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EVALUATION OF VIBRATORY TABLE DISPLACEMENT —ACCELERATION BEHAVIOR

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The objectives of this study were to (1) investigate if vibratory table calibration could be accomplished using accelerometers in place of LVDTs (linear variable differential transformers), (2) better understand the behavior of motions generated by different types of vibratory tables, and (3) determine if alternate vibratory table equipment could replace existing equipment. The study consisted of calibrating three different types of vibratory tables using the present calibration procedure and then instrumenting the calibration mass with accelerometers. The acceleration-time behavior of the tables was developed for different magnitudes of table displacement amplitude. The behavior of the tables was evaluated qualitatively and quantitatively with respect to both displacement and acceleration. Additional insight into the reliability of the vibratory tables was obtained. The investigation of alternate vibratory table equipment consisted of obtaining information from equipment manufacturers about commercially available test equipment that could provide performance comparable to equipment presently used by the Bureau of Reclamation.

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by

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December 1988

Geotechnical Services Branch
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SUMMARY

Study Objectives

The objectives of this study were (1) to investigate if vibratory table calibration could be accomplished using accelerometers in place of LVDTs (linear variable differential transformers), (2) to better understand the behavior of motions generated by different types of vibratory tables, and (3) to determine if alternate vibratory table equipment could replace existing equipment.

The study consisted of calibrating three different types of vibratory tables using the present calibration procedure and then instrumenting the calibration mass with accelerometers. The acceleration-time behavior of the tables was developed for different magnitudes of table displacement amplitude. The behavior of the tables was evaluated qualitatively and quantitatively with respect to both displacement and acceleration. Additional insight into the reliability of the vibratory tables was obtained.

The investigation of alternate vibratory table equipment consisted of obtaining information from equipment manufacturers about commercially available test equipment that could provide performance comparable to equipment presently used by the Bureau of Reclamation.

Vibratory Table Performance

Both electromechanical and electromagnetic vibratory tables do not produce pure simple vertical harmonic motion (figs. 1 and 2). Vibco model SCR 1000 mechanical table produces the best approximation of simple vertical harmonic motion; the accelerations generated are reasonably predicted mathematically using the assumption of simple harmonic motion. Both the electromagnetic Syntron model V-80 and model VP-75A tables produce greater vertical accelerations than those predicted mathematically using the assumption of simple harmonic motion. The VP-75A produces the greatest accelerations—followed by the V-80 and the SCR 1000 tables. Test results from previous Bureau studies involving these table types and different soil types indirectly confirm this trend [1].[1] These studies showed the VP-75A table yields higher maximum index unit weights than the V-80 table; the V-80 yields higher unit weights than the SCR 1000 table. The large accelerations exhibited by the VP-75A can be hypothesized to produce the greatest maximum index unit weight—followed by the V-80 and SCR 1000 tables.

[1] Numbers in brackets refer to entries in the bibliography.

The Bureau and ASTM (American Society for Testing and Materials) recommend the use of vertical double-peak displacement (double amplitude) to calibrate vibratory tables. Adoption of these calibration standards represented a major step toward producing consistent results for the maximum index unit weight of a cohesionless soil. However, even with calibration standards, different maximum index unit weights are still produced for the same soil using different types of vibratory tables. Consequently, maximum index unit weights obtained from different tables (assuming the mechanics of the test are performed to standard procedure) must be used judiciously. Note that differences in test results may reflect differences in the acceleration magnitudes even though the different tables may comply with the present displacement standard and the same tables (especially electromagnetic) are calibrated to the same displacement. This conclusion is in part reflected by both the multilaboratory and single operator precisions provided by ASTM: D 4253 for . . . judging the acceptability of maximum-index density test results . . . .[2].[2]

Calibration Feasibility

This study showed that using accelerometers instead of LVDTs, to calibrate vibratory tables, provides a more precise measurement of the mechanism responsible for densification of soil. While direct measurement of accelerations generated by a vibratory table is the most desirable method, additional research would have to be performed before this method of calibration could be responsibly implemented. The additional research would involve:

1. Evaluation of the relationships between vibratory table acceleration and the maximum index unit weight of a soil type. (This endeavor would have to be performed to establish an acceleration magnitude that would produce the desired dry unit weight.)

2. Identification of a "reference" value of maximum index unit weight for different soil types so that the magnitude of acceleration could be determined. (Also, it would be beneficial to establish the displacement amplitude with these data.)

3. Determination of the long-term performance and reliability of different vibratory tables. (This would help to establish guidelines for the required frequency of calibration.)

For fiscal years 1985, 1986, and 1987, the calibration program average cost was about $550 per table including staff salary, per diem, transportation, equipment repair, training, and miscellaneous expenses.

[2] Standard Test Methods for Maximum Index Density of Soils Using a Vibratory Table

Alternate Equipment

Investigations of alternate sources of vibratory table equipment identified only one additional manufacturer of electromechanical vibratory packing tables. Specifications for both electromechanical and electromagnetic equipment manufactured by Vibco and Syntron, respectively, indicated significant changes with respect to this testing application have not occurred. Because alternate equipment sources are rare, it is not desirable to investigate alternate equipment until the behavior of existing equipment is further examined and relationships between generated accelerations, amplitude, and index unit weight of a soil are quantified.

INTRODUCTION

Since the 1950s, the Bureau has used the concept of relative density to define the state of compactness of cohesionless soil relative to its minimum and maximum dry unit weights. While the concept of relative density is theoretically sound, its use has caused considerable debate regarding practicality because of problems associated with both procedures and equipment used to determine the minimum and maximum dry unit weights of soil. Research into test procedures and equipment has provided insight into the factors that affect test results; and investigations, therefore, have improved reliability of results by providing procedural and equipment guidelines.

The Bureau has been actively involved to improve the test method by conducting research and participating in development of standards for procedures and equipment. A major source of inconsistency in test results for the maximum dry unit weight of soil was corrected when procedures and equipment calibration standards were established for vibratory tables used to densify the soil. With calibration of the tables, more consistent results were produced by the Bureau's soil laboratories. However, the calibration program has required considerable resources. Within this context, current calibration procedures have been reviewed with the intent of providing recommendations for improving procedures and reducing the level of effort currently required by the Bureau to calibrate its vibratory tables.

DISCUSSION

Vibratory Densification

The mechanism of vibratory densification of cohesionless soils for obtaining their maximum dry unit weight has been extensively researched by many in the geotechnical community; development

of a standard test method has been vigorously pursued. The intensity of these efforts was evident in June 1972, when ASTM [3] sponsored an international symposium to discuss various aspects of test methods. The relevance of relative density as an engineering parameter was discussed at the symposium, which led to refinements in test procedures and equipment calibration.

During this study, a literature review was performed to identify recent research investigating vibratory densification of cohesionless soils. The findings are briefly summarized as:

- Densification of cohesionless soils by vibratory methods occurs when the force exerted by acceleration of the soil particle mass exceeds the shear strength of the interparticle contacts.

- Magnitude of acceleration imparted to the soil particles is a function of several factors including:

  - the nature of the motion (simple vertical harmonic motion or a combination of vertical and horizontal motion);

  - the frequency, amplitude, and acceleration of the vibratory system; and the damping of the test system.

- Interparticle shear strength of the soil particles is a function of the particles':

  - shape
  - size
  - distribution
  - mineralogy

- The interaction of these factors creates a complex test environment.

Test Factors

Currently, research has involved evaluation of many different factors affecting maximum unit weight such as:

Soil type	Duration of vibration
Vibration amplitude	Surcharge pressure
Vibration frequency	Specimen mass
Vibration acceleration	Wet or dry soil specimens

The factors that affect test results generally can be divided into primary and secondary factors:

Primary factors	*Secondary factors*
Vibration motion including simple vertical harmonic versus vertical-horizontal motion, frequency, amplitude, and acceleration	Test conditions (wet versus dry soil, compactness prior to vibration, surcharge pressure, and duration of vibration)
Soil parameters including particle shape, and grain-size distribution	Soil parameters including particle size

These groupings characterize the impact (major or minor) of test factors upon final test results and reflect test results of numerous researchers. Either the secondary factors have been found to have negligible effects, or their effects have been fairly well researched and reasonable guidelines established (in a standard test procedure). The parameters of moisture content (dry versus wet) and initial state of specimen compaction have essentially no impact on test results [4, 5]. The factors of vibration time and surcharge pressure can affect results.

However, research has proved that most densification occurs during the first few minutes of vibration after which the specimen continues to densify but at a much slower rate [4, 6, 7, 8]. Study results also indicate that an optimum surcharge pressure achieves maximum dry unit weight [4, 9]. With respect to particle shape, particle size, and particle-size distribution, particle size has little effect on the maximum dry unit weight [8].

The effect that the primary factors have on maximum dry unit weight has been investigated because it is recognized that test results are sensitive to variations in the previously discussed factors. In summary, maximum dry unit weight is dependent primarily on the nature of vibration and on particle shape and particle-size distribution of the soil. Therefore, maximum dry unit weight for a given soil is determined by the nature of vibratory motion.

It is noted that the maximum dry unit weight currently obtained, using either electromagnetic or electromechanical vibratory tables, does not produce the theoretical maximum dry unit weight of the soil. Researchers have used methods such as repeated straining by simple shear and impact compaction, as well as vibratory methods, to define the theoretical maximum dry unit weight for comparison purposes. The standardization of the test methods and equipment has improved the precision but not necessarily the accuracy of test results.

Vibratory Motion

If motion developed by vibratory tables is considered simple and vertical, the motion is described as sinusoidal and characterized by frequency, amplitude, and acceleration of the test system. Using the assumption of simple vertical motion, the behavior is characterized by:

$$a_p = 0.0511\ (2A)\ f^2 \tag{1}$$

where:

a_p = acceleration, g's

f = frequency, hertz

A = double peak displacement (double amplitude), inch

$$0.0511 = (2\pi)^2 \left(\frac{1 \text{ double-peak displacement}}{2 \text{ single-peak displacement}}\right) \left(\frac{1 \text{ ft}}{12 \text{ in}}\right) \frac{1\ g}{32.2 \text{ ft/s}^2}$$

In principle, specifying two of the parameters defines the third. Using this relationship, researchers could compare data from the various test systems regardless of which two of the three variables were measured. However, tests performed by various researchers on similar materials produced different maximum dry unit weights. The inability to obtain consistent test results led to the recognition of differences in vibratory motion produced by electromagnetic and electromechanical tables. Apparently, the frequency and amplitude specified for simple harmonic motion produced different results when a combination of vertical and horizontal motion was present [1, 4].

TABLE CALIBRATION

Calibration

The Bureau developed a procedure for using LVDTs to measure displacement amplitude of a calibration mass attached to the deck of a vibratory table [10]. With this system, power input to the table was regulated so the desired table amplitude could be achieved. The frequency of the electromagnetic table was maintained constant at 60 hertz (standard line frequency). Amplitude of vibration was monitored on an oscilloscope and was adjusted mechanically and/or by controlling voltage to the vibrator with a rheostat. This instrumentation scheme provided data on both amplitude and phase of vibration of the deck table (fig. 3).

In 1980 [5] and 1982 [1], the Bureau completed laboratory studies that evaluated impacts of manufacturers' changes to electromagnetic vibratory tables.

In the 1980 study, Syntron models V-80 and V-181 electromagnetic tables were compared. It was concluded that the maximum index unit weight of sands was generally unaffected by changing vibration amplitude while that of gravel mixtures showed dependency on vibration amplitude. Study results also alluded to an increase in maximum index unit weight when a "ragged" waveform was present.

The 1982 study investigated the relationship between maximum index unit weight and frequency with constant amplitude using a Vibco model SCR 1000 electromechanical table. A Syntron model VP-75A vibratory table also was evaluated instead of the V-80 model which is no longer manufactured. This work focused on various VP-75FA table modifications that would enable it to achieve 0.015 ± 0.002 inch double-peak displacement, which was the value used for the V-80 table. Study results indicated the VP-75A table could obtain the same double amplitude as the V-80 table with only minor modifications. Results from samples tested at various frequencies (35 to 65 Hz) at constant displacement (0.015 inch double-peak displacement) using the SCR 1000 electromechanical table indicated that *each sample has a specific frequency at which a maximum dry density may be obtained.* Also, it was postulated that there may be more than one combination of frequency and amplitude that could produce the maximum index unit weight.

In 1983, ASTM dropped standard D 2049 (69) [11][3] and separated the relative density test into two standards:

1) D 4253 (83), "Standard Test Methods for Maximum Index Density of Soils Using a Vibratory Table," and

2) D 4254 (83), "Standard Test Methods for Minimum Index Density of Soils and Calculation of Relative Density."

At a frequency of 60 Hz, ASTM: D 4253 (83) specifies a displacement (double amplitude) of 0.013 ± 0.002 inch.

It is important to note that the VP-75A table (as received from the factory) is capable of producing a double-peak displacement that corresponds to the lower limit (0.011 inch) currently specified by the Bureau and ASTM (0.013 ± 0.002 inch).

The acceleration of the test system provides the energy for densification; acceleration developed by some electromagnetic vibratory tables exceeds the magnitude of acceleration determined assuming simple vertical, sinusoidal motion. With the limitation of a constant frequency of 60 Hz for the electromagnetic table, the parameters affecting the magnitude of accelerations are the amplitude and the damping characteristics of the table.

[3] Standard Test Method for Relative Density of Cohesionless Soils.

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vibratory unit itself. Additional work may involve placement of a variable transformer in line with the electromagnetic vibrator to provide a constant line voltage to the table. In some instances, the line voltage requires boosting to achieve the required voltage.

EQUIPMENT DESCRIPTION

Presently, the Bureau uses Syntron models V-80 and VP-75A vibratory tables in its testing laboratories. Model VP-57A replaced model V-80 in 1980. Both tables are pulsating magnet-type tables that operate at high frequency (a constant 60 Hertz) and low amplitude. Model V-80 table is a cushioned impact-type table; model VP-75A is a solid impact-type table. The primary difference between these tables is that model V-80 impacts are dampened while the VP-75A impacts are not. Adjustment of vertical displacement requires adjusting the coil spring tension by trial and error.

It is important to note that model VP-75A tables are usually driven near full capacity to obtain 0.011 inch double-peak displacement with the 300-pound calibration mass as specified in the calibration standard.

Testing also was performed on a Vibco model SCR 1000 electromechanical vibrator. The SCR 1000 produces vibratory motion using rotating eccentric cams to create vertical oscillations. The frequency and displacement of this table can be adjusted over a wide range; adjustments are easily made. The frequency may be changed during operation; table noise is minimal. Adjustment of displacement is easily made by adjusting alignment of eccentric cams.

Electromagnetic table operation is noisy—about 113 decibels—hearing protection equipment is required during use. The electromechanical table operates at about 71 decibels. These devices are shown in Appendix A: Vibratory Table Specifications and Drawings.

TESTING

Testing Program

This testing program involved measurement of actual displacements and accelerations of the 300-pound calibration mass at varying calibrated displacements for both the electromagnetic and electromechanical tables.

Initial attempts to calibrate model VP-75A table to be used in this study resulted in a maximum double-peak displacement of 0.009 inch. A replacement electromagnetic unit was installed and attempts were made to recalibrate the table. However, the replacement unit was also only capable of reaching 0.009 inch double-peak displacement. The behavior of this table was monitored at 0.007 inch (two tests) and 0.009 inch (one test) double-peak displacements only. These test results are presented but were not used in the analysis.

Subsequent testing was performed on another model VP-75A table. The second table was calibrated at double-peak displacements of 0.007, 0.009, 0.010, and 0.011 inch. Then, the table was modified by inserting two thin metal shims beneath the leaf springs of the electromagnetic units; amplitude and acceleration measurements were made for 0.011 and 0.014 inch double-peak displacements.

Tests were performed on Vibco model SCR 1000 electromechanical table at double-peak displacements of 0.011, 0.013, 0.015, 0.017 (two tests), and 0.021 inch.

A single set of test data was obtained from Syntron model V-80 electromagnetic table at a calibrated double-peak displacement of 0.012 inch.

Test Sequence

The following procedure was used to calibrate each table before monitoring accelerations. The 300-pound calibration mass was fastened to the table deck. The data acquisition system consisting of two d-c LVDTs, two d-c amplifiers, and an analog oscilloscope were connected. Oscillation of the longitudinal area of the calibration mass (fig. 4) was monitored and the table adjusted so that both monitor points on the mass were oscillating in phase and at the required displacement. Then, an LVDT was positioned in the center of the mass and the displacement verified. A photographic record was made of both oscilloscope records (fig. 2). (Henceforth, this is referred to as the reference displacement.)

With the table calibrated, the following LVDT and accelerometer data were recorded using either the d-c LVDTs, d-c amplifiers, and a digitizing oscilloscope, or the d-c accelerometers, d-c amplifiers, and digitizing oscilloscope.

Data from additional special sequences were obtained from each table. The sequences consisted of placing combinations of LVDTs and accelerometers at selected locations; data were used to establish phase relationships for the displacement and acceleration of the entire calibration mass.

Sequence number	*Measured parameter*	*Direction*	*Location of measurement on mass*	*Mass axis*
1	Amplitude	Vertical	Right/left	Longitudinal
2	Amplitude	Vertical	Front/back	Transverse
3	Amplitude	Vertical	Center	
4	Acceleration	Vertical	Right/left	Longitudinal
5	Acceleration	Vertical	Front/back	Transverse
6	Acceleration	Vertical	Center	
7	Acceleration	Horizontal	Right/left	Longitudinal
8	Acceleration	Horizontal	Front/back	Transverse
9	Acceleration	Vertical/horizontal	Right	Longitudinal
10	Amplitude/acceleration	Vertical/horizontal	Right	Longitudinal

Test Results

The digitized outputs from both the LVDTs and accelerometers were reduced and plotted using a model HP-9816 microcomputer. These results were compared—both quantitatively and qualitatively—so table behavior could be assessed. Examples of output (obtained from each table) at each displacement are shown in appendixes B, C, and D for the SCR 1000, VP-75A-SC (SC refers to table location), and V-80 tables, respectively. The phase of the right, left, front, back, and center measurement points were correlated using the output from special sequences, which tied the table behavior to a common reference. Test data and calculation results for displacement and acceleration are tabulated in appendix E.

AMPLITUDE–DISPLACEMENT–ACCELERATION

Amplitude

Distinct differences occur in the shapes of the displacement-time curves from the three different tables.

Vibco model SCR 1000 electromechanical table exhibited an extremely well-defined sinusoidal curve for the longitudinal axis—the axis normally calibrated—for all displacements (fig. 5). However, transverse behavior differed by the displacement-time curves not being in phase with each other and the curves not exhibiting the well-defined sinusoidal behavior. The center displacement-time curve was a well-defined sinusoidal curve. Collation of the curves (from all five measurement points) revealed that:

- The back of the mass reached peak displacement slightly before the right and left points,

- The front reached peak displacement slightly after the right and left, and

- The center was in phase with the left and right.

The magnitude of displacement was generally in good agreement with the "reference" displacement for the right, left, and center measurement points. (The maximum difference between the "reference" and measured data was 0.0015 inch.) The front and back measurement points exhibited significantly greater measured peak displacements (ranging from 0.0035 to 0.007 inch greater than reference, with an average of 0.0049 inch). This trend in table behavior is shown on figure 6.

Syntron model VP-75A-SC table exhibited a much more irregular approximation of a sine wave that appeared to be caused by the superposition of two or more waves (fig. 7). This behavior was observed for all the displacements at which the table was tested, including the tests performed with the table after it had been modified with shims.

The general behavior of the table was more coincident than the SCR 1000 table in that all the measurement points appeared to be in phase, with only a slight shift in the front and back measurement points (fig. 7).

The measured double-peak displacement generally agreed well with the reference; the greatest deviation was 0.0035 inch, and the average deviation was 0.001 inch.

Two sets of measurements were made after shims were installed in the vibratory unit of the VP-75A-SC. The addition of the shims made it much easier to calibrate the table to 0.011-inch double-peak displacement and made it possible to obtain a double-peak displacement amplitude of 0.014 inch. However, table behavior changed using the shims. The transverse axis (front and back measurement points) showed increased displacements (fig. 8).

Syntron model V-80 table was tested at a double-peak displacement of 0.012 inch. The right, left, and center measurement point displacement-time histories indicated reasonable phase sinusoidal behavior. The curves for the front and back were less defined (fig. 9). Collated behavior of the calibration mass indicated that front and back measurement points were slightly out of phase with each other, and slightly out of phase with the right, left, and center measurement points.

Measured double-peak displacements generally agreed with the reference.

Displacement-Acceleration Relationship

Deviations of measured displacement from the reference would produce differences in the calibration mass acceleration. The magnitude of calibration mass acceleration was calculated assuming that the motion of the vibrating table deck—and, therefore, the calibration mass—is simple sinusoidal motion. The expression for vertical displacement of the mass is:

$$x = x_{peak} \sin(\omega t) \tag{2}$$

where:

x = vertical displacement, inch

x_{peak} = single peak displacement, inch

ω = $2\pi f$, frequency, radians per second

f = frequency, hertz

t = time, second

Acceleration is determined from the second deviative of vertical displacement with respect to time:

$$a = \frac{d^2x}{dt^2} = -\omega^2 x_{peak} \sin(\omega t) \tag{3}$$

where a equals acceleration, inches per second per second.

Since double-peak displacement is defined as:

$$2\, x_{peak} = x_{da} \tag{4}$$

where x_{peak} equals $x_{da}/2$ and substituting into (3):

$$a = \frac{(2\pi f)^2}{2} x_{da} \sin(\omega t) \tag{5}$$

where x_{da} equals double-peak displacement, inch.

Frequency of the vibratory table was assumed to equal 60 Hz, which is the line frequency of the power supplied to the electromagnetic tables; the frequency set for the mechanical table (the actual frequency of the electromagnetic table) fluctuated slightly around 60 Hz (refer to app. A).

Substituting 60 Hz for frequency, f, converting acceleration from in/s^2 to g, and realizing that x_{da} only occurs when $\sin(\omega t) = \pm 1.0$, equation (5) becomes:

$$g = \left(\frac{1}{12}\right) \frac{1}{32.2} \left(\frac{4\pi^2}{2}\right) 60^2 \, x_{da} = 183.9 \, x_{da} \tag{6}$$

Vertical accelerations associated with the measured double-peak displacement for SCR 1000 and VP-75A-SC tables were calculated; the results are presented on figures 10 and 11. The solid line represents the acceleration predicted from the "reference" displacement.

The results show that, for each change of 0.001 inch from the reference displacement, a change of 0.18 *g* occurs. The SCR 1000 data (fig. 10) show prominent differences in accelerations (about 0.5 *g*) and displacements of the transverse axis of the calibration mass.

Acceleration

Different tables exhibited distinctly different acceleration-time curves. Each individual table exhibited a different curve on the different axis of measurement. Acceleration magnitude also changed distinctly from one axis of measurement to another.

Vertical accelerations of Vibco model SCR 1000 electromechanical table exhibited a rough approximation of a sine wave (fig. 5). The accelerations on the longitudinal axis exhibited what appears to be a composite wave while the transverse waveforms were less complex. As with the displacement waveforms, transverse acceleration waveforms were out of phase with longitudinal waveforms. The center waveform provided the best approximation of a sine wave.

Measured vertical acceleration magnitudes generally agreed quite well with those predicted from reference displacements. The comparison is shown on figure 12. Accelerations on the longitudinal axis differed from the theoretical by a maximum of 16 percent with an average of 6 percent difference. Accelerations on the transverse axis exceeded the reference by as much as 85 percent with an average of 73 percent. Agreement between the longitudinal axis and center point vertical acceleration with the reference would support use of the simple harmonic motion approximation of acceleration from displacement. Also, it is noted that accelerations on the transverse axis were consistent in relationship to reference acceleration values. Accelerations of the front of the mass differed from the reference values by 73 to 85 percent; accelerations of the back of the mass differed from the reference values by 63 to 70 percent.

Agreement in magnitude between calculated reference accelerations and measured accelerations verified acceptable performance of the accelerometers.

Horizontal accelerations of the mass differed in that waveforms on the longitudinal axis consistently showed a ragged or scattered form while waveforms on the transverse axis were concise—however, not sinusoidal or discrete. The magnitude and direction of the waveforms confirmed consistency in measured values of acceleration.

The magnitude of horizontal accelerations also revealed the difference between the longitudinal and transverse axes (fig. 15). Horizontal accelerations on the transverse axis consistently exceeded those on the longitudinal axis almost by a factor of 10; that is, the longitudinal axis accelerations ranged between 0.27 *g* at 0.011 inch double-peak displacement to 0.70 *g* at 0.021 inch double-peak displacement while transverse axis accelerations ranged between 1.90 *g* at 0.011 inch double-peak displacement and 5.0 *g* at 0.021 inch double-peak displacement.

The Syntron model VP-75A-SC table acceleration waveforms were extremely rough and did not resemble a sine wave. Both the vertical and horizontal waveforms exhibited a period of intense positive and negative accelerations, which decayed between cycles (fig. 7).

Vertical accelerations measured from the calibration mass were all consistent in shape with the high-intensity accelerations occurring concurrently at all locations on the mass. Because the appearance of the waveform was not sinusoidal, the waveform was examined and acceleration data selected from two different time intervals of the waveform. Maximum accelerations were determined for each waveform; these test data were referred to as "scattered." The portion of the waveform that was more clearly defined was referred to as "discrete." Discrete data were arbitrarily selected to represent the decaying portion of the waveform at a location approximately halfway through the decaying cycle of data (fig. 14).

Assuming simple harmonic motion, discrete accelerations generally exceeded the reference accelerations calculated from table amplitude (fig. 15). Measured accelerations differed from the reference by as little as 5 percent to as much as 288 percent. A trend shows increasing acceleration with increasing table double-peak displacement; removing test data—obtained using the shimmed vibrator at 0.011 and 0.014 inch double-peak displacement—confirms the trend (fig. 16).

Scattered accelerations significantly exceeded the reference accelerations (fig. 17); a distinct trend of increasing acceleration with increasing displacement was evident. Acceleration increased significantly between 0.009 and 0.011 inch double-peak displacement. At 0.011 inch double-peak displacement, test data also exhibit the impact of using shims to facilitate calibration of the table. The change in table behavior can be seen as decreasing the magnitude of acceleration at 0.011

inch double-peak displacement. In addition, the slope of the data trend changed significantly (comparing figs. 17 and 18).

The trend of acceleration data, with respect to displacement, indicates (for the table tested) distinct changes exist in table behavior as the double-peak displacement rises above 0.009 inch; the change is significant in terms of the maximum acceleration (scatter) but not as significant with the discrete values.

Horizontal accelerations exhibited similar behavior and magnitude as vertical accelerations (both discrete and scatter response, figs. 19 through 22). These results confirmed the impact of modifying the vibratory unit with shims.

The Syntron model V-80 table exhibited acceleration-time waveforms similar to the SCR 1000 table; vertical acceleration waveforms were somewhat similar to those observed on the SCR 1000 table (figs. 5 and 9). Waveforms were concise, but only the longitudinal and center waveforms approximated a sine wave. Transverse waveforms were unusual. Horizontal longitudinal waveforms were also similar to the SCR 1000 in that the longitudinal waveforms were rough while the transverse waveforms were smooth; neither was sinusoidal.

At a double-peak displacement amplitude of 0.012 inch, vertical accelerations ranged from 2.9 to 4.9 *g* with an average of 3.5 *g* (reference equaled 2.2 *g*).

Horizontal acceleration waveforms from the V-80 table were similar to those observed from the SCR 1000 electromechanical table. Longitudinal waveform was ragged while transverse waveforms were concise. As with waveforms from both the VP-75A-SC and SCR 1000 tables, acceleration magnitude appears to decay after the peak displacement (maximum acceleration) occurs. The V-80 horizontal accelerations were extremely uniform, ranging from 3.0 to 3.2 *g*.

Measured Displacement-Acceleration Relationship

Since the behavior of the VP-75A-SC table was complex and measured magnitudes of vertical acceleration were greater than values predicted by simple harmonic motion, an attempt was made to correlate the table's displacement behavior with its acceleration behavior by determining the components of the displacement-time waveform using the Fourier analysis. Fourier analysis was used to derive an equation defining the shape of the displacement-time curve. The displacement-time expression was differentiated to obtain an acceleration-time waveform, and the theoretically determined acceleration-time history was compared with the measured acceleration-time history.

A displacement-time waveform from the VP-75A-SC table operating at a reference double-peak displacement of 0.010 inch was selected for analysis (fig. 23). A total of 280 data points from the central waveform were entered into Spectrum Software's Microcap II [12], and the waveform's Fourier coefficients were determined.

The waveform equation obtained from Fourier analysis is:

$$
\begin{aligned}
x(t) = 0.026642 &+ 0.00278 \cos(\omega_o t) + 0.07051 \sin(\omega_o t) \\
&+ 0.01817 \cos(2\omega_o t) - 0.00690 \sin(2\omega_o t) \\
&- 0.00614 \cos(3\omega_o t) - 0.00391 \sin(3\omega_o t) \\
&- 0.00545 \cos(4\omega_o t) + 0.00803 \sin(4\omega_o t) \\
&- 0.00006 \cos(5\omega_o t) - 0.00007 \sin(5\omega_o t) \\
&- 0.00009 \cos(6\omega_o t) - 0.00013 \sin(6\omega_o t) \\
&+ 0.00005 \cos(7\omega_o t) - 0.00017 \sin(7\omega_o t) \\
&- 0.00009 \cos(8\omega_o t) - 0.00010 \sin(8\omega_o t) \\
&- 0.00003 \cos(9\omega_o t) - 0.00005 \sin(9\omega_o t) \\
&- 0.00003 \cos(10\omega_o t) - 0.00040 \sin(10\omega_o t)
\end{aligned}
\tag{7}
$$

The waveform associated with this equation is shown on figure 24. The waveform generated from Fourier analysis exhibits excellent agreement with the waveform generated from test data. However, the noise from the amplifier (visible on fig. 23) is not discernable.

The displacement-time equation was differentiated twice with respect to time, and the following expression for acceleration was obtained:

$$
\begin{aligned}
a(t) = &- 0.00278 \cos(\omega_o t) - 0.07051 \sin(\omega_o t) \\
&- 0.07266 \cos(2\omega_o t) + 0.02759 \sin(2\omega_o t) \\
&+ 0.05532 \cos(3\omega_o t) + 0.03519 \sin(3\omega_o t) \\
&+ 0.08717 \cos(4\omega_o t) - 0.12846 \sin(4\omega_o t) \\
&+ 0.00155 \cos(5\omega_o t) + 0.00165 \sin(5\omega_o t) \\
&+ 0.00317 \cos(6\omega_o t) + 0.00454 \sin(6\omega_o t) \\
&- 0.00250 \cos(7\omega_o t) + 0.00843 \sin(7\omega_o t) \\
&+ 0.00557 \cos(8\omega_o t) + 0.00627 \sin(8\omega_o t) \\
&+ 0.00219 \cos(9\omega_o t) + 0.00373 \sin(9\omega_o t) \\
&+ 0.00310 \cos(10\omega_o t) + 0.03990 \sin(10\omega_o t)
\end{aligned}
\tag{8}
$$

An acceleration-time waveform for this expression was generated using the same time increments at which the displacement-time data were selected. The resulting waveform is presented on figure 25. The acceleration waveform is similar to the measured acceleration record for the center of the mass and exhibits the main characteristics of the measured waveform:

- A single peak magnitude acceleration, followed by a somewhat sinusoidal waveform that appears to decay.

- The acceleration magnitude of the center portion of the decaying waveform (similar to that selected as the discrete acceleration on the measured waveform) has a single amplitude of approximately 2.5 *g* while the measured discrete value was 2.1 *g*. The maximum acceleration predicted by Fourier analysis was approximately 5.0 *g*, and the measured value was 8.4 *g*. The agreement in the Fourier-developed acceleration waveform with the measured waveform reveals that LVDTs are sufficiently responsive to displacements generated by the electromagnetic vibratory table.

VIBRATORY TABLE

Table Comparison

Vertical accelerations of the SCR 1000, V-80, and VP-75A-SC tables were compared at approximately equal vertical double-peak displacements (SCR 1000 at 0.011 inch, V-80 at 0.012 inch, and VP-75A-SC at 0.011 inch; fig. 26).

The "discrete" acceleration at each measurement location on the mass is shown, as is the reference acceleration for 0.011-inch double amplitude. These results indicate the VP-75A-SC table produces greater accelerations than either the SCR 1000 or V-80 tables, which produce accelerations somewhat more consistent with those predicted assuming simple harmonic motion. These data also show that the V-80 and SCR 1000 tables produce greater accelerations on the transverse axis, which is perpendicular to the axis of the vibratory units on both tables.

While the VP-75A-SC table produces greater accelerations than the SCR 1000 or V-80 tables, the acceleration versus displacement study also indicated that, as VP-75A-SC table is pushed toward its maximum displacement, measured acceleration increased rapidly. This indicates that, by reducing the VP-75A-SC table displacement slightly, accelerations comparable to the V-80 and SCR 1000 tables could be achieved.

This does not seem like a feasible approach for the following two reasons:

1. Vertical accelerations of VP-75A-SC table appear to increase rapidly with displacements greater than 0.009 inch; an exact relationship has not been defined. Therefore, LVDTs could not presently be used to establish the table calibration. While accelerometers might be used to establish the desired acceleration, intuitively, the vertical displacement adjustment system of the vibratory unit would not provide sufficient sensitivity for the precision required using accelerometers.

