An attitude control system for the SIM Test Bed 3 (STB3)

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ABSTRACT

The Space Interferometry Mission (SIM) interferometers are required to reject slow (sub-Hz) motions of the spacecraft by feeding the attitude information from the bright-star tracking interferometers to the dim-star science interferometer, so that the photon-starved dim-star interferometer star tracking system can hold the science object in the field of view of the interferometer, without losing track of the interferometer fringes. The design is also required to reject translation-induced path-length errors in the science and the guide interferometers.

The SIM Interferometry Test Bed 3 (STB3) is the spaceborne-stellar-interferometer simulator for SIM, built and operating at JPL. Its construction details and performance are described elsewhere in this conference.[3]

The test bed consists of an interferometer system built on a large optical table, and a star simulator built on another large optical table placed directly across it. The optical tables float on independent, air-filled suspension legs simulating the SIM spacecraft and the distant stars it is to observe.

In order to demonstrate the performance requirements, a novel attitude control system (ACS) has been built and installed on the STB3. In this paper, the details of the design, construction and performance of the attitude control system are presented. The attitude control system has been used to meet certain SIM requirements. An example of this performance test is also included.

Keywords: Spaceborne interferometry, attitude control, star simulator

1. INTRODUCTION

The SIM Interferometry Test Bed 3 (STB3) is the spaceborne interferometer simulator for the Space Interferometry Mission (SIM). The Testbed consists of a test article which simulates the SIM stellar interferometers and a star simulator that mimics the distant stars the test article is to track to an accuracy of few micro-arc-seconds.

The existing test bed operates in air, and its accuracy is limited by the atmospheric turbulence its light beams travel through. To reduce the effects of atmospheric turbulence, the test article and the star simulator are placed fraction of a meter apart. The test article and the star simulator are built on large, standard optical tables that use passive, air-filled suspension supports to attenuate ground vibrations.

Both the test article and the star simulator drift independently on these supports while the photon-starved interferometers try to track the simulated star in an attempt to cancel the effect of the tables' motions. Since the relative motion of these tables is not of any particular interest, living with it simply reduces the signal-to-noise ratio of the instrument, badly limiting its performance.

However, a controlled relative motion of these tables is desirable in certain instances in order to measure and verify the motion rejection capability of the stellar interferometers.

The STB3 attitude control system is designed to provide both the relative motion reduction and controlled relative motion on demand between the test article and the star simulator. It consists of a sensor system that detects the motion in the six independent degrees of freedom between the test article and the star simulator, and a drive system that can apply force to the star simulator table in the six degrees of freedom, independent of the relative table position. An extended system is under construction that can apply force to both the test article and the star-simulator table.

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The system has been used in the open-loop mode to monitor and verify the relative table motion and to induce motion in particular degrees of freedom to test the motion rejection capability of the stellar interferometers. Motion rejection ability up to 80 dB at very low (0.01 Hz) frequencies has been demonstrated using this system. We expect the system to be fully functional in the closed loop mode, shortly after this conference.

2. REQUIREMENTS

The attitude control system for STB3 has three main requirements: To position STB3 test article within the tolerance band of the star simulator by moving the star simulator, to "boot" up the system by aligning the star simulator to the test article to display interferometric fringes from external metrology, and to simulate on-orbit attitude control system disturbances.

2.1. Bounds

The primary source of noise in STB3 is due to beam-walk in the transverse direction to the starlight and metrology beams. Translations in these directions with non-parallel star simulator beams (guide and science beams) generate apparent optical pathlength difference which gets detected as real signal. These translations are to be held to less than 1 mm by the attitude control system. Ideally, a servo-locked system should hold these displacements within a few microns.

Tilt offsets are easier to handle as the STB3 testbed has fast-steering mirrors and star-tracker CCDs. The attitude control system is to bring the star-simulator well within the $\pm 600\mu$rad range of the CCD star-tracker on the test article. The fast-steering mirror has a wider coverage by factor of two. In reality, these devices have nearly optimum positions for best interferometer alignment, and the ACS should bring the system into alignment very near this optimal position without using much of their range.

2.2. Initial alignment or "boot-up"

Due to the drift of the pneumatic vibration isolator legs, the position of the star-simulator drifts with respect to the position of the test article at the rate of about 30μm per hour. In a day, the system is usually mis-aligned and it has to be touched up by adjusting separate mirror mounts. This is a laborious procedure which is obsoleted by the attitude control system. As a result, the attitude control system is built to handle large DC loads for long periods of time.

