Chapter 2
Real-Time Structural Health Monitoring and Damage Detection

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Abstract Structural health monitoring (SHM) contains continuous structural vibration monitoring, extraction of damage sensitive features of structure from measurements, and statistical analysis of those features to detect and locate the damage in structures. In other words, SHM involves data collection, continuous monitoring and analyzing them in real-time. Changes in modal properties of structures during their service life are strongly related to damage in structures, which makes accurate estimation of modal properties an essential step in SHM. Therefore, both monitoring and accurate identification of real-time modal properties (modal frequency, damping ratio, and mode shape) are of crucial importance in order to have a good estimate in SHM. In this paper, a real-time modal identification techniques along with a damage detection algorithm based on inter-story drift calculation has been developed for SHM. The modal identification technique is based on the modification of standard spectral analysis tools for real-time data, and utilizes running time windows to keep track of time variations of structures' modal properties. On the other hand, the damage detection algorithm makes use of inter-story drifts, which is calculated by narrow-band filtering the recorded data around modal frequency and very sensitive to structural damage, by estimating the contribution of each identified mode of structure. A software package called **REC_MIDS** is developed for real-time modal identification. The software includes various user-selectable algorithms to identify modal properties, as well as options to plot their time variations and animations. The software has been tested with the ambient vibration data recorded from the Hagia Sophia Museum, a 1500 year-old historical structure in Istanbul, Turkey. Modal properties of the structure have been identified accurately in real-time. Results of the Hagia Sophia test have been compared with the previous studies conducted by different researchers. Comparison shows that the results of the **REC_MIDS** are in good agreement with that of the previous studies.

Keywords Real-time data processing • Modal identification • Damage detection • Structural health monitoring • Inter-story drift

2.1 Introduction

The term SHM involves continuous monitoring of the dynamic characteristics of a structure by digital instruments (e.g., acceleration sensors). The main objective in SHM is to keep track of the changes in the dynamic characteristics of the structural system in order both to detect and locate the damage, and to make a decision automatically whether the damage is in dangerous level for the structure or not. Damage detection typically involves data processing to explore changes both in the dynamic properties of structures (e.g., modal frequency, damping ratio, and mode shape), and inter-story drifts. Since the damage in structures causes loss in their stiffness's, and the dynamic properties of structure are directly related to the stiffness, it is logical to use the changes in natural frequencies as a damage indicator [1]. However, analyses of recorded data from structures clearly show that changes in natural frequency are not always a reliable indicator of damage as the response of the

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damaged structure is nonlinear, and in most case hysteretic. Moreover, various environmental factors (e.g., temperature) can change natural frequency of structures without any damage in the structure. Likewise, the inter-story drifts, if not calculated by integrating the band-pass filtered acceleration data, is not a reliable damage indicator as the errors generated by the noise in the records are exponentially amplified during such integration.

In this research paper, an attempt is made both to keep track of changes in modal properties of structures, and to calculate inter-story drifts accurately by utilizing the ambient vibration records, which are characterized by very low amplitudes and signal-to-noise-ratio (SNR). Ambient vibration data are always available in the structure and their length can be made infinitely long. These facts allow ambient records to be considered as stationary data (i.e., their frequency and temporal characteristics do not change with time). Moreover, since the ambient vibration records contain large number of excitation sources, it is quite reasonable to assume that the both the noise and the excitation are wide-band random processes, which make it possible for advanced stochastic techniques (e.g., statistical signal processing) to be utilized.

In buildings inter-story drift refers to the relative displacement between adjacent floors. The accuracy of inter-story drifts is extremely increased by narrow-band filtering the recorded data around modal frequencies before calculating the inter-story drifts. As long as the ambient vibration data contains large amplitudes (e.g., data taken from high-rise building), the developed algorithm to calculate inter-story drifts will yield accurate result. It should still be kept in mind that higher mode contributions to inter-story drift calculation cannot be accounted for due to low SNR in higher frequencies.

A software package, **REC_MIDS**, is developed for both real-time modal identification and inter-story drift calculation. The software includes various user-selectable algorithms to identify modal properties, as well as options to plot their time variations and animations. The software has been tested with the ambient vibration data recorded from the Hagia Sophia Museum, a 1500 year-old historical structure in Istanbul, Turkey. Modal properties of the structure have been identified accurately in real-time. Results are compared with the previous studies carried out by different researchers. Comparison shows that the results of the **REC_MIDS** are in good agreement with that of the previous studies.

2.2 Real-Time Data Processing and Modal Identification

A smart algorithm is developed to process the real-time data instantaneously. The developed algorithm works in the following way. The real-time data are segmented using two separate windows: *truncated window*, and *running window*, one within the other as show in Fig. 2.1. The real-time data in the *truncated window* is processed by means of successive *running windows*. The data in each *running window* is analyzed separately, and sequential analysis results are averaged in order to form the overall output for the *truncated window*, which is almost identical to the output that would have been obtained if the *truncated data*, free of noise, had been processed at a time. Once the analysis of the *truncated window* is finished, it is shifted in time, as shown in Fig. 2.1, by predefined overlap ratio, and the above procedure is repeated.

