NASA Contractor Report 198208

Mass Properties Calibration of the NASA Langley Low Frequency Vibration Test Apparatus

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Contract NAS1-19000

September 1995

National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

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ABSTRACT

This report presents a description and calibration results of the modified NASA Langley Low Frequency Vibration Test Apparatus. The description includes both the suspension system and the data acquisition system. The test apparatus consists of a 2 inch thick 21 inch diameter aluminum plate that is suspended from an advanced suspension system using a 40 foot long cable system. The test apparatus employed three orthogonally aligned pairs of Sundstrand QA-700 servo accelerometers that can measure accelerations as low as 1 micro-g. The calibration involved deriving the mass and moments of inertia of the test platform from measured input forces and measured acceleration responses. The derived mass and moments were compared to test platform mass properties obtained initially from measurements with a special mass properties instrument. Results of the calibration tests showed that using the product of the test apparatus mass and the measured accelerations, the disturbance force at the center of gravity (CG) can be determined within 4 percent on all three axes. Similarly the disturbance moments about the X, Y, and Z axes can be determined within 5 percent by using the product of the measured moments of inertia and the angular accelerations about the X, Y, and Z axes.

ACKNOWLEDGEMENTS

This work was performed at the NASA Langley Research Center under contract NAS1-19000 as part of Work Order 089-CB003 administered by Mr. Joseph C. Moorman, Mr. George F. Lawrence, and Dr. Bernard L. Garrett of the Utilization and Analysis Branch. The authors thank Dr. Howard M. Adelman, Dr. Michael G. Gilbert, and Mr. Robert Miserentino of the Structural Dynamics Branch of NASA Langley Research Center for providing facility support and technical expertise in the development of the Low Frequency Vibration Test Apparatus. The authors also thank Mr. David G. Kessler and Mr. Otto C. Ripley of the Structures and Materials Research Support Branch for their assistance in the installation of the test apparatus.

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INTRODUCTION

To assess the acceleration environment it is necessary to measure various disturbance source devices used in microgravity science facilities. A low frequency vibration test apparatus was developed to measure forces and moments associated with these small disturbance devices such as pumps, fans, and camera motors. The test apparatus must be capable of measuring forces as low as several ten thousandths of a pound. In order to define forces and moments it is necessary to know the mass properties of the test apparatus. This report presents the results of the calibration of the mass and moment of inertia values of the test apparatus. Mass and moment of inertia values of the test apparatus were derived from the ratio of applied force to output accelerations. The mass of the test apparatus is equal to the ratio of the force and acceleration at a particular frequency. The moment of inertia of the test apparatus is equal to the ratio of the applied moment to the angular acceleration. The force was applied with an impact hammer. These derived values were compared with those mass and moment of inertia values obtained from a special mass property measuring instrument. The units of mass in this report are pounds and the corresponding units of moment of inertia are pound-inches^2. These units are used because the units of acceleration as measured by the accelerometers are gs. A 1 pound force accelerates a 1 pound mass 1g.

DESCRIPTION OF TEST APPARATUS

The test apparatus consists of a 21 inch diameter solid aluminum plate with a thickness of 1.94 inches that is suspended from a Zero Spring Rate Mechanism (ZSRM) advanced suspension system [ref 1]. Figure 1 shows a schematic of the test apparatus with the suspension system. The circular plate has a 1 inch thick solid aluminum trapezoid keel that is 8 inches high, and 10 inches long at the top where it attaches to the plate and 1.375 inches long at the bottom. The keel is mounted under the circular plate so that its length is parallel to the X axis and the centroid of the XY plane aligns with the centroid of the XY plane of the circular plate. The circular plate is supported by three eyebolts that are located 120 degrees apart at a radius of 10 inches from the plate center. One of the eyebolts is on the X axis. Three 0.25 inch diameter threaded zinc rods approximately 14 inches long with turnbuckles are connected to the eyebolts. The zinc rods have ends that hook into three clearance holes on the bottom of a 1 inch diameter, 1 inch long cylinder. The 1 inch cylinder is suspended with a ball joint connection to the Kevlar cable. The 40 foot long suspension system consists of an a 7.33 foot long, 3/32 inch diameter twisted steel cable connected to a readily available 32.75 foot long, 0.17 inch diameter Kevlar cable.

In addition to suspending the apparatus with the Z axis vertical as shown in Figure 1, several of the calibration tests were performed with the test apparatus suspended from the +X edge of the 21 inch diameter circular aluminum plate. Figure 2 shows a schematic of the test apparatus suspended with the X axis being vertical. The purpose was to determine if the X axis derived moment of inertia was affected by the triangular suspension mechanism.

The test apparatus has three pairs of Sundstrand QA-700 servo accelerometers [ref 2] that are matched with respect to amplitude and phase angle. Each accelerometer pair is aligned along the X, Y, or Z orthogonal axis. The X axis accelerometers are located near the YZ plane and are mounted in 1.5 inch cubic blocks that are bolted to the top of the circular plate at a radius of 8 inches. The Z axis accelerometers are located near the YZ plane and are also mounted in 1.5 inch cubic blocks that are bolted to the top of the circular plate at a radius of 8 inches. Both the X axis and Z axis accelerometer pairs are separated by a distance of 16 inches. Both Y axis accelerometers are located near the XZ plane and are mounted below the plate on 1.5 inch cubic blocks. The top Y axis accelerometer block is bolted to the bottom center of the circular plate. The keel has a center cutout to clear this accelerometer. The bottom Y axis accelerometer is mounted to the bottom of the keel and is separated from the top accelerometer by a distance of 8 inches. The accelerometers have the sensitivity to allow acceleration measurements to 1 micro-g. The acceleration spectra data of all six accelerometers are used to compute the six degrees-of-freedom rigid body motion of the test apparatus. Figures 3a, 3b, and 3c show the dimensions and details of the test apparatus and the locations of the accelerometers.

ACCELEROMETER DATA ACQUISITION SYSTEM

The signal processing equipment includes a Servo Accel 85 Signal Conditioner, a Precision Filters Model 416 Filter/Amplifier, and a GenRad GR 2515 Test System. Figure 4 shows a schematic of the data acquisition system. The accelerometers were powered by a ±15 volt dc power supply in the Servo Accel 85 that was fabricated by the Instrument Research Division of NASA Langley Research Center. Each pair of accelerometers was matched with respect to amplitude and phase angle. The accelerometers were calibrated with the signal passing through both the Servo Accel 85 and the Precision Filters Model 416. For accelerometer calibration, the signal was not amplified except for the accelerometer external resistors that are located in the Servo Accel 85 that are set to nominal output acceleration levels of 5.4 to 6 volts per g. Appendix A to this report shows the magnitude and phase angle comparison for each matched pair of accelerometers. Furthermore the Servo Accel 85 provides a reference voltage level for each accelerometer to eliminate any DC acceleration signal. For the Z axis accelerometers the offset voltage due to the gravitational force is approximately 5.5 volts.

The output signal from the Servo Accel 85 was fed into the Precision Filters Model 416. The Precision Filter consists of a prefilter amplifier, a low pass filter, and a post filter amplifier. For each test condition, two sets of data were acquired. The high frequency data set was necessary to obtain data over the frequency range of interest and the low frequency data set allowed high resolution at the low frequencies. The low frequency data set included frequencies ranging from 0 to 32 Hz and had a resolution of 0.06 Hz. The high frequency data set had a range of 0 to 256 Hz and had a resolution of 0.5 Hz. The Precision Filter low pass filter was set at 50 Hz for the low frequency measurements and 350 Hz for the high frequency measurements. For both the high and low frequency data the prefilter amplifier was set to 1 and the post filter amplifier was set to 10. In addition, the gain on the Servo Accel 85 was set to 10. Thus the output signal from the Precision Filter into the GenRad ranged from 540 to 600 volts per g. Thus for 1 micro-g, the voltage is 5.5e-04 volts or 0.5 millivolts.

The output signal from the Precision Filters Model 416 was routed to the GenRad GR 2515 Test System that employs a 12 bit analog to digital converter. Thus for a full scale value of 1 volt on the GenRad computer, the minimum voltage resolution is 2.5e-04 volts or 0.25 millivolts. However for 12 bit analog to digital converters, the last bit generally is not consistent, so that the minimum voltage that can be reliably obtained for a full scale value of 1 volt is 0.5 millivolts. The GenRad system allows simultaneous acquisition of the data from all six accelerometers.

MASS PROPERTIES INSTRUMENT MEASUREMENTS

Mass, center of gravity, and moments of inertia of the test apparatus were measured initially using the Space Electronics Mass Properties Instrument Model KSR1320-1500[ref 3]. The measurements were made on all three axes. The Kevlar and steel suspension cables were not included in the mass property measurements. At the beginning of each day of testing, the instrument was calibrated using a known set of masses that had known mass, CG location, and moment of inertia. The next step was to determine the mass property information for the hardware items used to support the test apparatus. A V block was installed, such that it was aligned with the X axis and centered about the center of the instrument table. The mass, CG, and moment of inertia of the V block were measured and recorded. For each setup orientation, the mass properties instrument measures CG in two directions and moment of inertia about one axis.

For the X axis moment of inertia measurements, the test apparatus was set on edge on the V block. A level was used to align the Y and Z axes parallel to the instrument table and the X axis perpendicular to the plane of the instrument table. The 21 inch diameter aluminum plate was centered in the V block such that the geometric center of the plate was at the center of the instrument table. Thus the Y axis and Z axis CG locations and the X axis moment of inertia are referenced to the centroid of the 21 inch diameter aluminum plate. For the Y axis moment of inertia measurement, the same V block was used and the test apparatus was rotated 90 degrees in the XY plane. Again the X and Z axes CG locations and the Y axis moment of inertia are referenced to the centroid of the 21 inch diameter aluminum plate.

To measure the Z axis moment of inertia, the test apparatus must be installed such that the Z axis of the test apparatus is perpendicular to the instrument table surface. A pair of heavy parallel support blocks were used as supports in place of the V block. These were placed on the instrument table along the Y axis and located equidistant from the center of the instrument table. A 2 inch thick parallel support bar was placed on top of each of these blocks to ensure that the keel of the test apparatus was clear of the instrument table when the apparatus was placed on the bars. The mass property data were taken with the blocks and bars mounted on the instrument table. This data was recorded for later use in correcting the measurements to obtain the mass properties of the test apparatus. The test apparatus was placed such that the X and Y axes of the apparatus were aligned with the X and Y axes of the instrument table and the center of the 21 inch diameter aluminum plate was over the center of the instrument table. Thus the measurements of the X and Y axes CG locations and the Z axis moment of inertia were referenced to the geometric centroid of the 21 inch diameter aluminum plate.

The results of the mass, CG , and moments of inertia measurements are summarized in Table I. The mass of the test apparatus is 74.40 pounds. Table I shows that for the test apparatus, the X axis and Y axis CG locations are within 0.02 inches of the geometric center of the plate. The CG location for the Z axis is 1.11 inches below the top surface of the 21 inch diameter aluminum plate. The moment of inertia about the X axis is 23 lb-in^2 greater than the moment of inertia about the Y axis. This is because of the orientation of the keel plate. The moment of inertia about the Z axis is almost 75 percent higher than the moment of inertia about either the X or Y axis. The mass and moment of inertia values presented in Table I were used as the reference values for the calibration of the test apparatus.

Because of the problem with the bottom Y axis accelerometer being affected by the 400 Hz natural frequency of the keel, the derived moment of inertia about the X axis did not initially agree with the measured value. The X axis moment of inertia was changed to evaluate the reason for the discrepancy between the measured and derived X axis moments of inertia. This change was accomplished by adding two matched 2 inch square by 3 inch tall steel blocks that have a mass of 3.638 pounds each including the attach bolts. These blocks were mounted to the top of the 21 inch diameter aluminum plate on opposite sides of the center at a radius of 8 inches at an angle of 45 degrees with respect to the X and Y axes. The edges of the blocks were parallel to the axes of the test apparatus. The addition of the blocks increased the mass from 74.4 pounds to 81.68 pounds. Because the blocks are on opposite sides of the center of the plate the CG on the X and Y axes remains at the center of the plate. However, the Z axis CG shifts from 1.115 inches below the top of the plate to 0.882 inches below the top of the plate. The moments of inertia of the blocks about the X, Y, and new Z axes of the test apparatus were calculated to be 281.95 lb-in^2, 281.95 lb-in^2, and 472.06 lb-in^2 respectively. The corresponding moments of inertia about the X, Y, and Z axes of the test apparatus with the steel blocks were 2485.8 lb-in^2 , 2508.3 lb-in^2, and 4339.1 lb-in^2

respectively. Table I also lists the mass and the moments of inertia of the test apparatus with the blocks installed.

