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Accurate Estimation of Center of Gravity of Spacecraft Electronic Packages - Enhancing their Durability

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Abstract

The Center of Gravity (CoG), of spacecraft electronic packages, is an eminent parameter which contributes in determining the overall spacecraft mass properties. The CoG plays an important role on the dynamic response and fatigue life of the structural components. In conventional approach for determining the fatigue durability, the gravity loads of the structure is assumed to act on its CoG, as it contributes significantly on the stress levels. The CoG of the spacecraft varies due to the deployment of the appendages, rotating payloads and consumption of the propellant in orbit manoeuvring, during its entire service life. A variation in the calculation of CoG will affect the entire spacecraft propulsion system and jeopardise the mission. The spacecraft configuration is designed such that all the propulsion forces / loads act about its CoG.

This paper describes in brief, the different methods of estimating the CoG, and its importance in assessing the probable fatigue life of the electronic packages. The coordinates of CoG for a component, can be determined from the reaction forces measured through load cells, which are suitably placed on a platform. The moment balance principle can be applied in determining the coordinates of CoG in a horizontal plane along two axes. The measurement of the CoG along the third axis, poses a challenge when the object is quite delicate and its features are quite complex. A suitable tilting mechanism can be used to obtain a specified inclination of the platform, which will facilitate in measuring the CoG along the third axis using the mathematical relations. This set-up will help in measuring the CoG of an electronic package / payload along all the three axes, without repositioning, thus saving time and aiding in enhancing the durability of the spacecraft electronic packages.

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Introduction

The Center of Gravity (CoG) of any object is the point at which the object would balance, if it were possible to suspend it at that point. It is the theoretical point at which the entire weight of the object is assumed to be concentrated. The motion of any object in space can completely be described in terms of the translation of the CoG, from one place to another and the rotation of the object about its CoG if it is free to rotate.

Why CoG is important for spacecraft?

During the launch and its service life, the spacecraft undergoes deformation of its structures, due to complex loading conditions which vary with the time. Due to the variation in the calculation of CoG, the gravity load and other external loads acting on the spacecraft can cause change in its shape. This may result in unexpected loads coming on to the electronic packages and may introduce additional stress amplitude, which in turn will have significant influence on its fatigue life.

In the traditional approach, the fatigue of the electronic packages are due to the dynamic inertia loads combined with external loads coming on it, that varies with time. With small deformation in its shape the CoG of spacecraft changes dynamically with the time. This dynamic change of CoG will further add to the complexity of the stresses coming on the electronic packages. The need is to accurately estimate the CoG of the different spacecraft electronic packages, which in turn will be useful for accurate computation of the overall CoG of the spacecraft. This will reduce the severity of the stresses coming on to the electronic packages, by incorporating the efficient configuration of propulsion system, thereby increasing their durability and reliability [2].

This paper briefly describes a method to accurately determine the CoG of an electronic package / payload along all its three axes. This also provides an opportunity to analyze the uncertainties coming in the calculation of the mass properties of electronic packages / payloads, in real scenario.

Different methods to determine the CoG

There are several methods to find CoG of an object as described here under:-

Null point method

The null point method requires a platform that has two parallel knife edges several inches apart from each other. In this method the object is placed on the platform such that the CoG is in between the two knife edges. The platform is then tilted in either direction until the object balances on one knife edge. This indicates when the object CoG has rotated outside the stable zone between the knife edges. Thereafter the CoG along the third axis (along height) can be calculated from the two tilt angles. This method requires a special test rig [1].

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Weight balance method

The weight balance method balances the object on a rotating platform. Then a known mass is added to the platform to provide a torque. The amount the platform rotates will allow the height of the object CoG to be derived. Like the null point method this also requires a special test rig[1].

Pendulum method

This method swings the object at the end of a pendulum. Then the length of the pendulum arms is changed. Once again the object is swung on the pendulum. The change in the period of the oscillation will allow the CoG of the object to be computed.

