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The Effect of Semi-active Control on Nonlinear Response of Structures through Incremental Dynamic Analysis

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ABSTRACT: It this paper, incremental dynamic analysis (IDA) of the controlled structures is presented. Nonlinear dynamic analyses for controlled structures are performed through Force Analogy Method (FAM) and State-space. IDA curves are demonstrated for un-controlled structures, under optimal control and under semi-active control. Therefore, the influence of control system for structures and changes in its behavior could be observed. Introductions for IDA, structural control, Semi-active Hydraulic Damper (SHD) and Force Analogy Method (FAM) are explained in the article. Full Static Condensation Model (FSCM) is introduced as a recent method that could consider non-linear behavior (through FAM and State-Space), static condensation and full Rayleigh damping matrix. In this article, FSCM is extended for the structures which are protected by optimal or semi-active control system. Therefore nonlinear behavior of controlled structures was considered. Numerical examples for a 5-story frame under scaled earthquakes were presented. The structure, for both controlled and un-controlled conditions, was modeled by the way that it could consider non-linear behavior. Control algorithms that have been used in the program were optimal control and SHD semi-active control. MATLAB codes were developed and IDA curves for no-control, optimal control and SHD control (with different arrangements of SHD control tools) are calculated and illustrated. At the end of the numerical section, some results and interpretations were extracted from IDA curves of controlled and un-controlled frames. They are explained in details and could give better understanding for dynamic behavior of the structures.

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1. INTRODUCTION

The earthquake phenomenon has caused many problems for human societies. Structural engineers have been trying to predict structural behavior. Therefore, the emphasis of seismic design is concentrated on post-elastic domain. A better and more complete study on structural behavior under severe earthquakes is done by Incremental Dynamic Analysis (IDA). The researchers used IDA for a variety of cases but it was not used for controlled structures. On the other hand, structural members were modeled with linear behavior in structural control for almost all previous researches.

In this research, the IDA method for controlled structures is used for the first time and the comprehensive behavior of the controlled structures even in post elastic domain is studied. Therefore, it will be possible to determine the efficiency of each control system. IDA, structural control and FAM are presented in the following sections. Then, FSCM[1] [1] is introduced and modified for controlled structures. The results for a sample frame are presented by a numerical example after above mentioned sections.

1 Full Static Condensation Model

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2. INCREMENTAL DYNAMIC ANALYSIS (IDA)

The IDA method is one of the best methods for investigating the effects of various earthquakes on the behavior of structures. The responses for each scaled record are calculated and they will be plotted against the intensity in a coordinate system. Horizontal axis is for Damage Measure (DM). Maximum inter-story drift (θ_{max}) is mostly selected for DM. Vertical axis shows the intensity of the earthquake and is called Intensity Measure (IM). In this article, peak ground acceleration (PGA) has been selected for IM [2].

3. IDA CURVES FOR CONTROLLED AND UN-CONTROLLED STRUCTURES

The controlled structures were considered under a few numbers of accelerograms in previous researches. There are many voids for structural response for other excitations. Therefore, IDA curves for controlled structures and comparisons with IDA curve of un-controlled structure has been focused in this study.

4. AN INTRODUCTION TO STRUCTURAL CONTROL

In this part of the main paper, a brief introduction of structural control is presented, which is not written in this abstract (due to the limited number of pages).

5. A CONCISE INTRODUCTION FOR SEMI-ACTIVE HYDRAULIC DAMPER (SHD)

In numerical section of this article, SHD[1] is used for control of the sample frame. This control system was presented by Kurata et al. [3].

More details are not explained in this abstract (due to the limited number of pages).

6. FORCE ANALOGY METHOD (FAM)

Force analogy method (FAM) is a method for nonlinear analysis. Some stiffness matrices are defined at the beginning of the procedure and they remain unchanged during the linear and nonlinear period of the analysis. Any changes in stiffness during nonlinear stage, is being considered by use of *fictitious* forces [4].

More explanations are abandoned in this abstract (due to the limited number of pages).

7. INTRODUCTION AND EXTENSION OF FSCM FOR CONTROLLED STRUCTURES

FSCM is the method that is based on FAM and state-space and it considers the Rayleigh damping [1]. FSCM is extended in this section for the conditions in which structure is protected by control system.

Due to the limited number of pages, only important equations are re-written here. Consider equation of motion Eq.1:

$$\begin{bmatrix} M_{dd} & O \\ O & O \end{bmatrix}\begin{Bmatrix} \ddot{x}_d \\ \ddot{x}_s \end{Bmatrix}+\begin{bmatrix} C_{dd} & C_{ds} \\ C_{sd} & C_{ss} \end{bmatrix}\begin{Bmatrix} \dot{x}_d \\ \dot{x}_s \end{Bmatrix}+ \begin{bmatrix} K_{dd} & K_{ds} \\ K_{sd} & K_{ss} \end{bmatrix}\begin{Bmatrix} x_d \\ x_s \end{Bmatrix}=-\begin{bmatrix} M_{dd} & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} a_{dg} \\ 0_{sg} \end{Bmatrix} +\begin{bmatrix} K_{dd} & K_{ds} \\ K_{sd} & K_{ss} \end{bmatrix}\begin{Bmatrix} x''_d \\ x''_s \end{Bmatrix}+\begin{bmatrix} D_d \\ D_s \end{bmatrix} f_c \tag{1}$$

