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EARTHQUAKE ENGINEERING RESEARCH CENTER

PRELIMINARY EXPERIMENTAL INVESTIGATION OF A BROAD BASE LIQUID STORAGE TANK

by

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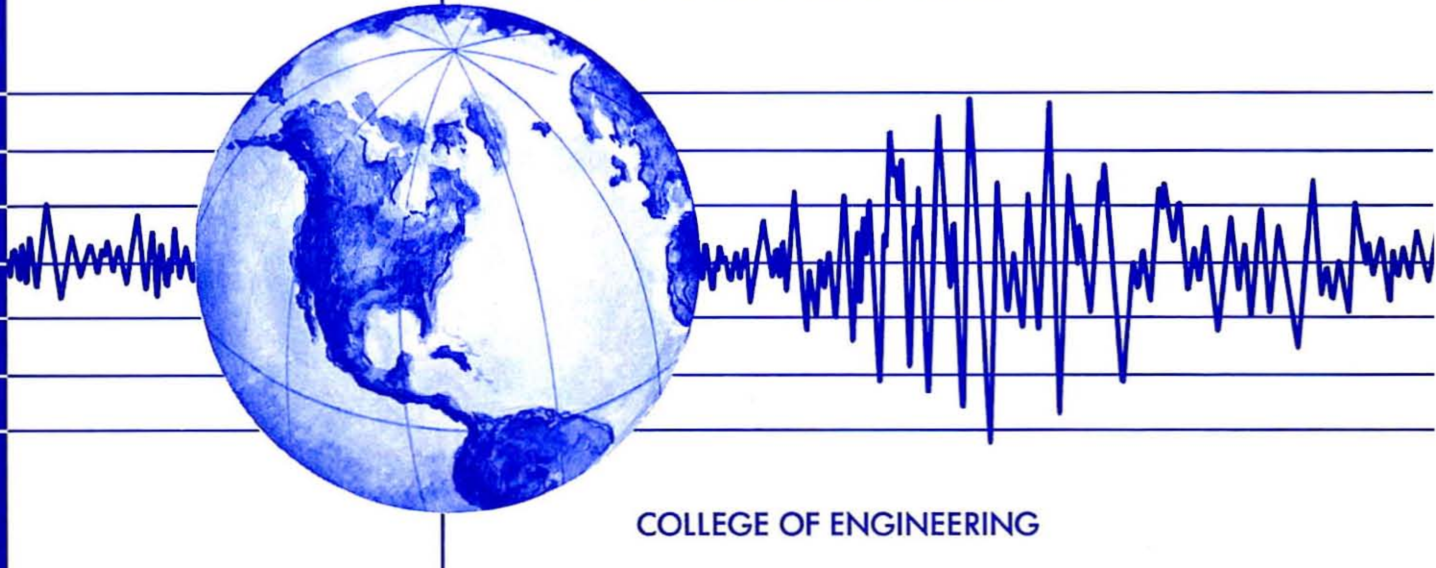
Report to the National Science Foundation



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ABSTRACT

The results of forced and ambient vibration studies of the dynamic behavior of a steel liquid storage tank with a diameter of approximately 115' and a height of 40' are presented. The water elevation in the tank was changing during the tests from 35'-6" to 38'0". Frequency response curves were determined from the ambient vibration tests; resonant frequencies, associated viscous damping factors, vertical and circumferential mode shapes, at 10' height in radial and tangential direction, from the forced vibration tests. Especially for the lower order modes significant radial and vertical (rocking motion) displacements at the base were observed.

1. INTRODUCTION

1.1 General

The design of structures subjected to dynamic forces resulting from foundation motions requires a consideration of both the characteristics of the ground motion and the dynamic properties of the structure. Ground motions as caused by an earthquake are random and, although not prescribable for aseismic design, have been fairly well studied for past earthquakes. The engineer is therefore mainly interested in the dynamic properties of the structure when designing for earthquake forces and is only indirectly concerned with the ground motion characteristics.

In order to accumulate a body of information on the dynamic properties of structures, especially when these structures have novel design features, a number of dynamic tests have been conducted on full-scale structures. The accuracy of available computer formulations has been assessed by comparing calculated and experimental results (Ref. 1,2,3,4).

This report describes the dynamic tests using forced and ambient vibrations of a broad water storage tank. Of the limited information on the earthquake response of liquid storage tanks what is available, only their qualitative behavior is known, demonstrating the need for experimental studies.

The tank is described in Chapter 2, and the results of the dynamic tests, from forced, as well as ambient vibration study, are given in Chapters 3 and 4, respectively.

1.2 Acknowledgement

The authors gratefully acknowledge the financial support by the National Science Foundation under Grant PFR-7908257. They also wish to thank the East Bay Municipal Utility District for making the tank available for this experimental study. They would especially like to thank Mr. John W. Houlihan of the engineering staff and Mr. D. P. Petersen of the operations staff for their cooperation and assistance in coordinating and carrying out the test program.

2. DESCRIPTION OF THE TANK

2.1 General

The investigated tank, Berkeley View No. 2 Reservoir (Fig. 2.1), forms together with a concrete tank, Berkeley View No. 1 Reservoir, a water storage unit for the city of Berkeley, CA. The tank is operated by East Bay Municipal Utility District (EBMUD), Oakland, CA and could not be taken out of the water supply system during the tests in July and August 1979.

2.2 Architectural Layout

The inner diameter of the cylindrical steel tank is 114'-10". The 40' high shell is constructed of welded steel plates of 8' height in five layers. The height to radius ratio is therefore 0.70 and the tank can be classified according to Ref. 5 as a broad tank. The roof, also built with thin welded steel plates, and supported by an internal structural frame, rests on the shell where bent steel plates (radius = 3'-0 $\frac{3}{16}$") provide a smooth connection to the roof. The roof is inclined at a ratio of 3/4" per foot (Fig. 2.2). Architectural elements, two vertical 6" diameter aluminum pipes, are positioned on twelve locations around the perimeter of the wall. Seventeen columns carry the weight of the roof as shown in Fig. 2.3. The locations of the valve pit with water-level indicator, the inlet-outlet, overflow and drain line are also shown in Fig. 2.3. The floor of the tank is comprised of ¼" steel plates which rest on dense graded aspalt concrete. The steel shell is supported on a ring footing which is shown in the floor detail in Fig. 2.4.