The *running window* moves within the *truncated window* with predefined overlap ratio as indicated in Fig. 2.1. Increasing the overlap ratio increases the number of successive running windows. The bigger the number of running windows the less the effect of noise in the overall analysis result. In other words increasing the number of *running windows* increases the accuracy in the overall output. However, increasing the overlap ratio also increases the elapsed time (i.e. total calculation time) to estimate the overall output for the *truncated window* due to increase in the number of *running windows*. Time delay in real-time operation occurs when elapsed time falls behind the real-time data streaming speed.

The length of *running window* is structure specific. It depends on the modal characteristics of the structure, especially on the smallest modal frequency of the structure. It must be at least two times bigger than the maximum modal period of the structure. Length of the *truncated window*, on the other hand, depends on the signal-to-noise ratio (SNR), also know as noise level, of the real-time streaming data. If real-time data contains too much noise, then the length of the *truncated window* should be such long that the affect of noise in the analysis result is minimized by means of increasing the number of *running windows*, and averaging. Too long *truncated window* may not provide sufficient accuracy in case of sudden change in environmental loads, whereas too short *truncation window* may not provide sufficient noise reduction due to decrease in the number of averaging. Apparently there is no unique solution to determine the optimum length for the *truncated window*. In order to define the optimum window lengths, it is strongly recommended to collect a set of experimental data (i.e. ambient vibration data) from structure under consideration, and then analyze them with varying window lengths and other parameters. Calculating the optimum window lengths is an ad hoc operation, which should be done separately for each structure by an engineer.

Common practice to calculate the displacements using acceleration data is to take double integration of the recorded acceleration data. Simple integration of acceleration signals produce significant amount of errors depending on the sampling resolution [2], moreover, shows that the integration and subtraction exponentially amplify the errors generated by the noise
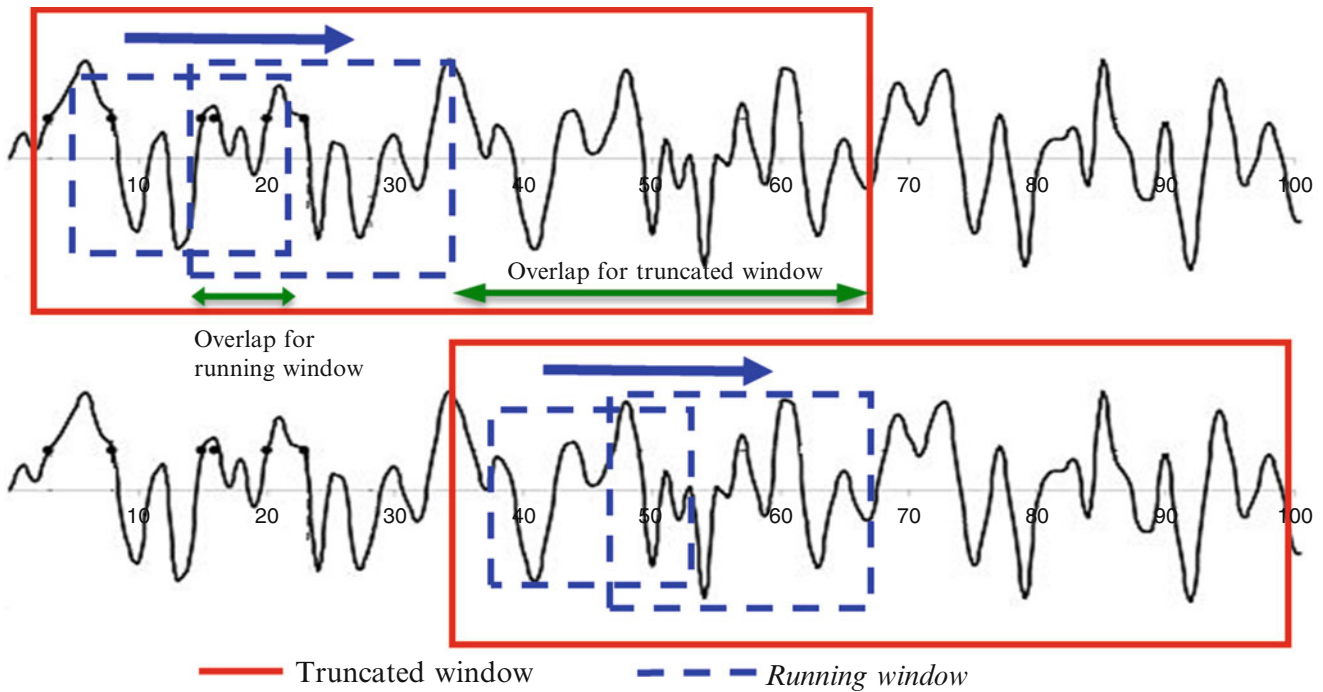
Fig. 2.1 Running window moves within the truncated widow by a predefined overlap ratio. The data in each running window is analysed separately, and sequential analysis results are averaged to form the overall output for the truncated window

