AMBIENT AND FORCED VIBRATION STUDIES OF A MULTISTORY PYRAMID-SHAPED BUILDING

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SYNOPSIS

The results of the ambient and forced vibration studies of the sixty-story Transamerica Building are presented and compared. The operational aspects and the feasibility of using a displacement-controlled mass system to introduce steady-state vibrations are presented and discussed. Five resonant frequencies and associated damping ratios in both principle directions (NS and EW) as well as two torsional resonance frequencies were determined from the forced vibration studies. Results are presented as translational frequency response curves and mode shapes. Experimental and analytical resonance data are compared.

INTRODUCTION

The dynamic forces a structure experiences when its foundation undergoes motion depend on both the characteristics of the motion and the dynamic properties of the structure. Modern computer techniques have been developed to an extent that the elastic and, for certain structural systems, inelastic response of structures subjected to earthquakes can be determined quite specifically. However, the final numerical results depend on the accuracy of the computer model formulation of the structure and its foundation. Hence, dynamic field test data covering the complete dynamic characteristics of full-scale structures and providing natural frequencies, mode shapes, and damping values have been considered essential in the development of computer-model formulation techniques. These test data are particularly important in determining the feasibility of special computer programs, which are principly developed for specific structural systems, such as rigid frames and shear-wall systems. However, to assess the feasibility of general purpose computer programs, in predicting accurately the earthquake response of buildings with complex configurations and novel structural systems to withstand earthquake induced lateral loads, field studies are essential.

For the above reasons the new, sixty-story, framed pyramid-shaped Transamerica Building in San Francisco has been studied using both ambient and force-controlled excitations.

DESCRIPTION OF BUILDING

The Transamerica Building is a multi-story pyramid-shaped steel structure, sixty stories in height, located in San Francisco, California, The 853 foot high building has a square plan and consists of a two-story high ground floor, a triangularly shaped tubular space truss around the perimeter between the 2nd and 5th floor levels and above this level, a moment resistant frame with the exterior walls sloping inward at an

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approximate ratio of 1 to 11. The upper 10 stories consist of an open-framed pyramid shaped structure which will not be occupied. On the east and west sides of the building, starting just below the 30th floor, shafts project from the building which contain elevators on the east side and a stairwell and duct shaft on the west side. In addition to the truss supported moment resistant exterior frames, the building interior moment resistant framing consists of four frames in each direction from the 5th floor to the 17th floor level and from the 17th floor to the 45th floor level two frames in each direction. Figure 1 shows the tower and the San Francisco skyline looking westerly. The exterior face of the building is faced with a reinforced concrete precast stone paneling as shown in Fig. 2. This paneling is structurally attached to the building frame and extends to the 50th floor. Over the upper 10 stories, the columns are faced with precast stone elements while the space between the columns is covered with an aluminum louvered paneling.

The tower rises more than 850 feet above the lobby or plaza level with the base plan some 174 feet square. Figure 3 shows the elevations of the building with the distances above the lobby level to various floors. The main structural framing is outlined in the figure with the various sized members indicated. The main columns are built-up-steel square box sections of varying cross-section and the beam elements are basically 27 inches deep wide-flange sections.

EXPERIMENTAL PROGRAM

In order to subject the building to forced vibrations two methods were employed. The first method used, incorporated rotating-mass force-vibration generators or shaking machines mounted on the 48th floor of the building and oriented so as to induce the maximum forces in the North-South and East-West directions as shown in Fig. 4. A complete description of the vibration generators is given elsewhere (1,2). Because of the nature of the rotating mass vibration generators it is very difficult to accurately operate at frequencies lower than 0.5 cps and develop sufficiently large forces to record accurately the motion of the building and to determine the resonant frequencies. Therefore, an alternate method for determining the lower resonant frequencies was developed, using a linear displacement-controlled mass vibration system. This system was used in the North-South direction only as shown in Fig. 4.

In this system a platform containing the mass was fitted with low friction rollers which were in turn set on round steel bars fixed to the floor. In this test the platform contained approximately 3,000 pounds and was moved horizontally by means of a closed loop servo-controlled double-acting actuator connected to the 48th floor as shown in Fig. 5. With a 3 gpm hydraulic supply and using a 1-1/2" diameter bore cylinder with a total displacement of 24 inches and a 5 gpm servo-valve a typical theoretical performance curve is shown in Fig. 6. A standard servo-control console and function generator supplied the input to the valve with the feedback in the displacement coming from a linear potentiometer with a total travel of 36 inches. Fig. 7 shows an overall view of the vibration generation and control equipment mounted on the 48th floor of the building.

