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Identification of Simplified Structural Models from Input-Output Time Histories and Application to Controller Design

A dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor of Philosophy in Mechanical Engineering

By

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T. Ma, Wrobleski, M. S., and Yang, H. T. Y., "Improved Sensor Fault Accommodation Neural Networks for Structural Responses," Proceedings of the 1st European Workshop on Structural Health Monitoring, edited by D. L. Balageas, Ecole Normale Supérieure, Cachan (Paris), France. July 10-12, 2002, pp. 1099-1106.

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Abstract

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A technique, based on methods taken from adaptive control, to identify simplified models of complex building structures using measurements of the input excitation and forces and the output displacement or acceleration of the structure, as well as some basic assumptions about the structure of the simplified model to be identified, has been developed. Examples are presented in which the input and output to relatively complex plane frame models are used to identify simplified models with significantly fewer degrees of freedom. One of the complex frames is taken from a widely regarded benchmark for controller design. The simplified models identified using the proposed technique are successfully used in controller design applications. One of these applications involves the design of multi-objective optimal controllers. Another application places the identified model in a building control and sensor monitoring system. In both of these applications, testing of the designed control system is performed using an evaluation model of the benchmark building provided by the authors of the benchmark study.

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Chapter 1: Introduction

1.1 General Background and Motivation

The response of structures to outside excitations, particularly excitation by wind and seismic activity, has long been of primary interest to engineers, since excitation by these forces can result in anything from occupant discomfort and inconvenience, to catastrophic failure of structures.

In this century alone, there have been numerous significant earthquakes throughout the world, causing thousands of deaths [1]. Within the past decade alone, the losses from the 1994 Northridge, USA; 1995 Kobe, Japan; and 2001 Gujarat, India earthquakes provide further motivation to study the effects of seismic activity on structures and to develop reliable lifeline engineering technology. Wind forces, though typically less destructive than earthquakes, can also significantly impact the safety and reliability of a structure.

Traditionally, structures have been designed to utilize their strength and energy-dissipation characteristics to resist earthquakes and wind. Over the years, the significant damage caused by earthquakes to structures designed this way has illustrated the limitations of this approach. This has also led to tremendous interest in the use of retrofit vibration and damage control techniques, which have been proven effective in mechanical and aerospace applications, for civil structural control. Thus, structural engineers and researchers are now expanding their efforts, utilizing interdisciplinary engineering concepts, model identification techniques, control schemes, specialized active/passive devices, and advancements in sensor technology and smart materials to improve the safety and reliability of civil structures.

1.2 System Identification Based on Input-Output Mapping

In order to implement a control technique for a structure effectively, whether the control system is part of an initial design or part of a retrofit, a dynamic model of the structure must be available. This model must be both accurate and simple. It must be accurate because control is only possible if a reasonable estimate of the structure's behavior is known. It must be simple because the calculations required for control of the structure must be made quickly, and as the complexity of the model increases, so does time or computational power needed to perform the calculations. The need for simple models to be used in computationally intensive situations is gaining increased recognition, as is illustrated in Farrar et al. [2].

Past modeling techniques for structural analysis and control of tall buildings fall into two categories, component level modeling and shear-beam modeling. In component level modeling, the detailed layout of all the individual elements (beams, columns, etc.) in a building is used, along with the properties of the materials, to develop a highly accurate, but very complex model of the building. This meets the requirement of accuracy, but the high level of complexity of these models does not lend itself to computation. In shear-beam modeling, the building is approximated by a series of springs and masses, allowing a very simple model at the cost of limited accuracy.

The modeling technique proposed in this dissertation combines the strengths of these two methods. A system identification scheme is used to identify the model based on input and output data. The structure of the model can be selected so that the level of complexity is no greater than that of a shear beam model. The parameters in this model are then identified so that the model's response closely follows the original system's response. Thus, a model with the simplicity of a shear-beam model is produced, but with much greater accuracy.

The models developed here are simplified models based on data from simulation of component level models. However, the character of the modeling technique, which requires only the excitation and response data, would allow data from a preexisting structure to be used to develop a simplified model. Thus, this modeling technique could be used both for future construction, and for structures undergoing seismic control retrofitting.

Chapter 2: Literature Review

In order to place the research performed into a proper perspective, a thorough review of existing literature on the subject of structural modeling and control has been performed.

2.1 System Identification & Model Development

Structural identification is a field of research that has received much attention in recent years. Studies by Hart and Yao [3], Kozin and Natke [4] and Natke [5] illustrate some of the fundamental identification methods. A very significant text on the subject is the work by Ljung [6]. Generally speaking, these techniques are applied either in the frequency domain [7], or in the time domain [8, 9, 10].

Iserman et al. and Saridis compared several online identification strategies [10, 11], while Kashyap [12] used the maximum likelihood estimate, and Beck [13] studied identification using linear models and earthquake records. Udwadia [14], Luco and Wong [15], Zhao and Safak [16], and Glaser [17] conducted soil property and building structural identification, using various specialized mathematical techniques. DiPasquale and Cakmak [18] examined the identification of serviceability limit states for civil systems, and Lin et al. [19] investigated real-time identification for degrading civil structures.

In addition to these, Ghanem and Shinozuka [20, 21] discussed an extended Kalman filter approach for identification, Mook and Junkins proposed a Minimum Model Error (MME) estimation approach [22], Juang and Pappa proposed an

Eigensystem Realization Algorithm (ERA) [23], and Crassidis et al. Combined the MME method with the ERA to develop the MME-ERA method [24].

Other methodologies proposed include the multivariable Augmented Identification (AUDI) algorithm [25], Recursive Least Squares [26, 27, 28] and adaptive estimation using modified Kalman filter estimates [29].

While most identification tools have been restricted to linear modeling, Ghanem and Shinozuka have examined the validity of this assumption for general nonlinear systems and outlined their limitations both numerically [20] and experimentally [21].

A primary goal of this dissertation is the development of a method for the identification of simplified models of structures based on the input-output response of the structure. The method developed is based on techniques used in the field of adaptive control.

2.2 Structural Control Algorithms

Yao [30], Yang [31], and Zuk [32], among others, contributed to the earliest work in the area of civil structural control. Numerous approaches are currently under consideration by a wide range of researchers, many of which are summarized in a survey article by Spencer and Sain [33]. These efforts include classical optimal control [34], wherein the controller minimizes a time-invariant quadratic cost; instantaneous optimal control [35, 36, 37], where a time-dependent quadratic cost functional is used; closed loop eigenvalue assignment [38, 39, 40]; independent modal space methods [41, 42, 43, 44, 45, 46, 47], where the structural modes are independently controlled; and bounded state control [48, 49, 50, 51, 52], where the state variables are constrained to satisfy magnitude bounds.

Alternatively, deterministic control theory, in which excitations and uncertainties need not be quantified statistically, have also been tested for civil structures. Some examples are found in studies performed by Kelley et al. [53], Barbat et al. [54], Luo et al. [55] and Rodellar et al. [56]. These studies used Lyapunov theory to synthesize controller meeting design objectives. Some other techniques such as matched-system nonlinear control guaranteeing uniform stability [57, 58, 59], unmatched-system nonlinear control [60, 61], and guaranteed cost control [62, 63, 64, 65] have also been developed and tested.

Methods based on modern control theory have also seen application. These approaches include adaptive control [66], frequency domain approaches using H_2 theory [67, 68, 69], digital control [70], H_∞ control [71, 72], robust design using H_∞ theory [73], disturbance rejection methods [74], autoregressive methodologies [75], sampled data control [76], dynamic controller designs and multiple objective LQG control methodologies [77, 78, 79], and hybrid control approaches [80].

Less traditional control methods have also been studied in recent years, including the use of neural networks to determine control inputs [81, 82, 83] as well as the use of genetic algorithms to optimize controller parameters [84].

Implementations of these control techniques on actual structures or test beds have also been performed, such as real-bridge motion control [85] and SUNY Buffalo case studies [36, 71, 86, 87, 88].

2.3 Structural Control Devices and Actuators

The devices and actuators available for structural control applications can be separated into three broad categories: passive devices, active devices, and hybrid devices. Passive devices generally require no outside energy source to serve their purpose, as opposed to active devices that use external energy to apply forces to a structure. Hybrid devices combine qualities of passive and active devices.

2.3.1 Passive Devices

Passive devices include tuned mass dampers, tuned sloshing dampers, viscoelastic dampers, and base isolators, among others. Early studies with passive devices were conducted by McNamara [89], Luft [90], and Ayorinde and Warburton [91, 92]. Mass dampers have been installed in buildings in several cities, including Toronto [93] and Boston [94]. Sun et al. [95] have studied tuned liquid dampers, while Tsai [96] and Makris and Deoskar [97] have studied the response of base-isolation systems. Other efforts involve nonlinear base-isolation [98], free rolling rods in isolation [99], and the use of lead-rubber bearings in isolator systems [100]. Articles by Jangid and Datta [101], Housner and Masri [102], and Hasebe et al. [103] surveyed research in base isolation and also presented case studies of isolator performance during actual earthquakes. Other applications of passive devices include the use of viscoelastic dampers in New York and Seattle [104, 105, 106], a frictional damping system [107, 108, 109], a mass damper using friction dissipating devices [110], a honeycomb damper system [111], and a joint damper system [112], to name only a few. The use of simple directional mass dampers has also been studied and their control performance evaluated [113, 114, 115].

2.3.2 Active Devices

Active mass drivers, active tendons, active variable stiffness systems, aerodynamic appendages, adaptive members, gyroscopic stabilizers, pulse generators, and smart materials such as piezoelectrics are some of the more common active devices. The use of such active devices has been attracting much attention recently, as is shown in [116, 117, 118] and the references therein. Active tendon systems have been studied numerically [119, 120, 121] and examined in laboratory tests [36, 122, 123]. Similarly, gas pulse generators, which produce forces by bursts of air jets, have also been studied analytically [124, 125] and experimentally [126, 127]. Piezoelectric elements have been use in the shape control of plates [128, 129], and in the vibration control of beams [130]. The Kajima Corporation of Japan has developed and tested an AVS (Active Variable Stiffness) system [75, 131], while the Taisei Corporation has studied the use of gyroscopic stabilizers to reduce tower vibrations [132].

2.3.3 Hybrid or Semi-Active Devices

Hybrid devices, also known as semi-active devices, evolved as alternatives to purely passive or purely active devices for control. They have many of the advantages provided by active control devices, with the additional benefit of a passive mode of operations that continues in the event of such failures as computer malfunctions or stoppages of external power. Examples of such devices that are commonly studied include active tuned mass dampers and active base isolators. Some active mass damper designs have been proposed by Ohsaki [133], Chang and Yang [134], and Ankireddi and Yang [135]. In other studies Kelly et al. [53] studied active base isolators using Lyapunov theory, Luo et al. [55] studied sliding mode control for active isolation, and Suhardjo et al. [67, 68, 69] used frequency domain based approaches for active mass damper design. Similarly, Yang et al. [80] experimentally studied hybrid control of bridges, Tanida et al. [136] experimentally investigated the use of hybrid dampers for bending-torsional response of buildings, and Barbat et al. [54] examined nonlinear active base isolation.

2.4 Sensors and Measurement Techniques

Numerous types of sensors, including foil strain gages, piezoelectric and magnetostrictive transducers, optical fiber based sensors, conventional and Micro-Electro-Mechanical Systems (MEMS) based accelerometers, displacement sensors, and chemical sensors, as well as many others, are available today. An overview of several of these is available in [118]. Research continues in improving the accuracy, reliability, and applications of these sensors, especially in the area of civil structures. Piezoelectric elements have been used as sensors for displacement [137], damage identification in composite plates [138], debonding of steel reinforced concrete [139], and other sensing applications, as well as being used as actuators. Their use as combined sensor/actuators has also been examined [140]. Sensors based on fiber optics have found common usage as strain gages [141, 142] and chemical sensors

[143]. The number of applications for optical fiber sensors is growing. New techniques include monitoring of fatigue damage [144], damage detection in composites [145, 146], and others. Another novel sensing technique involves displacement sensing through the use of Global Positioning System (GPS) signals and multiple receivers [147].

Sensor monitoring techniques are also an active area of research, as can be seen in work on wireless sensor monitoring by Lynch et al. [148] and Fuhr [149].

Chapter 3: Mathematical Derivations

One way to model a multi-story structure is to break up the model into several single input single output (SISO) systems in which the inputs are excitations and control forces and the outputs are floor displacements, velocities, or accelerations. In general, the input to output mapping of a SISO system can be described in the frequency domain as

$$y = \frac{N(s)}{R(s)}u = \frac{b_{n-1}s^{n-1} + b_{n-2}s^{n-2} + \cdots + b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + a_0}u. \tag{1}$$

Here u is the input signal, y is the output, and the a_i's and b_i's are parameters that define mapping.

The goal of the identification scheme described here is to obtain estimates of the numerator and denominator parameters for the system based on obtainable signals. The derivation below closely follows that found in [150]. Obtainable signals are either signals that can be directly measured (i.e. the input and output) or stable signals that can be obtained by applying stable filters to the measurable signals. To this end, the first concern is to separate the above relationship into a linear relationship between parameters to be identified and obtainable signals.

The first step in separating parameters and signals is to multiply both sides of equation (1) by the denominator polynomial, then moving all terms with a factor that is a parameter to be identified to the right hand side. This gives

$$ys^n = (b_{n-1}s^{n-1} + \cdots + b_0)u - (a_{n-1}s^{n-1} + \cdots + a_0)y. \tag{2}$$

This can be expressed in vector notation as

$$ys^n = \theta_b^{*T}\alpha_{n-1}(s)u - \theta_a^{*T}\alpha_{n-1}(s)y \tag{3}$$

where

$$\theta_b^* = \begin{Bmatrix} b_{n-1} \\ \vdots \\ b_0 \end{Bmatrix} \quad \theta_a^* = \begin{Bmatrix} a_{n-1} \\ \vdots \\ a_0 \end{Bmatrix} \quad \alpha_k(s) = \begin{Bmatrix} s^k \\ \vdots \\ s \\ 1 \end{Bmatrix}. \tag{4}$$

The signals u and y are the only ones that can be measured. In order to avoid differentiation, which is equivalent to multiplication by s, but is mathematically undesirable, a stable filter, $1/\Lambda(s)$, must be added to the system as follows

$$\frac{s^n}{\Lambda(s)}y = \theta_b^{*T}\frac{\alpha_{n-1}(s)}{\Lambda(s)}u - \theta_a^{*T}\frac{\alpha_{n-1}(s)}{\Lambda(s)}y \tag{5}$$

where

$$\Lambda(s) = s^n + \lambda^T\alpha_{n-1}(s), \qquad \lambda = \begin{Bmatrix} \lambda_{n-1} \\ \vdots \\ \lambda_0 \end{Bmatrix}. \tag{6}$$

Using the definition of $\Lambda(s)$ to expand the left-hand side of equation (5) gives

$$\frac{s^n}{\Lambda(s)}y = \frac{\Lambda(s) - \lambda^T\alpha_{n-1}(s)}{\Lambda(s)}y = y - \lambda^T\frac{\alpha_{n-1}(s)}{\Lambda(s)}y. \tag{7}$$

Replacing the left-hand side of equation (5) with this last expression and rearranging terms gives

$$y = \theta_b^{*T}\frac{\alpha_{n-1}(s)}{\Lambda(s)}u - \theta_a^{*T}\frac{\alpha_{n-1}(s)}{\Lambda(s)}y + \lambda^T\frac{\alpha_{n-1}(s)}{\Lambda(s)}y \tag{8}$$

or in a more compact form

$$y = \begin{bmatrix} \theta_b^{*T} & \left(\theta_a^{*T} - \lambda^T\right) \end{bmatrix} \begin{Bmatrix} \frac{\alpha_{n-1}(s)}{\Lambda(s)} u \\ -\frac{\alpha_{n-1}(s)}{\Lambda(s)} y \end{Bmatrix} = \theta^{*T} \phi . \tag{9}$$

This form gives the output of the system in terms of a linear relationship between the parameters to be identified and signals obtainable from measurements of the input and output.

