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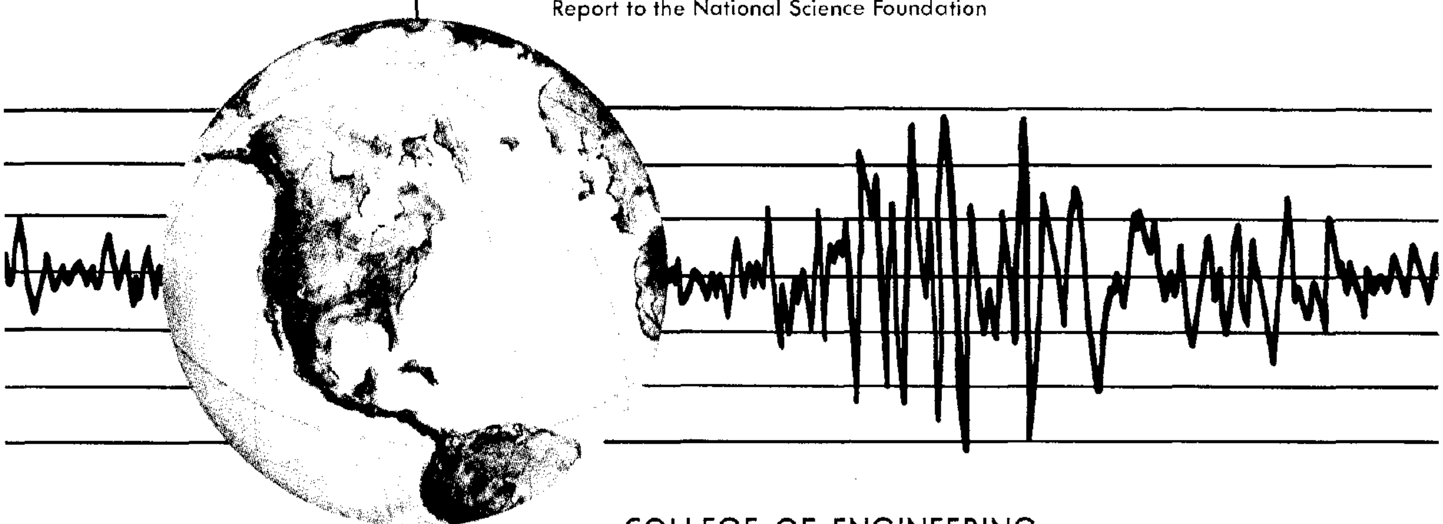
SYSTEM IDENTIFICATION OF STRUCTURES WITH JOINT ROTATION

by

JERRY S. DIMSDALE

Report to the National Science Foundation



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ABSTRACT

The goal of this research is to investigate the role of joint behavior in the identification of frame models from dynamic response data caused by seismic forcing functions. Including joint rotation and deformation in the mathematical model for even simple structures significantly affects the distribution of stiffness, and the accuracy with which response can be predicted.

An optical method has been devised for accurately measuring joint rotation of a structure during earthquake excitation. This method has been applied to a simple six story frame in which the columns have approximately the same stiffness as the girders. Response data have been collected for a variety of base motion histories. Also studied are data previously collected from a three story frame in which joint rotation information has been inferred from strain measurements.

A number of different mathematical models of these structures are evaluated using system identification. Each mathematical model depends on a number of parameters related to the characteristics of the structure. An iterative method is applied to calculate the values of these parameters which best reproduce the measured response of the structure. The form of the mathematical model has an effect on the degree to which the optimal parameters accurately reflect physical properties of the structure. Further, the form of the model influences not only the number of parameters and degrees of freedom, but also the set of response quantities necessary for calculating an optimal set of parameters.

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CHAPTER 1

INTRODUCTION

In studying the properties of a structure, the analyst typically has a continuum of models from which to choose. For many applications, the simplest and most coarse approximation to actual behavior will suffice. By adding greater refinement to critical portions of the analysis, prediction of response can be improved. This refinement takes its toll both in the analyst's time, and computational effort, usually in a computer. It would therefore be wise to add sophistication to a model in a logical manner.

To predict the response of a structure to a prescribed input using an analytical model, certain parameters reflecting physical properties of the structure must be known or determined. This may not always be trivial, both because the materials used may have some uncertainty, and also because the materials can be used in some unfamiliar way. For example, the properties of concrete subjected to triaxial stress are both variable and imperfectly understood. Further, while there are counter-examples, increasing a model's analytical complexity often increases uncertainty about physical parameters. An analytical model actually represents a continuum of models which, in practice, may be difficult to apply, since its parameters are difficult to estimate.

System identification is a tool which can be used to evaluate a model. By systematically adjusting the parameters to provide the best possible correlation between predicted and measured responses, the form of the analytical model can be appraised. System identification is a generic term for this optimization process, and there are many approaches to applying it to structural engineering. There have been many survey articles written on system identification [4,7,8,11,20,21], so this discussion need not be exhaustive. Evaluating models by adjusting parameters to fit known response data is known as parametric identification. Much of the literature in parametric identification has been devoted to the determination of modal characteristics [13,17]. While it is true that stiffness and damping matrices can be determined from modal properties, little can be inferred about the participation of individual structural elements. An algorithm used by Matzen [18] allows determination of element characteristics but, for economic reasons, is only applicable to a structure with a small number of degrees of freedom. Here, Matzen's algorithm is extended to allow identification using a structure with a relatively large number of degrees of freedom.

In a frame with even a small number of elements, accurately predicting response can require a large number of degrees of freedom. For instance, in frames commonly approximated by a simple shear model, it is well known that the inclusion of rotational stiffness at its joints significantly affects predictive accuracy [12]. Using data from a three story frame previously built by Clough and Tang [10,24], and a six story frame developed for this study, it is shown that not only the rotational response, but also the deformation of the joints, significantly affects a model's optimal precision.

The optimization algorithm to be used and its implementation in dynamic structural analysis are described in Chapter 2. In Chapter 3 its application to a frame already studied in some detail is discussed. Previously, accurate data concerning the dynamic rotation of frame joints has been unavailable. Chapter 4 describes an optical method of measurement which allows high resolution and accuracy. This method has proved to be extremely useful in the study of the effects of joint behavior on overall dynamic response. In Chapter 5 the application of both the optimization and rotation measurement methods in the identification of parameters of a six story frame are described and conclusions are presented in Chapter 6.

CHAPTER 2

ITERATIVE IDENTIFICATION

General System

Suppose we have a system subjected to a time dependent input p(t), which produces a set of measurable outputs $y_j(t), j=1,...,n$. If we have a model which we believe represents the system, this means we have some rule by which, given an input, p(t), and some information about the system in terms of a vector of constants, $\underline{b}$, we can predict the output of the system, $x_j(\underline{b},t)$. Here we include $\underline{b}$ as an argument to emphasize the dependence of the predicted output of the system on the information supplied to the model.

One measure of how well the predicted response matches the measured response is the squared-error loss function over a time interval 0<t<T:

$$J(\underline{b}) = \sum_{j=1}^{n} \int_{0}^{T} g_j [x_j(\underline{b},t) - y_j(t)]_m^2 \, dt \tag{2.1}$$

Again, $\underline{b}$ is included as an argument to emphasize the dependence of J on $\underline{b}$. If $J(\underline{b})=0$, then the predicted response would exactly match the measured response. We would like to know what value of $\underline{b}$, if any, makes J a minimum value.

Unfortunately, very few models permit a closed form solution for $\underline{b}$ which minimizes J globally. It is, however, often possible to generate an iterative scheme which will produce a $\underline{b}$ which is a local minimum.

Gauss Newton Method

Given a set of parameters $\underline{b}_i$, we would like a systematic method of discovering a new set $\underline{b}_{i+1}$ such that $J(\underline{b}_{i+1}) < J(\underline{b}_i)$. Repeated often enough, this will lead to a minimum for J. If the function J is approximately quadratic in a neighborhood of $\underline{b}_i$, there will be little error in the approximation

$$J(\underline{b}_{i+1}) = J(\underline{b}_i) + \nabla J^t(\underline{b}_i)(\underline{b}_{i+1} - \underline{b}_i) + \tfrac{1}{2}(\underline{b}_{i+1} - \underline{b}_i)^t \nabla^2 J(\underline{b}_i)(\underline{b}_{i+1} - \underline{b}_i) \tag{2.2a}$$

where

$$\nabla J_p = \frac{\partial J}{\partial b_p} \tag{2.2b}$$

and

$$\nabla^2 J_{ps} = \frac{\partial^2 J}{\partial b_p \partial b_s}. \tag{2.2c}$$

To minimize J, its gradient with respect to $\underline{b}_{i+1}$ is set to the zero vector. If the Hessian matrix is invertible, it follows that

$$\underline{b}_{i+1} = \underline{b}_i - \left[\nabla^2 J(\underline{b}_i)\right]^{-1} \nabla J(\underline{b}_i) \tag{2.3}$$

Since J will not, in general, be exactly quadratic, we will want to be able to adjust the size of the correction to $\underline{b}_i$. Thus we modify the equation by adding a step size variable, α:

$$\underline{b}_{i+1} = \underline{b}_i - \alpha\left[\nabla^2 J(\underline{b}_i)\right]^{-1} \nabla J(\underline{b}_i). \tag{2.4}$$

The components of ∇J and $\nabla^2 J$ are found by taking the appropriate derivatives of the error function:

$$\nabla J_p = \frac{\partial J}{\partial b_p} = 2\sum_{j=1}^{n} \int_0^T g_j \left([x_j(\underline{b},t) - y_j(t)]\, \frac{\partial x_j(\underline{b},t)}{\partial b_p}\right) dt \tag{2.5a}$$

$$\frac{\partial^2 J}{\partial b_p \partial b_s} = 2\sum_{j=1}^{n}\left[\int_0^T g_j\, \frac{\partial x_j(\underline{b},t)}{\partial b_p}\, \frac{\partial x_j(\underline{b},t)}{\partial b_s}\, dt + \int_0^T g_j\, (x_j(\underline{b},t) - y_j(t))\, \frac{\partial^2 x_j(\underline{b},t)}{\partial b_p \partial b_s}\, dt\right]. \tag{2.5b}$$

Experience has shown that the second integral, particularly when $\underline{b}_i$ is close to a minimum, is negligible when compared to the first. The Gauss-Newton iteration scheme, therefore, is to choose α and calculate

$$\underline{b}_{i+1} = \underline{b}_i - \alpha\left[\underline{AH}(\underline{b}_i)\right]^{-1} \nabla J(\underline{b}_i) \tag{2.6a}$$

where the approximate Hessian matrix, $\underline{AH}$, is defined as

$$\underline{AH}_{ps} = 2\sum_{j=1}^{n}\left[\int_0^T g_j\, \frac{\partial x_j(\underline{b},t)}{\partial b_p}\, \frac{\partial x_j(\underline{b},t)}{\partial b_s}\, dt\right]. \tag{2.6b}$$

The technique for choosing α is known as a line search algorithm since the multidimensional minimization problem has been reduced to a single dimension.

Line Search

By establishing a search direction, the error function is reduced to being a function of one variable

$$J(\alpha) = J[\underline{b}_i - \alpha A H^{-1}(\underline{b}_i)\nabla J(\underline{b}_i)] \tag{2.7}$$

whose derivative is

$$\frac{\partial}{\partial \alpha} J(\alpha) = -\nabla J'(\underline{b}_{i+1})\, A H^{-1}(\underline{b}_i)\, \nabla J(\underline{b}_i). \tag{2.8}$$

If we are pointed in the right direction, $J'(0)<0$. If the error surface were quadratic, then the exact minimum would be at $\alpha=1$. If $J'(1)>0$ then there must be a minimum for $0<\alpha<1$. In order to find a point closer to the minimum, a cubic polynomial is constructed so that its values and derivatives match J at the end points, and the minimum of the cubic is used as a new trial point. If, on the other hand, $J'(1)<0$ and $J(1)<J(0)$, then a quadratic extrapolation is made. In this way, successive approximations to the functional minimum are made until some stopping criterion is met.

The stopping criterion for the line search will affect the relative amount of time spent on finding search directions and doing line searches. In general, spending too much time on either is not economic. In practice, a good deal of trial and error is necessary to find a reasonable distribution of effort. In this case four or five iterations in the line search is probably a good compromise. It is also desirable to have the line search end fairly soon in the event a poor direction is chosen, since the improvement will be rather slight.

Structural Models

The mathematical model associated with dynamic behavior of an n degree of freedom linear elastic structure subjected to rigid base motion is

$$\underline{m}\, \frac{d^2 u}{dt^2} + \underline{c}\, \frac{du}{dt} + \underline{ku} = -\underline{mr}\, \frac{d^2 u_g}{dt^2} \tag{2.9a}$$

$$\frac{d\underline{u}(0)}{dt} = \underline{u}(0) = 0 \tag{2.9b}$$

where $\underline{m}$ is the mass matrix, $\underline{c}$ is the damping matrix, and $\underline{k}$ is the stiffness matrix. $\frac{d^2\underline{u}}{dt^2}$, $\frac{d\underline{u}}{dt}$, and $\underline{u}$ are vectors for relative acceleration, velocity, and displacement. $\frac{d^2u_g}{dt^2}$ is the base acceleration. $\underline{r}$ is a column vector whose elements are static displacements due to a unit displacement of the base of the structure.

It is possible to find a matrix, $\underline{P}$, so that $\underline{M}=\underline{P}^t\underline{mP}$ and $\underline{K}=\underline{P}^t\underline{kP}$ are both diagonal matrices: i.e., $M_{ij}=0$ if $i \neq j$. If we make the change of variables

$$\underline{u} = \underline{PY} \tag{2.10}$$

then the differential equation of motion can be rewritten

$$\underline{M}\frac{d^2\underline{Y}}{dt^2} + \underline{C}\frac{d\underline{Y}}{dt} + \underline{KY} = \underline{F}(t) \tag{2.11a}$$

where

$$\underline{C} = \underline{P}^t\,\underline{cP} \quad \text{and} \quad \underline{F}(t) = -\underline{P}^t\,\underline{mr}\,\frac{d^2u_g}{dt^2}. \tag{2.11b}$$

If the additional assumption of proportional damping is made; that is,

$$\underline{c} = a_0\underline{m} + a_1\underline{k}, \tag{2.12}$$

then $\underline{C}$, $\underline{M}$, and $\underline{K}$ will all be diagonal, and the n coupled differential equations will be decoupled into n equivalent uncoupled single degree of freedom equations. The coefficients a_0 and a_1 can be related to the damping ratios and frequencies by

$$E_i = \tfrac{1}{2}\left(\frac{a_0}{w_i} + a_1 w_i\right), \tag{2.13}$$

where E_i is the damping ratio, and w_i is the characteristic frequency of the i^{th} mode.

Structural Identification

Geometric and material information describing a structure can be organized into a vector $\underline{b}$, so that using the finite element method mass, damping, and stiffness matrices can be constructed which depend on $\underline{b}$:

$$\underline{m} = \underline{m}(\underline{b}) \quad \underline{c} = \underline{c}(\underline{b}) \quad \underline{k} = \underline{k}(\underline{b}). \tag{2.14}$$

By solving the differential equation

$$\underline{m}(\underline{b}) \frac{d^2 u}{dt^2} + \underline{c}(\underline{b}) \frac{du}{dt} + \underline{k}(\underline{b}) \underline{u} = -\underline{m}(\underline{b}) \underline{r} \frac{d^2 \underline{u}_g}{dt^2} \tag{2.15}$$

with boundary value

$$\frac{du(0)}{dt} = \underline{u}(0) = 0, \tag{2.16}$$

we arrive at a solution $\underline{x}(\underline{b})$ which is the predicted response of the structure, given $\underline{b}$, subjected to a ground motion $\underline{u}_g(t)$.

Given measured response histories at a number of locations, $y_i(t)$, the error of the model which the differential equation represents, over some time interval 0<t<T is defined as:

$$J(\underline{b}) = \sum_{j=1}^{n} \int_0^T g_j \left[x_j(\underline{b}, t) - y_j(t) \right]_m^2 dt \tag{2.17}$$

Applying the iterative scheme previously described requires calculating the sensitivities $\frac{\partial x_j(\underline{b})}{\partial b_p}$, and the responses $x_j(\underline{b})$. Given the structural matrices $\underline{m}$, $\underline{c}$, and $\underline{k}$, the differential equations could be solved directly. However, for even moderately small problems this can be quite time-consuming since there must be n+1 integrations each time ∇J and AH are calculated. Using modal decomposition this effort can be significantly reduced.

Using the modal equations

$$\underline{M}\ddot{\underline{Y}} + \underline{C}\dot{\underline{Y}} + \underline{K}\underline{Y} = \underline{F}(t) = -\underline{P}^t \, \underline{mr\ddot{u}_g} \tag{2.18}$$

$\underline{Y}$ can be calculated directly. The specific single degree of freedom integration algorithm will be described subsequently. Differentiating (2.18) we get

$$\underline{M} \frac{\partial \ddot{Y}}{\partial b_p} + \underline{C} \frac{\partial \dot{Y}}{\partial b_p} + \underline{K} \frac{\partial Y}{\partial b_p} = -\frac{\partial C}{\partial b_p} \dot{\underline{Y}} - \frac{\partial K}{\partial b_p} \underline{Y} - \frac{\partial P^t}{\partial b_p} \underline{mr\ddot{u}_g} \tag{2.19}$$

where it is assumed that

$$\frac{\partial M}{\partial b_p} = 0. \tag{2.20}$$

The time histories of the modal sensitivities are obtained from (2.19). This equation has the same form as (2.18), and the pseudo-forcing function on the right hand side of (2.19) is well known after (2.18) has been solved. The terms $\frac{\partial C}{\partial b_p}$, $\frac{\partial K}{\partial b_p}$, and $\frac{\partial P'}{\partial b_p}$ can all be calculated using finite differences. This may require great precision since $\underline{P}$ can be insensitive to changes in parameters. It may prove desirable to calculate these sensitivities concurrently with calculating the structural property matrices.

Once the modal sensitivities $\frac{\partial Y}{\partial b_p}$ are known, the sensitivities $\frac{\partial x_j}{\partial b_p}$ can be calculated from

$$\frac{\partial x_j}{\partial b_p} = \frac{\partial}{\partial b_p}\left[\underline{PY}\right] = \frac{\partial P}{\partial b_p} + \underline{P}\,\frac{\partial Y}{\partial b_p} \tag{2.21}$$

These can then be used to calculate a search direction for the Gauss-Newton iteration.

Numerical Integration Algorithm

The predicted dynamic response of a structure which has estimated structural property matrices $\underline{k}$, $\underline{m}$, and $\underline{c}$, depends to some extent on the algorithm by which the equations of motion are integrated. This can affect the values of identified parameters, particularly those which affect response at higher frequencies. In this work, we have chosen to use the Newmark-Wilson algorithm [5] for linear stepwise integration, primarily since it is unconditionally stable.

Model Specification

A number of physical constants are incorporated into a finite element model for a structure. These constants specify the geometric dimensions and material properties of the structure.

In general, it is neither practical nor possible to optimize the finite element model with respect to all the parameters describing a structure. As will be shown, some sets of parameters are not independent. Additionally, The computational effort required for a large number of parameters can be tremendous. Some parameters will be known with great precision, and may have a relatively small effect on response. Little time need be spent optimizing these. Other parameters, that are known less exactly, may have a pronounced effect on overall response. It would be wise to spend the bulk of the computational effort on these.

In structures with a repeated set of elements, the parameters associated with these elements may be known somewhat imprecisely. However, the analyst may be quite certain that all the elements of a certain type behave identically. With this in mind it is desirable to group all these parameters together. Thus, if one is studying the effective lengths of identical girders of a three story frame, it may be more appropriate to optimize a single parameter representing all these lengths. Thus, if the parameters describing a structure form a set p_k, the parameters to be identified will form a new set b_j. In general

$$p_k = b_j \text{ [initial estimate for } p_k\text{]} \tag{2.22}$$

for some j.

Redundant Degrees of Freedom

Suppose we model a structure that appears as though it had only two degrees of freedom;

Figure 2.1 Two degree of freedom frame

using symmetry, we use the reduced model

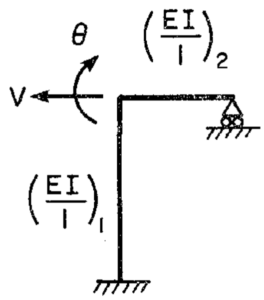

Figure 2.2 Symmetric simplification

Let $\alpha_i = \left[\frac{2EI}{L}\right]_i$, then the stiffness matrix for this model is

$$\underline{k} = \begin{bmatrix} 6\alpha_1 & 3\alpha_1 \\ 3\alpha_1 & 2\alpha_1 + \frac{3}{2}\alpha_2 \end{bmatrix}. \tag{2.23}$$

Noting that we are going to try to identify α_1 and α_2 using only lateral force F, we can apply static condensation:

$$\begin{bmatrix} F \\ 0 \end{bmatrix} = \underline{k} = \begin{bmatrix} 6\alpha_1 & 3\alpha_1 \\ 3\alpha_1 & 2\alpha_1 + \frac{3}{2}\alpha_2 \end{bmatrix} \begin{bmatrix} v \\ \theta \end{bmatrix} \tag{2.24}$$

so that

$$F = \left[\frac{3\alpha_1^2 + 9\alpha_1\alpha_2}{2\alpha_1 + \frac{3}{2}\alpha_2}\right] v \tag{2.25a}$$

$$\theta = \frac{-3\alpha_1}{2\alpha_1 + \frac{3}{2}\alpha_2}\, v. \tag{2.25b}$$

Now given any response pair (v_m, F_m), it is possible to identify

$$\frac{3\alpha_1^2 + 9\alpha_1\alpha_2}{2\alpha_1 + \frac{3}{2}\alpha_2}$$

but not α_1 and α_2 separately. Given any θ response data which satisfies the assumptions of static condensation, this cannot further reduce the problem.

However, suppose the structure we are studying is, in fact, accurately represented by a three degree of freedom model

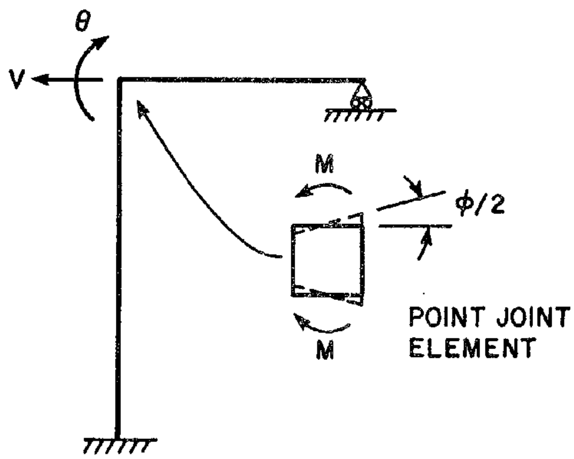

Figure 2.3 Three degree of freedom frame

where ϕ represents the distortion of a joint element, with no physical dimension. If the constitutive law of the joint is $M=k_j\phi$, the stiffness of this model is

$$\underline{k} = \begin{bmatrix} 6\alpha_1 & 3\alpha_1 & \frac{3}{2}\alpha_1 \\ 3\alpha_1 & 2\alpha_1+\frac{3}{2}\alpha_2 & \alpha_1 \\ \frac{3}{2}\alpha_1 & \alpha_1 & ½\alpha_1+k_j \end{bmatrix} \tag{2.26}$$

Applying static condensation:

$$\begin{bmatrix} F \\ 0 \\ 0 \end{bmatrix} = \underline{k} \begin{bmatrix} v \\ \theta \\ \phi \end{bmatrix} \tag{2.27}$$

we find that

$$\theta = \frac{-3\alpha_1}{2\alpha_1+\frac{3}{2}\alpha_2} v - \frac{\alpha_1}{2\alpha_1+\frac{3}{2}\alpha_2}\phi. \tag{2.28}$$

So, response data from a structure correctly modelled by the three degree of freedom model cannot satisfy the assumptions we used in identifying the two degree of freedom model (see Eqn. 2.23b). This problem will be amplified if, instead of measuring the joint rotation, we measure the rotation of the top of the column. Then, the measurement will be $\theta_m=\theta+\phi$. Thus, while using two response quantities from the three degree of freedom model, the basic assumptions made in this identification will be violated.

It appears that if identification fails to converge for a set of response data, but does converge when we include more data that we assumed was linearly related, this implies an underlying problem with the mathematical model, rather than anything about the parameters of the model that is being identified!

Statistical Interpretation of the Error Function

A dynamic structural model can be defined as a functional G which predicts a vector response $\underline{Y}(t)$ from an input function $v_g(t)$, and a vector of parameters $\underline{b}$:

$$\underline{Y} = G(v_g, \underline{b}) + \underline{\epsilon} \tag{2.29}$$

where $\underline{\epsilon}$ is a vector of error terms, and is often supposed to be normally distributed with zero mean.

A question which often arises is whether the complete set of parameters is needed in the model. In particular, if $\underline{b}$ is partitioned so that $\underline{b}' = (\underline{b}_1, \underline{b}_2)'$, an hypothesis which could be tested is whether $\underline{b}_2 = \underline{b}_2^*$, where $\underline{b}_2^*$ could be a zero vector. The test is based upon the relative reduction in the error function when all the parameters are estimated as compared with the error when $\underline{b}_1$ is estimated with $\underline{b}_2 = \underline{b}_2^*$. If the reduction is large, the hypothesis that $\underline{b}_2 = \underline{b}_2^*$ is untenable.

Suppose $\underline{b}_1$ has p parameters and $\underline{b}_2$ has q. Let $\underline{b}^*$ be the optimal set of parameters with $\underline{b}_2 = \underline{b}_2^*$. With appropriate statistical assumptions, the statistic

$$F = \frac{[J(\underline{b}^*) - J(\underline{b})]/q}{J(\underline{b})/(n-p)} \tag{2.30}$$

will approximately have what is called an F(q,n-p) distribution. This distribution is tabled in any of a number of sources [7]. The hypothesis that $\underline{b}_2 = \underline{b}_2^*$ is tested at the α level of significance by comparing F with the critical value $F_{1-\alpha}(q, n-p)$. If this critical value is exceeded, the hypothesis that $\underline{b}_2 = \underline{b}_2^*$ is rejected.

The use of a squared error loss function, therefore, is not only a good subjective measure of goodness-of-fit, but can be utilized as a quantitative tool for comparing alternative models.

CHAPTER 3

THREE STORY FRAME

Model Description

The test structure consisted of two parallel single-bay, three-story, moment resistant steel frames. The frames were fabricated from standard rolled shapes of ASTM A-36 grade steel. Detailed in Figure 3.1, the two frames designated A and B are separated by a distance of 6 ft. They are connected at floor levels by removable cross beams and bracing angles producing the effect of a floor diaphragm rigid in its own plane. The total height of the structure is 17 ft. 4 in. The story heights are 6 ft. 8 in., 5 ft. 4 in., and 5 ft. 4 in. The bar width is 12 ft. 0 in. Sections W5-16 and W6-12 are used for columns and girders, respectively.

Fully penetrated welded girder to column connections are used in this structure. Figure 3.2 depicts the details of these connections. The panel zone thickness is 1/4 in. (i.e. the column web thickness) for phase I of the experiments, and 1 in. (column web reinforced by 3/8 in. doubler plates on both sides) for phase II. Figure 3.3 lists the nominal section properties, and Figure 3.4 summarizes the estimated weights of the structure.

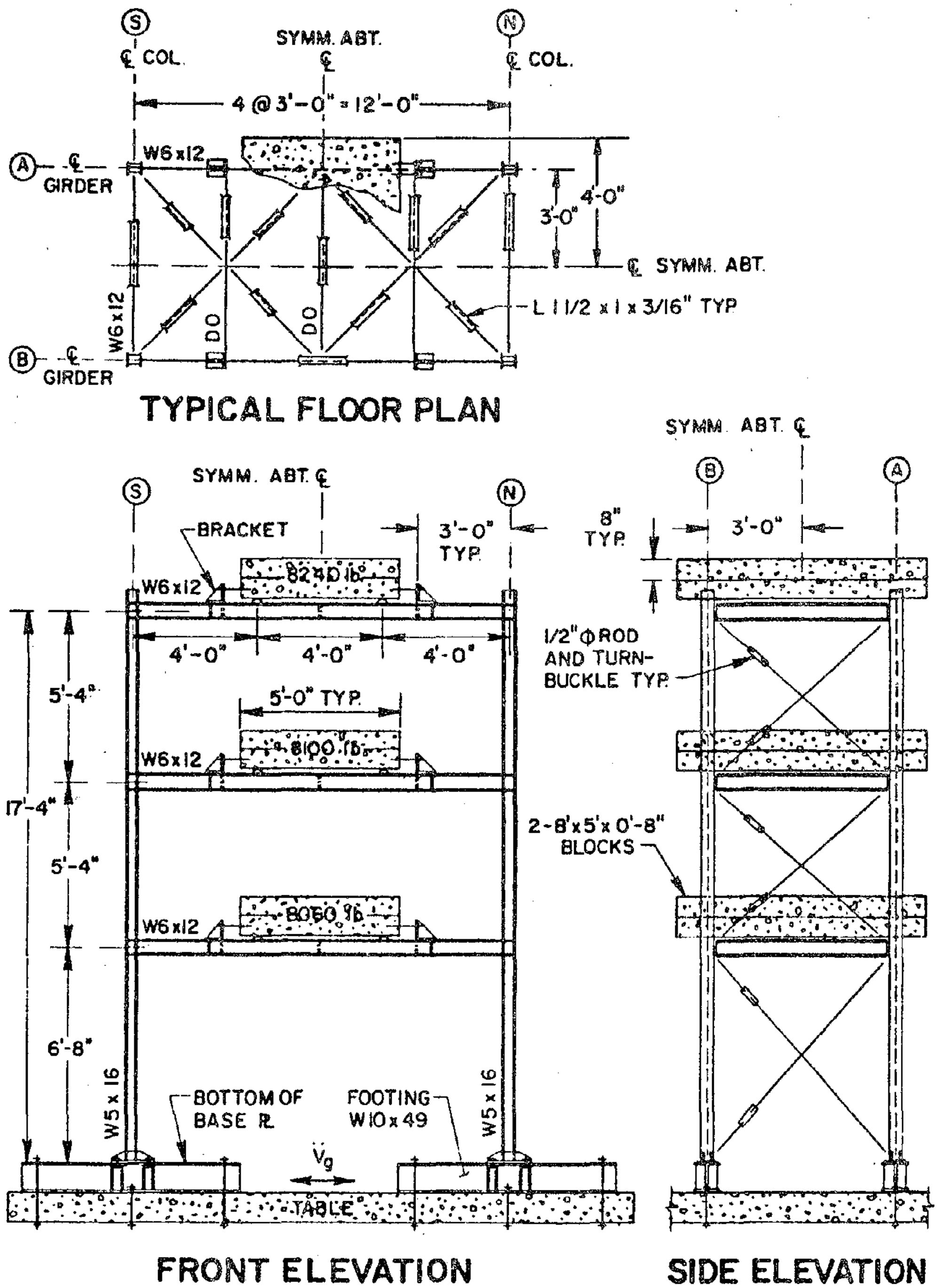

Figure 3.1 Structure plan and elevations
of the test structure

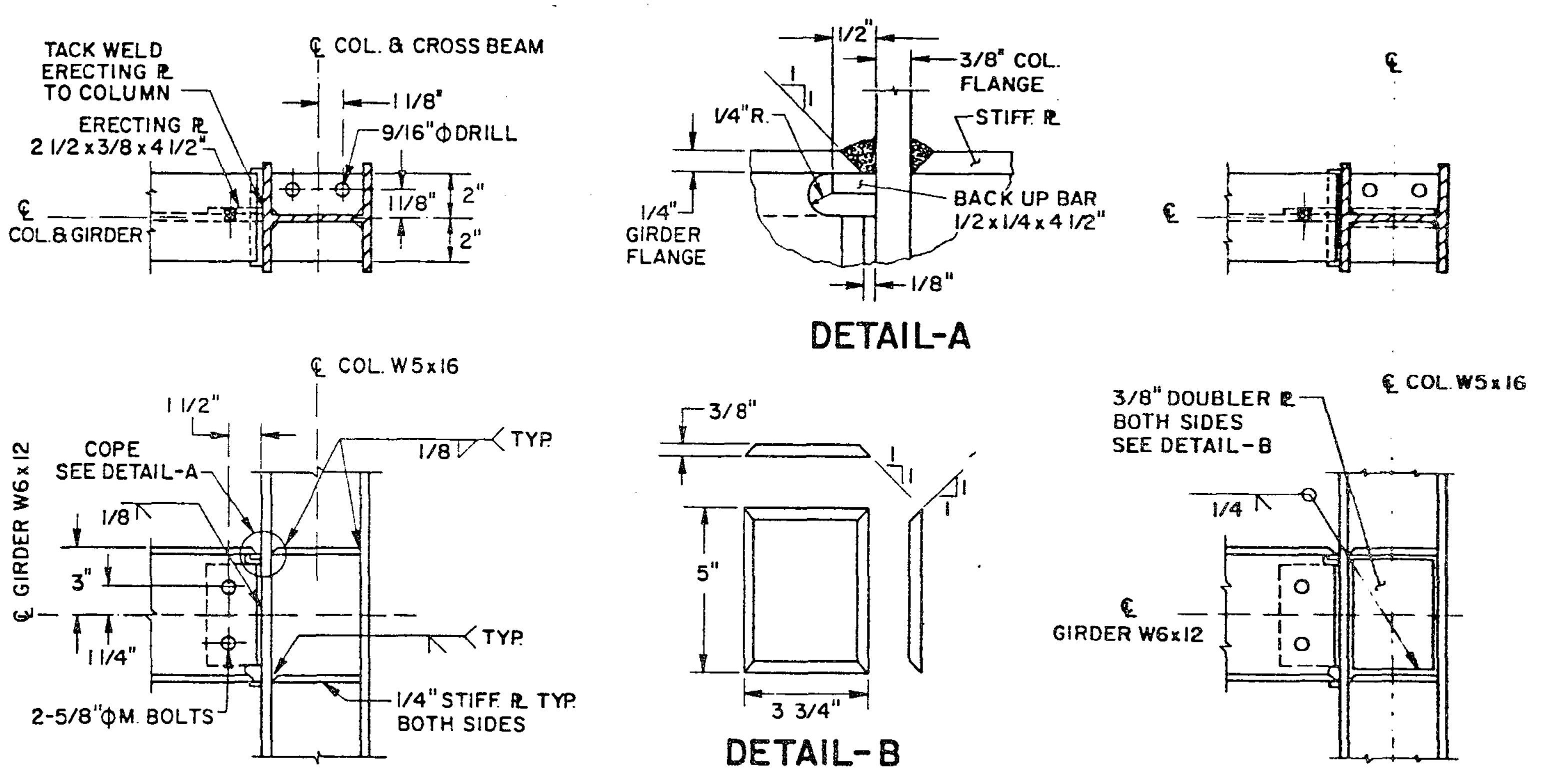

Figure 3.2. Details of girder-to- column connection

	Girder W6x12 Nominal	Column W5x16 Nominal
b(in)	4.00	5.00
d(in)	6.00	5.00
t_w (in)	0.23	0.24
t_f (in)	0.28	0.36
$A\ (in^2)$	3.54	4.70
$I_x\ (in^4)$	21.7	21.3
$S_x\ (in^3)$	7.25	8.53
$Z_x\ (in^3)$	8.23	9.61

Figure 3.3 Section properties

Floor	Weight
3	9300
2	9288
1	9290

Figure 3.4 Floor weights (lb)

Instrumentation

The frames were instrumented with linear potentiometers at each floor to measure floor translation. The frames had strain gauges attached to both flanges at the top and bottom of each column. Assuming a linear variation of bending strain along the length of the column, the relative rotation of the ends will be given by

$$\theta = \int_0^L \frac{1}{\rho} dx = \frac{1}{h} \int_0^L \left[\left(1 - \frac{x}{L} \right) \epsilon_a + \frac{x}{L} \epsilon_b \right] dx \tag{3.1}$$

$$= \frac{L}{h} \frac{\epsilon_a + \epsilon_b}{2}$$

where ϵ_a and ϵ_b are the bending strains at either end, L is the length of the column, h is its height, and ρ is its curvature.