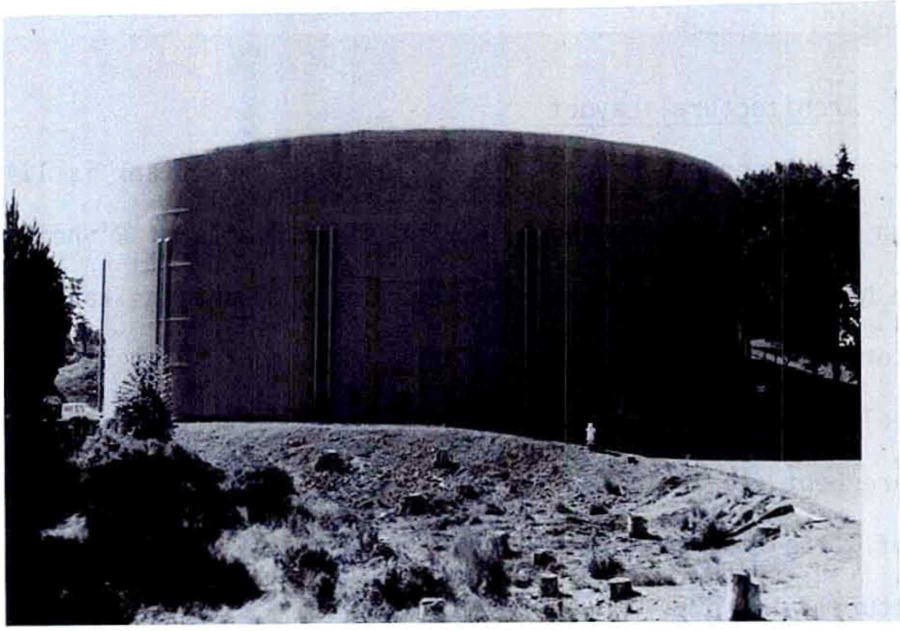

FIG. 2.1 BERKELEY VIEW NO. 2 RESERVOIR

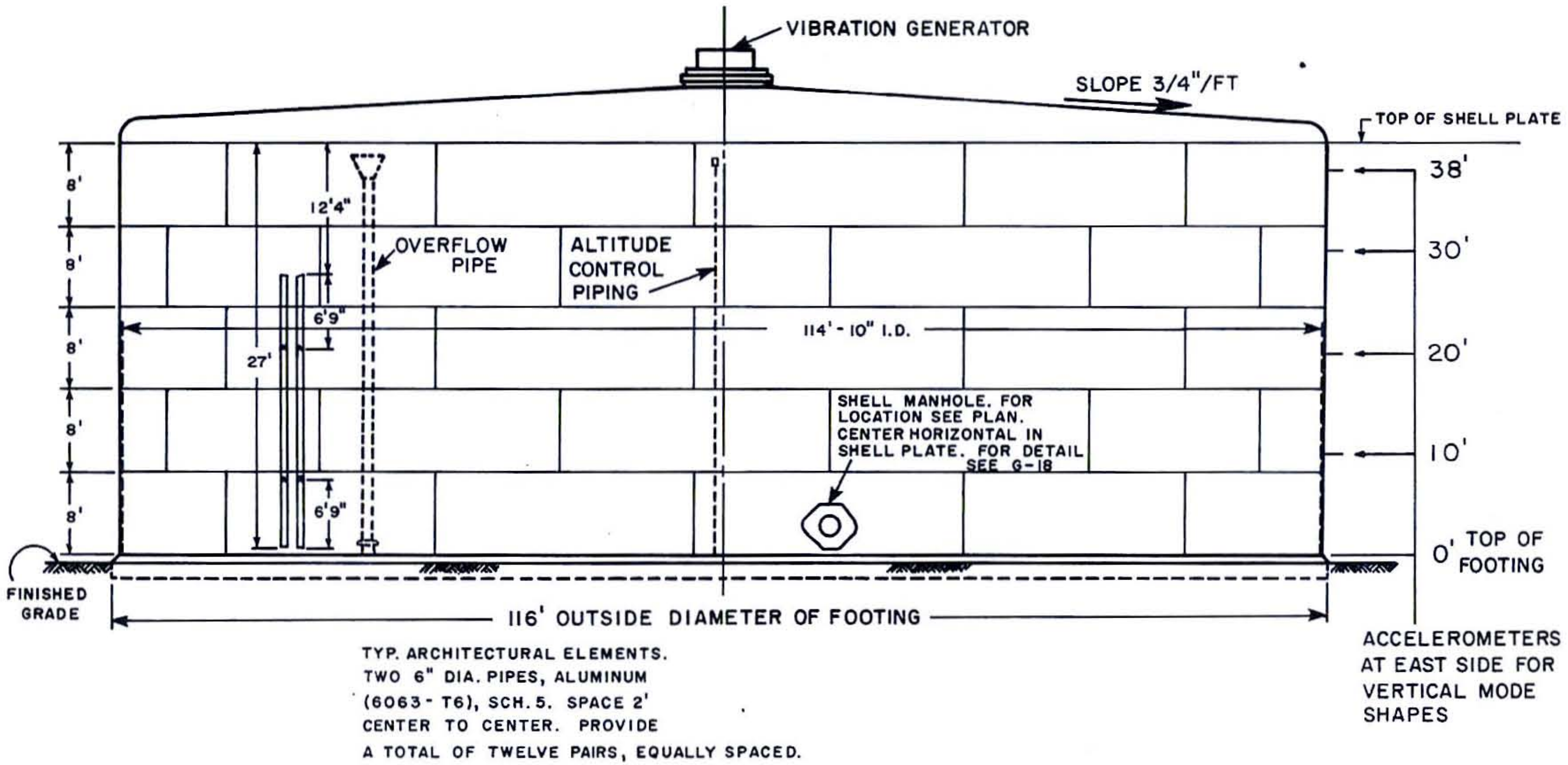

FIG. 2.2 ELEVATION OF TANK

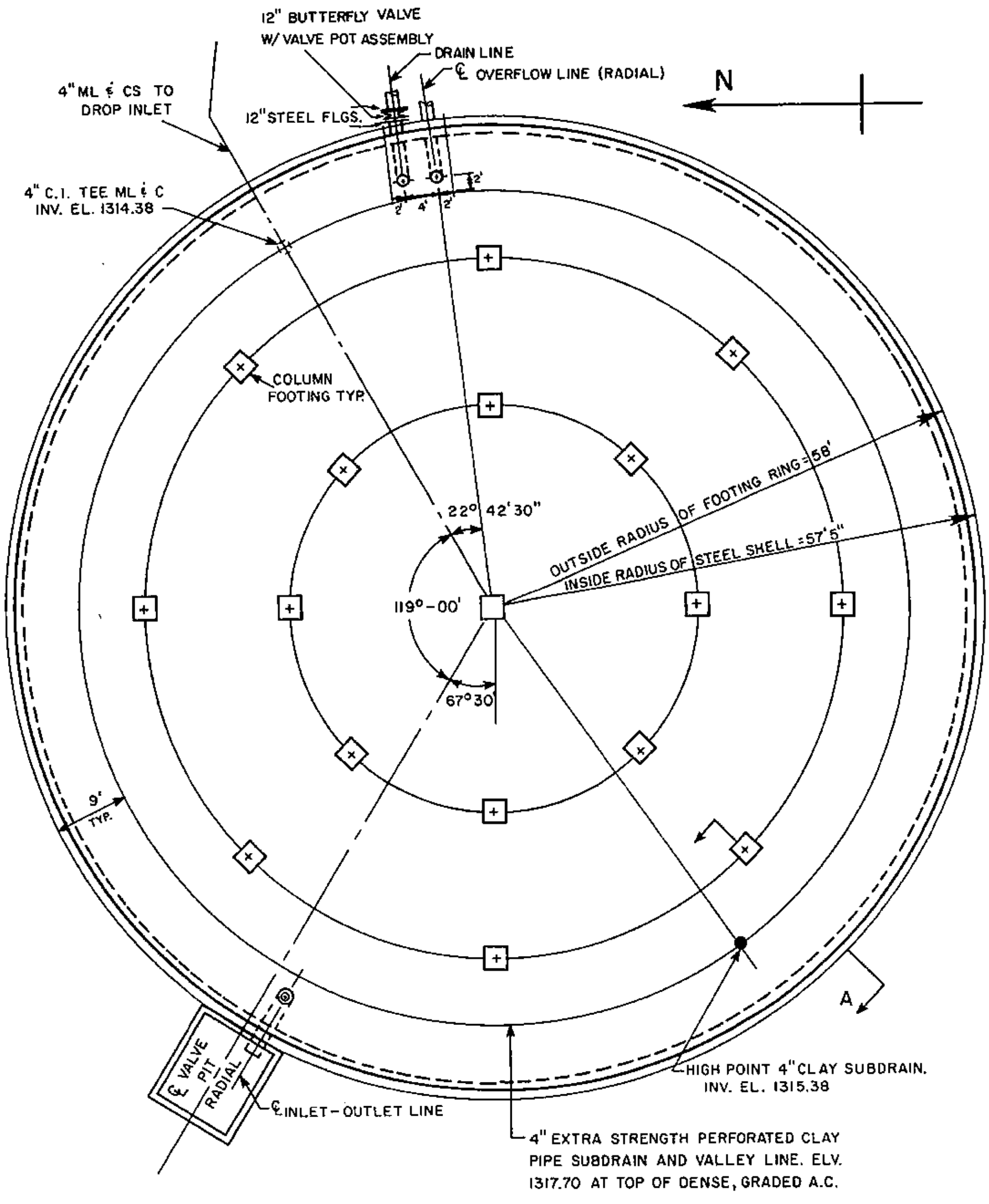

FIG. 2.3 FLOOR PLAN OF TANK

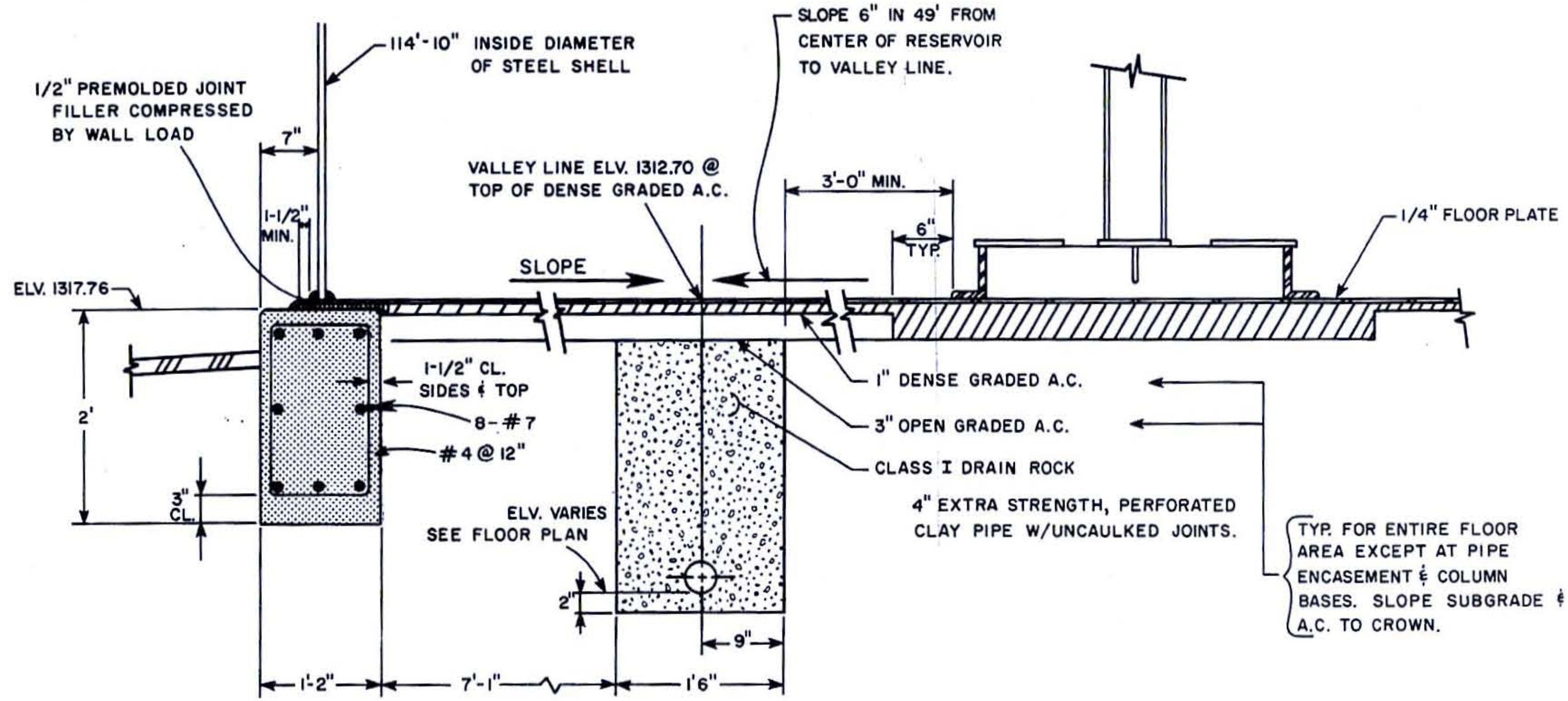

FIG. 2.4 F1OOR DETAIL WITH FOOTING RING

3. FORCED VIBRATION STUDY

3.1 General

The forced vibration study was carried out and completed during July and August 1979. The tank is part of the water supply system for the East Bay and because the tank could not be isolated in the system the water level was changing throughout the test program. The experimental apparatus employed in the dynamic test is decribed below. The general experimental procedures, equipment used, and procedures for data reduction applied, for forced vibration study conducted are also described. Finally, the experimental results are presented and discussed.

3.2 Experimental Apparatus

The experimental apparatus employed in the tests were one vibration generator, five accelerometers and equipment for the measurement and recording of the frequency responses. The apparatus is described in the following sections.

3.2.1 Vibration Generator

Forced vibrations were produced by a rotating-mass vibration generator or shaking machine, which is shown in Fig. 3.1 This machine was developed at the California Institute of Technology under the supervision of the Earthquake Engineering Research Institute for the Office of Architecture and Construction, State of California. The machine consists of an electronic motor driving two pie-shaped baskets or rotors, each of which produces a centrifugal force as a result of the rotation. The two rotors are mounted on a common vertical shaft and rotate in opposite directions so that the resultant of their centrifugal forces in a sinusoidal rectilinear force. When the baskets are lined up, a peak value of the sinusoidal force will be exerted.

