

Mass Properties Measurement Handbook-

by

Richard Boynton, President
and
Kurt Wiener, Chief Engineer

Space Electronics, Inc.
81 Fuller Way
Berlin, Connecticut 06037

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1.0 Abstract There has been some discussion at recent SAWE International Conferences regarding the creation of a SAWE sponsored mass properties seminar, with the ultimate goal being the certification of Mass Properties Engineers by the SAWE. This paper presents a review of the methods used to measure Center of Gravity Location, Moment of Inertia, Product of Inertia, and Weight. The authors have attempted to discuss all the elements of mass properties measurement, so that this paper can be used as a textbook. This will be condensed and edited at a later date for incorporation into the SAWE Weight Engineering Handbook.

Much of the material in this paper has been gleaned from previous papers written by the senior staff engineers at Space Electronics (Boynton, Wiener, and Bell). We have provided a bibliography at the end of this paper which references some of these papers, so that readers wishing to delve further into these subjects can obtain information on mathematical derivations of error sources, etc.

2.0 Steps in Making a Mass Properties measurement

There are 9 steps required to measure the mass properties of an object:

2.1 Define the particular mass properties you need to measure and the required measurement accuracy Sometimes this task has already been done by someone else, but other times you may be asked to measure mass properties without being given much guidance regarding what is to be measured or the accuracy required.

2.2 Choose the correct type of measuring instrument This choice will be driven by the availability of existing equipment, accuracy required, cost, and suitability for the measurement environment (i.e. production vs. research).

2.3 Define the coordinate system on the object to be used as the mass properties reference axes Any object has an infinite number of values for CG location, moment of inertia, and product of inertia, depending on where the reference axes are assigned. The axes may be related to the geometric centerline of the vehicle, a line of thrust, or may depend on the attachment interface to another stage of the vehicle.

2.4 Define the position of the object on the mass properties measuring machine There are an infinite number of ways a payload can be mounted on a mass properties machine. While the mass properties of the payload are fixed, the measured data will be dependent on the orientation of the payload relative to the measurement coordinate system. We are talking about basic position, not how accurate this position is. For example, a rocket can be mounted on the machine with its nose up or its nose down. The fins can be parallel to the X axis of the machine or the Y axis (or for that matter can be oriented at any angle). To avoid confusion, you need to make a drawing or sketch of the position of the payload on the machine, so you can interpret the measured data correctly. The X axis of the mass properties instrument will not necessarily correspond to the X axis of the payload.

2.5 Determine the dimensional accuracy of the object being measured This can be the limiting factor on accuracy. For example, you can't measure CG of a cylindrical object with an accuracy of 0.005 inch if the outer surface of the object has a runout of 0.020 inch.

2.6 Design the fixture required to mount the object at a precise location relative to the measuring instrument This will require a means of determining the location of the measurement axis of the instrument as well as a means of accurately supporting the object on the instrument.

2.7 Verify the position of the object on the instrument. There are clever techniques which can make this relatively easy.

2.8 Make the mass properties measurement. This can be the quickest part of the job.

2.9 Report the mass properties data After the measurement is made, you will have to report the data to someone else. You need to define which axis is X, which axis is Y, etc. Your X may be someone else's Y. Even within one company, one department may call the roll axis X and another department may call it Y. If you submit the data without defining the axes, each group will use its own set of coordinates in interpreting the data. These problems can be minimized by using the Recommended Practice for Mass Properties Reporting which is summarized in the figures below. No amount of discussion will replace the value of a single sketch showing the orientation of the payload and definition of the measurement coordinate system.