Additionally, in the Phase I experiments, LVDT's were attached to the first floor column bases to permit measurement of the column end rotation. In Phase II, the column bases were stiffened so that it was felt that the base would remain essentially rigid. Utilizing this information, the rotation of each joint relative to the base could be calculated.

Finite Element Model - Three Story Frame

In a previous study [15], Kaya and McNiven were able to show that by constructing a mathematical model of this frame, using system identification, they were able to gain physical insight into the seismic response. However, they found that when the effective column and girder lengths were adjusted to minimize the difference between the predicted and actual response, these lengths were substantially different from those in the real structure, particularly in the frame whose joints were not reinforced, suggesting that joint behavior was important in predicting total response. Their model did not include a joint element. They used static condensation to reduce the number of degrees of freedom to a size manageable for their identification method, but as was discussed in the previous chapter, this can lead to errors.

Developed here is a finite element model where joint panel zones are assumed rigid for flexural and axial deformations, but shear distortions are allowed. The column element stiffnesses will be given by

$$\underline{k} = k' \begin{bmatrix} 2+\beta & 1-\beta & 0 \\ 1-\beta & 2+\beta & 0 \\ 0 & 0 & \frac{A}{2I}(1+2\beta) \end{bmatrix}. \tag{3.2}$$

The girder stiffnesses will be given by

$$k = \frac{3EI}{L(1+2\beta)} \tag{3.3}$$

The joint stiffnesses will be given by

$$k = Gbht \tag{3.4}$$

where

$$k' = \frac{2EI}{L(1+2\beta)} \quad \beta = \frac{6EI}{L^2 A' G} \tag{3.5}$$

and E, I, A, and A$'$ denote Young's modulus, moment of inertia, section area, and effective shear area, respectively.

The displacement transformation matrices, A_i, for each element are given by (see Figure 3.5 for global coordinates)

Girders:

a) 0 0 0 1 0 0 -1/l 0 0 1 0 0 0 0

b) 0 0 0 0 1 0 0 -1/l 0 0 1 0 0 0

c) 0 0 0 0 0 1 0 0 -1/l 0 0 1 0 0

Columns:

a) -1/l 1/l 0 1 0 0 0 0 0 0 0 0 0 0

-1/l 1/l 0 0 1 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 1 -1 0 0 0 0 0 0

b) 0 -1/l 1/l 0 1 0 0 0 0 0 0 0 0 0

0 -1/l 1/l 0 0 1 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 1 -1 0 0 0 0 0

c) 0 0 -1/l 0 0 1 0 0 0 0 0 0 0 0

0 0 -1/l 0 0 0 0 0 0 0 0 0 1 1

0 0 0 0 0 0 0 0 1 0 0 0 0 -72

Joints:

a) 0 0 0 0 0 0 0 0 0 1 0 0 0 0

b) 0 0 0 0 0 0 0 0 0 0 1 0 0 0

c) 0 0 0 0 0 0 0 0 0 0 0 1 0 0

d) 0 0 0 0 0 0 0 0 0 0 0 0 1 0

Table spring:

0 0 0 0 0 0 0 0 0 0 0 0 0 72

The global stiffness matrix will be

$$\underline{K} = \sum \underline{A}_i^t \underline{k}_i \underline{A}_i \, . \tag{3.6}$$

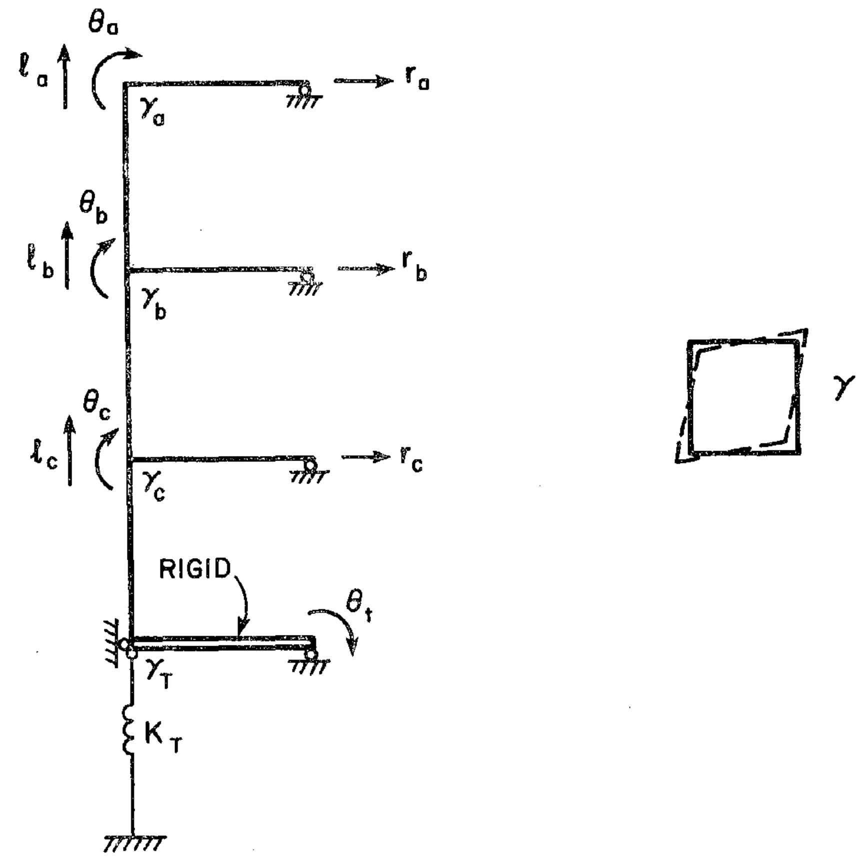

Figure 3.5 Three story frame
global coordinates

Identification

The primary goal of this study of the three story frame was to investigate the role of joint behavior in the overall response. Therefore, a sequence of models of increasing complexity is proposed. The nature and predictive power of each of these models is compared. In this way, a number of interesting facts about the behavior of the joints is revealed. Additionally, the identification algorithm is shown to be a valuable analytical tool.

In all cases the data being used are from the results of a test in which the El Centro earthquake record was used as a seismic forcing function. These earthquake records were scaled to produce elastic response in the test structure. In the phase II tests, the test earthquake was 40% of that recorded. In the phase I tests, the test earthquake was only 10% of that recorded.

Identification Using Displacement

The first four models were analyzed using only 6 seconds of displacement response in the identification. It is shown that displacement, while providing some useful information about stiffness distribution, offers limited capability for identifying many structural properties.

Model 1

In the first model, 4 parameters were used. The first three parameters were associated with the effective column lengths of the Phase I structure. All the columns on each floor were taken to have effective lengths that were their clear span times one of these parameters. One parameter was associated with mass proportional damping. The table stiffness was set very high, simulating a rigid base. All the other physical constants were set at their measured values.

The computer program converged from an error of 20.2 to an error of 0.35 in five steps. The rapid convergence can be seen in Figure 3.6.

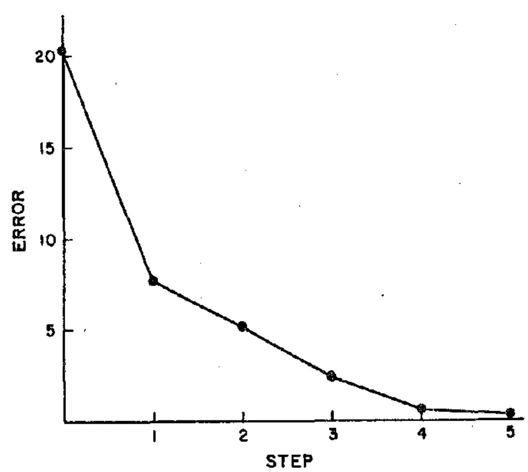

Figure 3.6 Algorithm convergence

The resulting effective column length factors were 1.05, 1.04, and 1.12 from the top of the structure down. The displacement time histories, both before and after identification can be seen in Figure 3.7. The resulting match can be seen to be quite close. The closeness of the first two column factors suggests that one parameter could be used for both floors.

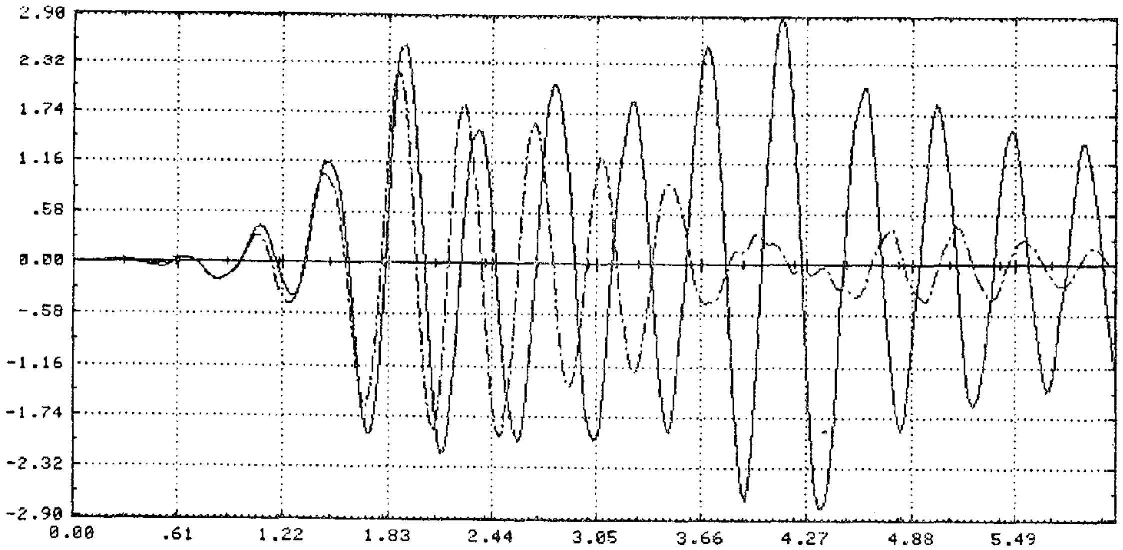

Figure 3.7a Third story displacement before identification (inches vs. seconds)

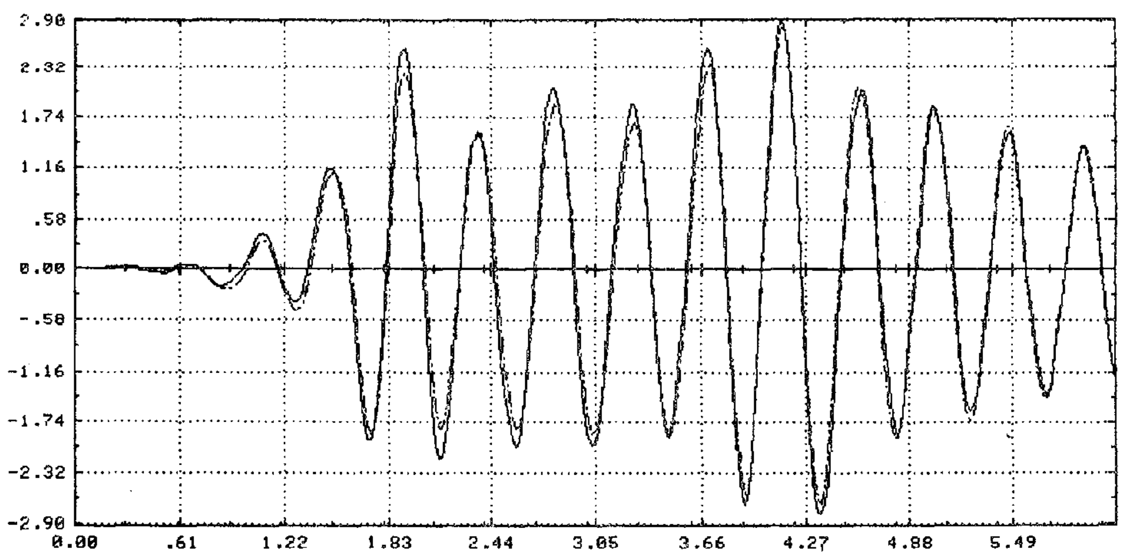

Figure 3.7b Third story displacement after identification (inches vs. seconds)

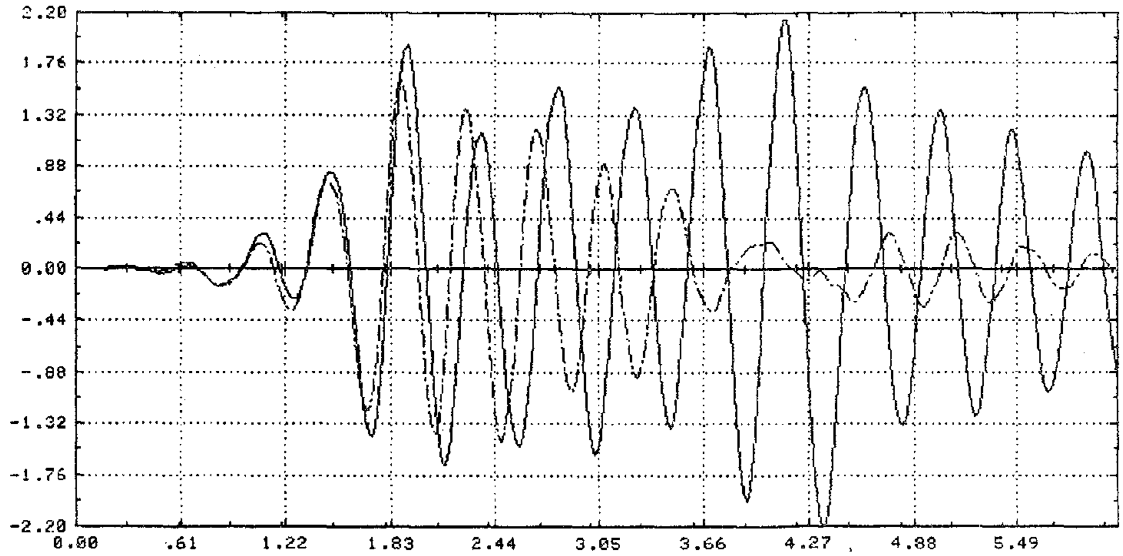

Figure 3.7c Second story displacement before identification (inches vs. seconds)

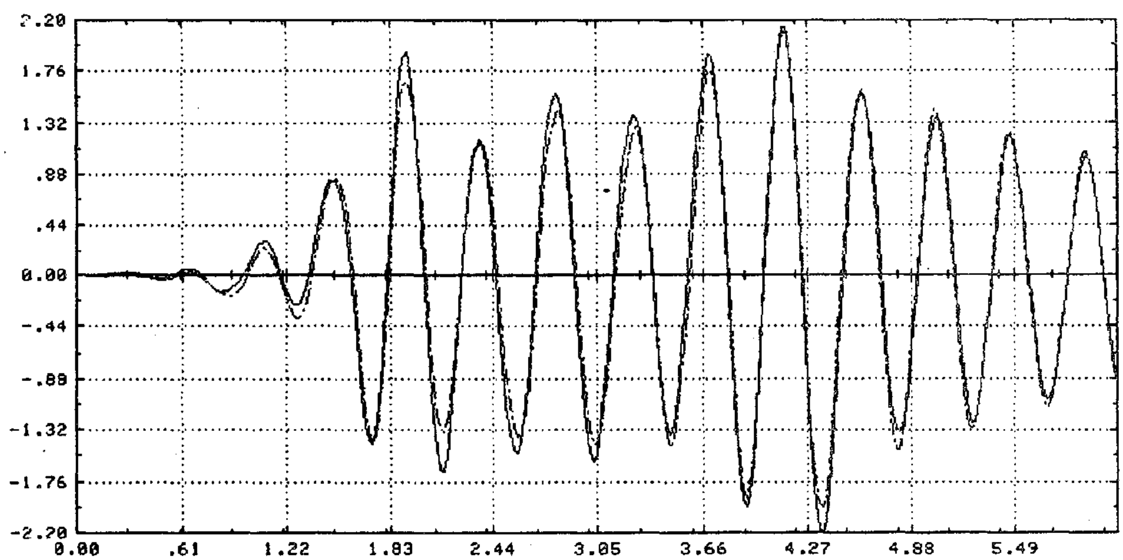

Figure 3.7d Second story displacement after identification (inches vs. seconds)

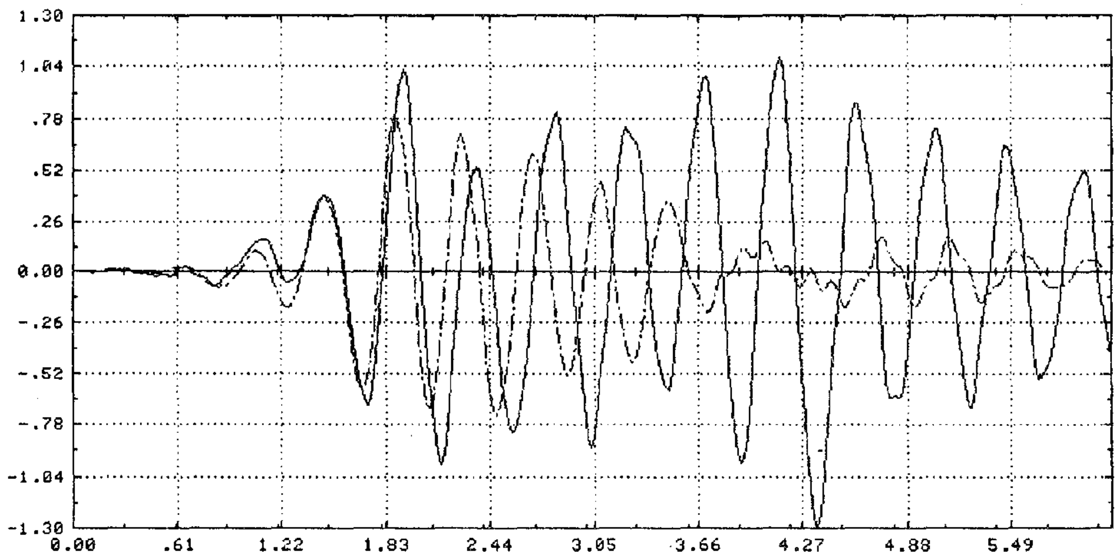

Figure 3.7e First story displacement before identification (inches vs. seconds)

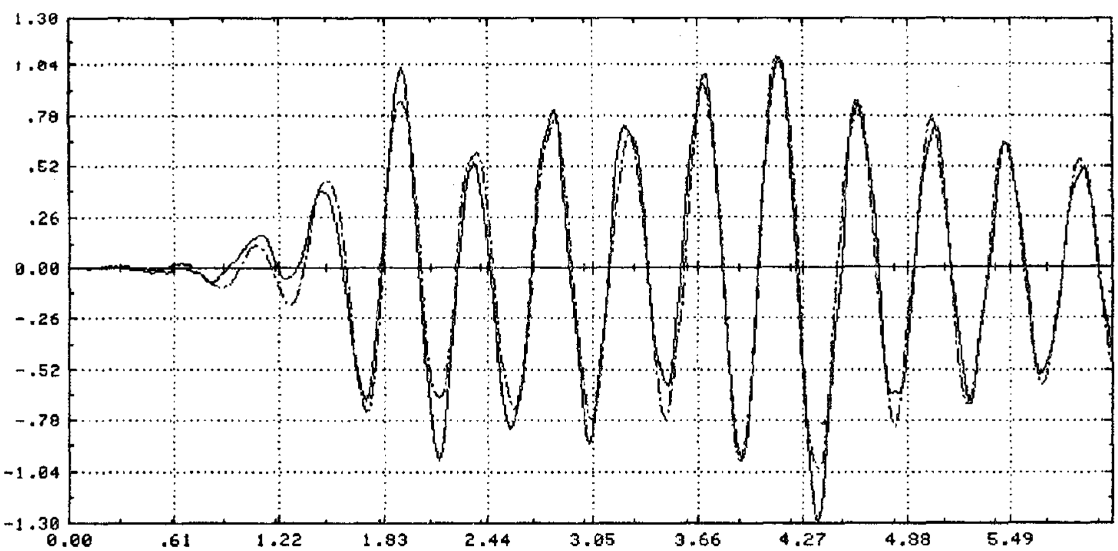

Figure 3.7f First story displacement after identification (inches vs. seconds)

Model 2

To determine the necessity of incorporating three parameters for effective column lengths, a new model was entered with only three parameters. One parameter was associated with the effective column lengths of the top two floors, one parameter with the first floor, and one parameter with mass proportional damping. Otherwise this model is identical to model 1.

Again, convergence of the algorithm is quite rapid, reducing the error from 20.4 to 0.35 in seven steps. The column length factors were 1.05 for the top two floors and 1.11 for the first floor. While the number of parameters has decreased, the error associated with the optimized parameters remains unchanged.

Model 3

It appears that the accuracy of the model is relatively insensitive to changes in distribution of parameters among the columns. To emphasize this, a new model was entered with 5 parameters. Only one of these was associated with the columns. One parameter was associated with the effective girder lengths at each of the three floors. Finally, one parameter was associated with mass proportional damping. Convergence was even more rapid, resulting in a final error of only 0.08 in 4 steps. More importantly, the resulting column effective length factor was 1.009. This indicates the variations in girder length are more critical than column lengths. However, the resulting girder length factors are far different than 1.0 - ranging from 0.32 to 52.3! The most reasonable explanation for this is that the girder lengths are not independent with respect to translation. That is, while the algorithm converges using only displacements, the identified parameters do not form an independent set. Thus one could expect another set of girder lengths to form a model with the same error. One could reasonably expect a whole class of models with the same error. In fact, investigations of the error surface in the vicinity of this minimum have shown the possibility of wide variations in parameter values, without significant change in the error function.

Identification Using Displacement and Rotation

It appears that the girder and column length factors do not form an independent set of parameters with respect to displacement response data. However, the rotation data, inferred from strain measurements, are not of the same magnitude as the displacement data. If used directly, identifying the parameters with the use of the rotation data could be expected to have little or no effect. The rotation data, therefore, are scaled by the modulus of elasticity of the steel, $E=29.6x10^6$ psi. While somewhat arbitrary, this constant causes the two sets of data to be of the same order of magnitude. It should be pointed out that the relative weighting of the response variables will undoubtedly have appreciable effect on the parameter values, as it influences the response that the identification procedure will attempt to accommodate. Subsequent identifications were performed utilizing approximately 12 seconds of data.

Model 4

This model was the same as Model 3, but all the response data was used to identify the phase II structure. After five iterations, the model had converged to an error of 3.84. Note that this error is summed over twice as many integrals as without the inclusion of the rotational response. The resulting effective column length factor was 1.12. The resulting effective girder length factors were 0.958, 0.721, and 0.694, listed from the top of the structure down. The apparent reduction in girder lengths and increase in column lengths was also noted in [15]. The important characteristic is that these factors are roughly equal.

Model 5

In Kaya and Tang [15,24] it was noted that the change in girder stiffness could be attributed to the pitching motion of the table. In the previous models, we used the effective table pitch stiffness as was suggested in Tang. Model 5 is the same as Model 4, with the addition of a table stiffness parameter. In the phase II structure this reduced the error to only 3.78. However, in the phase I structure, this model reduced the error to 0.53. In the phase I model the resulting column length factor was 1.15 and the resulting girder length factors were 0.53, 0.63, and 0.55. In both cases, the resulting table stiffness factor was about 0.6. It appears that the algorithm tends to soften up the system by increasing the base stiffness, and in order to compensate, decreases the effective girder lengths. Thus, it appears that the girder and base factors do not form an independent set.

Model 6

In the previous models, the parameter adjustment primarily took place in the effective girder lengths. In contrast, Model 6 is an attempt to permit the joints to accommodate the response. Thus, a four parameter model was entered, with one parameter associated with the columns, one parameter with the base stiffness, and one parameter with the effective joint panel thickness. After identification the errors in the phase I and phase II models were 0.632 and 4.08, respectively. This is only slightly larger than in Model 5, but the identification was done with two fewer parameters. The resulting parameter values are also interesting

parameter	Phase I value	Phase II value
column	1.09	1.07
base	0.96	0.97
joint	2.16	5.27
damping	1.35	1.54

Figure 3.8 Model 6 parameters

in that while the column and base parameters are much closer to the estimated values, the identified joint parameters accurately reflect the fact that the frame in the phase II experiments has reinforced joints. Thus, while it is possible to adjust the effective girder lengths to accommodate the behavior of the frame, it appears more sensible to attribute this behavior to the joints, particularly in light of the crude approximation inherent in the joint modelling. The results of the identification using this model utilizing the phase II data can be seen in Figure 3.9.