Active Moment Transducer Method

In this method the three basic moment measuring principle is used to measure the CoG of an object. The transducers (moment cell / torsional rods) are used to obtain readings when a load is applied. The accuracy of an axis depends on the mechanical characteristics of the spring.

High speed closed loop moment sensing transducer is used to measure the CoG of an object. The manual rebalance transducer is used to measure the CoG of an object which may be having less accuracy in the measurement[6]. The tall test objects to be measured will give inaccurate measurement because soft transducer system becomes unstable and requires vertical counterbalance.

Spherical gas bearing pivot

In this method the spherical gas bearing is used to support the object to be tested. The fixture (used to support the object), constrains the test object in order to prevent the turning of the object, passes through the center of the sphere. The test fixture is necessary in this instrument in order to get the useful mass properties instrument. A restraining fixture is used which keeps the test surface to be horizontal while measuring the CoG. The restraining fixture used here is a hollow tube which extends from the base of the spherical bearing. One end of the tube is attached to the cylindrical gas bearing (two gas bearings are used).

The cylindrical gas bearings, connected to the Moment transducers, are used to measure the deflection of the first gas bearing that is attached to the rigid base structure. This mechanism is made in such a way that the deflection of the second gas bearing is extremely small. The CoG of a test object is determined by measuring the overturning moment of the two bearings[6].

CoG measurement by using Central Flexure Pivot

In this method the CoG of an object is calculated by a basic instrument that consists of a weighing platform, on which the flexure point is located at the platform center. This contains a parallelogram structure to maintain levelling of the weighing platform. Moment transducers are used to support the platform.

The object is placed on the weighing platform (which is supported by a flexure point at the centre) and the two moment transducers are placed in such a manner that it supports the horizontal axes of the component. The weight of the object is measured by the flexure pivot. A force is applied by one of the moment transducers on the platform and by the data of the other transducer the total weight of the object is found. The location of the CoG along two axes of the object is determined by the output of the two moment transducers using algebraic equations[5]. The height of CoG is measured by tilting the object through a known angle, using following relation:

$$\text{CG height} = 1.732X_{\text{horizontal}} - 2X_{\text{tilted}} + \text{distance from the reference to tilt axis} \quad (1)$$

[5]

This method is more suitable for object having simple shapes like round, rectangular and square etc, wherein the nominal CoG may be known[5].

Estimation of a CoG of an object by using multiple robots

In this method the object is placed on multiple robots. Each robot has arms with load sensing devices to measure the weight as well as CoG of an object. The arms move along the Z axis by an arrangement of a ball screw.

The robots are placed around the object such that the position of the CoG of the object lies within the geometrical center of the robots, and to get maximum probability of success in lifting it. The weight of the object is measured and the readings are used to calculate its CoG along the two axes (i.e. X and Y) using the following relation[7]:

$$\begin{pmatrix} X \\ Y \\ t \\ 1 \end{pmatrix} = T^{-1} \begin{pmatrix} X^1 \\ Y^1 \\ u \\ 1 \end{pmatrix} \quad (2)$$

To measure the height of the CoG the robots tilt the test object and measure the load by finding the values of ‘t’ and ‘u’. This method is applicable to limited shape and size of an object and the robots lift the object at all its possible corners [7].

Another approach to calculate the Center of Gravity

Locating the CoG of an aircraft is a challenging task, which ensures its safe flight. Loads carried by the aircraft may vary significantly from flight to flight in terms of load distribution. The CoG of an aircraft must be maintained within the specified range for a given load.