INHERENT NATURAL FREQUENCIES OF TEST APPARATUS

There are several natural frequencies associated with the test apparatus suspension system. These include the pendulum swinging motion in the X and Y plane due to the suspension length from the ZSRM and the natural bounce in the Z direction due to the natural frequency of the ZSRM. There is also a torsion frequency about the Z axis. Finally, there is the natural frequency of the Kevlar cable in both the longitudinal or Z direction and the transverse direction or X and Y axes.

The pendulum swing of the test apparatus in both the X and Y directions was measured to be 0.15 Hz. This corresponds to the calculated frequency of 0.143 Hz that is computed from the suspension length (L) of 480 inches. The pendulum frequency is calculated as follows:

$$f = 1/(2\pi)\,(g/L)^{0.5} = 1/(2\pi) * (386/480)^{0.5} = 0.143 \text{ Hz.}$$

The natural frequency of the ZSRM in the Z direction was measured to be 0.30 Hz.

The torsion frequency about the Z axis was measured to be 0.05 Hz. This measured frequency is greater than the calculated torsion frequency of 0.009 Hz. This discrepancy is partially due to the assumption that the total suspension system is Kevlar and does not account for the fact that 20 percent of the suspension system is 3/32 inch diameter twisted steel cable. In addition, the increased stiffness introduced by the instrumentation cables also contributes to the difference between the measured and the calculated torsion frequencies. The computation is determined from the shear modulus elasticity of the Kevlar cable (G), the area moment of inertia of the Kevlar cable (K), the acceleration of gravity (g), the polar moment of inertia of the test apparatus about the Z axis ($J = I_{XX} + I_{YY}$), and the length of the suspension system (L) as follows:

$$f = 1/(2\pi)\,[(G * K * g)/(J * L)]^{0.5}$$

where $K = \pi/2 * (d/2)^4 = \pi/2 * (0.17/2)^4 = 8.2000*10^{-5}$ in^4,
$G = 2.54*10^5$ lb/in^2, $g = 386$ in/s^2, $L = 480$ in, and $J = 4430.2$ lb-in^2.

$$f = 1/(2\pi)\,[(2.54*10^5 * 8.200*10^{-5} * 386)/(4430.2 * 480)]^{0.5} = 0.009 \text{ Hz}$$

The natural frequency of the Kevlar cable in the longitudinal or Z direction was calculated to be 8.6 Hz. This was computed from the equation of a beam under tension that is determined from the cross sectional area (A), the modulus of elasticity (E), the weight of the test apparatus (W), and the length of the suspension system (L) as follows:

$$f = 1/(2\pi)\,[\,(A * E * g)/(W * L)\,]^{0.5}$$

where $A = \pi/4\ (0.17)^2\ in^2$, $E = 12{*}10^6\ lb/in^2$, $g = 386\ in/s^2$, $W = 74.4$ lb, and $L = 480$ in.

$$f = 1/(2\pi)\,[\,(0.0227 * 12{*}10^6 * 386)\,/\,(74.4 * 480)\,]^{0.5} = 8.64\ Hz.$$

We did not observe evidence of this natural frequency in the measurements.

The natural frequency of the Kevlar cable in the transverse directions or X and Y directions was calculated to be 4.0 Hz. Measurements showed that the suspension cable had a natural transverse frequency of 5 Hz in both the X and Y axes. The transverse natural frequency was computed from the equation of a string under tension that is fixed at both ends. This calculation was based on the total length and mass of the suspension cables, Kevlar and steel. The equation is dependent on the tension in the cable (T), the weight of the cable (W_K), and the length of the Kevlar cable (L_K) as follows:

$$f = 1/2 * [\,(T * g)/(W_K * L_K)\,]^{0.5}$$

where $T = 74.4$ lb, $g = 386\ in/s^2$, $W_K = 0.926$ lb, and $L_K = 480$ in.

$$f = 1/2 * [\,(74.4 * 386)/(0.926 * 480)\,]^{0.5} = 4.02\ Hz.$$

The natural frequencies associated with the test apparatus will be taken into consideration in the analysis of test data. The natural frequencies of the test apparatus will change slightly due to the change in mass and moments of inertia of the system when test article and interface components are installed.

TEST PROCEDURE

The acceleration in the three translational directions (X, Y, and Z) and the three rotational directions (R_X, R_Y, and R_Z) were computed from the six servo accelerometers placed on the apparatus [ref 4]. In the frequency bandwidth of interest, 0 to 256 Hz, the test apparatus behaves as a rigid body. The measurements from the six servo accelerometers were used to determine the rigid body motion of the test apparatus at each spectral line of data in the frequency bandwidth of interest. For most of the tests the test apparatus was suspended from the Kevlar cable with the Z axis vertical. However some of the tests were conducted with the test apparatus suspended with the X axis vertical. Figures 1 and 2 show these configurations.

The testing was conducted by using a small impact force hammer capable of generating a force spectrum that is relatively flat over the range of frequencies from 2 Hz to 256 Hz. For this calibration the effective mass and moments of inertia of the test apparatus were evaluated from measured force and acceleration data. A PCB Model 086B03 modally tuned impact hammer was used to apply forces and moments to the test apparatus. Tests 1, 2, and 5 employed an electromagnetic shaker that operated at a frequency of 10 Hz. The accelerometer responses were measured using the six accelerometers on the test apparatus. It is important to note that the X and Y axes accelerometers are aligned such that the signals are 180 degrees out of phase. Four different locations were selected for the force hammer impacts. For each case, the impact was repeated five times and the impact forces and acceleration responses were averaged.

The first point selected for impact was on the top surface of the 21 inch diameter aluminum plate along the -Y axis 5.5 inches from the center of the plate. Figure 5a shows the location of impact force hammer point 1. The impact was in the -Z direction. This resulted in a force applied in the Z direction and a moment about the X axis. The masses of the test apparatus, with and without the steel blocks, were derived from the ratio of the input forces to the Z axis accelerations at the CG. The input moment about the X axis is equal to the product of the impact hammer force and the distance from the X axis that was 5.5 inches. The X axis moments of inertia of the test apparatus were derived from the ratio of the input moments and the angular accelerations about the X axis.

The second point selected was on the top surface of the 21 inch diameter aluminum plate along the +X axis 5.5 inches from the center of the plate. Figure 5a shows the location of impact force hammer point 2. The impact was in the -Z direction, resulting in a force applied in the Z direction and a moment about the Y axis. The masses of the test apparatus, with and without the steel blocks, were derived from the ratio of the input force to the Z axis acceleration at the CG. The input moment about the Y axis is equal to the product of the impact hammer force and the distance from the Y axis which is 5.5 inches. The Y axis moments of inertia of the test apparatus were derived from the ratio of the input moments and the angular accelerations about the Y axis.

The third point of application of the impact force hammer was on the +X side of the 21 inch diameter aluminum plate in the XZ plane. It was located 1 inch from the top of the plate, which is the location of the Z axis CG. Figure 5b shows the location of impact force hammer point 3. The impact was in the -X direction. Since this impact force was applied in the X direction very close to the CG of the test apparatus, the moment about the Y axis is negligible. The masses of the test apparatus, with and without the steel blocks, were derived from the ratio of the applied forces to the X axis accelerations at the CG.

The fourth point of force application was underneath the test apparatus on the keel. It was applied in the Y direction at a distance of 4.5 inches from the XZ plane and 1.0 inches from the bottom of the 21 inch diameter aluminum plate. Figure 5c shows the location of impact force hammer point 4. Because the keel thickness is 1 inch, the force was applied 0.5 inches from the YZ plane. It should be noted that with the steel blocks the distances of the Y axis accelerometers from the CG are 1.81 inches and 9.81 inches respectively. The effective masses of the test apparatus, with and without the steel blocks, were derived from the ratio of the applied forces to the Y axis accelerations at the CG. The input moment about the Z axis is equal to the product of the impact hammer force and the distance from the Z axis which is 4.5 inches. The Z axis moments of inertia were derived from the ratio of the input moments and the angular accelerations about the Z axis.

CALIBRATION TEST RESULTS

To define the force and moment of inertia on each of the three orthogonal axes, 23 tests were conducted using the procedures described above. Each test was performed by applying a force at one of the four impact points, which resulted in an applied force along one of the axes and an applied moment about one or more axes. The force calibration and the moment calibration are discussed separately in the following sections. The complete test data set for the calibration tests are presented in Appendix B of this report.

Force Calibration

The force calibration involves deriving a mass of the test apparatus from the ratio of the applied force in the X, Y, or Z direction to the acceleration at the CG as measured by the respective X, Y, or Z axis pair of accelerometers. This derived mass is then compared to the measured mass presented in Table II. Table II presents a test summary including the test number, the test point location, the suspension axis, the applied force axis, the measured mass, the test force, the average acceleration response, the derived test apparatus mass, and the percent difference between the measured and derived masses. The table is divided into three sections, one for each of the three axes. The measured mass of the test apparatus without the steel blocks is 74.4 pounds and the measured mass with the steel blocks is 81.68 pounds.

Of the 23 tests, 13 of the tests involved applying a force parallel to the Z axis. The force was applied at points 1 and 2. Four of these 13 tests involved adding extra steel blocks to change the mass properties. Also four of these tests involved suspending the apparatus with the X axis vertical rather than the Z axis vertical as is normally done. The test results for the Z axis force calibration show that the average test apparatus masses as derived from the force to acceleration ratio were 1.6 percent less than the measured masses of the test apparatus. The largest discrepancy was -7.8 percent. It should be noted that there is no discrepancy between the impact hammer data and the 10 Hz shaker data obtained in test 5.

The next series of tests shown in Table II are for the X axis. Here the force was applied at point 3. Two of the five tests were conducted with the extra steel blocks. Also two of the five tests were performed with the test apparatus being suspended with the +X axis vertical. The test results show that for the X axis the derived masses of the test apparatus average 3.36 percent less than the measured test apparatus masses. The largest discrepancy was -5.3 percent.

The last series of tests shown in Table II are for the Y axis. Here the force was applied at point 4. Again two of the five tests were conducted with the extra steel blocks and two of the five tests were performed with the test apparatus being suspended with the +X axis vertical. The test results showed that for the Y axis the derived masses of the test apparatus average 0.70 percent more than the measured test apparatus masses. The largest discrepancy was +8.8 percent.

Results of the force calibration tests show that for all three axes, the differences between the average derived masses and the measured masses were less than 4 percent. This 4 percent discrepancy indicates that the procedure used to compute the translational mass properties is accurate. Therefore it is recommended that for this test apparatus, the measured masses be used to compute the applied forces from the acceleration responses for all three axes.

Moment Calibration

The moment calibration involves computing a moment from the applied force and the associated distance from the axis of rotation. This applied moment was then divided by the angular acceleration about the axis of rotation to obtain a derived moment of inertia of the test apparatus. The derived moments of inertia were then compared to the measured moments of inertia that were obtained using the Space Electronics mass properties instrument. Table III presents a test summary including the test number, the test point location, the suspension axis, the axis for the moment of inertia, the measured moment of inertia, the applied moment, the average acceleration response, the derived test apparatus moment of inertia, and the percent difference between the derived and measured moments of inertia. Table III is divided into three sections, one for each of the three axes.

