DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEVELOPING OFFLINE-TUNING TECHNIQUE TO BE USED FOR DAMAGE LEVEL ASSESSMENT OF A MODEL FRAME TYPE STRUCTURE AND APPLICATION OF SYSTEM IDENTIFICATION METHODS

by
Umut YÜCEL

July, 2014
İZMİR

DEVELOPING OFFLINE-TUNING TECHNIQUE TO BE USED FOR DAMAGE LEVEL ASSESSMENT OF A MODEL FRAME TYPE STRUCTURE AND APPLICATION OF SYSTEM IDENTIFICATION METHODS

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DEVELOPING OFFLINE-TUNING TECHNIQUE TO BE USED FOR DAMAGE LEVEL ASSESSMENT OF A MODEL FRAME TYPE STRUCTURE AND APPLICATION OF SYSTEM IDENTIFICATION METHODS"** completed by **UMUT YÜCEL** under supervision of **ASSOC. PROF. DR. ÖZGÜR ÖZÇELİK** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

Shake table experiments have important place and wide application area in structural engineering. These tests can be used to observe the behaviors of structural models under historical/artificial ground motions and obtain their modal parameters like natural vibration frequencies, mode shapes and damping ratios.

The main problem in shake table tests is the incompatibility between command and feedback signals. In other words, the shaker cannot track the command signal completely (trajectory tracking problem). Complexity of the components of shaker and shaker-specimen interaction can be shown as the main reasons of this problem. Solving the problem is very important for the health of the test data which represent the characteristic behaviors of the specimen. Offline Tuning Technique (OTT) is known as a technique which can solve this problem.

In this study, OTT and its effects on a shake table were examined and the solutions of the trajectory tracking problem were worked on. Parameters which have an effect on OTT were investigated to get better solutions. After, technique was examined when a three storey-one bay aluminum specimen was on the shaker. In this case, shaker-specimen interaction was observed and influences of this interaction on tracking trajectory ability of the shaker were investigated.

For system identification of the specimen, modal parameters were estimated by basic methods like Fourier Amplitude Spectra and Half-Power (Band-Width). To investigate the influences of OTT on system identification processes, modal parameter estimations were repeated before and after OTT and the results were compared.

Two diagonals were attached into first storey of the specimen to represent undamaged case. Damaged case was constituted by removing these diagonals. The constituted damage was studied to be estimated by Damage Index Method which is based on the changes in modal parameters. Finally, effects of OTT on damage estimation were examined and discussed.

Keywords: Shake table tests, trajectory tracking problem, Offline Tuning Technique, system identification, Fourier Amplitude Spectra Method, Half-Power (Band-Width) Method, Damage Index Method

ÇERÇEVE TÜRÜ MODEL BİR YAPININ HASAR DÜZEYLERİNİN BELİRLENMESİ İÇİN KULLANILACAK OFFLINE-TUNING TEKNİĞİNİN GELİŞTİRİLMESİ VE SİSTEM TANIMLAMA YÖNTEMLERİNİN UYGULANMASI

ÖZ

Sarsma tablası deneyleri yapı mühendisliğinde önemli bir yere ve geniş bir kullanım alanına sahiptir. Bu testler yapısal modellerin tarihi/sentetik yer hareketleri altındaki davranışlarının gözlenmesi ve doğal titreşim frekansları, mod şekilleri ve sönüm oranları gibi modal parametrelerinin eldesi amacıyla kullanılabilirler.

Sarsma tablası deneylerindeki temel problem, tablada oluşturulmak istenen komut sinyali ile tabla üzerinde oluşan geribildirim sinyali arasındaki uyuşmazlıktır. Başka bir deyişle, sarsma tablası komut sinyalini tam olarak takip edemez (yörünge takip problemi). Sarsıcıyı oluşturan bileşenlerin karmaşıklığı ve sarsıcı-numune etkileşimi bu problemin ana sebepleri olarak gösterilebilir. Problemin çözümü, numunenin karakteristik davranışını yansıtan verilerin sağlığı açısından çok önemlidir. Offline Tuning Tekniği (OTT) bu problemi çözebilen bir teknik olarak bilinir.

Bu çalışmada OTT ve tekniğin sarsma tablası üzerindeki etkileri incelenmiş ve yörünge takip probleminin çözümü üzerinde çalışılmıştır. Daha iyi sonuçlar elde edebilmek amacıyla OTT üzerinde etkili olan parametreler araştırılmıştır. Ardından, teknik üzerinde üç katlı-tek açıklıklı alüminyum numune bulunan sarsıcı durumunda incelenmiştir. Bu durumda, sarsıcı-numune etkileşimi gözlenmiş ve bu etkileşimin sarsıcının yörünge takip yeteneği üzerindeki etkileri araştırılmıştır.

Numunenin sistem tanımlaması için, modal parametreler Fourier Genlik Spectrumu ve Yarı-Güç (Band Genişliği) gibi basit yöntemlerle tahmin edilmiştir. OTT'nin sistem tanımlama yöntemleri üzerindeki etkinliğinin incelenebilmesi için, modal parametre tahminleri OTT'den önce ve sonra tekrarlanmış ve sonuçlar kıyaslanmıştır.

Hasarsız numune durumunu temsil etmek üzere numunenin birinci katına iki adet diyagonal yerleştirilmiştir. Hasarlı numune durumu da bu diyagonallerin çıkarılması ile oluşturulmuştur. Oluşturulan bu hasar, modal parametrelerdeki değişimleri esas alan Hasar İndeksi Yöntemi ile tahmin edilmeye çalışılmıştır. Son olarak, OTT'nin hasar tahmini üzerindeki etkinliği araştırılmış ve tartışılmıştır.

Anahtar kelimeler: Sarsma tablası deneyleri, yörünge takip problemi, Offline Tuning Tekniği, sistem tanımlama, Fourier Genlik Spektrumu Yöntemi, Yarı-Güç (Band-Genişliği) Yöntemi, Hasar İndeksi Yöntemi

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CHAPTER ONE
INTRODUCTION

1.1 Motivation and Objectives

Shake table experiments have an important place and a wide application area in mechanical and structural engineering. These kinds of tests can be used to test dynamic performances of the machinery components under dynamic loads and determine their dynamic properties in mechanical engineering. Besides, these tests can be used to observe the behaviors of structural models under historical or artificial ground motions and obtain their modal parameters like natural vibration frequencies, mode shapes and damping ratios in structural engineering. Also shake table tests can be used in education to make theoretical learning more understandable. Different types and sizes of shake tables are used in engineering experiments. Examples were given below in Figure 1.1.

In shake table tests, the main problem which is encountered mostly is the incompatibility between the command signal, which is wanted to be produced on the table, and the feedback signal, which occurs on table, in time and frequency domain. This means that shaker cannot track the command signal completely (trajectory tracking problem). Complexity of the components of the shaker and the shaker-specimen interaction can be shown as the main reasons of this problem.

Broad bandwidth signals (e.g., white noise signals, etc.) must be used to excite the all modes of specimens in shake table tests. But, because of the tracking problem, this situation cannot come true. So, solving the tracking problem becomes necessary and important for the health of the data which represent the characteristic behaviors of the specimen. Offline Tuning Technique (OTT) is known as a technique which can solve this problem.

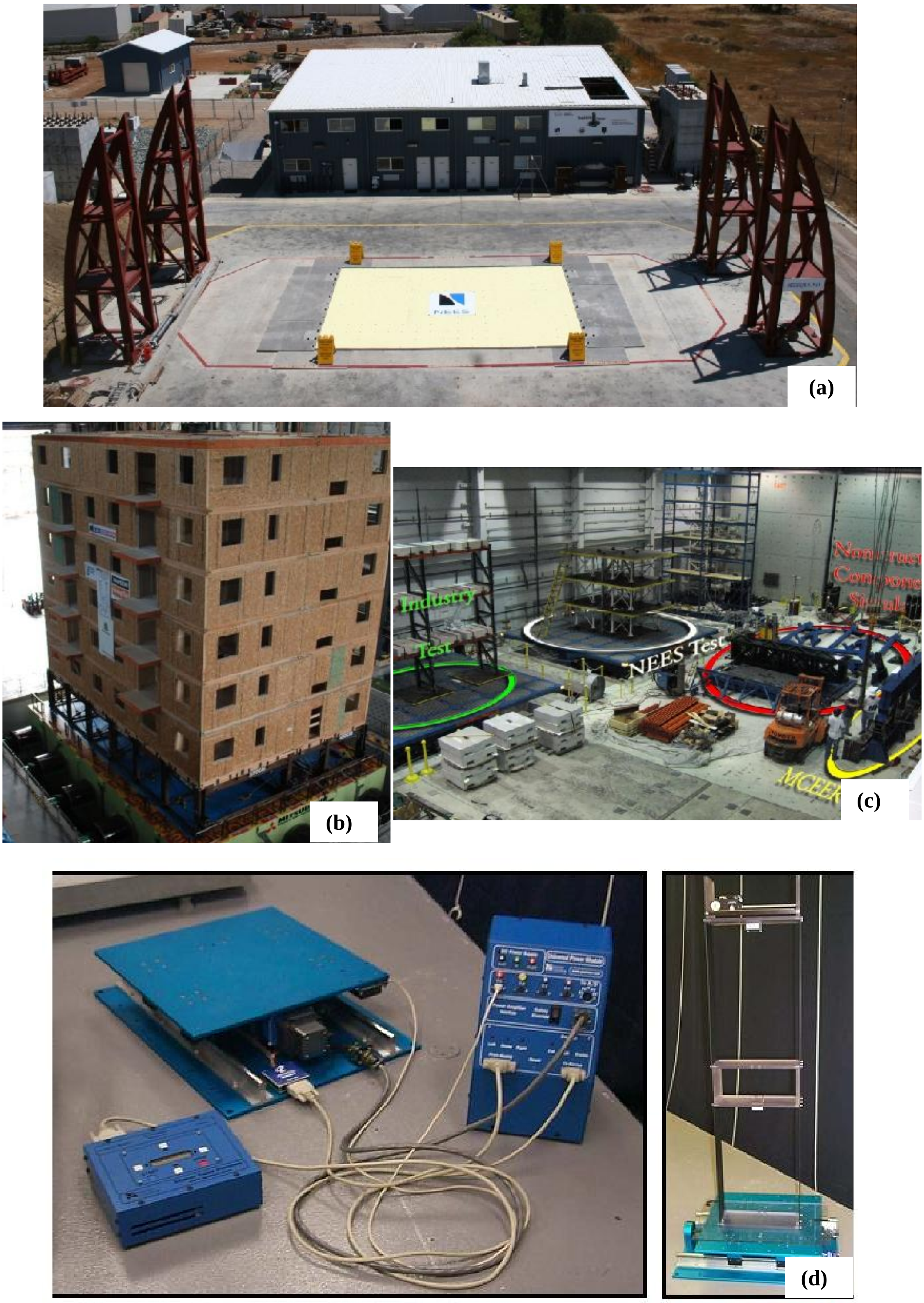


Figure 1.1 Different types of shake tables: (a) NEES San Diego Shake Table: First outdoor shake table in the world and greatest shake table in United States of America, (b) NIED Shake Table in Japan: Greatest shake table in the world, (c) NEES Buffalo Shake Table, (d) UCIST Purdue Mini Shake Table.

In this study, firstly a shake table without a specimen was considered. The command-feedback signal incompatibility (trajectory tracking problem) was investigated and worked on. OTT was used to solve this problem. Parameters which have an effect on OTT were investigated to get better solutions.

After understanding the main concepts of OTT, technique was examined when a specimen was on the shake table. For this purpose, a three storey-one bay aluminum specimen was produced. In these tests, shaker-specimen interaction was observed and influences of this interaction on tracking trajectory ability of the shaker was investigated.

In the following sections of the study, system identification of the specimen was performed by using only-output methods. Storey responses of the specimen under ground motion accelerations, which were produced by the shake table, were used to determine the modal parameters. To that end, modal parameters like natural vibration frequencies and mode shapes of the specimen were estimated by using Fourier Amplitude Spectra (FAS) Method and damping ratios were estimated by Half-Power (Band-Width) Method. To investigate the influences of OTT on system identification processes, modal parameter estimations were repeated before and after OTT and the results were compared.

Finally, damage detection process was performed on the specimen. For this purpose, Damage Index Method which is based on the changes in modal parameters (between damaged and undamaged specimen case) was used. To represent undamaged specimen case, two diagonals were attached into first storey. Damaged specimen case was constituted by removing these diagonals. Location of this constituted damage and its severity were studied to be estimated by using Damage Index Method. Finally, the effects of OTT on damage estimation were examined and discussed.

1.2 Literature Review

Dyke, Spencer, Quast & Sain (1995) worked on the effects of control system-structure interaction in their study. They showed that dynamic characteristics of an actuator and a structure are attached to each other and neglecting this interaction can cause wrong results. They developed a numerical model for interaction between the actuator and structure to define their problem. Transfer functions were used to describe the parameters like actuator characteristics, force applied by the actuator to the structural responses and feedback interaction between the structure and the actuator in the numerical model. Experimental data were used to prove the effectiveness of the numerical model and they found that there were excellent agreement between their model and the experiment results (Dyke, Spencer, Quast & Sain, 1995).

Twitchell & Symans (2003) indicated that dynamics of a simulator and a test structure must be taken into account to produce ground motions in dynamic tests because of the simulator-structure interaction and tracking problem. For this purpose, they worked on offline correction method to improve the tracking performance in their study. They constituted a analytical model for their seismic simulator to describe its dynamic behaviors. The simulator had two main parts: the actuator and the sliding platform. By neglecting the platform sliding bearing friction force and regarding the fluid properties in the actuator, transfer function of the actuator, which involves sliding platform-actuator interaction, was calculated. Volume and bulk modulus of the fluid inside actuator, piston head surface, force produced by actuator, platform displacement, actuator displacement of command signal, mass of the platform and three gain factors were used to define the transfer function. Experimental studies were performed by exciting the simulator platform with a white noise signal. Responses of the system were used to calculate the experimental transfer function of the actuator between the input and output signal. They used experimental data to calibrate the gain factors of analytical model. To improve the dynamic tracking performance, offline correction procedure was performed. To that end, a pre-filter was used to compensate for the dynamics of the system by multiplying the inverse transfer function by command signal and they obtained a corrected command signal. By driving the actuator with the corrected command signal, tracking problem was solved. Detailed results were given in their study (Twitchell & Symans, 2003).

For Luco, Ozcelik & Conte (2010), a shake table system includes a variety of mechanical, hydraulic and electronic components. In addition, there is an important dynamic interaction between table and the specimen which is mounted on the table. Because of this various components, various interactions arise and this situation causes shake table tracking problem in experiments. The authors worked on UCSD-NEES large high performance outdoor shake table at the University of California, San Diego and investigated signal reproduction (tracking) capacity of this table with different tuning and test amplitudes (Luco, Ozcelik & Conte, 2010; Ozcelik, 2008).

Thoen & Laplace (2004) showed in their study that the control performances of shake tables are affected by the interaction between the table and the test specimen because of the dynamic characteristics of the specimen. The resonant force feedback and damping of specimen are the main reasons of this effect. They determined that magnitude of these parameters, weight of specimen and table size can change the importance of the interaction effect. It can be said that, test specimen on the table increases the controller complexity of the table. Because of this reason, using controller tunings for bare table are not sufficient, new tunings are required if better control is desired. For the authors, the transfer function between command and feedback signals represents system and specimen parameters. This function has to be equal unity for linear systems. To obtain this equality, shake table system must be tuned by adjusting multiple control variables, such as gains, lead terms and notch filters. These parameters are changeable and obtained while the shake table is in motion. Parameters are adjusted to obtain unity transfer function. This iterative method is continued until the desired level of transfer function is obtained (Thoen & Laplace, 2004).

Trombetti et. al. (2004) worked on dynamic characteristics of two three-storey steel frame building structure models. One of the models was symmetric and the other was asymmetric in plan. Welded and bolted connections were used at connections of models. They performed shake table tests at Earthquake Engineering Center of the University of Bristol to obtain the dynamic parameters of the models. Imperial Valley 1940 earthquake (El Centro record) record was used in shake table tests for both models. Structural dampings were estimated by using snap back tests and the period of first mode vibration was obtained by free vibration tests. Also, they developed numerical models for their specimens. By comparing the experimental and numerical results, the authors indicated that a careful numerical modeling of the structure (especially connections) is required to obtain results correctly and similar to experimental ones (Trombetti et. al., 2004).

Liou & Jeng (1989) indicated that random vibration problems are important in dynamics of structures and spectral approaches (based on Fourier transform of finite data) can be used to estimate transfer functions. By using the amplitude and phase relations of these estimated transfer functions between two positions, modal parameters like natural vibration frequencies and mode shapes can be estimated. The authours used different algorithms to calculate the transfer functions and they worked on the effects of the different algorithms on the modal parameter estimation. Detailed results were given in their study (Liou & Jeng, 1989).

For He et. al. (2005), full-scale dynamic testing is very important to determine true dynamic characteristics (e.g., natural vibration frequencies, damping ratios and mode shapes, etc.) of a structure. These parameters can be used to determine structural safety and structural health monitoring. They divided dynamic tests into two groups as forced vibration tests and ambient vibration tests. It is indicated that force vibration tests give better results because of its adjustability property. The authors conducted dynamics tests on New Carquinez Bridge by using ambient vibration tests (based on wind) and forced vibration tests (based on controlled traffic loads). Responses of the bridge were measured and used in system identification methods like Fourier Amplitude Spectra Method (FAS) and Natural Excitation

Technique (NExT) paired with Eigensystem Realization Algorithm (ERA). By using these methods, natural vibration frequencies and mode shapes were determined. The two different methods gave similar results and the results were given in their study (He et. al., 2005).

For Amani, Riera & Curadelli (2007), structural monitoring can be classified as local or global methods. Local methods include X-rays, magnetic fields and acoustic emission. Global methods include vibration measurements and use changes in modal properties (e.g., natural vibration frequencies, mode shapes and modal damping), which depends on physical properties (mass, stiffness and damping), to estimate damage. These methods are known as non-destructive methods. The authors classified damage identification into four levels: (i) Detection, (ii) location, (iii) quantification and (iv) prediction. Detection level determines if damage is present, location level determines the location of the existing damage, quantification level evaluates the severity of damage and prediction level predicts the remaining life of the structure. They worked on a method to define changes in damping and stiffness properties of a structure through ambient vibration tests for determination of damage in structures. In addition, they gave examples of experimental results and numerical simulations in their study. Stochastic Subspace Identification (SSI-COV) Method (only-output system identification method) was performed to obtain the modal parameters (Amani, Riera & Curadelli, 2007).

Franchetti, Modena & Feng (2009) mentioned that damage detection based on changes in dynamic parameters has an increasing importance in aerospace, mechanical and civil engineering. They stated that changes in physical properties cause changes in modal parameters like natural vibration frequencies, mode shapes and damping ratios. Theoretical and experimental investigations for damage detection methods based on free vibration tests and nonlinear damping analysis were worked on in their study. They focused on structural damping, which was not sufficiently studied in damage detection before, and its change due to increasing damage level. Three precast reinforced concrete beams were tested for damage detection by using damping analysis in experimental studies. The damage detection method was applied before and after the constitution of controlled damage to the specimen. It was concluded that modal damping ratios increase when the specimens are damaged because of the energy dissipative mechanism in crack zones (Franchetti, Modena & Feng, 2009).

Kim, Lee & Huu (2007) stated that dynamic tests are important and give good information about how steel frames behave under dynamic loads compared to static tests. So, to demonstrate the second-order inelastic behavior of steel frames under dynamic loads, three two-storey steel frames were tested by shake table with dimensions of 5x3 m in Large-Scale Structural Testing Laboratory, Hyundai Institute of Construction Technology, South Korea. In tests, the earthquake acceleration which was sent to shake table (input signal) and the feedback acceleration which occurred on the table (output signal) were measured as different from each other. So, a calibration factor was used to fix this problem. After the calibration process, the problem was solved and the input-output signals became similar. Results were given in their study (Kim, Lee & Huu, 2007).

