

Measuring Mass Properties of Aircraft Control Surfaces

by

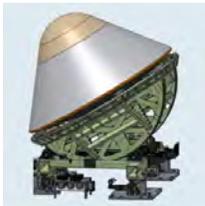
Richard Boynton, President
Kurt Wiener, Chief Engineer

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ABOUT THE AUTHORS

Richard Boynton is President of Space Electronics, Inc., Berlin, Connecticut, a company he founded in 1959. Space Electronics, Inc. manufactures instruments to measure moment of inertia, center of gravity, and product of inertia. Mr. Boynton 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 M.I.T. He is the author or co-author of over 70 papers, including 32 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).

Kurt Wiener is Chief Engineer of Space Electronics, Inc. Mr. Wiener holds a B.S. in Mechanical Engineering from M.I.T. and a M.S. in Industrial Education from Central CT State College. He is a former Associate Professor of Mechanical Technology at Vermont Technical College. Mr. Wiener is the principal instructor for the Mass Properties Seminars which are presented twice a year at Space Electronics. He has co-authored 14 papers for SAWE conferences. He won the L. R. "Mike" Hackney Award for Best Technical Paper at the International Conference of the SAWE in 1998.

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Abstract

Flutter is of great concern to any pilot, since excessive flutter has caused a number of aircraft to lose control and crash. Although any surface on an aircraft which is exposed to air flow can experience flutter, the most common type of flutter involves the control surfaces such as ailerons, elevators, and rudders. The mass properties of these control surfaces are very critical and have to be measured with great care to make certain that flutter is minimized. Many mass properties engineers ignore product of inertia when measuring control surfaces. We suspect that these engineers will be surprised to discover that the product of inertia unbalance of the control surface can be the key element in eliminating flutter, and that it is vital to measure this quantity.

Control Surface CG If the center of gravity of a control surface assembly is not located exactly on the hinge line, then a torque will be applied to the control surface whenever the wing (or other mounting surface) accelerates in a vertical direction. If the inertial forces acting through the CG of a control surface amplify the vibration of a wing, then the flutter amplitude will rapidly increase and can result in destruction of the aircraft. Small changes in control surface CG location can have a dramatic effect on flutter instability.

Control Surface Moment of inertia The moment of inertia of the control surface is also a critical parameter. If the wing (or other mounting surface) accelerates in a rotational sense due to twist, the position of the control surface will lag behind the wing due to the moment of inertia of the control surface. In other words, the orientation of the control surface will change relative to the orientation of the wing during wing twist, even if the control surface is statically balanced about the hinge line. Generally it is necessary for control surface MOI to fall within a narrow range of values, in order to avoid flutter problems. It is not sufficient to simply minimize control surface MOI, since it is important to avoid mechanical resonant modes whose frequencies are harmonics of each other. Note: It is possible to neutralize this MOI effect by moving the CG ahead of the hingeline. There is also another consideration involving moment of inertia: the frequency of the notch filter in the actuator circuitry which drives the control surface is based on the particular moment of inertia being driven. If this moment of inertia deviates significantly from the nominal value, the control circuit can become unstable.

Control Surface Product of inertia When a wing suddenly bends upward as the result of a gust of wind, mass on the outer end of the wing will experience a greater acceleration than mass near the fuselage. An aileron can be balanced statically but have a concentration of mass near the trailing edge on the outboard end and a corresponding concentration of mass near the leading edge on the inboard end. This will create an unstable condition when dynamic forces are applied.

POI can also aggravate twist of the airfoil. Although the control surface does not rotate, its rapid vibration creates inertial forces that can distort the shape of the wing.

Summary Aircraft performance requirements have become ever more demanding with less and less margin for error. Materials, especially composites, have become more complex and are inherently less homogeneous than the materials previously used. This has led to a situation where the mass properties of control surfaces may not always be within the tolerances required for safe and stable aircraft control over the full range of anticipated operating conditions. There is a

growing trend among experienced aerospace and mass properties engineers to require the measurement of the mass properties of aircraft control surfaces to ensure that they meet prescribed tolerances.

In this paper, we:

- review the deleterious effects of improper control surface balance and MOI
- explain why control surface POI is so important
- outline the procedures required for accurate mass properties measurements
- describe fixture designs which we have found to be successful
- describe case histories

This paper is divided into two parts. Part 1 explains why it is essential to accurately measure the mass properties of control surfaces in order to prevent flutter. Part 2 of this paper outlines the mass properties measurement process in detail.

Part One

1.0 Why the mass properties of control surfaces are so critical

An aircraft will fly safely as long as its CG remains within a fairly large envelope. Furthermore, the total mass properties of the aircraft change dramatically when the passengers, crew, and freight are loaded on the aircraft. For these reasons, it is generally not necessary to precisely measure the mass properties of the components of an aircraft. However, there is one exception to this rule: flutter can occur if the mass properties of control surfaces such as the leading and trailing edge flaps are not within precise limits. The following discussion summarizes some facts about flutter and gives a general overview of how CG and MOI affect flutter.

1.1 Flutter If you cut a thin strip of paper and hang it in front of a fan such that the air blows toward an edge and equally across both flat surfaces of the paper, the paper strip will twist back and forth. This is called flutter, and it is one of the types of instability known as “aeroelasticity”. Flutter is a condition of resonant oscillation of an aerodynamic surface and its associated structure which occurs when the surface is exposed to the airstream and is excited by turbulence, vortex shedding, inertial forces of maneuvering, or other non symmetrical and periodic loading. At low speeds, the oscillations will be damped. At the flutter speed they will persist at constant amplitude and at higher speeds, the oscillation amplitude will increase (diverge) and in many cases result in damage or destruction of the structure. Flutter requires two degrees of freedom. For example, an airfoil can bend up and down and it can twist about its elastic centerline. Flutter is related to the torsional and vertical stiffness of the object, and the shape of the airfoil.

1.2 Divergence is the condition most feared by pilots. This is when the flutter gets out of control and expands to destruction. Technically it is a static aeroelastic instability of a lifting surface or component that occurs when the structural restoring moment of the surface is exceeded by the aerodynamic torsional moment. Divergence of a lifting surface would likely result in loss of the air vehicle. Divergence of a component would likely result in loss of that component.

1.3 Control surface or tab flutter is possible at all flying speeds and historically has been the most common type of flutter. A typical control surface flutter scenario requires that the control surface is free to move to either side of center, so that the flutter energy can grow from one cycle to the next, feeding on the aerodynamic energy of the airstream flowing over the flight surfaces.

Control surface flutter occurs when both the structural and aerodynamic forcing frequencies match each other. A simplified airfoil-aileron flutter scenario proceeds as follows:

1. The airfoil hits a disturbance and lurches upward.
2. The unbalanced aileron trails in a downward position, compounding the problem by creating lift and a leading edge-down pitching moment.
3. Due to the extra lift, the airfoil continues its motion upward, but due to the leading edge-down pitching moment, it also begins to rotate about its pitch axis.
4. Eventually the airfoil pitches to the point that the lift becomes negative and the momentum of the unbalanced aileron diminishes to the point that the wing starts plunging downward and the process begins anew, only this time in the downward direction.

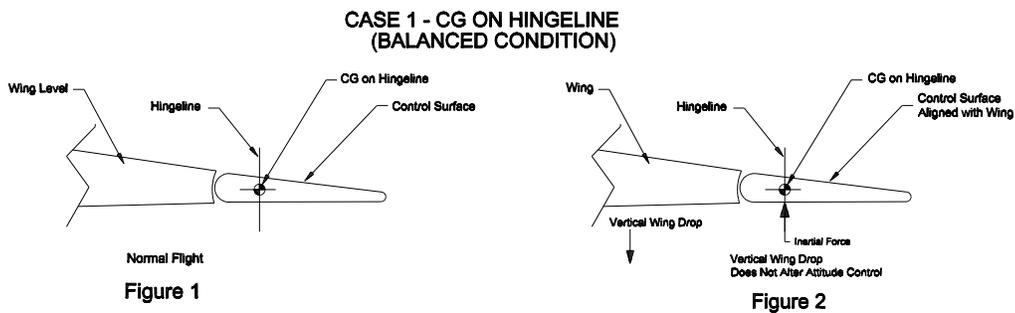
If the condition is divergent, the amplitude of the motion will grow exponentially until structural failure. (Typically all this occurs in less than the span of a second, so there is no time for pilot correction; and the smallest amount of play in the control linkages is usually enough to allow onset.)

Analyses are necessary to establish mass balance and stiffness requirements. These analyses should be done as part of the basic air vehicle design substantiation. Flutter is an extremely complex phenomenon. Even with high speed computers and sophisticated algorithms, unexpected flutter modes often occur in experimental aircraft. Furthermore, well designed high speed aircraft can experience flutter if there is a problem with quality control during the construction of the aircraft. For example, excessive play in the hinge axis of a control surface often results in flutter. Sloppy application of epoxy can displace the control surface CG sufficiently to create a dangerous condition.

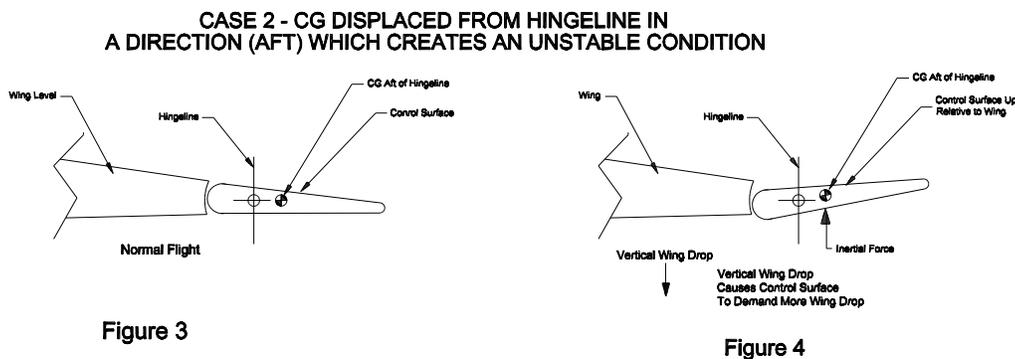
1.4 Coupling effect between a control surface and a wing As discussed in the abstract of this paper, there are three major modes of coupling which can occur between these structures: (1) coupling of a linear motion due to CG offset of the effective mass of the control surface assembly from the hinge line of the control surface, (2) coupling of a twisting of the wing due to the moment of inertia of the control surface assembly, and (3) coupling of a bending of the wing (or a roll maneuver) due to the product of inertia of the control surface. These effects are illustrated below.

1.4.1 CG Location Effect

Case #1: Control surface balanced about hinge line In figures 1 and 2, the center of gravity of the control surface is exactly on the hinge line. Therefore, a linear acceleration of the wing does not cause a torque to be applied to the control surface.



Case #2: Torque resulting from linear motion acting through CG In Figure 3 and 4, the CG is not coincident with the hinge line. An upward linear acceleration of the wing will cause the control surface to deflect downward. The amount of deflection is a function of the stiffness of the hinge joint. There is a flexibility of both the hinge structure and the linkage to the control surface, and in addition, there is a flexibility of the actuator. Actuator flexibility may vary with frequency of excitation, since the actuator is part of a closed-loop feedback servo. This is discussed in more detail in the section entitled “Aeroservoelasticity”.



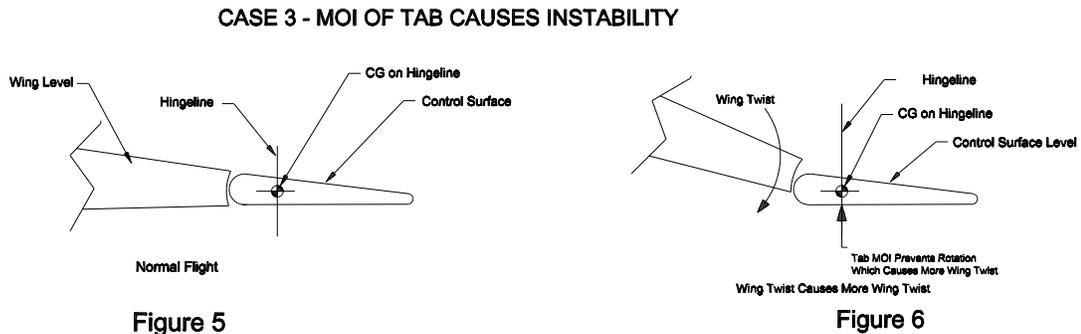
Important note: Small motion hinge stiffness can be as much as 100 times less than large motion stiffness, due to free play. This allows a flutter mode to start with little resistance. Once started, the forces can become enormous, so that the large motion stiffness is insufficient to damp the flutter. The solution is to place tight tolerances on free play. For a trailing edge control surface that extends outboard of the 75 percent span station of main surface, the total free play is normally limited to 0.13 degrees. Free play and hinge joint flexibility should be checked periodically to make sure it has not increased. This can happen due to fatigue, wear in the hinge joint or actuator linkage, or flexibility can increase if the actuator loop gain decreases (see section below entitled Aeroservoelasticity)

If there is inertial coupling between a control surface and a wing, as described above, and if the control surface also acts to move the wing, then a condition of positive feedback can exist. For example, assume that turbulence causes the wing to deflect downward as in Figure 4. If the CG of the trailing edge control surface is aft of the hinge line, then there is a moment created which causes the control surface to rotate counter clock wise relative to the wing. This in turn causes

additional downward wing motion. Since the wing and the control surface interact with each other, the motion of both is amplified. If the resonant frequencies of each mode are similar, then a dangerous condition is created.

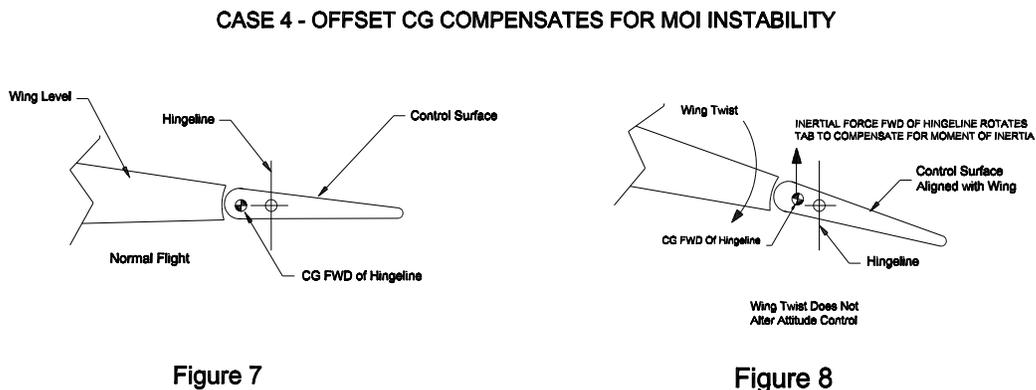
1.4.2 MOI Effect

Case #3: Torque resulting from the moment of inertia of the control surface In Figure 5 and 6, the trailing edge of the wing rotates downward due to twist of the wing. Since the control surface is not mounted with infinite rigidity, its moment of inertia resists its rotation and there is a small but significant difference between the angle of the wing and the control surface. The position of the control surface lags behind the rotational angle of the wing. Note that the larger the control surface MOI, the larger this effect becomes.



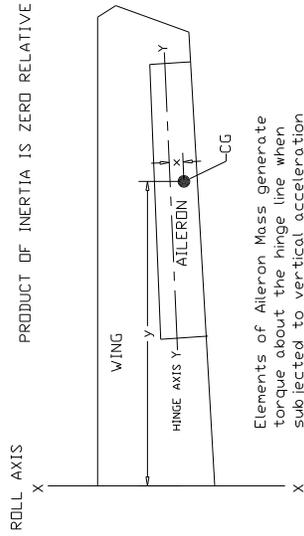
1.4.3 CG Compensation for MOI Effect

Case # 4: CG forward of hinge line to compensate for inertia effect - In some instances, it may be desirable to offset the control surface CG from the hinge line in a direction to counteract the interaction due to the moment of inertia of the control surface. Then any tendency to become unstable will be damped by this effect. Needless to say, the amount of CG offset is critical and must be carefully controlled. This compensation is shown in Figures 7 and 8



STATIC UNBALANCE

PRODUCT OF INERTIA IS ZERO RELATIVE TO HINGELINE



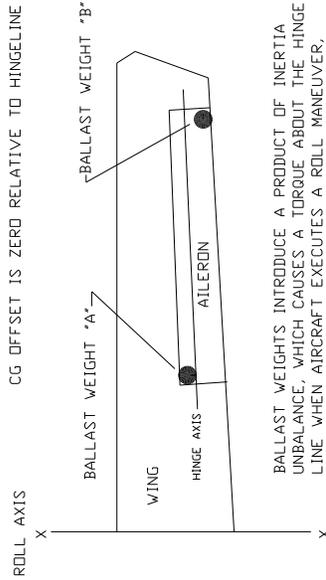
Elements of Aileron Mass generate torque about the hinge line when subjected to vertical acceleration

IF THE AILERON CG IS AFT OF THE HINGELINE, INERTIAL FORCES CAUSE THE AILERON TO DEFLECT IN A DIRECTION WHICH AMPLIFIES THE BENDING OF THE WING. CG OFFSET (STATIC UNBALANCE) IS EASY TO MEASURE. THE LINKAGE CAN BE DISCONNECTED, AND THIS QUANTITY MEASURED WHILE THE AILERON IS STILL ATTACHED TO THE WING.

SPENCER/USNA/NAVY/AFMRL/USMC/NAVY/AFMRL/USMC

DYNAMIC UNBALANCE

CG OFFSET IS ZERO RELATIVE TO HINGELINE



BALLAST WEIGHTS INTRODUCE A PRODUCT OF INERTIA UNBALANCE, WHICH CAUSES A TORQUE ABOUT THE HINGE LINE WHEN AIRCRAFT EXECUTES A ROLL MANEUVER, OR WHEN WING BENDS.

TO ILLUSTRATE THE EFFECT OF PRODUCT OF INERTIA, WE HAVE CHOSEN AN AILERON WHICH IS STATICALLY BALANCED, BUT HAS TWO WEIGHTS WHICH CAUSE A PRODUCT OF INERTIA UNBALANCE. WHEN THE WING BENDS, BALLAST WEIGHT B EXPERIENCES A LARGER INERTIAL FORCE THAN WEIGHT A, CAUSING A TORQUE. THIS TYPE OF UNBALANCE IS "INVISIBLE" TO CONVENTIONAL STATIC TESTS. POI UNBALANCE IS MEASURED BY DETERMINING ITS MOMENT OF INERTIA IN THREE DIFFERENT ORIENTATIONS. THIS MUST BE DONE BEFORE THE AILERON IS INSTALLED IN THE AIRCRAFT

1.4.4 Product of inertia effect

Most mass properties engineers are aware that the CG and MOI of a control surface must be carefully controlled to prevent flutter. However, very few engineers realize that product of inertia can be even more important for certain control surfaces which are attached to a surface that rotates about an axis perpendicular to the hinge line, such as ailerons.

