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Methodology of Instrumentation for Structural Health Monitoring of Buildings

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ABSTRACT: By the start of 21st century, the technological developments caused an evolution both at number and scope of Structural Health Monitoring applications. This development also paved the way for structural health monitoring to be one of the most realistic techniques for studying the dynamic building behavior, moving the civil engineering laboratories to real-world, and monitoring the health of a building in real-time. Meanwhile, many instrumentation possibilities and combinations entered into the picture which forces the researchers to choose the best fitting methodology.

In this study, different recent instrumentation possibilities in view of dynamic identification and modal analysis are covered in detail. Sensor selection, locations, digitizers, wireless/cabled solutions, wireless GPS synchronization, remote/ real-time monitoring, and software requirements are all included to this study. Ambient/forced vibration testing techniques are also covered. Methodologies and different installation architectures are compared. This forms a guideline for selection of appropriate SHM.

1 INTRODUCTION AND SCOPE

Every civil engineering structure has a certain lifetime. Engineering science intends to find and apply the most suitable and economical solution. At the end, the structure will fail either due to an excessive loading (i.e. earthquake, flood, explosion, deep excavation etc.) or repeated loading (fatigue) or the end of the operational life.

While approaching to this end, one of the following options will be chosen: (i) Either demolishing the structure controllably before the end of life without certain information, (ii) or let the structure to choose to time that it will fail itself, (iii) or monitoring the changes at the structure, trying to guess the time to failure and processing to perform repair and strengthening or demolishing it at the correct time with enough information and data.

First choice results in a big economic loss, second results in a bigger economic loss and even loss of life. Third one produces the most economical solution, prevents loss of life, and named as Structural Health Monitoring. Scope of this study consists of the instrumentation methods, devices, sensors, electronic systems, software and application practices used in structural health monitoring especially for buildings among a wide range of civil engineering structures.

Importance of seismic instrumentation increases even more at severe earthquake regions. Çelebi(2002) emphasizes the importance and positive contribution of seismic monitoring and accelerometer based structural health monitoring applications on buildings, describes the methods and recommends common use of seismic instrumentation on federal buildings in the report prepared for USGS(US Geological Survey). It has been stressed that the information that will be collected as a result of these monitoring studies will form a unique database of knowledge for the practice of earthquake resistant design.

Real-time structural health monitoring is one of the most recent technologies which produce unique results. Structural health monitoring has been used for buildings since 20th century. However, by the start of 21st century, health monitoring became more reachable at lower costs due to technological developments, and began to spread out rapidly. There are descriptions and directions about seismic instrumentation and application of accelerometers at high-rise buildings both at San Francisco Building Code(2014) and Los Angeles Tall Buildings Structural Design Council Consensus Document(2008).

1.1 Dynamic Identification

Structural health monitoring can be described as continuous or periodical monitoring and analysis of important identifying parameters of a structure. Although some static parameters like fracture, strain, tilt, etc. can be included into these parameters, primarily a dynamic identification is targeted. In general by the help of special accelerometers installed, it is possible to solve the dynamic behavior of a structure in real time which is considered as an identifying natural character of this structure. Natural frequency, damping ratios, modal frequencies, mod shapes, inter-storey drift ratios are all included in this analysis. Modal analysis is used in dynamic identification of structure.

1.2 Types of Modal Analysis (Input-Output / Output Only- Operational Modal Analysis)

It is possible to carry out real dynamic analysis of structures by experimental methods, using modal analysis techniques. These modal analysis techniques can be performed in 2 different ways. First, is the Input-Output technique, exciting the structure by applying defined and strong vibrations on the structure. Second is the operational modal analysis, relatively a newer technique which is merely based on the analysis of the output. Álvaro Cunha et al (2006) investigated in detail, the evolution of dynamic identification and structural health monitoring studies from input-output techniques towards operational modal analysis intensively today.

1.2.1 Ambient Vibration Testing and Operational Modal Analysis

Conventional modal analysis is carried out using known inputs and measured reactions. However, it is hard, costly and risky to try to apply known considerable forces to civil engineering structures. For this reason, operational modal analysis techniques which are quite practical and effective, are preferred especially for civil engineering structures. The theory of operational modal analysis is summarized at this section without going into the details of the mathematical model. Operational modal analysis is also called as ambient vibration testing as only the measurement of reactions are targeted under little vibrations. In this way it is possible to stay in the operational systematic of the structure and there is no need to externally force it. (Figure 1) On the other hand an important handicap should be overcome in this technique. Measuring and differentiating ultra low amplitude vibrations and oscillations under ambient conditions. Ultra low-noise and high precision accelerometers are required for being able to measure and acquire this micro-g level vibrations especially on buildings.