2. As a result of operation and manufacturing condition, each vibratory unit would exhibit a slightly different acceleration-displacement relationship. This relationship would be subject to change as a result of normal operation. Therefore, the acceleration-displacement relationship for a vibratory unit would have to be evaluated upon receipt from the manufacturer, after installation, and at established periods during use. Additional research would have to be performed to evaluate the acceleration performance of a table at periodic intervals.

The effect of acceleration on maximum index unit weight of a soil can be seen in some of the results presented by Krumdieck [1]. This testing involved a poorly graded gravel (labeled as mix No. 3, fig. 27). Results were obtained using the 0.50-ft^3 mold and are shown below.

Table type	*Double-peak displacement, inch*	*Maximum index unit weight, lbf/ft^3*
SCR 1000	0.016	138.4
V-80	0.016	142.0
VP-75A	0.013	148.2

These test results verify that the three different vibratory tables produce different maximum index unit weights. The fact that maximum index unit weights produced by the SCR 1000 and V-80 tables are significantly less than that produced by the VP-75A table—even when double-peak displacements of the SCR 1000 and V-80 tables were greater than the VP-75A—supports the conclusion that acceleration produced by the table has direct impact on the maximum index unit weight of a soil.

This trend also is observed in test data obtained by Krumdieck [1] with other soils tested in the 0.10-ft^3 mold.

Calibration/Table Performance Enhancements

Results from this study can be used to identify several areas in which existing calibration efforts could be improved. The study has shown that performance of a vibratory table based on vertical

displacement amplitude is misleading because of variations that can occur in acceleration. The study reveals that electromagnetic tables may not be able to sustain adequate levels of performance over time (sometimes only after 3 or 4 tests were performed) and that information is lacking on performance characteristics of currently used electromagnetic tables.

Several actions could be implemented to improve test results; i.e.,

1. Improving the calibration technique,

2. Reducing operating performance requirements of current test equipment (possibly resulting in a lower unit weight value),

3. Alternate vibratory table equipment, and

4. Using alternate test equipment.

Each of these actions is discussed below:

Calibration Technique

Continue the existing calibration procedure using LVDTs to measure displacement of a calibration mass bolted to the vibratory table. Advantages of using displacement measurements include:

- Current familiarity with use of LVDTs and signal measurement equipment

- Continued support of both Bureau and ASTM suggested calibration standards

- Reasonable cost of the calibration program (approximate figures)

However, to continue calibrating vibratory tables by measuring displacement with LVDTs perpetuates the incorrect assumption that all vibratory tables generate simple harmonic motion. Also, this ignores the fact that acceleration provides the energy for densification and contributes to discrepancies observed in test results. Using the present calibration specifications will preclude any effort to achieve any meaningful precision and bias values for the test.

Another action is to implement a new calibration procedure using accelerometers to measure table acceleration of a calibration mass bolted to the table.

Recognizing that acceleration generates the energy to densify a soil, the use of accelerometers provides a direct measurement of acceleration, which can be correlated with results obtained from the test. This action accommodates the fact that tables do not produce simple harmonic motion. Different types of tables can generate different magnitudes of acceleration at the same displacement, and even the same type of table at the same displacement can generate different acceleration magnitudes.

This action includes:

- Costs for establishing relationships between acceleration and maximum index unit weight

- Establishing the reliability of an accelerometer-based data acquisition system

- Training personnel in the use of a different calibration technique

Equipment Operating Requirements

Maintain existing equipment performance.–Using present equipment and calibration techniques implies that the maximum index unit weight currently accepted as reasonable for a specific soil type can be reproduced by any combination of equipment and calibration scheme. This approach accepts the current relative density data base "as is," including large deviations resulting from test equipment and procedure. The accumulated data provide the only reference for making comparisons even though the accuracy of comparisons is highly questionable.

Disadvantages of continuing use of present equipment and calibration techniques include the undocumented and unaccounted reasons for deviations in test results. Consequently, development of meaningful precision and bias values for test results is precluded.

Reduce the level of equipment performance.–This action allows:

- For a maximum index unit weight—which may be less than presently obtained using present test equipment and calibration techniques

- For expanding the potential for using test equipment that can provide a higher degree of reliability

- For requiring that test values obtained using different tables be compared to the existing data base.

However, any change in equipment should be evaluated on reliability and performance aspects. If a lower maximum index unit weight is generated with alternate equipment, other test requirements possibly can be reduced; and the precision of the value and its impact on calculated relative density must be evaluated. From a cursory review of the concept of relative density, decreasing the difference between the maximum and minimum index unit weights without increasing the precision of the test values increases the error associated with the dry unit weight determined at any value of relative density.

As noted, this action requires costs associated with studies to develop new correlations.

Based on these considerations, the following measure is suggested:

- Continue calibrating the vibratory tables by displacement measurements to the present standard in conjunction with measurement of associated accelerations. This approach minimizes the technical and cost impact of the program while developing more information about the relationship between table displacement and acceleration, and maintains the approximate existing magnitude of the maximum index unit weight value.

- Study table performance and reliability to provide more definite guidelines for table calibration.

- Develop a simple accelerometer data acquisition system that provides peak acceleration magnitudes for calibration.

- Initiate studies of the relationship of maximum index unit weight and acceleration for different soil types.

Alternate Vibratory Table Equipment

A solicitation was made to private industry to determine if alternate vibratory equipment was available that could replace equipment presently used by the Bureau. A specification presently used for acquiring vibratory tables was distributed by way of the *Commerce Business Daily;* only four responses were received.

Two responses were from manufacturers of vibrators used in the packing and vibratory feeder industry (Vibco, Inc., and the Cleveland Vibrator Company). The response from Vibco included literature currently available, which indicated that the product line was essentially unchanged. Model SCR 1000 used in this study was still available from Vibco. The response from the Cleveland

Vibratory Company (bulletin No. VF-77) contained a flat deck model table (model FA, used for settling and packing loose materials), which appeared similar to the tables currently in use. Model FA is an electromechanical table and is capable of generating approximately 0.050 inch double amplitude under 300 pounds mass at 60 hertz. (This corresponds to an acceleration of approximately 10 *g*.)

Two manufacturers of electronic test equipment responded to the solicitation but did not have products suitable for the requested application (C. W. Brabender Instruments, Inc., and Edison Systems Corporation).

Soiltest, Inc., was contacted regarding the electromagnetic vibratory table they market and distribute. Two models are available, both manufactured by Syntron. Model CN-166 has a rated double amplitude from 0.002 to 0.015 inch when driven using a Syntron model V-86 electromagnetic vibrator and is rated for 500-pounds mass capacity. The V-86 electromagnetic vibrator is a cushioned impact version that uses a rubber striking block. While this model meets the amplitude specified by ASTM, discussion with Soiltest, Inc. technical personnel indicated that accelerations of the tables have not been measured.

Soiltest, Inc. also markets the Vebe Consistometer for evaluating the consistency of concrete. While this table has been manufactured by the Vebe Corporation of Sweden, Soiltest, Inc. has recently contracted with Syntron for manufacture of this table. Performance specifications were not available.

A contact with the Materials Handling Equipment Division of the FMC Corporation, which manufactures the Syntron vibrators, revealed that model V-75 vibrator specifications have not changed.

Alternate Equipment

The desire to change from using existing electromagnetic vibratory tables is because of:

- The effort required to modify and prepare the tables for use initially
- The effort required to calibrate the tables
- The uncertainty regarding table reliability and performance.

However, changing from the existing equipment would require that the change benefit the Bureau's quality control efforts from both cost and technical perspectives.

As previously discussed, the average cost just to calibrate a vibratory table is $500 to $600. The total annual calibration cost for the Bureau's 14 current tables ranges from $7,000 to $8,400.

The four basic alternatives concerning index unit weight test equipment are:

1. Continue to use existing vibratory tables.

2. Modify the existing vibratory tables.

3. Replace the existing test equipment with commercially available equipment.

4. Replace the existing test equipment with specifically designed and developed test equipment.

The first alternative is to continue using the existing vibratory table equipment (Syntron models V-75A and V-80). Advantages of this alternative include present use of the equipment, and personnel familiarity with calibration and test activities. The VP-75A table is commercially available, and the cost of equipment and calibration is reasonably well known.

Disadvantages include difficulty in calibrating some tables, which reflects the variable behavior and performance of each individual table. Presently, data are lacking regarding the operating reliability and performance of the tables with time. However, indications are apparent that some tables do not remain in calibration after only three or four tests have been performed.

The second alternative is to modify existing tables to reduce operating requirements in an attempt to improve table performance and reliability. Advantages of this alternative could be reduced calibration efforts and improved table performance.

Disadvantages include the research required to evaluate the impact of the table modifications on the acceleration/index unit weight relationship as well as the reliability and performance of any modifications.

The third alternative involves acquisition of different commercially available test equipment. Possible advantages of this alternative include equipment that is easier to calibrate and equipment that could provide a greater degree of reliability and performance.

Disadvantages are the same as for the first and second alternatives in that the calibration and performance issues would have to be researched. Also, there are few manufacturers for this type of equipment.

The last alternative involves development of specific equipment for determining maximum index unit weight of a soil. Advantages of this alternative include the controlled development of test equipment that could be designed to provide required accelerations as well as simple calibration procedures. Potential exists for participation of the geotechnical community in developing a consensus specifications for vibratory equipment.

Disadvantages include the cost associated with design and development as well as research required to identify the appropriate magnitude of acceleration required for different soil types.

Each alternative demonstrates a need to develop further data regarding (1) relationship between acceleration and maximum index unit weight, and (2) reliability and performance aspects of the tables to provide better guidelines for calibration intervals. All alternatives except the first require additional research into equipment performance to compare with current reliable results. The cost of the program increases with each alternative, and performance of specific equipment is not absolutely guaranteed.

Therefore, the most prudent action is to continue using existing equipment while continuing to develop data pertaining to the relationship between acceleration and dry unit weight and equipment reliability and performance. This action would assist in providing clear guidelines for quantifying the use of acceleration in the soil densification process, and the interval between calibrations of the vibratory tables. This information would provide a firm basis for future evaluation of manufacturer changes to vibratory tables as well as new types of equipment.

BIBLIOGRAPHY

[1] Krumdieck, Colin W., memorandum to Supervisor, Unit 2, Soil Testing Section, Subject: "Maximum Density Study," Bureau of Reclamation, Denver, Colorado, April 1982.

[2] *Annual Book of ASTM Standards*, sec. 4, vol. 0408, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1984.

[3] Selig, E. T., and R. S. Ladd, *"Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils,"* ASTM STP 523, American Society for Testing and Materials, Baltimore, Maryland, July 1973.

[4] Chang, Pyoung Wuck, "Parametric Study of Vibration Densification Soils," Ph.D. Thesis, Rutgers University, State of New Jersey, 1982.

[5] Bernstein, Alfred I., memorandum to Supervisor, Unit 2, Soil Testing Section, Subject: "Soil Testing Procedure — Maximum Density," Bureau of Reclamation, Denver, Colorado, September 1980.

[6] Brand, E. W., "Some Observations on the Control of Density by Vibrations," *Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils*, ASTM STP 523, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 121–132, 1973.

[7] "Laboratory Tests to Refine the Maximum Density Procedures for Cohesionless Soils Using a Vibratory Table," Bureau of Reclamation Report No. EM–697, Denver, Colorado, March 1965.

[8] Young, T. L., "Factors Controlling Maximum and Minimum Densities of Sand," *Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils*, ASTM STP 523, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 98–112, 1973.

[9] Mehdiratta, G. R., and G. E. Triandafilidis, "Minimum and Maximum Densities of Granular Materials," *Geotechnical Testing Journal*, GTJODJ, vol. 1, pp. 34–40, March 1978.

[10] Kaufman, L. P., and E. D. Strickland, and A. A. Benavidez, "Suggested Method for the Calibration of Vibratory Tables for Maximum Index Density Testing," *Geotechnical Testing Journal*, STJODJ, vol. 2, No. 2, pp. 152–157, September 1979.

[11] "ASTM 2049–69, "Standard Test Method for Relative Density of Cohesionless Soils," *Annual Book of ASTM Standards*, Part 19, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1980.

[12] MICRO-CAP II Electronic Circuit Analysis Program, Spectrum Software, Sunnybrook, California.

Related References

"Development of a Maximum Density Test for Cohesionless Soil by a Vibratory Method," Bureau of Reclamation Report No. EM–577, Denver, Colorado, May 1961.

Compton, J.R., and W.E. Strohm Jr., "Compaction of Cohesionless Soil," *miscellaneous paper 5–68–15*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, August 1968.

Dobry, R., and R. V. Whitman, "Compaction of Sand on Vertically Vibrating Table," R72–23, *Soils Publication No. 302*, Massachusetts Institute of Technology, May 1972.

Johnston, M. M., "Laboratory Studies of Maximum and Minimum Dry Densities of Cohesionless Soils," *Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils*, ASTM STP 523, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 133–140, 1973.

Earth Manual, 1st ed., Bureau of Reclamation, U.S. Government Printing Office, Washington, D.C., pp. 467–474, revised 1963.

Earth Manual, 2d ed., Bureau of Reclamation, U.S. Government Printing Office, Washington, D.C., reprint 1985.

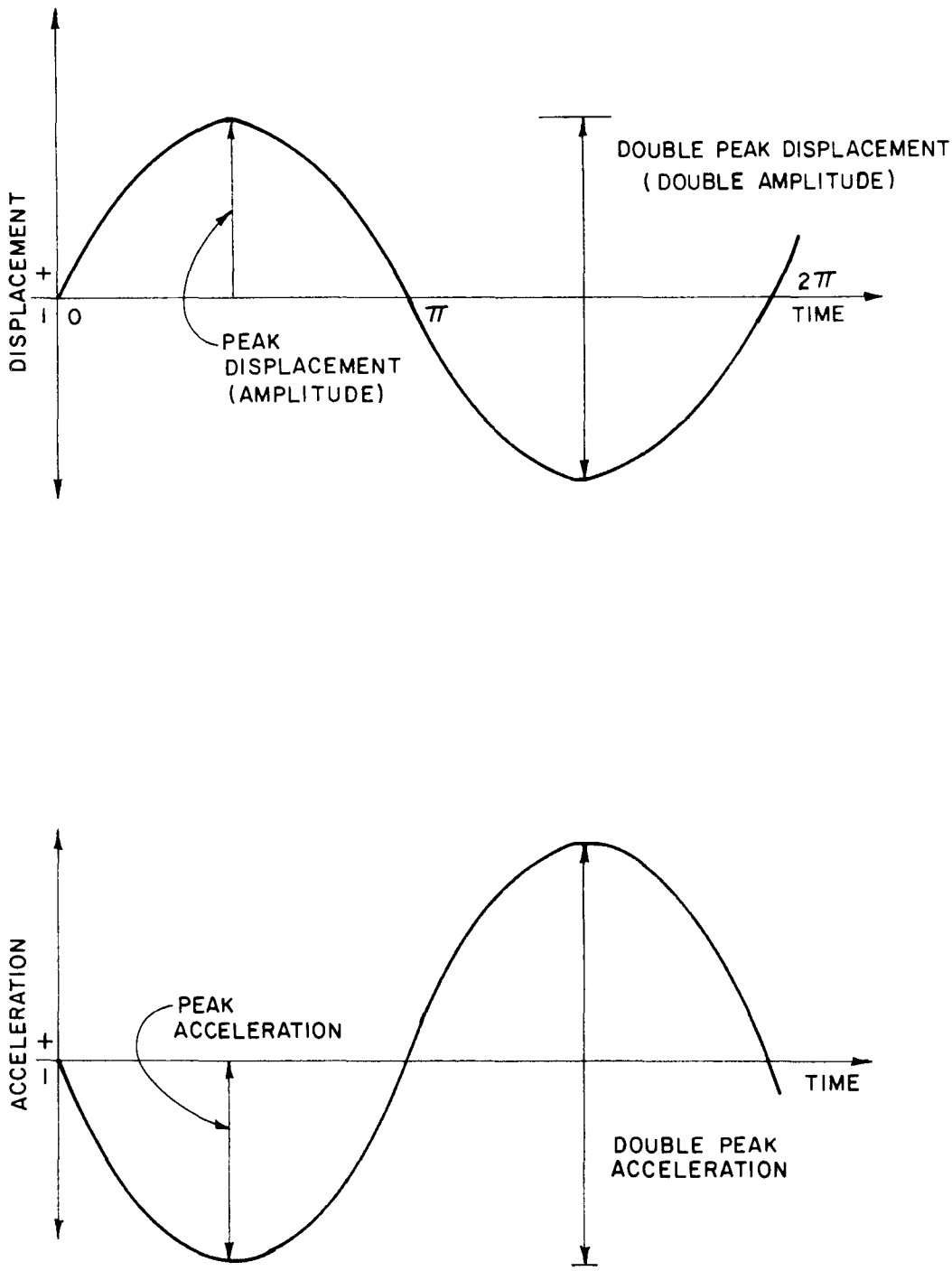
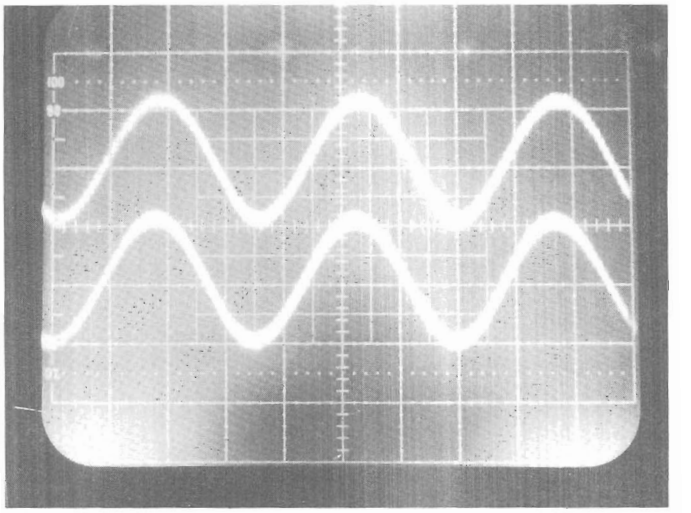


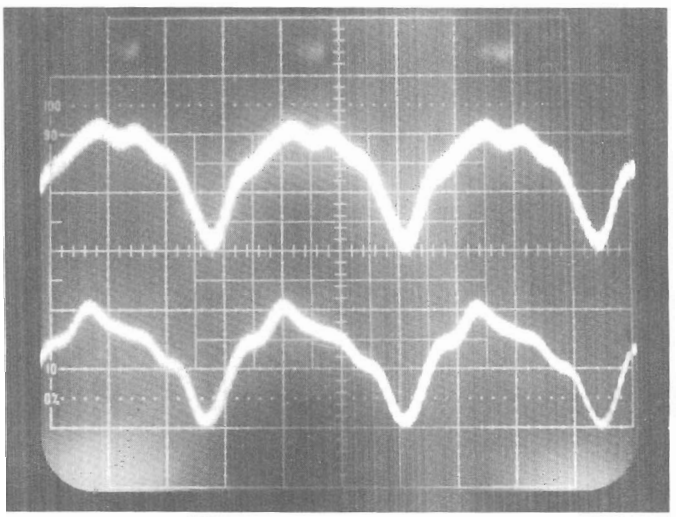
Figure 1. – Simple harmonic motion relationships.

SCR 1000 Table



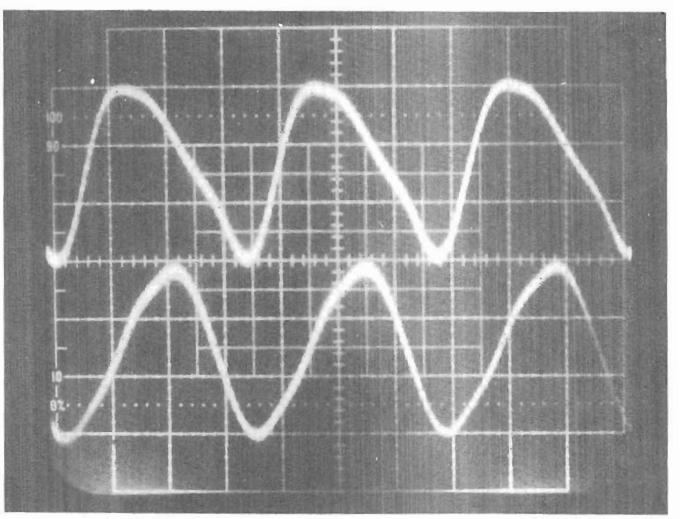
(a) Vibco SCR 1000 at 0.011 inch DA

VP-75A-SC Table



(b) Syntron VP-75A-SC at 0.011 inch DA

V-80 Table



(c) Syntron V-80 at 0.015 inch DA

Figure 2. – LVDT displacement-time record — vibratory table waveforms.

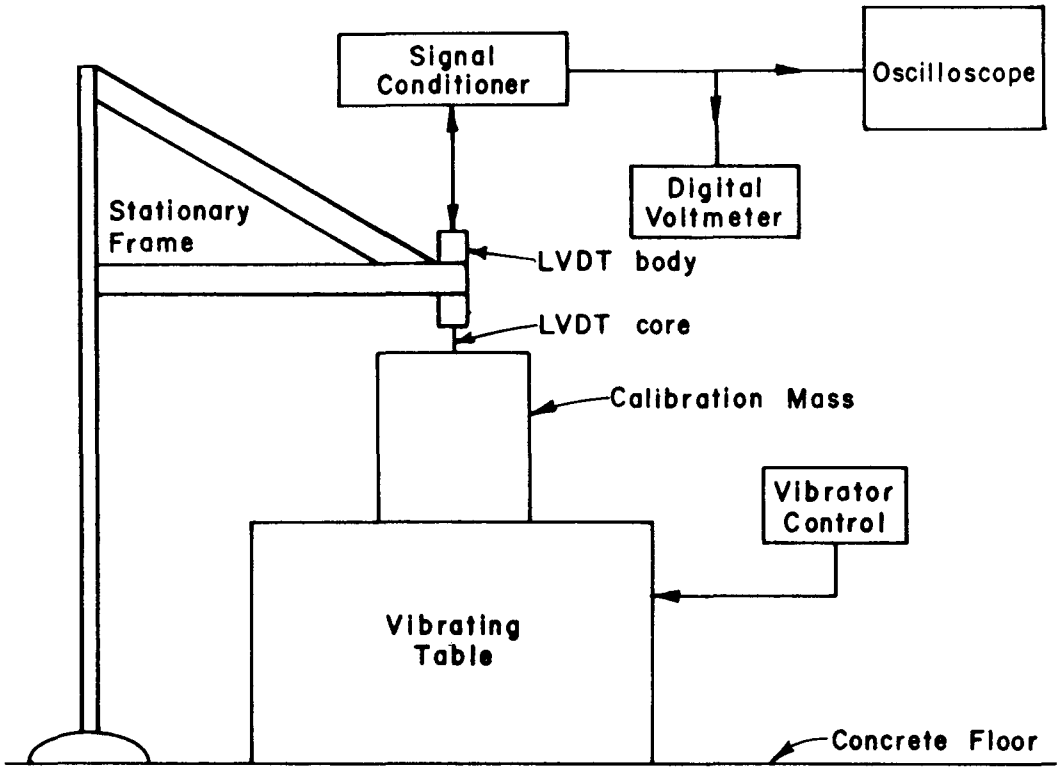


Figure 3. – LVDT calibration schematic.

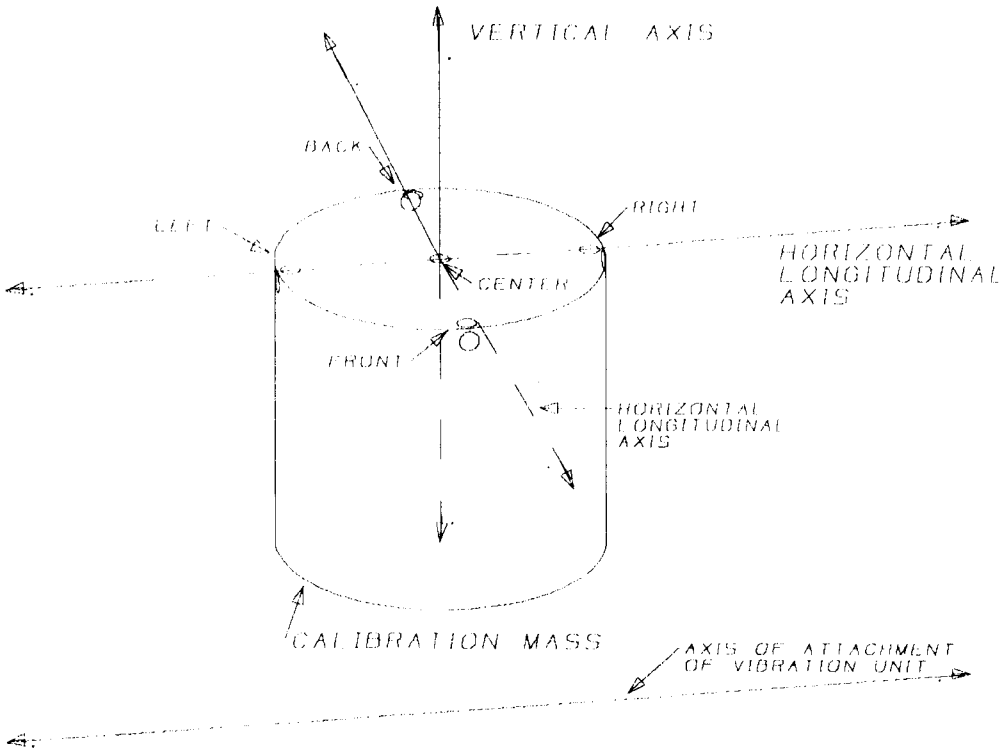


Figure 4. – Calibration mass instrumentation.

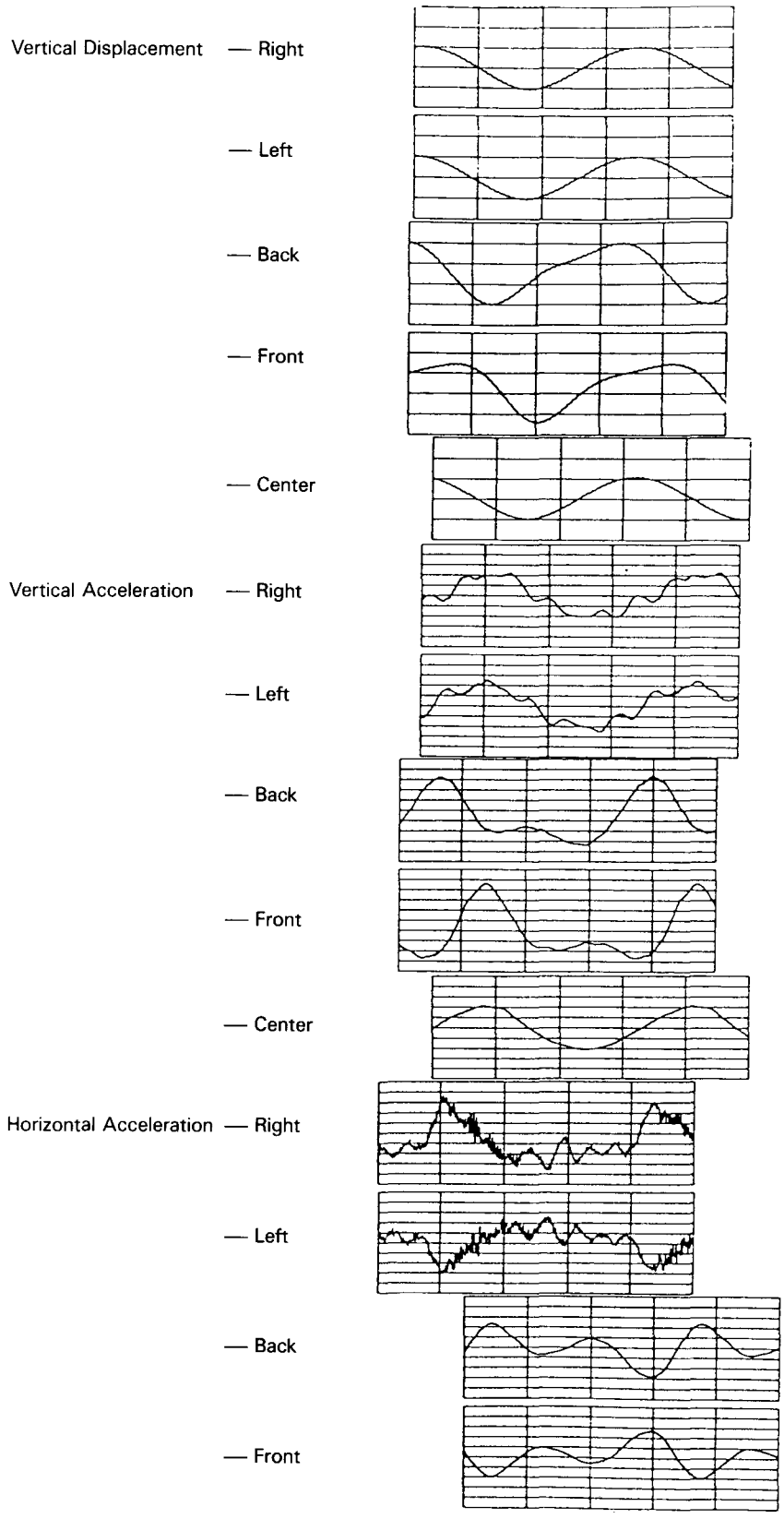


Figure 5. – SCR 1000 table waveform summary — double-peak displacement: 0.011 inch.

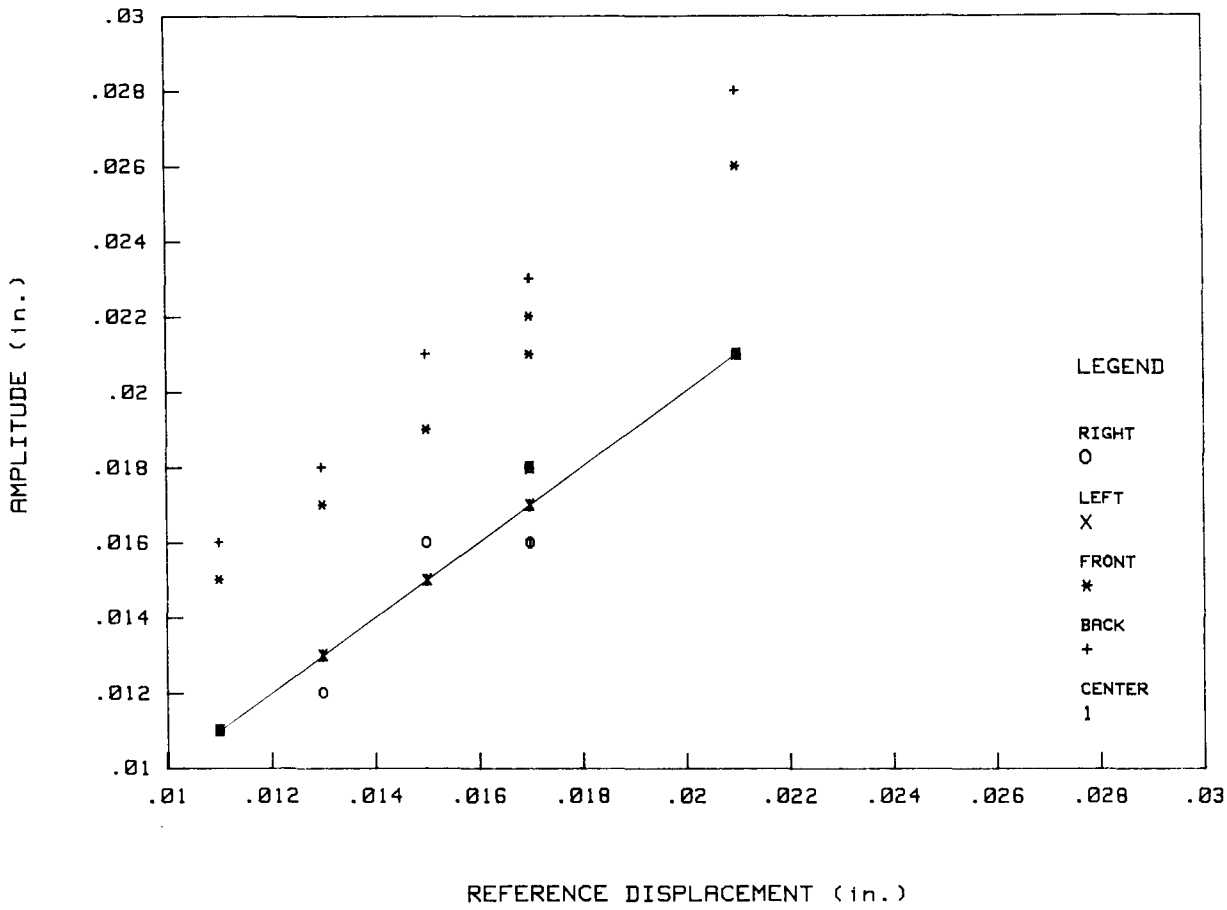


Figure 6. – SCR-1000 table vertical displacement — reference versus measured.