In this method, the system determines the vertical load on known points (i.e. the load cell is kept below the front or rear end of the landing gear) and then equilibrium position is maintained to determine the aircraft CoG. To determine the load / weight of the aircraft the Nose wheel is positioned on a load cell which is mounted on the flat surface. By taking the load from each load cell and performing moment calculation the CoG along longitudinal and lateral axes is determined, using the following relation,

$$L_m = \frac{L}{(1+\frac{P_m}{P_n})} \quad (3)$$

To determine the CoG along the vertical axis, the aircraft is inclined to a desired angle, using a mechanism to lift the aircraft (such as lever, jack etc.). Thereafter, the load on the nose wheel, inclination angle can be related and the CoG location along the vertical axis can be calculated by following relationship[9],

$$L'_m = \frac{P_n L}{(WT)\cos^2\theta} + L_m \tan\theta \quad (4)$$

Experimental

The Approach Proposed for measuring CoG along all 3-axes

Background

Other practices involve similar approach except that they look for balance points and then use fixtures or rigs to clamp the object on the platform. These procedures are slow, expensive and involve relative displacement between their fixtures and the test object which will add difficulty in calculating the CoG, especially when the object is irregularly shaped and their handling is complex and critical. There exists number of special equipments for determination of CoG for particular objects, such as spacecraft, missiles, aircraft loads and others which have known shapes (around which the locating apparatus can be designed). However, such specialized equipments could not be used effectively for smaller electronic packages / payloads having complex shapes, and are quite delicate in handling.

In the light of the above, a new method has been devised, which can provide an easy way to compute the CoG of the electronic packages / payloads in less time, and without making relative displacement in between the test object and the platform. The effort is to eliminate fixtures and clamping devices which are used to constraint the object on the platform because they create reaction forces between the object and locating devices.

The new method proposed in this paper, propounds the use of a swivelling platform on which the test object can be placed. The platform is supported on three load cells as shown in Figure-1. These load cells are placed on a Base Platform. The support points are spaced in an isosceles triangular pattern.

The platform is tilted about an axis which passes through the one of the load cell. Firstly, all the 3 load cells are in a horizontal plane which gives the total weight of the test object. The moment balance principle is used to calculate the CoG of the test object in horizontal plane. The platform is tilted to a small specified angle (< 15°) keeping the load cell L_1 at original position and then raising the load cells L_2 & L_3 vertically so as to freely support the inclined platform. This set-up enables to measure the CoG along the third axis of the test object as described in the following equations.

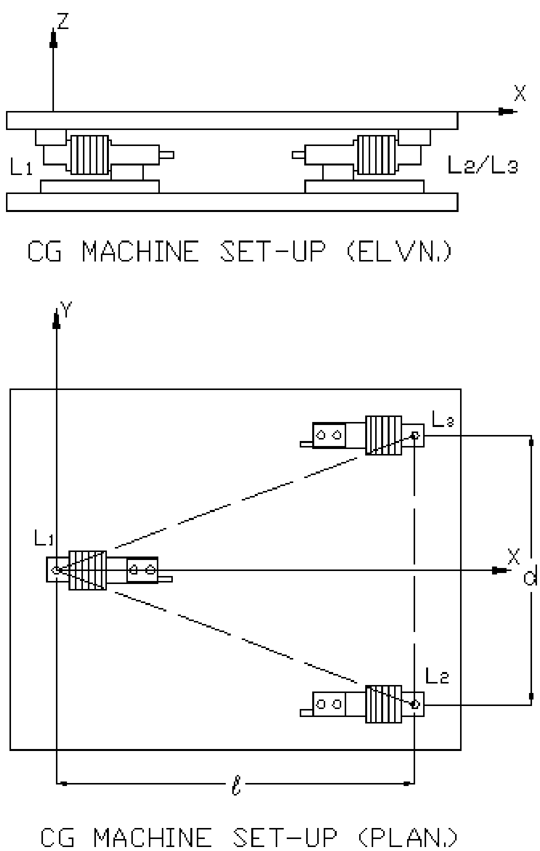

Figure 1: Schematic diagram of the CoG machine set-up

The line diagram of the apparatus setup is illustrated in Figure 2. The location of the CoG, in the horizontal plane, is at a distance of X and Y from L_1.