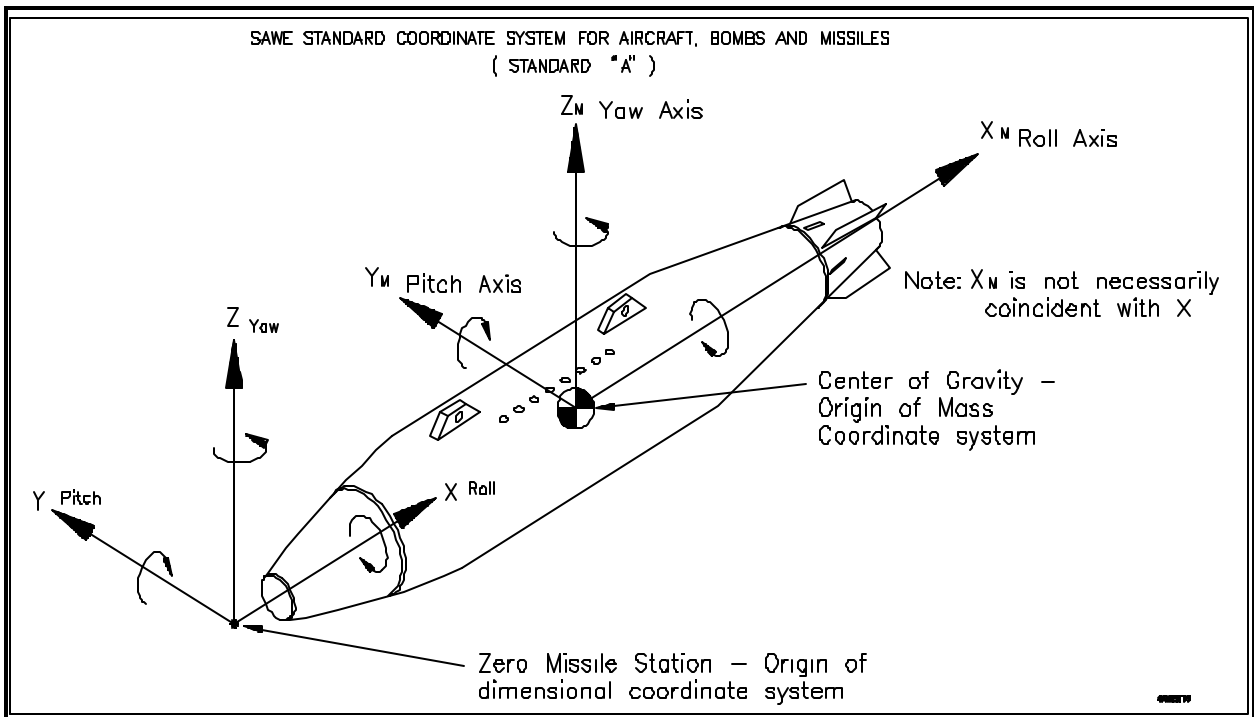


Figure 1 - Standard "A" for Aircraft, Bombs, and missiles

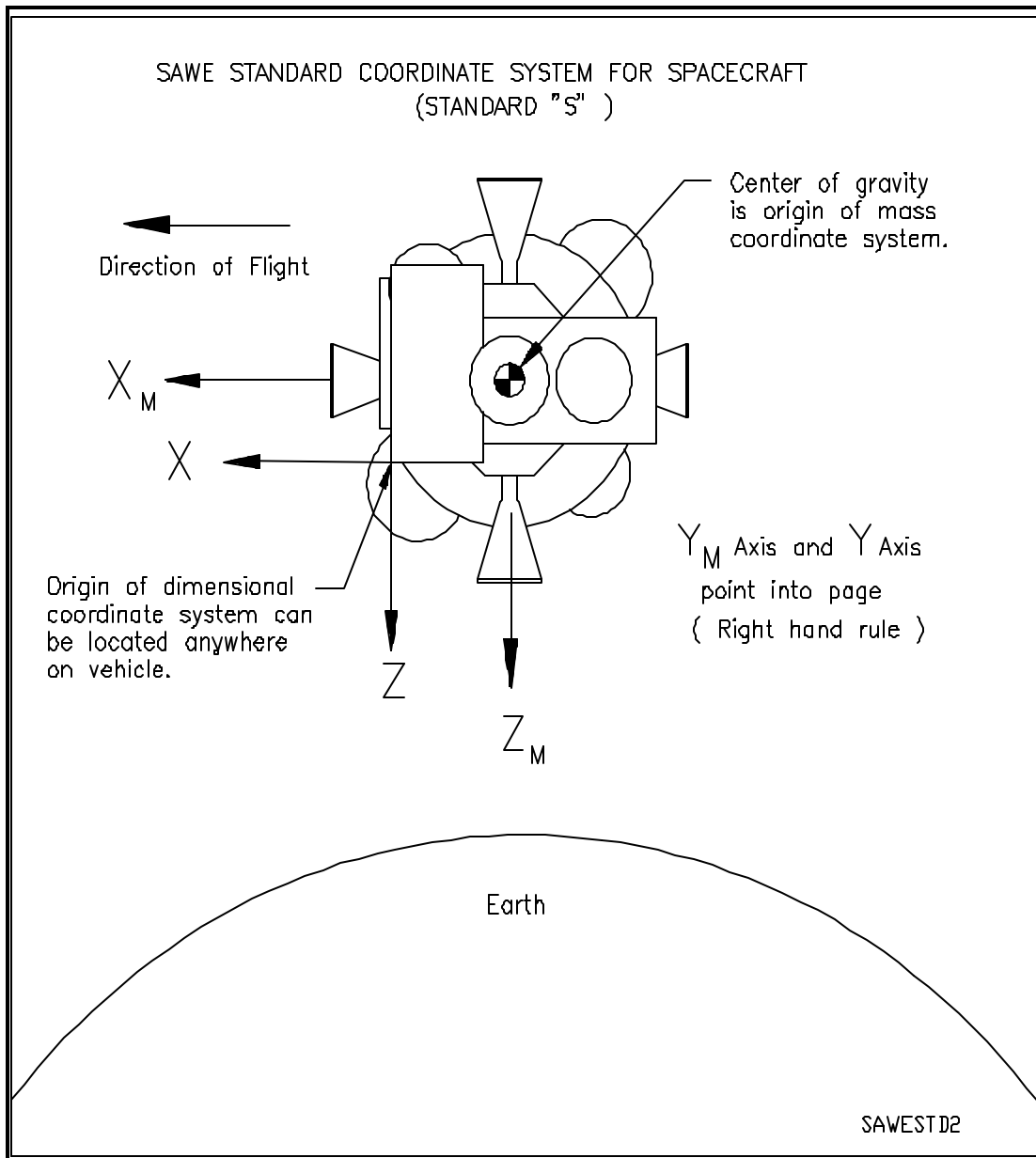


Figure 2 - Standard "S" for vehicles which orbit the earth

3.0 Establishing a frame of reference (relating payload and instrument coordinate systems)

3.1 Choosing the frame of reference The flight dynamics engineer works with two different vehicle frames of reference: the body frame, defined by the structure of the missile, and the inertial frame, defined by the mass properties of the vehicle. Many people involved with mass properties do not fully understand the difference between these two frames of reference, or how you translate vector quantities from one frame to the other (a process involving Euler angles and an ordered sequence of three matrix rotations about the axes of the source frame).

The body frame is a reference system which is related to the physical structure of the vehicle. This frame is easy to define for a perfect ideal vehicle shape, but may be hard to locate on a real vehicle, because of loose manufacturing tolerances and other practical problems.

The inertial frame is a reference system defined by the principal axes of the vehicle. This can be crudely calculated, but it is necessary to make measurements of the real vehicle to accurately determine the location of this inertial frame relative to the body frame. Measurements are made on a mass properties instrument which determines CG location, moments of inertia, and (if necessary) products of inertia. These measurements define the inertial frame relative to the body frame *within the tolerance limitations of both the structure and the measuring instruments*.

Often the goal is to align the two frames of reference so one principal axis coincides with the roll axis, etc. This is not always the goal, however. Certain reentry vehicles are deliberately designed with a misalignment to produce a coning action during reentry, and smart weapons scan the target in a circular pattern by using a similar misalignment.

3.2 Interpreting the data The following is a review of some general characteristics of mass properties data which must be observed when deciding on the orientation and coordinate system to be used for mass properties measurements.

3.2.1 Moment of inertia can only be positive, so there is never any uncertainty regarding sign. However, you should determine whether this magnitude should be expressed about the geometric centerline of the vehicle or about its CG, about an axis parallel to the geometric centerline or rotated so the data is about the principal axes. In most cases, there will not be a big difference in these three magnitudes. This can lead to confusion, since it will not be immediately obvious that the wrong data is being presented. Space Electronics mass properties instruments always report MOI and CG relative to the instrument centerline. If user data is entered, then these properties will also be reported relative to the payload datum and coordinate system.

