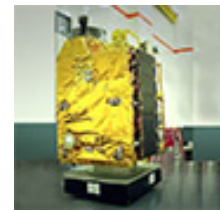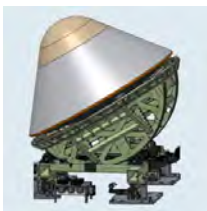# A New High Speed Mass Properties Instrument

By
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For Presentation at the 63rd Annual Conference
of
Society of Allied Weight Engineers, Inc.
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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 has designed many of the mass properties measuring instruments manufactured by Space Electronics. He has a B.E. degree in Electrical Engineering from Yale University and has completed graduate studies in Mechanical Engineering at Yale and MIT. He is the author or co-author of 75 papers, including 38 papers presented at SAWE International Conferences and 3 papers presented at Regional Conferences. Four of Mr. Boynton's papers have won the L. R. "Mike" Hackney Award for Best Technical Paper at the International Conference of the SAWE. He is the author of the SAWE Recommended Practice for Standard Coordinate Systems for Reporting the Mass Properties of Flight Vehicles. Mr. Boynton has been a member of SAWE for over 36 years and is currently Director of the Boston Chapter. In 1992 he was elected a Fellow and in 1998 was elected an Honorary Fellow of the SAWE. Mr. Boynton is also a member of the AIAA and the Society of Automotive Engineers, where he serves on the Balancing Subcommittee (which is currently involved with setting standards for jet engine balancing). Mr. Boynton is a former professional folksinger. In addition, he is an artist, specializing in pen and ink drawing. He recently illustrated a book of poems entitled "A Web of Longing and Desire" (Published by Lamentation Mountain Press).

Daniel Otlowski is Production Manager of Space Electronics, and a long-time employee, having joined the company in 1979. He is one of the two individuals who now run the day-to-day operation of the Company. He directly supervises all the production employees, and is responsible for production planning. In addition, he is an expert in adjusting and configuring the Company's instruments to achieve optimum accuracy, and has contributed to the development of many of the new products at Space Electronics.

Mr. Otlowski's electronics education has been supplemented with training received at Space Electronics in mechanical engineering and other technical disciplines. He is an amateur astronomer – a hobby that dovetails well with his professional life. He designs and builds CCD imaging cameras used to acquire multiple digital images, which are then aligned and averaged to create remarkable composite images He has also designed and fabricated telescope drives and mountings.

Dan is an avid outdoorsman who built his own house in the Connecticut hills. He enjoys hiking with his family, rock and ice climbing, and kayaking.

Abstract In certain industries, the amount of time required to make a measurement of moment of inertia and center of gravity can have a dramatic effect on manufacturing cost. For example, thousands of projectiles are measured every year at some proving grounds. This necessitates operating three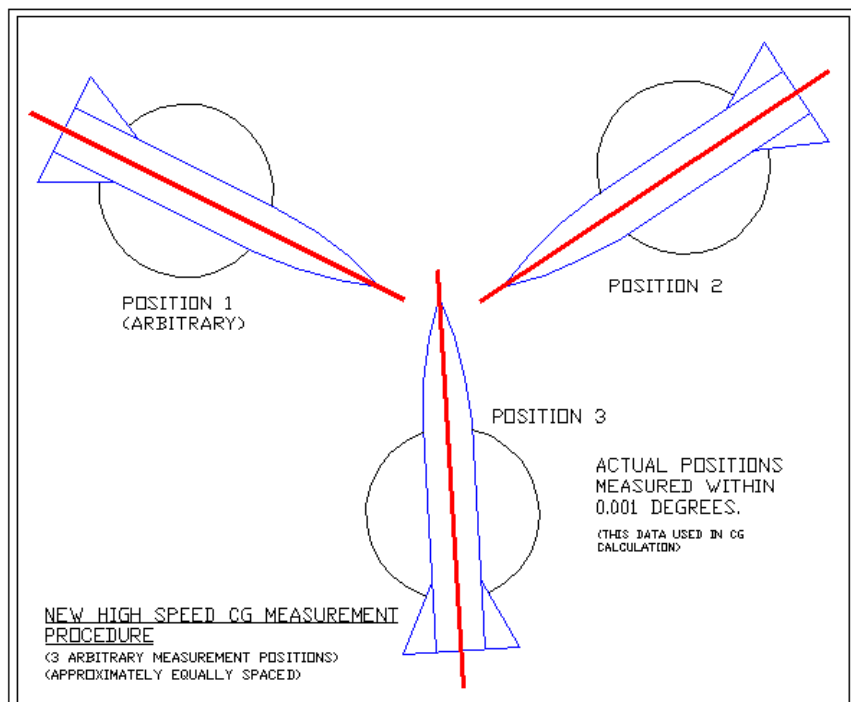 shifts and using more than one mass properties instrument at the facility. In an effort to reduce measurement cost, Space Electronics has developed a new mass properties instrument that is at least three times faster than our traditional KSR series instrument that has been used throughout the industry for over thirty years. This new instrument employs a different concept. The old instrument rotated to each of the four quadrants, stopped precisely at the correct angle, and then measured the CG offset moment. This required a variable speed motor drive that slowed down as it approached the correct angle, executed motions to damp out any vibration, and then edged slowly to its final destination. The new instrument coasts to a stop at three approximately equally spaced locations. An extremely precise optical encoder then measures the actual angle while a force-restoration transducer determines the moment to better than 0.01% accuracy. The on-line computer then uses this data to determine X and Y CG of the object being measured.

Figure 1   Model KSR 6000 Mass Properties Instrument

POSITION 1
0°

POSITION 2
90°

POSITION 4
270°

POSITION 3
180°

TRADITIONAL CG MEASUREMENT
PROCEDURE
(4 PRECISE MEASUREMENT POSITIONS)
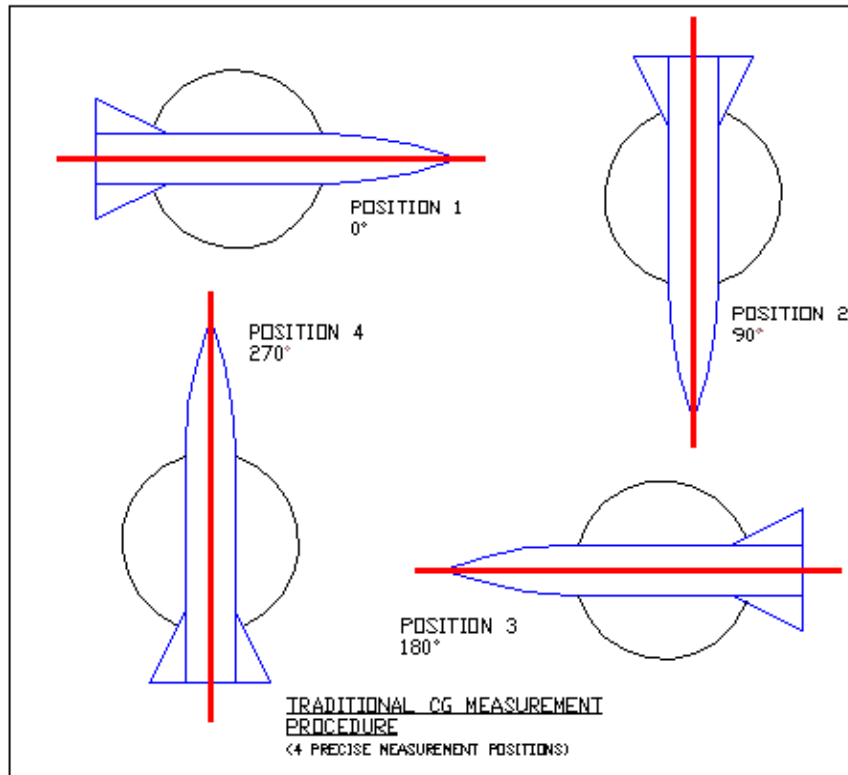
The old method (shown above in figure 2) required the object to be precisely positioned at four orientations. The new method (shown below in figure 3) requires only three measurements spaced at approximately 120 degrees. An optical encoder measures the actual angles and feeds this data to the computer.

POSITION 1
(ARBITRARY)

POSITION 2

POSITION 3

ACTUAL POSITIONS
MEASURED WITHIN
0.001 DEGREES.
(THIS DATA USED IN CG
CALCULATION)

NEW HIGH SPEED CG MEASUREMENT
PROCEDURE
(3 ARBITRARY MEASUREMENT POSITIONS)
(APPROXIMATELY EQUALLY SPACED)

Introduction There are times when an idea must wait for technology to catch up before it can be implemented. Such is the case with the new fast version of our KSR series mass properties instrument. Although there have been numerous improvements in the design over the last 30 years, the basic mechanical concept of our instrument has remained the same. Now with the advent of highly accurate optical encoders and the development at Space Electronics of the force restoration concept of moment measurement, it is possible to implement a new method of measurement that is both faster and more accurate.

