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TESTS TO EXPERIMENTALLY DETERMINE THE NATURAL FREQUENCIES OF THE SATURN S-IC TEST STAND, PHASE I

FOR THE NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

DAMES & MOORE ACCOUNT NO. 0164-018-02

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February 8, 1965

Director
Marshall Space Flight Center
Huntsville, Alabama

Attention: PR-RC
Contract No. NAS8-11842

Gentlemen:

Our report on "Tests to Experimentally Determine the Natural Frequencies of the Saturn S-IC Test Stand, Phase I, for National Aeronautics and Space Administration" is submitted.

A single copy of supplementary data including field records and data printout is being mailed under separate cover.

Should there be any questions, please contact us.

Very truly yours,

DAMES & MOORE

David J. Leeds

David J. Leeds,
Project Engineer
Engineering Seismologist

Vernon A. Smoots

Vernon A. Smoots

VAS DJL rb
(10 copies submitted)

TESTS TO EXPERIMENTALLY DETERMINE THE NATURAL FREQUENCIES OF THE SATURN S-IC TEST STAND

PHASE I

BY

DAVID J. LEEDS AND VERNON A. SMOOTS

FOR

MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA
UNDER CONTRACT NO. NAS8-11842

DAMES & MOORE
2333 WEST THIRD STREET
LOS ANGELES, CALIFORNIA

ACCOUNT NO. 0164-018-02 FEBRUARY 8, 1965

CONTENTS

ABSTRACT

TESTS TO EXPERIMENTALLY DETERMINE THE NATURAL FREQUENCIES OF THE SATURN S-IC TEST STAND

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The structural dynamic characteristics of the Saturn S-IC test stand at the Marshall Space Flight Center, Redstone Arsenal, Huntsville, Alabama, have been measured during forced horizontal vibrations at several force levels. As Phase I of the project a structural vibrator was used to produce vibrations at specific frequencies on the empty test stand. Response of the structure to precisely controlled input forces, activated separately for the two horizontal components and at two separate levels, was recorded. Resonant frequencies and damping values were computed from the records and are as follows:

234' level: North-south axis - 1.88, 2.66, 4.14
Damping 1.5%

East-west axis - 2.00, 2.12, 2.66
Damping 1.5%

144' level: North-south axis - 2.08, 3.30, 3.59
Damping 2%

East-west axis - 3.62
Damping 2%

(Underlined frequencies are considered predominant.)

As Phase II of this project, the structure will be tested with the fuel-loaded Saturn rocket in place. Then, the measured structural properties can be compared with the theoretically computed characteristics made for programming gimbal force during hot firing.

Author

LIST OF PLATES AND TABLES

I. INTRODUCTION AND SUMMARY

These tests were undertaken to measure the structural dynamic characteristics of the Saturn S-IC test stand and rocket at Huntsville, Alabama. In Phase I, the empty test stand structure was subjected to a series of controlled forced vibrations. These tests were conducted January 4 to 7, 1965, by Dames & Moore for the National Aeronautics and Space Administration's Marshall Space Flight Center, under Contract NAS8-11842.

The specific contract requirement was to determine the resonant frequencies of the stand. However, other spinoff results also were obtained. Thus, the tests yielded the following:

1. Direct measurement of resonant frequencies in two horizontal components from forces applied near the top of the steel structure and separately from forces applied at the top of the concrete structure.
2. Direct measurement of damping.
3. Measurement of the displacement response of the structure to given input forces.
4. Indication of a shift in resonant frequency of the test stand with a change in stress level.
5. The excitation of structural motion (acceleration and strain) for the checkout and calibration of existing test stand instrumentation.
6. Experimental data for comparison with theoretical computations of resonant frequencies and deflections.

Controlled sinusoidal dynamic forces were induced into the test stand by means of two structural vibrators. These vibrators, consisting of two contrarotating unbalanced weighted buckets, were arranged to force the stand into motion, principally in a single direction. Test stand response was measured with microtremor displacement seismographs. The vibrators were used singly, with motion generally recorded at the same elevation as the vibrator, and in the same component (direction). Vibrators and microtremor "pickups" were then turned 90 degrees to measure response in the other direction. Measurements were made of vibration induced near the top of the test stand superstructure (234-foot level), and at the top of the concrete substructure (144-foot level).

The large amount of existing test stand instrumentation permitted independent monitoring of structural motion at the control center. Thus, many channels of both acceleration and strain gage outputs were recorded by MSFC personnel, as well as by Dames & Moore. Telephone communications between the vibrator operator, the Project Engineer (who operated the displacement recorder on the test stand), and the control center, permitted the recording of simultaneous observations. This multiple collection of data by NASA and Dames & Moore will permit cross-checking of results.

The tests showed several resonant frequencies of the test stand, particularly in the upper part of the structure. These multiple frequencies were often found to have two slightly separated peaks. It is felt that in the case of the twin peaks, the lower frequency represents the torsional components of the induced frequency or resonance of the transverse component.

The predominant frequency is quite pronounced in the plots of response versus frequency. Table 1 presents the principal resonant natural frequencies of the test stand structure.

TABLE 1 - RESONANT FREQUENCIES (CPS)
OF SATURN TEST STAND S-IC

234-FOOT LEVEL		144-FOOT LEVEL	
NORTH-SOUTH	EAST-WEST	NORTH-SOUTH	EAST-WEST
1.88‡	2.00*	1.08	1.08
2.00	2.12‡	2.08*	2.16
2.15	2.66*	3.30*	2.70
2.66‡	4.04	3.59‡	3.29
3.19	4.29		3.62‡
3.98	4.59		
4.14*			

‡Predominant frequency
*Important frequency

With the vibrator mounted at the 234-foot level, deflections varied from 2 X 10^{-6} inches per pound of force away from resonance to approximately 40 X 10^{-6} inches per pound of force at resonance. With the vibrator mounted at the 144-foot level, deflections of 0.01 and 0.07 X 10^{-6} inches per pound of force occurred off resonance and at resonance, respectively.

Phase II of the tests, planned for late April, 1965, will repeat the measurements with the fuel-loaded Saturn in place. The calculation of stresses and deflections at firing loads can be more accurately extrapolated from the two sets of data.

II. DISCUSSION

A. SATURN S-IC STATIC TEST STAND

A large test stand has recently been constructed at Huntsville, Alabama, which will be used for static firing tests of Saturn rockets. The 270-foot-high test stand has a 126-foot-high structural steel superstructure. The lower 144 feet is a massive reinforced concrete section containing the flame bucket.

The structure is founded on the Tuscombia formation, which is limestone. Foundation investigations indicate that the limestone strata dip at a relatively uniform rate of 20 feet per mile. No faulting of any consequence is known, but some solution cavities exist in this formation.

B. TEST PROCEDURE

A structural vibrator was used to force the test stand to vibrate horizontally at a selected frequency; then at a second selected frequency, and at a third, etc. In this manner, the stand was subjected to a wide range of specific steady-state vibrations. The structural vibrator was operated at precisely controlled frequencies with output forces sufficiently large to cause vibration. The response of the structure, i.e., the displacement (deflection) was measured and recorded at each frequency of vibration. See Plate 1.