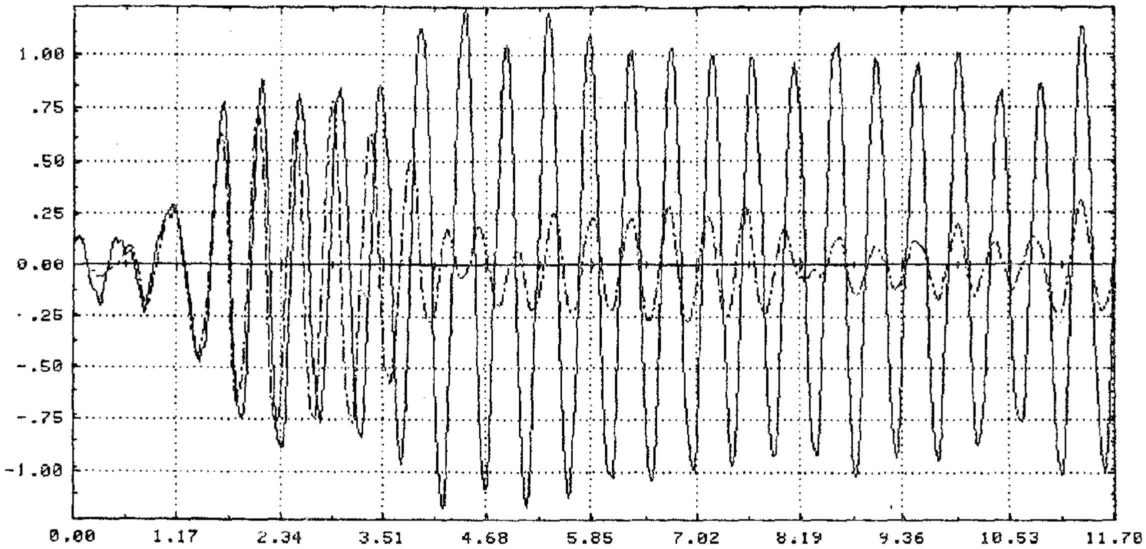

Figure 3.9a Displacement at floor 3, before identification (inches vs. seconds)

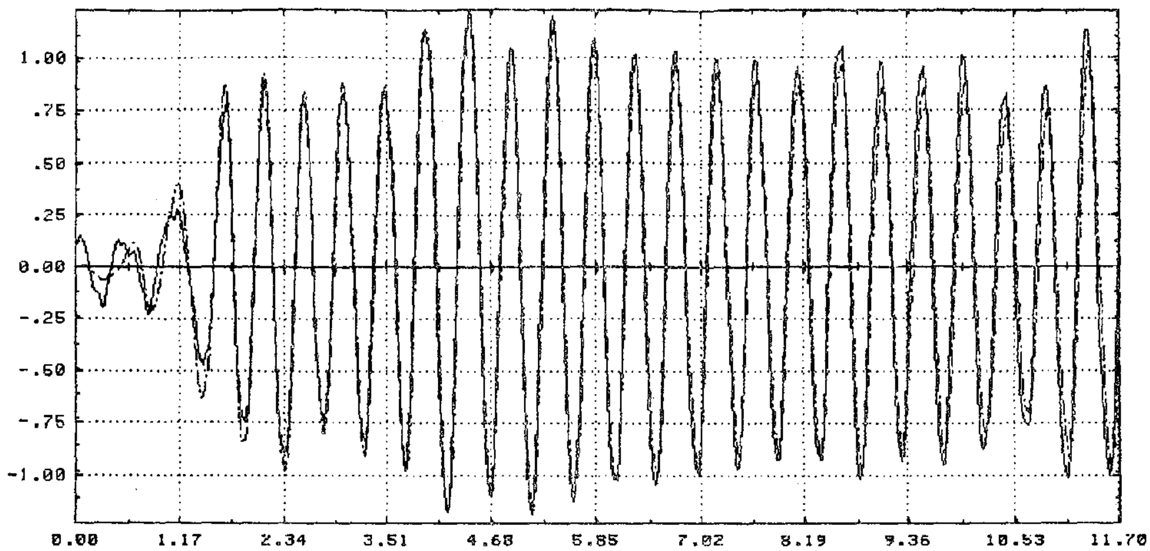

Figure 3.9b Displacement at floor 3, after identification (inches vs. seconds)

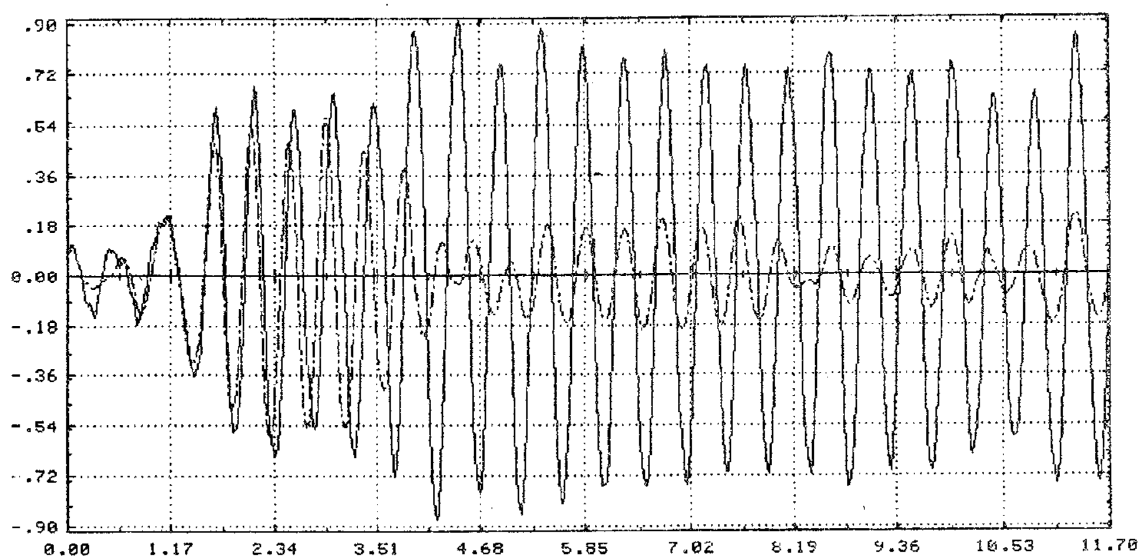

Figure 3.9c Displacement at floor 2, before identification (inches vs. seconds)

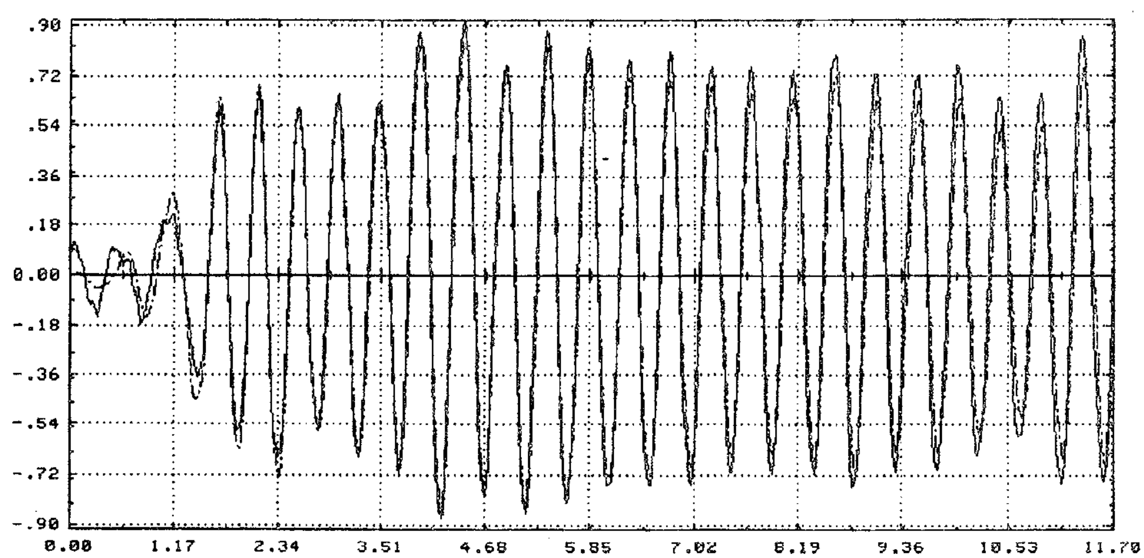

Figure 3.9d Displacement at floor 2, after identification (inches vs. seconds)

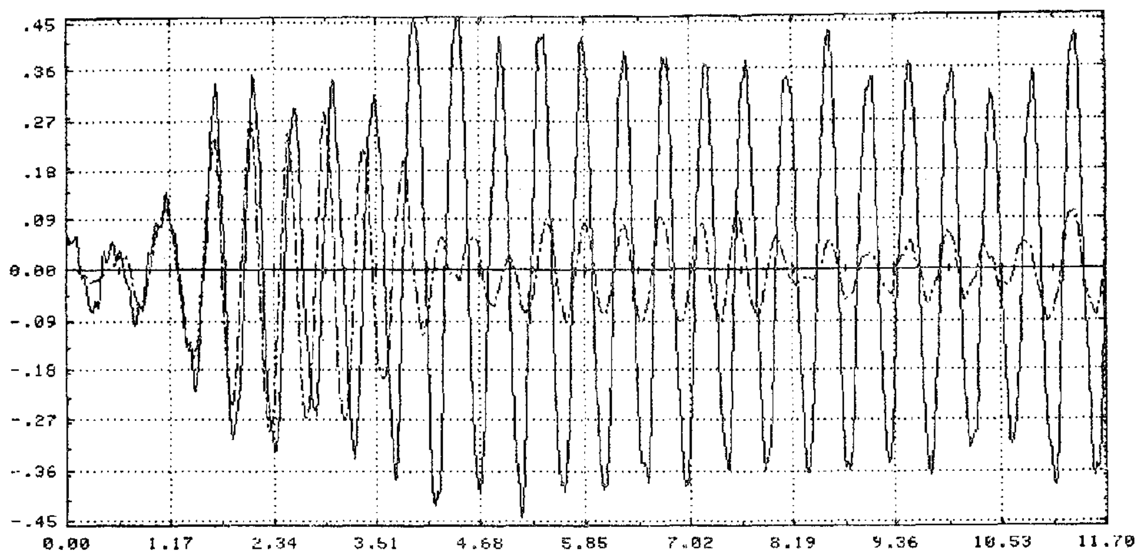

Figure 3.9e Displacement at floor 1, before identification (inches vs. seconds)

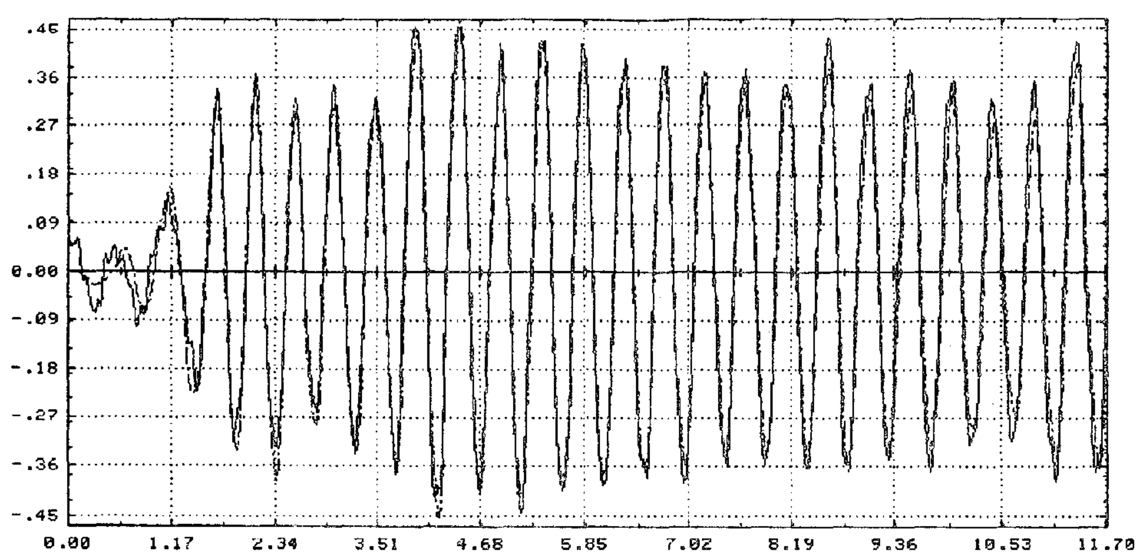

Figure 3.9f Displacement at floor 1, after identification (inches vs. seconds)

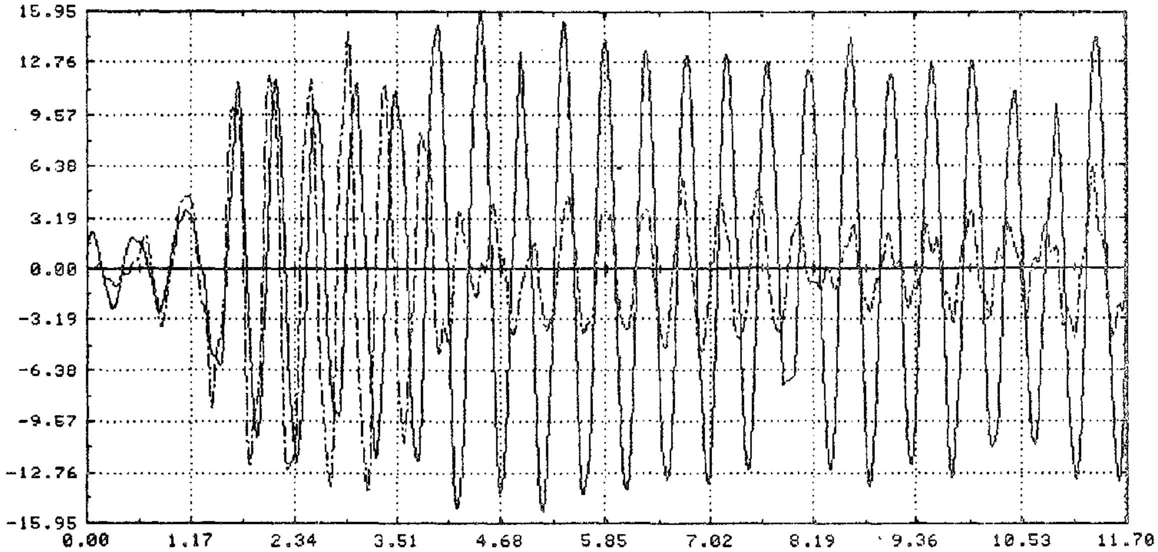

Figure 3.9g Rotation at floor 3, before identification (milliradians vs. seconds)

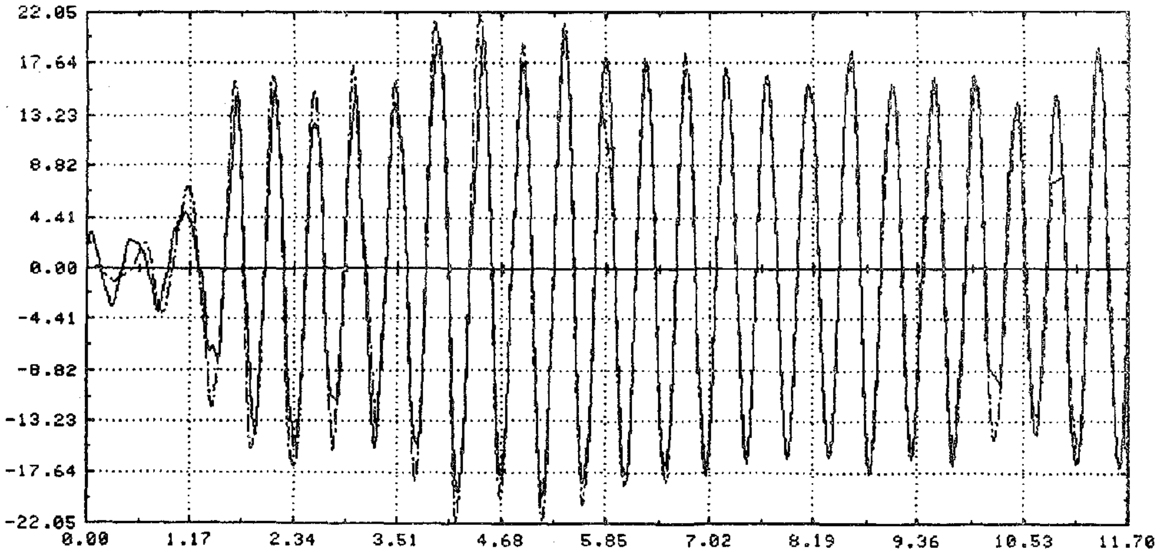

Figure 3.9h Rotation at floor 3, after identification (milliradians vs. seconds)

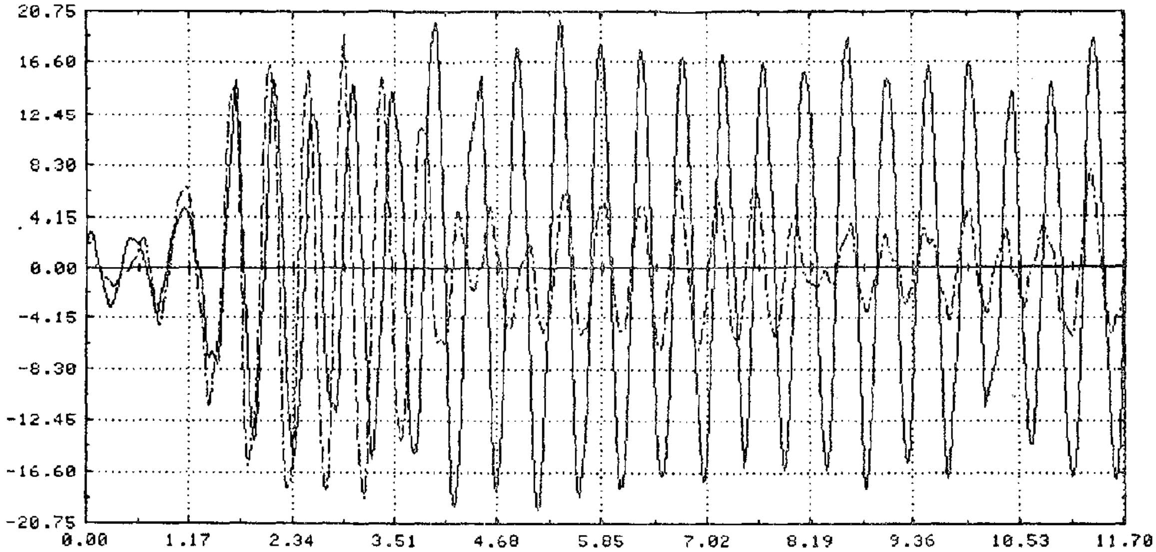

Figure 3.9i Rotation at floor 2, before identification (milliradians vs. seconds)

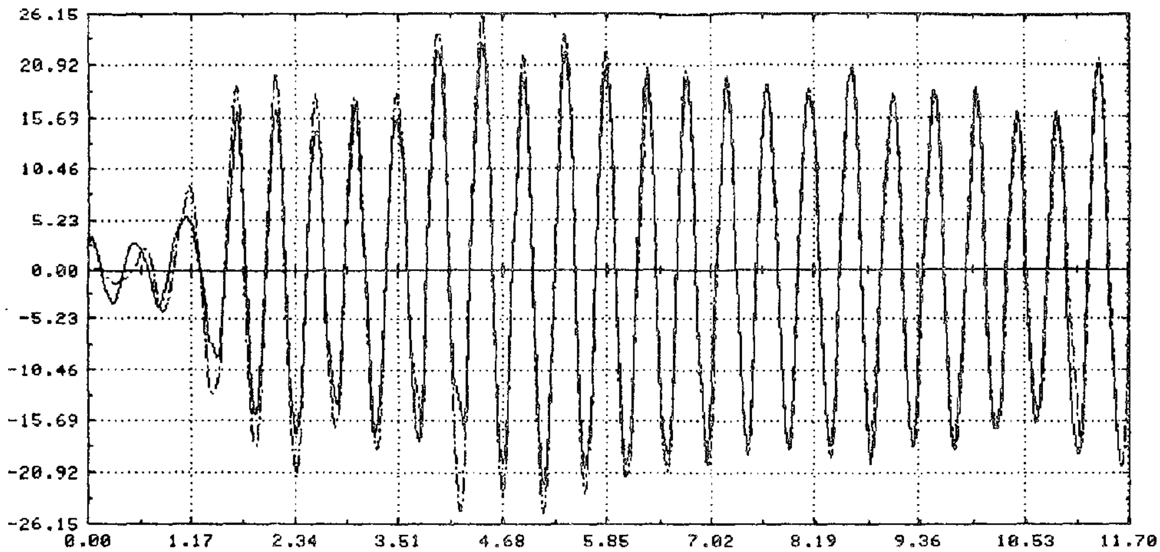

Figure 3.9j Rotation at floor 2, after identification (milliradians vs. seconds)

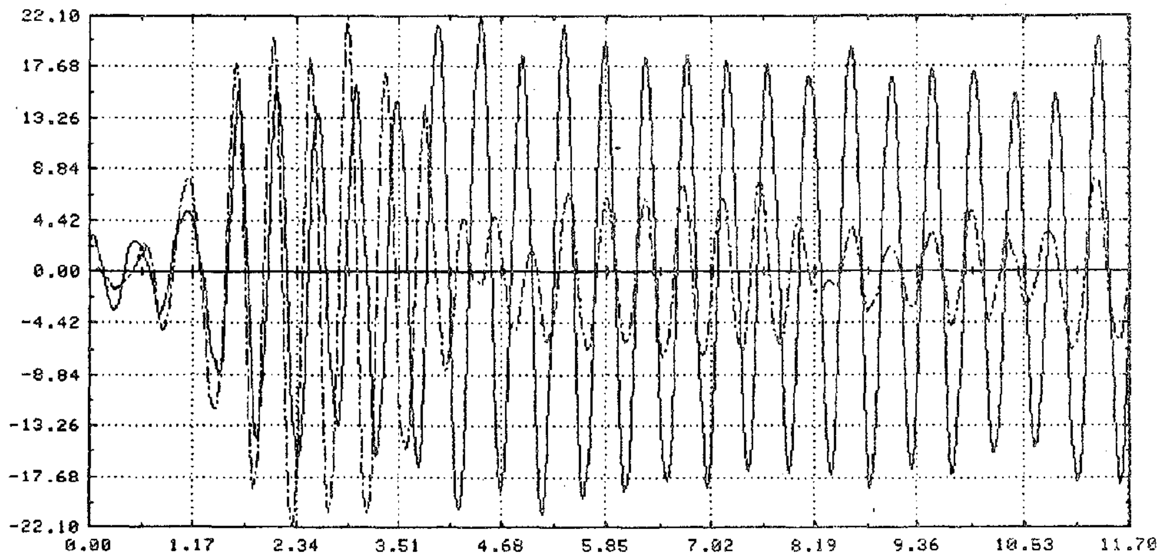

Figure 3.9k Rotation at floor 1, before identification (milliradians vs. seconds)

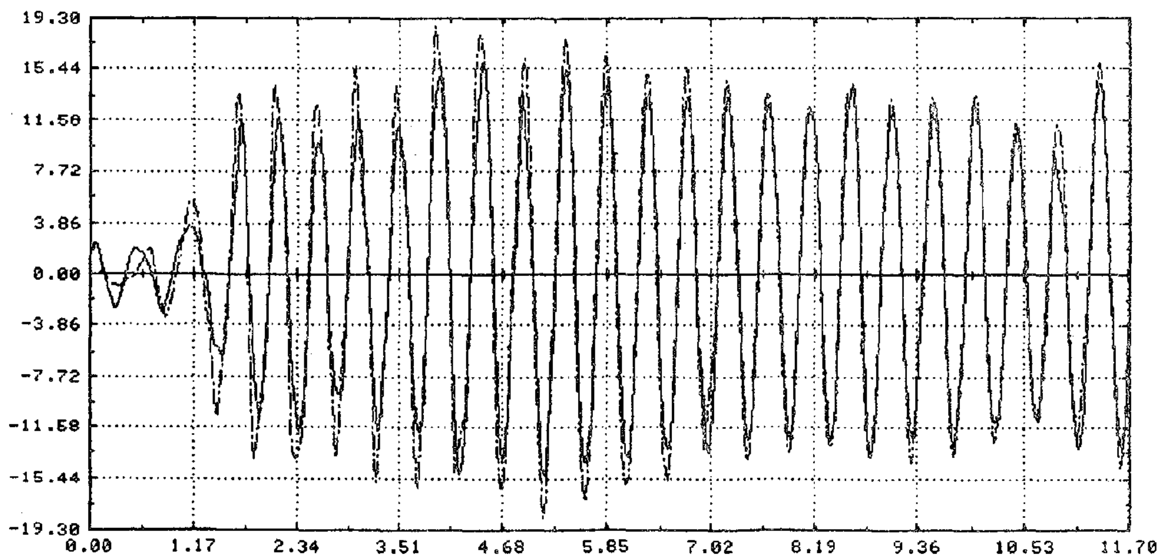

Figure 3.9l Rotation at floor 1, after identification (milliradians vs. seconds)

CHAPTER 4

DYNAMIC MEASUREMENT OF SMALL ANGLES

Design Objectives

Typically, structural models have fairly low frequency response - the highest frequency of interest being on the order of 100hz. Therefore, an angle measurement device capable of response up to 2 khz would be adequate. The maximum amplitude of rotational response is often in the milliradian range. This poses two problems:

(1) The instrument must be very sensitive.

(2) The instrument must be very insensitive to motions other than those which are to be measured.

It is very desirable, additionally, that the instrument be both economic, easy to fabricate, and easy to use.

Existing Methods

RVDT - Rotational Variable Differential Transformer

This is a transformer with variable coupling produced by moving a ferromagnetic core within the coils. In order to effect zero output for zero displacement, two secondary windings connected in electrical opposition are used. A mathematical analysis of the performance of this type of instrument was first described in detail by Atkinson and Hynes [3].

A number of manufacturers produce this type of device. A Schaevitz model RVDT was acquired to test its suitability. In static tests, the RVDT was capable of resolving 10^{-4} radians. However, when the device was subjected to vibration, such as tapping the case lightly with a pencil, the induced signal noise reduced the resolution by at least an order of magnitude. Thus, while an RVDT might prove useful in static small angle measurement, its dynamic behavior is not adequate.

LVDT With Stationary Arm

A balanced lever arm is attached to the structure on a pivot. A perfectly balanced arm will not rotate if its pivot is rotated or translated. This should permit measuring a distance change at the end of the arm with an LVDT. It is, however, difficult to balance the arm "perfectly". Further, the measurement apparatus at the end of the moment arm is likely to have significant effect. Clough and others have reported attempting this method without appreciable success.

Strain Gauge

If strain gauges are placed on opposite sides of the neutral axis of a beam, strains at the extreme fibers can be measured. Using a linear elastic analysis, one can calculate the relative rotation between the ends. Theoretically, this can be extended throughout a structure. Indeed, this method is quite straight-forward to implement. It relies heavily on two assumptions:

(1) The entire structure has linear elastic response.

(2) The method of connecting the beams does not contribute to relative rotation.

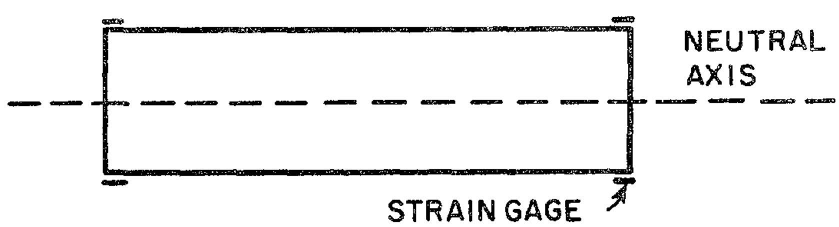

Figure 4.1 Strain gauge placement

Obviously, in a variety of situations, these assumptions will not be appropriate. Kaya [15] has done some analysis work with this type of measurement using data collected by Clough and Tang [10].

Rotational Accelerometers

There are a number of highly accurate rotational accelerometers built commercially, primarily for aerospace and military applications. Servo accelerometers are among the most accurate and stable.

Typically, the servo accelerometer is a closed loop, torque balance system. In the illustration below, relative motion of a balanced mass is detected by a position sensor whose output signal is applied to an electronic amplifier. The output current from the servo amplifier is applied to the torque motor. Thus mass is held in the same relative position. The current through the torque motor is accurately proportional to input acceleration.

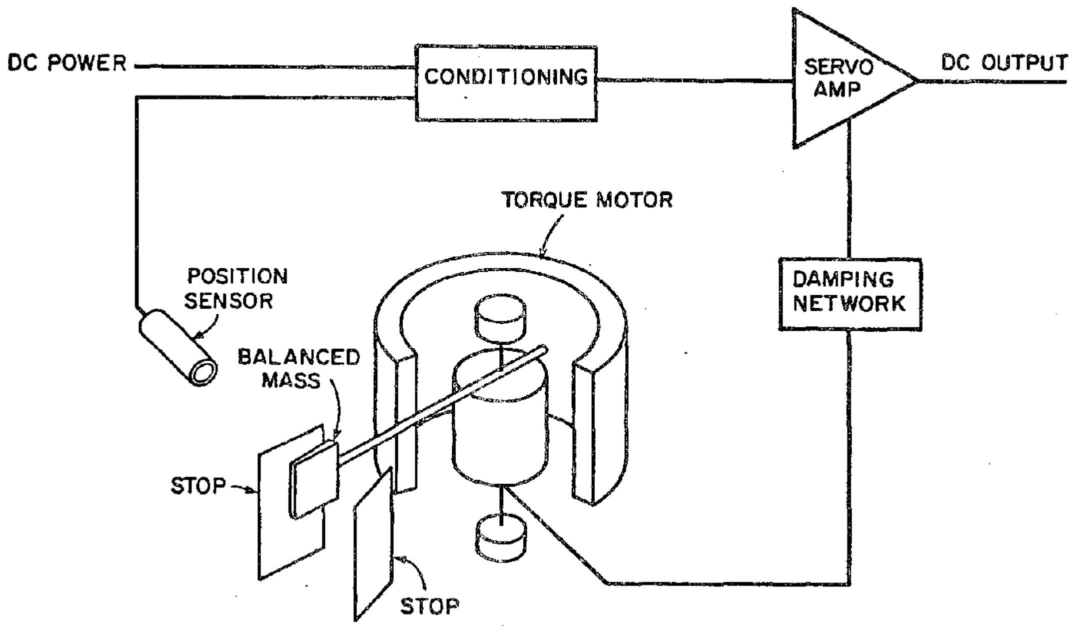

Figure 4.2 Rotational servo accelerometer

Specifications for a typical range of servo accelerometers are as follows [22]:

Range ($rad/\sec^2$)	Cross Axis Sensitivity ($rad/g-\sec^2$)	Natural Frequency (hz)
± 50	0.2	30
± 100	0.2	50
± 500	1.0	100
± 1000	2.0	120
± 1500	3.0	130

resolution:	0.0005% full scale
linearity:	0.1% full scale
hysteresis:	0.02% full scale

There are two main drawbacks in the use of these devices for structural testing. Most important, in a typical case, rotational acceleration will be far smaller than linear acceleration at a given point. This makes the cross-axis sensitivity an important factor. Second, these devices are only reliable at approximately 60% of their natural frequency. Generally, the higher the natural frequency, the greater the cross-axis sensitivity. These devices could be useful in a number of tests, particularly if it is possible to order special designs aimed at minimizing the shortcomings.

Ring Lasers

A ring laser is one which supports circulating light beams: independent oscillations for two counter-rotating beams. For instance, Figure 4.3 shows a resonator where three mirrors define a triangular path.

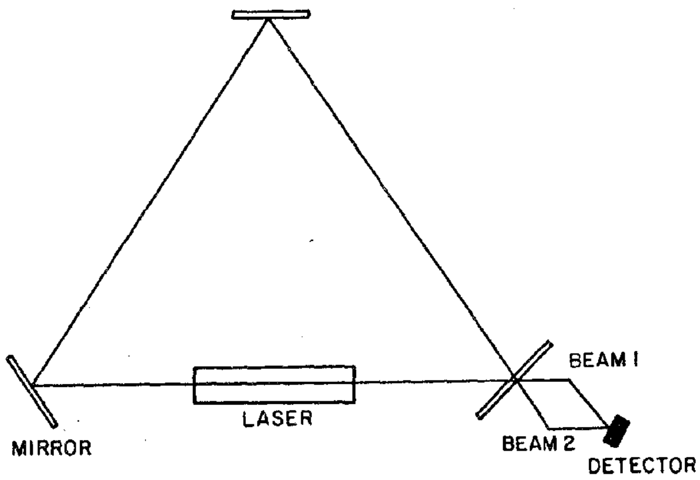

Figure 4.3 Ring laser

There are two mode conditions, one for each route around the ring:

$$P = q\,\lambda \tag{4.1}$$

where

P = optical perimeter of ring

q = an integer

λ = resonant wavelength.

If there is a region in the resonator where the velocities for the two directions are unequal, let them be (u+du) and (u-du). Then there are two oscillating frequencies:

$$f_i = f_0\left[1+(-1)^i \frac{\delta u}{u}\frac{l}{P}\right] \quad i=1,2 \tag{4.2}$$

where

$$f_0 = \frac{qc}{P}\,. \tag{4.3}$$

If samples of both beams are fed to a common detector, a beat frequency will be generated, given by

$$f_b = f_2 - f_1 = 2f_0\frac{\delta u}{u}\frac{l}{P}. \tag{4.4}$$

If the resonator is rotated about an axis perpendicular to its plane, the resolved component of translational velocity, at a given position in the path, is then added to the light velocity. An integration must be performed around the ring to find the net unbalance between the two beams [23].

For a beam length dl

$$\delta u = \Omega r \cos\theta \tag{4.5}$$

where

Ω = angular velocity
r = distance from rotation axis to dl
θ = angle between light path and translation velocity.

But $\cos\theta = r\frac{d\phi}{dl}$ where ϕ is angle about the axis, so

$$\int \delta u\, dl = \int \Omega r^2 d\phi = 2\Omega A \tag{4.6}$$

where A = the area enclosed by the resonating beams.

The beat frequency from rotation is then

$$f_b = \frac{4\Omega A}{\lambda P}. \tag{4.7}$$

For a square resonator with sides of length L, and a HeNe laser oscillating at 632.8 nm, this is

$$f_b = L\,\Omega\,(1.58x10^6). \tag{4.8}$$

Thus, a practical instrument can be constructed with very high resolution, digital output, and virtually no cross-axis sensitivity. In fact, a square resonator with L = 1m has been used to accurately measure the rotation of the earth! Since these devices are presently being constructed out of a single crystalline block, they should be quite durable and economic, if constructed in any quantity.

There are two principal disadvantages to using ring lasers to instrument a structure. First, they tend to drift, though some researchers have been able to achieve drift rates as low as 0.1 deg/hr [16]. Second, the size of the apparatus makes it unsuitable for small models. It would, however, be easily applied in instrumenting a real structure.

Optical Lever

A lever arm permits amplifying an angle change, therefore increasing the ease with which it may be measured. In several of the previous instruments, a mechanical lever is employed. The fundamental problem with most of these methods, in dynamic application, is the mass of the lever arm. A light beam has no mass and, from this point of view, is most desirable.

If a mirror is attached to a structure, and a beam of light directed at it, rotations of the mirror will cause the reflection of the beam to move. Statically, an observer can merely measure the deflection and, depending on his distance from the mirror, obtain any desired degree of accuracy.