Results and Discussion

Calculation of Coordinates of CoG in Horizontal Plane (X and Y)

The typical set-up of the machine consists of a Base Platform, on which 3 load cells will be mounted (Figure 1). These load cells will be supporting a Top platform on which the test object (electronic package/small payloads) will be mounted. The multi-point weighing method simultaneously measures both weight and CoG of the package. This method does not incorporate a rotary table, so it can be difficult to determine the location of the object relative to the instrument measurement axes. The CoG of the package placed on the upper platform is calculated by the difference in force measurements that are read by the load cell at these three interface points.

To determine the coordinate 'X' and 'Y' of the CoG, the test object is kept on a horizontal platform which in turn rests on three individual load cells. The weight of the object is first determined, which is nothing but the sum of the weight obtained from individual load cell. Then, the coordinates 'X' and 'Y' of the CoG are determined from moment calculations, involving effective normal forces acting on each load cell. The method is illustrated below,

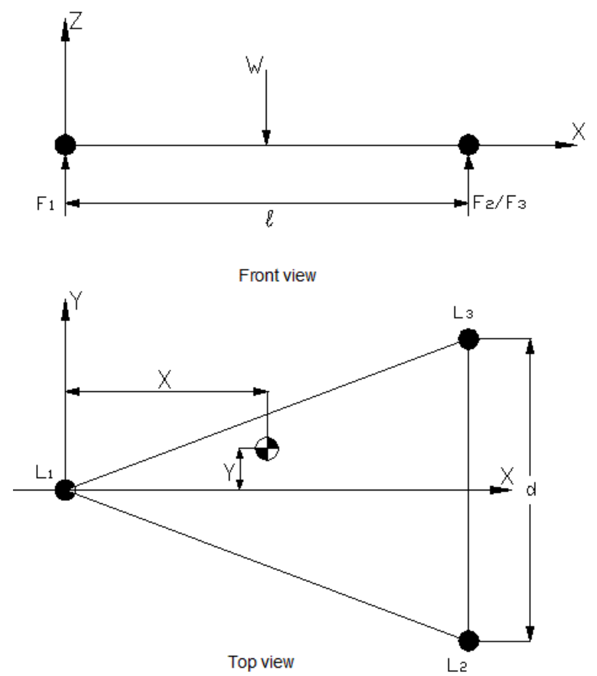

Figure 2: Line diagram for the CoG measurement machine

Where,
L_1, L_2, L_3 = Points represents the position of the load cells
F_1, F_2, F_3 = Reaction forces acting on load cells L_1, L_2 and L_3 respectively,
l = Distance parallel to X axis between L_1 and L_2, L_3
d = Distance parallel to Y axis between L_2 and L_3
X and Y are the coordinates of the center of gravity.

Total weight of the object is given by,

$$W = F_1 + F_2 + F_3 \tag{5}$$

Coordinates of CoG (X, Y) in horizontal plane is,

$$\left.\begin{aligned} X &= \frac{(F2 + F3) * l}{W} \\ Y &= \frac{(F3 - F2) * d}{2W} \end{aligned}\right\} \tag{6}$$

Why three number of load cells should be used?

Three load cells spaced at the bottom of the platform in an isosceles triangle shape provide the most convenient support. Three-leg weighing systems balance like a tripod, with load distribution being virtually automatic, and they only require minor balancing at installation. Arrangements of three load cells under the top platform in an isosceles triangle provide the advantage of positive loading of all the 3 load cells.

A four-point weighing system adds structural strength but requires more care in the installation process to balance the loading on the four points. With this type of support system, it is necessary to equalize, or level the base, to spread the load evenly among the four cells. Also the use of four load cells introduces indeterminacy error which will be erroneous for the calculations. For scales incorporating four load cells, which require accuracy equal to or greater than 0.1%, the base plate support surfaces must be surface finished at high degree. If one cell is mounted on a lightweight structure, that has a high deflection, it can sag and throw the load onto the two adjoining cells, possibly overloading them.