Before going into detail about this instrument, we would like to first back up a little and describe what it does. KSR series instruments measure both center of gravity and moment of inertia. The object being measured is mounted on a gas bearing rotary table that is essentially frictionless. This table oscillates when measuring moment of inertia, and rotates when measuring CG. The basic mechanical concept of the instrument is shown in Figure 4 below.
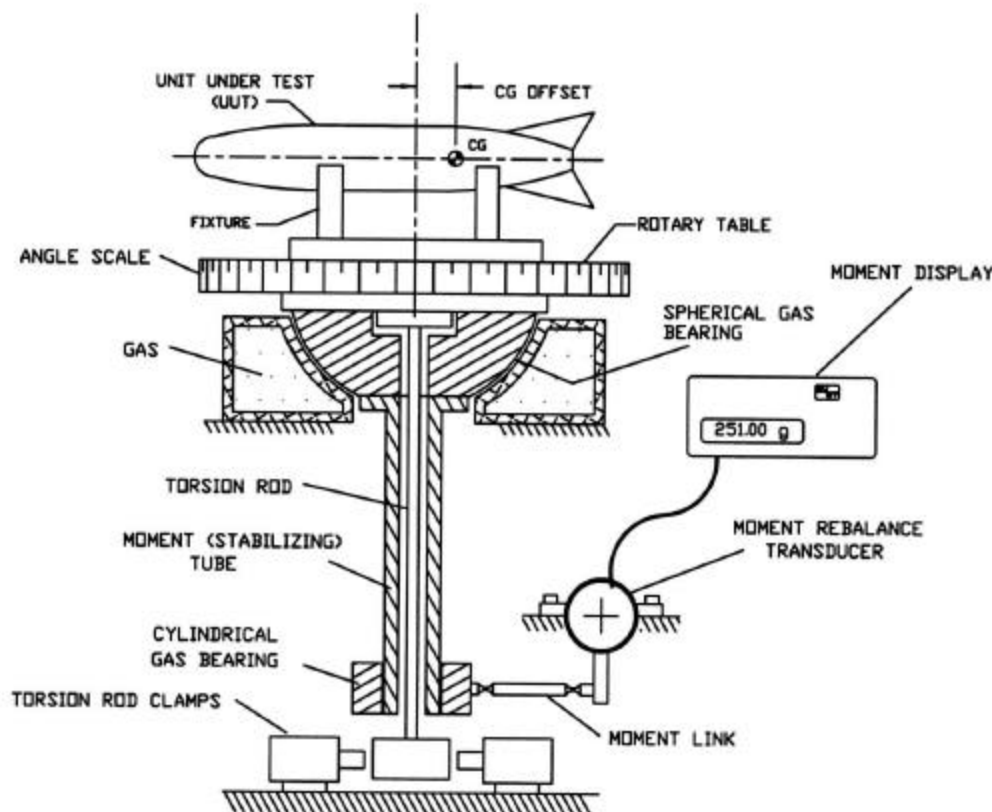

Figure 4 *Basic elements of the Space Electronics Model KSR instrument. The spherical gas bearing creates both a precision rotary table and a frictionless pivot. Active force-restoration transducer measures overturning moment due to CG offset from center of rotation. Moment of inertia is measured by the inverted torsion pendulum method.*
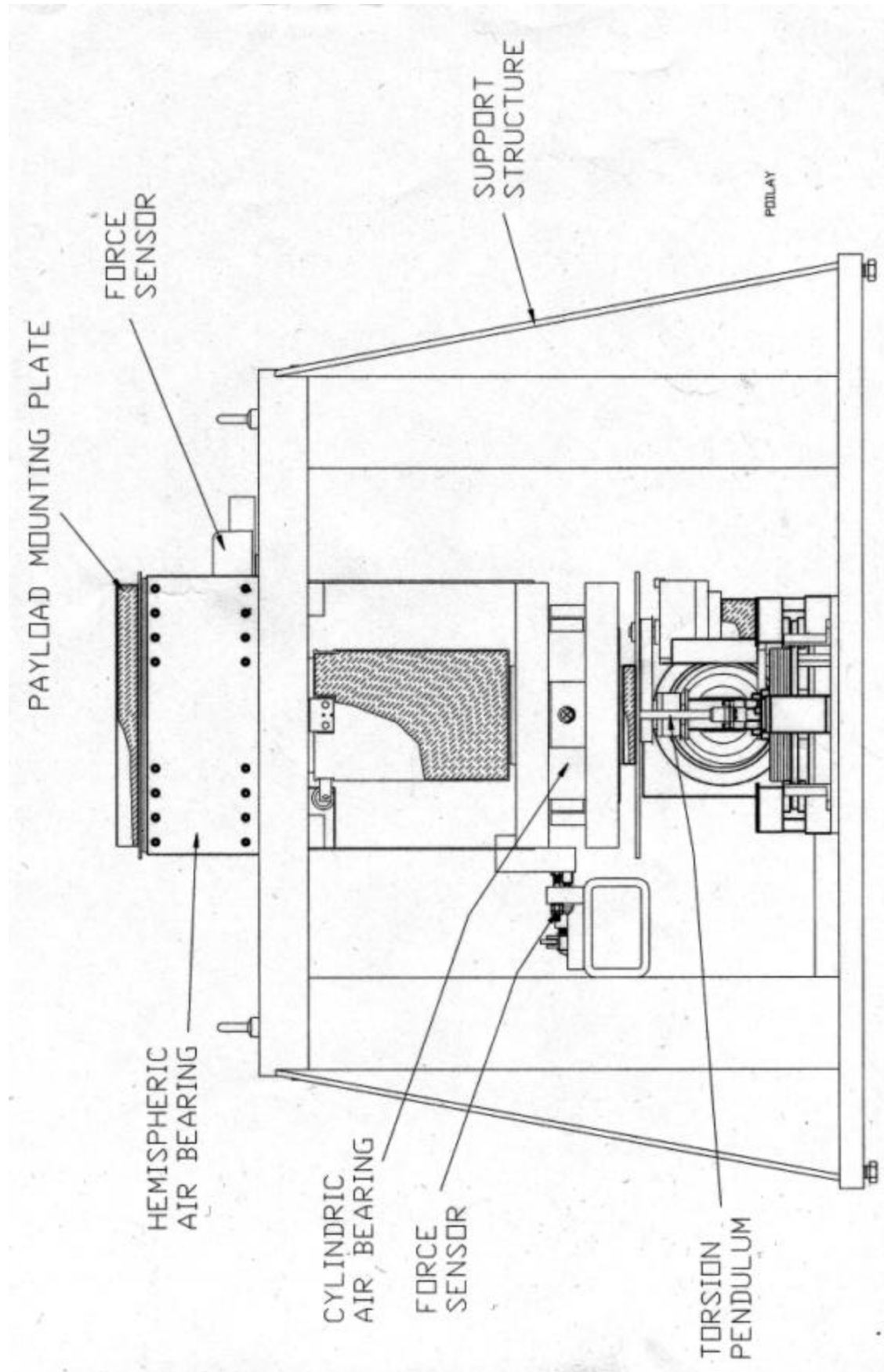
The test object is supported by a spherical air bearing, which is attached to a hollow tube that extends from the base of the spherical bearing. The lower end of this hollow tube is attached to a second (cylindrical) air bearing, which is connected through a moment restoration transducer string to the rigid instrument base structure, so that the deflection of this lower bearing is extremely small, even when large overturning moments are applied to the test surface of the instrument. The horizontal force on the lower bearing is proportional to the moment generated by the displacement of the test object CG from the rotational center of the instrument.

The bearing acts as both a pivot and a rotary table. The overturning moment produced by a displacement of the test object CG from the center of rotation of the table is sensed using a force restoration transducer. Measuring this moment and dividing by the test object weight will yield the CG displacement from the center. This type of instrument does not measure weight, so a separate scale must be used. The weight data can be automatically acquired by the mass properties machine software and used to calculate CG location.