For Caicedo, Dyke & Johnson (2004), it is important to detect damages and determine the structural safety of buildings and structures after natural disasters like earthquakes and hurricanes. Commonly used method is visual inspection method in damage detection. But this method cannot detect the damage in structural elements because of non-structural elements like walls and facades. Experimental methods like radiographs, magnetic or ultrasonic methods can be used to detect and localize damage in structural elements. Authors performed experiments on four storey, two bay by two bay (each bay is 1.25 m x 1.25 m in plan and 0.9 m high) laboratory scale model to detect location and severity of damage in this structural model. Different excitation types (e.g., wind, shaker) were used and six damage patterns were defined. The damage patterns were obtained by removing braces at storeys and loosening the beam-column connections. Analytic models of the structure were developed to compare with the experimental results. Damage detecting processes were performed by using acceleration measurements under ambient sources (generally unmeasurable). Both undamaged and damaged response data were used to obtain modal parameters by using Natural Excitation Technique (NExT) and Eigensystem Realization Algorithm (ERA) system identification methods. Stiffness loss was calculated by using modal parameters and then damage could be estimated (Caicedo, Dyke & Johnson, 2004).

For Moaveni et. al. (2008), structural health monitoring has a big importance in civil engineering to detect damage in structural members and estimate their remaining lives. It was stated that vibration based non-destructive damage identification methods use changes in dynamic characteristics (modal parameters) of a structure to identify damage. To obtain modal parameters, experimental modal analysis techniques (based on measured vibration data of a structure) can be used. It can be said that modal parameter estimation affects the damage detection process. The authors defined damage identification as occurrence of damage, localizing damage and estimation the extent of damage. A full-scale composite beam was tested at the University of California, San Diego for damage detection. Low amplitude vibration response data was obtained from the beam at various damage levels. Eigensystem Realization Algorithm (ERA) was applied to identify the modal parameters (e.g., natural vibration frequencies, damping ratios and mode shapes) of different damage states (including undamaged state) of the beam by using its responses. The identified modal parameters were used to damage detection of the beam by a finite element model updating method. It was seen that the detected damage by the method was consistent with the existing damage in the composite beam (Moaveni et. al., 2008).

Stubbs et. al. (2000), stated that non-destructive damage evaluation can be classified into four levels: (i) Level I methods, which can only identify if damage has occurred (Vandiver, 1995; Begg et. al., 1976; Loland & Dodds, 1976; Crohas & Lepert, 1982). (ii) Level II methods, which can identify if damage has occurred and determine the location of this damage (Pandey et. al., 1991; Chance et. al., 1994). (iii) Level III methods, which can identify if damage has occurred, determine the location and severity of this damage (Adams et. al., 1978; Stubbs et. al., 1990; Wu et. al., 1992; Elkordy et. al., 1994; Kaouk & Zimmerman, 1994). (iv) Level IV methods, which can identify if damage has occurred, determine the location, severity of this damage and evaluate its effects on the structure. The authors used Damage Index Method to detect and localize damage and estimate its severity. So, this method can be called as a Level III damage evaluation method. Method calculates damage index parameters for all members of the investigated system by using appropriate sectional stiffness properties of damaged and undamaged members. Mode shapes of damaged and undamaged system and stiffness matrices are used to calculate stiffness properties. By evaluating the damage index parameter, damage existence and its location can be estimated. Damage severity can be also calculated by using damage severity index parameter. The authors selected a portal steel frame of one storey-one bay. They constituted finite element model with 30 members of this frame. Damaged case was simulated by reducing the bending stiffness parameter EI by 10% of 15^{th} and 16^{th} members. Modal parameters were obtained and by using these modal parameters in Damage Index Method, the damage locations and the severity of these damages were estimated. It was observed that the results of Damage Index Method were similar to the results of the simulation (Stubbs et. al., 2000).

Park, Bolton & Stubbs (2006) evaluated the Damage Index Method in simulated data for one-third scale, two-bay by two-bay, four-storey steel frame structure. The structure was 3.6 m high with a total width of 2.5 m. All beam-column connections were assumed as rigid and storeys could only move in horizontal plane. The first 50 modes of the finite element model were used to generate simulated time domain acceleration response data at 16 horizontal degrees of freedom (two DOF in x direction and two DOF in y direction per storey). Each DOFs were represented by accelerometers in simulated model. The excitation of model was provided by white noise signals in x direction or in y direction and the response data were recorded. Damaged case was constituted by removing two lateral braces from the structure. Recorded response data were used to calculate modal parameters of the structure and these parameters were used in Damage Index Method. In this way, damage, its location and severity were estimated (Park, Bolton & Stubbs, 2006).

Kim & Stubbs (2002) defined structural damage as changes in geometric or material properties of structures that results unwanted responses in structures. They stated the importance of detecting damage in their study. The authors discussed a problem which uses changes in dynamic modal parameters of structures to detect, locate and estimate the severity of damage in structures. Different damage index algorithms (Damage Index A, B and C) were handled in their study. Main objectives of the study were presenting a new algorithm (Damage Index C) and compare this new algorithm with other ones. All of the algorithms were applied to a numerical two span continuous beam model with 51 nodal points to comparison. In studies, 10 different damage detection cases were investigated. Firstly, modal responses of the structural model (modal parameters of undamaged case) were calculated by using ABAQUS software program; secondly, a damage detection model of the test specimen was established and modal responses were calculated (modal parameters of damaged case); thirdly, all damage index algorithms were used by evaluating undamaged and damaged case modal parameters to detect, locate and estimate the severity of damage in test specimen; and finally the accuracy of algorithms were evaluated and compared. It is concluded that Damage Index C gave the best accuracy results for localization and severity estimation. Details were given in their study (Kim & Stubbs, 2002).

Elgamal (2003) stated that Fast Fourier Transform (FFT) and Power Spectrum Density (PSD) Function can be used to obtain natural vibration frequencies and mode shapes of systems. FFT and PSD Functions are useful for measuring the frequency contents of signals. FFT gives the average frequency content of a signal over the time. Besides, PSD Function gives the power as the mean squared amplitude at each frequency value but includes no phase information. So, Cross Power Spectral Density (CPSD) Function must be used to determine the phase difference between two signals. The author described Fourier Amplitude Spectra (FAS) Method, which can be used to estimate modal parameters of systems, and explained the method by examples in the study. This method can be defined as an only-output system identification method and includes FFT, PSD and CPSD analyses. FFT, PSD and CPSD Functions can be used to estimate natural vibration frequencies of systems.

Besides, CPSD Functions between different signals (different storeys) are used to estimate mode shapes of the investigated systems. Details of the method were given in related reference (Elgamal, 2003).

Mota (2011) emphasized that shake tables have a large portion of the earthquake engineering researches and provides an alternative to expensive and time consuming testing methods. Shake table tests give most realistic information about dynamic characteristics of the test specimens and these tests allow to investigate the inelastic responses of structures to ground motions. In addition, these tests include negations too. For example, the state of inability to simulate the command ground motion signals exactly (acceleration tracking performance of the shake table). The author investigated the effects of the tracking performance on inelastic responses and studied to identify the main parameters that have an effect on tracking performance in the study (Mota, 2011).

In past, numerous methods were used to damage estimation. Most of these methods focus on the change of natural vibration frequencies, which are known to diminish after damage (Beck, 1983). These methods can be found in literature easily. For instance; Salawu (1997) used natural vibration frequencies of undamaged and damaged structures for damage detection and estimated damage without location information. Pandey et al. (1991) used curvature mode shapes of undamaged and damaged structure for damage detection and they estimated damage with its location information. Bernal & Gunes (2004) used changes in modal flexibility matrices and put them into damage locating vector to localize damage.

1.3 Thesis Organization

In general this thesis includes five main chapters. Brief information and instructions about all chapters were given below.

Chapter 2 is a theoretical background chapter. In this chapter, a brief theoretical information about some notions, which were mentioned in this study, were given. These notions are: Offline Tuning Technique (OTT) to solution of tracking problem, Fourier Amplitude Spectra (FAS) Method and Half-Power (Band-Width) Method to system identification (obtain modal parameters) and Damage Index Method (DIM) to damage detection.

In Chapter 3, properties of the test equipments (e.g., electro-dynamic shake table and its components, data acquisition system, three storey-one bay aluminum specimen, etc.) and their usages were introduced.

Chapter 4 is the application chapter. This chapter includes experimental studies and applications of the theoretical part (Chapter 2). Results of the studies and experiments were given in this chapter too.

Chapter 5 is the part where conclusions and recommendations were given. In this chapter, all the results of this study were summarized, evaluated and discussed. In addition, information about future studies were given in this chapter.

CHAPTER TWO
THEORETICAL BACKGROUNDS

2.1 Offline Tuning Technique (OTT)

In small or big shake table tests, the main problem is the trajectory tracking problem. The trajectory tracking concept can be defined as the command tracking ability of a shake table. This problem results incompatibility between the command / input signal (desired motion on shake table) and feedback / output signal (formed motion on shake table). In other words, shaker cannot track the command signal completely (trajectory tracking problem). Complexity of the components of the shaker and the shaker-specimen interaction can be shown as the main reasons for this problem.

Broad bandwidth signals (e.g., white noise signals, etc.) must be used to excite the all modes of specimens in shake table tests. But, because of the tracking problem, the command signal loses its broad bandwidth property and this situation affects the results of system identification as well as damage detection (Luco et al., 2010). So, solving the tracking problem becomes necessary and important for the health of the data which represent the characteristic behaviors of the specimens. There are many methods available (PID based displacement control methods, adaptive control methods, PID + feedforward methods and offline tuning methods) to overcome this problem (Luco et al., 2010). In the scope of this study, Offline Tuning Technique was taken up.

Firstly in OTT, forward transfer function (FTF) between the command signal, which is sent to shake table, and the feedback signal, which occurs on the shake table, is estimated. This estimated FTF represents the transfer function and the dynamic characteristics of the shake table. Also, FTF gives information about influences of shake table on command signal. For example, in frequency domain, unit value in FTF means that shake table has an unit effect (no effect) on command signal, so command and feedback signals are equal (there is no trajectory tracking problem). Other values of FTF are the indicators of trajectory tracking problem. These notions can be understood by inspecting Figure 2.1 which includes a scheme about FTF for LTI systems in time and frequency domain.

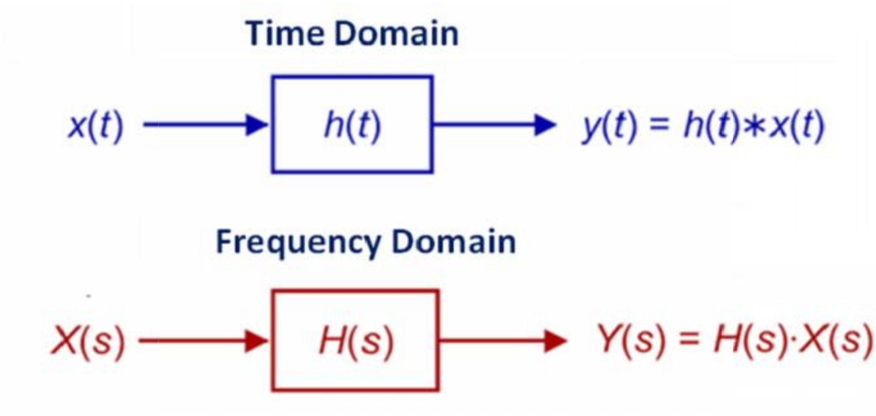


Figure 2.1 A scheme about FTF for LTI systems in time and frequency domain.

In Figure 2.1; $x(t)$, $X(s)$ are the input signals in time and frequency domain respectively. Similarly $y(t)$, $Y(s)$ are the output signals, $H(s)$ is the FTF and $h(t)$ is system's response to an impulse. In time domain, the convolution of the system's response and input signal equals output signal. But in frequency domain, product of these signals equals output signal. Considering the complication of convolution operation (see in Equation 2.1), it can be said that studying in frequency domain becomes easy and logical. So, Equation 2.2 can be used in analyses.

$$y(t) = h(t) * x(t) = \int_0^t h(\tau)x(t-\tau)d\tau \qquad (2.1)$$

$$Y(s) = H(s).X(s) \qquad (2.2)$$

In frequency domain, it was mentioned before that the product of FTF and input signal equals output signal and the trajectory tracking problem occurs because of the non-unit values of FTF. To overcome tracking problem, FTF must be regulated as a unit function. As it known, a function multiplied by its inverse equals unit function. From this definition, FTF multiplied by its inverse (Inverse Transfer Function / ITF) equals unit function too. FTF cannot be multiplied by its inverse to get a unit function. Because it is a system property and it is out of our control. So, the only parameter remaining is the input signal that we can play on it. In this section, a trick should be done to continue. By multiplying input signal by ITF, a new input signal (modified input signal / MIS) is obtained in frequency domain. Replacing the input signal with MIS in Equation 2.2 gives Equation 2.3. The bold parameters in this equation represent the MIS parameters. It is explicit that the product of the FTF and ITF equals unit value and input signal equals output signal.

$$Y(s) = H(s).\underbrace{\mathbf{H^{-1}(s).X(s)}}_{\mathbf{MIS(s)}} \Rightarrow Y(s) = X(s) \tag{2.3}$$

Equations and expressions above mean that, generating a signal on a shake table is possible when this desired signal is modified by ITF. Before sending MIS to shake table, time domain components of this signal must be calculated by using Inverse Fast Fourier Transform (IFFT) which was given in Equation 2.4. After this, the signal which occurs on the table is the desired signal which is wanted to be produced. In this manner, trajectory tracking problem can be solved. All the steps given above is called as "Offline Tuning Technique (OTT)" in literature.

$$MIS(t) = \frac{1}{N}\sum_{s=0}^{N-1} MIS(s)e^{j2\circledR ts/N}; \qquad \mathrm{t} = 0,.....N\ \text{-}1 \tag{2.4}$$

FTF estimation can be done by using Welch Method which was given in Equation 2.5. Here $j\mu = s$, $P_{yx}(j\mu)$ and $P_{xx}(j\mu)$ are cross and auto spectral density (equals power spectral density function) functions respectively. Cross spectral density function and auto spectral density function were given below in Equations 2.6 and 2.7. Here, n_d is the number of windows used for averaging, T is the length of these windows, f is frequency, $X_k(s,T)$ and $Y_k(s,T)$ are kth section of the stationary (ergodic) random response signal $x(t)$ and $y(t)$ respectively, t is time and asterisks ('*') are complex conjugate operator (Ozcelik & Salavati, 2013). In the scope of this study, all of these functions were estimated by using MATLAB® software.

$$\hat{H}(j\mu) = \frac{P_{yx}(j\mu)}{P_{xx}(j\mu)} \tag{2.5}$$

$$\hat{P}_{yx}(s) = \frac{1}{n_d T}\sum_{k=1}^{n_d} X_k^*(s,T) Y_k(s,T), \quad (k-1)T \le t \le kT, \;\; k = 1, 2, \ldots, n_d \tag{2.6}$$

$$\hat{P}_{xx}(s) = \frac{1}{n_d T}\sum_{k=1}^{n_d} X_k^*(s,T) X_k(s,T), \quad (k-1)T \le t \le kT, \;\; k = 1, 2, \ldots, n_d \tag{2.7}$$

Transfer functions include lots of important information (e.g., characteristics of shake tables, shaker-specimen interaction, etc.) just as the Black Boxes in airplanes. Therefore, these functions can be defined as the Black Boxes of shake table systems too. In the scope of this study, transfer function of the shake table system was estimated by using experimental data. But, it must be known that, these functions can be obtained numerically as a function of shake table and specimen properties for detailed studies.

It must be stated that, displacement, velocity and acceleration records can be used in OTT. As it is known, displacement and velocity records can be obtained by taking integral of acceleration records. Integral process acts like a low-pass filter. Therefore, acceleration records have richer frequency contents than others. This situation makes it convenient to use acceleration records in analyses to get better tracking results. Benefits of rich frequency content were detailed in following sections.

2.1.1 The Parameters Which Have Effects on Offline Tuning Technique

There are many parameters which have an effect on Offline Tuning Technique. Duration and frequency content of the command signal are some of them. Brief explanations about these parameters with examples were given in following sections.

2.1.1.1 Duration of the Input Signal

Duration of a signal improves the calculation of its frequency content, FFT, PSD and CPSD analyses and FTF estimations. Therefore, this parameter becomes important for OTT too. The effects of the length of the input signal can be understood by investigating the coherence functions. This function represents linearity relationship between two signals (input and output signals for shake table systems). The frequency bandwidth, where the amplitudes of function equal 1, represents linearity relationship between input and output signals. FTF estimations were done for LTI systems in OTT analyses as it was mentioned before, so the linearity relationship affects the results of the estimation too. FTF estimation becomes faulty when the linearity relationship is lost. Figure 2.2 shows the effects of different length white noise signals on coherence function estimation. By investigating the figure, it can be said that the signal which is 5 seconds long has a linearity relation (amplitudes equal 1) until 60 Hz. After this frequency value, the FTF estimation gives wrong results. For 10 seconds long signal, the limit for linearity has enlarged. But after 70 Hz, linearity is lost too. 20 seconds long signal has no distortions until 80 Hz frequency bandwidth. So, it can be concluded that the best choice for FTF estimation is the third one. Longer durations (e.g., 60 seconds, 2 minutes, 5 minutes, etc.) will give better results.

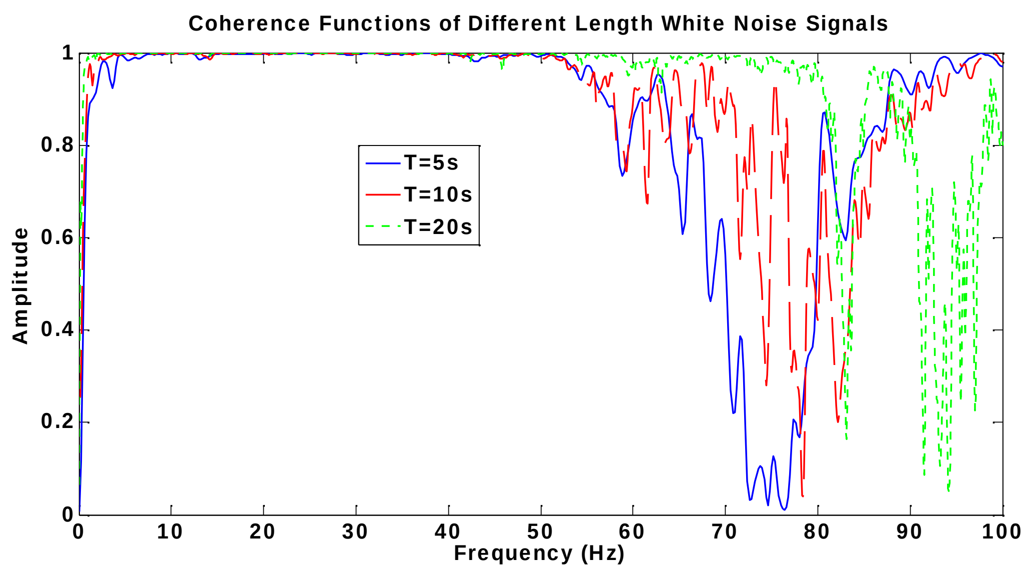
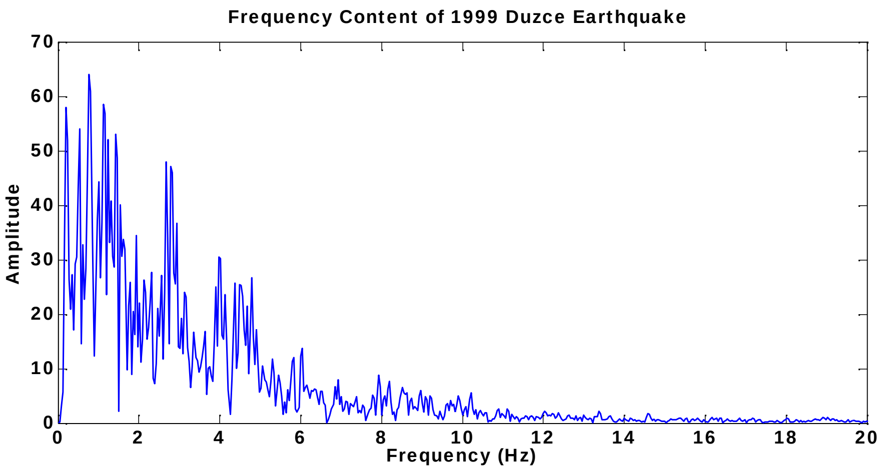


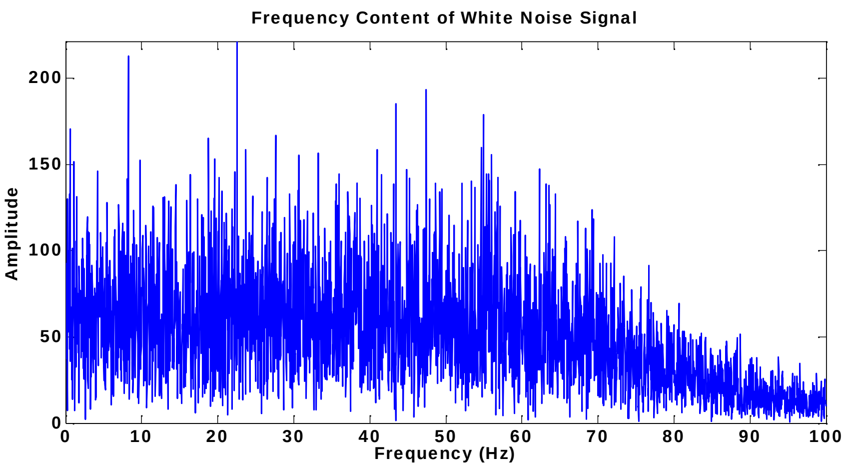
Figure 2.2 The effects of different length white noise signals on coherence function estimation.