Eight of the tests involved deriving the moment of inertia about the X axis. Two of the tests involved changing the test apparatus moment of inertia by adding the extra steel blocks. The effect of changing the suspension axis was investigated by switching the vertical axis from Z to X. Two of the tests involved suspending the apparatus from the +X axis. The measured test apparatus X axis moment of inertia is 2203.9 lb-in^2 or the calculated moment of inertia with the steel blocks is 2485.8 lb-in^2. Initial test results presented in Table III show that the average derived X axis moment of inertia is 18.2 percent less than the measured moment of inertia. Table III shows that there is no discrepancy between the tests with the vertical Z axis suspension and tests 15 and 19 that had the vertical X axis suspension. The source of underestimating the X moment of inertia by 18 percent was identified. The residual effect of the 400 Hz first bending mode of the keel was being measured by the Y axis accelerometer at the tip of the keel in the frequency range of 0 to 256 Hz. This residual response was observed as an apparent increase in the angular acceleration about the X axis. As previously stated, the moment of inertia was derived from the ratio of the applied moment to the angular acceleration. Thus an apparent increase in the angular acceleration will result in an underestimation of the moment of inertia. The X axis angular acceleration was adjusted by removing the residual effect of the keel bending mode from the acceleration of the bottom Y accelerometer. The resultant discrepancy between the derived and measured moment of inertia was -5.2 percent. It should be noted that this residual effect decreases as the measured frequency decreases from the 400 Hz. Adjusting the bottom Y measured acceleration for this residual effect had minimal effect on the Y translational acceleration at the CG, because of the proximity of the bottom Y accelerometer to the CG relative to the proximity of the top Y accelerometer.

The next series of tests shown in Table III are for the moment of inertia about the Y axis. The impact force was applied at point 2. Two of the five tests were conducted with the extra steel blocks. Also two of the five tests were performed with the test apparatus being suspended with the +X axis vertical. The measured test apparatus Y axis moment of inertia is 2226.3 lb-in^2 or the calculated moment of inertia with the steel blocks is 2508.3 lb-in^2. The test results show that for the Y axis, the derived moments of inertia of the test apparatus average 2.88 percent less than the measured test apparatus moments of inertia. The largest discrepancy was -8.6 percent.

The last series of tests shown in Table III are for the moment of inertia about the Z axis. The impact force was applied at point 4. Again, two of the five tests were conducted with the extra steel blocks. Also, two of the five tests were performed with the test apparatus being suspended with the +X axis vertical. The measured test apparatus Z axis moment of inertia is 3867.0 lb-in^2 or the calculated moment of inertia with the steel blocks is 4339.1 lb-in^2. The test results show that for the Z axis, the derived moments of inertia of the test apparatus average 4.04 percent more than the measured test apparatus moments of inertia. The largest discrepancy was 5.8 percent.

CONCLUSIONS

The product of the measured mass of the test apparatus and the average translational acceleration at the CG will result in computed disturbance forces at the CG that are accurate to within 4 percent for all three axes. The product of the test apparatus measured moments of inertia and the computed angular accelerations resulted in disturbance moments acting on the Y and Z axes that are accurate to within 4 percent. The product of the test apparatus measured moment of inertia of the X axis and the corrected Y axis computed angular accelerations resulted in disturbance moments acting on the X axis that are accurate within 5.2 percent. Adjusting the bottom Y axis accelerometer for the residual effects of the first bending moment of the keel had minimal effect on the translational acceleration at the CG. This is because of the close proximity of the top Y axis accelerometer to the CG relative to the bottom Y axis accelerometer.

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TABLE I

SUMMARY OF MOMENTS OF INERTIA OF TEST APPARATUS

	TEST APPARATUS ONLY	TEST APPARATUS WITH BLOCKS
WEIGHT, LB	74.40	81.17
CG-X, IN	-0.0166	-0.0166
CG-Y, IN	+0.0092	+0.0092
CG-Z, IN	-1.1145	-0.8816
IXX, LB-IN^2	2203.9	2485.8
IYY, LB-IN^2	2226.3	2508.3
IZZ, LB-IN^2	3867.02	4339.1

NOTE: Test Apparatus Only Column contains data measured with the Space Electronics Mass Properties Instrument Model KSR1320-1500.

Test Apparatus With Blocks column contains summation of calculated block mass and moment of inertia data added to the test apparatus data.

TABLE II
FORCE CALIBRATION DATA

TEST NUMBER	TEST POINT POSITION	APPARATUS SUSPENSION AXIS	MASS REFERENCE AXIS	REFERENCE MASS LBS	FORCE APPLIED LBS	MEASURED ACCEL G'S	CALC. MASS FORCE/ACCEL LBS	PERCENT MASS DIFFERENCE
						Z AXIS		
4	1	Z	Z	74.4	0.017	2.37E-04	71.7	-3.6
5	1	Z	Z	74.4	0.03	4.12E-04	72.8	-2.1
6	1	Z	Z	74.4	0.014	1.94E-04	72.2	-3
7	1	Z	Z	74.4	0.012	1.71E-04	70.2	-5.7
11	1	Z	Z	81.68	0.016	2.06E-04	77.7	-4.9
15	1	X	Z	81.68	0.018	2.24E-04	80.4	-1.6
19	1	X	Z	74.4	0.013	1.83E-04	71	-4.5
23	1	Z	Z	74.4	0.014	2.04E-04	68.6	-7.8
8	2	Z	Z	74.4	0.013	1.72E-04	75.6	1.6
12	2	Z	Z	81.68	0.015	1.76E-04	85.2	4.3
16	2	X	Z	81.68	0.017	2.05E-04	82.9	1.5
20	2	X	Z	74.4	0.015	1.97E-04	76.1	2.3
24	2	Z	Z	74.4	0.013	1.72E-04	75.6	1.6
					AVERAGE PERCENT DIFFERENCE			-1.68
						X AXIS		
10	3	Z	X	74.4	0.02	2.78E-04	71.9	-3.3
14	3	Z	X	81.675	0.021	2.60E-04	80.8	-1.1
18	3	X	X	81.675	0.015	1.94E-04	77.3	-5.3
22	3	X	X	74.4	0.018	2.49E-04	72.3	-2.8
26	3	Z	X	74.4	0.024	3.37E-04	71.2	-4.3
					AVERAGE PERCENT DIFFERENCE			-3.36
						Y AXIS		
9	4	Z	Y	74.4	0.02	2.47E-04	81	8.8
13	4	Z	Y	81.675	0.021	2.62E-04	80.2	-1.9
17	4	X	Y	81.675	0.019	2.39E-04	79.5	-2.7
21	4	X	Y	74.4	0.018	2.46E-04	73.2	-1.7
25	4	Z	Y	74.4	0.023	3.06E-04	75.2	1
					AVERAGE PERCENT DIFFERENCE			0.7

NOTE: All tests except Test 5 performed with an impact force hammer and data evaluated at frequency of 250 Hz.
Test 5 performed with minishaker at frequency of 10 Hz.

TABLE III
MOMENT CALIBRATION DATA

TEST NUMBER	TEST POINT POSITION	APPARATUS SUSPENSION AXIS	AXIS OF MOMENT OF INERTIA	REFERENCE MOM. OF INERT. LB IN^2	MOMENT APPLIED IN. LBS	MEASURED DIFFERENCE IN ACCEL - G'S	MOMENT * DIST/ACCEL LB IN^2	PERCENT DIFFERENCE IN MOI
						Y AXIS	DIST = 8 IN	
4	1	Z	X	2203.9	0.0956	3.88E-03	1971.7	-10.5
5	1	Z	X	2203.9	0.1688	6.50E-04	2075.7	-5.8
6	1	Z	X	2203.9	0.0788	3.60E-04	1750	-20.6
7	1	Z	X	2203.9	0.0675	3.10E-04	1739.7	-21
11	1	Z	X	2485.8	0.09	3.85E-04	1871.1	-25
15	1	X	X	2485.8	0.1013	3.98E-04	2033.1	-18.5
19	1	X	X	2203.9	0.0731	3.35E-04	1745.2	-20.8
23	1	Z	X	2203.9	0.0788	3.73E-04	1689.9	-23.3
					AVERAGE PERCENT DIFFERENCE			-18.2
						Z AXIS	DIST = 16 IN	
8	2	Z	Y	2226.3	0.0731	5.33E-04	2196	-1.4
12	2	Z	Y	2508.3	0.0844	5.87E-04	2299.1	-8.6
16	2	X	Y	2508.3	0.0956	6.34E-04	2414.8	-4
20	2	X	Y	2226.3	0.0844	6.19E-04	2180.2	-2.1
24	2	Z	Y	2226.3	0.0731	5.17E-04	2263.9	1.7
					AVERAGE PERCENT DIFFERENCE			-2.88
						X AXIS	DIST = 16 IN	
9	4	Z	Z	3867	0.09	3.52E-04	4090.9	5.8
13	4	Z	Z	4339.1	0.0945	3.30E-04	4587.4	5.8
17	4	X	Z	4339.1	0.0855	3.10E-04	4407.2	1.6
21	4	X	Z	3867	0.081	3.23E-04	4009.9	3.7
25	4	Z	Z	3867	0.1035	4.14E-04	3996.1	3.3
					AVERAGE PERCENT DIFFERENCE			4.04

NOTE: All tests except Test 5 performed with an impact force hammer and data evaluated at frequency of 250 Hz.
Test 5 performed with minishaker at frequency of 10 Hz.

