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USING A TWO PLANE SPIN BALANCE INSTRUMENT TO BALANCE A SATELLITE ROTOR ABOUT ITS OWN BEARINGS

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Using a Two Plane Spin Balance Instrument to Balance a Satellite Rotor

Abstract

This paper addresses the problem of statically and dynamically balancing a satellite mounted antenna rotor supported on its own bearings, and driven by a motor in the satellite body. The satellite body is considered a stationary platform, (stator) for this procedure and is not part of the balancing problem. The antenna rotor is isolated and balanced independently while spinning on its own bearings.

In order to measure the unbalance, a method is developed to utilize a two-plane vertical axis spin balance machine. Rather than using the gas bearing rotor of the measuring instrument and spinning the entire satellite, the satellite body (stator) is attached to the balancing machine table, which is held stationary, and the satellite "rotor" is spun on its own bearings. Forces due to the unbalance are measured by the Spin Balance Machine force transducers.

The method is compared to a similar procedure using a single plane spin balancer and to methods using "work reversal" methods to balance the rotor by spinning the entire satellite. The accuracy of this procedure is compared to the basic balance capability of the spin balance instrument when used in the conventional manner.

Introduction

This project was conducted in response to customer inquiries regarding balancing a satellite mounted rotor using the rotor bearings and on-board drive motor to spin it, rather than attempting to disassemble the satellite and balance its rotor on the standard gas bearing spindle of a spin balance instrument. The main satellite body is considered a stationary platform for this procedure. The customer has used this method on a single plane spin balancer. There are some inherent problems associated with single plane balancers and the intent is to show that these problems are avoided by using the two plane balancer.

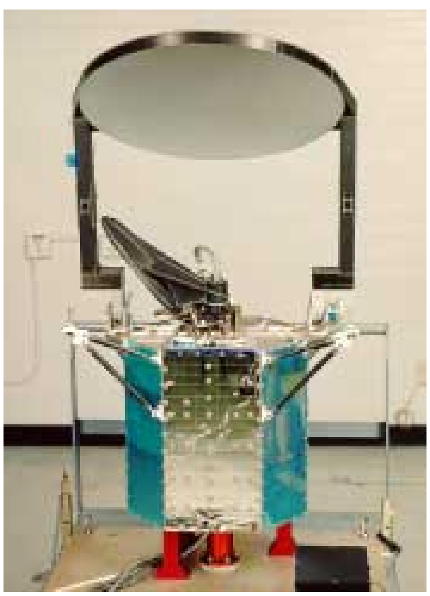


Figure 1:
Conically Scanning
Radiometer

There are satellite configurations that include rotors such as antennae, mirrors, and other assemblies, which rotate relative to the satellite body. These may be external or internal to the satellite. They rotate on their own bearings and are driven by an on-board motor. One such rotor is a conically scanning microwave radiometer shown in figure 1.

In most cases, the rotor must be statically and dynamically balanced independent of the satellite body. Dynamic balance is the most difficult to achieve. There are several dynamic balancing methods available. They fall into two groups; spinning methods, and the multiple Moment of Inertia (MOI) method.

Spinning methods measure the centrifugal forces generated by the unbalance while the rotor is spinning. A mathematical unbalance model is developed from the force data acquired in the spin tests. This model is equivalent to the actual unbalance and provides the data needed to determine ballast required to balance the rotor. Product of Inertia (POI) and CG offset moment are also calculated. This gives the operator a quantitative measure of the residual unbalance to compare with the allowable tolerance and to continue the procedure until tolerance is met.

The multiple (orientation) Moment of Inertia (MOI) method determines the Product of Inertia (POI) of the rotor by calculations based on measuring multiple Moments of Inertia (no more than 6) about various axes through the CG. This POI is used to develop a mathematical unbalance model equivalent to the actual unbalance. This model then provides the data needed to determine ballast required to dynamically balance the rotor. Static balance is accomplished by independent static methods. Quantitative residual unbalance is not easily or accurately measured. This method is best reserved for parts with high windage concerns.

This paper focuses on spin methods and specifically a method of spinning the rotor on its own bearings using the on-board rotor drive motor. The force transducers of a two-plane vertical spindle spin balance machine (POI machine) are used to directly measure the centrifugal forces generated by both static and dynamic unbalance of the rotor. The main satellite body (stationary platform) is represented by the POI machine gas bearing spindle, which is locked to prohibit rotation while maintaining its low-friction pivot characteristics. The force data recorded is manually entered into modified software in the POI machine to calculate the dynamic unbalance (POI), static CG offset unbalance, and required ballast in 2 planes to correct static and dynamic unbalance.

Overview of Spin Methods

A. Conventional two plane Spin balance

For a baseline, we can consider a rotor as an independent item to be balanced conventionally using a two-plane spin balance (POI) machine. A simplified cross section of such an instrument is shown in figure 2. It is assumed that the static and dynamic unbalance target is zero about the rotor axis.

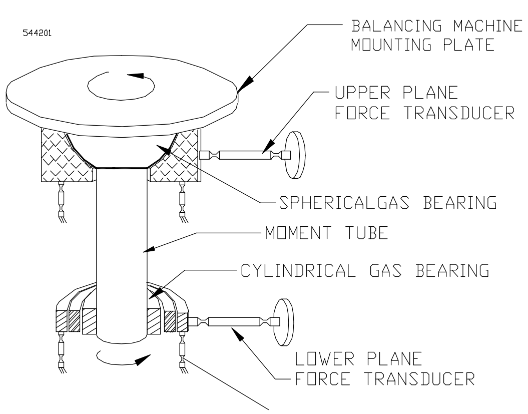


fig. 2
Two Plane POI Machine

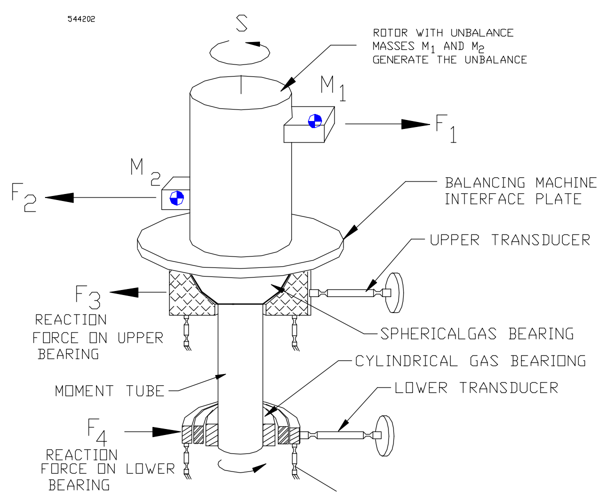
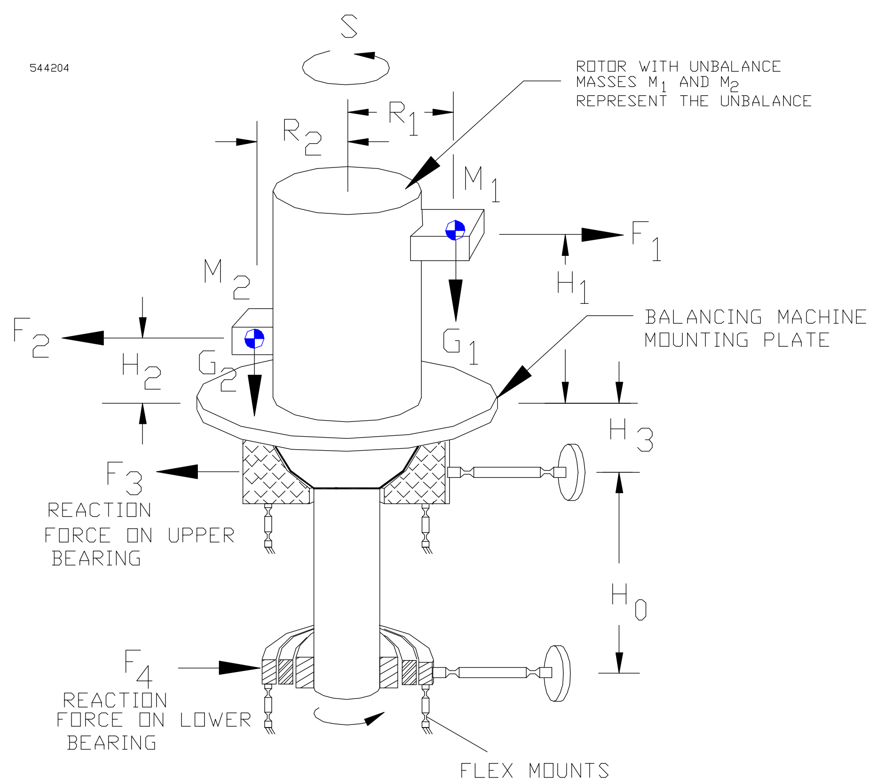