The essentially frictionless air bearing makes the ideal platform for an inverted torsion pendulum. A torsion rod extends from the upper surface of the bearing (the test table) to a clamping mechanism at the bottom of the rod. When this clamping mechanism is released, the spherical bearing is free to turn about the vertical axis. If the bottom of the torsion rod is clamped, and oscillation is initiated, the moment of inertia of the object can be calculated from the time period of oscillation.

$$\text{OFFSET MOMENT} = W \times d$$
$$\text{RESTORING MOMENT} = F \times L$$
$$\text{CG OFFSET} = \frac{F \times L}{W}$$
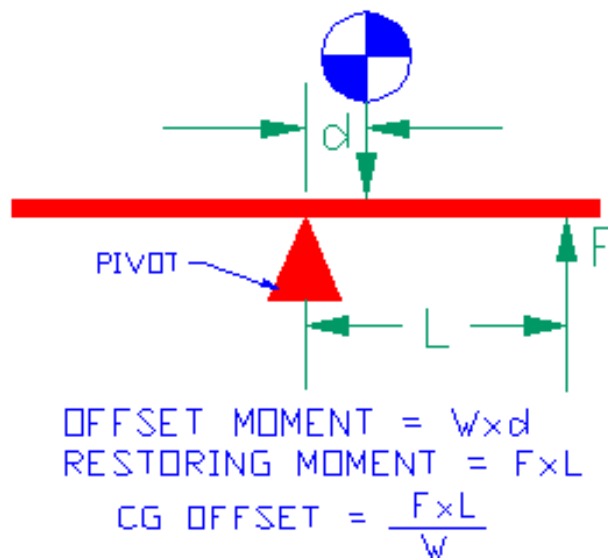
A DISPLACEMENT OF THE CG FROM THE PIVOT CENTER RESULTS IN AN OVERTURNING MOMENT THAT VARIES SINUSOIDALLY AS THE AIR BEARING TABLE IS TURNED. THIS ALLOWS US TO CALCULATE THE MAGNITUDE AND ANGLE OF CG OFFSET.

PAYLOAD MOUNTING PLATE

FORCE SENSOR

SUPPORT STRUCTURE

P00LAY

HEMISPHERIC AIR BEARING

CYLINDRIC AIR BEARING

FORCE SENSOR

TORSION PENDULUM

7

Air Bearing Pivot Air bearings consist of a precision rotor and a precision stator separated by an air gap that is less than 0.0005 inches thick. Air is introduced to the gap through jewel orifices that meter the air and provide dynamic centering of the bearing. Machining accuracy on these bearings is better than 30 millionths of an inch. This is what makes air bearings so expensive and difficult to make.

DISPLACING THE ROTOR TO THE LEFT CAUSES THE GAP TO DECREASE, WHICH RESULTS IN A GREATER PRESSURE IN THE GAP. THIS ACTS TO CENTER THE BEARING.
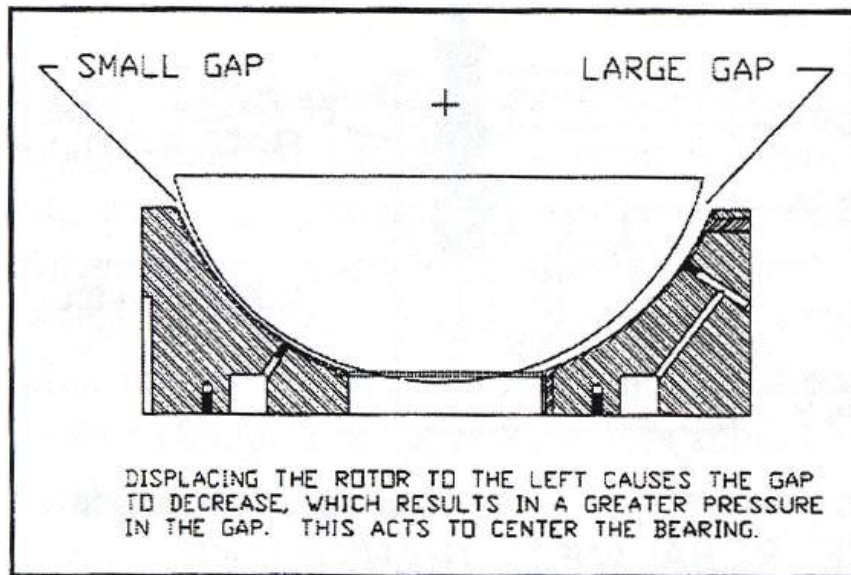
Dynamic centering action Contrary to intuition, air bearings have greater stiffness and precision than any other type of bearing. The reason is that an air bearing is a dynamic device. If air is supplied through a single opening to the gap between the ball and the cup of a spherical air bearing, then the bearing would only operate successfully if the external forces were exactly in the center of the upper plate. A side load would cause the rotor of the bearing to move sideways so that one edge rubbed against the stator. Increasing the amount of air pressure in the plenum of the bearing would not improve the situation, since the additional available air would flow out the side that had the larger gap. Air bearings made by Space Electronics minimize this effect by using independently supplied segments and small diameter jewel orifices that operate in a partially choked condition. Under conventional operation with the payload centered on the interface table, the amount of airflow through each orifice is such that a pressure drop of approximately one half the pressure in the plenum occurs. A minute movement of the rotor of the bearing results in a restriction of the flow on the side of the bearing that has the smaller gap and an increase in flow on the opposite side of the bearing. This produces a self-compensating or centering action of the bearing, since a reduction of the air flow on the low side increases the pressure in the gap on that side and an increase in flow on the high side reduces the pressure on that side. Proper selection of orifice sizes and cavity configurations permits the bearing to remain centered within about 0.0001 inch when subject to side loading.

Advantages of our method of locating CG

Our simple, straightforward method of locating CG has several inherent advantages:

A. This is a static system. In many cases, only simple fixturing is required. There is no danger of the test part getting loose in its fixture and being forcibly ejected from the instrument.

B. This system uses only one force transducer. Its accuracy is dependent on only two physical dimensions of the instrument and the accuracy of the test weight used to calibrate the force transducer. (Both quantities can be determined with extremely high precision and are traceable to the National Bureau of Standards). There are no dynamic errors and the product of inertia or tilt of the principal axis does not affect the indication of the instrument and does not have to be subtracted from the total unbalance readings.

C. The spherical gas bearing pivot of the instrument offers negligible friction with the highest possible stiffness: the total deflection under full load is less than 0.0005 inch. The moment resisting stiffness of the system is primarily a function of the stiffness of the moment transducer

D. The rotary table created by the spherical gas bearing greatly improves measurement accuracy. Most systematic errors are automatically eliminated or can be eliminated in machine setup.

E. The axis of measurement becomes the center of rotation of the table. This eliminates the need to accurately determine the relationship between the instrument pivot axis and the mounting surface of the instrument.

F. For cylindrical test parts, or parts that can be accurately located in a fixture with a cylindrical reference surface at the nominal CG location, a dial indicator may be used to bring the part or fixture centerline concentric with the center of rotation of the instrument to within extremely close tolerances. This eliminates zero-reference offset errors.

G. For tall cylindrical parts, two dial indicator readings may be made: one close to the table and another at a location well above the table. A tilt table, shimming, or other means of adjustment, will allow the operator eliminate errors due to the part axis leaning away from the machine rotational axis.

Figure 7   Using two dial indicators to adjust tilt

H. Another common system error occurs from improper leveling of the machine.   This causes

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lean, which may be interpreted as CG offset. With the rotary table machine, this error is eliminated by taking three readings that are 120 degrees apart. The lean error is equal for all measurements and is therefore subtracted from the result. Figure 8A illustrates the effect of the lean of the interface surface on the accuracy of center of gravity measurement. Even with a center of gravity instrument whose accuracy is better than 0.001", if the interface surface is not precisely perpendicular to the gravitational axis, then the test part center of gravity can be displaced by a considerable amount. This offset CG due to the lean of the table can be distinguished from true CG offset by turning the test surface through an angle of 180°. As the drawing indicates, an apparent CG offset due to the tilt of the test surface will not change as the table is turned, whereas true CG offset (figure 8B) of the test part results in an offset moment which changes as a function of test table rotation angle.