in records, particularly for high frequencies. This is due to so-called Brownian motion where the variance of an integrated noisy-signal (i.e. signal dominated by noise) increases by a factor of t (time), which obviously causes the integration to go to infinite. Thus this clearly demonstrates the fact that the integration will go to infinite because of existence of the noise in the entire frequency band of the signal. One-way of overcoming this problem is to band-pass filter the real-time data around each modal frequency (utilizing the frequency-band selections) to eliminate the frequency components that is dominated by noise. Even though the noise is still present in the pass band of the filter, the SNR of the filtered data will be higher than that of unfiltered one due to structural resonance effect within the pass band of the filter. This way one can make sure that the integration of narrowband filtered data will not go to infinite but yields to the modal displacement of structure.

In multi-story buildings, the term inter-story drift denotes the relative displacement between two adjacent floors whereas in this study the term refers to the relative displacements between any two sensors in a specified direction. Eventually inter-story drift controls structural damage based on the lateral displacements in multi-story buildings. The inter-story drifts that are calculated by taking the difference of double integrated acceleration data are usually inaccurate if the SNR of ambient records are low. However, for large amplitude vibration data (i.e. ambient vibration data of a high-rise structure), such inter-story drift values can be accurately calculated by narrow-band filtering the data around each modal frequency of the structure. Such filtering provide high SNR ratio. Therefore, one can calculate the inter-story drifts for each modal response of the structure by band-pass filtering though some of the higher mode contributions to inter-story drift cannot be calculated such accurately. This is because of the fact that even though the data is band-pass filtered around each modal frequency, the SNR of signal decreases at higher frequencies because the amplitude of modal response become such small that they are still buried by noise at higher frequencies. Therefore one has to decide how many modal responses of the structure can be calculated accurately and then the inter-story drifts are calculated simply summing up the contribution of all calculated modal responses. An automatic algorithm developed to calculate the contribution of each modal response to inter-story drifts

The developed algorithm calculates the inter-story drifts based on the estimated modal displacements of the structure. Raw data in *running window* is band-passed filtered separately around each modal frequency to calculate each modal response of the structure. The resulting filtered data is then double integrated to calculate the modal displacements. The total displacement of the structure is calculated by summing up the contribution of all of the calculated modal displacement. The calculated inter-story drifts are compared with different threshold values that correspond to different damage levels (i.e. performance levels) of the structure. The procedure is repeated for all inter-story drifts in the structure. Any inter-story drift exceeding specified threshold values indicates damage in structure. More detail about real-time data processing can be found in [3, 4].

2.3   Description of REC_MIDS

The capabilities of **REC_MIDS** include real-time data processing and analysis by using a large number of techniques, varying from standard Fourier analysis to stochastic-adaptive filters; real-time identification of structure's modal properties (modal frequencies, damping, and mode shapes); displacements and inter-story drifts; and 3D animations of total and modal responses. The software has the options to automatically give warnings when a response quantity exceeds specified threshold levels, to save any of the measured or calculated output parameters, and to generate and send automatic warning email to specified addresses.

A typical screen-shot of the **REC_MIDS** is shown in Fig. 2.2. The graphical display of the **REC_MIDS** is designed to allow the user to monitor the recorded structural response characteristics in real time, along with the estimated modal properties and the animations of vibrations in a single window.

Left-up window displays calculated displacements at user-selected sensor locations, whereas right-up window shows the smoothed Fourier Amplitude Spectra of the user-selected signals over an adjustable frequency range. Two left-bottom windows display the real-time calculated modal frequency and modal damping ratio of the structure. Right-bottom window animates user-selected structural mode estimated in real-time. All these windows are continuously updated in real-time to reveal the latest modal properties of the structure.

