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# INSTRUMENTATION, SOFTWARE AND REPORTING PRACTICES FOR STRUCTURAL HEALTH MONITORING

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## ABSTRACT
Technological developments in instruments caused an evolution both at the number and the scope of the structural health monitoring applications for civil engineering structures. This developments also paved the way for structural health monitoring to be the unique realistic technique for studying the dynamic building behavior, today, moving the civil engineering laboratories to real-world. Taking precautions and preventing failures against severe earthquakes and other effects started to become possible by monitoring the integrity of the structure in real time. A number of instrumentation combinations entered into the picture forcing the researchers, consultants, building owners and authorities to choose the best fitting methodology. Building codes are being modified today, including the instrumentation and monitoring. This study covers different instrumentation approaches based on real-world application experiences including high-rise buildings, hospitals, and historical structures. In this study, dynamic monitoring with accelerometers under ambient vibration is discussed. Static monitoring with tilt sensors, crack gauges, inclinometers are covered as well. Selection of the sensors, digitizers, sensor locations and installation architectures are also presented. Complementary real-time and post analysis software requirements, which acts as a decision support tool, leading the engineers to interpret the data into solid decisions and conclusions are also included to this study.

## KEYWORDS
Structural Health Monitoring, Ambient Vibration, Dynamic Identification, Modal Analysis, Force-Balance Accelerometer

## 1. INTRODUCTION

Every civil engineering structure has an estimated lifetime. Engineering science intends to find and apply the most suitable and economical solution. However, due to an excessive loading (i.e. earthquake, flood, explosion, deep excavation etc.) or repeated loading (fatigue) or aging, the structure can be damaged or become unsafe. Evaluating the risks on the structure to perform repair and strengthening or evacuating and demolishing the structure at the correct time with enough information and data is quite important. The process of mostly real-time monitoring as well as reporting the behavior and probable damage condition of civil engineering structures under earthquake or other severe damaging effects with the help of the installed sensors is named as Structural Health Monitoring(will be abbreviated as SHM). This leads to a decision support system about the safety of the building. 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 and among a wide range of civil engineering structures. 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). Guidelines and Implementing Rules on Earthquake Recording Instrumentation for Buildings (2015) defines the Structural Health Monitoring standards for high-rise buildings (above 50 meters) in Philippines. Strong Motion Instrumentation of buildings in New Zealand is summarized by Deam and Cousins (2002). Section 13.8 of Turkish National Earthquake Building Code published by Disaster Management Authority of Turkey (AFAD) brings the obligation to health monitoring of high-rise buildings above 105 meters.

## 1.1 Types of Structures to be Monitored

Nearly all types of civil engineering structures can be monitored by SHM solutions. However, the motivation to monitor, planning and philosophy of the instrumentation can change from structure to structure. This section classifies the structures, monitoring options and ideas according to needs.

### 1.1.1 High-Rise Buildings

High-rise buildings are one of the most vulnerable structures to the earthquakes. Due the increasing population on the earth high-rise buildings are being constructed rapidly. Cities located at earthquake zones are no exception. Many crowded cities are located on major earthquake zones. Although the building codes take a number of precautions to increase the earthquake resistance and the reliability of the high-rise buildings, unexpected failures have been observed even in last 2 decades, during major earthquakes, or less intense earthquakes, afterwards. Recorded responses of 2 high-rise buildings during the Loma Prieta earthquake were analyzed by Şafak and Çelebi(1991). When high-rise structures are monitored using accelerometers, modal analysis and finite element model update can be carried out, modal frequencies can be monitored for life-time. Any sudden or unexpected change in the modal frequencies after a severe earthquake will warn the decision makers to take precautions. After an earthquake, the damaged buildings can be detected to a certain probability within hours. Soyoz et al. (2010) studied the structural reliability estimation with vibration-based identified parameters. Furthermore the data gathered from these buildings will form the most realistic database to evaluate the effectiveness of the building codes, for next revisions.