ISOLATING TILT ANGLE ERROR FROM TRUE CG OFFSET

0°   180°

PLUS 1 INCH-LB   PLUS 1 INCH-LB

APPARENT CG OFFSET DUE TO TILT OF TEST SURFACE WILL NOT
CHANGE AS THE TABLE ROTATES 180 DEGREES

0°   180°

MINUS 1 INCH-LB   PLUS 1 INCH-LB

TRUE CG OFFSET OF THE TEST PART RESULTS IN AN OFFSET MOMENT
WHICH ROTATES WITH THE TEST TABLE. MAXIMUM AND MINUMUM
READINGS WILL BE DISPLACED BY 180 DEGREES.
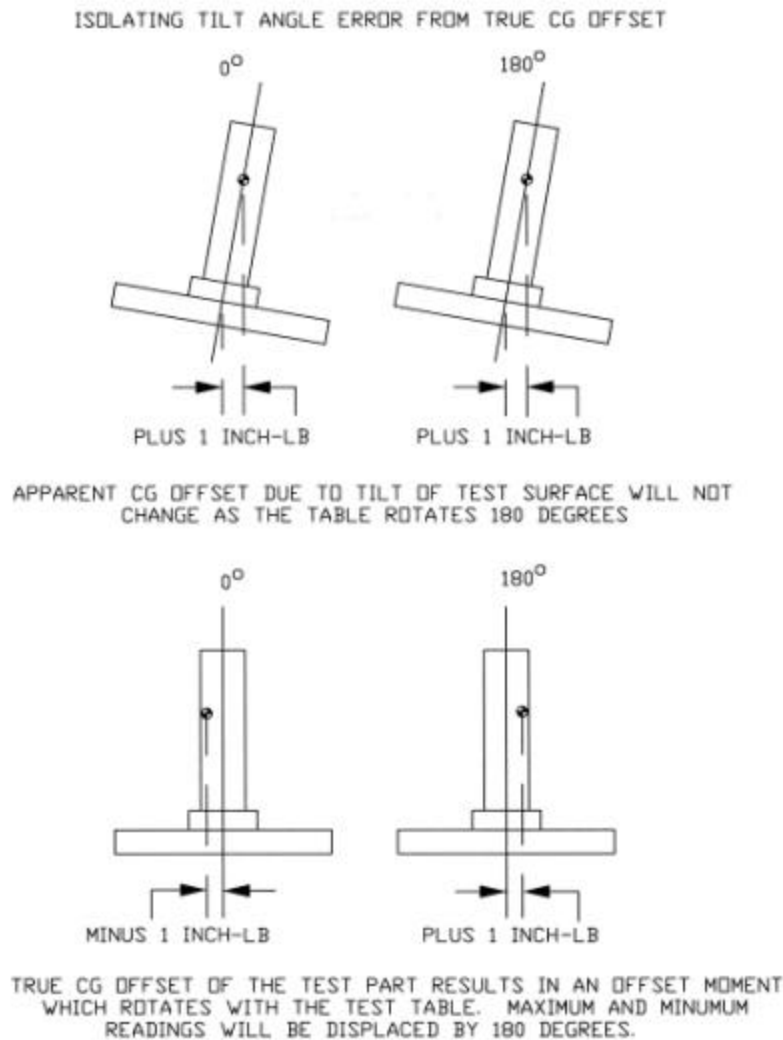
Figures 8A and 8B

I. Taking three readings spaced 120 degrees apart also eliminates other systematic errors such as transducer zero offsets.

Concept of Tare Measurement The part to be measured must be held in a fixed orientation with respect to the X and Y axes. A precision fixture is used to accomplish this. This fixture adds mass to the test. The mass properties instrument itself also has mass. In addition, although it would be possible to balance the instrument and fixture so that it had no unbalance moment about the rotation center of the instrument, it is easier to measure this unbalance and subtract it from the total moment of test object and fixture. Therefore, the measurement with the test object mounted in the fixture includes the mass contribution due to fixture and instrument. Two measurements and one calculation are required to determine the mass properties of the test object:

> 1. A separate measurement must first be made of the "tare" CG moment and moment of inertia of the fixture and machine. Those properties (CG moment and MOI) are saved in computer memory and recalled later.

> 2. The test part is then mounted in the fixture and the "total" CG moment and MOI are measured. This is also saved in computer memory.

> 3. The tare readings are then subtracted from total readings. The net results are for the test object. Cg measurement is in terms of offset moment. The weight of the test object is entered on the keyboard. The computer then divides the measured moment by the weight to determine CG offset distance.

In order for the tare concept to work, it is necessary for the mass properties of the fixture to be identical for both measurements. No adjustments can be made to the fixture between measurements. The measurements should be made as quickly as practical so that temperature variation is minimal between measurements. If mounting hardware is used with the fixture, then this should be installed in the fixture when the tare is measured (unless this hardware is considered part of the test object). Note: The tare mass properties can be measured <u>before</u> or <u>after</u> the measurement with the test part.

SUMMARY OF BENEFITS OF THE KSR SERIES INSTRUMENT

1. Both center of gravity and moment of inertia are measured in a single setup.

2. Accuracy is higher for this type of instrument than any other method.

3. Fixturing error is minimized since the rotary table allows cylindrical parts to be dial indicated.

4. Leveling and zero shift errors are eliminated by using the rotary table to take at least three data readings at test part locations that are separated by 120 degrees.
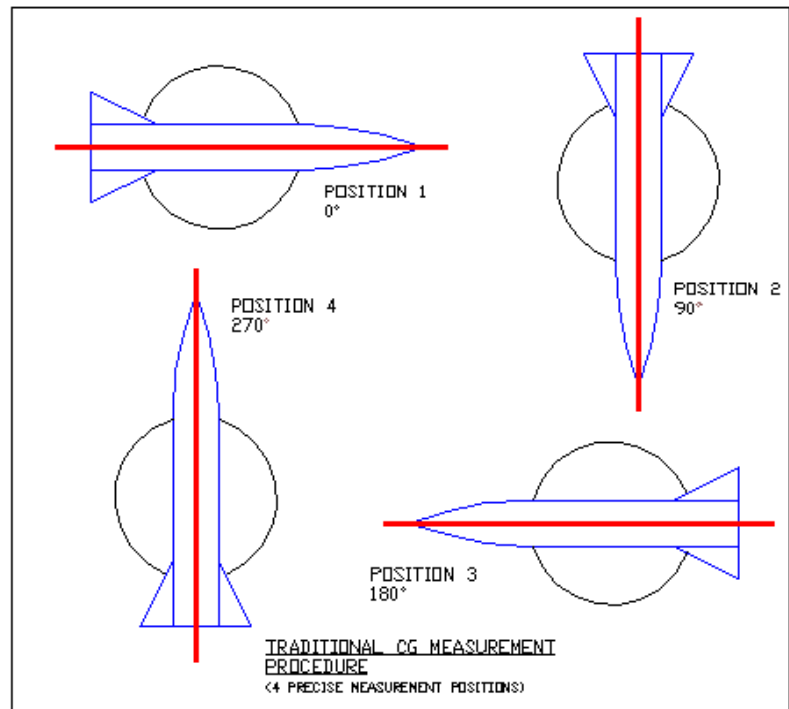
The old method When the KSR series instruments were first developed, accurate optical encoders did not exist. The angle at which measurements are made is a critical factor in the accuracy of the machine. To take an extreme example, if the CG of the object being measured was 10 inches from the center of rotation of the machine, then a 1 degree error in the angle at which measurement are made would result in a CG measurement error of 0.174 inch! If the CG were only 1 inch from the center of the machine, then the error would still be 0.017 inch. Our goal is to be able to measure CG within 0.001 inch for offsets 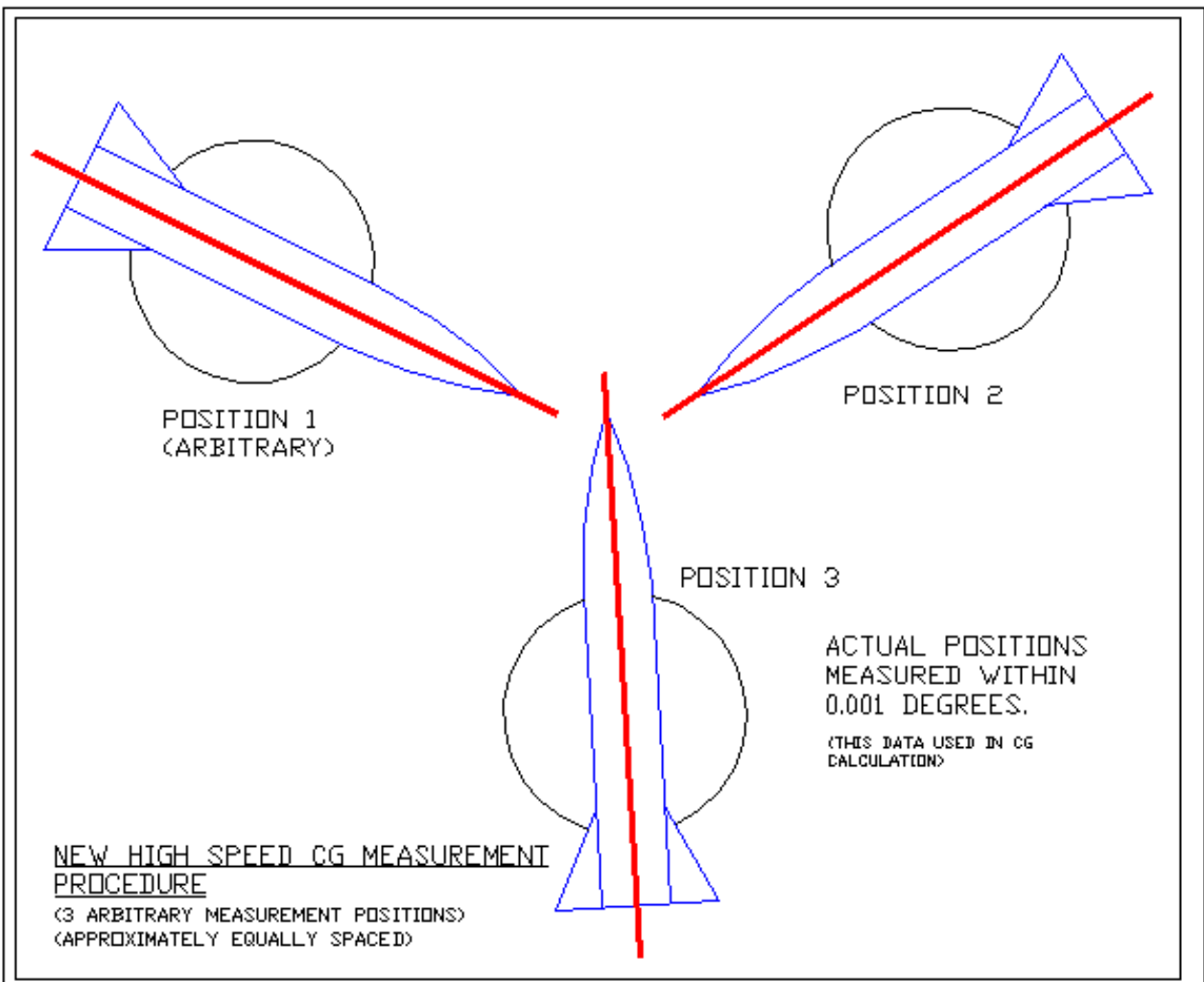as great as 5 inches. Therefore, the four rotations of the table had to be positioned within an accuracy of 0.01 degree. This positioning accuracy was difficult enough with a light table; it was almost insurmountable when a large heavy object was being measured, because the moment of inertia of the object would cause the table to want to rotate after the drive mechanism was de-energized. The solution was to slow the rotation as the table approached the desired angle, then stop the table completely and damp out any tremors at an angle that was 2 degrees from the desired final angle, and finally to edge the table forward extremely slowly to the final angle. Even when optimized by the on-line computer, this operation was extremely tedious and time-consuming. An improvement was achieved by measuring the moment of inertia of the object and using this number to select the drive torque and deceleration angle of the rotation motor. A laser beam was interrupted at the precise angle, and a photocell triggered the drive system.