2.1.1.2 Frequency Content of the Input Signal

Other parameter which has an effect on OTT is the frequency content of the input signal. This parameter shows itself in FTF and coherence function estimation. For example, an earthquake signal has a poor frequency content and narrow linearity relation bandwidth. In spite of this situation, white noise signals and impact loads have rich frequency contents and wider linearity relation bandwidth. Figures 2.3 and 2.4 demonstrate frequency contents and coherence functions of 1999 Düzce Earthquake, Turkey and 10 seconds long white noise signal whose root mean square (RMS) value (equals standard deviation for signals which has 0 mean) is 1 g and frequency bandwidth is 0-100 Hz.



(a)



(b)

Figure 2.3 Frequency content of (a) 1999 Düzce Earthquake, Turkey and (b) 10 seconds long white noise signal whose RMS value is 1 g and frequency bandwidth is 0-100 Hz.

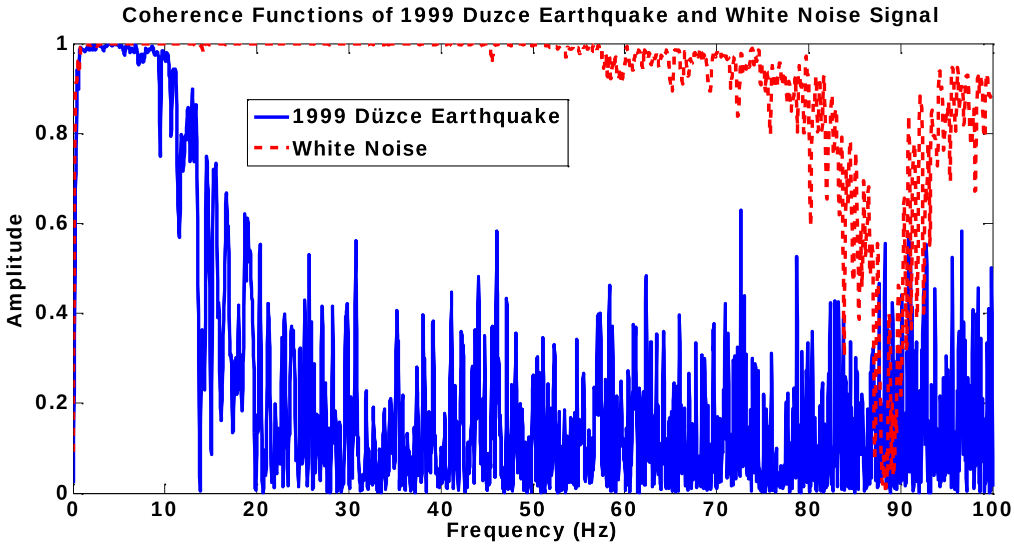


Figure 2.4 Coherence functions of 1999 Düzce Earthquake, Turkey and 10 seconds long white noise signal whose RMS value is 1 g and frequency bandwidth is 0-100 Hz.

By investigating the figures above, it can be obtained that rich frequency content results better coherence functions (wider frequency bandwidth of unit value) for FTF estimation. For earthquake signal, the linearity limit of coherence function is about 10 Hz. Beside this, for white noise signal, the limit is about 80 Hz. It must be stated that the distortions in coherence function of earthquake signal (about 10 Hz) have occurred because of the absence of higher frequency contents than 10 Hz in that signal. On the other hand, nonlinearity relations (about 80 Hz) because of the shaker components are the reasons of the distortions in coherence functions of white noise signal.

In the light of this information, it can be said that white noise signal is the best choice for FTF estimation and OTT. This is an expected conclusion. Because, FTF of a white noise signal represents all the frequencies just as the white noise signal. This situation allows someone to use the FTF of a white noise signal with other signal types (e.g., earthquakes, etc.) for better tracking performances. In this case, MIS equals the multiplication of the earthquake signal and ITF of white noise signal. The important point here is the necessity of selecting a white noise signal which has duration same as the earthquake signal.

2.2 Operational Modal Analysis Methods

The estimation of dynamic parameters of systems by vibration based methods are attracted attention over the past several ten years. These methods are commonly used in structural health monitoring (SHM). SHM becomes an important instrument that can be used for evaluation of existing structures, damage detection, model calibration and evaluation of structures before and after retrofit. SHM process includes continuous and / or in different time monitoring of structures by using sensors and detection the present state of structures by extracting the damage sensitive properties of them. The system identification methods which are used in SHM can be divided into two parts as input-output and only-output methods (Moaveni, 2007).

Civil engineering structures are big scaled structures. Because of this, it cannot be practical to excite them with properly measurable forces. In this situation, using ambient vibration effects (micro tremor, traffic, wind, etc.), that arises because of normally usage of structures, becomes only way to excitation. That's why, using only-output methods, which are also called as "Operational Modal Analysis Methods", are more convenient for modal parameter estimation in civil engineering structures (Ozcelik, Gundogan & Kahraman, 2013). Enhanced Frequency Domain Decomposition (EFDD), Stochastic Subspace Identification Method (SSI-COV), Natural Excitation Technique (NExT), Eigensystem Realization Algorithm (ERA) and Fourier Amplitude Spectra Method (FAS) can be listed as some operational modal analysis methods. In the scope of this study, FAS Method, basic method when compared with others, was used for modal analysis.

Broad bandwidth signals must be used to excite the all of the modes of specimens in operational modal analyses. These kinds of excitatives can be obtained by using shake tables and / or shakers which have different types of operation principles (eccentric mass, electro dynamic shake tables, etc.) as it can be performed by ambient vibration.

The main problem encountered mostly in operational modal analysis is the violation of the necessity to have broad band signal for input signals (Peeters & De Roeck, 2001). For example, this situation can be observed in experiments because of shaker-specimen interaction (Luco et al., 2010). The mentioned problem prevents to excite all of the modes of a system and causes to get wrong results from experiments.

2.2.1 Fourier Amplitude Spectra (FAS) Method

FAS Method is one of the operational modal analysis methods. These methods can be used in system identification processes as it was mentioned before. FAS Method has some advantages according to other operational modal analysis methods. For instance, this method is easier to understand and applicable. Besides, programming this method in MATLAB® or suchlike softwares is more simpler than other methods. Method is useful for systems whose modes are well separated and clear to detect from PSD Functions. Otherwise, it provides wrong results. Natural vibration frequencies, mode shapes and modal damping ratios of systems can be estimated by using the method. Details were given in following sections.

In FAS Method, acceleration response records (because of its richer frequency content than velocity and displacement records) of different points of the specimen which is wanted to evaluate are required. These points can be adjusted as locating at storey levels or at anywhere else between two storeys. In the scope of the method, each of these points represents different channels in analyses.

Firstly in method, power spectral density (PSD) functions of all the channels are calculated. Welch Method can be used for this purpose. The PSD Function gives power as the mean squared amplitude at each frequency line. But, this function does not include phase information. Phase information is an indicator between two signals that explains the directions of the signals with respect to each other. For example, while 0° phase angle means that signals are in same direction, 180° or -180° (π or -π) phase angle means that signals are in opposite direction. For determining the phase information of two signals, cross power spectrum density (CPSD) functions are useful tools. The CPSD Function can be defined as the distribution of power per unit frequency. Formulations of these functions were given before in Equations 2.6 and 2.7.

The frequency values which correspond to the peak values in PSD diagrams equal natural vibration frequencies of the investigated specimen. First frequency value is related to first mode, second related to second mode and goes on like this. This operation can be performed by calculating Fast Fourier Transforms (FFT) of signals too (see in Equation 2.8). But, PSD diagrams are smoother than FFT diagrams because of windowing process and this makes it easy to find peak values in PSD diagrams.

$$X(s) = \sum_{t=0}^{N-1} X(t) e^{-j2®ts/N}; \qquad s = 0,.....N\text{ -}1 \tag{2.8}$$

To obtain mode shapes of specimens, plotting the PSD diagrams of all channels in same figure and determining the peak values of these diagrams are required. These determined values represent the power of the signal and square roots of these peak values are required for mode shape estimation. The peak values of all channels, which are obtained after taking square root operations, at a specific natural vibration frequency (for example at first mode) represent the amplitudes of mode shape for this mode. After this, phase angle relations of CPSD Functions can be used to determine the directions (signs) of the amplitudes of mode shapes. These operations can be repeated to estimate mode shapes of other vibration modes too.

2.3 Half-Power (Band-Width) Method

Half-Power (Band-Width) Method can be used to estimate damping ratios of systems by experimental way. In this method, frequency response curves of systems are used and the damping ratios are determined from the frequencies at which the response amplitudes are reduced to the level $1/\sqrt{2}$ times its peak value. Steps of the method were itemized below (Chopra, 1995; Clough & Penzien, 2003):

1) Peak response of frequency response function is determined,

2) A horizontal line is constructed at 1/√2 times the peak response,

3) Two frequencies at which the horizontal line cuts the response curve are determined,

4) And last, the damping ratio can be calculated by Equation 2.9.

$$\P = \frac{f_2 - f_1}{f_2 + f_1} \qquad (2.9)$$

A schematic indication of the method was given below in Figure 2.5.

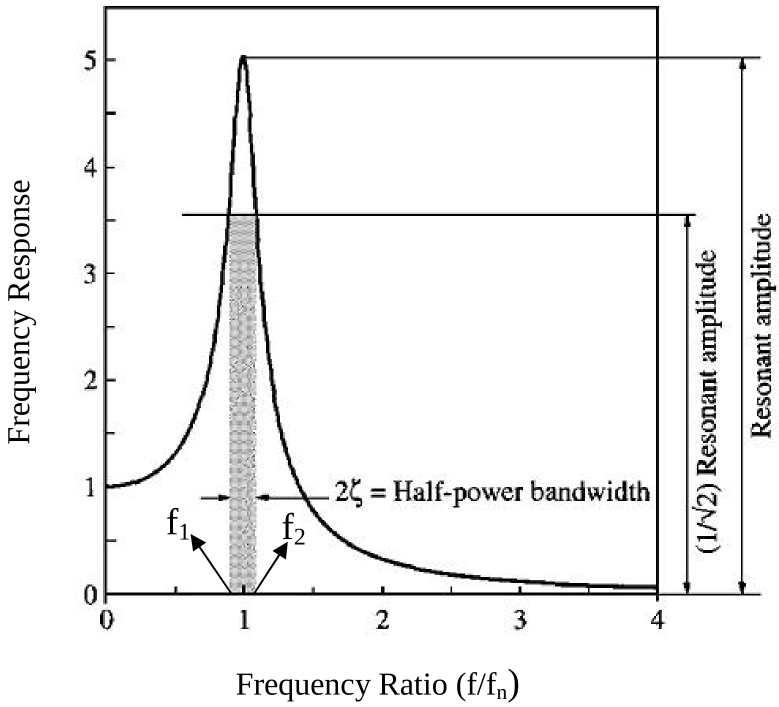


Figure 2.5 A schematic indication of Half-Power (Band-Width) Method.

With the broad bandwidth white noise assumption, PSD Functions of the response data can be used instead of frequency response functions (Shi, Shan & Lu, 2012). But, it must be stated that the windowing process of PSD Function affects the damping ratio calculation due to the influence on limb widths of the function. So, these calculated damping ratios should not be accepted as the real results. They only provide an idea about the order of the real damping ratios. In the light of this information, PSD Functions were used for damping ratio estimation in this study.

A scheme about summary of system identification methods, which includes FAS Method and Half-Power (Band-Width) Method, was given below in Figure 2.6

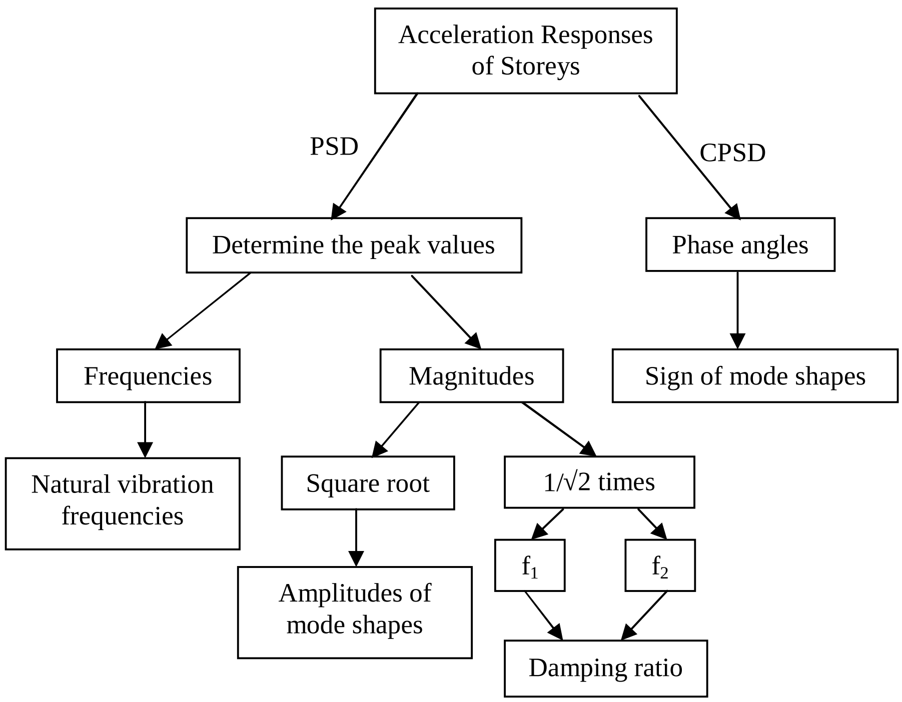


Figure 2.6 A scheme about summary of the system identification methods.

2.4 Damage Detection Methods

In structural engineering, damage can be defined as the changes in a structure that affects its structural performance. It has a critical importance to detect reliably the damage state of a structure which is exposed to natural disasters like strong earthquakes, storms or human-origin damage effects like collision, explosion and fire.

During the past years, a significant amount of research has been performed in the area of damage detection in existing structures. After studies, damage detection methods, which have no harm on structures (non-destructive) and use the changes in modal parameters of undamaged and damaged structures, were developed. (Park et al., 2006).

Similarly, basis of the vibration based structural health monitoring methods relies on the fact that the damage causes changes in stiffness, mass and energy absorption properties of a structure and this situation causes changes in measurable dynamic response of the structure like natural vibration frequencies, mode shapes, etc. (Farrar & Lieven, 2007).

Damage detection methods can be divided into four different grades according to development level. These are, (i) Level I methods: Those can detect the existence of damage, (ii) Level II methods: Those can detect the existence and the location of damage, (iii) Level III methods: Those can detect the existence, location and severity of the damage and (iv) Level IV methods: Those can detect the existence, location, severity and remain life of the damaged structure (prognosis). (Park, 1997; Stubbs et al., 2000; Park, Bolton & Stubbs, 2006; Amani, Riera & Curadelli, 2007).

Many damage detection methods in different development levels are available in literature. These methods can be sequenced as based on Bayes analysis, control theory, damage index, modal strain energy and finite elements model updating (Sohn and Law, 1997; Chase et al., 2005; Stubbs et al., 1992; Shi and Law, 1998; Mottershead and Friswell, 1993). In this study, these methods were only mentioned with their names and details were not given. Interested readers can investigate the related references.

In the scope of this study and analyses, "Damage Index Method", which was firstly developed by Stubbs et al. in 1992 for damage detection and upgraded in many articles later, was used. Damage Index Method can be classified as a Level III method (detect the existence, location and severity of the damage) and details were given in following sections (Park et al., 2006).

2.4.1 Damage Index Method (DIM)

The method is based on two essential assumptions: (i) Geometry of a member of system is not affected by the damage which occurs in that member. (ii) This damage only has an influence on modulus of elasticity of the member. And the method calculates a Damage Index Parameter by using the mode shapes of undamaged and damaged system. The formula of the Damage Index Parameter was given in Equation 2.10.

$$DI_{rj} = \frac{S_{rj}}{S_{rj}^{*}} = \left[\frac{(\phi_r^{*})^T [K_{j0}](\phi_r^{*}) + (\phi_r^{*})^T [K](\phi_r^{*})}{(\phi_r)^T [K_{j0}](\phi_r) + (\phi_r)^T [K](\phi_r)} \right] \frac{(\phi_r)^T [K](\phi_r)}{(\phi_r^{*})^T [K](\phi_r^{*})} \quad (2.10)$$

Here, *n* is the degrees of freedom of the system, *r, j* are the mode and member numbers respectively, DI_{rj} is the damage index parameter, S_j is the stiffness parameter, ϕ_r *(n x 1)* is the modal vector of the system, K_{j0} *(n x n)* is the contribution of the member stiffness matrix to the system stiffness matrix, *K (n x n)* is the system stiffness matrix. Besides, damaged states of all the parameters are denoted by asterisks ('*').

Calculated Damage Index Parameter provides information about the damage state of any member related to any mode. This parameter can be evaluated in three different cases: (i) $DI_{rj} \leq 1$ if there is no damage in the member, (ii) $DI_{rj} > 1$ if the member is damaged and (iii) $DI_{rj} = \infty$ if all the stiffness capacity of the member is lost.

By investigating the Equation 2.10, it can be said that the Damage Index Parameter of a member can be explained as the ratio of undamaged stiffness parameter to damaged stiffness parameter. From this point of view, Damage Severity Parameter can be derived as Equation 2.11.

$$\sim_{rj} = \frac{S_{rj}^{*} - S_{rj}}{S_{rj}} = \frac{1}{DI_{rj}} - 1 \tag{2.11}$$

Just as Damage Index Parameter, the Damage Severity Parameter can be evaluated in three different cases too: (i) $a_{rj} = 0$ if there is no damage in the member, (ii) $a_{rj} < 0$ if the member is damaged and (iii) $a_{rj} = -1$ if all the stiffness capacity of the member is lost. For an investigated member, the parameter a_{rj} approaches -1 value as the damage severity increases. But it must be noted that, this parameter does not define the changes in stiffness exactly; it defines the changes in stiffness parameter (S_{rj}). These notions are different from each other and it is important to pay attention to this difference.

