Measuring weight and all three axes of the center of gravity of a rocket motor without having to re-position the motor

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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 holds 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 72 papers, including 35 papers presented at SAWE International Conferences and 3 papers presented at Regional Conferences. Three 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 30 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).
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1.0 Abstract
Large live rocket motors are dangerous and time consuming to move. Therefore, it is advantageous to measure mass properties with a minimum of handling operations. This paper describes an instrument which is capable of measuring weight and all three axes of center of gravity in a single setup. Two axes are measured using a reaction type two axis CG instrument. The mounting surface of the machine then tilts to measure the third axis. By using force restoration technology and flexure pivots, CG measurement accuracy is in the order of a few thousandths of an inch. Weight and CG are measured independently by using a parallelogram structure with a single force transducer, upon which are mounted the X and Y moment measuring structure. This permits optimization of the design. This paper discusses details of the process and the means of verifying the accuracy of the instrument, using a mass properties standard that has been designed to permit the application of work reversal techniques.
2.0 Traditional Multiple Point Weighing Method --(also called "3-Point Weight and CG Instrument" or "Reaction Method")
The CG of an aircraft is traditionally determined by placing scales or load cell platforms under the three wheels of the aircraft and calculating the CG location from the difference in force measurement at these three points. An instrument can be constructed on this same principle, wherein a test platform is supported by three or more load cells, and the CG location is calculated from the difference in force measurement at these three points. In the past, the accuracy of this method has been limited by the dynamic range of load cells, so that these instruments were not suitable for projectile and missile measurements. The introduction of force restoration technology to CG measurement by Space Electronics in 1988 has reduced force measurement errors by a factor of 30. When this technology is applied to the Multiple Point Weighing Method, accuracy improvement is great enough so that this method now becomes acceptable for many applications. This instrument measures weight as well as CG.

![Figure 2 Traditional Multiple Point Weight and CG Machine - Fast and easy to use, but not as accurate as the instrument described in this paper.](image)
2.1 Calculating weight and CG location using a traditional 3 point design.

To determine part weight (W) and CG coordinates X and Y, three force transducers are typically used to support a frame which in turn supports the object. The weight is simply the sum of the force applied to the three transducers.

\[ W = A + B + C \]

where A, B, and C are force readings on the three force transducers.

To determine CG, take moments about A

\[
\begin{align*}
\Sigma M_x &= (B+C)L - WX = 0 \\
\Sigma M_y &= \frac{CD}{2} - \frac{BD}{2} - WY = 0 = \frac{D}{2} (C-B) - WY \\
X &= \frac{(B+C)L}{W} \\
Y &= \frac{(C-B)D}{2W}
\end{align*}
\]

where X and Y are the CG coordinates.

If all the transducers outputs are set to zero when fixturing is in place, the equations above can be used to determine the CG location of the test part. In practice, two measurements are made:

1. First the tare value are measured, with the fixture in place.

2. Then the test object is installed in the fixture, and a seconds set of A, B, and C force readings are made.

3. Tare readings are then subtracted from the part measurements to yield the net value of A, B, and C for the test object.

4. The equations above are then use to calculate the X and Y coordinates of the test object CG. The sum of the net values of A, B, and C is the weight of the test object.
Figure 4

TOP VIEW
<TEST OBJECT & INTERFACE PLATE REMOVED>

TEST OBJECT—

SIDE VIEW

TRADITIONAL 3-POINT WEIGHT & CG INSTRUMENT
<NOT THE BEST METHOD>
In the traditional method, the measurement of CG results from a small difference between three large numbers. Even with force restoration technology, the accuracy is limited by the fact that each transducer must be capable of supporting the full weight of the object being measured (assuming that the CG can be anywhere within the range of the instrument). The full scale load requirement of each transducer can be reduced to a smaller value by placing the transducers further apart, so that each transducer only has to support a fraction of the total weight. However, this now reduces the CG sensitivity, since the distances L and D become larger. If the range of anticipated CG offset is small, the transducers can be brought closer together. However, this increases the lean error (discussed in a later section), and in fact can result in an unstable system if the CG leans outside the outline formed by lines connecting the three transducers, so that one transducer experiences an upward (negative) force.