An estimate of the output, y can be obtained by substituting an estimate of the parameters, θ, in place of θ^*, the actual parameters, giving

$$\hat{y} = \theta^T \phi . \tag{10}$$

A normalized error between the actual and the estimated output is

$$\varepsilon = \frac{y - \hat{y}}{m^2} = \frac{y - \theta^T \phi}{m^2} \tag{11}$$

where $m > 1$, $\frac{\phi}{m} \in \ell_\infty$ i.e. $\frac{\phi}{m}$ is bounded.

An accurate model of the system should minimize this error over potential values of the parameters. To this end, define the cost function

$$J(\theta) = \frac{\varepsilon^2 m^2}{2} = \frac{\left(y - \theta^T \phi\right)^2}{2m^2} . \tag{12}$$

The definition of ε above guarantees that $J(\theta)$ is convex. Therefore, the gradient method for minimizing a cost function can be employed to give an update law for θ

$$\nabla J(\theta) = -\frac{\left(y - \theta^T \phi\right)\phi}{m^2} = -\varepsilon\phi \tag{13}$$

$$\dot{\theta} = -\Gamma \nabla J(\theta) = \Gamma \varepsilon \phi , \; \Gamma = \Gamma^T > 0 \tag{14}$$

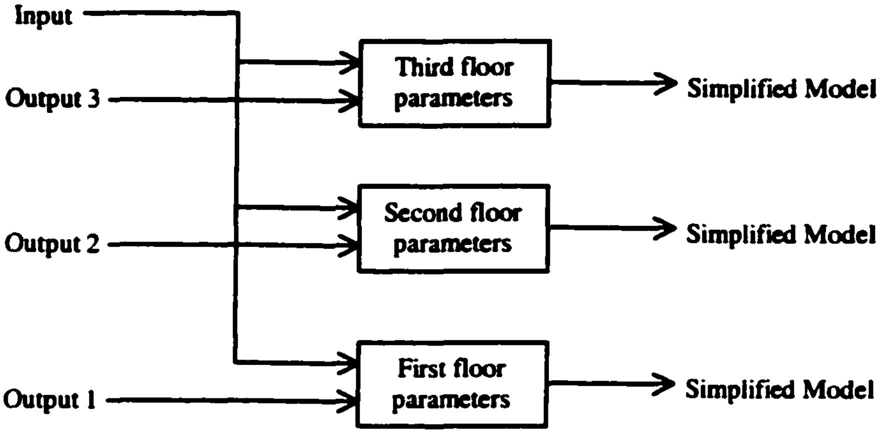
where Γ is known as the adaptive gain.

Some issues that must be noted when using this technique are persistence of excitation, signal richness and strength, and instability. In order for the method to converge to the correct values of the parameters, the input signal must be persistent, that is it must vary over time, or else the identification scheme will converge to a set of values for the parameters that will almost certainly be incorrect. Similarly, the signal must be sufficiently rich in frequency content and the excitation frequencies should be in the range of the modes of the system being identified and of high enough amplitude to adequately excite these modes. Otherwise the parameters may converge to incorrect values or not converge at all. Finally, the identification system itself can become unstable if the adaptive gain is too large or the frequencies involved are too high. More degrees of freedom in an identified model increase the identification system's sensitivity to these instabilities.

Making assumptions about the structure of the model being identified can make a further improvement to this technique. For example, shear beam models, which are essentially stacked springs, dampers, and masses, are often used to model buildings [151]. When such a model is transformed into the form given in equation (1), some of the parameters are found to be zero. By assuming these parameters to be zero in the simplified model identification, the number of parameters to be identified is reduced, with a subsequent reduction in the computational load.

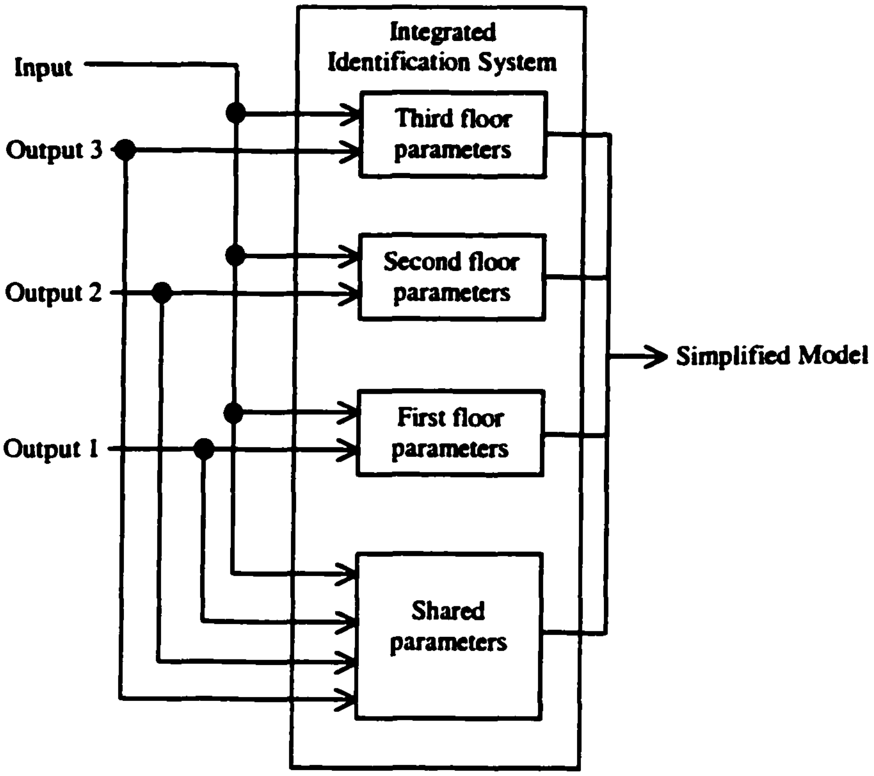
The procedure above can easily be adapted for use in the case of a single input multiple output (SIMO) system. The simplest way to do this is to assign each input to output pair its own transfer function and set up multiple identifiers in parallel as shown in Figure 1.

Figure 1. Parallel SISO Identification Systems



The number of parameters to be identified can be reduced once again, however, by taking advantage of the structure of the system. All of the input to output pairs share the same plant (the building under consideration) so it can be assumed that the denominator parameters, which represent the plant, are equal from one transfer function to the next. The integrated identifier shown in Figure 2 takes this assumption into account, calculating a set of separate parameters for each output and a single set of shared parameters that represent the plant.

Figure 2. Integrated Identification System



Identification of a multiple input multiple output (MIMO) system adds another layer of difficulty. This algorithm contains no means of distinguishing between the effects of separate inputs on the plant or on the outputs. Thus, separate identifications must be performed as described for the SIMO system for each input. Since the plant remains the same in each case, however, the models from these separate identifications can be combined by using model reduction techniques [152].

It is often desirable to use data from a limited duration excitation of the original structure. For example, the input excitation could be data from an earthquake record, which is by nature a limited duration event, or the complexity of the original structure might make an extended time history difficult to obtain. In order to use data that is of limited duration, the identification scheme is modified to be an iterative process. In each iteration, the entire record is used to modify the parameters according to the gradient method described above. The final parameter values for iteration are used as the initial values for the next iteration. Initial values for the first iteration are given some assumed values, usually zero.

This method has been implemented using the Matlab software package [153] and used in several examples.

Chapter 4: Numerical Examples

The following examples show how the algorithm described in the previous chapter may be used to calculate simplified models from the input-output response histories of more complex frame models.

4.1 Simple 3-Story, 1-Bay Frame

The first example is a relatively simple single bay, 3-story frame taken from Biggs [154]. Figure 3 shows the dimensions of this frame. The properties for the steel members used are taken from [155], and are as follows

Young's Modulus $E = 200GPa$

Density $\rho = 7.83\times10^{3}\,\frac{kg}{m^{3}}$

Column Elements

$W10\times45$ $I = 1.03\times10^{-4}m^{4}$ $A = 8.54\times10^{-3}m^{2}$

$W10\times21$ $I = 4.42\times10^{-5}m^{4}$ $A = 3.99\times10^{-3}m^{2}$

Beam Elements

$W24\times84$ $I = 9.86\times10^{-4}m^{4}$ $A = 1.59\times10^{-2}m^{2}$

$W21\times62$ $I = 5.54\times10^{-4}m^{4}$ $A = 1.18\times10^{-2}m^{2}$

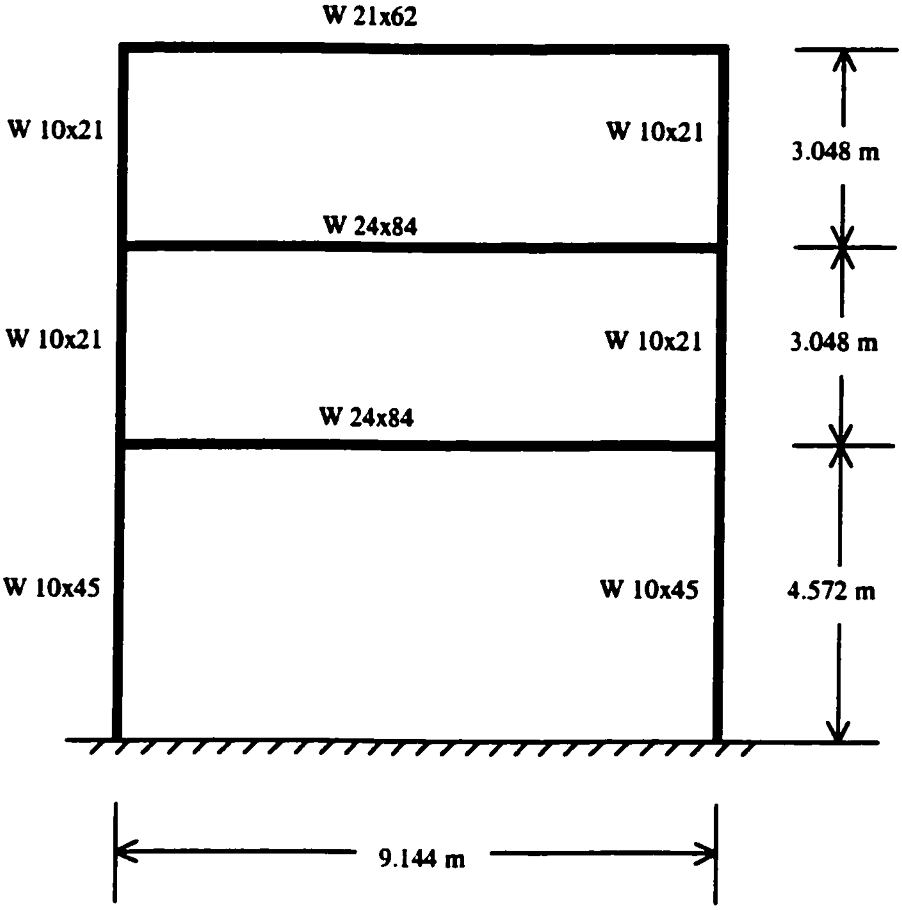
In addition, the following masses were added to the beam elements in order to model the mass of the floors that would be supported by the frame:

$M_1 = 2.46\times10^{4}kg$

$$M_2 = 2.31\times10^4 kg$$

$$M_3 = 1.16\times10^4 kg$$

Figure 3. Single Bay, Three Story Frame Model



The frame was modeled using beam and column elements with three degrees of freedom at each joint, i.e., two orthogonal displacements and a rotation. For the three story, six member frame, six elements were used in the calculations. The joints at the base are fixed, leaving 6 joints and 18 degrees of freedom for the frame model.

The first three modes of the structure, which are modeled by the identification process, are shown in Figure 4. The frequencies of these modes are $\omega_1 = 1.18Hz = 7.43 rad/s$, $\omega_2 = 3.50Hz = 22.0 rad/s$, and $\omega_3 = 5.24Hz = 32.9 rad/s$. Figure 5 shows some of the higher order modes that are to be disregarded by the identification process.

Figure 4. First 3 Modes of the 3 Story, 1 Bay Model

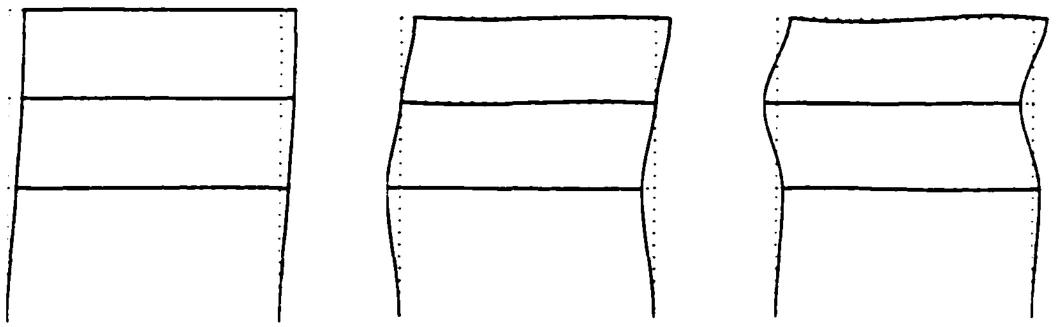
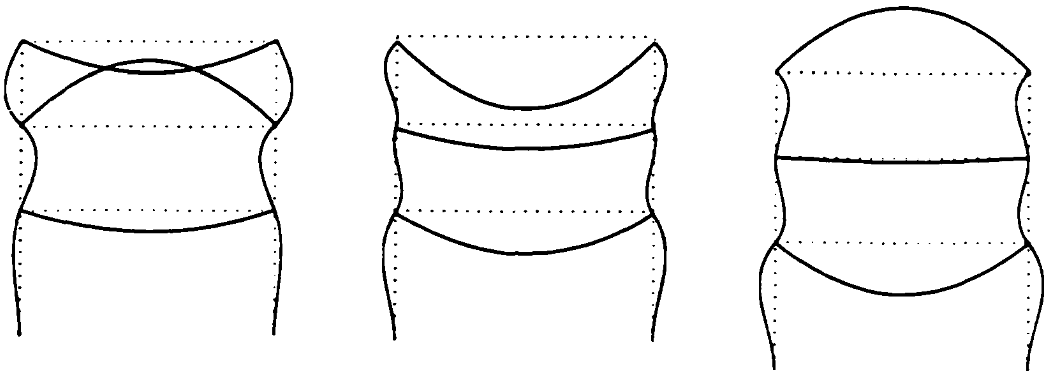


Figure 5. Higher Order Modes of the 3 Story, 1 Bay Model to be Ignored



The frame was excited by a time varying excitation corresponding to ground acceleration. The function used as the input excitation was a summation of sinusoids of varying frequencies and amplitudes chosen in such a way that the first three modes of the structure were adequately excited for the identification algorithm. This input and the calculated floor displacements are then used as the measurements for simplified model identification. The time history for the shared (denominator) parameters and the separate sets of (numerator) parameters for the first, second, and third floors are shown in Figure 6. This figure shows all of the parameters converging to some approximate values, which are given in Table 1. It should be noted that this figure uses a logarithmic scale along the parameter axis in order to show all of the parameters at once, so the initial value of the parameters, which in this case are all zero, do not appear.