### 1.1.2 Historical Structures

Historical structures usually miss the detailed engineering projects at the time of construction. Certain doubts can arise about the structural integrity when cracks or other signs of pre-failure are observed on the structure. The structure may be exposed to close earthquakes, land-slides or fatigue. Strengthening and restoration work is usually required. Construction work in order to rehabilitate the structures involves machines producing high levels of forced vibrations on the structure. Additionally some components of the structure may need to be demolished and re-constructed. Excavations may occur around the structure. All of this construction work temporarily multiplies the failure risk. Real-time monitoring of during construction activities will minimize the sudden failure risk. Crack, tilt, settlement and soil movement monitoring are most common options. Among these, the methodology of settlement monitoring with tiltmeters was developed by TDG and used at the subsequent projects. In addition, operational modal analysis of the structure before and after the strengthening would form a quantitative comparison base to evaluate the strengthening. Ultralow noise accelerometers and 24-bit resolution digitizers have to be used for this purpose. Few hours of synchronized acceleration data will be sufficient to carry out a dynamic identification by evaluating modal frequencies, mode shapes and damping ratios, before and after.

### 1.1.3 Bridges and Tunnels

Among all civil engineering structures, bridges & tunnels are two of the leading types that should be monitored by sensors due to their critical fatigue and creep behavior. Especially natural events such as earthquakes, floods, storms increase the importance of monitoring. Different types of instruments and sensors should be combined in health monitoring for railway/highway bridges, tunnels, tube crossings and subways. Although customization has a big importance in a specific SHM instrumentation project of a bridge or tunnel,accelerometers, strain/crack gauges, tilt, environmental sensors are the most preferred ones.

### 1.1.4 Hospitals with Seismic Isolators

Hospitals are special type of buildings that have to function 24/7 and 365 days. Uninterrupted functionality is even more important after a major earthquake. Vibration levels are critical for sensitive medical equipment that can easily be affected by high level of vibrations and surgery rooms. For all these reasons recent hospitals being constructed in seismic zones are isolated by seismic dampeners installed under the foundation. However, proper functioning of seismic isolator afterwards is critical. Therefore the structure should be instrumented by accelerometers below and above the isolators, to monitor the performance of the isolators. In section 3, case studies including the real-time SHM applications for 5 city hospitals in this aspect are described in more detail.

## 1.2 Static and Dynamic Monitoring

Structural Health Monitoring can be carried out in a more static way (logging data, in less frequent terms like minute/hour or day based), more dynamic way (including vibration analysis by accelerometers) or a combination of both. The period of the measurements is a very basic parameter in deciding the correct monitoring solution, and mostly determined by the (i) motivation behind the monitoring and (ii) the characteristics of the sensors. In dynamic monitoring, accelerometers are the main sensors. The data is generally logged at 100-200 samples per second per channel. All the accelerometer channels must fully synchronized up to 1 micro-second resolution. On the other hand, tiltmeters, crack-gauges, inclinometers are the main actors for static monitoring. In these solutions it also possible to make settlement analysis with tilt sensors, with a special technique developed by TDG, and well experienced on 4 monitoring projects involving historical structures. Data logging interval changes from minutes to hours generally.

## 1.3 Modal Analysis under Ambient Vibration

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. Conventional modal analysis is carried out using known inputs and measured reactions. However, it is hard, costly and risky 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 daily 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.