3.2.2 Center of gravity coordinates can be positive or negative. You should determine whether your positive axis agrees with the definition of axes used by the recipient of your data. Furthermore, CG distance can be expressed along a coordinate system defined by the geometry of the vehicle or along the principal axes. We recommend you provide a sketch which clearly shows the axes and their algebraic signs.

3.2.3 Product of inertia can also be positive or negative. Since this quantity is derived by multiplying the incremental masses by two different distances, the POI sign is even more prone to error than the sign of the CG data. We frequently hear the comment: "I can calculate POI, but I never get the sign right". What usually happens is not that the sign is wrong, but that the mass properties engineer and the recipient of his data are using different coordinate systems.

3.2.4 About vs. along Moment of inertia is expressed about an axis. CG coordinates can be expressed as a distance along an axis or as an unbalance moment about an axis (CG along X corresponds to the CG unbalance moment about Y or Z). POI is relative to two axes. (or it can be a tilt angle in a plane defined by two axes).

Six types of information are required to establish a mass properties reference system:

1. The location of the reference axes origin.
2. The mathematical symbols used to define the reference axes.
3. The zero point along each axis
4. The direction of positive values along each axis.
5. The positive direction for rotation about each axis
6. A zero rotation angle reference about each axis

3.3 Dimensional Errors - In the previous section we discussed the definition of axes and polarities. In this section we are concerned with the difference between the ideal and the real object. In order to make accurate measurements, the payload must have precisely defined measurement axes. If the object is a smooth ground cylinder, then it is obvious where the axes are located. However, on real parts,

- ! flat surfaces are not perfectly flat;
- ! round surfaces are not perfectly round;
- ! concentric surfaces are not exactly on the same center;
- ! perpendicular surfaces are not exactly perpendicular;
- ! some surfaces are soft or poorly shaped (cork, thick paint).

The effect of all these non ideal conditions is that the datum for the payload coordinate system can be no better than the accumulated uncertainties of the datum surfaces.

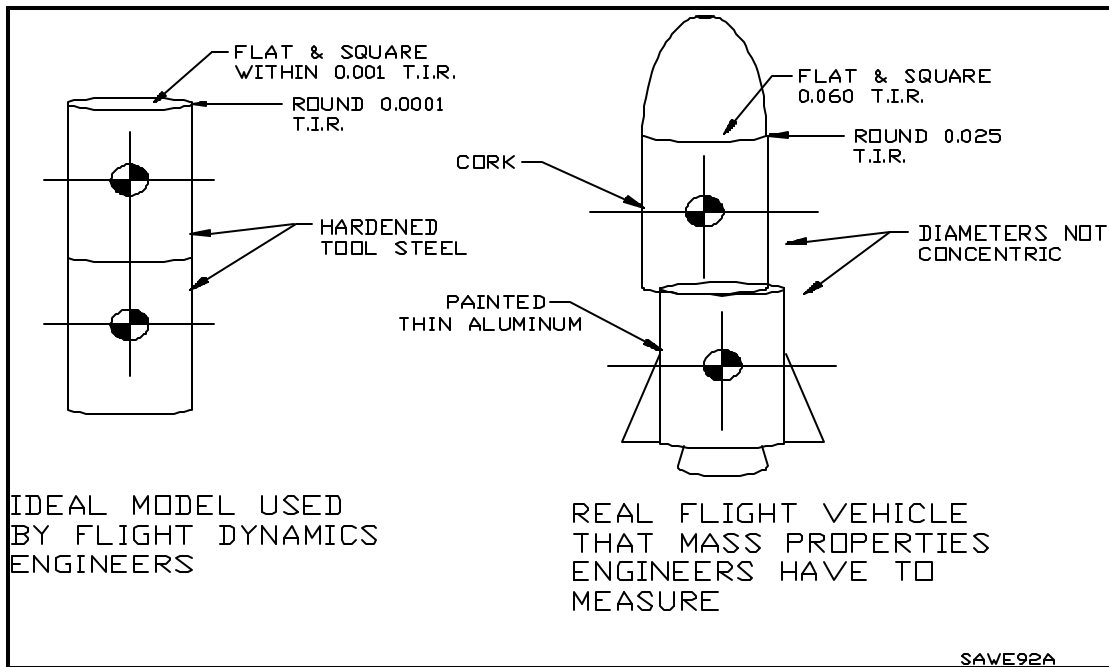


Figure 3

Often mass properties are defined relative to a coordinate system that includes the centerline of a vehicle, and two orthogonal axes located at a specific missile "station" (distance along the centerline). What do you do if the missile is made of three different sections, each with its own centerline? Until the measurement axes have been defined to the satisfaction of all parties involved with mass properties, there is no sense proceeding.