CHAPTER THREE
EQUIPMENTS USED IN EXPERIMENTS

3.1 Electro-Dynamic Shake Table and Its Components

In experiments, *APS 113 Electro-Seis* electro-dynamic mini shake table was used to perform ground motions. This is an one axis table and can be used in horizontal or vertical operation configuration. It has a frequency range of 0-200 Hz. The maximum displacement and velocity that the shaker can reach are 0.158 m (peak to peak) and 1 m/s respectively. Specimen capacity of the shaker for horizontal configuration is 225.54 N. This value falls to the level of 107.87 N for vertical configuration. The auxiliary table dimensions, the apparatus where specimens are mounted, are 0.254 m x 0.254 m and the overall shaker dimensions are 0.526 m x 0.213 m x 0.168 m. Total weight of the shaker is 353.02 N and the maximum force that shaker can apply is 133 N. Many kits are available for this shake table for different purposes. Auxiliary table kit (APS 0052) for horizontal tests, auxiliary table kit (APS 0077) for vertical tests, carrying handles, reaction mass assembly and steel cable kit are some of them. In Figure 3.1, appearances of APS 113 shake table with APS 0052 kit and with APS 0077 kit were given.

(a)

(b)

Figure 3.1 APS 113 shake table with (a) horizontal kit and (b) vertical kit.

Response spectrums of shake tables include valuable information about properties of shake tables like load, force, velocity and acceleration relationships. In addition, these spectrums provide knowledge about the operation limits of shakers in any frequency bandwidth. Response spectrum (about frequency-acceleration-load relationship) of APS 113 Shake Table was given in Figure 3.2.

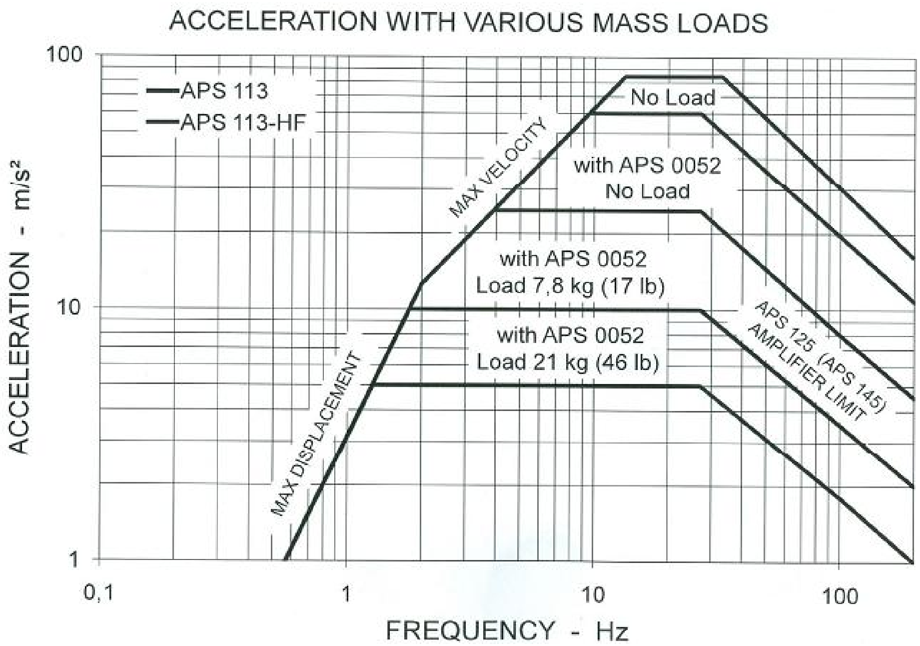


Figure 3.2 Response spectrum (frequency-acceleration-load) of APS 113 Shake Table.

To provide a drive power for shake table, APS 125 Power Amplifier (see in Figure 3.3) was used. By changing the gain knob of the amplifier, the command signal can be amplified or minimized before arriving at shake table. Another important role of this instrument is protecting the inside coil of shake table against current overload. It can also tolerate temperature and supply line variations while maintaining excellent stability.

Figure 3.3 APS 125 Power Amplifier.

3.2 Data Acquisition System

Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure or sound with a computer. A DAQ system consists of sensors, DAQ measurement hardware and a computer with programmable software. Compared to traditional measurement systems, PC-based DAQ systems exploit the processing power, productivity, display and connectivity capabilities of industry-standard computers providing a more powerful, flexible and cost-effective measurement solution.

CXL-GP Series Crossbow CXL04GP1 model capacitive accelerometers (see in Figure 3.4 (a)) were used in experiments. These are 1-axis accelerometers in range of ±4 g acceleration bandwidth and 0-100 Hz frequency bandwidth. 4.9 to 5.5 VDC power supply is required to operation and it is easy to interface to standard data acquisition systems. Sensors provide a direct high-level analog voltage output. The output requires no external signal conditioning electronics and may be directly interface to an A / D or other data acquisition hardware.

DAQ measurement hardware includes Data Acquisition Card and Data Acquisition Box (Junction Box). A DAQ card is put in a computer to establish a bridge between computer-accelerometers and computer-shake table system. This card has two main functions: (i) Sending analog (A) signal to shake table, (ii) collecting analog signals from accelerometers and converting them to digital (D) signals to save on computer and process (A / D and D / A converter). Data Acquisition Box is the chassis where accelerometers and shake table are connected. It can be defined as a bridge between DAQ card and accelerometers and / or shake table.

In experiments, NI PCle-6353 X Series Data Acquisition Card (see in Figure 3.4 (b)) and NI SCB-68 Data Acquisition Box (see in Figure 3.4 (c)) were used. The DAQ card has 16 analog inputs, sample rate of 1.25 MS/s and 16-bit resolution.

Maximum voltage range of this card is about ±10 V. The data acquisition box has 68 pin sockets.

(a)

(b)

(c)

Figure 3.4 (a) CXL-GP Series Crossbow CXL04GP1 model capacitive accelerometer, (b) PCle-6353 X Series Data Acquisition Card and (c) NI SCB-68 Data Acquisition Box.

The last part of the DAQ System is a computer with programmable software. This part is required for adjusting all relations between DAQ hardware (accelerometers, shake table, DAQ card, etc.). In this study, NI Labview 2012 software was used in experiments for this purpose.

3.3 Three Storey-One Bay Aluminum Specimen

For application of OTT with specimen on shake table, modal parameter estimation and damage detection studies; a three storey-one bay aluminum specimen was designed to use in experiments. Total height of the specimen, the storey height of which is 0.25 m, is 0.75 m. Plan dimensions are 0.15 m x 0.10 m and the plate thickness is 0.006 m. Weight of the specimen is 27.46 N. Additional loads (39.23 N per storey) were used to reduce the stiffness of the specimen. Finally, the total weight of the specimen is 145.13 N with additional loads.

There were two main limitations in material and dimension selection of specimen design. First one was the load capacity of the shake table (225.54 N in horizontal configuration) and the other one was the frequency range of shake table (0-200 Hz). Because of these reasons, aluminum material was selected due to its low weight and flexibility (aluminum is about three times lighter than steel and its elasticity module is one third of elasticity module of steel).

Before the specimen production, lots of specimens (having different dimensions and additional loads) were modeled and dynamic analyses were performed by the help of numerical methods and SAP2000® software. Specimens were modeled as shear frame in analyses. This assumption gives bigger natural vibration frequencies than real model behavior and let us in safe area about exceeding the frequency range of the shake table. After evaluations, ultimate state of specimen properties was decided to produce. Estimated natural vibrations frequencies of the specimen which was decided to produce are 8.004 Hz, 24.907 Hz and 41.075 Hz respectively. It was approved that these frequency values can show an alteration for real model because of workmanship, welded connections and shear frame assumption. Pictures and plans of the ultimate specimen were given below in Figures 3.5 and 3.6 respectively.

Figure 3.5 Different views of the specimen.

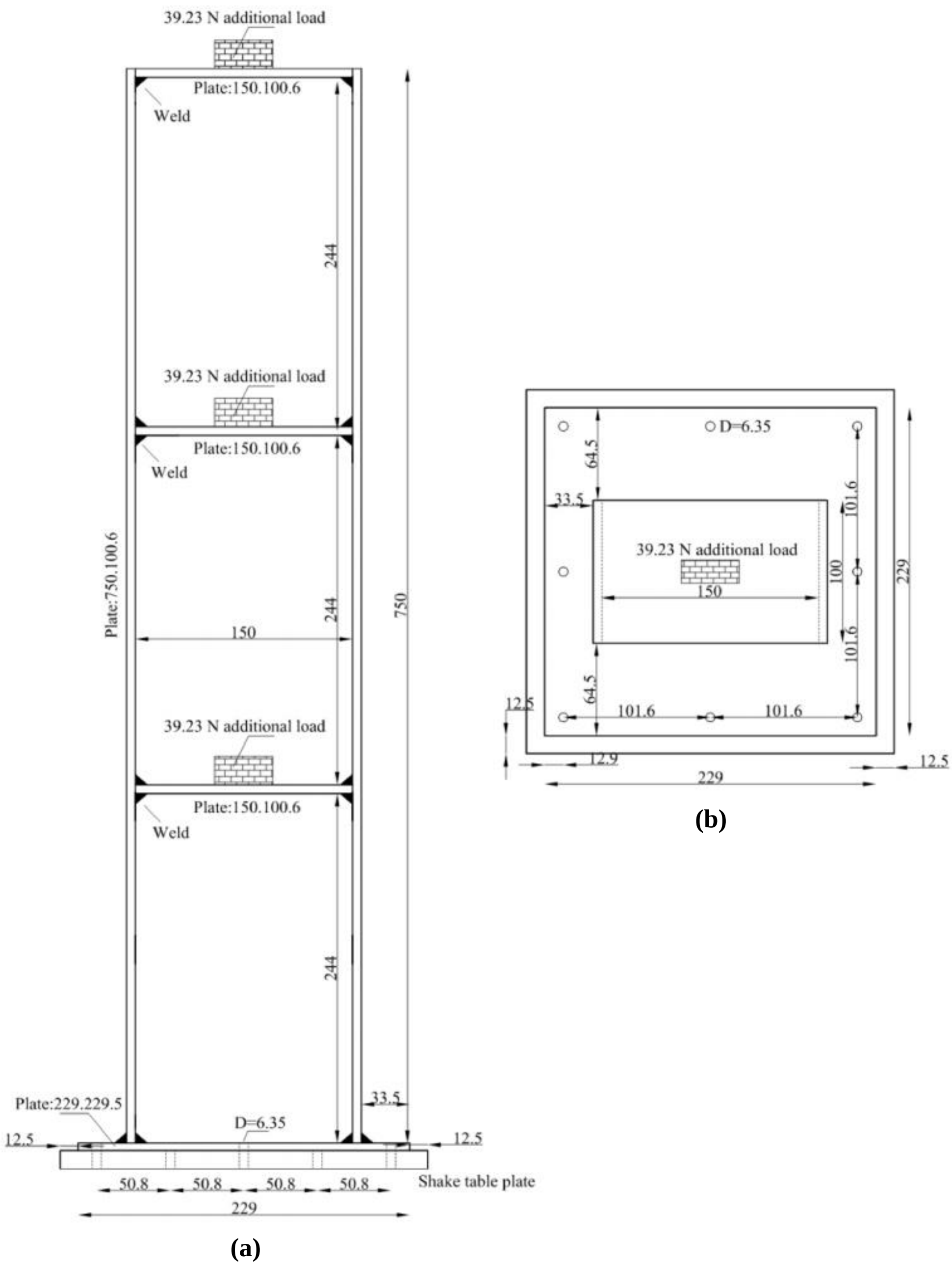


Figure 3.6 (a) Front view and (b) plan view of the specimen.

For representing the undamaged specimen case in damage detection studies, two opposing diagonals (see in Figure 3.7) were used at first storey of the specimen. The damaged specimen case was performed by removing these diagonals. Each diagonal has 0.235 m length, $2.83x10^{-5}$ m^2 cross sectional area and elasticity module of the material is about 7 GPa. Diagonals were attached to specimen at 57 degrees above horizontal line by using bolts.

Figure 3.7 A view of the diagonal which was used at first storey to represent undamaged specimen case.

After the introduction of equipments, the ultimate experiment setup was given below in Figure 3.8.

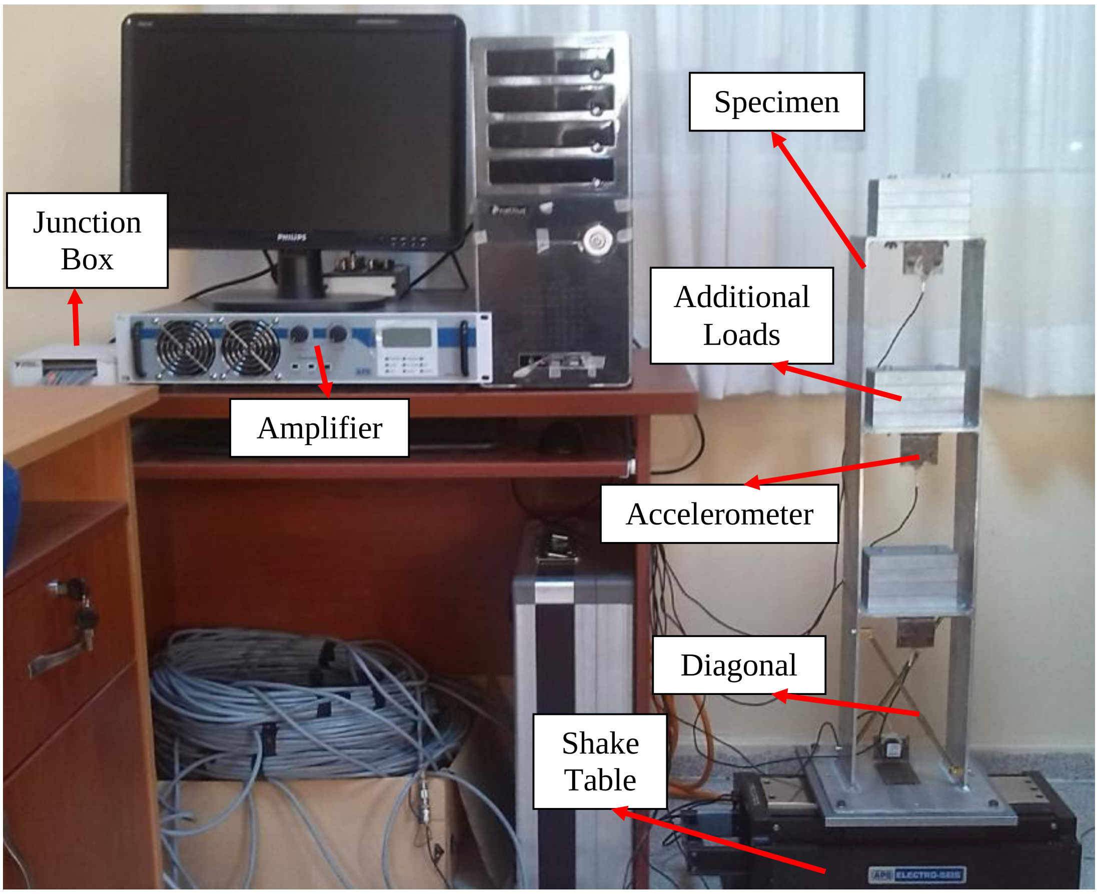


Figure 3.8 A view from ultimate test setup.

CHAPTER FOUR
EXPERIMENTAL STUDIES

4.1 Applications of Offline Tuning Technique

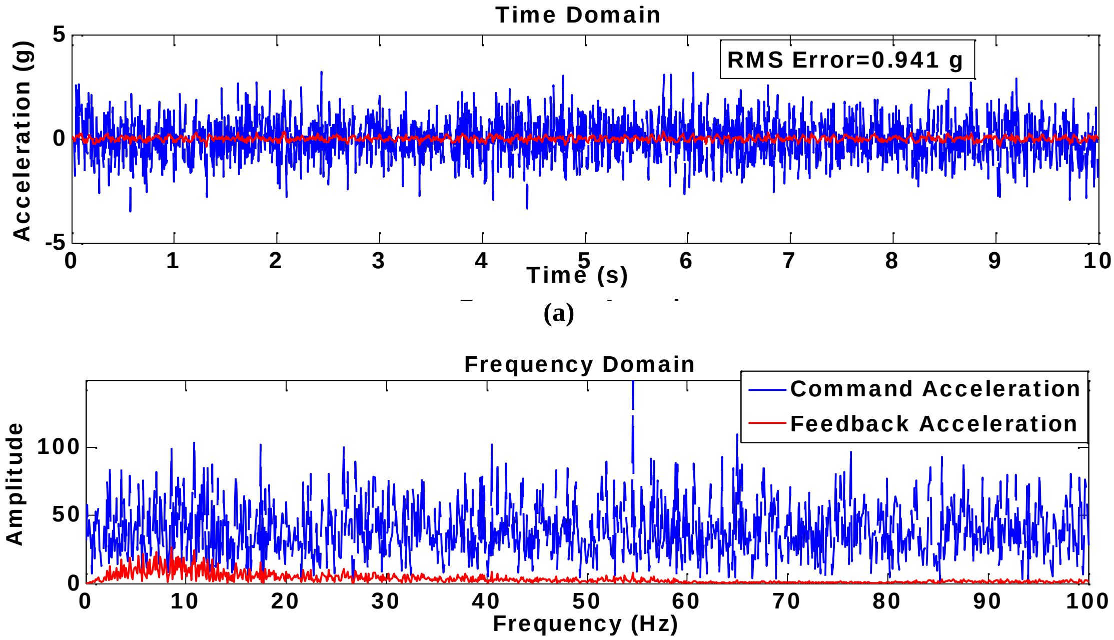
This section includes two main parts: (i) Application of OTT for shake table without specimen and (ii) application of OTT for shake table with specimen on it. Second one is a good example to investigate the shaker-specimen interaction. First of all, shake table without specimen state was investigated.

4.1.1 Offline Tuning Technique for Shake Table without Specimen

For this purpose, 10 seconds long white noise signal whose root mean square (RMS) value is 1 g and frequency bandwidth is 0-100 Hz was sent to the shake table. Formulation of RMS value was given in Equation 4.1. In formulation, N is the total point number of the signal and x_i is the value of the ith point of signal. During the experiments, while the shake table was shaking because of command signal, motion of the table was recorded by an accelerometer (feedback acceleration) which was mounted on the table before. Obtained results were given below in Figure 4.1.

$$X_{rms} = \sqrt{\frac{\sum_{i=1}^{N} \left(x_i\right)^2}{N}} \tag{4.1}$$

It is explicit in Figure 4.1 that there is a trajectory tracking problem between command and feedback signals in time and frequency domain. Shake table applied a minimization effect to command signal. It is possible to express the problem numerically by using RMS Error parameter. This parameter defines the similarity between two signals. Smaller values of the parameter mean good similarity and zero value means that the signals are same. Formulation of the parameter was given in Equation 4.2. Here, N is the total point number of the signal, $(x_i)_{cmd}$ is the value of the ith point of command signal and $(x_i)_{fbk}$ is the value of the ith point of feedback signal. For accelerations in Figure 4.1, the RMS Error value was calculated as 0.941 g. This value is meaningless when it is considered alone. However, it finds meaning when compared with another RMS Error parameter.