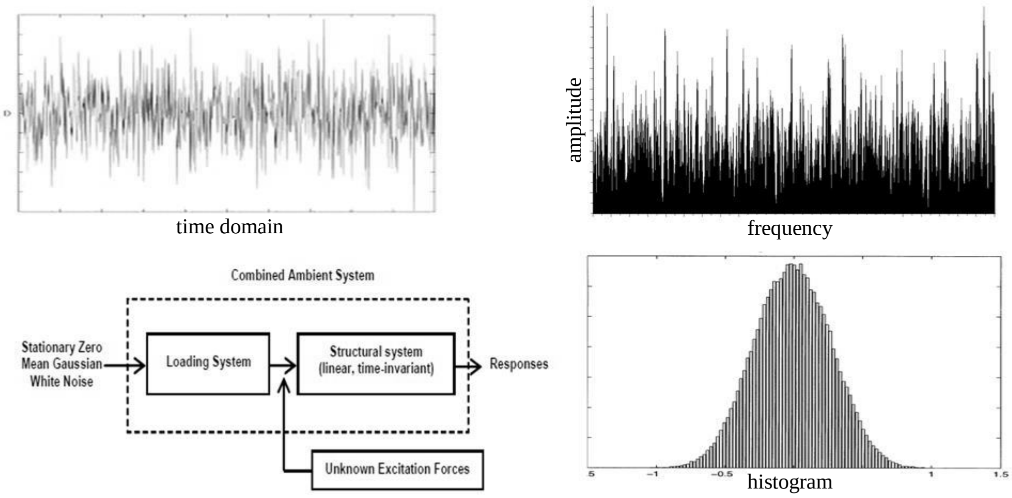

Figure 1. White Noise- Time/Frequency domain, histogram, Combined Ambient System concept.

After the necessary data is acquired, modal analysis stage begins. At this stage, besides simple techniques such as peak picking in frequency domain, more advanced techniques are proposed both in frequency and time domain. Frequency Domain Decomposition-FDD (Brincker et al 2001) in frequency domain and Stochastic Subspace Identification(SSI) (Peeters et al, 1999) in time domain are two of the most preferred techniques.

1.2.2 Input-Output Modal Analysis

Before technology and measurement precision reached current level, a relatively stronger force excitation is generally needed on buildings in order to get meaningful and measurable vibrations at such rigidity levels. This technique is called as forced vibration testing and carried out by placing a vibration exciter called eccentric mass shaker at certain level of a building. (Figure 2) Today it is still used for especially identifying the damping ratios more accurately.

Figure 2. TESTBOXTM-SHAKER Eccentric Mass Shaker in “Earthquake Performance Tests on Full Scale Existing Buildings” project conducted by Istanbul Technical University Civil Engineering Department.

2 APPLICATION OF REAL-TIME STRUCTURAL HEALTH MONITORING

Today as a result of technological developments, it is possible to perform structural health monitoring studies in real-time. In this way when a structure encounters an earthquake or a different weakening shock, in less than an hour it is possible to get the preliminary information of the change at the critical parameters which may be a sign of the change at the structural system. This makes structural health monitoring an important decision support system. However, in order decision makers to reach a more precise result, it should be supported by post analysis studies of the experts. Nevertheless, this data gathered from the real world under ambient vibration conditions provides a unique tool.

2.1 *Sensor Locations and Parameters to be Monitored*

Sensor locations is of vital importance in right structural health monitoring. Çelebi(2002) explained how the sensors should be located and the reasons in detail. Sensor location suggestions are presented at Figure-3. The older methodology in UBC(Uniform Building Code) is presented in (a) part of Figure 3 and states at least 3 tri-axial sensors should be located on the top, bottom and middle floor of a building. However this method is enhanced later as it is not accepted to be effective enough.

First of all, sensor locations are directly related to the parameters to be monitored. Basically, the parameters that should be monitored can be listed as: translational lateral x and y direction modes, torsional modes(about z axis), rigid rocking motion of the building on the soil(about x and y axis), soil-structure interaction or seismic isolator performance, top displacement, storey displacements and inter-storey drift ratios.

Even though according to the older methodology placing triaxial accelerometers to certain floors seem to be more practical for planning and installation, taking advantage of both uni, bi and triaxial accelerometers became a necessity in order to monitor more meaningful parameters.