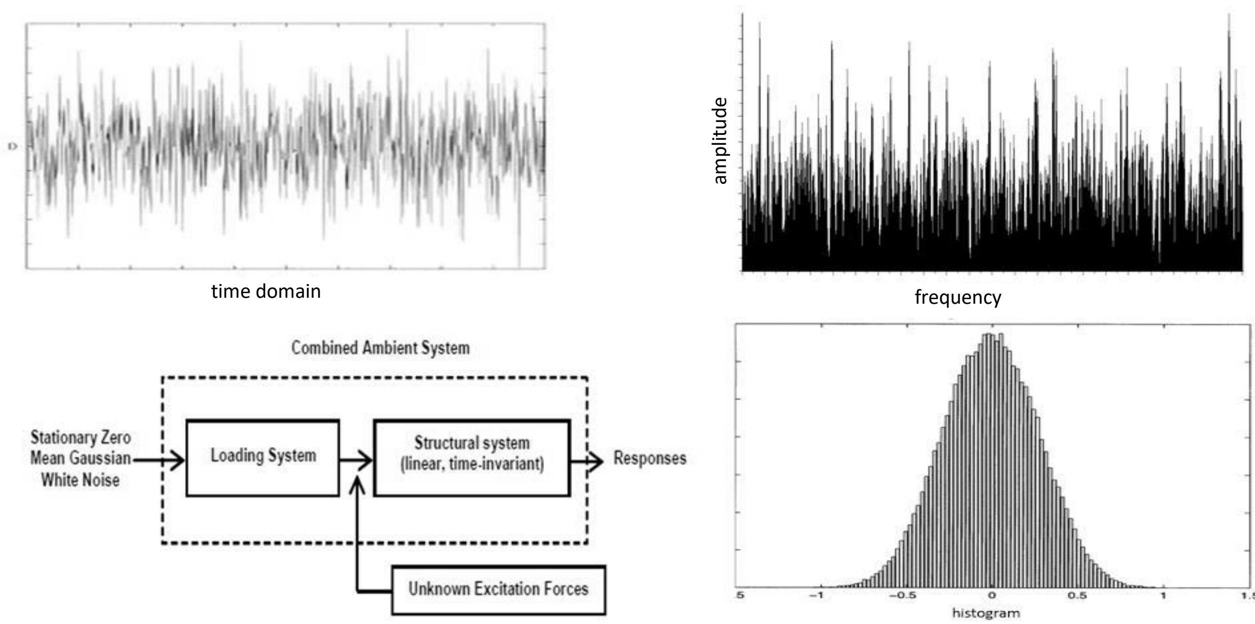


**Figure 1: White Noise-Time/Frequency domain, histogram, Combined Ambient System**

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.

## 2. APPROPRIATE SELECTION OF THE EQUIPMENT

Since SHM is a new and innovative technique, deciding the best fitting equipment can be confusing. An important number of monitoring projects fail because of the inappropriate instrument selection. Confusion is mostly caused because of the requirement to combine the different monitoring motivations/strategies and structure types with a bunch of different sensor technologies, resolution, sensitivity and precision requirements related to the measurement site, the distinguishable physical parameters to be reached at the end. The selection of the equipment should start with a solid proposal of the monitoring. This proposal should include "why this health monitoring project will be carried out", "which resulting parameters derived from the data will provide the adequate information to the decision maker", "the necessary minimum precision of the resulting data, considering the measurement site and the type of the structure". Only, afterwards it is possible to reach the minimum adequate resolution of the sensors which will lead to targeted derived/calculated data at the end. The resolution of the digitizer (which interprets the analog data coming from the sensors into digital quantitation) at least should be enough to support the precision of the sensors. Any sensor digitizer couple can be preferred as long as they together support the minimum precision of the data, fit to the environmental conditions, and fit to each other. Finally, the monitoring and reporting software options and data evaluation flowchart should be checked at the analysis and planning phase. An example of a proposal sentence can be “a high-rise building at the city center located at first degree earthquake zone will be monitored to check the structural integrity in real-time for life time. For this the dynamic parameters will be calculated and modal analysis will be carried out. The Fast Fourier Transform (FFT) and Power Spectral Density (PSD) of the gathered vibration data must be in adequate precision to let the decision makers to differentiate the modal frequencies among them.” This will lead to dynamic monitoring and use of accelerometers. However as this a high-rise building and the measurements will be taken under ambient vibration, the accelerometers should be ultra-sensitive (in enough precision and dynamic range) to support this. Best fitting digitizer will be a 24-Bit digitizer for this type of accelerometers with enough dynamic range. As modal analysis is targeted, the digitizer must able to perform simultaneous sampling for all input channels. Moreover, if there is more than one digitizer they must be able to synchronize in between. The precision of the time synchronization must at micro-second level to allow modal analysis. GPS time synchronization can be used for this among other possible methods. Finally the software requirements can be decided as, data logging, monitoring software that can transfer the data to a remote location. A 7/24 based server should store the data and should be able to make real-time trigger level analysis to warn the decision makers automatically. Reporting should be carried out periodically or event based, such as after a medium-magnitude earthquake. A post analysis software should be included at the package for modal analysis and dynamic identification. Report should include certain parameters.

