Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.IV)

6-1-9

EXPERIMENTAL ERROR GROWTH BEHAVIOR AND ERROR GROWTH CONTROL IN PSEUDO DYNAMIC TEST

Masayoshi NAKASHIMA[1] and Hiroto KATO[2]

[1]Department of Environmental Planning, Faculty of Engineering, Kobe University, Rokkodai, Nada, Kobe 657 JAPAN
[2]Production Department, Building Research Institute, Ministry of Construction, Tatehara, Tsukuba, Ibaraki 305 JAPAN

SUMMARY

This paper presents investigations into the experimental error characteristics of the pseudo dynamic (PSD) test. Experimental error sources were identified, and their effects on the PSD response were examined based on the results obtained from a series of PSD tests. Those effects were also studied analytically, and guidelines were provided with respect to the magnitude of the experimental error. Procedures to mitigate the experimental error were proposed, and their effectiveness was verified by PSD tests applied to two and seven story steel frames.

INTRODUCTION

The pseudo dynamic (PSD) test (also referred to as the on-line computer test control method) is a combined numerical analysis and experiment developed for the earthquake response simulation of structural components and systems. Because of the various advantages of the PSD test over the shake table test, known as the most direct method to simulate the earthquake response of structures, many research bodies in the world have employed this test in their studies (Ref.1). We should not overlook, however, that this test is not more than an approximate test procedure including many assumptions and simplifications and that the response obtained is not identical to the true response. Sources that produce errors in the PSD response can be classified into two types: i.e. intrinsic and experimental error sources. The intrinsic error sources are associated with the basic formulation of the PSD test, whereas the experimental error sources are generated because of the imperfect nature of the experimental hardware. Details of the intrinsic error characteristics are documented, for example, in Ref.1.

Many previous PSD tests reported that the PSD response was very sensitive to the experimental hardware employed and that the response was often distorted from the response to be (for example, Refs.1,2). To give more credit to the PSD test, it is believed important to examine and systematically evaluate the experimental error behavior in the PSD test. This paper presents investigations into the experimental error sources and their effects on the PSD response. In this paper, the distortion of the PSD response produced because of the imperfectness of the experimental hardware is designated as the experimental error. The objectives of the investigations include: 1) to identify experimental error sources and examine their relative effects on the experimental error; 2) to provide quantitative guidelines on the characteristics of the experimental error; and 3) to propose procedures to mitigate the experimental error and to demonstrate the validity of the proposed procedures by PSD tests.

EXPERIMENTAL ERROR SOURCES AND THEIR EFFECTS ON PSD RESPONSES

PSD Tests of 2DOF Steel Frame Considering the fundamentals of the PSD test, the major experimental error sources were found to be: 1) truncation and round-off generated in the A/D and D/A conversions; 2) miscalibration and finite resolutions of the displacement and force measuring sensors; and 3) limited accuracies of the load applying actuators to position the test structure at the exact target position. In order to examine the effects of those error sources on the experimental error, a series of PSD tests were performed. The test structure was a scaled two story steel frame shown in Fig. 1. The structure was treated as a 2 DOF system, with the mass and stiffness properties as indicated in Table 1. Using the setup shown in Fig. 2, the structure was tested many times (accordingly, the input motion was set small enough for the structure to behave elastically), each time using a different set of parameters. The parameters selected were: 1) type of loading procedures, 2) type of displacement sensors, 3) type of input ground motion, and 4) magnitude of the allowable error bound. Here, the allowable error bound was the bound set up around the target displacement, and, if the structure's displacement fell into this bound, the structure was presumed to have reached the target position. Major findings obtained from the tests follow:

1) The allowable error bound was the most critical parameter that affected the experimental error. Note that this bound was needed because of the finite capacity of the load applying actuators to lead the test structure to the exact target position.

2) If the allowable error bound was set as small as possible (±0.02mm in this test), the response obtained was reasonably close to the true response (represented by the numerical response since the test structure behaved only linear-elastically) (Fig. 3(a)), but the vibration having the frequency of 19 Hz was more promoted. This frequency of 19 Hz corresponded to the second natural frequency of the structure tested.

3) When the allowable error bound was small, the displacement error, defined as the displacement computed as the target displacement minus the displacement achieved after the actuator motion, scattered randomly with respect to the time as well as frequency (Fig. 4(a)).

