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# A New Spin Balance Machine

by

Richard Boynton, President, and Robert Bell, VP Engineering,

Space Electronics, Inc.

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Abstract This paper describes a new low speed vertical axis aerospace spin balance machine which takes advantage of recent advances in technology. This machine measures moment of inertia (MOI) in addition to product of inertia (POI) and center of gravity (CG) offset. Spin speeds as low as 15 RPM yield useful results. This machine has a number of unique features. The operation is totally automatic; even the conversion from spin balance to moment of inertia measurement can be accomplished without the operator touching the machine. Gas bearing technology is used throughout, resulting in unrivaled sensitivity and accuracy.

Balancing machines used to require a tedious procedure to adjust the plane separation controls. No matter how many times you did this procedure, it was so complex that you had to have the instruction manual handy as you worked your way through the steps. With the new Space Electronics POI Series Spin Balance Machine, this process is done automatically by the on-line digital computer which is supplied with the machine. This same computer also prompts the operator with user-friendly menus, so that it is rarely necessary to refer to the instruction manual while balancing the payload.

In addition to providing 2-plane correction weight locations, the on-line digital computer can store the location of a variety of ballast points for a specific vehicle and determine the best solution to the balancing problem. This system has the ability to map the available locations for unbalance correction weights (so that the machine will not specify a disallowed location). An optional removable hard disc ensures the safeguarding of secret data. This computer can also calculate the tilt of the principal axis.

This machine first rotates the payload at a slow speed and predicts the unbalance forces at the desired speed. If these forces are in excess of the ratings of the machine or the payload, then the operator is warned. He can then balance at a slower speed, or stop the machine and determine why the unbalance is so great. Digital filtering techniques are used to reject any forces which do not vary sinusoidally with the rotation speed. If the force transducer outputs include random variations due to air turbulence on the surface of the payload, then the filtering is automatically increased to smooth out this variation.

This paper includes a mathematical analysis of the errors of measurement as a function of the relative magnitudes of POI and CG unbalance, the moment equations which relate the transducer forces to payload POI and CG offset, and a practical discussion of fixturing and accessory equipment needed to properly balance an aerospace payload.

This instrument is probably the most accurate slow speed mass properties machine in the world. Although originally designed to have unbalance reduction ratios of 97%, ratios better than 99% are generally achievable, so that the object under test can usually be balanced in a single run. Center of gravity measurement is typically better than 0.001 inch. The machine produces an illustrated report of test data.

**Introduction** This mass properties machine is the culmination of a research effort at Space Electronics that began in 1980. Before this time most spin balance machines used analog computers to calculate plane separation and the majority of machines employed roller or hydrostatic oil bearings. Report generation was limited to a narrow strip printout of numerical data. There were machines available which measured dynamic balance accurately, but were unable to measure static CG or moment of inertia. Other single transducer type machines were successful in measuring static quantities, but dynamic accuracy was poor. Our goal was to create a fully automatic machine which could make high accuracy measurements of all quantities and also generate a final report which could be submitted to anyone without the need for further clarification or retyping.

**Basic Concept** This mass properties machine (balancing machine) is of the vertical type, whereby the test object may be mounted on the top surface of the machine without restriction as to height or diameter. It is not necessary to "make a rotor out of the part" by mounting it inside a special fixture with a shaft extending from either end (as would be necessary if a horizontal machine were used).

The machine is of the "hard bearing" type whereby the lowest mechanical resonance is above the operating speed, so that the machine is "permanently calibrated". This means that test objects of a variety of sizes and weights can be tested without the need to recalibrate the machine each time it is used.

This machine can be used to measure mass properties (center of gravity, moment of inertia and product of inertia), or it can be used to balance or correct a test object, with the ultimate goal being that the CG and product of inertia is reduced to zero (i.e. the principal axis of the test object is coincident with the spin axis of the machine).

| **Spacecraft balancing** | **Shaft balancing** |
|---|---|
| Vertical spin axis | Horizontal spin axis |
| Low speed (40-120 RPM) (requires gas bearing and special transducer technology) | High Speed (500-3000 RPM) |
| Spacecraft must be fixtured and aligned | Shaft needs no fixture and is self aligning (i.e. spins on its own bearing surfaces) |
| Goal is to align principal axis with thrust or flight axis | Goal is to increase bearing life by reducing unbalance forces |
| POI unbalance is not important if spacecraft doesn't spin | POI unbalance is critical and will have a very tight tolerance |
| Measurement accuracy is critical if spacecraft is not balanced at time of measurement | Measurement accuracy only influences number of iterations required to balance the shaft |

This is an "aerospace" balancing machine, as contrasted with the type of shaft balancing machine which might_ be used in the automotive industry.

Control Console The control console is dominated by the presence of the computer. Most control functions are accomplished through the computer. There is little need for an instruction manual with this system, since the computer displays the step by step operating procedure and cautions the operator if he selects what could be an inappropriate response. If a dangerous condition exists, then the computer shuts down the machine and displays the reason for the shutdown. The system generates a complete data report, which can be formatted to duplicate the mass properties report of a specific facility. Extra cost options include the capability of producing a CAD drawing of the test object showing the datum reference points.

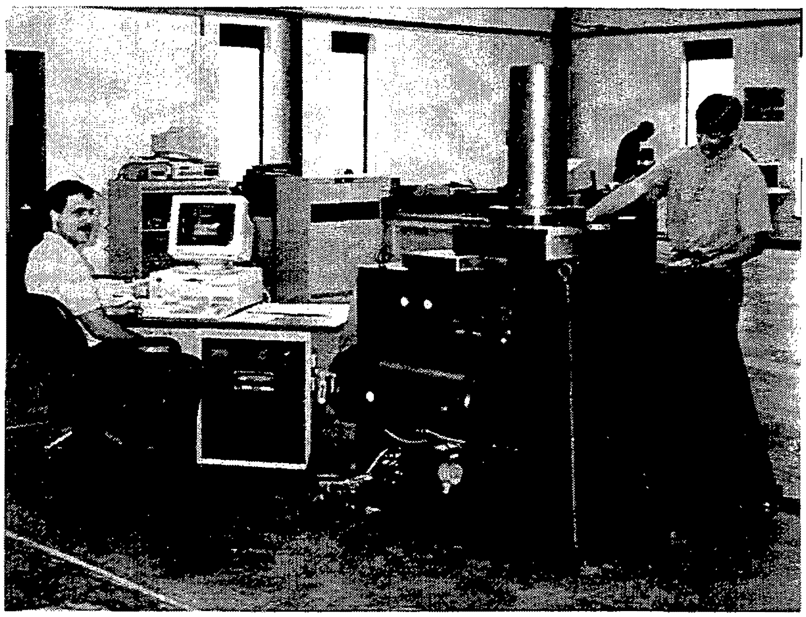


**Figure 1 Space Electronics Model POI-1000 Spin Balance Instrument**

Fully Automatic Operation Unlike older machines everything is automatic. To measure unbalance at a particular speed, the operator types in the speed and presses a function key. The machine accelerates to the exact speed (without need for adjustment by the operator), measures the unbalance, decelerates to zero, and prints out the answer. To measure moment of inertia, the operator presses another function key; the machine rotates automatically to $0^0$, a torsion rod clamps, oscillation is initiated, and the computer prints the moment of inertia. In addition to being efficient and fast, this fully automatic machine is a great labor saver in situations where the console must be located remotely from the machine. If the test object is radioactive, then this machine minimizes operator exposure. If a helium environment is used, th�n the automatic conversion from POI to MOI measurement means that the operator uses half as much helium as he would if he had to release the helium to the atmosphere in order to convert the machine from POI to MOI operation. (See Appendix A for a discussion of the use of helium).

**Speed Compensation** The rotation speed of the machine is controlled by the computer. The computer continuously measures the rotation speed of the machine. If the speed drifts slightly, then the unbalance calculations are corrected for this speed variation.

**Noise Rejection** The sensitivity of most balancing machines is limited by the noise floor. With this machine, the computer acquires the raw data, rejects any signals from the transducers which are not synchronous with the rotation speed of the machine, performs a best fit solution to a sine wave to further reduce noise, and then compares the answer with other blocks of data to verify that the variation is less than a preset level.

**Details of the Design** Figure 2 illustrates the basic mechanical configuration of the Space Electronics machine. The weight of the test object is carried by the upper spherical gas bearing, allowing it to tilt as well as turn. The overturning moment of the system is restrained by the lower cylindrical bearing. This bearing is supported by a gimballed mounting consisting of two pairs of crossed-web flexures. This results in a bearing system which is self aligning, has runout less than 50 millionths of an inch, and is so frictionless that the spindle will rotate for more than 40 minutes under its own inertia.

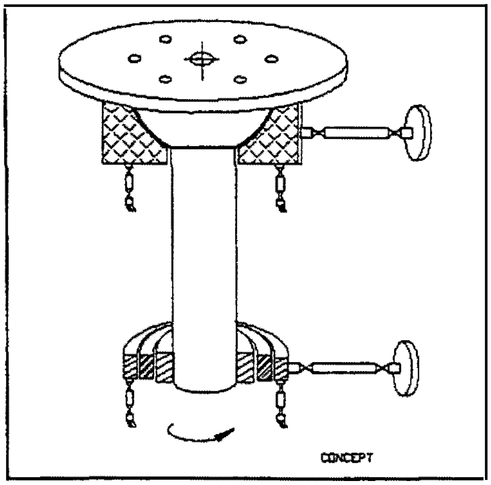



**Figure 2 Basic design of the machine. The test object weight is supported on an upper spherical gas bearing. A lower gimbal mounted cylindrical gas bearing resists the overturning moment due to unbalance.**

Both the upper and the lower bearing assemblies are mounted on a flexure system which is compliant along only one axis. The force on each bearing is measured along this axis. This measured force is used to determine both CG offset and product of inertia of the test part. The force transducers are oriented at right angles to each other to minimize plane separation error.

A torsion rod extends up through the center of the bearing tube. To measure moment of inertia, the lower end of this torsion rod is clamped, creating an inverted torsion pendulum. The period of oscillation is proportional to the moment of inertia of the oscillating assembly.

The structure of the machine is extremely massive. The base of the machine alone weighs more than the maximum payload capacity of the machine. This is necessary if the machine is to be a true "hard bearing" design (i.e. the first resonance is many times the highest spin speed, so that the machine is "permanently calibrated").