2.3. On-orbit disturbance simulation

The slow motions of the SIM spacecraft on orbit are to be rejected (or canceled-out) by detecting them with the guide interferometers that are looking at bright stars and feeding the detected signal into the science interferometer alignment devices to keep the dim star in the interferometer field of view. This general procedure is known as the Feed-Forward algorithm, and it contains an angular part that controls the direction jitter as well as a path-length part that controls the interferometer path-length jitter. Testing this on the STB3 requires the ACS to produce simulated spacecraft motions that may have large amplitudes to test large rejection values. Since the interferometer has a finite noise level (nominally 20 nm rms or so), to test large rejection values like 80 dB requires very large drive amplitudes of the order of a mm. The attitude control system is built to supply such amplitudes anywhere in the frequency range of 0 Hz to nearly 1 Hz. The star-simulator suspension resonance at about 1 Hz is avoided by the drive system. The ACS has further useful output up to 5 Hz at which the large table mass becomes to hard to move.

3. THE SENSOR SYSTEM

The sensor system is schematically shown in Fig. 1. It consists of four quadrant diodes placed on the test article illuminated by lasers placed on the star simulator table and three heterodyne gauge heads placed on the side star-simulator table monitoring the position of three corner cubes mounted on the side of the test article.

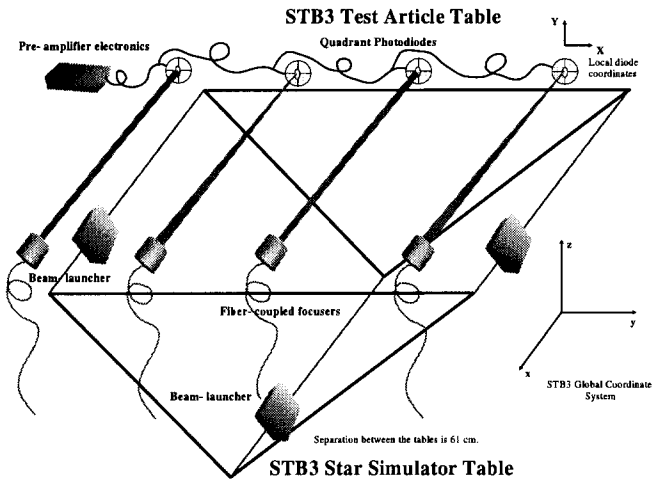

Figure 1. STB3 Attitude control system sensor placement.

3.1. The quadrant diodes

There are four quadrant diodes placed on the test article. The active area of these quadrant diodes is 1 cm in diameter.

The 635 nm, fiber collimated diode lasers mounted on the star-simulator table focus 5 mm diameter beams on two of these quadrant diodes. These quadrant diodes form the low-resolution, large dynamic range tracking system. Regardless of the orientation of the test article and star simulator table, these diodes always supply meaningful displacement signals which are used to bring the tables in coarse alignment. Since the focusing lenses are located at the laser end, the quadrant diodes are sensitive to displacement as well as tilt, both of which need to be detected.

Fig. 2 and Fig. 3 show the measured sensitivity of the low-resolution diodes in the local diode coordinate system with the test-article and the star-simulator tables are fully isolated on their air-filled supports. The detected noise level is just below 1 μm / $\sqrt{\text{Hz}}$ for the frequency range of 0.2 Hz to 187 Hz. The noise goes up as the atmospheric turbulence starts to go up sharply with decreasing frequency below 0.2 Hz.

Another lens system focuses 0.55 mm diameter beams on the remaining two quadrant photodiodes. These quadrant diodes form the high-resolution, low-dynamic range detection system. The noise level of these quadrant diodes is just below 100 nm / $\sqrt{\text{Hz}}$ in the frequency range where the atmospheric noise is not dominant over the actual motion, with the same light level as that on the low-resolution quadrant diodes.

The quadrant-diode and its electronics system have been tested in an enclosure with stagnant air[2] to yield angular detection levels of 1.6 nano-radians / $\sqrt{\text{Hz}}$ in the frequency range 1 Hz to 500 Hz with a laser spot diameter of about 80 μm. Fig. 4 shows the noise level in this arrangement.

Finally, the figures Fig. 5 and Fig. 6 show the quadrant diode and the heterodyne plate system before and after its protective scaffolding is installed.