Figure 6. Parameters from the 3-Story Identified Model Converging to Steady State Values

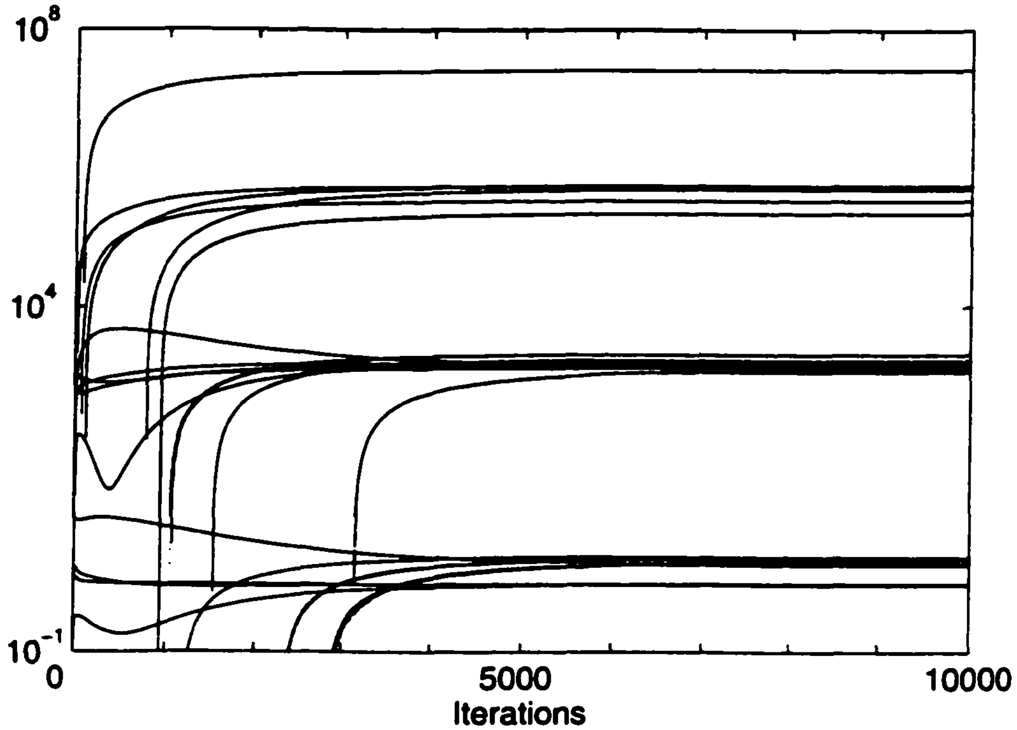


Table 1. Parameters for Simplified Model of 3-Story, 1 Bay Frame

i	5	4	3	2	1	0
Shared a_i	2.417	1.543e3	2.014e3	5.593e5	2.223e5	2.623e7
1st floor b_i	0	0.959	1.972	1.296e3	1.144e3	3.415e5
2nd floor b_i	0	0.989	1.882	1.531e3	1.398e3	5.032e5
3rd floor b_i	0	0.979	2.265	1.514e3	1.657e3	5.586e5

The floor displacements from simulations of the original frame and of the simplified identified model with the same excitation used in the identification are shown in Figure 7. The two sets of output are nearly indistinguishable in this example. Figure 8 shows similar simulations with the North-South component of the May 1940 El Centro earthquake used as the input excitation. Again, the outputs are nearly indistinguishable from one another. The extraordinary degree of agreement between the frame and the identified model lies in the simplicity of the original frame. With the additional mass of the floors included in this model, the frame and mass system is very much like a shear beam system, so the simplified identified model is able to pick up most of the dynamics of the system.

Figure 7. Displacements of the 3-Story, 1 Bay Frame and Corresponding Identified Model Subject to the Disturbance Used for Identification. a) 1st Floor/1st Degree of Freedom (DOF), b) 2nd Floor/2nd DOF, c) 3rd Floor/3rd DOF

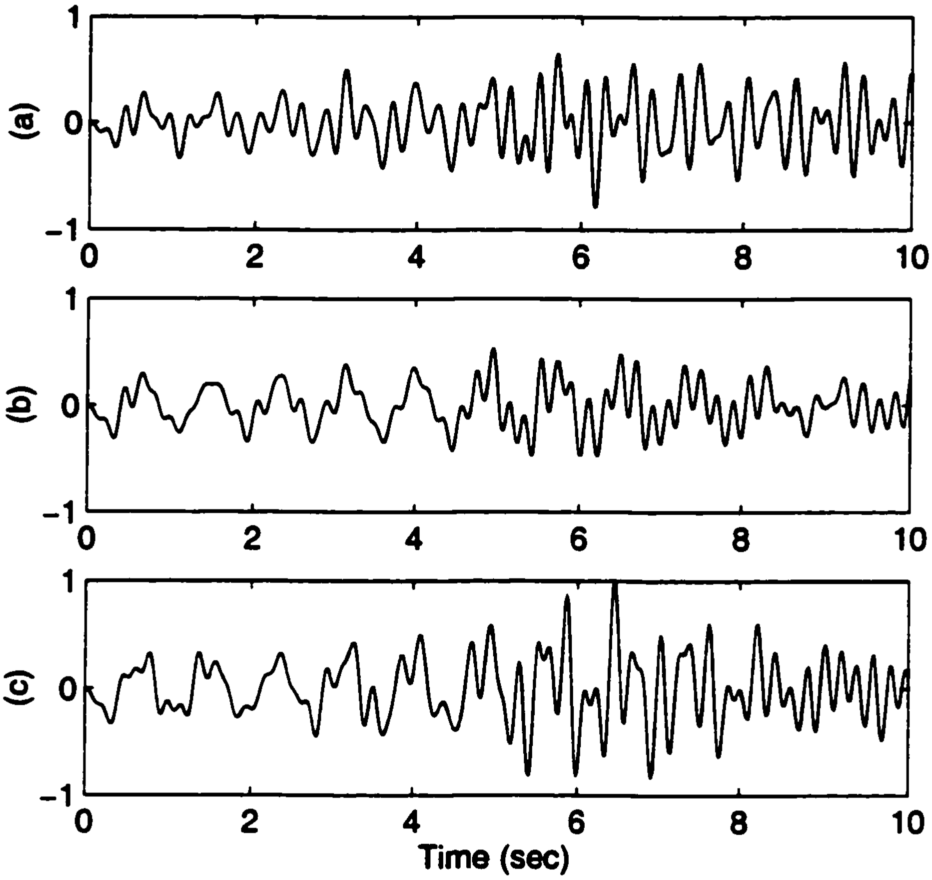
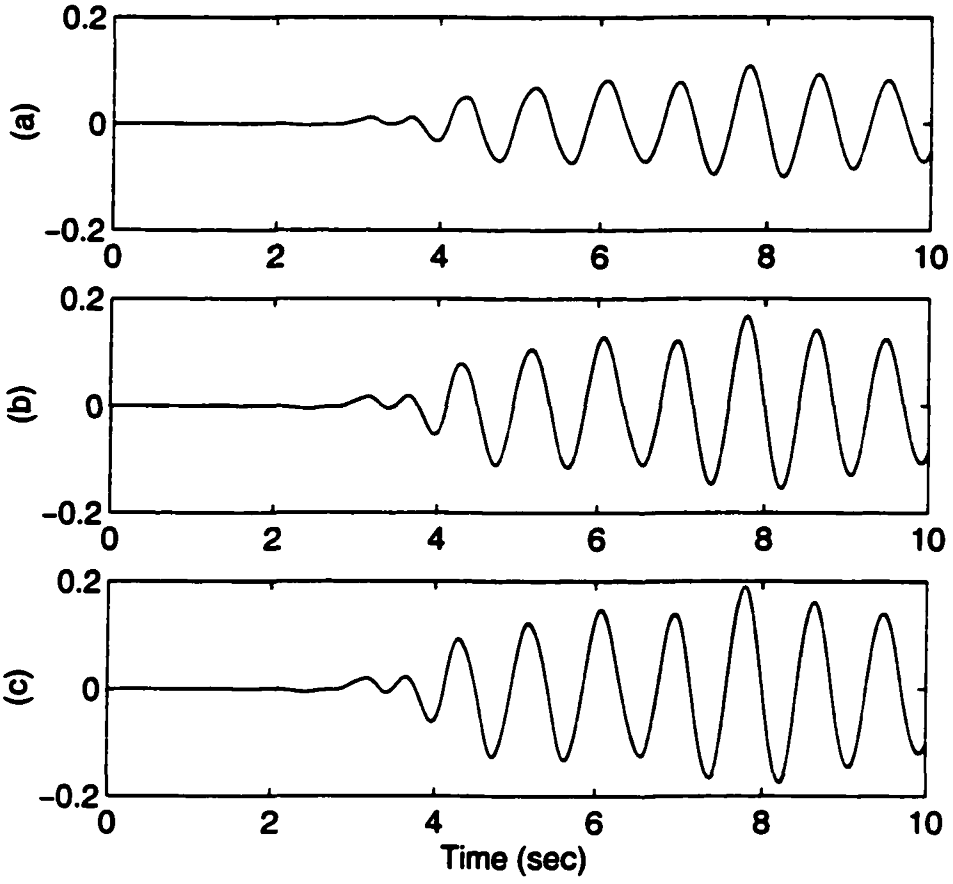


Figure 8. Displacements of the 3-Story, 1 Bay Frame and Corresponding Identified Model Subject to El Centro Earthquake. a) 1st Floor/1st Degree of Freedom (DOF), b) 2nd Floor/2nd DOF, c) 3rd Floor/3rd DOF



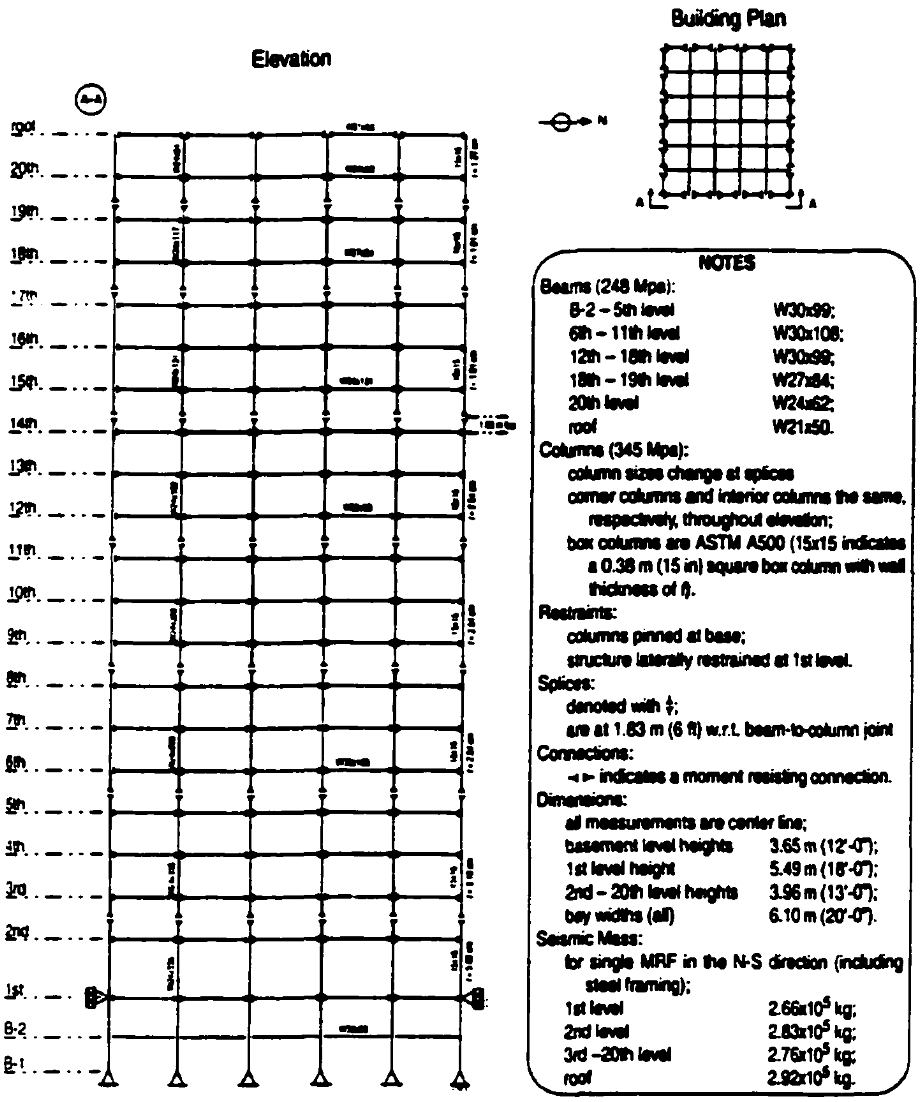
4.2 Second Generation Benchmark Structure - Displacement

In order to compare the effectiveness of various control strategies in the mitigation of seismic hazards, a benchmark structure has been designated [156]. The structure chosen is a 20-story steel building designed for the SAC Phase II Steel Project by Brandow & Johnston Associates according to seismic code for the Los Angeles, California region. Figure 9 shows the North-South moment resisting frame of this structure, which is used in the controller benchmark study and in the model identification in this example. This structure has been thoroughly studied in order to develop a model accurate enough to allow analysis of the effectiveness of controllers designed for the structure.

As with the previous example, the frame is simulated to obtain its output response. There are 284 elements and 180 joints in this benchmark frame. When the boundary conditions shown in Figure 9 are applied, the total degrees of freedom are reduced from 540 to 526. The first four modes of the frame are shown in Figure 10. Two inputs were used. The first is excitation due to ground movement. The second is a force applied at the roof of the building, which represents a potential actuator for building control applications, for example, an Active Mass Driver (AMD). In both cases, data from the North-South component of the May 1940 El Centro earthquake are used as the input excitation.

Three simplified models of the displacements of the benchmark structure have been identified. The first takes measurements of the displacement at the 7th and 14th floors and at the roof to identify a corresponding 3-degree of freedom model of the benchmark structure. Similarly, measurements of the displacements at the 5th, 10th, and 15th floors and at the roof are used to identify a 4-degree of freedom model. Finally, the displacements at the 4th, 8th, 12th, and 16th floors and at the roof are used to identify a 5-degree of freedom model of the benchmark structure.

Figure 9. North-South Moment Resisting Frame of the Second Generation Benchmark Building



NOTES

Beams (248 Mpa):

B-2 – 5th level	W30x99;
6th – 11th level	W30x108;
12th – 18th level	W30x99;
18th – 19th level	W27x84;
20th level	W24x62;
roof	W21x50.

Columns (345 Mpa):

column sizes change at splices
corner columns and interior columns the same, respectively, throughout elevation;
box columns are ASTM A500 (15x15 indicates a 0.38 m (15 in) square box column with wall thickness of f).

Restraints:

columns pinned at base;
structure laterally restrained at 1st level.

Splices:

denoted with ⇟;
are at 1.83 m (6 ft) w.r.t. beam-to-column joint

Connections:

◄► indicates a moment resisting connection.

Dimensions:

all measurements are center line;

basement level heights	3.65 m (12'-0");
1st level height	5.49 m (18'-0");
2nd – 20th level heights	3.96 m (13'-0");
bay widths (all)	6.10 m (20'-0").

Seismic Mass:

for single MRF in the N-S direction (including steel framing);

1st level	2.66×10^5 kg;
2nd level	2.83×10^5 kg;
3rd – 20th level	2.76×10^5 kg;
roof	2.92×10^5 kg.

Figure 10. First Four Modes of the Benchmark North-South Moment Resisting Frame

$\omega_1 = 0.26Hz = 1.63\frac{rad}{s}$ $\omega_2 = 0.75Hz = 4.71\frac{rad}{s}$

$\omega_3 = 1.30Hz = 8.26\frac{rad}{s}$ $\omega_4 = 1.83Hz = 11.5\frac{rad}{s}$

Since only the first three modes of the benchmark structure are easily excited, the identification scheme is modified for the cases of the 4 and 5-degree of freedom models. From analysis of the benchmark frame, the frequencies of the modes are known. Using these values of the frequencies and an estimate of the damping in the structure, the values for the parameters in the numerator of equation (1), which determine the frequencies of the identified model, are calculated. These parameter values are then used in the model and given zero gain to prevent them from changing. Higher order modes that are not excited are not identified using this modification, but it does allow identification of a higher order estimated model that includes the modes that are excited.