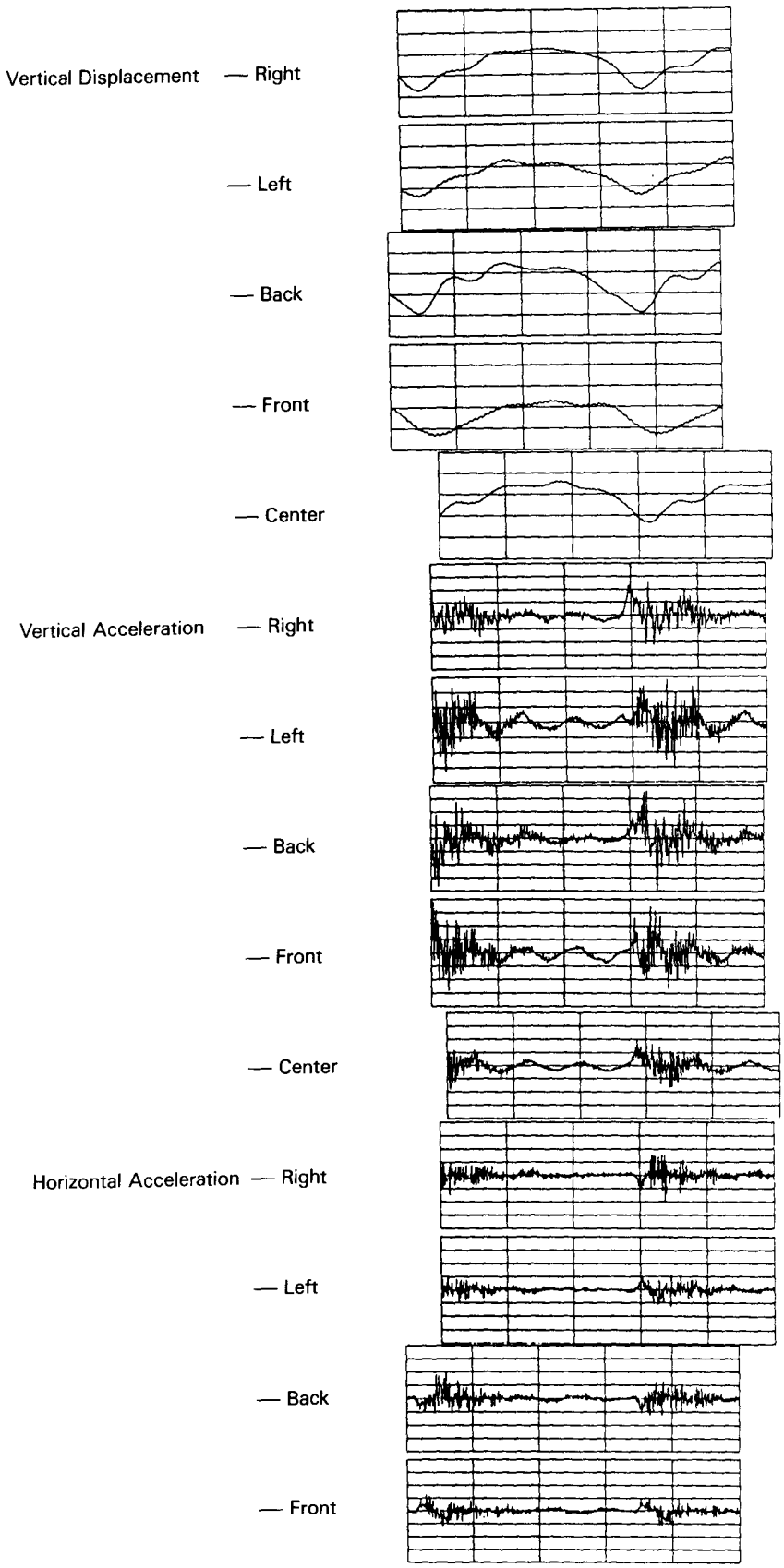


Figure 7. – VP-75A-SC table waveform summary — double-peak displacement: 0.010 inch.

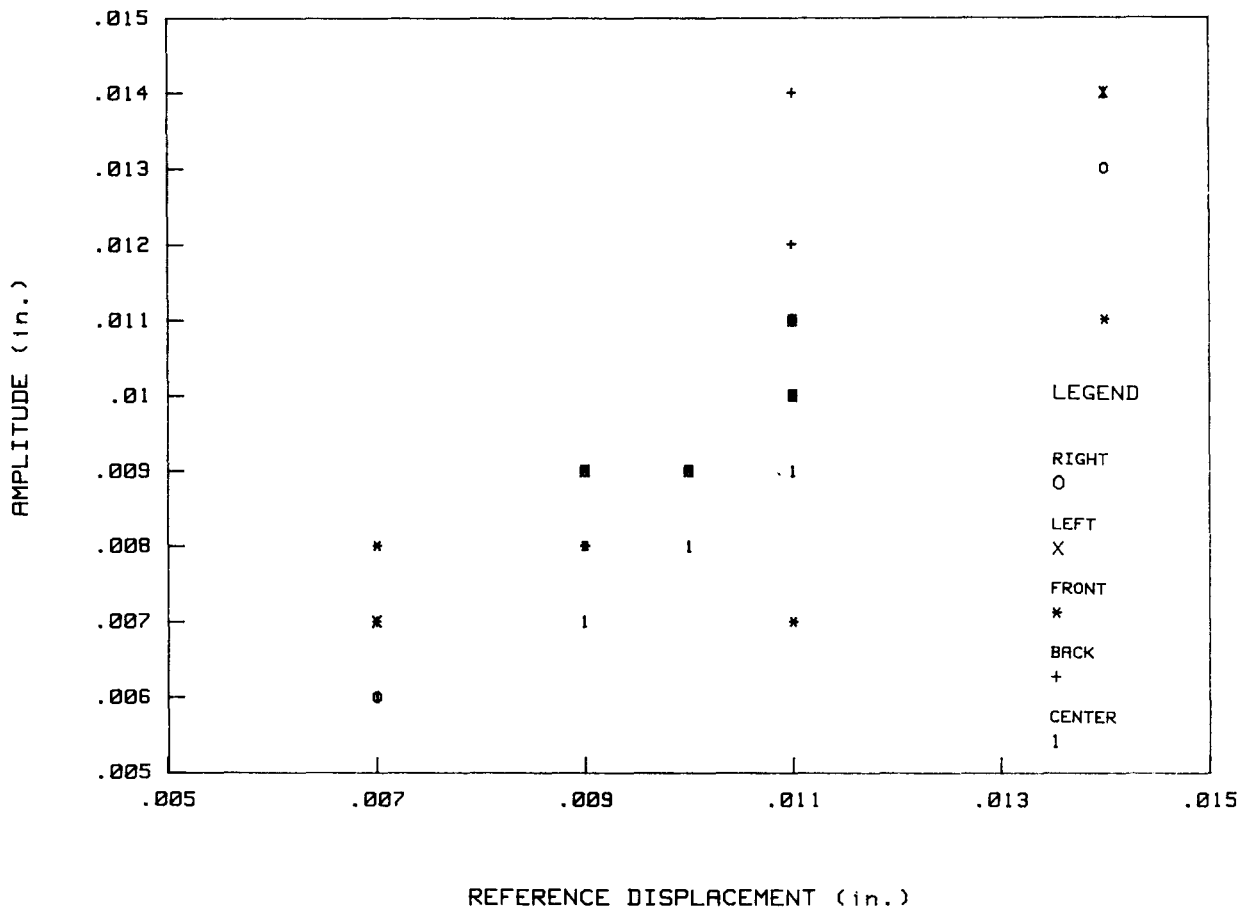


Figure 8. – VP-75A-SC table vertical displacement — reference versus measured.

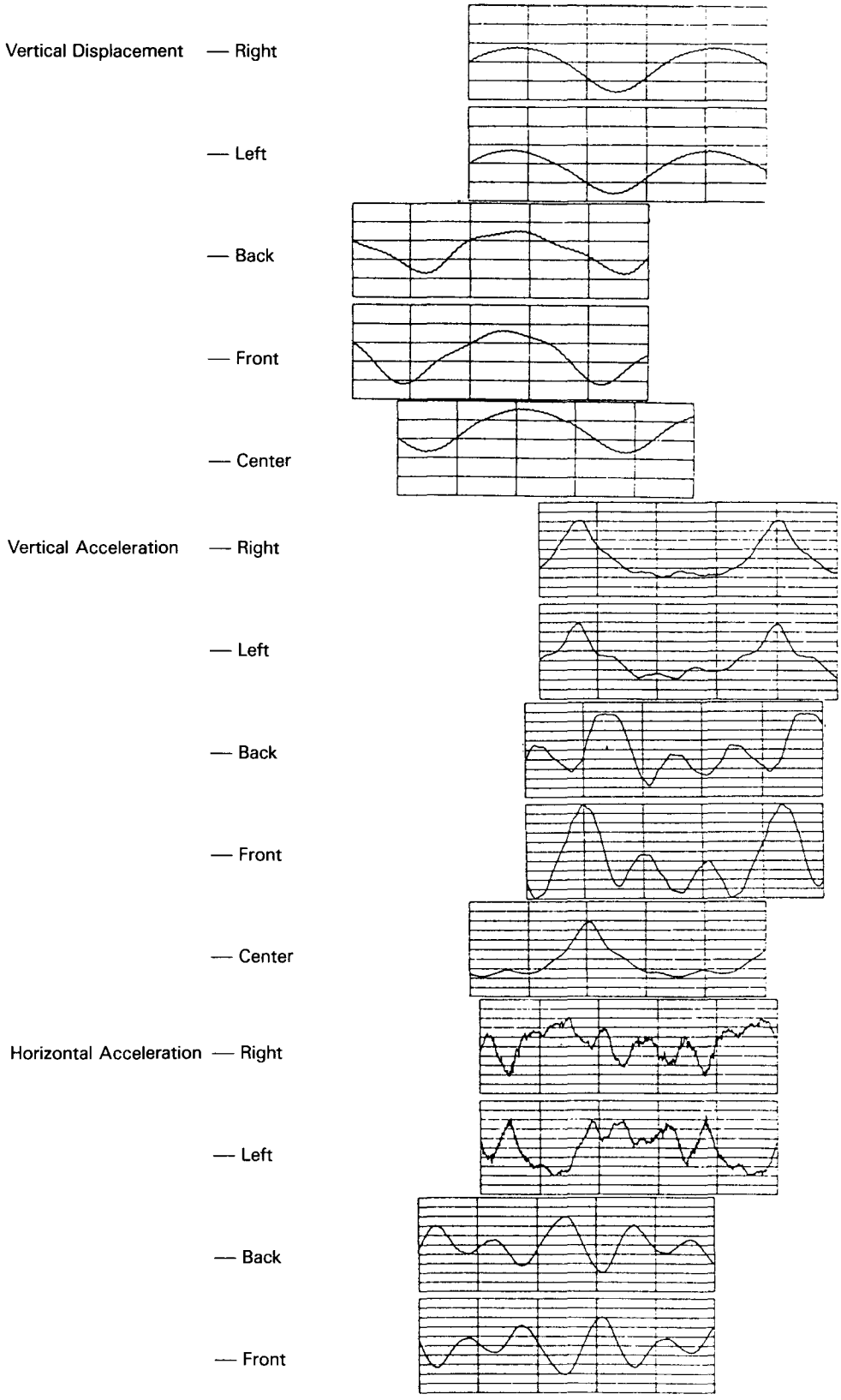


Figure 9. – V-80 table waveform summary — double-peak displacement: 0.012 inch.

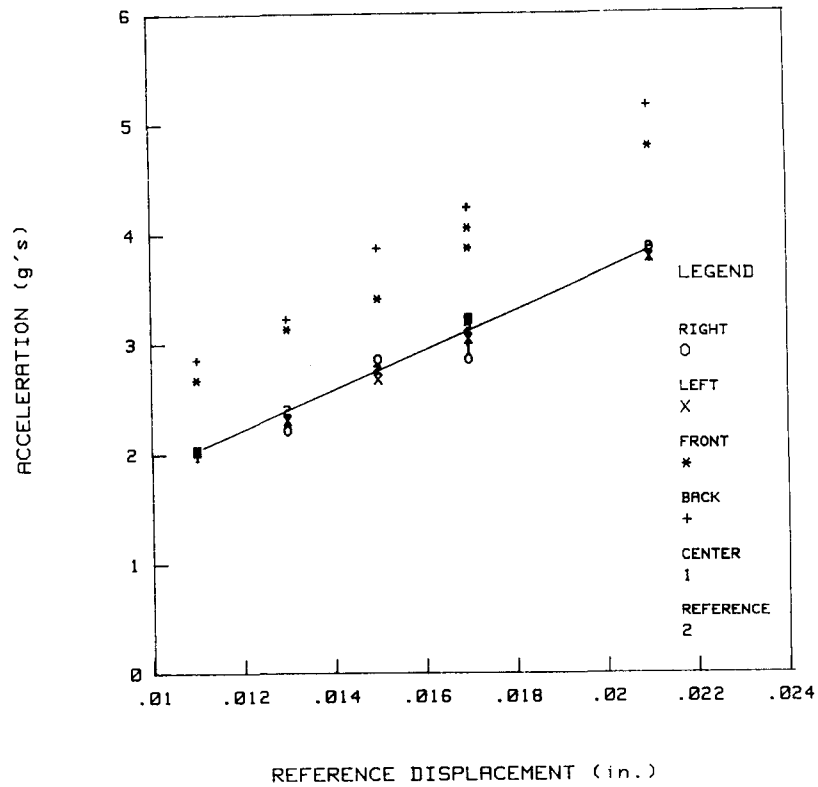


Figure 10. – SCR-1000 table predicted accelerations — based on table vertical displacements.

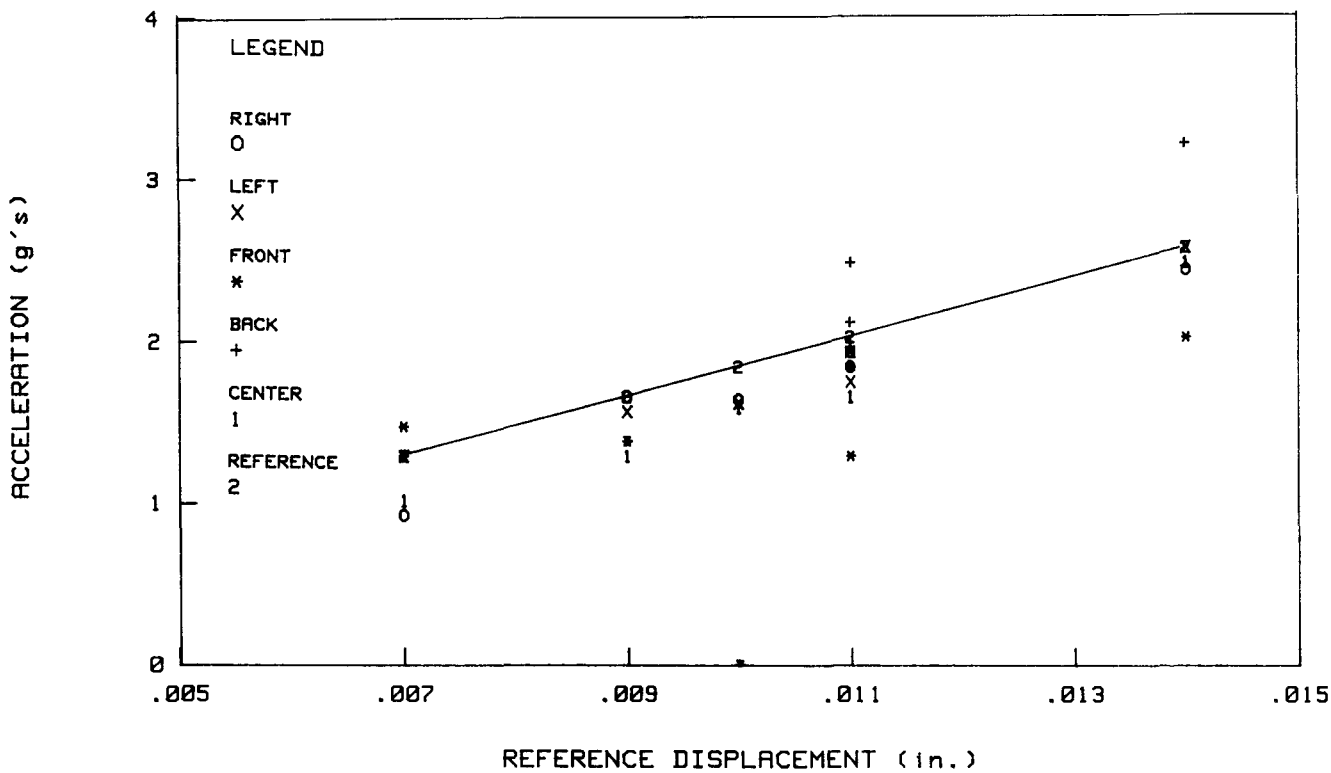


Figure 11. – VP-75A-SC table predicted accelerations — based on table vertical displacement.

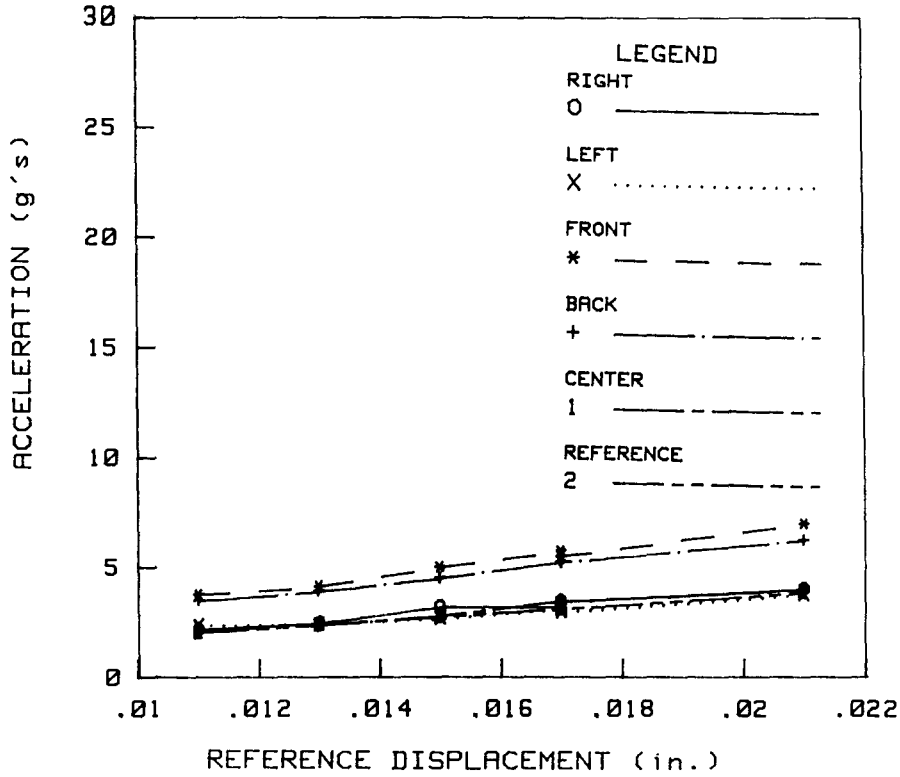


Figure 12. – SCR-1000 table — measured vertical accelerations.

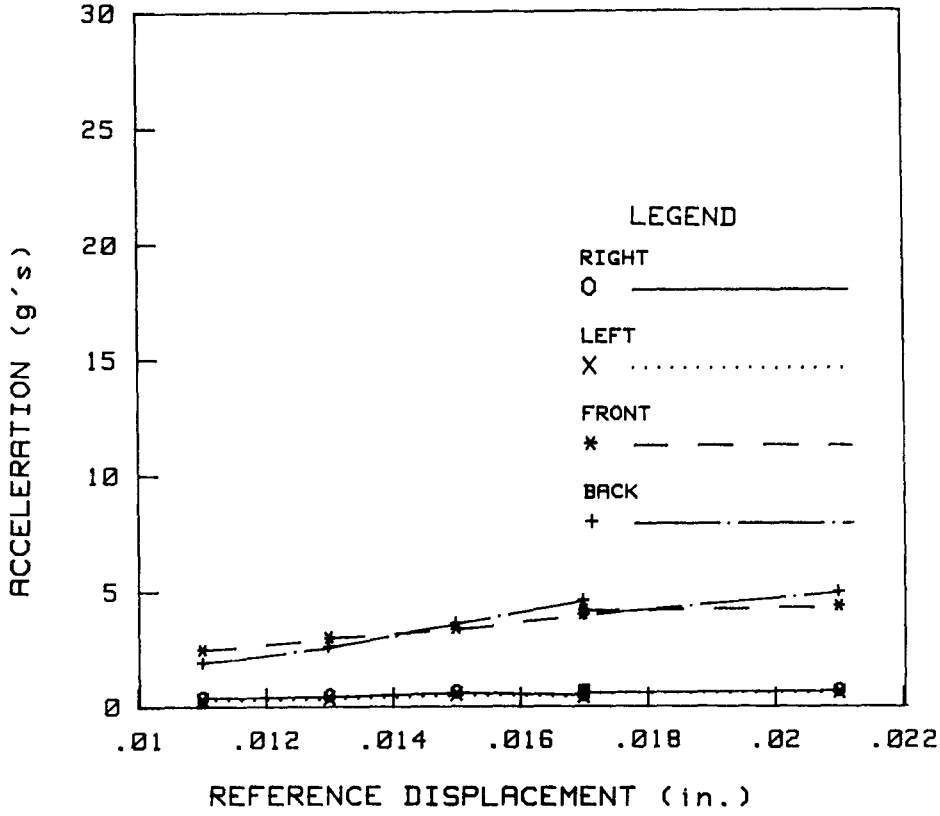
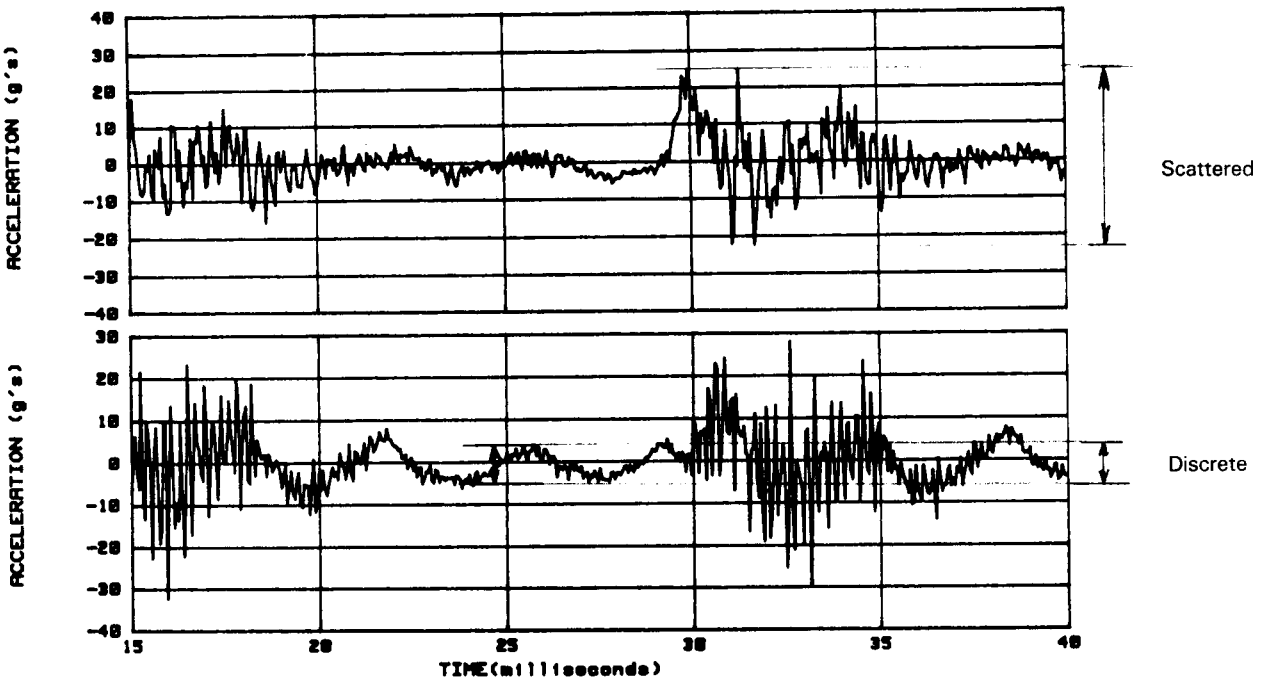
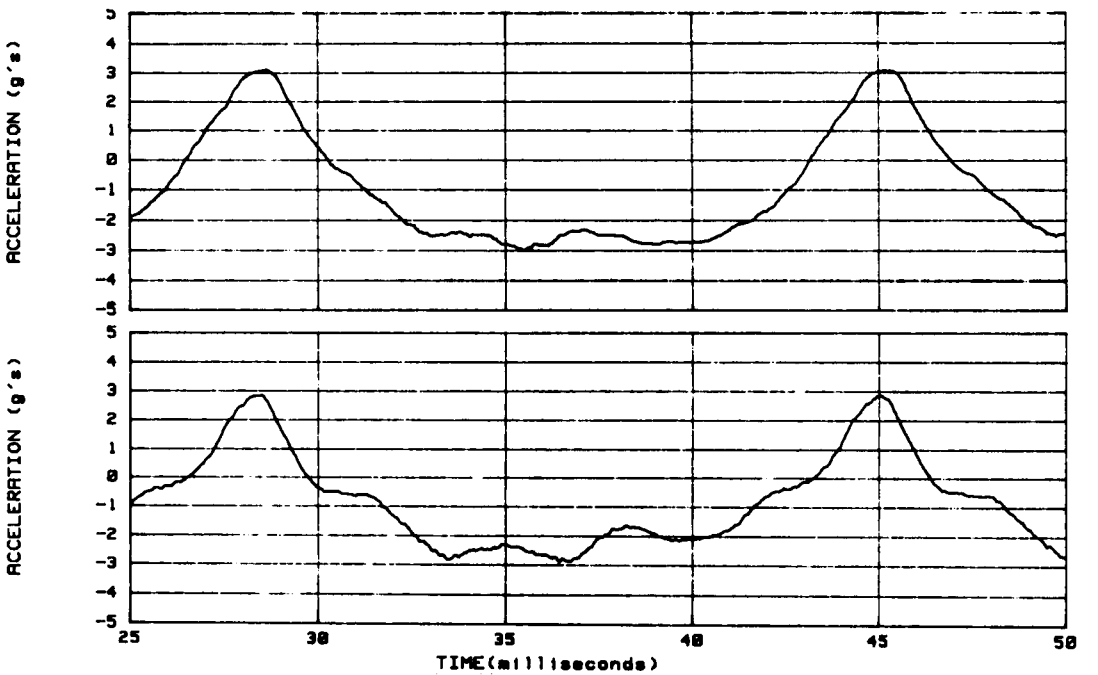


Figure 13. – SCR-1000 table — measured horizontal accelerations.



b. Syntron VP-75A-SC table at 0.010 inch



a. Vibco SCR 1000 table at 0.011 inch

Figure 14. – Vertical acceleration waveforms.

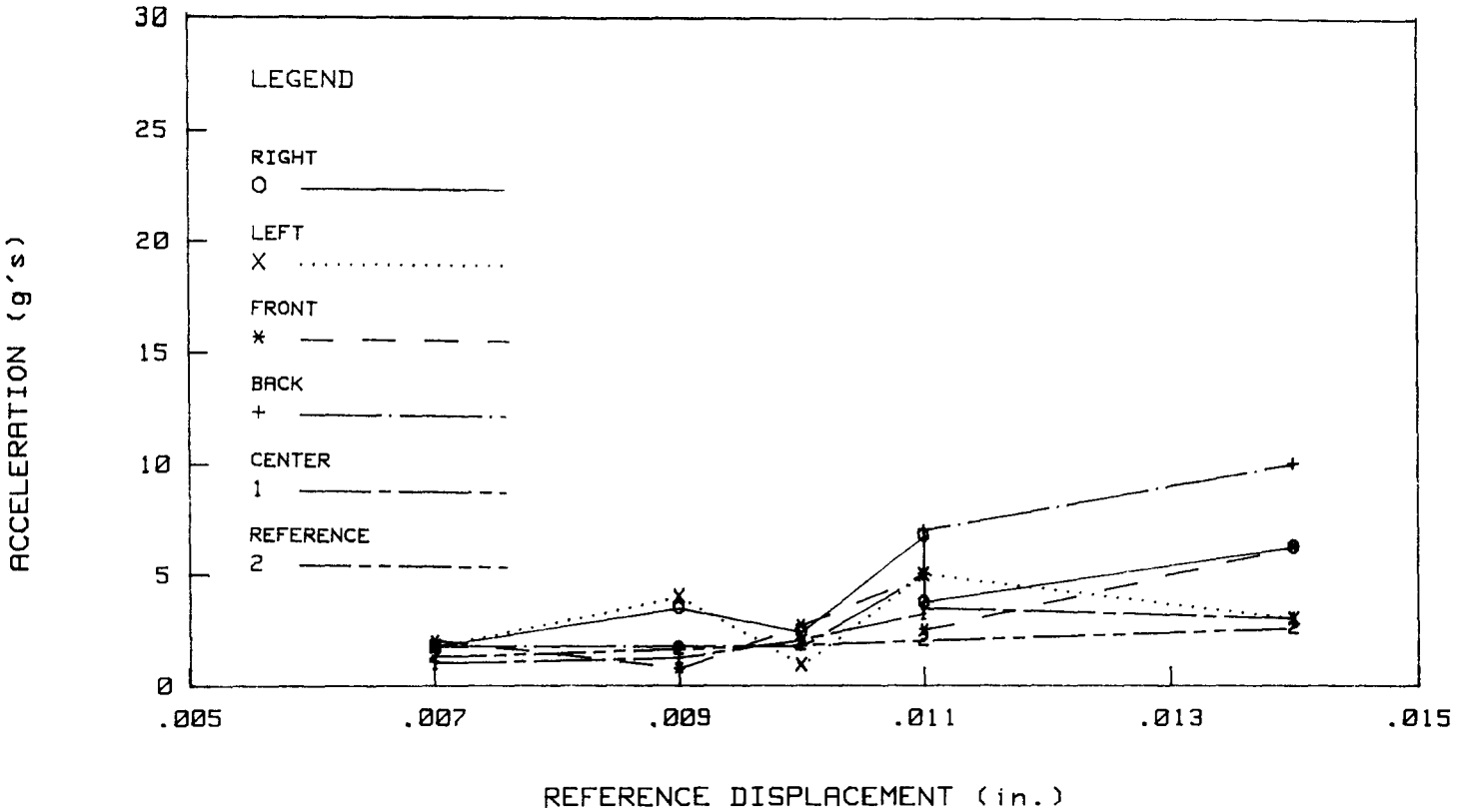


Figure 15. – VP-75A-SC table accelerations — measured vertical discrete accelerations.

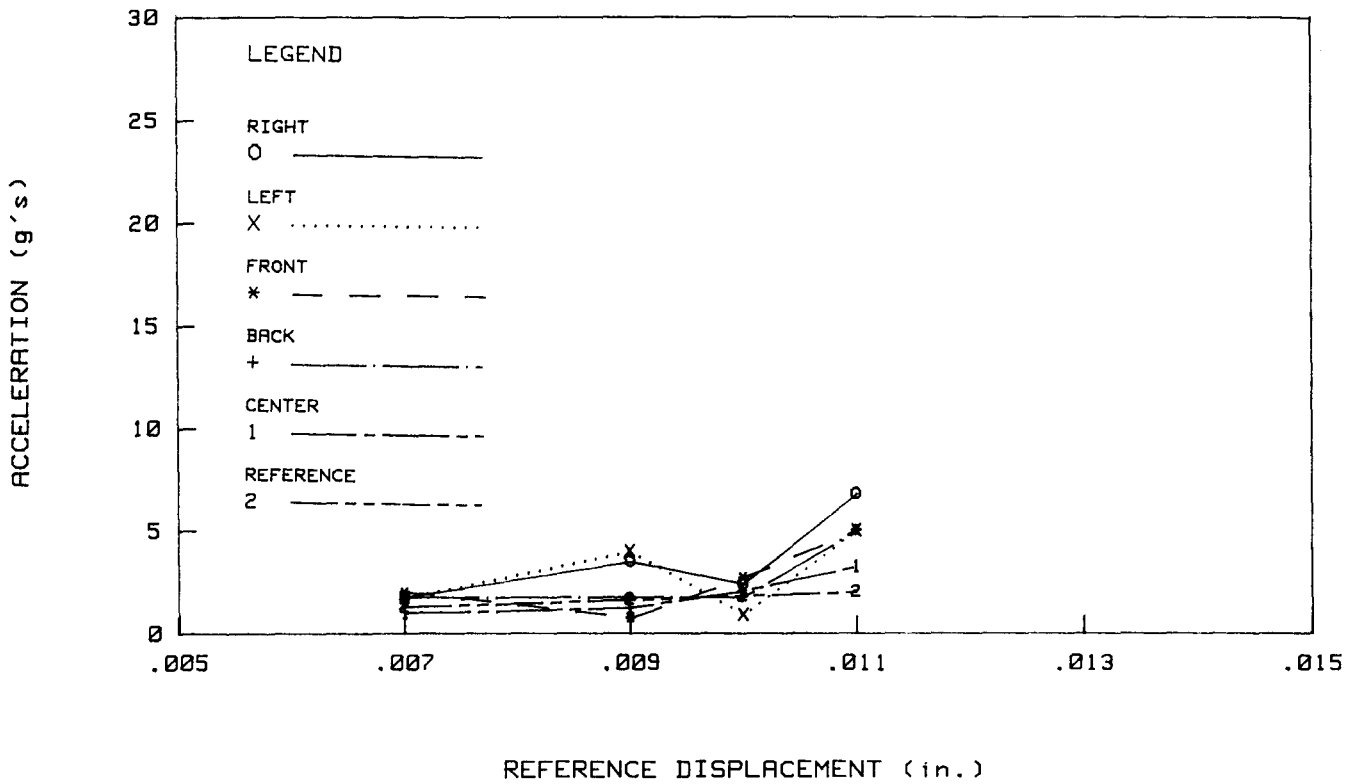


Figure 16. – VP-75A-SC table accelerations — measured vertical discrete accelerations (without shims).