Because the structural characteristics of the test stand were presumed to be different along the north-south axis than along the east-west axis, it was necessary to force the stand in each direction separately. Displacement detectors

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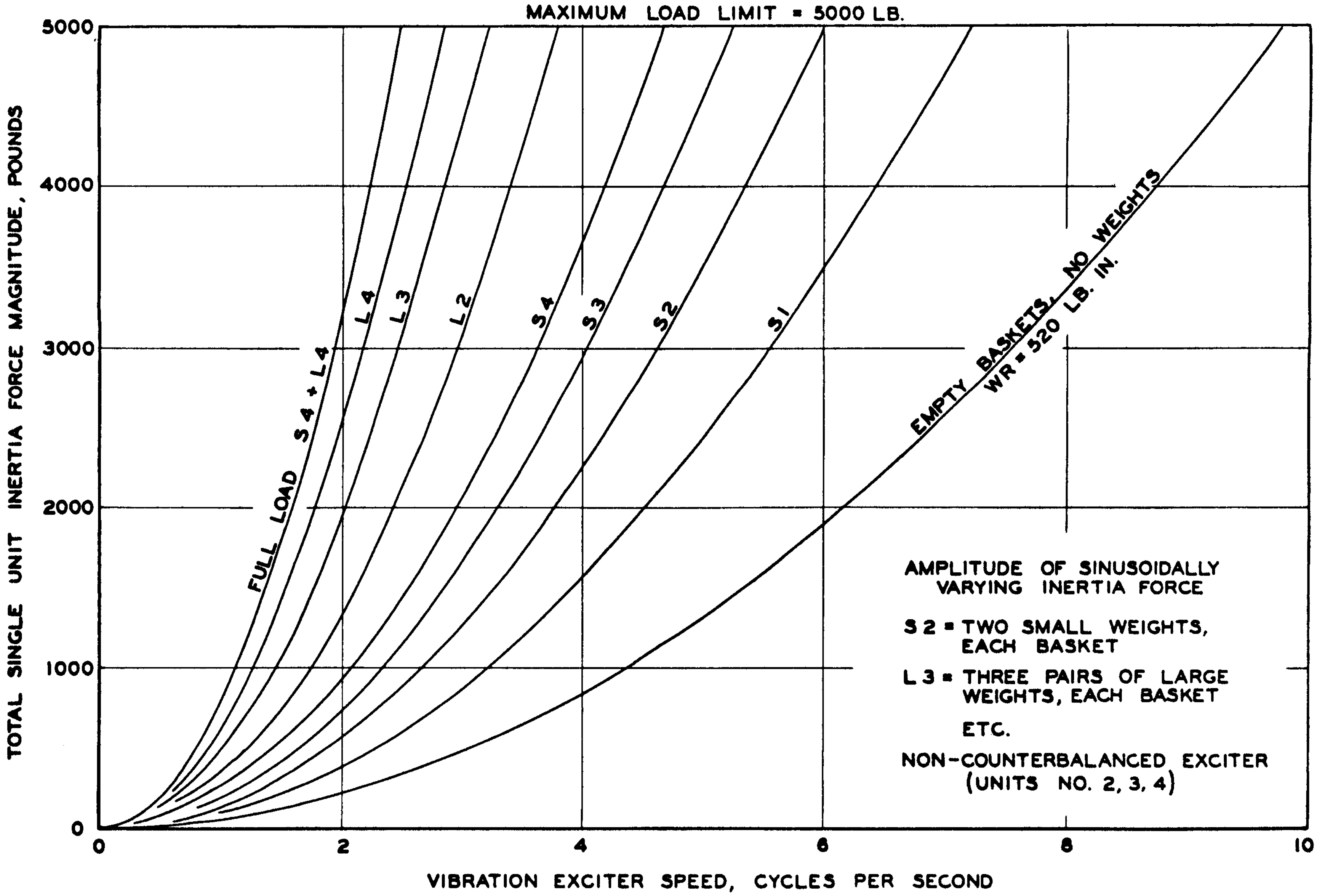

VIBRATION GENERATOR FORCE OUTPUT VS. SPEED - NON-COUNTERBALANCED

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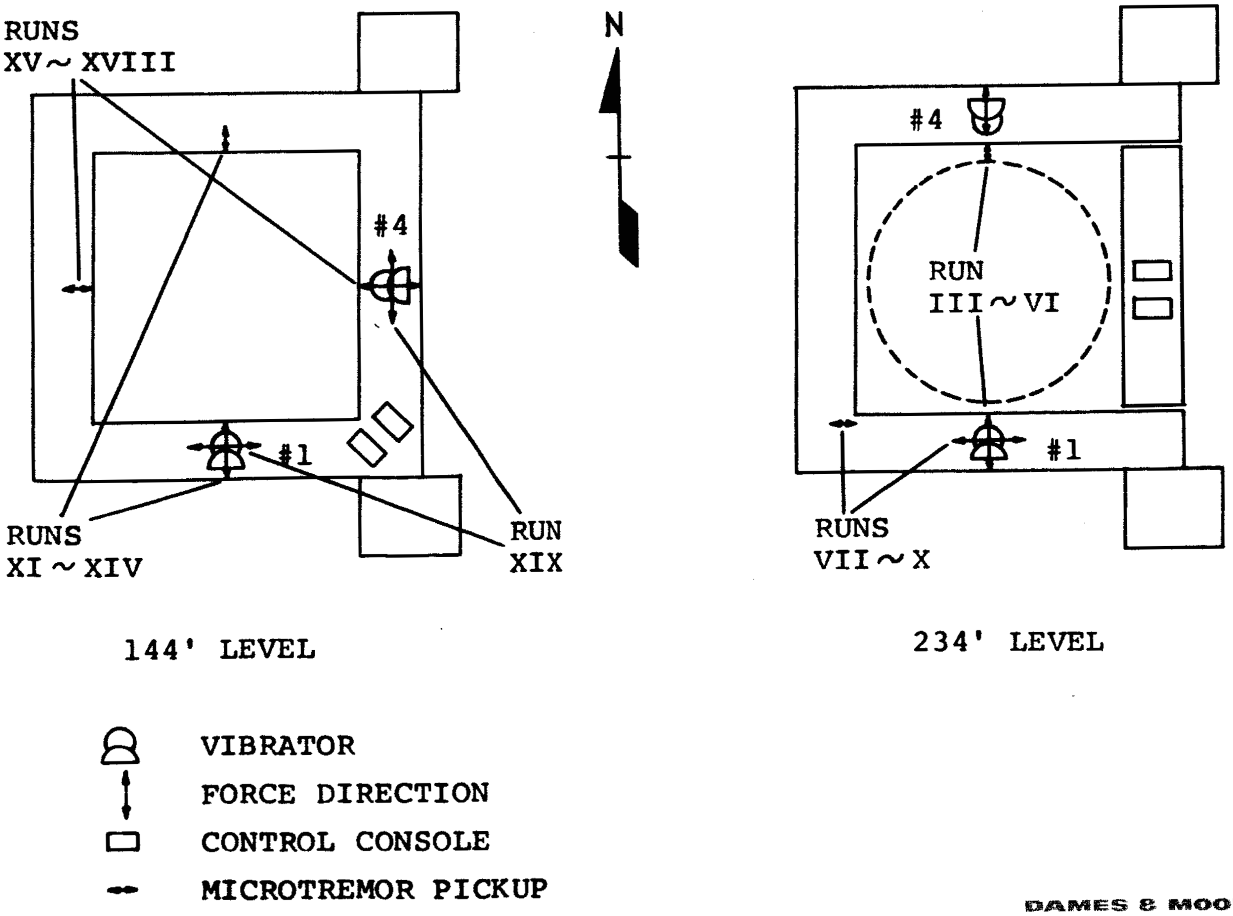
PLATE 1

(microtremor displacement seismographs) were used to measure and record the displacement in each single direction of motion. Two vibrators were available, but because of difficulty with synchronization, they were not operated simultaneously during most of the tests.

The vibrators were located along the north-south centroidal axis and symmetrically about the axis of symmetry in the east-west direction to achieve as simple a sinusoidal response as possible from so complex a structure. The locations selected for the mounting pads were over principal floor members and were selected in an effort to transmit forces along a single axis. The sketches below show the location of vibrators and microtremor pickups:



Two principal methods of operation were used--"coastdown" and "steady state".

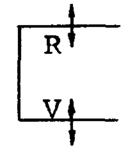
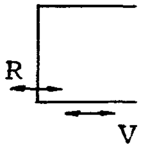
Coastdown: As a first approximation, the vibrator was driven up to its maximum speed (force) for a given loading and allowed to coast down to a stop. Resonant response was observed on the recordings; in addition, it was strongly felt by the personnel on the tower. Had resonance not occurred, response would have decreased as the speed of the vibrator decreased. However, resonance did occur and the resonant frequency was shown as a swell in the response envelope on the microtremor records.

Steady State: This method permitted more precise measurements of test stand response. The stand was force vibrated at fixed frequencies throughout the available range of the vibrator. These steady state runs were made at numerous points which were purposely close together at or near resonance. The vibrator was operated at two different test stand levels with four different weight loadings within the range of permissible frequencies as shown in Table 2. The loadings were dictated by the maximum load the vibrator bearings could safely tolerate. The use of these different vibrator loadings permitted an overlap in frequency coverage. Table 2 summarizes the test plan and shows the locations of the vibrators and microtremor recorder for each test.