The structural design of the machine limits the peak value of force to 5,000 lbs. This maximum force may be attained at a number of combinations of eccentric mass and rotational speed, since the output force is proportional to the square of the rotational speed as well as the mass of the baskets and the lead plates inserted in the baskets. The maximum force of 5,000 lbs can be reached for a minimum rotational speed of 2.5 cps when all the lead plates are placed in the baskets. At higher speeds the eccentric mass must be reduced in order not to surpass the maximum force of 5,000 lbs. The maximum operating speed is 10 cps, and the minimum practical speed is approximately 0.5 cps. At 0.5 cps with all lead plates in the baskets, a force of 200 lbs. can be generated. The relationship between output force and frequency of rotation of the baskets for different basket loads is shown in Fig. 3.2. A complete description of the vibration generator is given in Ref. 6.

3.2.2 Accelerometers

The transducers used to detect horizontal floor accelerations of the tank were Statham Model A39TC linear accelerometers, with a maximum rating of $\pm$ 5g.

3.2.3 Equipment for Measurement of Frequency

For the vibration generators, the vibration excitation frequencies were determined by measurement of the speed of rotation of the electric motor driving the baskets. A tachometer, attached to a rotating shaft driven by a transmission belt from the motor, generated a sinusoidal signal of frequency 300 times the frequency of rotation of the baskets. Hence, the maximum accuracy of frequency measurements was $\pm$ 1 count in the total number of counts in a period of 1 second (the gating period), i.e., $\pm$ 1/3 of 1% at 1 cps and $\pm$ 1/9 of 1% at 3 cps.

3.2.4 Recording Equipment

The electrical signals for all accelerometers were fed to amplifiers and then to a Honeywell Model 1858 Graphic Data Acquisition System with 8-in. wide chart. In frequency-response tests, the digital counter reading was observed and recorded manually on the chart alongside the associated traces. Because of the presence of high frequency vibrations the graphic data acquisition system could not be used to measure the magnitude of the response accelerations, but only to determine the relative phase relationship. To eliminate the high frequency vibrations the signals were fed from the graphic data acquisition system into a Rockland FFT 512/S Real-Time Spectrum Analyzer. This unit is a single unit analyzer with 512 spectral lines calculated but only 400 lines displayed to reduce aliasing errors. Twelve analysis ranges are provided from 0-2 cps to 0-10000 cps. The frequency range was set typically to 0-10 cps.

3.3 Experimental Procedure and Data Reduction

The quantities normally determined by a dynamic test of a structure are: resonant frequencies, mode shapes, and damping capacities. The experimental procedures and reduction of data involved in determining these quantities are described in the next section.

3.3.1 Resonant Frequencies

With the equipment described on the previous pages, resonant frequencies were determined by sweeping the frequency range of the vibration generator from 0 to 4 cps and observing the tank response at the 10 ft height in the radial direction on the south side for N-S forcing and on the east side for E-W forcing. Each time the frequency was set to a particular value the vibration response was given sufficient time to become steady-state, before the acceleration signals were transformed into the frequency domain by the

Rockland FFT 512/S Real-Time Spectrum Analyzer and measured. At the same time, the frequency of vibration, as recorded on a digital counter, was recorded. Plotting the vibration response at each frequency step resulted in the frequency-response curve.

Frequency-response curves in the form of acceleration amplitude versus exciting frequency may be plotted directly from the data on the recording chart. However, the curves are for a force which increases with the square of the exciting frequency, and each acceleration amplitude should be divided by the corresponding square of its exciting frequency to obtain so-called normalized curves equivalent to those for a constant force (assuming linear stiffness and damping for the structural system). If the original acceleration amplitudes are divided by the frequency to the fourth power, displacement frequency-response curves for constant exciting forces are obtained.

3.3.2 Mode Shapes

Once the resonant frequencies were found the mode shapes at each of these frequencies were determined for forcing in E-W direction. In this case, with five accelerometers available it was decided to evaluate radial and tangential components of the circumferential mode shapes by measuring the accelerations at four locations in each quandrant and keeping one accelerometer as a reference always on the east side. Measurements for the vertical mode shape were made on the east side at heights of 10 ft, 20 ft, 30 ft, and 28 ft. The radial tangential and vertical motion of the tank at the base was measured on the east side with reference to the accelerometer at 10 ft, also on the east side, again E-W forcing.

3.3.3 Damping Capacities

Damping capacities may be found from resonance curves in the normalized frequency-response curves by the formula:

$$\xi = \frac{\Delta f}{2f}$$

where

ξ = damping factor,

f = resonant frequency,

Δf = difference in frequency of the two points on the resonance curve with amplitudes of $1/\sqrt{2}$ times the resonant amplitude.

Strictly, the expression for ξ is only applicable to the displacement resonance curve of a linear, single degree-of-freedom system with a small amount of viscous damping. However, it has been used widely for systems differing appreciably from that for which the formula was derived, and it has become accepted as a reasonable measure of damping. In this respect, it should be remembered that in the case of full-size civil engineering structures, it is not necessary to measure damping accurately in a percentage sense. It is sufficient if the range in which an equivalent viscous damping coefficient lies is known. Meaningful ranges might be defined as: under 1%, 1-2%, 2-5%, 5-10% over 10% (Ref. 1).

3.4 Experimental Results

The vibration generator was bolted to two E-W oriented wide flanges and these were fixed with bolts to the roof access hatch as illustrated in Fig. 2.1. With the experimental apparatus as described previously the frequency response of the tank was observed in the range from 0 to 4 cps on the south side for N-S forcing and on the east side for E-W forcing radially at the 10 feet height. Forcing in the N-S direction, thus carrying the exciting forces of the vibration generator over the weak axis of the wide flanges to the roof plate resulted in a rocking motion of the generator. Therefore the frequency search was repeated for E-W forcing and, consequently, without rocking of the generator. For both, N-S and E-W forcing, little or no response was observed below 2.5 cps. It is not possible to generate large enough exciting forces below 0.5 cps and therefore the sloshing mode, whose frequency was calculated using Housner's mechanical analog (Ref. 5) to be 0.13 cps, could not be excited.

Whereas the frequency response curve for the south side for N-S forcing (Fig. 3.3) has a distinct peak of 2.70 cps, the response curves for the east side (Fig. 3.4) for E-W forcing are ambiguous at this frequency. Possible explanations for this behavior may be the nonlinear behavior of the tank and the smaller exciting forces for N-S forcing (392 lbs and 2392 lbs) than for E-W forcing (3392 lbs). Both graphs indicate after low values from 2.80 to 3.05 cps an increase in the response with a peak around 3.33 cps. The frequency search had to be stopped around 4 cps because of intolerable rocking of the vibration generator and loud rattling sounds of the roof plates. From the frequency response curves (Figs. 3.3 and 3.4) it can be easily observed that the curves are different, even for the same exciting forces, in magnitude, shape and the resonance frequencies. Possible reasons for this are the:

1.) changing water level in the tank throughout the test program (from 35'-6" to 38') with resulting change in the roundness of the tank;
2.) temperature changes of the tank shell (from approximately 45 to 190 degree Fahrenheit);
3.) large exciting forces that deformed the tank in the non-linear range (comparatively smooth frequency response curve for empty baskets and N-S forcing);
4.) test set-up. The vibration generator was fixed to the very flexible tank roof.

Viscous damping factors were determined for the E-W forcing between 0.4% and 0.8% for the peak around 2.7 cps and from 0.4% to 1.2% for the peak around 3.33 cps. The damping factors are indicated for the corresponding curves in Fig. 3.4.

Because of the changing water level and therefore shifting resonant frequencies the circumferential modes shapes, vertical mode shapes and the motion at the base are not associated with one distinct frequency but rather with a frequency range as indicated in Fig. 3.4.

The modes of a cylindrical tank can be described by two integer parameters, n, the number of circumferential waves and m, the number of vertical half waves (Ref. 7). For n = 1 the tank would behave like a vertical cantilever beam. Figure 3.5 illustrates the circumferential nodal pattern of these modes. The vertical mode shapes (Figs. 3.6 to 3.8) have all only one vertical half wave (m = 1). The radial and tangential components and their combinations for each mode, as recorded on 16 locations along the circumference are shown in Figs. 3.9 to 3.11. The lowest mode clearly is of fifth order (n = 5). The next higher mode (Fig. 3.10) is not so clear but seems to be of second order (n = 2). The highest mode (Fig. 3.11) is definitly of second order (n = 2). A comparison of radial and tangential motion (not to scale) is plotted under the letter (d) in Figs. 3.9 to 3.11. It can be observed that the number of circumferential waves, n, are the same for the radial and for the tangential components. The base motion for the three modes at the east side for E-W forcing is tabulated in Table 3.1 for the three modes. The signs are clarified in an attached sketch. The radial and vertical base motions for the fifth order mode (around 2.7 cps) are significantly lower than the base motion recorded for the two lower order modes when compared with the reference accelerometer at 10 feet in radial direction.

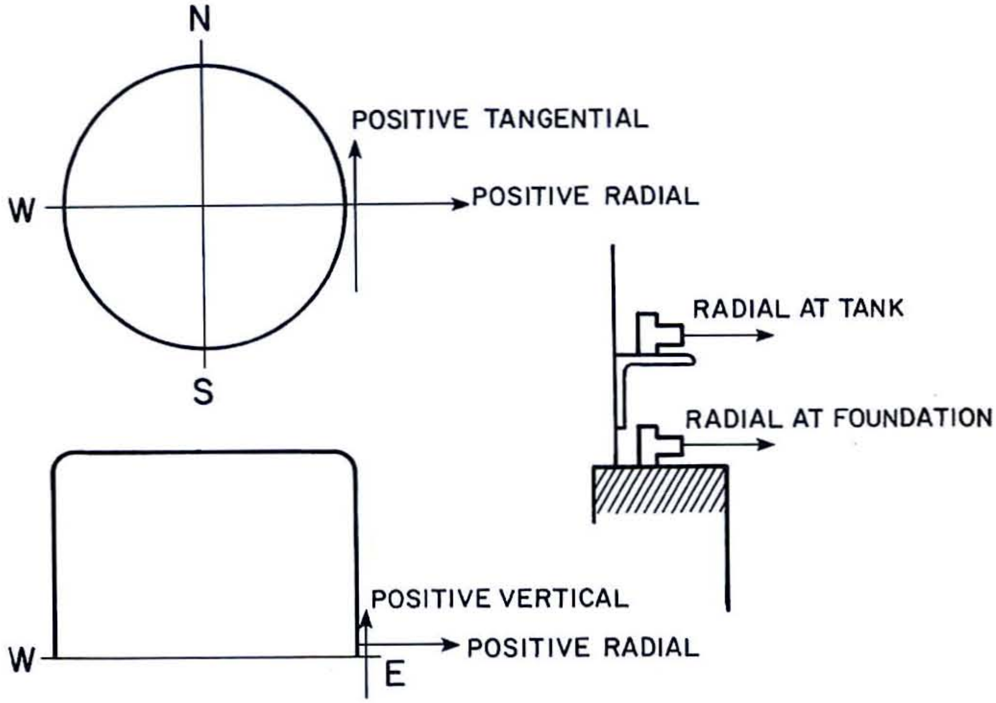

TABLE 3.1 Relative Base Motion at East Side for E-W Forcing
(Note: These are mv/v)