Consider the aileron in figure 9. Let's assume that this aileron is statically balanced and also has a zero product of inertia about the hinge line. Now we add ballast weights A and B such that the static CG is still on the hinge line. However, there is a large product of inertia created because the weights are on different ends of the aileron. Imagine that these weights are still attached to the aileron when we take the aircraft for a test flight. When the aircraft starts to do a roll maneuver, inertial forces act through both weight A and weight B. Since weight B is closer to the wing tip, it experiences a greater vertical acceleration and consequently a greater inertial force than weight A. This creates a moment about the hinge line. If the conditions are unfavorable, this can result in flutter and possibly loss of the aircraft.

Note that this same POI unbalance can be created by a sudden gust of wind. The wing bends, and the effect is the same as if the aircraft did a roll maneuver. This explains why some aircraft are stable in calm air but experience flutter when the wind is gusting.

Consider the case of a wing which rotates about the centerline of the airplane, (axis x-x) as in the case of airplane roll; it is desired to determine the effect on the aileron which is free to rotate about the aileron hinge line. If the element of mass dm rotates about the airplane center line (x-x axis), through some angle θ , the linear displacement is $S = y\theta$ and the linear acceleration of the element is:

$$\frac{d^2 S}{dt^2} = y \frac{d^2 \theta}{dt^2} \quad (1)$$

The inertia force is then

$$dF = y \frac{d^2 \theta}{dt^2} dm \quad (2)$$

and the inertia moment about the aileron hinge line (y-y axis) is

$$dM_{y-y} = x dF = xy dm \frac{d^2 \theta}{dt^2} \quad (3)$$

The total inertia moment about the aileron hinge line is therefore obtained by integrating over the aileron, or

$$M_{y-y} = \int_{Aileron} xy dm \frac{d^2 \theta}{dt^2} = \frac{d^2 \theta}{dt^2} \int_{Aileron} xy dm \quad (4)$$

or, if the product of inertia K is defined as

$$K = \int_{Aileron} xy dm \quad (5)$$

then

$$M_{y-y} = K \frac{d^2 \theta}{dt^2} \quad (6)$$

Thus the product of inertia K with respect to the x-x and y-y axes is equal to the torque induced about the y-y axis (aileron hinge line) by a unit angular acceleration about the x-x axis (airplane centerline). Now since a torque about the hinge line results in an angular acceleration about the hinge line which is proportional to the mass moment of inertia of the aileron about the hinge line,

$$M_{y-y} = I_{y-y} \frac{d^2 \beta}{dt^2} \quad (7)$$

where β is the rotation angle about the hinge line. Therefore,

$$\frac{K}{I_{y-y}} \frac{d^2 \theta}{dt^2} = \frac{d^2 \beta}{dt^2} \quad (8)$$

It can thus be seen that an angular acceleration $d^2 \theta / dt^2$ about the airplane centerline induces an angular acceleration about the aileron hinge line of $(K / I_{y-y})(d^2 \theta / dt^2)$. K/I is termed the *dynamic balance coefficient*.

For aircraft whose speed is less than 300 MPH, maximum permissible dynamic unbalance is given by the formula

$$\frac{K}{I} = 0.20 \left[6 - \left(\frac{V_p}{150} \right)^2 \right] \quad (9)$$

where:

K = product of inertia with respect to the axes under consideration

I = control surface mass moment of inertia about its hinge line

V_p = maximum permissible dive speed of airplane

Aeroelasticity is a very complex phenomena, and it is hard to make any general rules which apply to all situations. However, there is one rule that is always true: **for any control surface which rotates about an axis at right angles to the hinge line, the product of inertia about the hinge line must be very close to zero.** Control surfaces often have a complex internal structure and frequently contain composite material which is fabricated by hand. It is imperative that the POI be measured to verify the accuracy of the calculations used in the design, and to establish the worst case variation in the production process. It is almost certain that ballast weights will have to be added to reduce the POI unbalance. (Generally, all the mass properties are measured, and then a computer program in the mass properties instrument calculates the optimum weight values to simultaneously correct both static balance and POI.)

1.5 Aeroservoelasticity

A control surface is driven by an actuator. The pilot (or the autopilot) commands the control surface to move to a particular position. The actual position of the control surface is measured electronically, and an error signal is derived which controls the actuator. This closed-loop servo control must be stabilized so that response speed is maximized without compromising stability. The control surface has a fundamental resonant frequency which is a function of the moment of inertia of the control surface about its hinge line and the stiffness of the actuator and associated structure. Actuator stiffness is not a fixed number. Since it is a dynamic stiffness which is created by servo control, the stiffness will decrease as the frequency of disturbance is increased. The stiffness will decrease if the loop gain of the servo is decreased (which might be necessary because of stability considerations).

There are two ramifications of the resonance: (1) if excited, the control surface can be damaged; (2) since the motion of the control surface is driven by closed-loop servo control, it is possible for the actuator to become unstable at this resonant frequency. Damage at the resonant frequency can be minimized by mechanical damping to reduce the Q of the resonance. Instability can be minimized by using a notch filter at the resonant frequency which reduces the gain of the loop to compensate for the resonance.

The key to making the notch filter work is to align its center frequency with that of the mechanical resonance. The resonant frequency is related to the moment of inertia of the control surface about its hinge line. Hence the need for accurate knowledge of the MOI of the control surface and its 5 sigma variation as a result of variations in fabrication techniques.

1.6 Other Components Subject to Flutter

In addition to the analysis of control surfaces, flutter investigations should be performed on all airplane components which are exposed to the airstream such as leading edge flaps, trailing edge flaps, spoilers, dive brakes, canard surfaces, scoops, weapon bay doors, landing gear doors, ventral fins (fixed, retractable, or jettisonable), movable fairings, blade antennas, and blade seals. Generally, two degrees of freedom are required for a surface to exhibit aeroelastic instability. There is one exception: buzz is a single-degree-of-freedom flutter that is usually evidenced by a pure rotational oscillation of a control surface or, when support rigidities are such as to restrain the motion of the surface near one end, by a torsional windup oscillation. It is caused by aerodynamic phase lags associated with boundary layer and shock-wave effects and interactions which result in loss of aerodynamic damping. Buzz is usually limited in amplitude at

any given speed and altitude for a given lift coefficient. Buzz can lead to damage or destruction of the surface either by fatigue or by inducing greater than yield loads when the amplitude is sufficiently large.

1.7 Balance (ballast) Weights

If balance weights are used on control surfaces or tabs, the following guidelines should be followed:

Location of balance weights: When correcting a static unbalance, it is important to distribute several ballast weights so that the ballast itself does not create a dynamic unbalance (product of inertia). In most instances, the ballast weights and locations are selected to simultaneously compensate for three factors: (1) the CG offset from the hinge line, (2) the MOI of the control surface about the hinge line, and (3) a product of inertia unbalance relative to the hinge line. Addition of the ballast weights will reduce the POI to zero about the hinge line, while shifting the CG forward of the hinge line to counteract the MOI effect. (Space Electronics makes an instrument which measures these three quantities and computes the required ballast weights and locations). The process of ballasting a control surface is complicated by the fact that the surface may not be rigid at the frequencies encountered during flutter. Therefore, adding ballast to the wrong location can cause flexing and additional resonant modes. In some instances, numerous smaller ballast weights may have to be added at locations which couple directly to structural members in the control surface, so that the shape of the control surface is not altered by the dynamic forces acting through the ballast weights.

Compensation for ballast weight mass Note that any ballast weights which are added to the control surface increase its MOI. When the CG is offset forward of the hinge line to counteract the moment of inertia of the control surface, the MOI value used to calculate the mass of the ballast weights must include the additional MOI resulting from the ballast weights themselves. In other words, the CG must be slightly aft of where it would be if the ballast weights had no effect on total MOI.

Rigidity and strength of balance weight attachment: The natural frequencies of vibration of the balance weights as installed should be at least twice the highest frequency of the flutter mode for which the balance weight is required to be effective. Ballast weights shall be capable of remaining attached if subject to a limit inertia load factor of +/-100g and repeated inertial loads of +/-60g for 500 kilocycles in a direction normal to the plane of the control surface tab. In addition, they shall withstand a limit inertia load factor of +/-50g and repeated inertial loads of and +/-30g for 500 kilocycles in the other two mutually perpendicular directions of the control surface or tab. On airplanes which experience high-acceleration takeoffs, such as by catapulting or rocket assist, the mass balance weights and actuation systems for control surfaces and tabs should be designed to prevent control surface rotations resulting from inertia loads acting on the balance weights and actuating systems during acceleration.

Provisions for rebalancing: Provisions should be made to enable increasing or decreasing the mass-balance weights to compensate for effects of changes, repairs, and painting.

Dealing with control surface flexibility On very rigid structures, ballast weights can be added at any point in the structure to correct unbalance or MOI. However, most control

surfaces are very flexible, and there are a number of modes of resonance possible on these flexible structures. The point of ballast attachment is critical to avoid stimulating additional modes of resonance, and to minimize flexing.

Case Histories of flutter which was related to mass properties There have been a number of instances where flutter has led to the fatal crash of an aircraft. Two F-117 have been lost due to elevon vibration. The second F-117 crash is documented in Aviation Week September 22, 1997. Another type of aircraft, the Taiwanese IDF, was lost due to flutter problems. This crash and fatality is documented in World Airpower Vol 26 Autumn/Fall 1996. The NACA document RM-56112 lists 33 flutter incidents for US military aircraft in the ten year period of 1947-1956 and 16 of these involve control surface and tab flutter. The Joint Services Structures Specification Handbook lists a number of cases of the occurrence of flutter during testing of the aircraft. All of these aircraft were analyzed prior to flight, and no flutter problems were anticipated. Three of the examples given below from this handbook were corrected by adjustments in mass balance.

“A reconnaissance aircraft encountered two higher order, wing-aileron flutter mechanisms during operational use and subsequent flight testing. Analyses, ground vibration, and flight tests were accomplished to validate additional distributed aileron mass balance and a slight decrease in the limit speed operating envelope.”

“A trainer aircraft encountered aileron-wing flutter during flight flutter testing. Analyses and flight tests verified additional aileron mass balance was required.”

“An attack airplane undergoing developing flight tests, but subsequent to several months of operational flying, encountered elevator flutter following a sharp control actuator induced transient. Careful analyses, using re-measured horizontal stabilizer modal test data, showed that a modification of the elevator mass balance would provide stability.”

Not all instances of flutter can be corrected by adding ballast. For example: “A small attack airplane encountered rudder-fin coupled flutter during development testing. Mass balance failed as a fix. Prevention was effected by modifying the rudder geometry. The incident placed an interim operational speed restriction upon the airplane and delayed the delivery.”

1.8 Typical specification for mass properties measurement (extracted from MIL-A-8870C)

Control surfaces and tabs shall be designed to contain either sufficient static and dynamic mass balance, or sufficient bending, torsional and rotational rigidity, or a combination of these means, to prevent flutter or sustained limited amplitude instabilities of all critical modes under all flight conditions for normal and failure operating conditions of the actuating systems.

The occurrence of flutter within the flight envelope is likely to be catastrophic and measures necessary to improve the flutter characteristics usually cannot be introduced without structural redesign. Control surfaces and tab flutter are the most prevalent type of flutter problems. This type of flutter may occur on all sizes and types of air vehicles. In many cases flutter criteria will strongly influence control surface and tab design with

respect to actuator stiffness and mass distribution.

The following tests are required if the air vehicle is a new design or if changes in the design or manufacturing processes of the surfaces or tabs occur. The total weight, static unbalance, and mass moment of inertia about the hinge line of all control surfaces, tabs, leading and trailing edge flaps should be measured. {AUTHOR'S NOTE: PRODUCT OF INERTIA SHOULD ALSO BE MEASURED. APPARENTLY THE AUTHORS OF MIL-A-8870C WEREN'T AWARE AEROELASTIC INSTABILITY CAN BE CAUSED BY POI UNBALANCE} These tests should be made prior to first flight of a new air vehicle or prior to flight when changes to the surface or tabs occur. Static balance tolerance: The maximum allowable service static unbalance of each surface including tabs should be included in all control surface and tab assembly drawings and in appropriate user manuals. Accurate modes of vibration as used in the flutter analysis are important in determining proper mass balancing of control surfaces. Control surface flutter has occurred because of insufficient mass balance at the surface tip even though the original design was uniformly balanced. Control surface flutter has also occurred as a result of loss of balance weights. Note: Apparently MIL-A-8870C is no longer a requirement. The trend has been to determine CG and MOI analytically. This may change as a result of failures during flight test.

1.9 Summary--Part One

To assure aeroelastic stability of control surfaces, a condition of damping must exist over the full range of anticipated airspeeds, loading, and altitudes. Although damping can be improved by increasing structural stiffness and/or actuator stiffness to raise the flutter frequency or by introducing hydraulic shock absorbers, these methods have limited success and increase mass and complexity. The preferred method is to adjust the control surface mass properties to provide inertial forces which oppose the excitation. This method has been proven to be very successful and adds little cost. The procedure is to measure

- (1) CG offset from the hinge line;
- (2) Moment of inertia about the hinge line,
- (3) Product of inertia with respect to the hinge line.

Then a computer is used to determine the optimum ballast weights required to simultaneously reduce the POI unbalance to zero while shifting the CG aft of the hinge line the exact amount required to offset the MOI effect.

Note that it is important to measure control surface POI, since that is often a major contributor to flutter instability. We are aware that many facilities do not make POI measurements. This is unfortunate, since a POI unbalance about the hinge line can result in loss of an aircraft. There is no way to detect product of inertia unbalance by balancing an aileron on a knife edge or disconnecting the linkage and using a force transducer. That kind of test only detects static unbalance. What is needed is a dynamic method to measure product of inertia. Part 2 of this paper outlines this method in detail.

Part Two

2.0 Measuring the Mass Properties of a Control Surface

2.1 Steps in making a measurement

1. Determine which mass properties must be measured (CG, MOI, POI, Weight).
2. Design and fabricate the fixtures required to accurately support the control surface on the measuring instrument. Depending on the different measurements required, as many as six fixtures may be required for each control surface.
3. If necessary, design and fabricate handling equipment to facilitate loading the control surface into each fixture.
4. Choose the measuring equipment required. It may be necessary to purchase this equipment.
5. Perform the measurements.
6. When reporting the results of the measurement, include a drawing defining the measurement axes, so that there is no confusion regarding the interpretation of the data.

2.2 Fixturing of Control Surfaces

Aircraft control surfaces are large and unwieldy, and may need to be supported at several points during measurement. Designing fixtures for these objects is a challenge. Any uncertainties introduced by the fixtures will degrade the accuracy of the measurements. Because of the high accuracy of the commercial measuring instruments which are now available, fixturing error is almost always the major source of measurement error.

The three functions of a mass properties fixture are:

- locate the article to be tested in a repeatable manner
- accurately relate the test article coordinate system to the machine system
- secure the test article rigidly during measurement

To meet these requirements there are some general guidelines for fixture design. The fixture should:

1. locate the test article so its CG is coincident with the measurement axis
2. be balanced about the measurement axis
3. locate the article to be tested in a repeatable manner
4. be rigid
5. have minimum weight and minimum MOI
6. have a low CG and low profile
7. have low windage
8. have no detachable parts
9. have low thermal expansion and minimal center to datum distances
10. have realistic tolerances consistent with required measurement accuracy
11. have provision or accessories for loading the article to be tested
12. provide for verifying the location of datum surfaces
13. be simple to set up and easy to use

Several of these attributes, such as maximum rigidity, minimum weight, and minimum MOI are mutually contradictory, so compromise must be incorporated into the design.

The shape of most control surfaces and the need to measure mass properties relative to the hinge line makes it impossible to meet all of these basic attributes. As a result, fixture geometry and structure is more critical than for more 'normal' shaped test articles such as basic cylinders and rectangles.

2.3 Coordinate Systems

Selection of and relationship between coordinate systems is critical to good fixture design. For an aircraft control surface, the following coordinate systems must be considered.

2.3.1 The airframe design coordinate system.

This is the system into which the control surface mates and the system in which the overall weight and CG balance is calculated. It may be designated as x, y, and z, or pitch, roll, and yaw.

2.3.2 The control surface coordinate system.

This coordinate system may be parallel to the aircraft system (and use the same axis names) or it may use the hinge line as one axis, thereby rotating the coordinate system relative to the aircraft, requiring different axis names. It will usually have its origin on the control surface with offsets given to locate it relative to the aircraft system. The origin offsets and axis rotation angles from the aircraft system as well as the positive direction of x, y, and z for each system must be correctly and accurately used to convert from one system to the other.

2.3.3 The mass properties instrument coordinate system.

This is the coordinate system in which the mass properties will be measured and reported. For instruments such as the Space Electronics KSR Series, which also report the measurements in the user coordinate system, the offsets and rotation angles must be correctly and accurately entered. It is usually advisable to make test measurements with known answers to check the validity of coordinate system conversions. For example, the elevator would be mounted and measured as TARE. Ballast of known weight would be mounted at a known location, typically with a rather large CG offset, and the elevator, with ballast, measured as PART. The ballast weight would be entered as Part Weight. The report should report the CG location as the ballast location (which is known in both systems). Any errors are easily detected and the user coordinate system data entries corrected until the answers are correct. Errors are often made when parts are mounted 'upside down' to minimize CG height or to optimize access to mounting surfaces.

2.3.4 The principal axis coordinate system

The principal axes will be determined by MOI and POI calculations. The relationship between this system and the elevator system will allow analysis of unbalance and stability, particularly twist within the elevator. The relationship between this system and the aircraft system will determine the net effect of POI as measured and the overall effect on the aircraft.

2.3.5 Datum surfaces

Once the coordinate systems are sorted out, the datum surfaces (datum features) must be selected. These should be;

- surfaces whose locations are dimensionally well controlled
- surfaces whose geometry is simple
- surfaces which are machined to close tolerances.

For control surfaces, one interface is usually the hinge line, which also defines one axis.

2.4 Mounting the control surface

Datum surfaces are not to be confused with mounting surfaces, even though they may be one and the same. The mounting surfaces are responsible for supporting any loads which may be imposed on the airfoil and securing the airfoil to the fixture in a rigid manner. They must, ideally, fasten the airfoil to the fixture in such a way that the datum surfaces are drawn into intimate contact with the reference surfaces of the fixture. The hinge can often be utilized with great success as a mounting feature by using the actual hinge hardware, or an expanding shaft mandrel in place of the actual hinge pin. As in flight, it is critical that there be no free play in the hinge support.