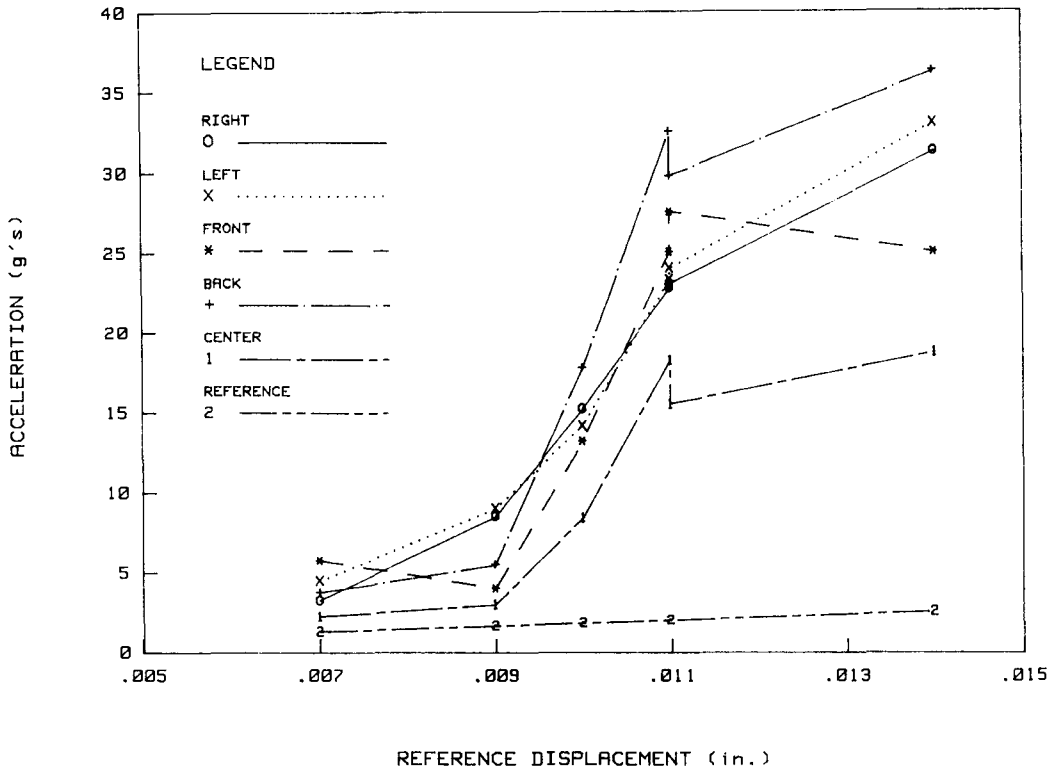


Figure 17. – VP-75A-SC table accelerations — measured vertical scattered accelerations.

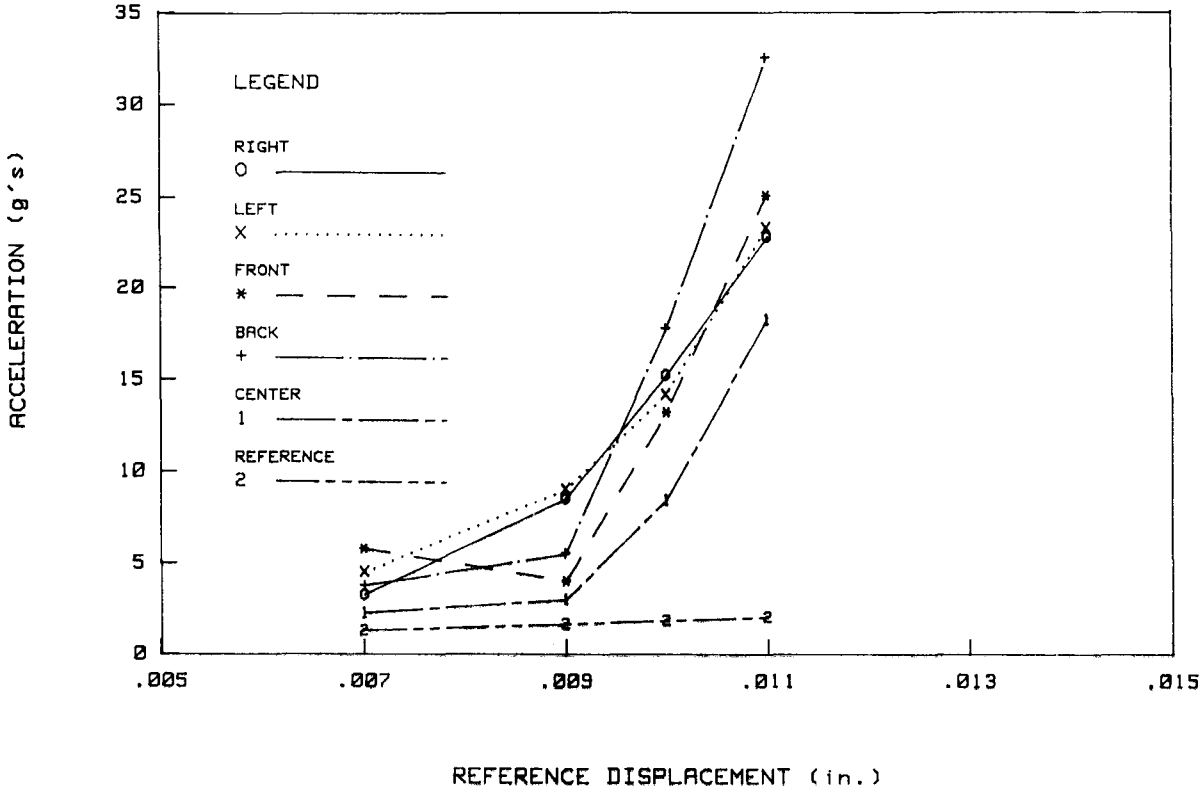


Figure 18. – VP-75A-SC table accelerations — measured vertical scattered accelerations (without shims).

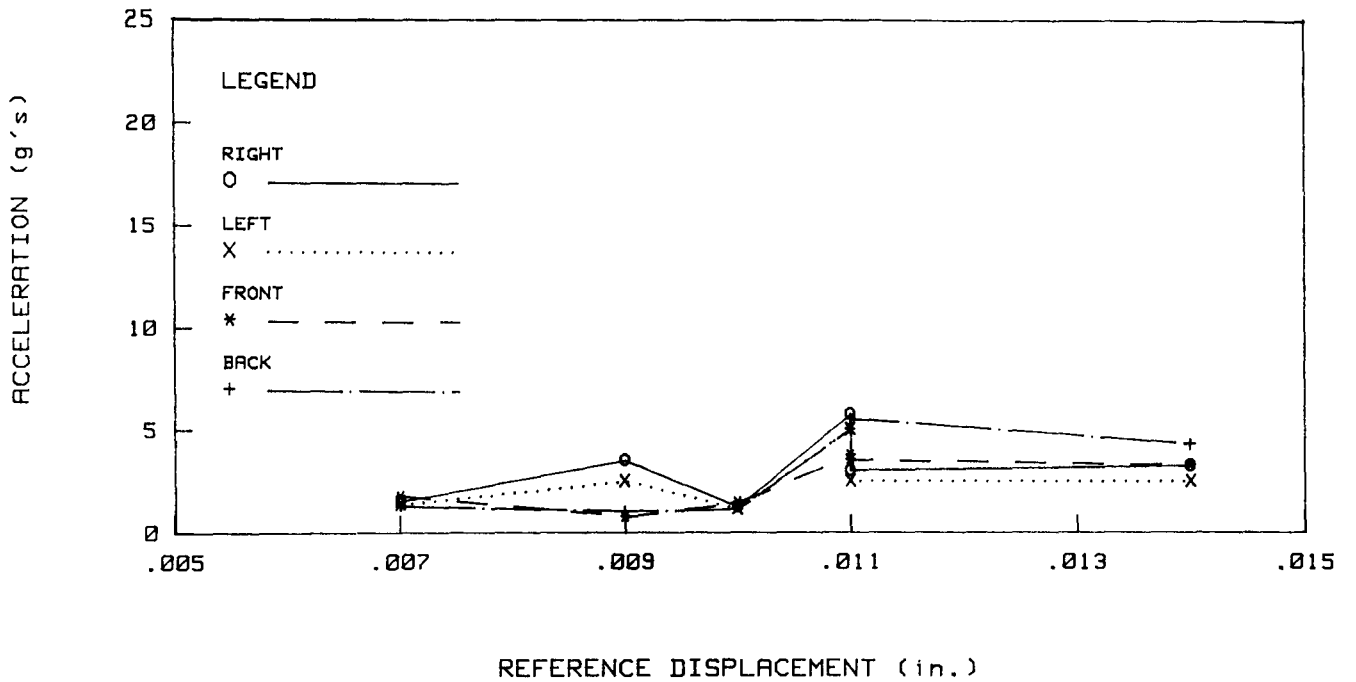


Figure 19. – VP-75A-SC table accelerations — measured horizontal discrete accelerations.

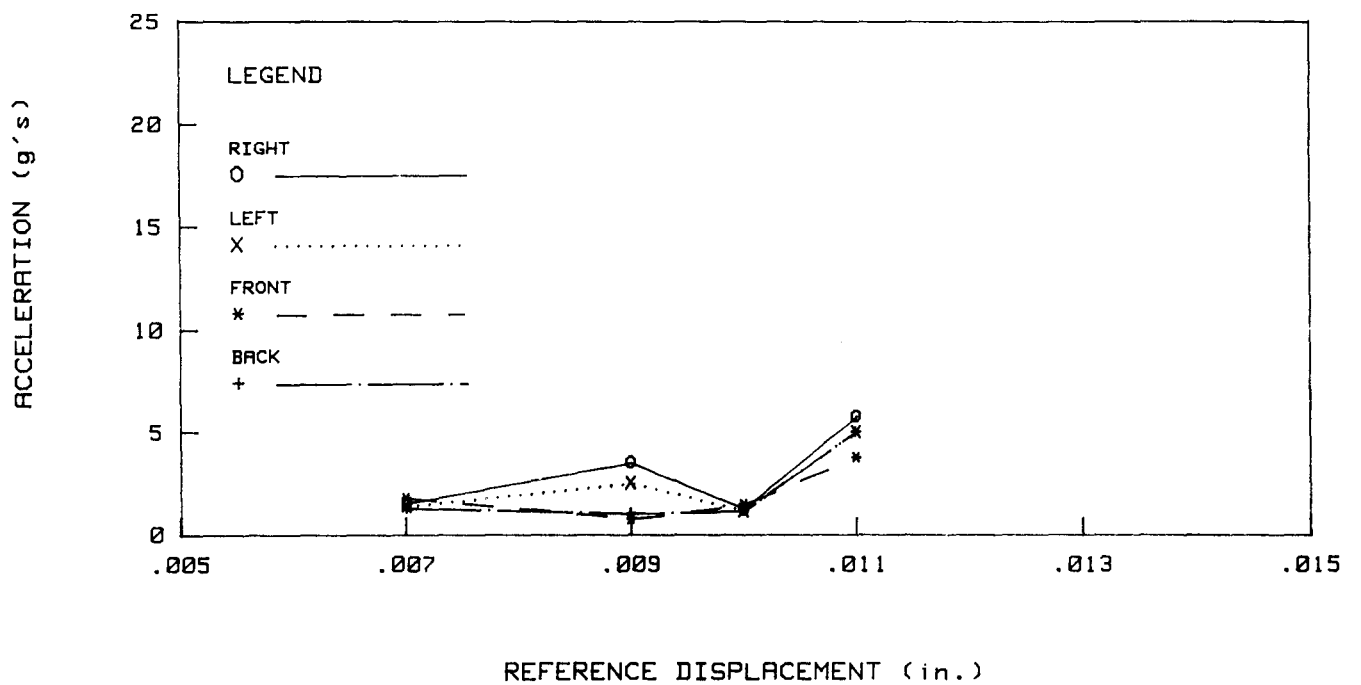


Figure 20. – VP-75A-SC table accelerations — measured horizontal discrete accelerations (without shims).

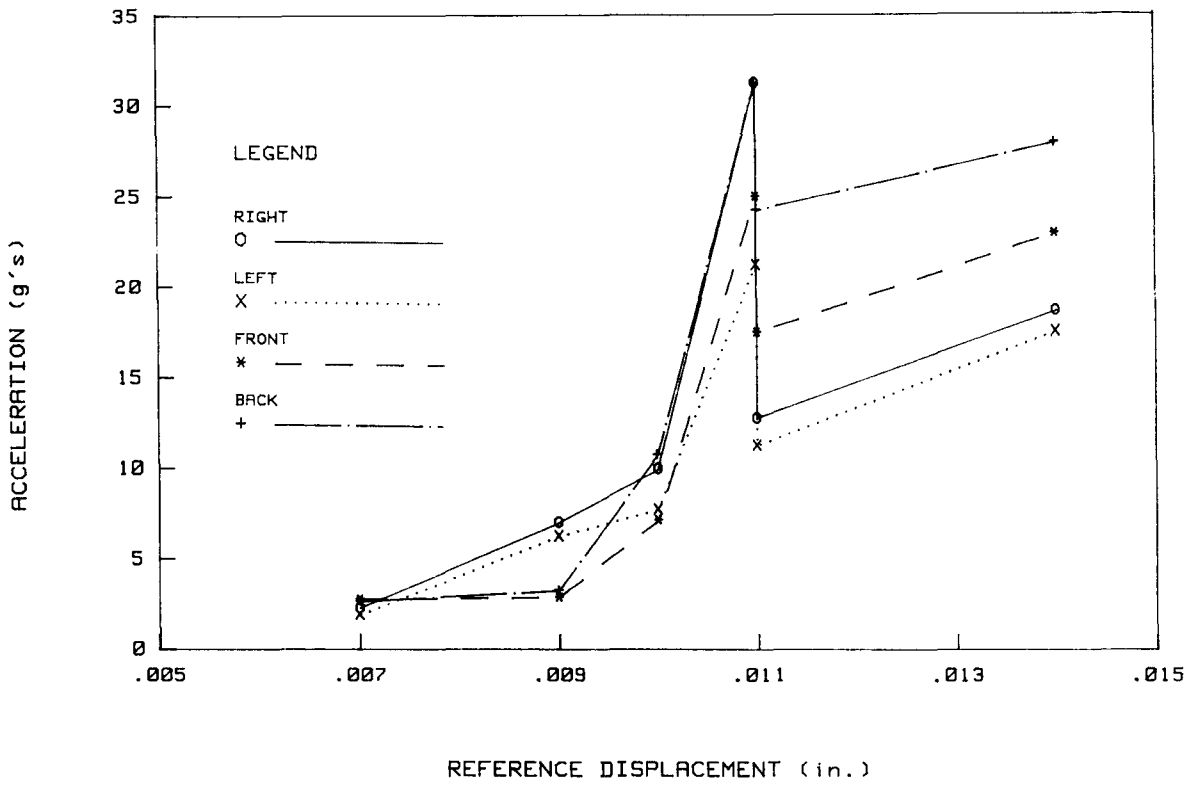


Figure 21. – VP-75A-SC table accelerations — measured horizontal scattered accelerations.

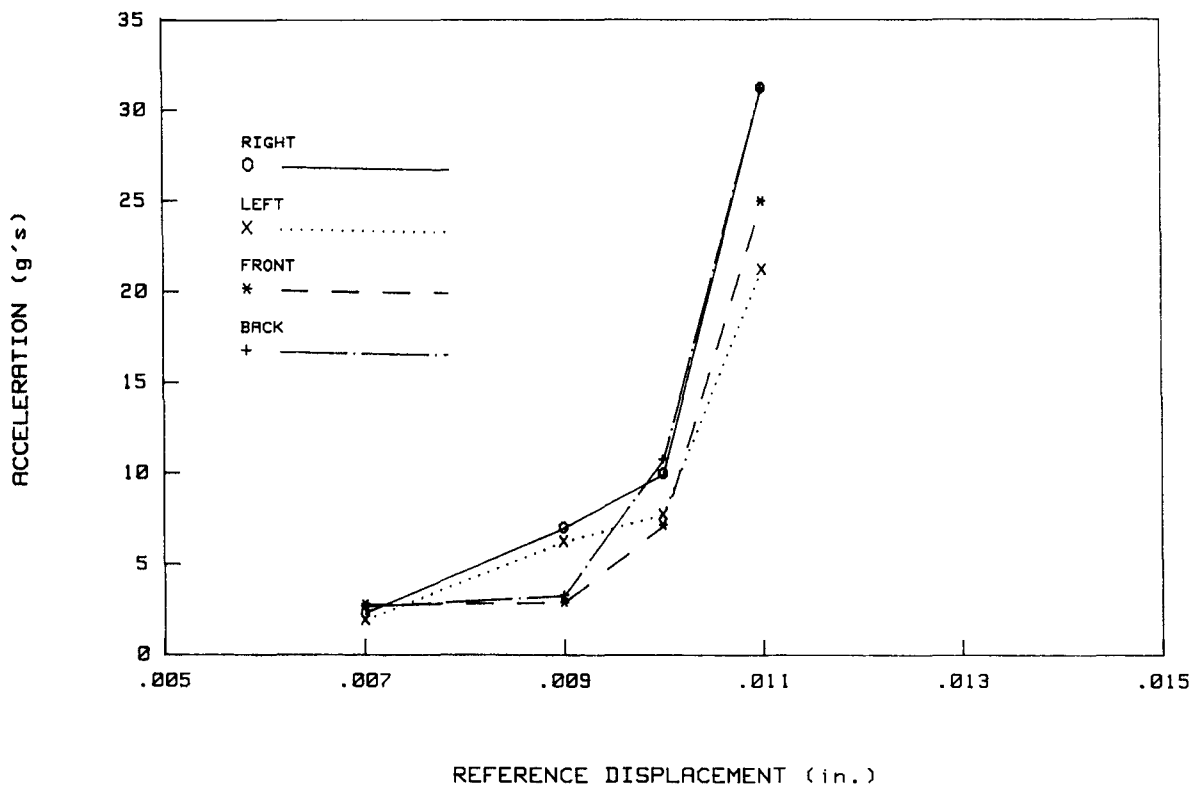
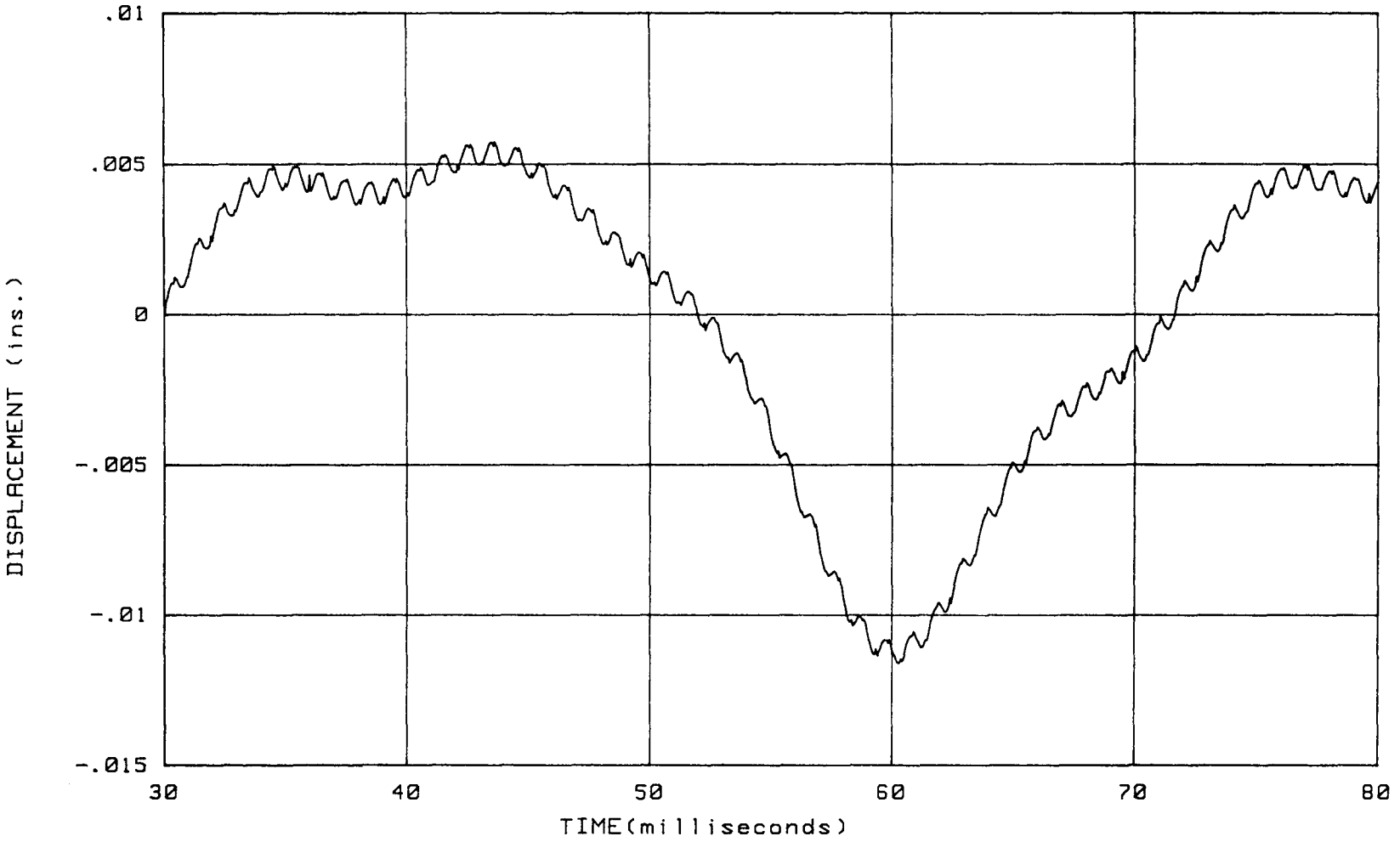


Figure 22. – VP-75A-SC table accelerations — measured horizontal scattered accelerations (without shims).



Test No.	33-S3-T3
Sequence No.	3 CENTER LVDT
Table Type	VP-75A-SC
Tested By	BACA
Date	8-9-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	.006	0.000
Min =	-.012	0.000
Amp =	.017	0.000

Figure 23. – Vibratory table displacement-time waveform.

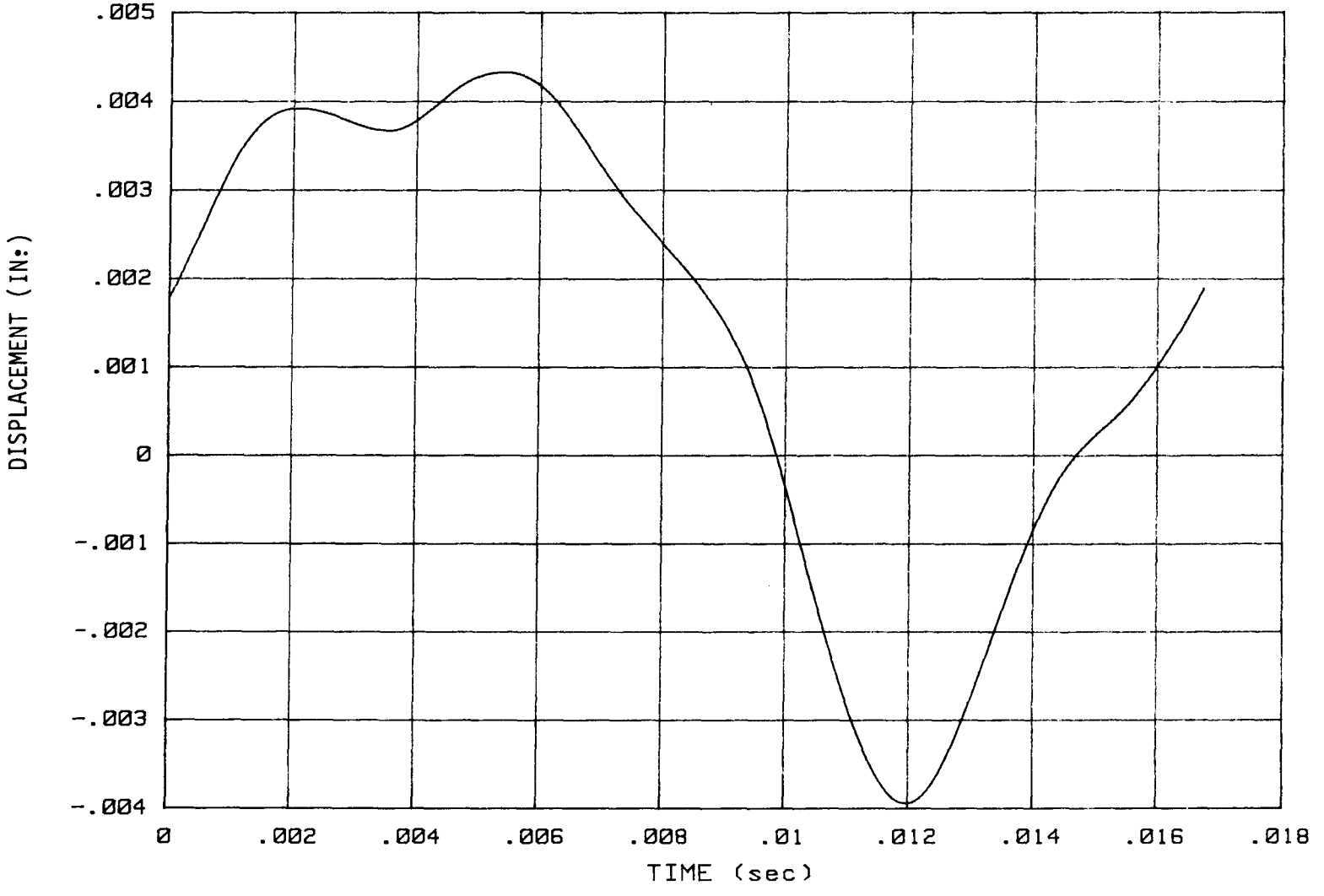


Figure 24. – Fourier analysis generated displacement-time waveform.

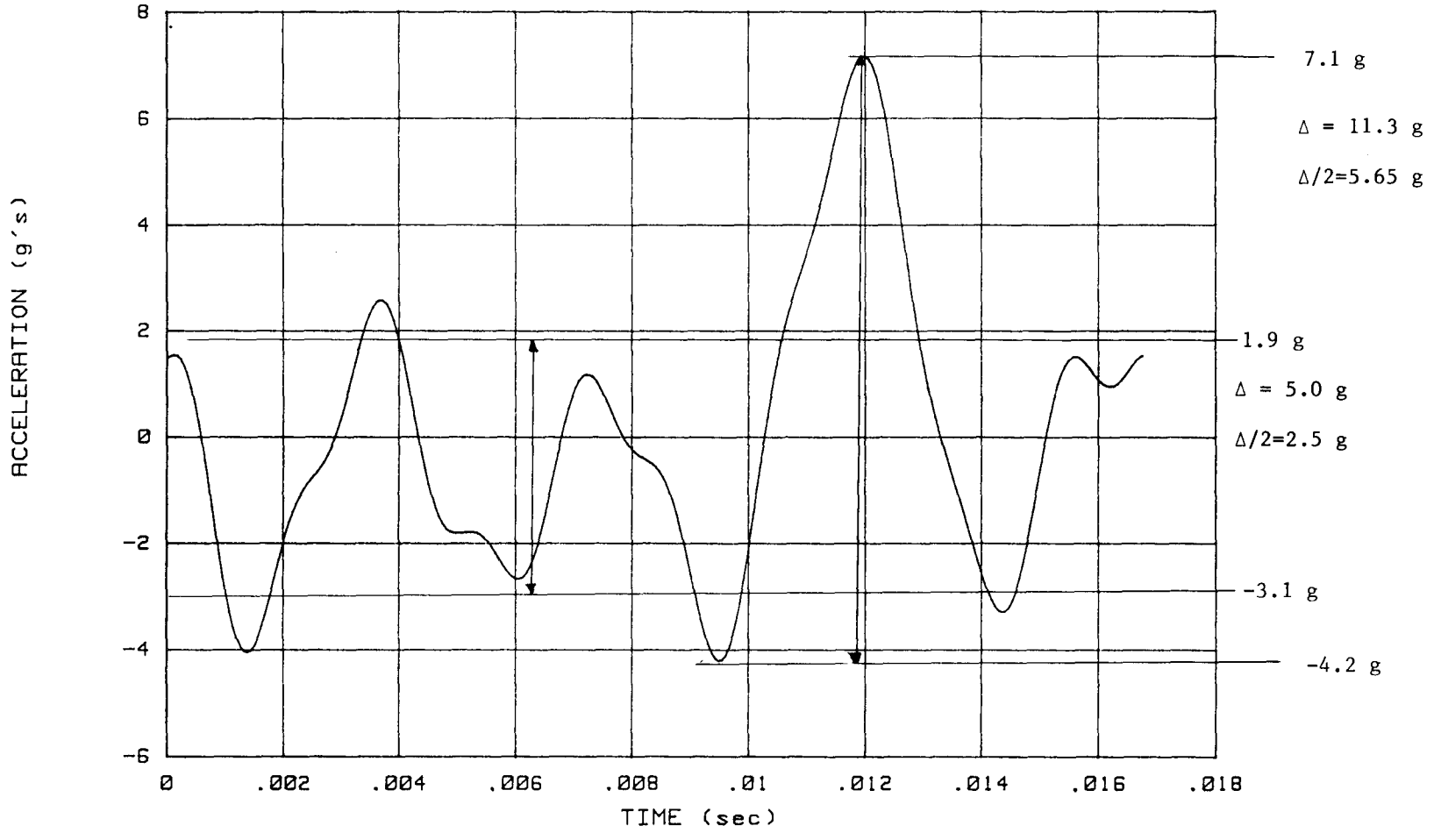
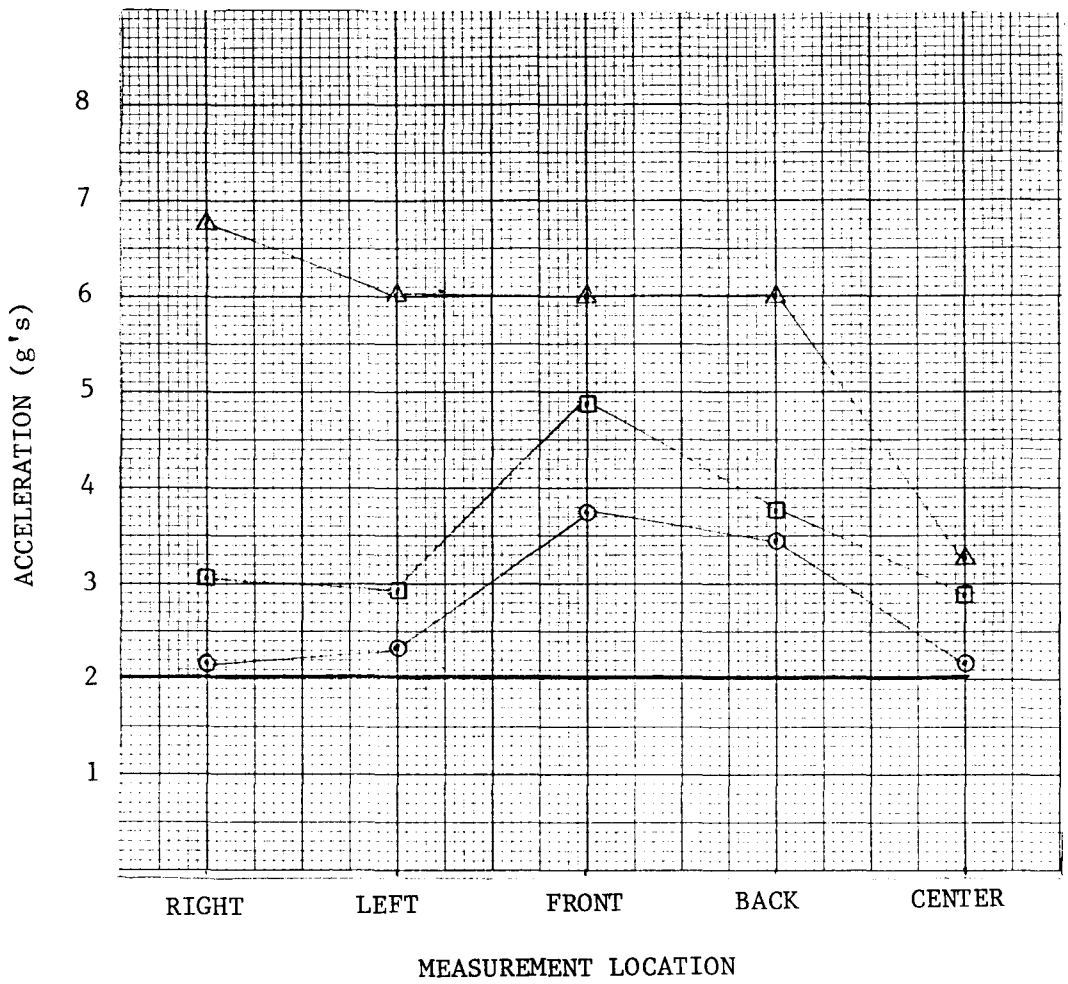


Figure 25. – Fourier analysis generated acceleration-time waveform.

