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PITCHING AND INTERACTION EFFECTS IN EERC SEISMIC SIMULATOR

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SUMMARY

Recent tests at the multi-degree of freedom shaking table at the University of California, Berkeley, showed an undesired pitching motion. The objective of this paper is to study the pitch effect on the response of test structures. The effect of pitching and interaction are investigated through transfer function measurements and through actual earthquake motions applied to a SDOF steel test structure with high overturning moment capacity. Although the effective motion was quite different from the earthquake record, the response of the structure can still be predicted from the earthquake record using the coupled structure properties.

INTRODUCTION

It was observed during the tests of heavy and tall structures on EERC shaking table that significant pitching, rolling and twisting can occur (Ref. 1). The objective of this research is to study the shaking table-structure interaction effects, and evaluate shaking table performance. In this paper the interaction effects are studied by transfer function measurements and actual earthquake records applied to a test structure, a test mass and to the bare table system.

EXPERIMENTAL PROGRAM

The interaction and performance of the table were studied under three different loading cases:

- The bare table was subjected to both random signals and earthquake signals. The random signals test was performed in order to establish the transfer functions between the table motions and the command displacement. Transfer functions can give a measure of system reproduction of the command signal, the frequency bandwidth and the stability of the table motion. In order to evaluate the interaction effects during normal test operation, two earthquake records were used: the 1952 Taft and the 1978 Miyagi-Ken-Oki.
- The table was then loaded with three concrete blocks (WxHxL=48x21.5x240 inches) having a total weight of 70.5 kips. Each block was anchored by three post tensioned steel rods to the table. Only random signals were applied to the table-mass system.
- A steel structure was then constructed so as to have similar dynamic characteristics to that of the US-JAPAN reinforced concrete model (Ref. 1) for which significant pitching was observed. The steel structure had a mass of 62.5 kips placed on the top. The center of mass was 200 inches from the table level. A sketch of the test structure is shown in Fig. 1. The structure was subjected to both random and earthquake signals.

IDENTIFICATION OF STRUCTURE PROPERTIES

Two separate tests were performed to identify the structure's vibration characteristics. First, the fixed base case was handled by placing a small shaker at the top of the structure, a random signal was applied to the small shaker mass and the induced inertia forces were adequate to estimate the frequency (2.87 Hz) and damping (0.3 %). Second, the coupled structure properties were evaluated by subjecting the structure to random command displacement. The transfer function of the relative mass acceleration with respect to the command was evaluated and circle fitting (Ref. 2) was performed to evaluate the frequency (2.54 HZ) and damping (3.33 %). These properties reflect the coupling due to both the horizontal and pitching degrees of freedom. In order to evaluate the coupled parameters in the pitching degrees of freedom only, another transfer function, the relative mass acceleration with respect to the horizontal table acceleration was used. During the second test, an independent estimate of the fixed base characteristics was also made by considering the rigid body movement of mass at the top of the structure $\ddot{x}_t+\ddot{\theta}h$ (effective acceleration). The transfer function between this input and the relative mass acceleration was estimated. Surprisingly a completely different estimate was obtained for the damping (0.8 %). This significant change in damping can be attributed to the fact that the mass was not rigidly attached to the structure. The movement of this mass can lead to friction and hence energy dissipation. It also was possible to estimate the fixed structure's frequency and damping from its response to the earthquake signals. The results are shown in Figs. 2a and 2b which clearly show the damping dependence on the response amplitude.

The frequency and damping of the SDOF test structure for the two earthquake signals used are listed in Table 1 for the fixed base case, for the pitch coupling case, and for the pitch and horizontal coupling case.

SHAKING TABLE PROPERTIES FROM MEASURED TRANSFER FUNCTIONS

In order to understand the table behavior, transfer functions between the command displacement and the actual table horizontal and pitch displacements were determined. The results, in Figs. 3a and 3b, show the transfer functions for the displacement and pitch respectively.