The airfoil must also be kept from rotating about the hinge. This may sometimes be accomplished using the actuator mounting locations or by using a trailing edge support (see figure 12). The problem with the actuator mount is that it is difficult to secure the dummy actuator arm in identically the same orientation and configuration for TARE as for PART measurement. It is important that the mounting hardware configuration be identical for PART and TARE.

The problem with using a trailing edge support is that the airfoil is not designed to be supported

by the skin and it is often difficult to find a structurally hard point at which a trailing edge support can be secured. The problem is complicated by the need to *securely* hold the trailing edge. This usually means applying clamping forces to the airfoil which may not be allowable.

2.5 Hypothetical case study

For purposes of this discussion, a hypothetical elevator is shown in Fig 10. For each combination of mass properties which may be required, a description of recommended equipment, typical accuracies of measurement achievable, and fixture requirements are discussed.

2.5.1 Detailed fixture design

Now that the coordinate systems, datum surfaces, and mounting considerations have been addressed, let us look at the geometry and requirements of control surface measurements and analyze how best to meet the fixture and measurement requirements given the constraints of control surface geometry.

Control surfaces must have large surface area to fulfil their function and are typically slender. Other than the hinge line and the actuator interfaces, there are few hard points or well controlled datum locations. Hinge bearings typically have a wide stance. The nominal CG location may be forward, aft, or on the hinge line. For the hypothetical elevator shown in Fig 10, all measurements are to be reported relative to a coordinate system in which the origin is the intersection of the hinge line and the inboard edge for the elevator. The hinge line is axis Y. Axis X is nominally the inboard edge of the elevator and axis Z is perpendicular to the plane XY passing through the origin. The maximum thickness of the elevator is just aft of the hinge line but forward of the CG.

To measure CG location along all three axes and MOI about the hinge line, two fixtures will be needed. One (fixture A) for CG_x and CG_y and a second (fixture B) for CG_x, CG_z, and MOI_y. If MOI_z is required it can be measured using fixture A. If MOI_x is required, a third fixture will be required.

Some support for the elevator, such as a foam pad, will also be required for the weight platform. Positioning of the elevator on the weight platform is not critical. If many similar parts are to be weighed, a fitted cradle lined with foam is often used.

2.5.2 CG_x, CG_y, and MOI_z Fixture (elevator horizontal)

Measurement accuracy is maximized if the test article CG is located over the machine centerline and as low as possible. This goal is easily met for this measurement since the elevator is laid on its side.

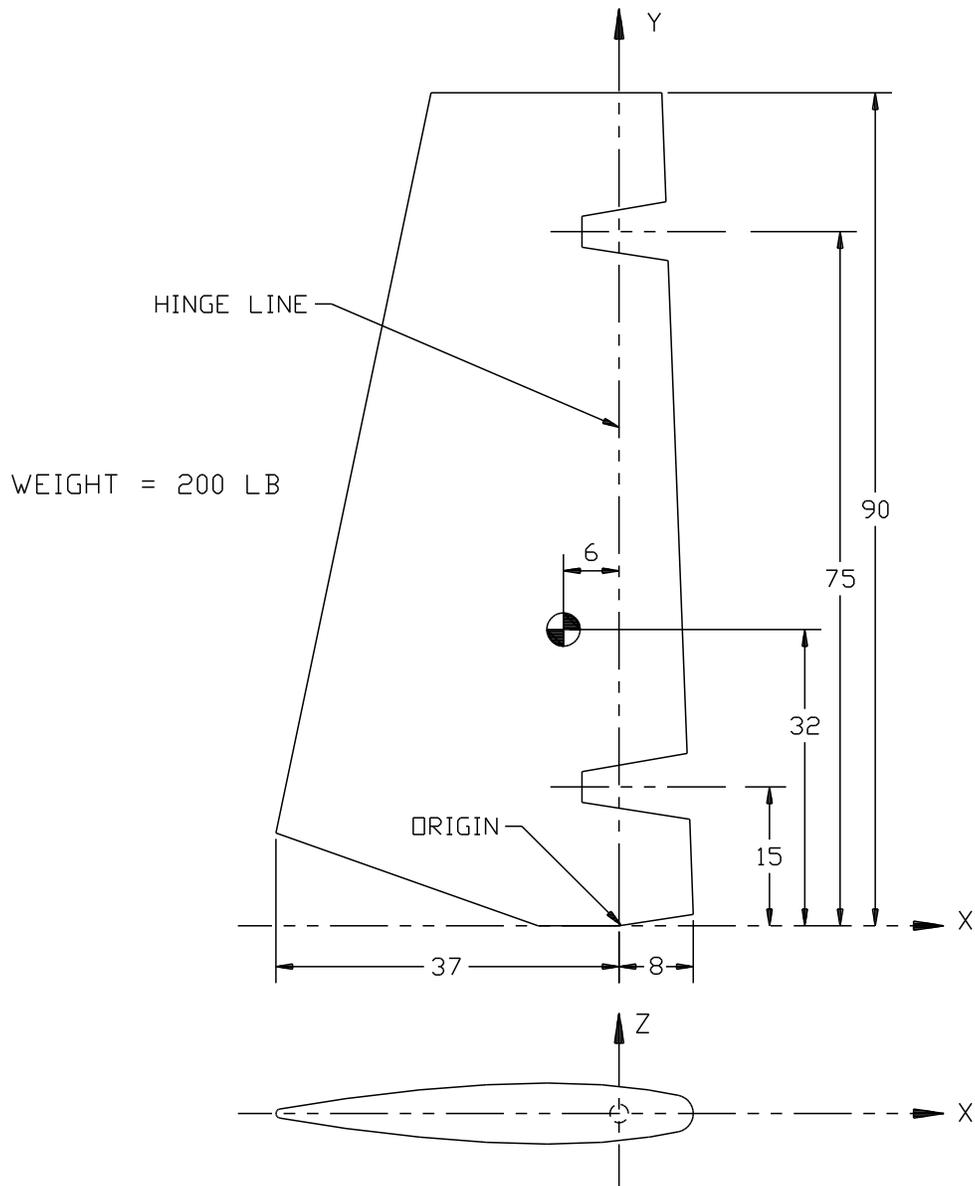
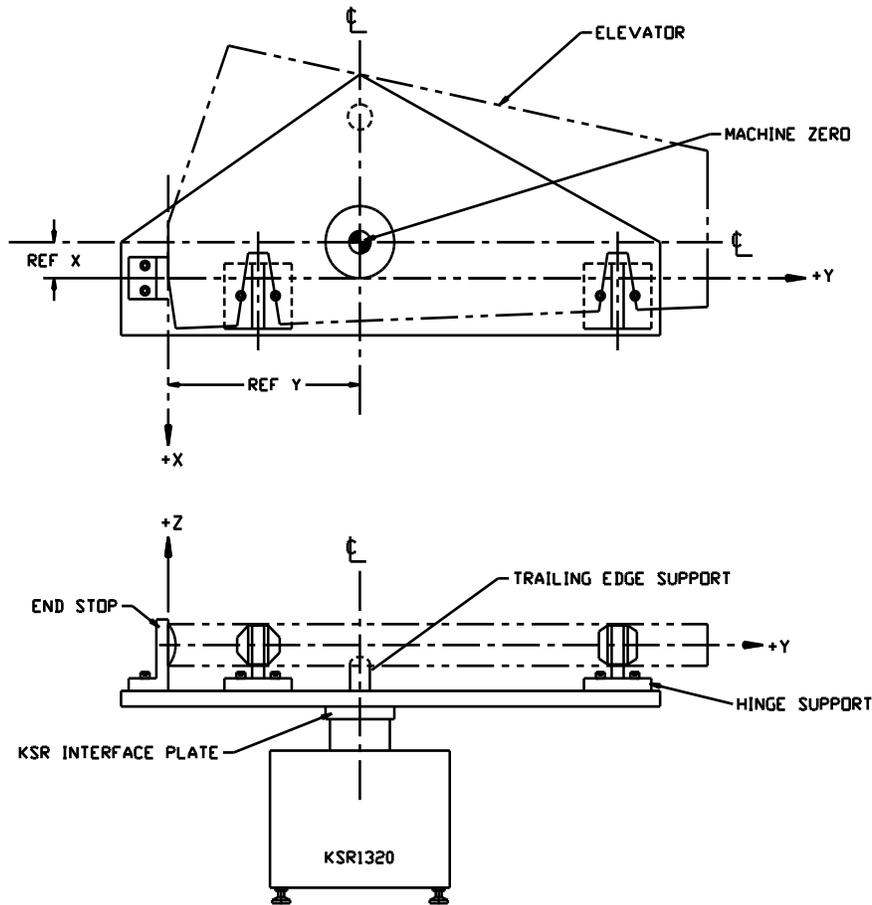


Figure 10 - Hypothetical Elevator Used in our Discussion

This fixture will support the elevator horizontally, low on the mass properties instrument. (See fig 11). The fixture will have a base plate on which to mount other components, a center pin to provide repeatable location on the instrument interface plate, and an angle alignment pin to provide repeatable angular alignment with the instrument interface plate. The other components to be mounted are; two hinge supports, an end stop, and a trailing edge support. Note that the base plate may have an unusual shape to assure that fixture A is balanced without adding ballast weights. It is always desirable to relieve weight rather than add ballast to balance a fixture as long as structural integrity is not compromised.



FIXTURE A
 MEASURING CG_x AND CG_y
 (MOI_z MAY ALSO BE MEASURED)

Figure 11

2.5.3 MOI_y , CG_x , and CG_z , Fixture (elevator vertical)

The requirement for measuring MOI accurately in this orientation (MOI_y) is extremely challenging. Many of the desired fixture attributes must be violated. Lets go back to the itemized list of 13 attributes and look at the problem areas.

Item 2. The fixture should be balanced about the measurement axis

To meet this requirement, a counterweight is required opposite the vertical support beam adding parasitic mass which in turn raises the MOI of the fixture considerably. In this way the fixture can be statically balanced. Since the fixture is to be used only for MOI and CG, the fact that it has an enormous POI does not detract from its usefulness. This configuration is *NOT* suitable for spin balancing, nor do we ever recommend that control surfaces be spun.

Item 4. The fixture must be rigid.

When measuring MOI, the fixture must not only support the test article weight without significant bending but it must have torsional rigidity at least 1,000 times greater than that of the instrument torsion rod. Any torsional flexibility in the fixture which will allow torsional resonances near the same frequency range as the oscillation frequency of the MOI measurement will degrade the measurement accuracy.

Item 5. The fixture should have minimum weight and minimum MOI.

“Minimum” is a relative term. In this case, the requirement for high rigidity and significant offset of the vertical support beam will cause a high moment of inertia relative to the part MOI. The only option is to use tubular construction to maximize torsional and bending stiffness with minimum weight. The tube wall must be thick enough to support the mounting hardware and resist denting. Aluminum should be used for most mass properties fixtures since the dimensions can be increased to achieve stiffness at lower weight than steel. The MOI changes due to thermal expansion are usually negligible and/or controllable.

It must be emphasized that the torsional requirements for the base beam are equally important to those of the vertical beam. The base beam will have a large twisting moment applied by the vertical beam inertial forces during oscillation.

Item 6. The fixture should have a low CG and low profile.

Low profile is impossible to achieve. The upper hinge location dictates the minimum vertical beam length. The CG location cannot be made any lower since it is a property of the elevator design.

Item 7. The fixture should have low windage.

The entire fixture violates this requirement. Some minor benefits might be achieved by streamlining the vertical tube but would add a weight and cost penalty. One should also keep in mind that the elevator itself presents a large frontal area to the air as it oscillates. This will cause damping so the number of oscillations to be measured should be set to no more than 5. Also, any drafts will cause large random errors in the measurement. Heat and air conditioning fans should be shut off during measurement and all traffic kept to a minimum. To minimize drafts it is also desirable to make these measurements in;

- the smallest available room,

or

- a corner of the only available room,

or

- an area surrounded by rigid partitions.

Item 9. The fixture should have low thermal expansion and minimal center to datum distances.

Since the elevator and fixture are both typically made of aluminum, differential expansion is not a problem. However, the large dimensions of both will cause the MOI of both to increase with increasing temperature. To minimize this effect, the system calibration (which uses an aluminum calibration beam), the TARE measurement, and the PART measurement should all be done at the same temperature within ± 2 degrees F.

Item 10. The fixture should have realistic tolerances consistent with required measurement accuracy

For MOI measurements of tall objects, the vertical alignment tolerance is very critical. For the elevator of this example, a tilt of the Y axis in the XY plane of only 0.1 degree can cause the MOI measurement to increase by as much as 1%. The hinge line offset is not quite as critical. Error in the 6 inch offset, at the CG height, will introduce about 0.1% MOI error per .01 inch offset error.

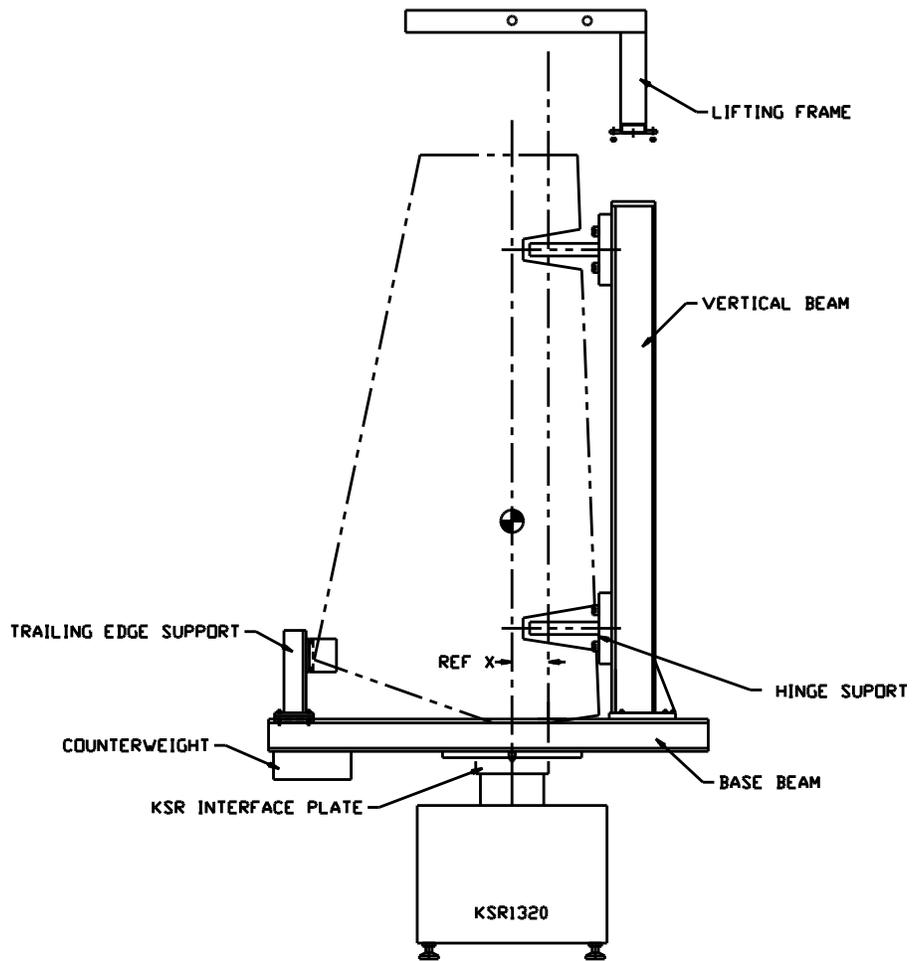
Item 12. The fixture should provide for verifying the location of datum surfaces.

For this fixture geometry, a cylindrical shaft weighing 20 to 30 lb could be mounted to the hinges concentric with the hinge pins and its CG location measured. Since its CG should coincide with the hinge offset, any error in the hinge offset would be easily detected and could be corrected or compensated for. The limitation is often the offset moment capacity of the instrument. A Space Electronics Model KSR1320-300 mass properties instrument allows for up to 300 lb-in offset moment so at 6 inches, up to 50 lb could be used for the dummy payload.

Item 13. The fixture should be simple to set up and easy to use.

In general, if a fixture is dedicated to one test article, it can be made relatively simple and thus easy to use. The test article, in this case, is the awkward item to handle. There are no good ways to lift and locate it in the fixture when the fixture is mounted on the mass properties instrument. To facilitate handling, a lifting frame as shown in fig 12 can be very helpful. It does not require tight tolerances, is removed during measurements so it does not add to the fixture weight, and significantly reduces the difficulty of handling the fixture and elevator. A typical measurement procedure would be to:

1. Attach the lifting frame to the top of the fixture vertical beam.
2. Secure a strap to the right hand hole in the lifting frame and lift the fixture off of the instrument using the lifting frame and an overhead crane. This hole is located above the combined CG of the fixture and lifting frame.
3. Lay the fixture flat on a table and maneuver the elevator into position.
4. Secure the hinge hardware and trailing edge clamp
5. Move the strap to the left hole in the lifting frame and pick up the fixture with the elevator and place it on the instrument. The left hole is located over the combined CG of the lifting frame, fixture and elevator. A hydraulic load positioner should be used to assure gentle placement of fixture on the instrument.



FIXTURE B FOR MEASURING MOI_y
 (CGX AND CG_z MAY ALSO BE MEASURED)

Figure 12

2.6 “Universal” Fixture Set

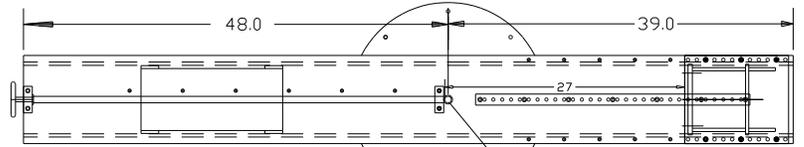
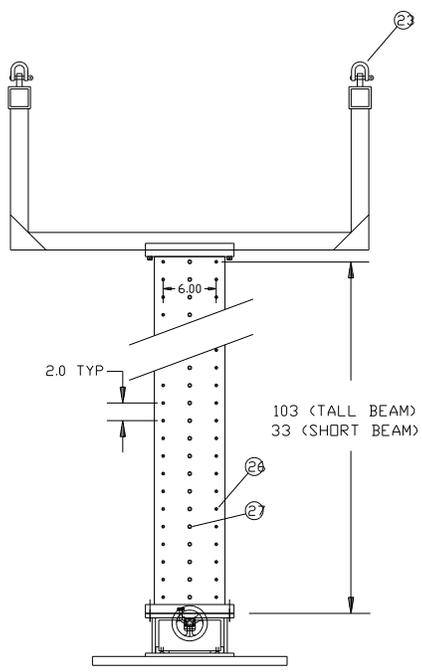
For aerospace manufacturers, fixtures can represent a large expenditure, particularly if each fixture is dedicated to a single test article and only a few parts of any configuration are to be measured. One approach to reducing the fixture cost per test article is to develop “universal” fixtures which will support several different test articles. These fixtures are generally more complex and thus more expensive than any one dedicated fixture. However, when the cost is spread over several test articles, the cost per article can be substantially reduced. Universal fixtures are generally not cost effective in a high production environment. The labor cost of adjusting the fixture for each configuration, over the long run, typically outweighs the lower effective fixture price.