In determining these lower North-South resonant frequencies the input displacement signal was maintained at the maximum displacement that the pump and valve would allow. Steady-state vibrations were induced for incrementally increased frequencies and the building response recorded. In the vincinity of the resonance peaks the frequencies were increased in increments of as low as 0.001 cps. Once the resonant frequencies were established for these two lower North-South modes the East-West resonant frequencies were determined using the standard rotating mass system. However, the control on this rotating mass system at the lower frequencies is very poor and very few points could be obtained accurately in establishing the frequency response curve for the East-West directions.

The transducer used to detect horizontal floor accelerations of the building were Statham A4 linear accelerometers, with a maximum rating of ± 0.25 g. The electrical signal from all accelerometers was fed via amplifiers to a Honeywell Visicorder ultraviolet recorder. For the translational motions the accelerometers were located near the center of the floor and oriented so as to pick up the appropriate North-South or East-West accelerations. For recording the torsional motion accelerometers were properly oriented near the center of two opposite walls. The floors selected for measurement of the accelerations are those indicated by the elevations shown in Fig. 3. To determine the resonant frequencies of the building the accelerometers were in general located at the 48th floor. The mode shapes were evaluated from records taken at the different elevations shown in Fig. 3, or in general at six-story intervals except in the upper tower where three-story intervals were used. Because of the open floor framing of this upper tower the accelerometers were placed on the exterior girders at the intersection of this girder and the center line of the building parallel to the forcing direction. Hence, the pick-up of any possible torsional motion of the upper tower, even while the building was subjected to a translational force-input, was minimized.

In order to allow a comparison of the dynamic structural properties determined from both forced and ambient vibrations the building response to ambient excitation was also determined. The ambient vibration pick-up was performed at approximately six-story intervals up to the 49th floor.

RESULTS

The vibration equipment was bolted to the 48th floor throughout the test program and with the appropriate adjustments to the vibration equipment it was possible to apply translational or torsional forces to the building. The first, second, fourth, fifth and sixth modes in both the N-S and E-W directions as well as two torsional modes were excited. The third translational mode could not be excited as probably the upper nodal point of both the N-S and E-W translational mode shapes lay close to the 48th floor level. During the torsional mode studies it was impossible to develop the 1st and 3rd resonance frequencies. However, at 1.05 cps and again at 1.45 cps the 48th floor went into a pure in-phase motion.

Frequency response curves, in the region of the resonant frequencies for these five modes for both the N-S and E-W directions are shown in Fig. 8. The curves are plotted in the form of normalized displacement amplitude versus exciting frequency. The ordinates were obtained by

dividing the measured acceleration by the square of the exciting frequency (cps) and then by the square of the circular frequency (rad/sec). Hence, the displacement amplitudes reflect the effect of a force amplitude that would be generated by the eccentric masses rotating at 1 cps. Damping capacities as shown in Fig. 8 were obtained from the normalized frequency response curves by the formula: $\zeta = (\Delta f)/(2f)$, where ζ = damping factor (% of critical damping), f = resonant frequency and Δf = difference in frequency of the two points on the resonance curve with amplitudes of $1/\sqrt{2}$ times the resonant amplitude.

The translational resonant frequencies and damping factors evaluated from the curves are summarized in Table 1 along with the results obtained for the two torsional resonant frequencies. Table 1 also summarizes the results from the ambient study along with preliminary analytical results for the first four translational and torsional resonant frequencies.

The mode shapes for the five translational N-S and E-W resonant frequencies obtained from the forced vibration studies are shown in Fig. 9. It should be noted that the normalized amplitudes above the 48th floor level have been reduced with a factor of 1/5.

CONCLUSIONS

The dynamic properties of five translational modes in both the N-S and E-W directions, as well as the resonant frequencies of two torsional modes of the Transamerica Building in San Francisco, were determined by full-scale dynamic tests.

The use of a linear displacement-controlled vibration system in determining the lower resonant frequencies was found to yield very accurate results. A comparison of the data presented in Fig. 8 for the first two modes in the N-S direction for which this system was used and similar results for corresponding E-W modes using the rotating-mass vibration generators, clearly shows that due to a better operational control of the first system, a higher data density and accuracy can be achieved.