3.2. The heterodyne gauges

The heterodyne gauge heads are the same ones used in author's 3-D metrology experiment.[1] These heads are capable of detecting picometer level distance changes in vacuum with cyclic-averaging and several nanometer level distance changes in air without cyclic averaging with a bandwidth of more than 10 kHz. Fig. 7 shows one of these heterodyne gauge heads. These heads have a maximum beam diameter of 3.0 mm. Recently, larger beam diameter (5 mm or more) gauge heads have been constructed by one of the authors (YG) and these will

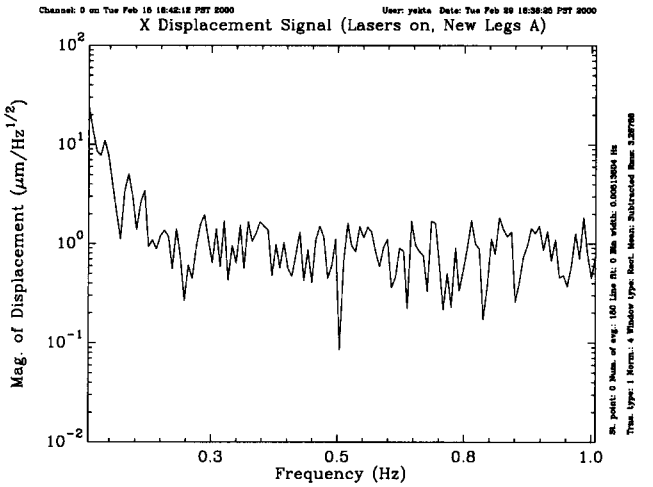

Figure 2. X motion signal from a low resolution quadrant diode in the local photodiode coordinates in the frequency range of 0-1 Hz while the star simulator and the test article are floating on the pneumatic supports.

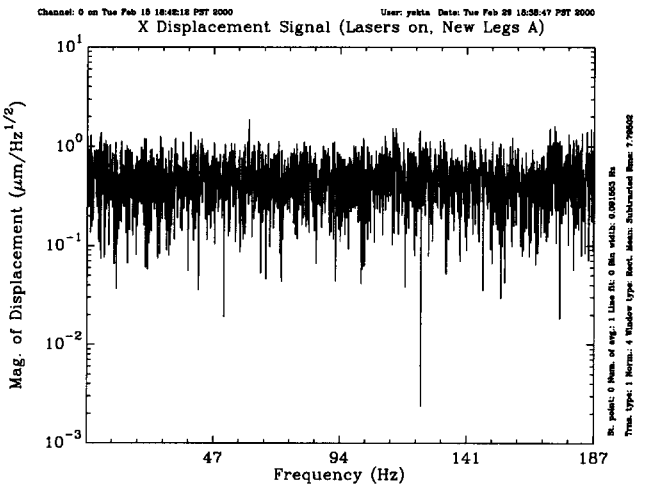

Figure 3. X motion signal from a low resolution quadrant diode in the local photodiode coordinates in the frequency range of 0-187 Hz while the star simulator and the test article are floating on the pneumatic supports.

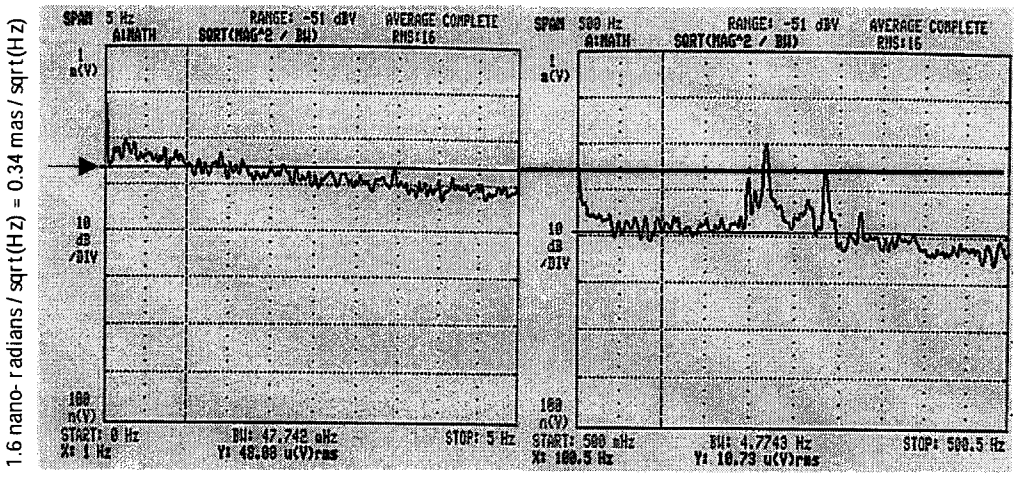

Figure 4. The ultimate angular sensitivity of the quadrant-diode system in stagnant air. The lens in front has a focal length of 20 cm in this angular detector arrangement and the air-path is 1.5 m long.