Frequency response curves of the original frame and of the identified models are shown in Figure 11 (ground motion to roof displacement) and Figure 12 (force applied at the roof to roof displacement).

Figure 11. Ground Excitation to Roof Displacement Frequency Response of Benchmark Frame and Identified Models

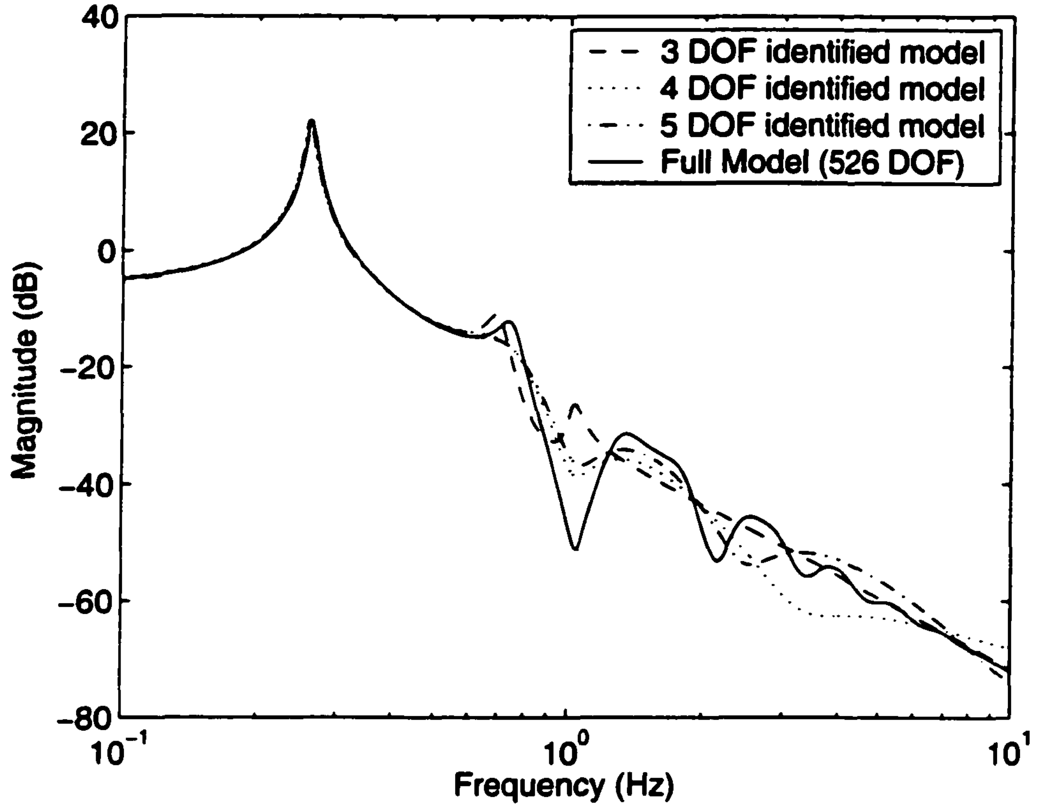


Figure 12. Roof Force to Roof Displacement Frequency Response of Benchmark Frame and Identified Models

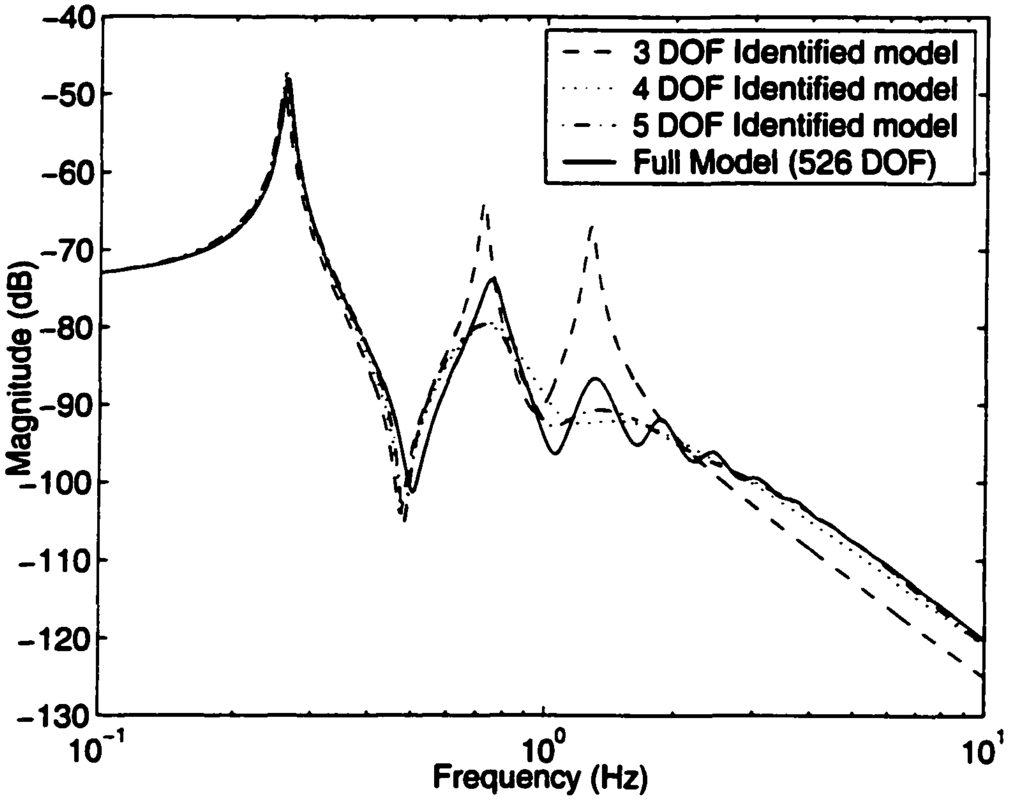


Figure 13 shows the response of the structure and the 3-degree of freedom simplified model to ground excitation from the El Centro Earthquake, which was used to identify the model. The responses to the North-South component of the January 1995 Kobe, Japan earthquake are shown in Figure 14. For the 4-degree of freedom simplified model, the responses for the El Centro earthquake are shown in Figure 15 and for the Kobe earthquake in Figure 16. The 5-degree of freedom simplified models' responses are shown in Figure 17 and Figure 18 for the El Centro and Kobe earthquakes, respectively. The roof displacements for the 3, 4, and 5-

degree of freedom simplified models, as well as the full benchmark model, are shown in Figure 19. These figures show that increasing the number of degrees of freedom in the simplified model at best only marginally improves the accuracy in this example. This is due to the fact that only the lower order modes are excited in this example, and only these modes are properly identified.

Figure 13. Displacement of the Benchmark Frame (solid) and 3-DOF Identified Model (dashed) with El Centro Earthquake as Disturbance for (a) 7th Floor / 1st DOF (b) 14th Floor / 2nd DOF and (c) Roof / 3rd DOF

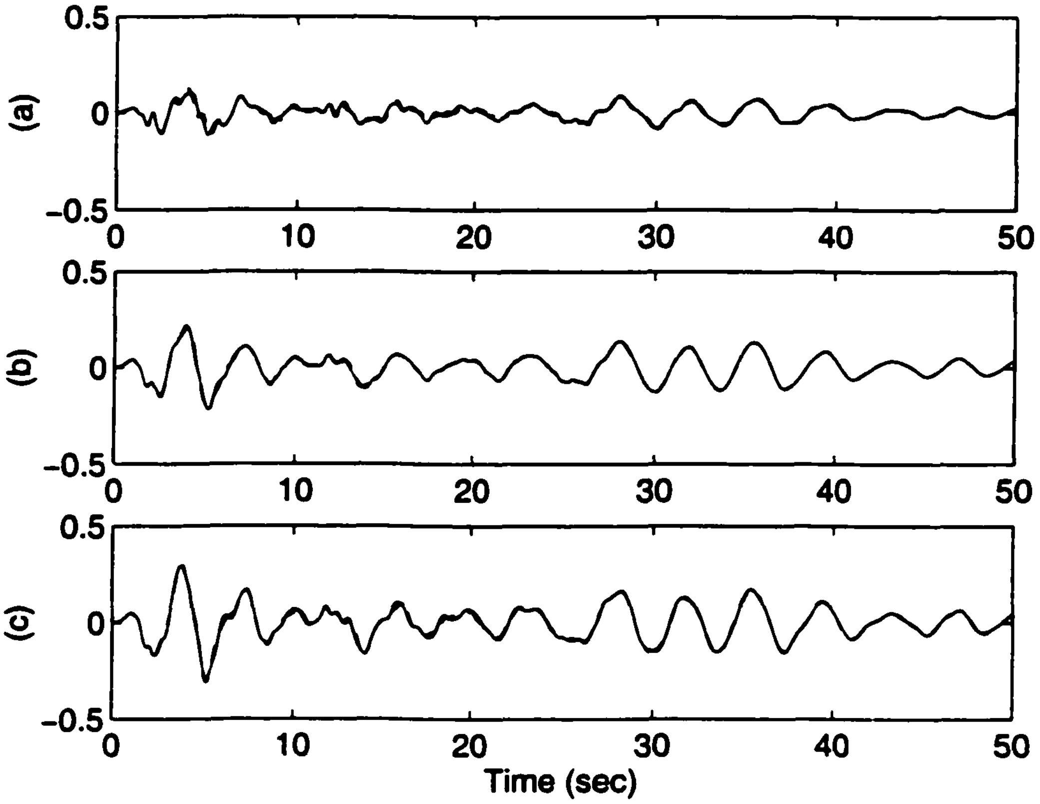


Figure 14. Displacement of the Benchmark Frame (solid) and 3-DOF Identified Model (dashed) with Kobe Earthquake as Disturbance for (a) 7th Floor / 1st DOF (b) 14th Floor / 2nd DOF and (c) Roof / 3rd DOF

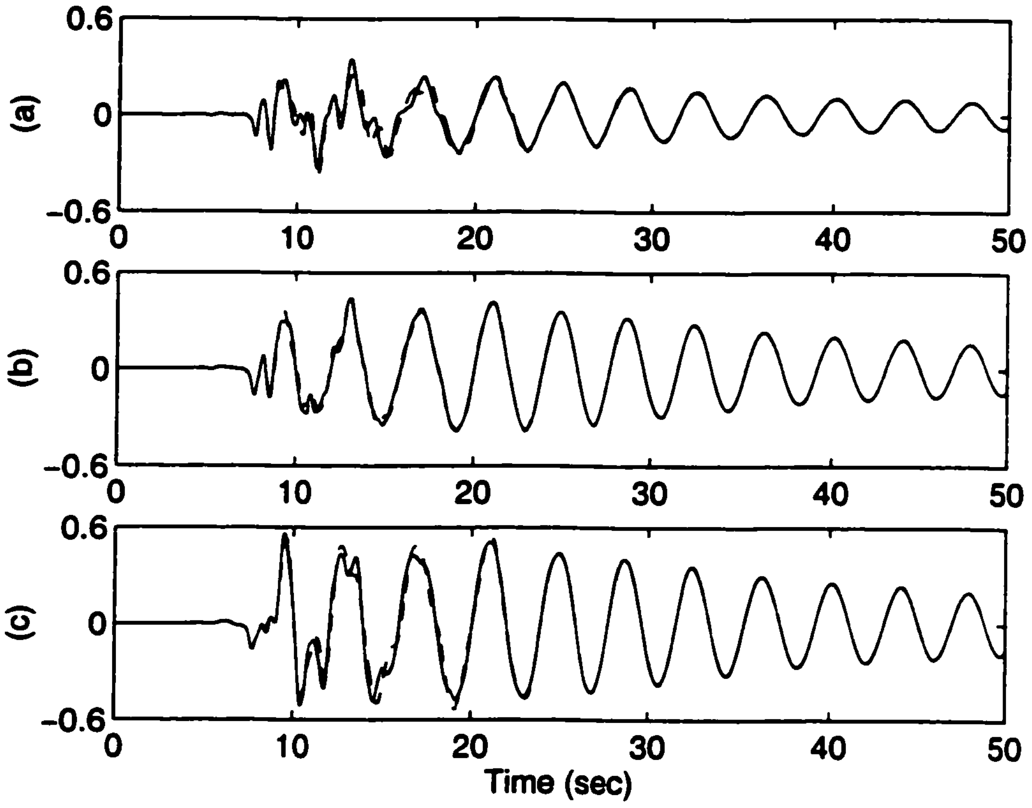


Figure 15. Displacement of the Benchmark Frame (solid) and 4-DOF Identified Model (dashed) with El Centro Earthquake as Disturbance for (a) 5th Floor / 1st DOF (b) 10th Floor / 2nd DOF (c) 15th Floor / 3rd DOF and (d) Roof / 4th DOF

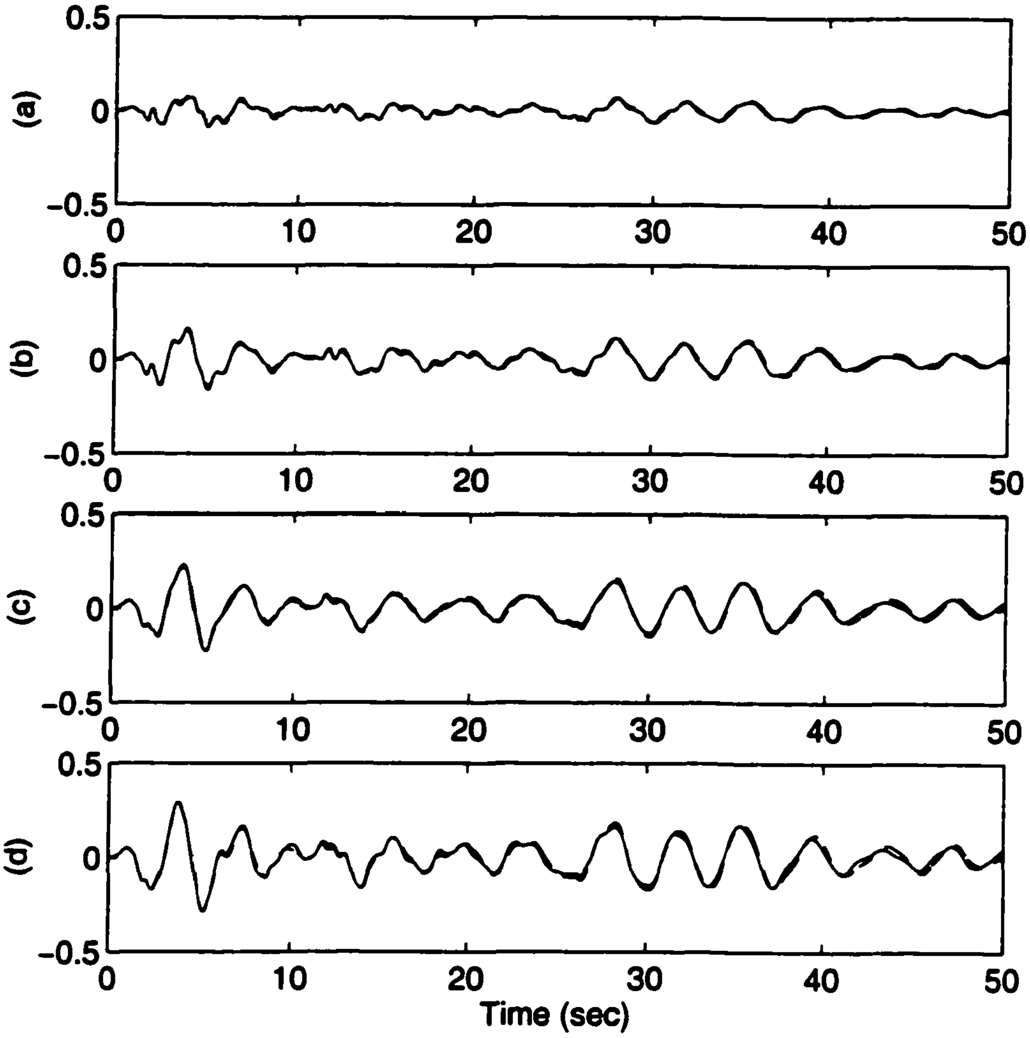


Figure 16. Displacement of the Benchmark Frame (solid) and 4-DOF Identified Model (dashed) with Kobe Earthquake as Disturbance for (a) 5th Floor / 1st DOF (b) 10th Floor / 2nd DOF (c) 15th Floor / 3rd DOF and (d) Roof / 4th DOF