LOCATION	2.68 cps		3.13 cps		3.32 cps	
10' Radial	4.58-2	1.00	3.48-2	1.00	9.50-2	1.00
Base-Radial	0.34-2	0.07	0.88-2	0.25	1.78-2	0.19
Base-Tangential	+0.05-2	0.01	-0.41-2	-0.12	+0.12-2	0.01
Base-Vertical	-0.32-2	-0.07	-0.88-2	-0.25	-1.64-2	-0.18
Foundation-Radial	+0.09-2	0.02	-0.22-2	-0.06	0.44-2	0.05

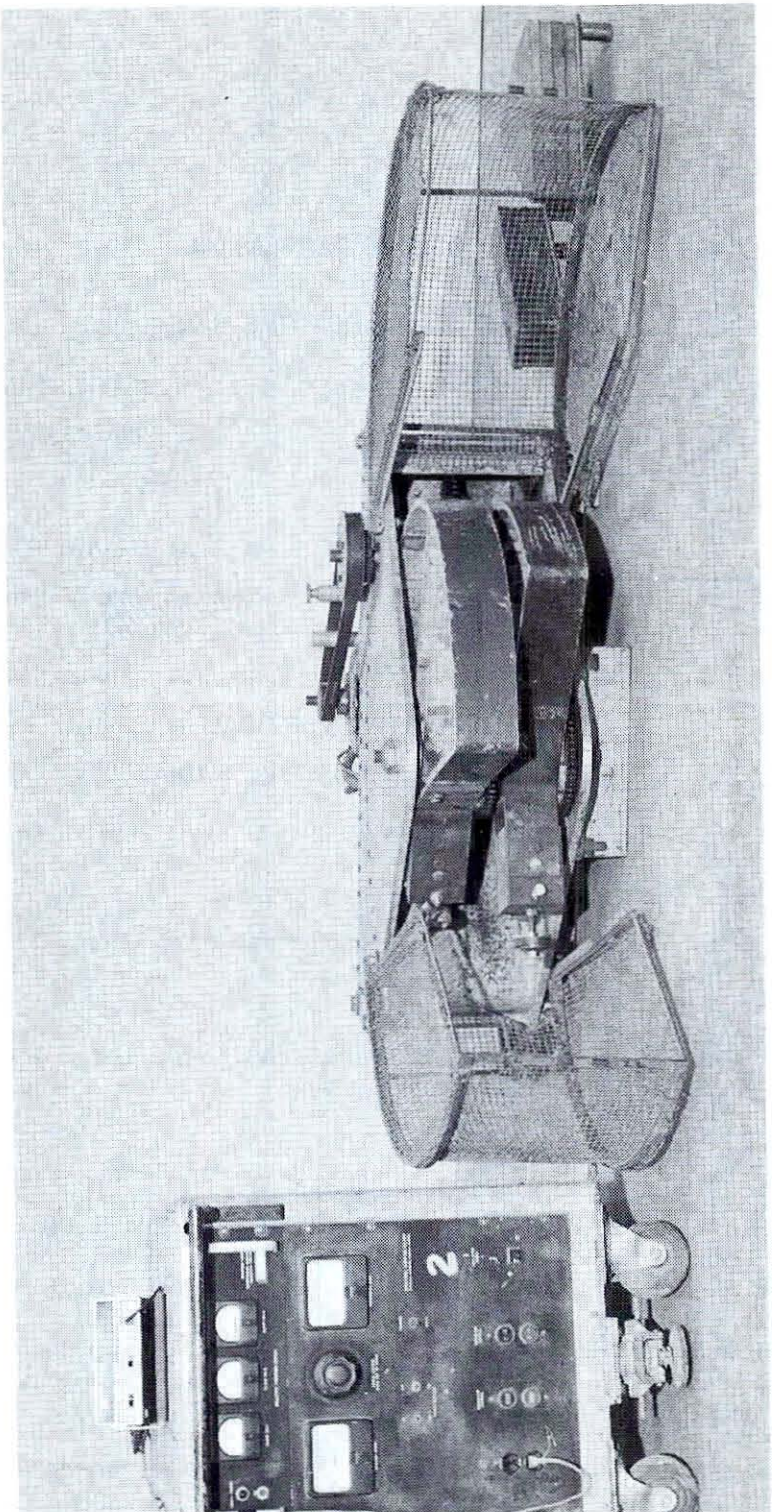

FIG. 3.1 VIBRATION GENERATOR