3.0 A Better Method of Measuring CG

A better design is to measure the weight of the object using a transducer which is independent of the CG measurement, and to support the majority of the object weight on a central pivot while measuring CG. In the illustration below, the pivot acts against a large load cell, which is capable of measuring the entire weight of the heaviest object which will be weighed. This pivot is located near the nominal CG of the object being measured, so that almost 100% of the weight acts against the large load cell. Two smaller cells (whose capacity might typically be 5% of the large cell) measure offset moments in the X and Y direction resulting from the displacement of the object CG from its nominal.

The central pivot must have extremely low friction and the inability to establish a precise center of rotation. One approach is to use two pairs of ball bearings, arranged in a configuration similar to the universal joint in a car. A better approach is to substitute crossed-web flexures for the bearings. These flexures are essentially frictionless and provide an extremely precise pivot center. The ultimate pivot is a spherical gas bearing. This is not justified for most applications, but is used in highly critical cases such as the measurement of turbine blade center of gravity.
The configuration shown in the illustration above has a fundamental deficiency: the central load cell deflects an amount that is proportional to the load applied, whereas the deflection of the smaller moment cells is indeterminate, since it depends on the CG offset of the object. If the object CG were coincident with the pivot, then the cells would have no deflection. With this design, the test object will tilt one way or the other, depending on the weight of the object and its CG offset. This in turn will introduce an error in CG measurement due to object lean. For objects with low CG height, this is of minor significance. The error can be large for tall objects.

There are three components of lean error. First there is the effect of leveling the machine. The sensitivity of the leveling technique, the operator skill in the leveling process, the stability of the floor on which the machine is mounted, and CG height of the test part above the machine loading plane all contribute to the lean effect due to leveling.
The second type of lean error is caused by the finite stiffness of the measuring system. That is, all measuring systems deflect somewhat under load. For test parts with large CG height, the CG will lean in the direction of the CG offset causing further CG offset. This effect can be compensated for by measuring the machine stiffness constant, entering the approximate CG height, and correcting the measured reaction force proportionately to compensate for the machine deflection. The force restoration system used by Space Electronics automatically re-levels the fixture when measuring offset moments, so that this effect is minimized.

Finally, the part may be caused to lean by inaccuracies in the support fixture. Generally, this can be determined by performing optical measurements on the object while supported in the instrument.

The effect of lean error can be minimized by designing the fixture to keep the CG height to a minimum, keeping CG offset minimum, and making the measuring system as stiff as possible consistent with required sensitivity and accuracy.

### 4.0 The best design

Figure 7 shows the basic outline of the Space Electronics Model WCG T1000 instrument. The basic instrument consists of a large weighing platform upon which a flexure pivot and two smaller moment scales are mounted. The weighing platform contains a parallelogram structure which maintains the level condition of the platform throughout its measurement range. Both moment transducers are supported on a rigid platform which remains parallel to the base independent of the object weight. Therefore, the lean error described in the previous case is eliminated.
The weight of the test object is supported primarily by a flexure pivot, which is located near the nominal CG of the object. The two moment transducers support the off axis components of the CG. The flexure pivot and the two moment transducers apply a force to the main weight platform, which reads the total weight of the tilting support structure and the PSRE. Test object CG location is measured relative to what is called the “Machine Zero Reference”. If the test object CG is directly above this reference, then no load is applied to the two moment transducers. The CG position of the test object is determined by the output of the two moment transducers. CG location along two axes is determined by solving algebraic equations involving these two readings, then subtracting tare readings, and dividing the calculated moment by the test part weight.
5.0 Measuring the third CG axis

The third CG coordinate may be measured by tilting the test object through a known angle (approximately 30 degrees), re-measuring CG, and comparing it with the CG location before tilting. If the object were tilted by 90 degrees, then the third axis could be measured with the full accuracy of the machine. However, the tilt angle is approximately 30 degrees, so the accuracy is one half of the accuracy for the other two axes. This does not represent a problem, since the machine is generally much more accurate than required. Furthermore, if the object to be measured is a rocket motor or other section of a rocket, the two radial CG components are the critical ones, since rocket thrust must be precisely aligned with the CG to prevent large moments during take off. The CG along the length is of minor importance.