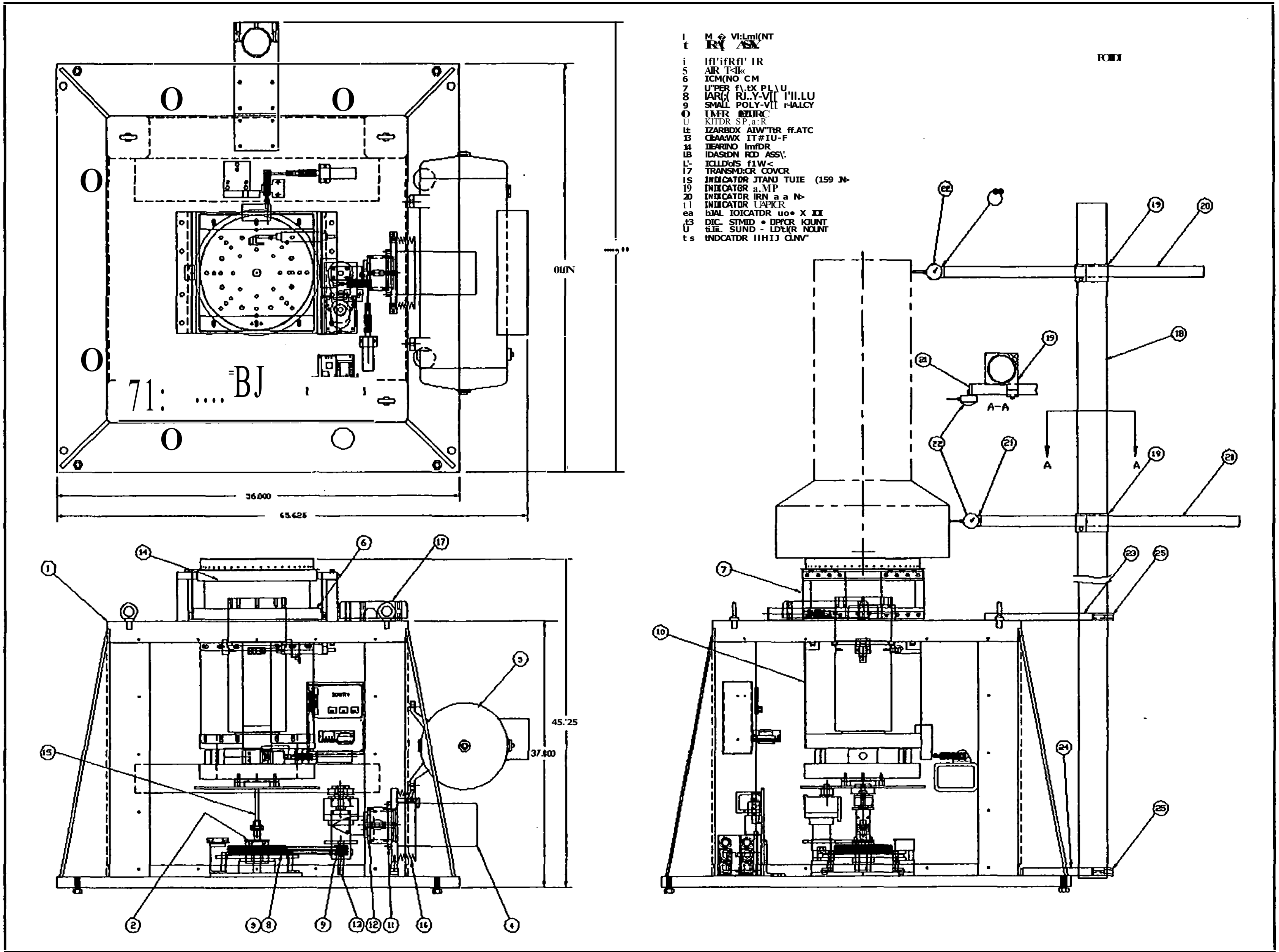



Figure 3 Assembly Drawing

Superficially, this machine resembles the static CG & moment of inertia measuring instrument which Space Electronics has been manufacturing for many years. However, there are a number of important differences. On our static machine, only the lower bearing force is measured. The upper bearing is mounted rigidly. As explained in later sections of this paper, two force measurements are necessary if the mass properties machine is to measure combined CG offset and product of inertia. Our static CG machine does not use the same massive rigid frame as this new instrument, since resonant frequency is of no consequence when making static measurements. The bearings of this dynamic machine must be deeper and larger since considerable side force is present when the machine is spinning. And, of course, the small positioning motor of our static machine is supplemented by a large variable speed motor for this new dynamic mass properties machine.

**Transducer Concept** The transducer used in a balancing machine must be very stiff to prevent the spring rate of the transducer from lowering the first resonance of the machine. Otherwise, there will be considerable angle error when measuring tall heavy objects. Horizontal forces on the bearings in our balancing machine are measured using a novel piezoelectric transducer. Conventional transducers contain a simple washer made of piezoelectric material which is compressed to generate an output voltage. Our machines use a high sensitivity force transducer which makes use of a transverse mode quartz element for best resolution. The measuring range extends from about $10^{-3}$ lb to 10 lb. In order to ensure extremely low sensitivity to thermal effects the quartz element is installed in the casing with no compressive preload and is supported on a rigid base. The force transmission section is centered and supported laterally in the casing by a thin membrane. The high rigidity and correspondingly high natural frequency of this transducer permits installation in the balancing instrument without appreciably affecting its dynamic behavior.

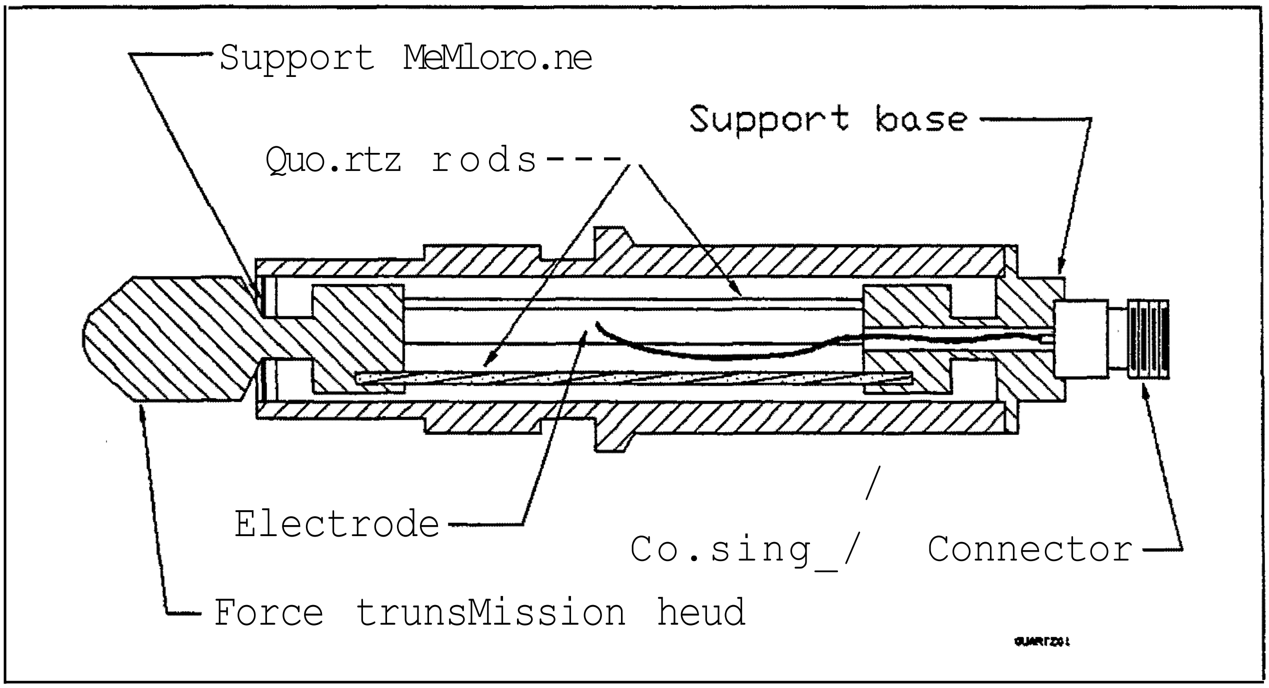



**Figure 4 Quartz Transducer Construction**

The construction of the transducer employs a tubular stainless casing with a support base attached to one end and the force transmission head located in the other end. The force transmission head is held centered in the casing by a thin membrane which absorbs any side loading and also prevents contamination of the interior of the transducer. Three quartz rods with a rectangular cross section are supported between the force transmission head and the support base with their long axis parallel to the axis of the transducer. This design makes the transducer practically insensitive to thermal effects. No preload is placed on the quartz element by the construction of the transducer. However, the design of the balancing instrument places a compressive preload equal to about one half of the transducer full scale on each transducer.

Each quartz rod has electrodes attached to the two opposing long sides. Wires connect the electrodes to the cable connector on the transducer. The quartz rods are oriented so that a longitudinal force on the rod causes charge to be generated at the electrodes along the sides of the rod. This design provides the maximum charge output for a given axial force and retains the typical high rigidity of the quartz transducer. The design also limits the sensitivity of the transducer to side loads to about 5% of the axial sensitivity. Design elements in the balancing instrument structure further reduce the effect of any side loads that might be placed on the transducer to a negligible amount.

The transducer is welded throughout, which minimizes changes due to aging and temperature, as well as preventing contamination by airborne impurities.

| **Piezoelectric transducer** | **Velocity pickup** | **Load Cell** |
|---|---|---|
| Transducer deflection less than 0.0001 inch for full scale force | Typical transducer deflection is 0.001 inch full scale | Typically deflects about 0.008 inch F.S. so any mechanical nonlinearities affect accuracy |
| F.S. Output voltage is 10 volts. High impedance makes it prone to electrostatic noise pickup, but it can be easily shielded. | F.S. Output voltage is 300 mv but decreases with speed, so slow speed operation is questionable. Transducer uses coil of wire which is prone to magnetic pickup. | F.S. Output voltage is only 30 mv -- susceptible to semiconductor noise |
| System is very stiff, so payload lean is minimal, and first resonance is 5 or 10 times higher than the highest operating speed | Moderate stiffness, so there may be a phase shift at higher speeds when measuring tall payloads | Low stiffness. When measuring tall payloads, lean increases error and system is useless at higher speeds |

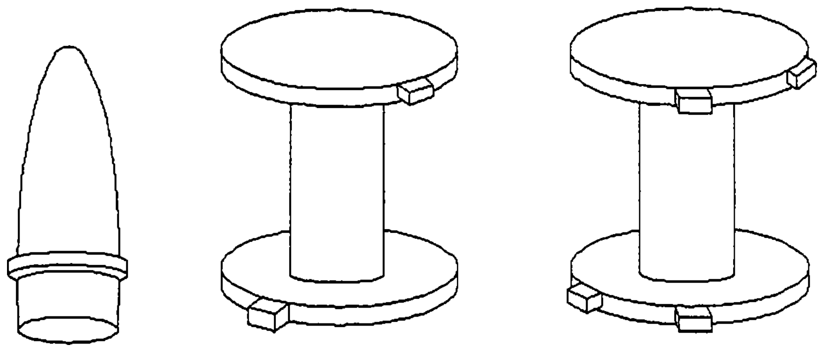
**.Piezoelectr1c transducers have several advantages over other types.**

| KEY SPECIFICATIONS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| MODEL | Recommended Payload Range (lbs) | Range of Spin Speeds (RPM) | Max Loading Moment (lb-in) | Maximum CG Height (lb @ inches) | Tare MOI (lb-in²) | MOI Accuracy (% of reading + lb-in²) | Full Scale Dynamic Unbalance (lb-in² @ RPM) | Minimum Achievable Readout (lb-in² @ RPM) | Unbalance Reduction Ratio (%) |
| POI 50 | 1-50 | 50-800 | 200 | 30 lb@40" @ 200 RPM | 180 | Q% reading + 0.1 | 1024@ 50<br>256@ 100<br>64@ 200<br>16@ 400<br>4@ 800 | 0.07@50<br>0.01@ 100<br>0.003@ 200<br>0.0007@ 400<br>0.0005@ 800 | % |
| POI 300 | 5-300 | 50-800 | 1000 | 200 lb@ 48" @ 200 RPM | 350 | 0.25% of reading + 0.2 | 14,000@ 50<br>3,500@ 100<br>875@ 200<br>220@ 400<br>55@ 800 | 0.25@ 50<br>0.05@ 100<br>0.012@ 200<br>0.005@ 400<br>0.002@ 800 | 95% |
| POI 1000 | 10-1000 | 30-300 | 5000 | 750 lb@ 53" @50RPM | 2800 | 0.25% of reading + 0.75 | 19,200@ 50<br>4,800@ 100<br>1,200@ 200<br>533@ 300 | 0.5@ 50<br>0.1@ 100<br>0.025@ 200<br>0.015@ 300 | 95% |
| POI 3500 | 50-3500 | 30-300 | 10000 | 2500 lb@ 60"@ 50 RPM | 8000 | 0.25% of reading + 2 | 76,800@ 50<br>19,200@ 100<br>4,800@ 200<br>2,130@ 300 | 1.5@50<br>0.3@ 100<br>0.07@ 200<br>0.03@ 300 | 95% |

| MODEL | Interface Diameter | Outline Size | | | < A chor.Locations• ••••.(9.i{IJlaxst if d i f>• | | Optional Dial Indicator Stand | | EJ tr ), )eq1 1itc:foc:ilt (\'C>Its/ 1Tips/J)ti1 1itX | 1ittN& ••••••i<(t)••• |
|---|---|---|---|---|---|---|---|---|---|---|
| | D | L | W | H | A | B | C | E | | |
| POI 50 | 12 | 48.5 | 51 | 31 | 45.50 | 36.00 | 56 | 27.75 | 220V/10A/l<J, | 2750 |
| POI 300 | 12 | 61 | 52 | 38 | 49.00 | 46.00 | 58 | 27.75 | 220V/10A/l<J, | 4200 |
| POI 1000 | 16 | 66 | 57 | 47 | 54.00 | 51.00 | 63 | 30 | 220V/10A/l<J, | 5850 |
| POI 3500 | 23 | 70 | 61 | 48.5 | 58.00 | 55.00 | 67 | 32 | 220V/15A/l<J, | 7500 |

