXX system and the Mt. Whitney system.

DIGITEXX System

The DIGITEXX system, a proprietary hardware and software system, digitizes the dense array data at 16bits, and streams it to client machines at 200sps. The COMET machine has a client

installed, and therefore has access to the dense array data when manually or automatically triggered. A real-time display of the data is available from: `www.r-shape.caltech.edu`

Mt. Whitney System

The Mt. Whitney digitizer system provides local storage of triggered data. There is a current proposal being developed to replace the Mt. Whitney system with Quanterra systems, in order to stream the data from the dense array directly into the SCEDC database. The Mt. Whitney system digitizes data at 19bits.

Broad Center: SCEDC Station CBC

Station CBC was added to the COMET system in the fall of 2003. The Broad Center network is comprised of eight Episensor channels of data: 1st floor N-S, E-W and Vertical; Roof level N-S, E-W and Vertical; and two additional Roof channels, N-S and E-W, located on the opposite corner of the building. These channels are continuously telemetered to the SCEDC archives and stored at 100sps on the COMET site.

USGS Office: SCEDC Station GSA

The USGS Office station, SCEDC station GSA, is comprised of a tri-axial Episensor and a 24bit Quanterra datalogger, located in the basement of 525 South Wilson. This station is commonly used as a reference station for data from other campus stations.

Robinson Building: SCEDC Station CRP

The station CRP is located approximately 18m below grade, in the Robinson Building telescope pit. This station is currently used as a test station, so the instrumentation varies.

The Athenaeum: SCEDC Station CAC

Station CAC, located in the basement of the Athenaeum faculty club on the Caltech campus, is digitized through a 19bit K-2 datalogger. Only triggered data from this station is stored in the SCEDC archives.

MILLIKAN LIBRARY RESEARCH

The Robert A. Millikan Memorial Library, located on the California Institute of Technology campus, has been studied intensively since its construction in the mid 1960s. The installation of the USGS/Caltech dense instrumentation network in 1998 and the SCEDC station MIK in 2001 have led to several recent investigations into the dynamic characteristics of the library, as well as the temporal evolution of these properties.

Ambient Studies

Ambient analysis of the data from station MIK has led to several important observations. The behavior of the library is seen to change on several timescales. In the time domain there is a daily cycle in ambient noise, and a daily long-period drift that are both obvious at a time scale of days/weeks (Figure 1). This section presents several illustrative examples of the type of information obtained from ambient analysis. The daily vertical stripes, representing low ambient noise, are due to the air conditioning system and other mechanical systems in the library, which are shut down daily from midnight to 4:00AM.

The fundamental mode of the library wanders by a small amount over a short time span. Figure 2 shows the first E-W mode of the library, along with smoothed and scaled versions to illustrate the small changes in natural frequency that occur over a time span of one week. The first N-S and Torsional modes behave similarly under ambient vibrations.

On a longer timescale, the change in fundamental frequency becomes much more apparent, as in Figure 3. In this figure, rainfall and windstorms are shown to have a strong effect on the frequency of the first E-W mode of the building. The Santa Ana wind event on January 6-7 temporarily increases the amplitude and decreases the frequency of the first mode response. The major rainfall from February 11-12, while not strongly affecting the amplitude of the response, creates a very clear increase in the E-W frequency, which takes several days to recover.