One particular universal fixture set described below and shown in figure 13, is used to measure MOI about the hinge line of 10 different, large, aircraft control surfaces. This fixture set was developed at Space Electronics, Inc. for one of our aircraft customers. This particular customer measured CG offset from the hinge line in a different setup with the airfoils lying flat. This CG location information was then used to set the CG over the MOI machine center for MOI measurements using this fixture set.

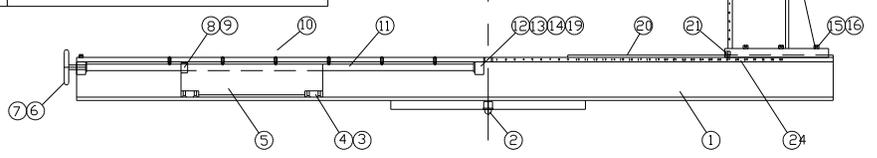
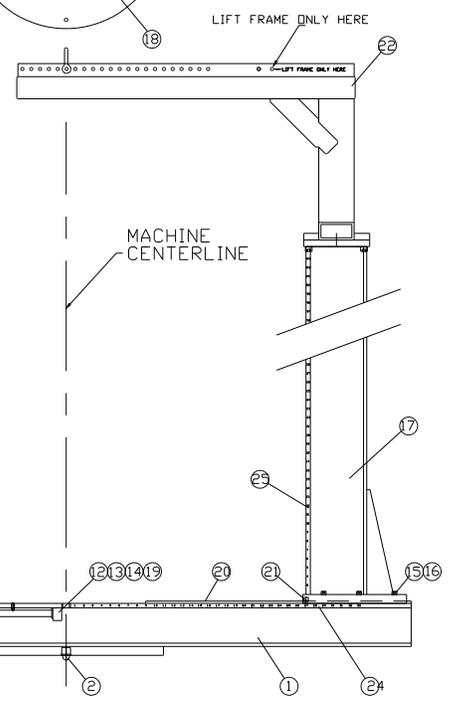
The airfoils ranged in weight from 45 to 500 lb, and in overall height from 70 to 140 inches. Overall widths ranged from 14 to about 115 inches. To accommodate this wide range of sizes and shapes, a 3 piece fixture set was designed with multiple, adjustable features. The set consisted of a base beam and two vertical beams. In addition, a removable lifting frame was designed to attach to either vertical beam. This frame is used to lift the fixture, with and without the airfoil, to move it from an assembly area to the mass properties measuring instrument. The assembly is shown in figure 13, and the 10 airfoils, mounted are shown in figure 14. The lifting frame, shown with all 10 airfoils, is removed during measurement. The location of the vertical beam is adjustable in 1 inch increments so that the CG is never more than $\frac{1}{2}$ inch offset from the machine centerline. This offset is known and the resulting MOI correction can be easily calculated.

2786010

REV	DATE	CHANGE	BY	CHK



DET	QTY	DESCRIPTION
1	1	BASE WELDMENT
2	1	CENTER PIN
3	4	COUNTERWEIGHT GLIDE
4	8	1/4-20 X 1/2 FLAT SHCS
5	1	COUNTERWEIGHT
6	1	CRANK HANDWHEEL
7	1	3/16 X 1 SPRING PIN
8	1	3/4-5 ACME NUT
9	4	6-32 X 1-1/4 SHCS
10	6	COUNTERWEIGHT CLAMP SET SCREW
11	1	3/4-5 ACME LEAD SCREW
12	2	LEAD SCREW SUPPORT BLOCK
13	2	1/2X5/8X1 DILITE BUSHING
14	4	5/16-18 X 1.25 SHCS
15	6	3/8-24 X 2 SHCS
16	6	3/8 HARD STEEL WASHER
17	1	VERTICAL BEAM WELDMENT
18	1	3/4X1X1/2 LONG HARD STEEL BUSHING
19	2	1/2 HARD WASHER
20	1	GAGE BAR
21	1	LOCATING PIN
22	1	LIFTING FRAME
23	2	SHACKLE
24	1	HORIZONTAL SCALE
25	1	VERTICAL SCALE
26	160	(ONE ON EACH VERT BEAM)
27	67	3/8 X 5/8 HARD STEEL BUSHING



SPACE ELECTRONICS, INC. BERLIN, CT.		DR. BY:	DISK:
FIXTURE ASSEMBLY		DATE:	DWG. NO. 2786010
		SCALE:	

Figure 13

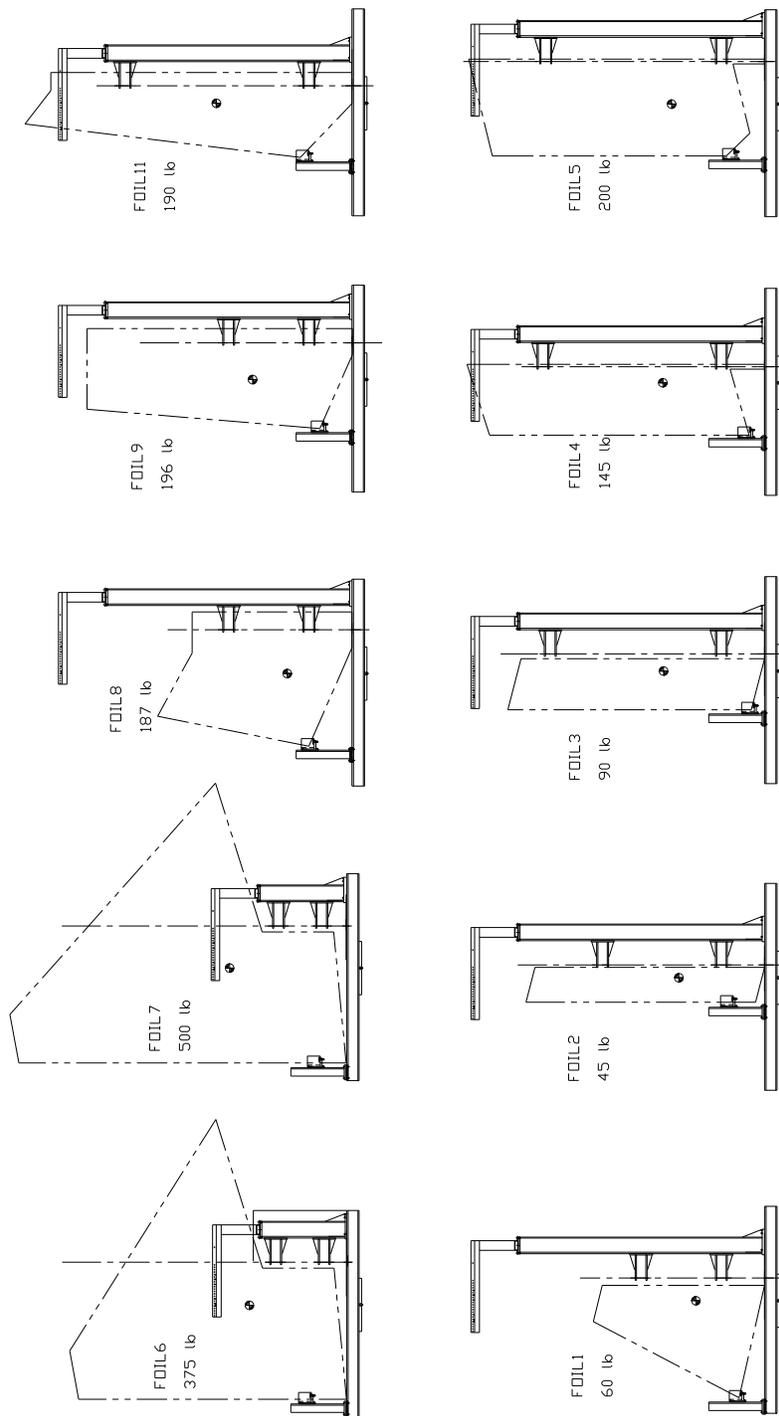


Figure 14

2.6.1 Universal Fixture Features

The adjustable features are:

- (2) vertical beams to accommodate a wide range of airfoil height
- multiple mounting locations for the vertical beams
- multiple mounting locations for the hinges
- multiple mounting locations for the trailing edge support
- moveable counterweight
- multiple pick points on the lifting frame

The vertical beam produces a large CG offset for the fixture. To compensate, a moveable counterweight is enclosed in the base beam. A handwheel (det 6, fig 13) is used to drive the counterweight to the location required to balance the vertical beam. This position is calculated knowing the weight of the vertical beam, with hinges, and the hinge line offset. The balance equation is shown in figure XX3. The final equations, solving for distance B with a known distance A, are:

Using the Short Vertical Beam $B = 43.7 - .655 * A$

Using the Tall Vertical Beam $B = 41.6 - 1.247 * A$

Moving the counterweight to position B as calculated above assures that the fixture will not introduce a large TARE unbalance. The counterweight is locked in position to permit moving the fixture.

It can be readily seen that while the fixture is statically balanced, there is an enormous dynamic (POI) unbalance. This is due to the inherent characteristic of high CG for the vertical beam and low CG for the counterweight. This type of fixture is *not* suitable for spin balance applications.

The lifting frame is a yoke which straddles the airfoil. The leading edge overhang of foils 6 & 7 and the height above the upper hinge of foils 4, 5, & 11 makes this shape necessary. The height of the lifting frame was largely dictated by the CG location of foil 7. In order to be stable when lifted, the lift point on the lifting frame must be above the composite CG of the load being lifted. The weight of the fixture lowers the overall composite CG to below the airfoil CG so that placing the lift point above the airfoil CG assures that the lift will be stable.

2.7 Selecting the instrumentation

The choice of measuring instrument depends on which mass properties you need to measure. The various choices are outlined below:

2.7.1 Measure both CG and MOI

If both CG & MOI measurements are required, a spherical air bearing rotary table mass properties instrument is the best instrument to use. The Space Electronics Model KSR1320-300 mass properties instrument would be a good choice for the elevator used for our example. The KSR1320 has a payload weight capacity of 1320 lb, CG offset moment capacity of 300 lb-inches and CG accuracy of .02 lb-inches + .0005 inch. This converts to CG location accuracy of $.02/200 + .0005$ or 0.0006 inch for this elevator example. The MOI accuracy is 0.1% of measurement.

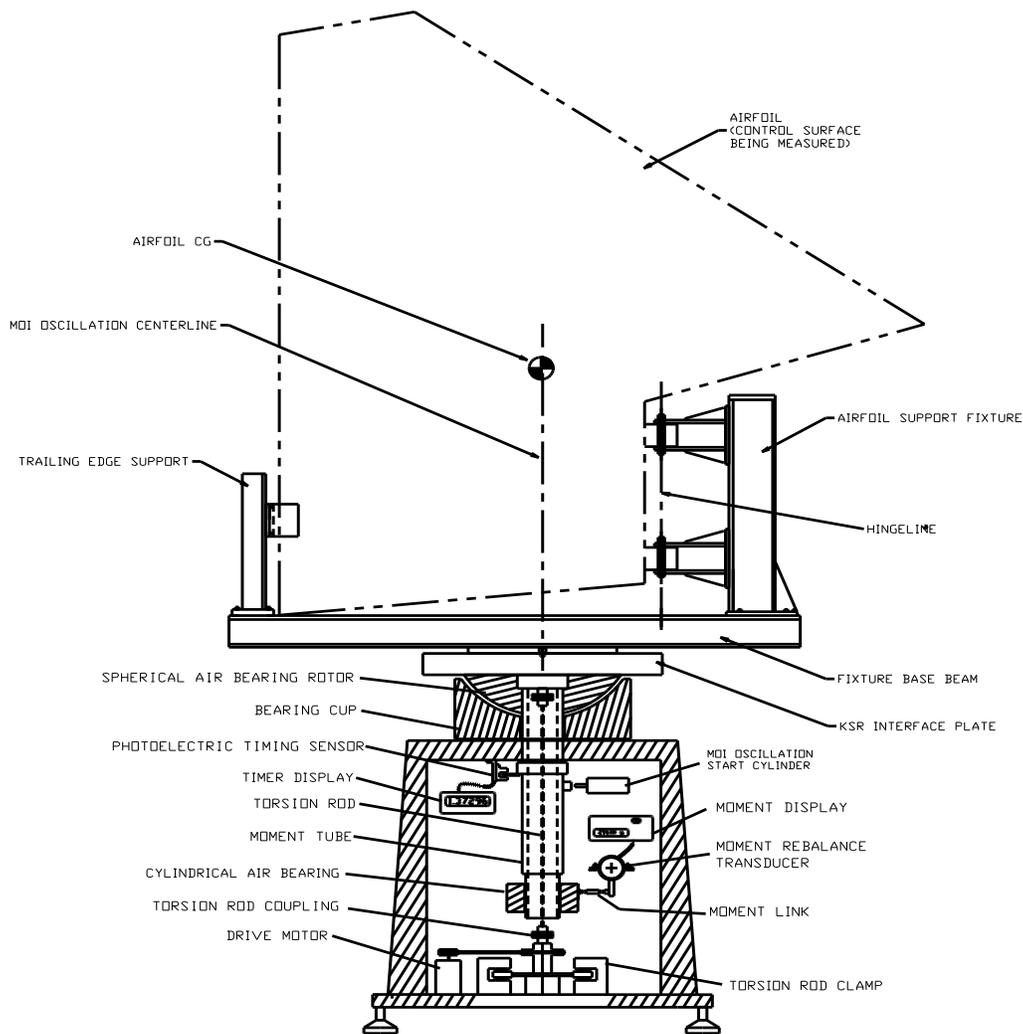


Figure 16 - Measuring CG and MOI Using Space Electronics KSR Series Instrument

2.7.2 Measure Moment of Inertia only

This choice is applicable only if there is no specific requirement for CG measurement and you do not need to measure POI. If, after careful consideration of the following discussion, it is decided that only MOI need to be measured, an MOI instrument such as the Space Electronics GB550AX may be used.

The overriding consideration is to determine which MOI measurements are required. Using the elevator example, if only the MOI about the hinge line and/or any other hard point reference axis is required, a suitable fixture can be fabricated to make the measurement on a MOI only instrument such as the Space Electronics GB550AX. The MOI accuracy is 0.1% , However, if MOI about the CG is required, as for determining POI, considerable error may be introduced because the effect of CG offset on MOI will not be accounted for. For an offset (r) and part weight (W) this effect (ΔI) = (Wr^2) . Fixturing for MOI is discussed under “CG and MOI”.

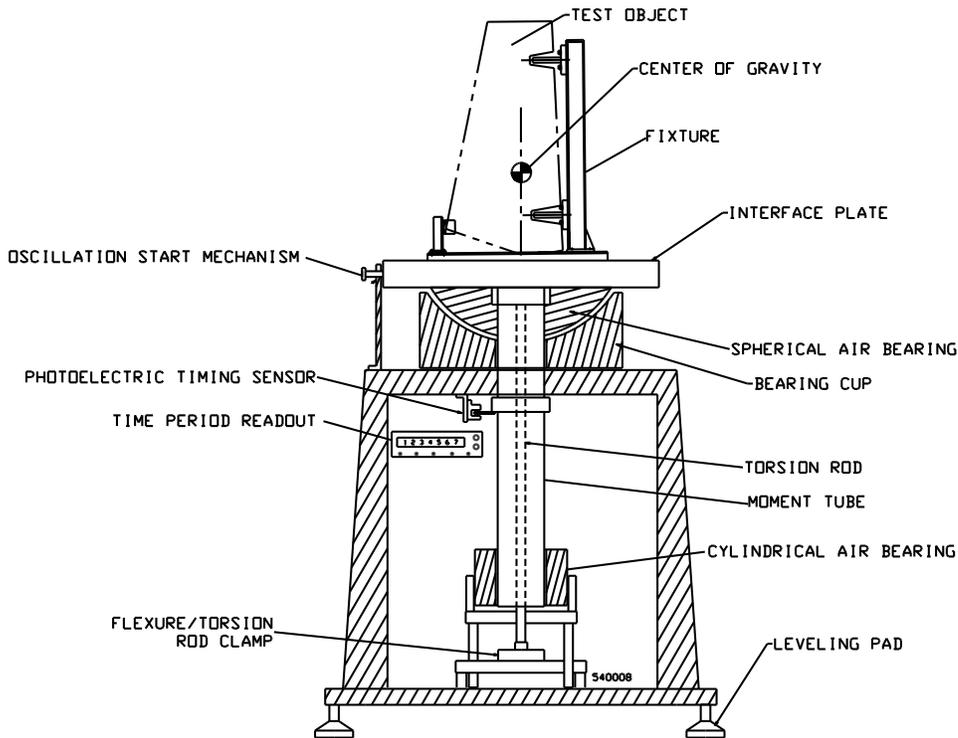


Figure 17 - The Space Electronics GB Series Instruments Measure MOI Only

2.7.3 Measure CG only

For CG only, a “Weight and CG” table may be adequate. This type of instrument consists of a flat table which is supported by 3 or 4 load cells. Two axis (X and Y) CG location is calculated from the difference in force on the load cells. Accuracy is not as good as the air bearing type instruments. This type of instrument is not very accurate if the item being measured is tall, since the load cells have a high deflection, resulting in a large lean error.

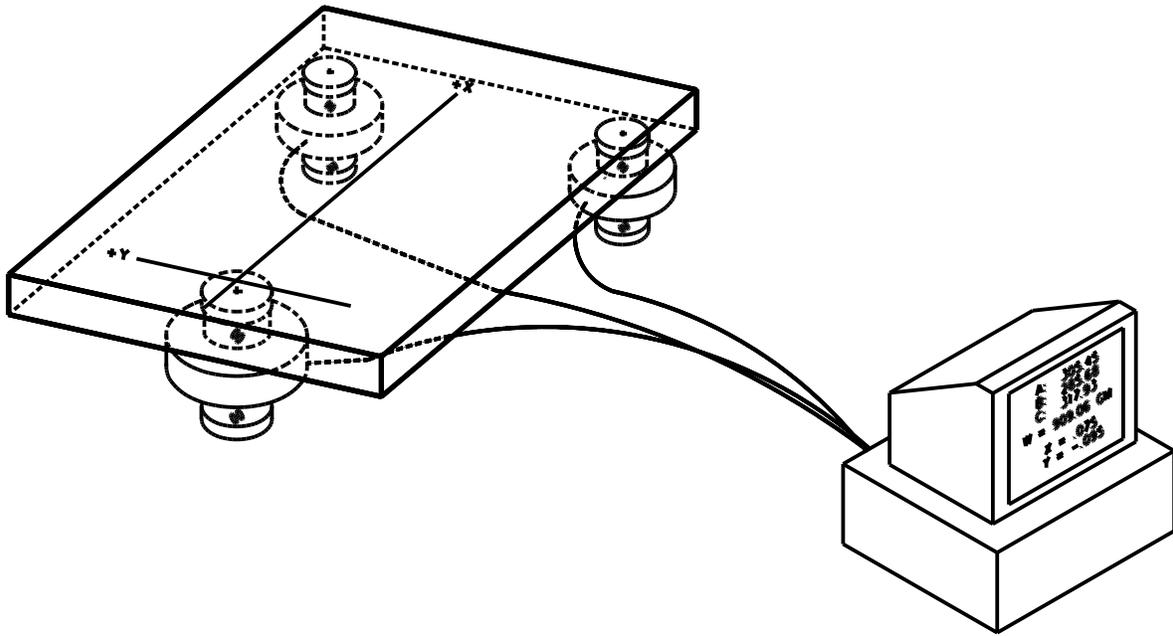


Figure 18 - Multiple Point Weighing CG Machine - Fast and easy to use - Moderate Accuracy

This type of instrument has the advantage that it measures weight as well as CG, so that a separate weighing platform is not required. Weight is computed by summing the outputs of the load cells.