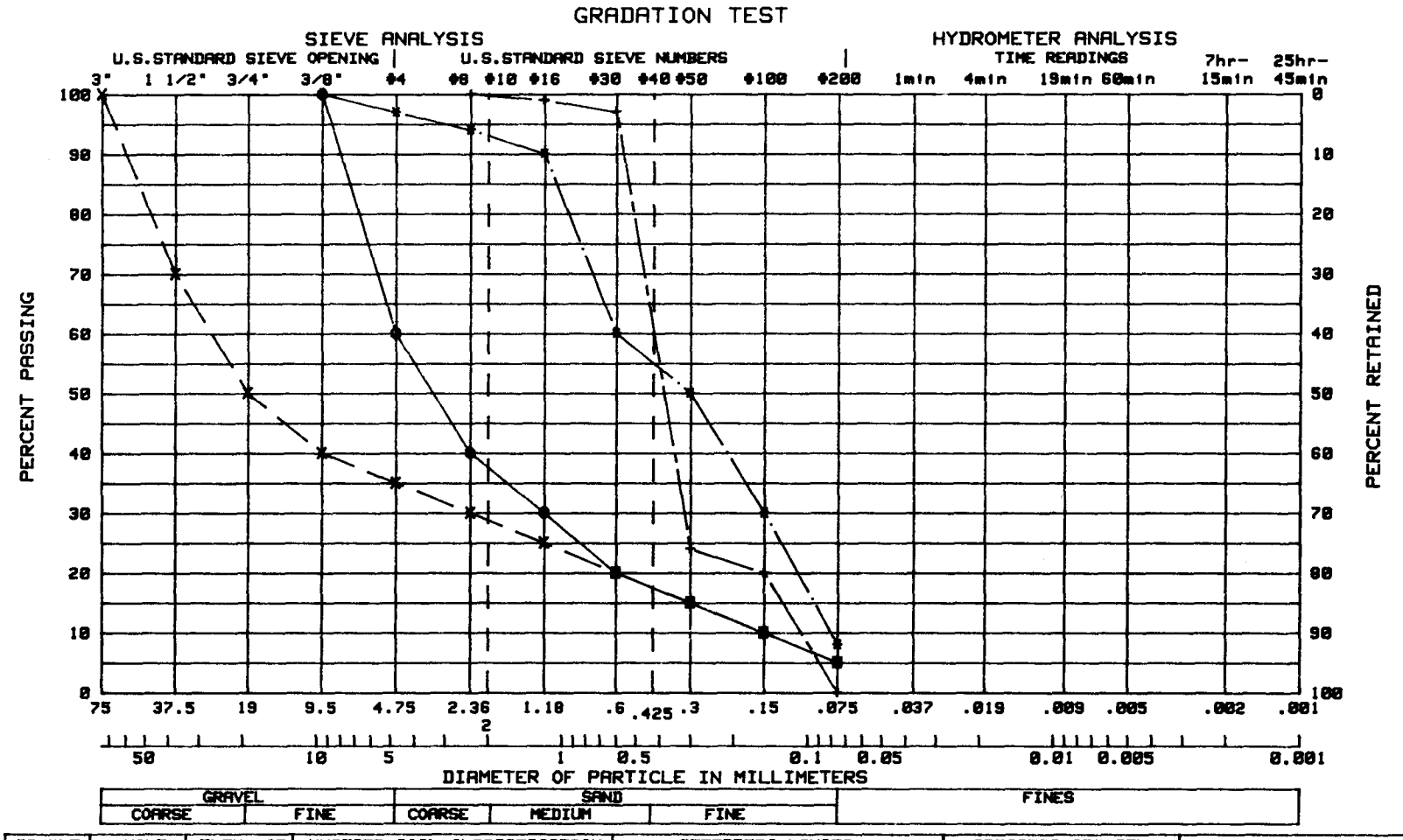


⊙ SCR 1000 Table at 0.011 inch double-peak displacements

⊡ V–80 Table at 0.012 inch double-peak displacements

△ VP–75A–SC Table at 0.011 inch double-peak displacements

Figure 26. – Discrete acceleration of different table types at comparable vertical double-peak displacements.



SAMPLE NO.	HOLE NO.	ELEV. OR DEPTH	UNIFIED SOIL CLASSIFICATION				ATTERBERG LIMITS			SPECIFIC GRAVITY	
			GROUP SYMBOL	% GRAVEL	% SAND	% FINES	LIQUID LIMIT(%)	PLASTICITY INDEX(%)	SHRINKAGE LIMIT(%)	MINUS NO. 4	OTHER
MIX #7	SUMMARY	OF THE	MIX	40	55	5					FROM
MIX#3	GRADATIO	NS FOR	THE MAX	65	32	3					KRUMDIECK
MIX #5	DENSITY	STUDIES		3	89	8					
MON SAND											

NOTES:
LEGEND
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+

PREPARED BY
CHECKED BY
FIGURE

Figure 27. – Gradation test.

APPENDIX A

Vibratory Table Specifications and Drawings

Vibco model SCR 1000

115 volts

4.2 amperes

3/4 horsepower

0-1,000 lbf or impact force

0-4,000 vibrations per minute

950-2500 r/min continuous duty

37 lbm

Model SCR 1000 consists of permanent magnet direct-current motor, SCR controller composed of solid-state, full-wave rectifier and overload protection.

Syntron model VP-75A

230 volts (60 cycle)

8 amperes

600 watts

3,600 vibrations per minute

114 lbm

Model VP-75A is controlled with a separate unit consisting of an operating switch, rheostat, and a rectifier.

Syntron model V-80

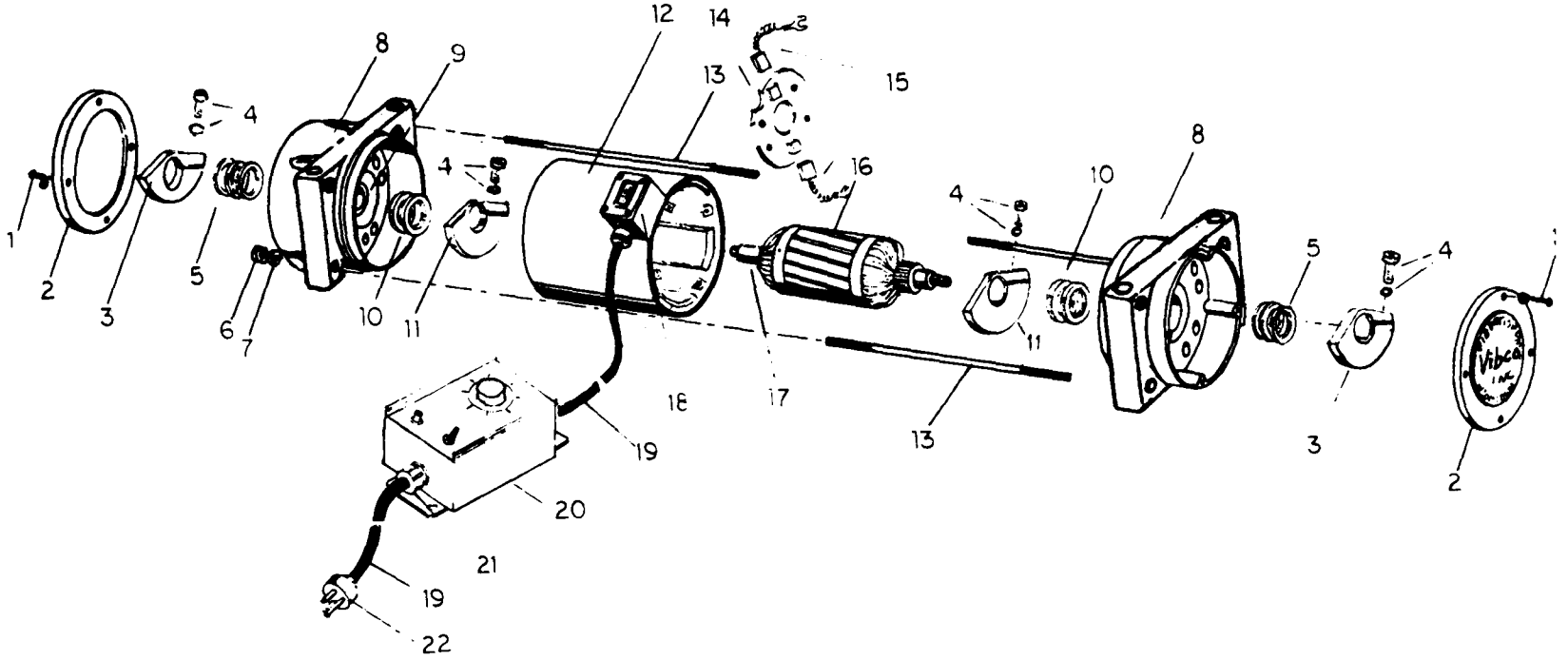
230 volt (60 cycle

8.0 amperes

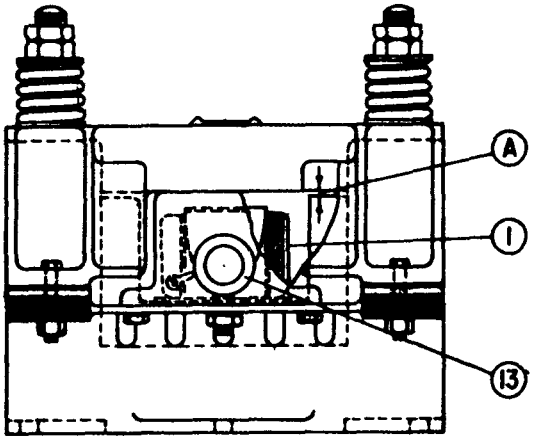
600 watts

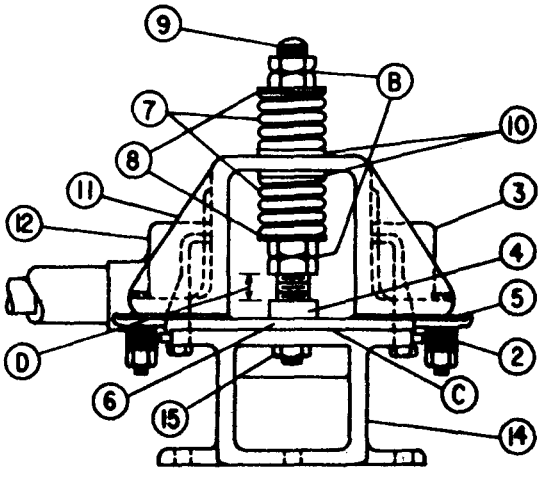
3,600 vibrations per minute

1	R. H. Machine Screw	9	Bearing	17	Shaft Bushing	19	Cable
	Lockwasher	10	Inside Spacer	18	Conduit Box	20	Control Box Complete
2	End Bell Cover	11	Inside Eccentric		Conduit Box Cover	21	Cable Connector
3	Outside Eccentric	12	Field		Conduit Box Gasket	22	Plug
4	Socket Head Cap Screw	13	Thru Rod		Grommet		
	Lockwasher	14	Brush Ring Assembly		R. H. Machine Screw		
5	Outside Spacer		R. H. Machine Screw		Lockwasher		
6	Hex Head Nut		Lockwasher		R. H. Machine Screw		
7	Lockwasher		Flat Washer		Lockwasher		
8	End Bell	15	Brushes		Nut		
		16	Armature		Cable Connector		



V-75

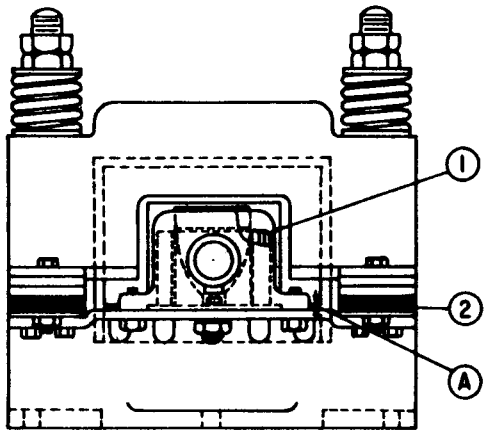


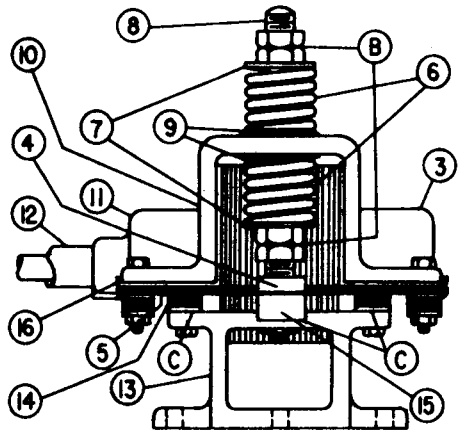


LIST OF PARTS

ITEM	DESCRIPTION	ITEM	DESCRIPTION
1.	Coil Assembly	10.	Inside Spring Seat
2.	Rbr. Transverse Spring	11.	Armature Casting
3.	Coil Cover (Plain)	12.	Coil Cover (Cable Side)
4.	Leaf Spring Clamp	13.	Cable Bushing
5.	Leaf Spring	14.	Core Assembly
6.	Striking Plate Assembly	15.	Stop Nut (5/8"-11)
7.	Coil Spring	A.	Air Gap
8.	Outside Spring Seat	B.	Lock Nuts
9.	Stud	C.	Location of shim
		D.	Lock Nuts/Leaf Spring Clamp Gap

V-80





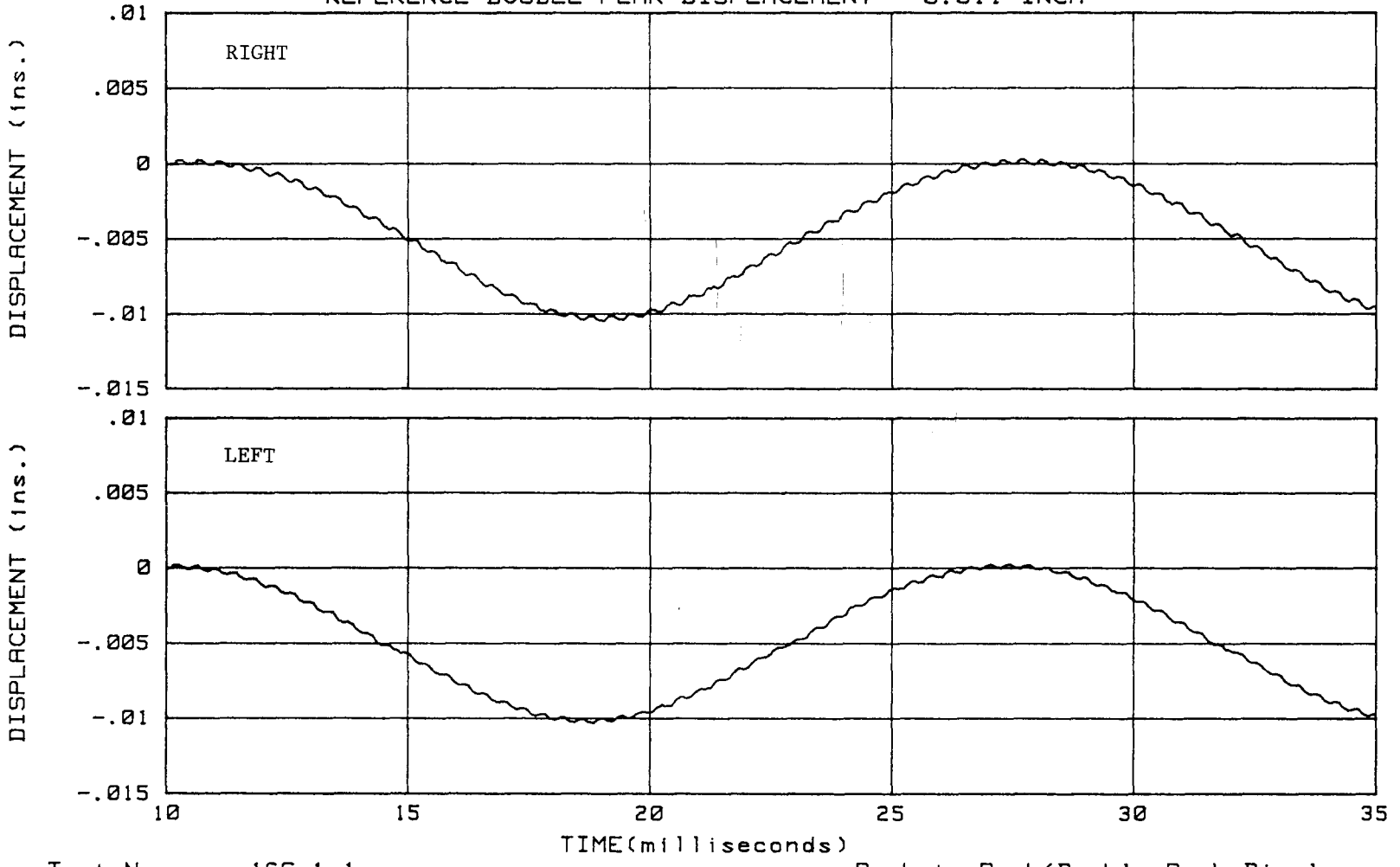
LIST OF PARTS

ITEM	DESCRIPTION	ITEM	DESCRIPTION
1.	Coil	11.	Coil Cover (Cable Support Side)
2.	Rbr. Transverse Spring Spacer	12.	Cable Strain Relief
3.	Coil Cover (Plain)	13.	Core Mounting Assembly
4.	Spring Clamp (Center)	14.	Vibration Dampener
5.	Leaf Springs	15.	Leaf Spring Spacer (Center)
6.	Coil Springs	16.	Leaf Spring Spacer (End)
7.	Spring Seats (Outer)	A.	Clearance Between Pole Faces
8.	Stud	B.	Lock Nuts
9.	Spring Seats (Inner)	C.	Location of Shims
10.	Armature Mounting Assembly		

APPENDIX B

SCR-1000 Table Waveforms at 0.011-Inch Double Amplitude

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH

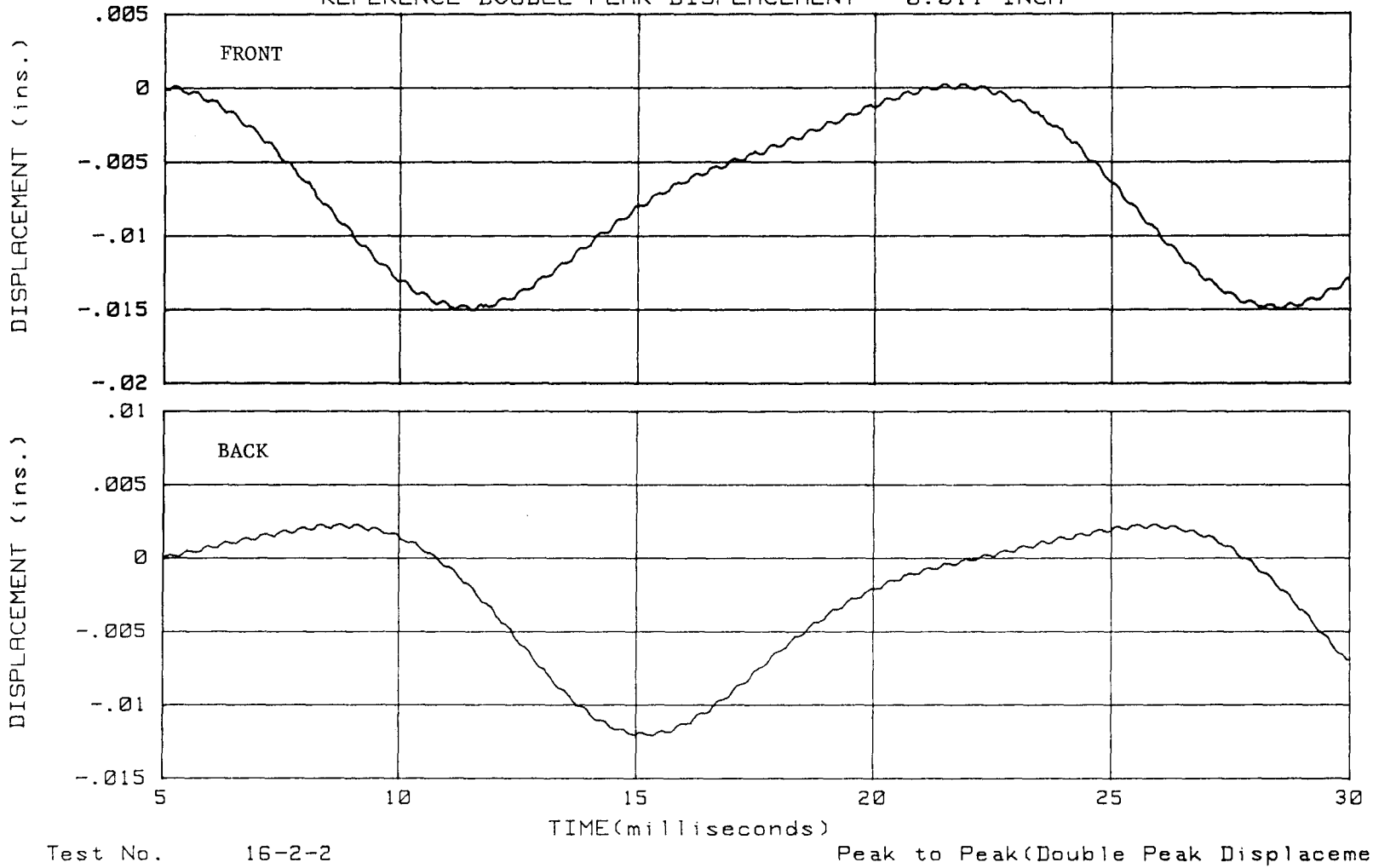


Test No.	16S-1-1
Sequence No.	1 RIGHT AND LEFT LVDT
Table Type	SCR-1000
Tested By	BACA
Date	6-17-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	0.000	0.000
Min =	-.011	-.010
Amp =	.011	.011

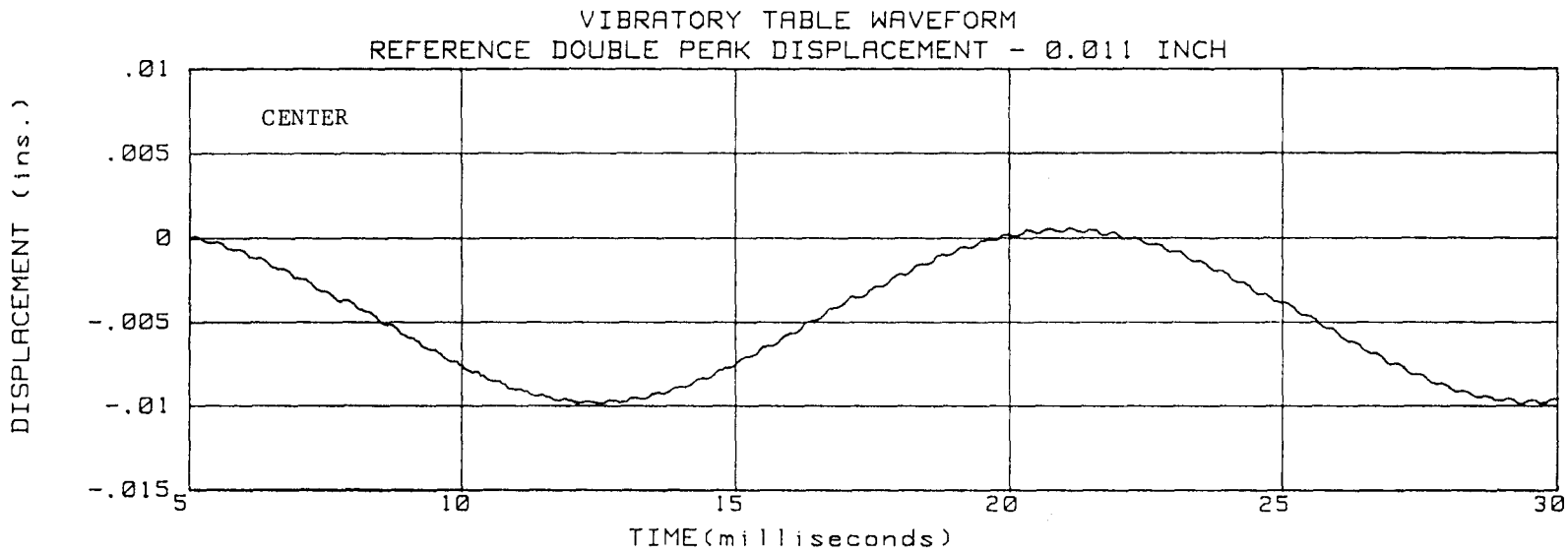
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH



Test No.	16-2-2
Sequence No.	2 FRONT AND BACK LVDT
Table Type	SCR-1000
Tested By	BACA
Date	6-17-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	0.000	.002
Min =	-.015	-.012
Amp =	.015	.014

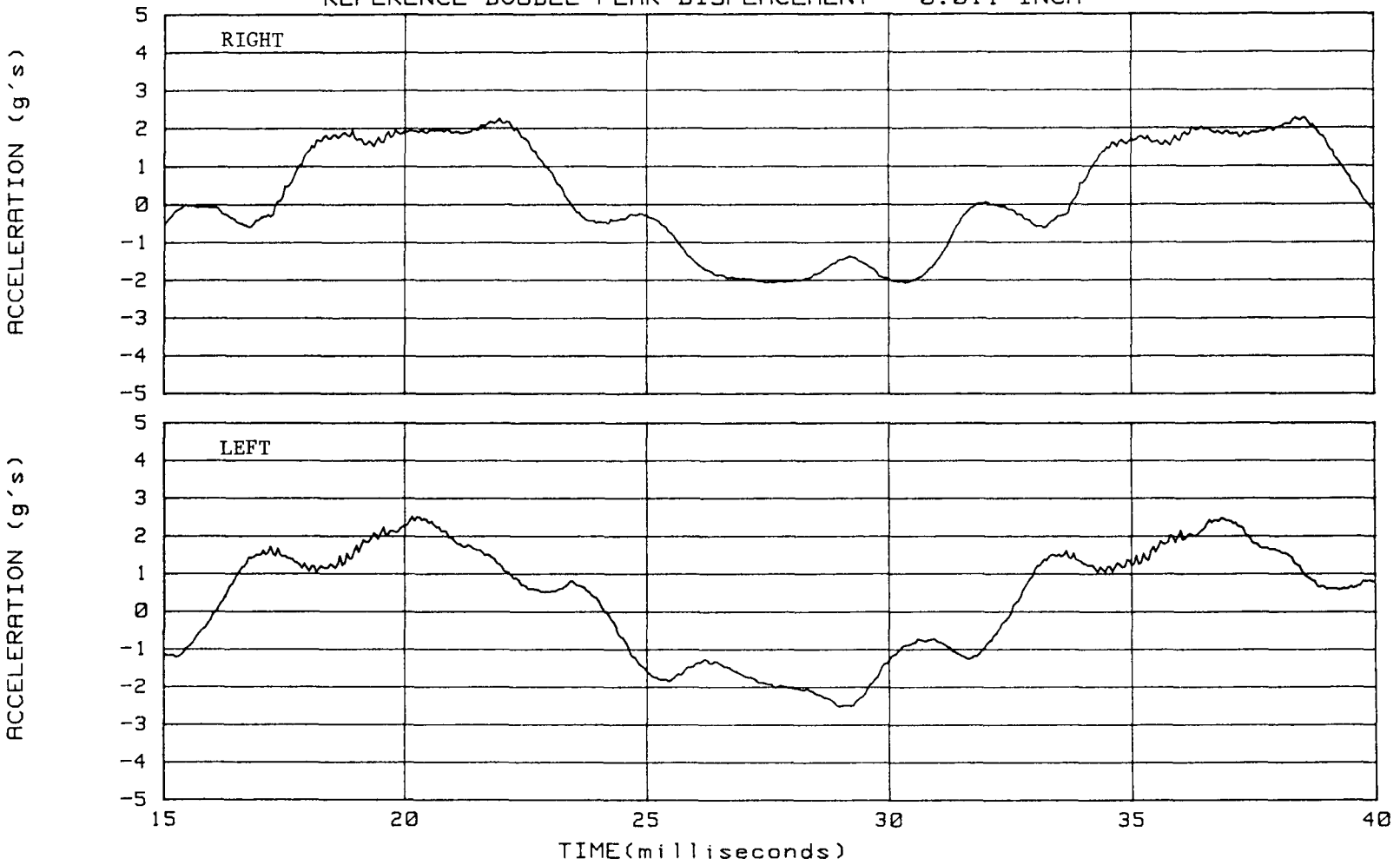


Test No.	16-3-3
Sequence No.	3 CENTER LVDT
Table Type	SCR-1000
Tested By	BACA
Date	6-17-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	.001	0.000
Min =	-.010	0.000
Amp =	.011	0.000

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH

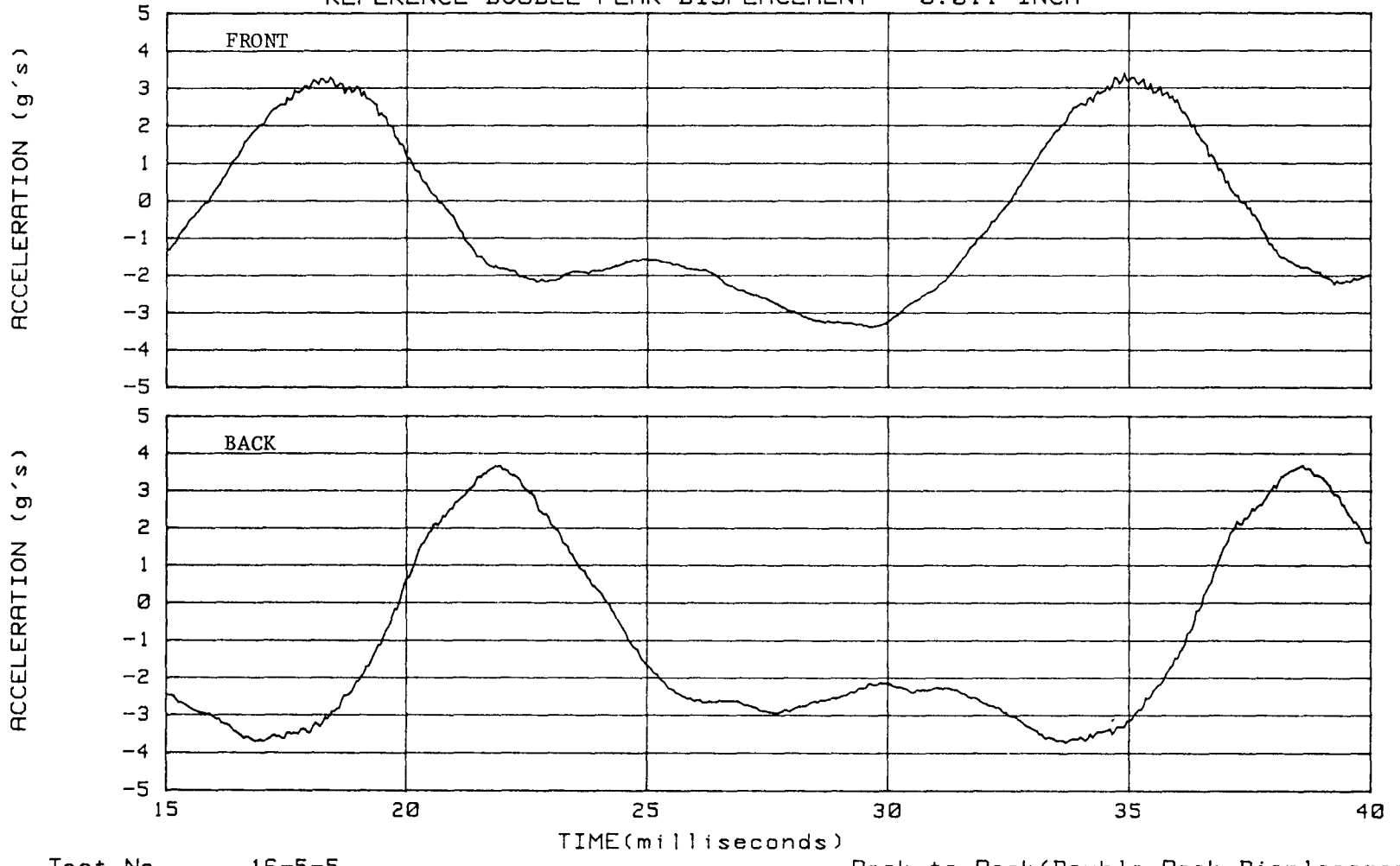


Test No.	16-4-4
Sequence No.	4 RIGHT AND LEFT VERT. ACCEL.
Table Type	SCR-1000
Tested By	BACA
Date	6-17-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