In **REC_MIDS**, the term inter-story drift refers to the relative displacement between any two sensors in a specified direction. The inter-story drift calculated between these two sensors is linearly distributed to the stories between these sensors. In ambient vibration conditions, noise can cause erroneous drift values, especially in higher modes, if the drifts are calculated from the original signals. Therefore, the inter-story drift calculations are not done on the original waveforms, but on modal waveforms in order to minimize the effects of noise in the signal. The band-pass filters are used to obtain modal waveforms. Drift waveforms can be monitored in the main window of **REC_MIDS** (Fig. 2.3). In theory, one can define in **REC_MIDS** as many inter-story drifts as the CPU of the computer can handle. However, the calculation of inter-story drifts involves large number of computations, and therefore defining too many inter-story drifts may cause delays in keeping up with the real-time data stream.
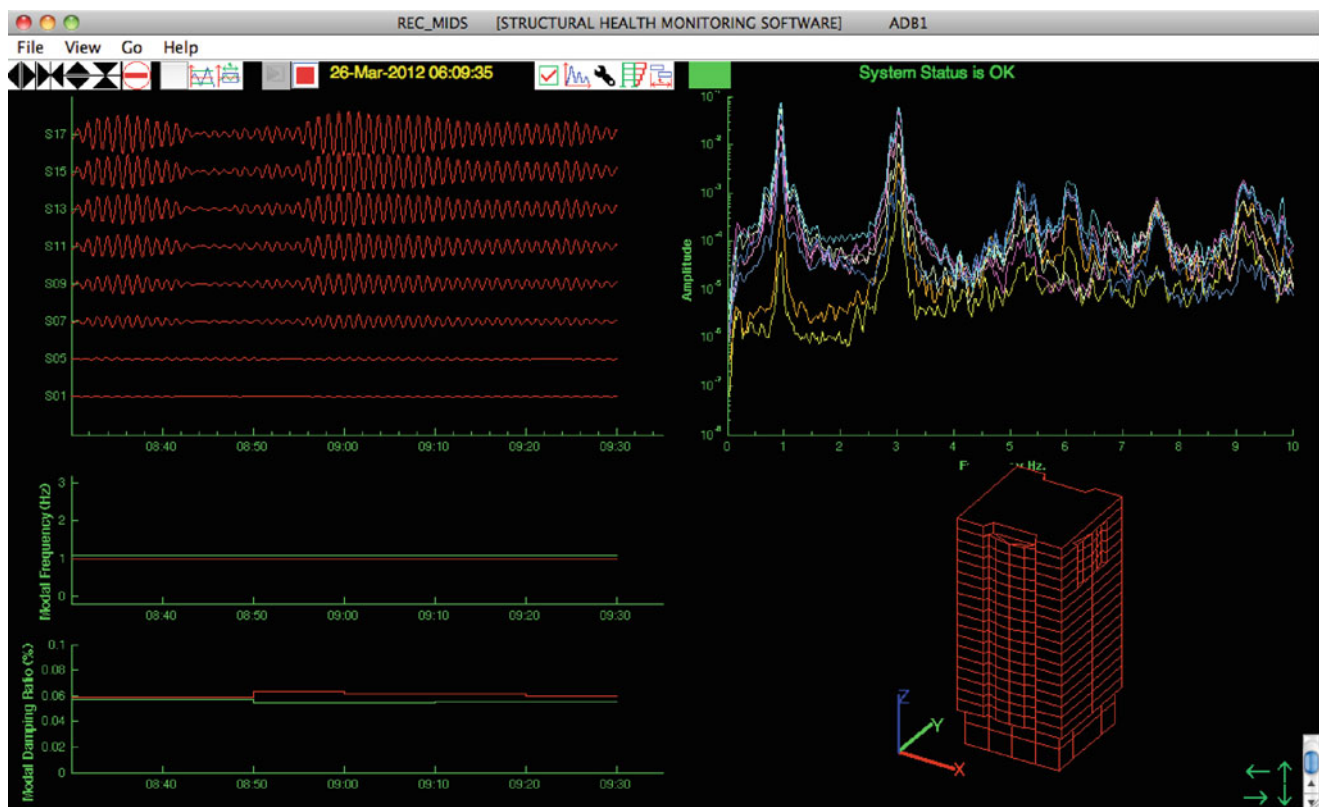