The natural frequencies determined from the forced and ambient vibrations agree very closely. The preliminary analytical results show with the exception of the first mode good agreement with the experimental data. The difference for the fundamental mode might result from a seemingly more flexible behavior of the upper tower, than reflected in the analysis. The top 10 stories of the building of the open framed tower exhibit namely very flexible characteristics as noted from the mode shapes, especially those for the upper three resonant frequencies. In Fig. 9 the displacement scale from the 48th floor up is 5 times larger than the scale below the 48th floor. In the sixth mode the displacements for the N-S and E-W directions at the 60th floor, or top of the tower, are some 18 and 13 times the displacement at the 48th floor respectively. The damping ratios for the forced vibration studies ranged between 1 and 2% of critical. For the ambient studies these ratios were less than 1% of critical.

ACKNOWLEDGEMENTS

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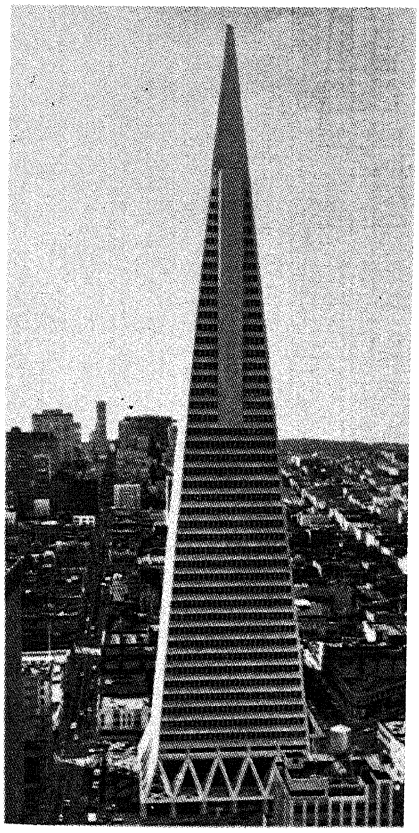
TABLE 1 COMPARISON OF RESONANT FREQUENCIES AND DAMPING RATIOS

TRANSLATIONAL

	NORTH-SOUTH					EAST-WEST				
NO	FORCED VIBRATION		AMBIENT		ANAL	FORCED VIBRATION		AMBIENT		ANAL
	FREQ cps	DAMP %	FREQ cps	DAMP %	FREQ cps	FREQ cps	DAMP %	FREQ cps	DAMP %	FREQ cps
1	0.345	0.9	0.352	0.78	0.258	0.345	1.4	0.338	0.78	0.250
2	0.635	1.4	0.632	0.38	0.553	0.635	1.6	0.617	0.38	0.516
3	-	-	0.866	0.29	0.863	-	-	0.866	0.29	0.820
4	1.17	1.5	1.146	-	1.09	1.13	1.5	1.11	-	1.08
5	1.62	1.2	1.514	-	-	1.53	1.8	1.50	-	-
6	1.85	0.9	1.735	-	-	1.85	0.7	1.74	-	-

TORSIONAL

1	-		0.455		0.357
2	0.895	2.6	0.793		0.870
3	-		1.058		1.45
4	1.395	2.2	1.275		1.56



