MEASUREMENT OF THE CENTER-OF-GRAVITY USING X-RAY COMPUTED TOMOGRAPHY

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INTRODUCTION

The quantitative capability of CT to measure the relative X-ray linear attenuation coefficient and position of small volume elements in a component also offers the potential to perform center-of-gravity (CG) measurements for rotating systems. Currently, the practice of engine vibration reduction is one of disassembly, iteratively checking balance and grinding off mass until the amount of imbalance is acceptable. This process is labor intensive. An alternative nondestructive method to measure the CG prior to disassembly could provide a cost effective method to minimize the labor effort in balancing operations.

In order to address the potential of CT to be used in the balancing of a complex system, such as a jet engine assembly, it is necessary to determine the capabilities of CT to accurately locate the CG of a part from CT data. In an initial experiment, the ability to measure the CG of a test phantom to better than 0.8 g-cm indicates that accuracies suitable to small jet engine testing can be achieved under controlled conditions.

The initial experiment used a test phantom consisting of a disk with a raised lip and center bushings of aluminum, in configurations where the CG could be calculated. The disk was 30 cm (12 inches) in diameter to correspond to the size of typical small engine components. Fig. 1 shows CG disk test phantom. The aluminum bushing mounts in a groove in the disk. Three bushings were fabricated. One was complete, one had 0.5 g of material removed and a third had 0.1 g of material removed. The removal of material at the bushing radius of 3 cm represents the typical position of grinding for the balancing of small jet engine parts. The raised lip and center bushing can be imaged as two concentric rings when a CT slice is taken just above the plane of the disk portion of the phantom.

DISCUSSION

Vibration must be kept to a minimum in jet engine assemblies, requiring extensive testing of subcomponents and the full assembly, with disassembly and

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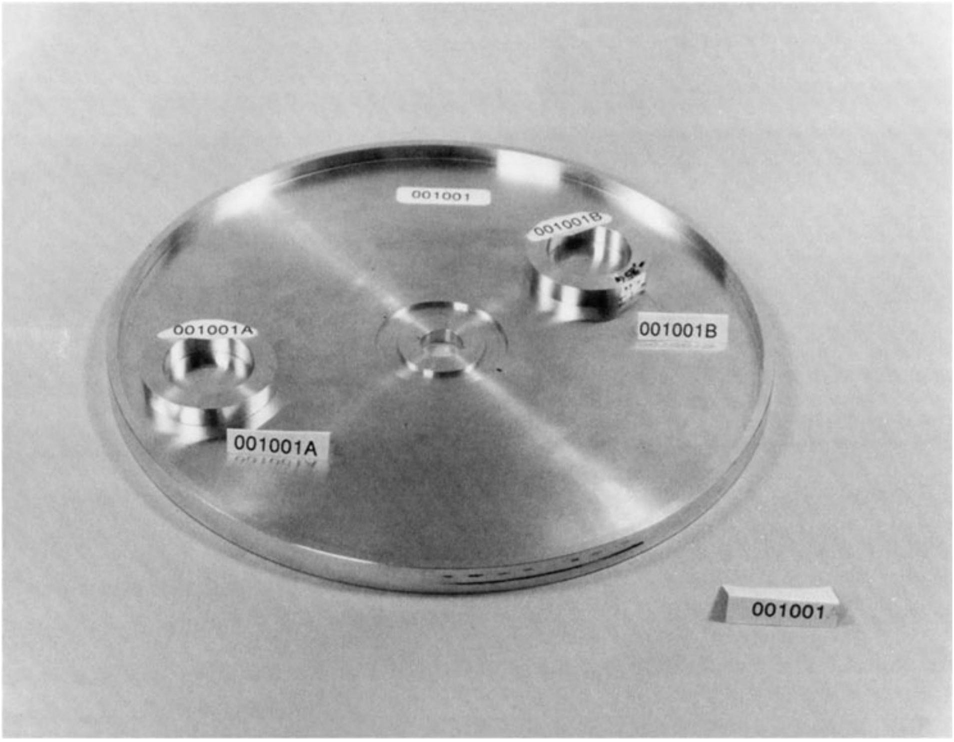

Fig. 1. CG disk test phantom, (PID #001001) with two of the three aluminum bushings (PID# 001001A and 001001B) laying on the disk.

rebalancing activities being iteratively performed until the system is in proper tolerance. For example, the Air Force repeats the cycle of dynamic balancing and grinding until the measurement is accurate to about 0.28 g at 3 cm (0.9 g-cm). CT cross section data on an engine contains measurements of the material and position such that the prediction of the CG of a component is possible. The accuracy of the prediction, based on CT data, will depend on a number of parameters such as the CT system resolution, contrast sensitivity, mechanical accuracy, and influence of adjacent features on the measurement of the feature of interest.