- For the bare table, the transfer function of the horizontal table displacement with respect to the command is shown by the long dash line. The system behaves as low pass filter with little attenuation for frequencies less than 10 Hz but almost completely attenuating frequencies over 25 Hz. The phase curve of the transfer function shows that table displacement frequencies above 12.6 Hz are out of phase with the command displacement. The bare table pitch consists mainly of high frequency response. It is out of phase with the command displacement at about 11.5 Hz and peaks around 12.5 Hz.
- The addition of the mass of 70.5 kips to the table caused a decrease in the frequency bandwidth as shown by the short dash line. The table displacement is out of phase with the command at about 8.5 Hz. The pitch transfer function had two prominent peaks at about 8 and 15 Hz. The pitch displacement is out of phase with the command at about 8 Hz.
- Adding the structure to the table had two clear effects on the horizontal transfer function as shown by the solid line. It decreased the frequency bandwidth and had a prominent peak (amplitude=2.2) and notch (amplitude=0.7) near the coupled table structure frequency. The table displacement was out of phase with the command at 9.6 Hz. Table pitch (Fig. 3b) occurs mainly at a frequency close to the coupled table-structure frequency.

TIME HISTORY COMPARISONS

In order to predict the response of the SDOF test structure to the command acceleration, to the measured horizontal table acceleration or to the measured effective table acceleration, it is essential to use the frequency and damping values which properly represent the coupling effects between the table and the structure.

Recognizing the dependence of the damping on the response amplitude it was necessary to identify the coupled properties from the measured responses. Transfer functions were evaluated for the relative mass acceleration with respect to the command signal, to the measured horizontal table acceleration and to the effective table acceleration. Damping values and frequencies obtained from transfer functions of the relative mass acceleration versus the command signal reflect the coupling effects due to the flexibility of the table in the rotational and translational degrees of freedom; those versus the horizontal acceleration reflect the coupling due to pitching only; while those versus the effective table acceleration reflect the fixed base properties of the structure (i.e. no coupling). The two earthquake signals used have some energy near test structure resonance. Transfer functions evaluated had no spikes corresponding to dividing by small input amplitudes. Circle fitting was performed near the peak amplitudes and corresponding damping and frequency estimates were obtained. The frequencies were 2.59, 2.71 and 2.86 Hz and the damping ratios were 1.8, 2.5 and 1.4 % respectively.

Fig. 4 shows plots of the measured mass acceleration together with those predicted from the three motions using the respective coupled properties. It is clear that the correlation is very good between the analytical and experimental results for the three cases.

RESPONSE SPECTRA COMPARISONS

The effective acceleration spectrum represent the peak response of a SDOF test structure with no coupling effects (i.e. with fixed base properties). The original spectrum in this case represent the maximum response of a SDOF test structure taking into account coupling in both the horizontal and pitching degrees of freedom. Response spectrum of the horizontal table acceleration represent the SDOF structure with pitch coupling.

Fig. 5a shows the response spectra of the original Taft acceleration record and the measured table acceleration record. It is clear that the spectrum of the table acceleration is slightly higher near the coupled table-structure period. The spectrum evaluated from the effective table acceleration $\ddot{x}_t+h\ddot{\theta}$ can be compared with the original Taft spectrum in Fig. 5b. Clearly the effective acceleration has a much higher response at periods greater than the fixed base structure period.

CONCLUSIONS

1) The response of the system for the bare table and rigid load conditions is acceptable within the operating frequency bandwidth.

2) In the case of the table loaded with a test structure, the horizontal table acceleration versus command signal transfer function shows a prominent peak and notch distortion near the resonant frequency of the structure. The table pitch response is mainly concentrated near the coupled frequency of the structure.

3) Time history responses of the structure can be predicted from either the command, horizontal table or effective table acceleration as long as the appropriate properties are considered. Structural frequency and damping should adequately represent the coupling between the table and structure.

4) Response spectrum of the horizontal table acceleration is reasonably similar to the spectrum of the command signal whereas the spectrum of the effective acceleration is quite different. However, in order to use these response spectra, adequate structural properties must be specified; appropriate coupled frequencies and damping need to be used for the command and the horizontal table acceleration spectra and fixed base values for the effective table acceleration spectrum.

5) As long as the frequency content of the input motion is not negligible near the frequency of interest, coupled frequencies and fixed base characteristics for the structure may be derived from transfer function measurements.