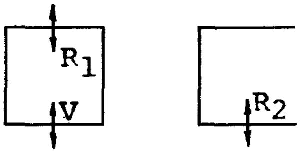
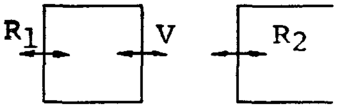
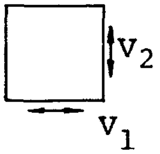
TABLE 2

VIBRATION TEST PLAN

VIBRATOR NEAR TOP DECK - 234-FT. LEVEL

RECORD NUMBER	7094 PRINTOUT PAGE	WEIGHTS	FREQUENCY (CPS)	LOCATION
III	2-3	4L+4S	1.00 - 2.23	
IV	4-6	2L	2.00 - 4.00	
V	7-9	2S	3.00 - 6.97	
VI	10	1S	6.03 - 8.14	
VII	11-12	4L+4S	1.00 - 2.20	
VIII	13	2L	2.00 - 2.37	
IX	14-16	2S	1.93 - 5.50	
X	17	1S	4.50 - 6.50	

VIBRATOR ON TOP OF CONCRETE - 144-FT. LEVEL

XI	18	4L+4S	1.00 - 2121	
XII	19	2L	2.00 - 3.40	
XII	20-21	2S	2.99 - 5.40	
XIV	22	1S	4.52 - 6.50	
XV	23	4L+4S	1.00 - 2.20	
XVI	24	2L	2.00 - 3.40	
XVII	25-26	2S	3.00 - 5.40	
XVIII	27	1S	4.17 - 6.50	
XIX	28	4S		

KEY: Weights: L = Large; S = Small
V Vibrator
R Recorder

C. EQUIPMENT

MICROTREMOR EQUIPMENT

The microtremor equipment used to measure the vibrations is a sensitive, Japanese-built, wide-range, seismic-type recording displacement seismograph. The period of the sensor (seismometer) is 1.0 second, but system response (see Plate 2) is flat over the broad band from 0.05 to 2.0 seconds (0,5 to 20 cycles per second). Maximum sensitivity is approximately 125,000 magnification. Attenuation can be introduced into the system in -2 db increments, up to -60 db. This high attenutation permits measurements of displacement up to approximately 0.10 inch.

The single-channel, smoked-paper recorder yields a visible record from either a vertical or horizontal sensor. The equipment is portable, self-contained, battery operated, with 150 feet of separation possible between the sensor and the recorder.

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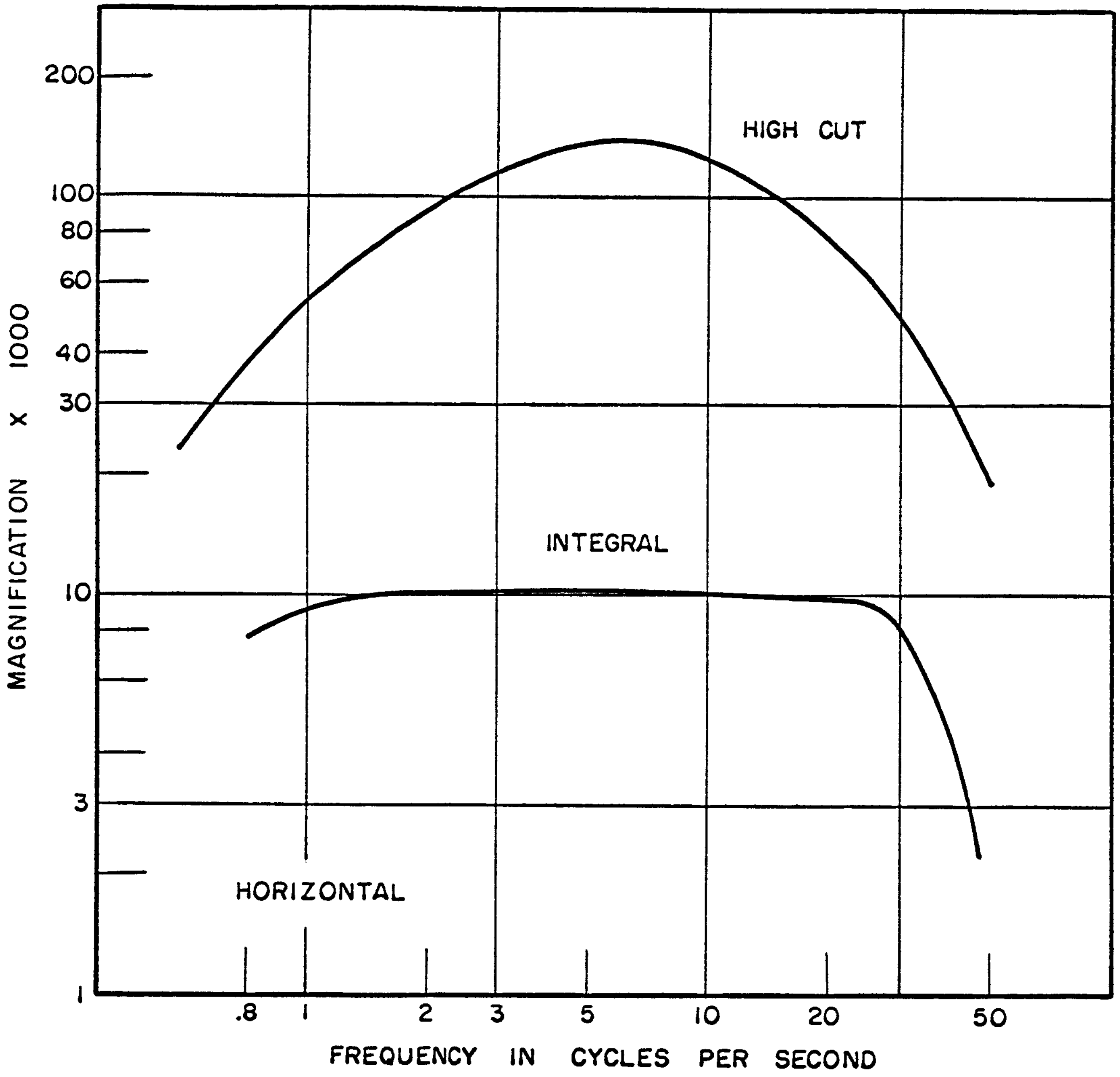

RESPONSE CHARACTERISTICS OF MICROTREMOR EQUIPMENT

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PLATE 2

STRUCTURAL VIBRATOR

The structural vibrators used, to provide the forced structural motion for the tests, are two identical recently developed models owned by the State of California, Office of State Architect. These vibrators were made available by the State of California because the test stand project was in the public interest and contributed to a better understanding of structural dynamics. The vibrators are shown on Plates 3 through 6.

The vibrators utilize the combined force of two horizontal contrarotating, off-center masses. A precisely controlled electrical synchronization device normally permits the vibrators to be operated simultaneously at the same speed. The force output, Plate 1, is from a maximum of 5,000 pounds at 10 cycles per second to 1,000 pounds each at 1 cycle per second. The vibrators can be so precisely controlled that periods of motion spaced as closely as 0.01 second apart can be selected and driven. This capability permitted a very high resolution of structural resonance.

The maximum weight of each demountable, air transportable unit does not exceed 500 pounds. The total weight of the entire system, including vibrator, motor, weights, control console and cables, is approximately 3,000 pounds.