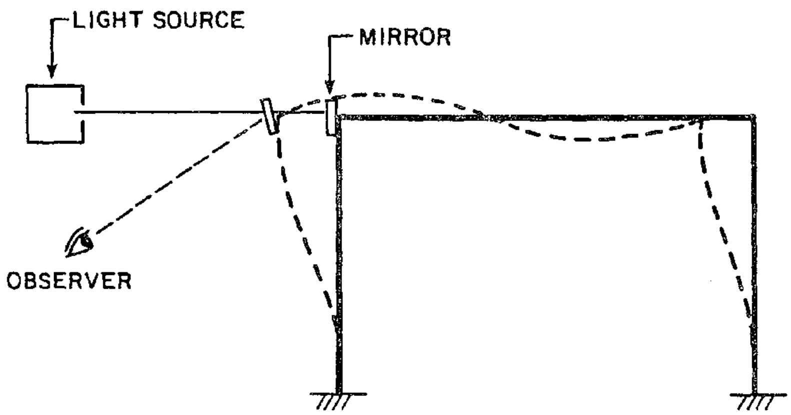

Figure 4.4 Mirror attached to frame

For small mirror angle change, θ, the deflection d will be given by $d = 2r\theta$, where r is the distance from the observer to the mirror.

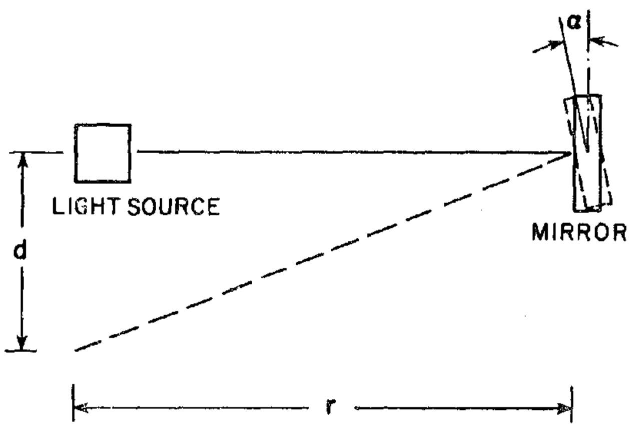

Figure 4.5 Measuring spot deflection

For example, from a 1 milliradian structural rotation, at a distance of 2 meters we could expect a 4 mm movement.

One of the simplest methods of electronically measuring the beam deflection is to direct the beam at a pair of adjacent photocells.

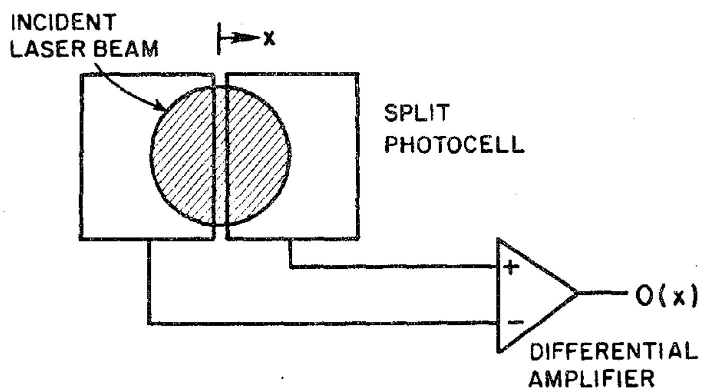

Figure 4.6 Adjacent photocells

As the spot moves onto either photocell, the output from that photocell will increase, and the output from the other photocell will decrease. The output from the differential amplifier will reflect the spot motion.

Since the detector will be some distance from the structure, and presently available photocells are fairly small, it is desirable to use a source with small dispersion. A typical helium neon laser has a dispersion of only about 1 milliradian. A simple two lense system can be employed to optimize the size of the spot.

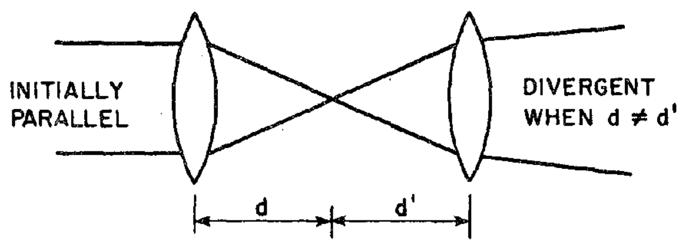

Figure 4.7 Beam dispersion

The response characteristics of the system depend, to a large extent, on the light source used. Lasers tend to have an approximately Gaussian distribution of intensity.

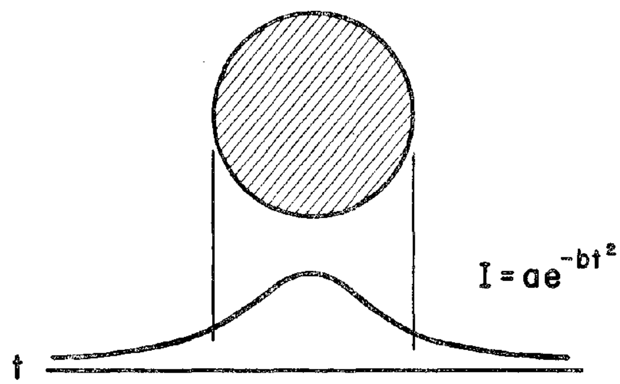

Figure 4.8 Gaussian intensity distribution

The differential amplifier output will therefore be approximately proportional to a cumulative normal distribution:

$$o(x) = C\int_0^x e^{-bt^2}dt. \tag{4.9}$$

Secondary Effects

If the spot is centered on two photocells with the same conversion characteristics, variations in ambient light will have little effect on differential photocell output. However, if the photocells are unbalanced, or the beam is not centered, ambient light can produce noise. This is primarily due to nonlinear photocell response at high intensity - particularly at the center of the laser spot. The simplest method of reducing this effect is to conduct tests in the dark. However, filters are available which can remove virtually all ambient light, leaving virtually all the laser beam intact. This application makes the monochromaticity of lasers extremely important.

It is difficult to place the laser, mirror, and detector collinear. If the detector is placed to the side, linear motion of the mirror will produce a deflection of the spot:

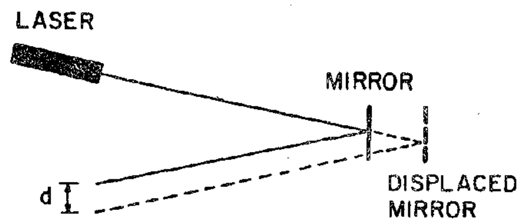

Figure 4.9 Induced secondary output

This deflection will be at right angles to the measurement we are interested in if the plane of the laser beam contains the motion of the mirror. Properly aligning the detector will minimize this effect.

Use of a pentagonal prism in place of the mirror will remove the effect of rotations orthogonal to those being measured:

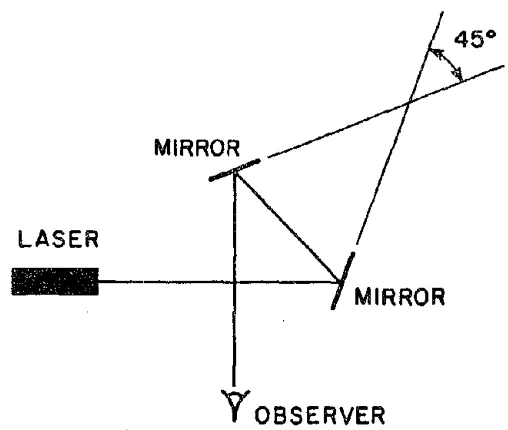

Figure 4.10 Pentagonal prism

Rotations of the prism about an axis out of the paper will not produce a beam deflection.

As was previously discussed, the output from the split photocells will not be a linear function of spot displacement. The instrument could be made linear by moving the photocells to keep the spot centered and measuring the movement of the photocells directly. The technique used for this linear measurement would depend on the maximum displacement and frequency response expected. The success of this approach would depend on the accuracy and rapidity with which the photocells can be positioned. A possible alternative is to keep the spot centered by rotating the mirror. The principal advantage of this system is that the mirror need only move a minor amount. It is conceivable that the mirror could be constructed out of a single piezoelectric crystal so that the motion of the mirror could be controlled by applying a voltage to the crystal. While providing a linear output, all these techniques require greater expense and development time than merely measuring photocell output. Further, the photocell output is close to linear over a large segment of its response.

The desired output is the difference of two relatively strong signals. It is necessary to minimize the effect of the magnitude of each photocell output on the measurement of the difference. Electronic devices designed to do this are known as instrumentation amplifiers. Fortunately, it is now possible to construct a high quality instrumentation amplifier incorporating only one integrated circuit. The circuit diagram and printed circuit layout for this device is shown in Figures 4.11 and 4.12.

While designed to measure joint rotation, it is interesting to note that this device has since proved valuable in measuring the physical properties of the materials used in a model structure. A rod of material was clamped at one end and set vibrating. The beam was aimed directly at the photocells with the material interposed. As less of the beam was interrupted, the photocell output increased. Thus, the characteristic frequency of the vibrating rod was measured by the photocell output. From this, the modulus of elasticity could be derived.

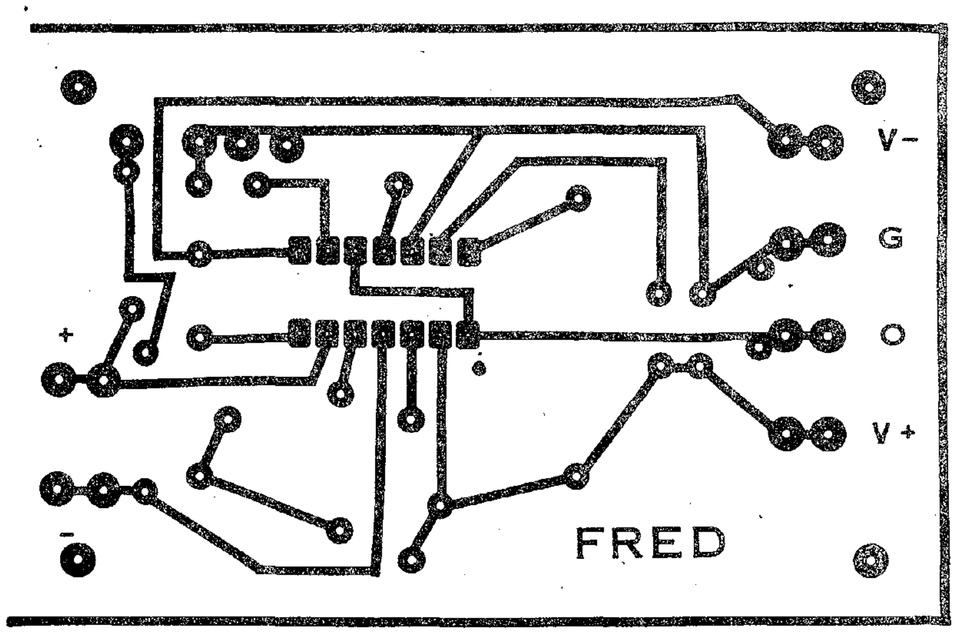

Figure 4.11 Printed circuit (2x) - Instrumentation Amplifier

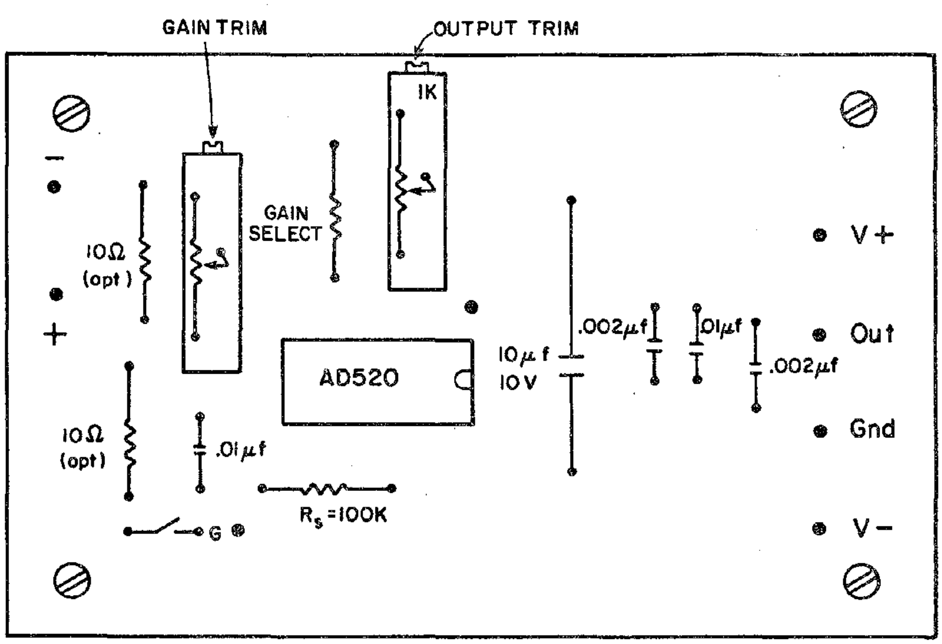

Figure 4.12 Parts layout (2x)-Instrumentation Amplifier

CHAPTER 5

SIX STORY FRAME

Studies of the three story frame proved quite fruitful - insight has been gained into both the behavior of the structure and the performance of the identification procedure. A number of questions were left open. To answer some of these, a new test model was developed.

The three story frame was a simple structure with relatively few degrees of freedom. We wished to determine the effect of increasing the number of degrees of freedom on the optimization procedure without greatly increasing the structure's complexity. In the hope of eventually being able to generalize previous speculations made by Kaya and McNiven [15] on data necessary for identification, the new structure was again a simple moment resistant frame, but with six stories.

The methods outlined in the previous chapter for making dynamic measurements of joint rotation, have not been applied in a structural test environment. While there are several advantages to being able to make kinematic measurements of rotation, testing the methods on a simple frame was essential. This also allows an assessment of their value in the identification of structural properties.

A Model Design Note

Data acquisition equipment is constrained to measuring a limited frequency bandwidth. Therefore, even when studying relatively simple frames, it is important to keep the important frequency content of response within the limits of the measuring apparatus.

In a model which has repetitive elements, it is desirable to be able to relate the modal frequencies of the whole structure to the modal frequencies of a single element. To illustrate, consider a shear structure model where each story has the same stiffness and mass.

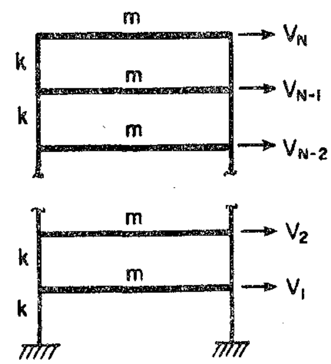

Figure 5.1 Repetitive shear model

The stiffness and mass matrices for this structure are given by

$$\underline{K}_N = \begin{bmatrix} k & -k & & & & \\ -k & 2k & -k & & & \\ & -k & 2k & . & & \\ & & . & . & . & \\ & & & . & 2k & -k \\ & & & & -k & 2k \end{bmatrix} \tag{5.1a}$$

$$\underline{M}_N = mI_{NxN} . \tag{5.1b}$$

The natural frequencies, w^2, of the structure will be given by the solutions of

$$P_N(w^2) = \det(K_N - w^2 M_N) = \det(K_N - mw^2 I_{NxN}) = 0 . \tag{5.2}$$

By expanding about the last column, the frequencies can be found as the roots of the recursively defined polynomials:

$$P_1(w^2) = k - w^2 m \tag{5.3a}$$
$$P_2(w^2) = m^2 w^4 - 3mkw^2 + k^2 \tag{5.3b}$$
$$P_n = (2k - w^2 m)P_{n-1} - k^2 P_{n-2}. \tag{5.3c}$$

If we use the change of variables $w^2 = tk/m$, we get

$$P_1(t) = k(1-t) \tag{5.4a}$$
$$P_2(t) = k^2(t^2-3t+1) \tag{5.4b}$$
$$P_n(t) = k[(2-t)P_{n-1}-kP_{n-2}]. \tag{5.4c}$$

The roots, t, of these polynomials will be the same as the roots of

$$P_1(t) = 1-t \tag{5.5a}$$
$$P_2(t) = t^2-3t+1 \tag{5.5b}$$
$$P_n(t) = (2-t)p_{n-1}-P_{n-2}. \tag{5.5c}$$

An alternative formulation can be obtained by expanding the determinant about the first column:

$$P_n = (k-w^2m)Q_{n-1}+k^2Q_{n-2} \tag{5.6}$$

where

$$Q_n = \det_{nxn}\begin{bmatrix} 2k-mw^2 & -k & & & & \\ -k & 2k-mw^2 & -k & & & \\ & -k & 2k-mw^2 & . & & \\ & & . & . & . & \\ & & & . & 2k-mw^2 & -k \\ & & & & -k & 2k-mw^2 \end{bmatrix}. \tag{5.7}$$

However, the Q_n have the same recursion formula as the P_n:

$$Q_n = (2k-mw^2)Q_{n-1} + k^2Q_{n-2} \tag{5.8}$$

with

$$Q_1 = 2k - w^2m$$
$$Q_2 = m^2w^4 - 4mkw^2 + 3k^2.$$

Hence,

$$\begin{aligned} P_n &= (k-w^2m)Q_{n-1} + k^2Q_{n-2} \\ &= [(2k-mw^2)Q_{n-1} + k^2Q_{n-2}] - kQ_{n-1} \\ &= Q_n - kQ_{n-1}. \end{aligned} \tag{5.9}$$

Applying the same change of variables, $w^2=tk/m$, to the Q's gives

$$Q_1 = k(2-t) \tag{5.10a}$$
$$Q_2 = k^2(t^2-4t+3) \tag{5.10b}$$
$$Q_n = k[(2-t)Q_{n-1}+kQ_{n-2}]. \tag{5.10c}$$

So the zeros of the P_n' may be discovered by using the alternative set of formulas:

$$P_n' = Q_n' - Q_{n-1}' \tag{5.11}$$

where the Q_n' are defined by

$$Q_n' = (2-t)Q_{n-1}' + Q_{n-2}' \tag{5.12a}$$
$$Q_1' = 2 - t \tag{5.12b}$$
$$Q_2' = t^2 - 4t + 3; \tag{5.12c}$$

hence,

$$
\begin{aligned}
P_n' &= Q_n' - Q_{n-1}' \\
&= (2-t)Q_{n-1}' + Q_{n-2}' - Q_{n-1}' \\
&= (1-t)Q_{n-1}' + Q_{n-2}'.
\end{aligned}
\tag{5.13}
$$

It is interesting to note that

$$
\begin{aligned}
P_1'(1) &= 0 \\
P_2'(1) &= -1 \\
P_3'(1) &= -1 \\
P_4'(1) &= 0 \\
P_5'(1) &= 1 \\
P_6'(1) &= 1 \\
P_7'(1) &= 0 \\
P_8'(1) &= -1
\end{aligned}
\tag{5.14}
$$

Since, by definition, $P_n'(1)=P_{n-1}'(1)-P_{n-2}'(1)$, this pattern evidently repeats. Hence,

$$
P_{3n+1}'(1) = 0 \quad n=0,1,2,\ldots \tag{5.15}
$$

Thus,

Proposition: A repetitive shear structure with 3n+1 stories has, as one of its modal frequencies, the same frequency as that of a single bay.

Asymptotic Behavior

Consider story i of an N story repetitive shear structure, with story shears V_i and V_{i-1}.

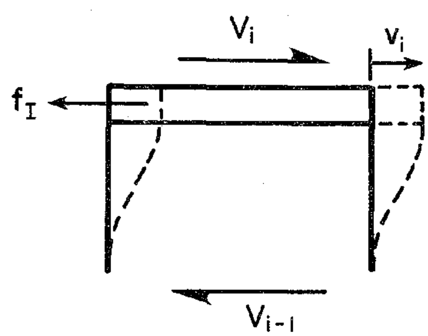

Figure 5.2 Single story of shear structure

Statics suggests that

$$V_i - V_{i-1} = f_I = m\frac{d^2v_i}{dt^2}. \tag{5.16}$$

This and the constitutive relation

$$k(v_i - v_{i-1}) = v_{i-1} \tag{5.17}$$

combine to give

$$m\frac{d^2v_i}{dt^2} = k(v_{i+1} - 2v_i + v_{i-1}). \tag{5.18}$$

If the time and distance scales of $v_i(x) = v(i,x)$ are changed by setting

$$u_N(s,t) = v(Ns,Nt) \quad 0 < s < 1 \tag{5.19}$$

where v is here extended differentiably between integer values of i, we have

$$\begin{aligned} m\frac{d^2u}{dt^2} &= N^2m\,\frac{d^2v}{dt^2} \\ &= N^2k(v_{i+1} - 2v_i + v_{i-1}) \\ &= k\frac{u(s+\frac{1}{N}) - 2u(s) + u(s-\frac{1}{N})}{\frac{1}{N^2}}. \end{aligned} \tag{5.20}$$

The effect of the distance translation is to make the domain of u independent from N. The last expression contains the second central difference of u so, as N approaches infinity, this becomes

$$\frac{\partial^2 u}{\partial t^2} = \frac{k}{m}\frac{\partial^2 u}{\partial s^2}. \tag{5.21}$$

Applying the technique of separation of variables, and applying the boundary conditions for a cantilever

$$\begin{aligned} u(0) &= 0 \\ u'(0) &= 0 \\ u''(1) &= 0 \\ u'''(1) &= 0, \end{aligned} \tag{5.22}$$

lead to

$$w^2 = n^2\,\frac{k}{m} \quad \textit{where } n = 1,3,5,7,\ldots \tag{5.23}$$

Thus, as N gets large, the roots of the P_n will have the approximate ratios 1^2, 3^2, 5^2, 7^2,...

n										
1	1.00									
2	0.38	2.62								
3	0.20	1.55	3.25							
4	0.12	1.00	2.35	3.53						
5	0.08	0.69	1.72	2.83	3.68					
6	0.06	0.50	1.29	2.24	3.14	3.77				
7	0.04	0.38	1.00	1.79	2.62	3.34	3.83			
8	0.03	0.30	0.79	1.45	2.18	2.89	3.48	3.86		
9	0.03	0.24	0.65	1.20	1.84	2.49	3.10	3.58	3.89	
10	0.02	0.20	0.53	1.00	1.56	2.15	2.74	3.24	3.66	3.91

Figure 5.3 Roots of polynomials P_n'

Design of the Six Story Frame

Utilizing the design considerations of the previous section, a frame was designed to be tested on a small shaking table test facility at the University of California at Berkeley (see Figure 5.4). The frame was designed to have a highest modal frequency of about 20hz, since that is the approximate limit of the response of this table.

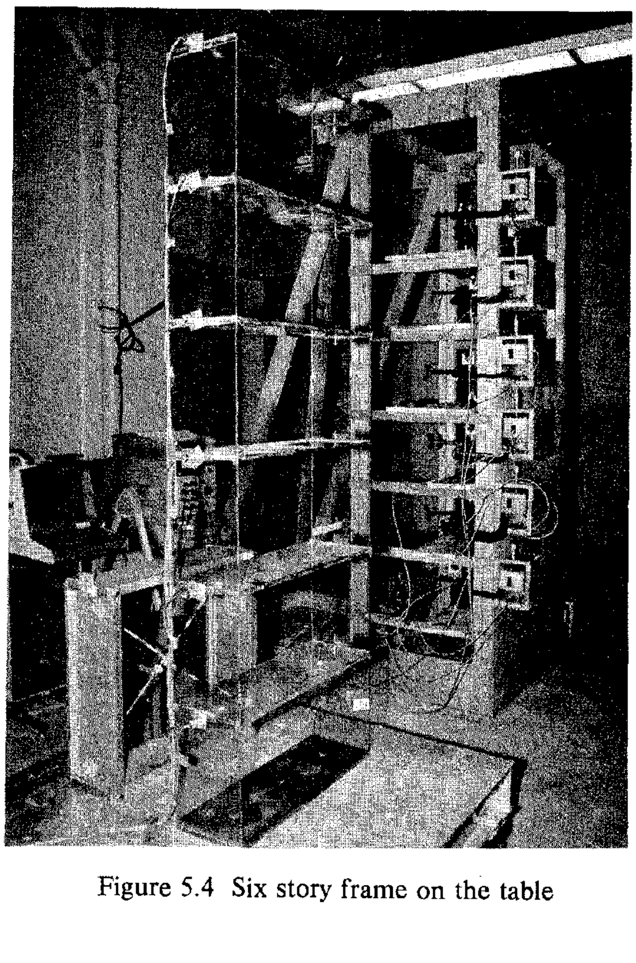

Figure 5.4 Six story frame on the table

To make the joints as simple and as continuous as possible, the columns were constructed out a single piece of material. The girders, also made of the same material were then set into the columns (see Figure 5.5).

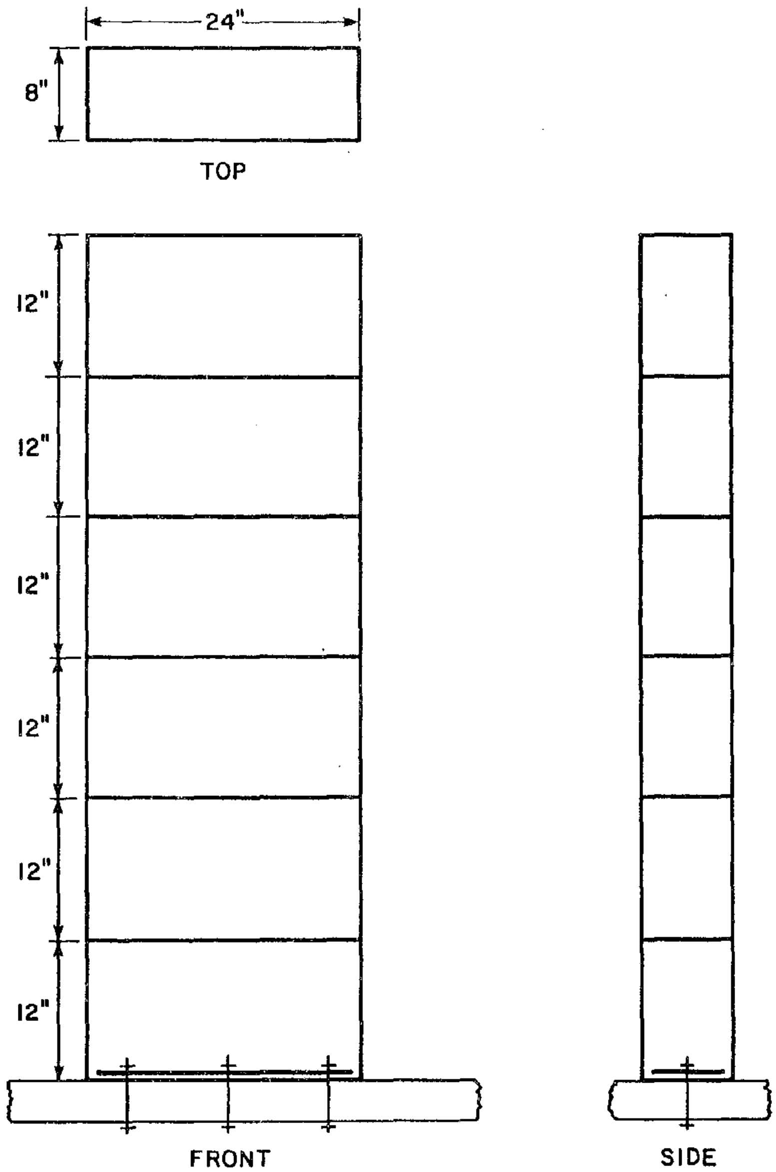

Figure 5.5a Geometry of six story frame

After testing the properties of several different materials, lexan was chosen since it was easy to machine, had material properties which were apparently independent of frequency, and could be glued with a solvent to produce very homogeneous joints.

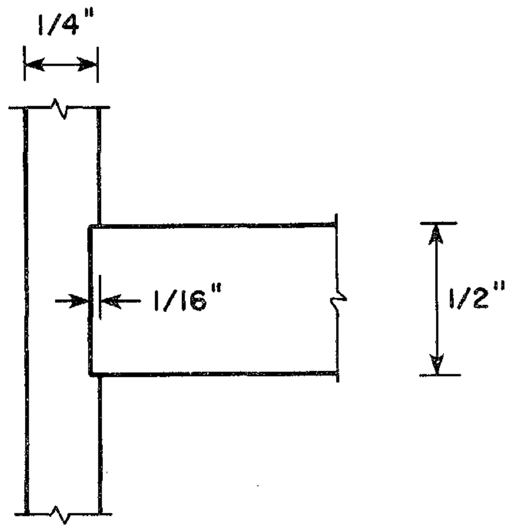

Figure 5.5b Joint detail

Instrumentation

Schaevitz LVDT accelerometers were attached to the joints on one side of the structure. These were chosen since they respond to frequencies up to about 100 hz, and also down to and including 0 hz. Mirrors were attached to the joints on the other side of the structure to become a part of an optical rotation measurement apparatus described in the previous chapter. The photocell targets were mounted on a stage which could be translated a controlled amount and measured with a micrometer.

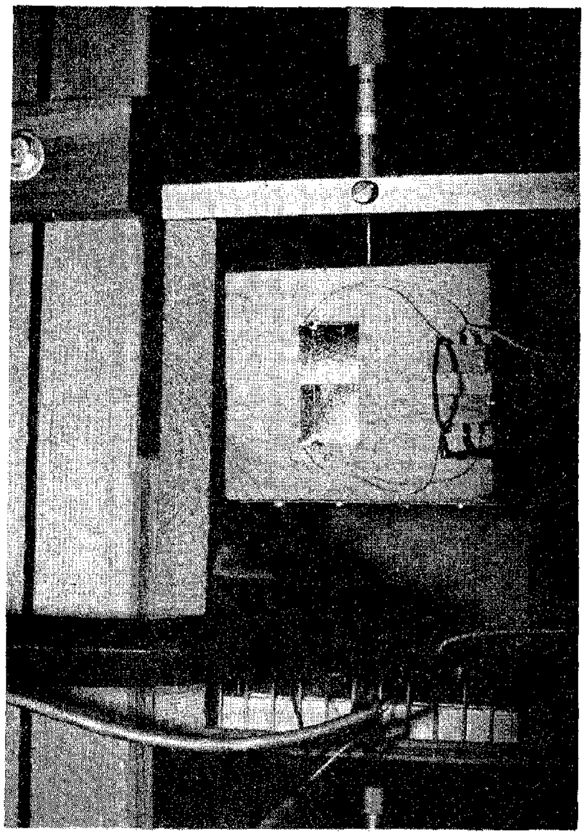

Figure 5.6 Photocell targets

Lasers and optical benches were mounted in a stable rack. This rack had adjustable shelves, permitting precise alignment and adjustment of the laser systems:

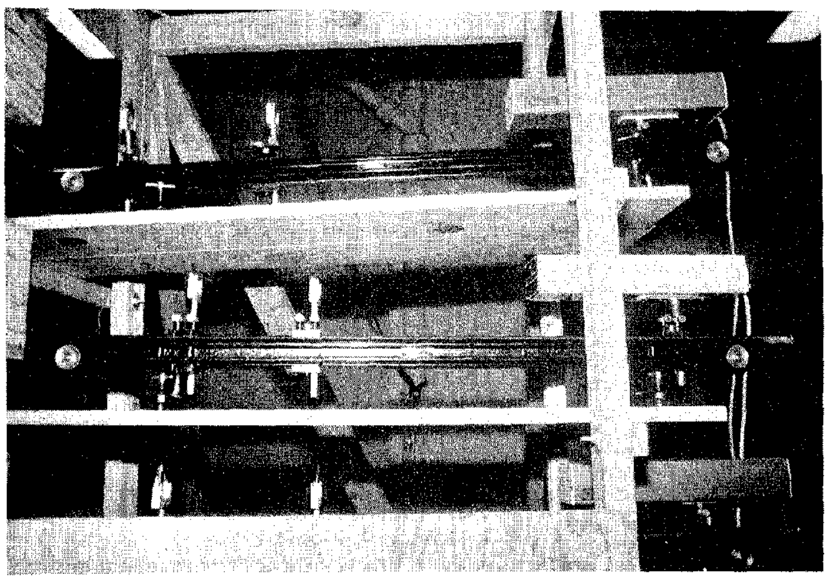

Figure 5.7 Lasers and optical benches

The lasers were carefully aligned to minimize parallax errors. As was noted in the previous chapter, the output of each target will only be linear over a moderate range. However, each photocell target was calibrated over a wide range. In this way, by fitting a polynomial to the calibration curves for the targets, the output of the apparatus could be linearized over a much larger range.

Finite Element Model - Six Story Frame

Developed here is a finite element model where joint panel zones and beams are allowed to distort both in shear and in flexure, but are assumed rigid for axial deformations. Using Figure 5.8 as a reference for global coordinates, the transformations from the local element coordinates to global coordinates will be given.