Figure 4 presents a summary of historical modal frequencies of the library, and Figure 5 presents spectrograms of station MIK data focusing on the fundamental modes of the library.
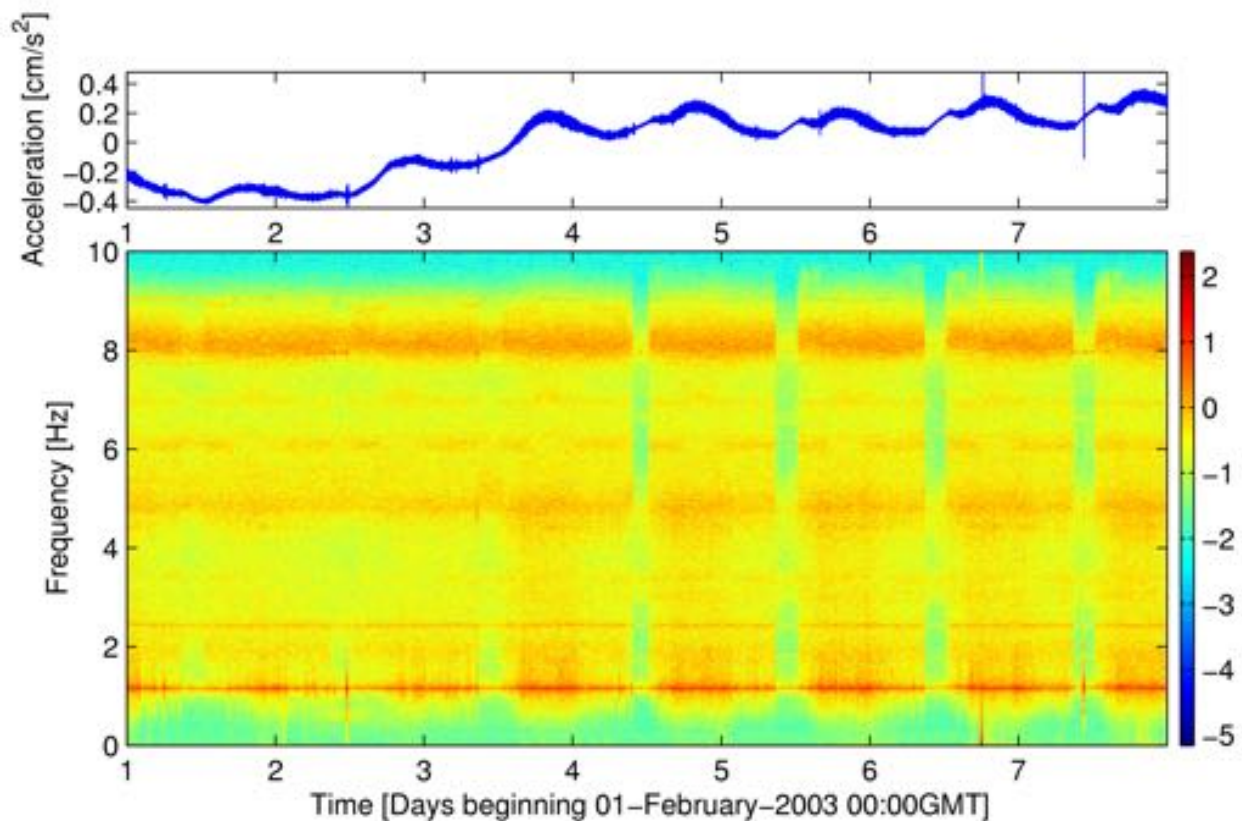