Nole: all dimensions are in inches

**Moment Equations--Test Object Spinning** The complex unbalance which results from both CG offset and product of inertia can always be represented in terms of its dynamic behavior by a perfectly balanced object to which has been attached one unbalance weight in each of two planes. These single weights in each plane can be further represented by two weights spaced 90 degrees apart in each plane (i.e. polar to rectangular conversion). This is illustrated in Figure 5. The forces on the transducers in the machine will be analyzed by considering the components at 0 and 90 degrees separately and then combining them at the conclusion.



A B C

**Figure 5 Real Object under test is shown in A. The unbalance equivalent of this real object can be simulated by a single weight in each of two planes as shown in B (angular difference between upper and lower planes can be any angle). As an aid to analysis, each single weight in the previous example can be replaced by two weights located at 0° and 90° as shown in C (i.e. polar coordinates have been replaced by rectangular). Each plane can now be analyzed separately.**

When the test object spins, then there are two forces acting on the unbalance of the object: gravity forces and centrifugal forces. Gravity forces act downward and centrifugal forces act in a horizontal plane as shown in Figure 6. The magnitude of the downward gravity force is:

$$\textit{Gravity Force (lbs)}\ G_1 = \textit{Weight of } \boldsymbol{M1} \textit{ in lbs}$$

The magnitude of the horizontal force is:

$$\textit{Centrifugal Force (lbs)}\ F_1 = M_1 \times R_1 \times S^2$$

where $M_1$ = mass of unbalance in slugs
$R_1$ = radius of CG of unbalance in feet
S = speed in radians per second

Converting the mass into weight and the speed into RPM:

$$\textit{Centrifugal Force (lbs)}\ F_1 = \frac{W_1 \times R_1 \times (RPM)^2}{35{,}207}$$

where $W_1$ = weight of unbalance mass in lbs
$R_1$ = radius of <u>CG</u> of unbalance in inches
RPM = speed in RPM
35,207 = constant to transform units

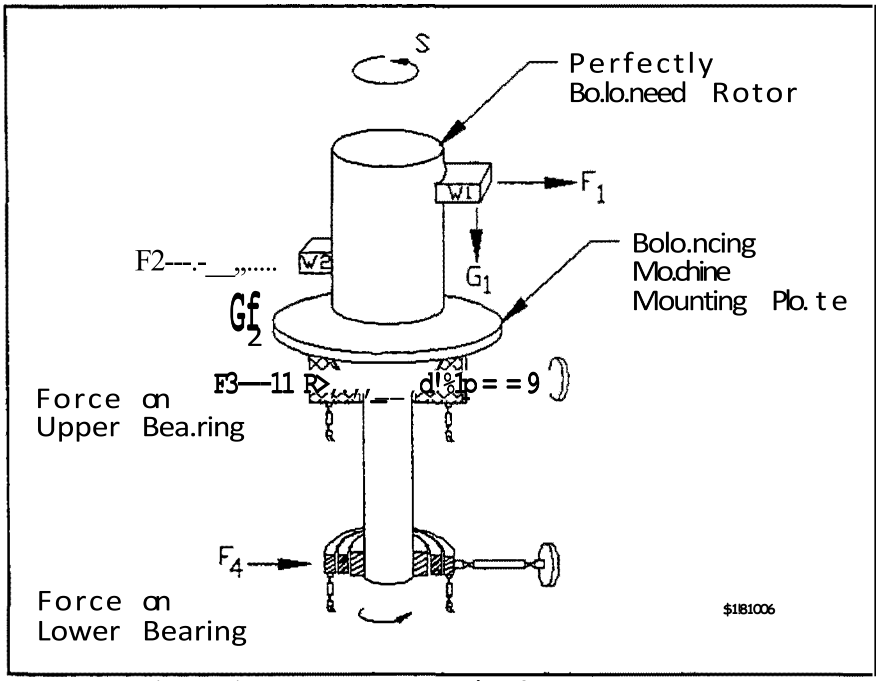



**Figure 6 When the test object spins, a constant gravity force acts downward through the CG of each unbalance, and a centrifugal force proportional to the square of spin speed acts horizontally.**

**Simplified Analysis--Pure Product of Inertia Unbalance** The relationship between unbalance and the forces on the two transducers may be calculated by summing moments about the transducers. The symbols used in this analysis are defined in Figure 7. To simplify the analysis, first consider only the zero degree plane, and furthermore, consider the case where the unbalance is only due to product of inertia (CG offset is zero). The gravity moments are equal and opposite, so they cancel. The centrifugal forces do not cancel; instead they create a couple which is-,resisted by the transducers on the bearings. In this special case, the forces on the transducers in the machine are identical. The force at zero degrees varies sinusoidally as the spindle of the machine- rotates. The direction of the force on one transducer opposes the force on the other (i.e. is 180° oufof.phase with the other). In order for equilibrium to be maintained, the couple due to the two unbalance, weights on the test object must be exactly equal and opposite the couple due to the forces on the transducers. Mathematically the peak forces for this special case can be represented by the equation:

$$F_4 \times H_0 = F_1 \times (H_1 - H_2)$$

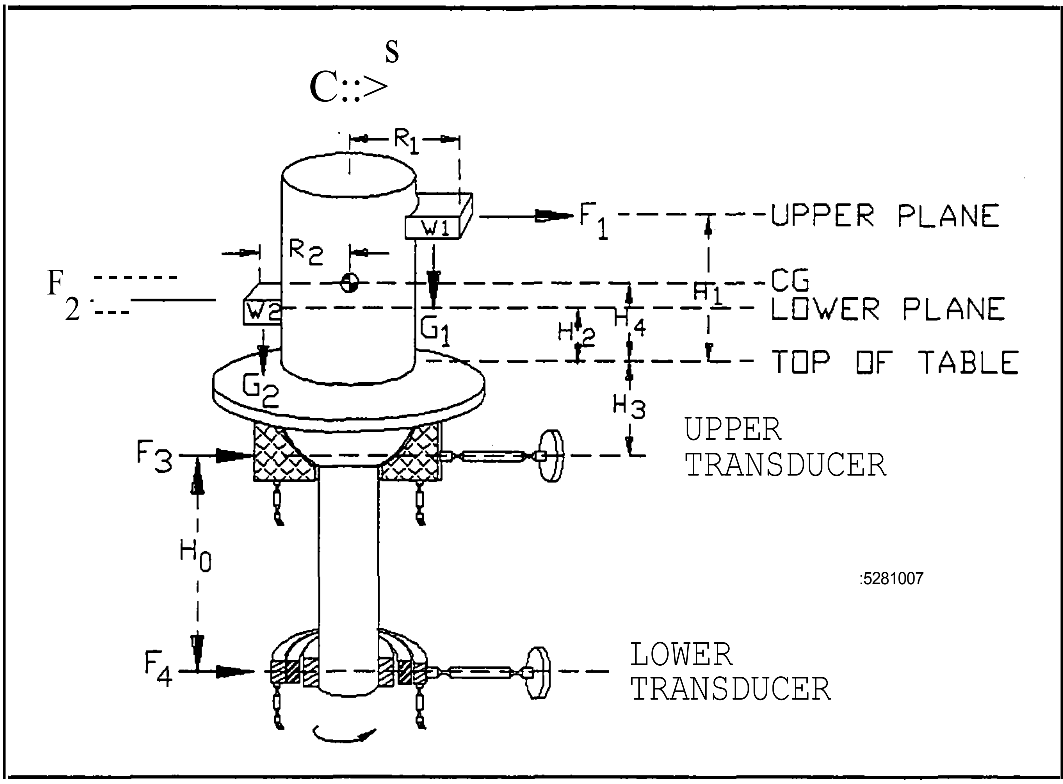



**Figure 7 This figure defines the symbols used in the analysis. Moments are swnmed about upper and lower transducers to calculate the relationship between unbalance and transducer force.**

Since the spindle rotates relative to the transducer, the equation above represents the peak force which occurs when the unbalance is in the plane of the transducer. To solve for the value of the transducer peak force, $F_4$, given the value of the unbalance weight $W_1$:

$$\text{Transducer Force (lbs) } F4 = \frac{W_1 \times R_1 \times (RPM)^2 \times (H_1 - H_2)}{35{,}207 \times H_0}$$

where $W_1$ = weight of unbalance mass in lbs
$R_1$ = radius of CG of unbalance weight in inches
RPM = speed in RPM
35,207 = constant to transform units
$H_1$ = distance mounting plate to upper plane (inches)
$H_2$ = distance mounting plate to lower plane (inches)
$H_0$ = vertical distance between transducers (inches)

The distance $H_0$ is more specifically the distance between the rotation centers of the two bearing systems (the center of the sphere for the upper bearing and the rotational center of the flexured girnbal system for the lower cylindrical bearing). The distance $(H_2 - H_1)$ is more specifically the vertical distance between the center of gravity of the upper unbalance weight and the center of gravity of the lower unbalance weight.

The equation above calculates the peak force on the transducer. The upper transducer experiences a sinusoidal force proportional to the square of the spin speed. The frequency of this force is the rotational speed of the machine. The lower transducer experiences an identical force in the opposite direction. The rotational angle at which the transducers experience the peak force is the same for both transducers (i.e. forces are in phase). (NOTE: This is only true for the case being described--namely pure POI unbalance. In the more common case where the unbalance is due to both CG offset and product of inertia, the forces on the transducers and the angle at which the peak force occurs are not equal.)

**Analysis of General Unbalance** If the test object unbalance is either pure couple (product of inertia) or pure CG offset, then only the force on the lower bearing need be measured to determine unbalance. However, this is rarely the case in real life. If both product of inertia and CG offset exist simultaneously, then the force on both transducers must be measured. Furthermore, these forces must be measured at the same rotational speed.

Let us now analyze the general case for the O degree axis where the upper and lower weights are not the same, resulting in both CG and POI unbalance. To determine the resulting forces on the transducers, we can sum moments around both transducers (the sum of the moments must be zero for the system to remain in equilibrium).

Summing moments around the upper transducer:

$$(W_1)(R_1)+(F_1)(H_1+H_3)-(W_2)(R_2)-(F_2)(H_2+H_3)-(F_4)(H_0) = 0$$

Summing moments around lower transducer:

$$(W_1)(R_1)+(F_1)(H_1+H_3+H_0)-(W_2)(R_2)-(F_2)(H_2+H_3+H_0)+(F_3)(H_0) = 0$$

From the previous page $F_1 = \frac{WI \ X \ R_I \ X \ (RPM)^2}{35,207}$ etc.