Recommendation: When you first receive an object to measure, do a dimensional inspection of the object. If the object outer surface is less accurate

3.3.1 Unrealistic CG tolerances Your CG measurement accuracy can only be as good as the machining accuracy of the reference datum. For example, if you must measure and correct the radial CG of a rocket within 0.003 inch of the centerline of the rocket motor flange, and you dial indicate this flange and find that it is out of round by 0.015" TIR, then the specification for CG accuracy is impossible to achieve. However, there may be a common sense compromise which will allow the measurement to proceed. For example, you might discover that the flange is close to an ellipse, so you can establish a center of the large and small diameter and relate the CG to that point. A "best fit circle" program is often used to locate a centerline for out of round cylindrical parts. You may find that there is a flat or other anomaly area on the flange, so you can ignore that part and base your center on the part that appears more round.

A better solution might be to find out what is really the point of the specification. For example, it might turn out that what is really required is that the CG be centered on the exit cone of the rocket

motor when this motor is rotated to a straight ahead position. If you know this, then you can negotiate a much more meaningful test which accomplishes the flight objective.

3.3.2 Determining realistic mass properties tolerances To determine if the stated tolerances are realistic, the payload uncertainties, fixture uncertainties, and instrument uncertainties must be determined and compared to the specified measurement tolerances. The sum of these three uncertainty sources must be less than the measurement tolerance by a factor of at least 3 with a factor of 5 or more being desirable. To determine the object uncertainties a two step analysis is recommended. Keep in mind, this analysis is just for the object. Another, similar, analysis must be performed as part of the fixture design process to be sure that the fixture does not use up more than 10 or 20 percent of the allowable mass properties measurement tolerance.

STEP 1 = Calculate the required mechanical dimensional tolerances necessary in order to be 10 times better than the accuracy specification for mass properties. For example, if CG accuracy required is 0.005 inch, then you must know the location of the reference axes to an accuracy better than 0.0005 inch. .

STEP 2 = Do a dimensional inspection of the object. If the object outer surface or other datum surfaces have accumulated tolerances less accurate than the tolerances calculated in step 1, then you have a problem.

In cases where there is no precise surface on the object and the critical axis is the aerodynamic centerline, then this can be determined using multiple measurements at different heights along the object and then entering this data in a computer program which determines the best fit solution. Space Electronics manufactures a system consisting of a very rigid dial indicator stand with two electronic dial indicators. The outputs of the dial indicators are connected to the computer, automating the process of determining the single line which represents the geometric centerline of the vehicle.

3.3.3 Dimensional tolerance for product of inertia measurement Objects which are spin balanced must generally be dimensionally defined even more accurately than those requiring CG measurement.

Tolerances for product of inertia are trickier to calculate. The best approach is to first calculate the axis tilt corresponding to the object POI tolerance, and then relate this to TIR runout of two reference diameters or between a reference diameter and a perpendicular axis.

3.3.4 Establishing hard points on the object If you have an influence in the early stages of a design, maybe you can convince the project engineer to add two precision datum rings to the object. This will give you a reliable interface for your fixture and will also give you something to measure to determine if the object is located correctly in the fixture. The example below is for a rocket. But could apply equally well to a satellite. Engineers who align the guidance system will find these rings invaluable. Motor nozzles can be located relative to these rings.