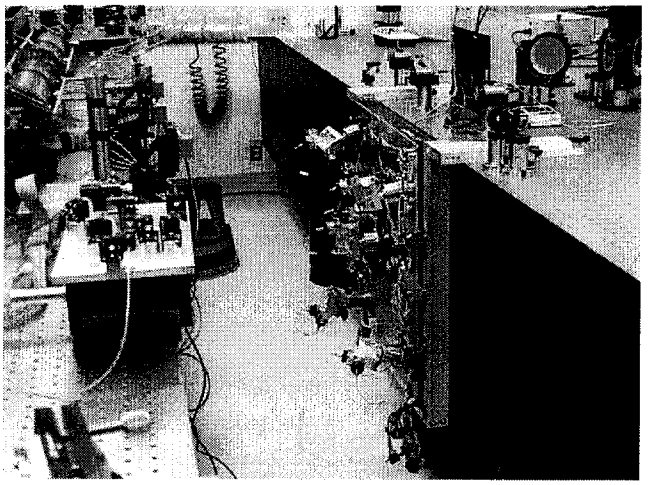

Figure 5. The attitude control system sensor array as installed. In this picture, the heterodyne heads on the side of the star simulator table has not yet been activated.

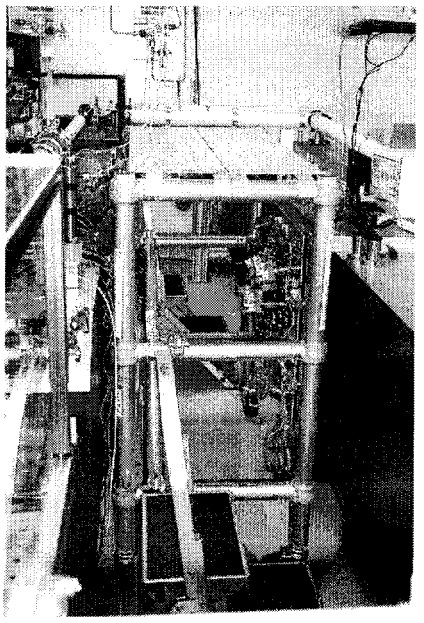

Figure 6. The attitude control system sensor array as installed with the protective shrouding.

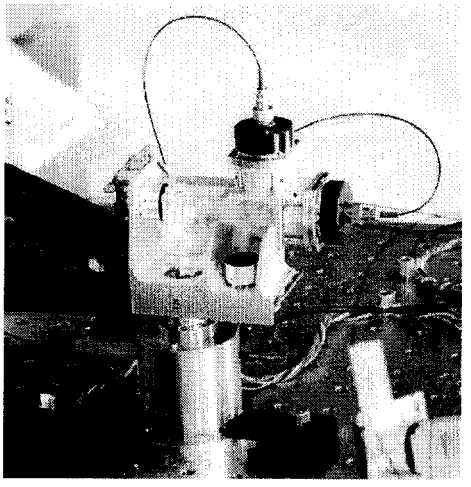

Figure 7. The heterodyne gauge head used in the ACS distance monitoring. This head has a 3 mm maximum diameter beam. Newer heterodyne gauge heads with a 5 mm diameter beam will be used as soon as we can install them.

be used in the ACS system to increase the tracking range while the relative motion between the test-article and the star-simulator is large compared to the heterodyne gauge head beam diameter.

4. THE DRIVE SYSTEM

The STB3 attitude control system drive directly applies restoring forces to the star-simulator table which is isolated from the ground vibrations on air-filled, passive vibration isolators. The drive system must let the table move in all degrees of freedom without mechanical interference and must not couple ground vibrations into the star simulator while applying sufficient restoring forces. In addition, no heat generating elements can be mounted on either the test article or the star simulator.

For the reasons stated above, a permanent-magnet-coil drive system is chosen. A small, cylindrical permanent magnet is mounted on the star-simulator table on its end and it generates no heat. A single coil rigidly mounted to the ground wraps around the magnet to apply forces along the long axis of the magnet. This is a one-dimensional force actuator that lets the table move in all three dimensions without losing actuation strength.

4.1. The permanent magnet

The 0.75" in diameter, 1.5" long, cylindrical permanent magnet is a Neodymium-Iron-Boron (this material not only produces the strongest magnets, but also the cheapest ones) magnet that has an internal energy density of 50 kilo-Gauss-Oersteds. The field strength on the surface at one end of the magnet is 6,400 Gauss and falls of rapidly like the field of a dipole with roughly the cube of the distance from the center of the magnet. The estimated field strength at the center of magnet is 14,400 Gauss.

Two such magnets will push each other out with a force of 9.6 Newtons when they are placed against each other like-poles facing with their centers 2.5" apart. The force increases rapidly if the magnets are forced to be closer together. It is nearly impossible for a human being to press them together with bare hands so that there is no air gap between the magnets with like poles facing each other. If two of these magnets are placed against each other with unlike poles facing, it is nearly impossible to separate them with bare hands by directly pulling them apart along the axis. A little tilt helps this situation.