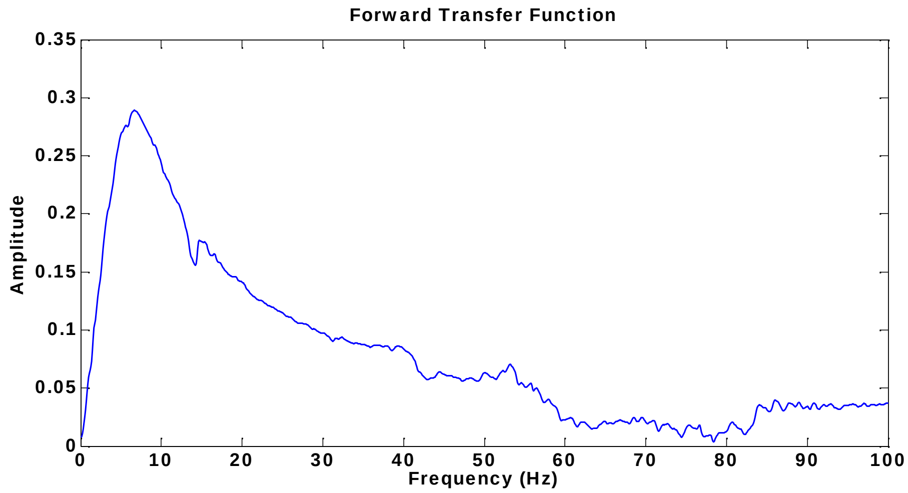
(b)

Figure 4.1 Command Signal-Feedback Signal relations without OTT (a) in time domain and (b) in frequency domain.

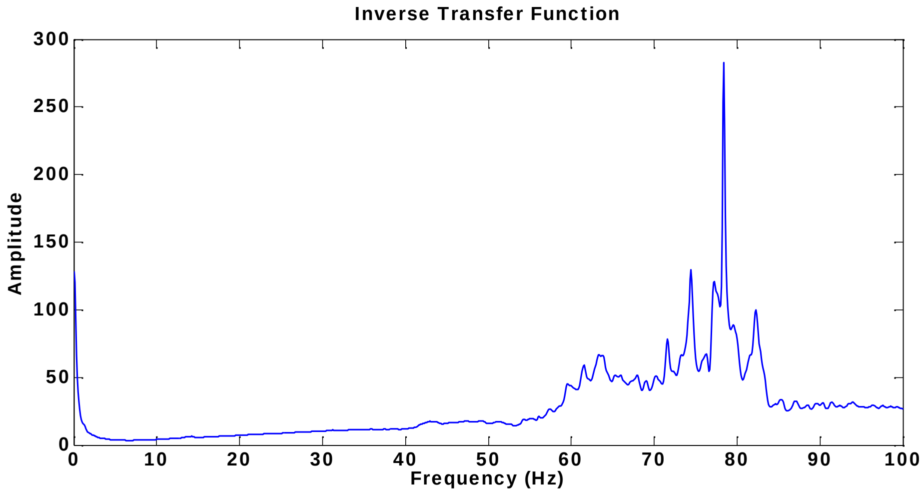
$$RMS_{error} = \sqrt{\frac{\sum_{i=1}^{N}\left((x_i)_{cmd} - (x_i)_{fbk}\right)^2}{N}} \tag{4.2}$$

To solve the trajectory tracking problem in Figure 4.1, FTF and ITF are required as it was mentioned before in detail in Chapter 2. These functions were estimated by using MATLAB® software and the results were given below in Figure 4.2.

By investigating the FTF in Figure 4.2 (a), it can be concluded that the shake table applies a minimization effect (which is more effective at higher frequency values) to whole frequency components of the command signal due to the amplitudes of FTF which are less than 1 in frequency domain. This situation causes problems in time domain too. If attention paid, a valley can be seen about 15 Hz in FTF. It is thought that the valley occurred because of internal components of the shake table.



(a)



(b)

Figure 4.2 (a) Forward transfer function and (b) inverse transfer function of shake table without OTT.

It is obvious in Figure 4.2 (b) that the command signal must be amplified for the solution of the trajectory tracking problem and in this way, modified command signal was constituted by multiplying real command signal and ITF in frequency domain. IFFT of this signal was taken to get the time domain components of modified command signal. Thus, a new command signal was obtained for shake table (see in Figure 4.3).

Here, a new problem is encountered. As can be seen in Figure 4.3, the modified command acceleration values are too large and it is impossible to send such a signal to shake table because of its limitations. Peak values after 60 Hz in Figure 4.2 (b) are the reasons of this problem. Therefore, this problem can be overcome by filtering these frequency contents. After this process, the obtained new command signal can be called as "Modified & Filtered Input Signal (MFIS)" and given in Figure 4.4.

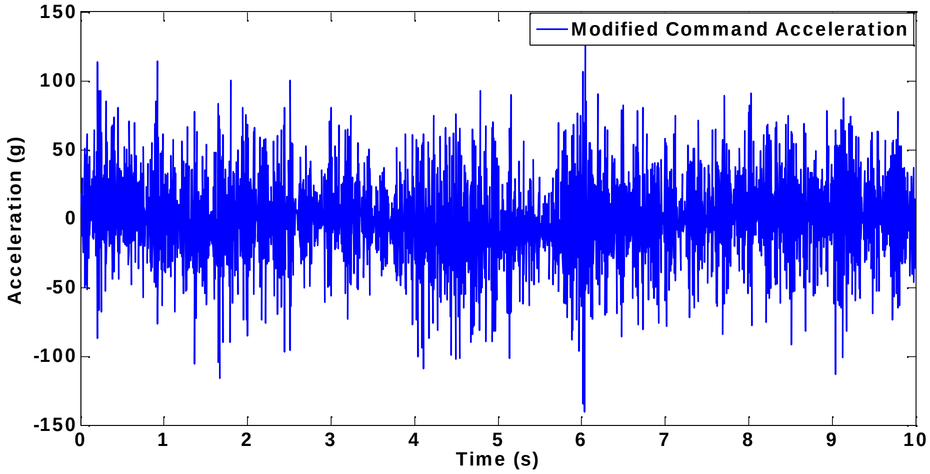


Figure 4.3 Modified command acceleration.

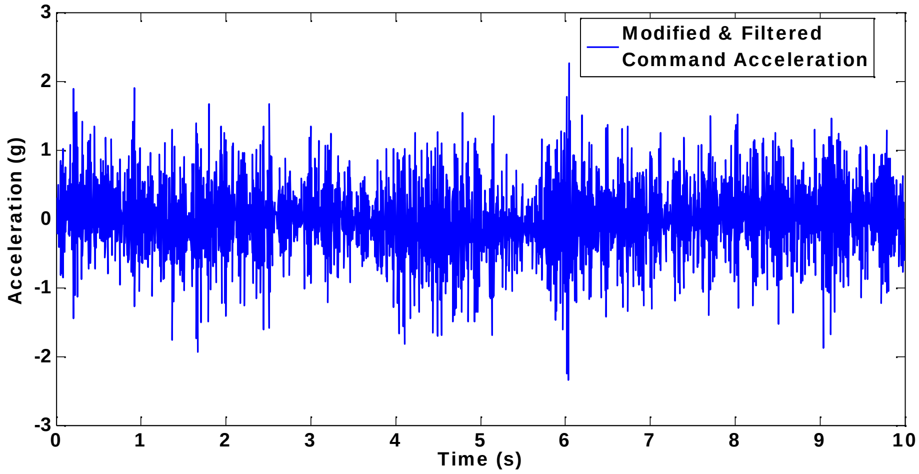


Figure 4.4 Modified & filtered command acceleration.

To understand the necessity of OTT in analyses, Tables 4.1 and 4.2 can be investigated. In Table 4.1, sine waves with 2 Hz angular frequency (amplitudes vary from 0.1 g to 3.2 g) were used as command (cmd) signals.

Table 4.1 Fdbk signal/cmd signal ratios for 2 Hz sine signals whose amplitudes vary from 0.1g to 3.2g

Cmd Peak (g)	**Fdbk Peak (g)**	**Fdbk/Cmd Ratio**	**Cmd Peak (g)**	**Fdbk Peak (g)**	**Fdbk/Cmd Ratio**
0.1	0.011	0.110	1.7	0.205	0.120
0.2	0.023	0.113	1.8	0.220	0.122
0.3	0.040	0.132	1.9	0.226	0.119
0.4	0.055	0.136	2.0	0.238	0.119
0.5	0.062	0.124	2.1	0.250	0.119
0.6	0.076	0.127	2.2	0.262	0.119
0.7	0.086	0.122	2.3	0.277	0.120
0.8	0.097	0.121	2.4	0.284	0.118
0.9	0.103	0.115	2.5	0.304	0.122
1.0	0.121	0.121	2.6	0.315	0.121
1.1	0.136	0.123	2.7	0.324	0.120
1.2	0.142	0.118	2.8	0.336	0.120
1.3	0.161	0.124	2.9	0.342	0.118
1.4	0.167	0.119	3.0	0.356	0.119
1.5	0.184	0.123	3.1	0.368	0.119
1.6	0.191	0.119	3.2	0.378	0.118
Average of the all Feedback/Command ratios=0.121					

It can be concluded from Table 4.1 that the amplitude of the command signal does not affect the fdbk signal/cmd signal ratio significantly and all the ratio values are close to each other. So, an average ratio can be calculated to represent the system. This ratio was calculated as 0.121 for the system which was defined above. It means that, if a 2 Hz sine signal with amplitude "A" is wanted to be produced on shake table, this signal must be divided by 0.121. After this process, the new signal, whose amplitude is A/0.121, must be sent to shake table. In the light of this information, it can be concluded that the fdbk signal/cmd signal ratio is unique for a specific frequency value and this value does not depend on the amplitude of the signal. In other words, tracking problem is simple and can be solved by using the Equation 4.3 which is obtained from Table 4.1 (OTT is not required).

$$X_{\text{modified}} = X_{\text{cmd}} \big/ 0.121 \qquad (4.3)$$

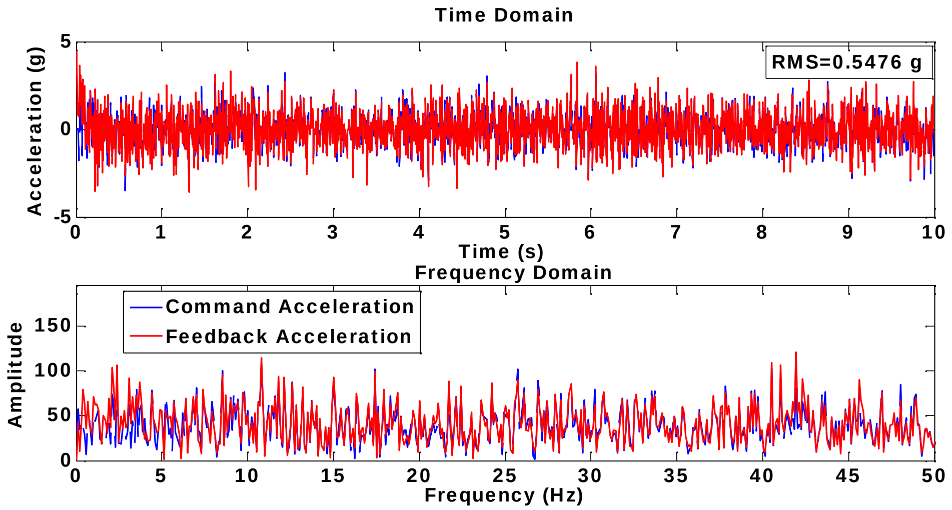
Analysis in Table 4.2 was performed to understand the effects of angular frequency values on modified signal. For this purpose, sine signals, whose amplitudes are 1 g and angular frequency values vary from 0.3 Hz to 4 Hz, were used as command signals for shake table. After, fdbk signal/cmd signal ratios were calculated and obtained results were given below in Table 4.2.

Table 4.2 Fdbk signal/cmd signal ratios for sine signals whose amplitudes are 1 g and angular frequency values vary from 0.3 Hz to 4 Hz

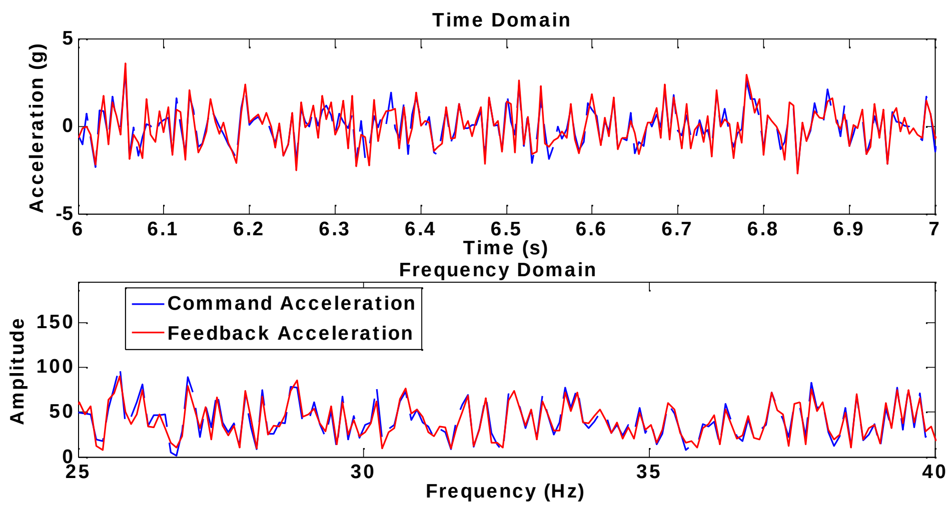
Frequency (Hz)	**Fdbk Peak (g)**	**Fdbk/Cmd Ratio**	**Frequency (Hz)**	**Fdbk Peak (g)**	**Fdbk/Cmd Ratio**
0.3	0.033	0.033	2.2	0.142	0.142
0.4	0.035	0.035	2.3	0.139	0.139
0.5	0.039	0.039	2.4	0.155	0.155
0.6	0.045	0.045	2.5	0.150	0.150
0.7	0.049	0.049	2.6	0.160	0.160
0.8	0.057	0.057	2.7	0.159	0.159
0.9	0.058	0.058	2.8	0.174	0.174
1.0	0.067	0.067	2.9	0.170	0.170
1.1	0.068	0.068	3.0	0.184	0.184
1.2	0.077	0.077	3.1	0.184	0.184
1.3	0.081	0.081	3.2	0.194	0.194
1.4	0.091	0.091	3.3	0.193	0.193
1.5	0.093	0.093	3.4	0.205	0.205
1.6	0.101	0.101	3.5	0.202	0.202
1.7	0.101	0.101	3.6	0.216	0.216
1.8	0.113	0.113	3.7	0.212	0.212
1.9	0.116	0.116	3.8	0.227	0.227
2.0	0.125	0.125	3.9	0.225	0.225
2.1	0.126	0.126	4.0	0.233	0.233
Average of the all Command/Feedback ratios=0.129					

It is explicit in Table 4.2 that fdbk signal/cmd signal ratio values differ from each other based on angular frequency values of the command signal. Therefore, using a unique ratio value (calculated average ratio) becomes meaningless and it is required to use OTT for the solution of tracking problem.

When MFIS was used as command signal, the obtained results were given below in Figure 4.5.



(a)



(b)

Figure 4.5 (a) Command and feedback signals in time and frequency domain after OTT was applied, (b) a detailed view of 6-7 sec. and 25-40 Hz bandwidth.

It is obvious in Figure 4.5 that the trajectory tracking problem was solved and better tracking performance was obtained. This result can be observed by investigating the RMS Error values too. Before OTT, RMS Error value was 0.941 g and after OTT this value reduced to 0.548 g (similarity between signals increased).

4.1.2 Offline Tuning Technique for Shake Table with Specimen

In this section, OTT was applied to a shake table with specimen on it (see in Figure 4.6). This situation also includes shaker-specimen interaction and important for modal analysis and damage detection as it was explained in following sections.

The steps of OTT which were applied here is same as before (OTT without specimen) and there are no big differences between them in operation sequences. Only difference is the specimen which was mounted on the shake table. This situation affects the transfer functions of the table because of the interaction.

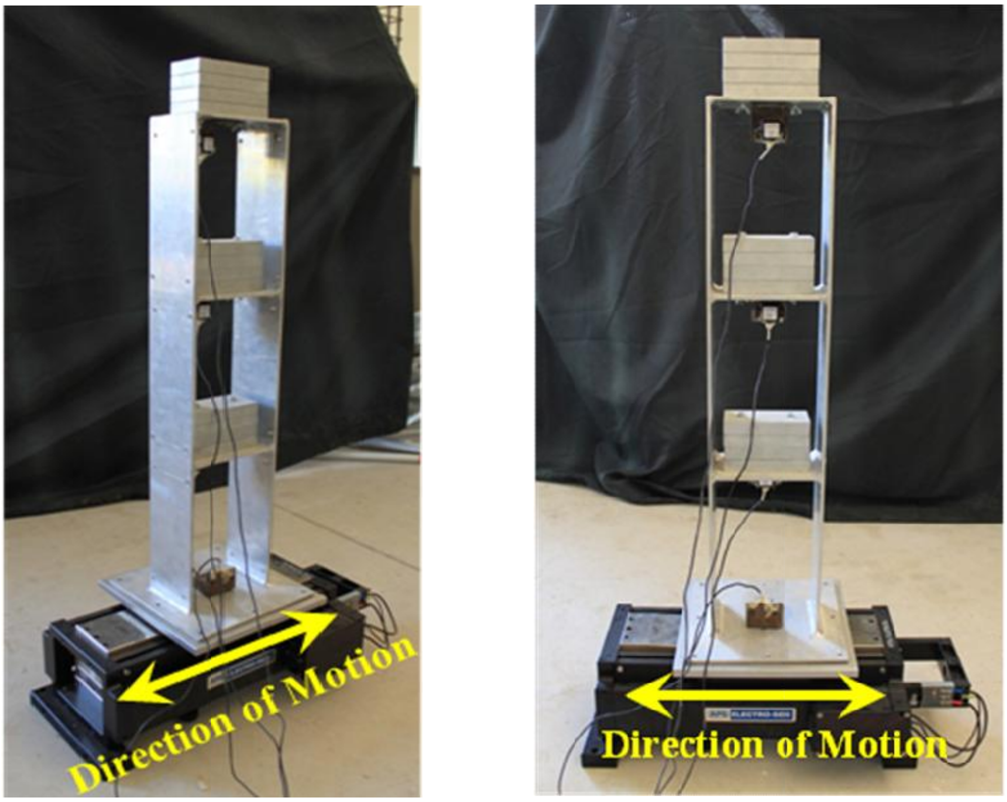


Figure 4.6 Different views of the shake table-specimen system.

In Figure 4.6, it can be seen that accelerometers were mounted at all storeys of the specimen. For now, these are meaningless for OTT except the accelerometer at base.

This base accelerometer can be thought as it is on the shaker and it records the motion of the shake table.

To investigate the OTT in such situation, firstly a 120 seconds long white noise signal, whose RMS value is 1 g and frequency bandwidth is 0-100 Hz, was sent to the shake table. White noise signal was selected as excitant because of the rich frequency content which includes the natural vibration frequency values of the specimen too. During the experiments, while the shake table was shaking because of command signal, motion of the table was recorded by the base accelerometer (feedback acceleration). Results were given below in Figure 4.7.