Fig. 3
POI Machine with Rotor

If a fixture is required to support the rotor, the fixture is mounted on the POI machine interface table and balanced to minimize unbalance loads in the TARE measurement. The fixture is then measured as TARE.

The rotor is mounted on the fixture such that its axis is coincident with the POI machine axis as shown in figure 3.

The POI machine is then spun at a suitable speed. Centrifugal forces due to both static and dynamic unbalance are measured. The TARE readings are subtracted from the PART (GROSS) readings and the net force data is used to calculate the equivalent unbalance model of the rotor using the equations shown in figure 4. Appropriate ballast is calculated to correct the unbalance.



$F_1(H_1 + H_3) - F_2(H_2 + H_3) - F_4 H_0 + R_1 G_1 - R_2 G_2 = 0$

$F_1(H_1 + H_3 + H_0) - F_2(H_2 + H_3 + H_0) - F_3 H_0 + R_1 G_1 - R_2 G_2 = 0$

MEASURE F_3 F_4 H_0 H_3

ASSIGN H_1 H_2 R_1 R_2

SUBSTITUTE EXPRESSIONS USING M_1 AND M_2 FOR FORCES G AND F

SOLVE FOR M_1 M_2

THEN CALCULATE POI, BALANCE WEIGHTS AND LOCATIONS

EXPRESSIONS USING M_1 AND M_2 FOR FORCES G AND F

$G_1 = M_1 g$

$G_2 = M_2 g$

$F_1 = M_1 \times R_1 \times S^2$

$F_2 = M_2 \times R_2 \times S^2$

Fig. 4
DYNAMIC UNBALANCE EQUATIONS

The equations, as shown, are simplified, in that they represent unbalance as though it existed in only one plane. In reality, a second set of equations is used to determine the unbalance model for a second plane at 90^{o} to the one shown. The results of the four equations is a set of four masses representing the Cartesian components of unbalance masses in the upper and lower planes which would cause the centrifugal forces measured. These can be combined vectorially to determine a single mass in the upper plane and a second mass in the lower plane of the model.

B. Single plane spin balance

A single plane spin balance instrument has only one force transducer. In order to measure both static and dynamic unbalance, a test article must be spun at 2 or more speeds to get sufficient data to solve for the two unbalance masses in the mathematical unbalance model. If the test article is driven by its own motor, it may be limited to a single speed or to a range of speeds too small to yield accurate results. If this is the case, to measure dynamic unbalance, the test article must first be statically balanced by independent means. The assumption can also be made that, by design, the test article is statically balanced "close enough", and only dynamic unbalance forces are significant during the spin measurement. This will result in balancing errors and final trial and error solutions. The single plane instrument can be used with any of the spin methods described but will always have the limitations described above.

C. Work reversal spin method (using a 2 plane spin balance instrument)

With this method the entire satellite, that is, body and locked rotor, are mounted on the spin balance instrument with the rotor vertical, parallel to the machine axis. The spin test is run, and the resulting unbalance forces are measured as TARE. The rotor is then turned 180 degrees relative to the satellite body and the test is re-run, measuring the satellite as PART (or Gross measurement). The difference between the two sets of force measurements is equal to twice the forces due to the unbalance of the rotor. The standard equations (figure 4) are used to determine the static and dynamic unbalance model. The resulting unbalance is divided by two.

The major weakness of this method is that the unbalance forces due to the spinning satellite body, which is not balanced, are likely to be large and mask the rotor unbalance signal, making the uncertainty of measurement large. To avoid this weakness, the entire satellite has to be balanced with the rotor in the first orientation.

A second significant disadvantage is that the satellite body is likely to weigh much more than the rotor to be balanced. This might require a larger capacity & therefore less sensitive and more expensive spin balance machine.

D. Spinning the Satellite Rotor only about its own bearings

(Using a 2 plane spin balance instrument)

Rather than utilizing the gas bearing spindle of the measuring instrument and spinning the entire satellite, the satellite body (stator) is attached to the balancing machine interface table, which is held stationary, and the satellite rotor is spun on its own bearings, driven by the on-board rotor motor. Forces due to rotor unbalance are measured by the upper and lower plane force transducers of the POI machine. Since only the rotor is spinning, and the unbalance target is zero, the TARE forces are manually entered as Zero and no TARE measurement is required. The weakness of this method is that the bearing system of the satellite rotor is likely to introduce more noise than the gas bearings of the POI machine. Also the rotor bearings are not as 'stiff' as the POI machine gas bearings, introducing deflections which are detrimental to measurement accuracy when comparing to the inherent measurement accuracy of the POI instrument.

Minimizing the mass of the satellite body provides a significant advantage. Reducing the parasitic mass improves the signal to noise ratio. If the rotor and its drive can be disconnected from the main satellite body, a smaller, more sensitive, and less expensive spin balance machine can be used.

Test Method

A primary goal is to determine the accuracy attainable using the rotor motor and bearings as compared with using the POI machine gas bearing spindle & drive.

The method uses a conventional 2 plane spin balance (POI) machine of the vertical shaft, hard bearing type which measures centrifugal forces to determine the static (CG offset) and dynamic (POI) unbalance.