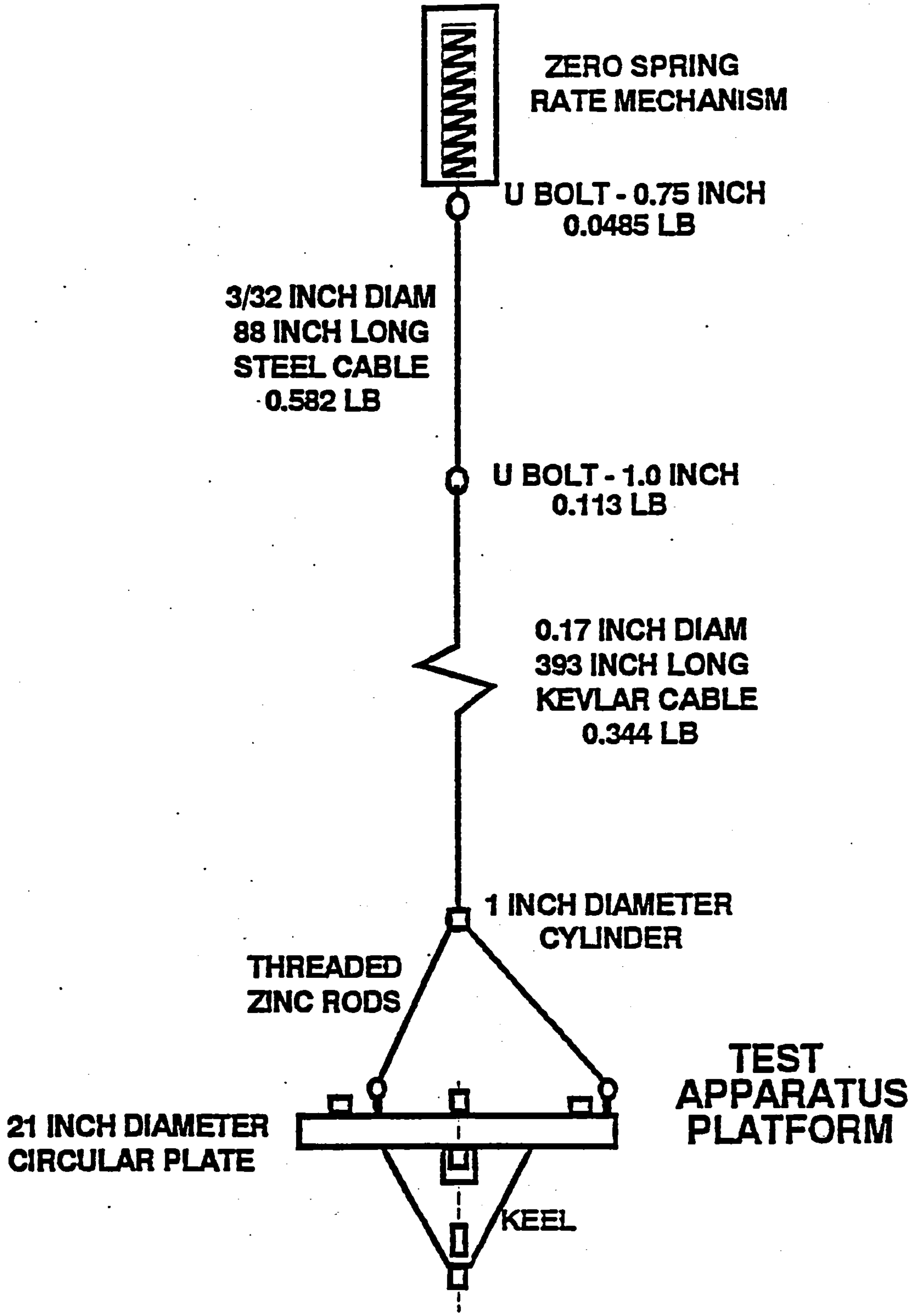


Figure 1. - Schematic of Test Apparatus Suspension System for Normal Operation

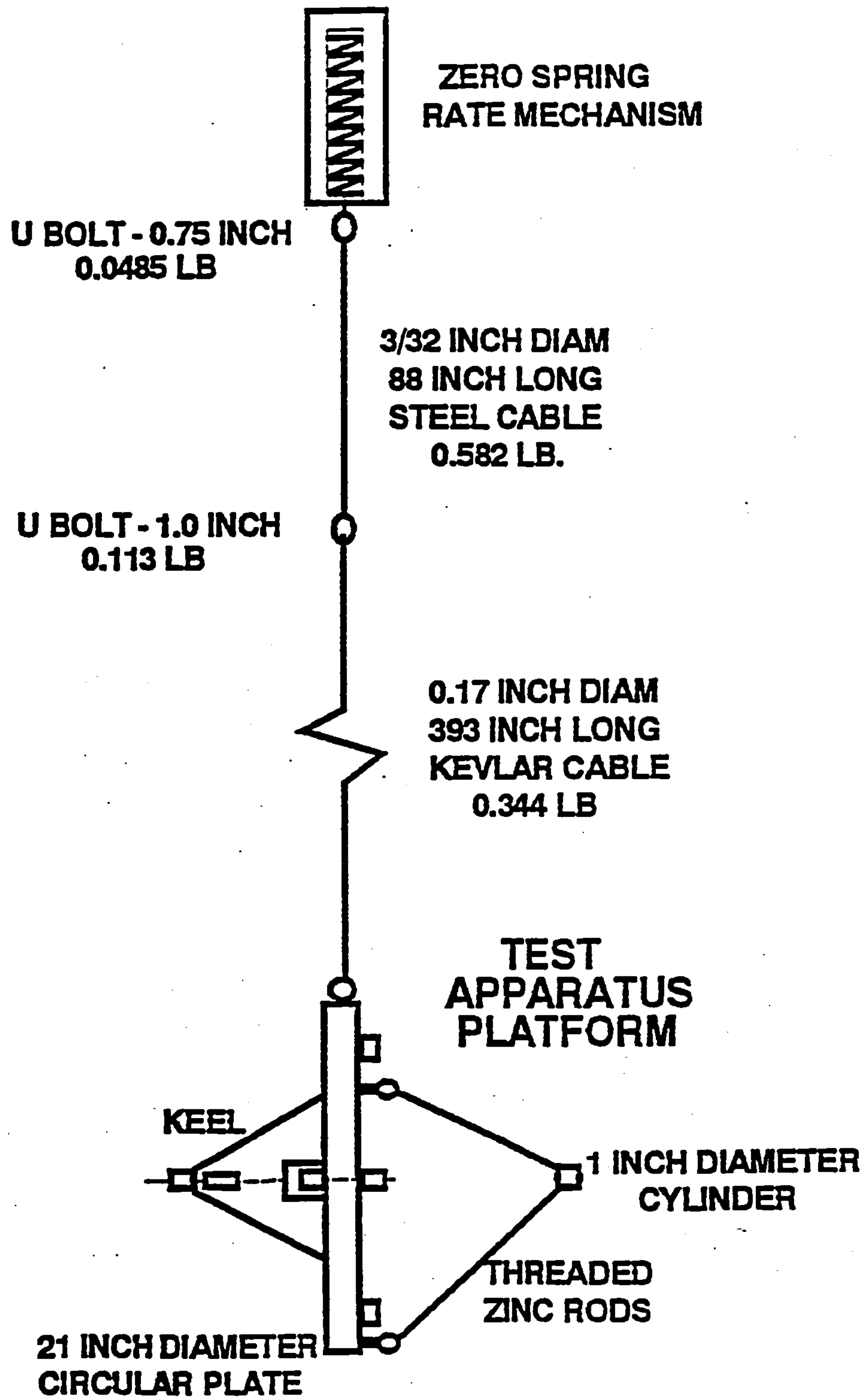


Figure 2. - Schematic of Test Apparatus Suspension System with X Axis Vertical

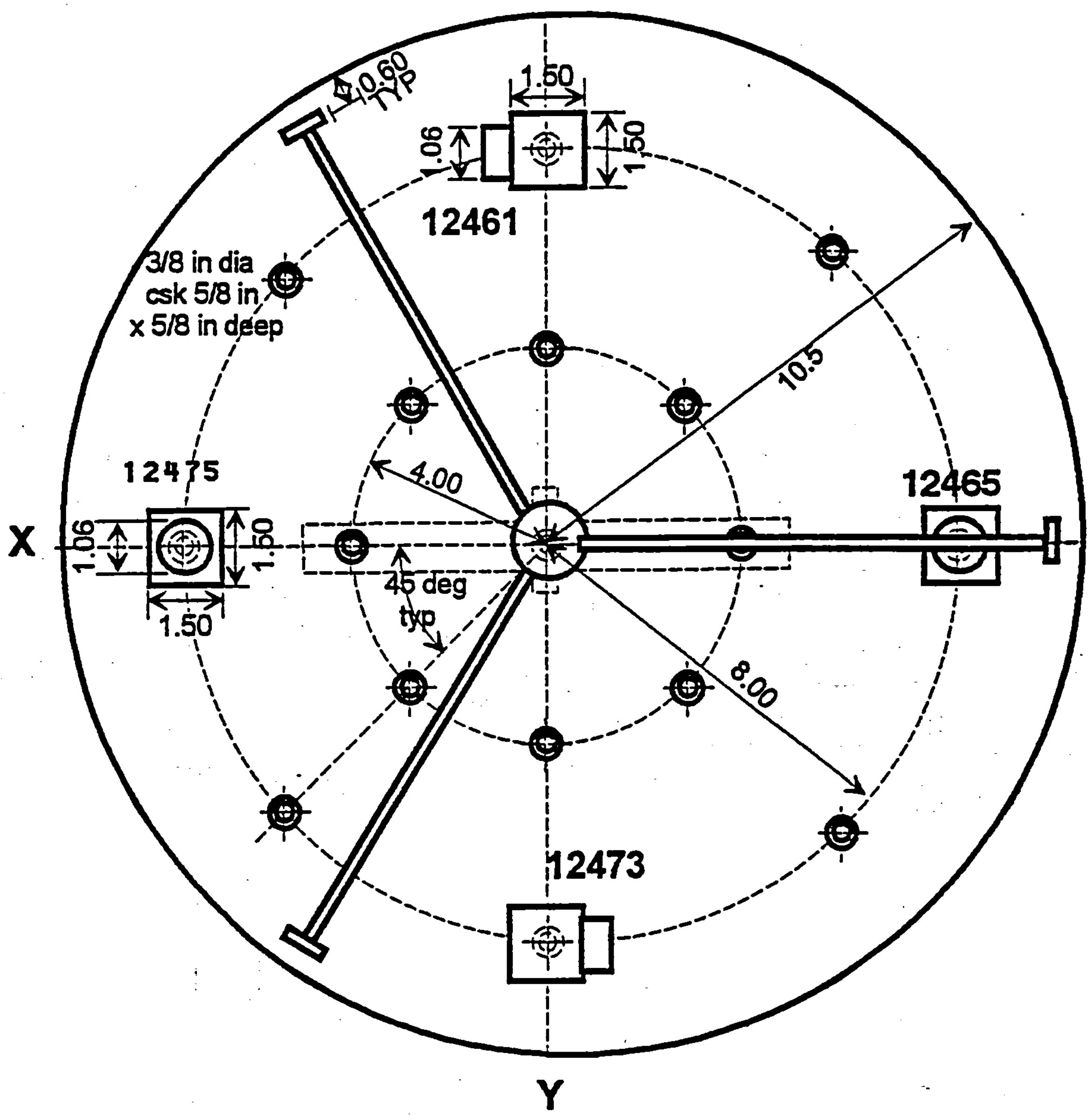


Figure 3. - Detailed Drawing of Test Apparatus Platform with Accelerometers
a. Top View - XY Plane

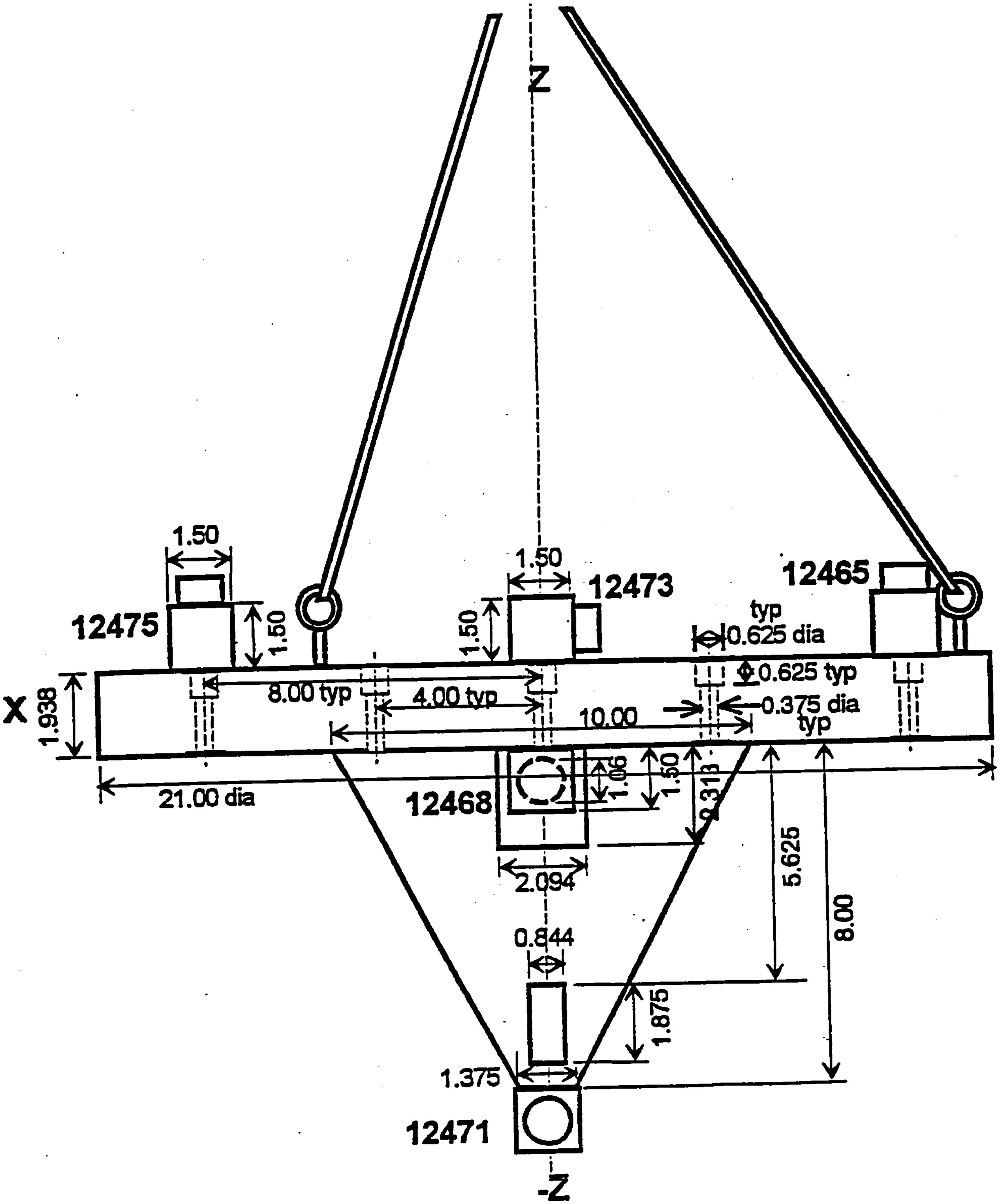


Figure 3. - Detailed Drawing of Test Apparatus Platform with Accelerometers
b. Side View - XZ Plane