For the elevator shown in our example, a “Weight and CG table” of 500 lb capacity would be ideal, allowing adequate capacity for the weight of the fixturing. There are two type of “Weight and CG” tables available:

1. Low accuracy instruments using strain gage load cells. One can expect weight accuracy on the order of .25 to .5 lb. For low profile objects, CG location accuracy will be on the order of .05 to .10 inch.
2. High accuracy weight and CG tables using force rebalance transducers which can measure weight of this magnitude to accuracy as close as .01 lb. CG location will be as close as .020 inch. This type of weight & cg instrument is only manufactured by Space Electronics.

These accuracies are for the instrument only and do not include uncertainties introduced by fixture and datum tolerances. .

It should be noted that *all* CG measuring instruments respond to CG offset *MOMENT* and are rated in terms of moment sensitivity or accuracy. The CG location accuracy (L) or sensitivity is equal to the moment sensitivity divided (M) by the test article weight (W). For a typical weight and CG table of 500 lb capacity and .25 lb weight accuracy, one could expect moment accuracy (M) on the order of 8 lb-inch. For the 200 lb elevator, this results in a CG location accuracy of $8/200 = .04$ inch.

If 3 axis CG is required, the weight and CG table can still be used but the higher CG location required to measure the Z component of CG location would require greater care in assuring that the table is level and fixturing does not introduce unacceptable uncertainties.

The elevator is shown on a weight and CG table with simple fixturing in fig 19 and 20. Figure 19 shows the elevator mounted horizontally to measure CGx and CGy. The Y zero reference is the end stop located at an offset, REF Y. The hinge line is located at an offset REF X. The instrument will report the location of the CG relative to the machine zero at the center of the table. By subtracting the reported CG location from the X and Y references, the CG location will be referenced to the elevator coordinate system. The Space Electronics WCG series Weight and CG tables have software which will accept the X and Y reference dimensions and automatically report the CG location from both the machine zero and the user (elevator) coordinate system zero.

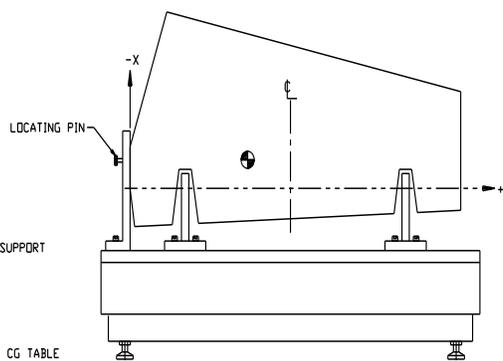
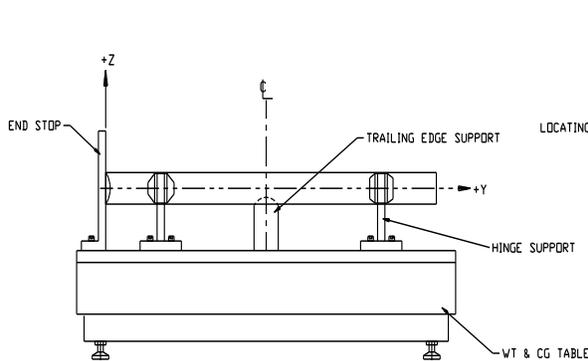
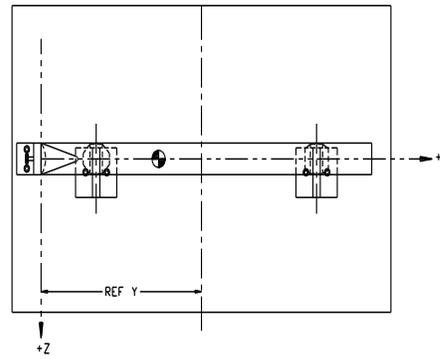
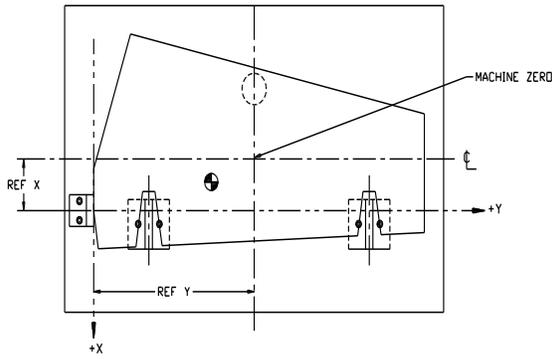


Fig 19
MEASURING WEIGHT, CG_x AND CG_y

Fig 20
MEASURING WEIGHT, CG_y , AND CG_z

Figure 20 shows the elevator mounted on edge to measure CG_y and CG_z . In this orientation some means must be developed to hold the elevator vertically rigid. This is often done using the actuator interface hardware. The locating pin is shown only to indicate that some means is required to provide vertical orientation in a rigid and repeatable manner. Any lean of the elevator or out of level condition of the table will quite dramatically introduce errors in the measurement of CG_z because the CG is quite high. The higher the CG, the more important it is to place the nominal CG location over the machine center to minimize lean due to instrument deflection.

2.8 Measuring Product of Inertia (single plane)

Although a spin balance machine such as the Space Electronics Model POI-1000 is generally used to measure product of inertia of satellites and other more compact shaped test articles, this type of instrument is not practical for the measurement of aircraft control surfaces. A better choice is, again, the KSR series rotary table static mass properties instrument. The POI measurement is made by measuring MOI of the object in several different orientations and calculating the POI. This method is described in the next section of this paper.

There are several reasons why a spin balance machine is not practical for measuring POI of control surfaces:

1. Air turbulence during spinning causes unpredictable forces which obscure the POI induced

forces, distorting the POI measurement. The effect of air turbulence can be reduced by shrouding enclosed fixtures, establishing a vortex in which to spin using external blowers, measuring in a vacuum chamber, or measuring in a helium atmosphere. Unfortunately, none of these methods yield predictable results.

The most effective way to eliminate the disturbances for turbulence from POI measurements is to fully enclose the part to be measured in a smooth cylindrical enclosure which rotates with the part. If the cylinder has to be removed to mount the part, then there is likely to be a large change in the tare POI between TARE and PART measurements.

Shrouding reduces turbulence but the measurement results are highly variable and dependent on the shroud geometry.

External blowers reduce the static air turbulence but add considerable noise to the measurement making the results very erratic.

Vacuum measurements eliminate the turbulence but the cost is extremely high for large airfoils. There may be a small error introduced by eliminating the entrained and entrapped air which would be present in normal service.

Measuring in a helium atmosphere is equivalent to measuring in a partial vacuum yielding similar results but at far lower cost.

The most effective way to eliminate the disturbances of turbulence from POI (spin test) measurements is to fully enclose the part to be measured and its support fixture in a smooth cylindrical enclosure which rotates with the part. While this effectively addresses the turbulence problem, it introduces others. The cylinder typically has to be removed or separated to mount the part, causing a large change in the tare POI between TARE and PART measurements. Secondly, all the mass of the cylinder is at a radius larger than the airfoil. This means that the TARE MOI is considerably larger than that of the airfoil being measured..

2. The large area of control surfaces require more power to spin than most other test articles so speed may be limited to between 20 and 50 rpm. All the methods described above to reduce turbulence will also reduce the power requirements but still leave the results uncertain.

3. The fixtures needed to support control surfaces are often highly non symmetrical and therefore introduce high TARE POI or require unacceptably large ballast weights. Any time that the TARE measurement is high, the ability to measure small unbalances, both static and dynamic, is reduced proportionately to the increase in TARE. To dynamically balance spin fixtures the TARE MOI, air resistance, and air turbulence will all grow dramatically.

2.8.1 Measure MOI to calculate POI (Single plane)

Recommended method of measuring POI

The method described below uses multiple MOI measurements to calculate POI. For our hypothetical elevator, only a single plane (XY plane) POI is likely to be required. This method for determining the product of inertia of an object uses a high accuracy torsion pendulum moment of inertia and CG instrument (Space Electronics KSR series). The method chosen requires only three different inertia measurements and minor calculations to determine the principal axes of the object in one plane.

Since the object moves very slowly during this measurement, there are negligible centrifugal and windage forces exerted on the object. Furthermore, if necessary, the mass of the entrapped and entrained air can be compensated for by making a second set of measurements in helium, and extrapolating the data to predict the mass properties in a vacuum. The helium method is described in the SAWE paper entitled "Using Helium to Predict the Mass Properties of an Object in the Vacuum of Space" by Richard Boynton, Robert Bell, and Kurt Wiener (paper number 2024).

In this illustration, a small missile control surface is used as the test article. The same method will work for any control surface which has a plane of symmetry. For non symmetrical airfoils, (those developing lift) three plane POI may be required. The method for three plane POI is similar to the single plane method but requires a total of 6 MOI measurements. A detailed discussion of the three plane method follows the single plane presentation.

Fixturing is designed so the article can be rotated about its center of gravity, to facilitate making inertia measurements at different angles relative to the reference axes. The center of gravity of the test article is determined on the same gas bearing (KSR) instrument in the same setup as the MOI measurement.

Most mechanical engineers are familiar with the interrelationship between moment of inertia and product of inertia. Standard textbooks on mechanics contain formulas which can be used to determine the moments of inertia about inclined axes, given the moment of inertia and the product of inertia of an object through two perpendicular axes. These formulas seem to suggest that product of inertia can be determined by making three moment of inertia measurements of the test object through different axes.

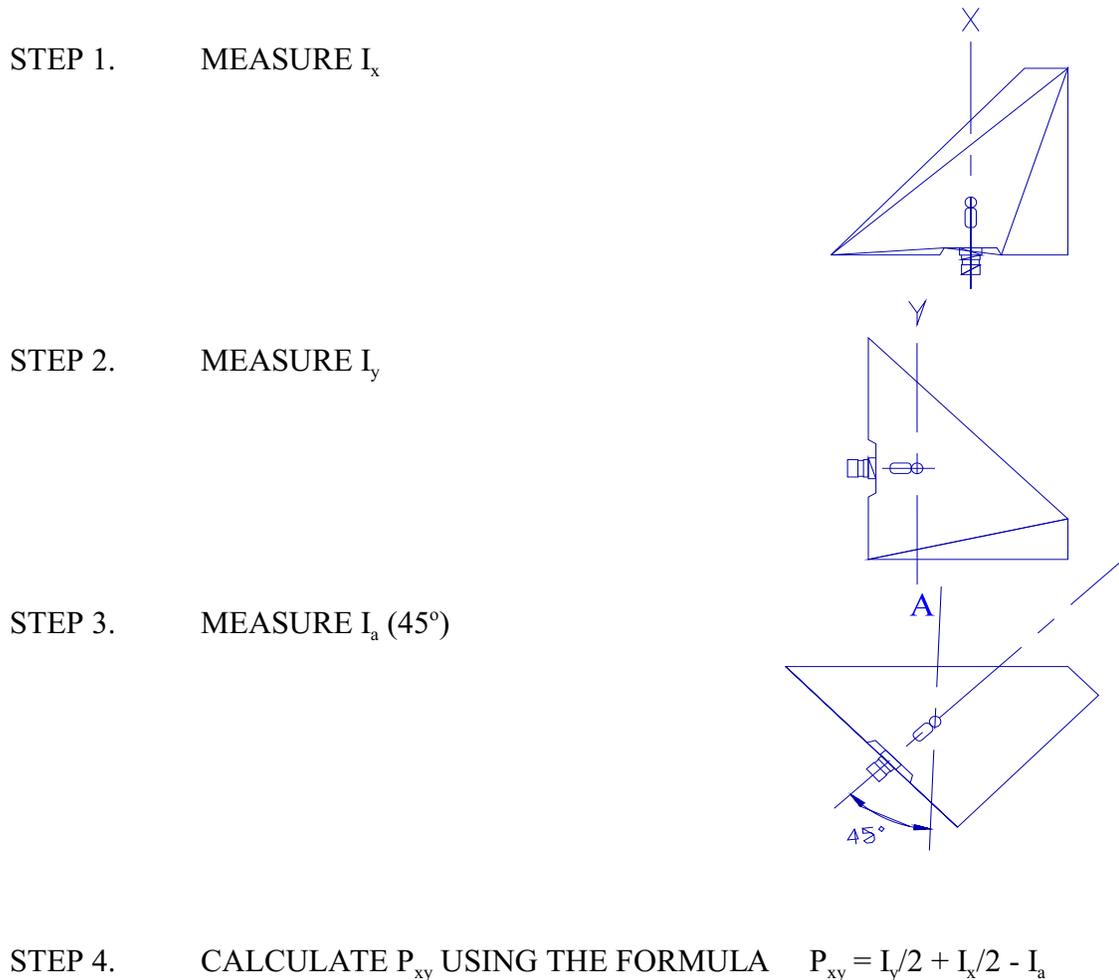


Figure 21 - Product of Inertia Measurement Steps

2.8.2 Review of Basics

Before we get into the details of this method, it is worthwhile to review the basic concepts of moment of inertia, center of gravity, product of inertia, and the interrelationship between these three quantities. Consider the missile control surface shown in Figure 22. This part rotates about an axis O-X. The CG of this object is located at the intersection of axes O-X and O-Y. The exact location of the CG (Point O) can be determined using a Space Electronics KSR series MOI and CG instrument. These instruments rotate the test object on a gas bearing, detect the unbalance moment about a well defined pivot axis, a computer then acquires X and Y moment data and prints out the coordinates of test object CG. The MOI is then measured for the same orientation without removing the test article or changing the fixture in any way.

The moment of inertia of the test object may be measured about the axis O-X, axis O-Y, or any other axis such as axis O-A or axis O-B. If the test object were a round disk of uniform thickness, then Point O, its CG, would be located in the center of the disk and the moment of inertia through any axis passing through Point O would be the same. For the missile control surface shown in Figure 22 (and for most real objects), the moment of inertia of the part will vary depending on the orientation of the axis and, in particular, will have a maximum value (in this

case, O-A) and a minimum value (O-B). These axes of maximum and minimum moment of inertia are known as the principal axes of the test part.

There are three important observations to make concerning the principal axes:

- a. They are at right angles to each other.
- b. The product of inertia is zero about either of the axes.
- c. The product of inertia reaches a maximum value 45° from the angle of a principal axis.

If we measure the moment of inertia about axis O-X, we will find that it falls between the minimum value measured about axis O-B and the maximum value measured about O-A. The

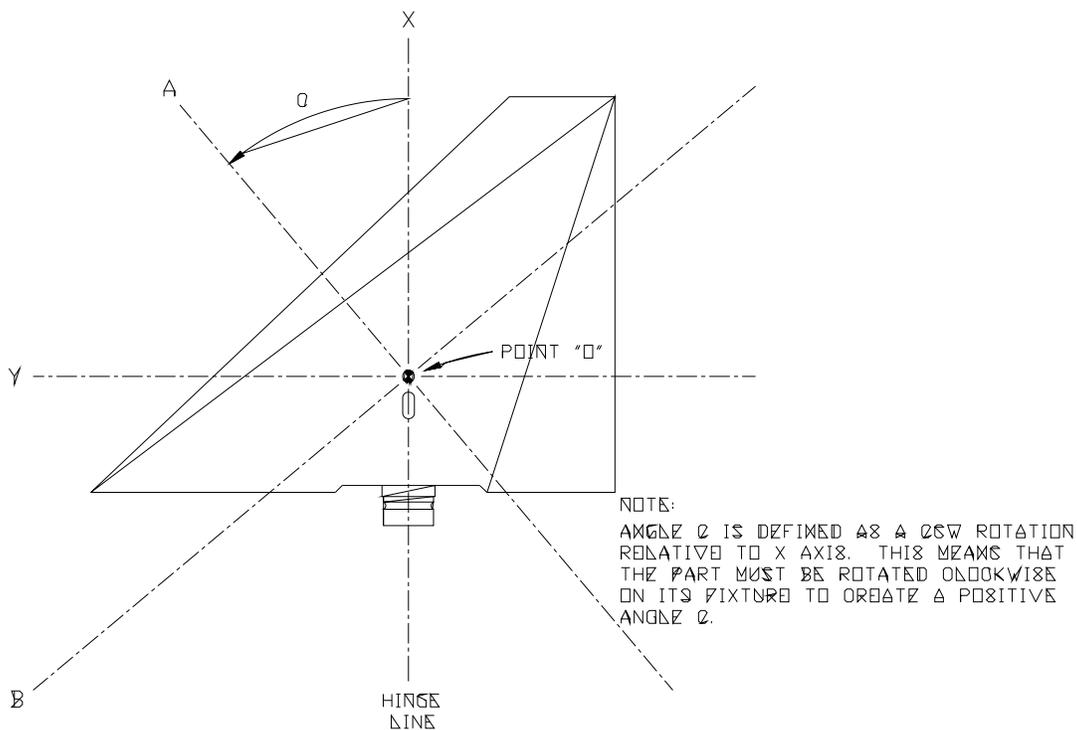


Figure 22 - Coordinate System Diagram for Missile Control Surface

product of inertia about axis O-X will be greater than zero and will be proportional to the difference in the moment of inertia about the two principal axes. (For the example using the uniform thickness *disk*, the moment of inertia difference is zero and the product of inertia is, therefore, zero about all axes.)

One way to determine the location of the principal axes of a test object is to construct a fixture whereby the test object can be pivoted about an axis passing through Point O, its CG. A series of moment of inertia measurements are then made for different orientations of the test part. If we define the angle of the axis of measurement as "Angle C," the counterclockwise rotation of the

measurement axis relative to axis O-X as shown in Figure 22, and we plot the measured moment of inertia as a function of this angle, then a sinusoidal curve similar to Figure 23 results. The points of maximum and minimum moment of inertia correspond to the angles of the principal axes of the test object relative to axis O-X, which in this case was arbitrarily defined as an axis parallel to the axis about which the test object rotates (because part CG is on the axis of rotation, "hinge line," axis O-X is the axis of rotation for this case).