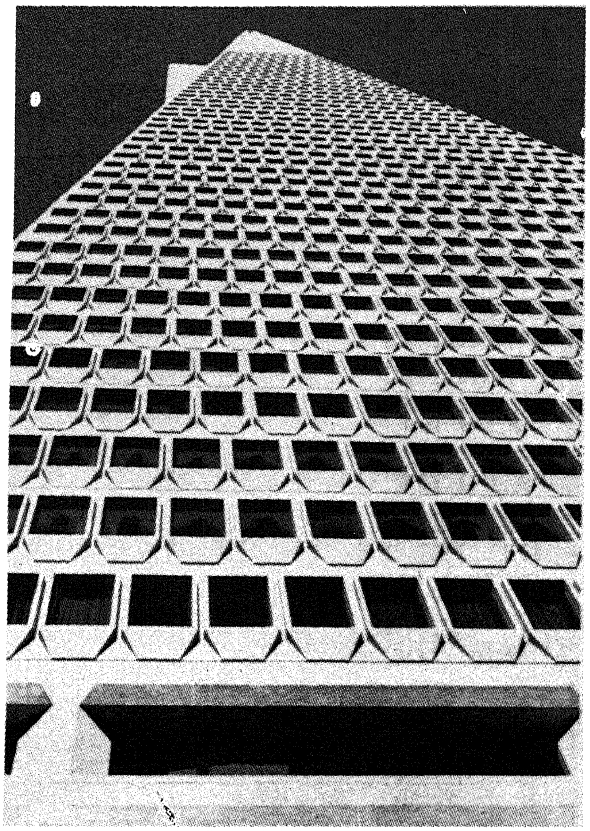


FIG. 1 TRANSAMERICA BUILDING, SAN FRANCISCO, CALIF

FIG. 2 EXTERIOR FACING OF TRANSAMERICA BUILDING

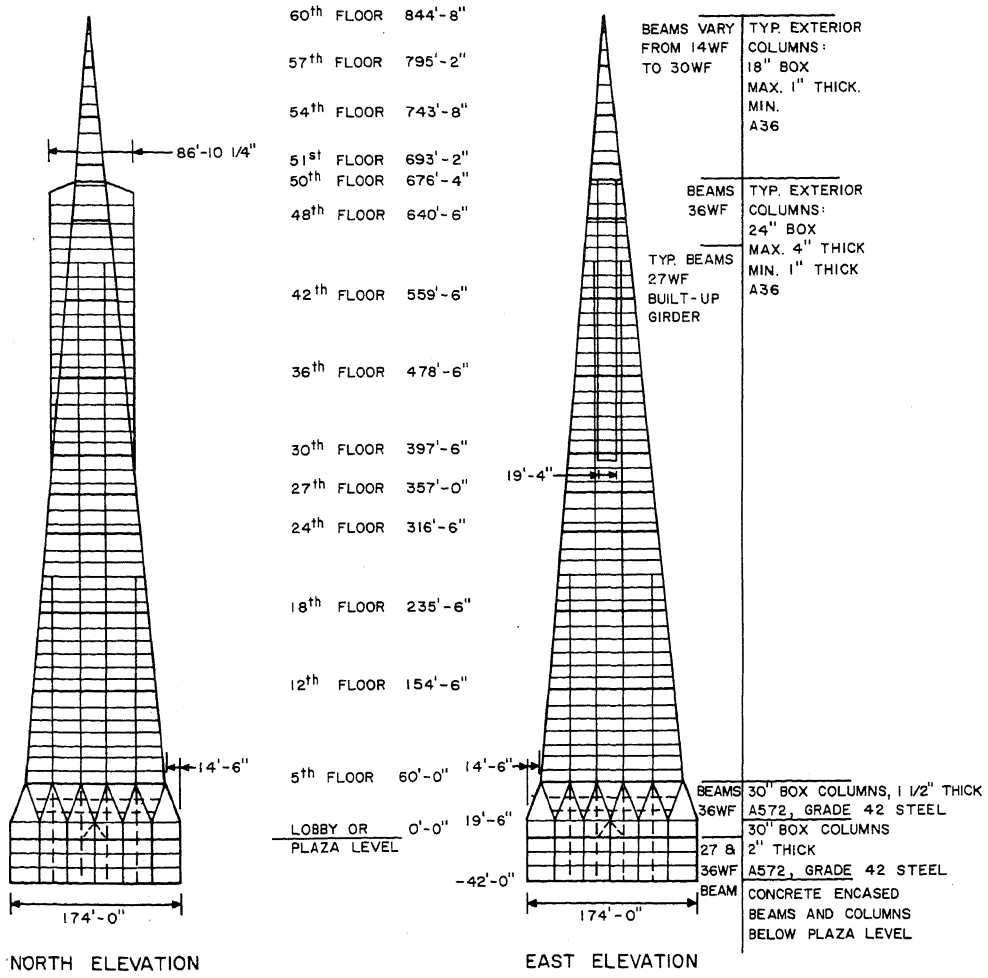