The above is a well-defined SHM project definition. When the structure type in the above definition is changed from high-rise building to a bridge, the accelerometer precision that can differentiate the ambient vibrations may change according to the type of the bridge. As the bridge may be less rigid, the amplitude of the acceleration response can be higher, which may allow to a less precise accelerometer. Sometimes it would be a good practice to test the ambient vibration amplitude level and measurement adequacy at the site, prior to the project. A completely different SHM project can be targeted related to a historical structure. In this case the most important parameters to be monitored can be tilt of the building and crack openings. This will lead the project into a quasi-static monitoring mostly. Then the precision of tiltmeters should be decided.

### 2.1 Accelerometers (Enough vs. More than Enough or Not Enough)

For dynamic monitoring, vibration, frequency and modal analysis under ambient vibration the most critical component of the system is the accelerometer. Taking sufficient selection parameters into consideration will dramatically affect the project budget. Under-qualified selection of the accelerometers will cause almost no interpretable data at the end. Another risk will be faced on the opposite side, with over-qualified selection of the accelerometers, which will directly increase the project budget considerably, generally resulting into insufficient number of sensors or totally unaffordable solution at the end.

#### 2.1.1 Results of the Conducted Ambient Vibration Tests

An important comparison test was conducted in TDG Scientific Facilities, Test & Measurement Laboratory, in 2016. This building is a 4 story concrete building including the basement floor. The test took place on the 2nd floor directly on the concrete area next to a column. The test was planned as an ambient vibration test which aim to log data over-night, when the vibration was at the minimum level. TESTBOX2010-4 channel digitizer was used. This digitizer has 4 24-bit, simultaneous sampling, input channels, 137dB dynamic range. 3 sensors compared: ($2^{nd}$ channel left empty.)
$1^{st}$ channel: R-Sensors-MTSS1031A, 130 dB dynamic range, 130 ng/√Hz noise density at 10 Hz, manufactured with force-balance based, Molecular Electronic Transducer (MET) Technology.
$3^{rd}$ channel: Silicon Designs SD1521, 100 dB MEMS technology. 5 μg/√Hz noise density.
$4^{th}$ channel: Colibrys-SiFlex SF1500A, 120 dB force-balance based, MEMS, 300 ng/√Hz. (obsolete now)
Test results showed that, while R-Sensors MTSS1031(green) and Colibrys SF1500A(red) successfully senses the modal frequencies under ambient vibration, base noise level of the SD1521(blue) was far over the building acceleration response level, not enough to differentiate the modal frequencies. (Figure 2)