Therefore:

$$(W_1)(R_1) + [(W_1)(R_1)(RPM)^2(H_1+H_3)] \ / \ 35207 - (W_2)(R_2) - [(W_2)(Ri)(RPM)^2(H_2+H_3)] \ / \ 35207 - (F_4)(Ho) = 0$$

$$(W)(R_1) + [(W)(R_1)(RPM)^2(H_1+H_3+Ho)] \ / \ 35207 - (W_2)(R_2) - [(W_2)(Ri)(RPM)^2(H_2+H_3+Ho)] \ / \ 35207 + (F_3)(Ho) = 0$$

These two equations can be solved simultaneously to yield the value of $W_1$ and $W_2$.

So far we have achieved the following: For the 0° plane, given a force $F_3$ on the upper bearing and a force $F_4$ on the lower bearing, we have calculated the equivalent weight $W_1$ at a radius $R_1$ and a height $H_1$ and the equivalent weight $W_2$ at a radius $R_2$ and a height $H_2$ which yield the same unbalance forces. If we were to do a similar analysis at the 90° plane and then obtain the resultant weight for each plane (i.e. perform a rectangular to polar conversion), and then add 180° to each resultant angle, we would have calculated the correction weight magnitudes and angles at the heights and radii of the CG of the weights $W_1$ and $W_2$ specified to balance the part. Rather than balance the part, let us continue the analysis to calculate the CG offset and product of inertia of the part for the 0° plane.

For a weight $W_1$ at 0° and a weight $W_2$ at 180°, part of each weight represents the CG offset and part represents the product of inertia. The part which represents the CG offset can be determined by noting that the CG unbalance moment is:

Unbalance Moment $$M = W_1 \, x \, R_1 - W_2 \, x \, R_2$$

This unbalance moment can be created by adding weight to each plane in such a way that the product of inertia is unchanged. In order to do this, the following equation must be satisfied:

$$F_1 \, x \, R_1 \, x \, (H_1 - H_4) - F_2 \, x \, R_2 \, x \, (H_4 - H_2) = 0$$

Finally, the two weights associated with the center of gravity offset are subtracted from the total weight in each plane to yield the contribution due to product of inertia unbalance.

**Cross Coupling (Plane Separation Error)** In order for the balancing machine to accuracy separate CG offset from product of inertia, the force applied to one transducer must not cause a change in the output of the other transducer. This effect can be minimized by making the support structure of the machine as rigid as possible. The Space Electronics machine solves this problem in two ways:

[1] The support structure is very massive and rigid.

[2] The two transducers are oriented 90° from each other so that the force applied to one is at right angles to the force applied to the other, minimizing interaction. This technique is only possible with the unique design of the Space Electronics machine, wherein the upper and lower bearings are entirely separate and may be supported by separate structures. This technique is not possible with machines that use a single bearing design.

**Moment of Inertia Measurement** The instrument is converted to moment of inertia measurement by clamping the lower end of the torsion rod to create an inverted torsion pendulum. In this mode, the test surface of the instrument oscillates back and forth in a rotational sense about a vertical axis at the center of the test surface. Moment of inertia measurements are made by first measuring the time period of oscillation with the test fixture mounted on the instrument (but without the test part). The test part is then mounted in the fixture and a second time period reading taken. The rotational moment of inertia for each of these two measurements may be computed by using the formula:

$$I = Ct2$$

where C is a calibration constant for the instrument and is related to the torsional stiffness of the torsion rod. The moment of inertia of the test part is then computed by subtracting the tare inertia from the total inertia (the inertia without the test part mounted on the instrument).

Using this inverted torsion pendulum, accuracies as high as 0.1 % have been achieved and measurement accuracies as great as 0.03 % are possible using specialized measurement techniques (such as the averaging of ten readings and the use of calibration weights which duplicate the mass and moment of inertia of the test object). Unlike hanging wires or other traditional moment of inertia measuring methods, this technique closely defines the axis of measurement and permits measurements to be made through an axis which does not coincide with the center of gravity of the test object, without introducing aberrant motions such as swaying. Since the instrument is capable of determining CG location, moment of inertia measurements may be corrected to give the value which would be obtained if a measurement were made through the center of gravity. This correction consists of squaring the deviation of the center of gravity from the measurement axis and multiplying it times the mass of the test part. This axis of translation moment of inertia value is then subtracted from the measured value to yield the value of moment of inertia through the test object center of gravity. This calculation is made automatically by the computer.

**Effect of Test Part Weight** Since the weight of the test part is totally supported by the spherical gas bearing and none of this force is applied to the torsion rod, the instrument is insensitive to test object weight and may be calibrated using a single test mass. The moment of inertia indication will then be linear over the full range of weight and moment of inertia specified for the instrument.

**Effect of Oscillation Amplitude** These instruments exhibit negligible change in oscillation period for differences in oscillation amplitude as great as 3 to 1. The highest accuracy versions of these instruments employ a second photoelectric sensing mechanism which re-sets the digital counter until a preset amplitude of oscillation is reached. Using this technique, the time period of oscillation is always measured at precisely the same oscillation amplitude, eliminating this variable.

Minimum Moment of Inertia Which Can be Measured The smallest moment of inertia which can be measured with a particular size instrument is primarily a function of the tare moment of inertia of the instrument. If the part inertia is 100 times the tare inertia of the instrument, then a small change in tare inertia will not appreciably affect accuracy. If the part inertia is 11100th of tare inertia, then a 2°F change in ambient temperature will introduce a 0.5 % error in the reading of the part inertia due to the small increase in tare. This means that frequent re-calibration and tare measurement are necessary to get meaningful results if the test part moment of inertia is much smaller than 1/20 of the tare moment of inertia of the instrument. Other factors which normally limit the minimum moment of inertia which can be measured with a torsion pendulum, such as random variations in time period measurement, are not of practical importance for this instrument, since repeatability is better than 1 part in 100,000 on time period measurement.

Since the fixture adds to the tare inertia of the measuring system, its moment of inertia should be made as small as possible when measuring parts with small moment of inertia.

Effects of Internal Damping in the Torsion Pendulum There are two common sources of damping in a torsion pendulum used to measure moment of inertia: first, the windage of the test part contributes some damping (depending on the diameter and the shape of the part); second, the centering bearing and the internal losses in the wire damp the oscillations. An important observation can be made with regard to internal damping. Since the effect of a given amount of damping, B, is inversely proportional to the moment of inertia of the oscillating assembly, increasing the amount of moment of inertia will decrease the effect of a given amount of damping. This observation assures us that if the basic damping of the torsion pendulum when measuring the tare moment of inertia is small enough so that its resulting change in time period can be neglected, then the damping of the basic torsion pendulum can also be neglected when measuring a test part. Or, stated very simply, if more than 100 oscillations are required for the peak amplitude of the torsion pendulum to decay to 1/10 of its original value, when no object is mounted on the torsion pendulum, then the effect of internal damping in the torsion pendulum can be neglected. This, in fact, is the case for all gas bearing torsion pendulums which have been constructed by Space Electronics.

A second observation can also be made with regard to the effect of damping. Since the change in the apparent moment of inertia is a function of the ratio of the viscous damping to the critical damping for the system, and since the critical damping is proportional to the square root of the torsion spring constant, then increasing the torsional spring constant will reduce the effect of viscous damping, whether it be internal in the instrument or due to windage of the test part. This means that a stiffer torsion pendulum will exhibit less error due to damping. This observation does not hold true when the velocity of the oscillating pendulum reaches the point where the air becomes turbulent.

The effect of windage damping may be minimized by operating the instrument in a helium environment. (See Appendix A for a discussion of the use of helium).

## POI Error Analysis

### Basic measurements and assumptions

Weight of base assembly is estimated at 1500 lb.
MOI of base about vertical axis is estimated at 326,000 lb-in$^2$.
MOI of base about horizontal axis through CG estimated at 286,000 lb-in$^2$ (62 slug-ft2).
CG of base is located approx. 16.5" above bottom plate.
Weight of bearings/moment tube assembly is approx. 48 lb.
CG of bearings/moment tube assembly is approx 7.52" below upper transducer.
Transverse MOI of bearings/moment tube assembly is approx. 1700 lb-in$^2$ (.367 slug-ft$^2$).

### Analysis of Math used in calculations

Required sensitivity from the specification:

| SPEED | CENTER OF GRAVITY | | | PRODUCT OF INERTIA | | |
|---|---|---|---|---|---|---|
| | SENS. | $F_3$ (lb) | $F_4$ (lb) | SENS. | $F_3$ (lb) | $F_4$ (lb) |
| 50 | .0022 lb-in | .0003 | .00018 | .09 lb-in$^2$ | .00016 | .00016 |
| 100 | .00071 lb-in | .00061 | .00025 | .022 lb-in$^2$ | .00020 | .00020 |
| 150 | .00033 lb-in | .00075 | .00027 | .01 lb-in$^2$ | .00021 | .00021 |
| 200 | .00019 lb-in | .00081 | .00027 | .0056 lb-in$^2$ | .00021 | .00021 |
| 250 | .00012 lb-in | .00084 | .00028 | .0036 lb-in$^2$ | .00021 | .00021 |
| 500 | .00003 lb-in | .00090 | .00028 | .001 lb-in$^2$ | .00021 | .00021 |
| 800 | .00001 lb-in | .0013 | .0004 | .0005 lb-in$^2$ | .00018 | .00018 |

(The above forces were derived from the moment summation equations for the instrument spindle and force measurement structure).

Assume that Max force error allowable is equal to 25 % of the worst case for each speed listed above. In almost all cases, the limiting specification is the required POI sensitivity. The actual required force sensitivities are listed below.

| SPEED | UPPER | LOWER |
|---|---|---|
| 50 | .000040 lb | .000040 lb |
| 100 | .000040 lb | .000040 lb |
| 150 | .000040 lb | .000042 lb |
| 200 | .000042 lb | .000042 lb |
| 250 | .000042 lb | .000042 lb |
| 500 | .000042 lb | .000042 lb |
| 800 | .000036 lb | .000036 lb |

. Conclusion: Force sensitivity required is approximately 0.000040 lb for 50-800 rpm for both upper and lower transducers.

The worst case threshold for the force transducers is 112 μ lb. Tests run at Space Electronics have determined that the typical threshold in our system is approximately 30 μ lb.

**Charge amplifier analysis** We were unable to locate a charge amplifier which met the very difficult noise and linearity specifications required for this instrument, so we developed an ultra low noise amplifier for this application. Integrated circuits are selected for low noise characteristics.

Transducer output is 115 pC/N (511.6 pC/lb). The required charge sensitivity for the force sensitivity derived in paragraph 2.3 is .0205 pC.

Since the feedback capacitor in the charge amplifier is 150 pf, the above charge sensitivity will yield a voltage sensitivity of 0.136 mV.

Charge amplifier noise analysis

Noise voltage of operational amplifier: 0. 7 μV P-P

Noise current of operational amplifier: 0.01 pA/ Hz. Since the source capacitance of the force transducer is 26 pf, the voltage gain of the first stage is 1.52. After making certain assumptions, this yields a noise voltage of 28 μV P-P at the first stage output. Since the maximum gain of the switchable gain stage is 10 and the noise contribution of the second stage amplifier is negligible, the noise at the output of the charge amplifier is 280 μV P-P.

The noise contribution of the servo feedback amplifier (IC7) is negligible because of its narrow pass band. Noise introduced by the D-A chip (IC4) is assumed to be negligible.

The nominal noise level at the charge amplifier output at maximum gain is therefore 280 μV. The charge amplifier output at the published sensitivity is 1.36 mV (a factor of 4.9 greater than the noise level).