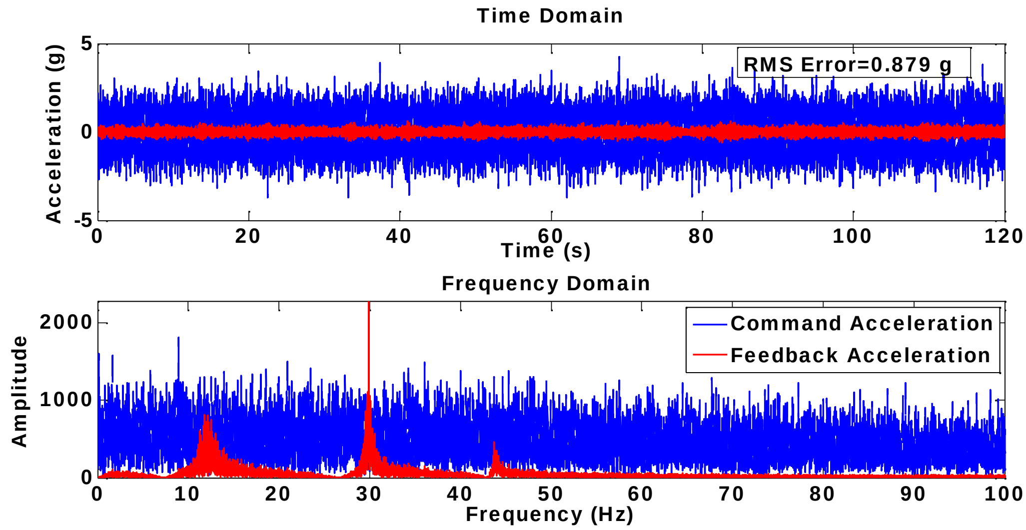
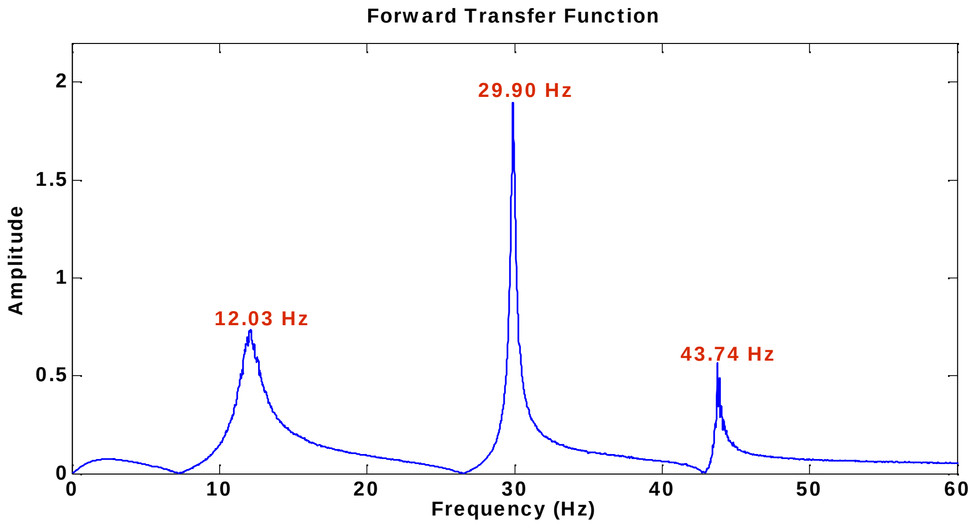
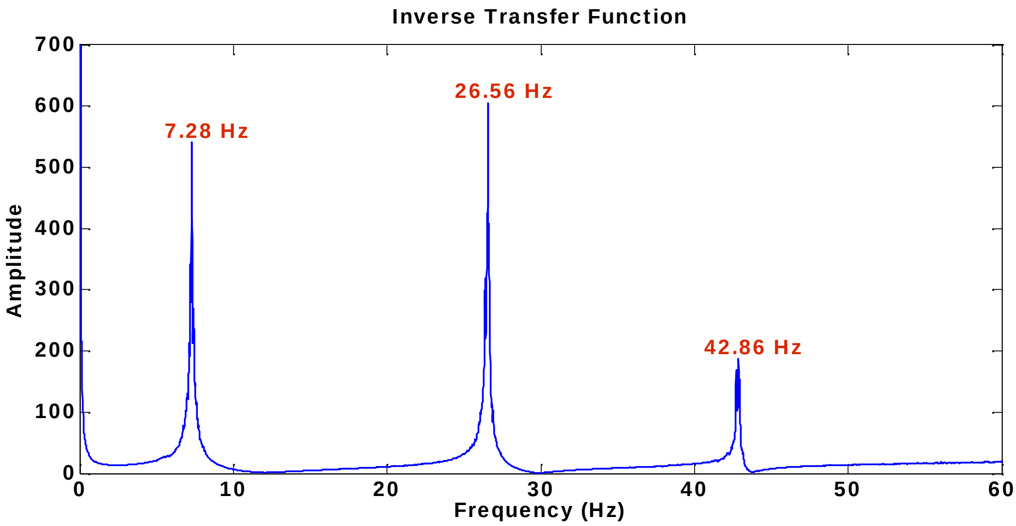


Figure 4.7 Command Signal-Feedback Signal relations in time and frequency domain for shaker-specimen system without OTT.

The figure above includes lots of important information inside it. First of all, there are huge differences between command and feedback acceleration values in time and frequency domain because of the tracking problem. By investigating the frequency domain, it can be observed that the feedback acceleration values are different from white noise signal. This state blocks to excite the specimen completely. And the peak values of feedback signal in frequency domain (about 12 Hz, 29 Hz and 43 Hz) are the proofs of shaker-specimen interaction. This interaction can be seen by investigating transfer functions (see in Figure 4.8) of the shake table too.



(a)



(b)

Figure 4.8 (a) Forward transfer function and (b) inverse transfer function of shake table-specimen system without OTT.

There are peak values (about 12.03 Hz, 29.90 Hz and 43.74 Hz) in FTF in Figure 4.8. These values occur because of the shaker-specimen interaction. The peaks in ITF (about 7.28 Hz, 26.56 Hz and 42.86 Hz), which correspond valleys in FTF, represent the natural vibration frequencies of the three storey specimen which were determined by impact hammer tests while the specimen was mounted on ground (to get rid of shaker-specimen interaction). Responses of all storeys of the specimen under impact effect were recorded. After this, PSD Functions of all storeys were calculated and the natural vibration frequencies of the specimen were extracted from the peak values of these functions as 7.71 Hz, 26.43 Hz and 42.76 Hz respectively. Results were given in Figure 4.9.

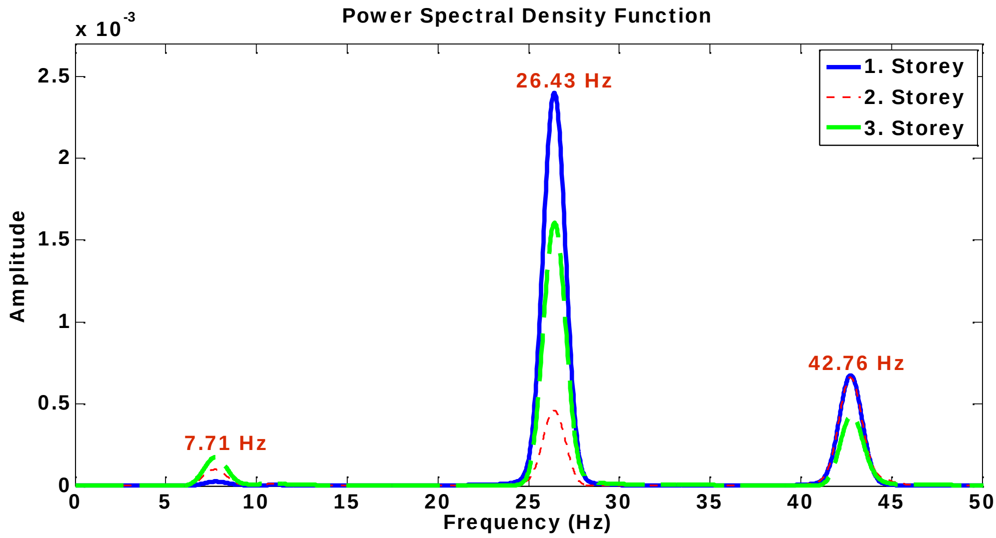


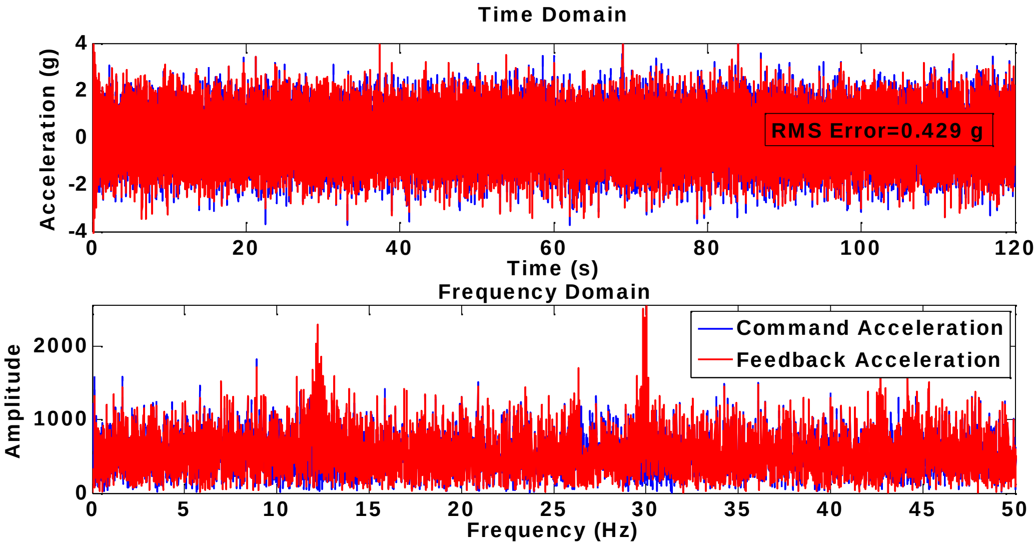
Figure 4.9 Estimated PSD Functions by using responses of impact hammer tests.

It was mentioned before that the valleys in FTF (in Figure 4.8 (a)) represent the natural vibration frequencies of the specimen. Curiously enough, these valleys, which occur because of shaker-specimen interaction, mean that the shake table blocked and did not produce these frequency values although it was wanted to be produced to excite the specimen. In other words, the broad banded spectrum input signal (white noise) has lost this property because of the interaction.

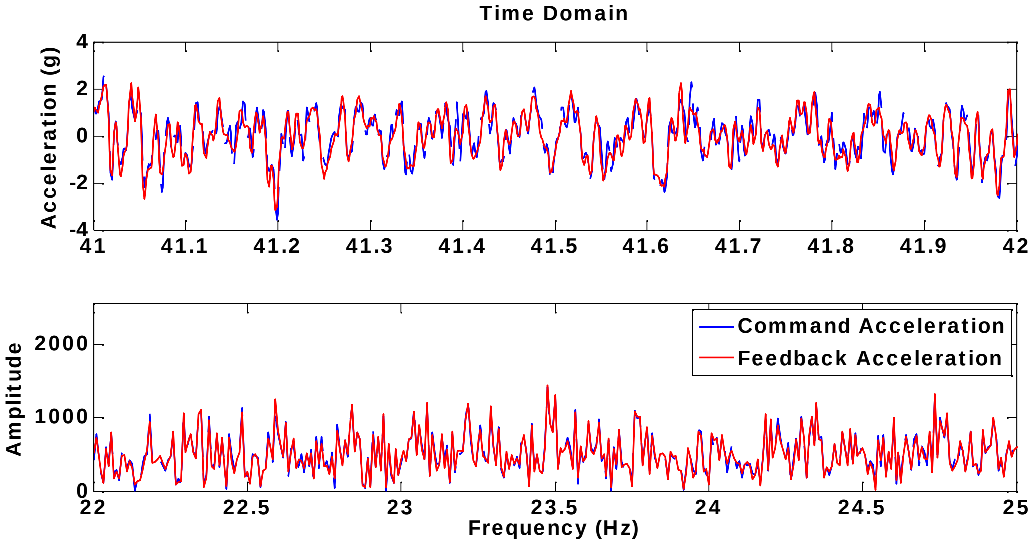
Real values of the natural vibration frequencies of the specimen (7.71 Hz, 26.43 Hz and 42.76 Hz) are different from the theoretically calculated frequency values (8.004 Hz, 24.907 Hz and 41.075) because of the shear frame assumption, welded connections, workmanship, etc.

To solve the trajectory tracking problem which was demonstrated in Figure 4.7, OTT was performed. The obtained results after OTT were given in Figure 4.10. As it can be seen in figure, command and feedback signals became more similar (almost same) in time and frequency domain after the application of OTT. In addition, RMS Error value of 0.429 g (it was 0.879 g before) also verifies this result in numerical manner. In the light of this information and observations, it can be concluded that

OTT is a successful method for shaker-specimen systems besides the success for shake tables without specimen.



(a)



(b)

Figure 4.10 (a) Command and feedback signals for shaker-specimen system in time and frequency domain after the application of OTT, (b) a detailed view of 41-42 sec. and 22-25 Hz frequency bandwidth.

4.2 Applications of Fourier Amplitude Spectra Method and Half-Power (Band-Width) Method on Three-Storey Specimen and Effects of Offline Tuning Technique on Modal Analysis

Firstly in this section, an application of FAS Method was given. For this purpose, shake table-specimen system (see in Figure 4.6) was used. Responses of the all storeys of specimen were measured by accelerometers under white noise signals (after the application of OTT). To show elementally concepts of the FAS Method, diagonals were not used in this stage of the tests. Results were discussed in following sections.

Before the estimations of PSD Functions, relative acceleration responses of the storeys must be calculated. For this purpose, Equation 4.4 can be used. Here, X_i is the absolute acceleration of the ith storey, X_{base} is the base acceleration which occurs on the shake table and $\mathbf{X}_i$ is the relative acceleration of the ith storey.

$$\mathbf{X}_i = X_i - X_{base} \tag{4.4}$$

After the calculations of relative acceleration values, PSD Functions of the relative storey responses were estimated and given in Figure 4.11.

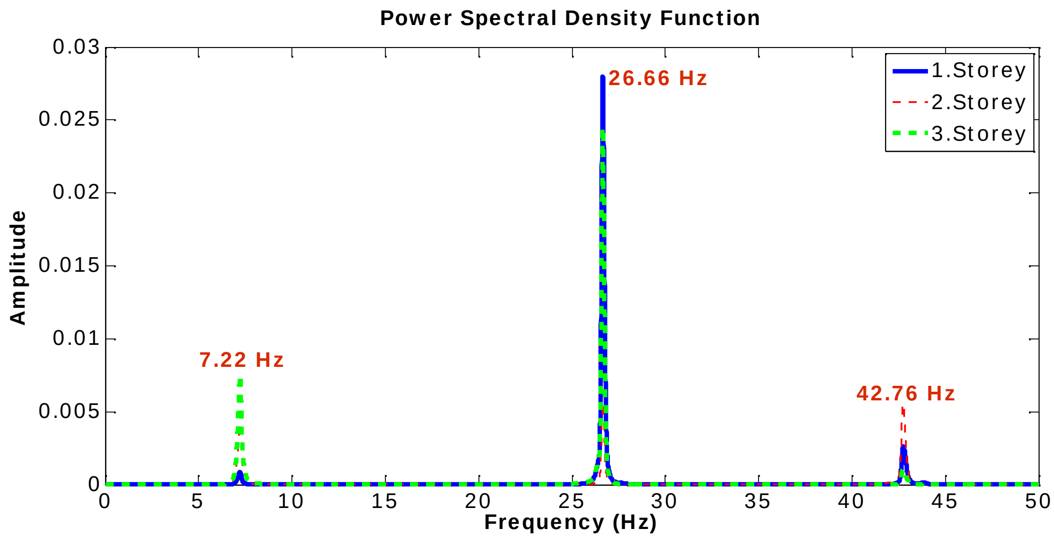


Figure 4.11 Estimated PSD Functions by using relative responses of storeys under white noise tests.

It can be seen from the figure that, peak values of all storeys occurred at same frequency value for a specific mode. The frequency values which are related to the peak values represent natural vibration frequencies of the specimen and were obtained as 7.22 Hz, 26.66 Hz and 42.76 Hz respectively. If care is taken, these frequency values are similar to the natural vibration frequency values of the specimen which were obtained before as 7.71 Hz, 26.43 Hz and 42.76 Hz from impact hammer tests.

As it was mentioned before in Chapter 2, for calculating the amplitudes of mode shapes, square roots of the peak amplitudes of PSD Functions are required. So, the Scaled PSD Functions were calculated by taking square roots of amplitude values of all storeys and the results were given in Figure 4.12. New peak values can occur in this type of PSD Function because of square root process. These are nonsense peaks and can be discounted in analyses.

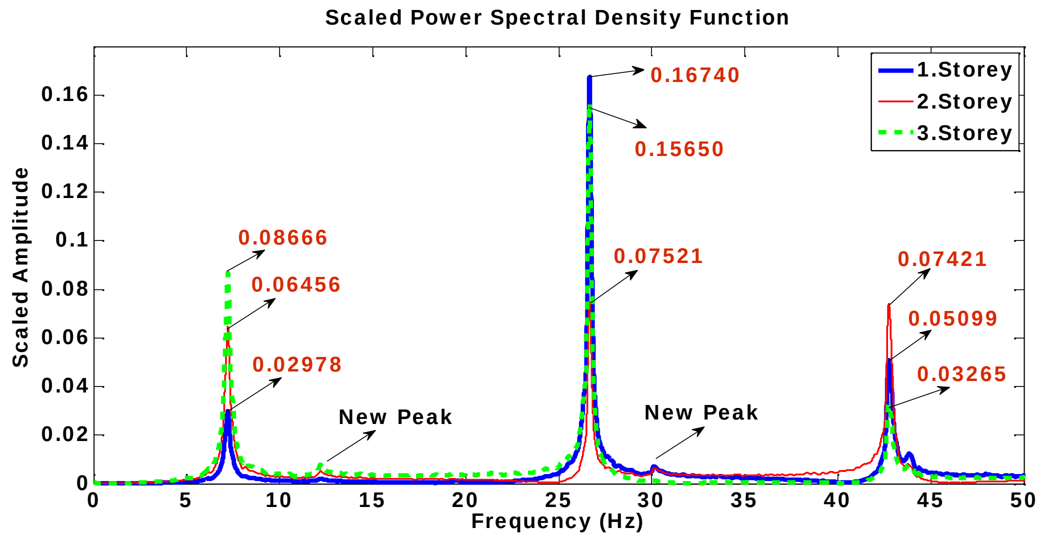


Figure 4.12 Scaled PSD Functions of all storeys for mode shape estimation.

Peak values in Figure 4.12 don't include sign information (positive or negative). For this purpose, CPSD Functions between all storey couples (e.g., between 1. and 2. storeys, between 1. and 3. storeys, etc.) are required. In this manner, CPSD Functions with their phase angle information were estimated and the obtained results were given below in Figure 4.13.