Figure 1. Seven days of station MIK, E-W component. The time-history is shown above, and a logarithmic spectrogram is shown below. Spectrogram is composed of 30-minute windows. The AC system is inactive from 12:00-4:00AM, which can be seen in the time and frequency domain as a stripe of low ambient noise.
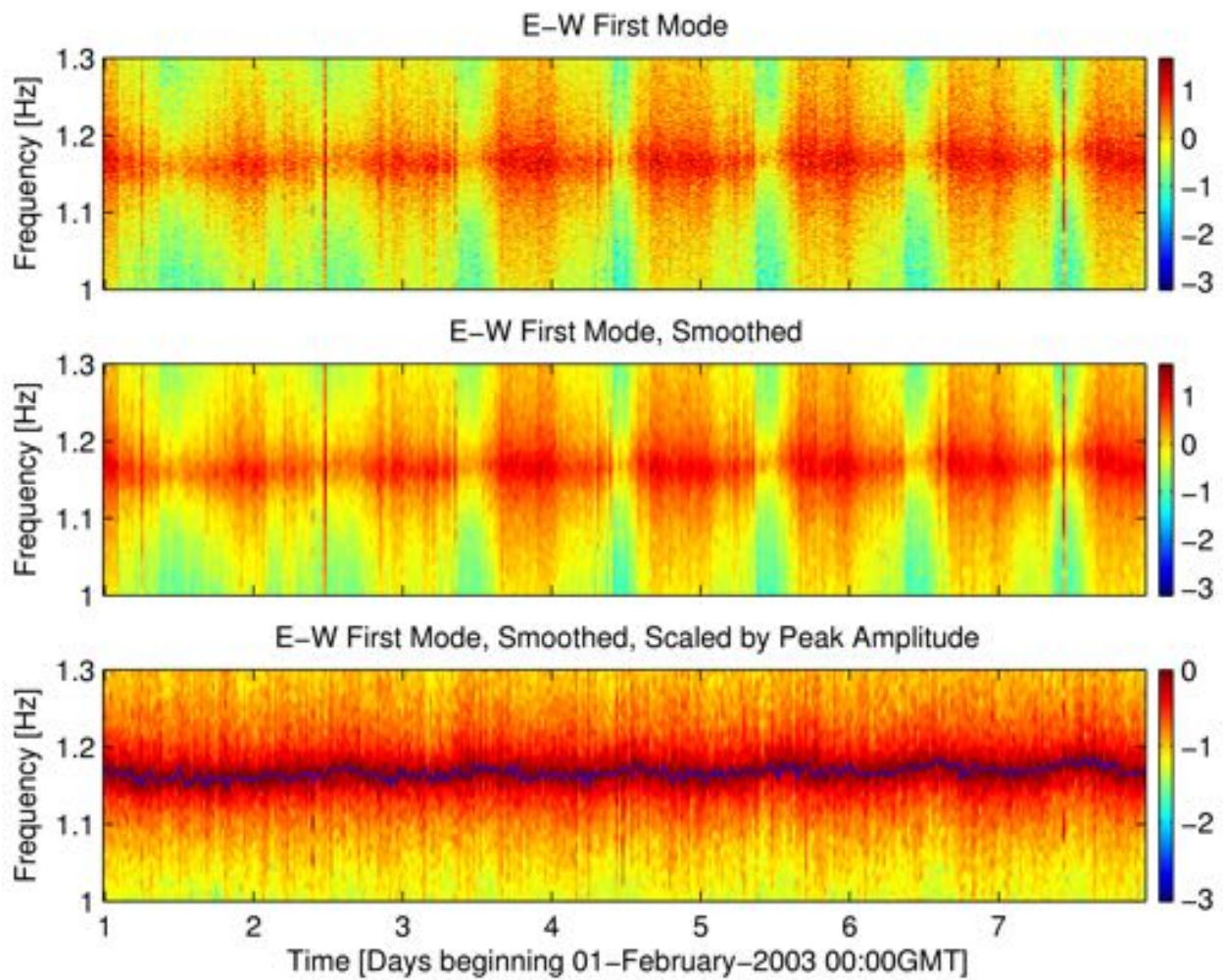
Figure 2. Seven days of station MIK, E-W component. E-W mode spectrograms, showing changes in relative amplitude and frequency of the first mode response of the library.
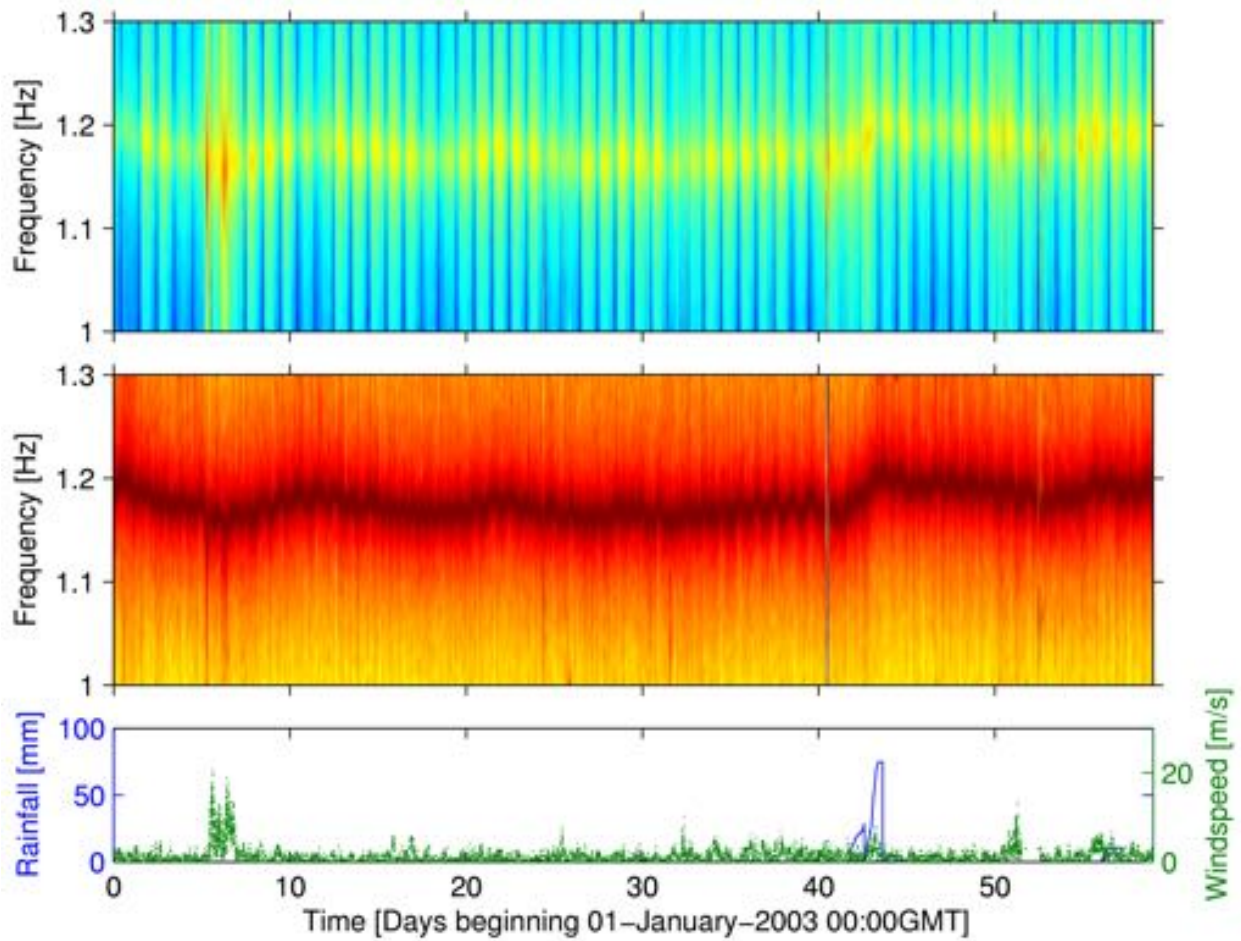