Even with this highly sophisticated system, measurement time for the four moment measurements could not be reduced to less than 15 minutes for average objects and could be as long as 25 minutes for large objects with high moment of inertia, such as a rocket in the transverse orientation.

This process could have been further improved by using only three measurements spaced 120 degrees apart, rather than four measurements spaced 90 degrees apart. However, there is a practical problem: it is extremely difficult to locate optical sensors at 120 degree spacing with an accuracy of 0.01 degree.


POSITION 1
0°

POSITION 2
90°

POSITION 4
270°

POSITION 3
180°

TRADITIONAL CG MEASUREMENT PROCEDURE
(4 PRECISE MEASUREMENT POSITIONS)

The new method Accordingly, in 2004 we introduced a new version of this instrument.

POSITION 1
(ARBITRARY)

POSITION 2

POSITION 3

ACTUAL POSITIONS
MEASURED WITHIN
0.001 DEGREES.

(THIS DATA USED IN CG
CALCULATION)

NEW HIGH SPEED CG MEASUREMENT
PROCEDURE
(3 ARBITRARY MEASUREMENT POSITIONS)
(APPROXIMATELY EQUALLY SPACED)

Rather than stop the rotation of the instrument at exact angles, the instrument is rotated to three measurement positions that are approximately 120 degrees apart. We no longer go through the elaborate process of slowing the drive motor as the angle is approached and edging forward to the final position. Instead, the drive simply decelerates to zero at approximately the correct angle. Depending on the moment of inertia of the object, the rotation may continue for as much as 20 degrees. However, the conditions are the same for each position, so that the spacing of the positions is approximately 120 degrees. An ultra-precision optical encoder then measures the exact angle of each measurement, and the computer solves the moment equations to yield the CG along two perpendicular axes..

NOTE: Since the three angles are arbitrary and only the difference is important, the first angle of measurement can be wherever the table stops from the previous measurement. Therefore, only two positionings are required, as compared to four for the older method.

We are preparing to apply for a patent on the concepts described in this paper.

ENCODER DISK
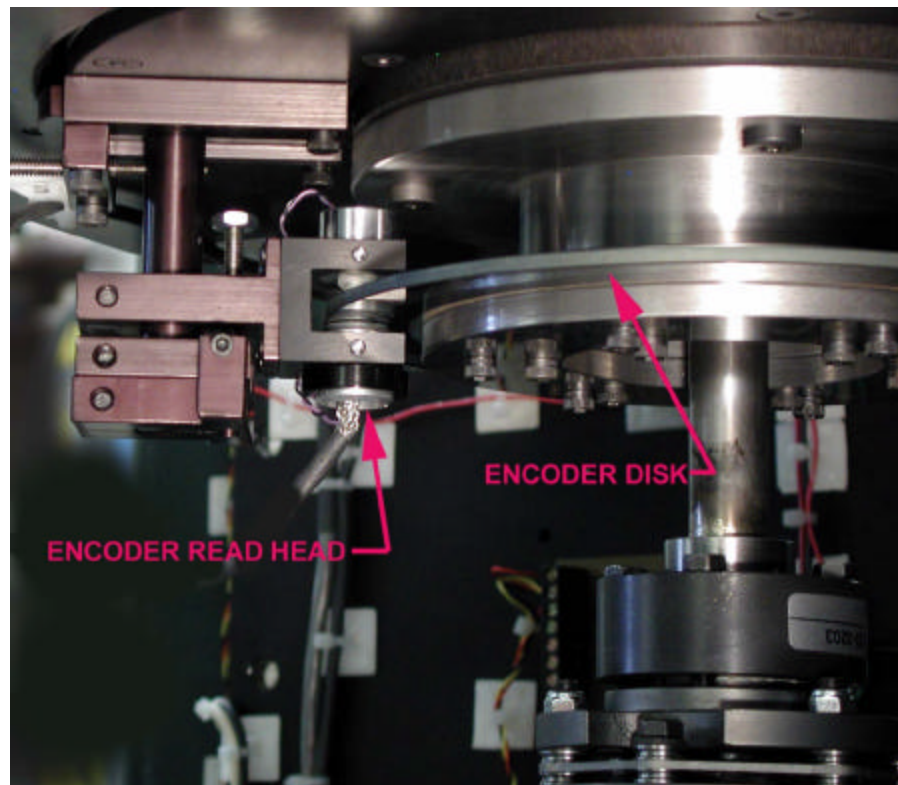
ENCODER READ HEAD

Optical encoder In order to get the required accuracy, we use a non-contacting (and consequently friction-free), absolute encoder. It has a 6" diameter glass disk with several metal deposited, optical patterns. The pattern is picked up by a Read-Head, passed to a combined decoder/interpolation module, and then to a digital I/O interface card located in our computer. It has a native resolution of 4096 bits/revolution and an interpolated resolution of 1,048,576 bits/revolution. This yields a final interpolated angular resolution of .00034 degrees per bit. The signal leaves the Read-Head as a series of analog signals: sine and cosine waves in conjunction with an indexing signal. The interpolation is accomplished by
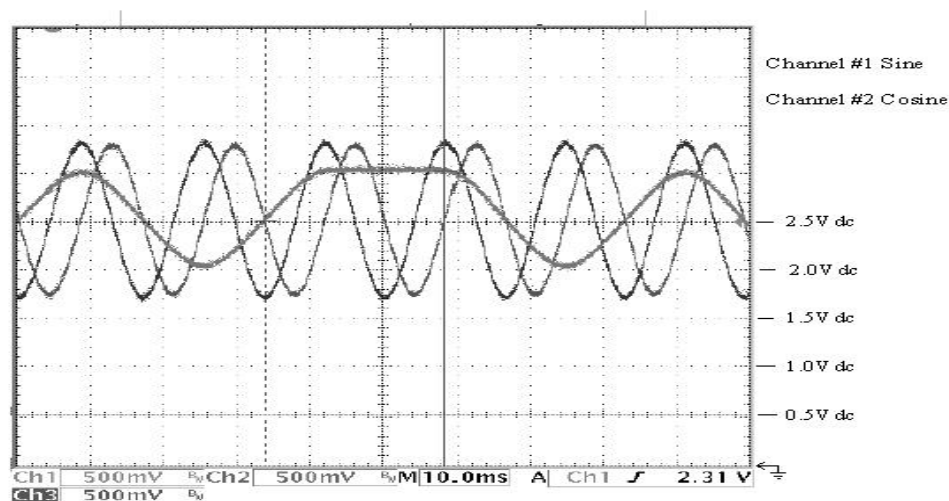
- Typical *Virtual Absolute* Voltage Signals
Note: Channel #3, Index Pulse, shown for ref only

analyzing the slope phase relationship of these waveforms. The interpolator passes the signal to the computer interface as an eight bit, digital TTL logic, data code plus a few auxiliary lines. The hi-resolution angle data is fed into a digital I/O and read-out in three bytes.