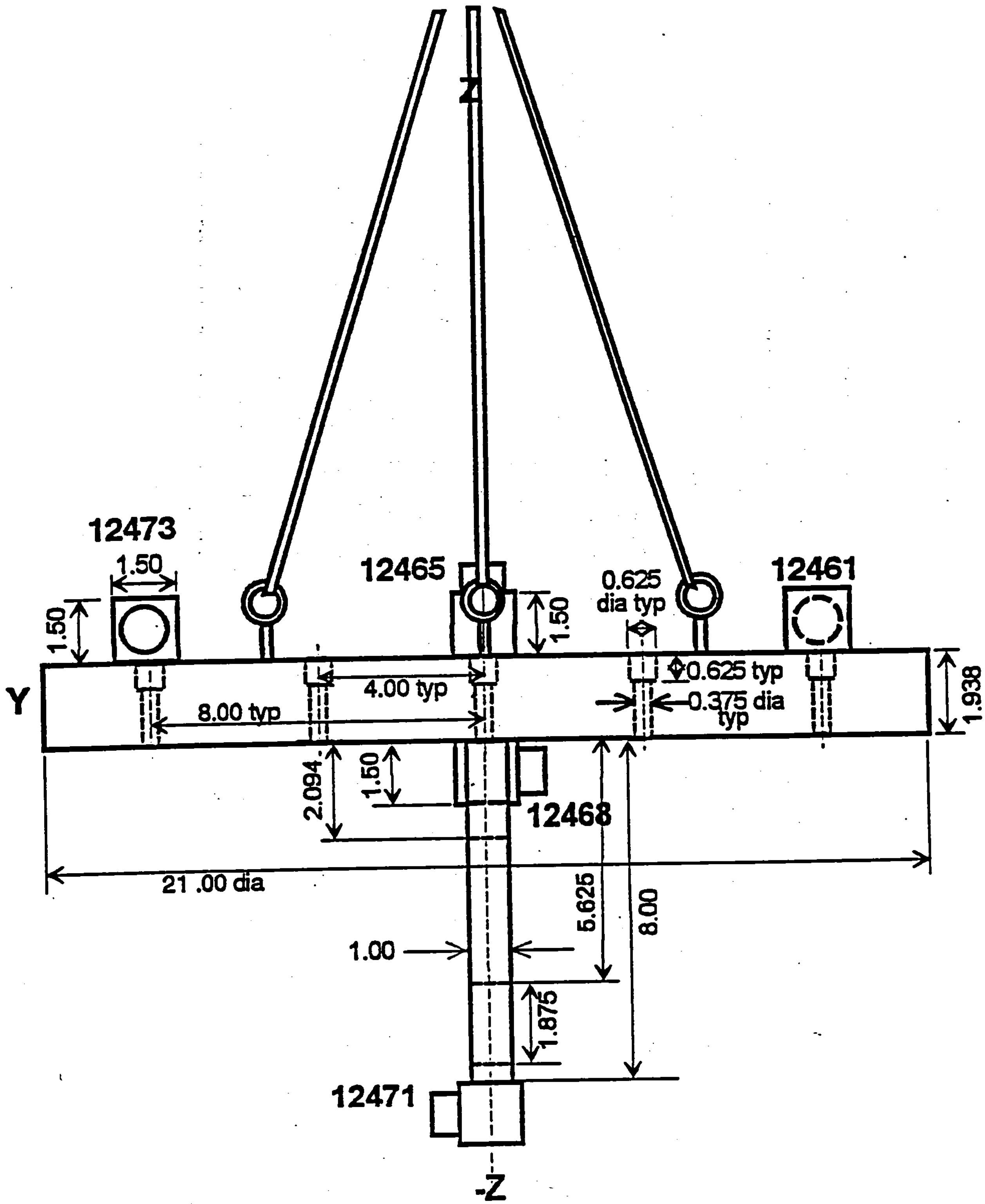


Figure 3. - Detailed Drawing of Test Apparatus Platform with Accelerometers
c. Side View - YZ Plane

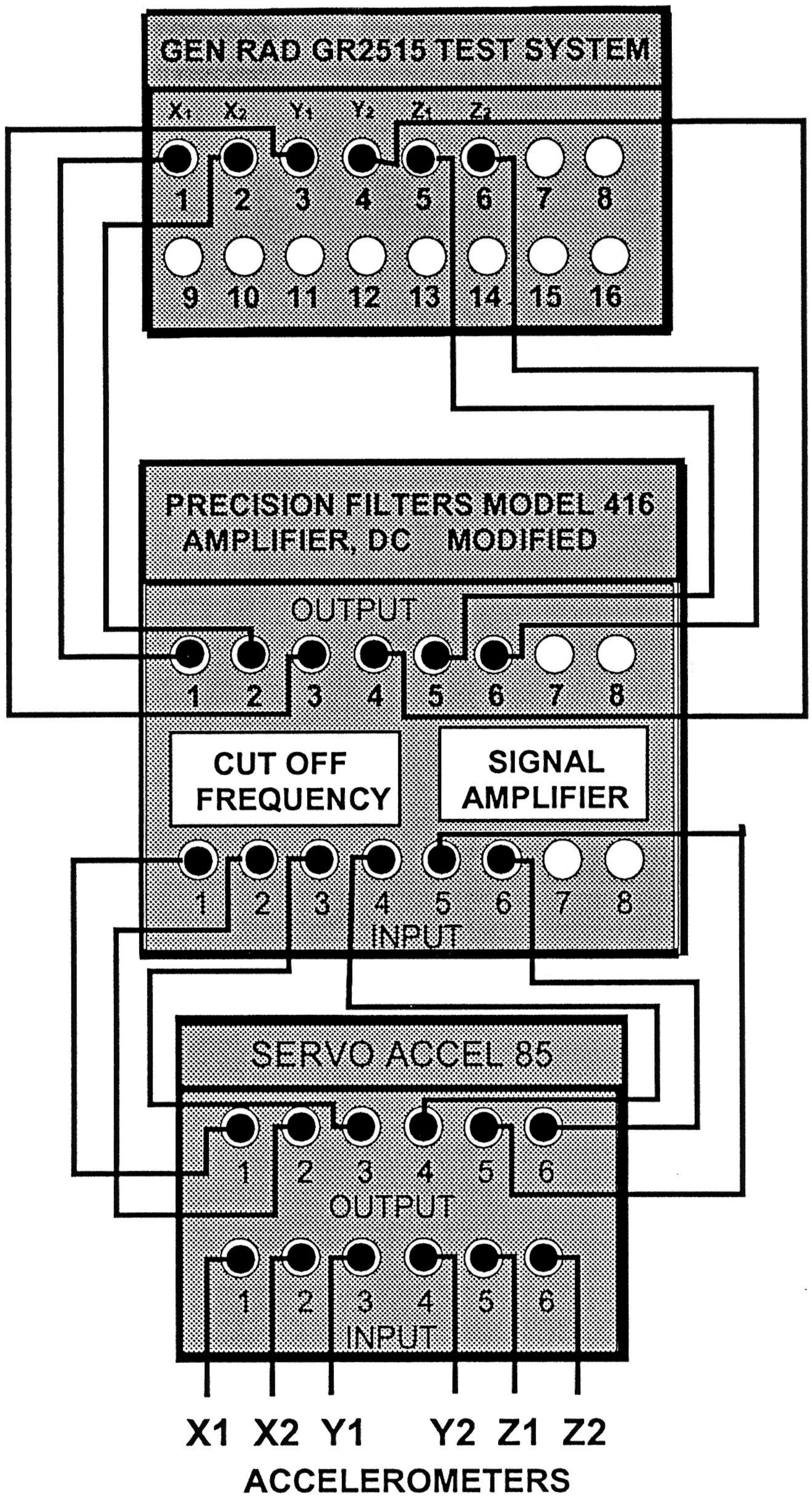


Figure 4. - Schematic of Accelerometer Data Acquisition System

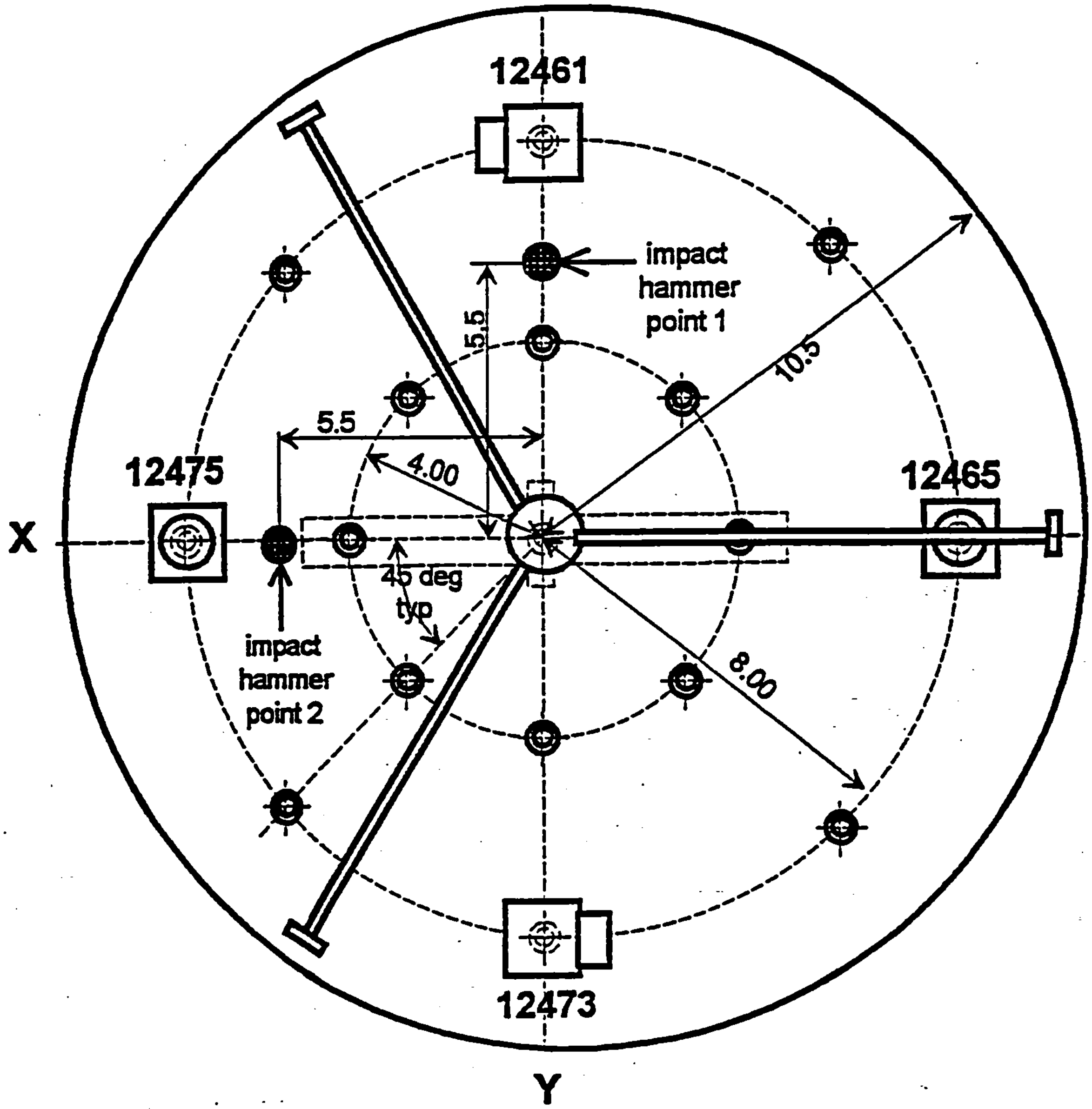


Figure 5.– Location of Force Application Points for Impact Hammer
a. Top View of Test Apparatus Showing Points 1 and 2