Figure 3. Sixty days of station MIK, E-W component. Spectrogram of E-W mode, and scaled E-W mode, to illustrate the changes in amplitude and frequency caused by weather events. Weather data from JPL weatherstation records; rainfall daily accumulation shown as a solid line, and wind speed as a dotted line.
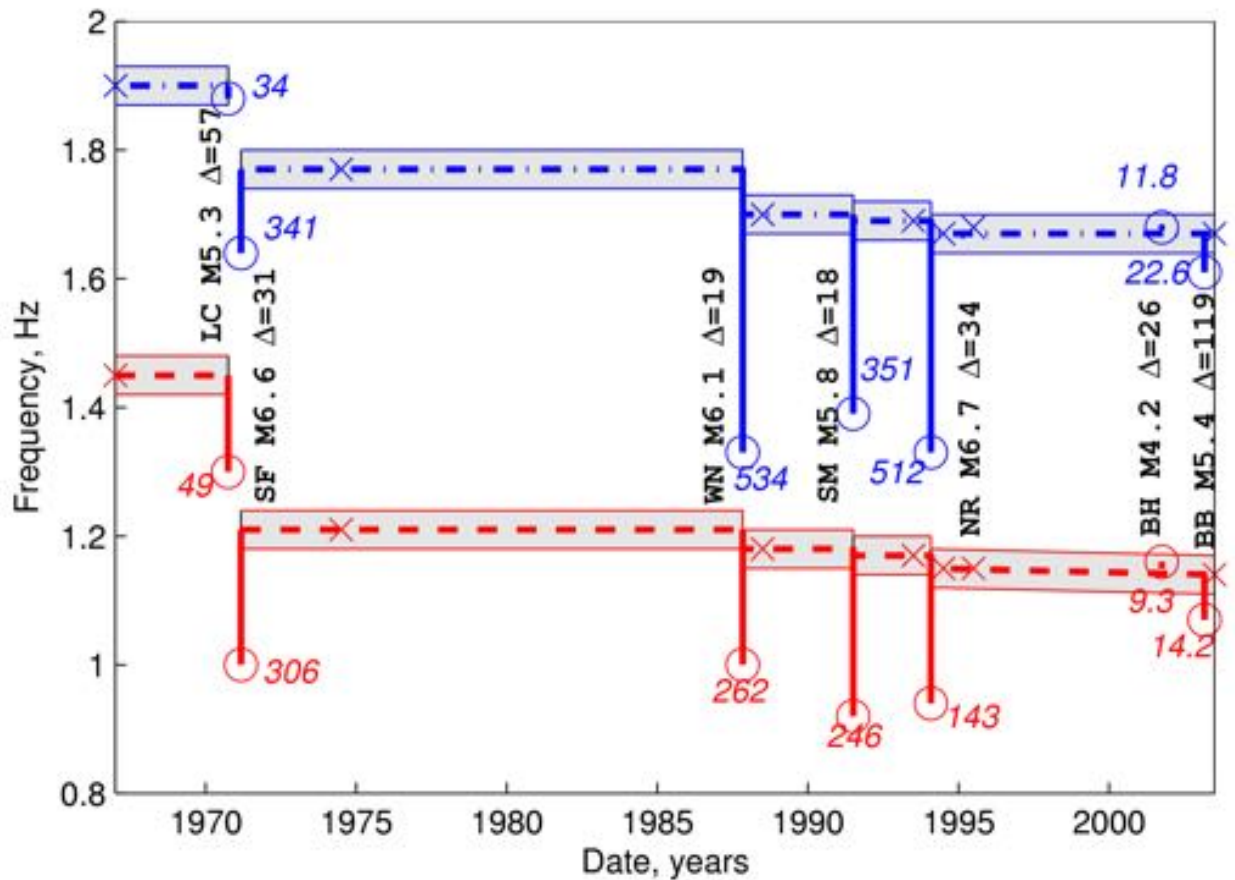
Figure 4. Historical Behavior of Millikan Library. Dashed lines represent the E-W natural frequencies and the dashed-dotted lines represent the N-S natural frequencies. Shaded area is the likely range of natural frequencies taking various factors into consideration - weight configuration in the shaker, weather