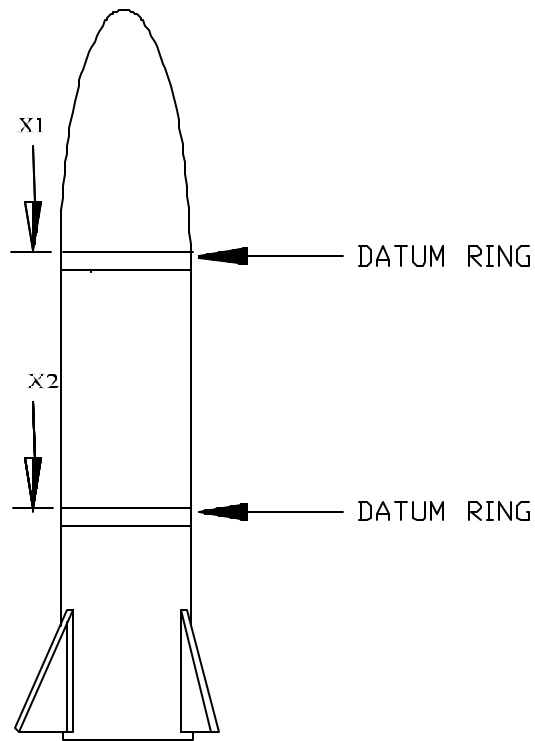


Figure 4 - Precision rings eliminate uncertainty regarding measurement axes

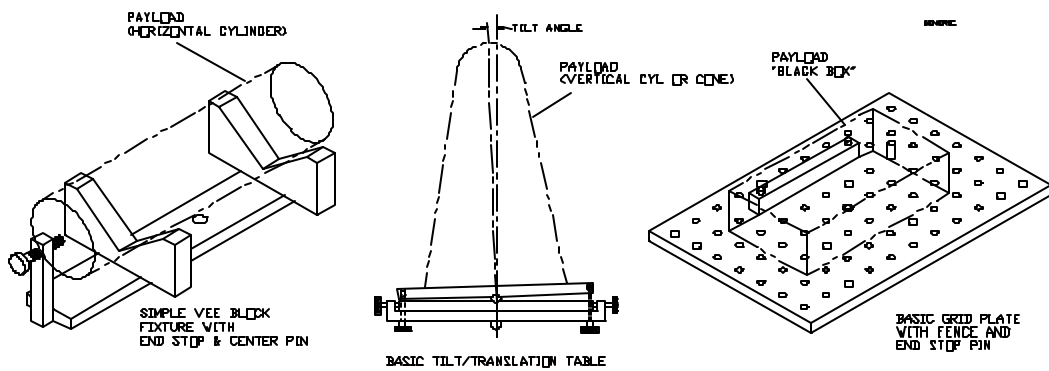


Figure 5 - Standard Generic Fixtures Available from Space Electronics

4.0 Choosing a fixture

The number one source of measurement error in most mass properties measurements is the inability to accurately position the object being measured relative to the measurement axis of the instrument. Traditionally this has been accomplished using a precision fixture which supports and locates the object. For horizontal measurements of cylinders, vee blocks are commonly used. For vertical cylinders or cones, an adjustable fixture is often used and the object is centered using dial indicators. Rectangular objects are usually fixtured using a grid plate fixture that has "fence" type end stops which interface with a precise pattern of holes on the fixture.

4.1 Importance of fixturing accuracy The accuracy of mass properties measurement is only as good as the accuracy of the fixture used to support the payload. If you are measuring a smooth ground cylinder, then fixturing accuracy of 0.001 inch is not hard to achieve. This is a typical accuracy when fixturing a shaft for a turbine rotor. Objects such as this have precision surfaces where the bearings are supported. Not only are these surfaces almost perfectly round and true, they also generally lie along a longitudinal axis within 0.001 inch TIR. When you're in the jet engine business, fixturing is relatively easy because everything is made so precisely.

Many satellites represents the mass properties engineer's worst nightmare. There is no outer skin or controlled "hard point". It is just a clutter of irregular objects attached to a thin walled structure, and is so fragile that it can only be held at certain places, none of which are dimensionally controlled within the tolerances required for the measurement accuracy needed.

4.2 Mass properties fixtures perform three basic functions:

4.2.1. The fixture must locate the object in a repeatable and rigid manner relative to the mass properties instrument. For maximum measurement accuracy, the nominal CG of the object should be as close as possible to the measurement axis of the instrument. For spin balancing, the axis of rotation of the object must be coincident with the axis of rotation of the balancing machine.