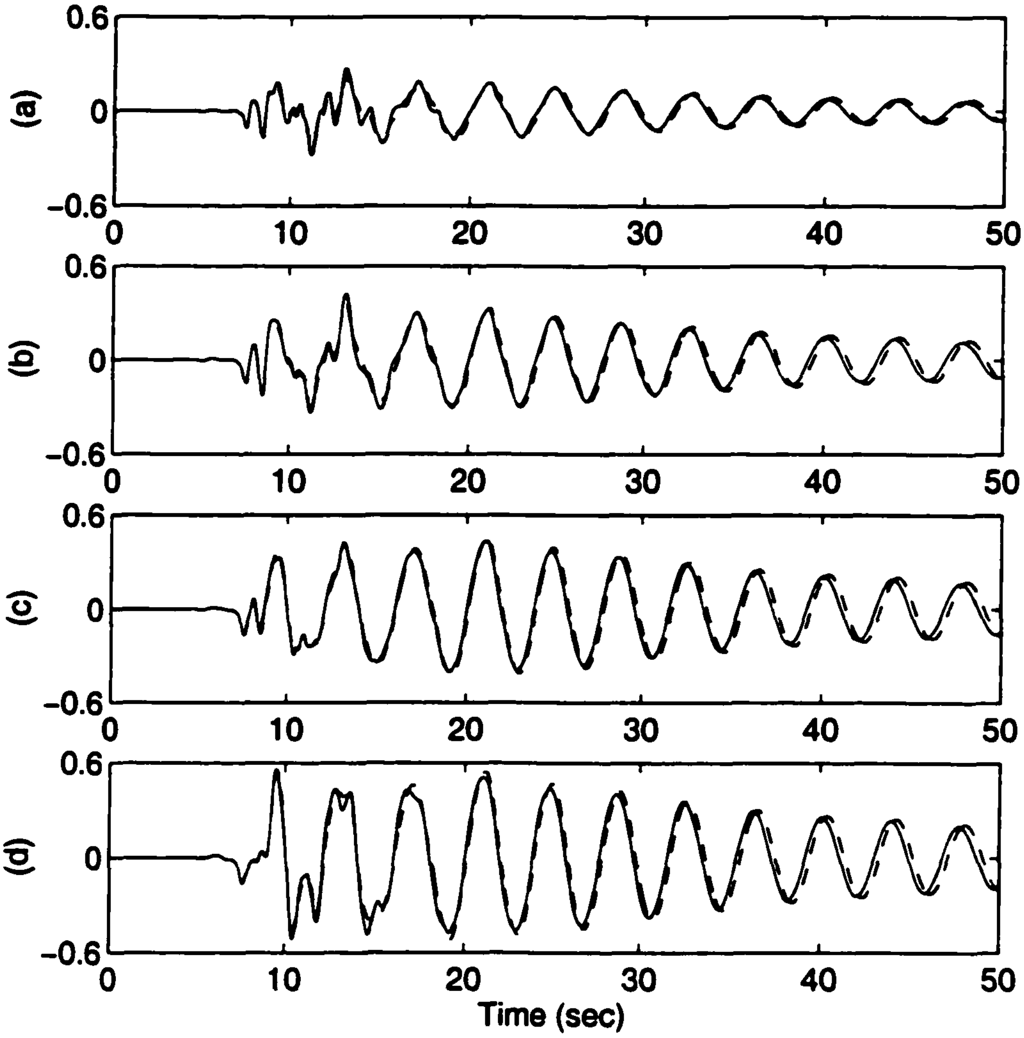


Figure 17. Displacement of the Benchmark Frame (solid) and 5-DOF Identified Model (dashed) with El Centro Earthquake as Disturbance for (a) 4th Floor / 1st DOF (b) 8th Floor / 2nd DOF (c) 12th Floor / 3rd DOF (d) 16th Floor / 4th DOF and (e) Roof / 5th DOF

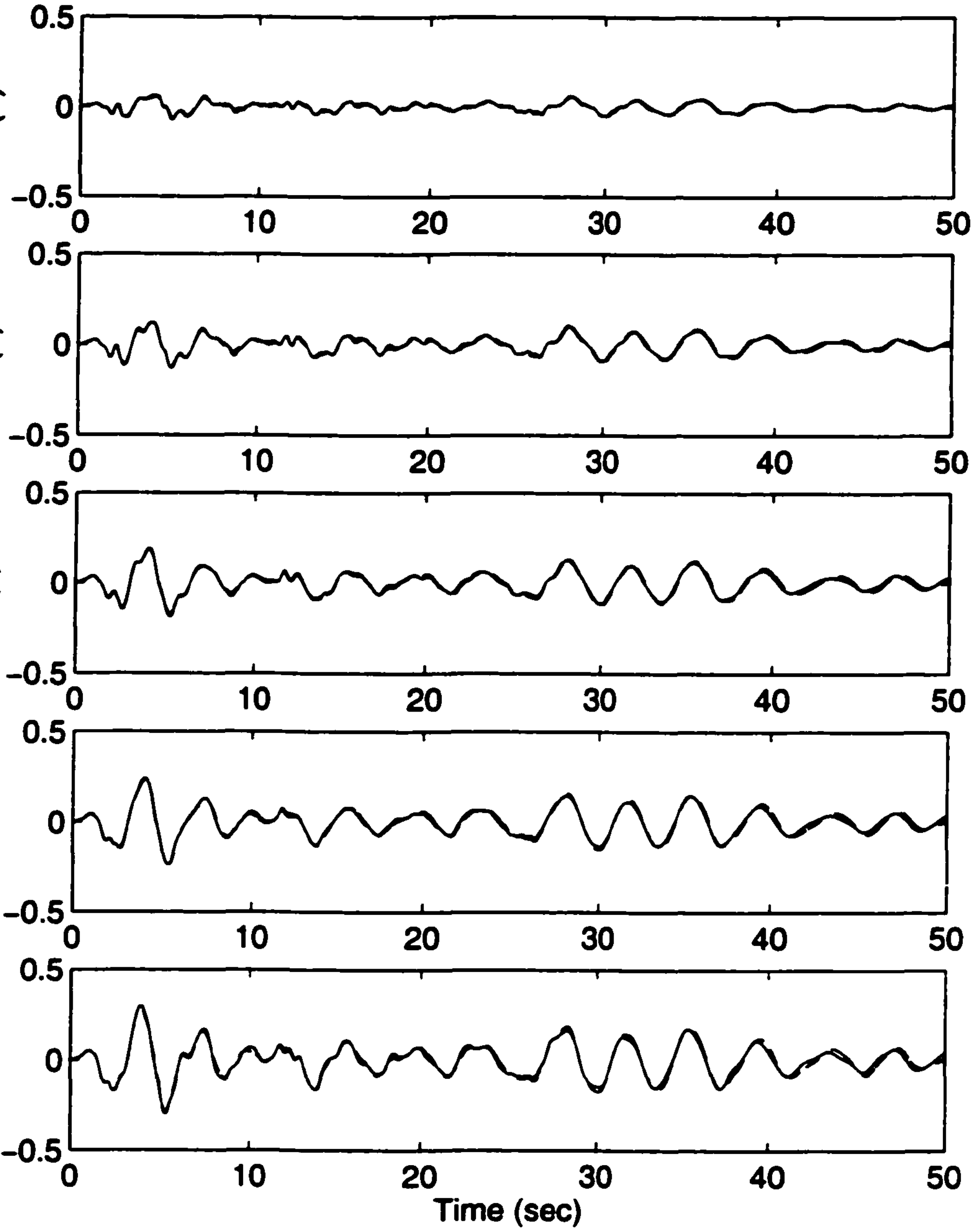


Figure 18. Displacement of the Benchmark Frame (solid) and 5-DOF Identified Model (dashed) with Kobe Earthquake as Disturbance for (a) 4th Floor / 1st DOF (b) 8th Floor / 2nd DOF (c) 12th Floor / 3rd DOF (d) 16th Floor / 4th DOF and (e) Roof / 5th DOF

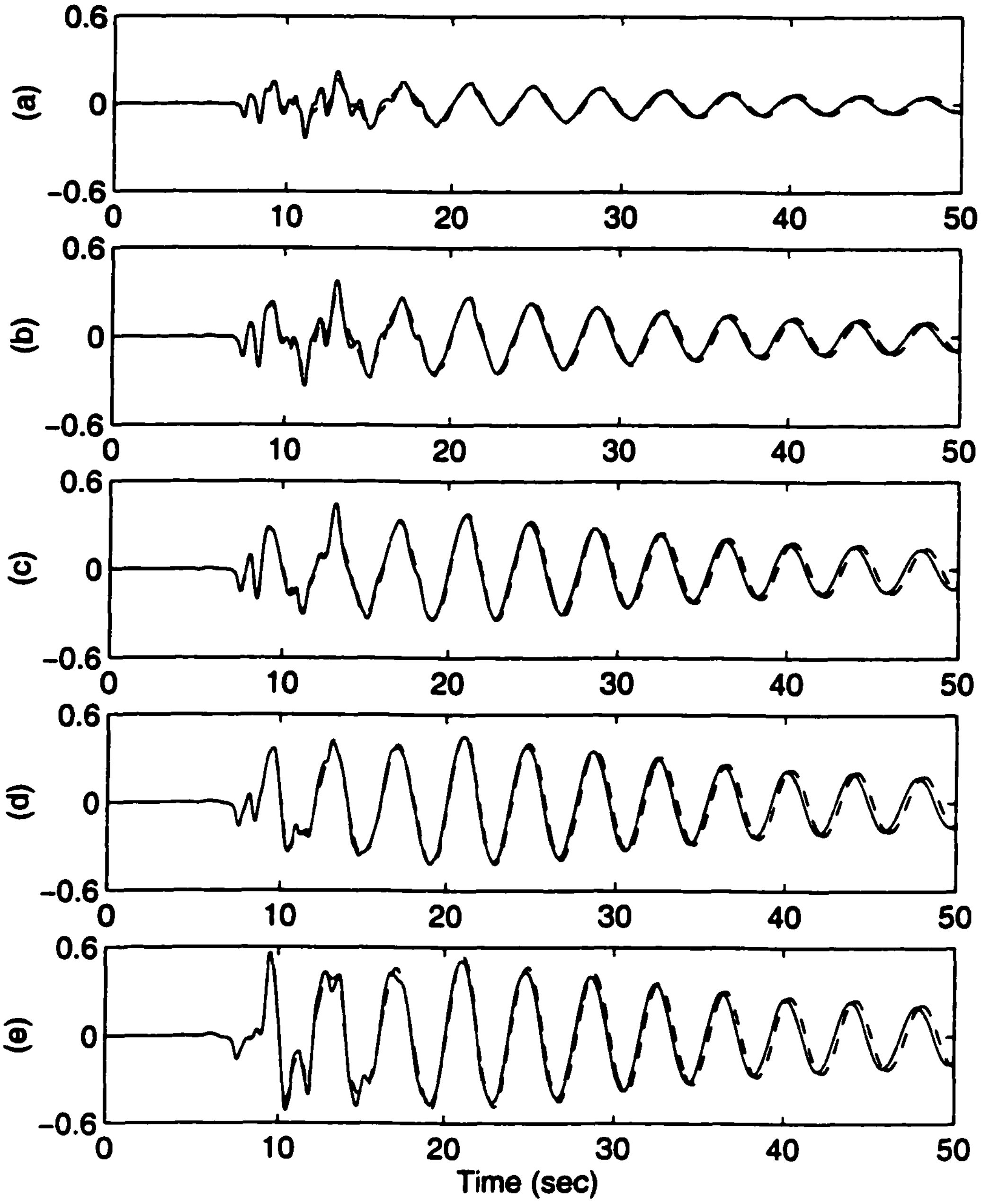
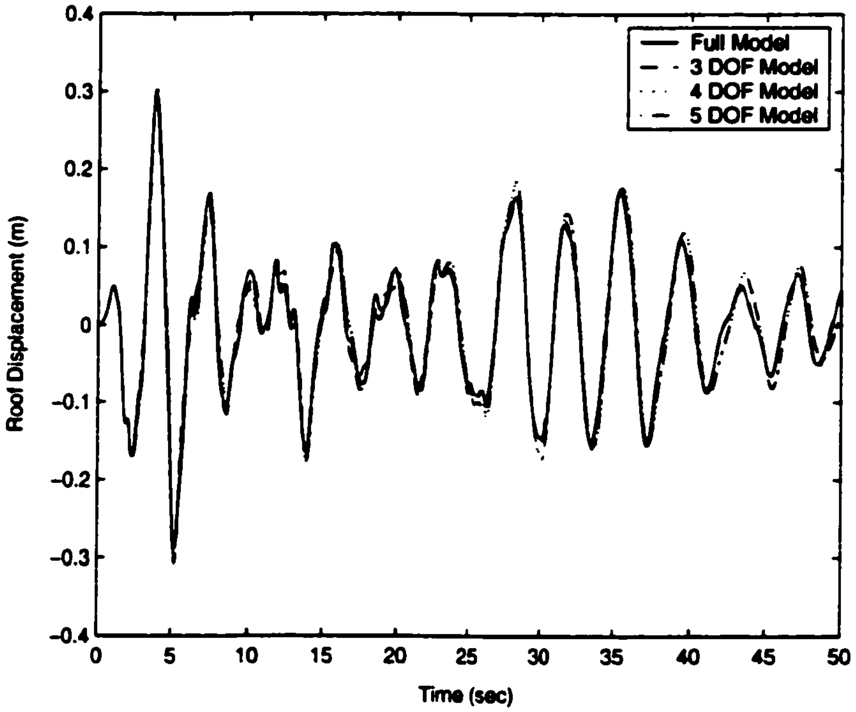


Figure 19. Comparison of Roof Displacements for the Various Models with the El Centro Earthquake as Disturbance