conditions at the time of the test, and experimental error. Crosses indicate frequencies obtained from forced vibration tests. Circles indicate natural frequency estimates from the strong motion record during earthquake events, and numbers in italics are peak roof acceleration recorded for the event (cm/s 2). [Earthquake Abbreviations: LC: Lytle Creek, SF: San Fernando, WN: Whittier Narrows, SM: Santa Monica, NR: Northridge, BH: Beverly Hills, BB: Big Bear] (from Clinton, 2004)
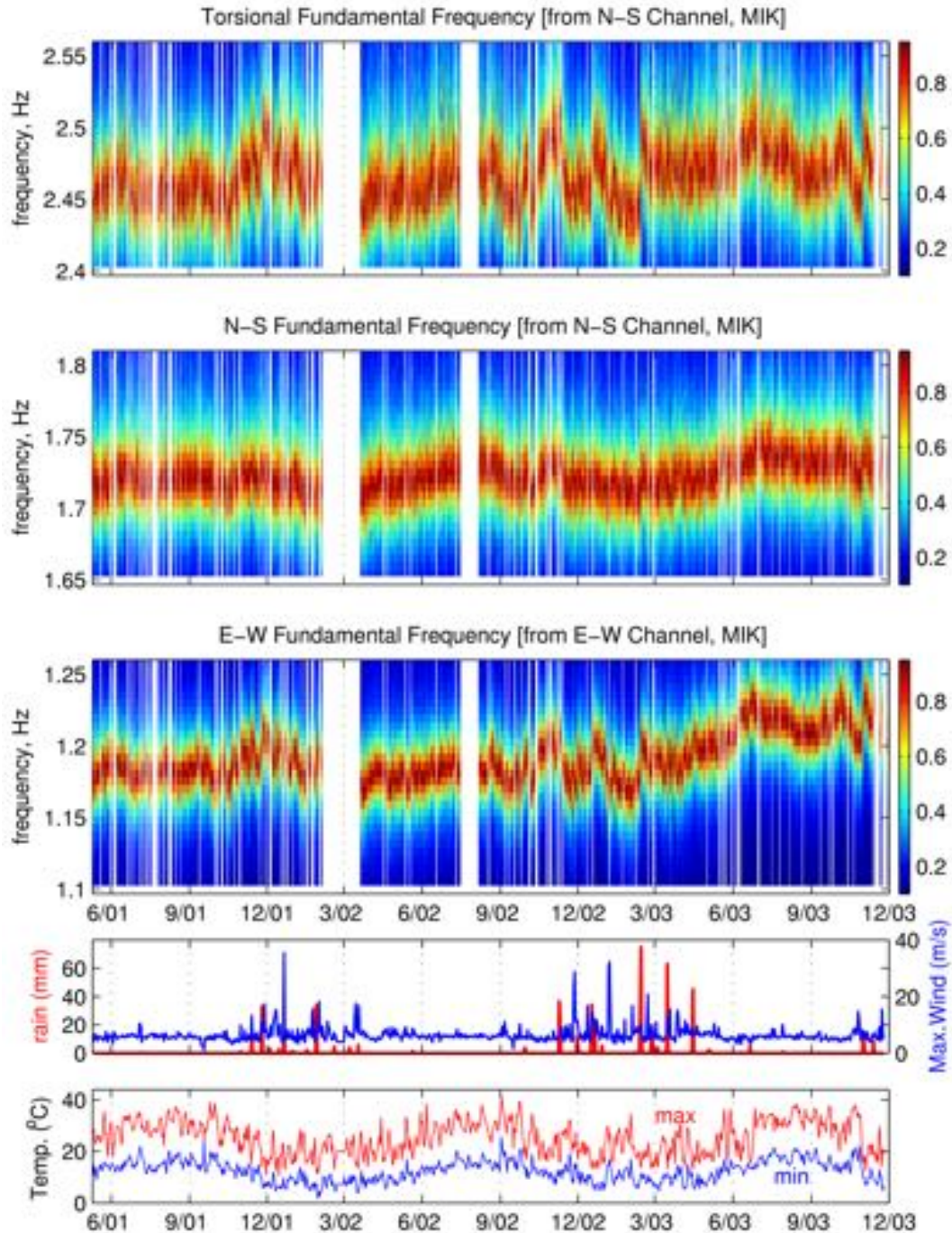
Figure 5. Spectrogram of natural frequencies as observed at MIK, May 2001 - Nov 2003. Spectrogram composed of 1-hour time windows, scaled by peak amplitude, and plotted with a linear colorbar. Weather data is from JPL weather station. Station glitches or instrument failures are represented as blank intervals. Time axis ticks represent the beginning of each month, at 00:00GMT. The peaks of the spectrogram, which represent the ambient natural frequencies, are seen to wander over the course of the 2.5 years of recorded data. Internal construction in late 2003 appears to have permanently increased the frequency of the E-W and N-S modes. A correlation with rainfall is also noted. (from Clinton, 2004)