4.2.2.. The fixture must provide a means to precisely relate the object coordinate system to the mass properties instrument coordinate system, so that measurements made relative to the machine axes can be expressed relative to the object axes.

4.2.3. The fixture should be balanced relative to the measuring instrument so that the full range of the instrument is available to measure the object. Static balance is adequate for CG and MOI measurements, but fixtures must be dynamically balanced for POI measurements. With the advent of computer controlled balancing machines, it is no longer necessary to have the fixture balanced perfectly. However, we recommend that fixture unbalance be no greater than 5 times the balance specification for the object.

4.3 No Detachable Parts Any detachable or movable parts or hardware on the fixture complicate the process of obtaining accurate tare measurements. Avoid using mounting hardware if possible to simplify measurement of fixture tare. For moment of inertia, all mounting hardware must be included in the tare readings. If hardware is necessary, then it

must be made rigidly captive so that it remains with the fixture when the tare reading is made. For CG measurements, the hardware should be symmetrical about the centerline so it does not introduce unbalance. If possible, the hardware should be oriented vertically, so that a change in the amount of thread engagement will not alter the tare CG or MOI.

4.4 Low Windage Design of the fixture should minimize aerodynamic drag. This is important for both POI and MOI measurements. Excess windage will result in increased damping during MOI measurements. The error due to drag can be reduced by measuring in a helium atmosphere (see SAWE Paper 2024 entitled "Using Helium to Predict the Mass Properties of a Object in the Vacuum of Space", by Boynton, Bell, and Wiener). If the fixture is used for spin balancing, the outer surface should be as smooth as possible to reduce the forces due to turbulence, which will obscure the forces due to unbalance, limiting the sensitivity of the machine. It may be desirable to make a shroud around the fixture. The shroud shape and clearance will influence the POI measurement.

4.5 Provisions for loading the object in the fixture If the object weighs more than about 75 pounds, then some thought must be given on how to mount it in the fixture. If these concerns are not addressed up front, considerable delay and cost may be incurred later.

4.6 Verifying object position If possible you should design the fixture so the position of the object can be verified after it is installed in the fixture. This may require that you provide access openings in the fixture so the object can be probed with a dial indicator. Never assume that the precision of the fixture will insure that the object is located correctly. Variations in object diameter and runout can result in unacceptable fixturing errors.

4.7 Defining the instrument axes High accuracy mass properties machines such as the Space Electronics KSR series have a mounting table which rotates, making it easy to determine the measurement axes with great precision. The measurement axis is simply the center of rotation of the object mounting table. Often the object can be dial indicated to align the object with this axis. The 0 degree mark on the mounting plate usually corresponds to the +X axis and the 90 degree mark corresponds to the +Y axis. One of the best ways to assure repeatable fixture positioning is to use a round pin to engage the instrument center bushing and a diamond pin (relieved locating pin) at a relatively large distance from the center to provide angular alignment.

CG instruments which use the 2, 3, or 4 point weighing method do not have a rotating mounting plate and therefore have no well defined measurement axis. This constitutes a major source of error and is one of the reasons why the three point reaction force method of CG measurement is less accurate than the rotating table method.

4.8 The four basic types of object/fixture interfaces There are four basic types of object/fixture interfaces:

4.8.1 attachment point interface, where the fixture emulates the actual interface between the object and a mating part. This is suitable for rocket/missile stages.

4.8.2 hard point interface, where a system of hard points or rings is used for inspection, alignment and assembly reference.

4.8.3 adjustable interface, where the object has no well-defined hard points and a sophisticated (and time-consuming) method must be used to determine the position of the axes. The fixture is then adjusted to move the object so its axes are coincident with the machine axes. A novel method of dealing with the problem of fixturing irregular objects involves the use of video imaging equipment. A TV camera is mounted above the object, and views the object as it is slowly rotated. A digital computer acquires the video images and calculates the mean center of the vehicle. If the object is a cone, then the camera can view two different heights and direct the operator to adjust both concentricity and tilt.