2.2 *System Components*

The components of a structural health monitoring system that will be used at a building can be listed as follows: (i) Dynamic sensors (accelerometers – 1/2/3 axial), (ii) Static sensors (if needed tilt meters, fracture gauges, strain gauges, environmental sensors such as temperature, wind, humidity sensors), (iii) Data Acquisition System(Digitizer), (iv)analog sensor cables(if needed), (v)Complementary equipment and network devices(if needed, local computer, wired or wireless Ethernet network, ADSL/3G modem-for remote monitoring), (vi) Software (real-time data acquisition, monitoring, recording, analysis software and post-analysis software)

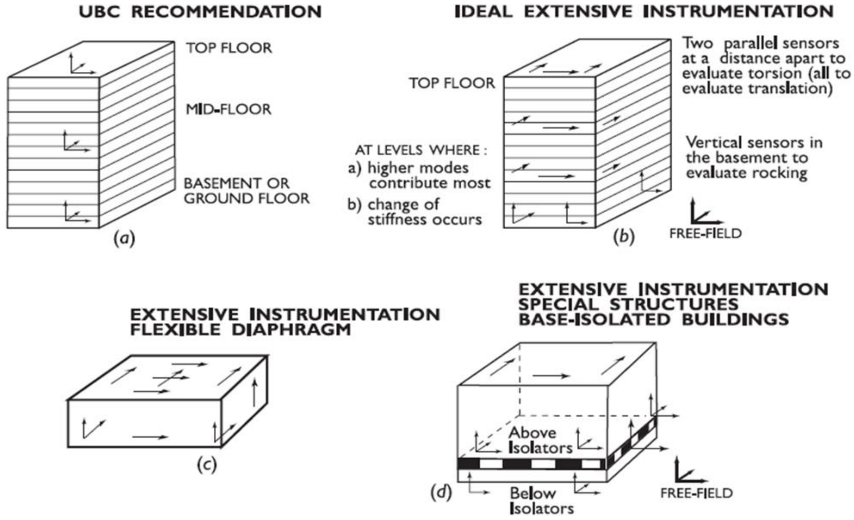

Figure 3. Sensor locations on buildings, taken from the report for which Çelebi(2002) prepared for USGS.

3 SELECTION OF THE RIGHT INSTRUMENTS FOR STRUCTURAL HEALTH MONITORING OF BUILDINGS

3.1 *Sensors*

As the main objective of structural health monitoring is dynamic identification and modal analysis, basically the real-time displacements are needed to be measured on a building. However, as it is very hard to measure the displacements without having a stationery reference, accelerometers are generally preferred which offer much more flexibility. In modal analysis studies, it is possible to get the displacements by double integrating the acceleration signal. The biggest challenge at this method arises from an undefined electronic noise in the acceleration signal, mainly coming from the sensor. The data acquired from any accelerometer involves some quantity of inevitable electronic noise inside. After applying various signal cleaning techniques, generally a band-pass digital filter is applied in order to get rid of this noise.

However, the most critical part is the selection of ultra-low noise, best-fitting sensor above all these. Since buildings are much more rigid when compared to other civil engineering structures in general, in order to reach meaningful data, low noise sensors should be used having a noise density figure less than at most 1 micro-g/Root-Hz or even better less than 300 nano-g/Root-Hz. The important parameters to be considered in sensor selection is presented in Table-1.

Table 1. Key specification that should be considered at accelerometer selection.

Specification	**Values**
Range (g)	±0,5 – ±3
RMS Noise Density (μg/√Hz)	<1 – <0.3 for better performance
Dynamic Range (dB)	110 – 120
Frequency Range (Hz)	0 or 0.1- 100
Sensor Type and Input Voltage	Compatible with the Digitizer
Shift with Temperture	In between tolerable range

Sensor type is also quite important apart from the above specifications. 4 different types can be considered at this stage.

1) Conventional Force Balance Accelerometers(FBA)- (Force feedback, for measuring long period signals)
2) MEMS Accelerometers- (Force feedback, best performance in 0.1-400 Hz, currently there is no acceptable noise level analog output sensor after Si-Flex^{TM} sensors became obsolete at year 2014)
3) FBA-MET Accelerometers- Force balance/ Force feedback (best performance for 0.1-120 Hz)
4) Piezo accelerometers- ICP/IEPE (for high frequency measurement especially in mechanical engineering)

Additionally a cost-performance comparison chart is presented in Figure-4.