Weather Patterns

One of the current areas of interest that has been discovered through the ambient studies is that of a correlation in building behavior with weather patterns. This has implications for structural health monitoring methods that use changes in modal frequencies to infer damages; clearly, systematic changes due to environmental conditions must be taken into account to avoid false alarms.

Rainfall

In 2001, after an analysis of rainfall records and the ambient vibration records from station MIK, it was hypothesized that rainfall was strongly affecting the fundamental frequencies of Millikan Library. Since that time, research has identified a significant change in building behavior that is strongly correlated with rainfall. During a rain event, the fundamental E-W and Torsional frequencies of the building can increase by 3-5%, with the building gradually recovering to pre-rain levels over the course of 1 to 2 weeks. The N-S direction is less strongly affected by rainfall. Figure 6 presents a summary of the Feb 11-12 rain event, showing the E-W, N-S and Torsional modes, along with weather data from the JPL archives. This phenomenon is not well understood, and is currently being investigated.

Wind Events

Strong winds affect the behavior of the library. During Santa Ana wind events, all fundamental frequencies decrease by 2-4%, and recover immediately after the strong winds. Millikan Library has been shown in previous experiments to have a non-linear force-deformation relationship, even at very low shaking levels; changing the exciting force will change the frequency of the building (Bradford et al., 2004). Figure 7 presents a summary of the January 6-7 wind event, along with the change in amplitude and corresponding change in frequency of the fundamental modes.
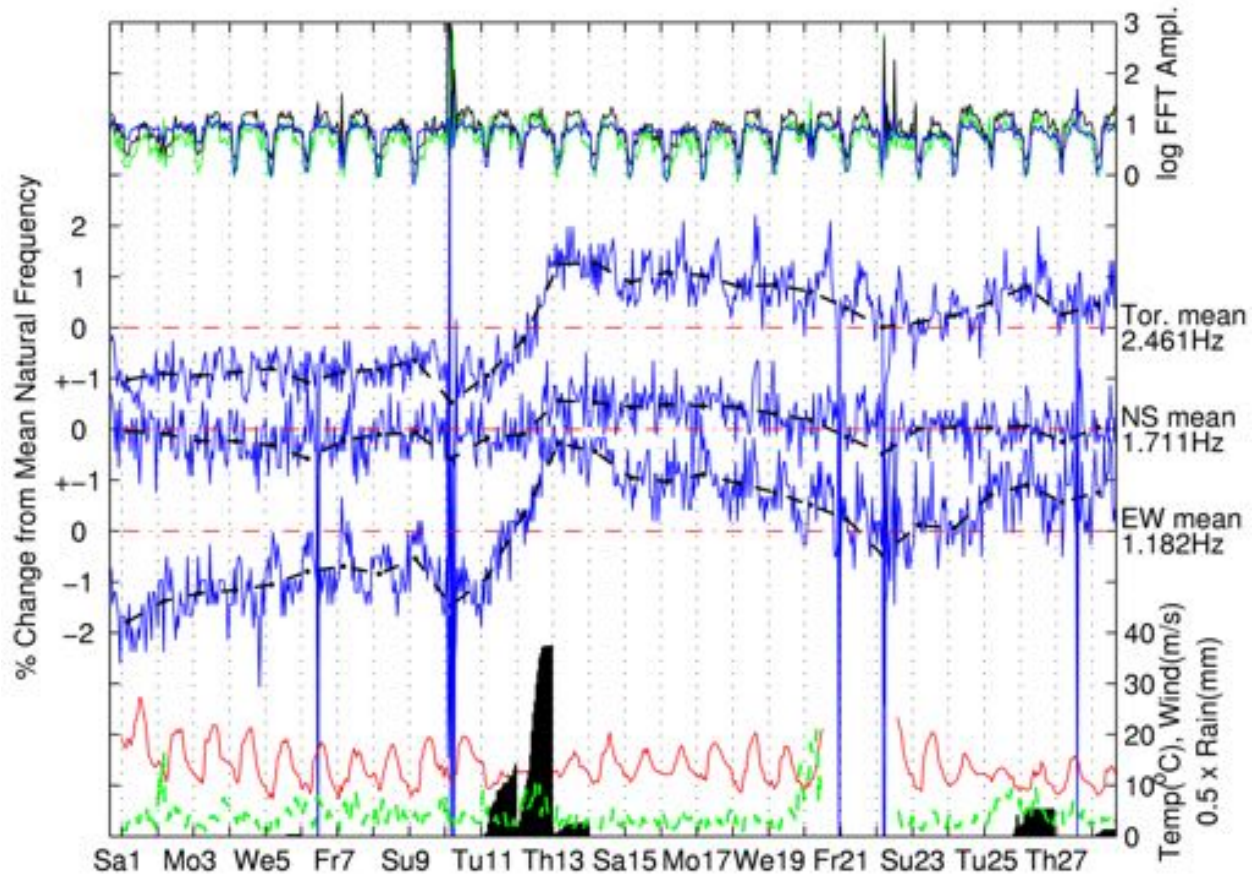
Figure 6. Summary of rainfall effects on the fundamental modes of Millikan Library. The frequency of the spectral peak is shown, along with weather records from the JPL weather station. The E-W and Torsional modes are more strongly affected by rain than the N-S mode. The horizontal dashed lines are the average modal frequencies for the month of February, the dash-dotted lines are the daily averages of the continuous (hourly) data. Large spikes in the data are from instrument glitches (Feb 6, 21, 27), forced vibration testing (Feb 10) and the Big Bear Earthquake (Feb 22). (from Clinton, 2004)

Earthquake Behavior

During earthquake events, there is an extreme drop in the fundamental frequencies. For smaller events, the building recovers after only a few minutes. For larger events, a permanent change in building behavior has been observed, as in Figure 4 (Clinton et al., 2004; Bradford et al., 2004).

Forced Vibrations

The Millikan Library has a synchronized vibration generator (shaker) permanently installed on the roof. This has allowed for many forced vibration tests of the library, e.g. (Foutch, 1976; Luco et al., 1986; Favela, 2004; Clinton, 2004; Bradford et al., 2004). Forced vibration tests have been used to determine the natural frequencies of the building and the associated mode shapes.