FIG. 3 ELEVATIONS OF MAIN FRAMES

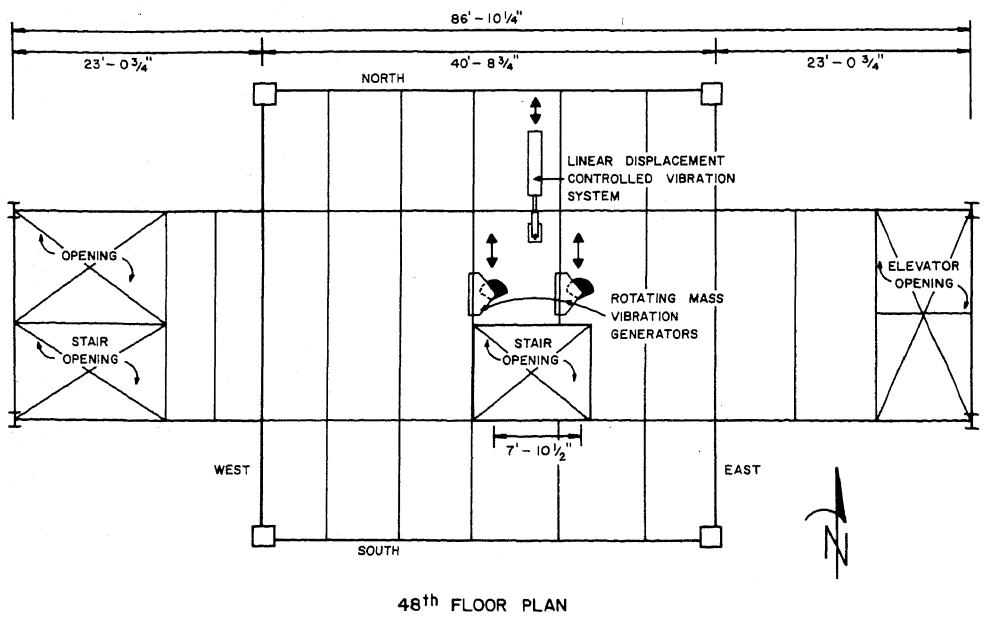


FIG. 4 LOCATION OF VIBRATION EQUIPMENT N-S FORCING DIRECTION