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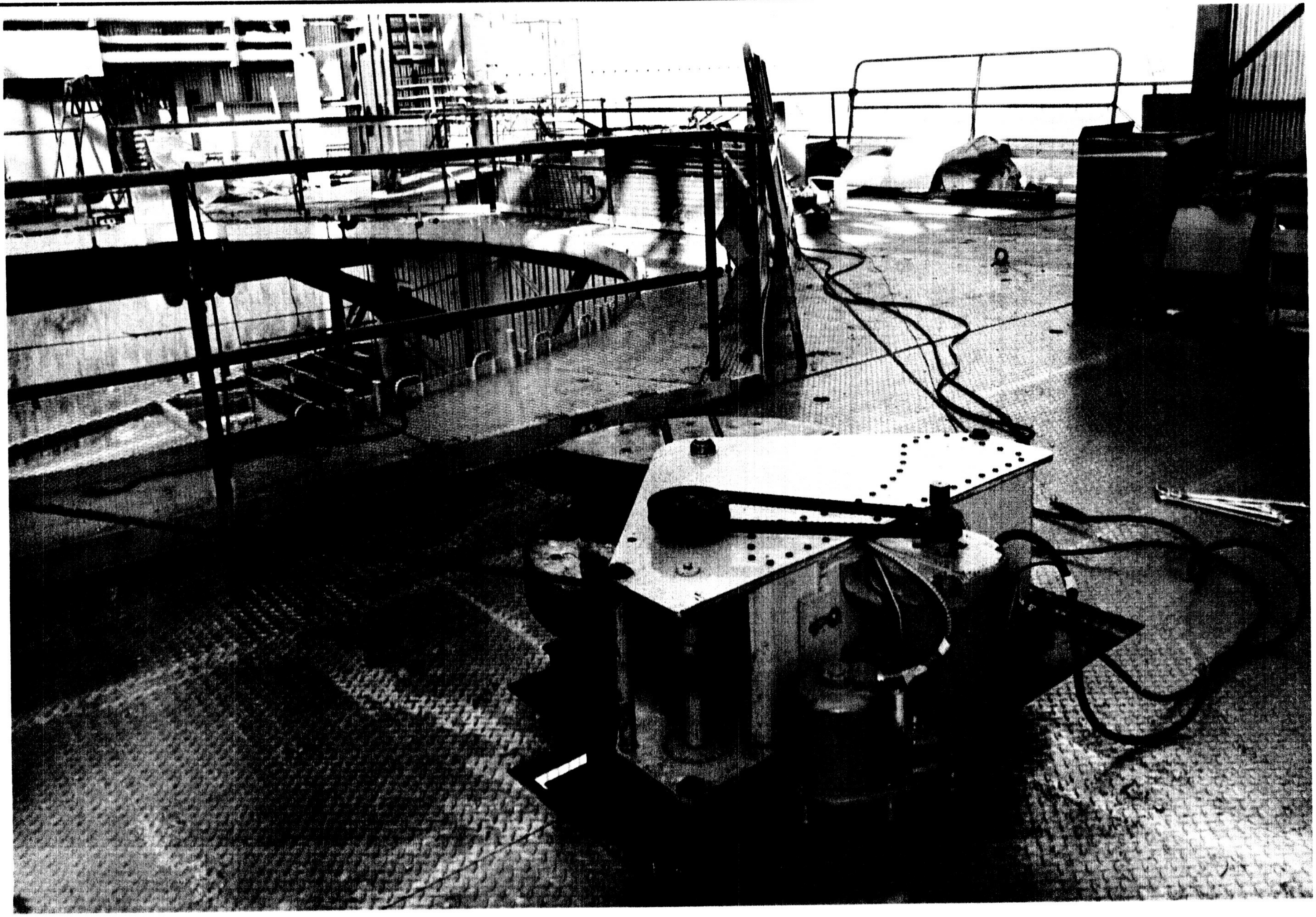

VIBRATOR ON 22nd LEVEL OF TEST STAND

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PLATE 3

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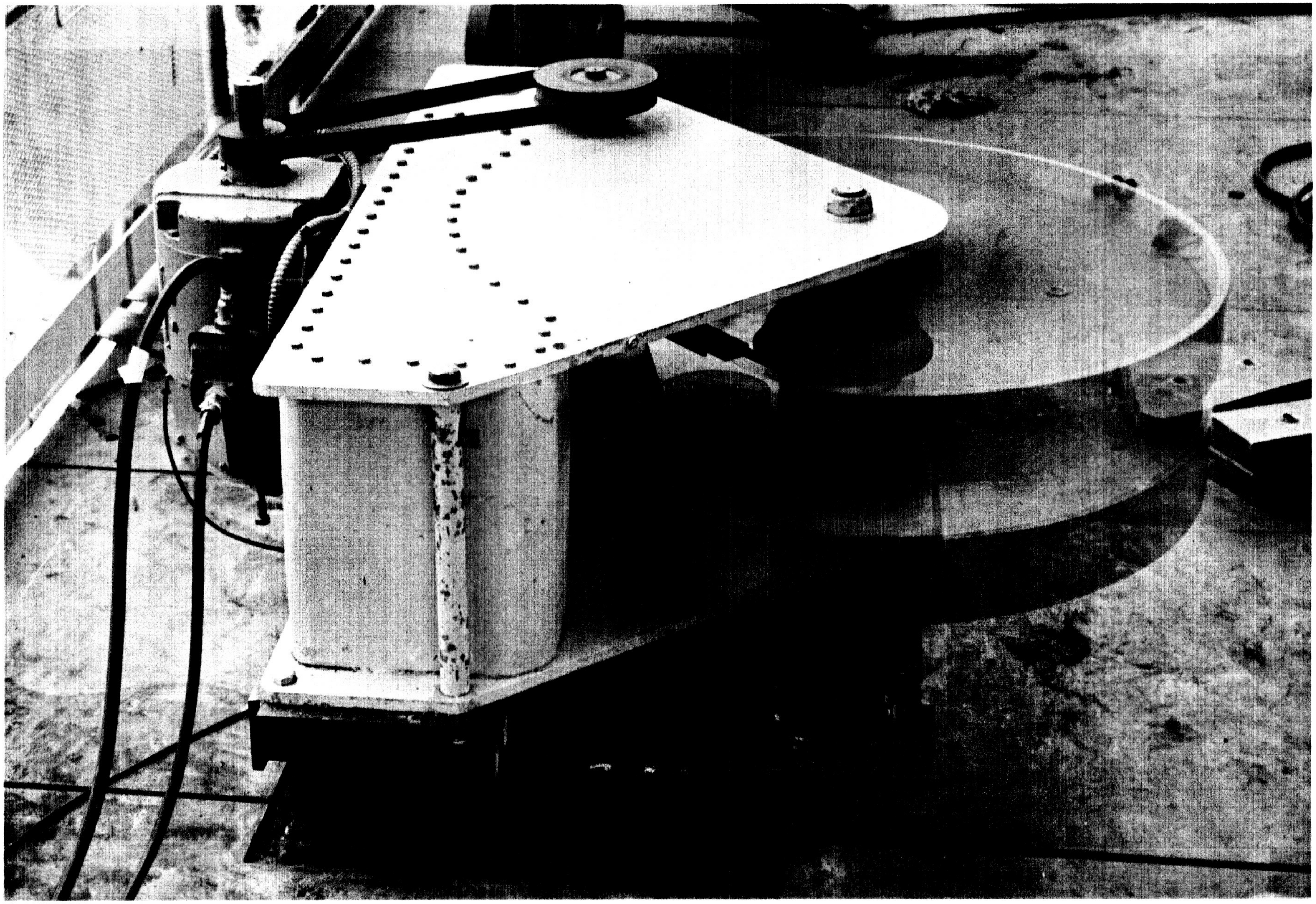