**Vibration of drive motor**

The drive motor balance tolerance allows a maximum of 0.0015 inch P-P motion for the 1750 RPM motor, measured at the bearing housings with the motor on soft mounts at rotation speeds above the basic resonance of the motor and mount system.

The motor and gearbox are rigidly mounted to a plate. The total weight of this assembly is approx 40 lb. Since the motor is located at one end of this assembly, we assume a moving mass of 1 slug. The stiffness of the two rubber mounts at the motor end of the assembly is 572 lb/ft in shear and 3120 lb/ft in compression.

Vertical resonance is 8.9 Hz. which corresponds to 533 RPM at motor and 122 RPM at the spindle.

Horizontal resonance is 3.8 Hz. which corresponds to 52 RPM at the spindle.

0.0015 inch **P-P** motion of the motor will result in .001 inch P-P motion of the motor assembly (because of the greater mass).

.001 inch **P-P** motion results in 0.048 lb P-P horizontal force and 0.26 lb P-P vertical force.

The machine base has the following basic characteristics:

The MOI about a horizontal axis through the instrument CG is approximately 62 slug-ft2

The total mass is about 47 slugs

The MOI of the suspended assembly about a horizontal axis through its CG is about 0.37 slug

The mass of the suspended assembly is about 1.5 slugs.

The way that the motor is mounted means that horizontal motor motion will result in horizontal base motion and rotation of the base about a horizontal axis parallel to the motor shaft axis. Vertical motor motion will result in vertical base motion and rotation of the base about a horizontal axis perpendicular to the motor shaft axis. Transducer forces resulting from vertical base motion will be small, second order effects. The other motion modes will result in direct reactions on one or both transducers. Horizontal motor motion will also result in rotation of the machine base about a vertical axis, but this also will introduce only second order forces on the transducers.

Considering the instrument geometry, it is possible to approximate the transducer forces resulting from the motor vibration. If the instrument base is assumed to be flexibly mounted to the floor so that only its mass resists the shaking of the motor assembly, then the peak force on the upper transducer will be 0.002 lb. The peak force on the lower transducer will be 0.0008 lb.

If the base is assumed to be rigidly mounted to a mass of concrete 6" X 6' X 6' (84 slugs) then the resulting force on the upper transducer will be 0.0004 lb and the force on the lower transducer will be 0.0002 lb. peak. These forces are respectively 10 and 5 times larger than the required force sensitivity for this instrument.

Since the motor assembly resonates at about 120 RPM, the forces on the upper transducer can be much larger at that speed (possibly as much as .0016 lb peak). Actual measurement data indicates that this resonance is not significant. The relatively high damping factor of the rubber mounts probably accounts for this.

The motor assembly is mounted to an aluminum channel that is attached at each end of the base supports. The resonant frequency of this system is 84 Hz (motor speed of 5040 RPM). This is 1.44 times the highest motor speed. No evidence of this resonance showed up in any of the test data.

At the maximum operating speed the drive frequency to the motor is 120 Hz. This is approximately the same as the measured mechanical resonance of the spindle assembly, but does not appear to introduce any additional excitation of this resonance.

**Accuracy of the computer A/D input board**

The measurement uncertainty in the A/D board is 0.003 % of reading and the resolution is 0.3 x $10^{-3}$ volt at the *AID* board input. 2.28 x10•$^{3}$ pico-coulombs referred to the charge amplifier input. This corresponds to a force resolution of 4.46 ½pound.

At the maximum gain, F.S. (lOV) at the A/D board input corresponds to 0.5 V at the feedback capacitor on the charge amplifier

For the 150 pf feedback capacitor, 0.5V corresponds to a charge of 75 pC.

Since our transducer sensitivity is 511.6 pC/lb, 75 pC corresponds to 0.147 lb.

The measurement uncertainty (0.003%) corresponds to 4.4 ½Lb force at the transducer.

4.4 *µLb.* (the effective *AID* accuracy reflected to the transducer) is much smaller than the required force resolution of 40 ½lb.

**Residual moment from torsion rod couplings**

We were unable to locate commercial couplings with the high torsional stiffness and required low bending moment stiffness and hysteresis required for this application, so we have designed custom couplings using a special high strength alloy.

Bending moment stiffness of the coupling was measured to be 12 in-lb/rad for small deflections.

The typical misalignment angle of the coupling is 0.0011 rad (.002 inch TIR runout at 0.875" distance from the element). The induced moment is therefore 0.0132 lb-in at both couplings.

The above moment will apply a force on the upper bearing of 0.0007 lb peak. The force on the lower bearing will be 0.0009 lb peak. These values correspond to 0.5% and .6% of the full scale forces for the respective transducers at maximum gain. These forces are 17.S and 22.5 times greater than the required force resolution for the upper and lower transducers respectively. However, hysteresis is very small so these forces occur in both tare and part measurement, and the difference is well within limits.

**Deflection of flexure plates**

The stiffness of the flexure plates in the plane of the plates (i.e. at right angles to the transducer axis) is 400,000 lb/in for both plates acting together. This value includes both shear and bending deflections of both the thin webs and the thicker section of the plates.

The stiffness of the transducer is 22,840 lb/in along its measurement axis. The stiffness in the transverse direction is much smaller than the transverse stiffness of the flexure plates. The transducer sensitivity to transverse loads is less than 5% of its sensitivity to normal loads.

From the above, the cross-axis output will be equivalent to 0.00125 lb with a full scale (5 lb) load applied at right angles. This corresponds to an angle error of 0.014 degrees.

**Transducer accuracy**

The linearity error for the transducer is less than ± I% of full scale, which predicts a maximum error of 0.1 lb.

The specified hysteresis for the transducer is ÷0.5% of full scale. This translates to a maximum error due to hysteresis of 0.055 lb.

The specified temperature sensitivity of the transducer is -0.02%/°C. This corresponds to an error force of .0022 lb/°C

**Angle error**

The angle resolution limit of the software is 0.02 degrees. Typical angle accuracy obtained during a measurement is ±0.1 degrees.

## Motor speed error

The following table illustrates the spin speed measurement accuracy required to meet the published POI and CG specifications at various nominal spin speeds.

| Spin speed accuracy required to meet CG or POI specification | NOMINAL SPIN SPEED | | | | | |
|---|---|---|---|---|---|---|
| | 50 | 100 | 150 | 250 | 500 | 800 |
| POI | 0.96 APM | 0.89 RPM | 0.68 RPM | 0.43 RPM | 0.31 RPM | 0.30 RPM |
| CG | 0.5 RPM | 0.32 RPM | 0.27 RPM | 0.15 RPM | 0.07 RPM | 0.04 RPM |

The system measures spin speed using a 6 digit auto-ranging timer with 50 parts per million stability over the operating temperature range. Absolute timing accuracy is not a factor because the same timer is used during system calibration. The relative error in spin speed measurement at 800 RPM resulting from the counter stability error is 0.04 RPM. The relative error at 50 RPM is 0.003 RPM.

## Conclusions

The transducers and charge amplifiers are accurate enough to meet the required system accuracy and resolution. The most significant factor is the force threshold of the transducer.

Semiconductor noise is not a limiting factor in the system accuracy.

Drive vibration can be a limiting factor, and care must be taken to limit its effect. The most effective method is to closely couple the instrument base to a large mass of concrete.

The accuracy and resolution of the *AID* circuitry are much better than necessary to meet the required system specifications.

The cyclic forces induced by the torsion rod couplings have a significant effect on system accuracy and resolution. The current design is adequate to meet the required system specifications.

The flexure plates used to suspend the spindle assembly do not have a significant effect on system accuracy.

Motor speed measurement accuracy is insignificant to overall system accuracy except at and near 800 RPM

**Error in measuring POI and CG when the test specimen has both forms of unbalance.**

One of the questions that users of spin balance machines ask most frequently is "How accurately can you measure CG"? This is a difficult question to answer because several factors affect CG accuracy In particular, the magnitude of POI unbalance will affect the error in CG offset determination. The following study outlines the elements which influence accuracy in dynamic balancing equipment and provides a method of determining the probable accuracy of the balancing machine under various conditions.

To begin, we consider the physical elements of the measurement system and the calculations performed by the computer. The known quantities are:

- Upper Transducer force (amplitude and phase of sinusoidal signal)
- Lower Transducer force (amplitude and phase of sinusoidal signal)
- Rotation speed
- Distance between transducers
- Distance from upper transducer to mounting plate of instrument
- Distance from mounting plate to test object CG
- Force measurement accuracy for each transducer
- Test object weight

The variables which are to be calculated from these values are:

- POI
- CG
- POI accuracy
- CG accuracy

The calculations in the POI instrument program replace the multitude of unbalances within a payload with a theoretical balanced test object where the total unbalance is represented by two weights located in the XZ plane (Z axis vertical), each weight at a known, but different height above the instrument mounting plate. Both weights are assumed at the same radius.

A similar pair of weights (generally of different mass) can be assumed to be located at the same heights and radii in the YZ plane, and after the masses are determined in both planes, they can be combined using vector summation.

Moments can be summed about the upper and lower transducers to develop two equations describing the upper and lower transducer forces in terms of the balance weights, heights, radius, rotation speed, and physical measurements of the instrument.

$$W_1 * R * \left[1 + \frac{RPM^2 * (H_1 + H_3 + H_0)}{35207}\right] + W_1 * R * \left[1 + \frac{RPM^2 * (H_2 + H_3 + H_0)}{35207}\right] + F_3 * H_0 = 0$$

$$W_1 * R * \left[1 + \frac{RPM^2 * (H_1 + H_3)}{35207}\right] + W_2 * R * \left[1 + \frac{RPM^2 * (H_2 + H_3)}{35207}\right] - F_4 * H_0 = 0$$

where:

$W_1$ = The mass of the upper unbalance weight
$W_2$ = The mass of the lower unbalance weight
RPM = The measurement speed in Revolutions per minute
$H_1$ = The height of the upper unbalance weight above the top of the table
$H_2$ = The height of the lower unbalance weight above the top of the table
$H_3$ = The distance between the table top and the upper transducer
$H_0$ = The distance between the upper and lower transducers
35207 = a constant for units conversion
$F_3$ = The force at the upper transducer
$F_4$ = The force at the lower transducer

In the POI program, the above equations are solved for the values of the unbalancing weights, and then POI and CG are derived from the weight values, heights, and radius. If the operator has elected to balance the test object, the program then makes use of the balancing plane heights and radii that he has entered to calculate correction weights for the test object unbalance.

In order to study the effect caused by inaccuracies in determining the transducer forces, we make use of the same equations used by the POI instrument. First we plug some typical force values into the above equations and then solve for the POI and CG. Then one or both of the transducer forces is changed by a small increment, representing the force measuring error, and the above calculations are run again. The change in the calculated POI and CG values is noted. By following this same procedure for many different force magnitudes, it is possible to tabulate the effect of force measurement accuracy for a wide variety of POI and CG values.

The form of the equations makes it extremely cumbersome to solve for the effect of an incremental change in transducer force on the POI and CG.