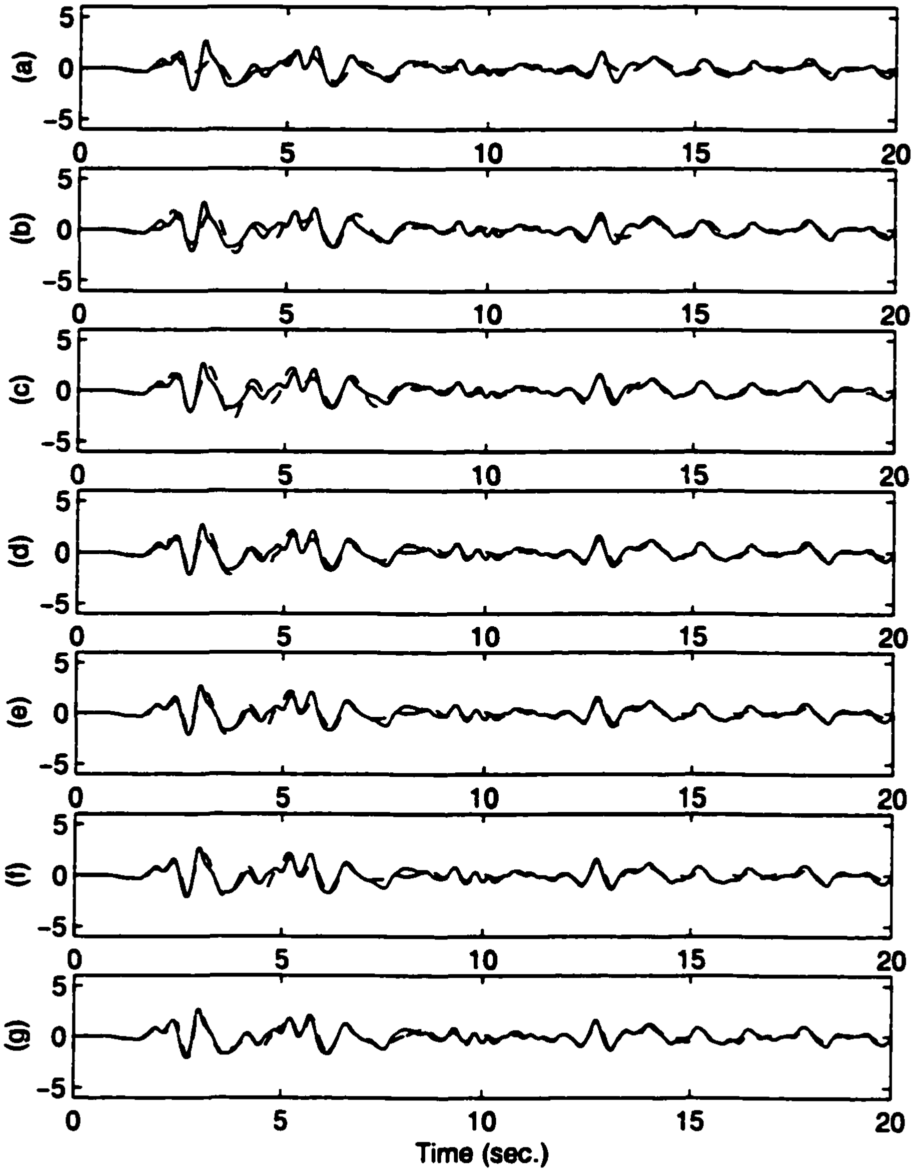
4.3 Second Generation Benchmark Structure – Acceleration

While the main damage mechanism for buildings in earthquakes is the displacement between stories, it is difficult to measure displacement directly. A much more common quantity to measure is acceleration, since accelerometers are generally accurate and inexpensive. Thus, it is desirable to extend the proposed modeling technique to acceleration modeling. Fortunately, this is a very straightforward process, involving a slight modification of the structure of the identified model and the use of acceleration data rather than displacement data.

The changes in the identified model structure for acceleration modeling involve the addition of extra parameters. Recall from Chapter 3 that certain parameters in the models were found to be zero, and thus did not need to be identified. In order to model acceleration accurately these parameters, which correspond to the two highest powers of s in the numerator and denominator polynomials, once again must be included in the identification process.

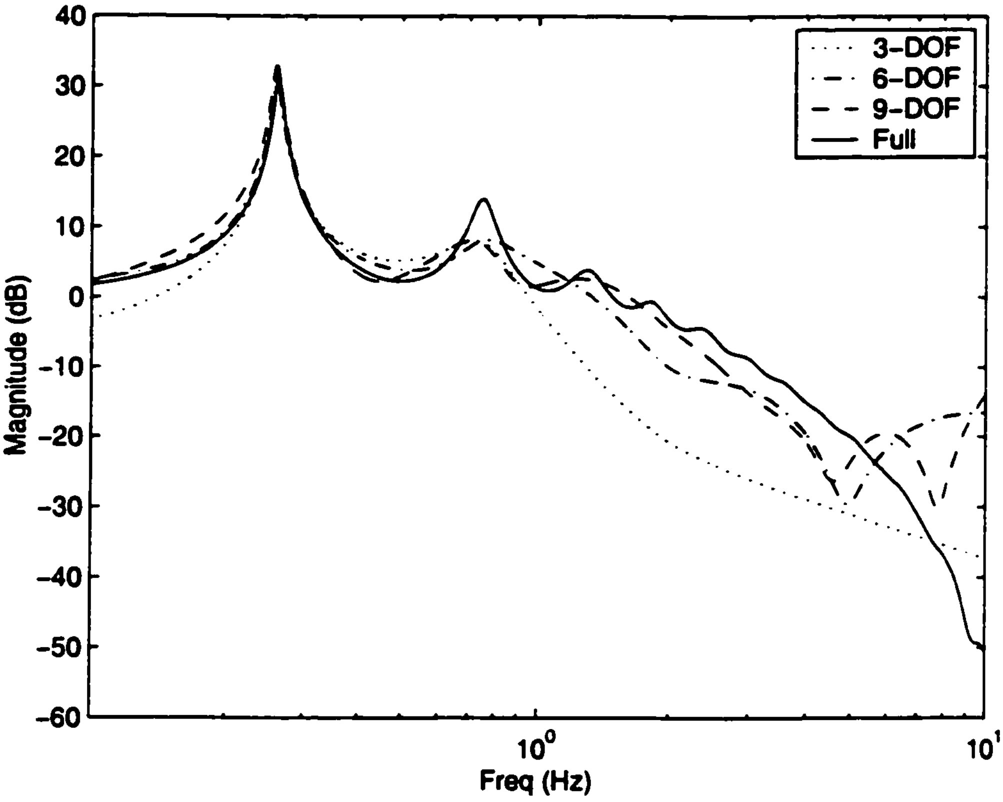
As in the case of displacement, the benchmark structure from Spencer et al. [156] was used as the original system from which a simplified model was identified. Several simplified models were identified for the acceleration response of the roof due to earthquake excitation over a range of the number of degrees of freedom. Figure 20 shows the time history for each of these models due to excitation simulated by the El Centro earthquake data. This figure shows that increasing the number of degrees of freedom in the identified model only marginally improves the time history response.

Figure 20. Acceleration Response of the Roof of the Benchmark Building (solid) Compared with Simplified Model Responses (dashed) with (a) 3-DOF, (b) 4-DOF, (c) 5-DOF, (d) 6-DOF, (e) 7-DOF, (f) 8-DOF, and (g) 9-DOF.



The reason increasing the degrees of freedom in the identified model gives only marginal improvement can be seen in Figure 21. The first two modes dominate the higher frequency modes, as can be seen from the greater height of the first two peaks. Each of the identified models captures these modes fairly well, with the differences coming from the far less significant higher order modes.

Figure 21. Ground Excitation to Roof Acceleration Frequency Response of Benchmark Frame and Selected Identified Models



Chapter 5: Example Applications

Two applications for the models identified using the method described are shown below. Both of these applications are in the area of controller design, since such applications are the main motivation for the development of this method. The first application simply uses a simplified model in a controller design algorithm. The second application also involves controller design, but in the context of a sensor fault detection and accommodation system.

5.1 Application to Multi-Objective LQG Controller Design

In Brown, Ankireddi, and Yang [79] a state space representation of a shear beam building model is used as the plant for design of multi-objective Linear Quadratic Gaussian (LQG) controllers. With some manipulation, the transfer functions produced by the identification method described above can be transformed into the required form for use in this controller design algorithm.

First, the parameters from the transfer function can be used to form a set of state space matrices of the form

$$\dot{x} = Ax + Bu\,, \quad y = Cx \tag{15}$$

where A, B, and C are in controller canonical form, that is

$$A = \begin{bmatrix} -a_{n-1} & -a_{n-2} & \cdots & -a_1 & -a_0 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix}, \tag{16}$$

$$B = \begin{Bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{Bmatrix}, \tag{17}$$

$$C = \begin{bmatrix} 0 & b_{1,n-1} & \cdots & b_{1,0} \\ b_{1,n-1} & \cdots & b_{1,0} & 0 \\ & \vdots & & \\ 0 & b_{n,n-1} & \cdots & b_{n,0} \\ b_{n,n-1} & \cdots & b_{n,0} & 0 \end{bmatrix}, \; b_{i,j} = \text{ith floor, jth parameter} \tag{18}$$

The $b_{i,j}$'s in equation (18) are the same as the numerator parameters from equation (1), which are identified by the process outlined in previous sections. The C matrix takes this form because the outputs required for the controller design algorithm are the displacements and velocities of each degree of freedom, and velocity in the frequency domain is displacement multiplied by s. Also, the transformation

$$A' = CAC^{-1}, \; B' = CB, \; C' = CC^{-1} = I \tag{19}$$

gives a system with

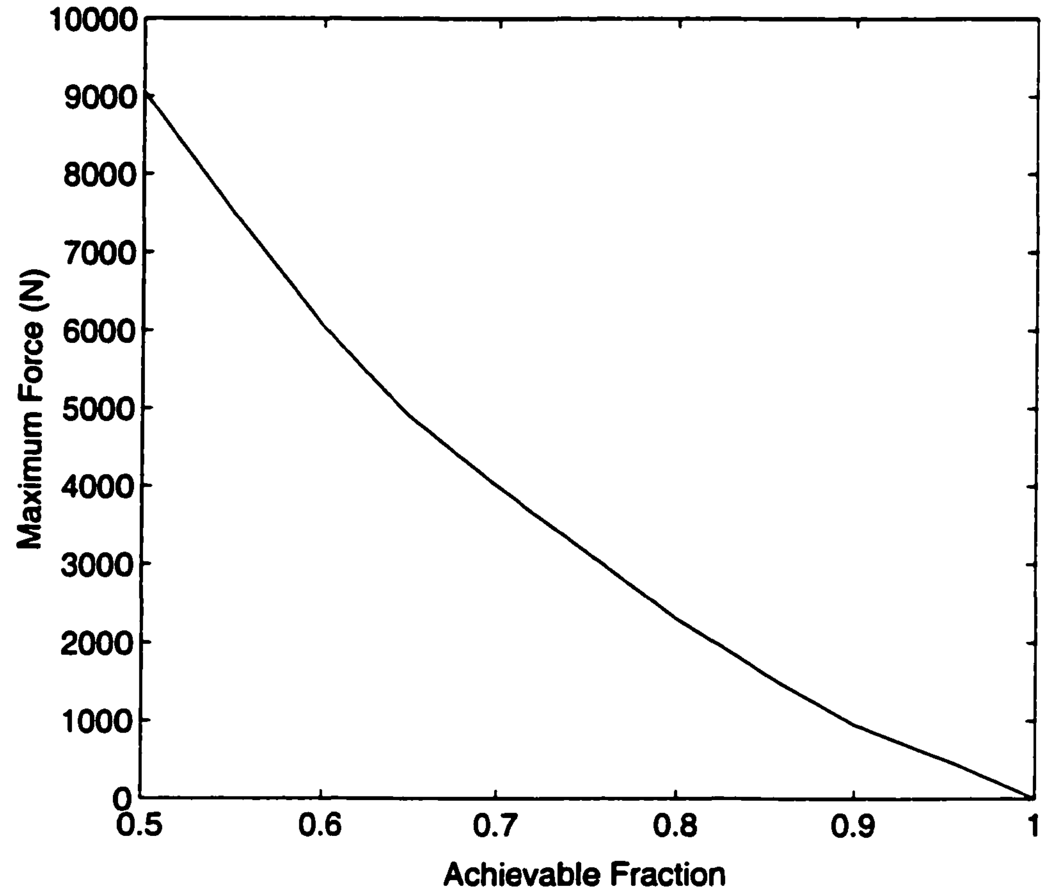
$$\dot{x}' = A'x' + B'u, \; y = x' = Cx \tag{20}$$

in which the output is the state of the system.

Using the 3-degree of freedom simplified model for displacement identified from the second-generation benchmark building example in section 4.2 above, a controller design can be made. It is assumed that an Active Mass Driver installed on the roof of the structure will generate the control force required. For the control objectives of reduction of maximum roof displacement to a fraction of its maximum uncontrolled value and the maximum force required to achieve a given fraction, a

Pareto optimal curve showing feasible controllers, calculated using a simulated filtered white noise earthquake as specified in Brown, Ankireddi, and Yang [79] is shown in Figure 22. This curve shows that a greater reduction in the maximum roof displacement requires greater maximum force.

Figure 22. Pareto Optimal Curve of Feasible Controllers with Control Objectives of Minimizing Maximum Required Control Force and Fraction of Maximum Controlled over Maximum Uncontrolled Roof Displacement



As part of the benchmark study by Spencer et al. [156], a highly accurate evaluation model of the benchmark building has been developed for Matlab [153] that can be used to test controller designs. This evaluation model has practically the same frequency response as the full benchmark model. However, through the use of a modified Guyan reduction scheme (Guyan [157], Craig [158]), the number of degrees of freedom in the evaluation model is reduced from 526 to 106, thus making the evaluation model more computationally feasible. Neglecting sensor and actuator dynamics in order to focus on the identified model and the controller design, this evaluation model was used to test a controller designed using the algorithm described in Brown, Ankireddi, and Yang [79]. A controller that attempts to reduce maximum roof displacement by 50% was chosen and simulated using the evaluation model. The roof displacement for the controlled and uncontrolled cases using the North-South components of the 1940 El Centro and 1995 Kobe earthquakes as disturbances to the evaluation model are shown in Figure 23 and Figure 24, respectively. Each shows a reduction in the maximum roof displacement of close to 50% with the controller active. This is as much as can be expected, since the controller design was performed with a simulated white noise earthquake, and thus a reduction of exactly 50% cannot be guaranteed for other earthquakes. Other, perhaps more aggressive, control design algorithms that can be applied to simple shear beam models of structures should also be effective with the simplified models identified using the technique described herein, since these types of models are mathematically very similar.

