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DEVELOPMENT OF A TWO AXIS MOTION SIMULATION SYSTEM FOR THERMAL/VACUUM SATELLITE TESTING

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ABSTRACT

A two-axis motion simulation system for thermal/vacuum testing of large satellites, in a space simulation chamber, has been developed. Satellites as large as 3000 kilograms with a 4-meter diameter and a 5-meter length can be tested. This motion simulator (MS) incorporates several unique features which result in a less complicated design with improved performance when compared to previous satellite motion simulators. The structure is welded aluminum and, with the exception of the slip ring, completely vented to the simulated space environment. The use of aluminum and large diameter direct drive motors produces structural resonances greater than 7 Hz and allows a passive cooling system to be used. A vented structure, which greatly simplifies the design and manufacturing tasks, is possible because AC servo motors and position transducers are used which have no corona or brush wear problems. The slip ring module is hermetically sealed and maintained at atmospheric pressure to eliminate corona from its exposed rings and brushes. Other components including the thermocouple multiplexing system, bearing lubrication, motors, and transducers are fully compatible with the high vacuum environment. Finally, the control system can produce motion with arc-second precision via local or remote computer interfaces. This cost effective solution fully meets the thermal/vacuum test requirements for axis stiffness and alignment, solar source shadowing, system reliability, position and rate accuracy, outgassing, corona, temperature stability, and data transmission.

INTRODUCTION

A two-axis motion simulation system has been designed and manufactured by Contraves Goerz Corporation (CGC) for testing satellites in a large thermal/vacuum space simulation chamber. This development has been completed under contract to the Indian Space Research Organization for use at their Satellite Center in Bangalore, India and will be operational in 1989. Figure 1 is an artist's concept of the motion simulator mounted inside the space simulation chamber.

THERMAL/VACUUM TEST REQUIREMENTS

Space Simulation Chamber

As shown in Figure 1, the space simulation chamber consists of a vertical cylinder with an intersecting horizontal auxiliary chamber which can achieve vacuum levels for testing of 5×10^{-5} millibar. The internal LN_2 shroud diameter of the vertical cylindrical chamber, is 8 meters and the MS rotates within this swing diameter. These shrouds, and shrouds mounted on the MS arms, are painted black and cooled to 100 degrees K to maintain a uniform cold space background. Finally, the solar simulation beam enters through the horizontal auxiliary chamber and illuminates the satellite which is being supported by the MS.

Satellite and Motion Simulator

The satellite, attached to the spin axis shaft, is shown in Figure 1 as a horizontal cylinder 4 meters in diameter and 5 meters in length, with a specified weight of 3000 kg. The satellite geometric center is aligned with the chamber centerline and

the centerline of the solar simulation beam. In addition to the orientation shown, the satellite can also be supported with its cylinder axis perpendicular to the MS spin axis, which requires the swing clearance to be 3.2 meters from the top of the tilt axis. In both orientations the MS is capable of rotating the satellite about the spin and tilt axes to accurately simulate orbital motions with a minimum of interference to the solar simulation. Connectors for more than 1000 instrumentation channels are mounted on the spin axis shaft, providing signal transmission capabilities as summarized in Table 1.