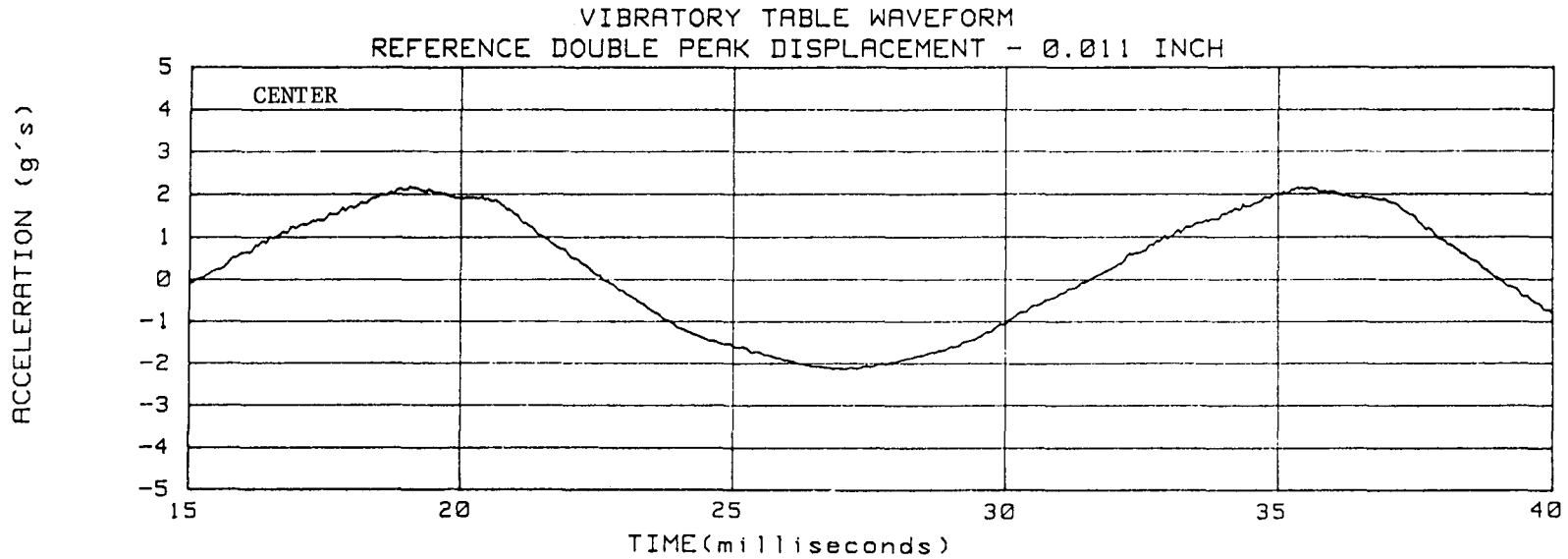
	Top Waveform	Bottom Waveform
Max =	2.275	2.519
Min =	-2.076	-2.514
Amp =	4.350	5.034

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH



Test No.	16-5-5
Sequence No.	5 FRONT AND BACK VERT. ACCEL.
Table Type	SCR-1000
Tested By	METCALF
Date	9-5-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)		
	Top Waveform	Bottom Waveform
Max =	3.402	3.677
Min =	-3.381	-3.713
Amp =	6.783	7.390

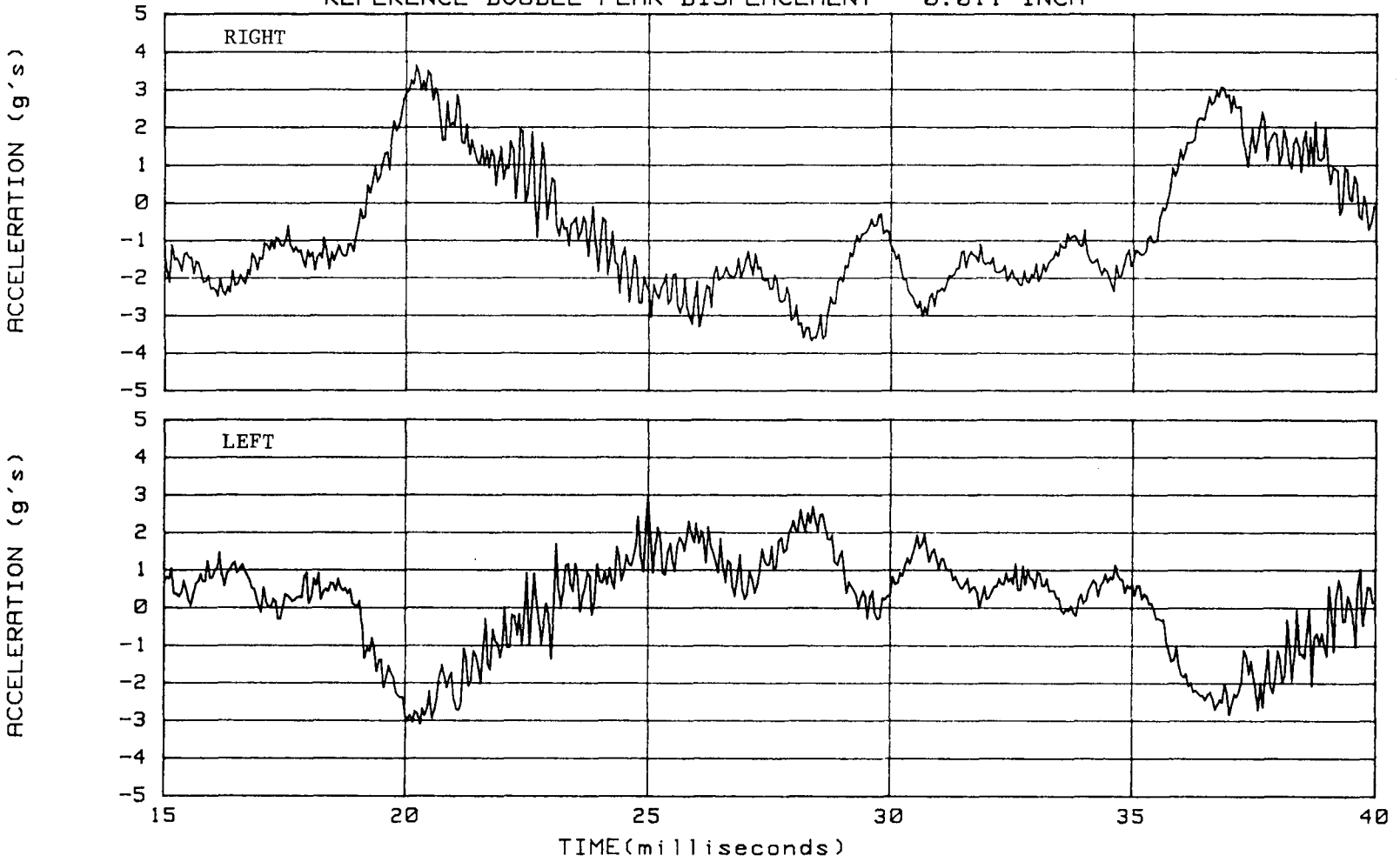


Test No.	16-6-6
Sequence No.	6 CENTER ACCELEROMETER
Table Type	SCR-1000
Tested By	METCALF
Date	6-5-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	2.183	0.000
Min =	-2.142	0.000
Amp =	4.325	0.000

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH

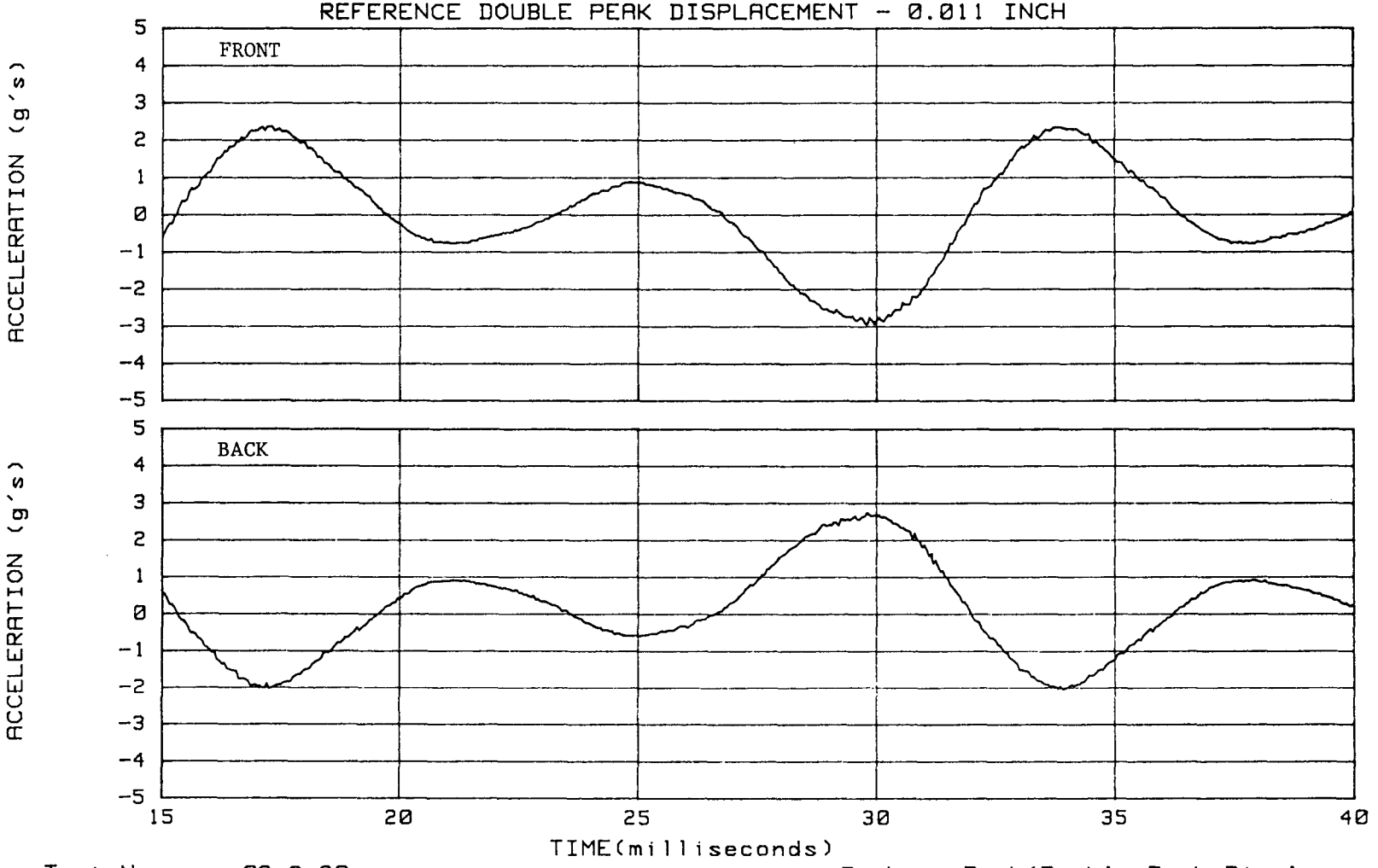


Test No.	16-7-7
Sequence No.	7 RIGHT AND LEFT HORIZ. ACCEL.
Table Type	SCR-1000
Tested By	METCALF
Date	9-5-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	3.646	2.994
Min =	-3.672	-3.106
Amp =	7.319	6.100

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH

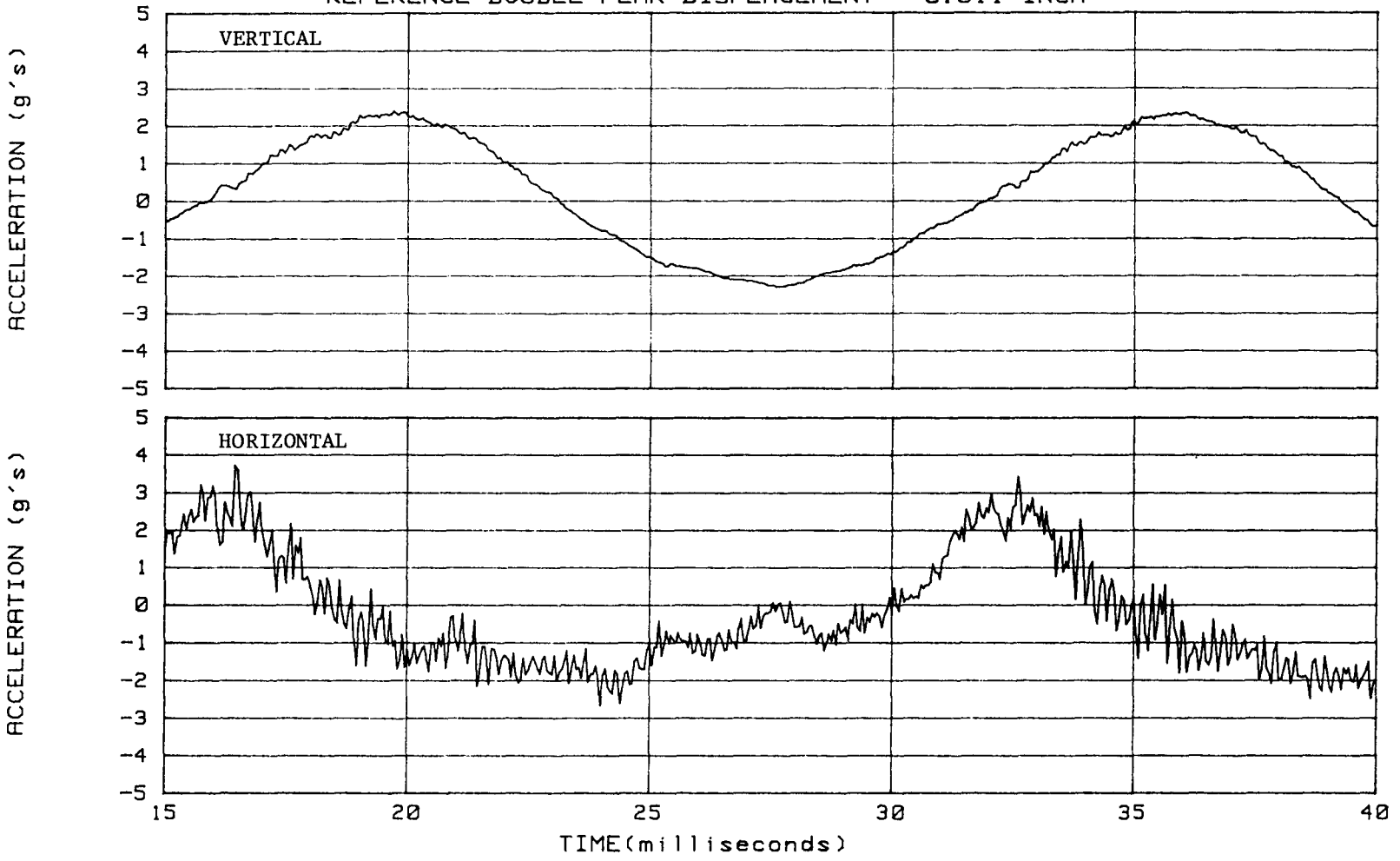


Test No.	A6-8-8A
Sequence No.	8 FRONT AND BACK HORIZ. ACCEL.
Table Type	SCR-1000
Tested By	METCALF
Date	9-5-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	2.382	2.764
Min =	-2.943	-2.035
Amp =	5.324	4.799

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH

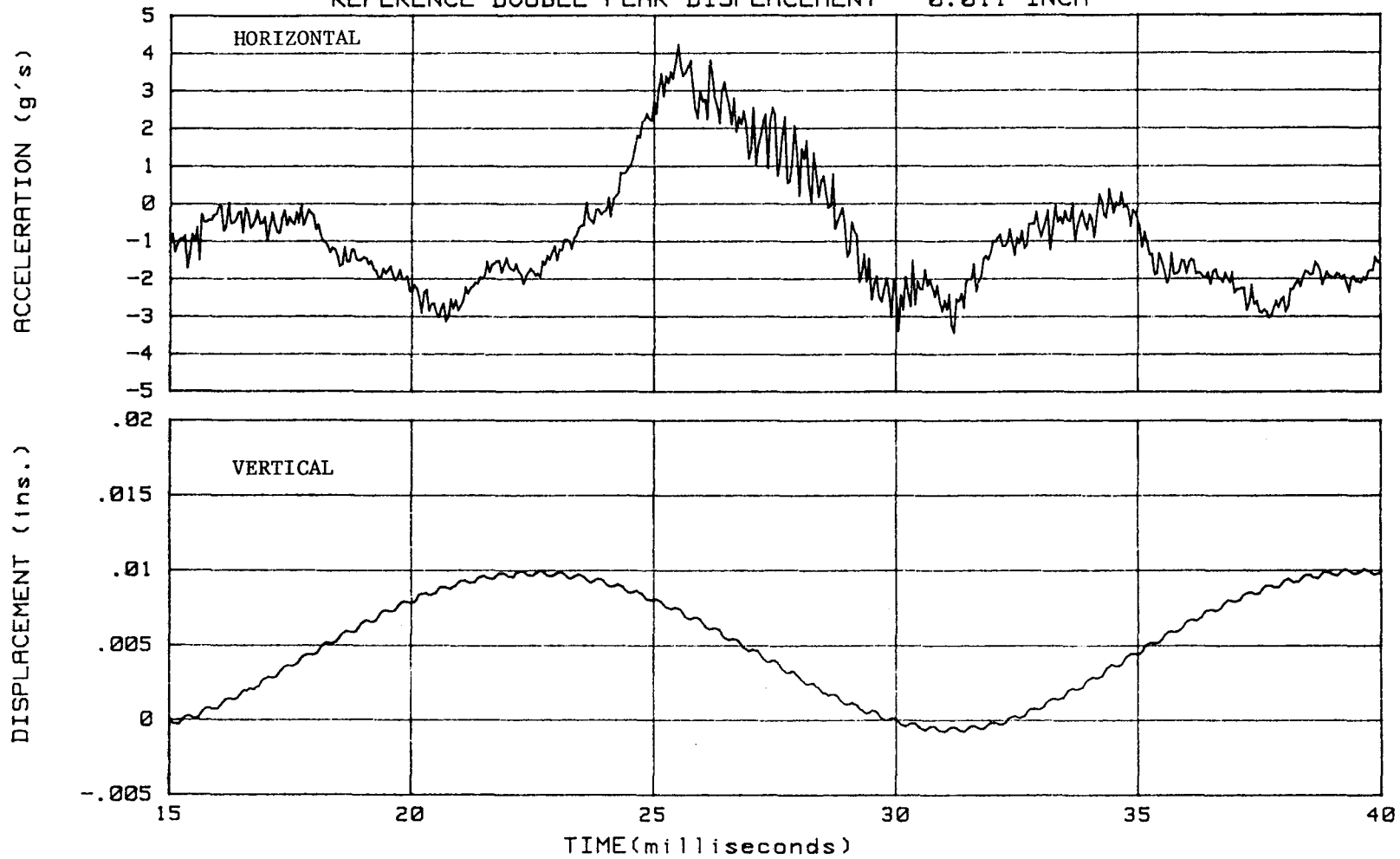


Test No.	16-9-9
Sequence No.	9 RIGHT VERT. AND HORIZ. ACCEL
Table Type	SCR-1000
Tested By	METCALF
Date	9-5-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	2.402	3.738
Min =	-2.305	-2.672
Amp =	4.707	6.411

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.011 INCH



Test No.	16-10-10
Sequence No.	10 RT HORIZ ACCEL & VERT LVDT
Table Type	SCR-1000
Tested By	METCALF
Date	9-5-87
Mass	300 lbm

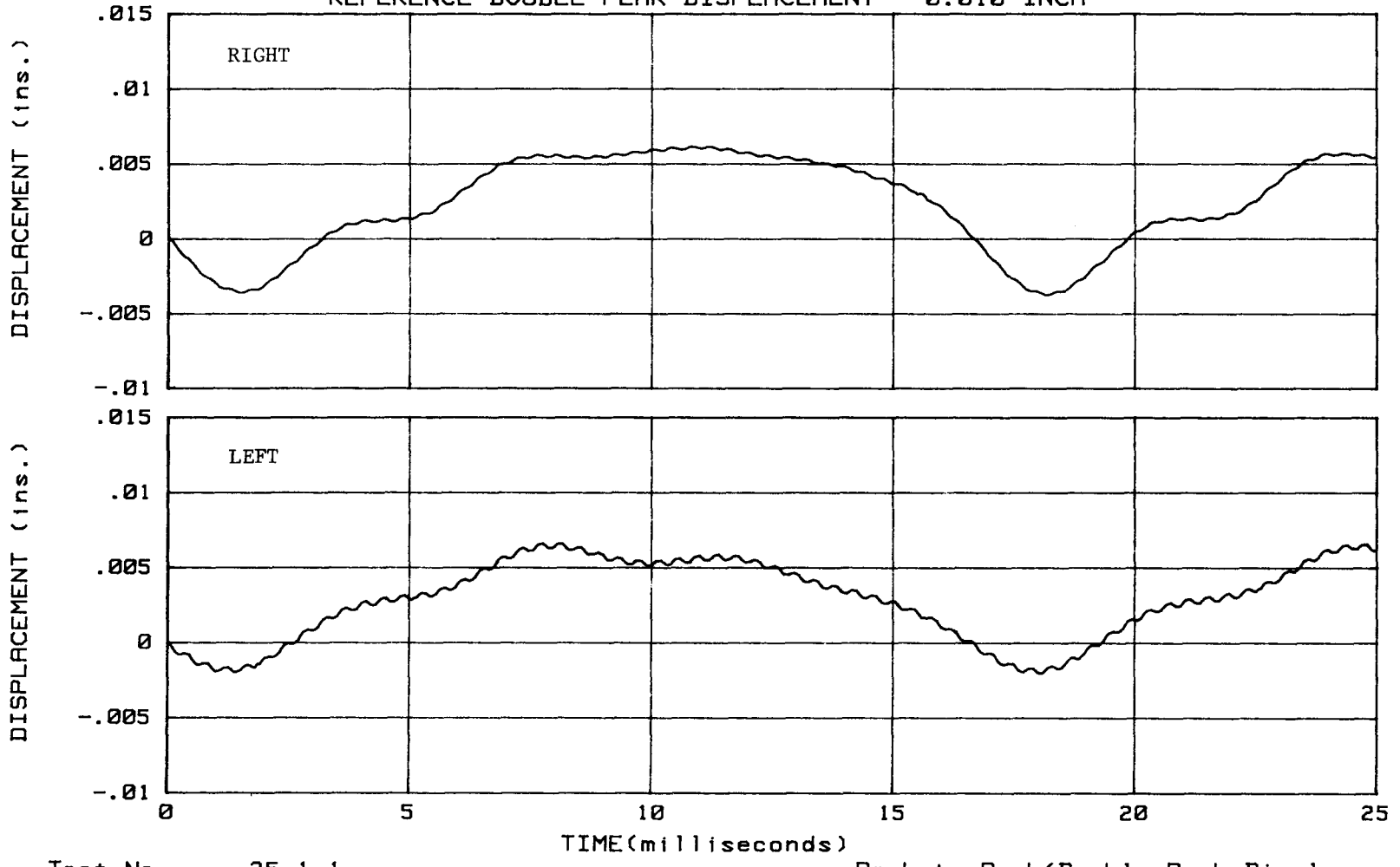
Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	4.233	.010
Min =	-3.443	-.001
Amp =	7.675	.011

APPENDIX C

VP-75A-SC Table Waveforms at 0.010-Inch Double Amplitude

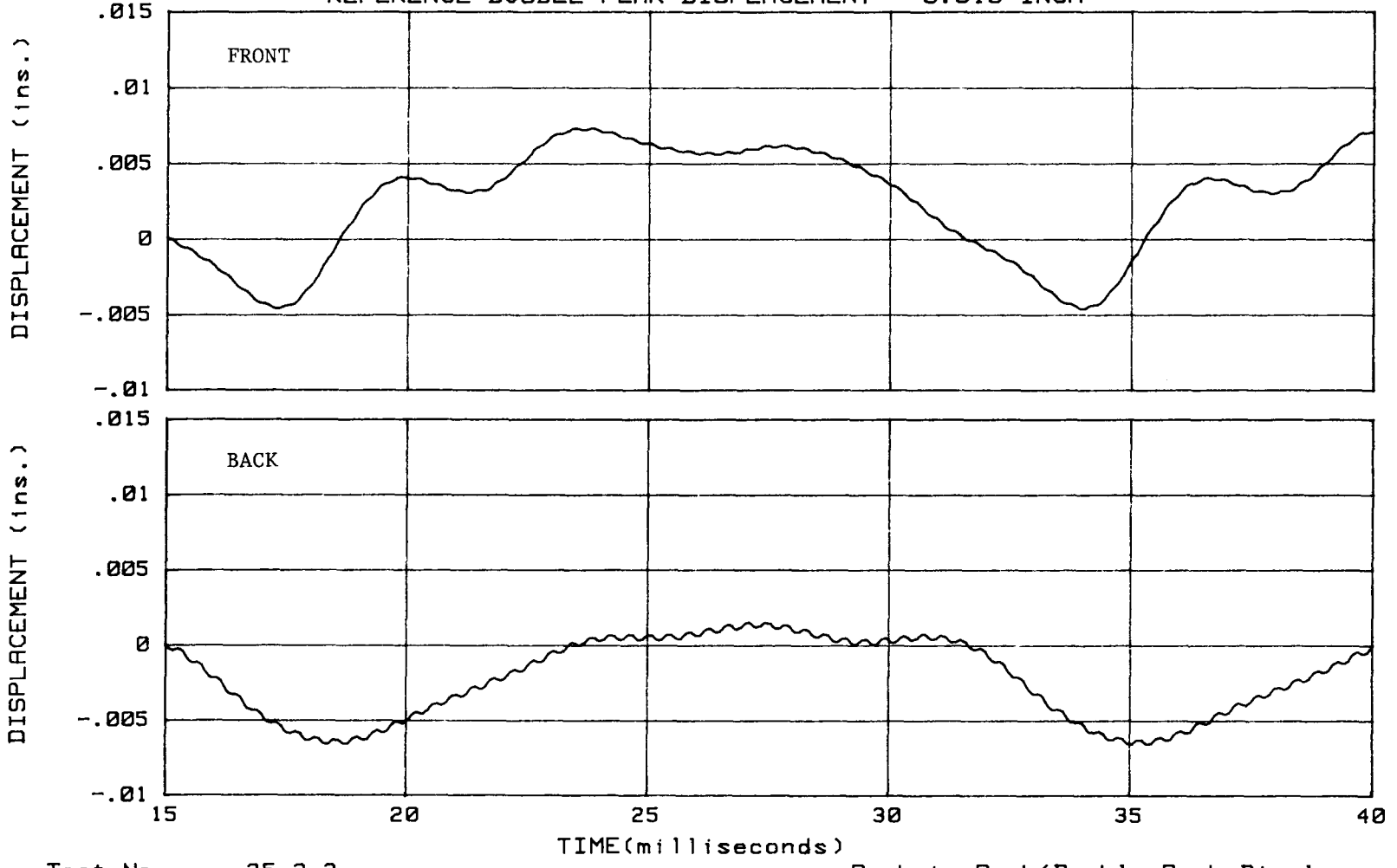
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH



Test No.	35-1-1
Sequence No.	1 RIGHT AND LEFT LVDT
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)		
	Top Waveform	Bottom Waveform
Max =	.006	.007
Min =	-.004	-.002
Amp =	.010	.009

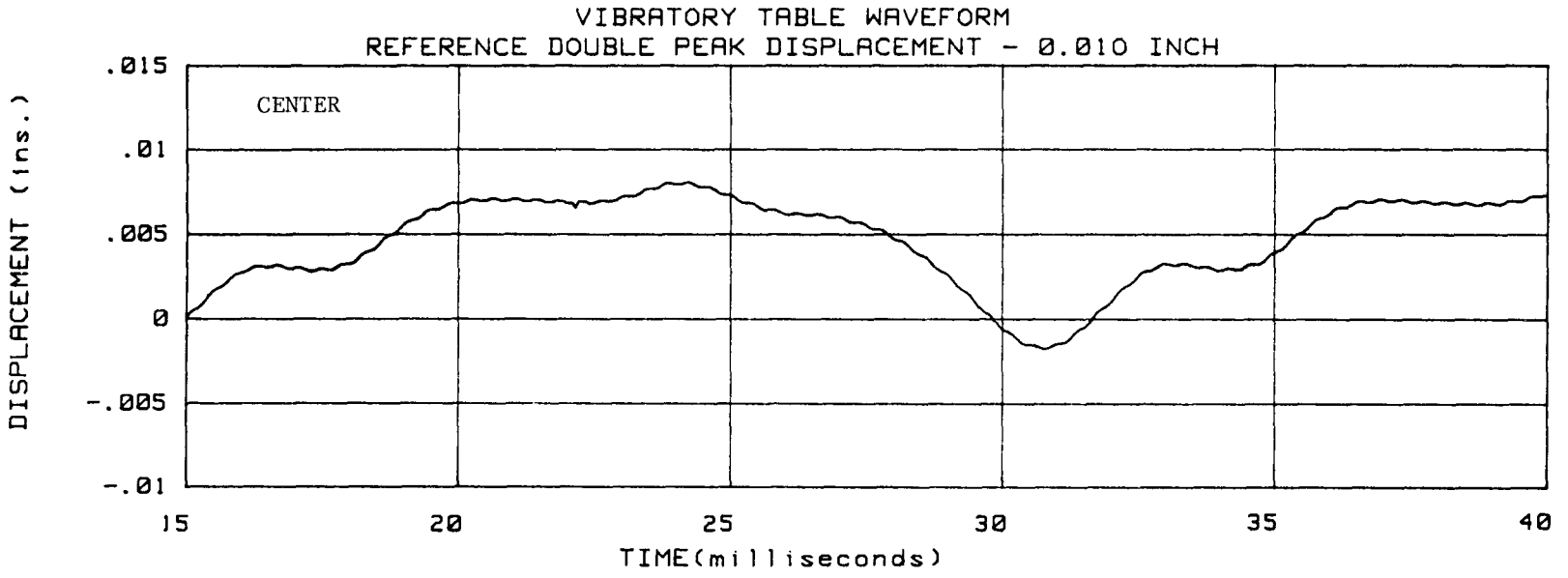
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH



Test No.	35-2-3
Sequence No.	2 FRONT AND BACK LVDT
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	.007	.002
Min =	-.005	-.007
Amp =	.012	.008

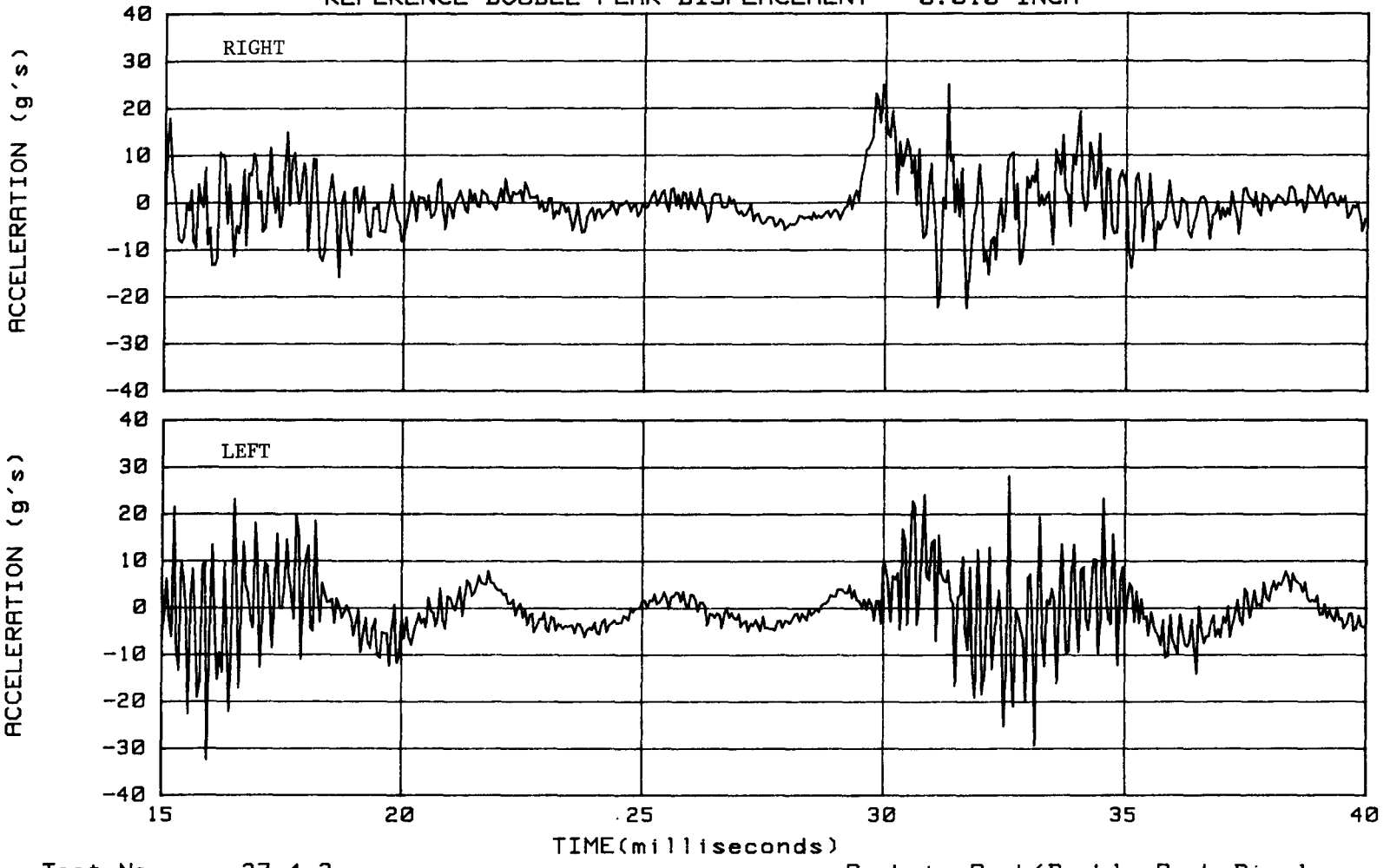


Test No.	35-3-5
Sequence No.	3 CENTER LVDT
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	.008	.008
Min =	-.002	-0.000
Amp =	.010	.008