The basic structure of the machine with the tilt feature is shown below. The interface plate or ring is attached to a pair of right angle brackets which are pivoted on bearings. An air cylinder causes the interface to tilt. The exact rotation angle is set by hard stops near the rotation axis. Improved accuracy results from the center of the tilt axis being close to the CG of the test object. This minimizes the force required to tilt the object, and also minimizes several second order sources of error.
The initial measurement is made with the interface in a level condition. The interface is then tilted and a second measurement made. The difference between the two measurements is then used to calculate the CG height of the test object:

\[
\text{CG height} = 1.732X_{\text{level}} - 2X_{\text{tilted}} + \text{distance from rocket motor reference to tilt axis}
\]
SPACE ELECTRONICS  MODEL WCGT 1000
WEIGHT & CENTER OF GRAVITY INSTRUMENT
SHOWN WITH CUSTOM ROCKET MOTOR ATTACHMENT RING

MEASURES THREE CG COORDINATES PLUS OBJECT WEIGHT

Figure 10
Figure 11 - Space Electronics Model WCGT1000 Weight and Center of Gravity Instrument with special fixture ring for attachment of rocket motor

Figure 12 - Instrument shown with rocket motor installed
6.0 System components

The instrument mainframe is connected to a display pedestal which in turn is connected to the system computer. The system computer provides the operator interface. We have developed menu driven software which is user friendly and guides the operator through all procedures with clear written messages.

The major instrument components are:

a. The measuring system consisting of:
   - the instrument structure
   - the test object interface
   - interface tilt system
   - the unloading mechanism
   - overtravel and overload protection
   - display pedestal

b. The controller station including:
   - desktop computer system
   - color inkjet printer
   - weight and CG calibration and measurement software
   - computer interfaces and cables

c. Standard moment calibration set traceable to NIST:
   - two 18 pound test weights with 0.75 dia. center pilots which mate with the bushings on the instrument
   - certified gage bar for measuring calibration distances.

Computer System - The model SE90113 weight and center of gravity instrument requires a certain amount of mathematics and logic to:

- read the output of three force cells
- calculate the weight and center of gravity of a test object
- correct for fixture error
- monitor the system gas pressure
- inhibit operation under hazardous conditions
- operate the overload protection system
- provide setup and diagnostic procedures

These functions are provided by the computer system with digital interfaces to the instrument. This system automatically exercises a startup routine and presents a main menu to the operator. The operator selects the desired operation and is presented with prompts to proceed. This computer system includes a printer so that a permanent report can be generated for each test item. This system includes the following items:
1. Computer system with printer, monitor and keyboard
3. Three RS232 digital interfaces
4. One 24 bit parallel digital I/O interface
5. Interconnecting cables

The connecting cables and the electronic components in the display pedestal and machine are configured for explosion proof operation. The computer system, however, is not explosion proof, and must be located in a remote non-hazardous area.

Figure 13 Sample measurement screen
6.1 Force restoration transducers
The base weight scale and the two moment transducers are of the **force restoration** type. With **force restoration** technology, when a force is applied, the transducer does not deflect, because of a servomechanism within the transducer which restores the mechanical transducer to its position before the load was applied. This is accomplished with an electromagnetic actuator similar in concept to the voice coil in a loudspeaker (only many times more powerful). When a load is applied, the transducer begins to deflect. A laser senses this deflection and increases the current to the coil to apply a restoring force through a closed loop control system until the unloaded geometry is restored. The applied current is then related to the applied force. Since the loaded geometry, after the restoring force is applied, is the same as the unloaded geometry, the transducer is inherently linear like the time honored balance beam scale. This is unlike a strain gage load cell which relies on the deformation of the fragile spring element to generate an output. Full scale signal levels are typically 20 volts, as compared to 20 millivolts for a strain gage load cell. Therefore, signal to noise ratio is 1000 times better than a strain gage cell. Force restoration transducers are better than strain gage load cells since they offer greater stiffness, dynamic range, linearity, and overload protection than load cells. As a result, the moment measurement sensitivity of this weight and CG instrument is better than 0.001% of full scale!