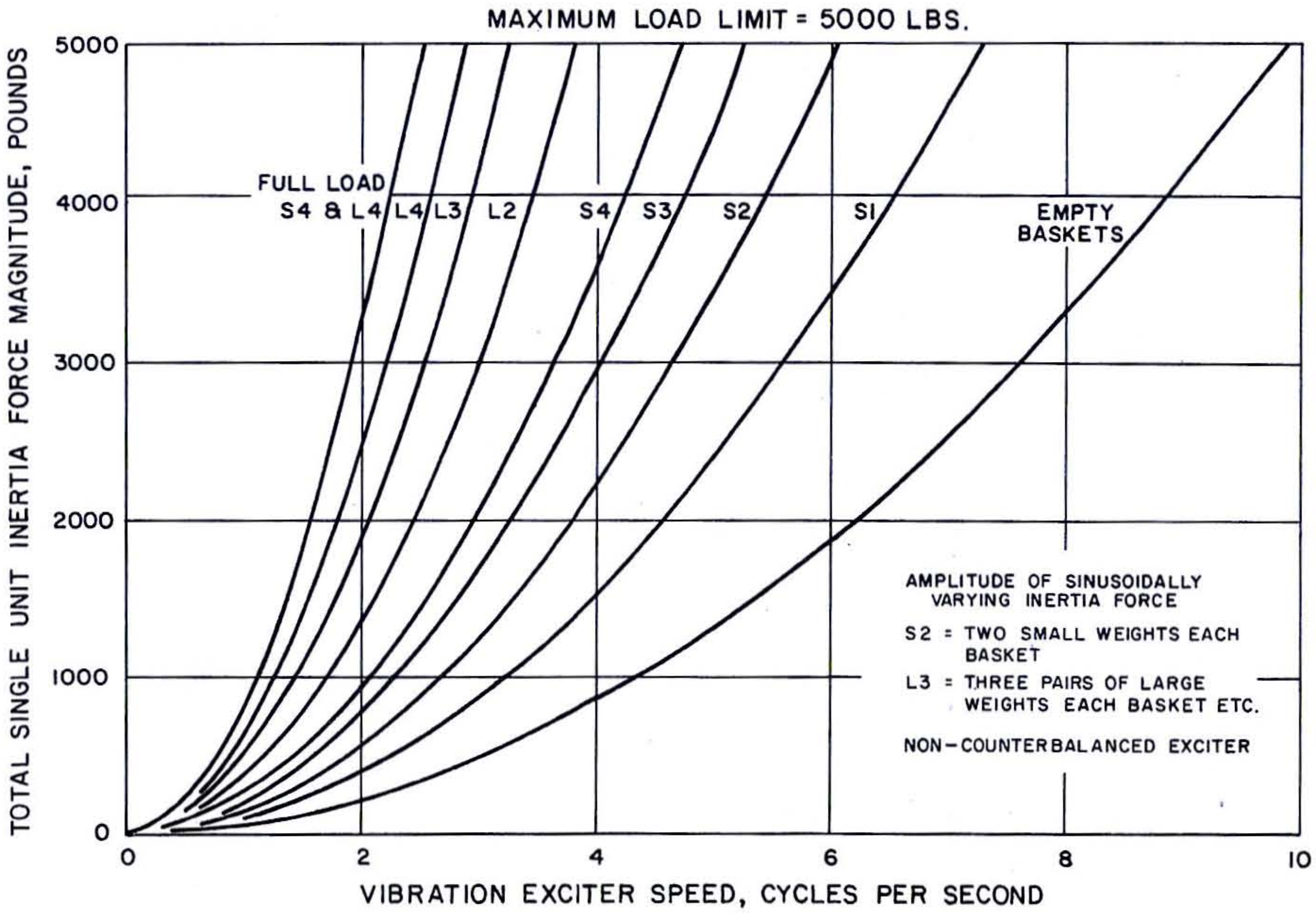

FIG. 3.2 VIBRATION FORCE OUTPUT VS. SPEED-NON-COUNTERBALANCED

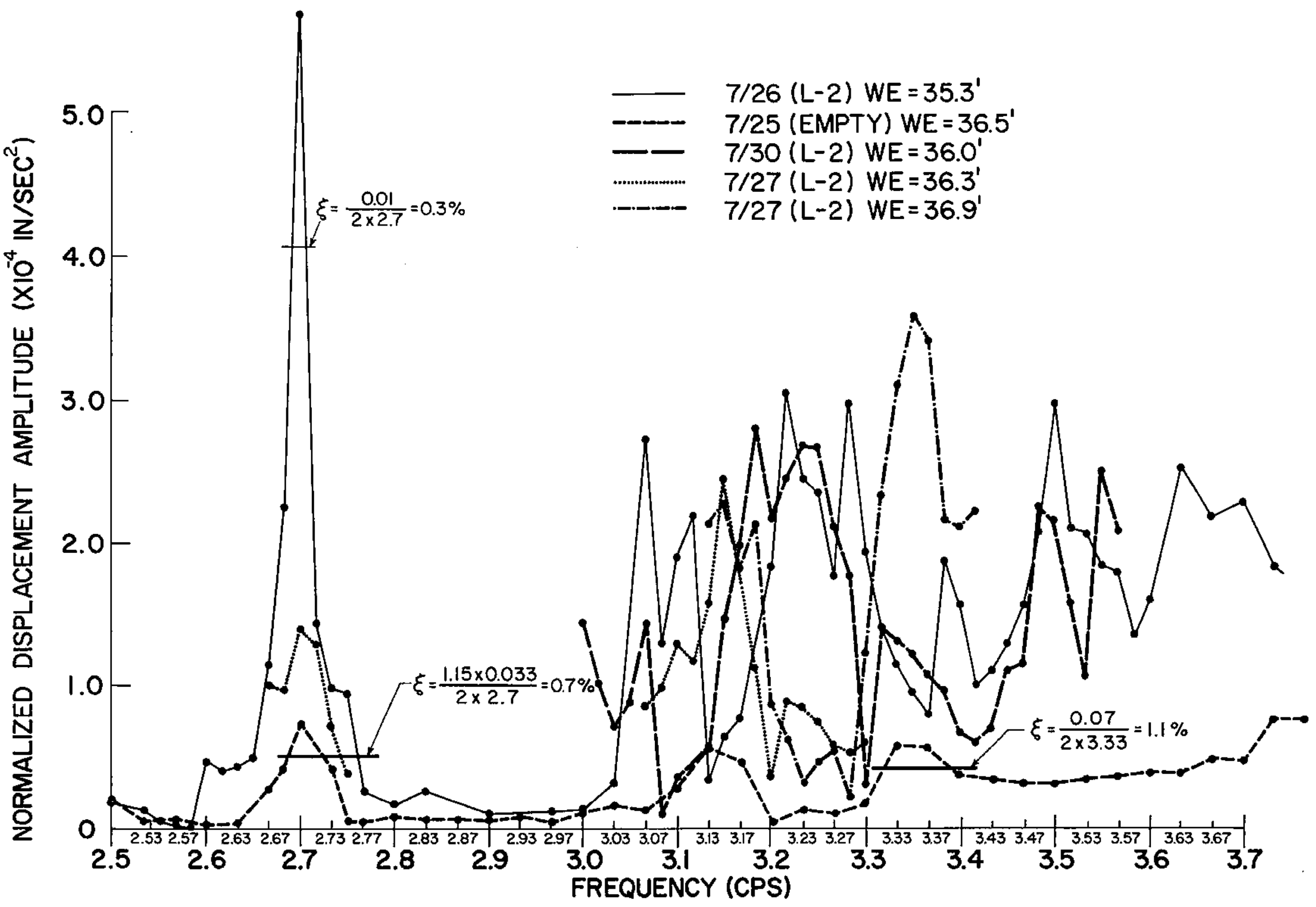

FIG. 3.3 NORMALIZED DISPLACEMENT FREQUENCY RESPONSE CURVES
(10' LEVEL, SOUTH SIDE, RADIAL)

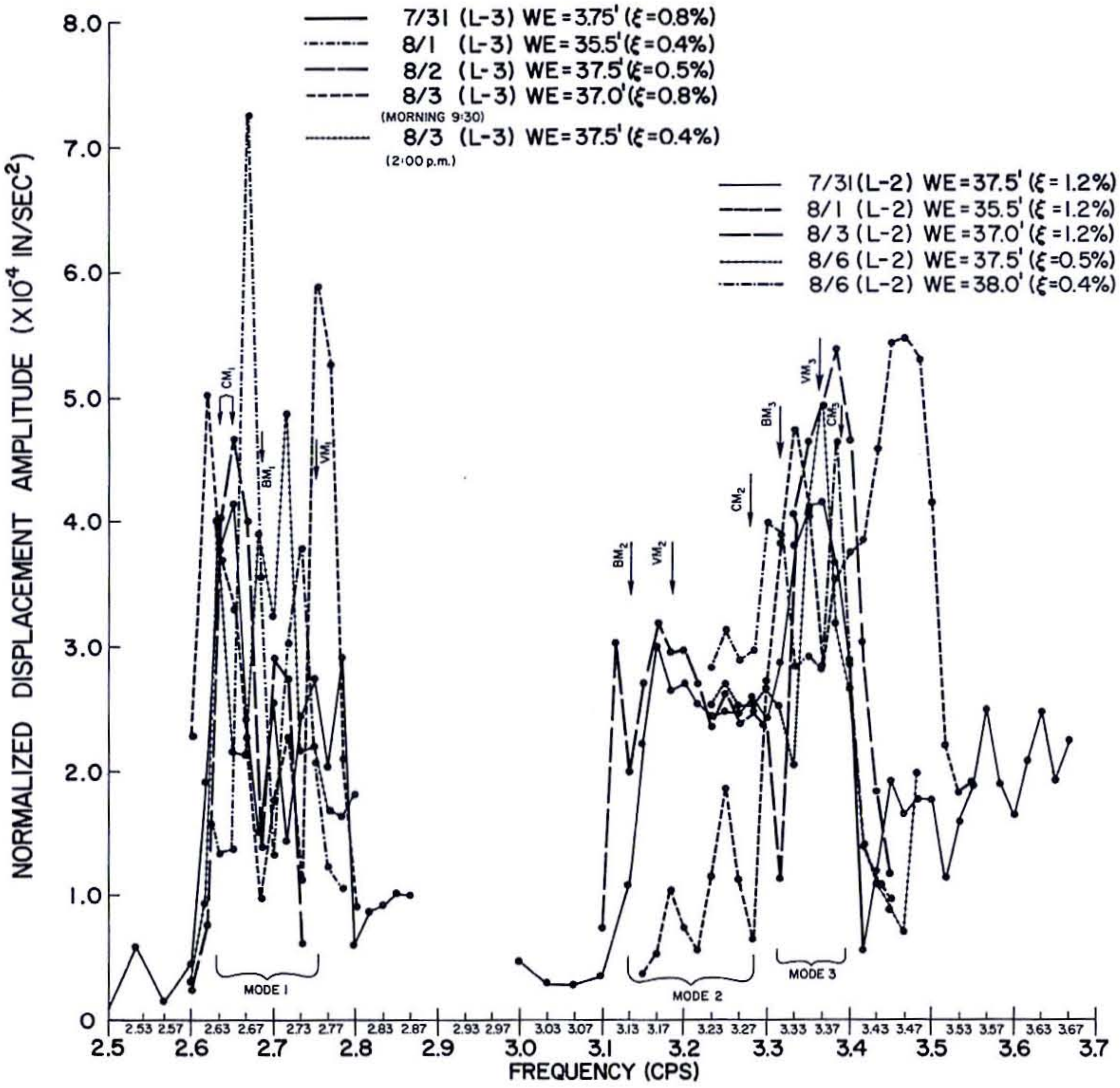

FIG. 3.4 NORMLAIZED DISPLACEMENT FREQUENCY RESPONSE CURVES
(10' LEVEL, EAST SIDE, RADIAL)