1. The balance machine is calibrated in the conventional manner using a proving rotor mounted to the machine interface and spun with known unbalance.
2. The proving rotor is removed and the satellite is mounted to the machine interface. The satellite should be mounted so that;
   a. the CG of the entire satellite is aligned with the POI machine spin axis. This minimizes the static loading on the force transducers.
   b. the satellite rotor (test rotor) axis is parallel to the POI machine spin axis.
3. An inductive proximity sensor is mounted to detect a physical feature (timing tab) of the test rotor and provide a timing pulse for rotational speed measurement. This is not required if the satellite itself generates a timing pulse.
4. The POI machine spindle is locked to prevent rotation.
5. The test rotor is spun and TARE measurement of centrifugal forces is made.
6. A known mass (unbalance) is mounted at a location which has a known angular location, height, and radius relative to the rotor coordinate system.
7. A PART measurement is made. The change in unbalance in this case, is caused by the unbalance mass only. This measurement establishes an angular reference datum and a force calibration correction factor to be applied to future calculations. (Other, similar, measurements will have to be done at each test speed.)
8. The unbalance mass is then removed, zeros are entered for TARE, and another PART measurement is made.
9. The data is entered into the customized software of the POI machine to determine the static and dynamic unbalance as well as correction ballast.
10. Appropriate ballast is applied and PART is re-measured.
11. The procedure is continued for 3 or more iterations until the unbalance is reduced to a point where it cannot be improved.

Equipment Description

Spin balance machine

Space Electronics POI-2200 30-300 rpm; 2200 lb max payload weight

Test Rotor

Rotor weight	approx 120 lb
Rotor diameter	10 inch
Rotor Length	24 inch
Rotor drive gear motor	90 VDC 0-125 rpm
Test speeds	30 to 125 rpm
Inductive Proximity Detector	
Siemens PX1200	15 V pulse 0.0-1.5 mm range

Scope:

Phase I: Establish as baseline of unbalance capability
A rigid cylindrical test rotor, similar to the POI calibration rotor was constructed. This will serve as the "Satellite Rotor". It was balanced in the conventional manner using the POI machine as shown in Figure 5. This was done to get a baseline of balance capability of the POI machine for comparison with alternate methods to be tested.

Figure 5

Results of Phase I:

The cylinder was balanced to a measured residual static unbalance of better than 0.01 lb-inch and dynamic unbalance from 0.04 to 0.45 lb-inch^2 depending on speed as shown in Table 1.

RUN #	RPM	POI lb-inch^2	STATIC lb-inch
3095	30	0.448	0.00670
3109	50	0.061	0.00034
3103	80	0.037	0.00210

Table 1 - Residual Unbalance
Air Bearing Drive

All attempts to improve on this resulted in residual measured unbalances similar in magnitude with large changes in the apparent angular location. The interpretation is that the residual unbalance is zero ± the measured residual unbalance. The same interpretation of results was used for all tests.

Phase II: Establish a viable test procedure using the satellite on-board rotor motor for spinning. A pedestal, with a gearmotor to drive the test rotor, was constructed (figures 6 & 7) to support the test rotor on the POI machine. A rotor bearing was mounted between the pedestal and an interface plate to which the test rotor could be secured. The interface plate was driven by a gearmotor with a 23/1 ratio gear train.

The test rotor interface plate had a small steel block on its periphery (figure 8) which was detected by an inductive proximity switch as the plate rotated. This provided the timing, or trigger, pulse to an oscilloscope, built into the POI machine diagnostic software, for angular reference of the unbalance forces relative to the test rotor coordinate system.