The CG for a 2 dimensional object can be broken out into x and y CG positions and represented mathematically as

$$X_{CG} = \sum\sum \rho_{ij} * x_i / \sum\sum \rho_{ij} \quad (1)$$

$$Y_{CG} = \sum\sum \rho_{ij} * y_j / \sum\sum \rho_{ij} \quad (2)$$

where ρ_{ij} is the density value at the ij position, x_i is the x dimension distance to the ith position and y_j is the y dimension distance to the jth position. In order to test the ability of CT slices to provide measures of the CG, the test phantom of Fig. 1 has been imaged at a height to form two concentric rings in the image, one of which may be a bushing that has missing (removed) material. The CT data from the phantom is appropriately processed to measure the CG.

Two computer codes (Centroid and Rradii) and a spreadsheet model have been developed to calculate the CG. Rradii searches from the edge of the data set until it finds a threshold density value then performs a bilinear interpolation on the previous pixels data to find the edge more precisely. It performs this process for 24 different angular orientations and then iteratively calculates the center of each radius from the detected edges. This calculation gives the physical center of the part in the data sets coordinate system.

The Centroid computer code uses the CT slice data to calculate the CG relative to the geometric center of the part obtained from Rradii. Centroid uses a threshold edge detection algorithm, where the threshold used was 50% of the material density of the test piece. Once the edge is detected then an algorithm is used to determine where the material is located in pixels that are only partially material and partially air. Once all of this is determined, the CG can be calculated using the option of uniform density (center of area) or a calculation using actual CT data density values. For a material of high density variation, the latter process may be more accurate. For typical engine materials, the area calculation is likely to be more accurate because it minimizes the distorting effects of CT image artifacts such as edge spreading and beam hardening.

The spreadsheet model allows the rapid calculation of the CG of multiple objects given their individual CG's. In the case of the test phantom which contains two rings this makes it possible to calculate the CG of the total phantom by using the information from Rradii for the centers of each ring, the physically measured dimensions and knowledges of the material densities.

RESULTS

CT scanning of the Fig. 1 test phantom was performed so that the CT slice imaged the outer ring and inner bushing. The CT slices were taken of the test phantom in five different configurations as designated in Table 1. The three inner bushings had 0, 0.5 and 1.0 g of material removed as a flat on the edge of the bushings. The scanning of the phantom was performed with flat oriented in the 0° or 180° position, so that a shift of the CG would occur between two such scans of each bushing with material removed.

Table 1. Phantom scanning conditions.

Condition	Flat Type	Flat Weight	Orientation
1	None	0.0 g	0°
2	Small	-0.5 g	0°
3	Small	-0.5 g	180°
4	Large	-1.0 g	0°
5	Large	-1.0 g	180°

The CG is calculated from the CT slice data using the Centroid code. A sensitivity study for threshold value found that as long as the same threshold value is used, for all scans of the same material, the CG and area are relatively unaffected by the value selected. The value selected was 50% of actual material density. The Centroid code allowed the use of either the appropriate (average) density for the material or the actual CT density data for the value of ρ_{ij} in equations (1) and (2) for all pixels inside the thresholded regions.

Fig. 2 and Fig. 3 show plots of the difference between the geometric center (R_x) and the CG (C_x) as a function of mass shift. Because the inner bushing has been rotated 180° between scans, the measurements show the effect of x axis CG. The change in CG from the 0° to the 180° rotation on the y axis is zero. Fig. 2 is for the case of 180° scanning on the CT system and Fig. 3 is for 360° scanning. In each image the plots are for ρ_{ij} values using average density value actual CT density values. The 360° scans show good agreement of the average and actual values whereas the 180° scans indicate a possible density variation across the image. The figures indicate the sensitivity of CT to changes in the CG of a system. Note also that the CG at 0 g mass shift is not at the center of geometry of the test phantom. This deviation, exaggerated in the 180° scans, occurs because the test phantom was not machined as having perfectly concentric rings.