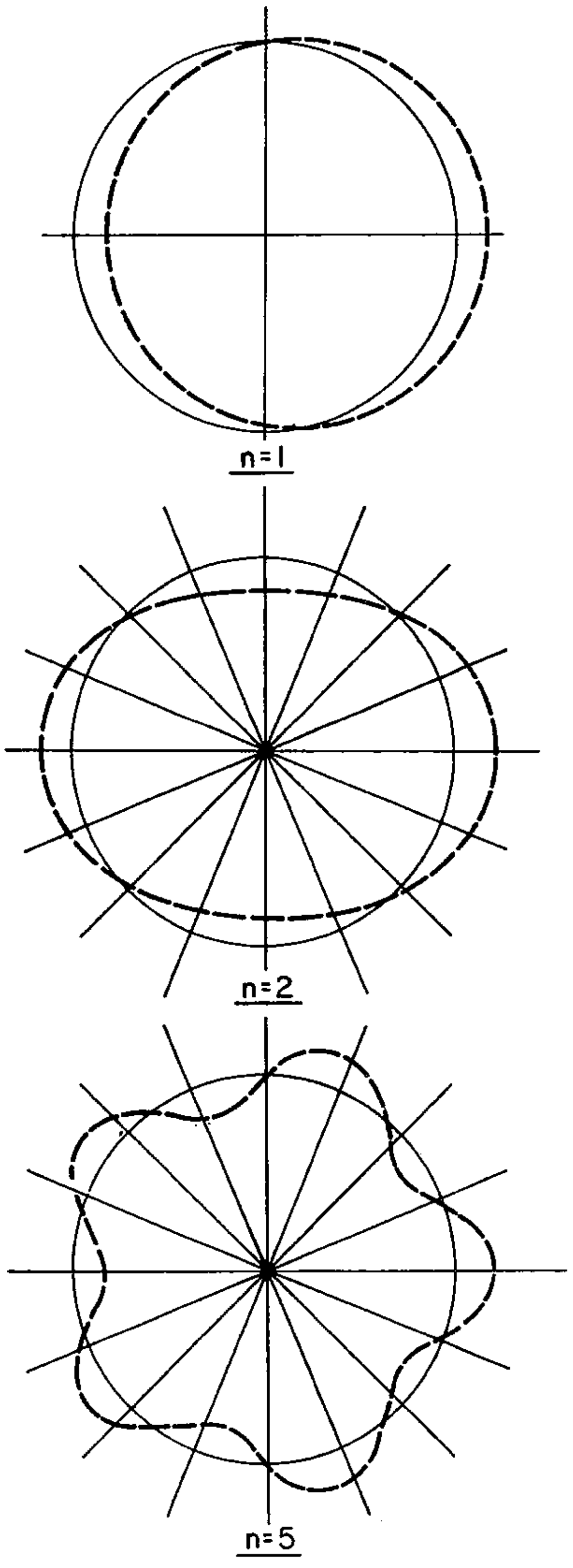

FIG. 3.5 CIRCUMFERENTIAL NODAL PATTERN OF THE VIBRATIONAL NODES OF CIRCULAR TANKS

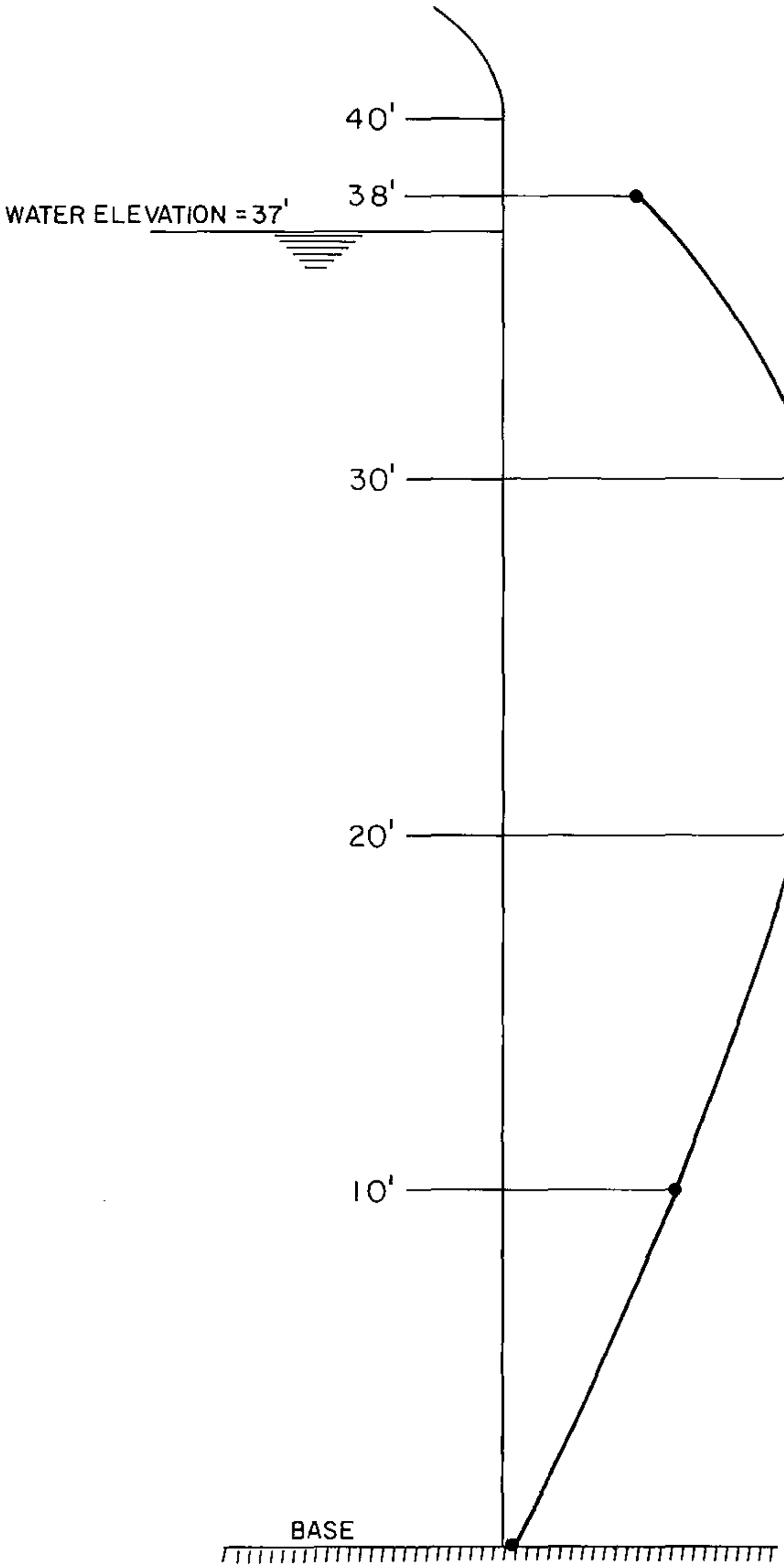

FIG. 3.6 VERTICAL MODE SHAPE 1 f = 2.75 cps

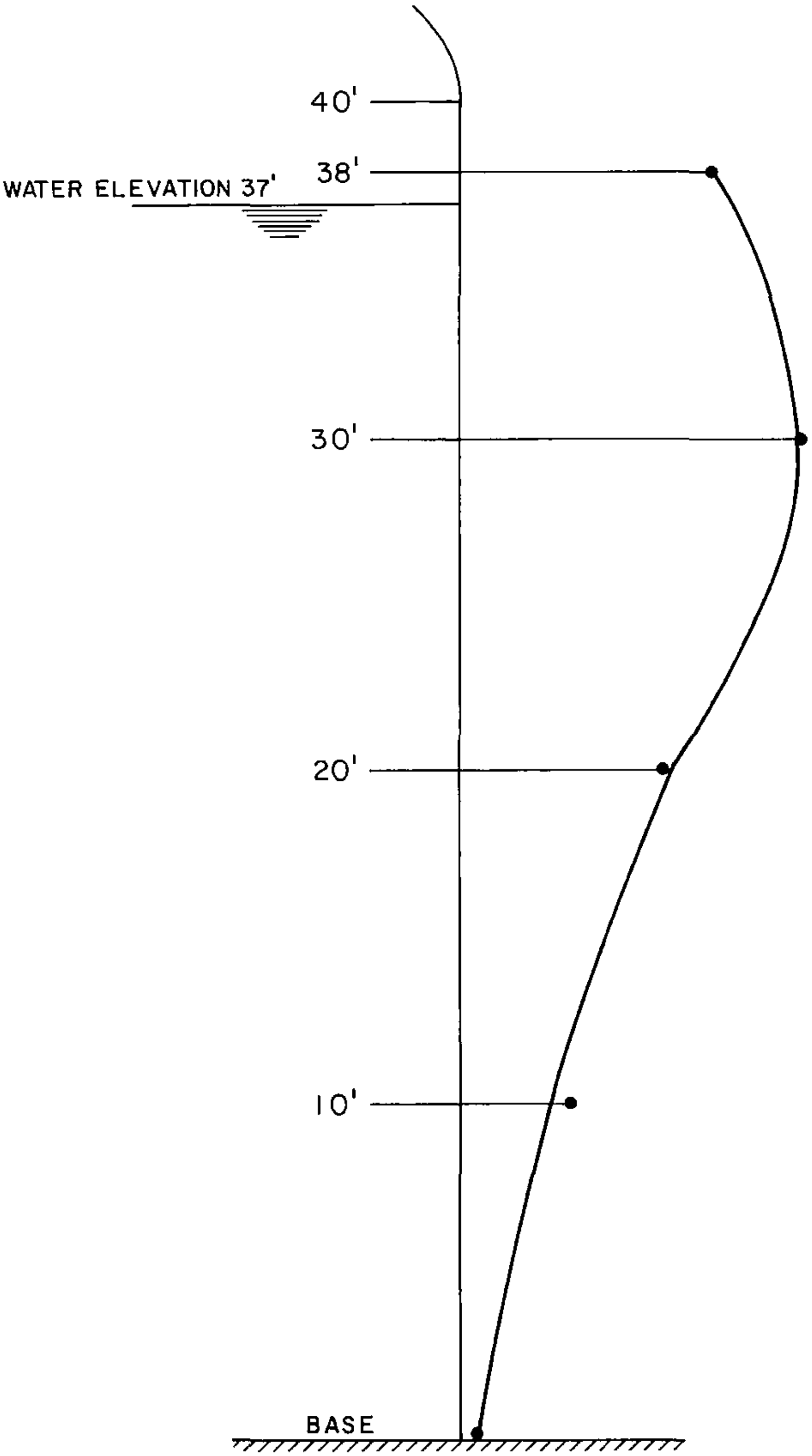

FIG. 3.7 VERTICAL MODE SHAPE 2 f = 3.18 cps

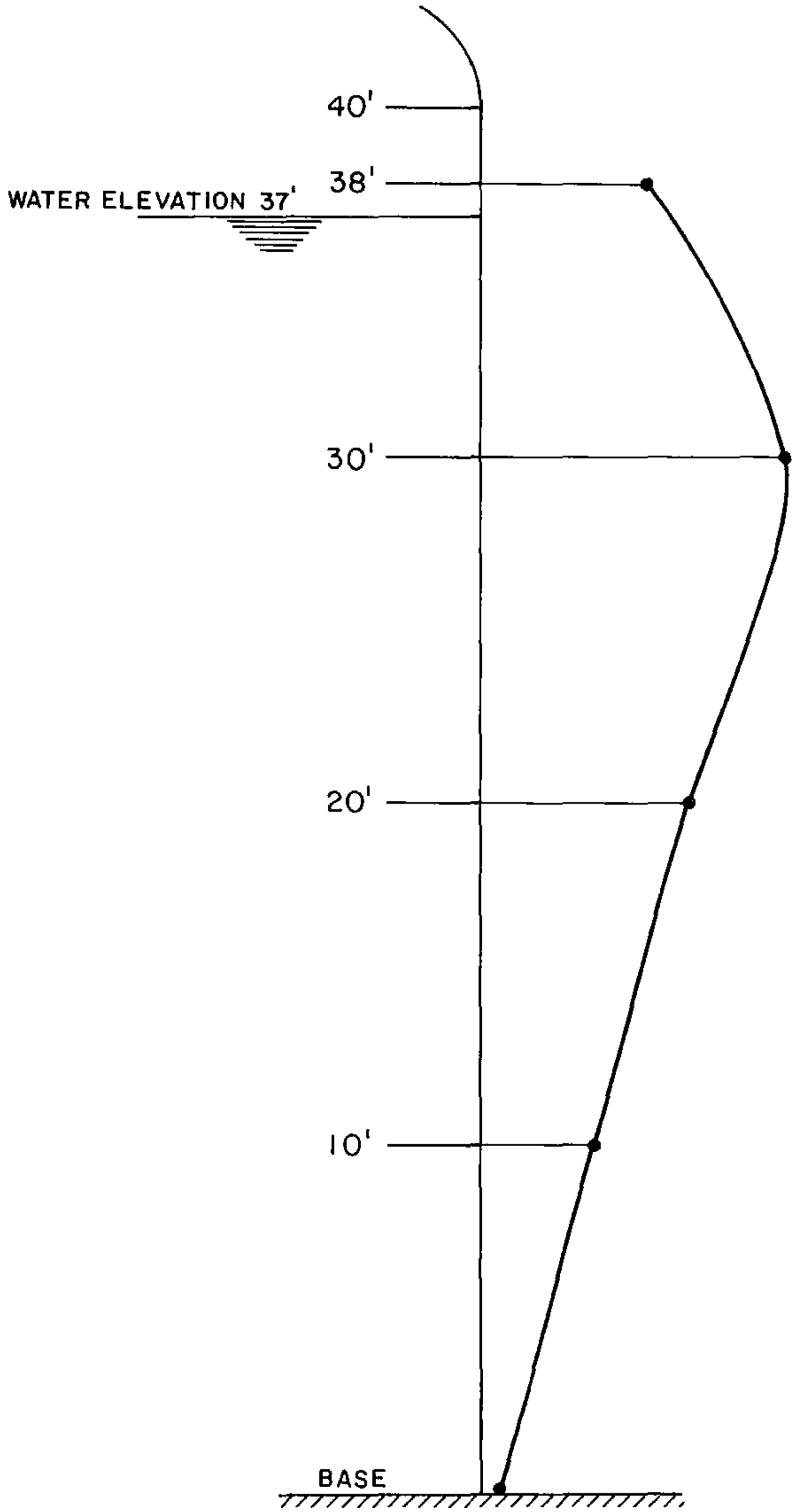

FIG. 3.8 VERTICAL MODE SHAPE 3 f = 3.37 cps

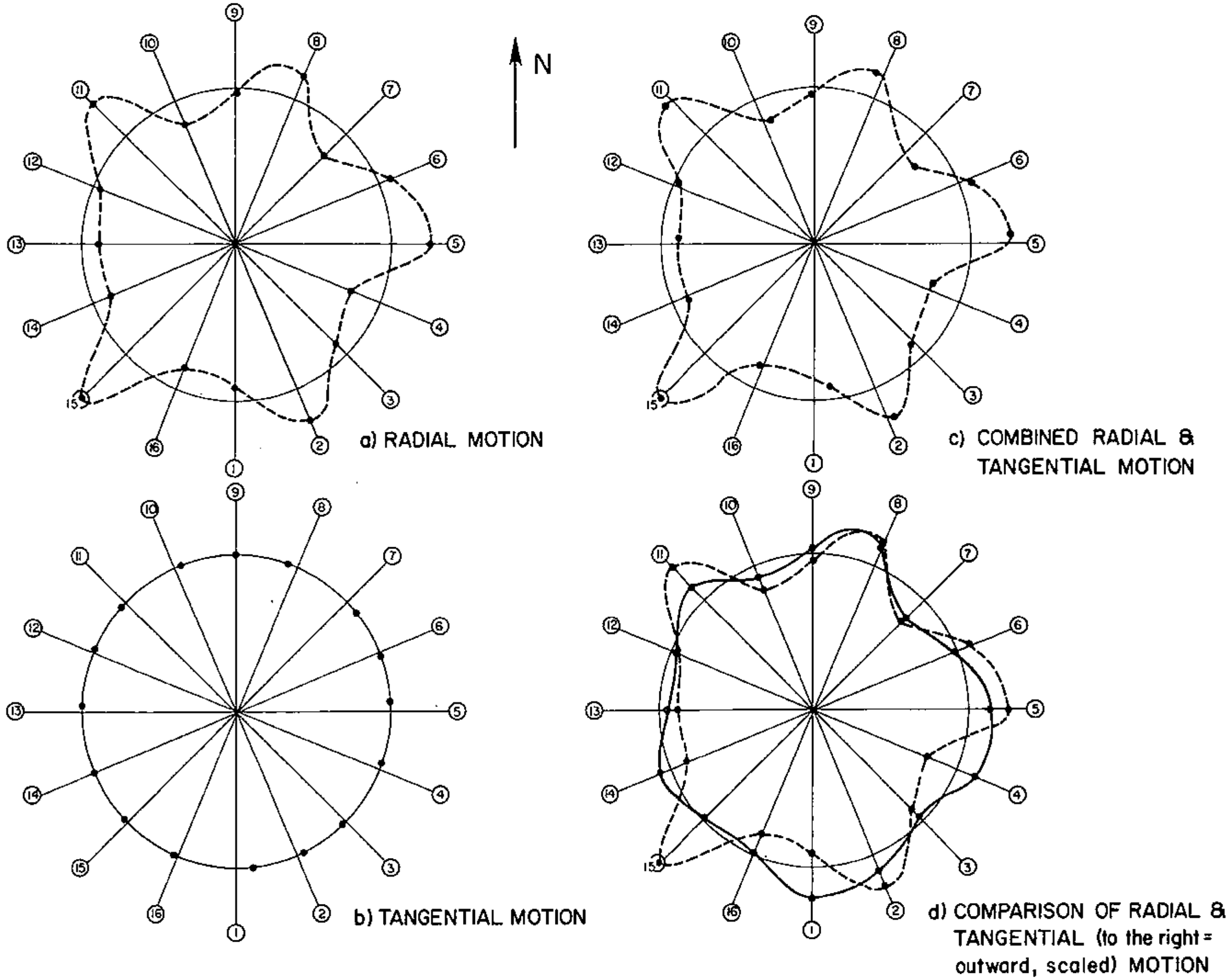