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH

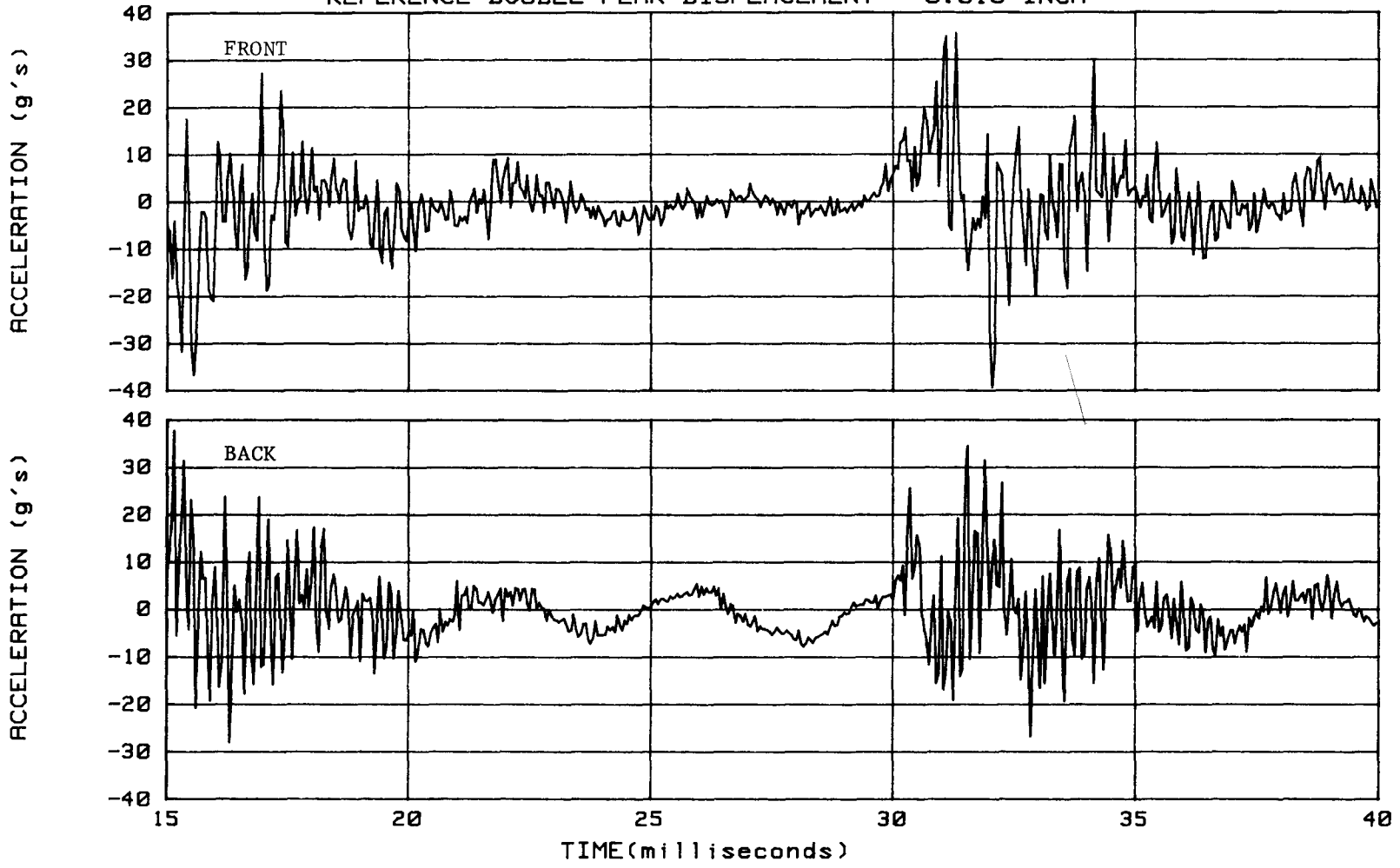


Test No.	37-4-3
Sequence No.	4 RT & LFT VERT ACCELEROMETERS
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	25.143	28.152
Min =	-22.440	-32.487
Amp =	47.583	60.639

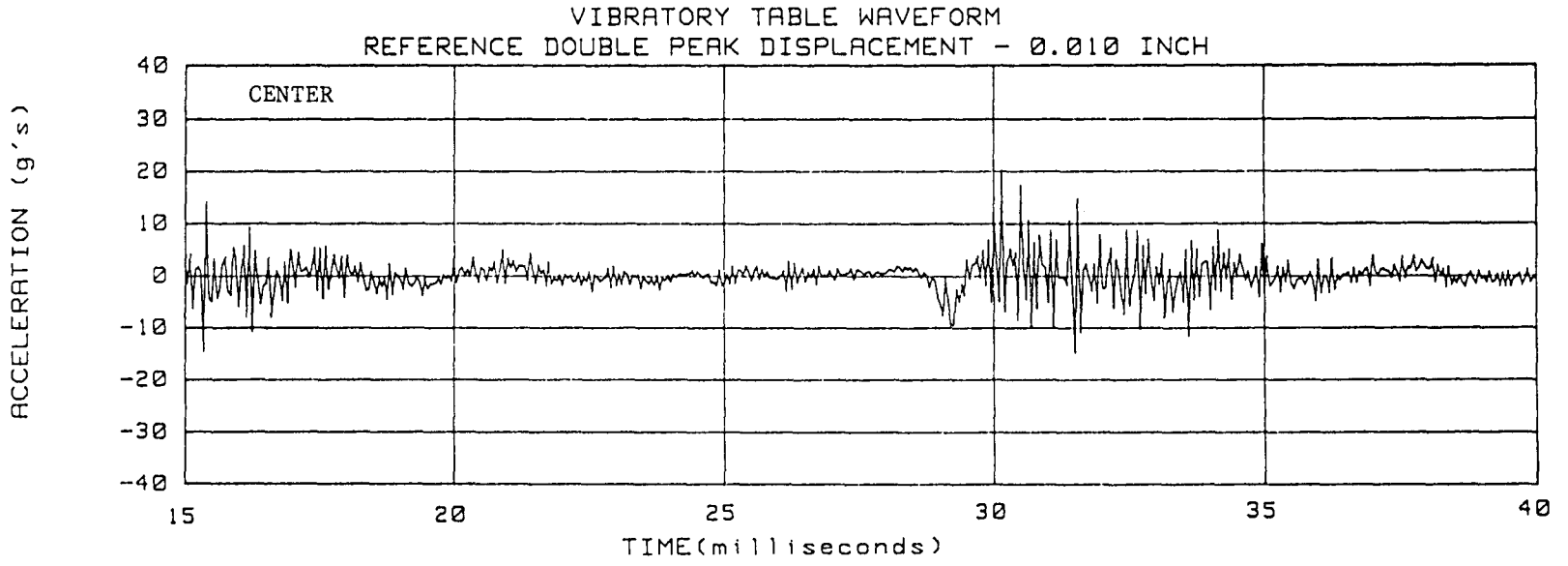
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH



Test No.	37-5-2
Sequence No.	5 FRT & BK VERT ACCELEROMETERS
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	35.649	37.842
Min =	-39.372	-28.152
Amp =	75.021	65.994

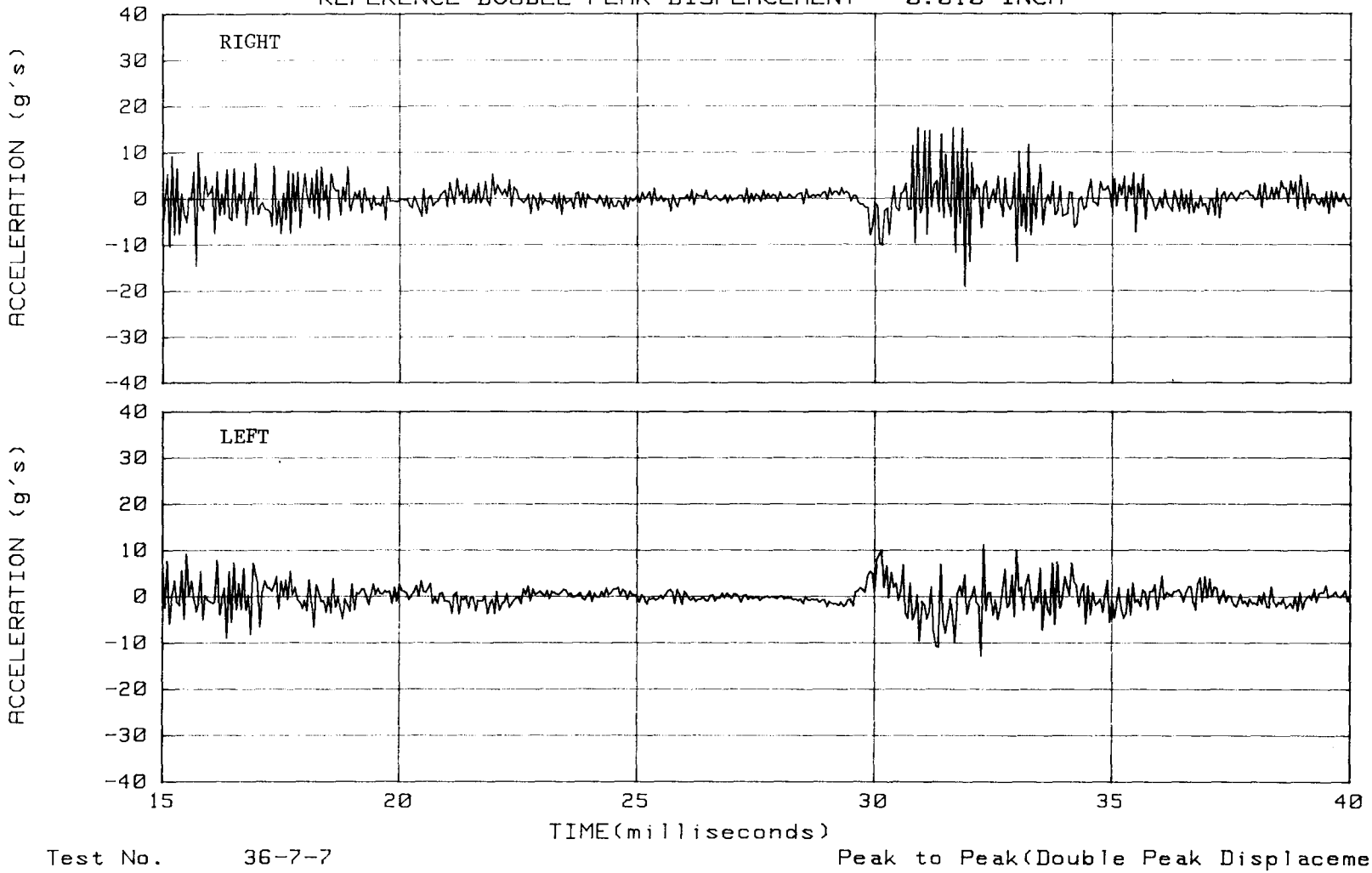


Test No.	37-6-1
Sequence No.	6 CENTER ACCELEROMETER
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	20.298	52.631
Min =	-14.994	52.631
Amp =	35.292	.001

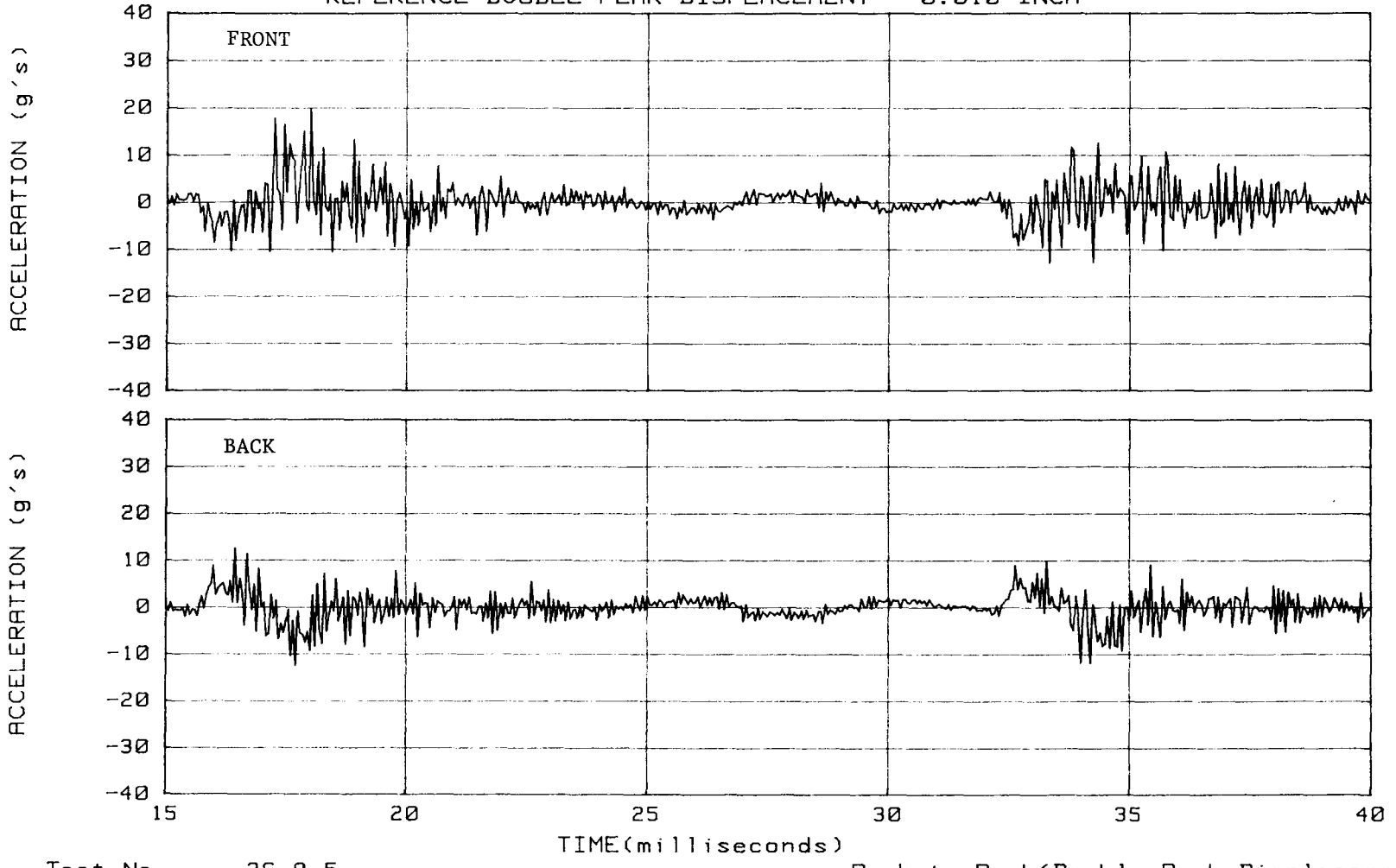
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH



Test No.	36-7-7
Sequence No.	7 RT & LFT HORIZ ACCELEROMETER
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)		
	Top Waveform	Bottom Waveform
Max =	15.453	11.271
Min =	-19.176	-13.005
Amp =	34.629	24.276

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH

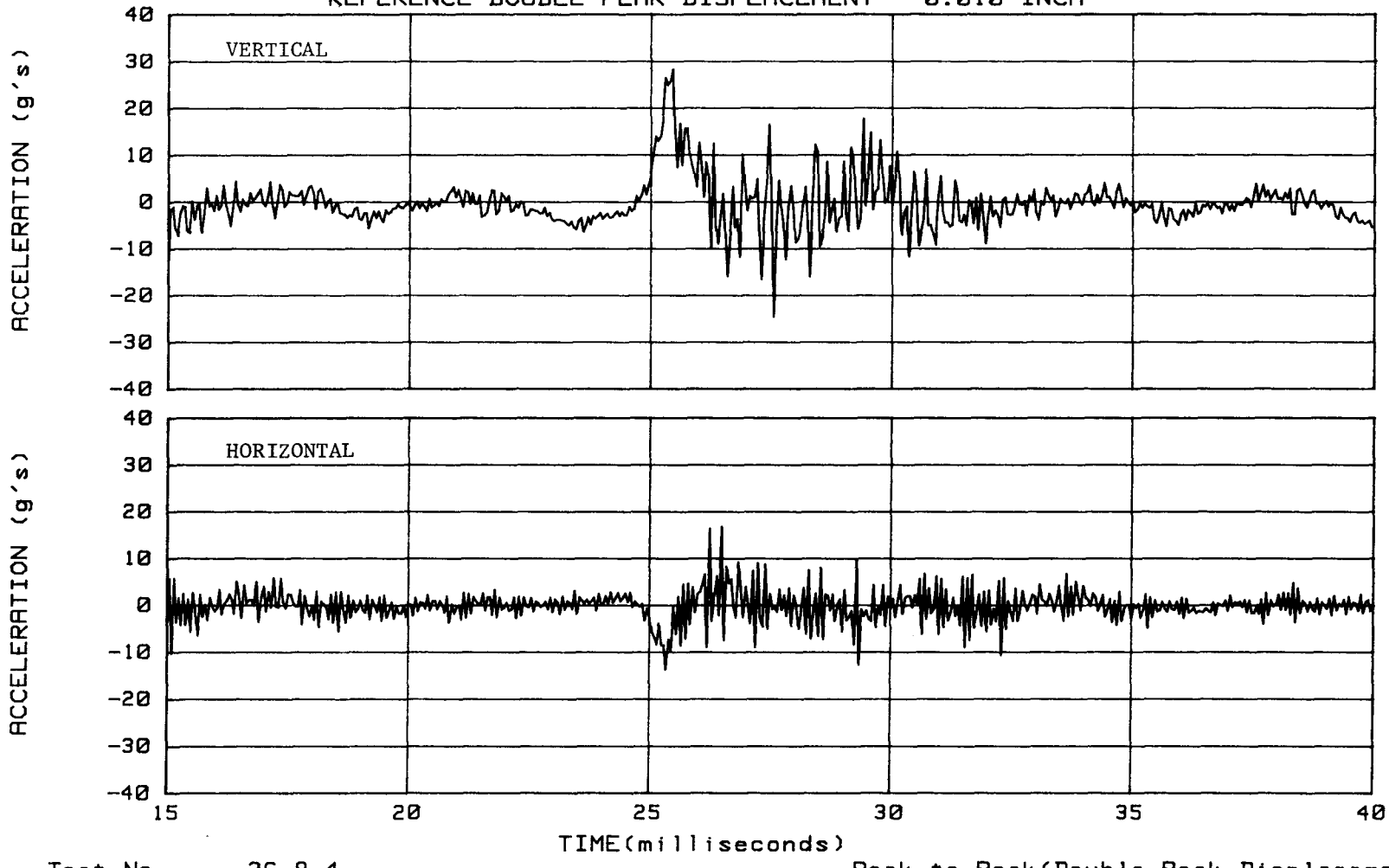


Test No.	36-8-5
Sequence No.	8 FRT & BK HORIZ ACCELEROMETER
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	19.788	12.648
Min =	-12.954	-12.546
Amp =	32.742	25.194

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH

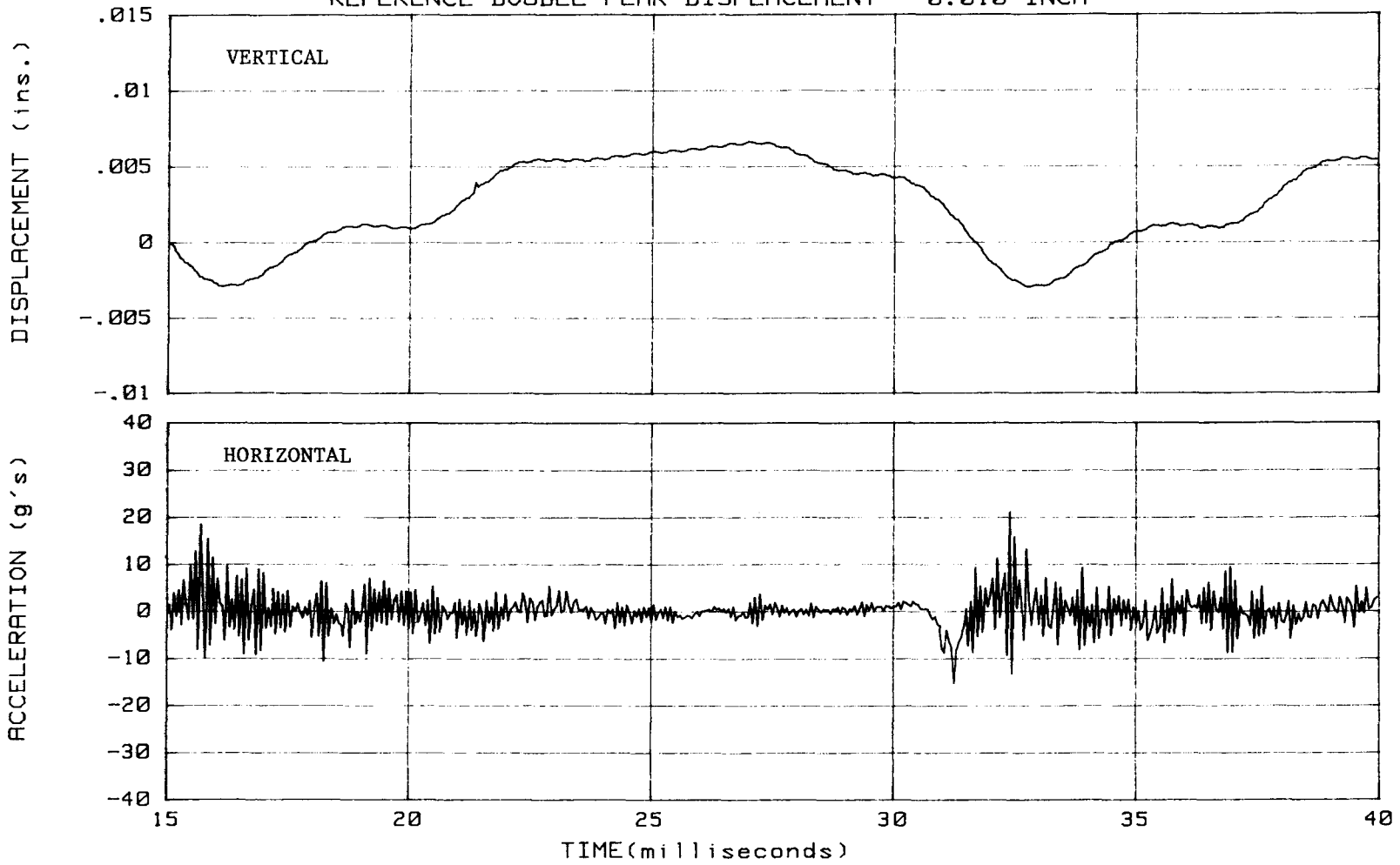


Test No.	36-9-4
Sequence No.	9 RIGHT VERT. AND HORIZ. ACCEL
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	28.254	16.983
Min =	-24.735	-13.770
Amp =	52.989	30.753

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.010 INCH



Test No.	36-10-3
Sequence No.	10 RT VERT LVDT & HORIZ ACCEL
Table Type	VP-75A-SC
Tested By	METCALF
Date	9/20/87
Mass	300 lbm

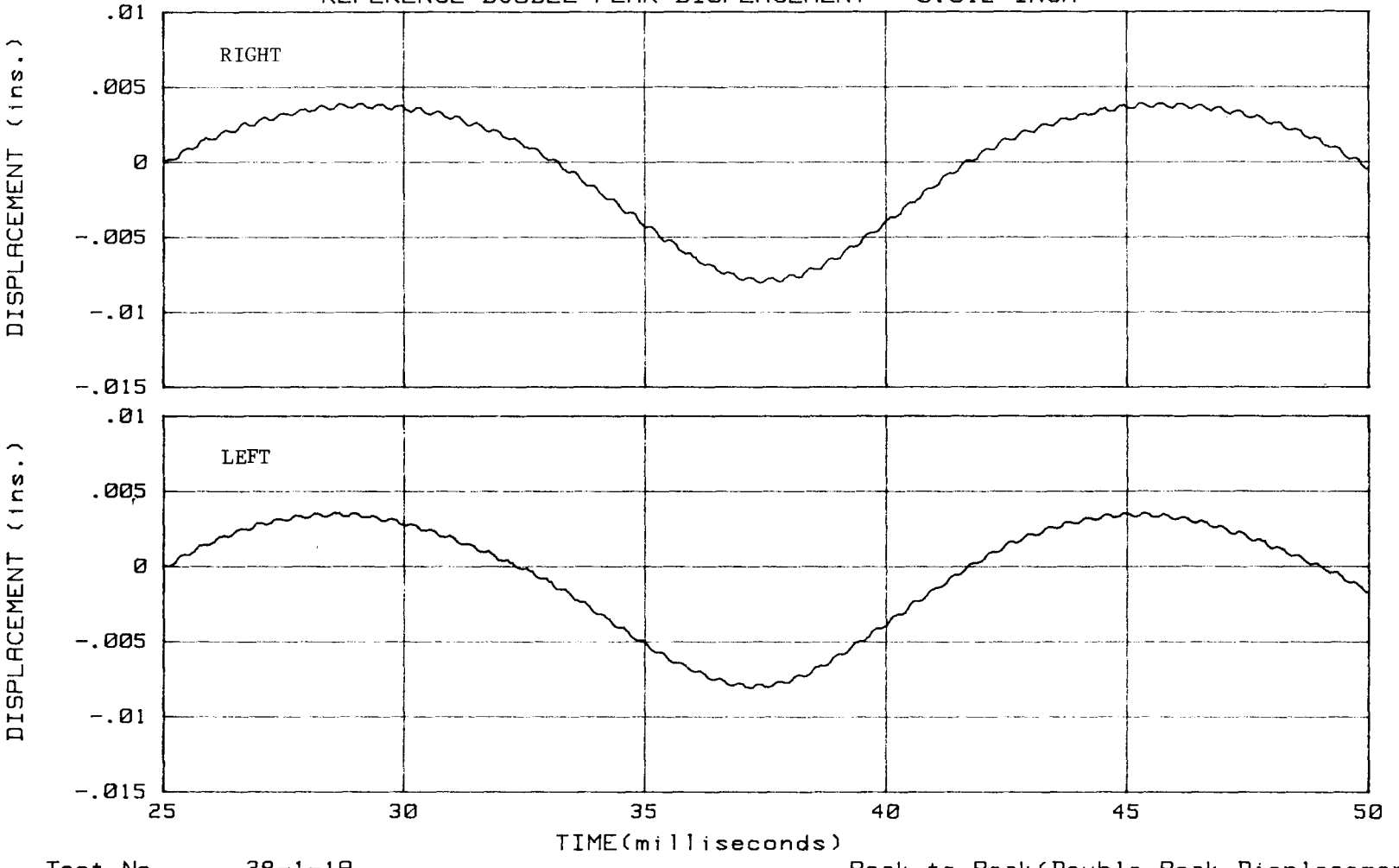
Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	.007	21.318
Min =	-.003	-15.351
Amp =	.010	36.669

APPENDIX D

V-80 Table Waveforms at 0.012-Inch Double Amplitude

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.012 INCH

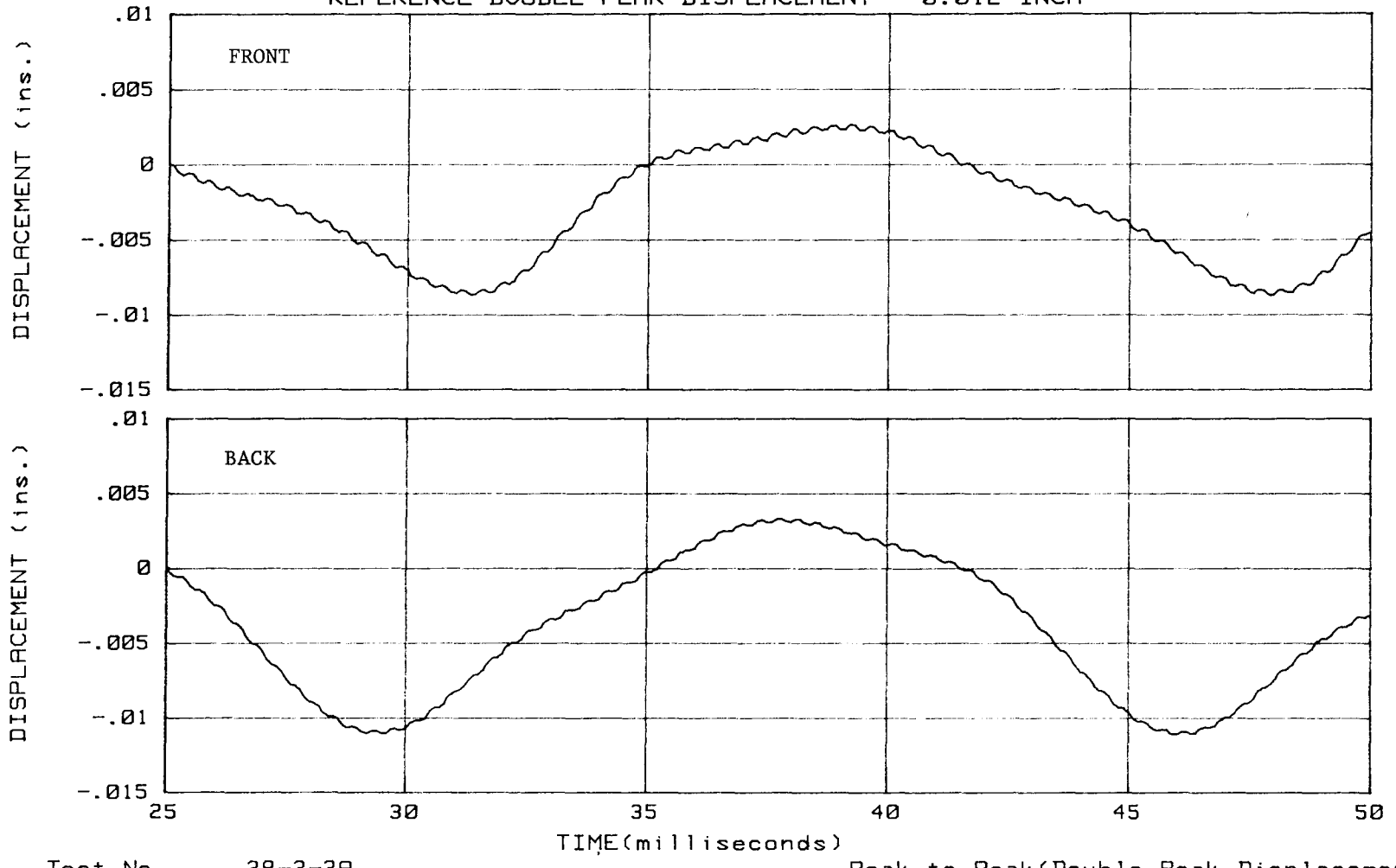


Test No.	28-1-1A
Sequence No.	1 RIGHT AND LEFT LVDT
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

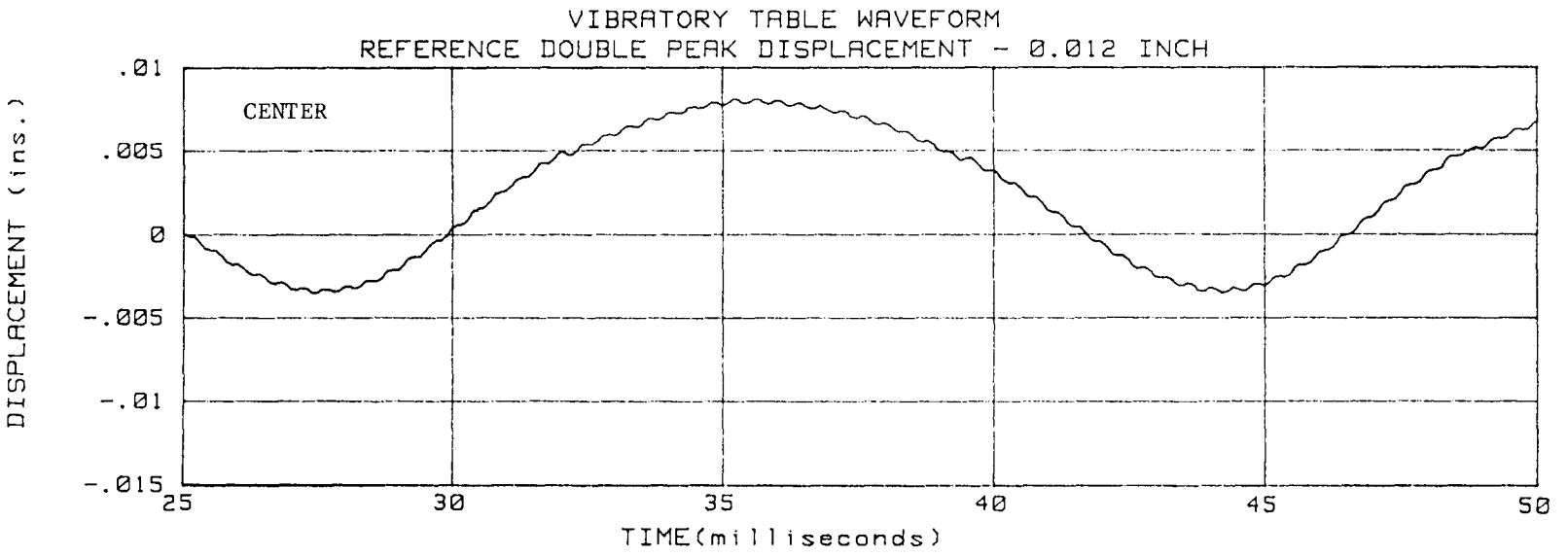
	Top Waveform	Bottom Waveform
Max =	.004	.004
Min =	-.008	-.008
Amp =	.012	.012