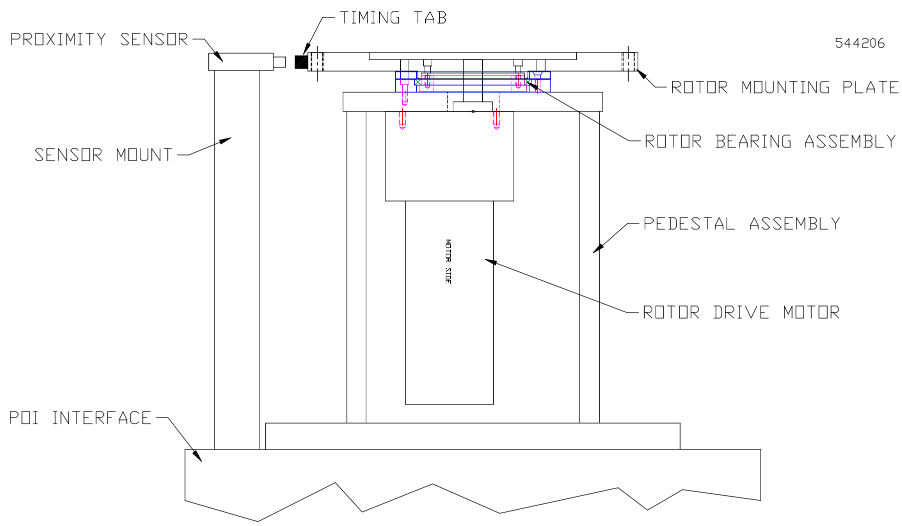


Figure 6

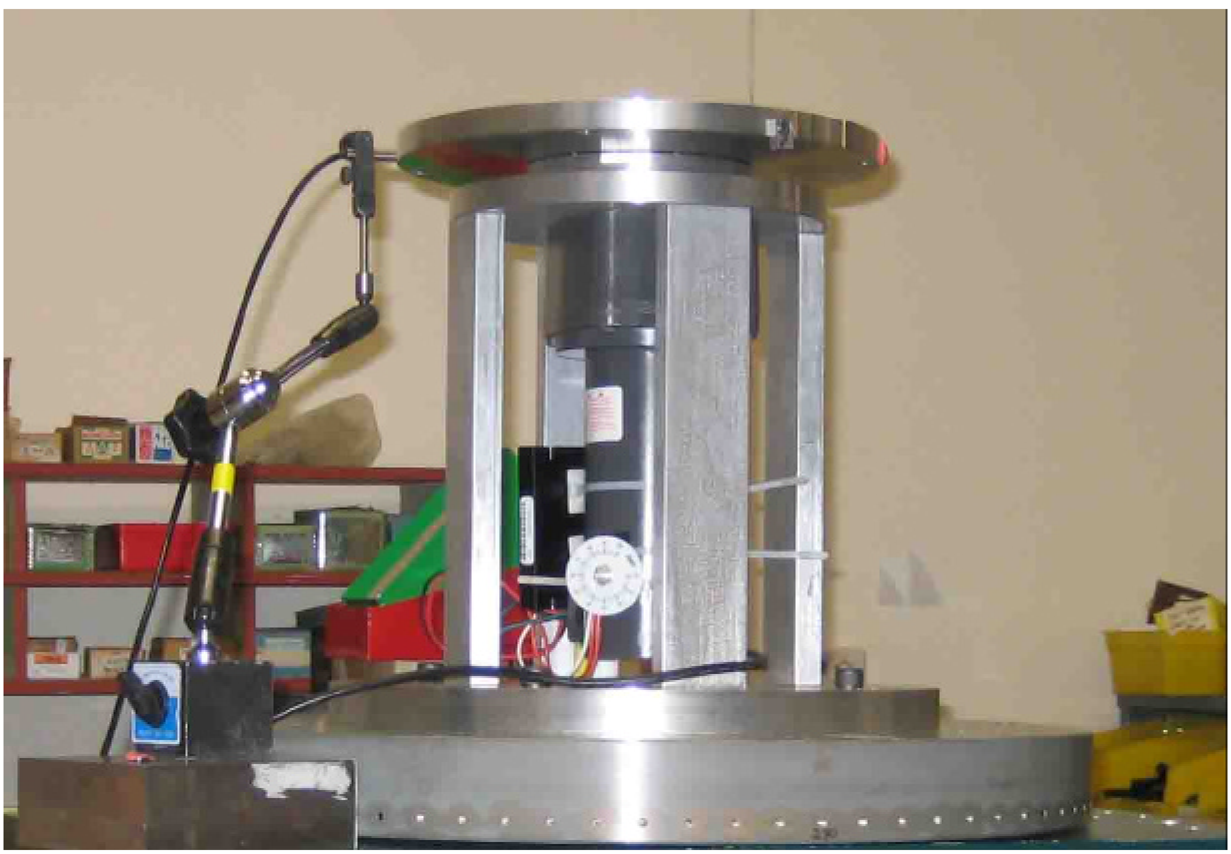


Figure 7

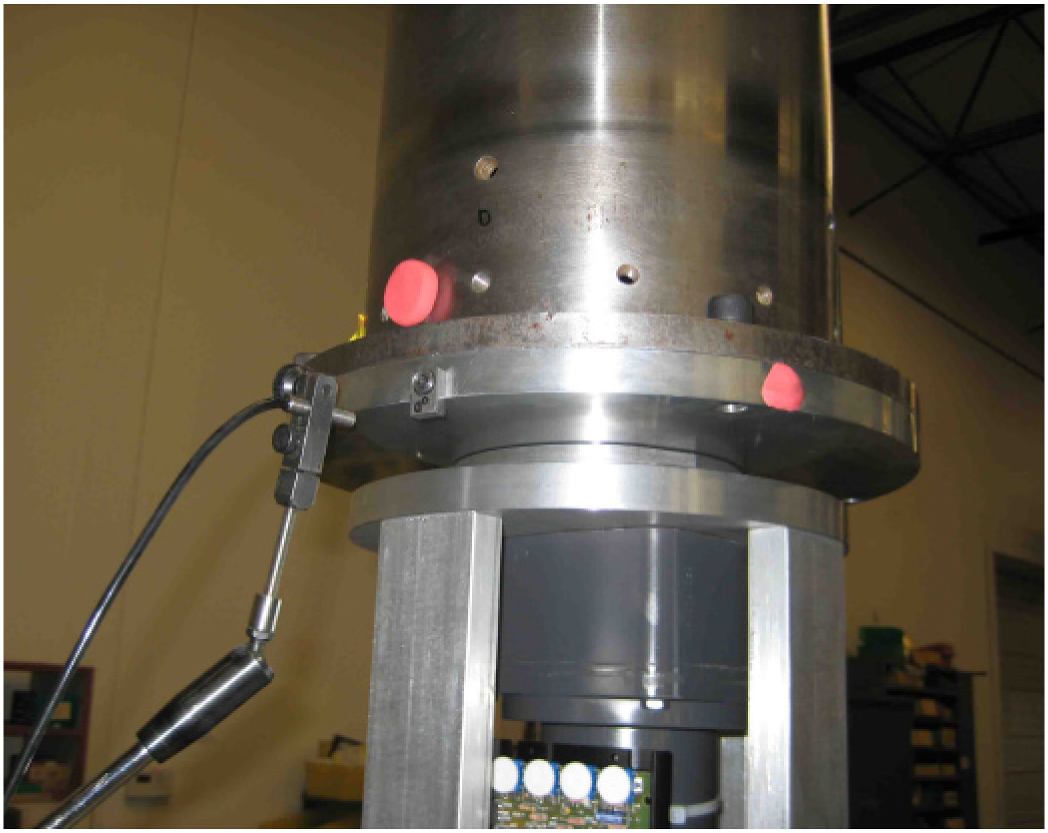


Figure 8

The POI machine circuitry was modified to accept this external trigger signal.

The force transducer signals from the POI machine were viewed using the digital oscilloscope function in the POI machine's diagnostic software.

Prior to mounting the pedestal on the POI machine, the POI machine was run at 50 rpm without any payload mounted to see the noise level of the bare spindle running in the gas bearing. This is shown in the oscilloscope screen of figure 9.

Next, the pedestal with test rotor interface, configured as in figure 7, was driven by the gearmotor and the force signals were observed to get an initial impression of the noise and signal levels without the rotor.

This signal showed a high level of noise at many frequencies. This confirmed our expectation that the drive motor, gear train, and bearing would introduce more noise than the POI machine gas bearing rotor. This signal, shown at the same gain as figure 9 is seen in figure 10.