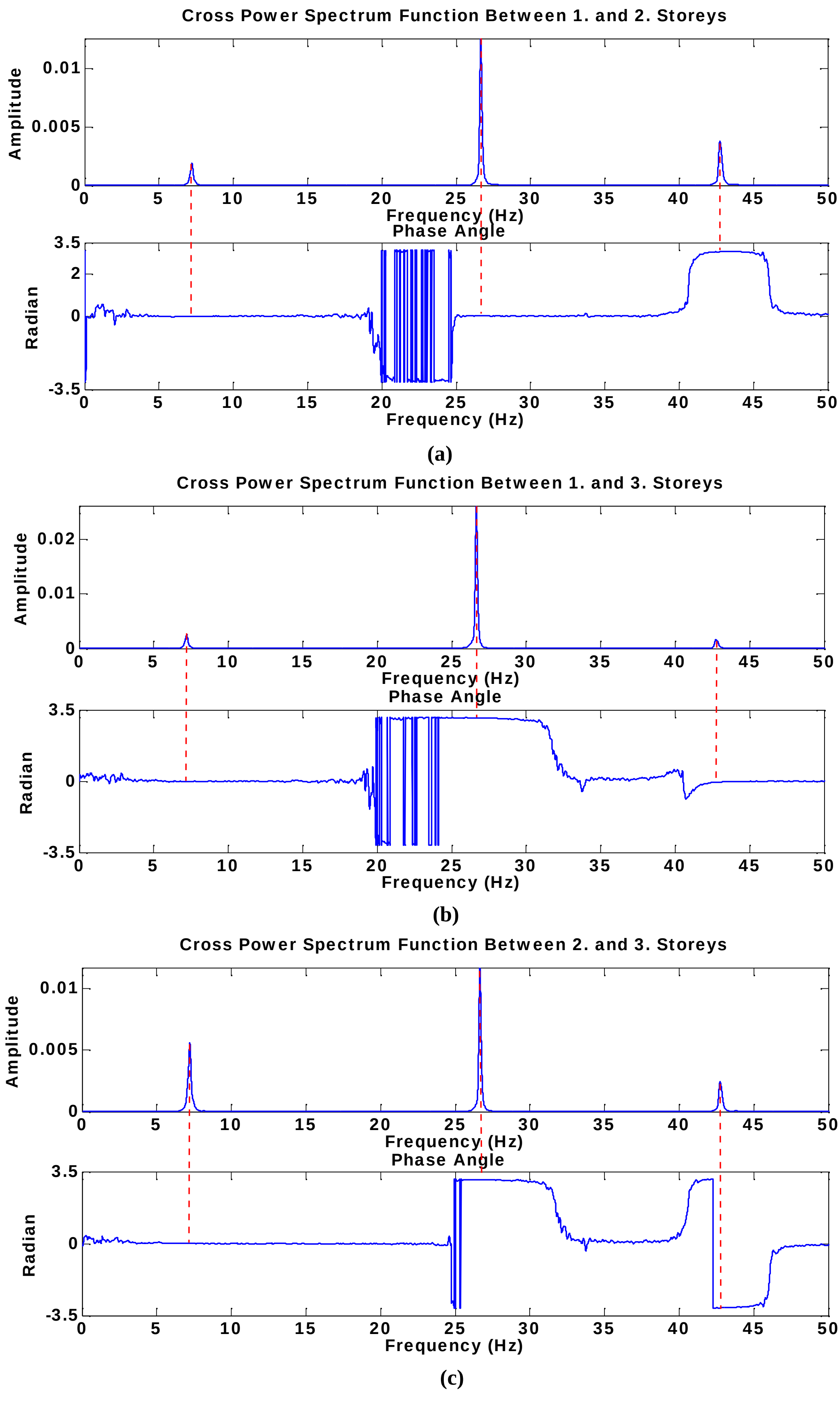


Figure 4.13 CPSD Functions and phase angle information between (a)1. and 2., (b) 1. and 3., (c) 2. and 3. storeys.

To extract the sign information (directions) of mode shapes, vertical lines should be drawn from peak values (at natural vibration frequencies of specimen) in CPSD Functions to phase angle function. The intersection points of the drawn lines and phase angle function correspond to phase angles between the investigated storeys. For instance in Figure 4.13 (a), phase angle between 1. and 2. storeys for second mode can be obtained as 0 radian. This means that, these storeys are in same direction in this mode. If it is assumed that the sign of first storey is (+), then the second storey has (+) sign too. In Figure 4.13 (b) (which is related to the relationship between 1. and 3. storeys), phase angle is obtained as 3.14 (π) radian for second mode. This means that, 1. and 3. storeys are in opposite direction in this mode. So the sign of third storey becomes (-). Finally, signs of first, second and third storeys can be obtained as (+, +, -) respectively for second mode of the specimen. Other CPSD Function and phase angle information (Figure 4.13 (c)) can be used for control. Here, there is -3.14 (-π) radian phase angle between second and third storeys. So the sign of the third storey becomes (-) as it was obtained before.

Similar operations can be performed to determine the signs of the mode shape amplitudes which are related to other modes. By combining these signs with amplitude values which were obtained in Figure 4.12, modal matrix (modal coordinates) of the specimen can be obtained. The modal matrix, which was normalized by the amplitude of first storey, was given below in Table 4.3. Here, the normalization process can be done by using another storey. This event does not affect the results.

Table 4.3 Modal matrix of the specimen

Storey Number	**Mode Number**		
	1.	*2.*	*3.*
1.	+1.000	+1.000	+1.000
2.	+2.168	+0.449	-1.456
3.	+2.910	-0.935	+0.640

By using the modal matrix, mode shapes of the specimen can be drawn. Experimental (obtained by FAS Method) and analytical (obtained by SAP2000®

Software) mode shapes were given together for comparison in Figures 4.14, 4.15 and 4.16 respectively. For analytical comparison of these mode shapes, Modal Assurance Criterion (MAC) can be used (Allemang & Brown, 1992). The closeness of the criterion to unit value is the indicator of the similarity between two mode shapes. Formulation of the criterion was given in Equation 4.5. In formula, $(\ddot{\ }_{SAP})_i$ and $(\ddot{\ }_{FAS})_i$ symbols represent the modal vector of ith mode which were estimated by SAP2000® and FAS Method respectively. Besides, $(\ddot{\ }^{T}_{SAP})_i$ and $(\ddot{\ }^{T}_{FAS})_i$ are the transposes of these notions. Because of being a visual process, normalization does not affect the calculation of MAC value in analyses.

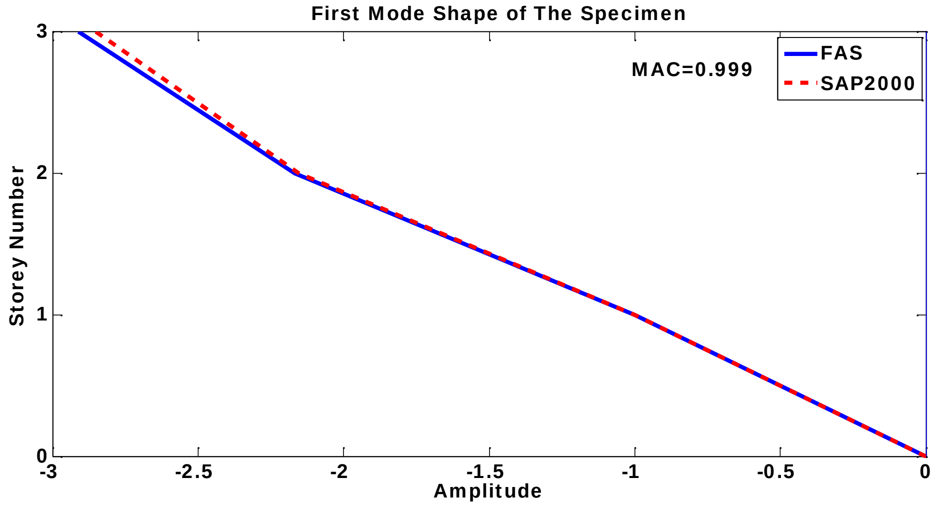


Figure 4.14 First mode shape of the specimen which was obtained from FAS Method and SAP2000®.

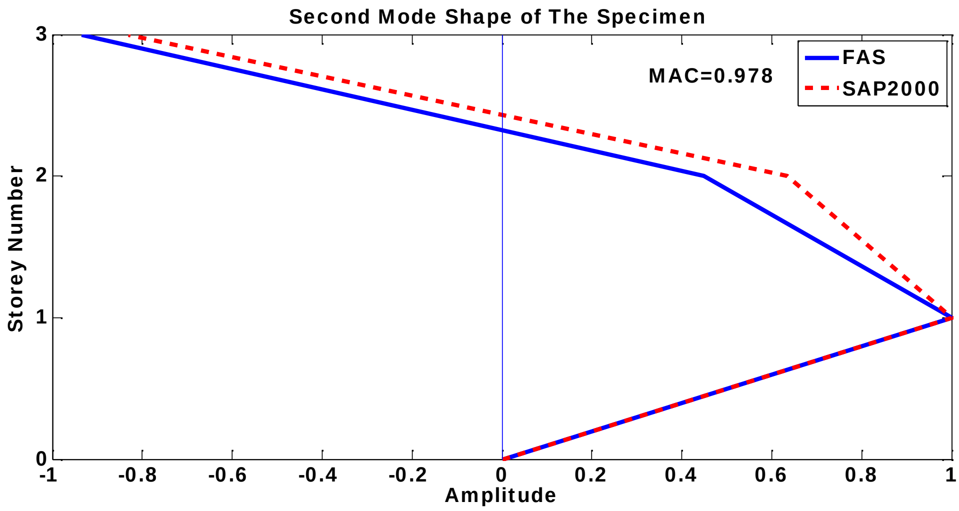


Figure 4.15 Second mode shape of the specimen which was obtained by FAS Method and SAP2000®.

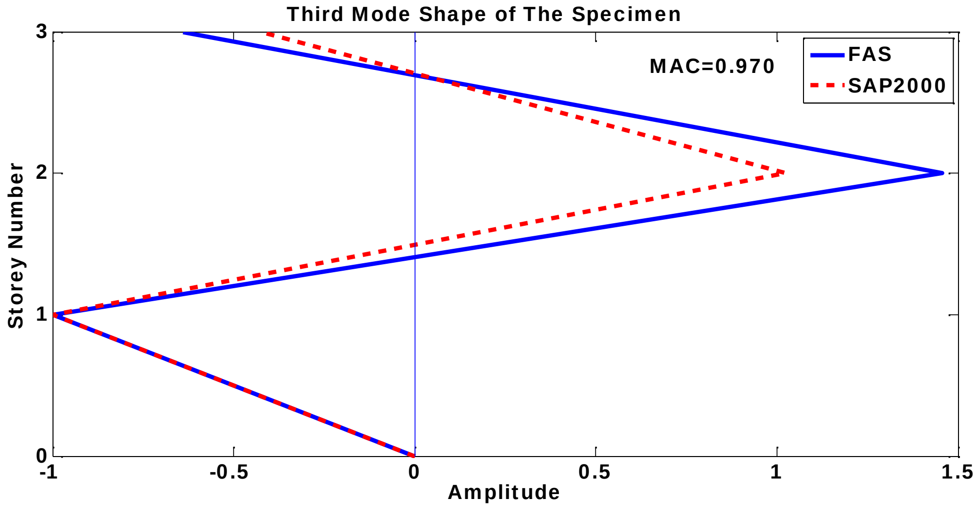


Figure 4.16 Third mode shape of the specimen which was obtained by FAS Method and SAP2000®.

$$MAC_i((\phi_{SAP})_i,(\phi_{FAS})_i)=\frac{((\phi_{SAP}^T)_i(\phi_{FAS})_i)^2}{((\phi_{SAP}^T)_i(\phi_{SAP})_i)((\phi_{FAS}^T)_i(\phi_{FAS})_i)} \tag{4.5}$$

When Figures 4.14, 4.15 and 4.16 are investigated, it can be observed that the mode shapes, which were estimated by different methods, are similar to each other. In addition, calculated MAC values for first, second and third modes (0.999, 0.978 and 0.970 respectively) verify this observation in numerical manner. Another way to verify the accuracy of the results is the coherence functions between storey couples (see in Figure 4.17). Unit values in coherence functions at the natural vibration frequency values, which were obtained before as 7.22 Hz, 26.66 Hz and 42.76 Hz, represent linearity between storey couples. This result is important for FAS Method which provides good results for linear systems.

Damping ratios of the specimen were estimated by using Half-Power (Band-Width) Method. An application of the method by using PSD Function of first storey at second mode of the specimen (other storeys and modes can be selected too) was given in Figure 4.18. Here, (i) firstly peak level of the PSD Function at second natural vibration frequency value (26.66 Hz) was determined. (ii) A horizontal line was constructed at 1/√2 times the peak level. (iii) Two frequencies (f_1 and f_2), where the horizontal line cuts the PSD Function curve, were determined. (iv) And last, the damping ratio was calculated as 0.24% by using Equation 2.10. Method was applied to other peak values in PSD Function to obtain the damping ratios of other modes. Results were given in following sections.

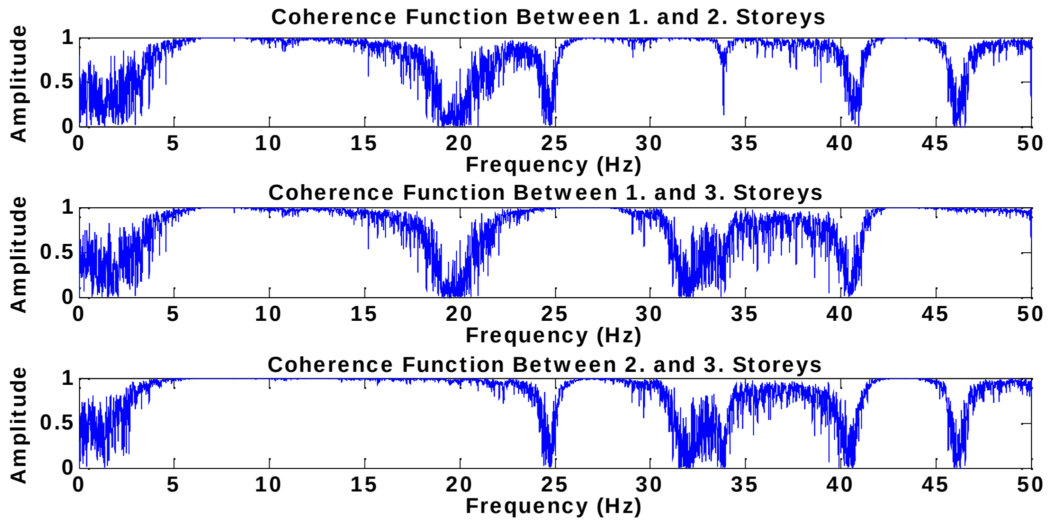


Figure 4.17 Coherence functions of storey couples.

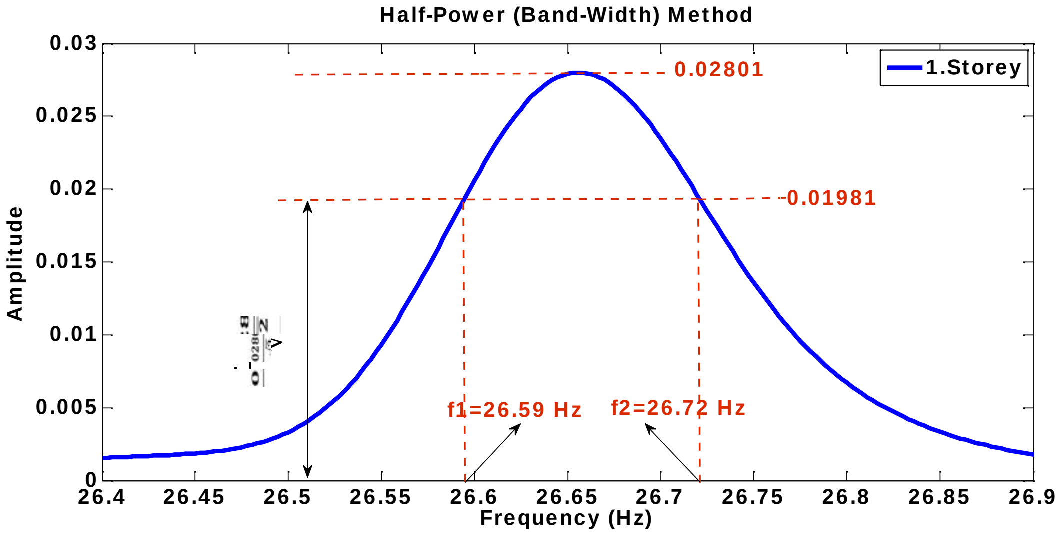


Figure 4.18 Half-Power (Band-Width) Method application for first storey second mode of the specimen.

To investigate the effects of the OTT on modal analysis, same operations above were performed without using OTT. In such case, command signal loses its broad band frequency content and cannot excite the specimen completely as it was mentioned before. The results, which were obtained with OTT and without OTT, were given below in Table 4.4 in comparison with other methods. Because of providing meaningless and unhealthful information for short duration signals, PSD Functions of impact hammer tests cannot be used to modal parameter estimation except natural vibration frequency determination.

Table 4.4 Comparison of the modal parameters which were estimated by different methods

Method	OTT		1. Mode	2. Mode	3. Mode	MAC With SAP2000		
						1. Mode	2. Mode	3. Mode
SAP2000	-	*Freq.(Hz)*	8.01	24.91	41.08	-	-	-
		Damping ratio (%)	-	-	-	-	-	-
Impact Hammer Tests	-	*Freq.(Hz)*	7.71	26.43	42.76	-	-	-
		Damping ratio (%)	-	-	-	-	-	-
FAS & Half Power Method	Not applied	*Freq.(Hz)*	11.92	29.98	43.86	0.995	0.795	0.916
		Damping ratio (%)	4.49	0.52	0.52			
	Applied	*Freq.(Hz)*	7.22	26.66	42.76	0.999	0.980	0.977
		Damping ratio (%)	0.99	0.23	0.22			
SSI	Not applied	*Freq.(Hz)*	11.92	29.98	43.80	0.996	0.790	0.925
		Damping ratio (%)	6.02	0.56	0.41			
	Applied	*Freq.(Hz)*	7.19	26.66	42.80	0.999	0.980	0.976
		Damping ratio (%)	1.22	0.23	0.25			
EFDD	Not applied	*Freq.(Hz)*	11.85	29.96	43.76	0.995	0.784	0.914
		Damping ratio (%)	5.92	0.64	0.66			
	Applied	*Freq.(Hz)*	7.21	26.66	42.77	0.999	0.979	0.975
		Damping ratio (%)	1.47	0.25	0.23			

Results of SSI and EFDD Methods, which were obtained by using ARTEMIS® Software, were given in Table 4.4 too. These methods are not the issues of this study. So, they were given here to comparison of the results and details of these methods were not mentioned. It is explicit in Table 4.4 that OTT has a great effect on modal analysis. Tests without OTT cause to obtain and interpret wrong results. Natural vibration frequencies and damping ratios were calculated greater than the actual. If care is taken, damping ratio of first mode, which was obtained without the usage of OTT, was calculated larger for such specimen. So, this value does not represent the reality. Besides, existence of OTT affects the calculation of the MAC values. Main reason of these differences is the violation of the excitation all modes of the specimen. Without OTT, the command signal (white noise) loses its broad bandwidth frequency property because of trajectory tracking problem. So, the signal which occurs on the shake table cannot excite the specimen properly. But with OTT, it is ensured to protect the frequency content of the command signal. This situation provides to excite all modes of the specimen and gives realistic results.

4.3 Applications of Damage Index Method and Effects of Offline Tuning Technique on Damage Estimation Process

In this section, Damage Index Method was used to damage estimation of the specimen. Algorithms of the method, which were mentioned before in Chapter 2, were programmed in MATLAB® software. Firstly, an application of the method was performed by using SAP2000® analysis program. For this purpose, the three storey specimen was modeled by using 4 bar members at each storey. Two different damage cases were established by reducing the elasticity module of the third member of first storey by 25% (Case I) and 90% (Case II). After, modal matrices of these cases were obtained to be used in Damage Index Method algorithms. Acquired parameters of the method for two cases were given below in Tables 4.5 and 4.6.

After the simulation studies, an application of the method was considered by using experimental data. Two diagonals were attached into first storey to represent the undamaged case of the specimen. Damaged case was established by removing these diagonals. Details were given in following sections.