Fig. 4 shows a plot of the CT CG measurement versus the mass shift. Fig. 4 contains plots for the theoretical shift that would be expected and for the 180° and 360° scanning using both uniform density and actual CT data values. These curves show that the CT measurements fall within about 0.03 mm (1.0×10^{-4} of the dimensions of the scanned part) of the theoretical prediction. The rotation of the bushings between + and - mass shift was not precisely measured which may account in part for the deviation from the theoretical curve for the + to - mass shift. The 360° uniform density values (center of area approach) curve contains an anomalous value for the 1.0 g shift, attributed to experimental error. This was also seen in Fig. 3.

Figures 2 and 3 show that in order to obtain the equivalent same results between the center of area method and the actual CT data density value method it was necessary to use a 360° tomographic scan. Generally the 180° scan provided CGs for the actual CT data values that were consistently offset in the same direction from the center of area CGs. The 360° scans provided CGs for the actual CT data values that agreed with the analytical spreadsheet model (theoretical curve) and the center of area CGs within 0.03 mm as shown in Fig. 4.

The volume of the CT slice taken through the body of the part is proportional to the CT slice thickness. Testing of the CT system with a slice thickness phantom has shown that the beam is of approximately uniform thickness over the scan plane of this part. An effective slice thickness of 2 mm was used for the CT scanning. Thus the CT measurements on the 10 mm thick bushings (for which 0.5 and 1.0 g of material had been removed) were actually indicating a sensitivity to 2/10ths of the bushing material (or 0.1 and 0.2 g respectively) of the material removed. Thus the ability to measure to an approximately 0.25 g mass shift accuracy from Figure 2 and 3 at the 3 cm bushing radius (0.75 g-cm) is a conservative estimate of sensitivity.

The CT data analysis also shows that the CT image area variation from multiple scans of the phantom is approximately 3 parts in 60,000, which is negligible for the whole assembly. This area error is 3 parts in 225 (1.3 percent) of the area change due to the change of 0.5 g in the aluminum bushing.

Attempts to experimentally determine the center of mass by the two scale method would have given 0.1 gram (±0.1 gram) at 30 cm sensitivity, we were looking for 0.1 gram at 3 cm (0.01 gram at 30 cm) in our measurement for the -0.5 gram case partial object slice. An attempt to check the calculations by having the assembly dynamically balanced is the next logical step, but this will require the design and fabrication of a more complex phantom.

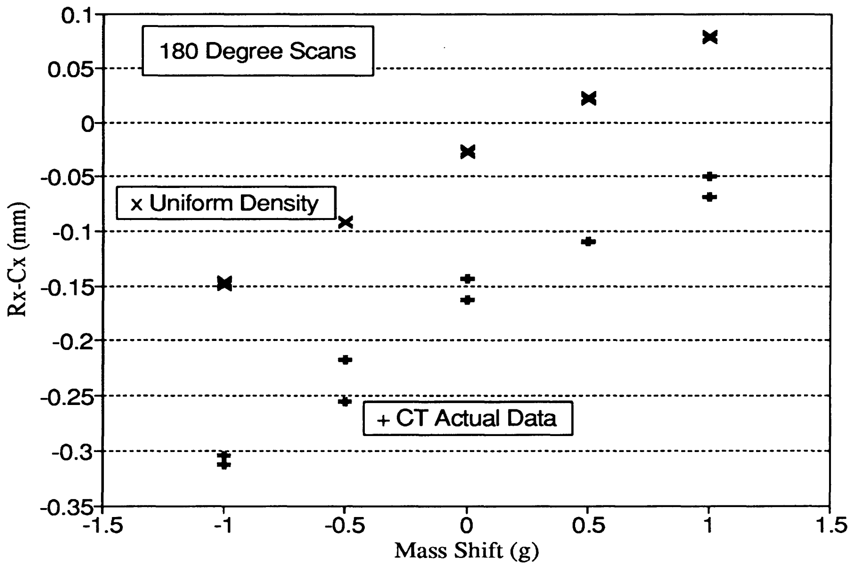

Fig. 2. Difference between center of geometry and CG for 180° scans.