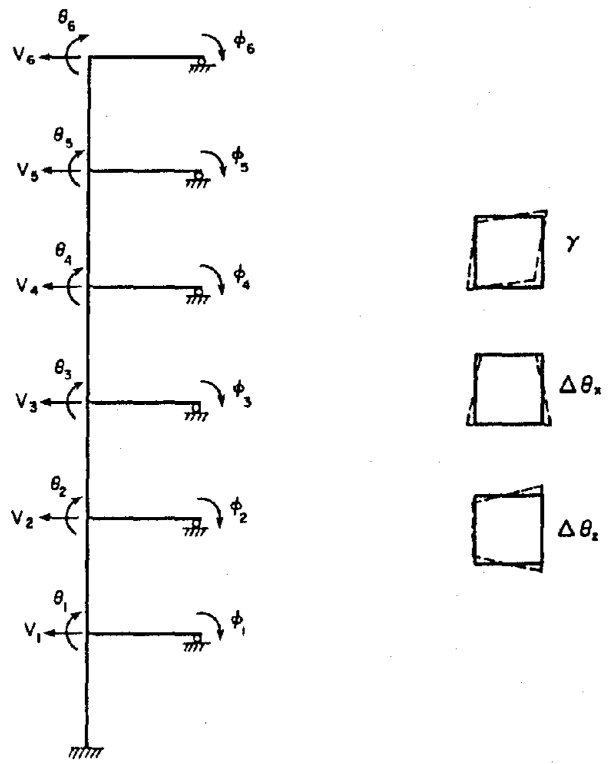

Figure 5.8 Six story frame global coordinates

Horizontal member i:

$$\underline{A}^h = [\underline{0}_{3x3} \cdots \underline{0}_{3x6}\ \underline{a}^h_{3x6}\ \underline{0}_{3x6} \cdots \underline{0}_{3x6}] \quad \textbf{(5.24)}$$

where

$$\underline{a}^h = \begin{bmatrix} 0 & 1 & \tfrac{1}{2} & -\tfrac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & -\frac{b}{2} & \frac{b}{4} & 0 & 0 & 0 \end{bmatrix} \tag{5.25}$$

Vertical member i:

$$\underline{A}^v = [\underline{0}_{4x3} \cdots \underline{0}_{4x6} \underline{a}^v_{4x6} \underline{b}^v_{4x6} \underline{0}_{4x6} \cdots \underline{0}_{4x6}] \quad 2 \leqslant i \leqslant 6 \tag{5.26a}$$

$$\underline{A}^v = [\underline{a}'_{4x3} \; b_{4x6} \, \underline{0}_{4x6} \; \cdots \; \underline{0}_{4x6}] \qquad i=1 \tag{5.26b}$$

where

$$\underline{a}^v = \begin{bmatrix} 0 & 1 & -\tfrac{1}{2} & 0 & -\tfrac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -\frac{h}{2} & -\frac{h}{4} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.27a}$$

$$\underline{b}^v = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -\tfrac{1}{2} & 0 & \tfrac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & \frac{h}{2} & \frac{h}{4} & 0 & 0 & 0 \end{bmatrix} \tag{5.27b}$$

$$\underline{a}' = \begin{bmatrix} -\tfrac{1}{2} & 0 & -\tfrac{1}{2} \\ 0 & 0 & 0 \\ -\frac{h}{4} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5.27c}$$

Joint i:

$$\underline{A}^j = [\underline{0} \; \cdots \; \underline{0} \, I_{3x3} \, \underline{0} \; \cdots \; \underline{0}] \qquad 1 \leqslant i \leqslant 6 \tag{5.28a}$$

$$\underline{A} = [\underline{I}_{3x3} \, \underline{0} \; \cdots \; \underline{0}] \qquad i = \text{base} \tag{5.28b}$$

The beam stiffness matrices will be given by

$$k = k_e - k_g \tag{5.29}$$

where

$$\underline{k}_e = \frac{2EI}{L^3} \begin{bmatrix} 2L^2 & L^2 & -3L & 3L \\ L^2 & 2L^2 & -3L & 3L \\ -3L & -3L & 6 & -6 \\ 3L & 3L & -6 & 6 \end{bmatrix} \tag{5.30}$$

$$\underline{k}_g = \frac{N}{30L}\begin{bmatrix} 4L^2 & -L^2 & -3L & 3L \\ -L^2 & 4L^2 & -3L & 3L \\ -3L & -3L & 36 & -36 \\ 3L & 3L & -36 & 36 \end{bmatrix}. \tag{5.31}$$

The beam mass matrices will be given by

$$\underline{m} = \frac{\bar{m}L}{420}\begin{bmatrix} 4L^2 & -3L^2 & -22L & -13L \\ -3L^2 & 4L^2 & 13L & 22L \\ -22L & 13L & 156 & 54 \\ -13L & 22L & 54 & 156 \end{bmatrix} \tag{5.32}$$

L is the length, $\bar{m}$ = mass/length, and N = normal force. The joint stiffness matrices will be given by

$$\underline{k}_J = \begin{bmatrix} Gbht & & \\ & \frac{EI_x}{b} & \\ & & \frac{EI_z}{h} \end{bmatrix}. \tag{5.33}$$

Material Properties

The total frame weighed 18.4kg. The consistent mass matrix was calculated using this number. In addition, the accelerometers and mirrors contributed to the frame's translational mass. The accelerometers and associated hardware averaged 65.5g. The mirrors with their hardware averaged 20.1g.

The modulus of elasticity of the lexan is listed as 1-300,000 by the manufacturer. To estimate this more exactly, a piece of material was clamped at one end, and a number of loads were applied to the end. By measuring the deflections at midspan, the modulus of elasticity in flexure was estimated at 237,000.

Modal damping ratios were determined by exciting the model in the n^{th} mode, and recording the exponential decay. For any two positive peaks m cycles apart, v_0 and v_m, the damping ratio ξ can be determined from

$$\ln\left[\frac{v_0}{v_m}\right] = 2m\pi \frac{\xi}{(1-\xi^2)^{1/2}} \tag{5.34}$$

which can be simplified for low damping to

$$\xi=\frac{v_0-v_m}{2\pi m v_m}. \tag{5.35}$$

For the six story model, modal ratios and frequencies were determined to be

Mode	Frequency (hz)	Damping Ratio (%)
1	1.95	0.6
2	5.85	0.4
3	9.95	0.5
4	13.9	0.6
5	17.5	0.6
6	19.9	0.2

The damping coefficients a_k and a_m can be derived from two sets of modal damping ratios ξ_i and natural periods T_i , as follows:

$$a_m = \frac{4\pi(T_2\xi_2-T_1\xi_2)}{T_2^2-T_1^2} \tag{5.36}$$

$$a_k = \frac{T_1T_2(T_2\xi_1-T_1\xi_2)}{(T_2^2-T_1^2)}. \tag{5.37}$$

In the six story model, using the first two modes we have

$$a_m = 0.13 \tag{5.38}$$

$$a_k = 0.00012 \tag{5.39}$$

Identification

The six story frame was subjected to a reproduction of the same El Centro earthquake record as the three story frame. As in the identification of the three story frame, the rotation measurements were scaled by the modulus of elasticity of the material to produce quantities of the same order of magnitude. In all of these identifications, both the acceleration and rotation time histories were used.

Model 1

The first model was developed using only two parameters - one for the columns, and one for mass proportional damping. In the six story frame, the column and girder parameters were not associated with the effective lengths, but rather with the moment of inertia. After three steps, the error had decreased from 23,400 to 7,199. The column parameter changed from 1.0 to 0.93, while the damping factor changed from 1.0 to 6.6. Thus while the overall response is approximated using close to the actual column geometry, it is apparent that some further investigation is required.

Model 2

The second model included one more parameter associated with the shear modulus of the joint. The estimate of shear modulus was derived from the measured elastic modulus by assuming a Poisson's ratio of 0.25. This produced still more improvement in response matching, producing an error of 5090 in five steps, with resulting parameters of 1.03 for the columns, 0.86 for the joint modulus, and 1.16 for the damping parameter. It is apparent that the inclusion of the joint parameter significantly improves response matching. It would seem that, for this model at least, the joint behaves more flexibly than would be expected from measurements of material behavior.

Model 3

Response history matching using the joint shear modulus parameter reflects the degree to which joint shear deformation accounts for the total response of the frame. In order to assess the relative effect of joint flexure, a new model was applied using four parameters - one again associated with the column moment of inertia, one with mass proportional damping, and one associated with each joint moment of inertia. In four steps, the error function arrived at 3149, with the column parameter reaching 1.04 and the damping parameter reaching 1.2. The joint moment of inertia parameters, however, became 0.18 and 1.4. Interestingly, while the flexural deformations seem to account for more error than the shear deformations, it is unclear from this analysis whether the two flexures were in fact different, or just impossible to identify separately. Since the construction of the frame was designed to keep the joints as homogeneous as possible, it seemed reasonable to assume that the joint parameters should be lumped together.

Model 4

In this model the joint moments of inertia were associated with a single parameter, and an additional parameter was included to represent the shear modulus. With the addition of the column and damping parameters, this model has four parameters. In 5 steps the error was reduced to 3077, which is not a very substantial improvement over Model 3. The column parameter was 1.04, and the damping factor was 0.75. The inclusion of the joint shear parameter is therefore relatively unimportant. Further, the shear factor became 0.34 while the flexural factor became 1.48, indicating that the two are not independent.

Model 5

In Model 5 the shear parameter of Model 4 was replaced by a parameter associated with the moment of inertia of the girders. If the joint flexural parameters are the logical set, the inclusion of the girder parameter should not decrease the error significantly, and also should not be independent. In fact, the error became 2700. This is only slightly smaller than in Model 4. The parameter associated with the girder became 0.86 while the parameter associated with the joint became 2.37. Figure 5.9 depicts the measured and predicted response histories of this model.

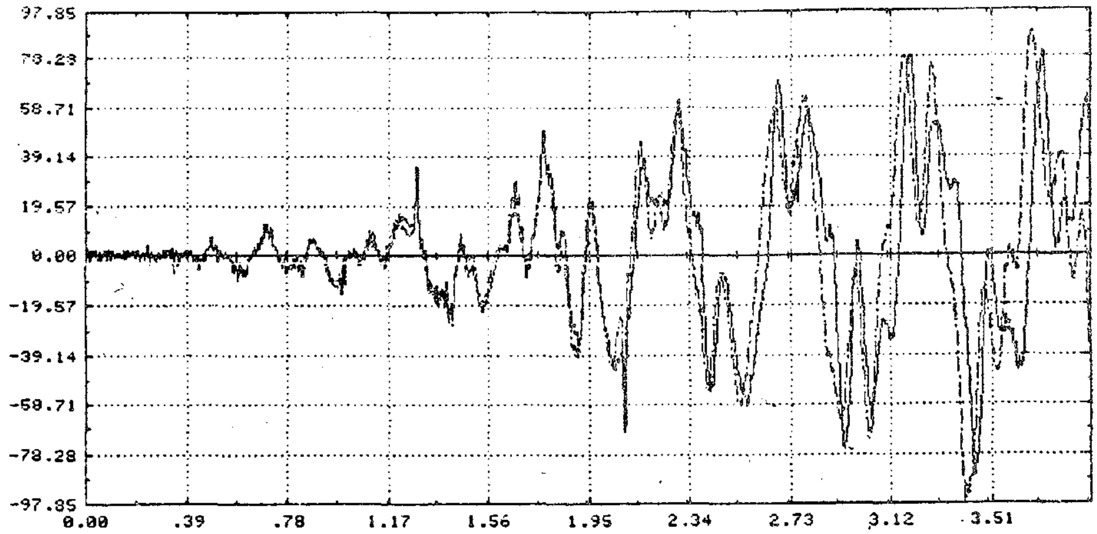

Figure 5.9a Sixth floor acceleration before identification (in/sec^2 vs. seconds)

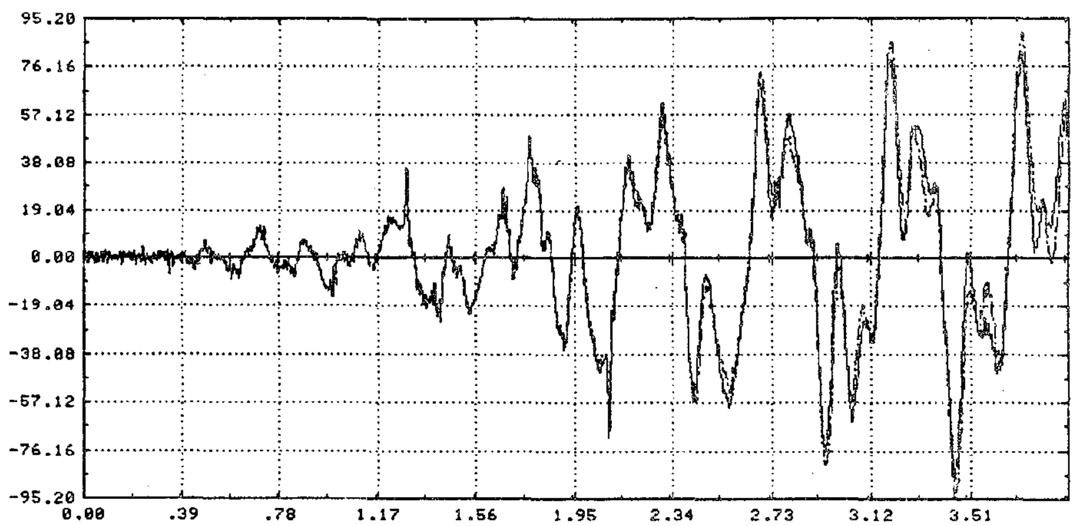

Figure 5.9b Sixth floor acceleration after identification (in/sec^2 vs. seconds)

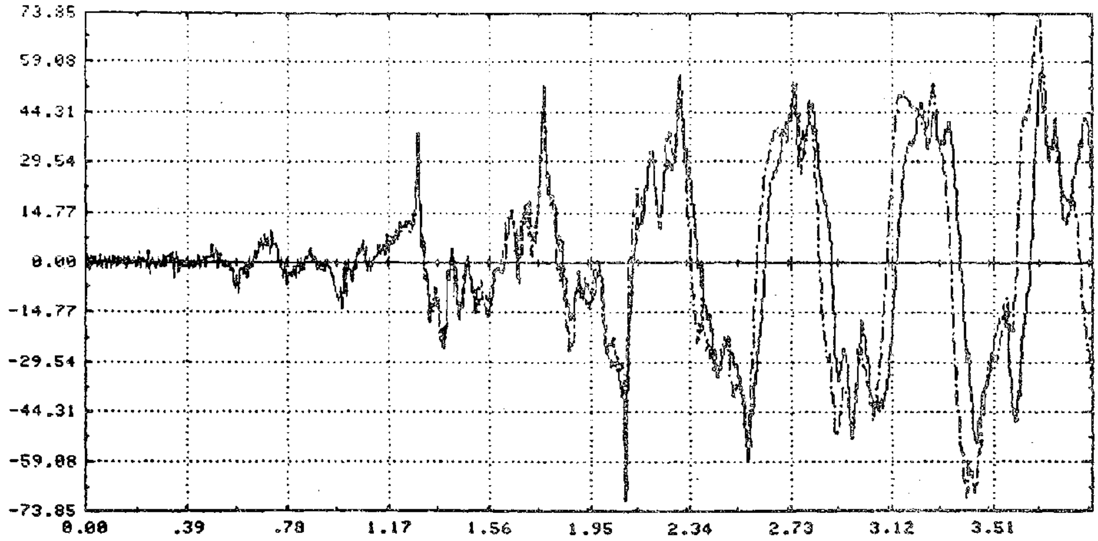

Figure 5.9c Fifth floor acceleration before identification (in/sec^2 vs. seconds)

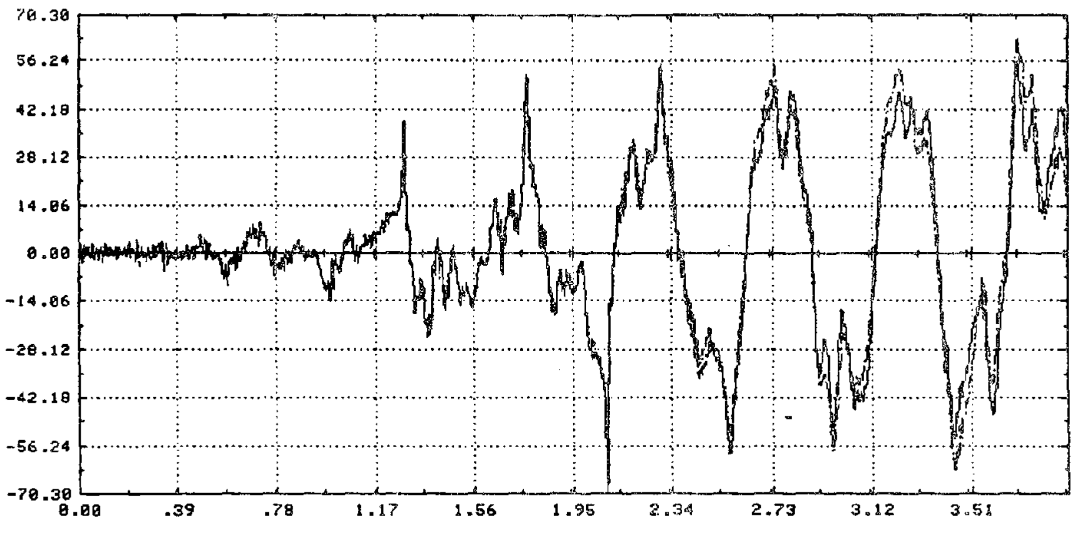

Figure 5.9d Fifth floor acceleration after identification (in/sec^2 vs. seconds)

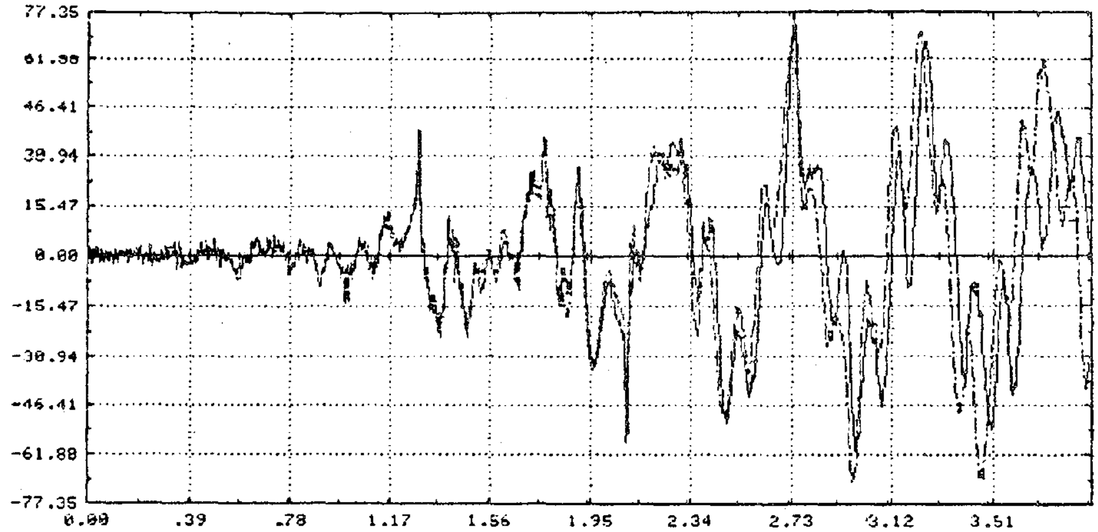

Figure 5.9e Fourth floor acceleration before identification (in/sec^2 vs. seconds)

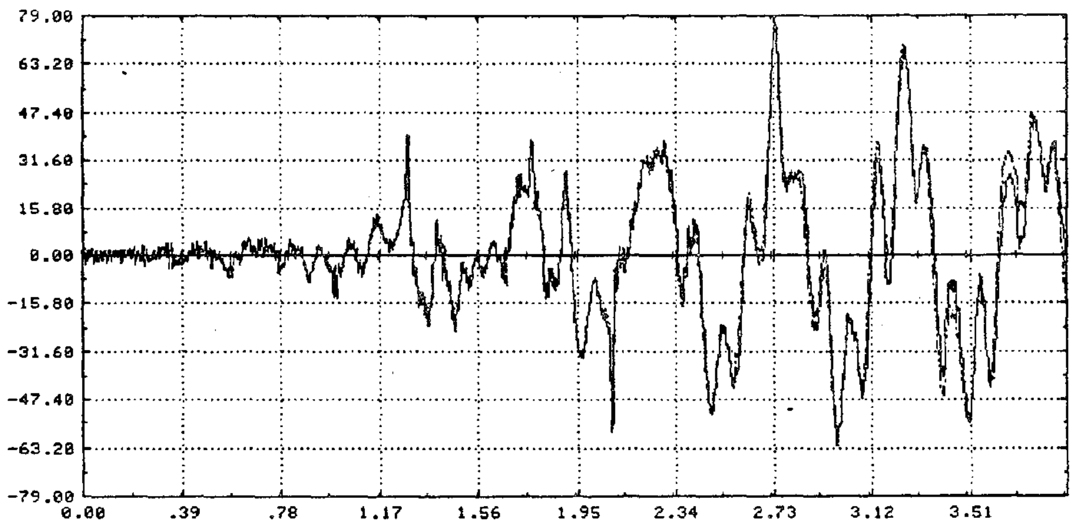

Figure 5.9f Fourth floor acceleration after identification (in/sec^2 vs. seconds)

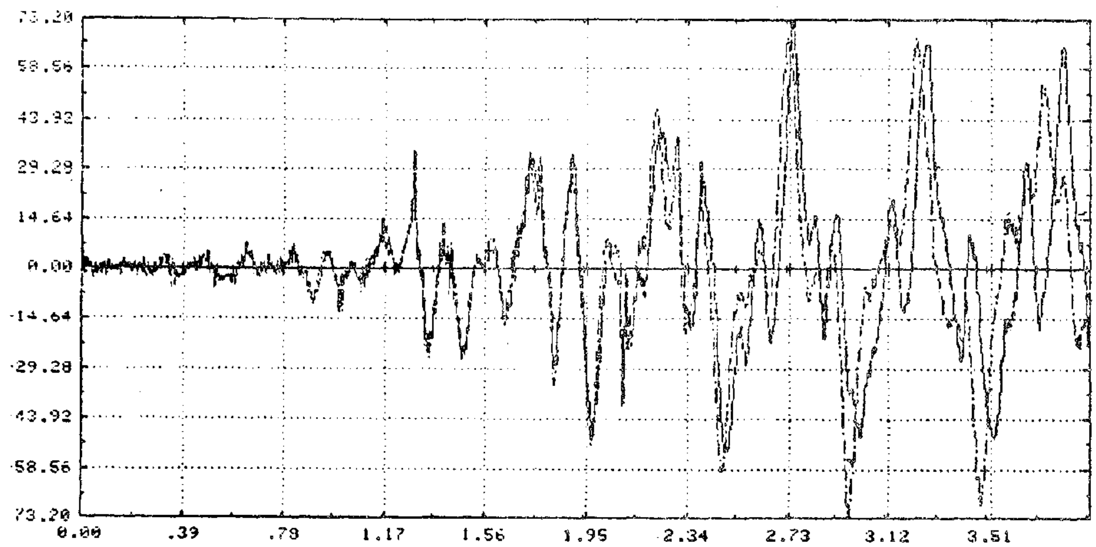

Figure 5.9g Third floor acceleration before identification (in/sec^2 vs. seconds)

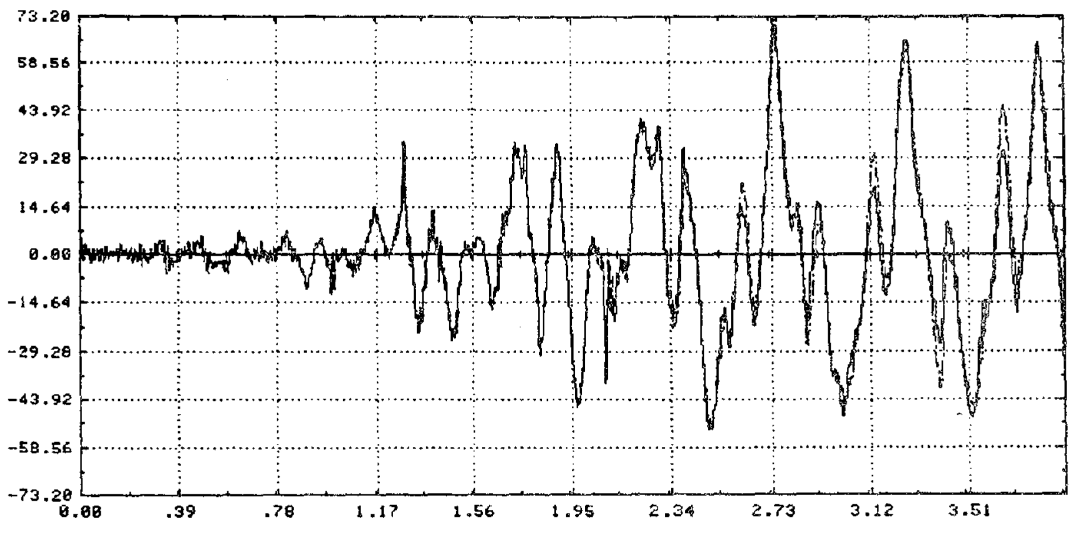

Figure 5.9h Third floor acceleration after identification (in/sec^2 vs. seconds)

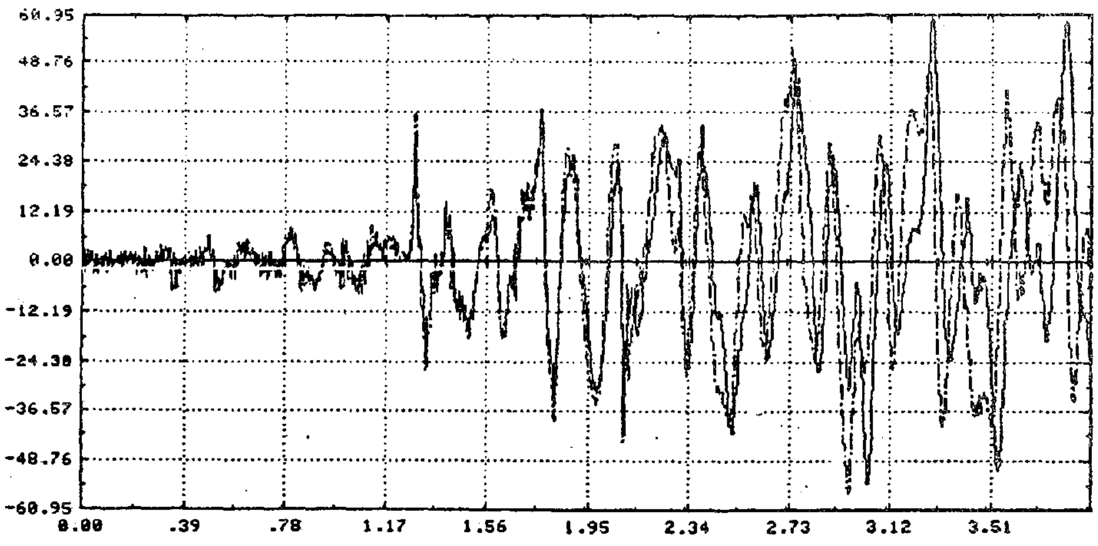

Figure 5.9i Second floor acceleration before identification (in/sec^2 vs. seconds)

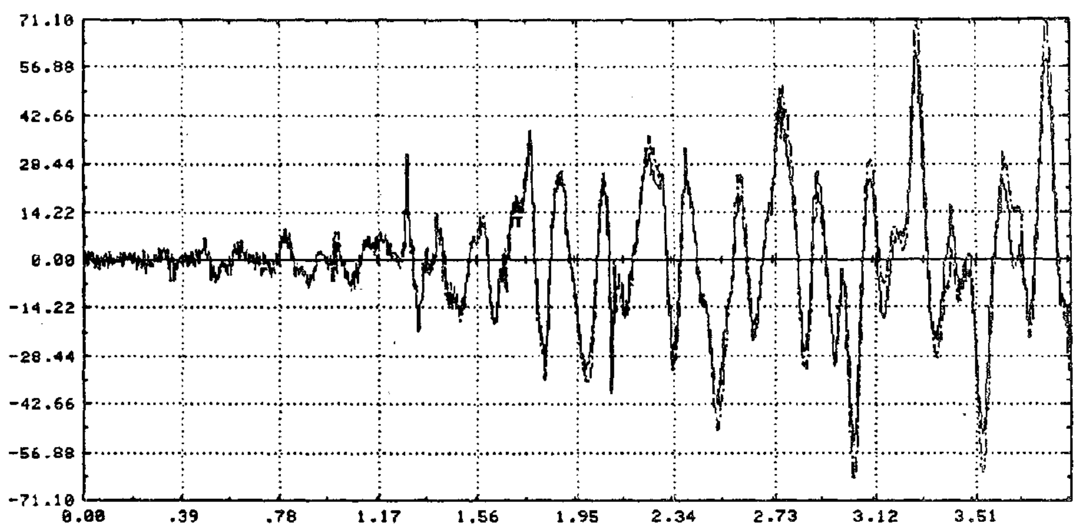

Figure 5.9j Second floor acceleration after identification (in/sec^2 vs. seconds)

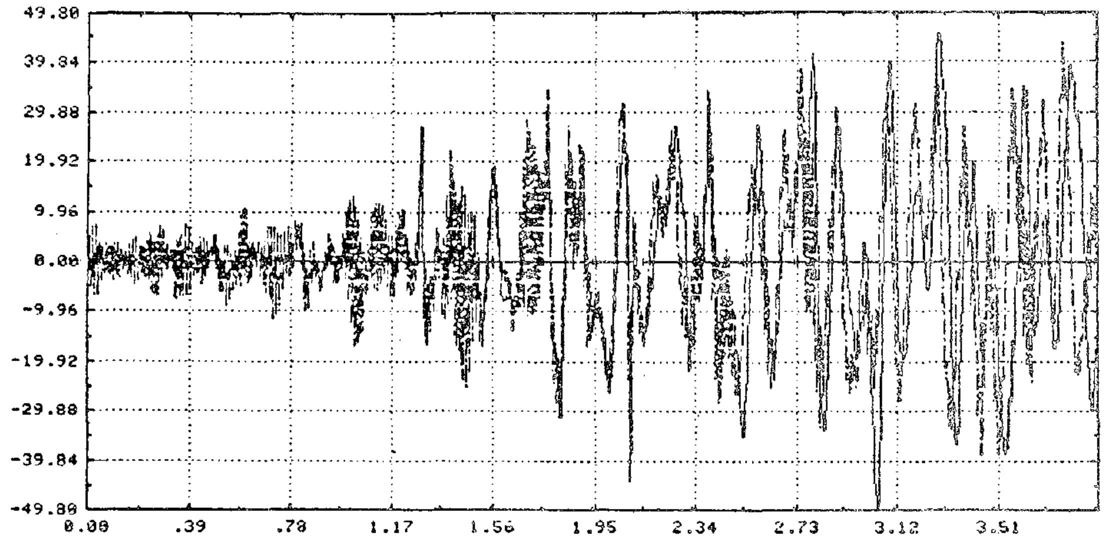

Figure 5.9k First floor acceleration before identification (in/sec^2 vs. seconds)