3.2 *Data Acquisition System (Digitizer)*

Selection of the data acquisition system is as important as the selection of the sensor. Data acquisition system can also be referred as digitizer. Fundamental functions of the digitizer are converting the analog data coming from different sensors simultaneously into digital then recording and transferring it to computer or to digital communication lines. Some basic terms have to be known before the selection of this critical component.

3.2.1 Resolution –Effective Resolution (ENOB)– Signal to Noise Ratio(SNR) –Dynamic Range(DR)

First of these critical parameters is measurement capability and precision. Precision is defined with terms like resolution, effective resolution, and signal to noise or dynamic range. Digitizers used in structural health monitoring of buildings should be 24-bit resolution. However, 24-bit resolution does not always mean all 24-bits are effective. Effective resolution is generally less than that. What researcher should really be concerned about is the effective resolution. Effective resolution is generally defined in terms of ENOB, which means effective number of bits. ENOB is defined in number of bits, in other word, how many bits out of 24 is meaningful.

Dynamic range and signal to noise ratio are closer terms. Signal to noise ratio is the ratio of highest measurable signal to the inevitable electronic noise. Under certain condition both terms can be accepted the same. Higher SNR and DR values corresponds to wider, more capable and more precise measurement. There is a relation between SNR and ENOB(1). For example the resolution of a 116 dB – SNR device is 19-bits. 120-130 dB digitizers are generally preferred at structural health monitoring studies, however this value is not enough to define the performance. In fact, SNR may change according to sampling speed for a certain device. Therefore it is important check the sampling rate at which this SNR value is given.

$$SNR(dB) = (6.02 \times ENOB) + 1.76 \tag{1}$$
$$f_{os} = 4^{w} \cdot f_s \tag{2}$$

At this stage, oversampling and downsampling techniques come into the picture. When data is sampled at a higher rate and then downsampled, dynamic range increases. For every w bit of increase in resolution, the signal must be oversampled 4^{w} times the original sampling rate(2), where w-desired increase in ENOB, f_{os}-oversampling rate, f_s-original sampling rate.

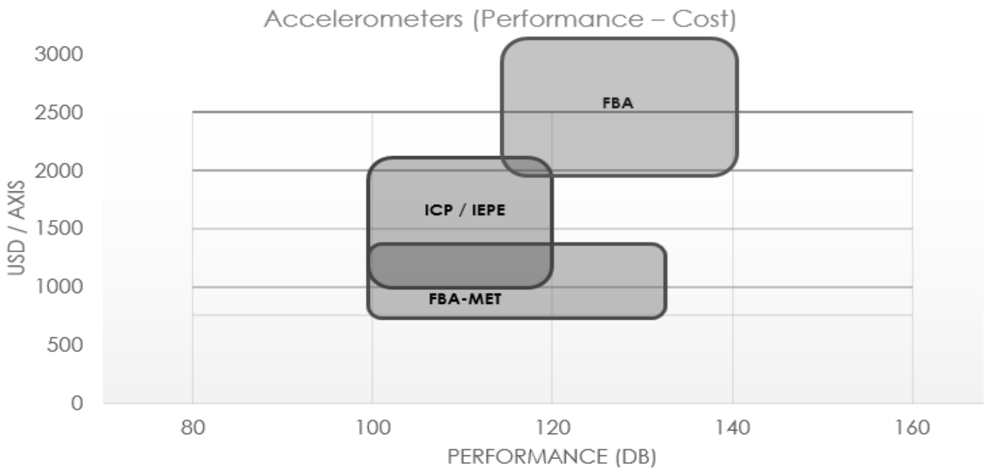

Figure 4. Cost-performance comparison chart according to sensor types

3.2.2 Selection of the Data Acquisition System (Digitizer)

Taking the above terms into consideration, 3 important points for selection of the digitizer can be summarized as follows: (i) Digitizer's performance should be better than sensor's performance, (ii) Digitizer should be simultaneous sampling, (iii) Digitizer should have analog anti-aliasing filters. When it is considered that sensors in structural health monitoring of buildings will be generally 110-120 dB performance at 0-120 Hz frequency band, as given in Table-1, it should be logical to prefer 120-130 dB performance digitizers at about 200 Hz sampling speed. Simultaneous sampling is essential for modal analysis. Generally about 1 micro-second synchronization level is acceptable. Anti-aliasing filters prevent the high and very-high frequency signals to create false and virtual effects at lower sampling rates. TESTBOX™/e-QUAKE™ series devices are developed according to the above specifications for structural health monitoring by Teknik Destek Grubu. (Figure-5)

3.3 GPS Synchronization

As stated above there should be a method for synchronizing the digitizers at different locations and so that acquiring the data suitable for modal analysis. One effective way of attaining simultaneous sampling is using GPS modules. In this way, each and every independent digitizer performs the analog to digital conversion operation synchronized to each other at 1 micro-second resolution of UTC. This solution is used in TESTBOX™/e-QUAKE™ series digitizers developed by Teknik Destek Grubu. The critical point which differentiates this solution and carries the synchronization at best performance is analog-digital convertors are directly driven by the synchronized timing signal from the satellite.