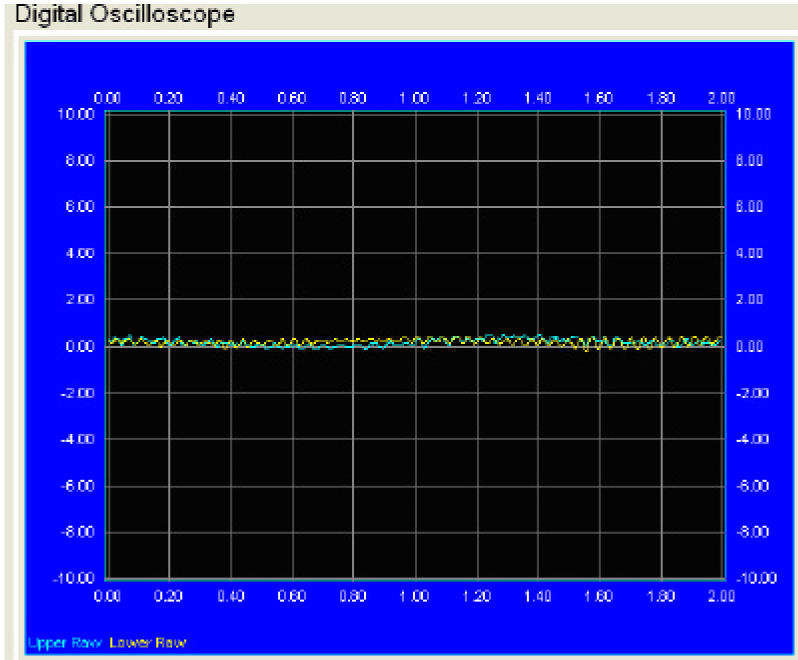


Figure 9:
Bare POI Machine Spindle Force Signals
50 RPM   Total Gain 5120

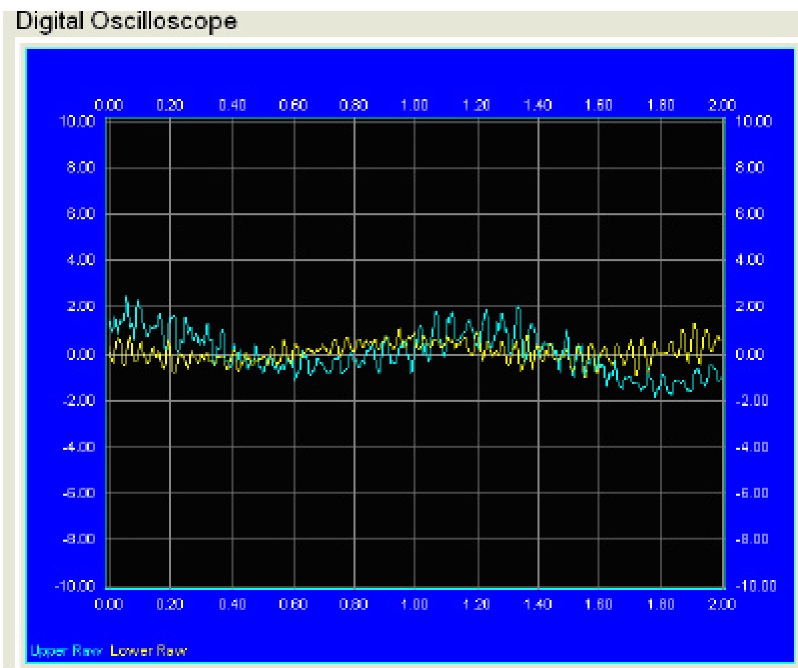


Figure 10:
Pedestal / Gearmotor Force Signals
50 RPM   Total Gain 5120

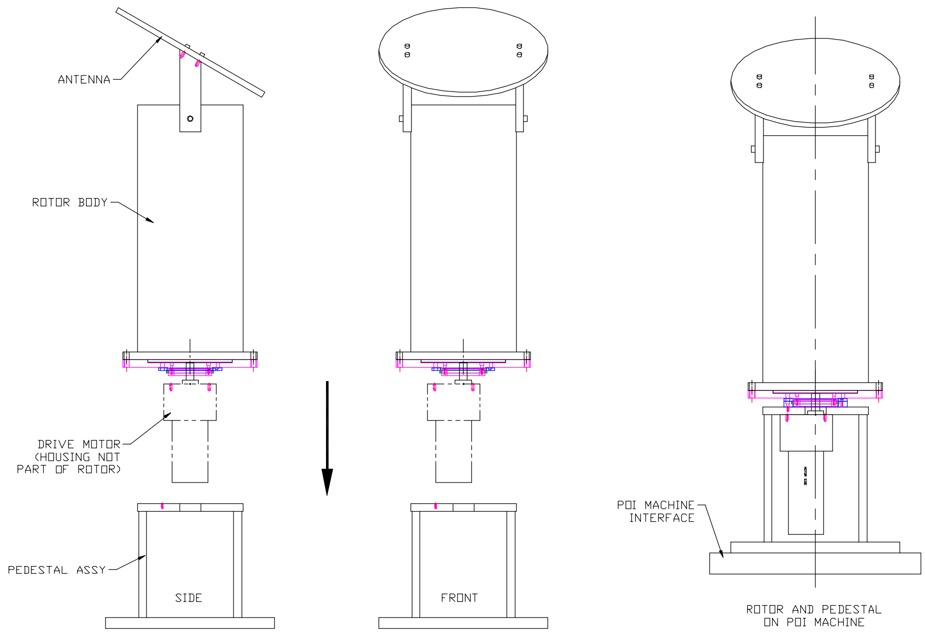


Figure 11:
Pedestal & Rotor as Mounted On POI Interface

Finally the test rotor body was mounted to the pedestal (figure 11) without the antenna. This assembly, less the motor housing, represents the satellite's rotating body. The pedestal assembly, motor housing, POI machine gas bearing spindle, and POI machine interface plate, represent the main satellite body, which is the fixed platform to which the satellite (test) rotor is mounted. The test rotor has numerous locations to mount weights to produce known dynamic and static unbalance and to mount ballast to correct the unbalance in accordance with calculations based on the force measurements obtained in the spin tests.

When the test rotor was mounted to the interface plate, additional noise sources appeared. These included rocking resonance due to insufficient stiffness in the bearings of the test rotor, and several resonances in the POI machine structure and transducer mounting. At this point we made some observations.

The first observation is based on Figures 9 & 10. In both figures, the oscilloscope screen is shown at the same gain levels. Figure 9 shows the signals from the force transducers at 50 RPM when the POI machine spindle, without a payload mounted, is rotating on its own gas bearing and driven by its own vector drive system.. Figure 10 shows the output of the transducers, again at 50 rpm when the gas bearing spindle is locked and the 'satellite' rotor drive motor is driving the rotor mounting table only (the configuration shown in figure 6). The oscilloscope signals represent the inherent noise level associated with the drive and bearings. As a given unbalance is corrected and approaches zero, the signal to noise ratio, a measure of the ultimate machine sensitivity, will be far better for the gas bearing spindle than for the gearmotor drive used for this exercise. Based on this alone we draw several conclusions.

1. We should not expect to balance any payload as well using our gearmotor drive as when we use the POI machine in its normal gas bearing/drive configuration.

2. Given the cost of our gearmotor drive, bearing, & controller (less than $1000), we should expect a higher quality drive system on any billion dollar satellite
3. With a better drive system, we should expect better balance on a true satellite rotor than we achieved on our demo model.

The second observation is that using the POI machine in its normal mode of operation, we can consistently achieve dynamic unbalance better than 0.5 lb-inch^2 and static unbalance to better than .01 lb-inch for the bare rotor we are using as a satellite rotor demo model.

Third, with the ‘antenna’ mounted, the residual unbalance, using the POI machine in its normal air bearing drive mode, we anticipated unpredictable and inconsistent windage forces to make the achievable residual unbalance greater than without the antenna. We were surprised to find that the results with and without the antenna were limited by our ability to make small, accurate ballast changes and by the inherent sensitivity of the POI machine not by the windage forces. This result cannot be expected for real satellites with larger appendages.

The residual unbalance values found using the normal air bearing drive mode of operation are the basis for comparison with using the on-board satellite rotor motor to drive the rotor.

Initial transducer force readings were taken using a separate oscilloscope and visually interpreting the signals for magnitude & phase angle. The peak-to-peak magnitude of the force signals could be estimated from the scope with reasonable accuracy. However, the angular location relative to the timing pulse, (phase angle), could not be accurately measured. Errors in this angle, and the errors in the estimated force magnitude, limited the balancing capability to approximately 16 lb-inch^2 and the static unbalance to approximately 4 lb-inch.

To improve upon this, the POI machine software was modified to accept the timing pulse from the proximity switch instead of the normal POI machine rotor timing pulse. POI machine analytical software capability was then available. This allowed the POI software to analyze the force data to determine a best fit sine wave for the noisy force signal. The magnitude and phase angle of the clean, best fit, sine wave is then determined by the software.

The data is acquired and analyzed using diagnostic functions. The results (voltages) are then entered manually in the calculations data entry screen. The final results are presented in a report as static and dynamic unbalance. The report also specifies required ballast weights & locations to correct the unbalance. Sample reports are shown in Figures 12A and 12B.

To verify the accuracy of the tests, a known dynamic unbalance of 87 lb-inch^2 with unknown but very small static unbalance was mounted on the test rotor and measured. The measured value was 76 lb-inch^2, or within about 15%. This error, assuming it occurs in all measurements, explains, at least in part, why several iterations of balance are necessary to achieve greater than 95% reduction in unbalance. With an incorrect original measurement, the specified ballast will either under or over correct.