Fig. 2.2 A typical screen-shot of **REC_MIDS** that contains different windows to monitor the latest modal properties of the structure
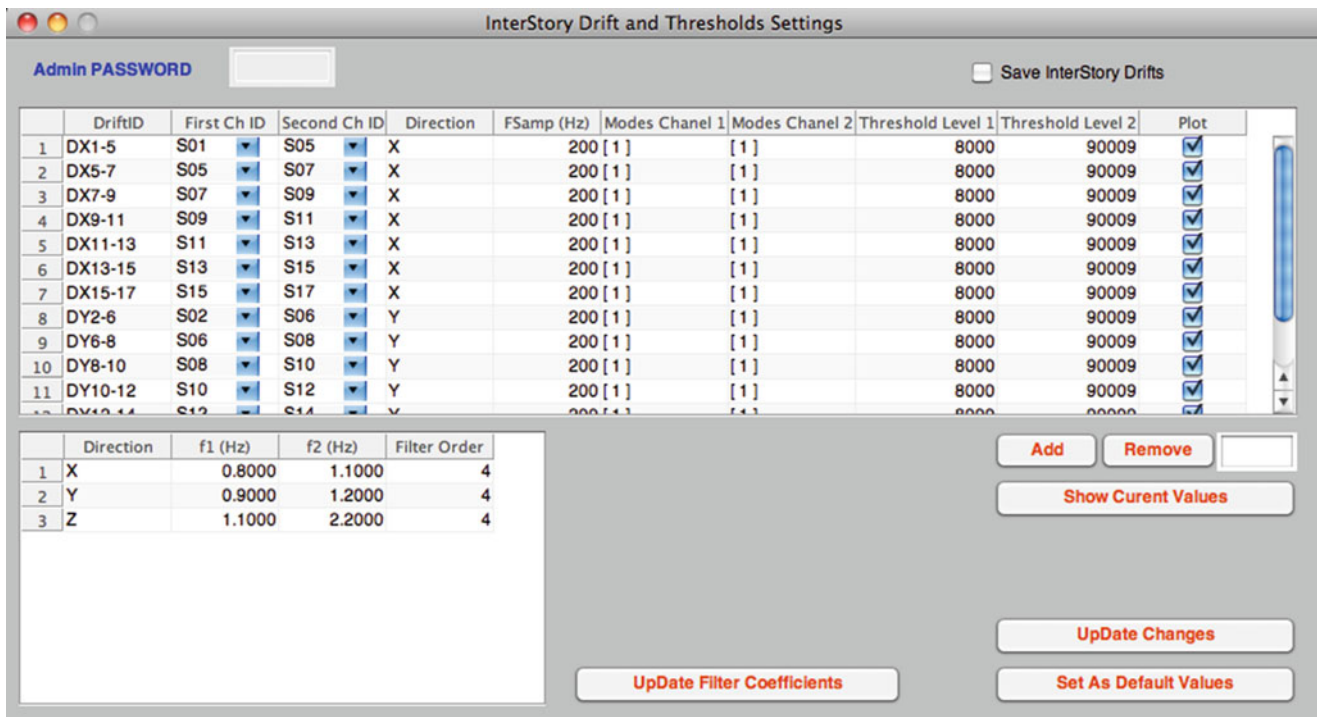
Fig. 2.3 The inter-story drift and threshold settings window. The user can define as many inter-story drifts as the CPU of the computer can handle

The *Event Detection Settings* window, shown in Fig. 2.4, is used to set up the channels and the threshold values that will be used to detect possible damage, and to issue warnings and alerts in case of an event that pushes the response of the structure to critical levels.

By default, the event detection algorithm embedded in *REC_MIDS* runs every 1 s using the past 4 s of data. These values are user adjustable. A smart algorithm embedded in *REC_MIDS* determines how many inter-story drifts and acceleration values exceeded the specified threshold values, as well as the top-floor displacement threshold value and wind speed threshold value. Based on the different combinations of the threshold value exceedance, and an automatic notification message/email are issued to user specified recipients. More detail about the event detection algorithm can be found in user manual [4], which can be downloaded from www.koeri.boun.edu.tr.

2.4   Application of REC_MIDS at Hagia Sophia Museum

Hagia Sophia (in Turkish Ayasofya) as seen in Fig. 2.5 is one of the most magnificent buildings in Istanbul, Turkey. Hagia Sophia museum suffered from several earthquakes and as a result partially destroyed. The eastern part of the dome collapsed along with the arch and semidome on the side of the church on May 7th, 1558. It is rebuilt with new design of the dome (less shallow so as to reduce the lateral stresses). An earthquake damaged the western side of the building on February 9th 1869, which is repaired in 1879. A violent earthquake resulted in collapse of the western apse and caused partial damage to the dome on October 25th, 1968. The church interior suffered very much in the Latin sack of Constantinople in 1204, when it was stripped of all its sacred relics and other precious objects. During the Latin occupation, Hagia Sophia served as the Roman Catholic cathedral of the city. Following the recapture of Constantinople by the Byzantines in 1261, Hagia Sophia was re-consecrated as a Greek Orthodox sanctuary. In 1348, the eastern half of the dome collapsed, and was afterwards repaired.