4) If the allowable error bound was set relatively large (±0.1mm), the obtained response exhibited divergent behavior (Fig. 3(b)), forcing to terminate the test at an early stage, and the vibration having the second mode natural frequency utterly dominated the response.

5) When the allowable error bound was relatively large, the displacement error had a dominant frequency component of 19 Hz and exhibited a property of "undershoot" (Fig. 5). Here, the undershoot was the condition in which, at a given step, the displacement increment achieved after the actuator motion was smaller in its absolute value than the displacement increment computed at that step.

6) Numerical analysis including the effect of the experimentally obtained displacement errors provided the response very close to the experimental responses (Fig. 6). This numerical results indeed proved that the displacement error was the major cause that distorted the response.

PSD Tests of 6DOF Steel Braced Frame In the previous PSD tests, the allowable error bound could be set close to the resolution (0.01mm) of the displacement sensors, and, if it was indeed set that small, the responses obtained were found accurate. In those tests, however, it often took much time to lead the test structure within the bound mainly because of the interaction between the two actuators. In general conditions, say, when more actuators are to be controlled and/or the test structure is made stiffer, the allowable error bound need be selected large enough so that the test can be implemented without spending unduly much time in the loading. The experimental error characteristics were also

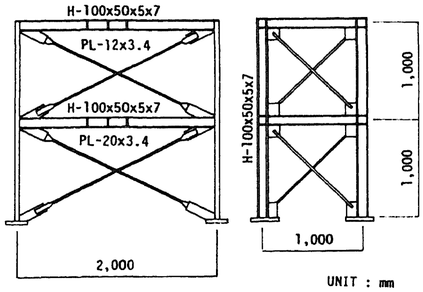


Fig.1 2 Story Steel Frame Used in PSD Test

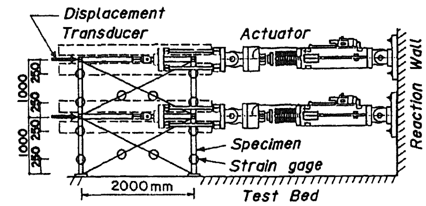
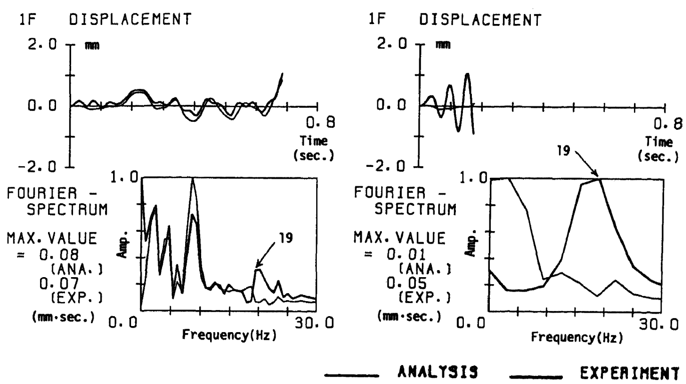


Fig.2 Test Setup Used for PSD Test

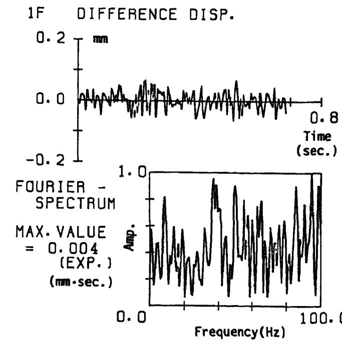
Table 1 Structural and Vibrational Properties of 2 Story Steel Frame

	Mass (kg·sec²/cm)	Stiffness (kg/cm)		Natural Frequency (Hz)	Vibration Mode 2F	Vibration Mode 1F
2F	2.28	10,290	1st Mode	7.94	1.0	0.451
1F	2.31	18,420	2nd Mode	19.2	-0.454	1.0
	*No Damping					