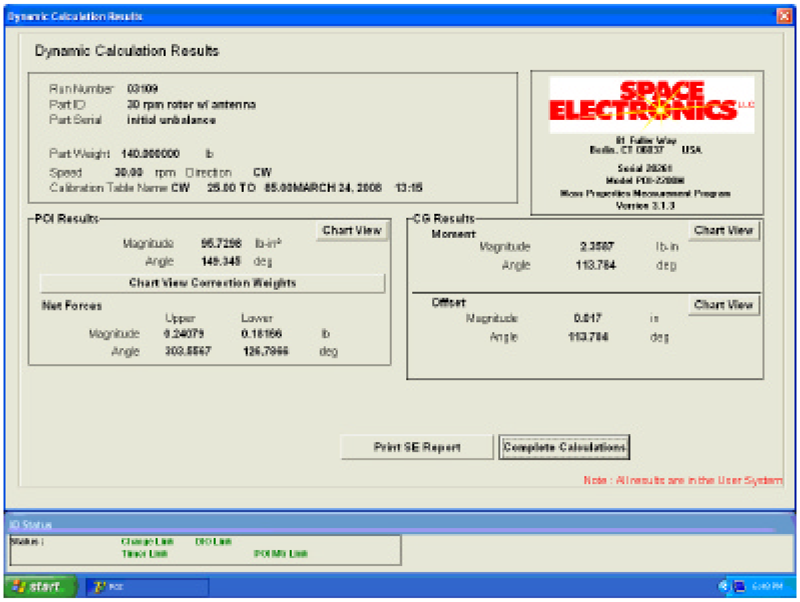


Figure 12A:
Sample Test Report – Unbalance

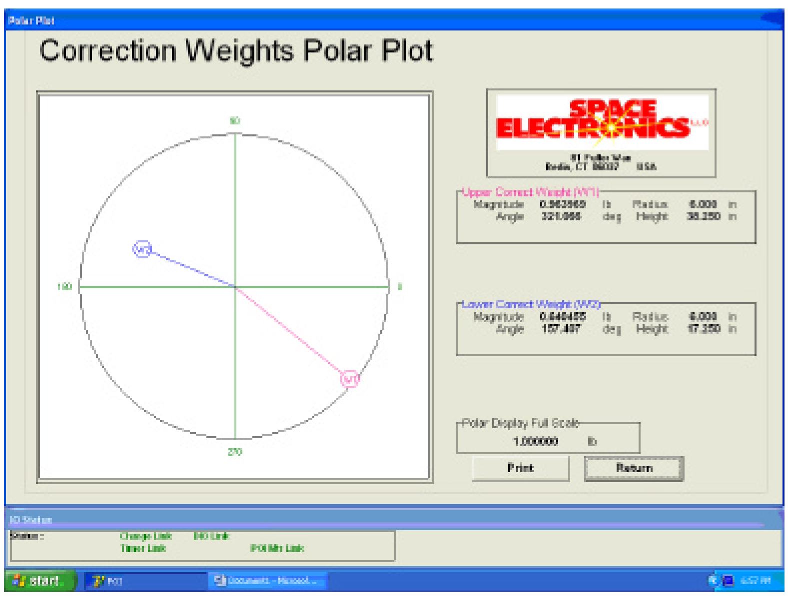


Figure 12B:
Sample Report – Correction Weights

A brief description of the various configurations tested is shown in Table II below. A more complete description of these configurations is given in Appendix A.

	Description	Purpose	Speed (RPM)
A	Rotor body only directly mounted on POI-2200 interface. No motor or pedestal. Conventional spin balance using the POI-2200	To determine a base line for accuracy of unbalance measurement and amount of uncertainty in residual unbalance	30 50 80
B	Pedestal with drive motor, rotor bearing, and rotor mounting plate driven by rotor motor. POI spindle locked.	To determine a noise level for the 'on-board' drive system.	30 50 80
C	Pedestal with rotor body mounted. Rotor motor used to spin the rotor.	This will be a TARE measurement at each speed for configuration D	30 50 80
D	Known unbalance weight mounted on the rotor at a known orientation. Uses configuration C as TARE	Determine the calibration and phase angle correction factors at each speed.	30 50 80
E	Same data as C but used as PART measurement. Zeros are manually entered for TARE	Determine initial static and dynamic unbalance	30 50 80
F	Add ballast to balance E as necessary to balance the rotor	Determine the ability to balance and magnitude of residual unbalance	30 50 80
G	Remove ballast from F, mount antenna, measure unbalance, and add ballast to balance	Determine the ability to balance and magnitude of residual unbalance for large integral POI and indeterminate windage	30 50 80
H	Move entire pedestal & rotor assembly off center	Determine the effect of large CG offset with offset axis	50

Table II: Test Configurations

Results of Phase II:
The use of the POI software improved the results considerably. The residual unbalance was reduced to 1.0 lb-inch^2 or better. No attempt was made to improve on the 1.0 lb-inch^2 dynamic and 0.2 lb-inch static unbalance obtained after one balance iteration. By comparison, at 50 and 80 rpm, two and four iterations respectively were performed, and static balance was improved by an order of magnitude. Results in Table III below show the initial and residual unbalance of the rotor.

The test configurations below were run after the POI-2200 is calibrated by normal methods. A sensor was mounted for configurations C through H to sense speed and angle data.

BARE ROTOR = rotor motor drive							
RPM		RUN #	DATE/TIME	POI MAG	POI ANG	CG MOMENT	CG ANG
30	Initial	2963	4/4 11:58	22.18	174.60	1.10	228.68
	Final	2965	4/4 12:08	1.09	181.17	0.24	79.95
50	Initial	2955	4/4 11:17	18.62	162.01	1.20	229.43
	Final	2959	4/4 11:36	0.37	212.12	0.02	350.70
80	Initial	2942	4/4 10:13	24.38	172.62	1.17	232.61
	Final	2950	4/4 10:52	1.06	168.03	0.02	277.89

Table III
Summary of Phase II Results

A procedure was developed to empirically optimize the POI machine performance for each measurement speed. Similar optimizing can also be done for specific payload configurations. On the POI machine used for this exercise, this was done only for the 50 rpm tests. This is, in part, the reason for better performance at 50 rpm in all modes of operation.

PHASE III:
The antenna (shown in figure 11) was then mounted to represent a mirror or antenna with significant, unknown, dynamic and static unbalance. In addition to the dynamic unbalance due to the tilt of the antenna, windage forces are also generated by the antenna. These windage forces increased the uncertainty of the unbalance measurements and reduced the quality of the balance attainable. Again, the table below shows initial and final unbalance. We were not able to achieve better than 3.0 lb-in^2 at 30 and 80 rpm.

ROTOR W/ ANTENNA & CG OFFSET -- rotor motor drive							
RPM		RUN #	DATE/TIME	POI MAG	POI ANG	CG MOMENT	CG ANG
30	Initial	2986	4/7 11:57	95.73	149.35	2.36	113.78
	Final	2998	4/7 13:04	3.10	343.61	0.05	150.70
50	Initial	2975	4/7 10:15	95.43	147.82	2.50	115.27
	Final	2983	4/7 11:19	0.30	93.87	0.01	274.55
80	Initial	3006	4/7 13:13	110.46	147.25	2.48	116.44
	Final	3014	4/7 14:16	3.08	338.53	0.06	105.81

Table IV Summary of Phase III Results

More complete data is presented in Appendix B.