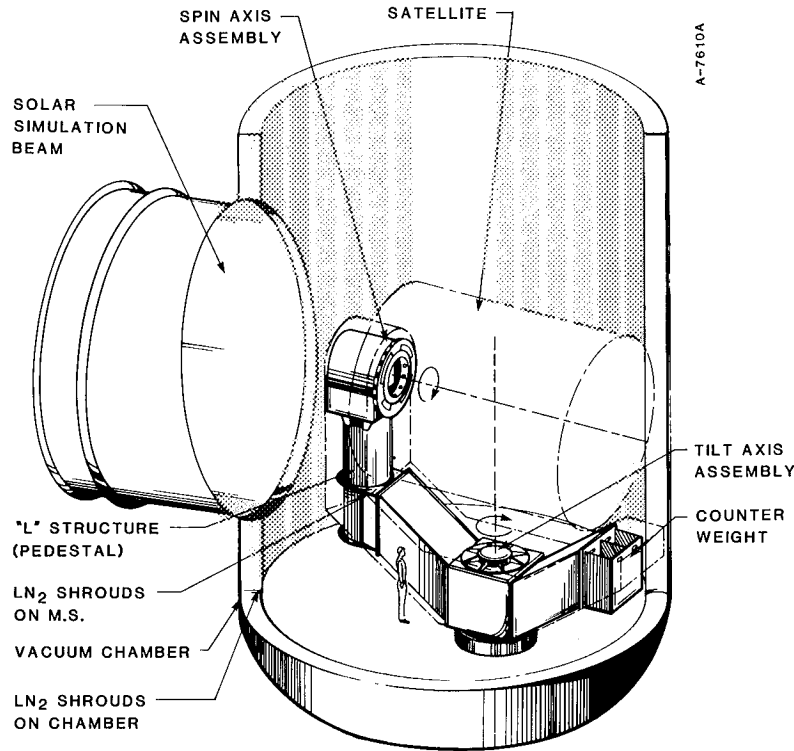


Figure 1. Artist's Concept of Motion Simulator

TABLE 1. SATELLITE SIGNAL TRANSMISSION REQUIREMENTS

Pressurized Slip Ring Assembly

DC Lines	350
Direct Thermocouple Channels	50
Co-ax Slip Ring Channels (up to 400 Mz)	15
RF Rotary Joint Channels (Up to 8 GHz)	2

Thermocouple Multiplexing System

Number of Channels	640
Accuracy	±1 degree C

MOTION SIMULATOR DESIGN PHILOSOPHY

To develop this two-axis motion simulator CGC integrated its experience in producing inertial guidance test equipment and range tracking instruments with requirements for thermal/vacuum testing of a large satellite. Typically, inertial guidance test

equipment and range tracking instruments require high stiffness structures, precision bearings, precise axes alignments, direct drive motors, and arc second resolution rotary transducers. In addition, the control system must produce a wide variety of high accuracy motion scenarios, including Earth rates and independent axis operation, through manual or remote computer control. Finally, the payload mechanical and electrical interfaces are critical and must provide stable mounting flanges, clear line of sight, and signal-power transmission via slip rings.

This MS for thermal/vacuum satellite testing requires all of these capabilities and combines them with the need to operate in a space simulation chamber while supporting a satellite the size of a truck. For this project, CGC's previous experience with "off-the-shelf" brushless AC motors, resolvers, and Inductosyns* and their supporting control electronics meshed very well with high vacuum operation. Thus, the general approach was to vent as much of the MS as possible to the high vacuum and avoid the complexities and cost of pressurizing and sealing the MS's internal volume. As a result, the principal design challenges of this project were supporting this large payload, while minimizing the solar source shadowing, and achieving compatibility with, and reliability in the high vacuum and thermal extremes of the space chamber.

MOTION SIMULATOR DESCRIPTION SUMMARY

The MS assembly is shown in Figure 1 with its major components labeled. The overall simulator weight, less the satellite, is 30,000 pounds and the lowest structural resonance is 7 Hz. The spin axis is supported on top of the "L" shaped MS structure with its rotating axis horizontal and intersecting the chamber center. Attached to the structure, opposite the spin axis, is a counterweight which minimizes the overturning moment that the tilt axis and mounting stand must support. The tilt axis supporting the satellite, spin axis, and "L" structure also intersects the chamber center. Table 2 is a performance specification summary of the tilt and spin axes.

TABLE 2. PERFORMANCE SPECIFICATION SUMMARY

	<u>Spin Axis</u>	<u>Tilt Axis</u>
Rotational Limit	Continuous	±180 degrees
Position Resolution	0.0001 degrees	
Position Accuracy	±0.003 degrees	
Rate Resolution	0.0001 degrees/second	
Rate Accuracy	0.0005 percent of setpoint	
Rate Drift	Essentially Zero	
Maximum Rate	±10 RPM	±1.0 RPM

Spin Axis

A cross-sectional drawing of the spin axis is shown in Figure 2. This axis is capable of continuous rotation up to ±10 RPM by using a 500-line slip ring assembly which transmits electrical signals from the rotating shaft to the stationary housing. The slip ring assembly is maintained in a atmospherically pressurized and sealed module. The dynamic seal is a ferrofluidic unit and the electrical feedthroughs are molded epoxy in stainless steel fittings. With the exception of this slip ring module, the entire MS is completely vented to the space chamber environment. Rotating inside the spin axis shaft is one-half of the thermocouple multiplexing system.