Table 4.5 Damage parameters of Damage Index Method for Case 1

Storey	Member	DI_{rj}			a_{rj}		
		1. Mode	2. Mode	3. Mode	1. Mode	2. Mode	3. Mode
1	1	1.0010	1.0003	0.9999	-0.0010	-0.0003	0.0001
	2	***1.0072***	***1.0032***	1.0004	***-0.0071***	***-0.0032***	-0.0004
	3	***1.0050***	***1.0017***	0.9999	***-0.0050***	***-0.0017***	0.0001
	4	0.9970	0.9977	0.9991	0.0030	0.0023	0.0009
2	5	0.9992	1.0003	0.9998	0.0008	-0.0003	0.0002
	6	0.9965	1.0014	0.9994	0.0035	-0.0014	0.0006
	7	0.9965	1.0014	0.9994	0.0035	-0.0014	0.0006
	8	0.9992	1.0003	0.9998	0.0008	-0.0003	0.0002
3	9	0.9997	0.9994	1.0002	0.0003	0.0006	-0.0002
	10	0.9987	0.9976	1.0009	0.0013	0.0024	-0.0009
	11	0.9987	0.9976	1.0009	0.0013	0.0024	-0.0009
	12	0.9997	0.9994	1.0002	0.0003	0.0006	-0.0002

Table 4.6 Damage parameters of Damage Index Method for Case 2

Storey	Member	DI_{rj}			a_{rj}		
		1. Mode	2. Mode	3. Mode	1. Mode	2. Mode	3. Mode
1	1	1.0017	0.9972	0.9979	-0.0017	0.0028	0.0021
	2	***1.0314***	1.0025	0.9943	***-0.0304***	-0.0025	0.0058
	3	***1.1115***	***1.0505***	1.0081	***-0.1003***	***-0.0481***	-0.0080
	4	0.9754	0.9823	0.9939	0.0252	0.0181	0.0062
2	5	0.9905	1.0034	0.9983	0.0096	-0.0034	0.0017
	6	0.9588	1.0158	0.9929	0.0430	-0.0155	0.0072
	7	0.9588	1.0158	0.9929	0.0430	-0.0155	0.0072
	8	0.9905	1.0034	0.9983	0.0096	-0.0034	0.0017
3	9	0.9968	0.9935	1.0022	0.0032	0.0065	-0.0022
	10	0.9853	0.9732	1.0098	0.0149	0.0275	-0.0097
	11	0.9853	0.9732	1.0098	0.0149	0.0275	-0.0097
	12	0.9968	0.9935	1.0022	0.0032	0.0065	-0.0022

As it can be seen in Tables 4.5 and 4.6, DI_{rj} parameter (represents damage when larger than 1) and a_{rj} parameter (represents damage when smaller than 0) detected damage about second and third (really damaged) members (bold, italic and underlined values in tables). This means that, these parameters can detect the damage location accurately. There are other values that represent damage in tables too. But, these values become meaningless (very small in absolute value) when compared with the parameters which represent the real damage locations. So, locations which were detected by these parameters must be considered as fake locations and must be discounted. And it is important to state that, all modes of a member must be considered and taken into account before the decision of the damage location. This evaluation can lend assistance to eliminate the fake locations. Another important information that can be extracted from tables above is the fact that the damage parameters of a member grow in value when the damage severity of this member is increased. For instance, DI_{rj} parameters of damaged location in Table 4.6 (90% damaged case) are larger than the parameters in Table 4.5 (25% damaged case). Similarly, absolute values of a_{rj} parameters in Table 4.6 are larger than the parameters in Table 4.5.

After numerical analyses, experimental studies were performed for damage detection with Damage Index Method. For this purpose, firstly modal parameters of the specimen which has two diagonals (undamaged specimen case) at first storey were obtained by FAS Method. Modal parameters were estimated after OTT was applied to get accurate results. The obtained modal parameters of specimen with diagonals were given in Table 4.7 with a comparison to parameters of specimen without diagonals. Here, damping ratios of specimen (with diagonals) could not be calculated by FAS Method due to the difficulty of picking peak values from PSD Functions. By investigating the table, it can be said that the diagonals made the specimen stiffer than before. Increments in natural vibration frequency values and damping ratios of the specimen can be demonstrated as the evidences of this result. Obtained modal matrix of the specimen with diagonals was given below in Table 4.8.

Table 4.7 Modal parameters of specimen without and with diagonals

Method	Diagonals		1. Mode	2. Mode	3. Mode
SAP2000	Without	Frequency (Hz)	8.01	24.91	41.08
	With		10.27	32.19	55.44
Impact Hammer Tests	Without	Frequency (Hz)	7.71	26.43	42.76
	With		8.47	35.81	56.23
FAS & Half Power Method	Without	Frequency (Hz)	7.22	26.66	42.76
		Damping ratio (%)	0.99	0.23	0.22
	With	Frequency (Hz)	8.78	35.93	55.14
		Damping ratio (%)	0.98	-	-
SSI	Without	Frequency (Hz)	7.19	26.66	42.80
		Damping ratio (%)	1.22	0.23	0.25
	With	Frequency (Hz)	8.55	36.01	58.56
		Damping ratio (%)	2.50	2.32	3.68
EFDD	Without	Frequency (Hz)	7.20	26.66	42.77
		Damping ratio (%)	1.47	0.25	0.23
	With	Frequency (Hz)	8.51	36.10	58.74
		Damping ratio (%)	1.75	2.56	3.10

By using the modal matrices in Tables 4.3 and 4.8 for specimen without diagonals and with diagonals respectively, mode shapes of the specimen were constituted (see in Figures 4.19, 4.20 and 4.21).

Table 4.8 Modal matrix of the specimen with diagonals

Storey Number	**Mode Number**		
	1.	*2.*	*3.*
1.	+1.000	+1.000	+1.000
2.	+4.762	+2.645	-0.690
3.	+7.606	-3.071	+0.295

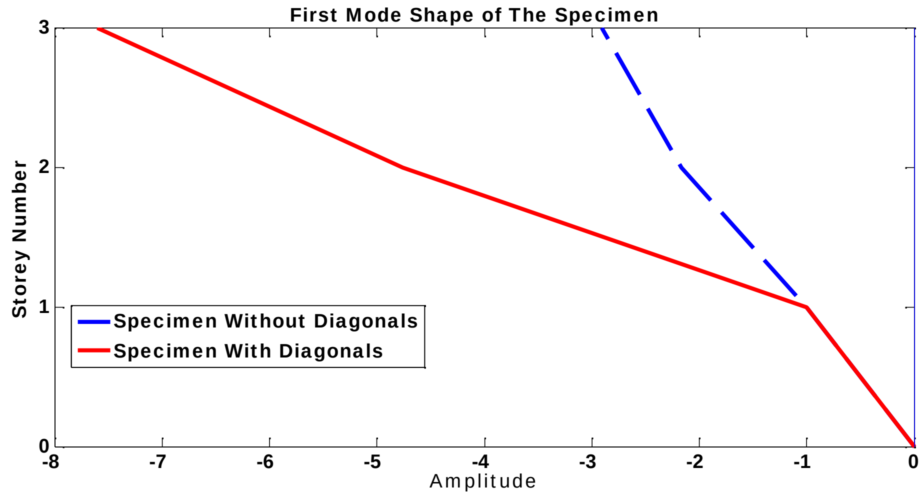


Figure 4.19 First mode shape of the specimen without and with diagonals.

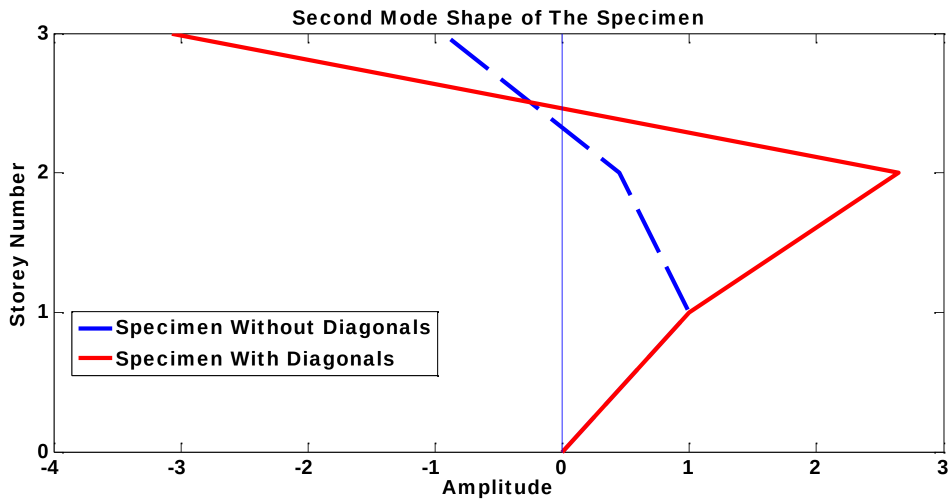


Figure 4.20 Second mode shape of the specimen without and with diagonals.

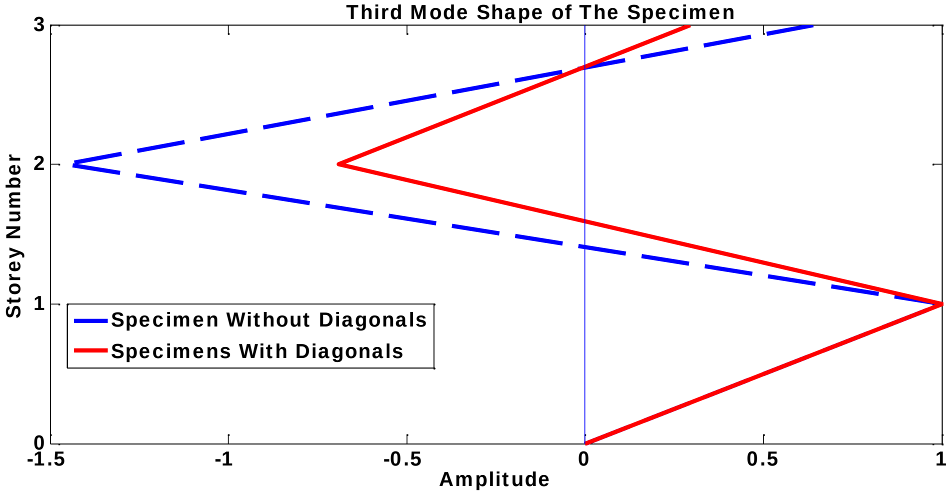
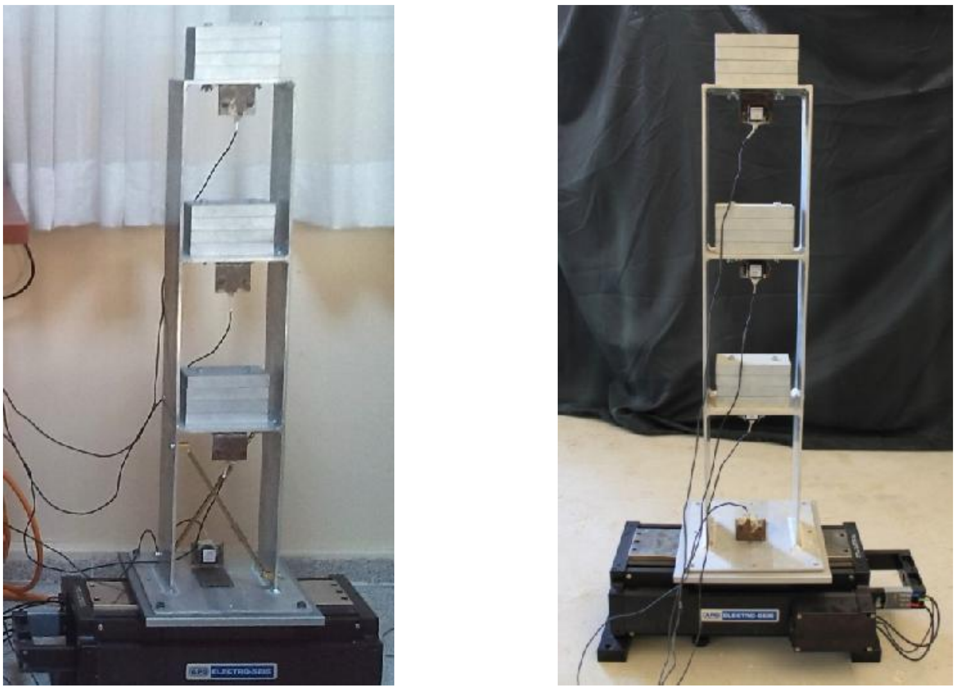


Figure 4.21 Third mode shape of the specimen without and with diagonals.

After the modal parameter estimation of the undamaged specimen case, parameters of the Damage Index Method were calculated by using modal parameters of undamaged (with diagonal) and damaged (without diagonal) specimens (see in Figure 4.22).



(a) **(b)**

Figure 4.22 A view of (a) undamaged specimen (with diagonals) and (b) damaged specimen (without diagonals).

Calculated Damage Index Method parameters were given in Table 4.9. The bold, italic and underlined values (values that are larger than 1 for DI_{rj} and smaller than zero for a_{rj}) represent the parameters which detect damage. By evaluating all modes, it can be concluded that the method detected damage at first storey. As it is known, first storey is the really damaged storey because of removing diagonals. Accordingly, it can be said that the Damage Index Method detected the damage location properly. If care is taken, DI_{rj} and a_{rj} parameters detect damage at second and third storeys too (bold and italic written parameters). These values represent the fake damage locations and must be discounted as it was mentioned before.

Table 4.9 Parameters of the Damage Index Method for three storey specimen

Storey	DI_{rj}			a_{rj}		
	1. Mode	**2. Mode**	**3. Mode**	**1. Mode**	**2. Mode**	**3. Mode**
1	***1.4538***	***1.5093***	0.8171	***-0.3121***	***-0.3374***	0.2238
2	0.7843	0.9749	***1.0320***	0.2750	0.0258	***-0.0310***
3	0.8317	0.6941	***1.2534***	0.2023	0.4407	***-0.2022***

To examine the effects of OTT on Damage Index Method, modal parameters of undamaged and damaged specimen cases were estimated again. But this time, OTT was not performed on shake table. So, it must be stated that, these modal parameters do not reflect the truth. Damage Index Method Parameters, which were obtained by using modal parameters with and without OTT, were given in Table 4.10 for comparison.

In Table 4.10, it can be concluded that the existence of the OTT in analyses affected the damage parameters in value but did not change the detection process of the damage location (bold, italic and underlined values). For now, generalizing this conclusion can cause irremediable faults. Therefore, this obtained conclusion must be tested on more complex structural models to verify.

Table 4.10 Parameters of the Damage Index Method for three storey specimen without and with using OTT

OTT	**Storey**	DI_{rj}			a_{rj}		
		1.Mode	**2.Mode**	**3.Mode**	**1.Mode**	**2.Mode**	**3.Mode**
Not applied	**1.**	***1.402***	***1.772***	0.863	***-0.287***	***-0.436***	0.159
	2.	0.834	0.791	1.081	0.199	0.264	-0.075
	3.	0.838	0.693	1.149	0.193	0.443	-0.129
Applied	**1.**	***1.4538***	***1.5093***	0.8171	***-0.3121***	***-0.3374***	0.2238
	2.	0.7843	0.9749	1.0320	0.2750	0.0258	-0.0310
	3.	0.8317	0.6941	1.2534	0.2023	0.4407	-0.2022

CHAPTER FIVE
CONCLUSIONS, RECOMMENDATIONS AND FUTURE STUDIES

In this study, solution of the trajectory tracking problem which is encountered mostly in shake table tests was considered. Offline Tuning Technique (OTT) is one of the methods to overcome the tracking problem and this technique was used in the scope of the study. Firstly, technique was applied on an electro-dynamic shake table. After, effects of the technique were investigated on shake table with a three storey-one bay aluminum specimen on it. In this situation, shaker-specimen interactions were observed.

System identification of the specimen was performed. Dynamic characteristics like natural vibration frequencies and mode shapes were obtained by using Fourier Amplitude Spectra (FAS) Method and damping ratios of the specimen were estimated by using Half-Power (Band-Width) Method. These parameters were calculated before and after OTT to investigate the effects of the technique on system identification.

Finally, damage detection processes were performed on the specimen. For this purpose, Damage Index Method, which is classified as a Level III damage detection method and uses the changes in modal parameters, was used. To represent the undamaged specimen case, two diagonals were used at first floor. Damaged specimen case was established by removing these diagonals. Modal parameters of these specimen cases were acquired before and after the application of OTT to investigate the effects of OTT on damage detection process.

All results and observations which were obtained from the study were listed below:

Trajectory tracking problem was observed in shake table tests without and with specimen on it.

For shake table without specimen, trajectory tracking problem was solved and the shake table was provided to track the command signal more accurately in time and frequency domain by the usage of OTT.

Importance of time duration and frequency content of the command signal on FTF estimation and OTT process was put forward. Therefore, selecting long duration white noise signal was decided to be the best choice for this purpose.

It was observed that, for a shaker-specimen system, valleys (zeros) of FTF and peaks (poles) of ITF represent the natural vibration frequencies of the specimen.

By investigating the FTF of shaker-specimen system, it was found that the valleys occur at natural vibration frequency values of the specimen. This means that, shake table cannot produce motion which includes natural vibration frequency values of the specimen because of the shaker-specimen interaction, although it is required to excite the specimen properly.

Broad bandwidth signals must be used to excite the all modes of specimens and obtain accurate modal parameters. But, it was found that, this situation cannot come true. Since, the broad bandwidth signals lost their rich frequency contents due to tracking problem and shaker-specimen interaction.

By the usage of OTT for shake table-specimen system, tracking problem was solved and the shake table was provided to track the command signal more accurately in time and frequency domain by decreasing the shaker-specimen interaction.

Broad bandwidth signals could be constituted on shake table by using OTT. And in this way, specimen could be excited properly and modal parameters could be estimated more realistic.

It is observed that the modal parameters which were obtained by using different methods like EFDD, SSI, FAS, SAP2000® and impact tests were similar to each other. This situation is important for the accuracy and consistency of the results.

By using FAS Method, natural vibration frequencies of the specimen, which were obtained before and after the application of OTT, were obtained as 11.92 Hz, 29.98 Hz, 43.86 Hz and 7.22 Hz, 26.66 Hz, 42.76 Hz respectively.

Damping ratios of the specimen, which were obtained before and after the application of OTT, were calculated as 4.49%, 0.52%, 0.52% and 0.99%, 0.23%, 0.22% respectively by using Half-Power (Band-Width) Method. Because of the extraction from PSD Functions, these ratios were not considered as real values, they were accepted as guides.

Stiffer specimen was formed by the usage of diagonals at first storey. Increments in natural vibration frequency and damping ratio values of the specimen are the indicators of this result.

Natural vibration frequencies of the specimen with diagonals at first storey (after the application of OTT) were obtained as 8.78 Hz, 35.93 Hz and 55.14 Hz by using FAS Method.

Due to the difficulty of picking peak values from PSD Functions, damping ratios of the specimen could not be calculated by Half-Power (Band-Width) Method. Damping ratios were obtained as 2.50%, 2.32%, 3.68% and 1.75%, 2.56%, 3.10% from SSI and EFDD respectively.

Undamaged specimen case was constituted by using diagonals at first storey and damaged specimen case was obtained by removing these diagonals. This created damaged storey was detected by Damage Index Method.

It was observed that the existence of the OTT in damage detection analyses changed the damage index parameters in value, but did not affect the estimation of damage location. But, this conclusion must be verified on more complex structural models before the generalization of this result.

By the light of the results and information which were obtained from this study, it will be useful to improve and/or upgrade the obtained results by performing future studies. For this purpose, TÜBİTAK Project studies will be carried out in the near future. In this scope, studies which were planned to be realized were listed below:

As it was mentioned before, transfer function of the shake table and/or shake table-specimen system was estimated by using experimental data in the scope of this study. It is planned to estimate this function numerically as a function of shake table and specimen properties. So on, transfer function will be estimated more accurately and the effects of OTT will be obtained in detail.

In this study, OTT was performed on a small specimen. It is planned to excite 1:2 scaled one storey-one bay reinforced concrete frame by a shake table on it. By this way, effects of OTT on a bigger specimen will be tested.

System identification of the new specimen will be carried out by using different methods (e.g., FAS Method, EFDD, SSI, NExT, ERA, etc.). In this study, EFDD and SSI Methods were performed by ARTEMIS® Software. It is planned to program all of these methods in MATLAB® software.

Damage detection of the new specimen at different damage levels will be estimated by using Damage Index Method and more complex methods to comparison. Relations between the damage state and damping ratios of the specimen will be studied to be obtained.

Effects of the OTT on tracking problem, system identification and damage detection processes will be investigated by using the new specimen. For this purpose, all of the analyses will be performed before and after the application of OTT. And in analyses, transfer functions of different situations (e.g., bare table, shaker-undamaged specimen system, shaker-damaged specimen system at specific damage levels, etc.) will be used and the results will be compared and investigated.

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