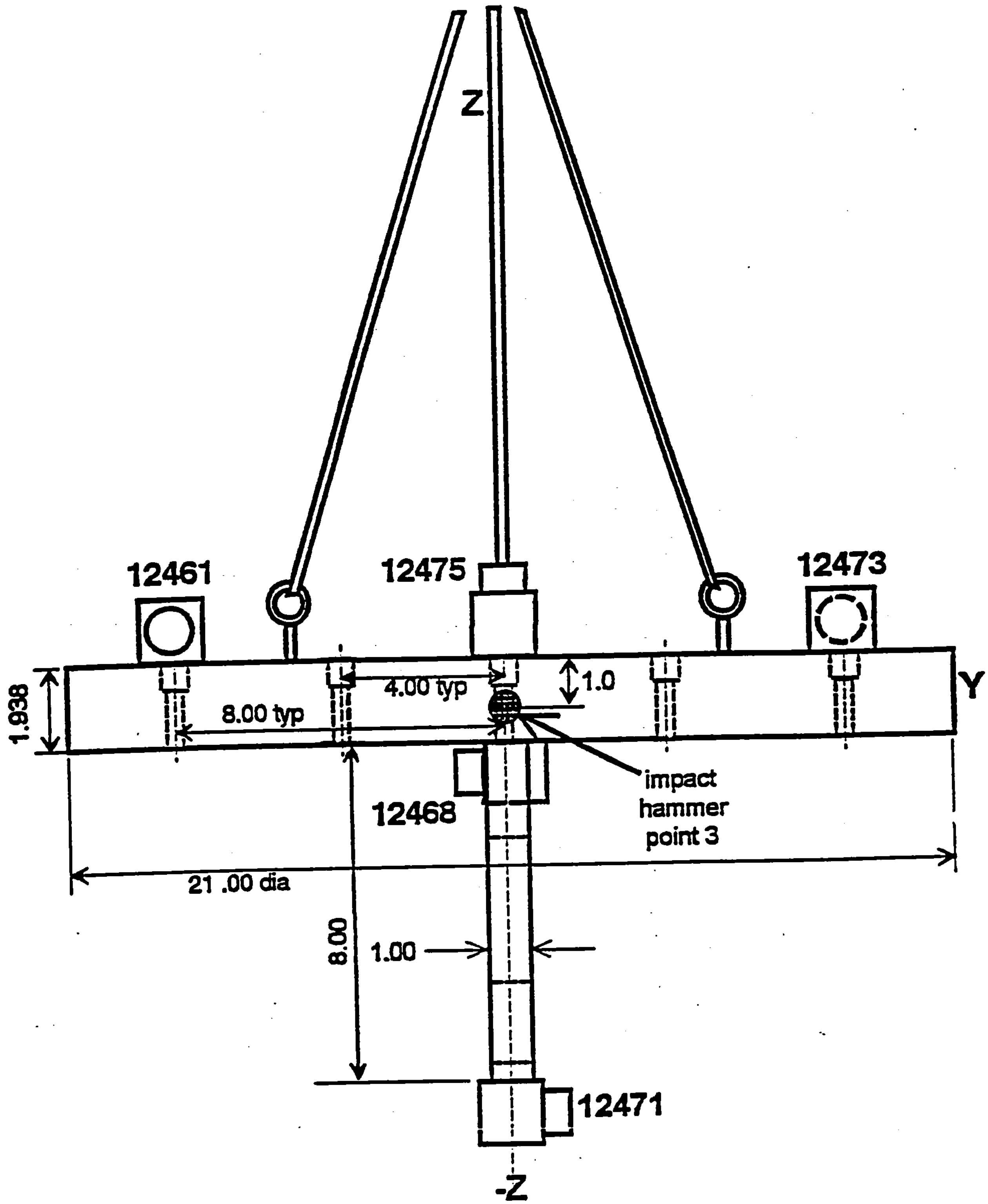


Figure 5. - Location of Force Application Points for Impact Hammer
b. Side View of Test Apparatus Showing Point 3

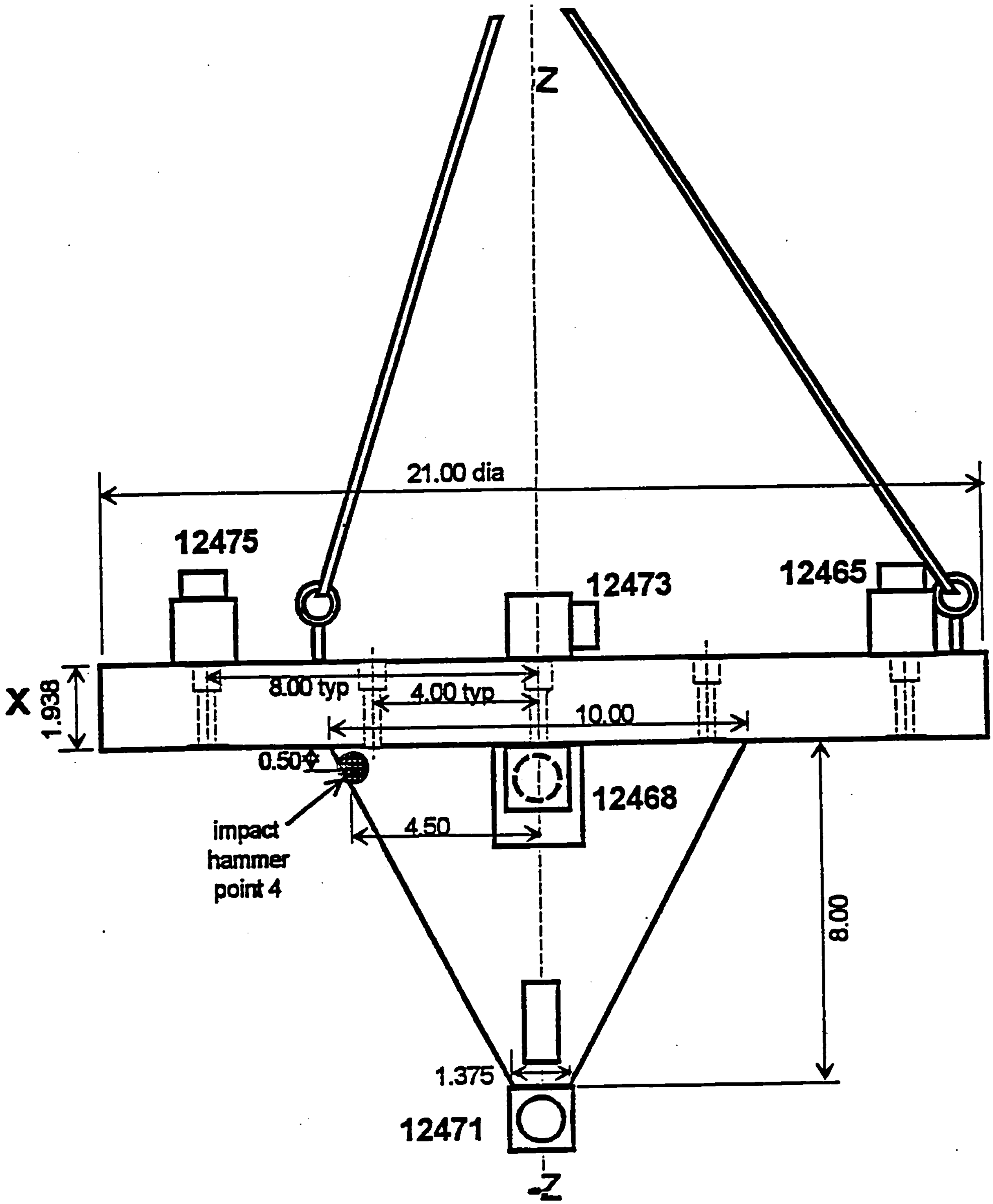


Figure 5. - Location of Force Application Points for Impact Hammer
c. Side View of Test Apparatus Showing Point 4

APPENDIX A

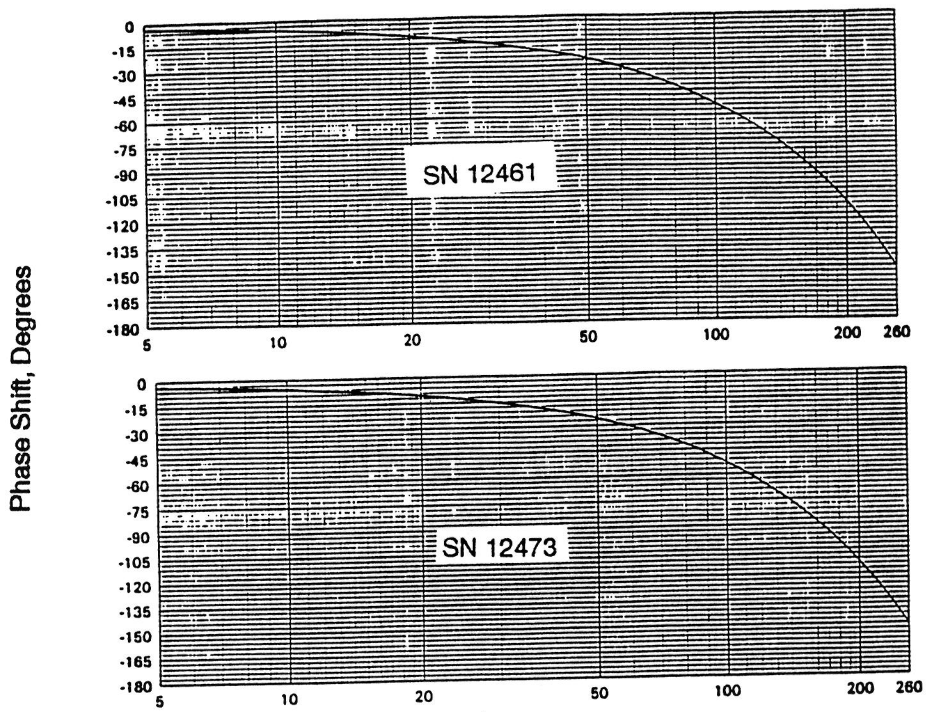
ACCELEROMETER CALIBRATION TEST RESULTS

FOR

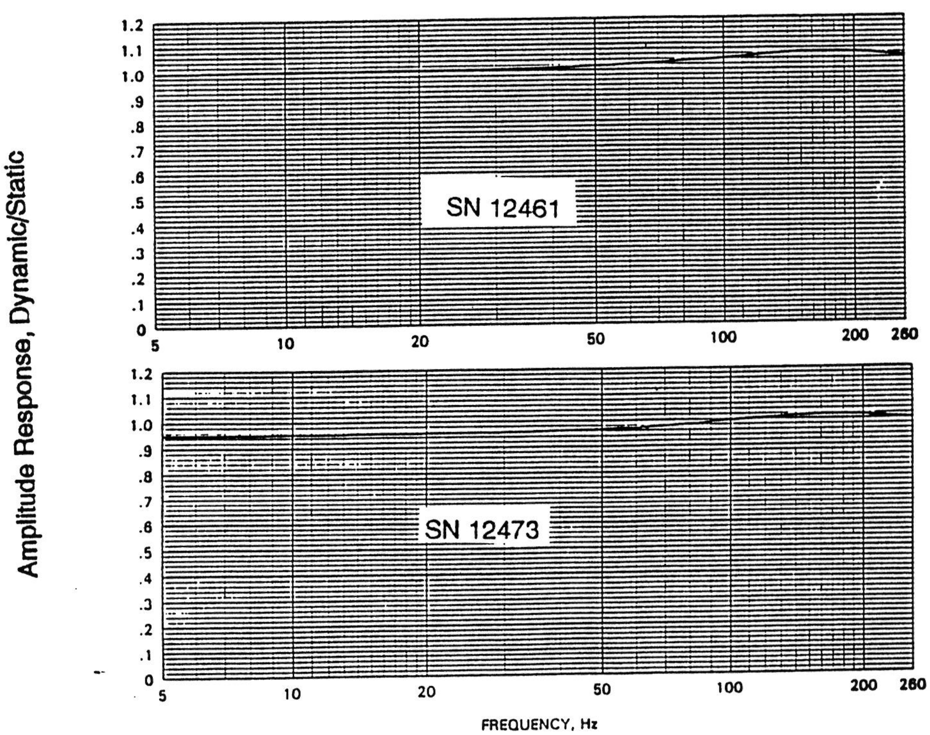
NASA LANGLEY LOW FREQUENCY VIBRATION TEST APPARATUS