VIBRATOR OPERATING

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PLATE 4

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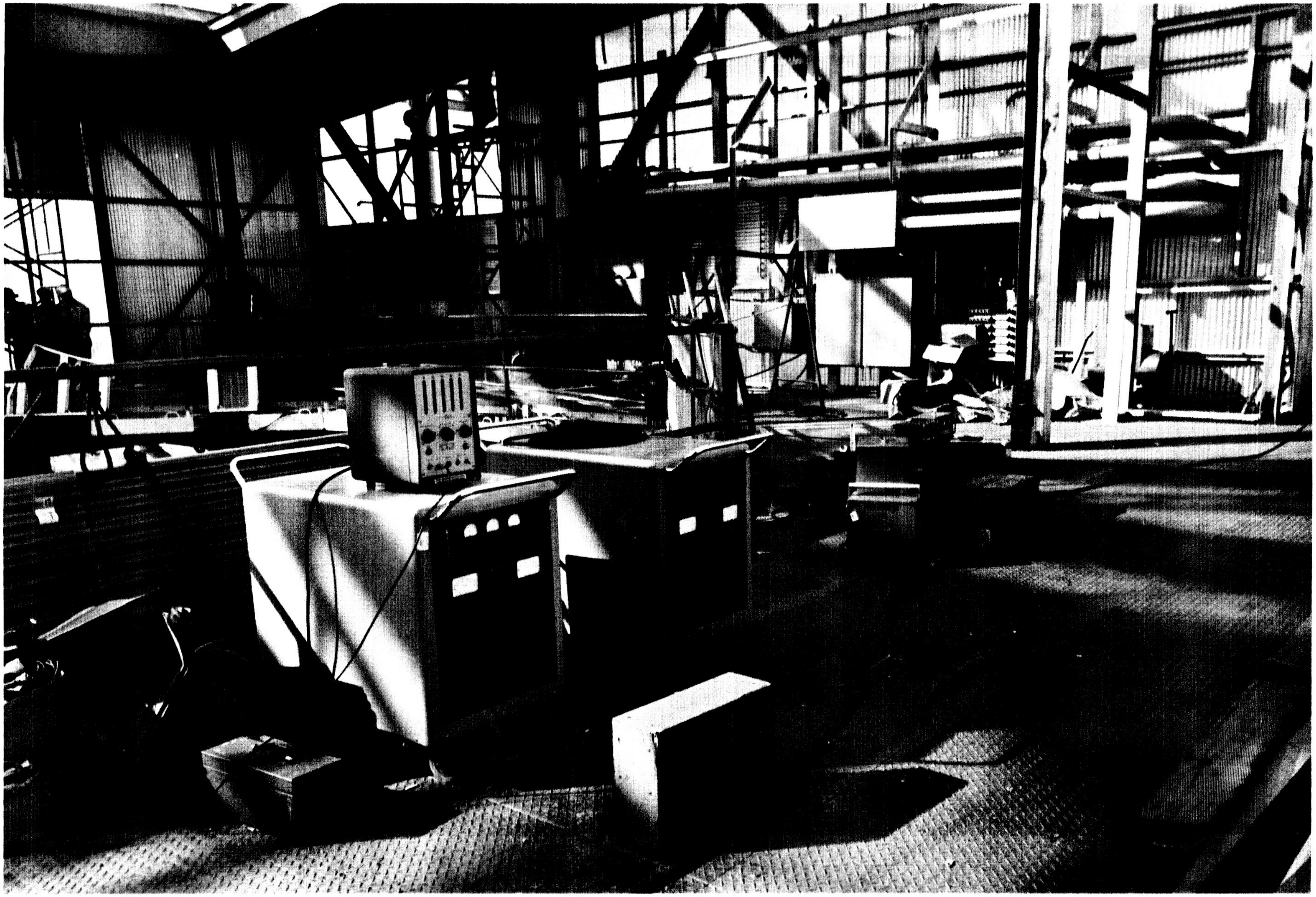

VIBRATOR CONTROL CONSOLES WITH MICROTREMOR EQUIPMENT

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PLATE 5

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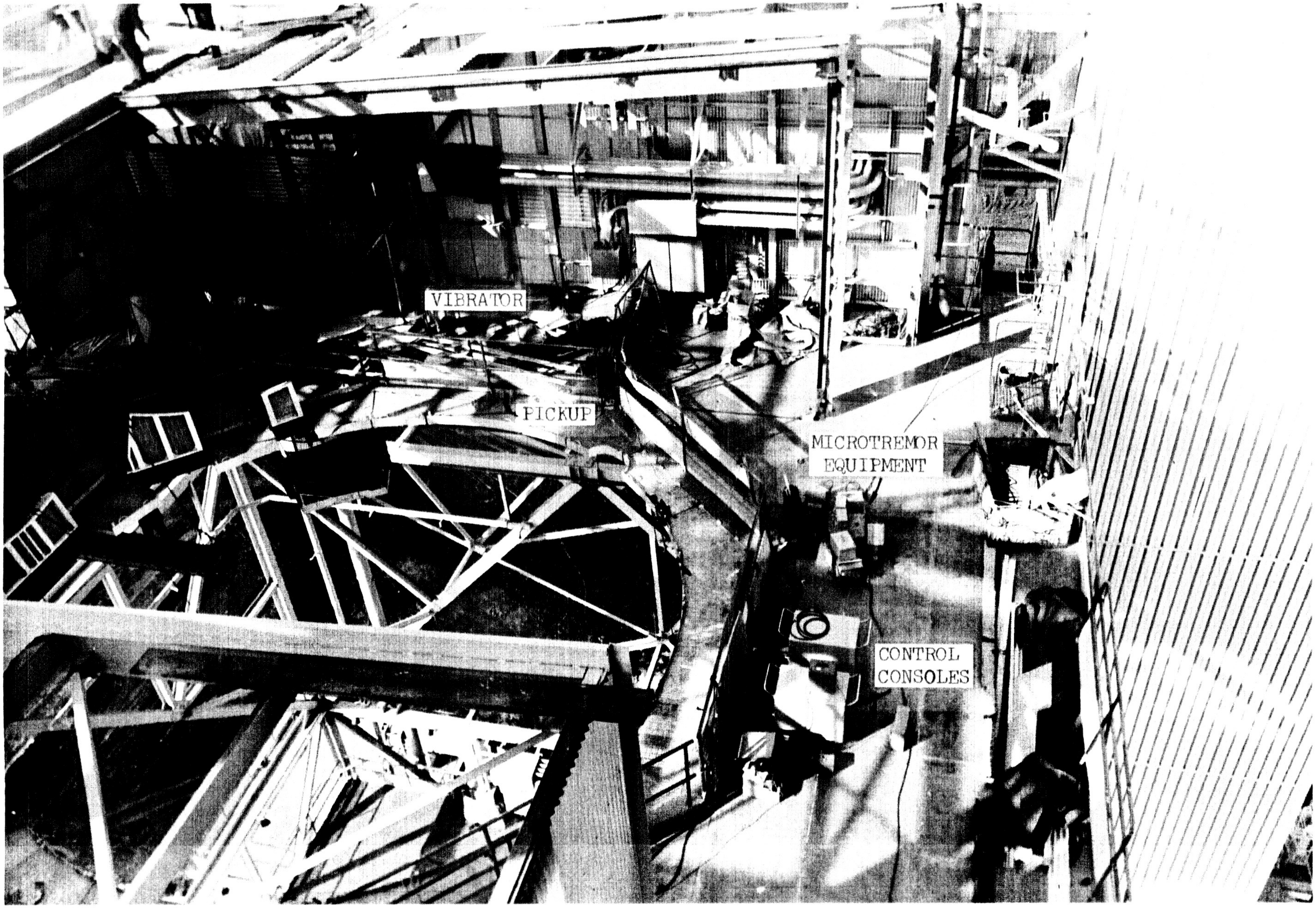

OVERALL VIEW ON 22nd LEVEL OF TEST STAND
SHOWING LOCATION OF VIBRATOR

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PLATE 6

D. DATA REDUCTION

Displacements were calculated from the microtremor records. Because the calibration of the microtremor recorder included both its frequency sensitivity and attenuation, a number of arithmetical calculations are necessary to reduce the recorded trace amplitude to physical motion. This procedure is detailed on the Sample 7094 Computer Printout, Plate 7.

The next step was to "normalize" the data. The force output of the vibrator is proportional to the square of the frequency, so that:

$$F = K f^2 \sin w t$$

where F is in force pounds, K is a constant, depending on the unbalanced loading, and f is frequency in cycles per second.

The following equation was used to express the force magnitude in pounds:

$$\text{Inertia force (pounds)} = 0.102 \times WR \text{ lb. in.} \times (\text{rps})^2$$

where WR = unbalanced moment (i.e., $0.102 \times WR = K$).

The WR values for the weight loadings used were as follows:

WEIGHT	WR
4L + 4S	8999
2L	3350
4S	2228
2S	1374
1S	947

where L = large vibrator weights and S = small weights.