Figure 5. TESTBOX™/e-QUAKE™ series instruments developed for structural health monitoring.

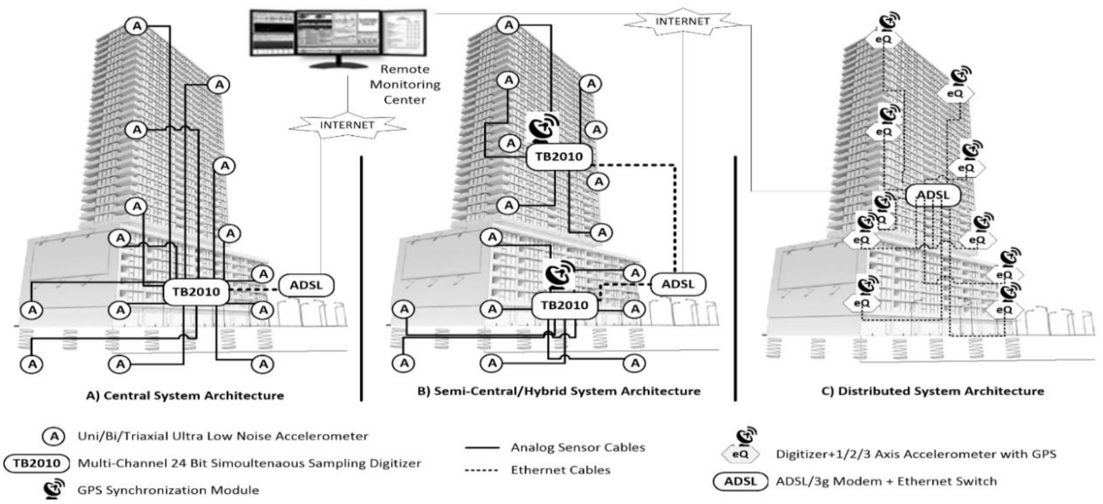

Figure 6. Three different architectures for installing instruments and sensors on buildings.

3.4 Different Architectures for Structural Health Monitoring

Central systems (Figure 6-a) and hybrid systems (Figure 6-b) are generally preferred for permanent installations and 7/24 continuous real-time monitoring. Although it is harder to install analog sensor cables, it is much more reliable for undisturbed operation. Distributed systems (Figure 6-c) basically depend on integrated sensor and digitizer, which are synchronized by GPS and transfer data over ethernet. They are preferred for temporary measurements or for buildings which it is hard to install analog sensor cables.

4 CONCLUSION

In this study current instrumentation possibilities are evaluated in detail. Especially by the start of 21st century, number of structural health monitoring applications for buildings against earthquake and other risks rapidly increased due to developments in the instruments, analysis methods and decreasing costs. Operational modal analysis, and output-only dynamic identification under ambient vibration form the fundamental of the current structural health monitoring studies of buildings. As the computer power and communication bandwidth increased, real-time structural health monitoring became possible with the support of analysis software. Today real-time health monitoring provides a unique decision support system for engineers, decision makers and experts.

Sensor and digitizer selection are the two most critical points for structural heath monitoring. New approaches are accepted for locating the sensors. Vibration monitoring sensors evolved from tri-axial accelerometers to uniaxial and biaxial accelerometers which offer more flexibility. Accelerometers in 0.1-120 Hz frequency band, and having a internal noise density <1-0.3 micro-g/Root-Hz are needed for determining the modal frequencies of buildings under ambient vibration. Digitizers should be 24-bit resolution, at least 120-130 dB dynamic range, simultaneous sampling and include analog anti-aliasing filters. Synchronization should be about 1 micro-second level. GPS based synchronization is the most effective method when independent digitizers at different locations are needed to be synchronized. It is possible to install monitoring systems at central or distributed architectures with today's technology. Remote real-time monitoring is possible by the help of internet (ADSL/3G).

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