COMPARISON OF PHASE ANGLE AND AMPLITUDE CALIBRATIONS FOR X AXIS ACCELEROMETERS

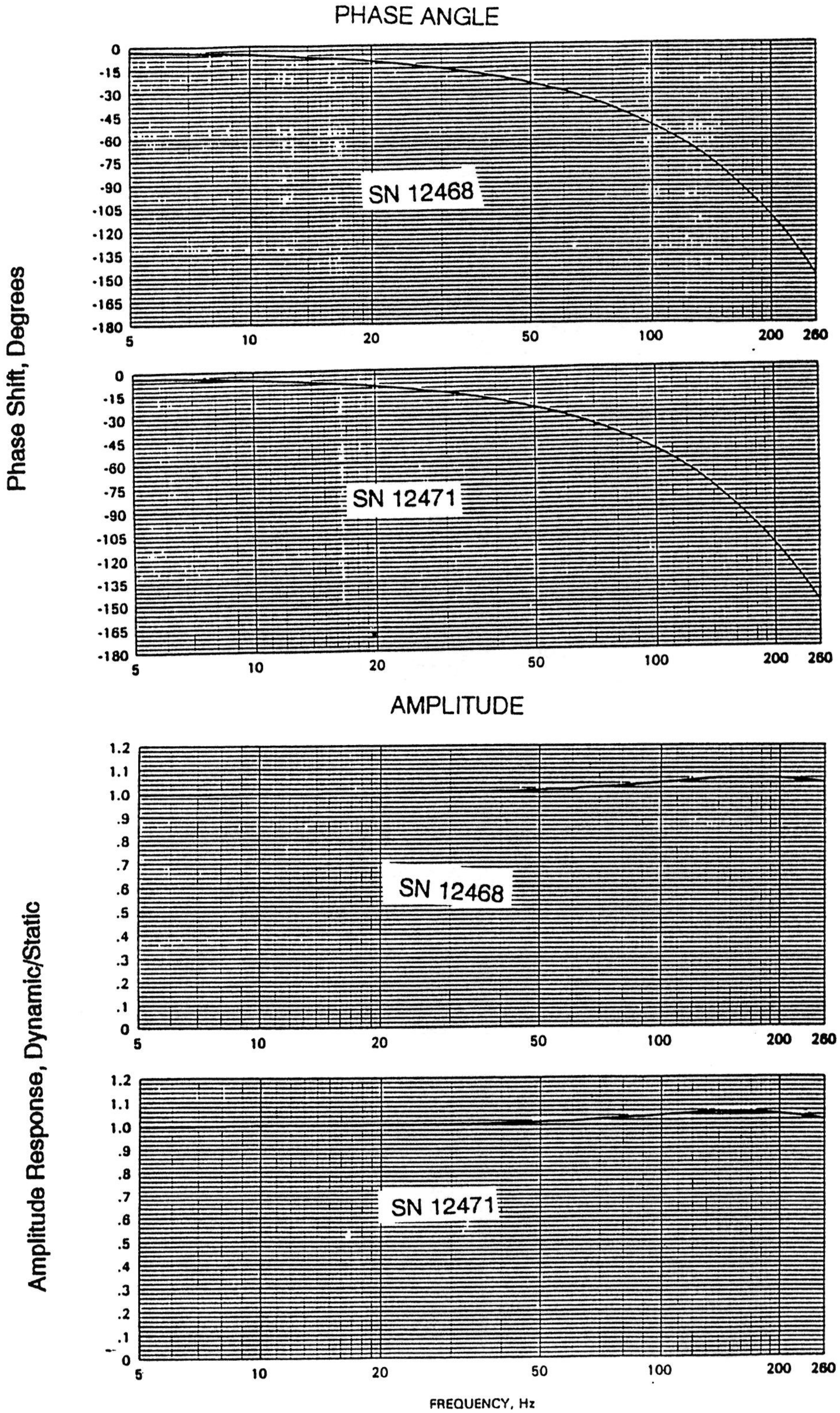
PHASE ANGLE



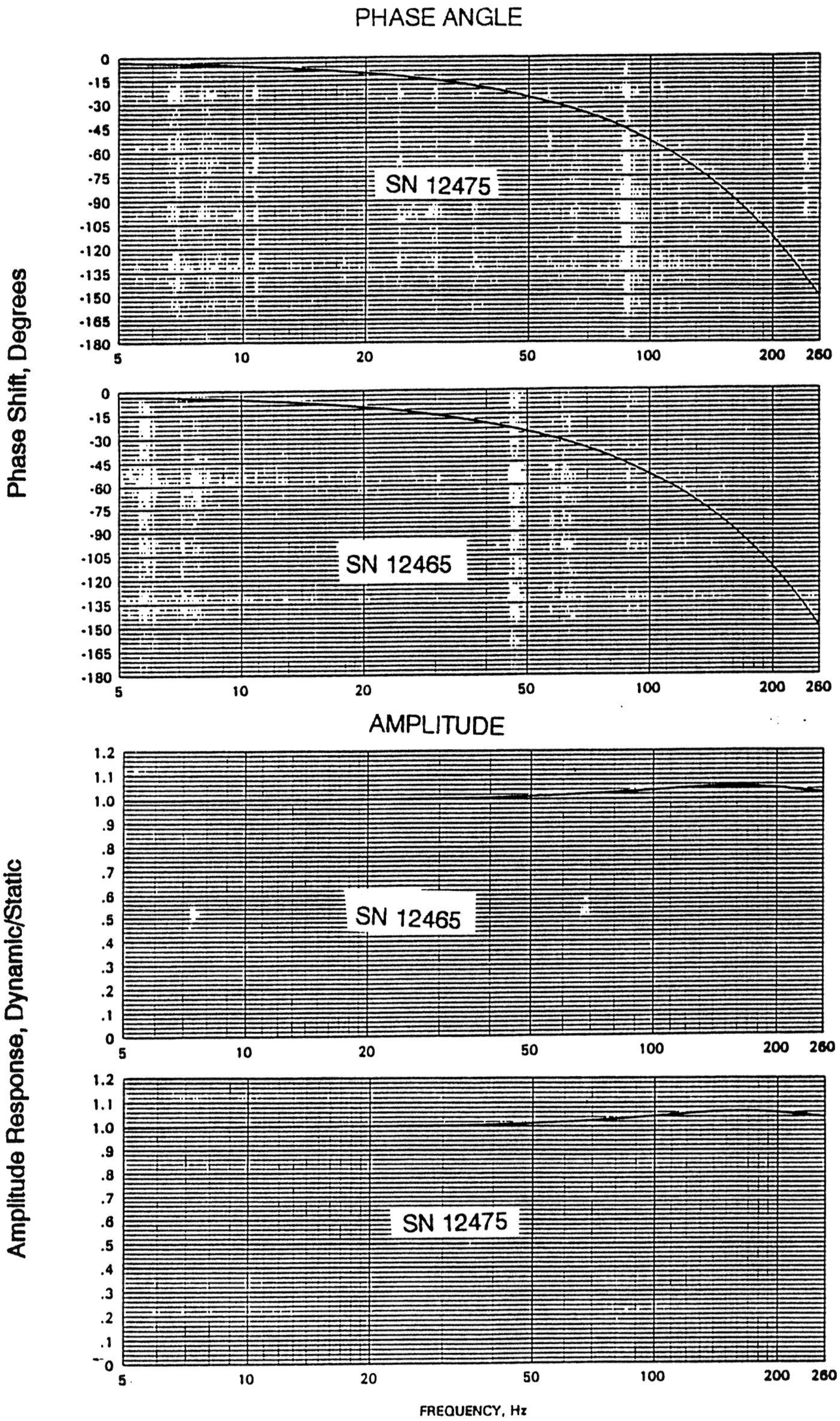
AMPLITUDE



COMPARISON OF PHASE ANGLE AND AMPLITUDE CALIBRATIONS FOR Y AXIS ACCELEROMETERS



COMPARISON OF PHASE ANGLE AND AMPLITUDE
CALIBRATIONS FOR X AXIS ACCELEROMETERS



APPENDIX B

CALIBRATION TEST DATA SET

FOR

NASA LANGLEY LOW FREQUENCY VIBRATION TEST APPARATUS

		Test Parameters		
Test No				
Test1(f=10 Hz) (FIX)	Excitation point X=0.0, Y=-5.625, Z=0.0	Gravity Dir	Force DIR	Rigid Masses
Test2(f=10 Hz) (FIX)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test3(Impact) (FIX)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test4(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test5(f=10 Hz) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test6(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test7(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test8(Impact) (FLT)	Excitation point X=5.625, Y=0.0, Z=0.0	Z	Z	NO
Test9(Impact) (FLT)	Excitation point X=4.5, Y=0.5, Z=-2.5	Z	Y	NO
Test10(Impact) (FLT)	Excitation point X=10.5, Y=0.0, Z=-1.0	Z	X	NO
Test11(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	YES
Test12(Impact) (FLT)	Excitation point X=5.625, Y=0.0, Z=0.0	Z	Z	YES
Test13(Impact) (FLT)	Excitation point X=4.5, Y=0.5, Z=-2.5	Z	Y	YES
Test14(Impact) (FLT)	Excitation point X=10.5, Y=0.0, Z=-1.0	Z	X	YES
Test15(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	X	Z	YES
Test16(Impact) (FLT)	Excitation point X=5.625, Y=0.0, Z=0.0	X	Z	YES
Test17(Impact) (FLT)	Excitation point X=4.5, Y=0.5, Z=-2.5	X	Y	YES
Test18(Impact) (FLT)	Excitation point X=10.5, Y=0.0, Z=-1.0	X	X	YES
Test19(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	X	Z	NO
Test20(Impact) (FLT)	Excitation point X=5.625, Y=0.0, Z=0.0	X	Z	NO
Test21(Impact) (FLT)	Excitation point X=4.5, Y=0.5, Z=-2.5	X	Y	NO
Test22(Impact) (FLT)	Excitation point X=10.5, Y=0.0, Z=-1.0	X	X	NO
Test23(Impact) (FLT)	Excitation point X=0.0, Y=-5.625, Z=0.0	Z	Z	NO
Test24(Impact) (FLT)	Excitation point X=5.625, Y=0.0, Z=0.0	Z	Z	NO
Test25(Impact) (FLT)	Excitation point X=4.5, Y=0.5, Z=-2.5	Z	Y	NO
Test26(Impact) (FLT)	Excitation point X=10.5, Y=0.0, Z=-1.0	Z	X	NO