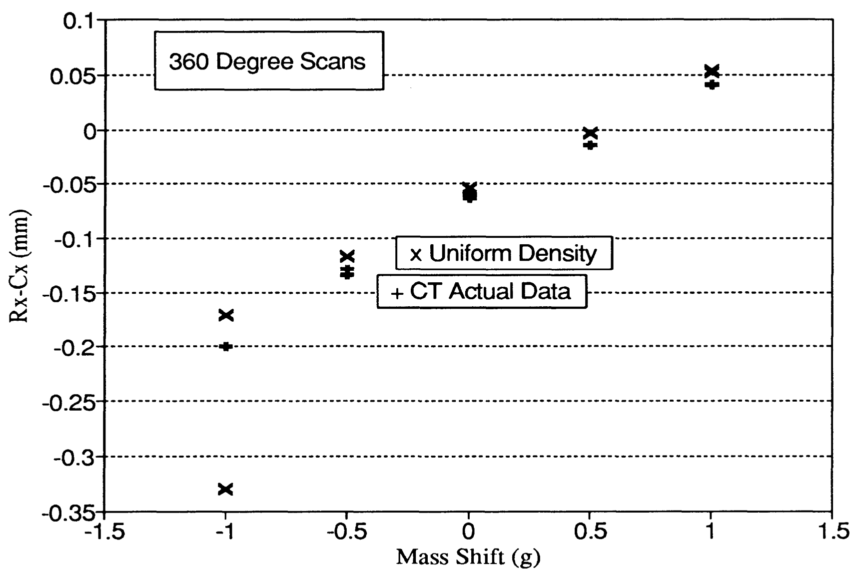

Fig. 3. Difference between center of geometry and CG for 360° scans.

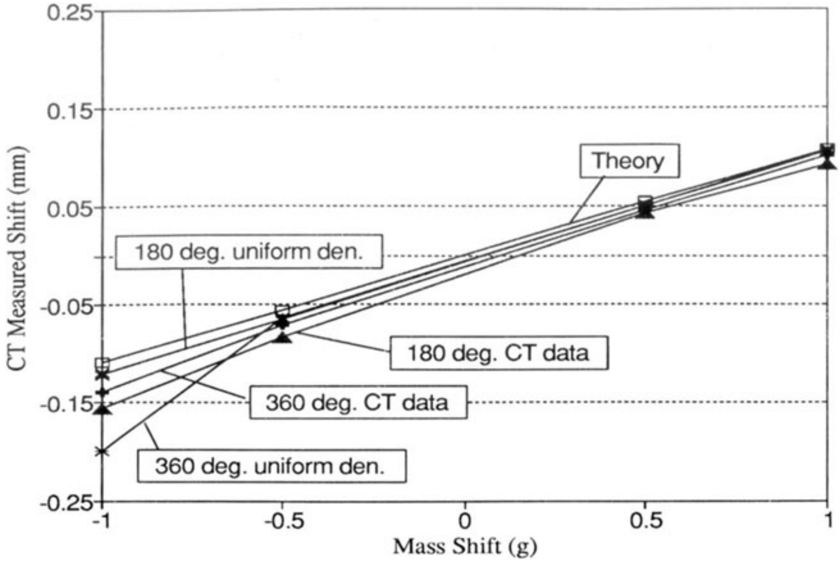

Fig. 4. Comparison of the shift in the CG for a mass shift in the test phantom including the curve for the theoretical shift.

SUMMARY

Experiments using a test phantom show that it is technically feasible to use CT data for calculation of the CG. The method as demonstrated with a ring test phantom is accurate to better than 0.8 g-cm for homogeneous materials. Preliminary analysis indicates that for non-homogeneous materials the accuracy is reduced but is valid with constraints. The position of the CG can be determined to within about 1/10,000 of the part diameter, even when the material variations occur close to the center of rotation. It should be noted that this technique is not limited to circular or high degree of symmetry parts but is readily applicable to parts with complex geometry.

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