Bradford et al. (2004) describes one series of forced vibration tests that took place over several months during the summer of 2002.
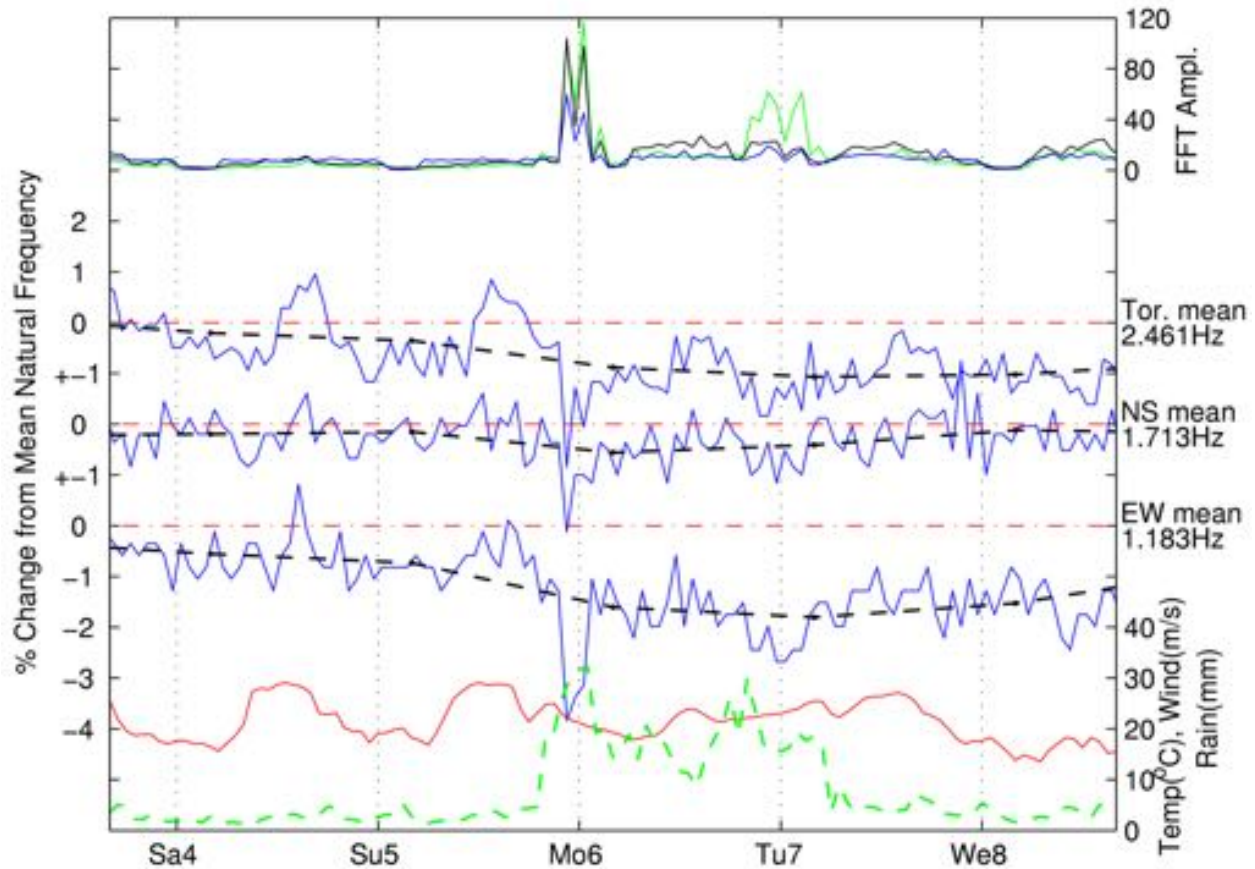
Figure 7. Summary of wind effects on the fundamental modes of Millikan Library. The peak resonance is shown, along with weather records from the JPL weather station. The horizontal dashed lines are the average modal frequencies for the month of January, the dash-dotted lines are the daily averages of the continuous (hourly) data. (from Clinton, 2004)

Rainfall test: February 2004

    To address the behavior of Millikan Library in its rain-affected state, we have begun a suite of tests to examine the behavior of the library during rainfall. The first set of tests took place over a week in February, 2004, during a winter storm; this is the first such test performed on the Millikan Library and the data is currently being analyzed. Using the results from this test, both for the fundamental frequencies and the fundamental mode shapes, the authors will be able to create a more refined model of the building and describe more quantitatively how rain is affecting the behavior of the building.

BROAD CENTER RESEARCH

The Broad Center for the Biological Sciences was completed in 2002. Ambient analysis of the Broad Center data has led to similar developments as the Millikan Library research, but analysis is still underway to determine the temporal evolution of its dynamic properties.

CONCLUSIONS

The COMET site, along with the Caltech monitoring network, provide a useful tool for real-time structural monitoring. Ambient studies of the Millikan Library and Broad Center have revealed that the natural frequencies of structures can wander at many time scales. Weather patterns have been shown to be an important factor in the temporal variations of natural frequency. An understanding of the ambient behavior of structures is necessary for structural health monitoring; the strong effect of weather patterns on the dynamic characteristics of the library can cause problems for monitoring techniques that use a change in fundamental frequency as damage criteria. More investigation is required into the mechanisms of the relationship with weather patterns.

ACKNOWLEDGEMENTS

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