To determine the effects that various changes to the basic rotor body would have on the ability to correct unbalance, the entire pedestal with rotor assembly was moved 1.5 inches off center on the POI machine interface. This generated a large static unbalance on the POI machine structure as well as a large (1.5 inch) misalignment between the rotor axis and the POI machine centerline. This offset did not produce any performance degradation, so no further changes in mounting or unbalance relative to the POI centerline were made.

Conclusions:

Based on the results of our exercise, we have demonstrated that the use of a two-plane spin balance machine provides a logical and deterministic approach for dynamically balancing a rotor about its own bearings. By removing the spin capability of the POI machine and using the satellite's on-board motor to drive a satellite rotor, we create a highly effective method of obtaining both static and dynamic balance of the rotor. A relatively high degree of measurement accuracy is possible thereby providing the tool necessary to achieve small unbalances.

For best results when using this balancing method, several factors should be addressed. They include:

- The satellite's on-board drive system and bearings must be stiff and quiet enough to allow favorable signal to noise ratio as balance is improved.
- There must be at least one location on the satellite rotor with accurately known radius, axial location, and angular relationship to the satellite coordinate system where a relatively large calibration mass can be mounted.
- On the satellite rotor, there must be access to ballast locations in two vertically separated planes where the axial location is known or can be measured with reasonable accuracy.
- As with any dynamic balancing problem, the ballast locations for all angles need not all be in the same planes but ballast at small radii and plane separations will require larger weights and introduce greater uncertainties of placement.
- For best results, the POI machine should be optimized for the desired rotational speed.
- The rotor must provide an electrical pulse at a known angular relationship to the rotor coordinate system

  or

  There must be an external feature at a known angular location which can be sensed by a proximity sensor to provide a timing pulse

  or

  There must be a known angular location where a timing tab can be affixed to the surface of the rotor which can be sensed by a proximity sensor to provide a timing pulse

If the factors above are met, this method may very well be the most accurate and cost effective method for static and dynamic balance of a self driven satellite rotor.

Appendix A
Description of Test configurations

For configuration A, the POI machine was used in its conventional configuration, as shown in figure 2, to balance the rotor body only. This was done to determine a base line of balance capability for the POI-2200 machine. All other tests were compared to this baseline.

For configuration B, the pedestal; with drive motor, rotor bearing, and rotor mounting plate, was mounted on the POI machine interface. See figure below. The POI spindle drive shaft was then

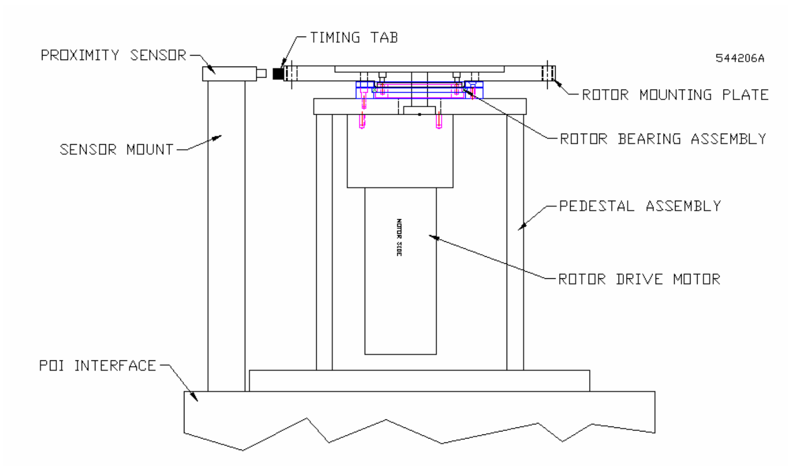


Figure A1:
Pedestal W/Drive Motor, Bearing Assembly & Rotor Mounting Plate

locked using the brake normally used to lock the lower end of the shaft when the machine is used for MOI measurements. The lock is controlled by a diagnostic command within the POI software. The rotor motor is used to rotate the bearing assembly and rotor mounting plate, and any other payload items, in this and all other configurations.

A proximity sensor was mounted on the POI interface to sense the passing of a feature on the rotor mounting plate. This feature has a known angular relationship to the rotor coordinate system. The sensor gives a pulse once per revolution which is used to set and record the operating speed. This same pulse is sent to an oscilloscope as a trigger (reference) signal.

The force signals from the POI machine upper and lower force transducers are also sent to the oscilloscope. In this (configuration B) test, we are only looking for the level of background unbalance & noise due to the motor & bearing assembly various test speeds. No attempt will be made, at this time, to make any balancing corrections.

For configuration C, the rotor (body only) is mounted on the rotor mounting plate as shown in figure 7a. This test, run at several speeds, provides the TARE data for Configuration D tests. The force & speed setup is the same as in test configuration B.

For configuration D, a known, large, (7.3 lb) unbalance mass is mounted on the rotor at a known angular location, height, and radius as shown in figure A2. This test provides the PART, or GROSS, data. When the TARE data from configuration C tests are subtracted, the resulting net force measurement data is displayed. The test object in this test is only the unbalance masses. All effects of the rotor body are subtracted. A correction factor is calculated to correct for the error between the known, calculated, value of the forces and the measured values. Since the angular location if the unbalance is also known, the angle of the peak net forces can be related to the rotor coordinate system to define a phase angle correction. This entire process is repeated at each test speed.

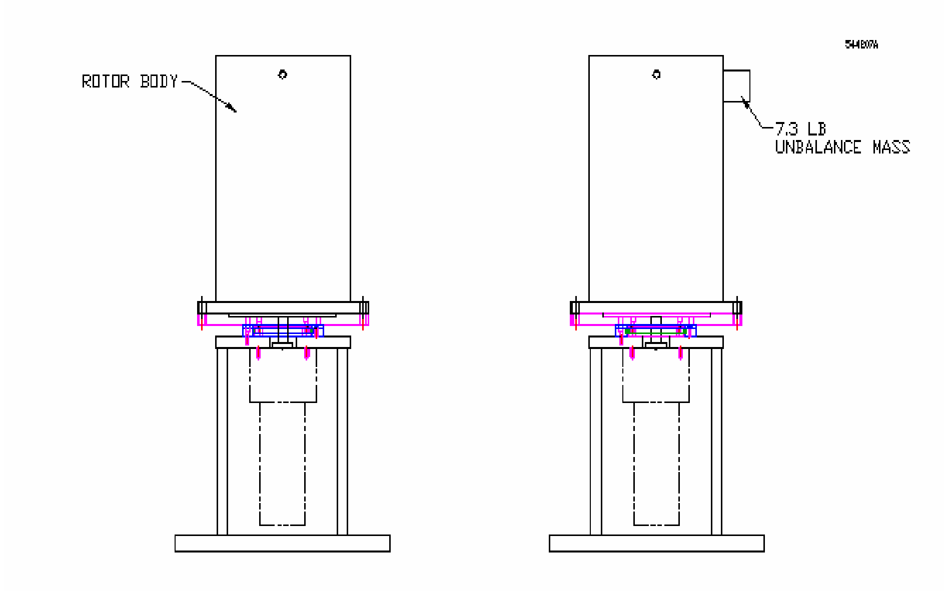


Figure A2:
Rotor without and with Unbalance Mounted

For configuration E, the known mass is removed. The rotor is spun at the various test speeds using manually entered zero values for Tare unbalance. This is appropriate because, when using the rotor motor as a drive, only the parts to be balanced are spinning and, if there were no unbalance, the measured forces would be zero. The force transducers are sensitive only to changing forces so that any stationary loads applied to the POI interface, such as the proximity sensor mounting block, will not be measured.