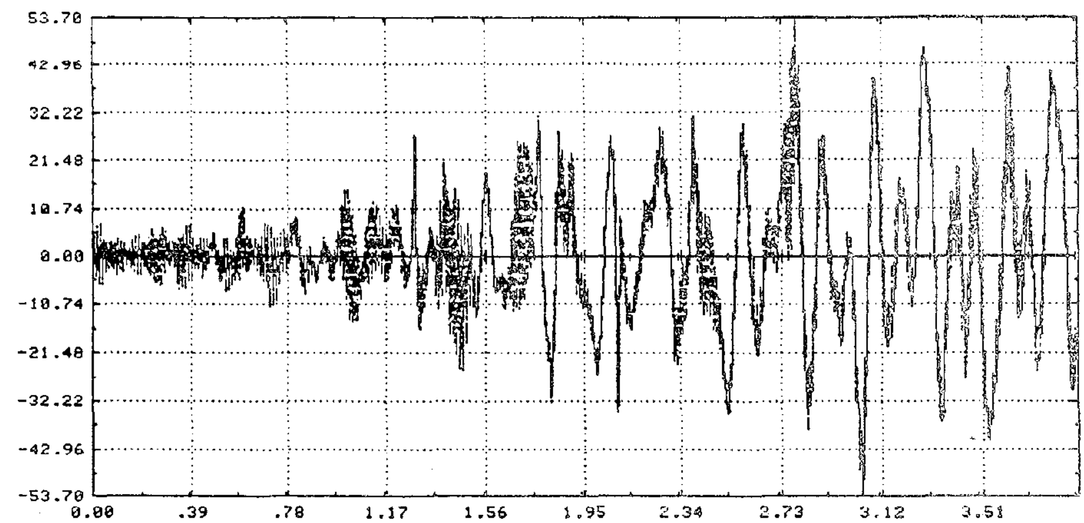

Figure 5.9l First floor acceleration after identification (in/sec^2 vs. seconds)

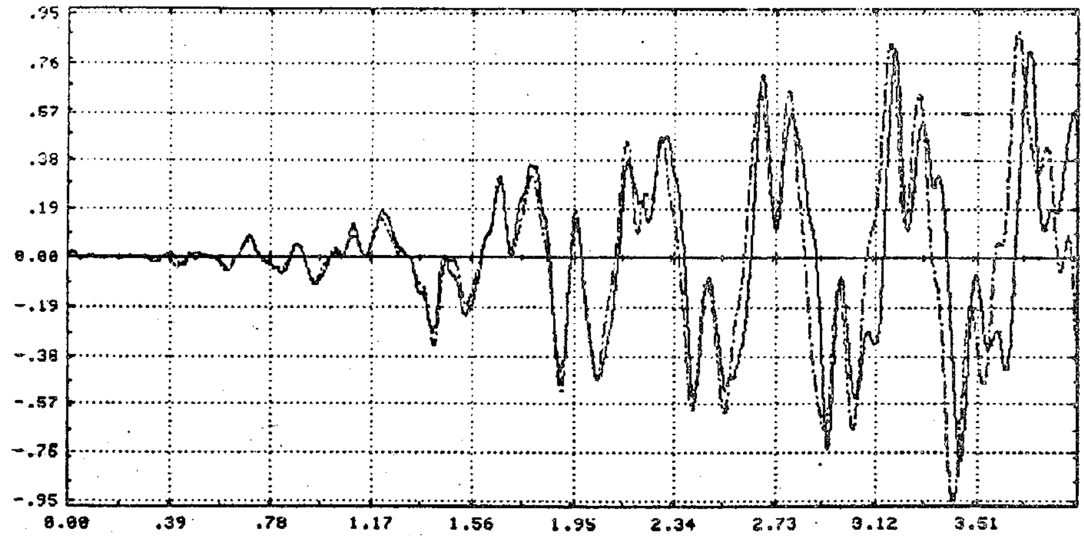

Figure 5.9m Sixth floor rotation before identification (milliradians vs. seconds)

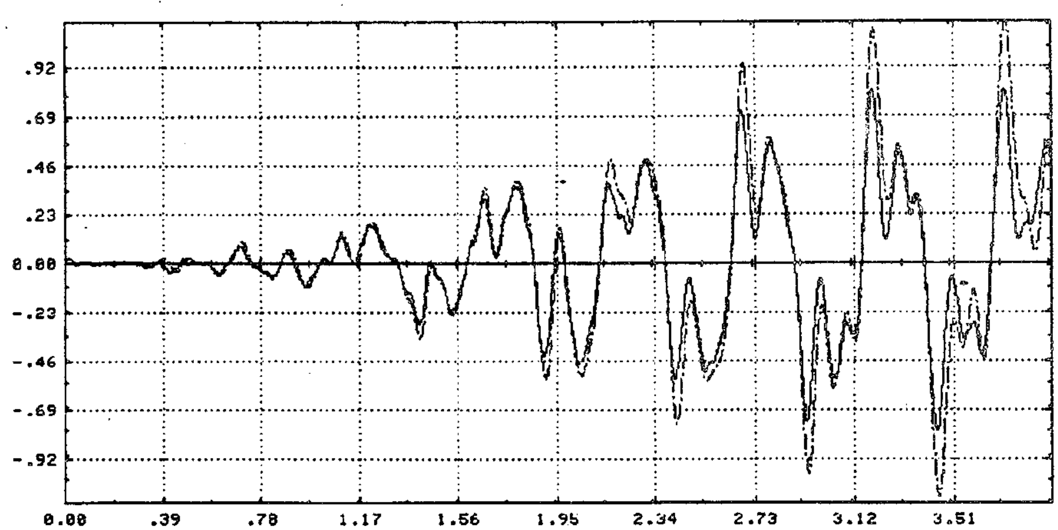

Figure 5.9n Sixth floor rotation after identification (milliradians vs. seconds)

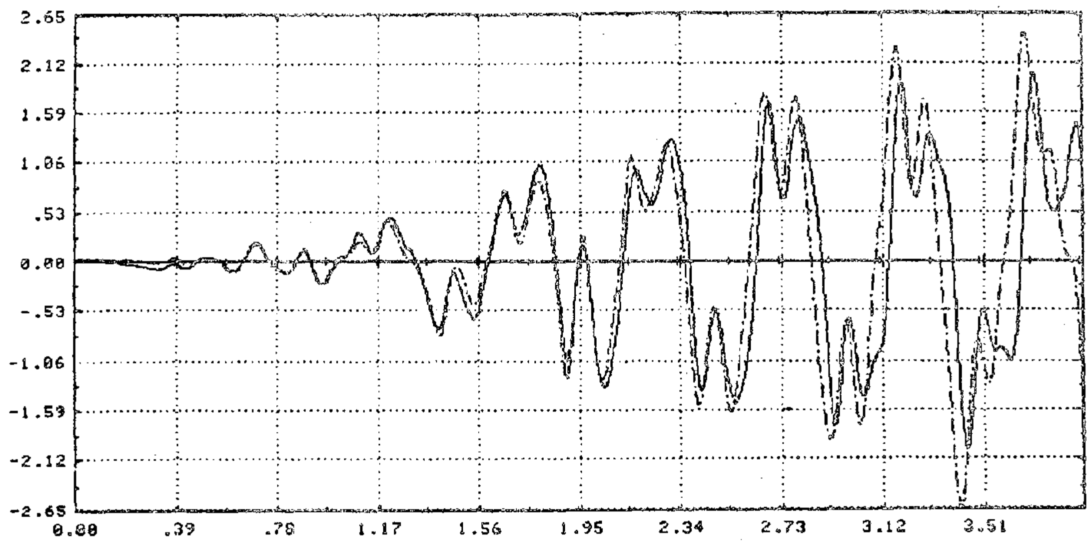

Figure 5.9o Fifth floor rotation before identification (milliradians vs. seconds)

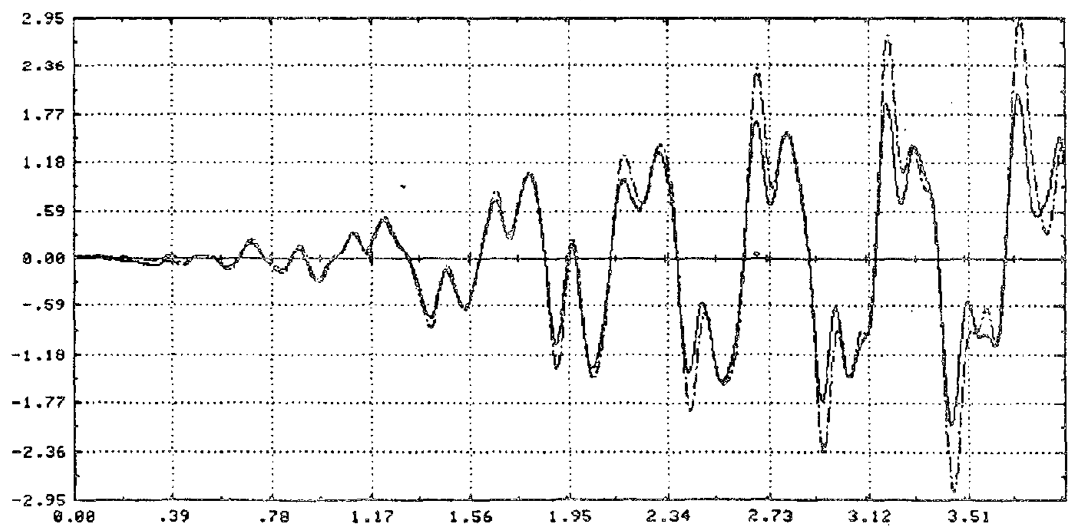

Figure 5.9p Fifth floor rotation after identification (milliradians vs. seconds)

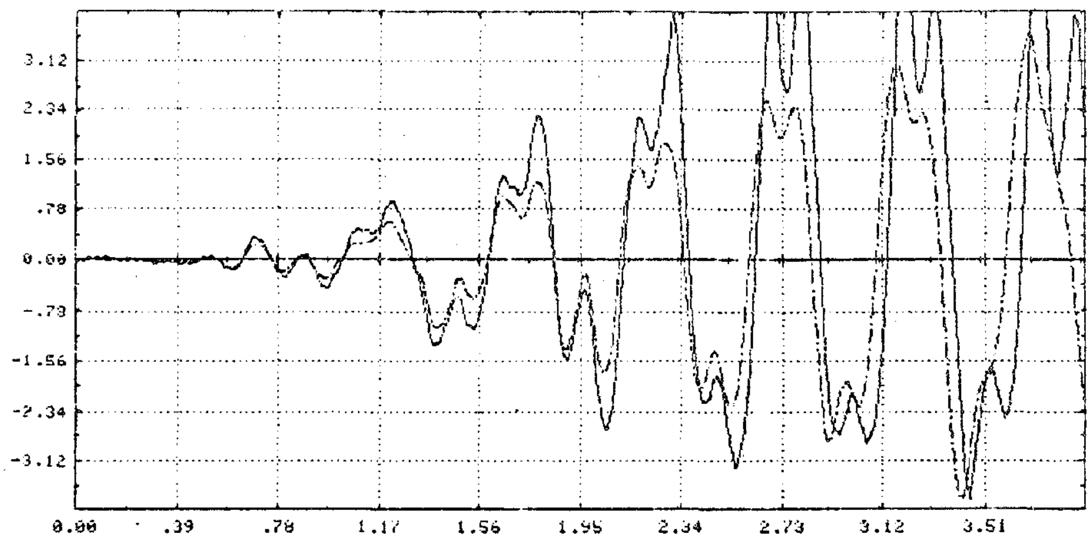

Figure 5.9q Fourth floor rotation before identification (milliradians vs. seconds)

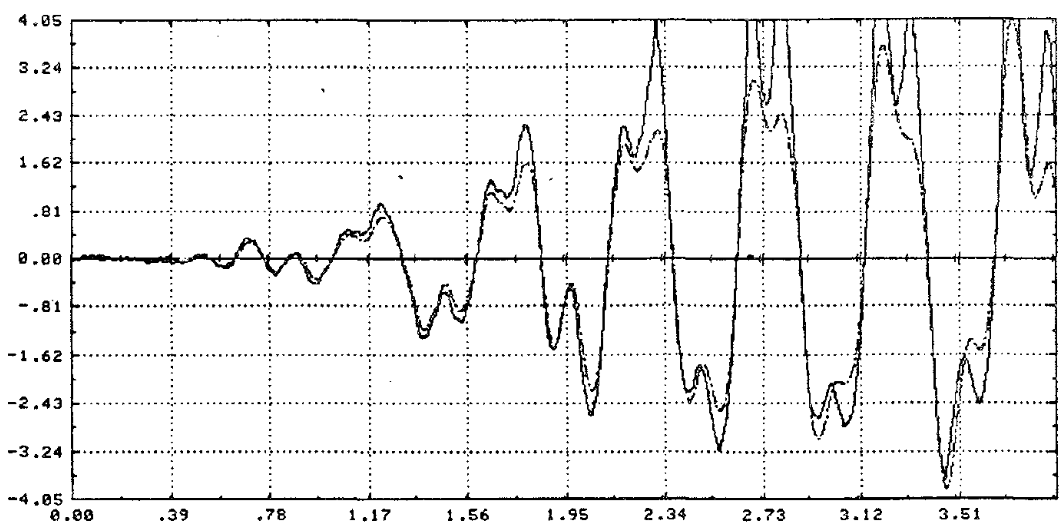

Figure 5.9r Fourth floor rotation after identification (milliradians vs. seconds)

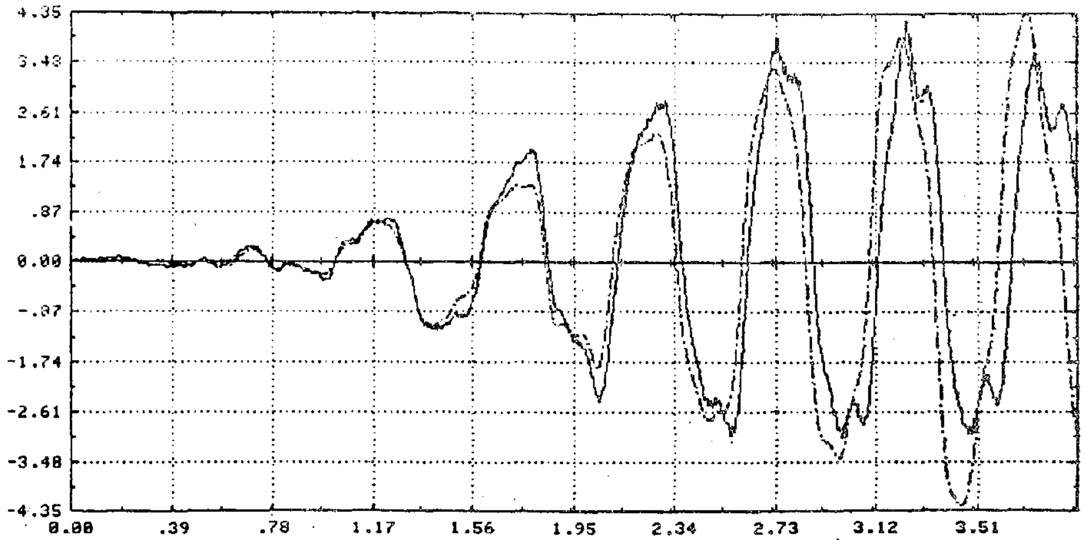

Figure 5.9s Third floor rotation before identification (milliradians vs. seconds)

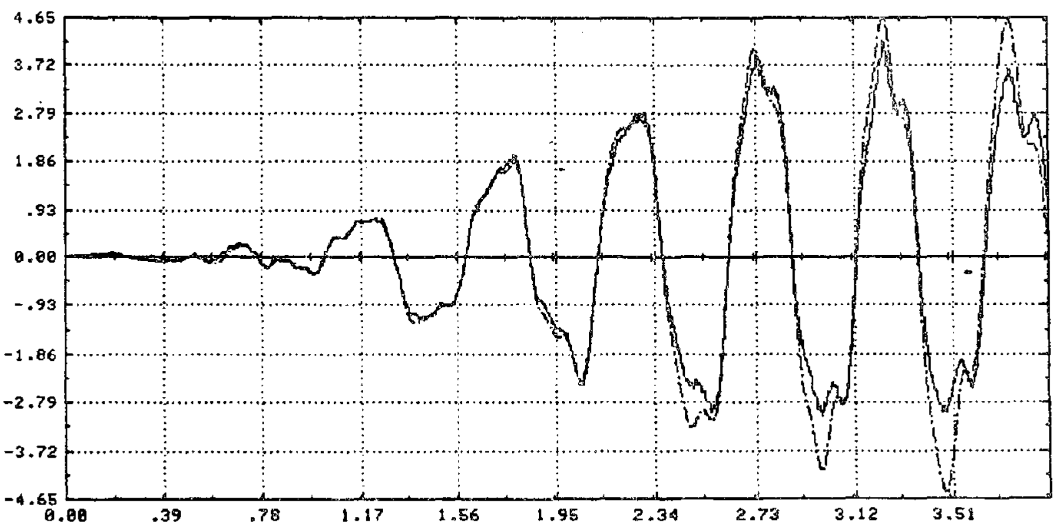

Figure 5.9t Third floor rotation after identification (milliradians vs. seconds)

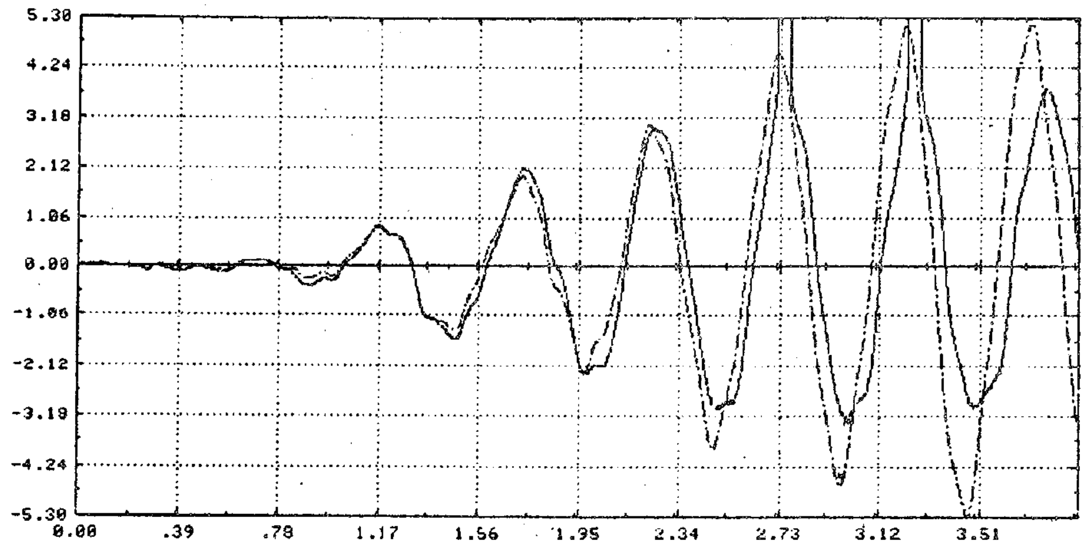

Figure 5.9u Second floor rotation before identification (milliradians vs. seconds)

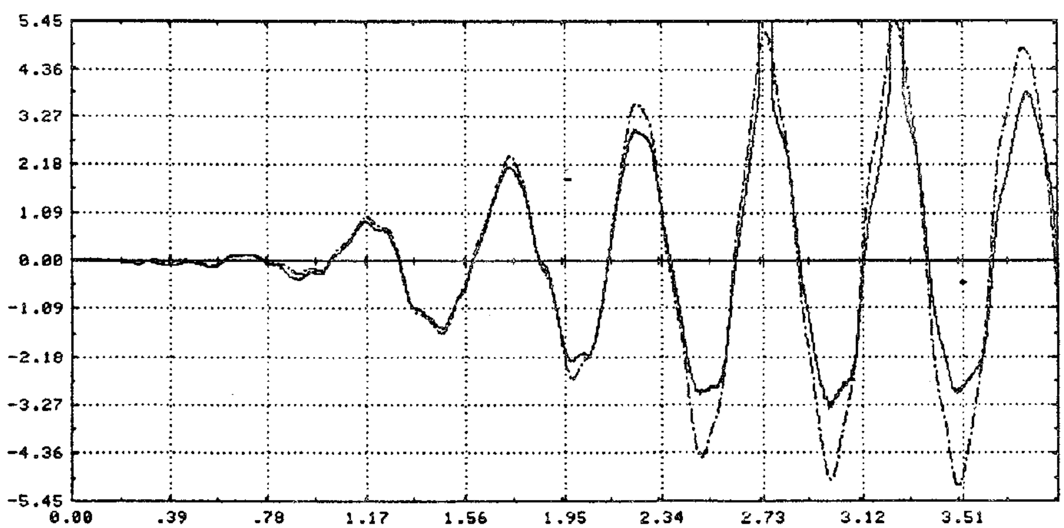

Figure 5.9v Second floor rotation after identification (milliradians vs. seconds)

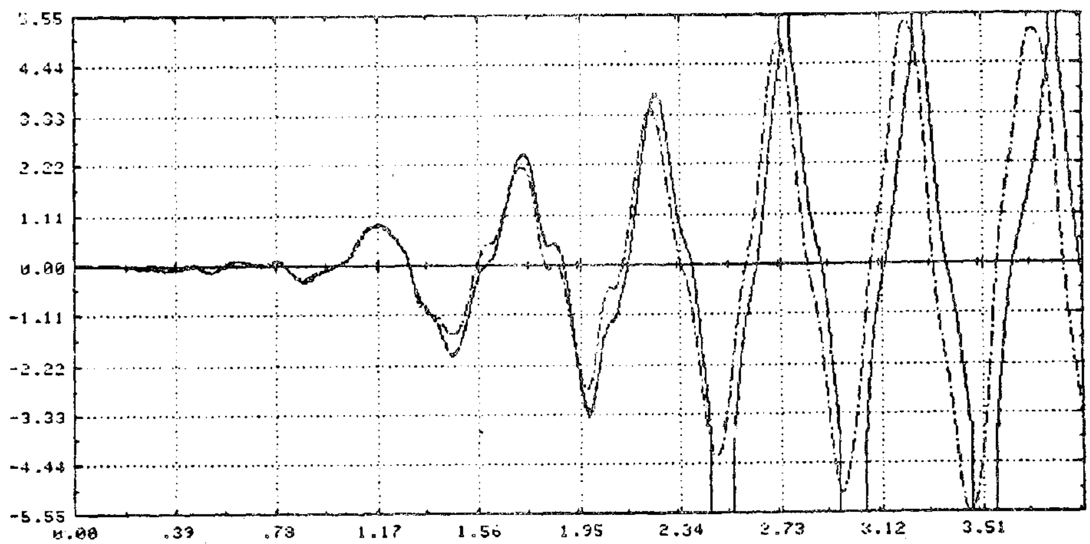

Figure 5.9w First floor rotation before identification (milliradians vs. seconds)

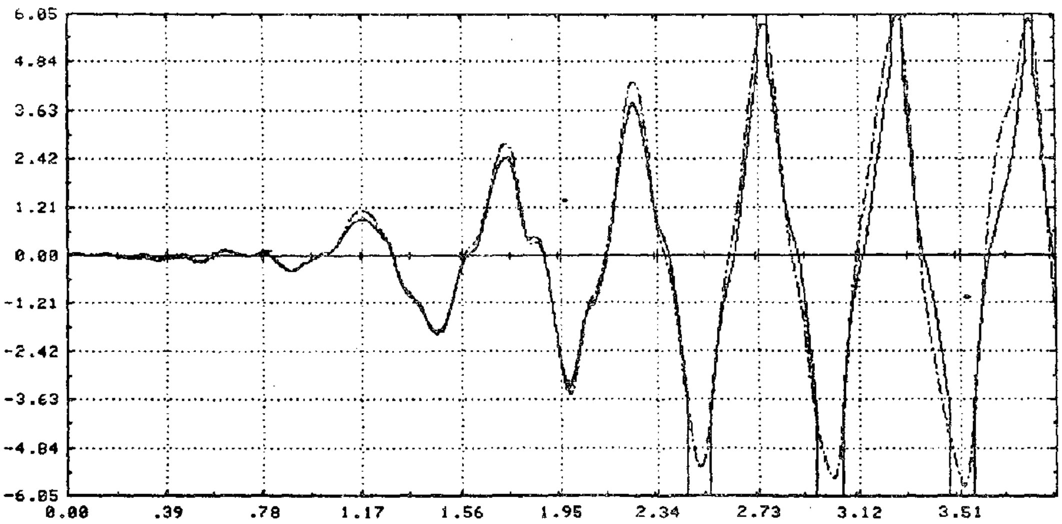

Figure 5.9x First floor rotation after identification (milliradians vs. seconds)

CHAPTER 6

CONCLUSIONS

It has been shown that the use of modal decomposition in the Gauss-Newton iterative identification procedure greatly reduces the computational effort required. At the same time, the technique appears to be quite stable, and converges rapidly.

This technique was applied to data resulting from seismic tests of a pair of three story frames previously investigated in some detail. It was discovered that even though the frames were very similar the identification procedure was able to determine accurately which of these frames had reinforced joints, but only when the identification included information gathered about the rotation of the joints in addition to their translations.

This data, however, was not kinematic in nature. Rather, it was inferred from strain measurements using the assumption that the whole frame remained linear and elastic. An optical technique was developed for the dynamic measurement of joint rotation.

A new six story frame was built, and instrumented with these optical instruments. This frame was built with joints that were as homogeneous as possible. With the use of the rotational data, it was found that the joint behavior still plays an important role in the structure's behavior, and in the identification.

Therefore, a tool has been developed for the identification of elements in structures with a relatively large number of degrees of freedom. This tool, when applied to the data made available through the use of the optical instrumentation, is valuable in describing structural behavior.

BIBLIOGRAPHY

1. Analog Devices, "AD520 Integrated Circuit Instrumentation Amplifier".

2. Astrom, K.J., and Eykhoff, P., "System Identification - A Survey," Automatica, 7:2,123-62, March 1971.

3. Atkinson, P.D. and Hynes, R.D., Analysis and Design of a Linear Differential Transformer. Elliot J. (London) 2; 144-51 (1954)

4. Bard, Y., "Comparison of Gradient Methods for the Solution of Nonlinear Parameter Estimation Problems," Journal of Numerical Analysis, SIAM, 7:1,157-86, March 1970.

5. Bathe, K., and Wilson, E.L., "Numerical Methods in Finite Element Analysis," Prentice-Hall (1976).

6. Beck, J. L., "Determining Models of Structures from Earthquake Records," Ph.D. Dissertation, California Institute of Technology, 1979.

7. Beck, J.V., and Arnold, K.J., "Parameter Estimation in Engineering and Science", John Wiley and Sons (1977).

8. Bekey, G.A., "System Identification - An Introduction and a Survey," Simulation, vol.4, no. 4, October 1970, pp 151-66.

9. Clough, R.W., and Penzien, J., "Dynamics of Structures," McGraw-Hill (1975).

10. Clough, R.W. and Tang, D.T. Earthquake Simulator Study of a Steel Frame Structure, Vol. I: Experimental Results," Report No. EERC 75-6, Earthquake Engineering Research Center, University of California, Berkeley (1975).

11. Hart, G.C., and Yao, J.T.P., "System Identification in Structural Dynamics," ASCE/EMD Specialty Conference on the Dynamic Response of Structures: Instrumentation, Testing Methods and System Identification, UCLA Extension, Los Angeles, March 1976, pp 61-85.

12. Hurty, W.C., and Rubinstein, M.F., "Dynamics of Structures", Prentice-Hall (1964).

13. Ibanez, P., "Identification of Dynamic Structural Models from Experimental Data," Report No. UCLA-ENG-7225, University of California, Los Angeles, March 1972.

14. Joos, G., Theoretical Physics, Blackie, London (1953).

15. Kaya, I., and McNiven, H.D., "Investigation of the Elastic Characteristics of a Three Story Steel Frame Using System Identification," Report No. EERC 78-24, Earthquake Engineering Research Center, University of California, Berkeley (1978).

16. Killpatrick, J. IEEE Spectrum. 4; 44 (October 1967).

17. Klosterman, A.L., "On the Experimental Determination and Use of Modal Representations of Dynamic Characteristics," Ph.D. Dissertation, University of Cincinatti, 1971.

18. Matzen, V.C., and McNiven, H.D., "Investigation of the Inelastic Characteristics of a Single Story Steel Structure Using System Identification and Shaking Table Experiments," Report No. EERC 76-20, Earthquake Engineering Research Center, University of California, Berkeley (1976).

19. Rea, D., and Penzien, J., "Dynamic Response of a 20 ft x 20 ft Shaking Table," Proceedings of the Fifth World Conference on Earthquake Engineering, Rome, Italy, 1972, pp. 1447-56.

20. Rodeman, R., and Yao, J.T.P., "Structural Identification - Literature Review," Report No. CE-STR-73-3, Civil Engineering, Purdue University, Ind. 1973.

21. Sage, A.P., "System Identification - History, Methodology, Future Prospects," System Identification of Vibrating Structures; Mathematical Models from Test Data, D. Pilkey and R. Cohen, eds., Winter Annual Meeting of ASME, 1972, pp 1-22.

22. Schaevitz Corp., Linear and Angular Servo Accelerometers. Technical Bulletin 4501B.

23. Smith, R.C., and Watkins, L.S., Ring Lasers: Principles and Applications, Proc Instn Mech Engrs, vol 183 pt 3D (1968).

24. Tang, D.T., "Earthquake Simulator Study of a Steel Frame Structure, Vol. II: Analytical Results," Report No. EERC 75-36, Earthquake Engineering Research Center, University of California, Berkeley (1975).

25. Udwadia, F.E., and Sharma, D.K., "Some Uniqueness Results Related to Building Structural Identification," Siam J. Appl. Math, 34;1,104-18, January 1978.