*Trademark of Farrand Inc., Valhallen, New York.

The spin axis supports the large cantilevered satellite using an aluminum structure and wire race cross roller bearings lubricated with a fluoroether grease. A direct drive AC servo motor drives the axis, and a separate modular readout package provides rate and position feedback for the servo control and motor drive systems. The readout package contains an Inductosyn*, two resolvers, and a DC tachometer. All of these components, except the tachometer, are brushless non-contacting transducers. During times when the axis must be stationary, a pin and bushing stow lock is provided. Finally passive cooling and active heating are used to maintain safe operating temperatures.

An additional feature of the spin axis is that it can be operated as a stand alone unit. A complete set of in-line connectors is provided at the mounting flange. Thus, this assembly can be mounted on a separate support stand in the chamber to provide single axis test simulations.

Tilt Axis

A cross sectional drawing of the tilt axis is shown in Figure 3. It has a limited rotational freedom of ± 180 degrees and can rotate at a maximum speed of 1.0 RPM. A simple twist cable passes all electrical signals from the rotor to stator and a cushioned stop prevents excessive over travel and damage to the flexible cable. This axis is essentially the same design as the spin axis assembly except the rotors and stators are reversed. That is, the same bearings and grease, motor, readout package, stow lock, and temperature control system are used but the housing rotates and the shaft is stationary. This approach simplified the design process and enhances commonality for training, spares, and maintenance. Figures 4, 5 and 6 show the spin axis and tilt axis assemblies in various stages of manufacture.

Control Console

The servo control console is located in the system control room. In addition to providing independent control for each axis of the motion simulator, it also contains the safety interlock status chassis, temperature control system chassis, and the receiver chassis for the thermocouple multiplexer (MUX).

Closed loop feedback control is achieved by using the position and rate information from the readout transducers to generate torque commands to the motor drive console. Positions can be commanded with a resolution of 0.0001 degrees and angular rates with a resolution of 0.0001 degrees per second using manual keyboard entries or an RS-232 computer interface. A separate digital display for each axis provides, at the operator's choice, real-time position or rate information. Safety interlocks including engaged stow locks, overtravel, and power amplifier faults are displayed on the interlock chassis. The computers, which control the entire thermal/vacuum test process, can command the MS and determine the status of all safety interlocks.

Motor Drive System

A motor drive console is located in a separate room away from the sensitive instrumentation, and has its own isolated power supply. This isolation prevents interference from the high-power pulse-width-modulated (PWM) signals, which drive the AC servo motors.

The motor drive console receives torque commands from the servo controller and powers the AC servo motors using a PWM high current, high voltage signal. Position