Calculation of CoG coordinates along third axis.

The measurement of the CoG along the third axis, in an object poses a challenge when they are very delicate and its features are quite complex, and requires critical handling procedures especially in the case of the electronic packages/payloads. A suitable tilting mechanism will be used to lift the top platform above the load cell and then rotate it about an axis along the line joining the other two load cells (L_2 & L_3), to a specified angle ‘θ’ **(**Figure-3**).** Thereafter the load cell (L_2, L_3) will be lifted to the designated height which correlates with the specified angle of rotation of the top platform. The interface of the load cell with the top platform will have point contact by employing ball-cup arrangement **(**Figure-6**),** which will ensure the transfer of the load on the load cells in vertical direction, even after the tilt of the top platform.

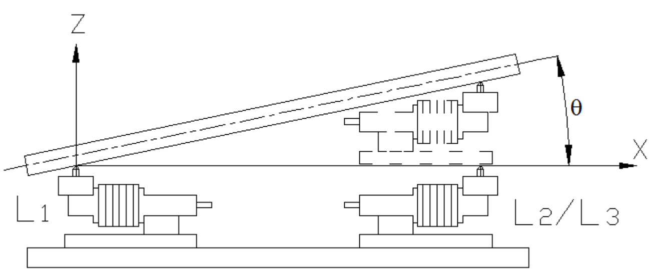

Figure 3: Top platform of the CoG machine rotated by ‘θ’

This mechanism will facilitate the measurement of the CoG along the third axis (vertical axis) using the mathematical relations, in continuation with the other two axes in horizontal plane. This set-up will help in measuring the CoG along all the three axes without any movement and repositioning the test object, thus saving time and without any relative motion along the test object and the platform. The height of the CoG can be measured by lifting the test platform through a known angle ‘θ’.

The method is illustrated (Figure-4**)** via the schematic diagram for arriving at the mathematical relations in computing CoG along the third axis.

The notations used are as follows:-

X' = Distance of the CoG (after tilting the top platform) from L_1 load cell along X-axis,
Z = Height of the CoG, when top platform is horizontal,
Z' = Height of the CoG after the top platform is tilted,
R = CoG distance from L_1.
α = angle between the position of CoG and the horizontal X-axis before tilting,
θ = Tilt angle (angle between the original location of CoG and the location of CoG when the top platform is tilted),

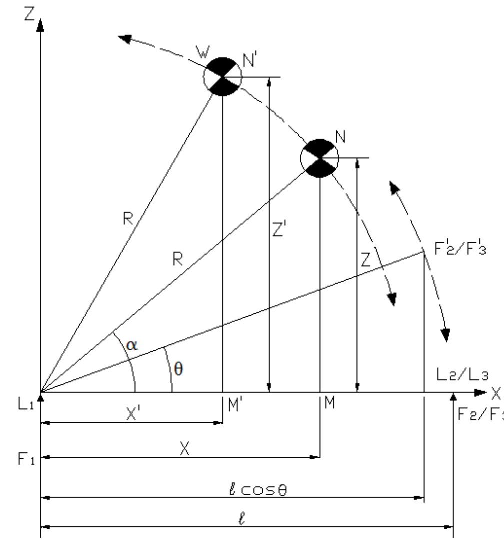

Figure 4: Schematic diagram for arriving at the mathematical relations in computing CoG along the third axis.

The angle ‘θ’ is also equal to the tilt angle of the top platform with respect to X-axis.

F'_2 and F'_3 = Component of reaction forces along Z axis at after lifting (These values are obtained from load cell measurement after lifting).