6.2 Unloader cylinder
The model WCGT1000 utilizes a pneumatic cylinder and spring to prevent excessive forces from being applied to the transducers during loading and removing of the test object. The spring lifts the upper assembly (payload interface) off the moment transducers at all times except when a measurement is being taken. The computer commands a solenoid valve to apply compressed air to the unloader cylinder to compress the spring during measurement.
7.0 Establishing the zero reference and calibrating moment and weight readout

One disadvantage of this type of instrument is that there is no inherent zero point. Unlike rotary table machines, the object cannot be dial indicated. Fixturing errors may be relatively large. For this reason, to obtain maximum accuracy, a precision dummy part should be used to determine the zero reference of the instrument. This dummy part should interface with the instrument fixture in the same manner as the real objects to be measured. The location of the CG of the dummy part must be precisely known.

For the instrument described in this paper, a precision dummy rocket motor was constructed out of aluminum. The weight was adjusted to be the nominal weight of the rocket motor. Care was taken to ensure that the attachment dimensions were identical to the rocket motor, so that this dummy could be used to correct for fixturing location as well as serve as a zero reference. The dummy was reinforced so that it would retain its dimensions over time. This standard was sent to NIST for certification. The CG of the standard was then measured on a certified Space Electronics Model KSR 2200 instrument. Measurement accuracy of this instrument is better than 0.001 inch. Fixturing uncertainty has to be added to this accuracy.

Moment calibration was accomplished using precision cylindrical weights with center pilots that mated with ground inserts on the machine. Moving the weights from one location to another resulted in a precise moment change.

This standard was designed so it could be rotated 180 degrees to verify X and Y CG coordinates, and also could be mounted in the fixture upside down to verify CG height.
The weight accuracy was 0.002% of full scale.
CG error in X, Y, and Z (including fixturing uncertainty) was less than 0.005 inch.
Repeatability including fixturing uncertainty was +/-0.002 inch.

Baseline measurement  
Weight = 600.46  cg X = 248.730  cg Y = 100.000  cg Z = 100.002

Weight - calibration weight added to center of PSRE simulator
simulator weight as (certified)  600.417 lb
 calibration weight  18.451 lb

Calculated total weight  618.868
Measured total weight  618.92

Weight error  0.05 lb  (0.002% of full scale)
Allowable variation  0.60 lb

Center of gravity using special y-z test weight  
Weight placed near hole A  248.855  100.344  99.656
Weight moved to near hole B  248.854  99.658  99.660
Weight moved to near hole C  248.855  100.344  100.346

test distance A-B = A-C = 42.407 in, test wt = 9.8805 lb
change in moment = 42.407*9.8805 = 419.002 lb-in

calculated change in cg = 419.002/610.35 = 0.6865  0.6865
measured change in cg = 0.686  0.690
deviation = 0.0005  0.0045
Allowable deviation = 0.020 (+0.010) 0.020 (+0.010)

Center of gravity height using special cg X weight  
Weight down  248.642  100.135  100.000
Weight up  248.206  100.133  100.001

test distance (vertical change) = 22.822 in
test weight (certified) = 11.6292 lb
change in moment = 22.822*11.6292 lb-in = 265.402

calculated change in cg = 265.402/614.10 = 0.432
measured change in cg = 0.436
Deviation = 0.004
Allowable deviation = 0.080 (+0.040)
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8.0 Summary of Major Benefits and Shortcomings of this Instrument

Benefits of this CG measurement method

1. Measures both CG and weight.

2. This is the fastest CG measurement method. Total time to make a measurement of weight and 2 axis CG is less than 30 seconds. The third axis requires another 60 seconds (most of which involves the tilting operation).

3. All three axes of CG can be measured in a single setup, eliminating the cost and risk associated with re-orienting the rocket motor on its side.

4. It is most suitable for very heavy parts with moderately precise CG location tolerances (such as +/-0.005 inch). By using the latest force restoration transducers and optimum geometry, sensitivity can be adequate for most applications.

5. This type of instrument is very easy to use.

6. For a given CG offset moment capacity and part weight, it is often the lowest cost automatic system.

Shortcomings of this CG measurement method

1. A separate instrument must be used to measure MOI if this quantity is required.

2. It is highly sensitive to and not readily correctable for lean error caused by leveling.

3. The machine axis zero point is difficult to define. It is best determined using a precision standard which simulates the part to be measured.

4. Accuracy is not as high as can be obtained with a gas bearing rotary table type instrument which measures CG at four quadrants and subtracts the offset automatically (such as the Space Electronics KSR type instrument).