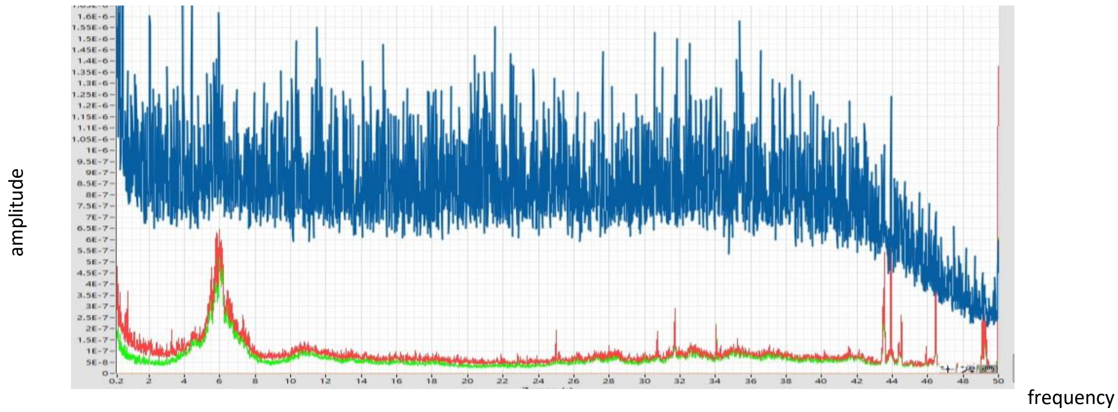


**Figure 2: FFT Building Response under Ambient Vibration / 3 Accelerometers Compared**

### 2.1.2 Precision (Dynamic Range – Noise Density)

Most confusions about the precision of the accelerometers arise from the conflicting figures on the data sheets prepared by the manufacturers. Some data sheets present dynamic ranges, while the others give noise density figures. Even the dynamic range of the same sensor models may differ in different data sheet versions of the same sensor. Furthermore, the noise density for a specific sensor can be different for different frequency ranges. For example a very high dynamic range (DR) can be observed for 0.1- 1 Hz, and the DR is considerably lower for 1-10 Hz or for 10-100 Hz. Manufacturers generally present the highest DR they observe. Although extremely high figures (more than 150 dB) exist on some parts of the data sheet, this does not represent overall sensing performance. The positive conclusion among all these conflicts is that, an accelerometer over 120 dB overall DR successfully detects the building response under ambient vibration. DR above 120-130 dB, while dramatically increasing the sensor costs, is usually more than enough for buildings. For more flexible structures like bridges, there are well examples that even 100 dB sensors can lead to meaningful data. But, for buildings, less than 120 dB accelerometers would be useless.

### 2.1.3 Measurement Range

In general what is expected from an accelerometer used in SHM under ambient vibration, is the ability to differentiate the modal frequencies (mentioned in detail above) and at the same time to log the unclipped acceleration data during an earthquake. For this reason generally a range of ±2 g is preferred.

### 2.1.4 Frequency Response

Modal frequencies for a structure starts from 0.2-5 Hz and can go up to 50 Hz for higher degree modes. When the building is a high rise one (above 100 meters) the 1$^{st}$ mode can is generally below 1 Hz. For these reasons a frequency response of 0.1 Hz to 50 Hz (or 100 Hz) will be adequate for all cases.

### 2.1.5 Manufacturing Technology

Manufacturing technology is not a major parameter in sensor selection. Tests and data sheets show that accelerometers with different technologies can satisfy the major parameters for ambient vibration analysis. Conventional force-balance technique is the oldest manufacturing method. Even this technique has capacitive and inductive sub-solutions. Alternately, Molecular Electronic Transducer (MET) based force balance, piezo-electronic and MEMS based force balance technologies exist. As far as the literature survey conducted by the writers, no MEMS based force-balance sensor on the market can meet the above requirements at the moment. Other technologies have reliable solutions for ambient vibration monitoring. Force-balance based MEMS sensor Colibrys SF1500A was a suitable model. The test described on section 2.1.1 also supports this information. This sensor is obsolete for now. However a MEMS based fitting solution produced in the past shows that future MEMS based solutions may also be possible, even not one of them exists at the moment. Additionally a cost-performance comparison chart is presented in Figure-3.

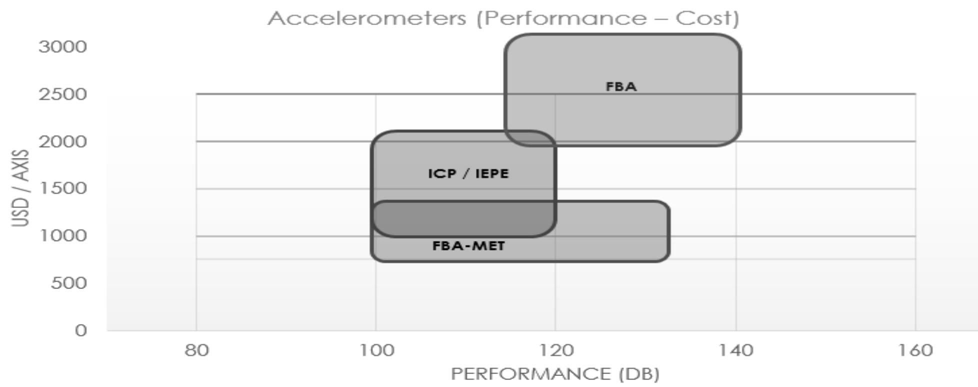


**Figure 3: Cost-Performance Comparison Chart according to Manufacturing Technology**

### 2.1.6 Summary of the Main Selection Criteria for SHM under Ambient Vibration

Table 1 presents the summary of the parameters that should be considered for accelerometer selection.