As an alternative, a spreadsheet can be set up to perform the above calculations. If the specific software program employed provides a goal-seeking capability, it is possible to determine forces that result in a specific CG and POI configuration. Of particular interest are forces that result from a large CG offset and a small POI or from a large POI and a small CG offset. The spreadsheet is used to tabulate the effect of small force measurement errors on a range of magnitudes of the above configurations.

| RPM | UPPER FORCE | LOWER FORCE | CG (lb-in) | POI ($lb\text{-}in^2$) | CG ERROR (lb-in / lb) | POI ERROR ($lb\text{-}in^2$ / lb) |
|---|---|---|---|---|---|---|
| 20 | 1.00 | -1.00 | 0.00 | 3581 2 | 0.880 | 153.4 |
| 20 | 1.00 | -0.7688 | 20.34 | 0.00 | 0.885 | 155.9 |
| 20 | 50.0 | -50.0 | 0.00 | 179,061 | 0.889 | 156.5 |
| 20 | 50 | -38.44 | 1017 | 0.00 | 0.889 | 154.9 |
| 20 | 1.00 | 1.00 | 176.0 | 27,408.3 | 0.871 | 153.4 |
| 30 | 1.00 | 1.00 | 78.24 | 6,707.6 | 0.387 | 41.08 |
| 30 | 1.00 | -1.00 | 0.00 | 1,591.7 | 0.387 | 41.08 |
| 30 | 1.00 | -0.616 | 15.00 | 0.00 | 0.387 | 41.07 |
| 50 | 1.00 | 1.00 | 28.17 | 1,405.8 | 0.139 | 9.796 |
| 50 | 1.00 | -1.00 | 0.00 | 572.99 | 0.139 | 9.796 |
| 50 | 1.00 | -0.4209 | 8.156 | 0.00 | 0.139 | 9.796 |
| 100 | 1.00 | 1.00 | 7.041 | 245.04 | 0.0349 | 1.922 |
| 200 | 1.00 | 1.00 | 1.76 | 54.61 | 0.00872 | 0.448 |
| 200 | 50.0 | 50.0 | 88.02 | 2730.5 | 0.00889 | 0.457 |
| 400 | 1.00 | 1.00 | 0.440 | 13.237 | 0.00218 | 0.110 |
| 800 | 1.00 | 1.00 | 0.110 | 3.283 | 0.000545 | 0.0273 |

The above data are calculated for a Space Electronics model POI-1000 instrument with 50 lb force transducers. Similar data can be calculated for other instruments.

Once these data are determined, it is possible to write equations to describe the data. The first conclusion obtained from the data is that for any speed, the expected POI error and CG error are each approximately proportional to the largest of the forces measured by the two transducers. It is thus possible for any given rotation speed to derive a factor for POI or CG error and multiply by the largest measured transducer force to predict the probable error. From the appearance of the data, equations are assumed to be of the form:

$$POI\ ERROR = MAXFORCE \left( A + \frac{B}{RPM} + \frac{C}{RPM^2} + \frac{D}{RPM^3} \right)$$

$$CG\ ERROR = MAXFORCE \left( F + \frac{G}{RPM} + \frac{H}{RPM^2} \right)$$

The process of linear regression is employed to determine the best coefficients to fit the error data from the spreadsheets. The resulting equations are then programmed into the report generator in the POI software.

The preceding analysis makes it possible to make some suggestions for maximizing the accuracy of measurements made on spin balance machines.

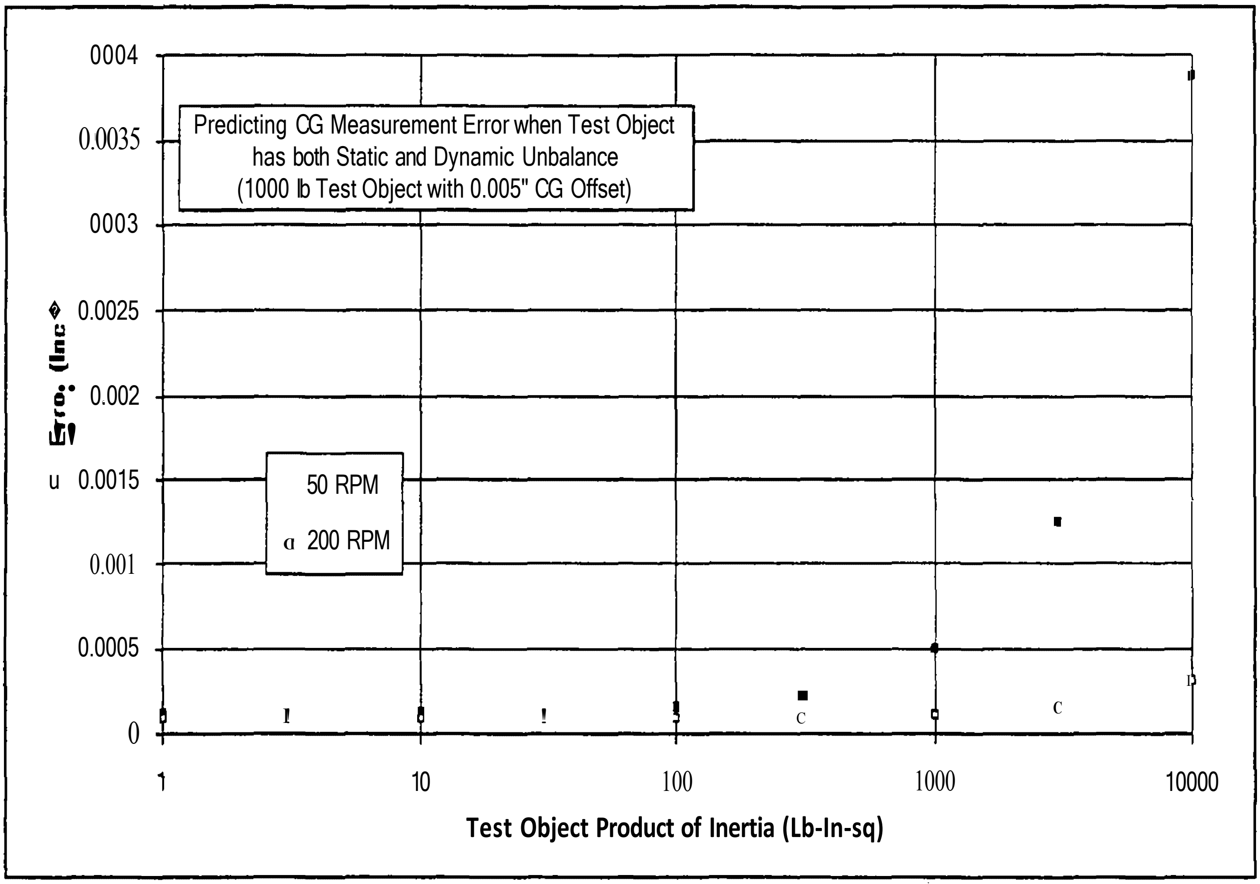



**Figure 8**

1. Fixture the part for minimum CG height and radial CG offset. CG height and radial offset both increase the maximum force at the transducers (particularly the upper transducer), and POI and CG measurement error both increase in proportion to maximum transducer force.

2. Balance the fixture. Forces contributed by the fixture unbalance frequently add to those contributed by the part unbalance and thus increase the measurement error resulting from transducer inaccuracy. Also, tare forces must be subtracted from measurement forces during calculations, and the small force measurement uncertainty (approximately 1% of reading) will be magnified if the net forces are smaller than the tare or combined measurement forces.

3. Measure at a moderate speed if the test object has a significant CG offset. The force transducer accuracy is best when they are loaded near the middle of their measurement range. There is a static moment component due to CG offset which predominates at speeds below 40 RPM, and this tends to cover up the very small dynamic components caused by POI at these speeds.

4. Balance the test object. It is very difficult to obtain accurate measurements on a test object which has a large inherent imbalance. For example, in order to obtain accurate POI measurements on a test object with a large CG offset, it may be best to correct the CG offset first. Then the POI may be measured accurately, and if necessary, the effect of the CG correction weights allowed for.

5. Use the most accurate force transducers available for the force range expected. Space Electronics has expended great time and effort to provide the best transducers and signal conditioning available with current technology.

6. Measure at a moderate to high speed if the test object and fixture have small unbalances. For balanced parts, the most significant accuracy factors are the force threshold of the transducers, combined with the noise induced by floor vibration, electromagnetic pickup, and internal sources. For relatively small, smooth objects, use a high measurement speed in order to produce larger force values at the transducers. For large or rough objects, use a moderate speed to obtain the best compromise between transducer force and windage errors. The speed can be increased if you use a helium atmosphere. (See Appendix A for a discussion of the use of helium).

**Gas Bearing** One key to the outstanding performance of this mass properties instrument is the choice of bearing. Older balancing machines used roller bearings which were carefully preloaded for maximum stiffness. Even the best roller bearing is 1000 times less stiff than a good gas bearing, since some clearance must be permitted or the roller bearing will seize when it changes temperature. Even more important, the performance of a roller bearing rapidly deteriorates as it wears or becomes contaminated. A roller bearing has an inherent limit in runout and bearing noise, since the rollers can never be made exactly the same diameter.

| **Gas Bearings** | **Ball or Roller Bearings** |
|---|---|
| Runout: 0.000,001 inch | Runout: 0.000,050 inch |
| Small deflection stiffness: 1,000,000 lb/inch | Small deflection stiffness depends on preload and can be as low as 1000 lb/inch |
| Wear: none | Wear: depends on unbalance, preload, and speed |
| Resistance to dirt: excellent | Resistance to dirt: very poor |
| Friction: less than 0.01 lb-in | Friction: varies with preload and temperature; typical balancing machine spindle is at least 1 lb-in and can be 50 lb-in |

**Gas bearings are better than ball or roller bearing in every way**

As described previously, this mass properties machine uses a spherical gas bearing to support the weight of the test part and a cylindrical gas bearing to provide the restraint to overturning moment. Hydrostatic gas bearings contain no rollers or balls. Instead, the lubrication is provided by a continuous flow of gas in a narrow precision gap between the rotor and stator. Gas is injected through small diameter orifices which meter the flow and provide the dynamic action of the bearing. These orifices are formed from a synthetic sapphire jewel through which has been drilled a small flared hole. These bearings have extraordinary stiffness due to their active feedback; as the gap is closed, the flow is reduced, resulting in pressure buildup which tends to force the bearing rotor back to its central position. Gas bearings are self centering due to their dynamic action, and noise and runout are almost unmeasurably low. There is no wear in a gas bearing if it is properly operated. We have seen gas bearings which have been in daily operation for 20 years without any sign of deteriorated performance. Because clean dry gas flows out of the bearing during use, it is inherently self cleaning and is the least sensitive of all types of bearings to dirt in the environment. The only drawback to a gas bearing is its high cost.

The Space Electronics Model POI2200 mass properties machine uses a 14 inch diameter spherical upper bearing and a 6 inch diameter cylindrical bearing which is 6 inches long.

Disadvantages of an Oil Hydrostatic Bearing This instrument could conceivably be made with an oil hydrostatic bearing. This bearing is similar to a gas bearing, but it uses high pressure oil in place of air or nitrogen for the lubricating medium. High pressure oil hydrostatic bearings have some of the advantages of gas bearings. Because there are no balls or rollers, the runout is almost as small as a gas bearing. Bearing noise is higher than a gas bearing, due to the turbulent flow of the high pressure oil. There is a basic danger when using a pressurized oil bearing--if the hydraulic power supply fails, then the bearing will touch down before the machine can be brought to a stop, destroying both the bearing and the item under test. Gas bearings do not have this problem, since as much as 2 minutes of gas can be stored in a tank located right next to the bearing; if a check valve is placed at the input of the tank and a pressure switch installed on the other side of this check valve, then the motor drive can be shut down before the gas pressure at the bearing drops below safe levels. Oil is incompressible, so that a similar system cannot be used with an oil bearing. (This basic drawback with an oil hydrostatic bearing can be partially overcome by incorporating a second mechanical bearing as a backup.) Bearings using high pressure oil are not suitable for use in a clean room environment, since the oil mist contaminates the air. There are also two minor nuisances with oil bearings: the hydraulic power supply tends to be noisy, and there is usually a film of oil throughout the machine, making it somewhat messy to work near.