ACKNOWLEDGMENTS

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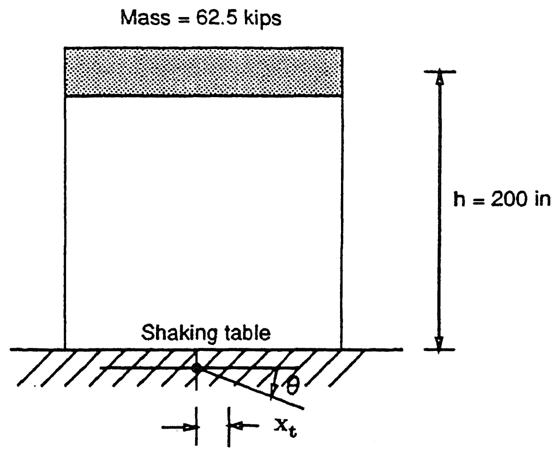
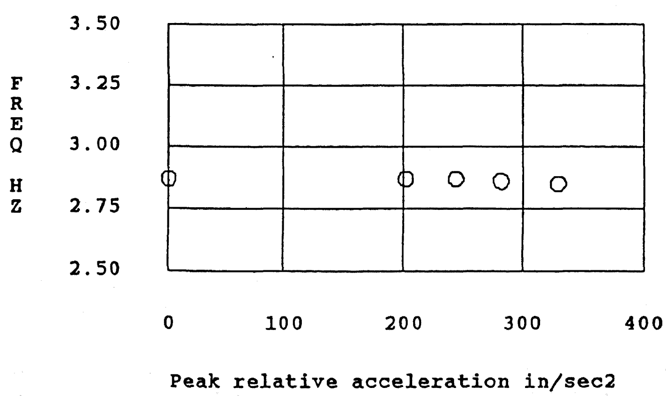


Fig. 1 Steel structure mounted on EERC shaking table

Fig. 2: Variation of Frequency and Damping with Response Amplitude

a) Frequency



b) Damping

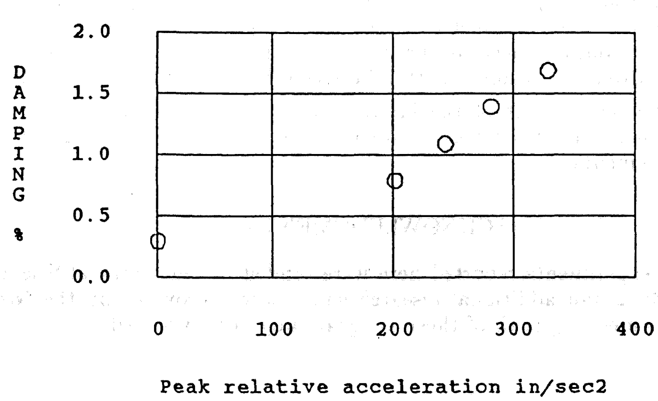


Fig. 3: Transfer Function w.r.t. Command Displacement

a) Table Horizontal Displacement.

b) Pitch Translation (angle times height)

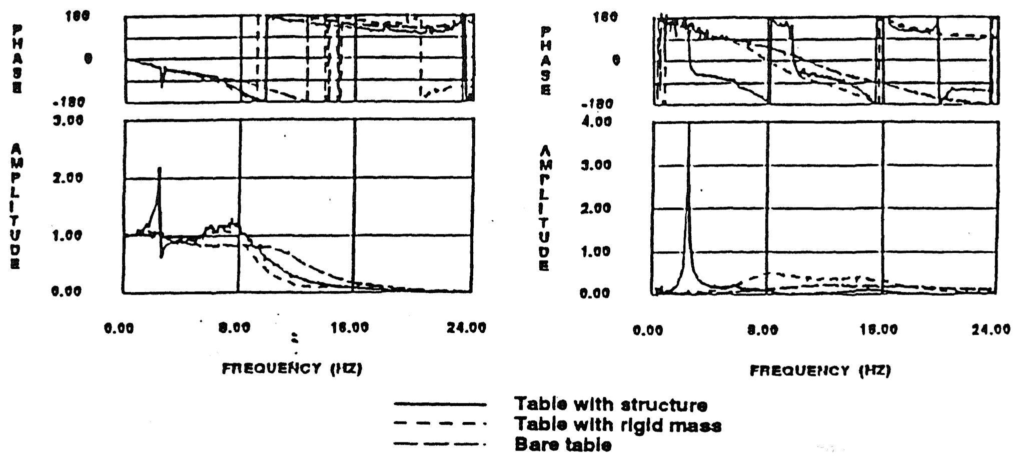
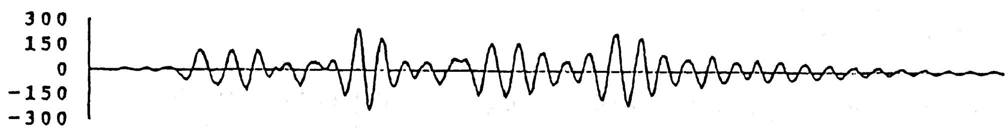
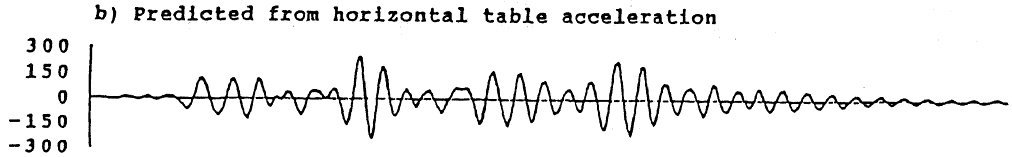