**Table 1: Accelerometer Selection Criteria for SHM under Ambient Vibration**

| Parameter | Appropriate Values |
|---|---|
| Precision (based on Dynamic Range) | 120 dB (min.) |
| Precision (based on Noise Density) | 300 ng/√Hz (max.) |
| Measurement Range | ±2 g |
| Frequency Response | 0.1-50Hz (or 100 Hz) |
| Manufacturing Technology | Conventional Force-Balance or MET or Piezo |

### 2.2 Digitizers

The digitizer is the component of the system that converts and interprets the analog data to the digital value that can be logged, monitored and analyzed by computers. Like the sensor itself the digitizer is the vital part of the system. Even the appropriate sensor is chosen, unsuitable digitizer selection will make the SHM system fail. For some parameters there are directly digital output sensors, meaning the analog to digital conversion completed inside. Even these sensors generally will need another digitizer-like component to organize the data and manage the complete system. The major issue with directly digital output sensors is the synchronization. If the SHM project requires modal analysis under ambient vibration generally analog sensors and simultaneous sampling digitizers should be used.

### 2.1.1 Resolution, Dynamic Range, SNR

The golden rule for the digitizer precision is to select it according to the highest sensor precision, in the SHM system. For SHM under ambient vibration, only 24-Bit digitizers will support the accelerometers discussed in the previous section. Resolution itself is not the only parameter. Dynamic range should also be considered. Different 24-bit digitizers generally have different dynamic ranges. If the accelerometer is selected as 130 dB the digitizer should be slightly above that. Usually digitizers between 130-140 dB would meet the requirements.

### 2.1.2 Sampling Frequency and Synchronization

As the maximum frequency response of the accelerometers will change between 50-100 Hz, digitizers with 100-200 Hz (100-200 samples per second per channel) should be used according to Nyquist theorem. Besides, for dynamic monitoring for operational modal analysis with accelerometers, time synchronization is the main issue. The synchronization can be classified as (i) the synchronization between the channels inside one multichannel digitizer and (ii) the synchronization between more than one digitizer. For the first one, a multi-channel digitizer must be chosen to be fully simultaneous sampling among its input channels. The second issue is generally solved with GPS based time synchronization. For this all the separated digitizers should have a GPS antenna and be able align their time base with respect to satellite time.

## 3. MONITORING PRACTICES

In last 5 years TDG completed a number of monitoring projects. In this section the scope of some of these projects are described briefly in order to contribute to the planning of future projects.

### 3.1 High-Rise Building Practices

Buildings 1,2: (Emaar Square Libadiye-Uskudar Istanbul) : Two Building with 30-31 Floors -Centralized Solution – For each building 8 channel digitizers, 1 triaxial and 5 units of uniaxial 130 dB force-balance accelerometers were installed on the building, with a minimum configuration. (Figure 4) Building 3: (Levent 199, Sisli/Istanbul) : 40 Floors, 161 meters, One of the highest buildings in Istanbul – Centralized Solution – 16 channel digitizer, 16 units of uniaxial 130 dB force-balance accelerometers were installed on the building. Buildings 4,5,6,7: (Zorlu Center, Besiktas Istanbul) : 4 Towers with 20 Floors, 161 meters– Centralized 16 channel digitizer, 16 units of uniaxial 130 dB force-balance accelerometers were installed on the building.

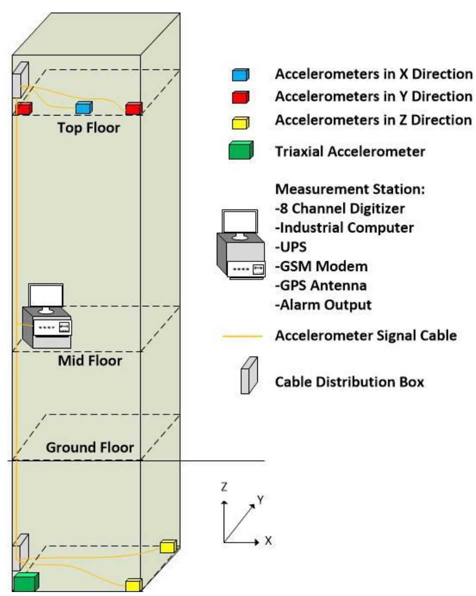


**Figure 4: System Layout for High-Rise Buildings 1, and 2**

### 3.2 Hospitals with Seismic Isolators

5 recently built City Hospitals of Turkey with seismic isolators (2 in Bursa, 1 in Eskisehir, 1 in Corum and 1 in Isparta) were instrumented with accelerometers in 2017 and 2018. (Figure 5) The Primary motivation behind was to monitor the performances of the seismic isolators. The general strategy was installing triaxial accelerometers below and above the isolators. In some hospitals another accelerometer was installed at the top floor. In this way it is possible to record the seismic acceleration on the ground,

then above the foundation of the building isolated by the dampeners, then the maximum acceleration of the building at the top.130 dB force balance based Molecular Electronic Transducer(MET) type accelerometers were used.