In order to take full advantage of the high resolution provided by the encoder, we need to ensure that its metal deposited optical pattern is concentric with the rotational spindle axis of our machine. Concentricity errors directly affect the read-out angular accuracy verses the corresponding true position. The tolerance for this is approximately 0.0005" T.I.R. when evaluated with regard to machine accuracy. The problem is that no mechanical surface on the encoder is guaranteed to run concentric with the optical pattern. This leaves us with the burden of making a true surface that we can count on later when dial indicating on the machine. To do this, we true the optical pattern to our stainless steel adaptor, then use the adaptor as the "good" surface when the assembly is mounted into the machine. We start out on a Space Electronics Bearing Measurement Machine with our stereomicroscope and a special graduated reticule. We center the adaptor hub with a precision electronic gage and secure it into place. Next, we gently adjust the glass until the optical pattern runs true to the hub. We secure the glass with our, manufacturer specified, quasi-resilient clamp.
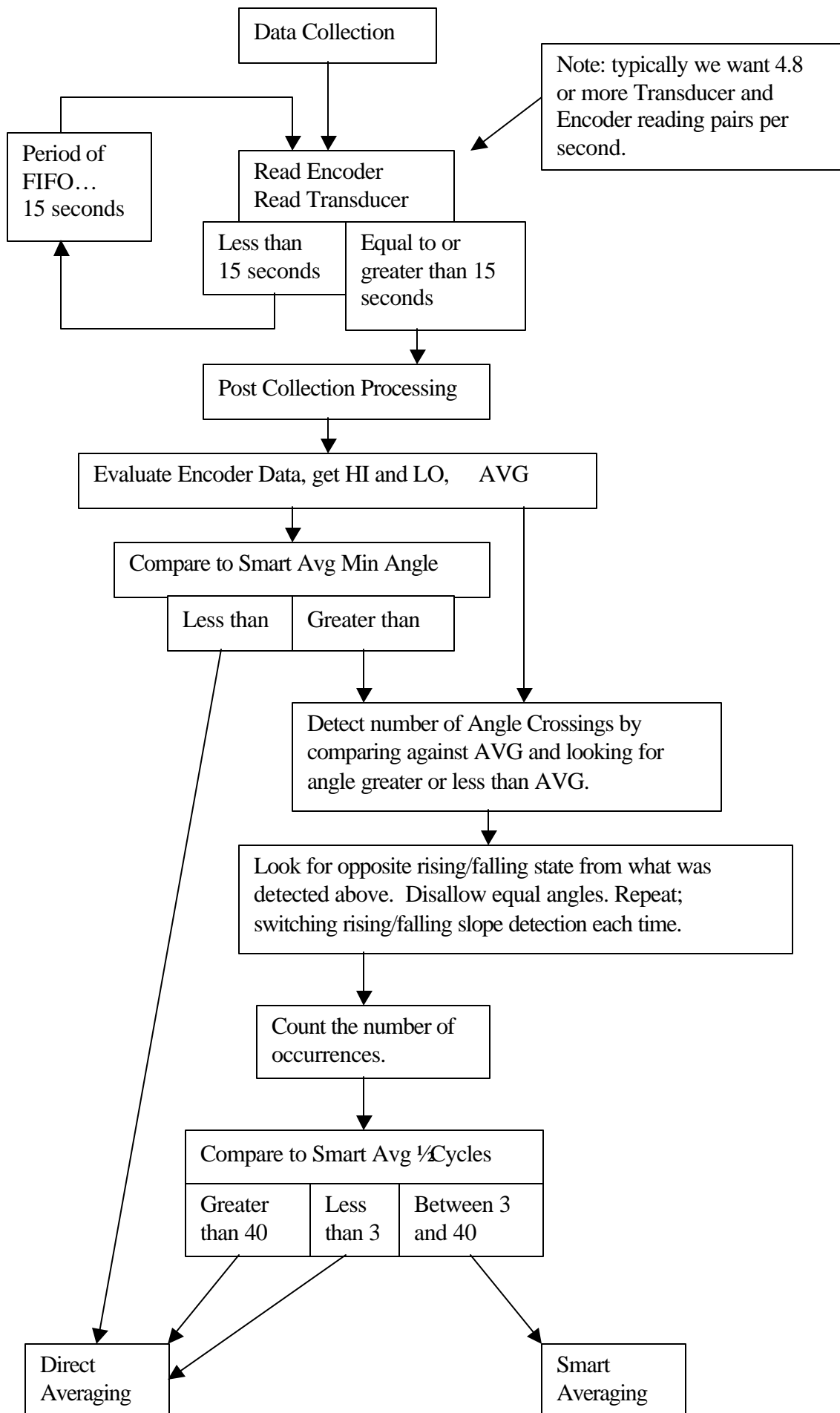
Synergy…the controller, the math, the encoder, and the technique
An analysis of our older systems showed that a large portion of our CG measurement time was spent fine positioning at very specific angles, and controlling the payload so that the data was steady and valid. Our old math relied on exact targeting and achievement of position at 0, 90, 180, and 270 degrees. In order not to overshoot the angle we had to creep up on the final target very slowly. The practical maximum speed allowed, was related to the inertia of the payload. Basically, the larger the payload, the slower the speed. This was all controlled by an elaborate inertia prediction scheme, which was based on time vs. acceleration mechanics. Because the prediction was limited in accuracy , we always setup to err on the side of caution. Once we exactly targeted our angle, we still had to wait a substantial period of time to allow residual oscillations to damp out. When we released the drive roller, an additional kick would occur forcing us to take more data in order to ensure our averaging algorithm worked properly. All this served to slow the CG tests down. To boot, the phenomena of CG torsional pendulum effect would also create an error in true position, which was proportional to the CG moment unbalance and the out-of-level condition of the machine.
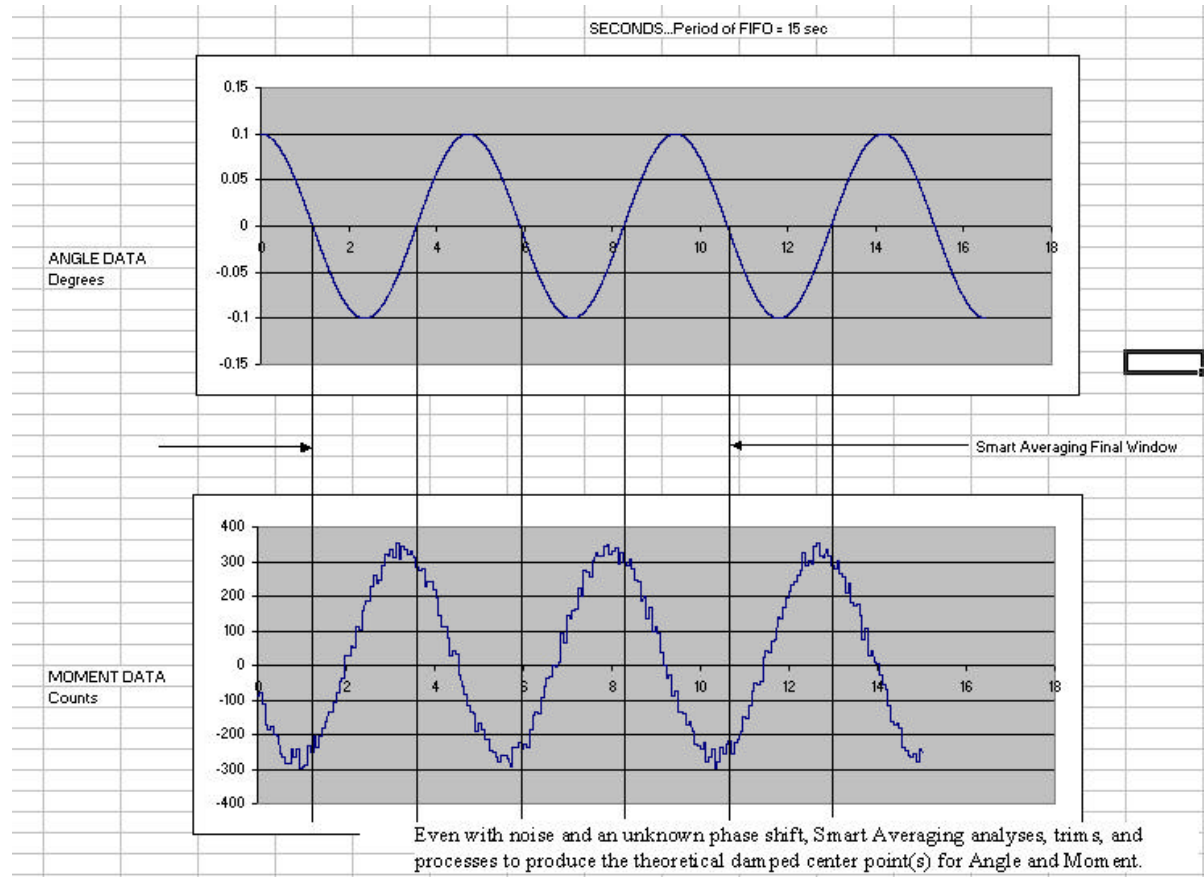
The new method eliminates most of the problems of the old system. Our new math matrix equation no longer requires us to rotate to any particular angle. In fact, we take our first reading at the arbitrary angle that we happen to be sitting at when the test begins. This eliminates the first rotation sequence. As discussed previously, we no longer take four quadrants of data. The data acquisition has been reduced to three sectors of data with no appreciable degradation in performance. The three angles are roughly targeted to be 120 degrees apart, but there is no requirement for exact positioning. The new math matrix works with practically any angles as long as you know what they are. Our new encoder handles that quite nicely. Once we are at the approximate target angle, we tame, but not eliminate, the residual oscillations, and take data. A new acquisition algorithm called "Smart Averaging" enables us to get valid data even though we have not damped all oscillations. Furthermore,