FIG. 3.9 MODE SHAPE 1 f = 2.65 cps

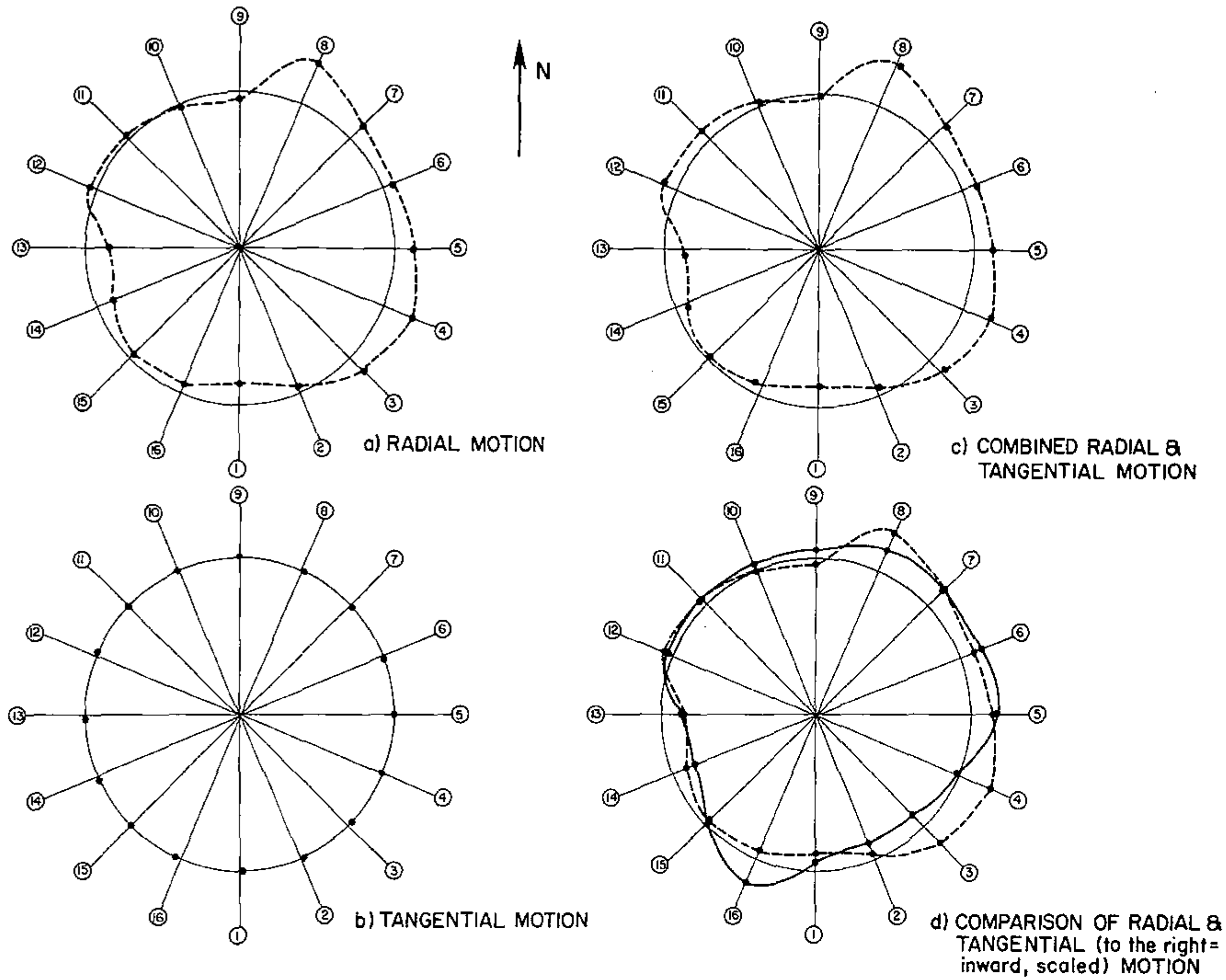

FIG. 3.10 MODE SHAPE f = 3.28 cps

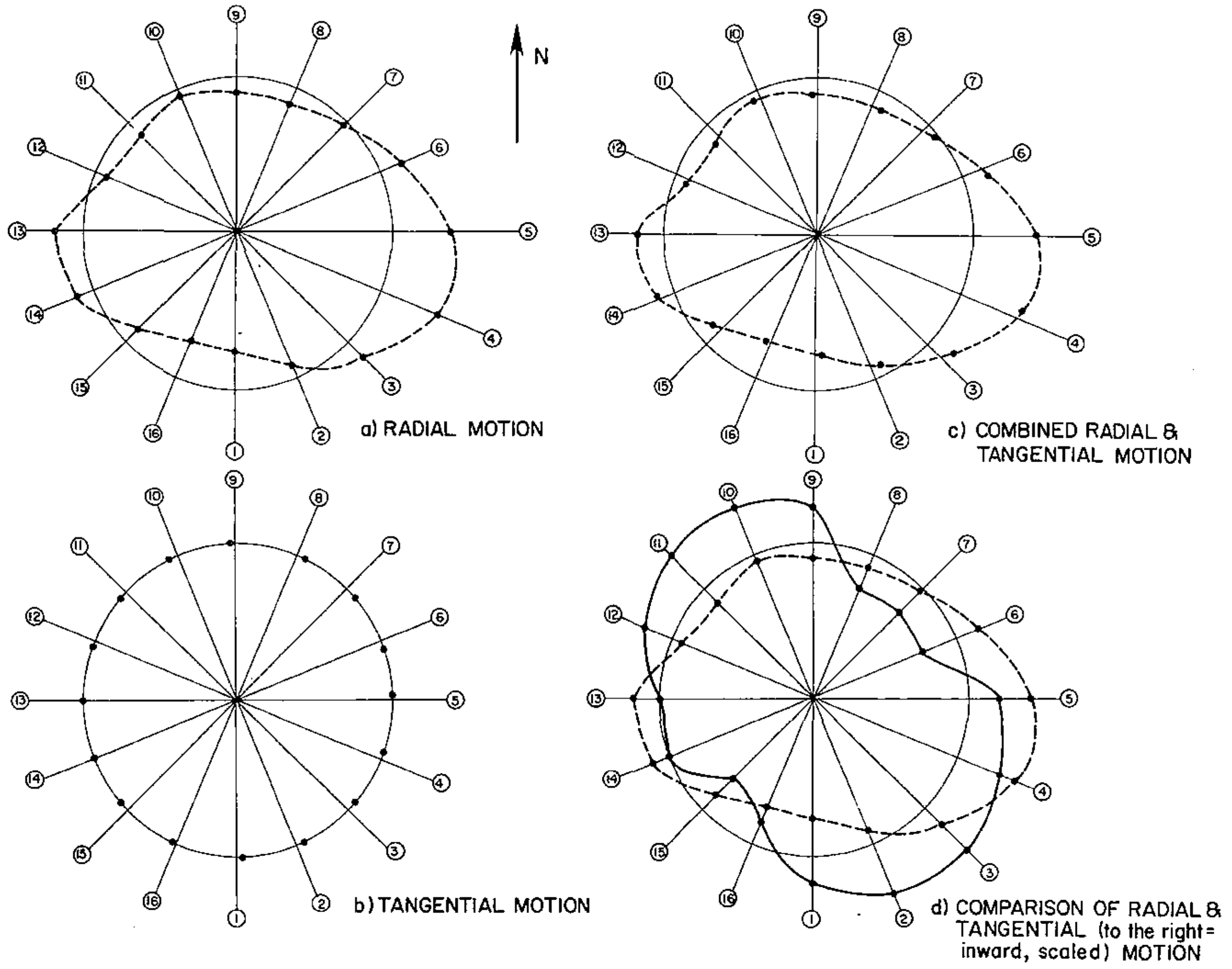

FIG. 3.11 MODE SHAPE f = 3.38 cps

4. AMBIENT VIBRATION TESTS

4.1 General

As an initial test an ambient vibration study of the tank was performed on July 18, 1978. The measuring equipment is described and the results are presented.