Figure 23. Controlled and Uncontrolled Responses of Benchmark Evaluation Model with LQG Controller and El Centro Earthquake as Disturbance

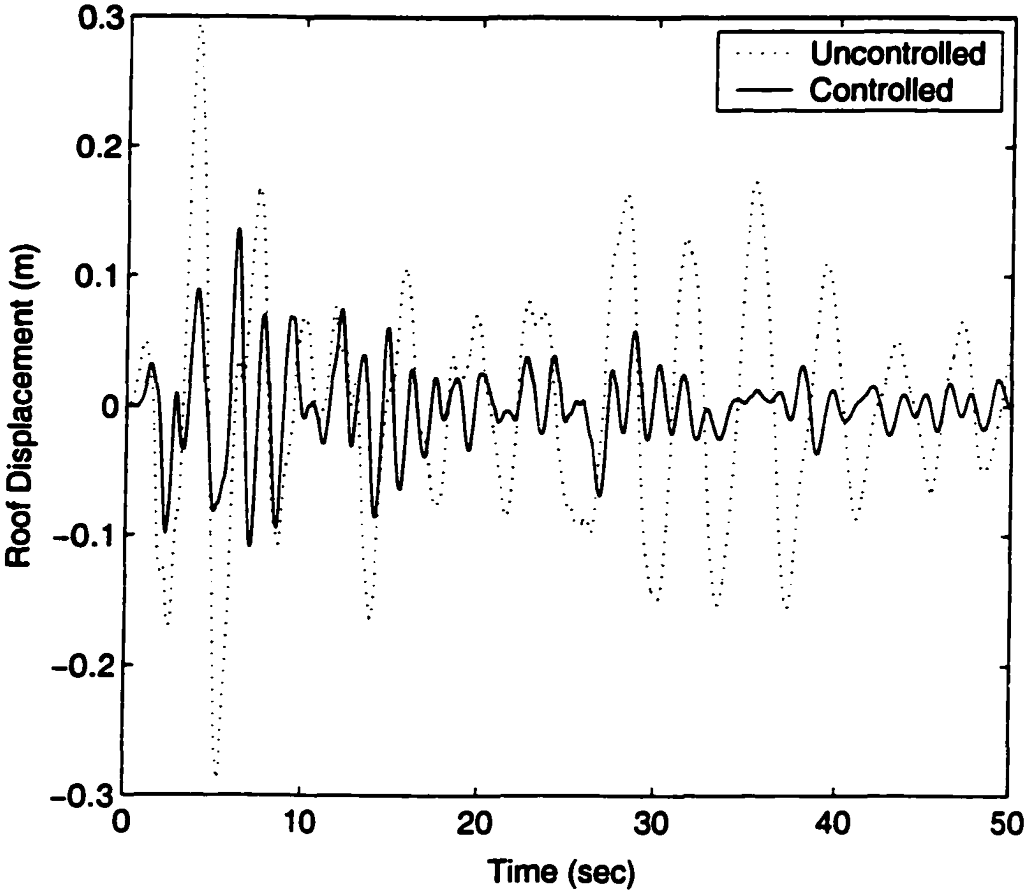
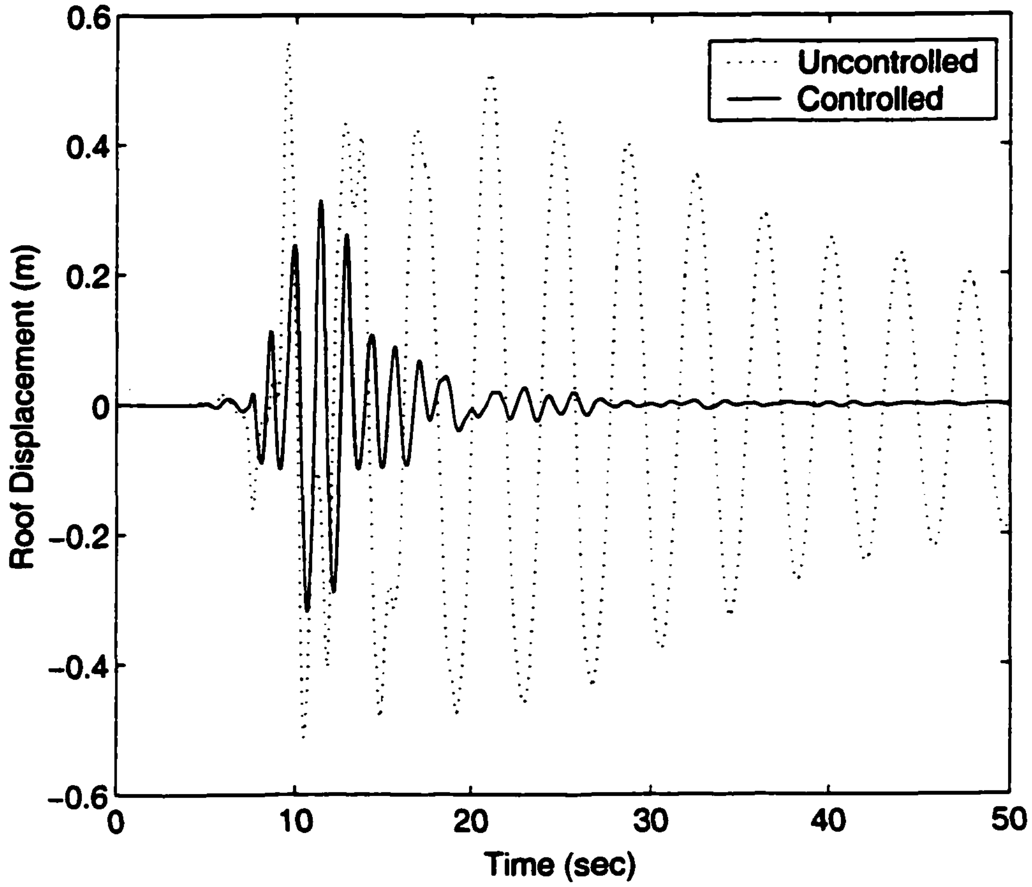


Figure 24. Controlled and Uncontrolled Responses of Benchmark Evaluation Model with LQG Controller and Kobe Earthquake as Disturbance



5.2 Application to Fault Detection and Accommodation Neural Networks for Structural Control

The 3 degree of freedom model for floor displacement identified from the second-generation benchmark building example in section 4.2 above has also been used in a control system integrated with a neural network sensor monitoring system as described in Wrobleski, Ma, and Yang [159]. Two kinds of neural networks were used in this example. They are the sensor Failure Detection Neural Network (FDNN) and Failure Accommodation Neural Network (FANN).

As the name suggests, an FDNN is used to detect sensor failures online. The network is trained off line by existing healthy sensor measurements, which in this example are simulated values. Then the network is provided with real measurements (once again simulated in this example) during an actual earthquake event to monitor the behavior of the sensors. Once failure is detected, the FANNs are used to provide estimates of the output the failed sensor would provide if it continued to function.

An FDNN is a single-layer feed-forward type neural network whose input is a measurement of the frequency content of the signal from a sensor. This frequency content is provided by passing the sensor measurement through a Fast Fourier Transform (FFT). The output of the FDNN is chosen to be an arbitrary constant representing a healthy sensor (1 in this example). The network is trained using standard neural network training algorithms available in MATLAB [153] until it reliably reproduces the target constant (within a small envelope of uncertainty) from healthy sensor data, and deviates from that value for a failed sensor.

After being trained, a network can be connected to the sensor that it will monitor online. Separate individual neural networks are required for each sensor monitored by the FDNN.

Once sensor failure is reported by the FDNNs, FANNs take over for the failed sensor(s) to provide the necessary information for control force calculations. In other words, the lost measurements due to sensor failure(s) are recovered by the FANNs. For the FANNs, a multi-layer feed-forward type neural network is used. The input to an FANN is the time history from an originating sensor and the output is the estimated time history of a target sensor. The training of the FANNs is done off line by using existing uncorrupted measurements. During training, the network is provided with the most recent past values from the originating sensor as input and the time history of the target sensor as the desired output. The number of past values taken from the originating sensor is equal to the number of input nodes in an FANN. The FANNs, like the FDNNs, are trained using standard neural network training algorithms. In addition, an Intelligent Decision-Making System (IDMS) refines the estimates from multiple FANNs by taking a weighted average of their values. Details of how this weighting is performed may be found in Wrobleski, Ma, and Yang [159].

In this example, as before, the 7th and 14th floors and the roof of the benchmark structure correspond to the three degrees of the simplified model. The FDNNs have been set up with 30 input nodes and one output node. The 30 input nodes correspond to the first 30 frequencies from a 512-point FFT. In order to focus the FFT on the most recent data, and thus reduce failure detection time, only the previous 50 measurements are used in the FFT. Each FANN is a two-layer feed-forward network with 30 input nodes, 10 hidden nodes, and 1 output node. The output is the estimate of the present value of the target sensor. The 30 inputs correspond to the previous 30 measurements from an originating sensor (assumed to be healthy). The FDNNs and FANNs were trained using simulated measurements from simulations whose ground excitation were filtered white noise with frequency content similar to that of the North-South acceleration component of the May 18, 1940 El Centro earthquake.

Figure 25 shows the output of a trained FDNN for the roof (20^{th} floor) of the Benchmark Structure. The straight line is the output of the FDNN for a healthy sensor. Also shown is the FDNN output when a sensor fails at t=10 sec. Sensor failure is detected by the deviation from the target value. The excitation for this simulation is very similar to the excitations used for the training data sets, however. In Figure 26 the same FDNN is tested using measurements corresponding to excitation by the January 17, 1995 Kobe earthquake. As in Figure 25, failure of the sensor is quickly detected. Since the FDNNs monitor frequency content of the measurements, which is more dependent on the structural characteristics than the exogenous disturbances, it is clear the FDNNs are robust in terms of the excitation affecting a structure.

Figure 25. FDNN Output for El Centro Earthquake and Sensor Failure at t=10 sec.

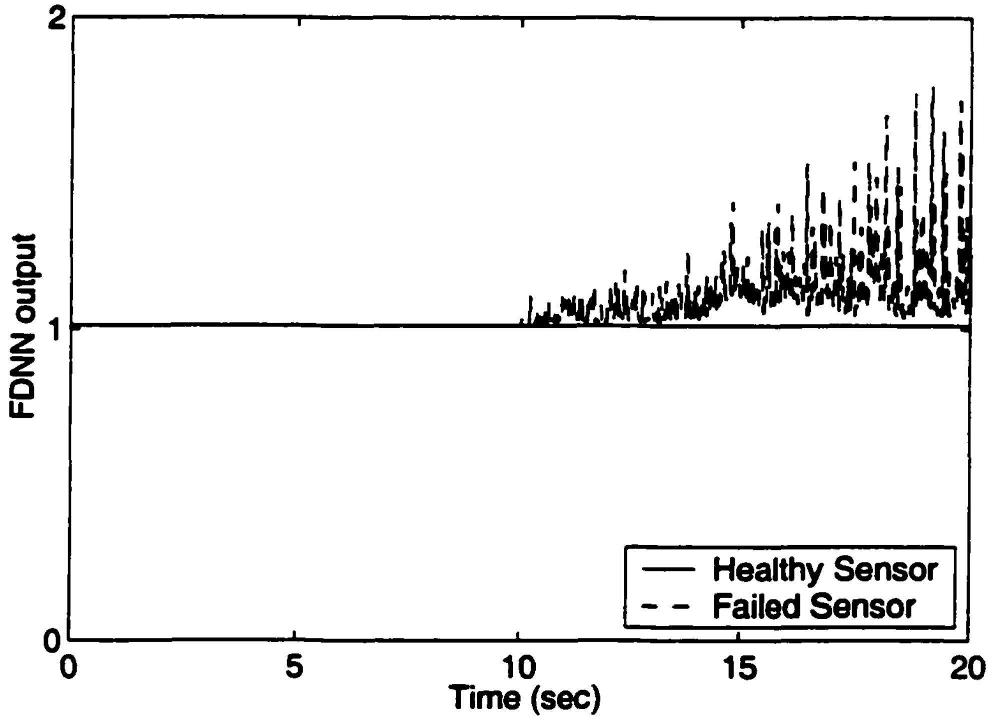
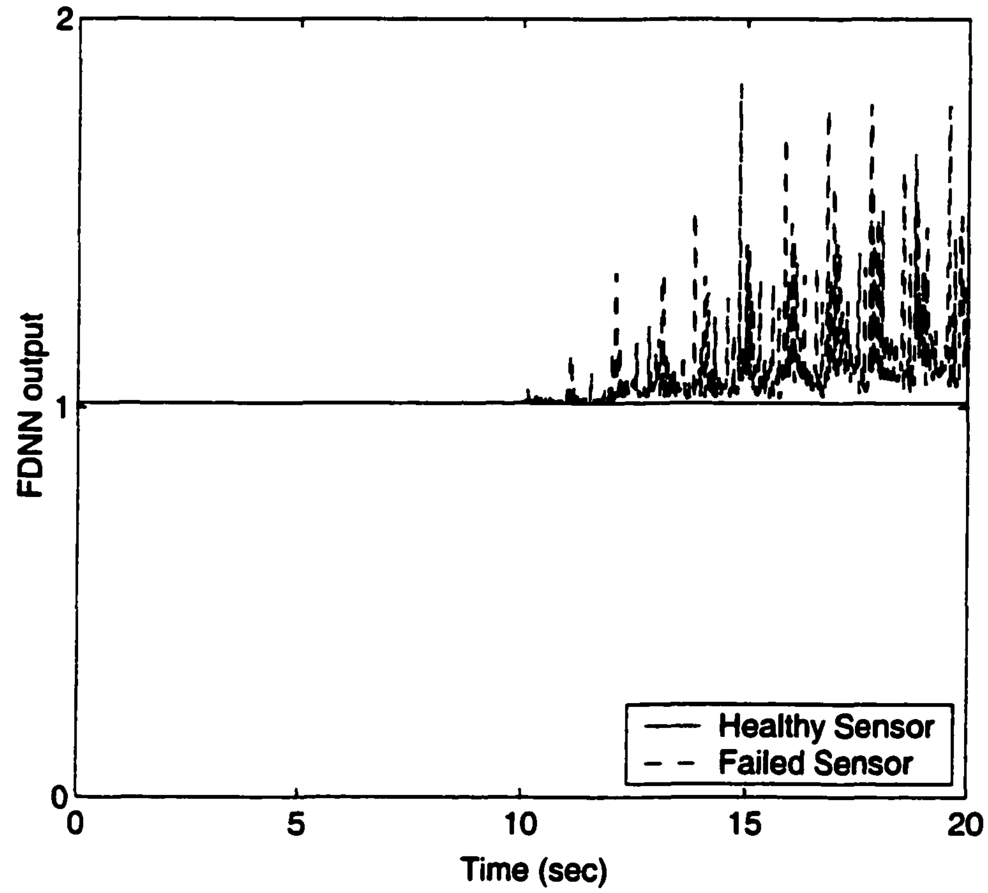


Figure 26. Performance of FDNN Tested by Kobe Earthquake



The results for a trained FANN when the excitation is the same as that used in the neural network training are shown in Figure 27. The actual displacement and the estimate are virtually identical in this case. Other combinations of originating sensor and target output show similar precision. This high degree of accuracy is due to the fact that the training data set has been used. This accuracy does not hold for cases when the excitation is different from the training set, however. Since it can not be reasonably expected to know the excitation of an earthquake *a priori*, multiple FANNs and the IDMS are required. The performance with the complete (multiple FANNs and IDMS) estimation system in place for the 14th floor is shown in Figure 28.

Figure 27. Output for FANN Estimating 14th Floor Response from 7th Floor Data Trained and Simulated with El Centro Earthquake Excitation