The biggest disadvantage of a hydrostatic oil bearing is that the amount of friction is too great to be used as an inverted torsion pendulum to measure moment of inertia, so an additional gas bearing has to be mounted on top of the basic machine to provide moment of inertia capability. This type of flat gas bearing has very poor overturning moment stiffness, resulting in instability when tall test items are measured.

Performance Tests Some manufacturers of mass properties machines go to great lengths to restrict the conditions of the performance tests so that the machine will not experience the more difficult environment of a typical item under test. The following warnings should be observed:

[l] Any balancing machine will give the right answer when measuring either a pure product or a pure CG offset. The unbalance weights should be selected so they result in both CG offset and product of inertia simultaneously (for example, place the upper weight at 900

from the lower weight).

[2] The test rotor should ideally have significant mass. Any machine has a much higher resonant frequency when test weights are mounted directly on the table, rather than placing them on a test rotor whose weight is 50% of the capacity of the machine (spin speed may have to be restricted for heavy rotors).

[3] Machine readout should be digital. If the readout is a meter or a dot on a polar graph, then different operators can read different answers, and the evaluation of performance becomes a question of what angle to look at the meter or what interpretation to give a large dot on a fine grid.

## Balancing Machine Installation

**NOTE: Although this was written as a guide to installing balancing machines manufactured by Space Electronics, the information presented here in applicable to any mass properties measurement machine. Because of their extremely massive construction, Space Electronics spin balance machines are less sensitive to foundation type than most balancing machines. However, optimum operation will occur if the following recommendations are observed. Environmental considerations such as expansion due to temperature change are a fact of nature, not peculiarities of our machine, and will occur with any balancing machine.**

## Optimum Location

**Ground Vibration** The full sensitivity of the balancing machine will never be realized if the location chosen for the machine has a high level of ground vibration. There is no practical way to isolate a balancing machine, since the frequency of rotation of the machine is as low as 0.17 HZ, requiring the resonant frequency of the spring mass isolation system to be below 0.001 HZ. Even an air spring system with a huge concrete block usually has too high a resonant frequency, and any isolation system would not provide the rigidity and the level stability required. There is simply no substitute for a quiet location.

Conventional vibration measuring equipment such as accelerometers or velocity pickups are not capable of measuring vibrations of the frequency and level that affect a balancing machine. The balancing machine is sensitive to horizontal ground vibration in the frequency range 0.05 HZ to 20 HZ with amplitude as small as 2 millionths of an inch displacement (peak-to-peak). The only vibration measuring equipment capable of detecting such vibrations is the type of pickup used to measuring seismic vibrations in oil exploration. However, the problem is somewhat more complex, since the tracking filter in the balancing machine rejects vibrations which are not synchronous with the rotation of the machine, so that it is difficult to predict what effect a certain level of vibration will have. Here are some guidelines for the location of the balancing machine:

> BAD LOCATIONS: Do not locate the balancing machine near compressors, vacuum pumps, vibration test equipment (shakers), punch presses or other machine tools that have a reciprocating motion. Stay away from aisles where there is continuous lift truck traffic.

GOOD LOCATIONS: The lowest ground vibration is generally found in small remote outbuildings, corners of a building, office areas, areas near clean rooms or light assembly.

**Size of Room** Usually the size of the room is defined by the size of the largest payload to be balanced. A minimum of 36 inches clearance should be provided between the payload and any partitions. This will minimize the air turbulence which occurs when any protrusions on the object pass the partition. If the largest payload is less than the diameter of the calibration beam supplied with the instrument, then this becomes the limiting factor. The calibration beam is used to determine the moment of inertia calibration constant.

Ceiling height will also depend on the size of the maximum test part to be installed on the instrument. It is important to also consider the following:

1. Most overhead cranes require a minimum of 36 inches height for the crane mechanism.

2. Most slings, chains, and cable assemblies require from 12 to 36 inches of additional height.

3. Many fixtures require that the test object be raised a minimum of 24 inches straight up in order to extract the test object from the holding fixture.

4. If measurements are made in a helium or shrouded air atmosphere, it may be necessary to lift the shroud straight up until its lower edge clears the highest part of the test object.

In areas where ceiling height is a problem, it may be possible to provide a pit in the foundation to reduce the apparent height of the instrument. This pit must be large enough to provide clearance all around the instrument for maintenance. The area around the instrument should be closed with removable steel decking, so no one will accidentally fall into the pit and also to provide a surface to stand on while installing the payload in the fixture.

**Foundation** Hard bearing (force measuring) balancing machines require a heavy solid foundation. The ideal foundation consists of a mass which weights 100 times the maximum test part weight. This gives the balancing machine rotor something to react against. In a force measuring machine, transducers measure the forces against the bearings of the machine due to part unbalance. One side of the transducer is connected to the bearing stators and the other side is connected to the balancing machine frame. It is impractical to make this frame weight more than about 2000 lbs. If the frame were mounted on a soft spring, then the frame would move in response to unbalance in the test part, reducing the sensitivity of the machine, and producing angle errors due to phase shift. In order to increase the effective mass of the frame, this frame should be rigidly coupled to a heavy concrete mass.

For a machine with 2200 pound maximum test item weight, the ideal foundation would be a concrete block 24 inches thick and 25 ft by 25 ft wide set in the ground (do not use isolation under the pad, but separate this foundation from the rest of the floor by installing styrofoam pads against the existing floor before pouring the concrete). An 8 inch thick concrete floor which is not tied to the walls of the building and which is a minimum of 10 ft by 10 ft is satisfactory. A 6 inch thick concrete floor which is a minimum of 12 ft by 12 ft isn't too bad. For Models POI-50 and POI-150 an ordinary concrete floor 4 inches thick is adequate.

A heavy foundation is useless unless the balancing machine is rigidly attached to it. We recommend that the machine be anchored to the foundation, using lag bolts which are at least 5/8 inch in diameter. The type of anchors used should be capable of holding when the nuts on top of the lag bolts are tightened to close to their maximum recommended limit. One inch long expansion type anchors will pull right out and should• not be used. The balancing machine sits on steel levelling pads. After mounting the anchors and moving the machine into position, temporarily lift the machine, clean the concrete under the feet, and smear a thin coat of a grout or epoxy on the cement under the feet. This grout provides additional coupling between machine and floor. Spray the underside of the feet with mold release (otherwise the machine will be permanently stuck to the floor). Then lower the machine into position and tighten the lag nuts, so that all of the excess grout is squeezed out. The type of grout used should be hard when set, but capable of curing even when in a thin layer. Don't forget the mold release on the underside of the feet. Otherwise you will need a sledge hammer to loosen the feet if you ever want to move the machine. Level the machine before tightening the hold down nuts (these nuts can be loosened and the machine re-levelled at a later date if desired without upsetting the grout).

Larger instruments must have the complete area beneath the instrument base filled with a layer of grout. Holes are provided in the instrument base for pouring the grout, and directions are supplied with the instrument.

**Temperature Range** Temperature has two effects on measurement accuracy: first, temperature affects the properties of the part itself (an increase in temperature will increase the moment of inertia of the part; sudden changes in temperature along one side of the part will bend the part, causing unbalance); second, temperature CHANGES will introduce errors in the measurement. Both of these limits are a basic fact of physics and not a defect in the design of the balancing machine.

**Storage temperature** The minimum temperature recommended is 33 degrees F. Below that temperature the water in the air dryer freezes. The maximum storage temperature is 131 degrees F. (computer limit).

**Operating temperature** The balancing machine will operate at any temperature between 50 degrees F and 120 degrees F. More important is the rate of change of temperature. Temperature change causes a number of problems:

a. Moment of inertia limit The tare moment of inertia of the instrument changes with temperature. This is the primary limit on the minimum moment of inertia which can be measured. For small test parts, the tare moment of inertia of the instrument may be larger than the moment of inertia of the part. If this tare MOI changes between the time is measured alone and the measurement of part and machine, then this will result in an error in measured part MOL This can be checked by repeating the measurements several times and noting the variation in measurement. The tare MOI of the instrument is about 1280 lb-in$^2$. A one degree F change in temperature will change the tare MOI by 0.03 lb-in$^2$ (and introduce an error of 0.03 lb-in$^2$ in the measurement if this change occurred between tare and part measurement sequences). This is the minimum error due to temperature; if a fixture is used, then its MOI must be added to the machine tare before computing the resulting error.

b. There is some temperature related variation in force output due to changes in the A/D converter and thermal expansion/contraction of the mechanical parts of the machine. Of significance is the change in output which occurs between the time the data is taken at O degrees and 180 degrees. For static CG this time interval is about 2 minutes; for spin balancing the time interval between the first and last measurement varies with speed but averages about 2 minutes. To meet the specified accuracy, the temperature should not change faster than 0.5 degree F per minute. This can be readily achieved by locating the machine is an area which is free of drafts, and shrouding the machine by placing it in a small room or surrounding it by sheets of plywood, etc. so the air in the vicinity of the machine changes very slowly. Do not have an air conditioner or heater duct near the machine. Do not locate the machine near an overhead door, even if this door leads to the inside of the building (the machine will absolutely not function if it is located near an overhead door which leads outside-- whenever the door is opened the rate of change of temperature would be 100 times greater than can be tolerated). If the machine is located near an outside wall, then it may be necessary to plug air leaks in the wall and/or add insulation to the wall in order to get full accuracy from the machine in the winter.

Calibration temperature range (If machine _has moment of inertia measurement option)

Calibration relies on the length of the calibration beam. This aluminum beam has a temperature coefficient of 12 PPM per degree F. The calibration moments and MOI values have been determined at 72 degrees F. This means that a 1 degree error in temperature will only cause a 0.001 % error in static CG calibration and a 0.002 % error in MOI calibration. The absolute temperature when calibrating is therefore not significant. Temperature CHANGE is again the critical factor. If the heating/air conditioning system can cause rapid changes in temperature (ie more than 0.5 deg F/minute), then we recommend that there be a means of shutting off the heating/air conditioning during each calibration sequence.

Electrical Power The instrument control console requires three wire 208/230 V, 60 Hz. single phase 15 amp power. The computer requires 115 V, 50/60 Hz power which can be obtained from the 208/230 V source if it is balanced with 115 V available from each leg. A ten foot long cable with a standard 230 V plug is provided. The user should provide a wall shutoff for the 230 V power.

**Instrument** Air The instrument requires a source of clean, dry, oil-free air of 90 - 100 PSIG, 3 CFM. The recommended dew point is 36 degrees F or lower, and the air should be filtered to 5 micron. Filters are provided at the instrument base to protect against occasional problems with the air supply. A storage tank is provided on the instrument mainframe to protect the instrument against sudden interruptions in the air supply while the instrument is operating. Usually the system quoted includes an air supply. Some cost saving will result if this air supply is eliminated. However, if the quality or reliability of the available air is questionable, it is recommended that the customer purchase a dedicated laboratory air supply from Space Electronics. Air supplies provided by Space Electronics are designed so that vibration and electrical noise will not degrade instrument performance.

**Materials Handling Equipment** If the test item weighs less than 50 pounds, then it can be loaded by hand. If it is heavier than this, the user must provide means of placing test objects and fixtures on the instrument interface. Overhead traveling cranes are ideal. It is essential that the device be capable of positioning parts with at least 1/8" precision in the horizontal directions. It must also be possible to lower heavy parts VERY gently onto the instrument interface. A hydraulic load positioner can be inserted between the lifting device and the test object to allow precise control during lowering. For parts weighing between 51 and 1000 lb, rolling gantries or boom cranes may also be suitable.

**Safety** Some protection should be provided for the operator against the possibility of loose objects left on the instrument interface or test object becoming airborne when the machine starts to spin. Even small balance weights or hardware may cause injury when ejected at several hundred RPM. For this reason, energy absorbing partitions such as welding curtains may be located between the instrument and the control console. Such partitions also serve to limit drafts and possible interference from onlookers.