4.2. The drive coil and its former

The drive coil is wound around a completely enclosed aluminum coil former. The aluminum former contains internal water cooling channels to take the excess heat out of the winding when needed. A temperature sensor (thermistor) placed inside the winding monitors wire temperature. The enclosed aluminum former also acts like a safety heat shield preventing burns resulting from direct contact with the hot windings. Another function of the aluminum former is to serve as a motion damping element by eddy currents as the magnet moves inside the well-conducting metal cup.

The coil has about 2,300 turns and its nominal DC resistance is about 77.6 Ohms at 25 degrees Celcius. Fig. 8 shows the winding DC resistance as a function of the winding temperature. Fig. 9 illustrates the change in coil's DC resistance as a function of current through the coil. Fig. 10 and Fig. 11 show the DC voltage across the coil as a function of DC current through the coil and the power dissipated in the windings as a function of DC current through the coil respectively.

The coil, as designed, with its all-metal former has a much lower self-inductance at low frequencies than that of an air-spaced coil. Its inductive reactance equals its direct current resistance at about 50 Hz. At frequencies below 50 Hz, the inductive reactance of the coil is equal to or less than that of an air spaced coil. In fact, the coil inductive-reactance follows a power-law with an exponent less than 1 as a function of drive current frequency as shown in Fig. 12.

Due to its designed-in high DC resistance, the coil can be driven by 50 to 75 ohm output impedance function generators directly, even at very low frequencies.

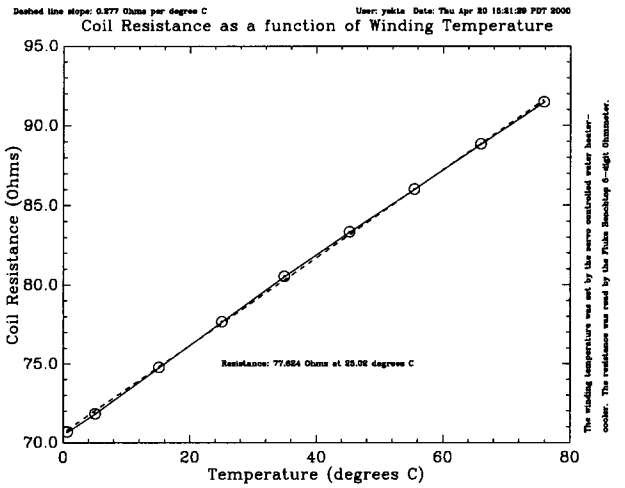

Figure 8. The drive coil winding resistance as a function of winding temperature.

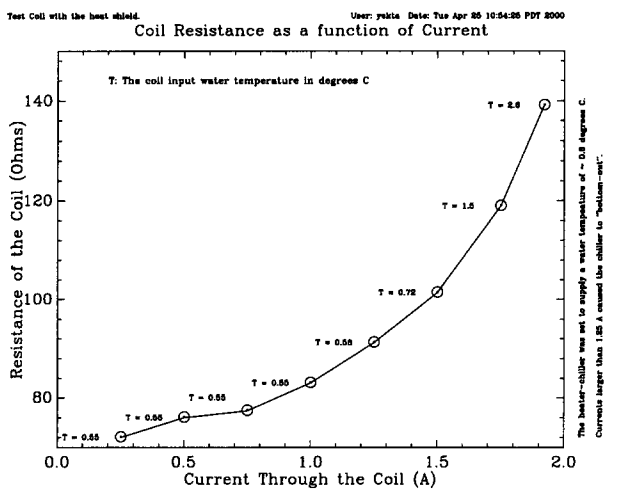

Figure 9. The drive coil winding resistance as a function of current through the winding.

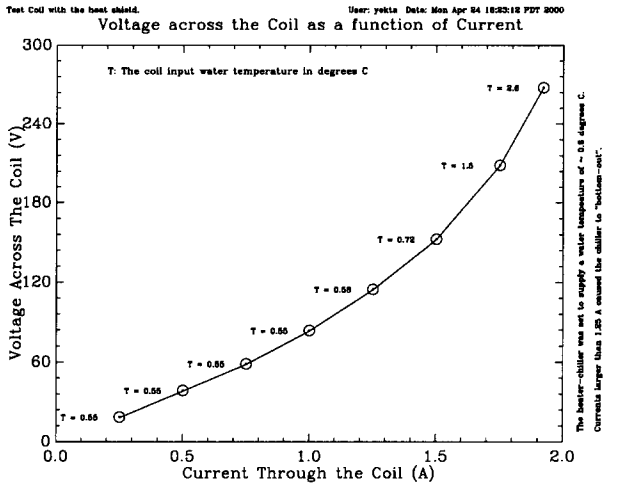

Figure 10. The drive coil voltage as a function of the drive current through the winding at DC.