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DB	T	FREQ	A	V	K	DELTA	FORCE	RESPONSE
40	1.000	1.000	0.130	0.900E 04	1.000E-02	0.144E-02	0.805E 03	0.180E-05
40	0.950	1.053	0.140	0.920E 04	1.000E-02	0.152E-02	0.892E 03	0.171E-05
40	0.940	1.064	0.150	0.920E 04	1.000E-02	0.163E-02	0.911E 03	0.179E-05
40	0.900	1.111	0.160	0.930E 04	1.000E-02	[illegible]	0.993E 03	0.173E-05
40	0.890	1.124	0.180	0.930E 04	1.000E-02	0.194E-02	0.102E 04	0.191E-05
40	0.850	1.176	0.200	0.960E 04	1.000E-02	0.208E-02	0.111E 04	0.187E-05
40	0.840	1.190	0.210	0.960E 04	1.000E-02	0.219E-02	0.114E 04	0.192E-05
40	0.810	1.235	0.240	0.960E 04	1.000E-02	0.250E-02	0.123E 04	0.204E-05
40	0.800	1.250	0.260	0.960E 04	1.000E-02	0.271E-02	0.126E 04	0.215E-05
40	0.760	1.316	0.280	0.970E 04	1.000E-02	0.289E-02	0.139E 04	0.207E-05
40	0.730	1.370	0.320	0.980E 04	1.000E-02	0.327E-02	0.151E 04	0.216E-05
40	0.730	1.370	0.340	0.980E 04	1.000E-02	0.347E-02	0.151E 04	0.230E-05
40	0.720	1.389	0.360	0.980E 04	1.000E-02	0.367E-02	0.155E 04	0.237E-05
40	0.700	1.429	0.390	0.980E 04	1.000E-02	0.398E-03	0.164E 04	0.242E-05
40	0.680	1.471	0.410	0.980E 04	1.000E-02	0.418E-03	0.174E 04	0.240E-05
40	0.660	1.515	0.450	0.990E 04	1.000E-02	0.455E-02	0.185E 04	0.246E-05
40	0.650	1.538	0.490	0.990E 04	1.000E-02	0.495E-02	0.190E 04	0.260E-05
40	0.640	1.563	0.550	0.990E 04	1.000E-02	0.556E-02	0.196E 04	0.283E-05
40	0.620	1.613	0.560	0.100E 05	1.000E-02	0.560E-02	0.209E 04	0.268E-05
40	0.600	1.667	0.600	0.100E 05	1.000E-02	0.600E-02	0.223E 04	0.268E-05
40	0.600	1.667	0.680	0.100E 05	1.000E-02	0.680E-02	0.223E 04	0.304E-05

S A M P L E

DB = Decibel attenuation of microtremor amplifier

T = Scaled period in seconds (from microtremor record; paper speed is 1 cm/sec.)

FREQ = Reciprocal of scaled period

A = Scaled trace double amplitude in inches (from microtremor record)

V = Microtremor magnification (from characteristics curve, Plate 2)

K = Attenuation (from db value)

DELTA = Actual ground motion in inches (A/VK)

FORCE = Vibrator output in pounds of force (computed from WR value, a constant, and square of frequency)

RESPONSE = Normalized response in inches per pound of force

SAMPLE 7094 COMPUTER PRINTOUT

The test results were "normalized" or adjusted, to express response output in units of displacement per unit of input force. These normalized displacement values were then plotted against the vibration frequency. As the structure approaches resonance, the normalized displacement for the test stand becomes greater than the displacement recorded at other vibration frequencies. For convenience in plotting and compatibility with structural response data on other test stands, these normalized displacement units are discussed in terms of inches X 10^{-6} per pound of force.

To eliminate arithmetic errors as much as possible, these computations were programmed into an IBM 7094 digital computer. This computer program also normalized the data.

III. RESULTS

The vibration data obtained from Phase I have been plotted graphically (Plates 8 through 11). Several comments may be deduced from these plots, as follows:

A. RESONANCE

Several resonance modes of vibration develop in the test stand as a result of dynamic excitation. The predominant frequency for each portion of the test program as well as the additional important frequencies, are shown in Table 1.

More frequencies go into resonance in the superstructure than in the concrete base. A comparison of Plates 8 and 9 with Plates 10 and 11 indicate many modes of vibration in the upper level of the test stand structure.

B. DISPLACEMENT RESPONSE

The general response of the superstructure at frequencies not in resonance can be compared with the response at the top of the concrete base. This ratio is approximately 200:1, and it is even higher at resonance.

C. DYNAMIC SYMMETRY

There is a pronounced lack of dynamic symmetry in the superstructure, as indicated by the differences in the response of the north-south and the east-west axes. In the concrete structure there appears to be symmetry, except for the data of Run No. XI. Therefore, there is a question of the validity of this run. If these values have a computational error of 10 (which is possible) they would fall into line.

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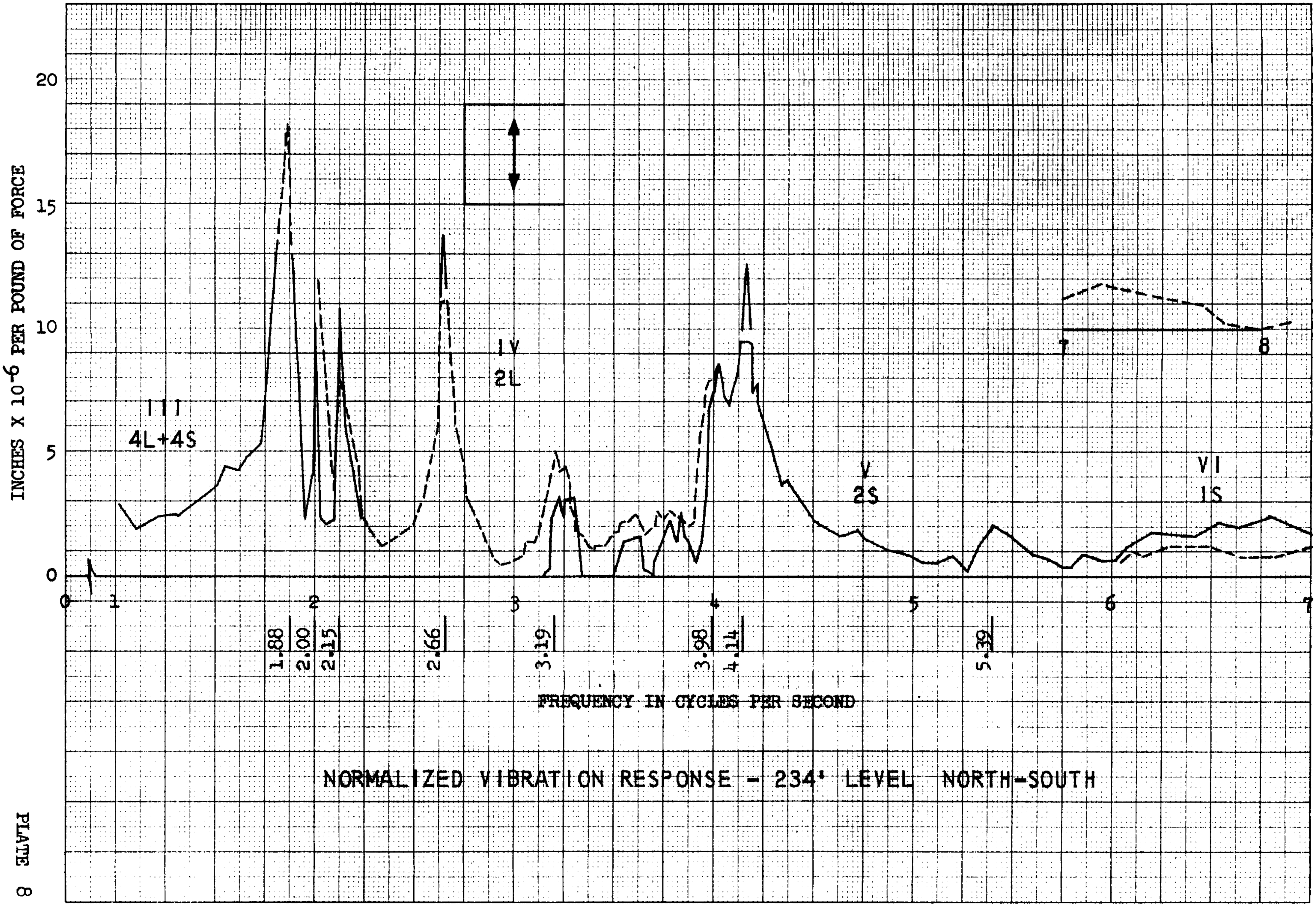