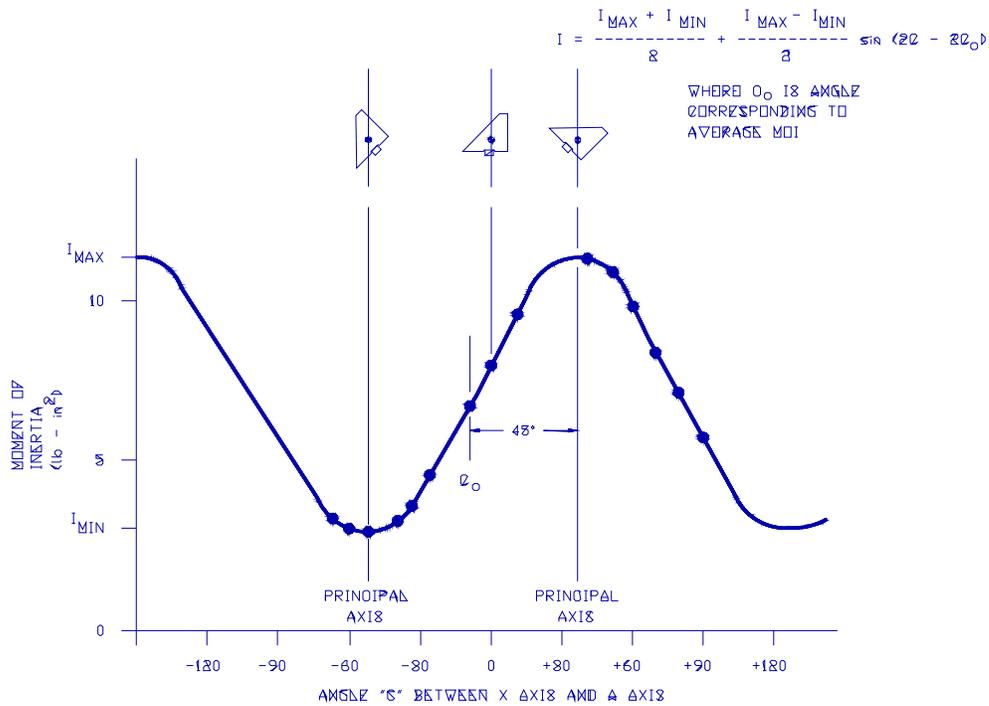


Figure 23 - Moment of Inertia versus Tilt Angle

The method just described requires a large number of measurement to be made. A simpler technique exists to determine the location of the principal axes of the test object. The product of inertia through an axis such as O-X may be determined mathematically from the measurement of moment of inertia through three axes: O-X, O-Y, and O-A. O-X and O-Y are two axes 90° apart; O-A is an axis at any angle C measured counterclockwise from axis O-X .

The moment of inertia of the test object through axis O-A is defined in Equation 10 below:

(10)

Solving for P_{xy} yields an expression involving the three measured values of moment of inertia and the angle C as shown in Equation 11 below:

(11)

The angle of the principal axis relative to the axis O-X, p , may now be determined through the formula in Equation 12:

(12)

2.8.3 Procedure for Measuring Product of Inertia of a Missile Control Surface

The part measured is shown in Figure 22. This missile control surface is symmetrical about its thickness so that the determination of product of inertia involved only two axes (single plane).

The first step in measuring the part is to determine the location of its CG.. The test object was fixtured using an aluminum angle bracket (Figures 24 and 25). Anticipating the eventual need to pivot the test object about its CG, a bracket with a long base was chosen. .The KSR series CG and MOI instrument determines CG by measuring unbalance moments about a pivot axis defined by a spherical gas bearing rotary table. MOI is measured on the same machine by oscillating the object on the gas bearing inverted torsion pendulum and measuring the period of oscillation

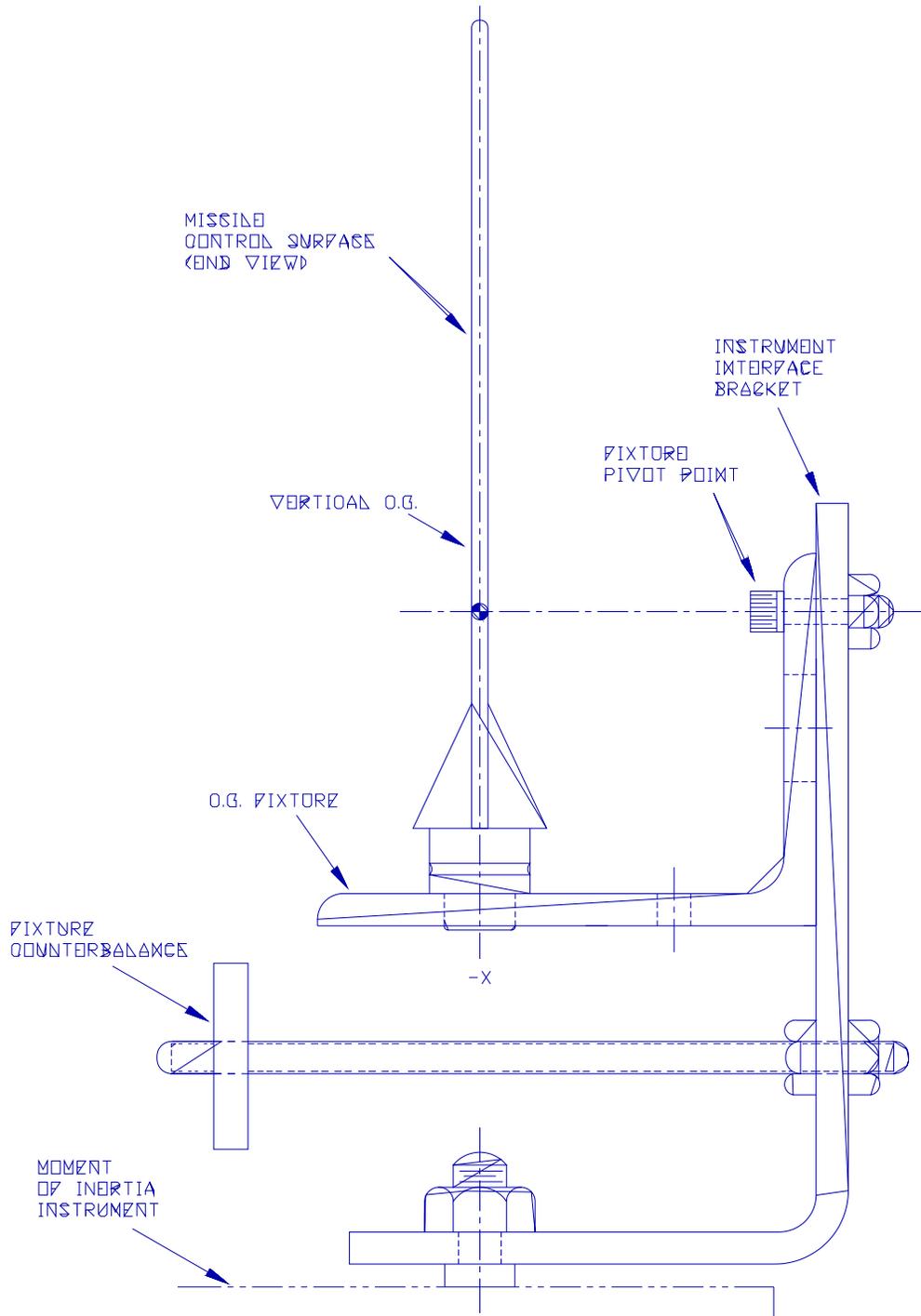


Figure 24 - Fixture for Determining Control Surface POI

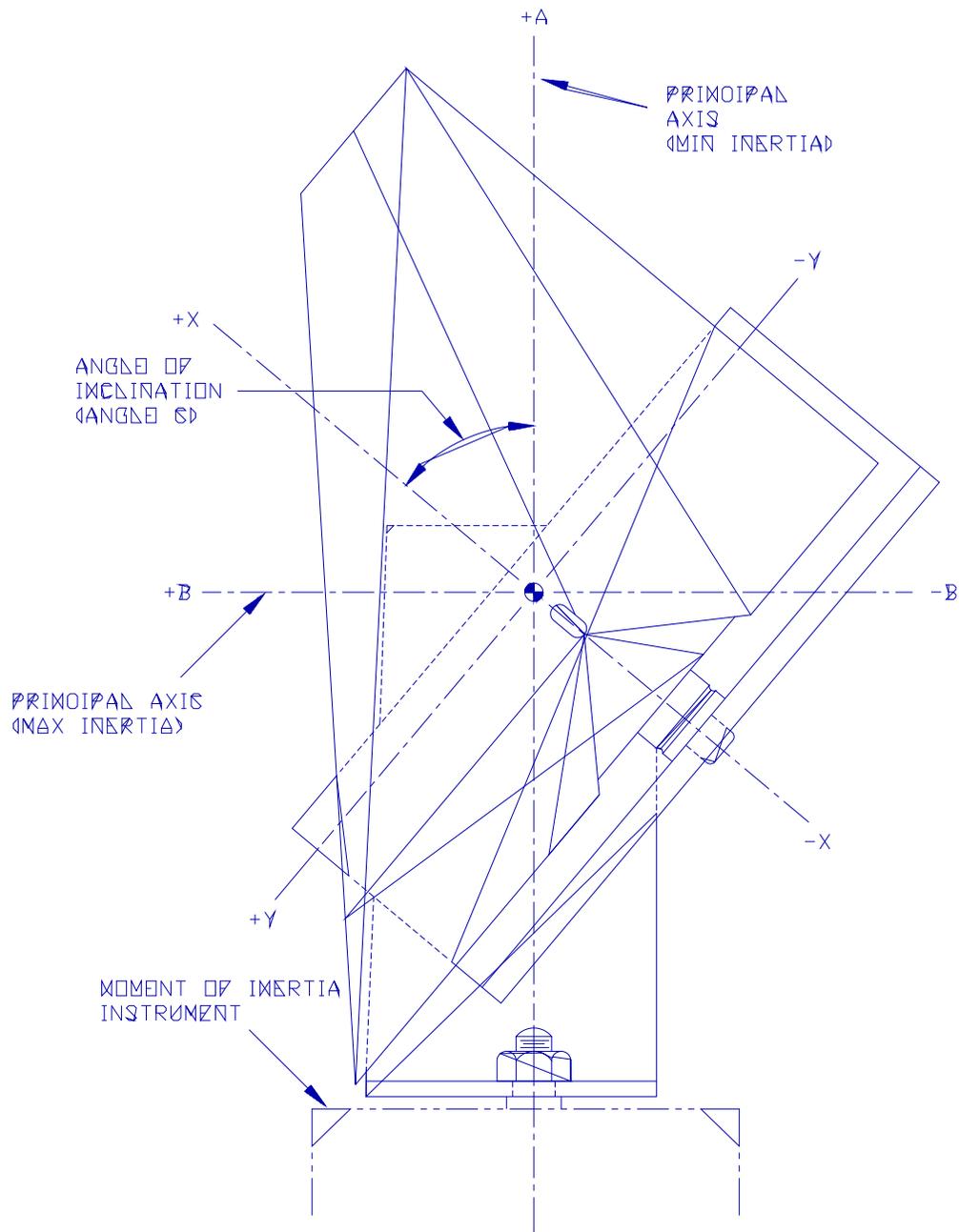


Figure 25 - Control Surface Rotated to Principal Axes

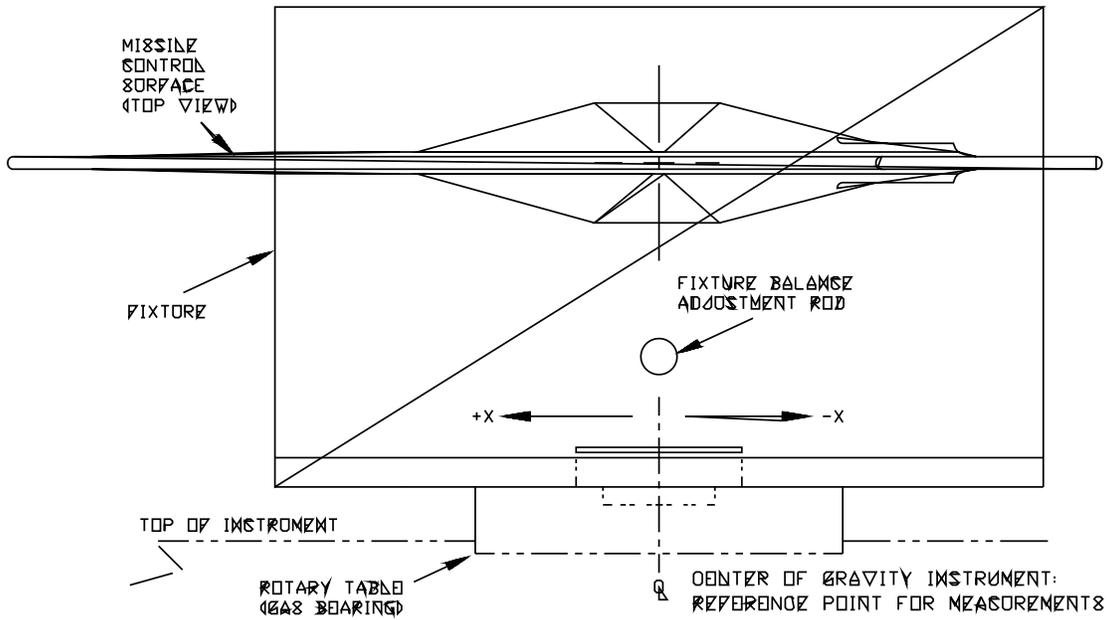


Figure 26 - Center of Gravity Measurement - Missile Control Surface

The test object was then mounted in place on the fixture and the entire assembly placed on the CG instrument (Figure 26). The counterbalance weight shown in the photograph was adjusted so that the CG of the fixture was approximately on its center. (Theoretically, the location of the CG of the fixture has no effect on the determination of the product of inertia of the part. However, balancing the fixture minimizes the need for leveling the moment of inertia instrument and makes subsequent steps easier.)

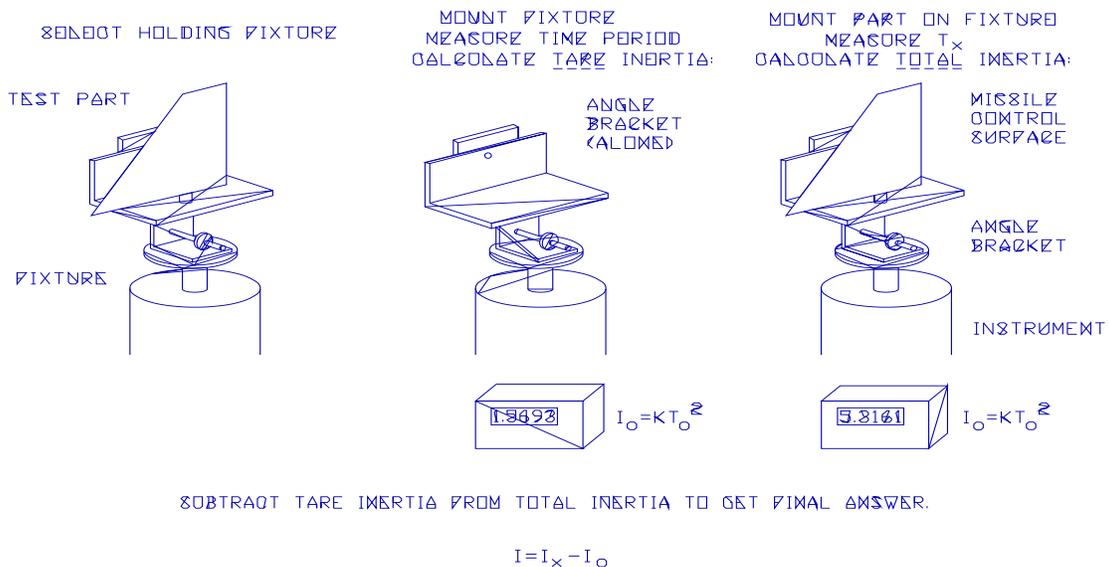


Figure 27 - Method of Measuring Moment of Inertia

To measure the product of inertia of the missile control surface, it is necessary to make three moment of inertia measurements of the part.

One measurement must be made about an axis parallel to the axis of rotation of the part (i.e., the axis about which we are interested in determining product of inertia). Since the test object CG lies directly on the pivot axis, then the first measurement, I_x , is directly through the pivot axis of the part.

A second measurement, I_y , must be made at right angles to the first.

A third measurement, I_a , must be made at some other angle. If the product of inertia is nominally zero through I_x , then the ideal angle is 45° . The angle of this third measurement is determined from the counterclockwise rotation of the new axis, O-A, from the axis, O-X. To produce a counterclockwise rotation of the measurement axis, the test object is rotated in a clockwise direction. It is essential that this convention be followed in order for the mathematics in this paper to give the right answer (see Figure 22 for axes orientation).

Each moment of inertia measurement actually consists of two measurements. The test object is first turned to the desired angle (Figure 27), and a moment of inertia measurement made (I_1). The test object is then removed and the "tare" moment of inertia of the instrument and fixture determined (I_0). The moment of inertia of the part alone, I , is then the difference between the two readings:

(13)

The test object is then rotated to a new orientation and the process repeated, etc.

Although it is not necessary, the labor required to measure the product of inertia of the part can be reduced by designing the fixture so that its moment of inertia remains constant for different rotational angles. Using a fixture with constant moment of inertia eliminates the need for taking repeated tare readings at each angle - a single tare reading is used for all measurements. Furthermore, if a number of similar parts are tested with this fixture, then tare need be measured only once at the start of the day and the test object product is then determined by making three moment of inertia measurements.

The product of inertia of the test object can now be calculated from Equation (2). If the angle, C , has been chosen as 45° , then this equation is simplified to the following relationship:

(14)

2.8.4 Error Analysis

The accuracy of this method is limited by three factors:

- a) Accuracy of the moment of inertia instrument.
- b) Tare moment of inertia of the instrument and fixture as compared to the moment of inertia of the test object.
- c) Tilt angle accuracy (error in angle "C").

Moment of inertia instruments are among the most accurate physical measuring devices in the world. Even the least expensive instruments (Space Electronics XR series) have measurement errors less than 0.25 percent; high accuracy instruments (Space Electronics XKR series) can be made with errors as small as 0.01 percent. If the tare moment of inertia of the instrument and fixture is small relative to the moment of inertia of the test part, then the product of inertia error will be proportional to the moment of inertia of the part. This results in the very desirable characteristic that the product of inertia error decreases as the size of the part decreases. This characteristic is not true of spin balancing machines - spin balance error is constant, independent of the size or moment of inertia of the part.