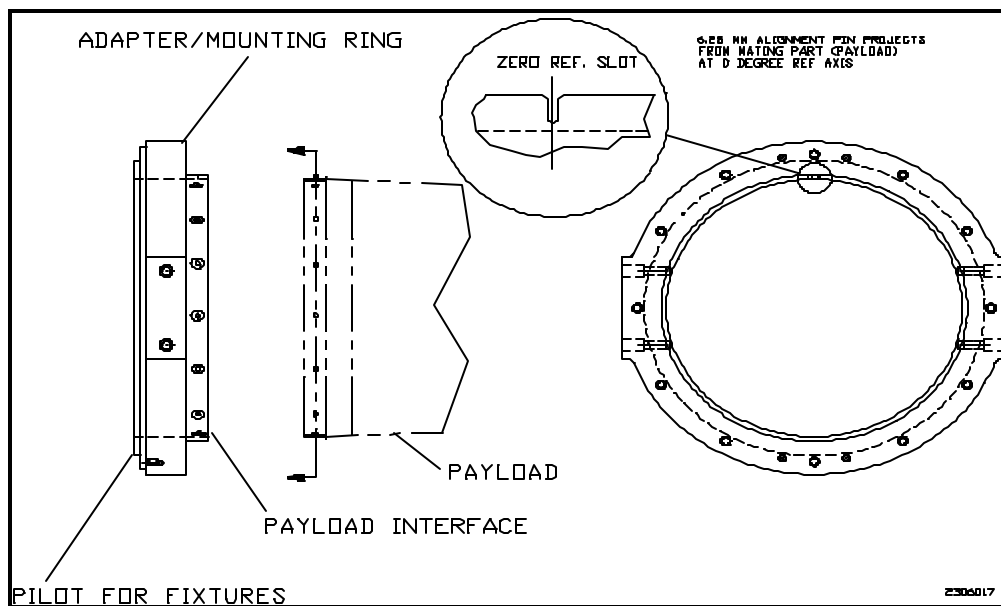


Figure 6 – Adapter/Mounting Ring Fixture Simulates the Actual Attachment Surface

4.8.4 **calculated interface**, where the object is placed in approximately the correct position, a measurement is made with the object in this position, electronic probes sense the position of the object relative to the machine, and the data is then corrected mathematically so it is expressed relative to the object axes.

4.9 Vee block fixture Cylindrical objects are often supported in a vee block fixture. The vee block does not depend on exact fit between diameters, since the cylinder sits tightly in the vee, no matter what its diameter is. One end of the object can be slid against a stop to establish the location along the length (X axis). The object can be rolled to an angle of 0°, 90°, 180°, and 270° to allow you to measure both radial axes..

4.10 Measurement tricks - turning uncertainties into correctable errors It's easy to measure the mass properties of a perfect cylinder. Not only can the object be located precisely relative to the instrument, but if the object is fixtured in a vee block, several valuable tricks can be used to maximize measurement accuracy.

4.10.1 Trick number 1. The cylinder can be turned end for end and re-measured. This establishes the location of the end stop. If the cylinder were a uniform solid and it were fixtured so one half its length were exactly on the centerline of the instrument, then turning the cylinder end for end would give the same CG location. In practice, the CG is not usually centered along the length, and the end stop is not located at exactly half the distance from the center of rotation of the instrument. However, if we know the length exactly (which is easy to measure), and we make a CG measurement from either end, then we can eliminate the fixture end stop uncertainty and correct the end stop position error. This method works for real test objects as well as cylinders as long as the test object can be turned end for end in the fixture.

First measure the CG from one end as shown in position 1, the left view of figure 7. This gives the distance from the machine center CG1. Then turn the part end for end and measure CG2 as shown in position 2. The two CG locations (for any object) will be equidistant from the mid line of the part at L/2. This attribute permits calculating the CG offset (d) from the end stop (for position 1).

$$d = L/2 + (CG1 - CG2)/2$$

If several test objects of the same type are to be measured, the true end stop location may also be determined and used as a reference datum distance (R) as measured from the measurement axis. This distance will be:

$$R = L/2 - (CG1 - CG2)/2$$

For successive part measurements the CG offset from the datum (d) then becomes R + CG1.

In practice, you should locate the end stop so the nominal payload CG location is as close as possible to the measurement axis of the instrument to eliminate second order uncertainties.