NORMALIZED VIBRATION RESPONSE - 234' LEVEL NORTH-SOUTH

PLATE 8

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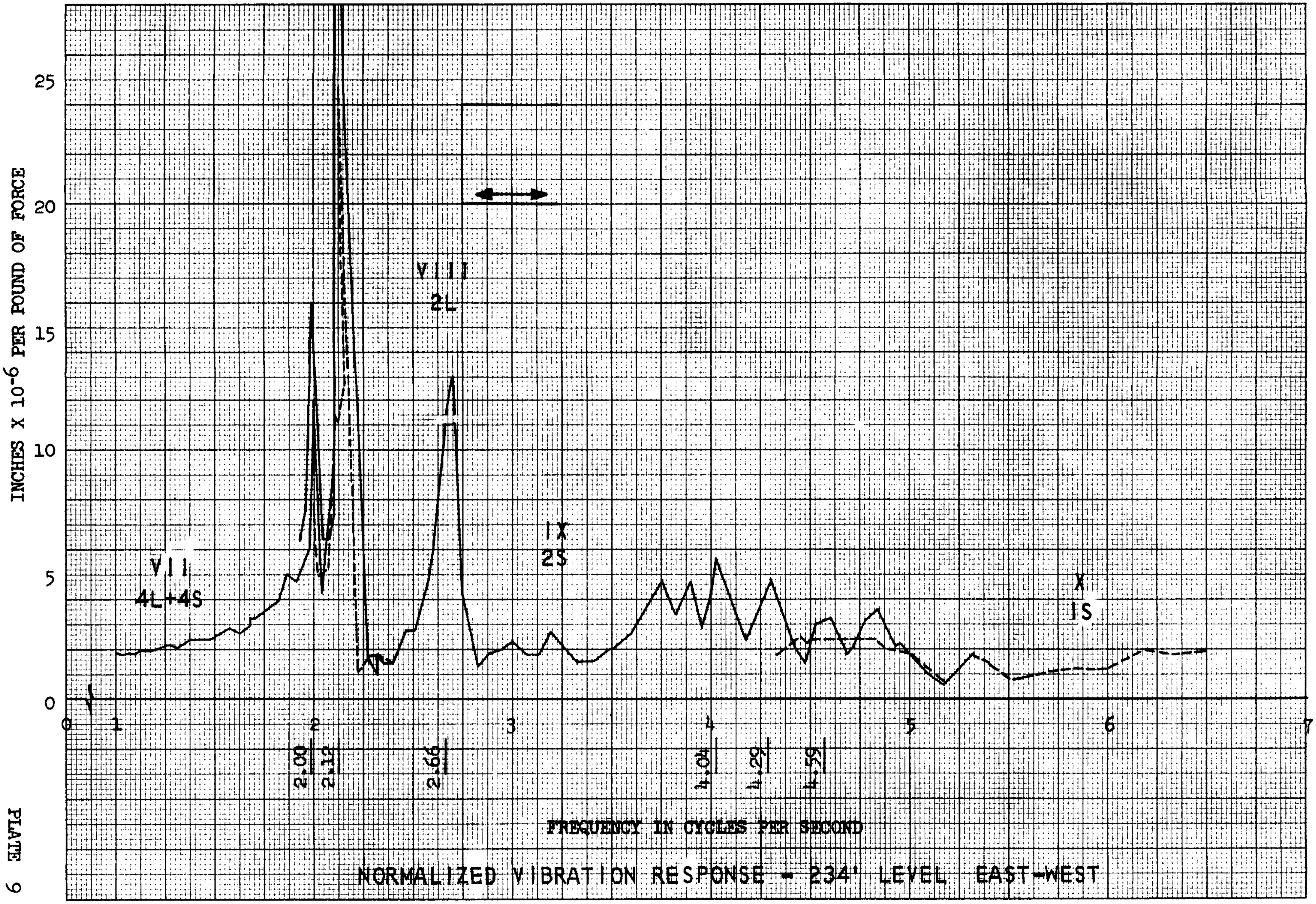

NORMALIZED VIBRATION RESPONSE - 234' LEVEL EAST-WEST

PLATE 9

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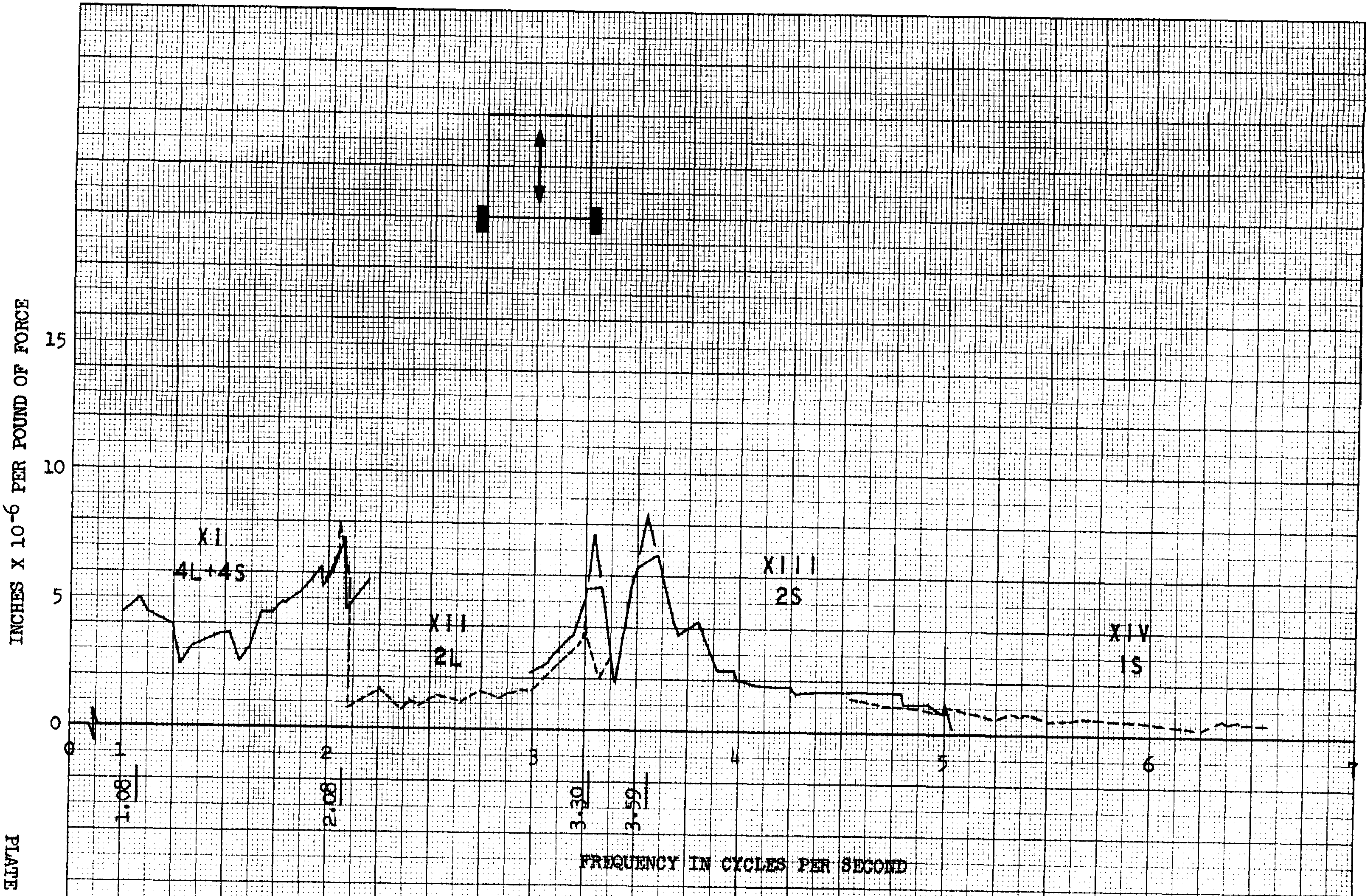