It is further recommended that trenches be provided for the cables and hoses. If this is not possible, then on-grade protection must be provided where the bundles cross traffic areas.

**Discussion of Options** Several options are available which can simplify the use of a dynamic balancing machine. In many cases, the cost of the option is very small compared to the time saved. Some options make it possible to make measurements that cannot otherwise be done.

**Dial Indicator Stand** This is a tooling stand capable of holding two measurement indicators (displacement gages, optical correction plane locators, contour following pickups, etc.) at each of the two randomly selectable heights. Each device is adjustable in three different axes. Vertical adjustment is along a massive 4" diameter post which can be as high as 80 inches above the instrument mounting plate. The extremely rigid design minimizes the effect of vibration. The stand is mounted to the instrument base at a distance of approximately 30 inches from the centerline of the machine's rotational axis and is easily removable to accommodate large test objects. Two dial indicators are provided with the stand.

The dial indicator stand provides a means to accurately position test objects and fixtures on the instrument. Using the two indicators, tall, cylindrical test objects can be precisely aligned with the instrument rotation axis at several heights, verifying angular alignment and straightness. If the Tilt/Translation fixture described below is mounted on the instrument, the dial indicator stand provides the means to adjust it quickly to align any cylindrical test object.

Shrouds Installing a shroud around the test object can also improve instrument function. A properly designed shroud will provide operator protection from loose objects which may be ejected from the spinning test part. The shroud must be made from a strong, energy absorbing material such as lexan if it is to function in this capacity.

Another function of a shroud is to protect the test object from drafts. Drafts impinging on the test object are a major cause of error in MOI and CG measurements. Random air disturbances will also increase POI error and increase the time required to complete a measurement. Shrouds whose sole purpose is to eliminate drafts may be constructed of any material, even cardboard or paper. However, the shroud design must include sufficient structure to prevent the shroud from being drawn into contact with the spinning part by the considerable airflow around it.

Finally, a shroud may be used to contain a special atmosphere around the test object during the test. Specially designed shrouds have been used to make measurements in a vacuum, but this frequently causes practical problems for the spin balance machine. A more efficient method is to use a shroud to contain a helium atmosphere around the part. Most mass properties vacuum tests can be simulated accurately in helium at far lower cost. Shrouds made for this purpose are light and easily removed so they won't impede measurements when they are not needed.

Weight Platform This is one piece of auxiliary equipment that is frequently overlooked. An accurate weight value is necessary for determining the CG of a test object. Modern weighing platforms make use of the magnetic force rebalance transducer and can provide resolutions of one part in 300,000. Space Electronics can provide state of the art platforms which are directly connected to the host computer so that accurate weight data is automatically inserted into the CG and POI calculations.

Tilt/Translation Fixture This fixture has provision for both X and Y horizontal translation plus tilt in two directions. A dial indicator can be used to measure runout at the lower end of the payload, and a second indicator will indicate runout at the tip of the payload (see description of dial indicator stand). By adjusting the translation and the tilt, the runout at both the upper and lower indicators can be minimized, so that the geometric center of the payload is aligned with the axis of rotation of the instrument. The total weight of this fixture is less than 25 pounds, so that its tare moment of inertia has a negligible effect on the accuracy on the roll moment of inertia measurement.

Angle of inclination software For many applications, the objective of POI and MOI tests is to determine the angle of tilt of the test object principal axis. When this is the case, optional software can be installed on the host computer which automatically calculates the angle of inclination from the measured data. This greatly reduces the possibility of data entry and calculation errors.

**Data management software** The hard disc on the computer supplied with the mass properties measuring system is capable of storing the data from hundreds of measurements. However, without data base management routines, it becomes very difficult to retrieve the desired data. Data management software can be provided which consists of two software routines:

1. Software within the mass properties measurement program which writes the test results to the hard disk in a format that can be read by a compiled dBase program.

2. A custom-configured Dbase-compatible program that allows the operator to import new data, delete data, search, print, edit and display the data in a user specified format. All operations are selected from a user-friendly menu, so that knowledge of dBase is not required.

Because each user's data needs are different, this option is individually configured to create the report format required. If desired, spin data can be integrated with data produced by static balance or weight and CG machines.

Appendix A Using a helium environment to reduce the effects of air mass Mass properties measurements of lightweight objects designed to operate in the vacuum of outer space have traditionally been made in a vacuum chamber, in order to eliminate the errors due to the mass of the air surrounding the object. Vacuum chambers are expensive and inconvenient to use. Furthermore, a spin balance machine will not operate in a vacuum chamber unless extensive modifications are made (a different gas bearing is required, and cooling must be provided to the drive motors and to all electronic circuits).

The helium method consists of measuring the object first in an air environment and then in a helium environment. Since helium has 117th the density of air, the MOI due to both entrapped and entrained air will be reduced by surrounding the payload with helium. The MOI of the test object in a vacuum can then be extrapolated from these two measurements.

Since the helium is at atmospheric pressure, there is no need for a thick-walled chamber. Even a thin plastic enclosure will work. We have developed a proprietary method which prevents the mixing of air and helium. Since Space Electronics balancing machines are fully automatic and can measure both MOI and spin balance without operator adjustments being required, measurements can be made in a helium environment without the need to replenish the helium between POI and MOI measurements.

A further advantage of using a helium environment is that helium will not support combustion, so that the machine becomes inherently explosion proof.

This process is discussed in detail in SAWE paper number 2024 entitled Using Helium to Predict the Mass Properties of an Object in the Vacuum of Space by Richard Boynton, Robert Bell, and Kurt Wiener.

## Appendix B Hazardous Environment

Grounded Mounting Plate Since this machine uses a gas bearing, there is no electrical contact between the rotating spindle and the base of the machine. This could result in a static charge being generated in the payload. If the payload contains explosive or inflammable material, or could be damaged by static charge, then we can provide a special grounding brush which reduces the resistance between base and rotor to about 5 ohms. There is no need to lower this resistance below this value, since even a resistance of 100,000 ohms is sufficient to bleed off all static charge.

Explosion Proormg If the machine is to be operated in an explosive environment, then it must be constructed so that it cannot ignite any significant volume of explosive gas or powder, or if this gas is ignited, the flame is contained in a very rugged enclosure. The generally method of accomplishing this safety is to provide a positive pressure air purge inside the instrument, and have monitoring means which shut off the electrical power if this pressure falls below a preset level. There are two classes of explosion proofing, with two "divisions" for each class, and a number of "groups" within each division. We have found that most people haven't the slightest idea what all this means, so they order the safest type, even though it is more expensive and harder to use that the type they really need. The following summary describes the different classes, types, and groups:

CLASS I (Flammable Gases or Vapors) This is the class you need if flammable solvent vapors are present, or, God forbid, there is hydrogen or propane present. If the testing is done is a rocket assembly plant, then I recommend this class, since there are so many very dangerous vapors and gasses present, and the consequences of an accident are catastrophic.

Division 1 This is the kind of situation when the dangerous gas or vapor is present much of the time. Specifically, it:

1. Exists under normal conditions
2. May exist because of:
    - repair operations
    - maintenance operations
    - leakage
3. Released concentration because of:
    - breakdown of equipment
    - breakdown of process
    - faulty operation of equipment
    - faulty operation of process which causes simultaneous failure of electrical equipment

Division 2 This describes a situation where is it safe most of the time, but you don't want to take a chance.

1. Liquids and gases in closed containers or systems are:
    - handled
    - processed
    - used
2. Concentrations normally prevented by positive mechanical ventilation
3. Adjacent to a Class I, Division 1 location

Groups There are different groups for different kinds of vapors and gasses. Some are more dangerous than others (starting with acetylene which is the most dangerous).

Group A

Atmospheres containing acetylene

Group B

Atmospheres such as butadiene, ethylene oxide, propylene oxide, acrolein, or hydrogen (or gases or vapors equivalent in hazard to hydrogen, such as manufactured gas).

Group C

Atmospheres such as cyclopropane, ethyl ether, ethylene, or gas or vapors of equivalent hazard.

Group D

Atmospheres such as acetone, alcohol, ammonia, benzine, benzol, butane, gasoline, hexane, lacquer solvent vapors, naphtha, natural gas, propane, or gas or vapors of equivalent hazard.

CLASS II Combustible Dusts If you are testing assembled rocket motors, satellites, etc. then this is usually the class that applies to you. Powder or dust doesn't get into equipment as easily as gas or vapor, so the safety requiremen� are easier to meet. For example, under class I, you must purge the system with positive pressure long enough to allow 4 complete volumes of air to be exchanged, whereas for Class II, you turn on the positive pressure and you are ready to go.

Divisions The same rules apply as for Class I. Division 1 is for a frequent danger, and Division 2 is for a danger that only occurs if something goes wrong.

Division 1

1. In air under normal conditions
2. Ignitable mixture produced by:
    - mechanical failure of machinery
    - mechanical failure of equipment
    - abnormal operation of machinery
    - abnormal operation of equipment and provide source of ignition from:
        - □ simultaneous failure of electrical equipment
        - □ simultaneous failure of operation of protection devices
        - □ other causes
3. Electrically conductive dusts may be present

Division 2

1. Not normally in the air
2. Accumulations normally sufficient to interfere with normal operation of electrical equipment or other apparatus
3. In air as result of infrequent malfunctioning of:
    - handling equipment
    - process equipment
4. Accumulations sufficient to interfere with safe dissipation of heat from electrical equipment
5. Accumulations may be ignitable by abnormal or failure of electrical equipment

Group E Atmospheres containing combustible
- metal dusts regardless of resistivity
- dusts of similarly hazardous characteristics having resistivity of less than 100,000 ohm-centimeter
- electrically conductive dusts

Group F Atmospheres containing combustible
- carbon black, charcoal, or coke dusts which have more than 8 percent total volatile material
- these dusts sensitized so that they present an explosion hazard, and having resistivity greater than 100,000 ohm-centimeter but equal to or less than 100,000,000 ohm-centimeter

Group G Atmospheres containing combustible
- dusts having resistivity of 100,000 ohm-centimeter or greater
- electrically nonconductive dust

Don't choose Class I unless you need it. It is more expensive, and you have to wait about 10 minutes after you tum on the power switch until the 4 volume air purge is complete and you can use the machine. (We can provide a key switch to disable the explosion proof feature if you use one of these machine in a non-explosive environment).

Normally the computer and electrical console are located in a safe area remote from the machine so these items do not have to be explosion proof. However, on occasion we have mounted the computer in an air purged enclosure so it can be right next to the machine. This is hard to use, and you can get eye strain trying to look at the computer screen through a blast proof window.

## About the Authors

Richard Boynton is President of Space Electronics, Inc., Berlin, Connecticut, a company he founded in 1959. Space Electronics, Inc. manufactures instruments to measure moment of inertia, center of gravity, and product of inertia. Mr Boynton holds a B.E. degree in Electrical Engineering from Yale University and has completed graduate studies in Mechanical Engineering at Yale and M.I.T. He is the author of over 57 papers, including 21 papers presented at SAWE conferences. Mr. Boynton has been a member of SAWE for 25 years and was.elected a Fellow of the SAWE last year. He is currently Director of the Boston Chapter. He has designed many of the mass properties measuring instruments manufactured by Space Electronics. Also, Mr. Boynton is the Chief Executive Officer of Mass Properties Engineering Corporation, and is a professional folksinger.

Robert Bell is Vice President of Engineering at Space Electronics, Inc. Mr. Bell received his engineering education at Worchester Polytech. He has over 28 years experience in mass properties and has designed numerous instruments and fixtures for mass properties measurement. He is the author of previous SAWE papers.