The accuracy of this method of determining product of inertia is primarily limited by the accuracy with which the tilt angle can be determined. In most cases, it is desirable to know this angle within the tolerance of plus/minus 0.1° . This restriction also occurs when using a dynamic balance machine. However, the dynamic balance machine method requires only one position of the part, and this position is generally defined by a shaft or a mounting ring; the part is positioned for minimum runout. The moment of inertia method requires three positions - the dial indicator method of alignment cannot be used for two of them.

Referring to Equation (11), the magnitude of the term $\sin(2c)$ approaches zero for an angle of 0° , 90° , 180° , etc. The magnitude of product of inertia would therefore approach infinity when the A axis is close to either the X or Y axis if it were not for the fact that the difference in the moment of inertia terms becomes very small. This means that the angle, C, must be chosen between 10° and 80° or very large errors will result in product determination as a result of angle error. Furthermore, it is desirable that the X axis (and therefore the Y axis) lie near a principal axis of the test object. Small errors in angle C will then not appreciably affect the determination of I_x and I_y . This was not the case for the example given in this paper.

2.8.5 Fixturing large airfoils for POI measurement

The previous example used a rotating fixture. This type of fixture is not practical for large airfoils. Figure 28 shows a typical design using three separate fixtures to create the three orientations required for POI measurement.

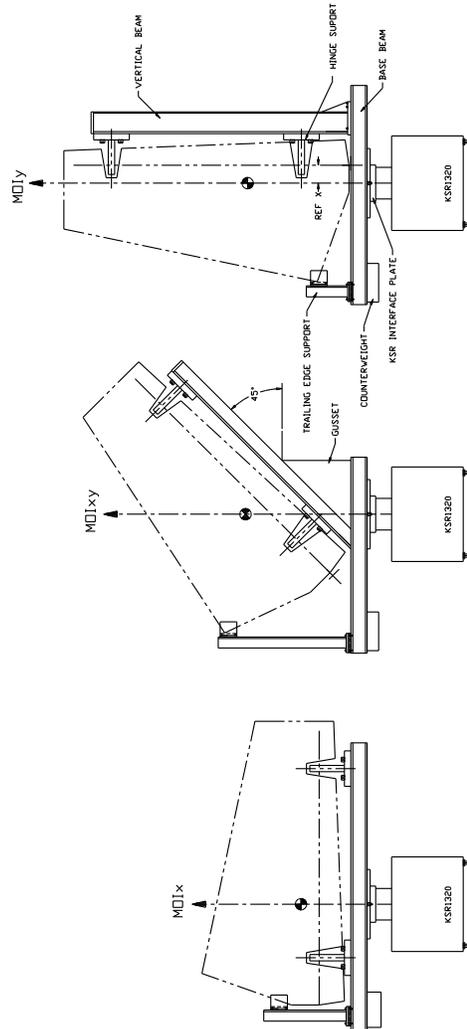


Figure 28
FIXTURES FOR MEASURING POI_{xy} USING MOI METHOD

2.9 Three dimensional POI using the MOI method

This section of our paper gives step-by-step instructions on how to measure 3 components of product of inertia on a torsion pendulum. Special fixtures must be constructed to move the object to the six positions while keeping both the object and the fixture CG near the center of oscillation. We have included design details of such a fixture. Since vacuum data was required, measurements were made in a chamber which could be filled with helium.

To illustrate this method, we have used as an example real measurements which were made of airfoil control fins manufactured by one of our customers. Figure 29 shows the airfoil used in this project. For this example, we determined all mass properties: weight, center of gravity along three axes, moment of inertia about three axes, and product of inertia in three planes, all referred to vacuum conditions. This data was used to develop a statistical data base for a highly non-symmetrical airfoil. This required making 9 MOI measurements to determine the 3 dimensional POI of the airfoil. The individual MOI values as well as 3 axis CG location components were also required. The intent was to measure a significant number (at least 150) of these airfoils to determine the variation due to manufacturing and materials differences. The results would determine the level of inspection and measurement required for final production runs.

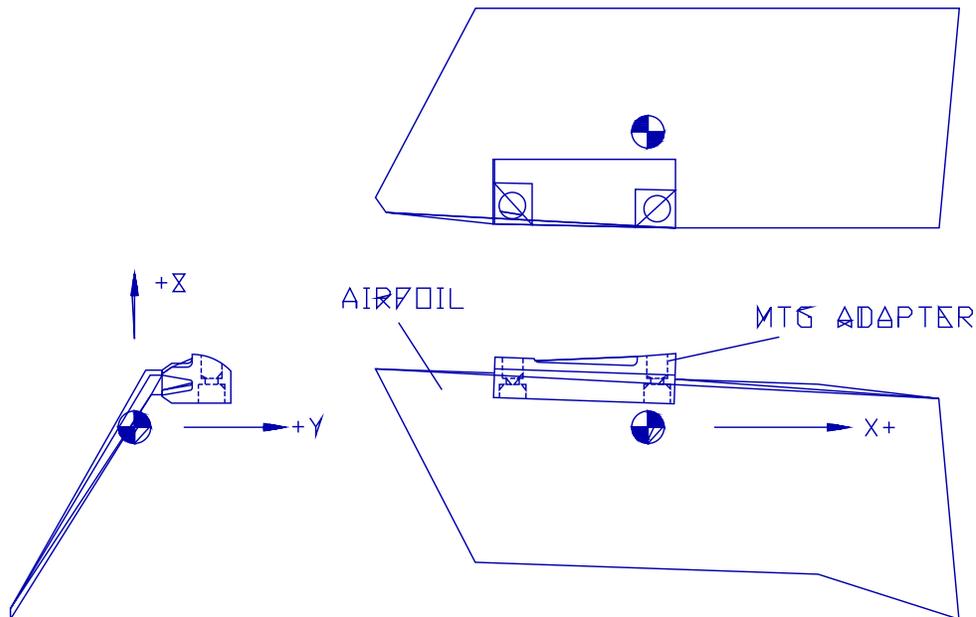


Figure 29

The MOI method of POI determination requires the use of an extremely accurate moment of inertia instrument. This instrument must also be capable of measuring center of gravity. The only type of instrument which we know of that has the required accuracy is a gas bearing supported torsion pendulum such as the Space Electronics KSR Series instruments.

Typical POI accuracy required by airframe manufacturers is 1%. The typical accuracy obtained by the proposed MOI/Helium atmosphere method is on the order of 0.5%.

2.9.1 Number of MOI Measurements For the general case, the total number of MOI measurements needed for POI calculations is nine: three in each of three mutually perpendicular planes. If the intersections of these planes are selected to be the coordinate axes, then the MOI about each of these axes will be common to two planes, thus reducing the total number of measurements to six: three about the X, Y, and Z axes, and three about axes at 45 degrees between the X-Y, Y-Z, and Z-X axes. If vacuum data is required, the same six MOI measurements must also be repeated in a helium atmosphere.

2.9.2 Calculations for 3 Axis POI The coordinate system for the MOI method (fig. 30) has its origin (O) at the test part CG. The axes will be designated X, Y, and Z passing through the CG.

If the test part were fixtured so that it could be rotated through an angle C about a horizontal axis (i.e. the Z axis) and MOI measured about numerous axes in the X-Y plane, including the X and Y axes, the MOI would be found to vary sinusoidally. If the angle C ranges over 180 degrees, the maximum and minimum values of MOI can be seen in a plot of MOI vs C. (fig. 30).

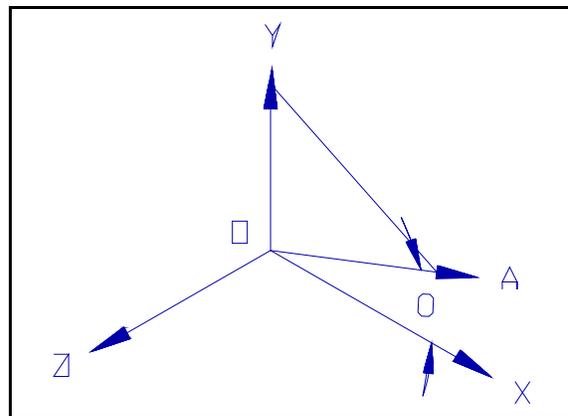


Figure 30

The axes about which the maximum and minimum MOIs are measured are the Principal Axes. For all other axes the moment of inertia I_{Axy} , about an axis (A) in the X-Y plane at an angle C from the +X axis, and the product of inertia P_{xy} , are related through the equation:

$$(15)$$

Solving this equation for P_{xy} forms the basis for the MOI method of POI determination.

$$(16)$$

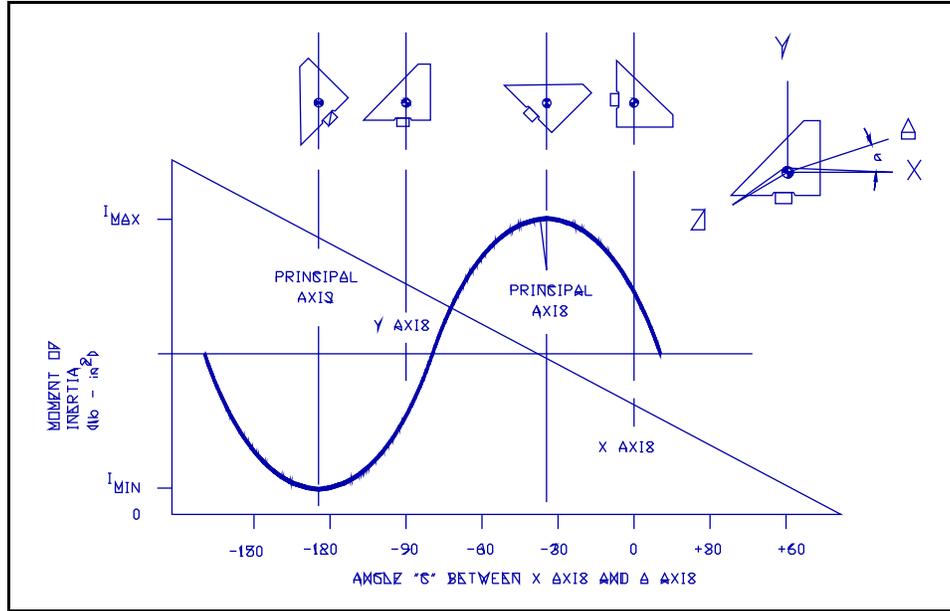


Figure 30A

The POI in each of the three machine coordinate planes, X-Y, Y-Z, Z-X is calculated from MOI data taken about three axes in each plane. For best accuracy the three axes will be the two coordinate axes (i.e. X and Y in the X-Y plane) and an axis at 45 degrees between the coordinate axes. This third axis is referred to as the A axis and the MOI about this axis in the X-Y plane would be referred to as I_{Axy} . If, due to mechanical limitations, the 45 degree orientation cannot be achieved, any angle in the reference planes may be used. The accuracy of the calculated POI value will be degraded as the deviation from 45 degrees increases.

The equation used to calculate the POI in the X-Y plane when A is at 45 degrees is:

$$(17)$$

Similarly, the POI for the Y-Z and Z-X planes would be calculated from MOI data about axes in those planes such that :

$$(18)$$

and

$$(19)$$

At this point, all MOI and POI values are known for the reference X, Y, Z coordinate system, therefore, they can be determined for any other coordinate system using the standard axis rotation and translation equations when the rotation angles are known.

The next step is to determine the orientation of the principal axes and the angle of inclination. This is not as straight forward as axis rotation and translation because the angles between the reference axes and the principal axes are not known.

2.9.3 Principal Axis Orientation The most common need for principal axis information is to determine angle of inclination. For a two dimensional object in the X-Y plane (or an object where the X-Y plane is a plane of symmetry) the angle of inclination (P) between the X axis and the principal axis X', can be calculated from:

(20)

For a three dimensional part, the same form of equation may be used, but the values of POI and MOI must be relative to axes which lie in a plane defined by the reference axis and corresponding inclined principal axis, i.e Z and Z'. Refer to figure 31 where the axes have been re-defined for the general case.

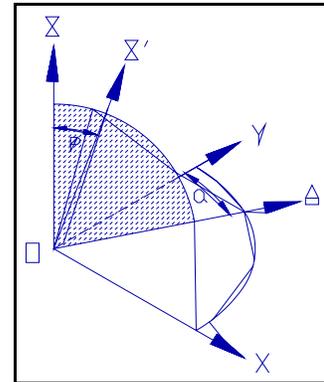


Figure 31

The Z-Z' plane will be at an angle (a) relative to the +X axis such that:

(21)

Let (O-A) be an axis in the X-Y plane at an angle (a) from the +X axis. It is, in fact, the intersection between plane Z-Z' and plane X-Y.

The equation can now be re-written:

(22)

From our original MOI measurements, only I_z is known. However, we also know angle (a) so that we can use eq.1 to determine I_{AA} :

(23)

and then determine

(24)

The same method may be used to find the angle between the X and X' and Y and Y' axes. However, if the orientation of the principal axes and moments of inertia about the principal axes must all be known, it may be more practical to apply matrix solutions.

ACCURACY REQUIRED	<u>REQUIRED</u>	<u>ACTUAL</u>
Accuracy was required to be within the tolerances listed here.	WEIGHT	± 0.1%
The measured values are within the tolerances shown in the "Actual" column. The uncertainties were determined from the error analysis.	CG-X (in)	± 0.1 in
	CG-Y (in)	± 0.1 in
	CG-Z (in)	± 0.1 in
	I _{XX}	± 1.0 %
	I _{YY}	± 1.0 %
	I _{ZZ}	± 1.0 %
	P _{XY}	± 1.0 %
	P _{YZ}	± 1.0 %
	P _{ZX}	± 1.0 %

2.9.4 The Test Procedure It is important to organize the measurement procedure to minimize:

the total number of measurements to be made

the number of tare measurements to be made

the number of fixture setups to be used,

the number of helium measurements to be made (if needed)

Since the orientation of the test part is different for each measurement, the locating fixture will also, in all probability, have a different MOI in each position. Therefore, a tare measurement for each position is also required. If the fixture is very repeatable, the tare measurements may only have to be made once and stored for use with successive part measurements. This may require a special software data storage and retrieval program, since the typical standard program stores only one tare measurement.

2.9.5 Test Positions

The six MOI test positions are shown and identify the test sequence in Figure 5. CG and MOI were measured in each position so that MOI about CG could be determined.

The CG locations as measured in positions 1A, 3A, and 4B were recorded as the "official" test part CG location relative to the airfoil coordinate system datum.

Notice that even though there are 3 positions in each plane required for POI calculations, there are only six different positions since 3 positions are common to 2 planes. The duplicate positions are noted in figure 32. This is most apparent in the drawing for fixture C. Only the intermediate (45 degree) position need be measured since the Moment about Z was already measured in position 1 using fixture A, and MOI about axis Y was measured in position 4 using fixture B.

2.9.6 Sequence of Measurements

If the standard software is used or there is only one test part to measure, the sequence of tare and part measurements can be arranged to minimize the number of times the part must be mounted/dismounted as described below. (Positions are shown in figure 32)

1. Setup fixture A, position 1, and measure tare position 1.
2. Mount part, measure part position 1.
3. Rotate part to position 2, measure part position 2.
4. Remove part, measure tare position 2.
5. Rotate fixture to position 3 measure tare, position 3.
6. Mount part, measure part position 3.
7. Setup fixture B, position 4, measure tare position 4.
8. Mount part, measure part, position 4.
9. Rotate to position 5, measure part position 5.
10. Remove part, measure tare position 5.
11. Setup fixture C, position 6, measure tare position 6.
12. Mount part, measure part, position 6.

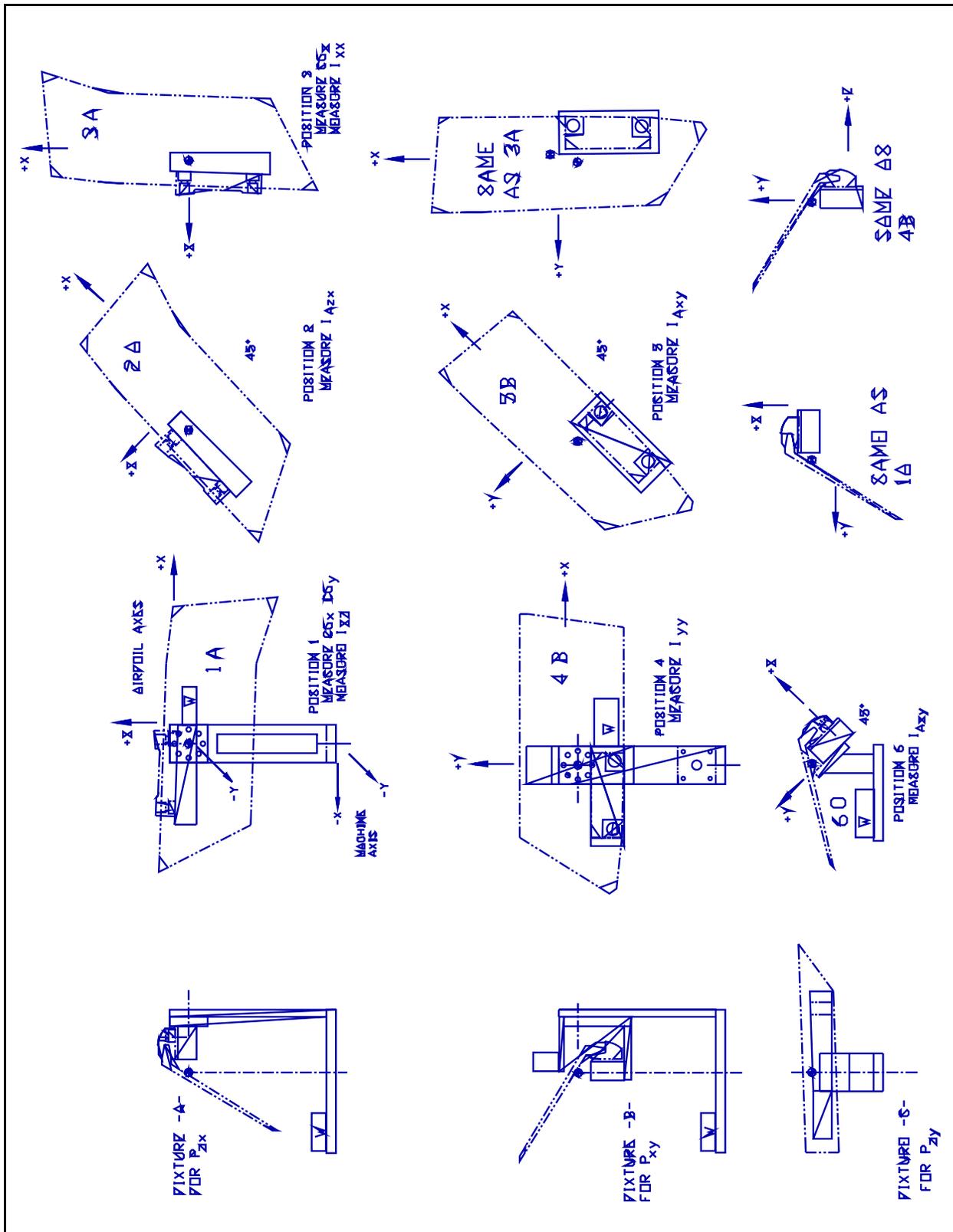


Figure 32

In each test position, the CG location as well as MOI should be measured. This will allow the machine to report MOI through the CG. CG location data is often required as well as MOI. If the nominal CG location is on an axis passing through the fixture pivot, and the CG location is very close to nominal, the error introduced in the MOI measurement will be small. This is because the MOI error is proportional to the ratio of the CG offset and radius of gyration squared. Typically, the radius of gyration for airfoils and similar shapes is large compared to the CG offset. If this ratio is smaller than 1/100 the MOI error due to CG offset will be negligible.