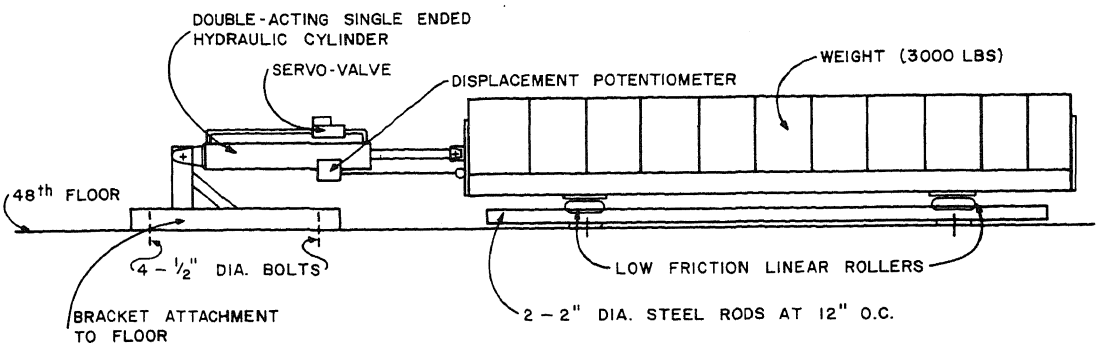


FIG.5 SCHEMATIC OF LINEAR DISPLACEMENT CONTROLL VIBRATION SYSTEM

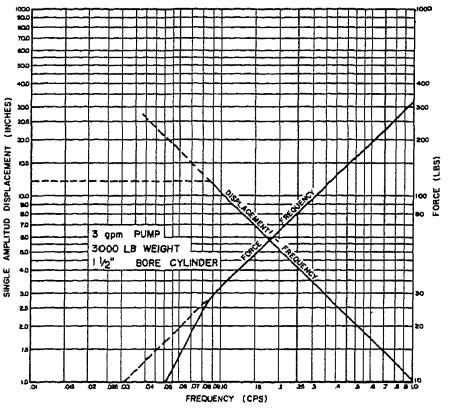


FIG.6 THEORETICAL PERFORMANCE CURVE