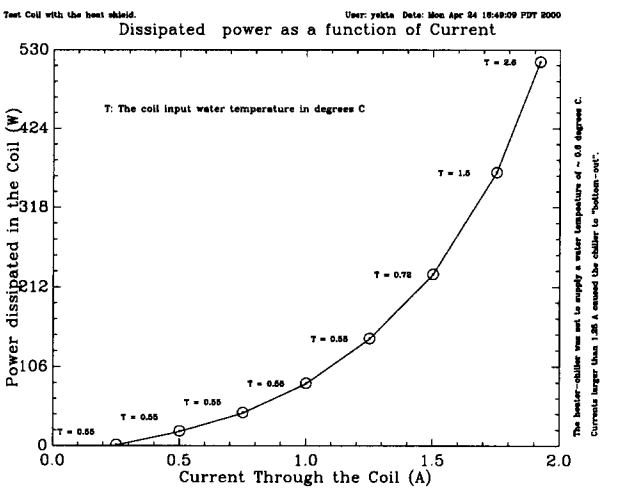

Figure 11. The power dissipated in the drive coil winding as a function of the drive current through the winding at DC.

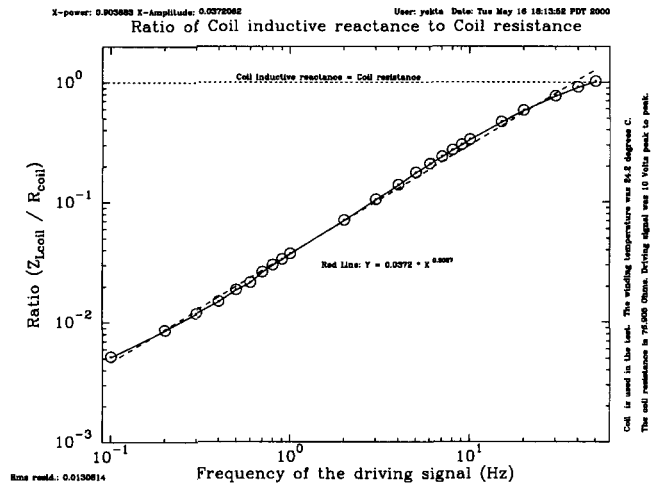

Figure 12. The drive coil inductive reactance to drive coil DC resistance ratio as a function of drive current frequency.

4.3. The coil-magnet system

The permanent magnet and the coil as described above form the 1-dimensional force actuator when the center of the magnet is placed at a distance equal to about one HALF the RADIUS of the coil from the center of the coil winding on the axis of the coil with the magnet pointing along the same axis.

This placement is critical. It is well known that if an ideal magnetic dipole is placed on the axis of a coil with a single turn, the axial force on the dipole goes through a maximum as the dipole comes closer to the coil. The maximum force point is exactly one half of the radius of the coil away from the ideal center of the coil with a single turn.

If the dipole is placed at the maximum force point, then to first order in the dipole position along the axis of the coil as measured from the maximum force point, the force on the dipole is independent of the dipole position, by the definition of maximum as the first derivative of the force on the dipole as a function of this distance vanishes.

Furthermore, if the dipole is constrained not to rotate away from the axis, there is no transverse force on the dipole as it moves off-axis transversely without rotation to the same order.

The diameter of the coil and the number of turns of the winding is chosen such that the coil produces sufficient force on the chosen permanent magnet while maintaining position independence over a few mm in all directions as described above.

The coil-magnet system is first tested on a gravity balance. The magnet is attached to the "basket" of the balance and the tares are adjusted so that the beam is balanced. The coil is attached to a vertical slider, and supplied with a fixed DC current. The coil is brought over the magnet, and the tares are adjusted to compensate for the average force over the region that contains the maximum force point. The coil is then moved back and forth slowly until the beam deflection is a maximum. This is the optimum coil-magnet separation.

Fig. 13 shows the coil applying a force of 1270 grams of weight to the magnet on the gravity balance. Fig. 14 shows the force applied by the coil as a function of DC current through the coil at the maximum force point.