For example, let us assume the CG offset is 0.060 inches and the radius of gyration (K) is on the order of 6 inches, a ratio of 1/100. The ratio of CG offset to K squared is;

$$(0.06)^2/(6)^2 = 0.0036/36 = 0.0001 \text{ or } 0.01\%$$

This means that for most measurements of this type, the error due to CG offset for **any one** MOI measurement will be on the order of 0.01%. There is however an accumulation of error since three MOI measurements are used for each POI calculation. The design constraints on the fixture are also less severe if CG measurements are made for each MOI measurement.

2.9.7 Hardware The hardware required for these tests is:

- Mass Properties measuring system including instrument, computer, monitor, keyboard, & interfaces. An accurate weight platform is also required. This method requires a mass properties instrument which can measure both MOI and CG. We used the Space Electronics Model KSR-330. This instrument is capable of measuring CG with an accuracy of 0.001 inch and measures moment of inertia with an accuracy of approximately 0.1 %. The instrument will report the MOI about the center of rotation of the test table and also about about the CG of the test object.
- Fixture system, including test part/fixture interface and fixtures to locate object in 6 positions
- Helium chamber system including helium supply, piping, flow control, and helium/oxygen monitor if it is necessary to eliminate the effects of entrained and entrapped air..

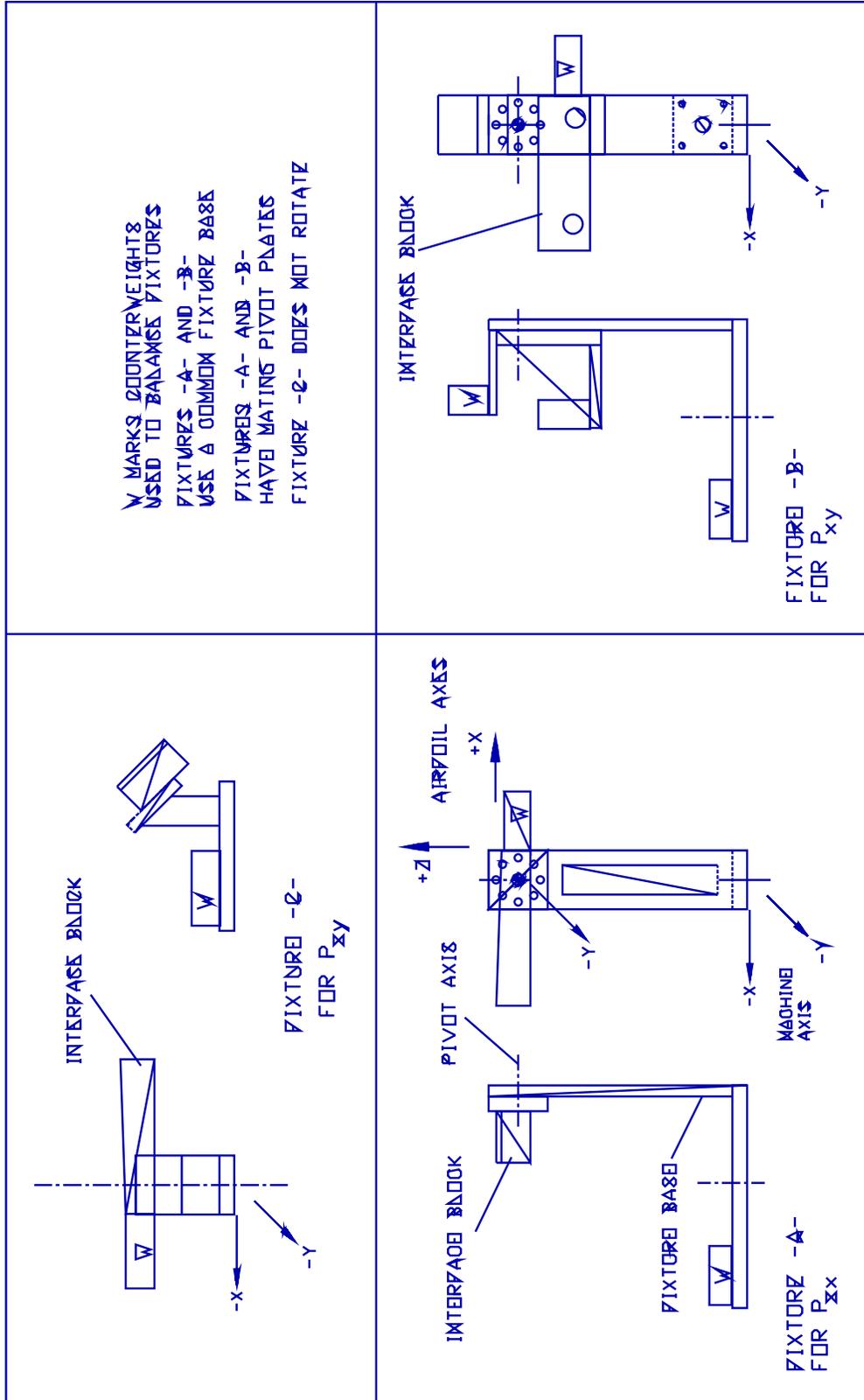


Figure 33

2.9.8 Fixture System

With six required measurements, six different fixtures could be used. It has been our experience that three fixtures are adequate. One fixture is designed to support the test part on a pivot along one axis (i.e. Y) so that three measurements can be made with another axis (i.e X) located at zero, 45, and 90 degrees from the vertical, resulting in three data points in the vertical Z-X plane. The second fixture supports the part on a pivot along the part Z axis and allows the part X axis to be at zero and 45 degrees to the vertical adding two data points in the X-Y plane. Finally, a third fixture locates the part X axis horizontal and the Y axis at 45 degrees to the horizontal so MOI can be measured about an axis midway between the Z and Y axes giving the third data point in the Y-Z plane. Figures 5 & 5A show the 3 fixtures and the associated test positions used. The fixture system (see fig. 33) for the given test part configuration consisted of:

- one test part/fixture interface block
- one fixture base with pivot
- two pivoting locating fixtures
- one non pivoting fixture

Each of these elements is critical to the overall ease of operation and accuracy of the fixture system. Any non-repeatabilities or dimensional uncertainties in the critical dimensions will directly add to the CG location uncertainty and indirectly to the MOI uncertainty.

It is the function of the test part/fixture interface block to mate with the test part and to establish three reference axes which are parallel to the test part datum axes. It must also mount to the fixture in such a way to orient the axes planes parallel to the machine reference axes at known offset distances.

The fixture base (with pivot) provides a sturdy support for the test part which mounts to the measuring instrument in a highly repeatable manner. If the test part geometry permits, this base may be used to support more than one of the locating fixtures. In the case under discussion it supported 2 locating fixtures.

The locating fixture elements serve the purpose of orienting the datum planes of the interface block correctly and mounting the test part on the base pivot. The locating fixture rotates with the part and interface block to each test position.

The non-rotating fixture serves the same purpose as the other locating fixture elements but does not rotate. It, therefore, orients the test part for only one MOI measurement.

The fixtures were designed to place the nominal CG location of the airfoil directly over the center of oscillation. In addition, the fixtures were balanced so the CG of the bare fixture was also close to the center of oscillation. It was expected that the actual location of the CG would vary considerably from the nominal location so only the MOI about true CG was used for POI calculations.

2.9.9 Fixture Design Fixture design for the MOI method of POI determination is typically constrained by six major considerations:

1. The fixture should interface with the test part so the test part coordinate axes and the machine coordinate axes are parallel.
2. The origin (datum) of the test part coordinate system must be positioned at a well defined, known location relative to the machine origin (center of machine rotation).
3. The fixture(s) must permit rotation or orientation of the test part to the six test positions in such a way to locate the nominal test part CG on the machine origin (center of machine rotation). That is, the test part must rotate about its nominal CG.
4. The fixture must provide adequate clearance for the test part above the test instrument as it rotates to each test position.
5. The fixture must have minimum weight and MOI consistent with adequate structural rigidity so that the difference in loading between tare and part measurement does not permit deflections which cause measurable errors in MOI or CG location.
6. The fixtures should be reasonably well balanced about the machine center in all test positions.

Airfoils, typically, do not have simple geometric shapes such as rectangles and cylinders. The coordinate axes of airfoils are well defined geometrically in terms of the air frame and theoretical aerodynamic contours. Unfortunately, loose manufacturing tolerances and complex geometry often make it very difficult to identify the datum accurately in terms of hardware details.

The mounting adapter is a piece of flight hardware which is fastened to the airfoil and is used to mount the airfoil to the airframe. It is considered an integral part of the airfoil for all tests.

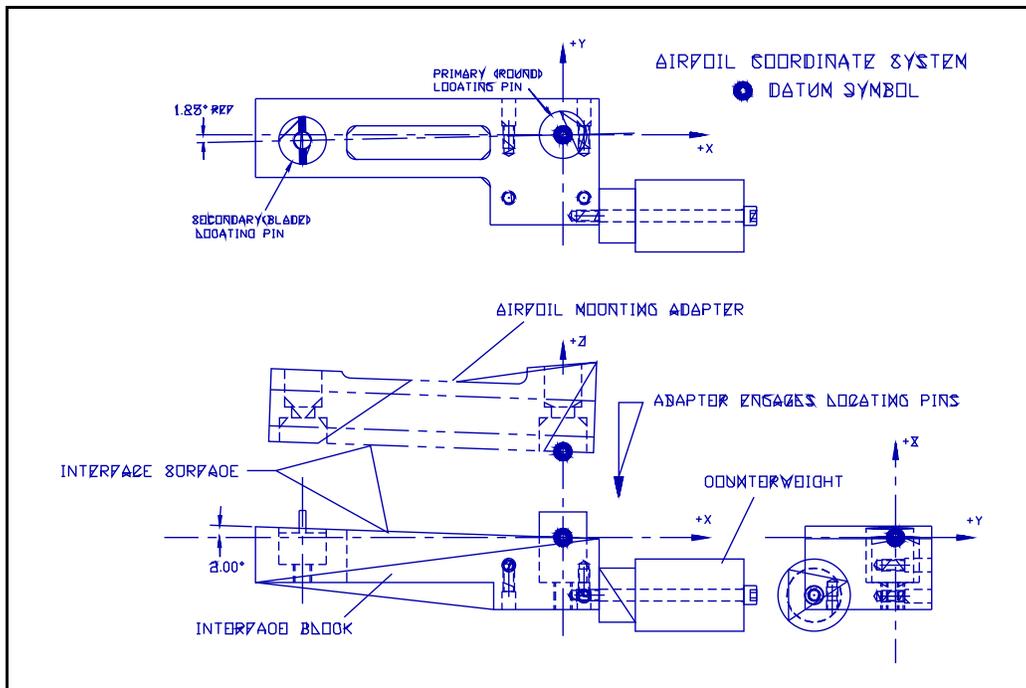


Figure 34 - Interface Between Airfoil and Fixtures

Interface Block An interface block (fig. 34) was devised to provide a rectangle with faces parallel to the airfoil coordinate system. It was relieved as much as possible to reduce weight without sacrificing structural rigidity. A counterweight was attached to the interface block so the fixture with the interface block was statically balanced about the fixture pivot axis.

This interface block has a round pin and a blade pin to locate the airfoil mounting adapter in a highly repeatable manner. This two element method of locating parts on a fixture is very effective when two holes with parallel centerlines are available. One hole is designated the primary location reference and mates with a round pin. The second hole aligns the part. Since there is always a dimensional tolerance in the hole to hole distance, the second pin cannot be round if there is to be a close fit between the hole and the pin. Instead, a diamond or blade shaped pin is used. The blade is placed perpendicular to a line between the hole centers. This configuration permits some variation in the hole to hole distance without any appreciable angular variation. Hardened, diamond shaped pins (relieved bullet nosed pins) are available commercially in fractional sizes for this purpose to mate with hardened bushings. For the odd sizes encountered on this test part, the blade configuration was used.

Datum Location The coordinate system datum for this test part is at the intersection of the centerline of the primary mounting hole in the airfoil mounting adapter and the base of the airfoil mounting adapter. Mounting the airfoil on the interface block locates the coordinate system origin at known X, Y, and Z distances with reference to the machine coordinate system and nominal airfoil CG location.

The actual location of the test part datum was determined by making a tare measurement with the bare interface block and a special mounting screw. The CG Locator Weight, (fig. 35) was then mounted in the Interface block for part measurement. The CG of the Locator Weight is on the centerline of the weight (reference system Z axis) at a known location ($Z=+1.386''$) relative to the center of the cross pin. The cross pin line of contact on the interface block is at $Z=0.000$. The cross pin positions the locator weight accurately along the Z axis.

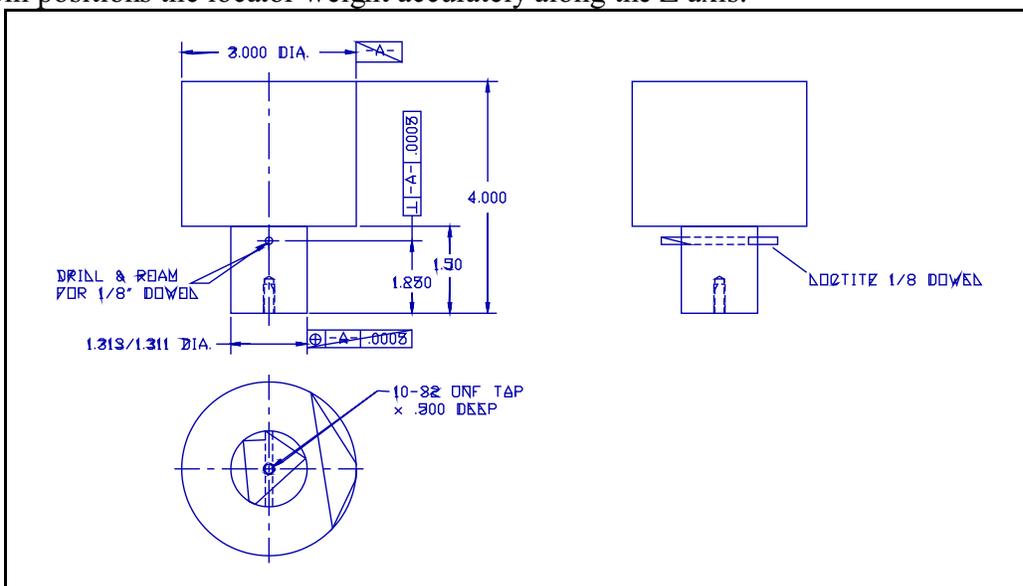


Figure 35 - CG Locator Weight

3.0 Conclusions

To predict (and eliminate) flutter, it is necessary to have accurate center of gravity, moment of inertia, and product of inertia values for each control surface on an aircraft. Measurement error must be very small (whereas the mass properties of other components on an aircraft are not that critical). Failure to accurately measure control surface mass properties can result in the death of the pilot and loss of the aircraft. These mass properties can be predicted from analysis, but it is essential to also measure them to verify the range of variation as well as the true nominal values. This is particularly important with the new designs that make extensive use of composites, which are notoriously variable in density and mass distribution.

Measuring control surface mass properties is a tricky task. These surfaces are often large and very flexible. Small misalignment angles can have a major effect on measurement accuracy. In this paper we have described specific fixture designs which we have found to be successful. These fixtures can be purchased from Space Electronics; however, enough detail was provided in this paper so the user can design and fabricate his own fixtures based on our design concepts. The method we have described to measure POI is complex, but it is the only practical method that we know of, and has yielded good results for the many hundreds of measurements of this type which we have made over the last 20 years. We have included specific step-by-step measurement procedures in this paper, so that other engineers can be aware of the details of this process. The procedure for measuring POI is particularly challenging. It is essential that all of the precautions described in this paper are followed in order to achieve accurate measurements.

Experiencing flutter can be a terrifying experience for a pilot. The key element in eliminating flutter is accurate mass properties measurement and ballasting of control surfaces. Our intent has been to provide sufficient information so any mass properties engineer can achieve the necessary measurement accuracy.

References

The calculation of CG location to compensate for the inertia effect is discussed in the SAWE paper Number 2462 entitled “Effect of Control Surface Balance on Flutter” by Mary Scheulen.

More detail on the measurement of CG and MOI can be found in SAWE paper Number 2444 entitled Mass Properties Measurement Handbook by Richard Boynton and Kurt Wiener.

Using a helium atmosphere to reduce the mass properties measurement errors due to windage of a control surface is discussed in detail in SAWE paper number 2024 entitled “Using Helium to Predict the Mass Properties of an Object in the Vacuum of Space” by Richard Boynton, Robert Bell, and Kurt Wiener. (The title of this paper is a little misleading....although helium is useful for simulating a space environment, it also is the best way to minimize measurement errors of control surfaces).

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ABOUT THE AUTHORS

Richard Boynton is President of Space Electronics, Inc., Berlin, Connecticut, a company he founded in 1959. Space Electronics, Inc. manufactures instruments to measure moment of inertia, center of gravity, and product of inertia. Mr. Boynton 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 M.I.T. He is the author or co-author of over 70 papers, including 32 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).

Kurt Wiener is Chief Engineer of Space Electronics, Inc. Mr. Wiener holds a B.S. in Mechanical Engineering from M.I.T. and a M.S. in Industrial Education from Central CT State College. He is a former Associate Professor of Mechanical Technology at Vermont Technical College. Mr. Wiener is the principal instructor for the Mass Properties Seminars which are presented twice a year at Space Electronics. He has co-authored 14 papers for SAWE conferences. He won the L. R. “Mike” Hackney Award for Best Technical Paper at the International Conference of the SAWE in 1998.