FOR LINEAR DISPLACEMENT CONTROLLED SYSTEM

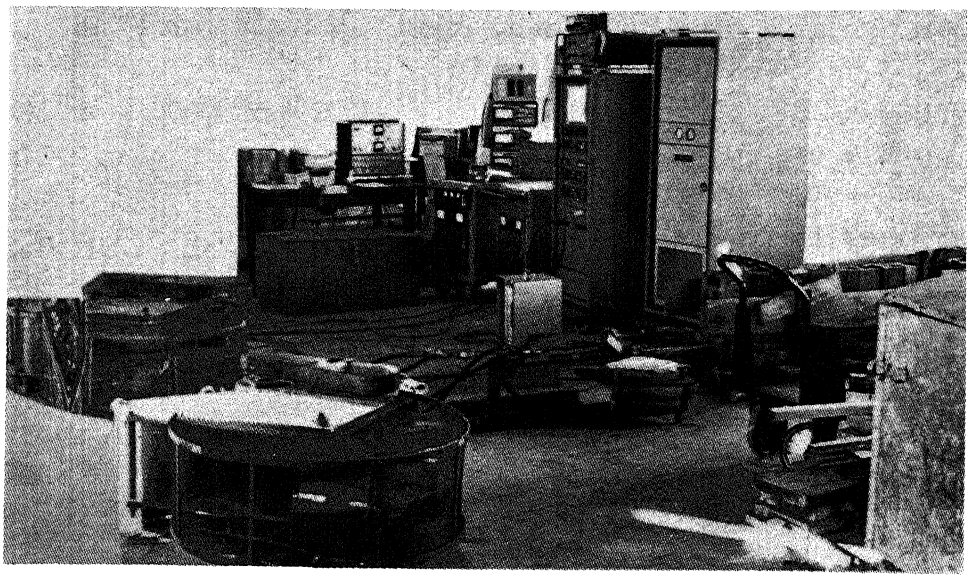
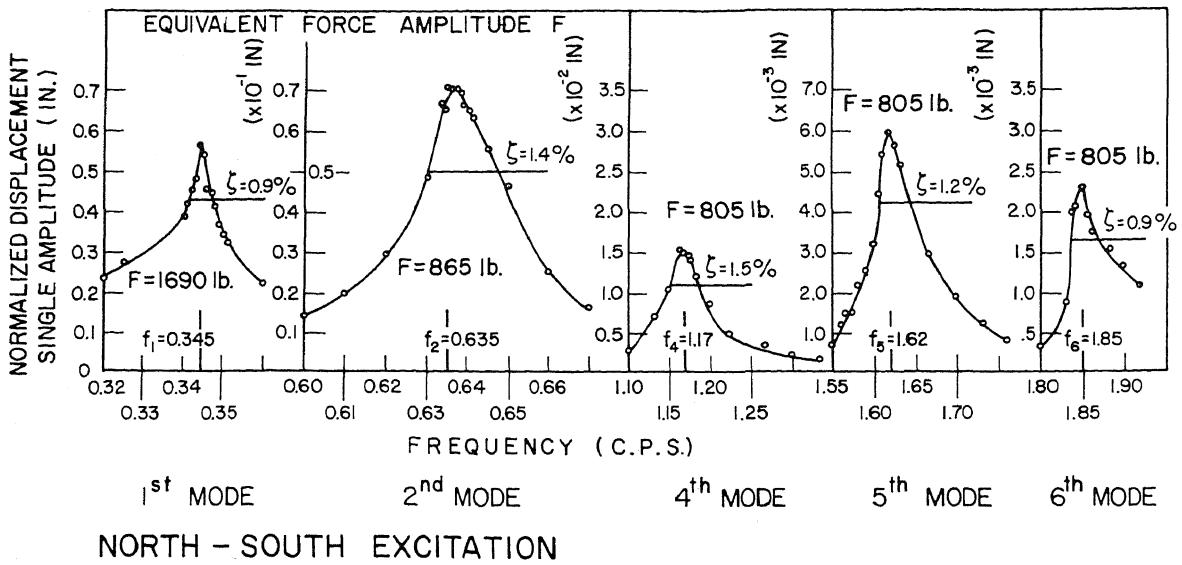
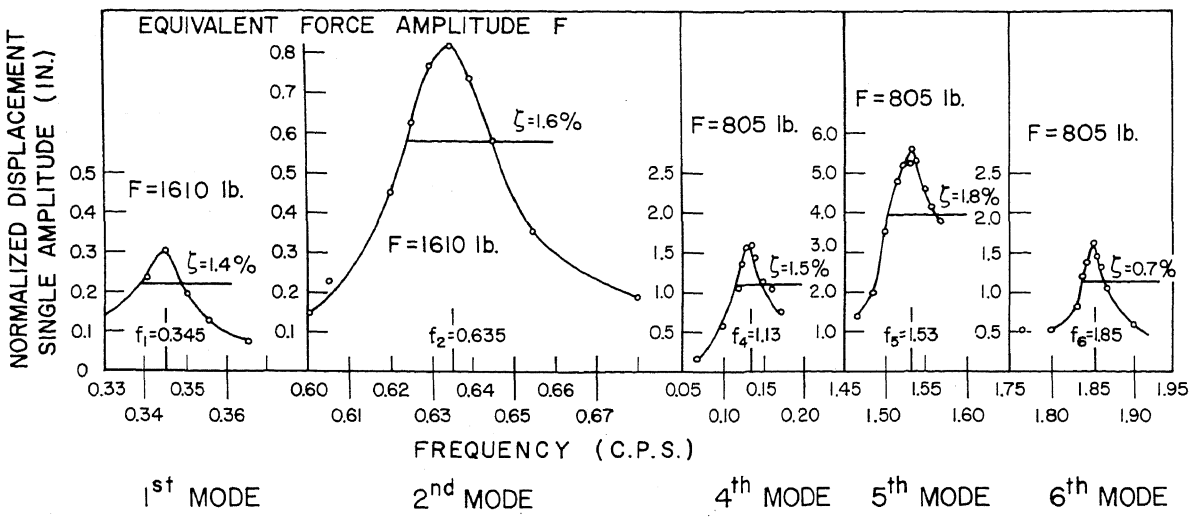