The initial static and dynamic unbalances are measured at the various test speeds.

For configuration F, appropriate ballast is calculated and mounted. The configuration F test is repeated as often as necessary (typically 2 or 3 times) until no further improvement in balance is possible at the lowest speed. Then, without removing ballast, the next higher speed test is run and an attempt is made to improve the ballast. This is typically the case because the forces increase with speed, improving the signal to noise ratio.

For configuration G, the ‘antenna’ is mounted. This adds a small static unbalance, a large dynamic unbalance, and unknown forces due to windage. The assembly unbalance is again measured at the various speeds, ballast is calculated and the assembly is balanced as in configuration F. The initial dynamic unbalance measured after mounting the antenna should be 66.44 lb-inch^2 as calculated below.

For this configuration, though the transducer sensitivity increase with speed, the random windage forces also increase so the highest speed may not be the optimum speed for testing.

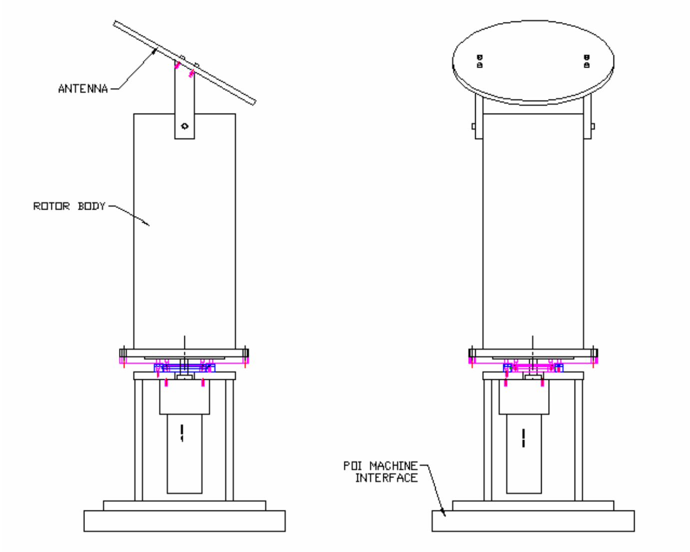


Figure A3:
Complete Satellite Rotor
Model Mounting Configuration

The predicted POI due to the antenna is calculated by finding the polar moment of inertia (I_p), and the MOI about the horizontal radius (I_r) and using these to calculate the POI at 30^o tilt.

Antenna radius (R) =	7.914 inch
Antenna Weight (W) =	9.814 lb
Antenna thickness (t) =	0.511 inch

$I_p = (WR^2)/2 =$ 307.33 lb-in^2

$I_r = W(3R^2 + H^{2)}/12 =$ 153.88 lb-in^2

The POI at 30^o tilt angle (a) is calculated using the equation:

POI = $.5(I_p – I_r) \sin 2a$ = **66.44 lb-in^2**

The minor POI introduced by the mounting screws, holes, and angle cuts on the end of the supports is ignored in this calculation.

<u>For configuration H</u>, entire the assembly is moved on the POI interface to determine the effects of having the entire satellite CG offset from the POI machine axis and the effect of having the rotor spin axis displaced from the POI axis. This will show up any non-linearities in the force measurement string.

APPENDIX B

BARE UNBALANCED ROTOR USED AS PART

RPM	RUN #	DATE/TIME	UPPER WT	UPPER ANG	LOWER WT	LOWER ANG	POI MAG	POI ANG	CG MOMENT	CG ANG
30	2963	4/4 11:58	0.240641	8.416	0.156324	132.839	22.18	174.596	1.0974	228.675
	2965	4/4 12:08	0.016373	294.308	0.031044	242.626	1.0882	181.171	0.2373	79.945

50	2955	4/4 11:17	0.203889	2.522	0.168204	111.698	18.6236	162.005	1.1966	229.428
	2957	4/4 11:25	0.029599	218.223	0.023158	337.858	2.7981	21.032	0.1491	86.186
	2959	4/4 11:36	0.00256	51.66	0.00537	195.339	0.373	212.124	0.0191	350.704

80	2942	4/4 10:13	0.257566	7.401	0.185541	132.719	24.3805	172.621	1.1733	232.608
	2944	4/4 10:20	.105117	204.662	0.077185	348.431	10.5481	14.427	0.3443	71.452
	2946	4/4 10:29	0.048913	21.247	0.048476	196.548	5.3714	199.585	0.0211	282.655
	2948	4/4 10:38	0.020218	184.741	0.024613	337.761	2.3378	353.944	0.0593	103.479
	2950	4/4 10:52	0.009214	357.122	0.01091	154.028	1.0611	168.029	0.0229	277.892

ROTOR WITH ANTENNA & SMALL CG OFFSET WT USED AS PART
ANTENNA FACING 0 DEGREES CG OFFSET WT AT 90

RPM	RUN #	DATE/TIME	UPPER WT	UPPER ANG	LOWER WT	LOWER ANG	POI MAG	POI ANG	CG MOMENT	CG ANG
30	2986	4/7 11:57	0.963969	321.066	0.640455	157.407	95.7298	149.345	2.3587	113.784
	2988	4/7 12:10	0.104225	127	0.081922	302.165	10.4643	304.402	0.1303	324.499
	2992	4/7 12:32	0.039747	271.556	0.049112	69.028	4.922	76.729	0.1031	198.178
*	2994	4/7 12:42	0.070226	146.421	0.051266	8.383	6.3336	348.726	0.2583	279.545
	2996	4/7 12:51	0.043097	20.364	0.05668	204.778	5.657	203.323	0.0741	38.379
	2998	4/7 13.04	0.022971	166.579	0.03151	342.204	3.1022	343.605	0.0461	150.695
	3000	4/7 13:15	0.025743	352.201	0.034765	174.122	3.4417	173.5	0.0477	359.579

50	2975	4/7 10:15	.980219	319.836	0.625625	155.919	95.4336	147.822	2.5009	115.267
	2977	4/7 10:38	0.090514	147.688	0.055179	267.65	6.9075	298.655	0.4348	4.899
	2979	4/7 10:56	0.018915	278.316	0.013305	77.28	1.6812	87.355	0.0423	134.633
	2981	4/7 11:11	0.005766	159.328	0.006874	324.31	0.7044	329.582	0.0104	95.447
	2983	4/7 11:19	0.001266	273.08	0.003703	94.044	0.3027	93.87	0.0128	274.545

80	3006	4/7 13:33	1.099544	320.542	0.741939	153.68	110.456	147.249	2.4784	116.443
	3008	4/7 13:46	0.247654	106.297	0.09506	355.659	14.9506	310.959	1.2754	263.739
	3010	4/7 13:59	0.1101358	291.87	0.105702	91.789	11.2996	99.455	0.1908	198.587
	3012	4/7 14:07	0.036356	76.208	0.038685	224.09	4.0115	236.136	0.1096	336.304
	3014	4/7 14:16	0.024606	170.591	0.030693	332.302	3.0846	338.526	0.0559	105.813

* Note: an obvious error was made in this step since both POI and CG offset moment increased as a result of the correction

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