			Measured Accelerations			
Test No	Ax (g's)	Ay (g's)	Az (g's)	Arx (g's)	Ary (g's)	Arz (g's)
Test1(f=10 Hz) (FIX)	9.08E-06	5.35E-04	3.00E-03	5.22E-04	1.36E-06	2.82E-06
Test2(f=10 Hz) (FIX)	1.24E-04	2.16E-04	2.90E-03	4.74E-04	2.28E-05	1.37E-05
Test3(Impact) (FIX)	7.06E-06	9.30E-06	2.32E-04	5.06E-05	1.09E-06	6.75E-07
Test4(Impact) (FLT)	9.32E-06	1.51E-05	2.37E-04	4.85E-05	2.35E-06	1.02E-06
Test5(f=10 Hz) (FLT)	2.00E-05	5.59E-06	4.12E-04	8.13E-05	1.08E-05	2.20E-06
Test6(Impact) (FLT)	8.75E-06	1.72E-05	1.94E-04	4.50E-05	1.83E-06	9.00E-07
Test7(Impact) (FLT)	8.08E-06	1.39E-05	1.71E-04	3.88E-05	1.25E-06	9.84E-07
Test8(Impact) (FLT)	1.25E-05	7.06E-06	1.72E-04	1.71E-06	3.33E-05	5.68E-07
Test9(Impact) (FLT)	9.41E-06	2.47E-04	8.55E-06	2.15E-05	1.53E-06	2.20E-05
Test10(Impact) (FLT)	2.78E-04	1.05E-05	7.60E-06	1.10E-06	3.42E-06	2.26E-06
Test11(Impact) (FLT)	1.14E-05	1.52E-05	2.06E-04	4.81E-05	5.27E-06	1.32E-06
Test12(Impact) (FLT)	1.66E-05	4.45E-06	1.76E-04	6.01E-06	3.67E-05	4.19E-07
Test13(Impact) (FLT)	8.17E-06	2.62E-04	9.63E-06	1.95E-05	1.12E-06	2.06E-05
Test14(Impact) (FLT)	2.60E-04	4.31E-06	1.02E-06	1.08E-06	5.89E-06	1.34E-06
Test15(Impact) (FLT)	1.34E-05	1.95E-05	2.24E-04	4.98E-05	5.40E-06	1.59E-06
Test16(Impact) (FLT)	1.57E-05	1.35E-05	2.05E-04	5.32E-06	3.96E-05	1.73E-06
Test17(Impact) (FLT)	1.7.93e-6	2.39E-04	4.12E-06	1.85E-05	1.31E-06	1.94E-05
Test18(Impact) (FLT)	1.94E-04	6.12E-06	5.68E-06	7.78E-07	5.91E-06	1.82E-06
Test19(Impact) (FLT)	1.10E-05	1.28E-05	1.83E-04	4.19E-05	1.26E-06	1.24E-06
Test20(Impact) (FLT)	1.25E-06	1.22E-05	1.97E-04	1.36E-06	3.87E-05	1.26E-06
Test21(Impact) (FLT)	6.45E-06	2.46E-04	3.40E-06	1.50E-05	5.59E-07	2.02E-05
Test22(Impact) (FLT)	2.49E-04	3.16E-06	1.70E-05	4.47E-07	3.80E-06	1.33E-06
Test23(Impact) (FLT)	1.01E-05	2.25E-05	2.04E-04	4.66E-05	2.08E-06	1.10E-06
Test24(Impact) (FLT)	1.79E-05	8.77E-06	1.72E-04	1.34E-06	3.23E-05	7.55E-07
Test25(Impact) (FLT)	1.97E-05	3.06E-04	1.03E-05	2.09E-05	2.24E-06	2.59E-05
Test26(Impact) (FLT)	3.37E-04	1.17E-05	6.19E-06	9.67E-07	3.06E-06	2.73E-06

			Measured Force			
Test No	Force X (v)	Force Y (v)	Force Z (v)	F-sen (lb/v)	Force (lb)	
Test1(f=10 Hz) (FIX)			0.0851	2.0	0.170	
Test2(f=10 Hz) (FIX)			0.0807	2.0	0.161	
Test3(Impact) (FIX)			0.0016	10.0	0.016	
Test4(Impact) (FLT)			0.0017	10.0	0.017	
Test5(f=10 Hz) (FLT)			0.0150	2.0	0.030	
Test6(Impact) (FLT)			0.0014	10.0	0.014	
Test7(Impact) (FLT)			0.0012	10.0	0.012	
Test8(Impact) (FLT)			0.0013	10.0	0.013	
Test9(Impact) (FLT)		0.0020		10.0	0.020	
Test10(Impact) (FLT)	0.0020			10.0	0.020	
Test11(Impact) (FLT)			0.0016	10.0	0.016	
Test12(Impact) (FLT)			0.0015	10.0	0.015	
Test13(Impact) (FLT)		0.0021		10.0	0.021	
Test14(Impact) (FLT)	0.0021			10.0	0.021	
Test15(Impact) (FLT)			0.0018	10.0	0.018	
Test16(Impact) (FLT)			0.0017	10.0	0.017	
Test17(Impact) (FLT)		0.0019		10.0	0.019	
Test18(Impact) (FLT)	0.0015			10.0	0.015	
Test19(Impact) (FLT)			0.0013	10.0	0.013	
Test20(Impact) (FLT)			0.0015	10.0	0.015	
Test21(Impact) (FLT)		0.0018		10.0	0.018	
Test22(Impact) (FLT)	0.0018			10.0	0.018	
Test23(Impact) (FLT)			0.0014	10.0	0.014	
Test24(Impact) (FLT)			0.0013	10.0	0.013	
Test25(Impact) (FLT)		0.0023		10.0	0.023	
Test26(Impact) (FLT)	0.0024			10.0	0.024	

			Measured moments			
Test No	M X (in-lb)	M Y (in-lb)	M Z (in-lb)			
Test1(f=10 Hz) (FIX)	0.9574					
Test2(f=10 Hz) (FIX)	0.9079					
Test3(Impact) (FIX)	0.0900					
Test4(Impact) (FLT)	0.0956					
Test5(f=10 Hz) (FLT)	0.1688					
Test6(Impact) (FLT)	0.0788					
Test7(Impact) (FLT)	0.0675					
Test8(Impact) (FLT)		0.0731				
Test9(Impact) (FLT)	0.0265		0.0900			
Test10(Impact) (FLT)						
Test11(Impact) (FLT)	0.0900					
Test12(Impact) (FLT)		0.0844				
Test13(Impact) (FLT)	0.0278		0.0945			
Test14(Impact) (FLT)						
Test15(Impact) (FLT)	0.1013					
Test16(Impact) (FLT)		0.0956				
Test17(Impact) (FLT)	0.0251		0.0855			
Test18(Impact) (FLT)						
Test19(Impact) (FLT)	0.0731					
Test20(Impact) (FLT)		0.0844				
Test21(Impact) (FLT)	0.0238		0.0810			
Test22(Impact) (FLT)						
Test23(Impact) (FLT)	0.0788					
Test24(Impact) (FLT)		0.0731				
Test25(Impact) (FLT)	0.0304		0.1035			
Test26(Impact) (FLT)						

			Calculated Masses			
Test No	Mass Calc (lb)	Mass Meas (lb)	MASS % Diff	Force DIR		Gravity Dir
Test1(f=10 Hz) (FIX)	56.7	74.4	-23.7	Z		Z
Test2(f=10 Hz) (FIX)	55.7	74.4	-25.2	Z		Z
Test3(Impact) (FIX)	69.0	74.4	-7.3	Z		Z
Test4(Impact) (FLT)	71.7	74.4	-3.6	Z		Z
Test5(f=10 Hz) (FLT)	72.8	74.4	-2.1	Z		Z
Test6(Impact) (FLT)	72.2	74.4	-3.0	Z		Z
Test7(Impact) (FLT)	70.2	74.4	-5.7	Z		Z
Test8(Impact) (FLT)	75.6	74.4	1.6	Z		Z
Test9(Impact) (FLT)	81.0	74.4	8.8	Y		Z
Test10(Impact) (FLT)	71.9	74.4	-3.3	X		Z
Test11(Impact) (FLT)	77.7	81.675	-4.9	Z		Z
Test12(Impact) (FLT)	85.2	81.675	4.3	Z		Z
Test13(Impact) (FLT)	80.2	81.675	-1.9	Y		Z
Test14(Impact) (FLT)	80.8	81.675	-1.1	X		Z
Test15(Impact) (FLT)	80.4	81.675	-1.6	Z		X
Test16(Impact) (FLT)	82.9	81.675	1.5	Z		X
Test17(Impact) (FLT)	79.5	81.675	-2.7	Y		X
Test18(Impact) (FLT)	77.3	81.675	-5.3	X		X
Test19(Impact) (FLT)	71.0	74.4	-4.5	Z		X
Test20(Impact) (FLT)	76.1	74.4	2.3	Z		X
Test21(Impact) (FLT)	73.2	74.4	-1.7	Y		X
Test22(Impact) (FLT)	72.3	74.4	-2.8	X		X
Test23(Impact) (FLT)	68.6	74.4	-7.8	Z		Z
Test24(Impact) (FLT)	75.6	74.4	1.6	Z		Z
Test25(Impact) (FLT)	75.2	74.4	1.0	Y		Z
Test26(Impact) (FLT)	71.2	74.4	-4.3	X		Z

		Calculated Mass Moment of Inertia				
Test No	MOIX (lb-in^2)	MOIY (lb-in^2)	MOIZ (lb-in^2)	MOIX %Diff	MOIY %Diff	MOIZ %Diff
Test1(f=10 Hz) (FIX)	1834.05			-16.7		
Test2(f=10 Hz) (FIX)	1915.35			-13.1		
Test3(Impact) (FIX)	1778.66			-19.3		
Test4(Impact) (FLT)	1971.65			-10.5		
Test5(f=10 Hz) (FLT)	2075.65			-5.8		
Test6(Impact) (FLT)	1750.00			-20.6		
Test7(Impact) (FLT)	1739.69			-21.0		
Test8(Impact) (FLT)		2195.95			-1.4	
Test9(Impact) (FLT)	1230.70		4090.91	-44.1		5.8
Test10(Impact) (FLT)						
Test11(Impact) (FLT)	1871.10			-25.0		
Test12(Impact) (FLT)		2299.05			-8.6	
Test13(Impact) (FLT)	1424.77		4587.38	-42.9		5.8
Test14(Impact) (FLT)						
Test15(Impact) (FLT)	2033.13			-18.5		
Test16(Impact) (FLT)		2414.77			-4.0	
Test17(Impact) (FLT)	1358.76		4407.22	-45.5		1.6
Test18(Impact) (FLT)						
Test19(Impact) (FLT)	1745.23			-20.8		
Test20(Impact) (FLT)		2180.23			-2.1	
Test21(Impact) (FLT)	1587.60		4009.90	-27.9		3.7
Test22(Impact) (FLT)						
Test23(Impact) (FLT)	1689.91			-23.3		
Test24(Impact) (FLT)		2263.93			1.7	
Test25(Impact) (FLT)	1455.93		3996.14	-33.9		3.3
Test26(Impact) (FLT)						

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (leave blank)

2. REPORT DATE
September 1995

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE
Mass Properties Calibration of the NASA Langley Low Frequency Vibration Test Apparatus

5. FUNDING NUMBERS
C NAS1-19000
WU 963-89-00-01

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
NASA CR-198208

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: Dr. Roger A. Breckenridge

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category - 18

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report presents a description and calibration results of the modified NASA Langley Low Frequency Vibration Test Apparatus. The description includes both the suspension system and the data acquisition system. The test apparatus consists of a 2 inch thick, 21 inch diameter aluminum plate that is suspended from an advanced suspension system using a 40 foot long cable system. The test apparatus employed three orthogonally aligned pairs of Sundstrand QA-700 servo accelerometers that can measure accelerations as low as 1 micro-g. The calibration involved deriving the mass and moments of inertia of the test platform from measured input forces and measured acceleration responses. The derived mass and moments were compared to test platform mass properties obtained initially from measurements with a special mass properties instrument. Results of the calibration tests showed that using the product of the test apparatus mass and the measured accelerations, the disturbance force at the center of gravity (CG) can be determined within 4 percent on all three axes. Similarly the disturbance moments about the X, Y, and Z axes can be determined within 5 percent by using the product of the measured moments of inertia and the angular accelerations about the X, Y, and Z axes.

14. SUBJECT TERMS
vibration test apparatus; vibration force; acceleration measurement; microgravity measurement.

15. NUMBER OF PAGES
42

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SUCURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL