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Standard Coordinate Systems for Reporting the Mass Properties of Flight Vehicles

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Table of Contents

Introduction 3

Elements common to both standards 3

Standard "A" 4

Pitch & Yaw axes 5

Standard "S" 6

The coordinate system defined by the mass properties of the vehicle 7

About vs. along 7

Moment of inertia 7

Center of gravity 8

Product of inertia 8

Definition of the right hand rule 9

Hard points 9

Providing precision reference datum rings 10

The Inertia Tensor 11

Introduction Anyone who has worked in the mass properties field for any length of time knows the problem: one person's **X** is another person's **Y**. Since the numerical values of the mass properties of an object are entirely dependent on the coordinate system chosen, it is essential that engineers include a precise definition of their coordinate system along with the mass properties data. To minimize confusion and to make the job of defining your coordinate system easier, the SAWE has adopted two standard coordinate systems:

Standard "A" is used for aircraft or any other vehicle which "flies"

Standard "S" is used for objects which orbit the earth

The intent of this Standard is to reduce errors and costs associated with improperly defined coordinate axis systems. <u>Although mass properties engineers will often be forced to use coordinate systems dictated by other parties, the SAWE strongly encourages you to use one of these standards whenever you have the freedom to choose your own coordinate system</u>. The success of a standard of this type depends on its widespread use. You are encouraged to make copies of this standard and to attempt to influence flight dynamics engineers and others at an early stage of the design of a flight vehicle. It is very difficult to change coordinate definitions once a project in underway.

For either standard you should:

- Specify <u>what standard</u> you are using ("A" or "S").
- <u>Include a drawing of the object being measured</u> and show the location of the axes.
- Show exactly what <u>hard points on the object</u> were used to accurately locate the axes.

Elements common to both standards

- Both standards use the right hand rule to define relative axis location.

- Both standards use the right hand rule for rotations. This rule applies to rotation angles, torques, and angular velocities.

The location of the origin and the orientation of the axes is determined by the physical dimensions of the object. The origin of these systems is not necessarily coincident with the nominal CG location.

To define the coordinate system on a flight vehicle, eight types of information are required:

1. The exact location of the three reference axes.
2. The location of the hard points on the vehicle which define the location of the reference axes.
3. The mathematical symbols used to define the reference axes.
4. The direction of for rotation about each axis.
5. The origin of the axes.
6. The positive direction for rotation about each axis.
7. The location of a rotation angle of zero degrees.
8. The units used.

STANDARD "A"

Standard "A" is generally used for aircraft, missiles, torpedoes, bombs, and any cylindrical objects whose dimensions along the length are based on the "fuselage station" concept (i.e. dimensions become more positive when progressing aft). Most aircraft mass properties engineers already use this standard, and it is closely related to the standard used by the marine engineers. There are well-established names for the axes when using this standard:

X = Roll Axis (fuselage station or missile station)
Y = Pitch Axis (butt line)
Z = Yaw axis (waterline)

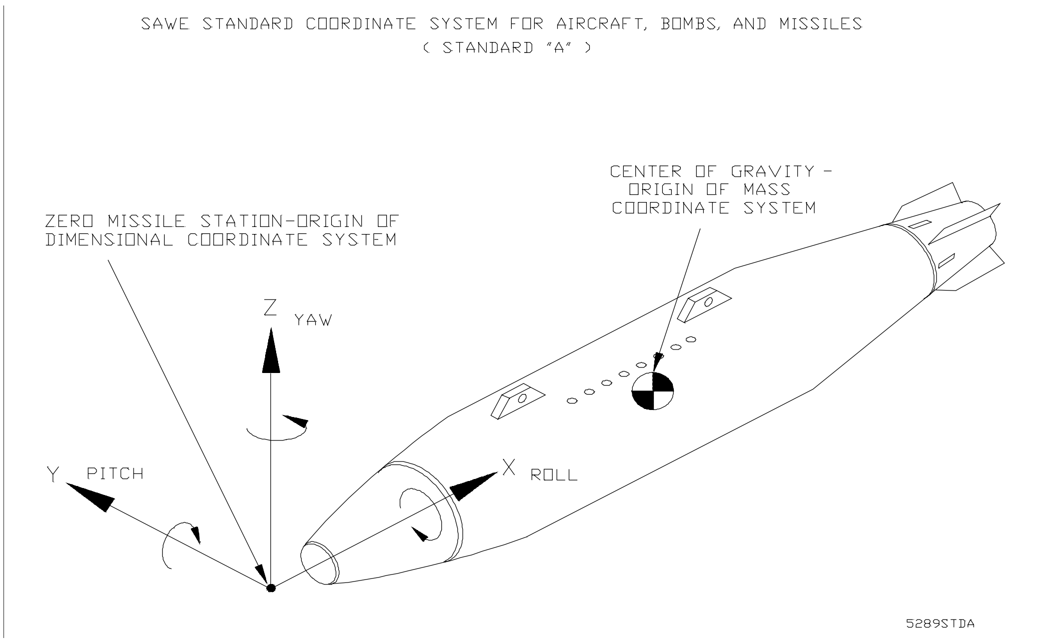

Figure 1 - Standard "A" for aircraft, bombs, and missiles

The roll axis on an aircraft is a line from the tail to the nose of the aircraft; the pitch axis is a line from one wing tip to the other; and the yaw axis is a vertical line through the CG of the aircraft.

Standard "A" conforms to MIL-A-8591G, a specification which defines a standard coordinate system for the presentation of mass properties data for "stores" which are suspended from aircraft, and is often used by the Air Force as a standard for other measurements. Standard "A" is not in accord with the sign convention for the **X** axis in ANSI/AIAA R-004-1990 "Recommended Practice for Flight Vehicle Coordinate Systems". However, flight dynamics engineers in many companies expect the data to be in the form of SAWE Standard "A". They then transform the data so that X starts at the CG and is positive toward the nose.

Pitch & Yaw axes There is no question where the pitch and yaw axes are for an aircraft. However, for a bomb or a missile, pitch and yaw are somewhat arbitrary, since the object doesn't fly horizontally in a fixed orientation relative to the ground. In these instances, the definition of the axes must be coordinated between organizations, so they will all use the same axis definitions. Once this has been done, however, then the "SAWE STANDARD" will dictate the other choices, such as symbols used, zero points, direction of positive values, relative orientation of X, Y, and Z axes. If there is a single plane of symmetry, then the yaw axis should be oriented so it lies in that plane. For example, in the illustration for Standard "A", the yaw axis is in a plane which passes through the center of the lug.

STANDARD "S"

Standard "S" is generally used for satellites, reentry vehicles, or any other flight object which orbits the earth. In this standard, the **X** axis points in the direction of motion during orbital flight, and the **Z** axis points toward the earth. If the object spins, then the decision of which axis is **Y** and which is **Z** must be agreed upon. If the vehicle has only one plane of symmetry, then the **X** and **Z** axes should fall on this plane.

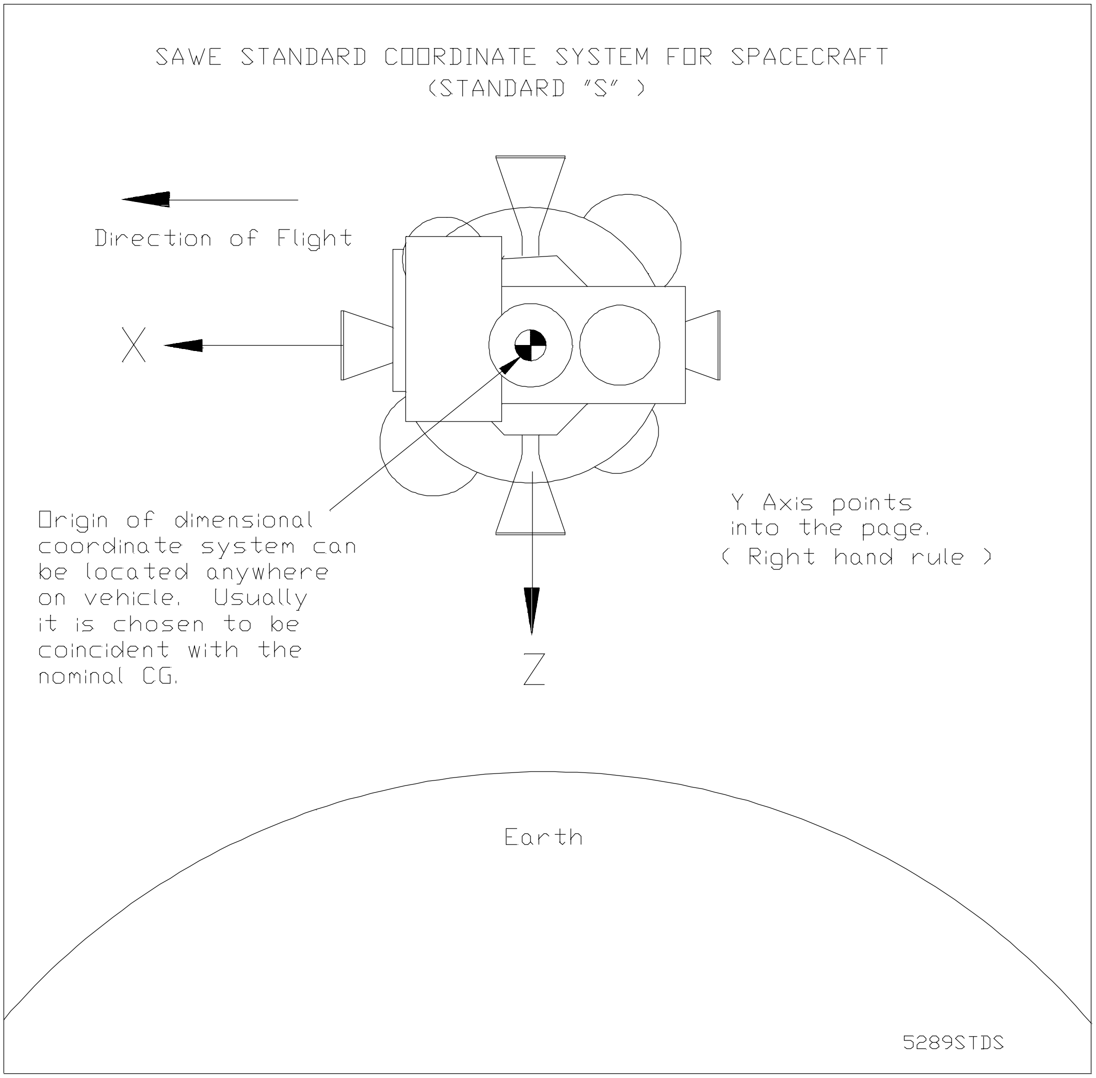

Figure 2 - Standard "S" for vehicles which orbit the earth

The origin of the three dimensional ("body") axes can coincide with the nominal CG of the vehicle, or this origin can be located at any well-defined hard point on the vehicle. If the vehicle has thrusters, usually the centerline of the thrusters passes through the nominal CG. The intersection of thruster centerlines usually is the origin of the coordinate system.

The coordinate system defined by the mass properties of the vehicle. Previous discussion has been concerned with the coordinate system defined by the geometric shape of the vehicle (also called the dimensional or "body" system). In the mass system, the origin is usually on the centerline of the vehicle. Every vehicle also has a mass coordinate system. In this system, the origin is at the CG, the product of inertia is always zero, and the axes of the system are the principal axes of the object. There is only one unique mass properties coordinate system for any object. For a satellite in space, the motion of the satellite is always relative to this coordinate system. For an object flying in air, aerodynamic forces on the surface of the object also affect its motion. Often, correction weights are added to the vehicle to make the mass coordinate system parallel to the dimensional coordinate system. The vehicle must be measured on a mass properties instrument to determine the location of this mass coordinate system. Note that the mass and dimensional coordinates will not necessarily be parallel to each other, nor will they necessarily have the same origin.

Recommended symbols for the principal axes:

U is the principal axis which is closest to the **X** body axis.
V is the principal axis which is closest to the **Y** body axis.
W is the principal axis which is closest to the **Z** body axis.

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

Moment of inertia is measured about each of the geometric axes. It can only be positive, so there is never any uncertainty regarding sign. However, you should determine whether this magnitude should be expressed through the geometric centerline of the vehicle or through its CG about an axis parallel to the geometric centerline or rotated so the data is through 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.

1. MOI can be expressed about each geometric axis of the vehicle.

2. MOI can be expressed about 3 axes parallel to the geometric axes, said axes passing through the CG of the vehicle.

3. MOI can be expressed about the true principal axes of the vehicle (which may be inclined relative to the geometric axes due to product of inertia).

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.

Recommended Symbols for Moments of Inertia about the body (dimensional) axes

$\mathbf{I_{xx}}$ is the moment of inertia about the X axis
$\mathbf{I_{yy}}$ is the moment of inertia about the Y axis
$\mathbf{I_{zz}}$ is the moment of inertia about the Z axis

Recommended Symbols for Moments of Inertia about the principal axes.

$\mathbf{I_{uu}}$ is the moment of inertia about the U axis
$\mathbf{I_{vv}}$ is the moment of inertia about the V axis
$\mathbf{I_{ww}}$ is the moment of inertia about the W axis

Center of gravity 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. CG data is measured relative to the geometric axes. Thus the CG would be 10 inches from the nose of a vehicle, rather than having the nose be 10 inches from the CG.

Recommended Symbols for CG (distance from origin along an axis)

x is the distance along the X axis to the CG
y is the distance along the Y axis to the CG
z is the distance along the Z axis to the CG

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. Product of inertia is expressed as the product of a mass times a distance along one axis times a distance along another axis. It can also be expressed in terms of the angle of inclination, which is the tilt between the geometric axes and the principal axis (i.e. a space vehicle is never unbalanced; instead if it spins, then the geometric axis tilts so that spinning occurs about the principal axis).

Recommended Symbols for Product of Inertia (unbalance in a plane)

$\mathbf{I_{xz}}$ is the product of inertia in the XZ plane
$\mathbf{I_{xy}}$ is the product of inertia in the XY plane
$\mathbf{I_{zy}}$ is the product of inertia in the ZY plane

Definition of the right hand rule If you extend the thumb, index, and middle fingers of your right hand so they are mutually perpendicular, and you then point your thumb in the direction of the X axis and your index finger in the direction of the Y axis, then your middle finger will point in the direction of the Z axis. Both standards use the right hand rule for rotations. Angles increase in a clockwise direction when looking in the direction of an axis. If your thumb points in the direction of an axis, then your fingers curl in the direction of positive rotations. This rule applies to rotation angles, torques, and angular velocities.

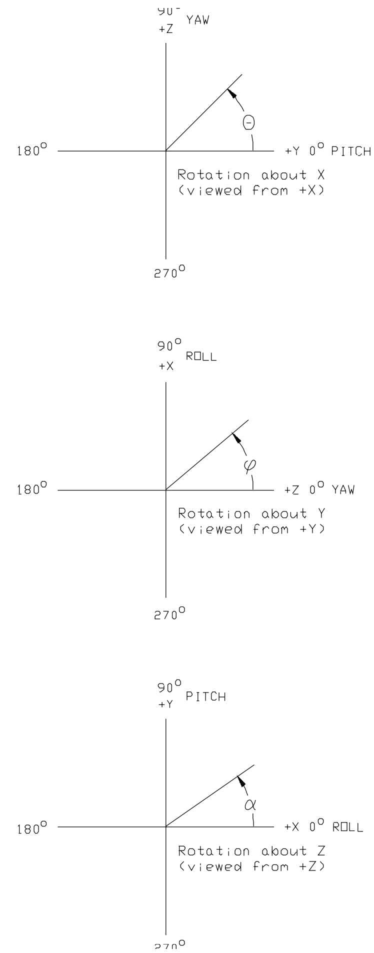

Figure 3. Rotation about an axis

"Hard points" The first step in calculating or measuring mass properties is to establish the exact location of the reference datum points used to define the X, Y, and Z axes. The accuracy of the calculations (and later on the accuracy of the measurements to verify the calculations) will depend entirely on the wisdom used in choosing these datum points. If the test object were perfectly round with perfectly square ends, these datum points could be at any location relative to the object being considered. However, in real life, unless the datum points are chosen to be at a location which can be accurately measured and identified, the calculations are meaningless. These points are usually selected to coincide with interface mounting rings on the object, with accurately located details, or with key features such as thruster nozzles. An axis should always be located relative to a surface which is rigidly associated with the bulk of the object. Don't locate an axis relative to a bolted fitting or other poorly defined feature. The reference should be a precision machined surface rather than a rough casting or a surface that is not square with the body of the vehicle. The nose of a vehicle is often not a reliable reference point. For example, projectiles and bombs are often tested without the fuse installed, so that the true "nose" is not available. Rockets often have plastic radomes that are not dimensionally controlled. Reference axes must be located at physical points on the object which can be accurately measured. Although the centerline of a ring may exist in midair, it can be accurately measured and is therefore a good reference location.

Providing precision reference datum rings in the design of the object Whenever possible we recommend that a flight vehicle be **designed** with two reference datum rings per section to define the reference axes. These rings can be precision attachment points which are used to interface the object with another section of a space craft or rocket, or they can be rings which were provided solely for the purpose of alignment and/or measurement of mass properties.

Precision reference surfaces serve three purposes:

1. They provide a reference for the calculated values of mass properties.

2. They provide a reference for the alignment of thrusters, rocket motors, and guidance components.

3. They provide a contact surface for fixtures which are used to support the vehicle during mass properties measurement.

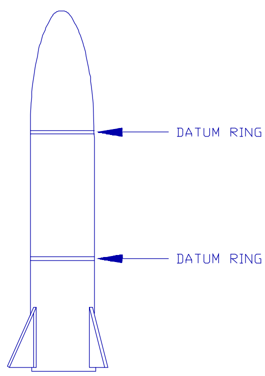

Figure 4. Many problems are eliminated if precision datum surfaces are built into the design of the vehicle.

These precision reference surfaces must have the following characteristics:

A. They must be accessible at all stages of production. In other words, they cannot be covered by the outer skin of the vehicle, and they should be integral with the basic frame of the vehicle, so that they can be used as an alignment reference during assembly.

B. The precision of the reference surface must be greater than the mass properties accuracy requirements. For example, if radial CG of the vehicle must be adjusted so it is within 0.015 inch of the geometric centerline, then the reference rings should not have a runout of greater than 0.003 inch (5 times better than CG tolerance).

C. The reference surface must be capable of supporting the weight of the vehicle, since it will contact the fixtures which are used to support the vehicle during mass properties measurement. The design of the reference surface must be compatible with the fixture design. Otherwise, it may not be possible to make accurate mass properties measurements.

Note: The reference rings shown above are suitable for cylindrical objects. There are many other type of precision surfaces which can be used for a reference. Their design depends on the shape of the vehicle.

Inertia Tensor The SAWE has adopted the traditional method used by most mass properties engineers to define the inertia tensor:

$$I_{xy} = \int_0^i x_i y_i dm$$

$$I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix}$$

Flight dynamics engineers defines the inertia tensor in a different way:

$$I_{xy} = -\int_0^i x_i y_i dm$$

$$I = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}$$

It is important that the flight dynamics engineers be made aware of the SAWE standard, or they may assume the second version shown here, resulting in vector directions which mirror the actual directions.