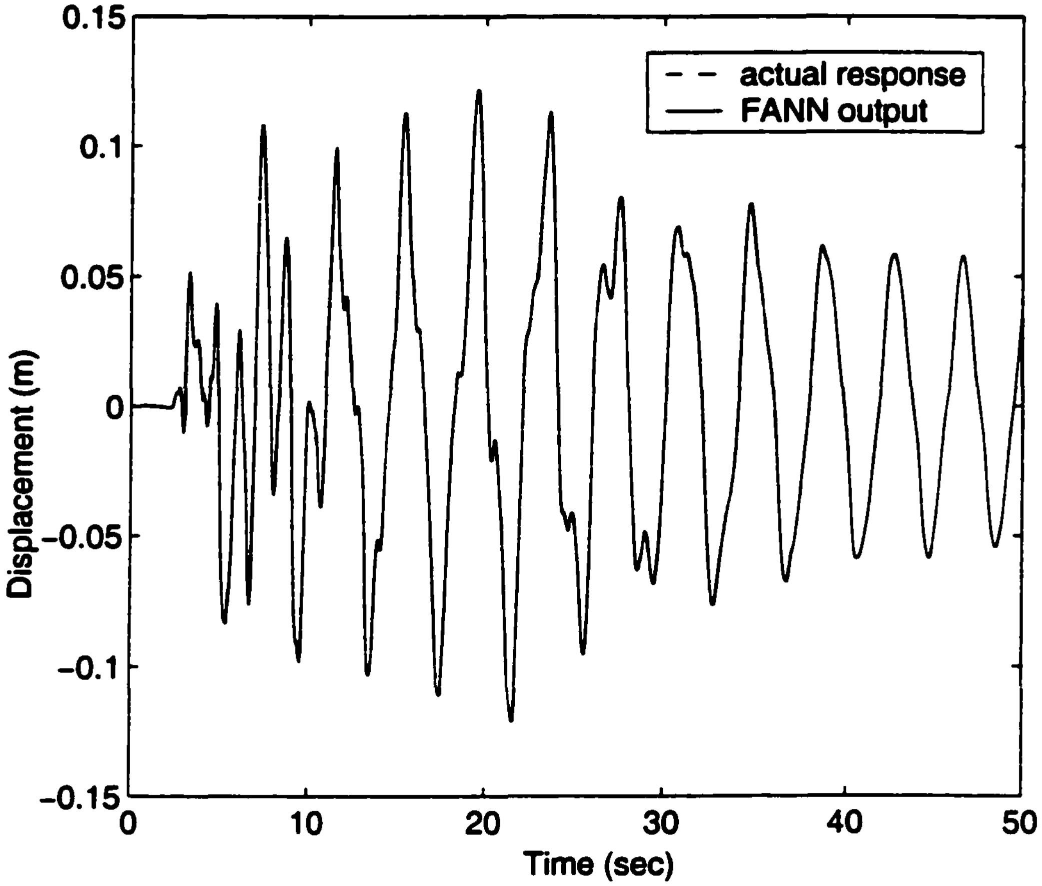
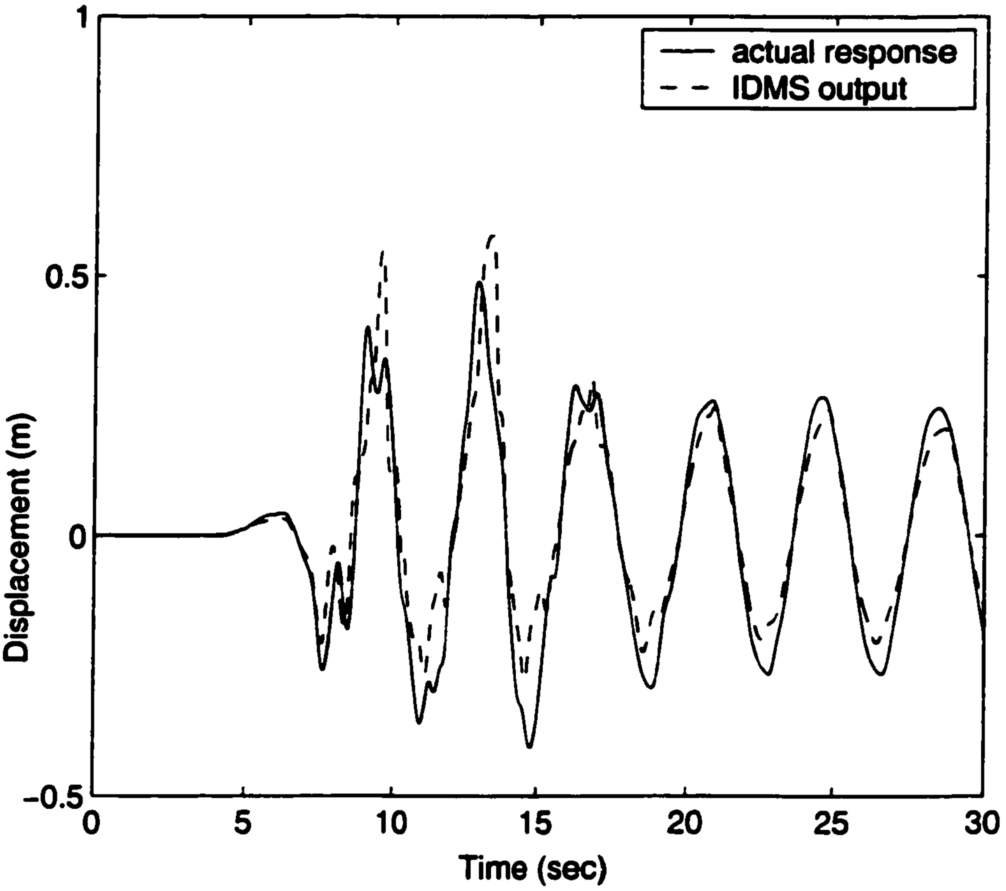


Figure 28. Estimate of 14th Floor Using Data from 7th Floor and Roof Using Multiple FANNs and IDMS



Using the evaluation model developed in Spencer, Christenson, and Dyke [156], a Linear Quadratic Gaussian (LQG) controller with Kalman filter for state estimation designed using the simplified 3-degree of freedom model, and the failure detection and accommodation systems described above, the structural responses of the benchmark model have been simulated for four cases; uncontrolled, controlled with no sensor failure, controlled with undetected sensor failure, and controlled with sensor failure detected and accommodated for. The excitation in these cases was the May 16, 1968 Hachinohe City earthquake, and for the cases with sensor failure, the 14th floor (second degree of freedom) sensor is assumed to read random noise after t=10 sec. Figure 29 shows the roof displacements in the uncontrolled case and in the controlled case with unaccommodated sensor failure. The roof displacement in the controlled case with a failed sensor is as bad as or worse than the uncontrolled case after the sensor fails. This is due to the failed sensor providing false measurements and the control force generated based on these measurements is unproductive. The uncontrolled case is compared to the case where the sensor failure is detected and accommodated in Figure 30. This figure illustrates significant improvement when fault detection and accommodation are present. Finally, Figure 31 compares the controlled case with fault detection and accommodation to the limiting case of control with a perfectly healthy sensor. The performance in these two cases is similar.

Figure 29. Roof Displacement of Uncontrolled and Controlled with Undetected Failed Sensor Cases

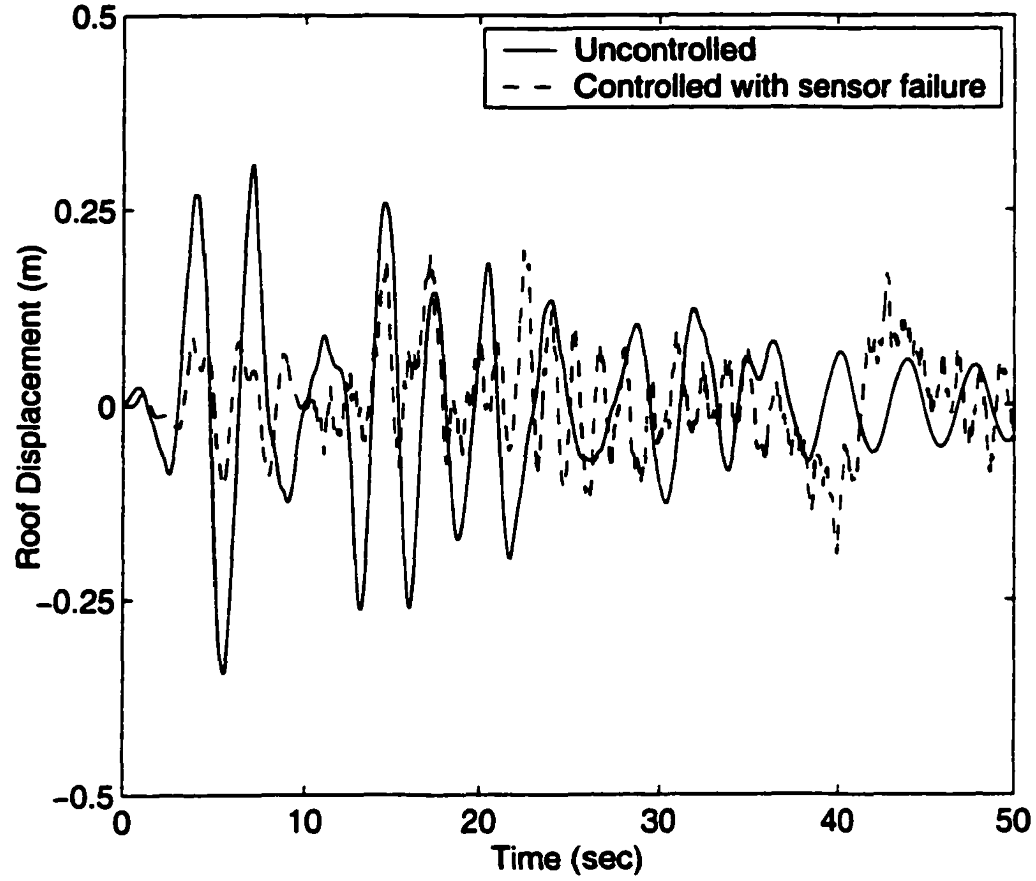


Figure 30. Roof Displacement of Uncontrolled and Controlled with Fault Accommodation Cases

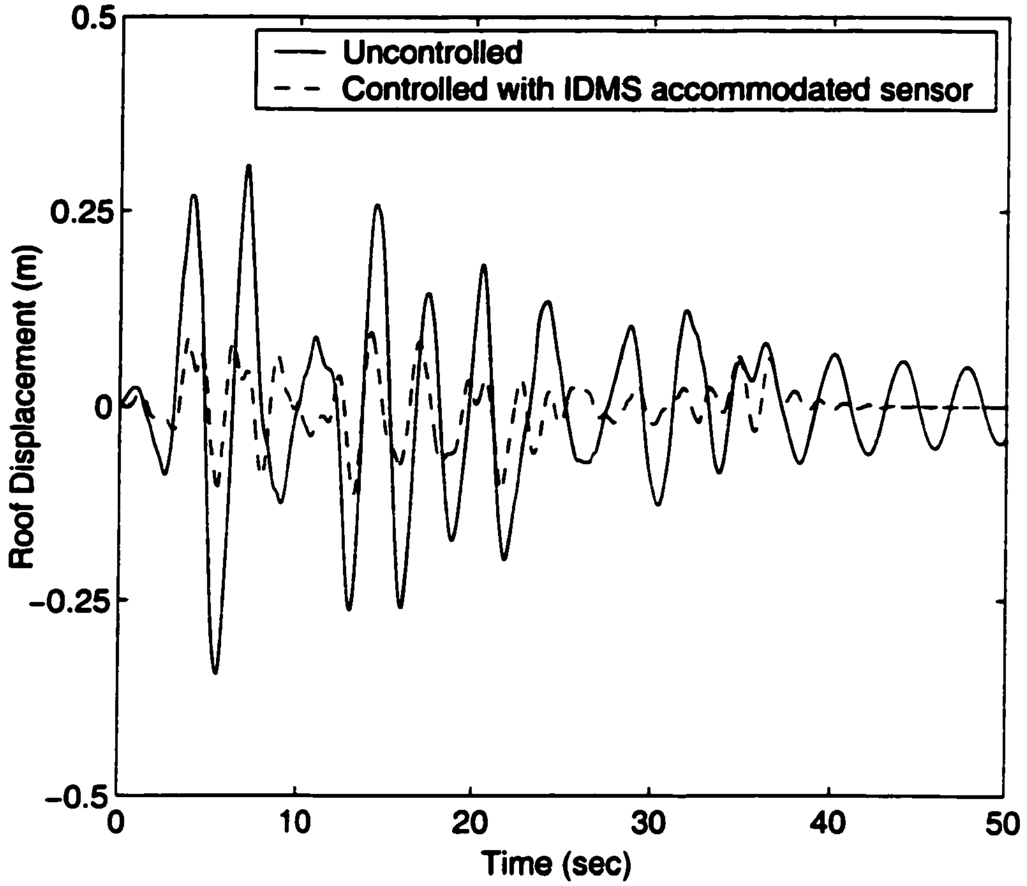
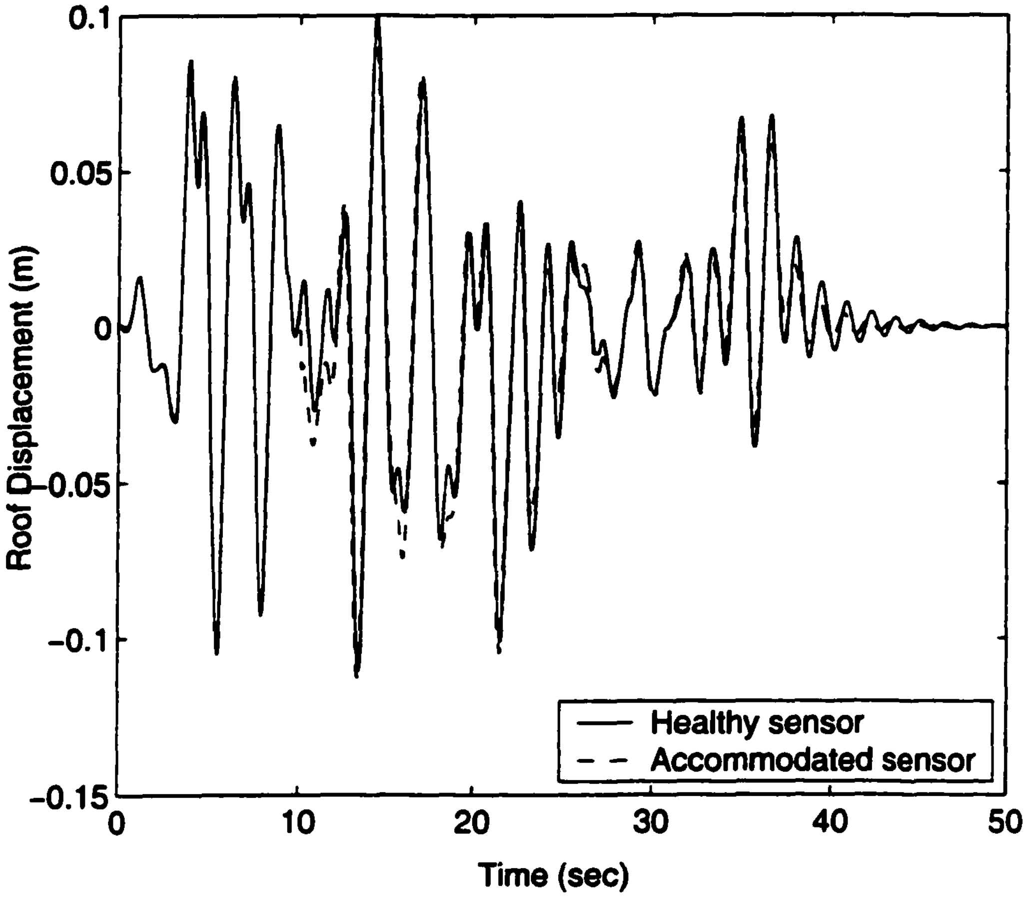


Figure 31. Controlled Roof Displacement with Healthy and Accommodated Sensors



Chapter 6: Conclusion

6.1 Summary

A method has been presented for identifying simplified models of buildings using input and output data. These models have improved accuracy over other simple models because of the system identification process that is used, without adding additional degrees of freedom to the model.

The proposed technique has been used to produce simplified models of relatively complex simulated example structures. In these examples, it has been shown that the quality of the models identified using this technique is high. Also, models of both displacement and acceleration responses have been successfully identified, showing the versatility of the proposed modeling method.

Models identified using this method have been used in controller design applications and tested using data from actual earthquake measurements. Using an evaluation model of the benchmark building provided by the creators of the benchmark system, these controller designs have been tested and proven successful. The models have also been successfully used in a more elaborate building monitoring and control system that involves sensor health monitoring and failure compensation, as well as controller components.

6.2 Future Work

There are several areas of potential for extension of this work. First, all of the original, complex models used in the examples shown are simulations of component level models. It would be useful to test this technique using data from actual experiments, either on actual buildings or scale models. Successful determination of a simplified model of an actual building from data taken from that building would be very desirable. However, such data may be difficult to obtain, since the occupants of the buildings would be greatly inconvenienced. Data from scale models could be obtained more easily, and multiple tests on such a model could be used as identification and verification data sets.

Another extension of this work could be into the area of discrete time modeling. It is quite possible that a discrete time analogue of this work would be simpler computationally. It should even be possible to use the discrete time models to estimate continuous time models, and vice versa.

Another application for the models provided using this technique could be the estimation of stresses and strains in the original models. Since the failure of a structural member is due to these factors, estimation of their value could be very useful. It may even be possible to design a controller based on such estimates of stress and strain. It would also be possible to use this technique to directly model the input to output relationship of building excitation to the strain in a specific member, and design a controller based directly on these measurements.

Knowledge about damage or failure of certain members in the original complex model could also be used to calculate revised simplified models for use in an adaptive controller design. If a complex model of a structure exists, it would be straightforward to model failure of a given member in that structure. The input to output behavior of this model could then be simulated and used to produce a simplified model of the structure with the failed member.

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