The state-space method is used for solving Eq.1 and Z vector is defined as Eq.2:

$$Z=\begin{Bmatrix} x_d \\ x_s \\ \dot{x}_d \end{Bmatrix} \tag{2}$$

State-space presentation of equation of motion is:

$$\dot{Z}=AZ+Ha_{dg}+F_p^c x''+Bf_c \tag{3}$$

Matrixes that are used if Eq.3 are as below:

$$A=\begin{bmatrix} 0 & 0 & I \\ -K'_d & -K'_s & -C'_d \\ -M_{dd}^{-1}K''_d & -M_{dd}^{-1}K''_s & -M_{dd}^{-1}C''_d \end{bmatrix} \tag{4a}$$

$$H=\begin{bmatrix} 0 \\ 0 \\ -I \end{bmatrix} \tag{4b}$$

$$F_p^c=\begin{bmatrix} 0 & 0 \\ K'_d & K'_s \\ M_{dd}^{-1}K''_d & M_{dd}^{-1}K''_s \end{bmatrix} \tag{4c}$$

$$B=\begin{bmatrix} 0 \\ D' \\ M_{dd}^{-1}D'' \end{bmatrix} \tag{4d}$$

$$x''=\begin{Bmatrix} x''_d \\ x''_s \end{Bmatrix} \tag{4e}$$

The solution to Eq.3 in i^{th} time step from the data in previous time step is [4]:

$$Z_i=F_sZ_{i-1}+H_d^{(EQ)}a_{dg,i-1}+ F_px''_{i-1}+G*f_{c,i-1} \tag{5}$$

Inelastic displacement of previous time step (x''_{i-1}) that has been appeared in the right-hand side of Eq.5, is calculated by FAM.

8. NUMERICAL SECTION – SAMPLE FRAME MODEL

A five story frame is selected for numerical section of this paper. Choosing the locations of control tools in the structure for many reasons can be a challenge, but IDA could offer a useful help. IDA curves for different control tool installations for a frame is drawn beside each other. Therefore, decision making will be more precise. Table 1, shows different arrangements of control tools and Figure 1 shows the corresponding IDA curves for the sample frame.

When one control tool is installed on each floor (case III), the behavior of the controlled structure is not much different from the un-controlled structure (case I), as it could be observed in Figure 1. When three SHDs are installed on each floor (case IV - totally 15 numbers), the structural behavior is greatly improved, but the cost increases due to the large number of tools that have been used. To examine the

1 semi-active hydraulic damper

Table 1. Arrangements of control tools on sample frame

Case No.	Description	Total SHD No.s
I	No Control	Not used
II	Optimal control	Not used
III	One SHD in each story	5
IV	3 SHDs in each story	15
V	2 SHDs for first story and one SHD in any other story	6
VI	2 SHDs in each of first and second story, one SHD in any other story	7

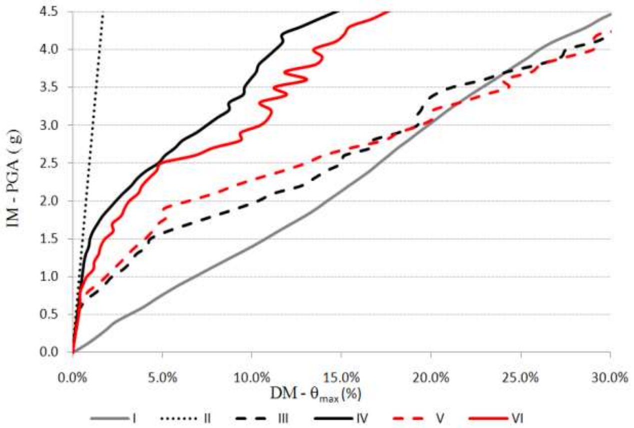

Fig 1. IDA curves for sample frame under El Centro earthquake for different SHD arrangements

structural behavior with less number of tools, two other cases (Cases V and VI) were also investigated. It can be observed that case V is not significantly different from cases I and III. But the results of case VI are similar to case IV. In other words, by using smaller number of tools, the achievements are similar to case IV.

In this way, it is possible to identify un-safe cases (relatively large amounts of θ_{max}), non-economic cases (due to the use of a large number of SHDs) and the best option which is both safe and economical.

In addition to the results that are obtained from the IDA curves in Figure 1, more results can be extracted from IDA:

- Identifying IMs which pushes θ_{max} to a predetermined level, for different cases of control tool installation.
- Calculation of θ_{max} for different cases of control tool installation, for a certain amount of θ_{max} in un-controlled structure.

9. CONCLUSION

In this research, a combination of the IDA and nonlinear dynamic analysis of controlled structures is presented and the behavior of frames with structural control in nonlinear domain is studied.

In the numerical section, the plotted IDA curves for different cases were discussed. The most important contributions of proposed method are:

- Plotting the IDA curve of the controlled structure leads to better understanding of the structure's seismic behavior.
- Choosing the position of installation and the appropriate number of control tools could be done with the help of IDA, features of different cases are identifiable and finally best option will be selected.

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