The imperial gate leads to the central nave of Hagia Sophia. The dome is approximately 55 m high and 32 m wide. Due to repairs and earthquakes over the centuries, the dome lost its original shape and not completely circular anymore. The ceiling is completely covered with mosaics. The dome rests on four large arches, which are supported by four pillars. Weight of the dome is transmitted to semi-domes in the north and south, and to the lower sections. The interior contains 107 columns, 40
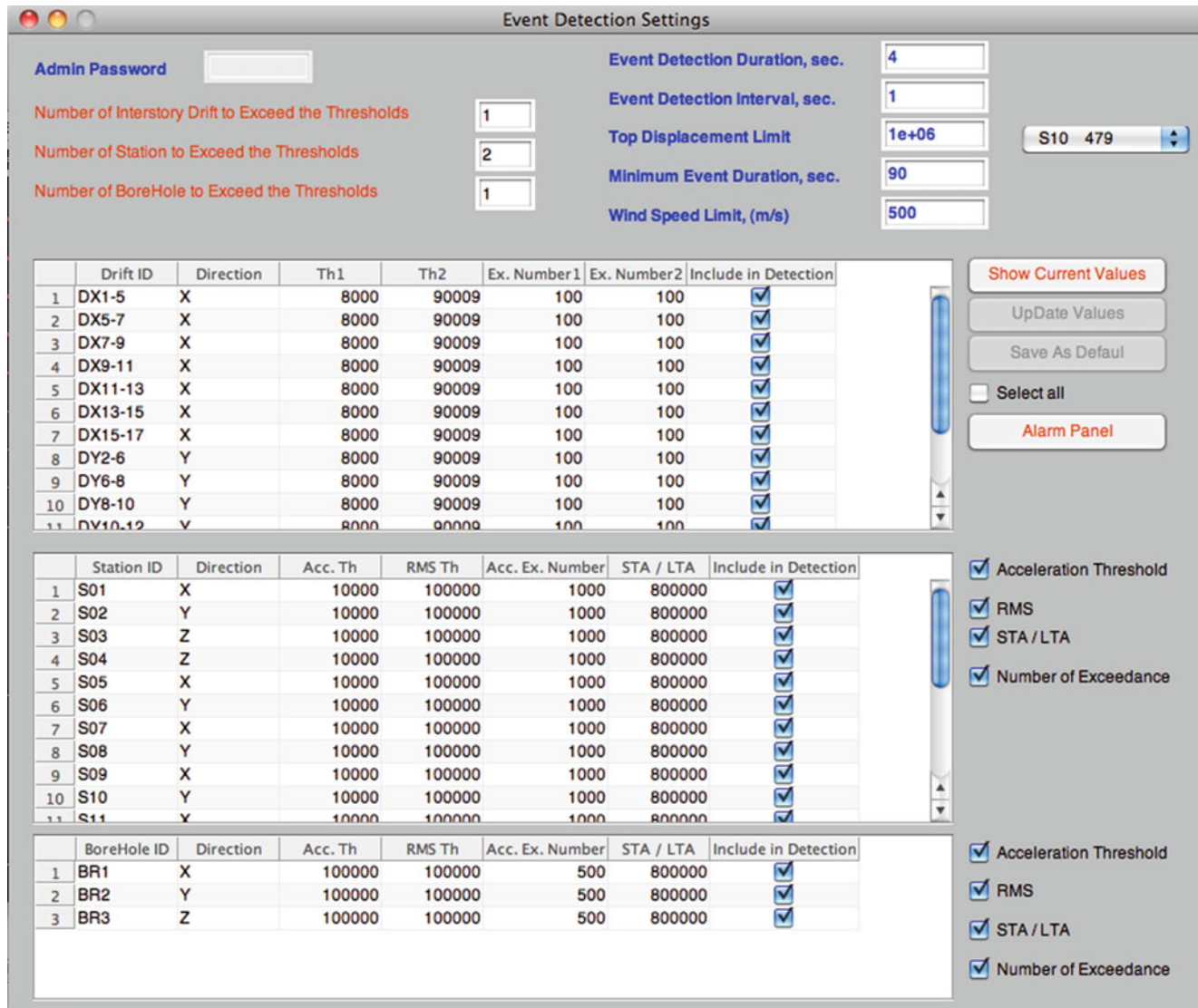
Fig. 2.4 Event Detection settings window. The user can set up the channels and threshold values that is used to detect possible damage, and to send automatic warning and alert emails in case of an event

of these are found on the ground floor and the rest are up in the gallery. Over the years, buttresses have been built outside, against almost every wall, to lessen the stress of the building and to counteract the damage caused by earthquakes.

2.5 Instrumentation of the Structure

The first strong motion network that has been installed in the structure was in August 1991 though many changes have been made since then. The latest instrument setup that is present at the museum can be seen in Fig. 2.2. The instruments basically cover the three different levels of the structure. One instrument is at the ground level while four of them are located at cornice level next to the springing points of the four main arches. The last four instruments are located at dome base level on the crowns of the main arch. All instruments are Guralp system CMG-5 accelerometers that are compact triaxial, force-feedback instruments, and suitable for rapid deployment.