the quality of the final data is better than before. Firstly, CG torsion pendulum effect is factored out because we now know the actual angle the machine settles to. Secondly, as the machine continues to oscillate slightly, both the encoder and moment readout produce sinewave responses, which are read by the computer. The computer then analyses the encoder signal to pick out the fundamental frequency and chops up both the encoder and moment readout sinewaves so that only full oscillation cycle(s) are processed. Full cycles are the only accurate way to average the final data. Picture this; if you had a repetitive sinewave with three positive peaks, but only two negative peaks, a simple averaging would yield results that were too positive in value. We use the encoder signal instead of the moment readout to do the original analysis because it has no phase shift tied to oscillation frequency (no slew delay), and is not as subject to noise such as buffeting by windage. At some point, when the payload inertias are small, the residual oscillations are so fast that we can't read them properly without aliasing/sampling errors. The problem is that we are limited in our encoder read speed by either hardware or software overhead or both. This creates a sampling mismatch where the fundamental is too fast for our sample rate. Because of this, we have implemented a method where at the slower oscillation frequencies; we use Smart Averaging, at fast frequencies where we start to get aliasing, we switch to a Direct Averaging scheme. The Direct Averaging method simply takes all the data and averages it together without trimming to exact, full cycle sinewave(s). This method works for higher oscillation frequencies because at some point, when you get enough cycles in your dataset, the effects of numerically mismatched peak counts, becomes mathematically insignificant.

No matter how sophisticated we make the CG read algorithms, it is still desirable to have the payload be settled before taking data. There is a small amount of energy imparted onto the Interface Plate when the drive roller releases. This kick is due to the geometry of our release mechanism. The amount of drive release kick is angularly, fairly large at small inertial loads, and smaller with higher inertias, whereas the residual rotation energy oscillations are bigger for larger payloads than smaller ones. These two differing conditions are served by the introduction of a few more new software parameters. These parameters control the "wait for no motion" algorithm functioning. The first of these parameters is the *Wait No Motion Sample Encoder Angle Resolution*. This is set to 0.1 degrees and it protects us at the faster oscillations where we might be in the direct averaging mode. This parameter is set by experimental methods. Basically, we mount the Calibration Beam, rotate the table to 90 degrees, where we clamp the brakes. Weights are added to the beam to create a full-scale moment. The beam is experimentally oscillated at various amplitudes. The configuration exploits all the weaknesses in the system. This inertia, and thus its oscillation period, is representative of the crossover point between smart and direct averaging, and is deemed acceptable for the purpose of this determination.   As mentioned earlier, direct averaging does not even attempt to compensate for uneven peak counts. This practice is acceptable if the number of complete cycles is high enough. There is however, another way to minimize the effects of uneven peak-count: keep the amplitude low. If there were no motion, then there would be no change in CG moment magnitude. At each of the oscillation amplitudes, the data was plotted in EXCEL and a manual version of smart vs. direct averaging was done. The results showed what had been predicted, the smaller oscillations yielded direct averaging results, which were

Data Collection

Note: typically we want 4.8 or more Transducer and Encoder reading pairs per second.

Period of FIFO…
15 seconds

Read Encoder
Read Transducer

| Less than 15 seconds | Equal to or greater than 15 seconds |

Post Collection Processing

Evaluate Encoder Data, get HI and LO,   AVG

Compare to Smart Avg Min Angle

| Less than | Greater than |

Detect number of Angle Crossings by comparing against AVG and looking for angle greater or less than AVG.

Look for opposite rising/falling state from what was detected above. Disallow equal angles. Repeat; switching rising/falling slope detection each time.

Count the number of occurrences.

Compare to Smart Avg ½ Cycles

| Greater than 40 | Less than 3 | Between 3 and 40 |

Direct Averaging

Smart Averaging

within a few counts of the true average. The empirically determined crossover point seen as acceptable was at 0.1 degrees. Several CG positioning rotation sequences were done and the machine was proven to quickly obtain this 0.1 degree payload stability within a few seconds.

SECONDS...Period of FIFO = 15 sec

ANGLE DATA
Degrees

Smart Averaging Final Window

MOMENT DATA
Counts

Even with noise and an unknown phase shift, Smart Averaging analyses, trims, and processes to produce the theoretical damped center point(s) for Angle and Moment.

CG Error analysis Total measured moment error is well below the limits specified for the machine, as shown in the graph below. If a 6000 pound object were being measured, then the worst case error of 2 lb-inch would correspond to a CG measurement error of 0.0003 inch.

Static CG Error VS Applied Moment
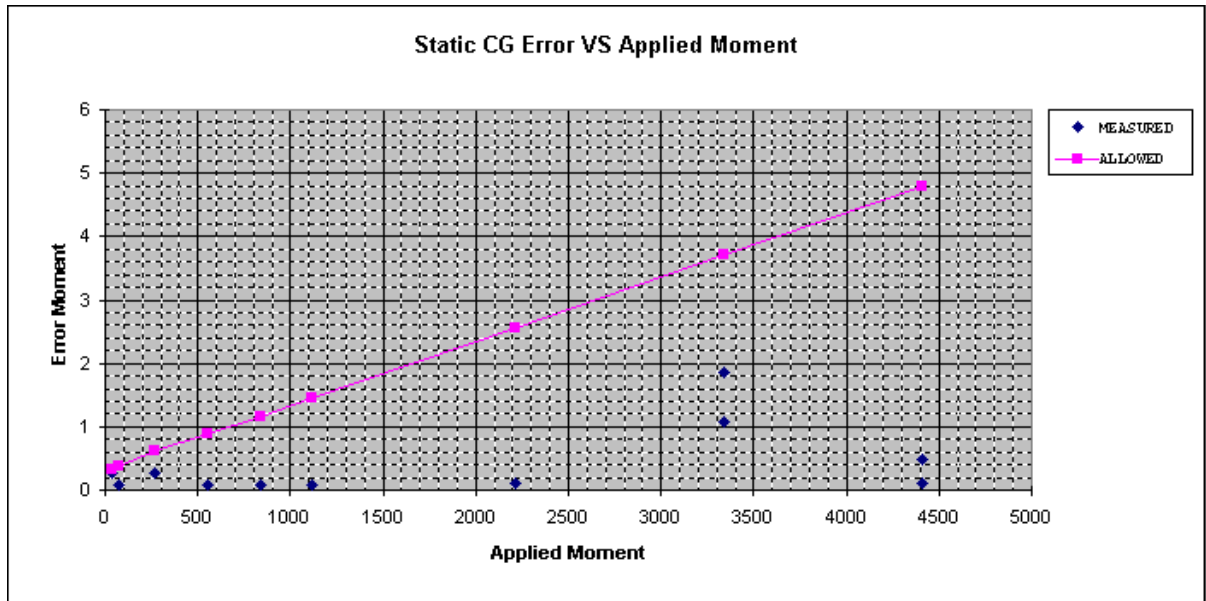
Pivot Axis Error

The pivot axis on this instrument is a gas bearing. The gap in this bearing is typically less than 0.001"; the dynamic centering action of the choked orifices of the bearing result in a stability of pivot axis typically less than plus/minus 0.0002" over the full range of weight of test parts, and independent of the moment being measured.