4.4. The actuator placement

The STB3 star-simulator table rides on six Newport I-2000 pneumatic, auto-leveling vibration isolators connected in pairs to form a three-point, kinematic support system. This support system has a dead-band of ± 0.25 mm at each support before the auto-leveling regulators detect the tilt and adjust the air flow. A 9.6 Newton force

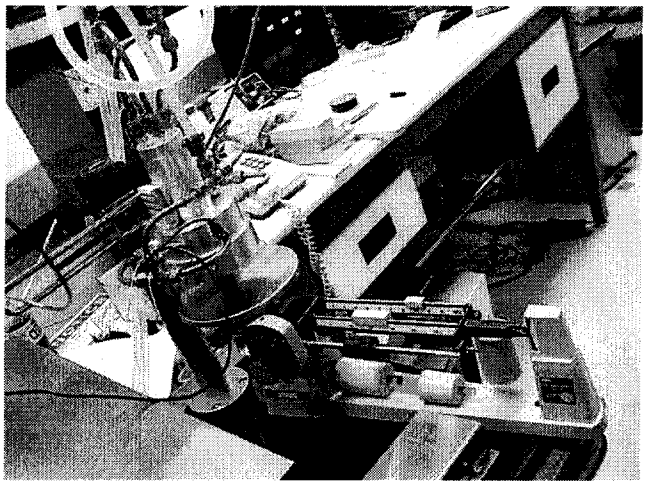

Figure 13. The drive-coil-permanent-magnet force calibration set-up.

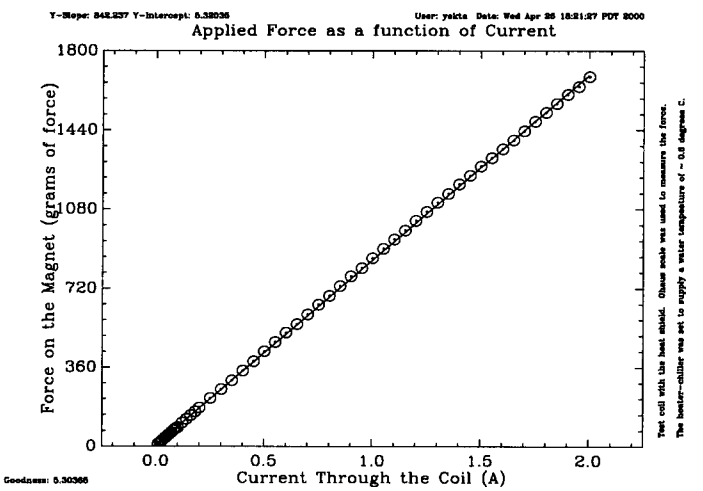

Figure 14. The force applied by the drive coil to the permanent magnet at the critical magnet location as a function of the current through the coil at DC.

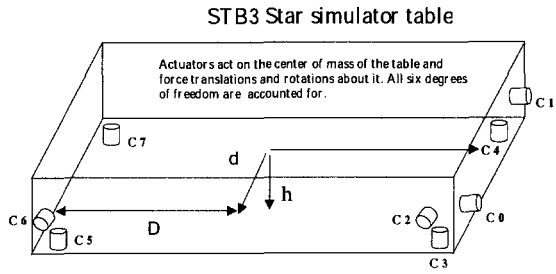

Figure 15. The attitude control system actuator placement diagram for the STB3 star simulator table.

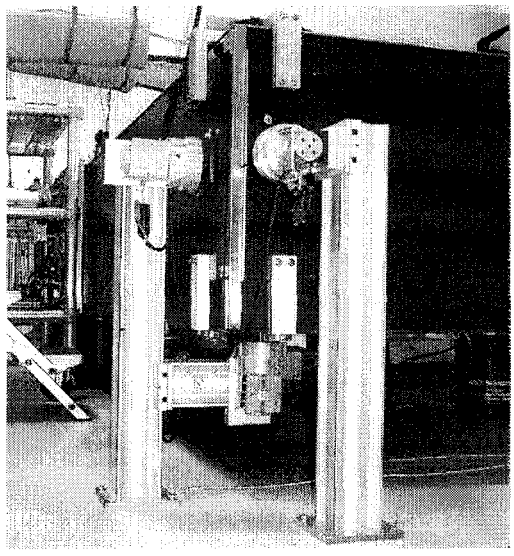

Figure 16. The attitude control system drive actuators as mounted near one corner of the STB3 star-simulator table.

applied at one edge of the table produces about 0.5 milli-radians of tilt. It is clear that the coil-magnet actuator system is sufficient to move the star-simulator table within the dead-band of the auto-leveling regulators.

The lateral isolation for the table is supplied by an inverted-pendulum suspension built into the pneumatic isolator. There is no air adjustment regulator for these degrees of freedom.

We have chosen eight actuators to place around the table instead of the minimum six. The actuator placement is shown in Fig. 15. Note that at the nominal ±10 N of force per actuator (the actuators can supply nearly twice this amount easily), we have at least ±20 N of force available per degree of freedom of the star-simulator table with this arrangement. Some of the degrees of freedom (like the direct lift against gravity of the star-simulator table) get ±40 N of force nominally. Fig. 16 shows the actuators as mounted.