Coordinate of CoG after tilting are given here under,

$$X' = \frac{l \cos\theta \, (F'2 + F'3)}{W} \qquad (7)$$

The height of the CoG can be calculated by following relation,

$$\left.\begin{aligned} \alpha &= \tan^{-1}\left[\cot\theta - \left(\frac{X'}{X \sin\theta}\right)\right] \\ Z &= R \sin(\alpha) \end{aligned}\right\} \qquad (8)$$

Assembly drawing of CoG measurement Equipment

3D Model of CoG measurement equipment

Base platform: The base platform acts as a rigid platform to place the load cells. This base platform is levelled, so that no errors should occur in case of the readings of the load cells. By levelling this base platform, the lean error which is obtained during the measurement of the third axis will be minimized.

Top platform: The top platform is used to place the electronic package / payload with the help of the reference points on it, for the measurement of its CoG and weight. Isogrid structure is provided under the platform for the homogeneity and to maintain the isotropic property of the material. Interface holes are provided at the bottom of the platform, so that the load cells can be interfaced to the platform easily.

Load cell: The CoG of the electronic packages / payload should be always computed with better accuracy so that the overall CoG of the spacecraft can be more precise. So the load cell which has to be chosen should have quite precise specifications. The type of load cell chosen should be capable of reading very small errors in linearity, hysteresis and repeatability. The different types of load cells are studied, their parameters are understood and a comparison is made between them so as to have a specific type of Load Cell for this machine.

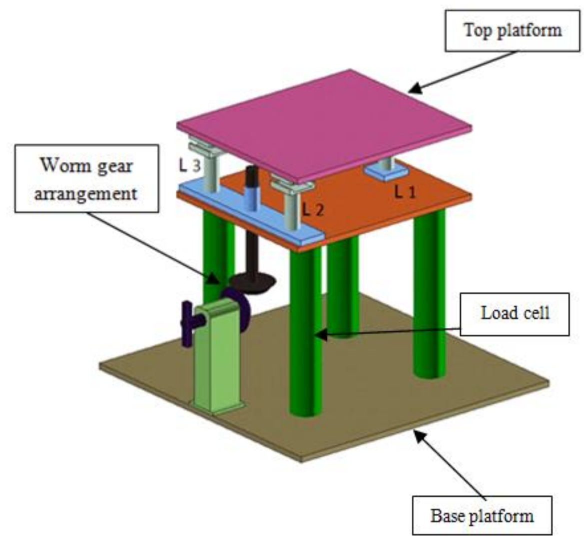

Figure 5: 3D model of CoG measurement machine

Worm gear arrangement: Worm gears are used to lift the top platform along with the test object. These are designed with high precision and incorporated with the base platform.

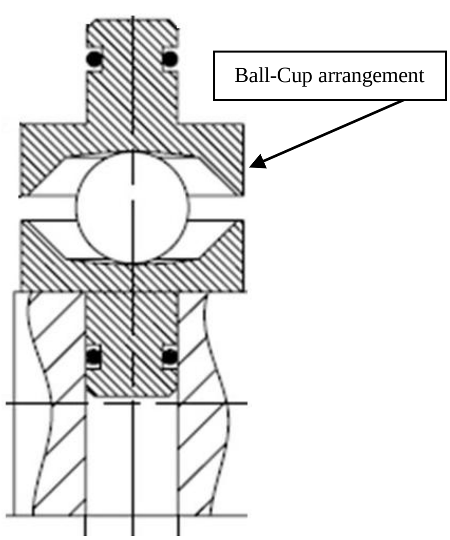

Figure 6: Showing the ball and cup arrangement

Conclusions

The accurate estimation of the CoG of the electronic packages / payloads will provide valuable input in the design and configuration of the spacecraft. This in turn will reduce the load path for the external loads acting on the different subsystems / payloads of the spacecraft. This will result in the accurate estimation of the dynamic stresses coming on the spacecraft. With the accurate estimation of the stresses, the design parameters can be controlled to realise the electronic package / payloads with better durability and reliability. This machine will also provide an ease of estimating the CoG along all the 3 axes in one set-up, and thus good amount of time is saved. Further, the position of the CoG along all the 3-axes can be determined without repositioning the test object. The accuracy of the CoG can be optimised by decreasing the tilt angle.

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