APPENDIX

COMPUTER PROGRAMS

Computer Program Input

1. Integration parameters

    δ, α, θ for integration

2. Rank parameters

    NP - number of parameters

    NDOF - # of total degrees of freedom

    NINDF - # of recorded degrees of freedom

    NXNT - # of modes for integration

    NGP - # of global coordinates

3. Parameter specification - for each range of same values

    E_i - fixed value associated with global parameter i

    IE_i - code for computing global coordinates:

    -i same as global parameter i

    0 fixed

    i xβ_i

    IGPS - start of range

    IGPE - end of range

4. NFN - # of normal forces

    f_i^N - normal forces, if any

5. NDEL - # of dof to delete from stiffness matrix

    degrees of freedom, if any

6. NCNDNS - # of dof to condense

    degrees of freedom, if any

7. R_i - static displacements for i=1,...,N

8. Measurement identification

For i=1,...,NINDF IR_i =

1 displacement

2 velocity

3 acceleration

IDF_i = dof for this measurement

9. End tolerance

SLMIN - minimum slope for line search termination

IT - maximum iterations

ENDTOL - necessary improvement for continuing

DDF - factor for finite differences

10. Initial estimates. $\beta_i; i=1,...,NP$

If absent, use data file TEMP.

```
c ***********************          ROUTINES FOR THREE STORY FRAME
c
      subroutine addk(tm,sm,n,ncall)
      dimension tm(ncall,ncall),sm(ncall,ncall)
      do 100 i=1,n
      do 100 j=1,n
      tm(i,j)=tm(i,j)+sm(i,j)
100   continue
      return
      end
     subroutine afix
     common /gpl/ e(69),ieval(69),fn(6)
     common/gp/esteel,ri(6),area(6),areap(6),rl(6),ra(3),rb(3),g(4),
    *  tablek,tw,ak,am,ngp
     common/transf/ag(14,3),ac(3,14,3)
       ag(7,1)=-1./rl(4)
       ag(8,1)=-1./rl(5)
       ag(9,1)=-1./rl(6)
       dl=1./rl(1)
       ac(1,1,1)=-dl
       ac(2,1,1)=-dl
       ac(1,2,1)=dl
       ac(2,2,1)=dl
       dl=1./rl(2)
       ac(1,2,2)=-dl
       ac(2,2,2)=-dl
       ac(1,3,2)=dl
       ac(2,3,2)=dl
       dl=1./rl(3)
       ac(1,3,3)=-dl
       ac(2,3,3)=-dl
     return
     end
     subroutine dir(b,k,m,level,dk,ks,err,grad,ah,u,dudb,f,ncall
    * ,db,alpha,dj)
     real k,m,ks
     common /wrflg/iwr
     common/gp/esteel,ri(6),area(6),areap(6),rl(6),ra(3),rb(3),gj(4),
    *  tablek,tw,ak,am,ngp
     common /fperr/ perr(39)
     common /reduce/ phi(39,39),dphi(39,39,10)
     common /first/mfix,xm(39,39),xmr(39)
     dimension phitmr(39),dphtmr(39,10)
     common /inpt/ vgc(2),v(39),g(39)
     common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
    *    ,rintt,ndof,np,delt2
    *                 ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
     common /gpl/ e(69),ie(69),fn(6)
     dimension b(1),k(ncall,1),m(ncall,1),dk(ncall,10),
    *   grad(1),ah(ncall,ncall),
    * dudb(6,ncall,1),u(6,1),f(1)
    * ,ks(ncall)
    *   ,tdudb(10),teu(39)
    *   ,db(1),bt(20),temtu(39)
      common /static/ ir(39),idf(39),r(39)
      common /fdiff/ df,ddf
      common /index/ i11,i21,i31,i12,i22,i32
      ifd=0
      da=alpha*ddf
      do 70 i=1,np
      grad(i)=0.0
      do 60 l=1,3
      do 60 ll=1,nxnt
      dudb(l,ll,i)=0.0
   60 continue
      do 70 j=1,np
      ah(i,j)=0.0
   70 continue
   90 call mfind (k,m,dk,ncall,b)
        do 95 i=1,nxnt
        phitmr(i)= 0.0
        do 91 ii=i,np
91      dphtmr(i,ii)=0.0
        do 95 j=1,ndof
        phitmr(i)=phitmr(i)+phi(j,i)*xmr(j)
        do 93 ii=1,np
93      dphtmr(i,ii)=dphtmr(i,ii) + dphi(j,i,ii)*xmr(j)
95      continue
      a1k=1.+a1*ak
      a01m=a0+a1*am
      err=0.0
      ic=0
      rewind 1
      read (1) npts,delt
      read (1) vgc(1),(v(lll),lll=1,nindf)
      if (iwr.eq.0) go to 101
      write (3) npts,delt
      z=0.0
      write (3) (z,lll=1,nindf+1)
101     continue
      do 105 j=1,nxnt
      perr(j)=0.
      ks(j)=1./(k(j,j)*a1k+m(j,j)*a01m)
      do 102 i=1,3
      u(i,j)=0.0
  102 continue
  105 continue
  110 ic=ic+1
      if (ic.ge.npts) go to 205
      k1=1
      k2=mod(ic,2)+1
      if (k2.eq.1) k1=2
      itk1=3*(k1-1)
      itk2=3*(k2-1)
      i11=1+itk1
      i21=i11+1
      i31=i21+1
      i12=1+itk2
```

```
      i22=i12+1
      i32=i22+1
      iover=0
      read (1) vgc(k2),(v(lll),lll=1,nindf)
      ugc =386.1 * (vgc(k1)+theta*(vgc(k2)-vgc(k1)))
      do 115 i=1,nindf
  115 if (abs(v(i)).gt.100.) iover=1
      do 120 i=1,nxnt
      f(i)=-phitmr(i)*ugc
120     continue
      call xnt (k1,k2,f,u,ks,ncall,1,m,k)
      if (iover.eq.1) go to 135
      do 130 i=1,nindf
      idft=idf(i)
      irt=ir(i)
      if (irt.eq.0) go to 130
      is=irt+itk2
      tu=0.0
      do 121 kj=1,nxnt
      tu=tu+phi(idft,kj)*u(is,kj)
  121 continue
      terr=tu-v(i)
      t2=terr*terr*g(i)
      err=err+t2
      teu(i)=terr
      temtu(i)=tu
      perr(i)=perr(i)+t2
  130 continue
        if(iwr.ne.0) write (3) vgc(k2),(temtu(jj),jj=1,nindf)
  135 continue
      do 150 l=1,np
      do 140 i=1,nxnt
        dyp=u(i21,i)+theta*(u(i22,i)-u(i21,i))
        dy=u(i11,i)+theta*(u(i12,i)-u(i11,i))
        if (l.ne.ie(39)) go to 136
        f(i)= -e(39)*dyp
        go to 140
136     if (l.ne.ie(38)) go to 138
        f(i)=-e(38)*k(i,i)*dyp
        go to 140
138     f(i)= -dk(i,l)*(ak*dyp+dy)-dphtmr(i,l)*ugc
  140 continue
      call xnt(k1,k2,f,dudb,ks,ncall,l,m,k)
  150 continue
      if (iover.eq.1) go to 110
      do 203 j=1,nindf
      idft=idf(j)
      irt=ir(j)
      if (irt.eq.0) go to 203
      i1=irt+itk1
      i2=irt+itk2
      do 160 jj=1,np
      tdudb(jj)=0.0
      do 155 kk=1,nxnt
c     tdudb(jj)=tdudb(jj)+phi(idft,kk)*dudb(i1,kk,jj)
        tdudb(jj)=tdudb(jj)+phi(idft,kk)*dudb(i2,kk,jj)+dphi(idft,kk,jj)*
     #  u(i2,kk)
  155 continue
  160 continue
      do 202 ip=1,np
      grad(ip)=grad(ip)+teu(j)*tdudb(ip)*g(j)
      do 200 is=1,ip
      ah(ip,is)=ah(ip,is)+tdudb(ip)*tdudb(is)*g(j)
  200 continue
  202 continue
  203 continue
      go to 110
  205 err=err*delt
      do 206 i=1,nindf
  206 perr(i)=perr(i)*delt
      do 210 i=1,np
      grad(i)=delt2*grad(i)
      do 210 j=1,i
      ah(j,i)=delt2*ah(i,j)
      ah(i,j)=ah(j,i)
  210 continue
      dj=0.0
      do 300 l=1,np
  300 dj=dj-db(l)*grad(l)
      return
      end
        subroutine getck(ck,if)
      common/gp/esteel,ri(6),area(6),areap(6),rl(6),ra(3),rb(3),g(4),
     *  tablek,tw,ak,am,ngp
        dimension ck(3,3)
        trl=rl(if)
        beta=15.6*ri(if)/(trl*trl*areap(if))
        pk=esteel*2.*ri(if)/(trl*(1.+2.*beta))
        ck(1,1)=pk*(2.+beta)
        ck(1,2)=pk*(1.-beta)
        ck(1,3)=0.0
        ck(2,1)=ck(1,2)
        ck(2,2)=ck(1,1)
        ck(2,3)=0.0
        ck(3,1)=0.0
        ck(3,2)=0.0
        ck(3,3)=area(if)*esteel/trl
        return
        end
      program iden
      common /first/mfix,xm(39,39),xmr(39)
      common /ib/ibdof
      common /static/ ir(39),idf(39),r(39)
      common /gpl/ e(69),ie(69),fn(6)
      common/gp/esteel,ri(6),area(6),areap(6),rl(6),ra(3),rb(3),rg(4),
     *  tablek,tw,ak,am,ngp
      dimension b(10),k(39,39),m(39,39),dk(39,10) ,ks(39),grad(39),
     *   ah(39,39),u(6,39),dudb(6,39,10),f(39),db(39),bn(39)
```

```fortran
      common /fperr/ perr(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                  ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      common /inpt/ vgc(2),v(39),      g(39)
      common /wrflg/iwr
      real k,m,ks
      common /fdiff/ df,ddf
      character *3 bound,yes,no
      data l/0/,yes/3hyes/,no/2hno/
      open (1,file='data/dyn',form="unformatted")
      open (2,file='temp')
      rewind 1
      read (1) npts,delt
      rewind 1
      rewind 2
c     initialize integration parameters
      call init
      read (*,*)np,ndof,nindf,nxnt,ngp,iwr
      if (iwr.eq.0) go to 9
      open (3,file='idenout',form="unformatted")
      rewind 3
9       continue
      ibdof=ndof
      if (nxnt.eq.0) nxnt=ndof
      write (*,1004)
      write (*,2001) np,ndof,nindf,nxnt,ngp
2001    format (" number of parameters ",t32,
     # i10/" model degree of freedom",t32,
     # i10/" input degrees of freedom ",t32,
     # i10/" integration degrees of freedom",t32,
     # i10/" number of global properties ",t32,i10)
  996 format (8i10)
 1000 format (5i10)
 1002 format (8f10.0)
  999 format (f10.0,3i10)
   10 read (*,*)te,ite,igps,igpe
      do 20 i=igps,igpe
      e(i)=te
      ie(i)=ite
   20 continue
      if (igpe.lt.ngp) go to 10
      write (*,2002)
      do 30 i=1,ngp
30      write (*,2003) i,ie(i),e(i)
2002    format (////"global parameter definitions"//
     1  5x,"global      mode     factor")
2003    format (1x,2i10,1x,e9.3)
        read (*,*) nfn
        if (nfn.le.0) go to 34
        write (*,2014)
2014    format (////" normal forces"//10x,"i",5x,"fn(i)")
        read (*,*) (fn(i),i=1,nfn)
        do 32 i=1,nfn
32        write (*,2005) i,fn(i)
34        continue
      read (*,*)ndel
      if (ndel.le.0) go to 35
      read (*,*) (idel(i),i=1,ndel)
35      continue
      read (*,*) ncndns
      if (ncndns.gt.0) read (*,*) (icndns(i),i=1,ncndns)
        mfix=0
      iusefd=0
      ncall=39
      read (*,*) (r(i),i=1,ndof)
      write (*,2004)
      do 40 i=1,ndof
40      write (*,2005) i,r(i)
2004    format (////" pseudo-static coefficients"//7x,"dof",5x,"coeff")
2005    format (1x,i10,1x,e9.3)
      numit=0
      write (*,2006)
2006    format (////" input list"//8x,"dof  response  factor")
      do 50 i=1,nindf
      read (*,*) ir(i),idf(i),g(i)
50      write (*,2003) idf(i),ir(i),g(i)
      bound=no
      preerr=1e10
 1004 format (" LINEAR DYNAMIC IDENTIFICATION PROGRAM"/" WRITTEN BY "/
     #   "JERRY DIMSDALE ON OR ABOUT 6/81"///)
  100 l=l+1
      read (*,*) slmin,it,endtol,ddf
    3 format(f10.0,i10,2f10.0)
c        input initial estimates
      read (*,*,end=170) (b(i),i=1,np)
        go to 180
 1001 format (8f10.0)
  170 read (2,3001) (b(i),i=1,np)
        rewind 2
  180 if (abs(ddf).gt.1.e-10) iusefd=1
        write (*,2011)
        do 185 i=1,np
185     write (*,2012) i,b(i)
2011    format (////" initial parameter estimates"//9x,"np",7x,"estimate")
2012    format (1x,i10,1x,e14.7)
      df=1.0+ddf
        call did
  190 numit=numit+1
      level=3
      call dir(b ,k,m,level,dk,ks,err,grad,ah,u,dudb,f,ncall,db,0.0,dj)
  945 format (1x,"step ",i2//6x,"np",5x,"parameter",5x,
     +    "gradient",8x,"direction")
  946 format (6x,i2,4x,e12.6,4x,e12.6,4x,e12.6)
 1005 format (9x,"interpolation:"//20x,"first point",
     +    19x,"second point"/14x,24(1h-),6x,24(1h-),7x,"inter-"/
     +    74x,"polated  boundary"/11x,2(5x,"alpha",5x,"error",5x,"slope")
     +    ,5x,"alpha   reached"/)
```

```
      intr=0
c      if(err.gt.preerr) go to 9006
      if (abs(err-preerr).le.endtol) go to 600
      erra=err
      preerr=err
  200 do 210 l=1,np
  210 db(l)=grad(l)
        call mprint(ah,np,np,ncall,'ah')
      call symsol(ah,db,np  ,1,0,ncall)
      print 945,numit
      do 215 i=1,np
      print 946,i,b(i),grad(i),db(i)
215   continue
      alphaa=0.0
      dja=0.0
      do 220 l=1,np
      bn(l)=b(l)
      dja=dja-db(l)*grad(l)
  220 continue
      if(numit.gt.it) go to 700
      print 1005
      alphab=1.0
      call check(b,bn,db,alphab,alphab,okb)
      call dir(bn,k,m,level,dk,ks,errb,grad,ah,u,dudb,f,ncall,db,alphab
     *    ,djb)
  226 if (abs(djb).lt.slmin) go to 450
      intr=intr+1
      if (djb) 300,450,227
  227 alphan=cubic(erra,dja,errb,djb,alphaa,alphab)
      if ((okb.lt.1.0).and.(intr.eq.1)) bound=yes
      print 6,alphaa,erra,dja,alphab,errb,djb,alphan,bound
      bound=no
    6 format (11x,7e10.3,7x,a3)
      do 230 l=1,np
  230 bn(l)=b(l)-alphan*db(l)
      call dir (bn,k,m,level,dk,ks,errn,grad,ah,u,dudb,f,ncall,db,
     *    alphan,djn      )
      if (abs(djn).lt.slmin) go to 455
      if (djn) 240,455,245
  240 erra=errn
      dja=djn
      alphaa=alphan
      go to 400
  245 errb=errn
      djb=djn
      alphab=alphan
      go to 400
  300 if (errb.gt.erra) go to 227
      alphan=sq(erra,dja,errb,djb,alphaa,alphab)
      call check(b,bn,db,alphan,alphab,okn)
      if (okn.lt.1.0) bound=yes
      print 6 ,alphaa,erra,dja,alphab,errb,djb,alphan,bound
      bound=no
      call dir(bn,k,m,level,dk,ks,errn,grad,ah,u,dudb,f,ncall
     * ,db,alphan,djn)
      if (abs(djn).lt.slmin) go to 455
      if (djn) 320,455,245
  320 if (errn.le.errb) go to 245
      erra=errb
      alphaa=alphab
      dja=djb
      go to 245
  400 if (intr.lt.5) go to 226
      go to 455
  450 continue
      if (errb.gt.erra) go to 227
      err=errb
      alphan=alphab
      print 6,alphaa,erra,dja,alphab,errb,djb,alphan,bound
      go to 460
  455 err=errn
  460 do 465 l=1,np
  465 b(l)=bn(l)
      bound=no
      go to 190
 9006 print 2007
 2007 format (" increasing error")
  700 print 3000,dja,erra
 3000 format (1h0,"final slope:",g12.6/" final error:",g12.6)
3001  format (1x,8e15.7)
  600 write (2,3001) (b(i),i=1,np)
        write (*,"('final parameters: ')")
        write (*,*) (b(i),i=1,np)
      stop
      end
      subroutine init
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                    ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      common/transf/ag(14,3),ac(3,14,3)
      read (*,*) delta,alpha,theta
 1000 format (4f10.0)
      tau=theta*delt
      a2=1.0/(alpha*tau)
      a0=a2/tau
      a1=a2*delta
      a3=.5/alpha-1.0
      a4=delta/alpha-1.0
      a5=.5*tau*(a4-1.0)
      a6=delt*(1.0-delta)
      delt2=2.0*delt
      a7=delt*delta
      dtt=delt*delt
      a9=alpha*dtt
      a8=.5*dtt-a9
      rint=theta-float(ifix(theta))
      rintt=1.0-rint
      do 100 i=1,3
```

```
      do 100 j=1,14
      ag(j,i)=0.0
      do 100 kk=1,3
      ac(kk,j,i)=0.0
100     continue
        ag(4,1)=1.
        ag(10,1)=1.
        ag(5,2)=1.
        ag(11,2)=1.
        ag(6,3)=1.
        ag(12,3)=1.
      ac(1,4,1)=1.
      ac(2,5,1)=1.
      ac(3,7,1)=1.
      ac(3,8,1)=-1.
      ac(1,5,2)=1.
      ac(2,6,2)=1.
      ac(3,8,2)=1.
      ac(3,9,2)=-1.
      ac(1,6,3)=1.
      ac(2,13,3)=1.
      ac(2,14,3)=1.
      ac(3,9,3)=1.
      ac(3,14,3)=-72.
      return
      end
      subroutine mass (bm,rl,n,hm)
      dimension hm(n,n)
      rrl=rl*rl
      b=(bm/420.)*rl
      brrl=b*rrl
      brl=b*rl
      tm=4.*brrl
      hm(1,1)=tm
      hm(2,2)=tm
      hm(2,1)=-3.*brrl
      hm(3,1)=-22.*brl
      hm(3,2)=13.*brl
      hm(3,3)=156.*b
      if (n.eq.3) return
      hm(4,1)=-hm(3,2)
      hm(4,2)=-hm(3,1)
      hm(4,3)=54.*b
      hm(4,4)=156.*b
      return
      end
      subroutine mck(k,m,ncall,b)
      common /static/ ir(39),idf(39),r(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                      ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      dimension b(10),ck(3,3)
      dimension tt(39,39)
      real k(ncall,1),m(ncall,1)
      common/gp/esteel,ri(6),area(6),areap(6),rl(6),ra(3),rb(3),g(4),
     *  tablek,tw,ak,am,ngp
      common /gpl/ e(69),ieval(69),fn(6)
      dimension gpe(69)
      common/transf/ag(14,3),ac(3,14,3)
      common /first/ mfix,xm(39,39),xmr(39)
      common /reduce/ phi(39,39),dphi(39,39,10)
      equivalence (gpe(1),esteel)
      icm=1
      if (mfix.eq.0) icm=2
      mfix = 1
      do 20 i=1,ncall
      do 20 j=1,ncall
      k(i,j)=0.0
      if (icm.eq.2) m(i,j)=0.0
   20 continue
      do 100 l=1,ngp
      ie=iabs(ieval(l))
      if (ieval(l)) 40,50,60
   40 gpe(l)=gpe(ie)
      go to 100
   50 gpe(l)=e(l)
      go to 100
   60 gpe(l)=e(l)*b(ie)
  100 continue
      call afix
      do 500 if=1,3
      call getck(ck,if)
      call mconj(ck,ac(1,1,if),tt,3,14,ncall,3,3)
      call addk(k,tt,14,ncall)
      ifg=if+3
      beta=3.9*ri(ifg)/(areap(ifg)*rl(ifg)*rl(ifg))
      gk=esteel*3.*ri(ifg)/(rl(ifg)*(1.+2.*beta))
      call mconj(gk,ag(1,if),tt,1,14,ncall,1,1)
      call addk(k,tt,14,ncall)
500     continue
        do 600 if=1,4
        kk=if+9
        k(kk,kk)=k(kk,kk)+g(if)*tw*32.967
600     continue
        k(14,14)=k(14,14)+5184.*tablek
        call delet(k,ncall)
        if (icm.eq.1) return
        m(1,1)=.00602
        m(2,2)=.00604
        m(3,3)=.00611
        m(14,14)=311.
        call delet(m,ncall)
        do 700 i=1,ndof
        xmr(i)=0.0
        do 700 j=1,ndof
        xmr(i)=xmr(i)+m(i,j)*r(j)
700     xm(i,j) = m(i,j)
        return
        end
```

```
c ********************************************** ROUTINES FOR SIX STORY FRAME
c
c
      subroutine afix
      common /gpl/ e(69),ieval(69),fn(6)
      common /gp/ rev(6),reh(6),rej(7),riv(6),rih(6),rijx(7),rijz(7),
     *   rlv(6),rlh(6),rgj(7),rb,rh,barm,ak,am
      common /transf/ av(4,8),ah(3,6),nv,nh,istv,isth,idisp(8)
      do 100 i=1,4
      do 100 j=1,8
100     av(i,j)=0.0
        do 110 i=1,3
        do 110 j=1,6
110     ah(i,j)=0.0
      av(1,2)=1.0
      av(2,6)=1.0
      av(3,1)=1.0
      av(4,5)=1.0
      ah(1,2)=1.0
      ah(2,6)=1.0
      av(1,3)=-.5
      av(1,4)=-.5
      av(2,7)=-.5
      ah(1,4)=-.5
      av(2,8)=.5
      ah(1,3)=.5
      rh2=rh/2.
      rh4=rh/4.
      rb2=rb/2.
      rb4=rb/4.
      av(3,2)=-rh2
      av(3,3)=-rh4
      av(4,6)=rh2
      av(4,7)=rh4
      ah(3,2)=-rb2
      ah(3,3)=rb4
      return
      end
        subroutine diff(a,b,n)
        dimension a(n,n),b(n,n)
        e = 0.0
        do 100 i=1,n
        do 100 j=1,n
        d =  abs(a(i,j)-b(i,j))
        if (d.gt. .00001) write (*,*)i,j
        e = e + d
100     continue
        write (*,*) e
        return
        end
      subroutine dir(b,k,m,level,dk,ks,err,grad,ah,u,dudb,f,ncall
     * ,db,alpha,dj)
      real k,m,ks
      common /wrflg/iwr
```

```
      common /gp/ rev(6),reh(6),rej(7),riv(6),rih(6),rijx(7),rijz(7),
     *   rlv(6),rlh(6),rgj(7),rb,rh,barm,ak,am
      common /fperr/ perr(39)
      common /reduce/ phi(39,39),dphi(39,39,10)
      common /first/mfix,xm(39,39),xmr(39)
      dimension phitmr(39),dphtmr(39,10)
      common /inpt/ vgc(2),v(39),g(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                     ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      common /gpl/ e(69),ie(69),fn(6)
      dimension b(1),k(ncall,1),m(ncall,1),dk(ncall,10),
     *   grad(1),ah(ncall,ncall),
     * dudb(6,ncall,1),u(6,1),f(1)
     * ,ks(ncall)
     *   ,tdudb(10),teu(39)
     *   ,db(1),temtu(39)
      common /static/ ir(39),idf(39),r(39)
      common /fdiff/ df,ddf
      common /index/ i11,i21,i31,i12,i22,i32
      ifd=0
      da=alpha*ddf
      do 70 i=1,np
      grad(i)=0.0
      do 60 l=1,3
      do 60 ll=1,nxnt
      dudb(l,ll,i)=0.0
60    continue
      do 70 j=1,np
      ah(i,j)=0.0
70    continue
90    call mfind (k,m,dk,ncall,b)
        do 95 i=1,nxnt
        phitmr(i)= 0.0
        do 91 ii=i,np
91      dphtmr(i,ii)=0.0
        do 95 j=1,ndof
        phitmr(i)=phitmr(i)+phi(j,i)*xmr(j)
        do 93 ii=1,np
93      dphtmr(i,ii)=dphtmr(i,ii) + dphi(j,i,ii)*xmr(j)
95      continue
      a1k=1.+a1*ak
      a01m=a0+a1*am
      err=0.0
      ic=0
      rewind 1
      read (1) npts,delt
      read (1) vgc(1),(v(lll),lll=1,nindf)
      if (iwr.eq.0) go to 101
      write (3) npts,delt
      z=0.0
      write (3) (z,lll=1,nindf+1)
101     continue
      do 105 j=1,nxnt
```

```
      perr(j)=0.
      ks(j)=1./(k(j,j)*a1k+m(j,j)*a01m)
      do 102 i=1,3
      u(i,j)=0.0
  102 continue
  105 continue
  110 ic=ic+1
      if (ic.ge.npts) go to 205
      k1=1
      k2=mod(ic,2)+1
      if (k2.eq.1) k1=2
      itk1=3*(k1-1)
      itk2=3*(k2-1)
      i11=1+itk1
      i21=i11+1
      i31=i21+1
      i12=1+itk2
      i22=i12+1
      i32=i22+1
      iover=0
      read (1) vgc(k2),(v(lll),lll=1,nindf)
      ugc =386.1 * (vgc(k1)+theta*(vgc(k2)-vgc(k1)))
      do 115 i=1,nindf
  115 if (abs(v(i)).gt.500.) iover=1
      do 120 i=1,nxnt
      f(i)=-phitmr(i)*ugc
120     continue
      call xnt (k1,k2,f,u,ks,ncall,1,m,k)
      if ((iover.eq.1).and.(iwr.eq.0)) go to 135
      do 130 i=1,nindf
      idft=idf(i)
      irt=ir(i)
      if (irt.eq.0) go to 130
      is=irt+itk2
      tu=0.0
      do 121 kj=1,nxnt
      tu=tu+phi(idft,kj)*u(is,kj)
  121 continue
      temtu(i)=tu
      if (iover.eq.1) go to 130
      terr=tu-v(i)
      t2=terr*terr*g(i)
      err=err+t2
      teu(i)=terr
      perr(i)=perr(i)+t2
  130 continue
        if(iwr.ne.0) write (3) vgc(k2),(temtu(jj),jj=1,nindf)
  135 continue
      do 150 l=1,np
      do 140 i=1,nxnt
        dyp=u(i21,i)+theta*(u(i22,i)-u(i21,i))
        dy=u(i11,i)+theta*(u(i12,i)-u(i11,i))
        if (l.ne.ie(69)) go to 136
        f(i)= -e(69)*dyp
        go to 140
136     if (l.ne.ie(68)) go to 138
        f(i)=-e(68)*k(i,i)*dyp
        go to 140
138     f(i)= -dk(i,l)*(ak*dyp+dy)-dphtmr(i,l)*ugc
  140 continue
      call xnt(k1,k2,f,dudb,ks,ncall,1,m,k)
  150 continue
      if (iover.eq.1) go to 110
      do 203 j=1,nindf
      idft=idf(j)
      irt=ir(j)
      if (irt.eq.0) go to 203
      i1=irt+itk1
      i2=irt+itk2
      do 160 jj=1,np
      tdudb(jj)=0.0
      do 155 kk=1,nxnt
c     tdudb(jj)=tdudb(jj)+phi(idft,kk)*dudb(i1,kk,jj)
        tdudb(jj)=tdudb(jj)+phi(idft,kk)*dudb(i2,kk,jj)+dphi(idft,kk,jj)*
     #  u(i2,kk)
  155 continue
  160 continue
      do 202 ip=1,np
      grad(ip)=grad(ip)+teu(j)*tdudb(ip)*g(j)
      do 200 is=1,ip
      ah(ip,is)=ah(ip,is)+tdudb(ip)*tdudb(is)*g(j)
  200 continue
  202 continue
  203 continue
      go to 110
  205 err=err*delt
      do 206 i=1,nindf
  206 perr(i)=perr(i)*delt
      do 210 i=1,np
      grad(i)=delt2*grad(i)
      do 210 j=1,i
      ah(j,i)=delt2*ah(i,j)
      ah(i,j)=ah(j,i)
  210 continue
      dj=0.0
      do 300 l=1,np
  300 dj=dj-db(l)*grad(l)
      return
      end

      program iden
      common /first/mfix,xm(39,39),xmr(39)
      common /ib/ibdof
      common /static/ ir(39),idf(39),r(39)
      common /gpl/ e(69),ie(69),fn(6)
      dimension b(10),k(39,39),m(39,39),dk(39,10) ,ks(39),grad(39),
     *   ah(39,39),u(6,39),dudb(6,39,10),f(39),db(39),bn(39)
      common /gp/ rev(6),reh(6),rej(7),riv(6),rih(6),rijx(7),rijz(7),
```

```
     *   rlv(6),rlh(6),rgj(7),rb,rh,barm,ak,am
      common /fperr/ perr(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                       ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      common /inpt/ vgc(2),v(39),       g(39)
      common /wrflg/iwr
      real k,m,ks
      common /fdiff/ df,ddf
      character *3 bound,yes,no
      data l/0/,yes/3hyes/,no/2hno/
      open (1,file='data/dyn',form="unformatted")
      open (2,file='temp')
      rewind 1
      read (1) npts,delt
      rewind 1
      rewind 2
c     initialize integration parameters
      call init
      read (*,*)np,ndof,nindf,nxnt,ngp,iwr
      if (iwr.eq.0) go to 9
      open (3,file='idenout',form="unformatted")
      rewind 3
9       continue
      ibdof=ndof
      if (nxnt.eq.0) nxnt=ndof
      write (*,1004)
      write (*,2001) np,ndof,nindf,nxnt,ngp
2001    format (" number of parameters ",t32,
     #  i10/" model degree of freedom",t32,
     #  i10/" input degrees of freedom ",t32,
     #  i10/" integration degrees of freedom",t32,
     #  i10/" number of global properties ",t32,i10)
  996 format (8i10)
 1000 format (5i10)
 1002 format (8f10.0)
  999 format (f10.0,3i10)
   10 read (*,*)te,ite,igps,igpe
      do 20 i=igps,igpe
      e(i)=te
      ie(i)=ite
   20 continue
      if (igpe.lt.ngp) go to 10
      write (*,2002)
      do 30 i=1,ngp
30      write (*,2003) i,ie(i),e(i)
2002    format (////"global parameter definitions"//
     1  5x,"global      mode     factor")
2003    format (1x,2i10,1x,e9.3)
        read (*,*) nfn
        if (nfn.le.0) go to 34
        write (*,2014)
2014    format (////" normal forces"//10x,"i",5x,"fn(i)")
        read (*,*) (fn(i),i=1,nfn)
```

```
        do 32 i=1,nfn
32      write (*,2005) i,fn(i)
34      continue
      read (*,*)ndel
      if (ndel.le.0) go to 35
      read (*,*) (idel(i),i=1,ndel)
35      continue
      read (*,*) ncndns
      if (ncndns.gt.0) read (*,*) (icndns(i),i=1,ncndns)
        mfix=0
      iusefd=0
      ncall=39
      read (*,*) (r(i),i=1,ndof)
      write (*,2004)
      do 40 i=1,ndof
40      write (*,2005) i,r(i)
2004    format (////" pseudo-static coefficients"//7x,"dof",5x,"coeff")
2005    format (1x,i10,1x,e9.3)
      numit=0
      write (*,2006)
2006    format (////" input list"//8x,"dof  response  factor")
      do 50 i=1,nindf
      read (*,*) ir(i),idf(i),g(i)
50      write (*,2003) idf(i),ir(i),g(i)
      bound=no
      preerr=1e10
 1004 format (" LINEAR DYNAMIC IDENTIFICATION PROGRAM"/" WRITTEN BY "/
     #   "JERRY DIMSDALE ON OR ABOUT 6/81"///)
  100 l=l+1
      read (*,*) slmin,it,endtol,ddf
    3 format(f10.0,i10,2f10.0)
c          input initial estimates
      read (*,*,end=170) (b(i),i=1,np)
        go to 180
 1001 format (8f10.0)
  170 read (2,*) (b(i),i=1,np)
        rewind 2
  180 if (abs(ddf).gt.1.e-10) iusefd=1
        write (*,2011)
        do 185 i=1,np
185     write (*,2012) i,b(i)
2011    format (////" initial parameter estimates"//9x,"np",7x,"estimate")
2012    format (1x,i10,1x,e14.7)
      df=1.0+ddf
        call did
  190 numit=numit+1
      level=3
      call dir(b ,k,m,level,dk,ks,err,grad,ah,u,dudb,f,ncall,db,0.0,dj)
  945 format (1x,"step ",i2//6x,"np",5x,"parameter",5x,
     +   "gradient",8x,"direction")
  946 format (6x,i2,4x,e12.6,4x,e12.6,4x,e12.6)
 1005 format (9x,"interpolation:"//20x,"first point",
     +    19x,"second point"/14x,24(1h-),6x,24(1h-),7x,"inter-"/
     +    74x,"polated  boundary"/11x,2(5x,"alpha",5x,"error",5x,"slope")
```

```
     +    ,5x,"alpha    reached"/)
      intr=0
c      if(err.gt.preerr) go to 9006
      if (abs(err-preerr).le.endtol) go to 600
      erra=err
      preerr=err
  200 do 210 l=1,np
  210 db(l)=grad(l)
        call mprint(ah,np,np,ncall,'ah')
      call symsol(ah,db,np  ,1,0,ncall)
      print 945,numit
      do 215 i=1,np
      print 946,i,b(i),grad(i),db(i)
215   continue
      alphaa=0.0
      dja=0.0
      do 220 l=1,np
      bn(l)=b(l)
      dja=dja-db(l)*grad(l)
  220 continue
      if(numit.gt.it) go to 700
      print 1005
      alphab=1.0
      call check(b,bn,db,alphab,alphab,okb)
      call dir(bn,k,m,level,dk,ks,errb,grad,ah,u,dudb,f,ncall,db,alphab
     *    ,djb)
  226 if (abs(djb).lt.slmin) go to 450
      intr=intr+1
      if (djb) 300,450,227
  227 alphan=cubic(erra,dja,errb,djb,alphaa,alphab)
      if ((okb.lt.1.0).and.(intr.eq.1)) bound=yes
      print 6,alphaa,erra,dja,alphab,errb,djb,alphan,bound
      bound=no
    6 format (11x,7e10.3,7x,a3)
      do 230 l=1,np
  230 bn(l)=b(l)-alphan*db(l)
      call dir (bn,k,m,level,dk,ks,errn,grad,ah,u,dudb,f,ncall,db,
     *    alphan,djn      )
      if (abs(djn).lt.slmin) go to 455
      if (djn) 240,455,245
  240 erra=errn
      dja=djn
      alphaa=alphan
      go to 400
  245 errb=errn
      djb=djn
      alphab=alphan
      go to 400
  300 if (errb.gt.erra) go to 227
      alphan=sq(erra,dja,errb,djb,alphaa,alphab)
      call check(b,bn,db,alphan,alphab,okn)
      if (okn.lt.1.0) bound=yes
      print 6 ,alphaa,erra,dja,alphab,errb,djb,alphan,bound
      bound=no
      call dir(bn,k,m,level,dk,ks,errn,grad,ah,u,dudb,f,ncall
     * ,db,alphan,djn)
      if (abs(djn).lt.slmin) go to 455
      if (djn) 320,455,245
  320 if (errn.le.errb) go to 245
      erra=errb
      alphaa=alphab
      dja=djb
      go to 245
  400 if (intr.lt.3) go to 226
      go to 455
  450 continue
      if (errb.gt.erra) go to 227
      err=errb
      alphan=alphab
      print 6,alphaa,erra,dja,alphab,errb,djb,alphan,bound
      go to 460
  455 err=errn
  460 do 465 l=1,np
  465 b(l)=bn(l)
      bound=no
      go to 190
 9006 print 2007
 2007 format (" increasing error")
  700 print 3000,dja,erra
 3000 format (1h0,"final slope:",g12.6/" final error:",g12.6)
3001  format (1x,8e15.7)
  600 write (2,3001) (b(i),i=1,np)
        write (*,"('final parameters: ')")
        write (*,*) (b(i),i=1,np)
      stop
      end
      subroutine init
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                      ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      common /transf/ av(4,8),ah(3,6),nv,nh,istv,isth,idisp(8)
      read 1000,delta,alpha,theta
 1000 format (4f10.0)
      tau=theta*delt
      a2=1.0/(alpha*tau)
      a0=a2/tau
      a1=a2*delta
      a3=.5/alpha-1.0
      a4=delta/alpha-1.0
      a5=.5*tau*(a4-1.0)
      a6=delt*(1.0-delta)
      delt2=2.0*delt
      a7=delt*delta
      dtt=delt*delt
      a9=alpha*dtt
      a8=.5*dtt-a9
      rint=theta-float(ifix(theta))
      rintt=1.0-rint
```

```
      idisp(1)=0
      idisp(2)=1
      idisp(3)=2
      idisp(4)=4
      idisp(5)=6
      idisp(6)=7
      idisp(7)=8
      idisp(8)=10
      return
      end
      function kpt(j,id,ist)
      common /transf/ av(4,8),ah(3,6),nv,nh,istv,isth,idisp(8)
      kpt=ist+idisp(j)
      if (id.ne.1) return
      if (j.lt.5) kpt=kpt+1
      return
      end
      subroutine mass (bm,rl,n,hm)
      dimension hm(n,n)
      rrl=rl*rl
      b=(bm/420.)*rl
      brrl=b*rrl
      brl=b*rl
      tm=4.*brrl
      hm(1,1)=tm
      hm(2,2)=tm
      hm(2,1)=-3.*brrl
      hm(3,1)=-22.*brl
      hm(3,2)=13.*brl
      hm(3,3)=156.*b
      if (n.eq.3) return
      hm(4,1)=-hm(3,2)
      hm(4,2)=-hm(3,1)
      hm(4,3)=54.*b
      hm(4,4)=156.*b
      return
      end
      subroutine mck(k,m,ncall,b)
      common /static/ ir(39),idf(39),r(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                    ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      dimension b(10),vm(4,4,2),hm(3,3,2)
      dimension tt(39,39)
      real k(ncall,1),m(ncall,1)
      common /gp/ rev(6),reh(6),rej(7),riv(6),rih(6),rijx(7),rijz(7),
     *   rlv(6),rlh(6),rgj(7),rb,rh,barm,ak,am
      common /gpl/ e(69),ieval(69),fn(6)
      common /transf/ av(4,8),ah(3,6),nv,nh,istv,isth,idisp(8)
      dimension gpe(69)
      common /first/ mfix,xm(39,39),xmr(39)
      common /reduce/ phi(39,39),dphi(39,39,10)
      equivalence (gpe(1),rev(1))
      icm=1
      if (mfix.eq.0) icm=2
      mfix = 1
      do 20 i=1,ncall
      do 20 j=1,ncall
      k(i,j)=0.0
      if (icm.eq.2) m(i,j)=0.0
   20 continue
      do 100 l=1,69
      ie=iabs(ieval(l))
      if (ieval(l)) 40,50,60
   40 gpe(l)=gpe(ie)
      go to 100
   50 gpe(l)=e(l)
      go to 100
   60 gpe(l)=e(l)*b(ie)
  100 continue
      call afix
      do 500 if=1,6
c   calculate vertical member stiffness vm(i,j,1)
      pl=rlv(if)
      ppl=pl*pl
      pppl=pl*ppl
      avk=2.*rev(if)*riv(if)/pppl
      avkg=fn(if)/(30.*pl)
      tk=(avk*2.-avkg*4.)*ppl
      vm(1,1,1)=tk
      vm(2,2,1)=tk
      vm(2,1,1)=(avk+avkg)*ppl
      tk=(avk-avkg)*3.*pl
      vm(3,1,1)=-tk
      vm(4,1,1)=tk
      vm(3,2,1)=-tk
      vm(4,2,1)=tk
      tk=avk*6.-avkg*36.
      vm(3,3,1)=tk
      vm(4,3,1)=-tk
      vm(4,4,1)=tk
c   calculate horizontal stiffness hm(i,j,1)
      pl=rlh(if)
      ppl=pl*pl
      pppl=pl*ppl
      avk=2.*reh(if)*rih(if)/pppl
      tk=avk*2.*ppl
      hm(1,1,1)=tk
      hm(2,2,1)=tk
      hm(2,1,1)=tk/2.
      tk=avk*3.*pl
      hm(3,1,1)=-tk
      hm(3,2,1)=-tk
      hm(3,3,1)=6.*avk
      if (icm.eq.1) go to 102
c   calculate vertical mass
        tbm=barm*8.0
        bmv=tbm*rb
```

```
      bmh=tbm*rh
      call mass (bmv,rlv(if),4,vm(1,1,2))
c   calculate horizontal mass
      call mass (bmh,rlh(if),3,hm(1,1,2))
  102 do 106 ii=1,icm
      do 103 kk=2,4
      kk1=kk-1
      do 103 jj=1,kk1
  103 vm(jj,kk,ii)=vm(kk,jj,ii)
      do 104 kk=2,3
      kk1=kk-1
      do 104 jj=1,kk1
  104 hm(jj,kk,ii)=hm(kk,jj,ii)
  106 continue
  110 continue
115     do 200 kk=1,icm
      call mconj(vm(1,1,kk),av,tt,4,8,ncall,4,4)
      ist=4+6*(if-2)
      do 130 i=1,8
      ii=kpt(i,if,ist)
      if (ii.lt.1) go to 130
      do 130 j=1,8
      jj=kpt(j,if,ist)
      if (jj.lt.1) go to 130
      if (kk.eq.1) go to 120
      m(ii,jj)=m(ii,jj)+tt(i,j)
      go to 130
  120 k(ii,jj)=k(ii,jj)+tt(i,j)
  130 continue
      call mconj (hm(1,1,kk),ah,tt,3,6,ncall,3,3)
      ist=4+6*(if-1)
c  add in translational mass
      if (kk.lt.2) go to 132
      m(ist,ist)=m(ist,ist)+8.*rh*(rlh(if)+rb)*barm
  132 do 140 i=1,6
      ii=i+ist-1
      do 140 j=1,6
      jj=j+ist-1
      if (kk.eq.1) go to 135
      m(ii,jj)=m(ii,jj)+tt(i,j)
      go to 140
  135 k(ii,jj)=k(ii,jj)+tt(i,j)
  140   continue
        if (kk.eq.2) go to 200
      i1=if+1
      ist=ist+2
      k(ist,ist)=k(ist,ist)+rgj(i1)*rb*rh*8.
      ist=ist+1
      k(ist,ist)=k(ist,ist)+rej(i1)*rijx(i1)/rb
      ist=ist+1
      k(ist,ist)=k(ist,ist)+rej(i1)*rijz(i1)/rh
  200 continue
  500 continue
      k(1,1)=k(1,1)+rgj(1)*rb*rh*8.
      k(2,2)=k(2,2)+rej(1)*rijx(1)/rb
      k(3,3)=k(3,3)+rej(1)*rijz(1)/rh
      if (icm.eq.1)  go to 600
      call delet(m,ncall)
      do 550 i=1,ndof
      xmr(i)=0.0
      do 550 j=1,ndof
      xmr(i)=xmr(i)+m(i,j)*r(j)
  550   xm(i,j)=m(i,j)
  600   continue
      call delet(k,ncall)
      return
      end
```

```
c *********************************
c
c
      subroutine check(b,bn,db,alpha,alphab,ok)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                       ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      dimension b(1),db(1),bn(1)
      ok=1.0
      almax=alpha
      do 50 l=1,np
      a = b(l)/db(l)
      if((almax.gt.a).and.(a.gt.0.0)) almax=a
50      continue
        if (alpha.le.almax) go to 60
        ok=0.0
        alpha=.5*almax
        if (alphab.le.almax) alpha = .5*(almax+alphab)
60      continue
      do 100 l=1,np
 100  bn(l)=b(l)        -alpha*db(l)
      return
      end
      function cubic(y1,d1,y2,d2,x1,x2)
      equivalence (a,coeff(1)),(b,coeff(2)),(c,coeff(3))
      dimension t(4,4),coeff(4),id4(4)
      t(1,4)=1.0
      t(2,3)=1.0
      t(2,4)=0.0
      t(3,4)=1.0
      t(4,3)=1.0
      t(4,4)=0.0
      do 100 k=2,4
      km=5-k
      t(1,km)=x1*t(1,km+1)
      t(3,km)=x2*t(3,km+1)
  100 continue
      coeff(1)=y1
      coeff(2)=d1
      coeff(3)=y2
      coeff(4)=d2
      t(2,1)=3.0*x1*x1
      t(2,2)=2.0*x1
      t(4,1)=3.0*x2*x2
      t(4,2)=2.0*x2
      call solveq(t,coeff,4,1,4,id4)
      if (abs(a).lt.1.0e-10) go to 1000
      disc=b*b-3.0*a*c
      if (disc.lt.0.0) go to 1060
      disc=sqrt(disc)
      ta=3.0*a
      amin1=(disc-b)/ta
      amin2=(-disc-b)/ta
      cubic=amin1
      test=6.0*a*amin2+2.0*b
  150 if(test.gt.0.0) cubic=amin2
      return
 1000 if (abs(b).lt.1.0e-10) go to 1050
      amin2=-c/(2.0*b)
      cubic=x2
      test=2.0*b
      go to 150
 1050 print 5
    5 format (* cubic interpolation appears constant*)
 1060 cubic=x2
      return
      end
      subroutine delet(rm,ncall)
      common /ib/ibdof
      dimension rm(ncall,ncall)
      common /static/ir(39),idf(39),r(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                       ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      ndof=ibdof
      if (ndel.eq.0) return
      ii=ndel+1
      do 400 i=1,ndel
      ii=ii-1
      idi=idel(ii)
      ndof=ndof-1
      if (idi.eq.ndof) go to 400
c xxxxxxxx delete matrix elements xxxxxxxxxxxxxxxxxxxxxx
      do 300 j=idi,ndof
      idi1=idi-1
      do 280 jj=1,idi1
  280 rm(jj,j)=rm(jj,j+1)
      do 290 jj=j,ndof
  290 rm(j,jj)=rm(j+1,jj+1)
  300 continue
  400 continue
      do 500 j=1,ndof
c  fill in lower triangle
      do 500 jj=1,j
  500 rm(j,jj)=rm(jj,j)
      return
      end
      subroutine did
      common /static/ir(39),idf(39),r(39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                       ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
cxxxxxxx do not use input for deleted dof ***************************
      do 60 i=1,ndel
      l=1
20      if (l.gt.nindf) go to 60
25      if (idf(l).ne.idel(i)) go to 40
        nindf=nindf-1
```

```
      if (l.gt.nindf) go to 60
      do 30 j=l,nindf
30    idf(j)=idf(j+1)
      go to 25
40    l=l+1
      go to 20
60    continue
      ii=ndel+1
      if (ndel.eq.0) return
      do 400 i=1,ndel
      ii=ii-1
      idi=idel(ii)
      ndof=ndof-1
c xxxxxxx adjust input pointers xxxxxxxxxxxxxxxxxxxxxxxxxx
      do 100 l=1,nindf
  100 if (idf(l).gt.idi) idf(l)=idf(l)-1
  400 continue
      return
      end
      subroutine dsymsl (a,b,nn,ll,m,ncall)
c     m=0 triangularize and solve
c     m=1 triangulize only
c     m=2 forward r+duction and back substitution only
      double precision a(ncall,ncall),b(ncall,ll),d
c
      if (m.eq.2) go to 500
      do 400 n=1,nn
      if (n.eq.nn) go to 500
      d=a(n,n)
      if (d.eq.0.0) print 2000,n
      n1=n+1
      do 300 j=n1,nn
      if (a(n,j).eq.0.0) go to 300
      a(n,j)=a(n,j)/d
      do 200 i=j,nn
      a(i,j)=a(i,j)-a(i,n)*a(n,j)
  200 a(j,i)=a(i,j)
  300 continue
  400 continue
c     forward reduction and backsubstitution
  500 if (m.eq.1) return
      do 700 n=1,nn
      do 600 l=1,ll
  600 b(n,l)=b(n,l)/a(n,n)
      if (n.eq.nn) go to 800
      n1=n+1
      do 700 l=1,ll
      do 700 i=n1,nn
  700 b(i,l)=b(i,l)-a(i,n)*b(n,l)
c
  800 n1=n
      n=n-1
      if (n.eq.0) return
      do 900 l=1,ll
      do 900 j=n1,nn
  900 b(n,l)=b(n,l)-a(n,j)*b(j,l)
      go to 800
c
 2000 format (39h0***zero diagonal term equation number      ,i4)
      end
      subroutine mconj(rm,rt,rconj,nm,nt,ncall,nmcall,ntcall)
c   computes (transpose t)*m*t where m is nm*nm,  t is nm*nt
      dimension rm(nmcall,nm),rconj(ncall,1),rt(ntcall,nt),tem(39)
      do 310 ncol=1,nt
      do 210 i=1,nm
      tem(i)=0.0
      do 200 j=1,nm
      tem(i)=tem(i)+rm(i,j)*rt(j,ncol)
  200 continue
  210 continue
      do 300 nrow=1,nt
      rconj(nrow,ncol)=0.0
      do 290 kk=1,nm
      rconj(nrow,ncol)=rconj(nrow,ncol)+rt(kk,nrow)*tem(kk)
  290 continue
  300 continue
  310 continue
      return
      end
      subroutine mfind(k,m,dk,ncall,b)
      dimension k(ncall,1),m(ncall,1),bt(39),dk(ncall,10),
     +   b(1),tk(39,39),tm(39,39)
      common /reduce/phi(39,39),tp(39,39,10)
      common /fdiff/ df,ddf
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     +    ,rintt,ndof,np,delt2
     +                  ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      real k,m
      call mck(k,m,ncall,b)
      call red(k,m,ncall,phi)
      do 250 i=1,np
      do 50 j=1,np
   50 bt(j)=b(j)
      bt(i)=b(i)*df
      div=ddf*b(i)
      call mck(tk,tm,ncall,bt)
      call red(tk,tm,ncall,tp(1,1,i))
      do 100 l=1,nxnt
      dk(l,i)=(tk(l,l)-k(l,l))/div
      do 100 ll=1,ndof
      tp(ll,l,i)=(tp(ll,l,i)-phi(ll,l))/div
  100 continue
  250 continue
      return
      end
      subroutine mprint(a,ii,jj,mm,aname)
      dimension a(mm,1)
      nn=(jj+8)/9
```

```
      jb=0
      do 100 n=1,nn
      ja=jb+1
      jb=min0(jj,ja+8)
      write(6,2000)aname,(j,j=ja,jb)
      do 100 i=1,ii
      write(6,2001)i,(a(i,j),j=ja,jb)
100   continue
      return
2000  format(//5x,7hmatrix,a10//3x,7hrow/col,i9,8i13)
2001  format(i6,4x,9e13.5)
      end
        subroutine pget (xk,xm,ndof,ncall,nxnt,xphi,xeig,ierr)
        dimension xphi(ncall,ndof),xeig(ncall),xk(ncall,ndof),xm(ncall,ndof)
        double precision k(39,39),m(39,39),wk1(39),trial(39),oe,x,e,
     #  phi(39,39),eig(39),machep
        do 20 i=1,ndof
        do 20 j=1,ndof
        k(i,j)=xk(i,j)
        m(i,j)=xm(i,j)
20      continue
        call dsymsl(k,wk1,ndof,1,1,ncall)
        machep=.00001
        maxit=40
        t=1.0/sqrt(float(ndof))
        ierr=0
        do 500 n=1,nxnt
                do 50 i=1,ndof
50                      trial(i)=t
                oe=0.0
                nex=0
                do 480 it=1,maxit
                        if (n.eq.1) go to 140
                        do 110 i=1,ndof
                                wk1(i)=0.0
                                do 105 j=1,ndof
                                        wk1(i)=wk1(i)+m(i,j)*trial(j)
105                             continue
110                     continue
                        do 130 l=1,n-1
                                x=0.0
                                do 115 j=1,ndof
                                        x=x+phi(j,l)*wk1(j)
115                             continue
                                do 120 i=1,ndof
                                        trial(i)=trial(i)-phi(i,l)*x
120                             continue
130                     continue
140                     do 150 i=1,ndof
                                phi(i,n)=0.0
                                do 145 j=1,ndof
                                        phi(i,n)=phi(i,n)+m(i,j)*trial(j)
145                             continue
150                     continue
                        call dsymsl(k,phi(1,n),ndof,1,2,ncall)
                        e=0
                        do 180 i=1,ndof
                                x=0
                                do 160 j=1,ndof
                                        x=x+m(i,j)*phi(j,n)
160                             continue
                                e=e+x*phi(i,n)
180                     continue
                        c=1.0/sqrt(e)
                        do 190 i=1,ndof
190                     trial(i)=phi(i,n)*c
                        emoe=e-oe
                        if (nex.eq.5) go to 490
                        if (abs(emoe).le.machep) nex=nex+1
                        oe = e
480             continue
                ierr=n
                return
490             do 495 i=1,ndof
                xphi(i,n)=trial(i)
495             phi(i,n)=trial(i)
                xeig(n)=c
                eig(n)=c
500     continue
        return
        end
      subroutine red(k,m,ncall,phi)
c
c red returns
c         diagonalized elements of k
c         diagonalized elements of m
c         phi(ndof,nxnt)
c
c
      common /first/ mfix,xm(39,39),xmr(39)
      dimension phi(ncall,ncall),t(39,39)
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *   ,rintt,ndof,np,delt2
     *                 ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      real k,m
      dimension eig(39),k(ncall,1),m(ncall,1)
      do 100 i=1,ndof
      do 100 j=1,ndof
100     t(i,j)=xm(i,j)
        call pget(k,t,ndof,ncall,nxnt,phi,eig,ierr)
        if (ierr.ne.0) go to 900
        do 200 i=1,nxnt
        m(i,i)=1.
200     k(i,i)=eig(i)
        return
900     write(*,"('error in pget')")
        stop
        end
```

```
      subroutine solveq(a,b,nn,ll,max,id)
c
      dimension a(max,max),b(max,1),id(1)
c
c     set i.d. array
c
      do 50 n=1,nn
   50 id(n)=n
c
      do 475 n=1,nn
      n1=n+1
c
c     locate largest element
c
      d=0.0
      do 100 i=n,nn
      do 100 j=n,nn
      if (abs(a(i,j))-d) 100,90,90
   90 d=abs(a(i,j))
      ii=i
      jj=j
  100 continue
c
c     interchange columns
c
      do 110 i=1,nn
      d=a(i,n)
      a(i,n)=a(i,jj)
  110 a(i,jj)=d
c
c     record column interchange
c
      i=id(n)
      id(n)=id(jj)
      id(jj)=i
c
c     interchange rows
c
      do 120 j=n,nn
      d=a(n,j)
      a(n,j)=a(ii,j)
  120 a(ii,j)=d
c
      do 130 l=1,ll
      d=b(n,l)
      b(n,l)=b(ii,l)
  130 b(ii,l)=d
c
c     form d(n,l)
c
      do 150 l=1,ll
  150 b(n,l)=b(n,l)/a(n,n)
c
c     check for last equation
c
      if (n-nn) 200,500,200
c
  200 do 450 j=n1,nn
c
c     form h(n,j)
c
      if (a(n,j)) 250,350,250
  250 a(n,j)=a(n,j)/a(n,n)
c
c     modify a(i,j)
c
      do 300 i=n1,nn
  300 a(i,j)=a(i,j)-a(i,n)*a(n,j)
c
c     modify b(i,l)
c
  350 do 400 l=1,ll
  400 b(j,l)=b(j,l)-a(j,n)*b(n,l)
  450 continue
  475 continue
c
c     back-substitution
c
  500 n1=n
      n=n-1
      if (n) 700,700,550
c
  550 do 600 l=1,ll
      do 600 j=n1,nn
  600 b(n,l)=b(n,l)-a(n,j)*b(j,l)
c
      go to 500
c
c     reorder unknowns
c
  700 do 950 n=1,nn
      do 900 i=n,nn
      if (id(i)-n) 900,750,900
  750 do 800 l=1,ll
      d=b(n,l)
      b(n,l)=b(i,l)
  800 b(i,l)=d
      go to 950
  900 continue
  950 id(i)=id(n)
c
      return
c
      end
      function sq (y1,d1,y2,d2,x1,x2)
      equivalence (a,coeff(1)),(b,coeff(2))
      dimension t(3,3),coeff(3),id3(3)
      t(1,3)=1.0
```

```
      t(2,3)=1.0
      t(3,2)=1.0
      t(3,3)=0.0
      sqmax=5.0*x2
      do 150 k=2,3
      km=4-k
      t(1,km)=x1*t(1,km+1)
      t(2,km)=x2*t(2,km+1)
  150 continue
      t(3,1)=2.0*x2
      coeff(1)=y1
      coeff(2)=y2
      coeff(3)=d2
      call solveq(t,coeff,3,1,3,id3)
      if (a.lt.1.0e-10) go to 200
      sq=-b/(2.0*a)
      if(sq.lt.sqmax) return
  200 sq=x2-y2/d2
      sq=amin1(sq,sqmax)
      return
      end
      subroutine symsol (a,b,nn,ll,m,ncall)
c     m=0 triangularize and solve
c     m=1 triangulize only
c     m=2 forward r+duction and back substitution only
      dimension a(ncall,ncall),b(ncall,ll)
c
      if (m.eq.2) go to 500
      do 400 n=1,nn
      if (n.eq.nn) go to 500
      d=a(n,n)
      if (d.eq.0.0) print 2000,n
      n1=n+1
      do 300 j=n1,nn
      if (a(n,j).eq.0.0) go to 300
      a(n,j)=a(n,j)/d
      do 200 i=j,nn
      a(i,j)=a(i,j)-a(i,n)*a(n,j)
  200 a(j,i)=a(i,j)
  300 continue
  400 continue
c     forward reduction and backsubstitution
  500 if (m.eq.1) return
      do 700 n=1,nn
      do 600 l=1,ll
  600 b(n,l)=b(n,l)/a(n,n)
      if (n.eq.nn) go to 800
      n1=n+1
      do 700 l=1,ll
      do 700 i=n1,nn
  700 b(i,l)=b(i,l)-a(i,n)*b(n,l)
c
  800 n1=n
      n=n-1
      if (n.eq.0) return
      do 900 l=1,ll
      do 900 j=n1,nn
  900 b(n,l)=b(n,l)-a(n,j)*b(j,l)
      go to 800
c
 2000 format (39h0***zero diagonal term equation number      ,i4)
      end
      subroutine xnt(k1,k2,fs,u,ks,ncall,idp,m,k)
c
c       this program performs numerical integration
c
      dimension u(6,ncall,1  ),ks(ncall)  ,m(ncall,1),k(ncall,1)
     * ,fs(1)
      common /index/ i11,i21,i31,i12,i22,i32
      common/gp/esteel,ri(6),area(6),areap(6),rl(6),ra(3),rb(3),g(4),
     *  tablek,tw,ak,am,ngp
      common /kdyn/ a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,delta,theta,delt,rint
     *    ,rintt,ndof,np,delt2
     *                    ,nindf,nxnt,ndel,ncndns,idel(39),icndns(39)
      real k,ks,m
      do 120 j=1,nxnt
      tu=u(i11,j,idp)
      tud=u(i21,j,idp)
      tudd=u(i31,j,idp)
      fs(j)=(m(j,j)*((a0+am*a1)*tu+(a2+am*a4)*tud+(a3+am*a5)*tudd)+
     *   k(j,j)*ak*(a1*tu+a4*tud+a5*tudd)+fs(j))*ks(j)
  120 continue
      do 150 i=1,nxnt
      u11=u(i11,i,idp)
      u21=u(i21,i,idp)
      u31=u(i31,i,idp)
      t=a0*(fs(i)-u11)-a2*u21-a3*u31
      u32=u31+(t-u31)/theta
      u(i22,i,idp)=u21+a6*u31+a7*u32
      u(i12,i,idp)=u11+delt*u21+a8*u31+a9*u32
      u(i32,i,idp)=u32
  150 continue
      return
      end
```