Moment Error

The unbalance moment in the instrument is measured using a moment arm and force restoration transducer.   Linearity of the transducer is better than 0.001% of full scale. The lengths of the moment arm and transducer arm determine the moment amplification factor for the machine.   The effective length of these arms remains constant within 0.01% provided the ambient temperature does not vary more than plus/minus 10° F.   (Another advantage to our fast measurement cycle is that it minimizes the effect of temperature change.)   Since the weight of the test object is supported by the pivot axis, not the moment transducer, the full-scale range of the moment readout may be chosen for any desired accuracy by selecting the appropriate transducer and moment arm length.   However, higher accuracy requires a smaller maximum over-turning moment.   The 120° rotation feature of the instrument eliminates any error that might be introduced by transducer zero shift. Since the resolution of the instrument is so high, useful readings can be obtained for moments as small as 0.01% of full scale. Using proper calibration techniques and a dual range transducer, moment readings as small as 0.001% of full scale may be obtained.

Calibration Weights - Center of Gravity

Several certified and traceable calibration weights are supplied with these instruments. These weights, when placed in precisely located holes (certified and traceable), permit the creation of a precise overturning moment, and allow the computer to develop accurate calibration constants which correct the moment readout so that maximum accuracy is obtained for even small test parts.

System Rigidity

The spherical gas bearing combined with the stabilizing shaft and lower bearing results in an extremely rigid measuring system. Negligible error is introduced by system flexibility for test objects whose CG height is equal to or less than the maximum specified for each instrument size. Tall thin parts may result in a small shift in measured CG due to the deflection of the test part if the test part CG is not centered, or if there is considerable tilt to the instrument. This effect can easily be compensated for by centering the test part accurately and re-leveling the instrument after the test part has been mounted in place. A further improvement in accuracy is achieved by a height compensation algorithm in the software.

 Moment of Inertia Measurement

This instrument readily lends itself to the measurement of moment of inertia. A torsion rod extends from the upper surface of the bearing to a clamping mechanism at the bottom of the rod. During CG measurement, this clamping mechanism is released, and the bearing is free to turn about the vertical axis.   During MOI measurement, the lower end of the torsion rod is temporarily clamped to create an inverted torsion pendulum. The test surface of the instrument (and test object) is automatically twisted to an initial angle and released. A photoelectric assembly mounted on the instrument measures the period of oscillation.

The natural undamped period of oscillation of a torsional pendulum is described by the equation:

$$I = CT^2$$

where C is a calibration constant which is experimentally determined and is primarily a function of the spring rate of the torsion rod. A calibration weight is supplied with the instrument. The weight is first placed at a known distance from the center of the table and the period of oscillation (T_x) is measured. The weight is then placed at the center of the table and a second period of oscillation (T_o) is measured. The difference in these periods is due purely to the change in MOI between the first and second readings.

This change I is the known value $I = WR^2$ where W is the calibration weight, and R is the offset. The calibration constant is then calculated:

$$C = I/(T_x^2 - T_o^2)$$

Since the system is linear, only a single point calibration is needed for the full range of MOI measurements.

Before the MOI of a test part can be determined, a TARE period of oscillation (T_t) must be measured for the machine and any necessary fixturing. The part is then mounted and a period of oscillation (T_p) is measured. The part MOI is then calculated:

$$I = C(T_p^2 - T_t^2)$$

where C is the calibration constant previously determined.

Moment of inertia measurement error Total error is well below the maximum allowed for the machine. For example, for moment of inertia values above 50,000 lb-in^2 , maximum error was less than 50 lb-in^2, which is less than 0.1% of value.
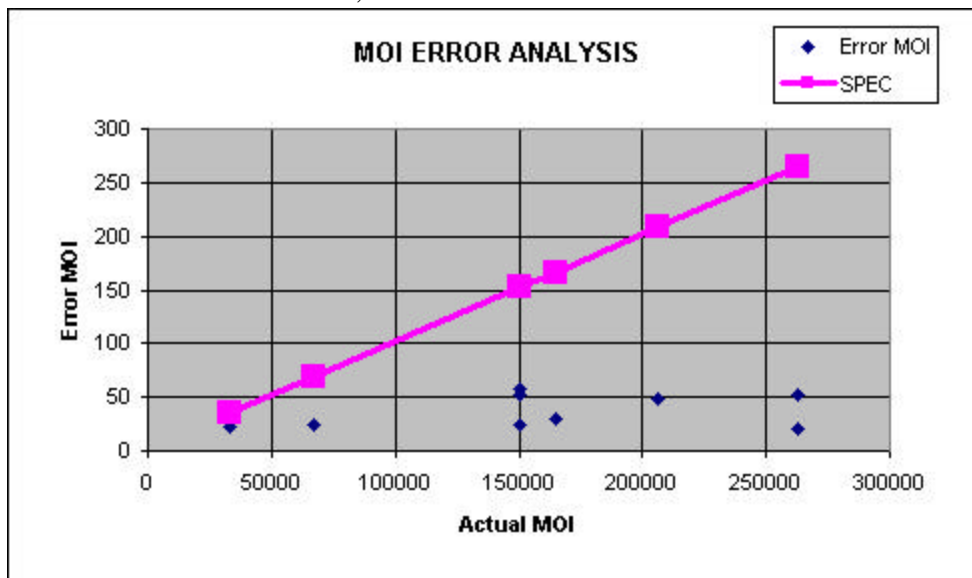
Product of inertia Although this instrument does not measure product of inertia directly, it is possible to determine product of inertia by making a series of MOI measurements at different orientations relative to the measurement axis of the machine. This is described in detail in SAWE Paper # 2093 "Using the MOI method of measuring Product of Inertia".

Improvement in CG measurement time For objects with large moment of inertia, the traditional "old" method required at least 14 minutes to make a measurement of two-axis CG. The same objects can now be measured in less than 4 minutes. Objects with small moment of inertia can be measured in as little as 2 ½minutes.

Conclusion A high speed mass properties measuring instrument has been developed that measures CG at least 3 times faster than the conventional Space Electronics KSR series instrument, which has been the standard of the industry for many years. No sacrifice in accuracy occurs at this higher measurement speed.

This new instrument employs a different concept. The old instrument rotated to each of the four quadrants, stopped precisely at the correct angle, and then measured the CG offset moment. This required a variable speed motor drive that slowed down as it approached the correct angle, executed motions to damp out any vibration, and then edged slowly to its final destination. The new instrument coasts to a stop at three approximately equally spaced locations. An extremely precise optical encoder then measures the actual angle while a force-restoration transducer determines the moment to better than 0.01% accuracy. The on-line computer then uses this data to determine X and Y CG of the object being measured.

APPENDIX

Instrument models currently available from Space Electronics

MODEL	Recommended Payload Weight Range (lb)	Full Scale Moment (lb-in)	MOI Accuracy (lb-in^2)	CG Accuracy (lb-in)
KSR330-6	0.25 – 20	6	0.1% + 0.03	0.1% + 0.0005
KSR330-16	1 – 40	16	0.1% + 0.03	0.1% + 0.001
KSR330-60	3 – 120	60	0.1% + 0.03	0.1% + 0.003
KSR1320-150	50 – 800	150	0.1% + 0.2	0.1% + 0.01
KSR1320-300	50 – 800	300	0.1% + 0.2	0.1% + 0.02
KSR1320-600	100 – 1320	600	0.1% + 0.2	0.1% + 0.04
KSR1320-1500	100-1320	1500	0.1% + 0.2	0.1% + 0.06
KSR2200	100 – 2200	2500	0.1% + 0.7	0.1% + 0.1
KSR6000	200 – 6000	5000	0.1% + 2	0.1% + 0.3
KSR8000	200 – 8000	5000	0.1% + 2	0.1% + 0.3
KSR13200	500 - 13200	8000	0.1% + 4	0.1% + 1.5
KSR17000	500 - 17000	16000	0.1 + 10	0.1% + 8
KSR20000	1000 - 20000	36000	0.1 + 10	0.1% + 8