NORMALIZED VIBRATION RESPONSE - 144' LEVEL NORTH-SOUTH

PLATE 10

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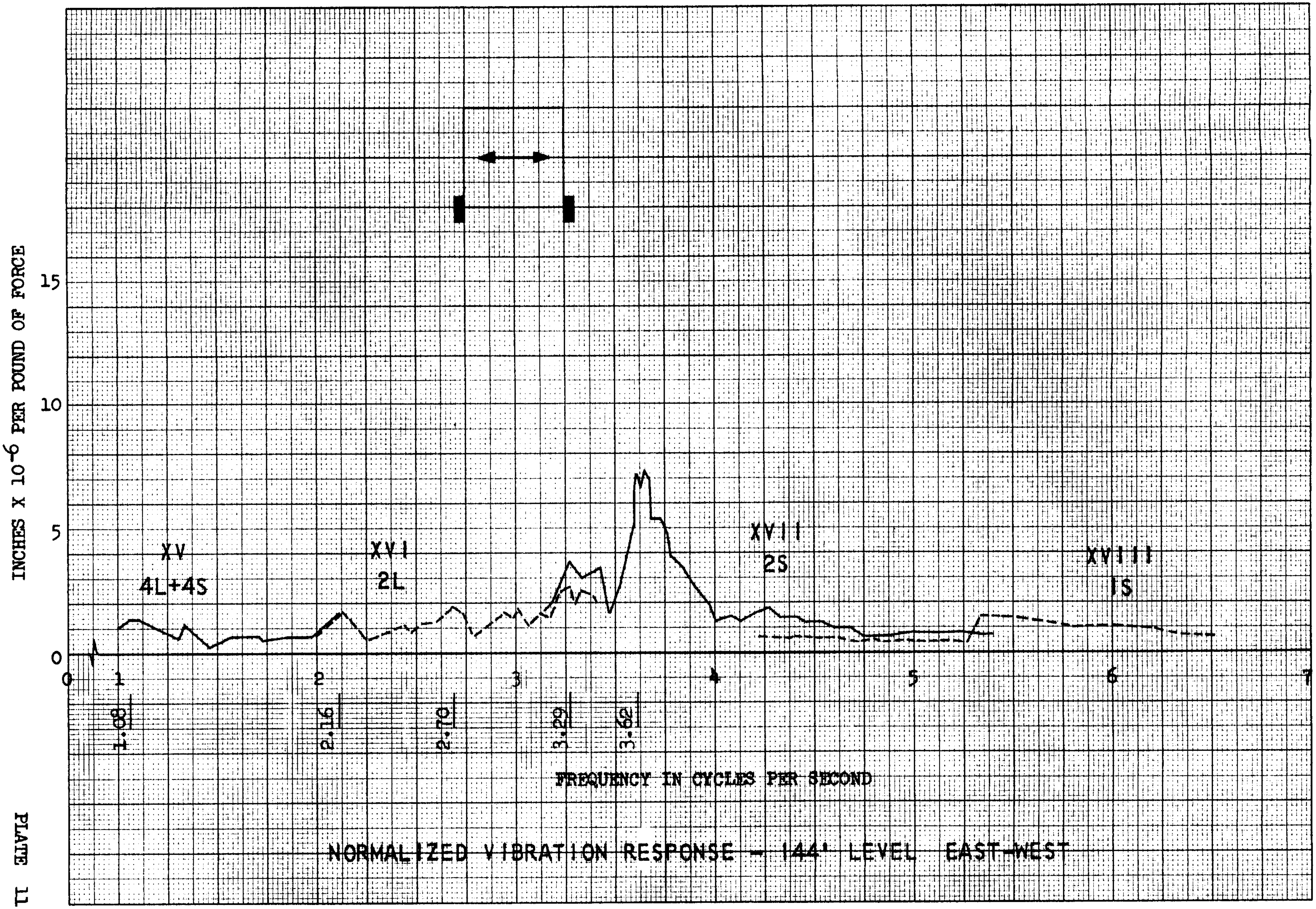

NORMALIZED VIBRATION RESPONSE — 144' LEVEL EAST-WEST

PLATE 11

D. ROTATION (TORSION)

Forced vibration of the test stand was applied along a single axis. Structural response to uniaxial loading was primarily in the same direction but motion in the transverse axis and/or in rotation was also observed. The twin peaks of the response curves appear to be a result of this transverse or rotational (torsional) motion. Higher modes are, of course, also present.

E. FREQUENCY SHIFT WITH CHANGE IN STRESS LEVEL

The forced vibrations were repeated with varying unbalanced forces. There is an indication of a slightly higher resonance frequency at lower stress (force) level. This is perhaps best illustrated in the north-south vibration of the superstructure at frequencies between three and four cycles a second.

F. STRUCTURAL DAMPING

The low damping characteristics of the superstructure were shown by the following two items:

1. A small force was required to put the superstructure into resonance. Vibrator forces of less than 400 pounds put the test stand into resonance. Force values are tabulated in the computer printout or can be read from Plate 1.
2. Graphic data presentation, either in terms of absolute displacement or displacement per unit of force, shows extremely sharp peaks.

Damping is difficult to measure experimentally, and also is difficult to calculate theoretically. There is no single step input to the structure from which overshoot or decay can be observed. In the coast down test, the vibrator continues to apply some load until it stops. Even after the vibrator coasts to a stop there is some motion of the test stand which can be examined. The slope of this decay curve, after the vibrator stops, can be used to compute damping.

One assumption is that the damping forces are principally viscous and that Jacobsen's principle of "equivalent viscous damping"* can be used.

It is not the intent of this report to theoretically analyze the contribution of the various forms of viscous or non-viscous damping. The usual method for a single degree of freedom system can be used, evaluating the width of the normalized response curve at 0.707 X the resonant amplitude where:

$$\text{Damping, } \beta = \frac{\text{Width of the normalized response curve at 0.707 X the resonant amplitude (in cps)}}{\text{2 X resonant frequency (in cps)}}$$

Damping values computed by this method range from 1.5 percent in the superstructure to 2 percent at top of the concrete.

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*Jacobsen, L.S., "Steady Forced Vibration as Influenced by Damping", Transactions of the American Society of Mechanical Engineers, APM-52-15, 1930.

An even simpler field method useful for small damping, compares the ratio of the normalized resonant peak amplitude with the normalized off-resonance amplitude*:

$$\frac{A_o}{A_n} = \frac{1}{8\beta}$$

where A_o is resonant amplitude and A_n is normal off-resonance amplitude. Damping values of approximately 1.5 percent are obtained.

G. COMPARISON WITH OTHER TEST STANDS

As indicated in the proposal for these experimental tests, the techniques used follow very closely a previous investigation by the Project Engineer, David J. Leeds, of the dynamic performance of Rocketdyne's Engine Test Stand IB at Edwards Rocket Base, California, in August, 1962. The results of these earlier tests are reported in the following technical paper:

> Leeds, David J. and Joseph D. Turner, "Forced Vibration Test of a Rocket Engine Test Stand"; to be presented to the American Society of Civil Engineers-Engineering Mechanics Division Specialty Conference, University of California, Los Angeles, April 1965. (This paper has recently been released by Rocketdyne and NASA and is <u>in press</u> for distribution at the conference.)

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*Nielsen, N. N., "Dynamic Response of Multi-Story Buildings", Ph.D. Thesis, California Institute of Technology, Pasadena, California, May 1964.

In the Rocketdyne tests, the static load was varied by changing the fuel loading in the superstructure fuel tanks. The tests were repeated under a variety of static fuel load conditions. Response to hot firing loads could be extrapolated from the changes in response to forced dynamic input at the varying fuel (static) loads. The steel superstructure of the Saturn S-IC test stand at Huntsville is 122 feet high, compared with only 60 feet for the IB stand at Edwards. Response of the S-IC stand at resonance was from 20 to 40 X 10^{-6} inches per pound of force, while the IB stand responded at 50 to 110 X 10^{-6} inches per pound of force, depending on the static load. This indicates that the S-IC stand has more damping. The higher general response level of the S-IC stand away from resonance indicates it is less rigid than the IB stand. The single external structural frame of the Huntsville stand is larger and higher than the squat, double-framed Edwards engine test stand. The open center of the S-IC stand contributes to its tendency to respond in torsion.

IV. CONCLUSIONS AND RECOMMENDATIONS

The field techniques and instrumentation used provided a satisfactory means of experimentally measuring the dynamic properties of the Saturn S-IC test stand. These measured properties included resonant frequencies and damping. In our opinion, the contractural objectives of Phase I of the current program (Contract No. NAS8-11842) have been achieved.

It is believed that similar data can be obtained in Phase II. From these two phases, a more reasonable extrapolation can be made of hot firing performance.

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Respectfully submitted,

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