Fig. 2.5 General view of Hagia Sophia

Fig. 2.6 Strong motion instrumentation in Hagia Sophia covers three different levels of the structure: ground level, cornice level, and dome base level
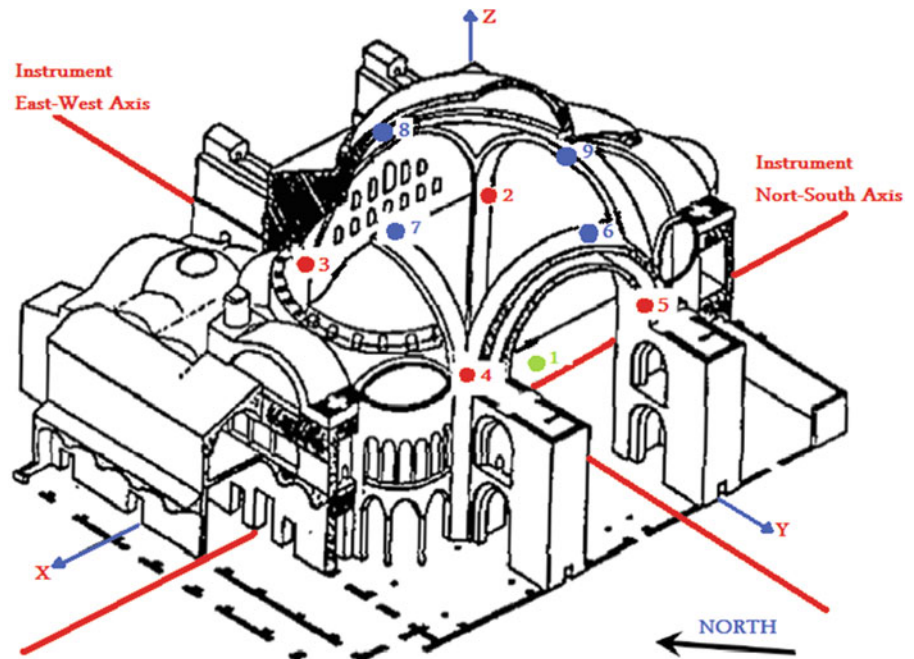
2.6 Data Collection and Results

Value of certain parameters of **_REC_MIDS_** has to be set up before analyzing the ambient vibration data of Hagia Sophia Museum. The necessary parameters are the decimation order, the filter corner frequencies and filter order, smoothing window length, frequency band limits, and modal property calculation methods. The sampling interval of the records is 200 Hz. All records from structure are decimated by 2, and standard 4th order of band-pass Butterworth filter with corner frequencies of 0.2 and 20 Hz is applied to the decimated data.

The running window length is selected as 1 min. The truncated data is further divided into equal size of running windows each have a length of 30 s. Each running window is overlapped with 90% and Hamming type of smoothing window is used to smooth the calculated FAS. The optimum smoothing window length is estimated as seven.