FIG. 7 OVERALL VIEW OF VIBRATION EQUIPMENT

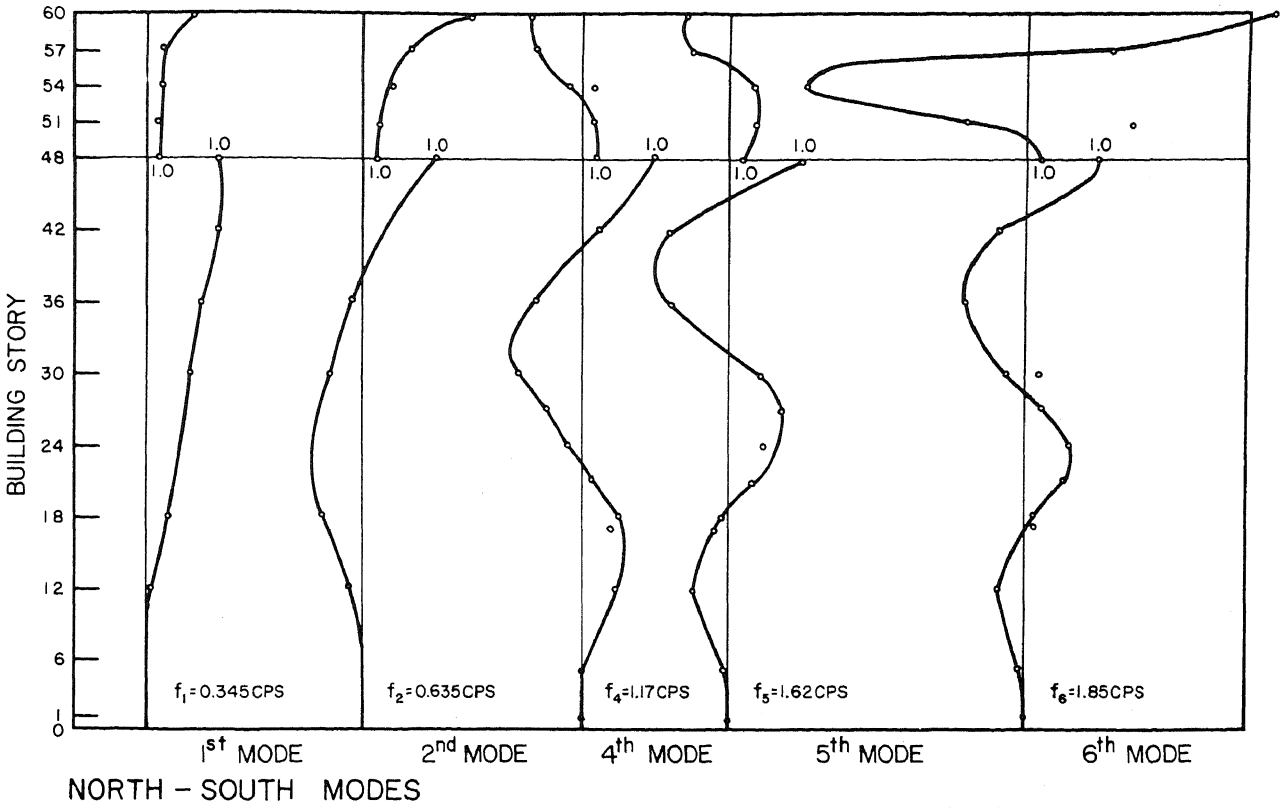


NORTH - SOUTH EXCITATION

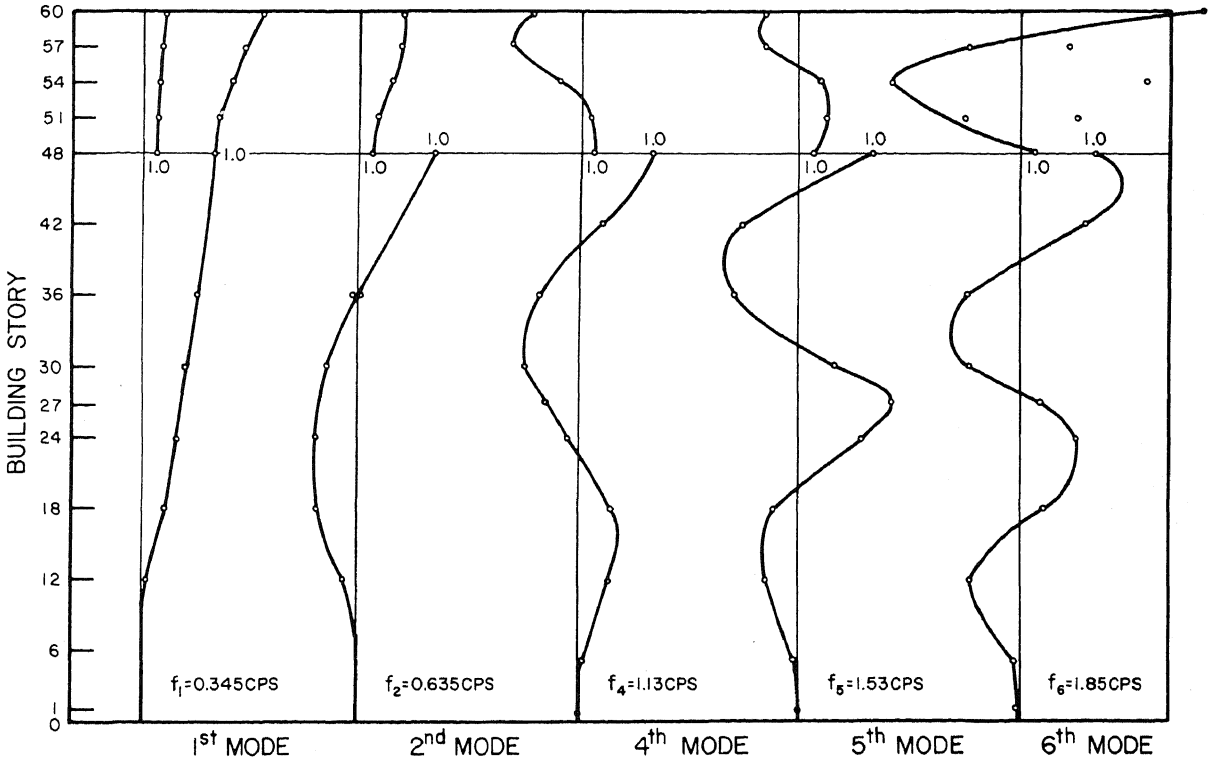


EAST - WEST EXCITATION

FIG. 8 TRANSLATIONAL FREQUENCY RESPONSE CURVES 48th FLOOR



NORTH – SOUTH MODES



EAST – WEST MODES

FIG. 9 TRANSLATIONAL MODE SHAPES

269