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UCB/EERC-77/01 "PLUSH - A Computer Program for Probabilistic Finite Element Analysis of Seismic Soil-Structure Interaction," by M.P. Romo Organista, J. Lysmer and H.B. Seed - 1977 (PB81 177 651)A05

UCB/EERC-77/02 "Soil-Structure Interaction Effects at the Humboldt Bay Power Plant in the Ferndale Earthquake of June 7, 1975," by J.E. Valera, H.B. Seed, C.F. Tsai and J. Lysmer - 1977 (PB 265 795)A04

UCB/EERC-77/03 "Influence of Sample Disturbance on Sand Response to Cyclic Loading," by K. Mori, H.B. Seed and C.K. Chan - 1977 (PB 267 352)A04

UCB/EERC-77/04 "Seismological Studies of Strong Motion Records," by J. Shoja-Taheri - 1977 (PB 269 655)A10

UCB/EERC-77/05 Unassigned

UCB/EERC-77/06 "Developing Methodologies for Evaluating the Earthquake Safety of Existing Buildings," by No. 1 - B. Bresler; No. 2 - B. Bresler, T. Okada and D. Zisling; No. 3 - T. Okada and B. Bresler; No. 4 - V.V. Bertero and B. Bresler - 1977 (PB 267 354)A08

UCB/EERC-77/07 "A Literature Survey - Transverse Strength of Masonry Walls," by Y. Omote, R.L. Mayes, S.W. Chen and R.W. Clough - 1977 (PB 277 933)A07

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UCB/EERC-77/09 "SUBWALL: A Special Purpose Finite Element Computer Program for Practical Elastic Analysis and Design of Structural Walls with Substructure Option," by D.Q. Le, H. Peterson and E.P. Popov - 1977 (PB 270 567)A05

UCB/EERC-77/10 "Experimental Evaluation of Seismic Design Methods for Broad Cylindrical Tanks," by D.P. Clough (PB 272 280)A13

UCB/EERC-77/11 "Earthquake Engineering Research at Berkeley - 1976," - 1977 (PB 273 507)A09

UCB/EERC-77/12 "Automated Design of Earthquake Resistant Multistory Steel Building Frames," by N.D. Walker, Jr. - 1977 (PB 276 526)A09

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UCB/EERC-77/15 Unassigned

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UCB/EERC-77/17 "Earthquake Simulation Testing of a Stepping Frame with Energy-Absorbing Devices," by J.M. Kelly and D.F. Tsztoo - 1977 (PB 273 506)A04

UCB/EERC-77/18 "Inelastic Behavior of Eccentrically Braced Steel Frames under Cyclic Loadings," by C.W. Roeder and E.P. Popov - 1977 (PB 275 526)A15

UCB/EERC-77/19 "A Simplified Procedure for Estimating Earthquake-Induced Deformations in Dams and Embankments," by F.I. Makdisi and H.B. Seed - 1977 (PB 276 820)A04

UCB/EERC-77/20 "The Performance of Earth Dams during Earthquakes," by H.B. Seed, F.I. Makdisi and P. de Alba - 1977 (PB 276 821)A04

UCB/EERC-77/21 "Dynamic Plastic Analysis Using Stress Resultant Finite Element Formulation," by P. Lukkunapvasit and J.M. Kelly - 1977 (PB 275 453)A04

UCB/EERC-77/22 "Preliminary Experimental Study of Seismic Uplift of a Steel Frame," by R.W. Clough and A.A. Huckelbridge 1977 (PB 278 769)A08

UCB/EERC-77/23 "Earthquake Simulator Tests of a Nine-Story Steel Frame with Columns Allowed to Uplift," by A.A. Huckelbridge - 1977 (PB 277 944)A09

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UCB/EERC-78/19 "Rational Design Methods for Light Equipment in Structures Subjected to Ground Motion," by J.L. Sackman and J.M. Kelly - 1978 (PB 292 357)A04

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UCB/EERC-78/25 "Investigation of the Nonlinear Characteristics of a Three-Story Steel Frame Using System Identification," by I. Kaya and H.D. McNiven - 1978 (PB 301 363)A05

UCB/EERC-78/26 "Studies of Strong Ground Motion in Taiwan," by Y.M. Hsiung, B.A. Bolt and J. Penzien - 1978 (PB 298 436)A06

UCB/EERC-78/27 "Cyclic Loading Tests of Masonry Single Piers: Volume 1 - Height to Width Ratio of 2," by P.A. Hidalgo, R.L. Mayes, H.D. McNiven and R.W. Clough - 1978 (PB 296 211)A07

UCB/EERC-78/28 "Cyclic Loading Tests of Masonry Single Piers: Volume 2 - Height to Width Ratio of 1," by S.-W.J. Chen, P.A. Hidalgo, R.L. Mayes, R.W. Clough and H.D. McNiven - 1978 (PB 296 212)A09

UCB/EERC-78/29 "Analytical Procedures in Soil Dynamics," by J. Lysmer - 1978 (PB 298 445)A06

UCB/EERC-79/01 "Hysteretic Behavior of Lightweight Reinforced Concrete Beam-Column Subassemblages," by B. Forzani, E.P. Popov and V.V. Bertero - April 1979(PB 298 267)A06

UCB/EERC-79/02 "The Development of a Mathematical Model to Predict the Flexural Response of Reinforced Concrete Beams to Cyclic Loads, Using System Identification," by J. Stanton & H. McNiven - Jan. 1979(PB 295 875)A10

UCB/EERC-79/03 "Linear and Nonlinear Earthquake Response of Simple Torsionally Coupled Systems," by C.L. Kan and A.K. Chopra - Feb. 1979(PB 298 262)A06

UCB/EERC-79/04 "A Mathematical Model of Masonry for Predicting its Linear Seismic Response Characteristics," by Y. Mengi and H.D. McNiven - Feb. 1979(PB 298 266)A06

UCB/EERC-79/05 "Mechanical Behavior of Lightweight Concrete Confined by Different Types of Lateral Reinforcement," by M.A. Manrique, V.V. Bertero and E.P. Popov - May 1979(PB 301 114)A06

UCB/EERC-79/06 "Static Tilt Tests of a Tall Cylindrical Liquid Storage Tank," by R.W. Clough and A. Niwa - Feb. 1979 (PB 301 167)A06

UCB/EERC-79/07 "The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 1 - Summary Report," by P.N. Spencer, V.F. Zackay, and E.R. Parker - Feb. 1979(UCB/EERC-79/07)A09

UCB/EERC-79/08 "The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 2 - The Development of Analyses for Reactor System Piping,""Simple Systems" by M.C. Lee, J. Penzien, A.K. Chopra and K, Suzuki "Complex Systems" by G.H. Powell, E.L. Wilson, R.W. Clough and D.G. Row - Feb. 1979(UCB/EERC-79/08)A10

UCB/EERC-79/09 "The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 3 - Evaluation of Commercial Steels," by W.S. Owen, R.M.N. Pelloux, R.O. Ritchie, M. Faral, T. Ohhashi, J. Toplosky, S.J. Hartman, V.F. Zackay and E.R. Parker - Feb. 1979(UCB/EERC-79/09)A04

UCB/EERC-79/10 "The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 4 - A Review of Energy-Absorbing Devices," by J.M. Kelly and M.S. Skinner - Feb. 1979(UCB/EERC-79/10)A04

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