Twenty three hour length of real-time ambient vibration data was collected from Hagia Sophia Museum and was analyzed using **_REC_MIDS_**. The starting time of the real- time vibration data is 08:00 am, 17th of March, 2009 and the end time is 06:00 am, 18th of March, 2009. One-hour duration of real-time raw data is depicted in Fig. 2.7 for all stations installed in Hagia Sophia Museum. It is observed that the maximum mean acceleration amplitudes at the top of main arches are amplified
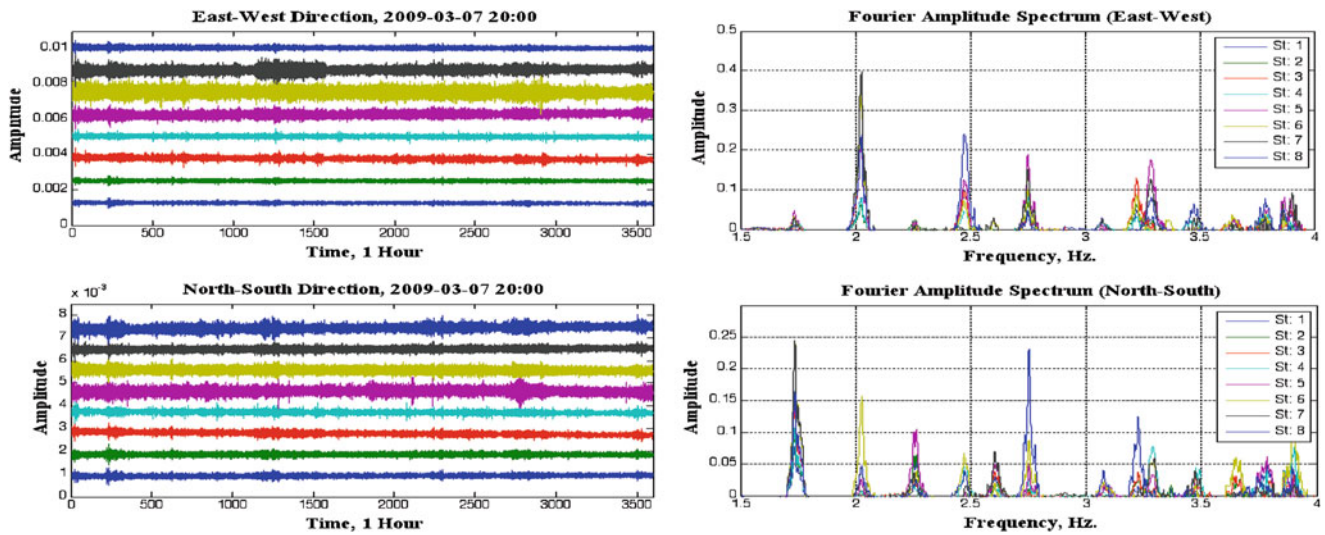
Fig. 2.7 Ambient vibration data of Hagia Sofia for 23 h and for all channels
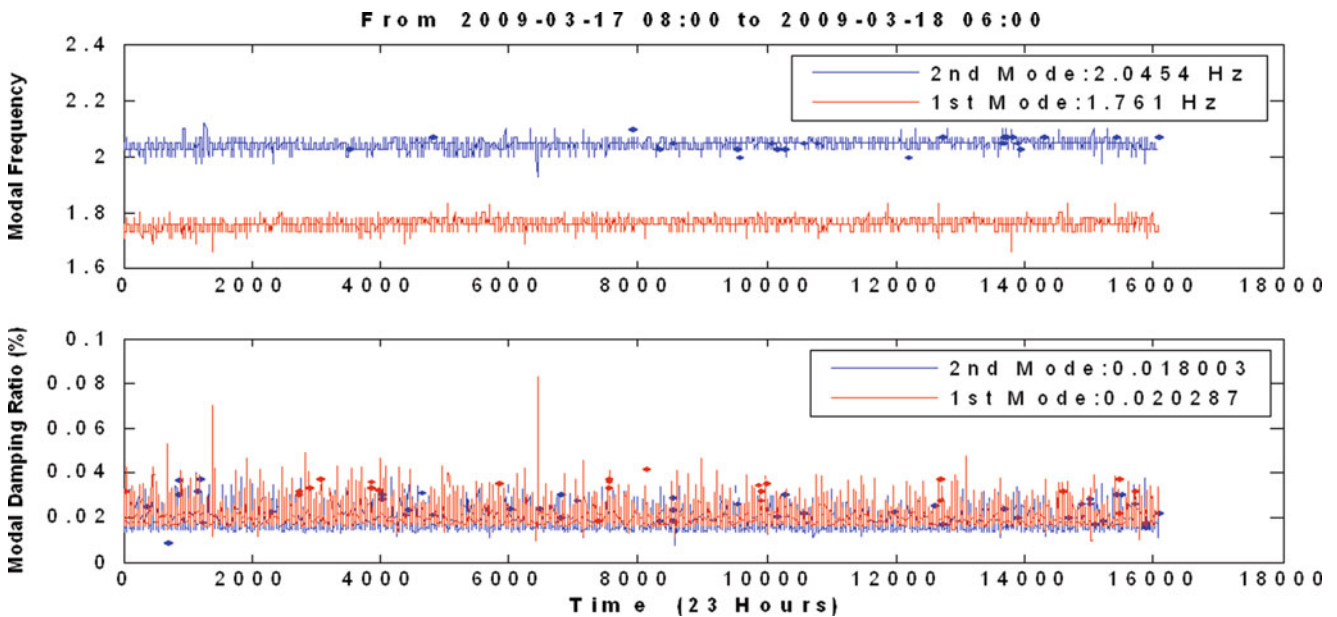

Fig. 2.8 Result of 23-h processing shows the variation of predominant modal frequencies and damping ratios of the structure with respect to time (23 h)

by a factor of at least two in both East-west and in North-south directions when compared to that of the amplitudes at the top of main columns. Modal frequencies can be clearly seen from the FAS of the recorded ambient data. Some of the modal frequencies of the structure are estimated as 1.7, 2.26, and 2.75 Hz in North-south direction whereas 2.02 and 2.47 Hz in East-west direction, respectively.

The result of the modal identification shows that the mean value of the first two predominant modal frequencies, as shown in Fig. 2.8, for measurement location 1 during 23 h duration are 1.761 and 2.045 Hz in East-west and North-south directions, respectively. Time variations of the first two predominant modal frequencies do not show any significant variations for the measurement location number 1 as seen in Fig. 2.8. Nevertheless, these results could not be correlated with respect to temperature and wind velocity because those data were not measured during the ambient vibration. The modal damping ratios of the first two modes are very small. It is well known that the damping in structure is proportional to the amplitude of the vibration. Since the amplitudes of the vibrations (real-time acceleration data) during the ambient vibration are not large enough, the damping in the structure is not considerably large.

2.7 Conclusion

For structural safety, it is important to detect and locate damage in structures as soon as they occur. SHM provides the best tools for this. Accurate estimation of dynamic properties of structures is the critical component of SHM. Since the SHM data flow in real time, the data analysis should also be done in real time. This study presents some tools and techniques for real-time data analysis. It includes on-line data processing methods and real-time modal identification tools. A MATLAB-based software is developed for this purpose. The developed software, ***REC_MIDS***, has been tested using the data from the SHM system at the Hagia Sophia Museum in Istanbul, Turkey. It has been proven that the model identification can be done with significant accuracy by ***REC_MIDS***. More detail about the software can be found in [4] on www.koeri.boun.edu.tr.

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