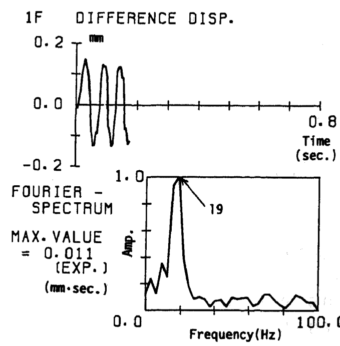


(a) Allowable Error of 0.02 mm (b) Allowable Error of 0.10 mm

Fig.3 1st Story Disp. Response of 2 Story Steel Frame



(a) Allowable Error of 0.02 mm



(b) Allowable Error of 0.10 mm

Fig.4 1st Story Disp. Error Response of 2 Story Steel Frame

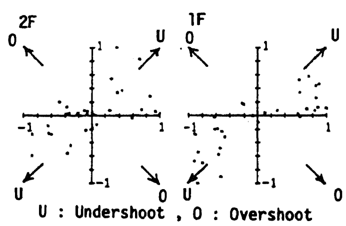
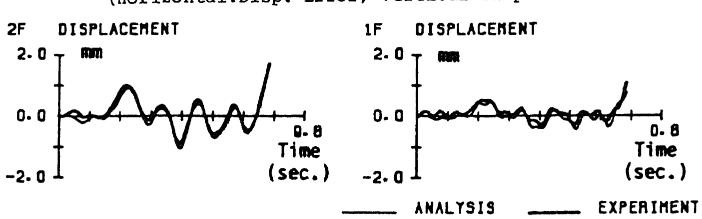
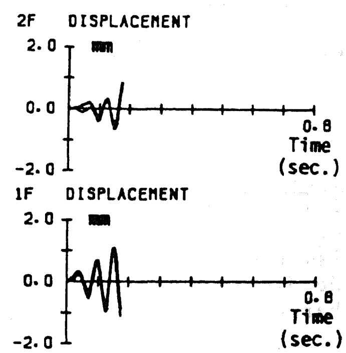


Fig.5 Undershoot Behavior of 2 Story Steel Frame
(Allowable Error of 0.10 mm)
(Horizontal:Disp. Error; Vertical:Disp. Increment)



(a) Allowable Error of 0.02 mm



(b) Allowable Error of 0.10 mm

Fig.6 Numerical Disp. Responses with Disp. Errors investigated using a six story full scale braced frame prepared for the U.S.-Japan Cooperative Research Program (Ref.3), and it was confirmed that; 1) the displacement error was the major source that affected the responses; 2) it had a tendency of having the undershoot; and 3) the response corresponding to the highest mode (contributing to the vibration) was more promoted. Details of the error characteristics of this test are documented in Ref.4.

ANALYTICAL EVALUATION OF EXPERIMENTAL ERRORS

Experimental Error Under Random Displacement Errors It was found from the previous PSD tests that the displacement error had a random nature if the allowable error bound was set very small. Mahin and Shing (Ref.2) conducted an comprehensive study into the experimental error behavior in the PSD response and concluded that the experimental error caused by random displacement errors increases with the increase of the integration time interval. This statement means that, in an MDOF system, the response corresponding to a higher mode is more promoted. The test results agreed with their analytic observation. Figure 7 shows the relationship between the integration time interval and the displacement amplitude of the experimental error given for a linear-elastic SDOF system sustaining random displacement errors.

Experimental Error Under Undershoot The undershoot was found to appear because the loading was established so that the test structure gradually and incrementally approached the target displacement. Because, in the integration, the measured force (including the error force) was combined with the computed displacement, this undershoot had the effect of adding energy into the test structure. This was the reason why the PSD tests having the undershoot exhibited divergent behavior. In the linear-elastic SDOF system having a constant undershoot value (δ), the magnitude of the experimental error can be evaluated analytically. Considering the balance between the energy added by the undershoot and the energy dissipated by the viscous damping, we obtain the relationship shown in Fig. 8 for the displacement error growth with respect to the time. Details are given in Ref.4. Figure 8 indicates that the experimental error is made more significant for a smaller viscous damping and that, for each damping ratio, the response reaches a constant amplitude. Comparing Fig. 7 with Fig. 8, it can be found that, if the structure tested is lightly damped and the integration time interval is kept small, the undershoot is more harmful than the random displacement errors. In a strict sense, the relationship thus formulated is valid only for the ideal condition (i.e. the system being linear-elastic and the undershoot remaining a constant value), but it still enables us to estimate the bound of the growth of the experimental error. In an MDOF system, the undershoot was found to promote the vibration of the highest mode most significantly. Considering the fact that the undershoot is not independent of but subject to the displacement response obtained, the reason why the undershoot promotes the highest mode is not trivial. Nevertheless, it is correct and was proven in Ref.4.