Fig. 4: Comparisons of Measured and predicted Mass Acceleration (in/sec2). (measured: solid, predicted: dotted)

a) Predicted from effective table acceleration



b) Predicted from horizontal table acceleration



c) Predicted from command acceleration

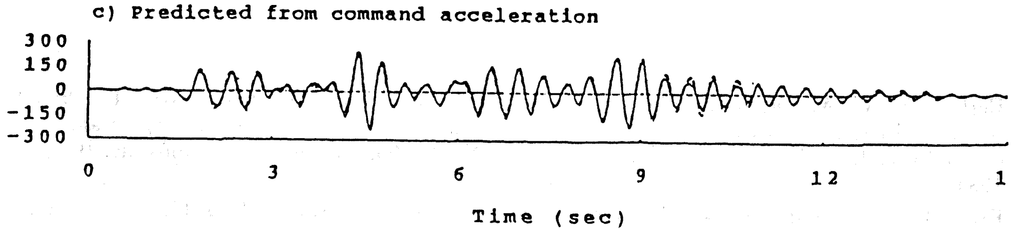
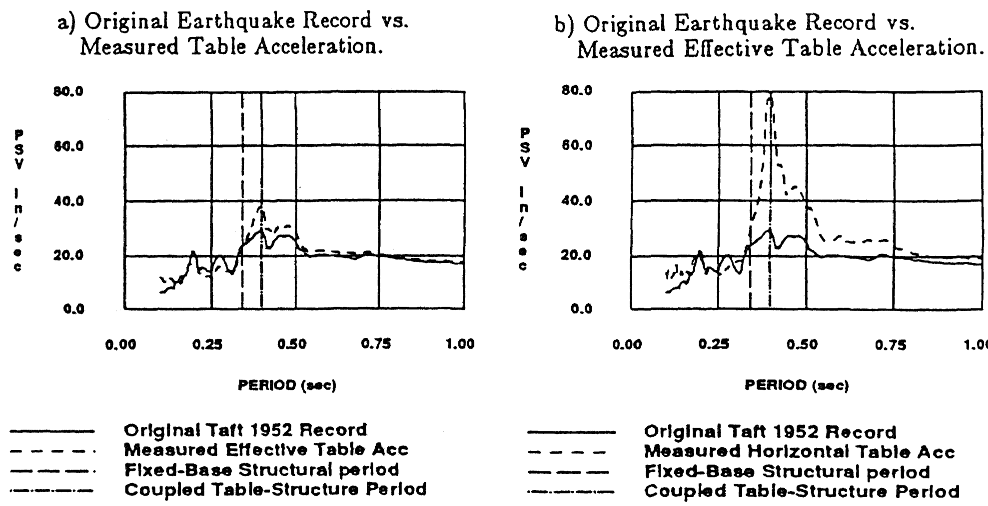


Fig. 5: Comparisons of Pseudo Velocity Spectra (5% Damping)



EARTHQUAKE RECORD	Fixed base		Base rotation coupling		Transl. and rot. coupling	
	FREQ (Hz)	DAMP (%)	FREQ (Hz)	DAMP (%)	FREQ (Hz)	DAMP (%)
Miyagi span 270	2.87	1.2	2.71	2.3	2.62	2.0
Miyagi span 350	2.86	1.4	2.71	2.5	2.59	1.8
Taft span 200	2.86	1.7	2.70	1.0	2.58	2.4

Table 1: Vibration characteristics of the structure for three boundary conditions and three different records.

REFERENCES

1. Bertero, V. V., Aktan, A. E., Charney, F. A., Sause R. "US-JAPAN Cooperative Earthquake Research Program: Earthquake Simulation Tests And Associated Studies of a 1/5 scale Model of a 7 Story R.C. Test Structure" EERC Report No. 84/05, University of California, Berkeley, 1984.

2. Ewins D. J., "Modal Testing: Theory and Practice". Research Studies Press LTD. John Wiley and Sons Inc. 1984 (pp 158-168)