5. THE CONTROL SYSTEM

The control system for the STB3 ACS consists of three parts: Sensor readout, feedback computation, and actuator drive.

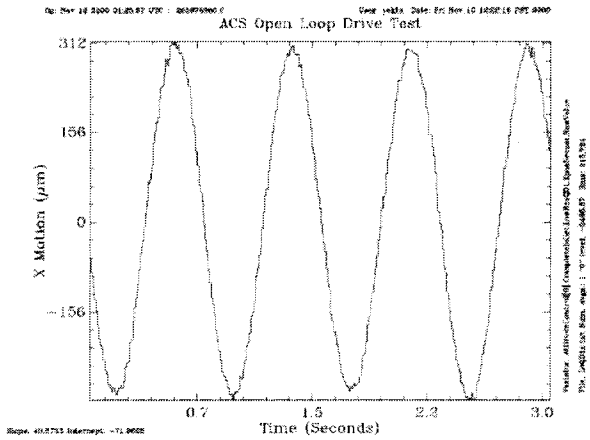

Figure 17. An early test of the ACS open-loop drive: Coils drive the table at a frequency (1.33 Hz) slightly higher than the table suspension resonance. The table motion is monitored with a low-resolution ACS quadrant photodiode.

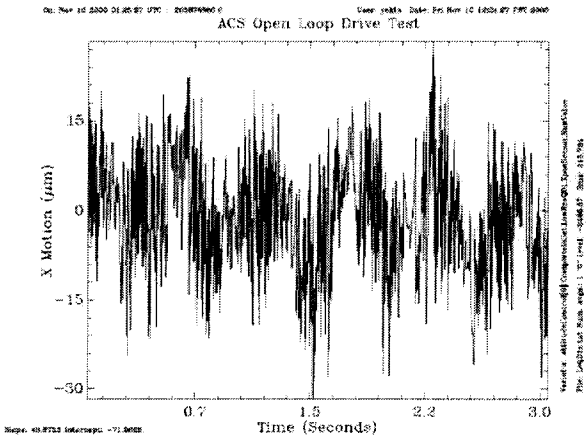

Figure 18. An early test of the ACS open-loop drive: The drive frequency is fitted out in Fig. 17 leaving atmospheric turbulence and the table suspension resonance.

5.1. The sensor readout

The quadrant diode amplifier outputs (X, Y and SUM in the local quadrant diode coordinates) are directly fed into bipolar, 16 bit analog to digital converters in a VME crate. The heterodyne gauge photo-detector outputs go to post-amplifiers that convert the sinusoidal signals to square waves with phase information. These square waves are then fed into a phase digitizer residing in the same VME crate. These digitized readings are interpreted by the STB3 real-time control software running on a real-time CPU in the VME crate to produce the relative motion of the test article with respect to the star simulator in the global coordinates. The interpreted data can be recorded or displayed by the real-time control software on a remote display workstation.

5.2. The feedback computation

The feedback computation simply takes the relative motion of the test article with respect to the star simulator and computes and filters the feedback signals that are to be applied to the coils to steer the star simulator table to the desired target location or target motion in the closed-loop mode. The open-loop mode of this software which simply moves the star simulator table as prescribed while recording the sensors is fully developed and running. Fig. 17 shows and early test of the open-loop system as the coils drive the star-simulator table near the resonance of the table at 1.33 Hz. Fig. 18 shows the residual motion after the drive sinusoidal waveform has been fitted out. The table resonance which is at a slightly lower frequency is evident in the residual motion. We expect the closed-loop mode to be active shortly after this conference.

5.3. The actuator drive

The drive signals computed by the real-time CPU are sent to 16 bit digital to analog converters that reside in the ACS VME crate. The output of the digital to analog converter for each actuator goes through a Techron 7520 stereo power amplifier that is wired to drive the coil in the push-pull mode to double the range of the amplifier. These amplifiers can apply ± 90 Volts to the coils. The outputs of the amplifiers are wired directly to the coils to produce the force needed to steer the star simulator table. The thermistors in the coil windings are read independently with an OMEGA thermistor thermometer and the results are directly displayed to provide a live temperature monitor for each coil as a safety measure.

6. CONCLUSION

We have developed an attitude control system (ACS) for the SIM Interferometry Test Bed 3 (STB3). The system has been used in the open-loop drive mode to demonstrate the spacecraft motion rejection (80 dB rejection at 0.01 Hz) performance of STB3. We expect the ACS system to be fully functional in the closed-loop mode shortly after this conference, enabling us to automatically align the test article to the star simulator as well as supplying some additional amount of vibration and drift cancellation.

ACKNOWLEDGMENTS

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