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.012 INCH



Test No.	28-2-2A
Sequence No.	2 FRONT AND BACK LVDT
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)		
	Top Waveform	Bottom Waveform
Max =	.003	.003
Min =	-.009	-.011
Amp =	.011	.014

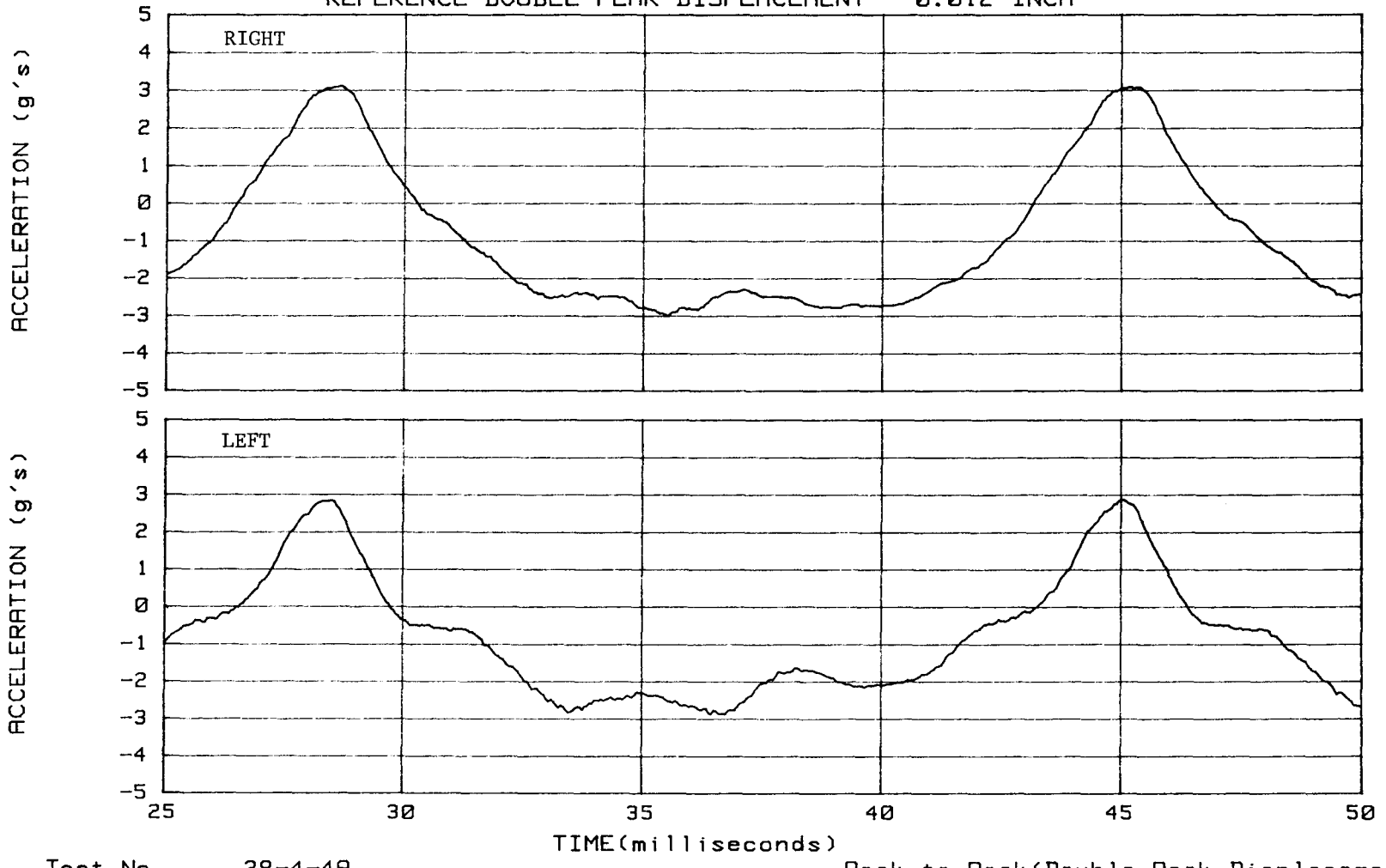


Test No.	28-3-3A
Sequence No.	3 CENTER LVDT
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	.008	0.000
Min =	-.004	0.000
Amp =	.012	0.000

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.012 INCH

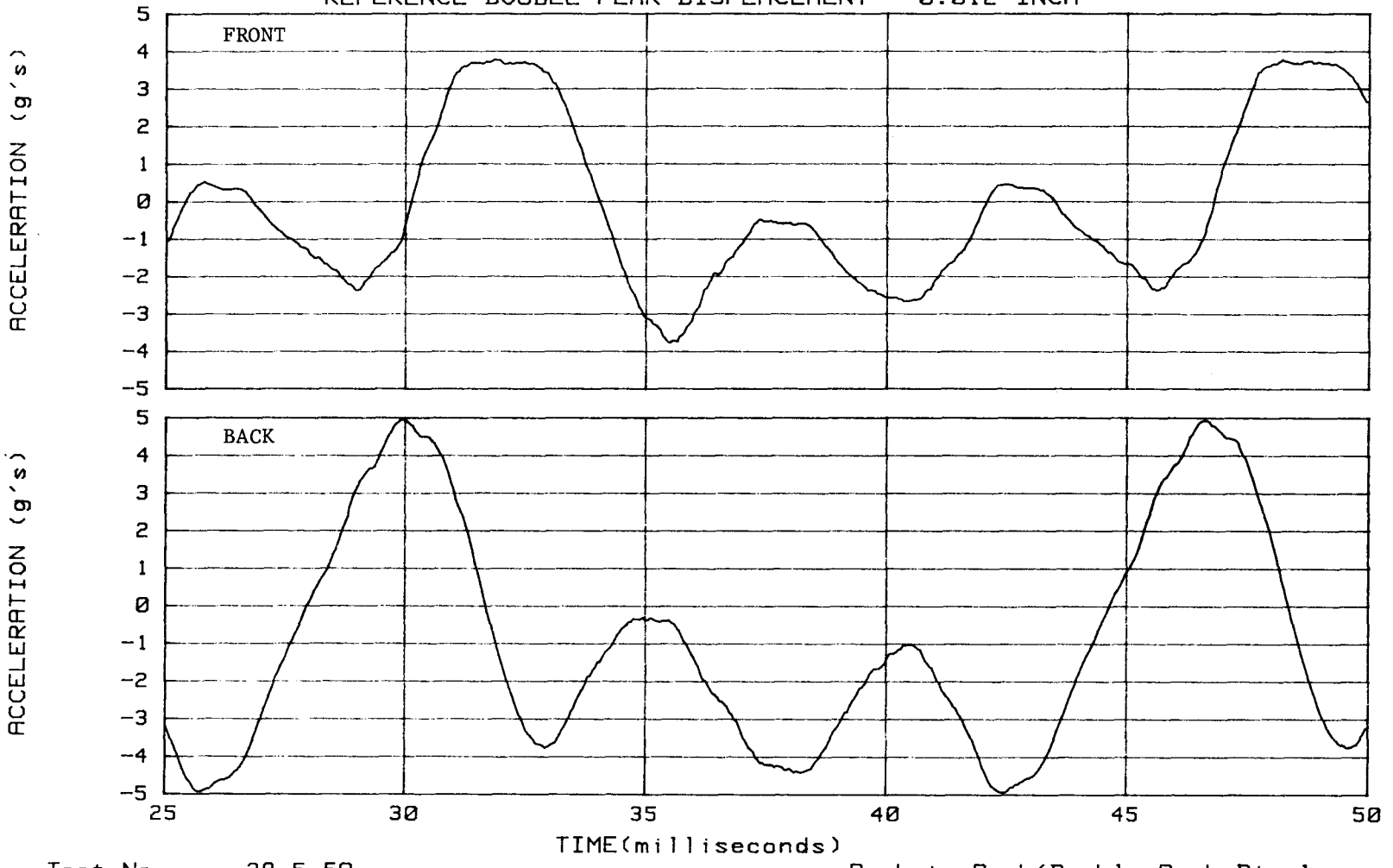


Test No.	28-4-4A
Sequence No.	4 RT & LFT VERT ACCELEROMETERS
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	3.121	2.876
Min =	-3.009	-2.887
Amp =	6.130	5.763

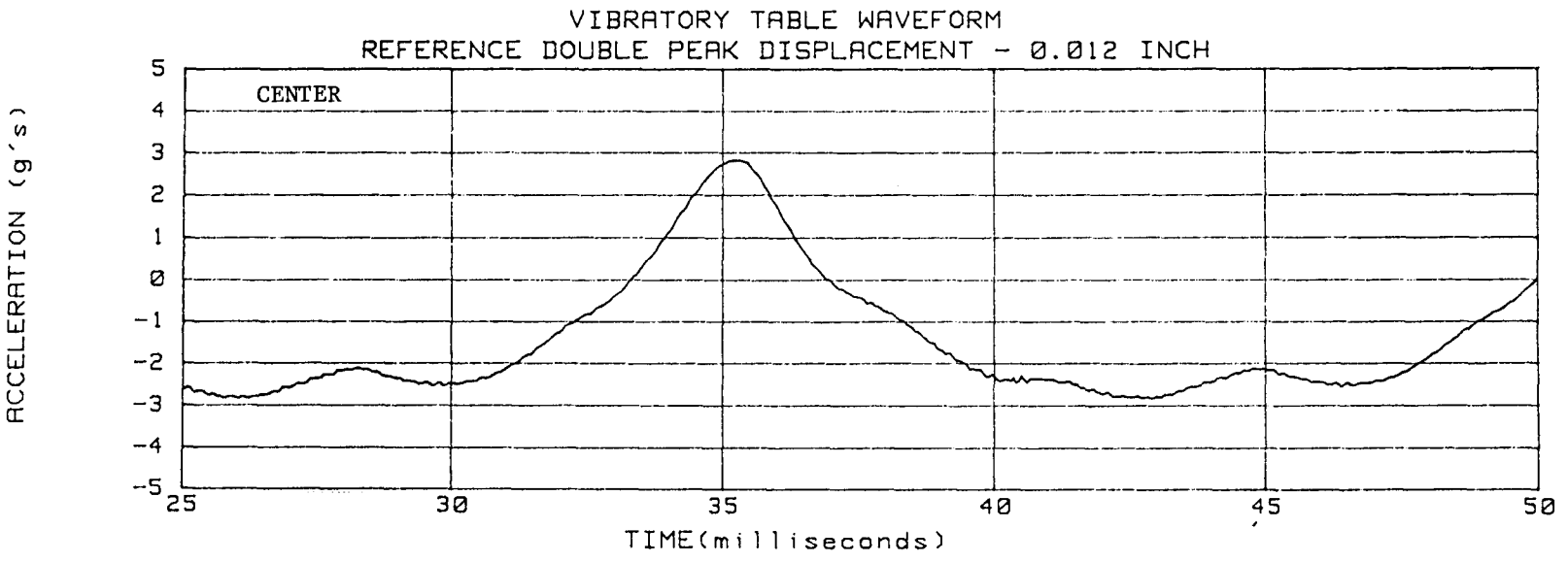
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.012 INCH



Test No.	28-5-5A
Sequence No.	5 FT & BK VERT ACCELEROMETERS
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	3.784	4.962
Min =	-3.779	-4.942
Amp =	7.563	9.904

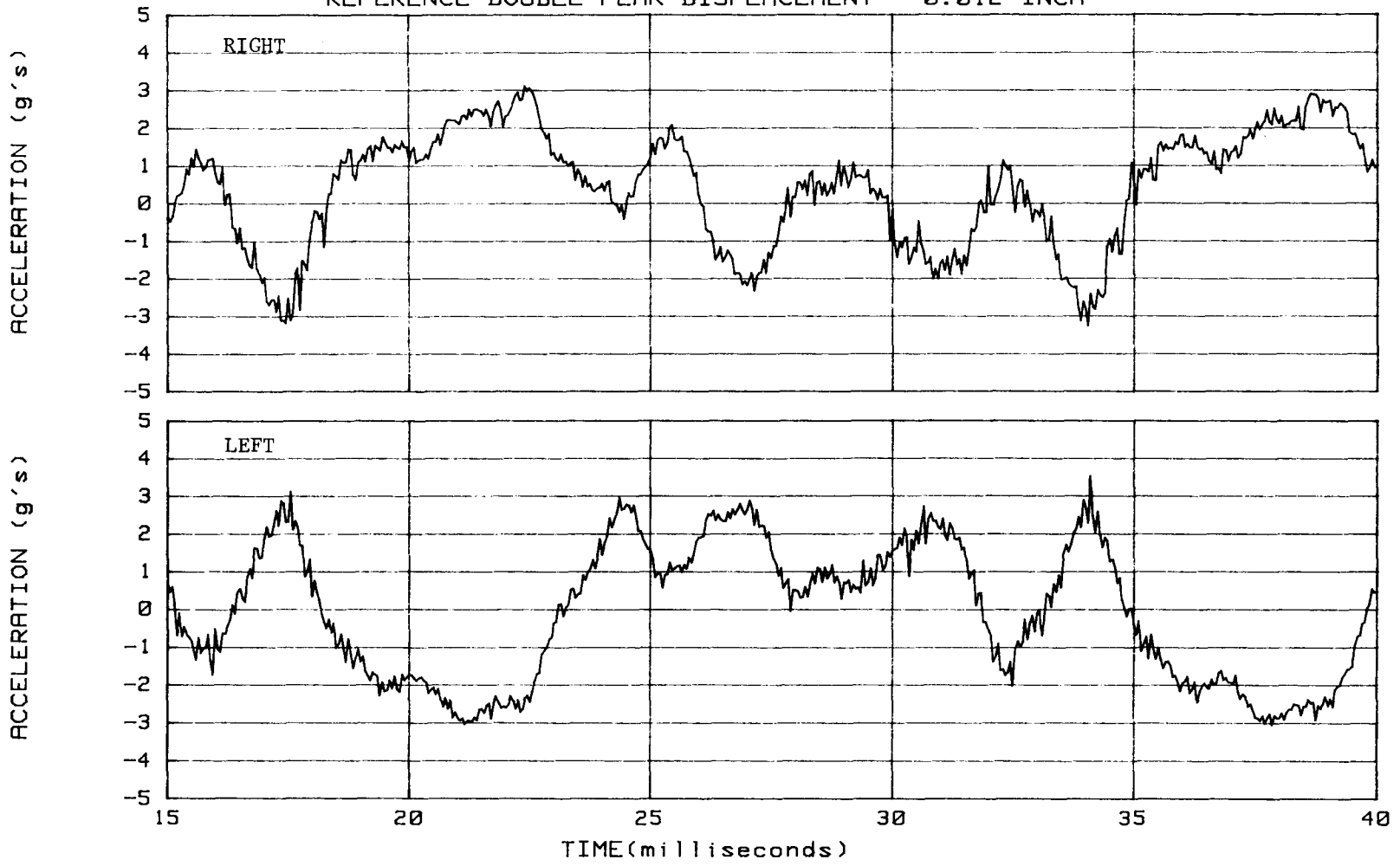


Test No.	28-6-6A
Sequence No.	6 CENTER ACCELEROMETER
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	2.846	0.000
Min =	-2.851	0.000
Amp =	5.697	0.000

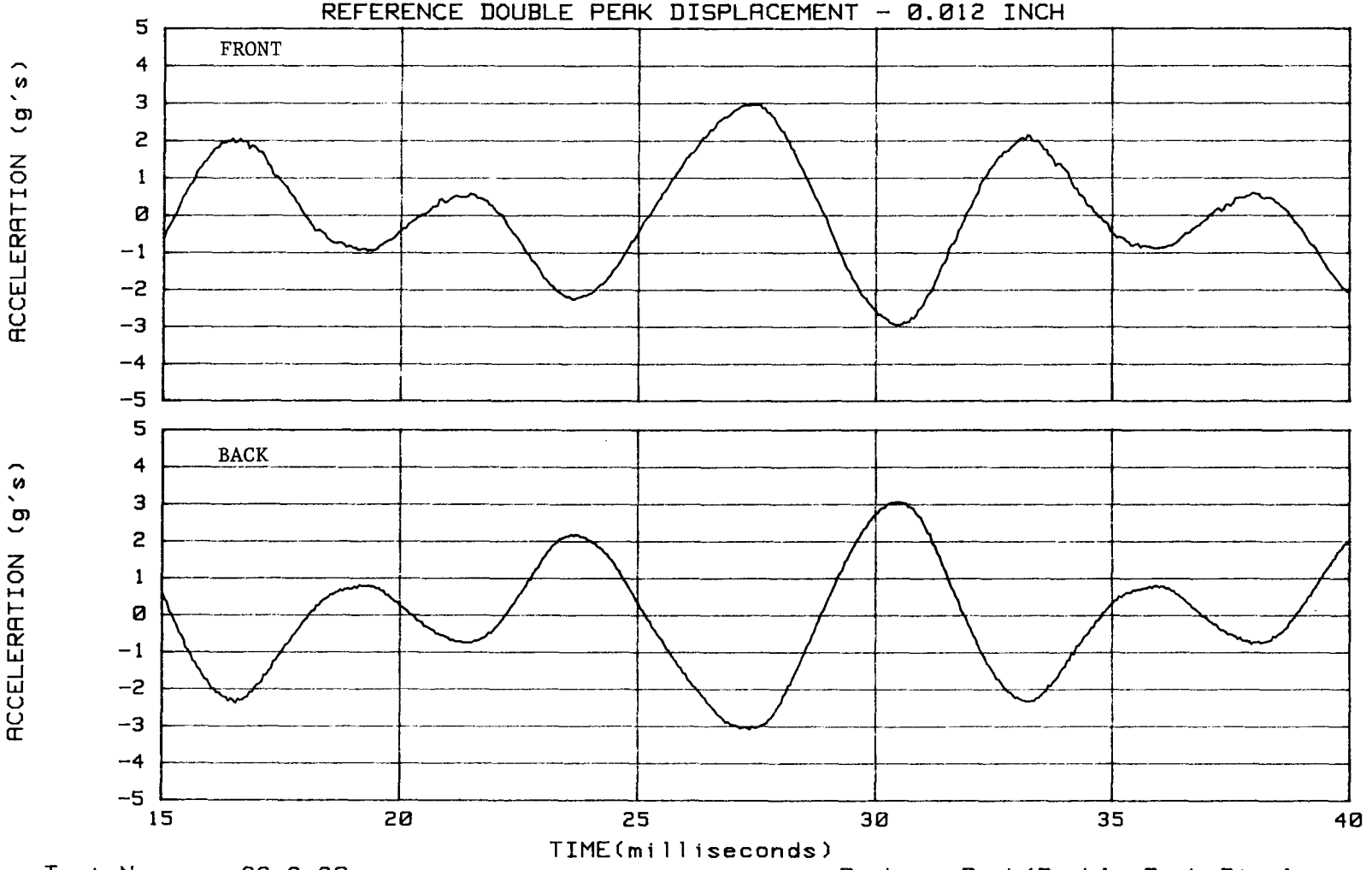
VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.012 INCH



Test No.	28-7-7A
Sequence No.	7 RT & LFT HORIZ ACCELEROMETER
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)		
	Top Waveform	Bottom Waveform
Max =	3.121	3.555
Min =	-3.259	-3.055
Amp =	6.380	6.610

VIBRATORY TABLE WAVEFORM
REFERENCE DOUBLE PEAK DISPLACEMENT - 0.012 INCH



Test No.	28-8-8A
Sequence No.	8 FT & BK HORIZ ACCELEROMETERS
Table Type	V-80
Tested By	KUNZER
Date	9-28-87
Mass	300 lbm

Peak to Peak(Double Peak Displacement)

	Top Waveform	Bottom Waveform
Max =	2.968	3.065
Min =	-2.953	-3.096
Amp =	5.921	6.161

VIBRATORY TABLE SUMMARY DATA SHEET
(NOTE; COLUMNS F THROUGH AR CONTAIN TEST DATA; COLUMNS AU THROUGH CO CONTAIN REDUCED DATA)

TABLE TYPE	REFERENCE AMPLITUDE	SEQUENCE NO.	VERTICAL DISPLACEMENT SEQUENCE NO. 1 RIGHT	SEQUENCE NO. 1 LEFT	SEQUENCE NO. 2 FRONT	SEQUENCE NO. 2 BACK	SEQUENCE NO. 3 CENTER	SEQUENCE NO. 4 RIGHT DISCRETE	SEQUENCE NO. 4 RIGHT SCATTER	SEQUENCE NO. 4 LEFT DISCRETE	SEQUENCE NO. 4 LEFT SCATTER	VERTICAL ACCELERATION SEQUENCE NO. 5 FRONT DISCRETE	SEQUENCE NO. 5 FRONT SCATTER	SEQUENCE NO. 5 BACK DISCRETE	SEQUENCE NO. 5 BACK SCATTER	SEQUENCE NO. 6 CENTER DISCRETE	SEQUENCE NO. 6 CENTER SCATTER	HORIZONTAL ACCELERATION SEQUENCE NO. 7 RIGHT DISCRETE	SEQUENCE NO. 7 RIGHT SCATTER	SEQUENCE NO. 7 LEFT DISCRETE	SEQUENCE NO. 7 LEFT SCATTER	SEQUENCE NO. 8 FRONT DISCRETE	SEQUENCE NO. 8 FRONT SCATTER	SEQUENCE NO. 8 BACK DISCRETE	SEQUENCE NO. 8 BACK SCATTER	SPECIAL SQUENCES SEQUENCE NO. 9 RIGHT VERTICAL DISCRETE	SEQUENCE NO. 9 RIGHT VERTICAL SCATTER	SEQUENCE NO. 9 RIGHT HORIZONTAL DISCRETE	SEQUENCE NO. 9 RIGHT HORIZONTAL SCATTER	SEQUENCE NO. 10 RIGHT DISCRETE	SEQUENCE NO. 10 RIGHT HORIZONTAL DISCRETE	SEQUENCE NO. 10 RIGHT HORIZONTAL SCATTER	MEASURED DOUBLE AMPLITUDE (IN.) (INPUT AMPLITUDE/2) REFERENCE	RIGHT	LEFT	FRONT	BACK	CENTER
VP-75-UTAH	0.007		0.016	0.016	0.015	0.017	0.015	22.0	66.0	16.0	55.0	23.0	43.0	17.0	63.0	4.6		4.0	72.0	4.0	54.0	9.0	67.0	12.0	48.0	18.0	70.0	6.0	46.0	0.016	7.0	67.0	0.007	0.00775	0.00775	0.00725	0.0085	0.00765
	0.007		0.011	0.014			0.014	24.0	24.0	7.0	23.0	14.0	31.0	5.0	21.0	8.5	11.5	4.5	17.0	4.5	13.0	9.0	22.0	7.0	28.0	16.0	20.0	5.0	9.0	0.010	6.0	8.0	0.007	0.0055	0.00685	0	0	0.007
	0.009						0.013	22.0	55.0	16.0	65.0	22.0	79.0	26.0	64.0	17.0	47.0	8.0	72.0	7.0	50.0	13.0	55.0	14.0	100.0	10.0	70.0	22.0	66.0	0.017	4.0	68.0	0.005	0	0	0	0	0.0066
VP-75A-LAB	0.007		0.010	0.014	0.016	0.014	0.011	7.0	13.0	7.0	18.0	8.0	23.0	7.0	15.0	4.0	9.0	6.0	9.0	5.5	7.6	7.0	11.0	5.0	10.5	10.0	9.0	6.0	8.5	0.011	5.5	9.0	0.007	0.005	0.007	0.008	0.007	0.0055
	0.009		0.018	0.017	0.015	0.015	0.014	14.0	34.0	16.0	36.0	3.0	16.0	7.0	22.0	5.0	12.0	14.0	28.0	10.0	25.0	14.0	28.0	10.0	13.0	16.0	35.0	12.0	26.0	0.016	12.0	31.0	0.009	0.009	0.0085	0.0075	0.0075	0.007
	0.010		0.018	0.018			0.017	9.5	60.8	3.6	56.6	10.8	52.7	7.0	71.0	8.3	33.7	4.9	39.8	4.5	30.9	5.8	28.5	4.6	42.9	11.8	41.2	8.2	48.8	0.018	10.1	77.9	0.010	0.0089	0.0088	0	0	0.00865
	0.011		0.021	0.021	0.020	0.023	0.022	27.0	91.0	20.0	93.0	20.0	100.0	20.0	130.0	13.0	73.0	23.0	125.0	20.0	85.0	15.0	100.0	20.0	125.0	33.0	103.0	20.0	100.0	0.022	20.0	81.0	0.011	0.0105	0.0105	0.01	0.0115	0.01075
w/shims	0.011		0.020	0.019	0.014	0.027	0.018	15.0	92.0	20.0	96.0	10.0	110.0	28.0	119.0	14.0	62.0	12.0	51.0	10.0	45.0	14.0	70.0	22.0	97.0	15.0	71.0	10.0	54.0	0.019	10.0	59.0	0.011	0.01	0.0095	0.007	0.0135	0.009
w/shims	0.014		0.027	0.028	0.022	0.035	0.027	25.0	125.0	12.0	132.0	25.0	100.0	40.0	145.0	12.0	75.0	13.0	75.0	10.0	70.0	13.0	92.0	17.0	112.0	28.0	200.0	15.0	82.0	0.027	14.0	92.0	0.014	0.01325	0.014	0.011	0.0175	0.0135
VP-80-LAB	0.012		0.024	0.023	0.028	0.022	0.023	12.2		11.7		13.5		15.0		11.5		12.7		12.0		12.0		12.0		11.5		12.0		0.024	12.0		0.012	0.01175	0.0115	0.014	0.011	0.0115
VIBCO-LAB	0.011		0.022	0.022	0.025	0.031	0.022	9.6		9.4		15.0		11.8		8.6		1.5		1.1		9.8		7.6		9.4		1.3		0.022	1.6		0.011	0.011	0.011	0.0145	0.0155	0.01075
	0.013		0.024	0.025	0.034	0.035	0.025	9.8		9.6		16.5		15.6		9.5		1.8		1.5		12.0		10.4		9.8		1.6		0.027	1.9		0.013	0.012	0.0125	0.017	0.0175	0.0125
	0.015		0.031	0.029	0.037	0.042	0.030	12.8		12.7		20.0		18.0		11.2		2.5		2.1		13.5		14.5		13.0		2.4		0.031	2.9		0.015	0.0155	0.0145	0.0185	0.021	0.015
	0.017		0.031	0.033	0.042	0.046	0.033	12.8		12.6		20.0		21.0		14.0		2.0		1.7		16.0		18.5		11.3		2.0		0.033	1.2		0.017	0.0155	0.0165	0.021	0.023	0.0165
	0.017		0.035	0.035	0.044	0.046	0.032	13.8		12.0		22.0		21.0		13.8		2.5		2.5		16.7		16.0		16.5		2.7		0.035	3.3		0.017	0.0175	0.0175	0.022	0.023	0.016
	0.021		0.042	0.041	0.052	0.056	0.041	15.1		15.1		28.0		25.0		16.0		2.8		2.5		17.5		20.0		18.2		3.4		0.040	5.5		0.021	0.021	0.0205	0.026	0.028	0.0205

VIBRATORY TABLE SUMMARY DATA SHEET
(NOTE; COLUMNS F THROUGH AR CONTAIN TEST DATA; COLUMNS AU THROUGH CO CONTAIN REDUCED DATA)

TABLE TYPE	REFERENCE AMPLITUDE	SEQUENCE NO.	THEORETICAL ACCELERATIONS (g's) BASED ON AMPLITUDE DATA (MEASURED DOUBLE AMPLITUDE * 183.9) REFERENCE	RIGHT	LEFT	FRONT	BACK	CENTER	AVERAGE	RIGHT MEASURED ACCELERATIONS (g's) (INPUT DATA / 4) RIGHT DISCRETE	RIGHT SCATTER	LEFT DISCRETE	LEFT SCATTER	FRONT DISCRETE	FRONT SCATTER	BACK DISCRETE	BACK SCATTER	CENTER DISCRETE	CENTER SCATTER	ACCELERATIONS - PERCENTAGE DIFFERENCES FROM REFERENCE HORIZONTAL RIGHT DISCRETE	RIGHT SCATTER	LEFT DISCRETE	LEFT SCATTER	FRONT DISCRETE	FRONT SCATTER	BACK DISCRETE	BACK SCATTER	VERTICAL RIGHT DISCRETE	RIGHT SCATTER	LEFT DISCRETE	LEFT SCATTER	FRONT DISCRETE	FRONT SCATTER	BACK DISCRETE	BACK SCATTER	CENTER DISCRETE	CENTER SCATTER
VP-75-UTAH	0.007		1.287	1.425	1.425	1.333	1.563	1.407	1.688	4.250	16.500	4.000	13.750	5.750	10.750	4.250	15.750	1.150	0.000	1.000	18.000	1.000	13.500	2.250	16.750	3.000	12.000	230.148	1181.753	210.728	968.127	346.671	735.081	230.148	1123.491	10.666	100.000
	0.007		1.287	1.011	1.260	0.000	0.000	1.287	1.615	3.500	6.000	1.750	5.750	3.500	7.750	1.250	5.250	2.125	2.875	1.125	4.250	1.125	3.250	2.250	5.500	1.750	7.000	171.887	366.092	35.943	346.671	171.887	502.035	2.898	307.830	65.074	123.336
	0.009		1.655	0.000	0.000	0.000	0.000	1.214	1.434	5.250	13.750	4.000	16.250	5.500	19.750	6.500	16.000	4.250	11.750	2.000	18.000	1.750	12.500	3.250	13.750	3.500	25.000	217.201	730.766	141.677	881.814	232.306	1093.281	292.726	866.709	156.782	605.927
VP-75A-LAB	0.007		1.287	0.920	0.287	1.471	1.287	1.011	1.453	1.750	3.250	1.750	4.500	2.000	5.750	1.750	3.750	1.000	2.250	1.500	2.250	1.375	1.900	1.750	2.750	1.250	2.625	35.943	152.466	35.943	249.569	55.364	346.671	35.943	191.307	22.318	74.784
	0.009		1.655	1.655	1.563	1.379	1.379	1.287	1.784	3.500	8.500	4.000	9.000	0.750	4.000	1.750	5.500	1.250	3.000	3.500	7.000	2.500	6.250	0.750	2.875	1.000	3.250	111.468	413.564	141.677	443.774	54.686	141.677	5.734	232.306	24.476	81.258
	0.010		1.839	1.637	1.618	0.000	0.000	1.591	1.337	2.375	15.200	0.900	14.150	2.700	13.175	1.750	17.750	2.075	8.425	1.225	9.950	1.125	7.725	1.450	7.125	1.150	10.725	29.146	726.536	51.060	669.440	46.819	616.422	4.840	865.198	12.833	358.129
	0.011		2.023	1.931	1.931	1.838	2.115	1.977	2.363	6.750	22.750	5.000	23.250	5.000	25.000	5.000	32.500	3.250	18.250	5.750	31.250	5.000	21.250	3.750	25.000	5.000	31.250	233.679	1024.623	147.170	1049.340	147.170	1135.850	147.170	1506.604	50.660	802.170
w/shims	0.011		2.023	1.839	1.747	1.287	2.483	1.655	2.207	3.750	23.000	5.000	24.000	2.500	27.500	7.000	29.750	3.500	15.500	3.000	12.750	2.500	11.250	3.500	17.500	5.500	24.250	85.377	1036.982	147.170	1086.416	23.585	1259.434	246.038	1370.661	73.019	666.227
w/shims	0.014		2.575	2.437	2.575	2.023	3.218	2.483	3.062	6.250	31.250	3.000	33.000	6.250	25.000	10.000	36.250	3.000	18.750	3.250	18.750	2.500	17.500	3.250	23.000	4.250	28.000	142.756	1113.781	16.523	1181.753	142.756	871.025	288.410	1307.986	16.523	628.268
VP-80-LAB	0.012		2.207	2.161	2.115	2.575	2.023	2.115	2.639	3.050		2.925		4.875		3.750		2.875		3.175		3.000		3.000		3.000		38.209		32.545		120.908				69.929		30.279
VIBCO-LAB	0.011		2.023	2.023	2.023	2.667	2.850	1.977	2.712	2.150		2.350		3.750		3.450		2.150		0.365		0.275		2.450		1.900		6.283		16.170		85.377		70.547		6.283	
	0.013		2.391	2.207	2.299	3.126	3.218	2.299	3.108	2.450		2.400		4.125		3.900		2.375		0.458		0.363		3.000		2.600		2.480		0.389		72.544		63.132		0.657	
	0.015		2.759	2.850	2.667	3.402	3.862	2.759	3.660	3.200		2.675		5.000		4.500		2.800		0.625		0.525		3.375		3.625		16.005		3.027		81.258		63.132		1.504	
	0.017		3.126	2.850	3.034	3.862	4.230	3.034	4.027	3.200		3.125		5.750		5.250		3.500		0.488		0.425		4.000		4.625		2.357		0.042		83.923		67.930		11.953	
	0.017		3.126	3.218	3.218	4.046	4.230	2.942	4.156	3.450		3.000		5.500		5.250		3.450		0.625		0.625		4.175		4.000		10.354		4.040		75.927		67.930		10.354	
	0.021		3.862	3.862	3.770	4.781	5.149	3.770	5.039	4.025		3.775		7.000		6.250		4.000		0.700		0.625		4.375		5.000		4.223		2.250		81.258		61.837		3.576	

GPO 858-561

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.