4.2 Measuring Equipment

The wind induced vibrations were measured using Kinemetrics Ranger Seismometers, Model SS-1. The seismometer has a strong, permanent magnet as the seismometer inertial mass moving within a stationary coil attached to the seismometer case. Small rod magnets at the periphery of the coil produce a reversed field which provides a destabalizing force to extend the natural period of the mass and its suspension.

The resulting seismometer frequency was 1 Hz. Damping was set at 0.7 critical. The output for a given velocity is a constant voltage at all frequencies greater than 1 Hz and falls off at 12 dB/octave for frequencies less than 1 Hz.

The Kinemetrics Signal Conditioner, Model SC-1 (Fig. 4.1) was used to amplify and control simulataneously four seismometer signals. The four input channels have isolated circuitry to integrate and differentiate the amplified input signal. All outputs are simultaneously or independently available for recording. A modification to the signal conditioner allows for outputing each channel separately or for taking the sum or difference on two channels and outputing the average of those channels. Each channel provides a nominal maximum gain of 100,000. An 18 dB/octave low pass filter is available with a cut-off frequency continuously selectable between 1 Hz and 100 Hz for each channel.

A Rockland FFT 512/S Real-Time Spectrum Analyzer was used in order to facilitate the rapid determination of the resonant frequencies.

4.3 Experimental Results of the Ambient Vibration Study

The Fourier amplitude response spectra as obtained from the Rockland FFT Analyzer for the radial motion as recorded at different locations on the base of the tank are presented in Figs. 4.1 to 4.2. The Fourier spectra shows peaks in the E-W direction at 2.90 cps, 3.85 cps, and 6.1 cps, and in the N-S direction at 2.90 cps, 3.25 cps, 3.75 cps and 6.2 cps. The difference in the resonant frequencies obtained from forced vibrations (2.70 cps and approximately 3.33 cps) may be due to the strong non-linear behavior of the tank under large excitation.

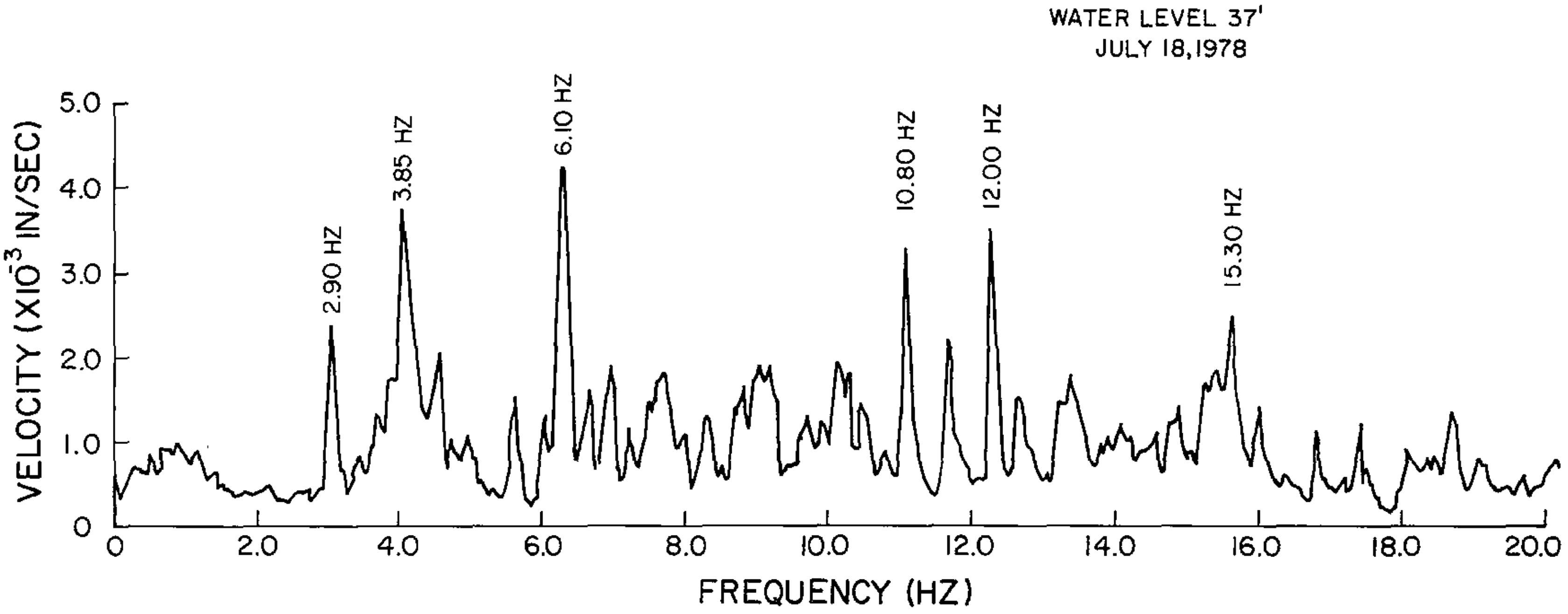

FIG. 4.1 AMBIENT VIBRATION FREQUENCY RESPONSE CURVE-RADIAL E-W

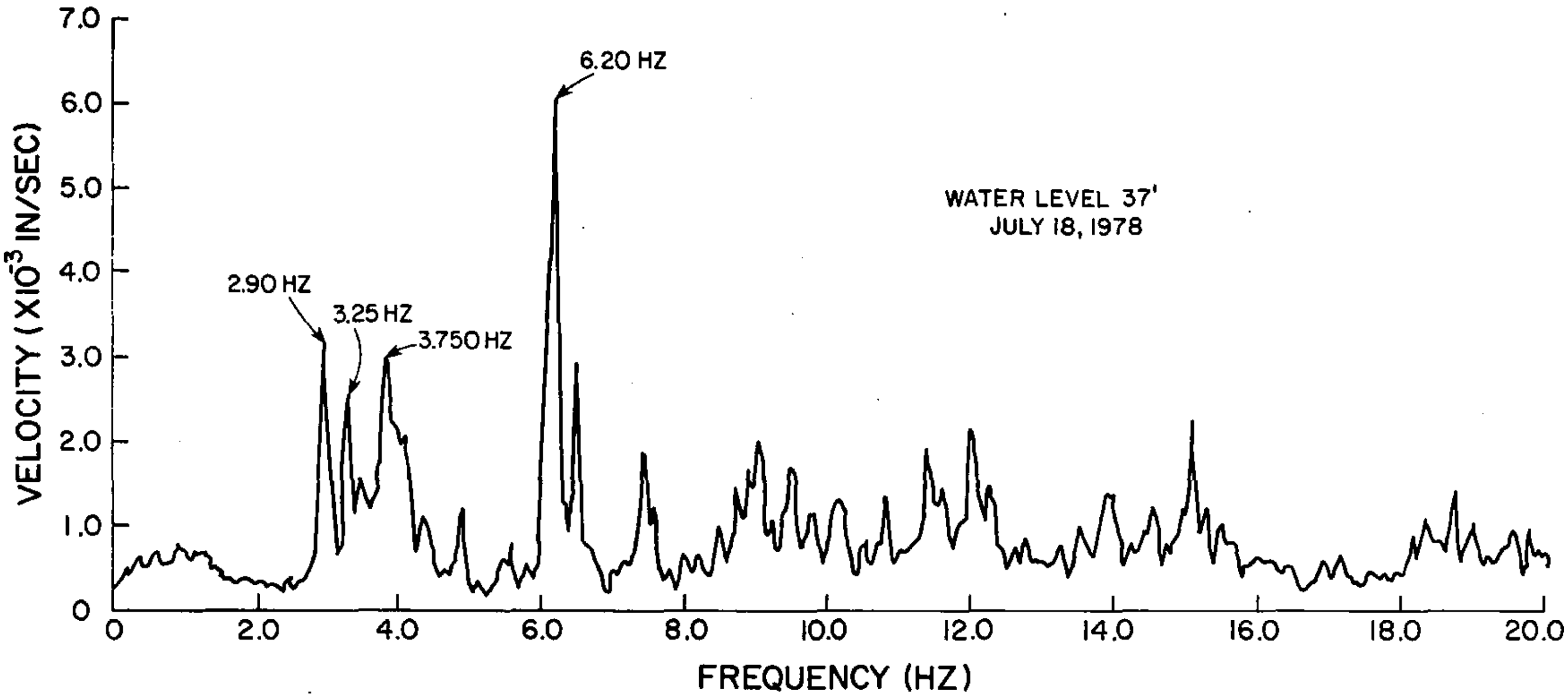

FIG. 4.2 AMBIENT VIBRATION FREQUENCY RESPONSE CURVE-RADIAL N-S

5. CONCLUSIONS

The forced vibration study of the broad liquid storage steel tank was affected by the changing water level. Although the difference in water level from 35'-6" to 38'-0" was only 2.5' it casued because of structural nonlinearity a change in shape of the frequency response curves and a shift of the resonance frequencies. Other reasons for this extreme non-linear behavior may be temperature changes, the large exciting forces and the flexibility of the tank roof on which the vibration generator was positioned. The difference in the frequency response curves for forced and ambient vibrations also clearly demonstrates the strong non-linear behavior of the tank. Equivalent viscous damping factors from the forced vibration tests were found to be rather small (around 1%).

Three circumferential mode shapes, the lowest of fifth order, the other two of second order were measured radially and tangentially. It was observed that the number of circumferential waves was the same for the radial and tangential components in each mode. The corresponding vertical modes were all of first order. Whereas only small radial and vertical motion at the base was recorded for the fifth order mode, a significant rocking motion was observed for the second order modes.

The study described on this report should be regarded as an exploratory test indicating several factors which may affect the dynamic characteristics of steel thin-plate liquid storgae tanks. In general the results indicate that the efficiency of forced vibration studies of this type of structure is questionable at least when the vibration generator is attached directly to the tank. Using base excitation with high-grade pick-up equipment would most likely provide a higher degree of test accuracy.

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