Bursa, Kestel　　Bursa, Şevket Yılmaz　　Corum　　Isparta

**Figure 5: Monitoring of City Hospitals with Seismic Isolators**

### 3.3 Historical Structures undergoing Strengthening and Restoration Work

2 most extensive monitoring projects were Galataport Project in Istanbul and Ulu Mosque in Sivas Divrigi. In both, a combination of static and dynamic monitoring were used. In Galataport 5 different buildings were instrumented. (106 tiltmeters, 21 accelerometers, 5 environmental, 13 units of multi-channel digitizers). Tiltmeters were used there for the first for settlement analysis. In Sivas Divrigi, Ulu Mosque project, tilt and crack monitoring were established, mainly. (8 tiltmeters, 25 crack meters, 11 accelerometers, 4 laser displacement sensors, 2 in wall humidity sensors, 6 wall surface temperature sensors, 6 environmental, 5 units of 16 channel digitizers) Force-balance 130 dB conventional and MET type accelerometers were installed in both projects. Another comprehensive project was in Ankara. Historical headquarters of Ziraat Bank, being one of the first structures of Republic of Turkey, was instrumented during a strengthening process. Settlement analysis with tiltmeters method was re-used in this project. (30 settlement, 26 tiltmeters, 8 crack, 2 environment, 6 inclinometers, 4 units of 16 Channel, 1 unit of 8 Channel Digitizers). Crack gauges were installed and inclinometers were used to monitor the soil movement. Clock Tower and Oshki Church in Erzurum, Selimiye Mosque in Edirne, Eyup Sultan Mosque in Istanbul were some of the other monitored historical structures by TDG. (Figure 6) For all projects the data was transferred to the Monitoring Center of TDG and backed up on the Cloud. Real-time analysis software was active to trigger alarms 7-24 to the project owners. A web-based frontend allowed the engineers to follow the data online. Monitoring systems were very effective ensuring the safe construction work all the project long.


**Figure 6: Extensive Monitoring Practices of Historical Structures**

## 4. CONCLUSION

Structural health monitoring today is the unique technique for studying the dynamic behavior of existing buildings, moving the civil engineering laboratories to real-world. Taking precautions and preventing failures against severe earthquakes and other effects started to become possible by monitoring the integrity of the structure in real time. Building codes are being modified today, including the instrumentation and monitoring. High-rise buildings, historical structures, hospitals with or without seismic isolators, bridges and tunnels are the main types of structures commonly being monitored in recent years. Both dynamic and static monitoring are being applied on these structures. From a number of current instrumentation possibilities selection of the accelerometers and digitizers are of vital importance. Among current accelerometer technologies (i) conventional, electro-mechanical force-balance (FBA), and (ii) molecular electronics (MET) type FBA accelerometers are the best-fitting and commonly used technologies. However any accelerometer having a dynamic range above 120 dB, noise density below 300 ng/√Hz, measurement range of at least ±2 g, and a frequency response at least in between 0.1-50Hz DC is adequate for operational modal analysis under ambient vibration. One main difficulty when selecting a sensor among the above parameters comes from the conflicting figures and the inconsistencies on the data sheets prepared by the manufacturers. For the digitizers, the specifications should be at least equal to or slightly higher than the accelerometers to record adequate data. A minimum of 24-bit resolution, 130 dB dynamic range with a sampling frequency of at least 200 Hz/channel is needed. One vital parameter for the digitizers is synchronization. Simultaneous sampling is required for operational modal analysis. When the digitizers have to be separated 1-10 micro-second timing resolution is required and this is generally reached by GPS time synchronization. Whenever possible, centralized or semi-centralized installation architectures (centralized multi-channel digitizers connected to the sensors with low-noise analogue cables) should be preferred. This preference will overcome the time synchronization issues and dramatically increase the long-term reliability of the system. There are a number of solid examples of high-rise buildings, hospitals and historical structures being currently monitored in Turkey using the methodologies described.

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