ALGORITHMS TO SUPPRESS EXPERIMENTAL ERROR

Algorithms to Suppress Experimental Error We should be reminded that the displacement error is generated because of the insufficiency of the load applying actuators to lead the test structure at the exact target position but that the displacement measuring sensor is accurate enough (in a relative sense) to detect the displacement that the test structure is positioned. Considering those characteristics of the displacement error, developed were the following

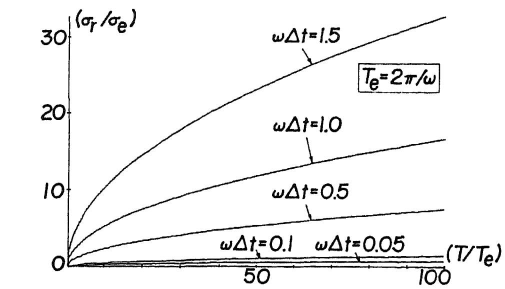


Fig.7 Experimental Error Growth with Random Disp. Errors

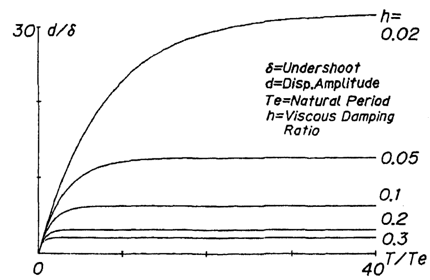


Fig.8 Experimental Error Growth with Undershoot

Table 2 Structural and Vibrational Properties of Structures Used in PSD Tests with Procedure Proposed

(a) 2 Story Frame

Story	Mass ($kg\cdot sec^2/cm$)	Stiffness (kg/cm)		Natural Frequency (Hz)	Vibrational Mode	1F	2F
1	85.0	52,280	-63,840	2.19	1st	1.0	1.736
2	85.0	-63,840	126,900	6.99	2nd	1.0	-0.576

(b) 7 Story Frame

[Stiffness Matrix: ton/cm]

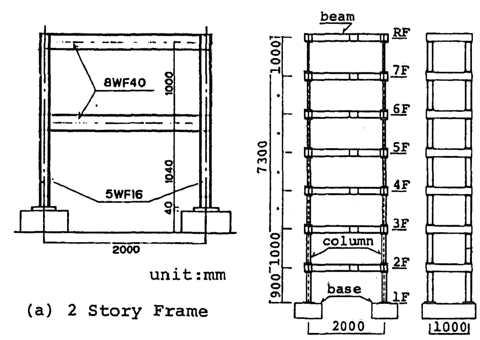
	7F	6F	5F	4F	3F	2F	1F
7F	3.39						
6F	-3.39	8.56			sym.		
5F	0	-5.58	15.2				
4F	0	0	-9.91	23.6			
3F	0	0	0	-14.4	30.5		
2F	0	0	0	0	-18.4	36.4	
1F	0	0	0	0	0	-20.5	40.9

[Mass: $ton\cdot sec^2/cm$]

0.006	0.006	0.006	0.006	0.006	0.006	0.006

[Natural Frequency: Hz]

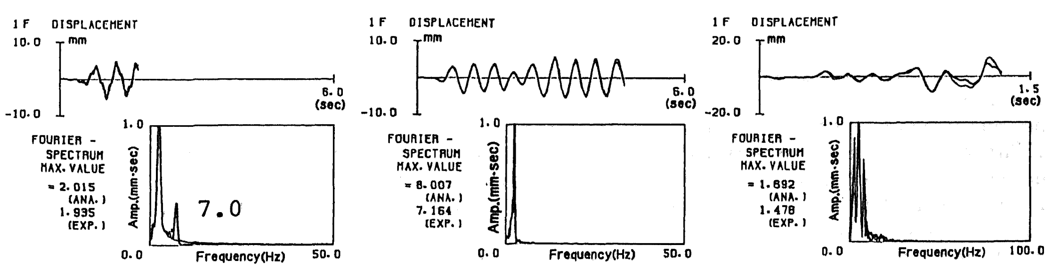
1st	2nd	3rd	4th	5th	6th	7th
1.59	3.64	5.78	8.06	10.3	13.2	15.9



(a) 2 Story Frame

(b) 7 Story Frame

Fig.9 2 and 7 Story Steel Frame Used in PSD Tests with Procedure Proposed

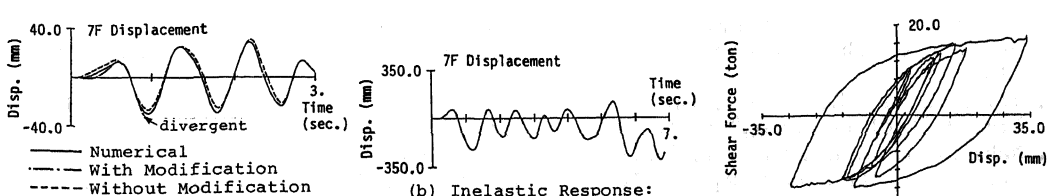


(a) Without Modification (elastic response) (allowable error of 0.15 mm)

(b) With T-Modification (elastic response) (allowable error of 0.15 mm)

(c) With I-Modification (inelastic response) (allowable error of 0.02 mm)

Fig.10 Disp. Responses of 2 Story Steel Frame with Procedure Proposed



(a) Elastic Response: Allowable Error of 1.0 mm

(b) Inelastic Response: Allowable Error of 0.05 mm

(c) 1st Story Hysteresis in Inelastic Response

Fig.11 Disp. Responses and Hysteresis of 7 Story Steel Frame with Procedure Proposed algorithms. Here, the measured reactional forces, {f}, are modified to:

$$\{\bar{f}\} = \{f\} + [k](\{x_c\} - \{x_m\}) \quad (1)$$

And the modified forces $\{\bar{f}\}$ are incorporated into the equations of motion. The matrix, [k], is the stiffness matrix of the structure tested. If [k] is correct, $\{\bar{f}\}$ should be the reactional force corresponding to the exact target position. Two alternatives for [k] were considered. One is [k] representing the initial elastic stiffness matrix (I-Modification), while the other [k] estimated as the secant stiffness matrix between the last and present time steps (T-Modification). Further, the secant stiffnesses are to be estimated by applying the techniques of the system identification to the displacements and forces continuously collected during the loading in each step.

To verify the effectiveness of the algorithms proposed, a series of PSD tests were performed using scaled two story steel frames (Figs. 1 and 9(a)) and a scaled seven story steel frame (Fig. 9(b)). Those frames were treated as a 2 DOF and a 7 DOF systems respectively. Basic properties of the frames tested are shown in Table 2. Major findings obtained from those tests follow:

1. If the algorithms developed were not applied, the responses diverged (Figs. 10(a) and 11(a)). If either the I- or T-Modification, was employed, the responses obtained were accurate (Figs. 10(b), (c), and 11(b)).
2. In the I-modification, additional error forces were generated in the inelastic range, because the stiffnesses in that range were no longer the same as the initial stiffnesses. The response, nevertheless, was found reasonable (Fig. 10(c)). This good result was obtained, because, in the inelastic range, the energy dissipated by the hysteresis dominated and the error forces created affected only minimally. It is to be commented that the effect of the displacement error relative to the overall response is reduced with the increase in the hysteretic damping.

CONCLUSIONS

A summary and major conclusions drawn in this study follow:

1. A series of PSD tests were performed, and the displacement error was found as the major source of the experimental error.
2. The displacement error often had the property of undershoot, which, in turn, had the effect of adding energy into the structure tested.
3. The magnitude of the experimental error caused by the displacement error was evaluated analytically.
4. Algorithms to mitigate the experimental error were proposed, and their effectiveness was verified by PSD tests applied to two and seven story steel frames.

REFERENCES

1. Takanashi, K and Nakashima, M.,"Japanese Activities on On-Line Testing," Journal of the Engineering Mechanics, ASCE, Vol.113, No.7, pp.1014-1032, (1987).
2. Mahin, S. A. and Shing, P. B.,"Pseudodynamic Method for Seismic Testing," Journal of the Structural Engineering, ASCE, Vol.111, No.7, pp.1482-1503, (1985).
3. Yamanouchi, H., et al.,"Inelastic Behavior of Full-Scale Concentrically K-Braced Steel Building," to be presented at 9WCEE (1988).
4. Nakashima, M. and Kato, H.,"Experimental Error Growth Behavior and Error Growth Control in On-Line Computer Test Control Method," Research Paper, Building Research Institute, Ministry of Construction, No.123, 144pp. (1987).