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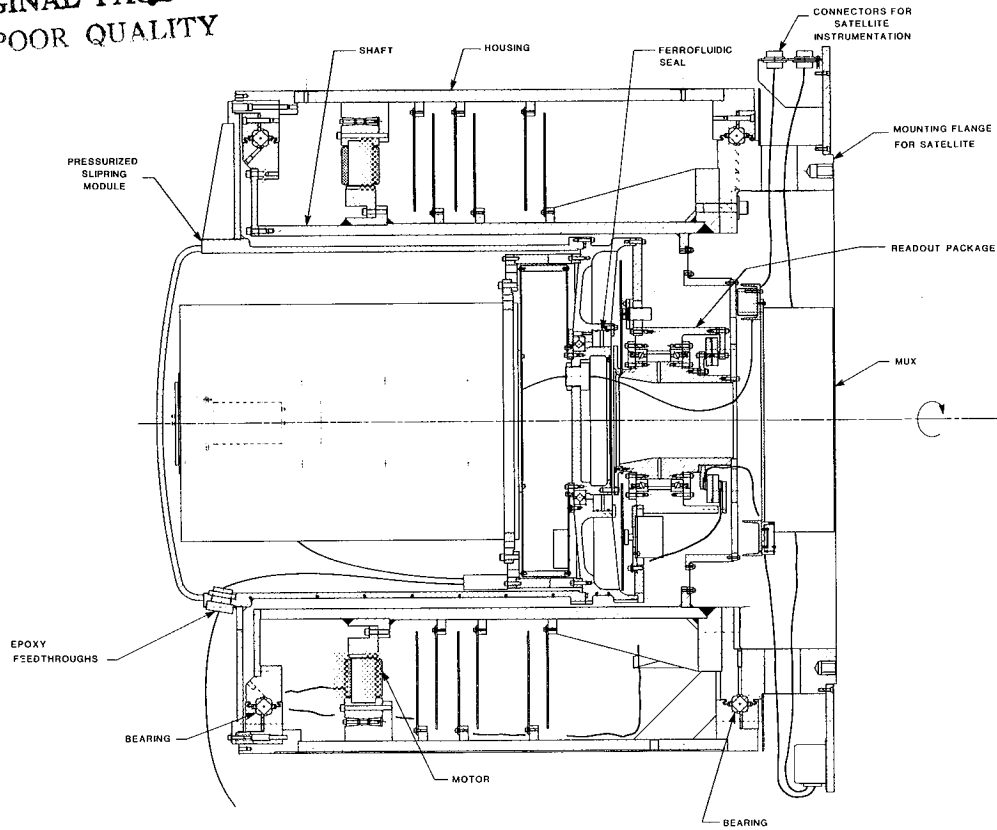


Figure 2. Spin Axis Assembly

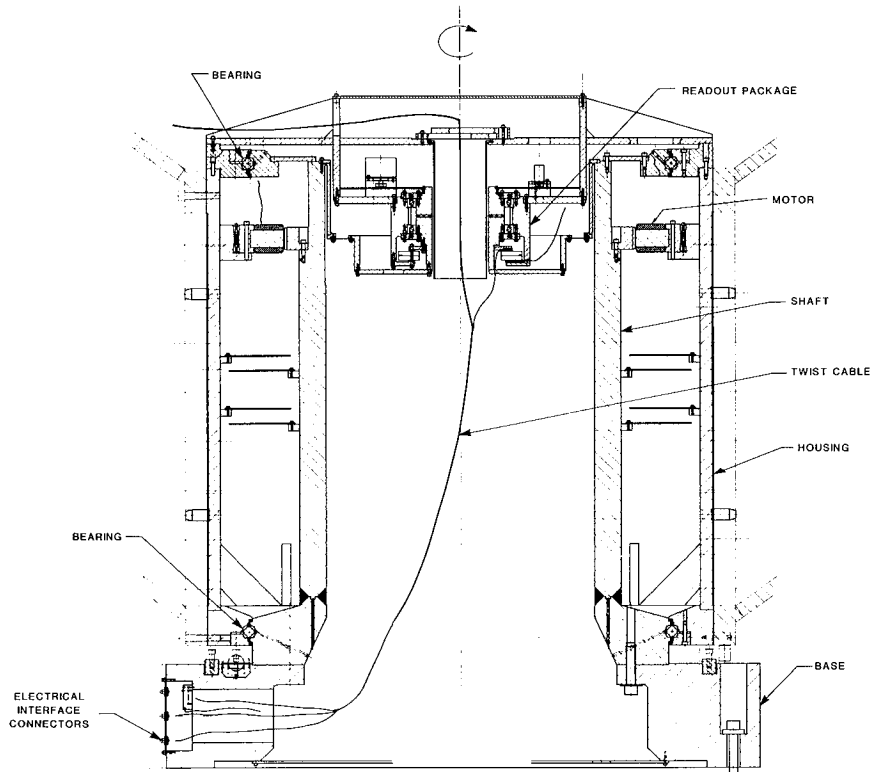


Figure 3. Tilt Axis Assembly

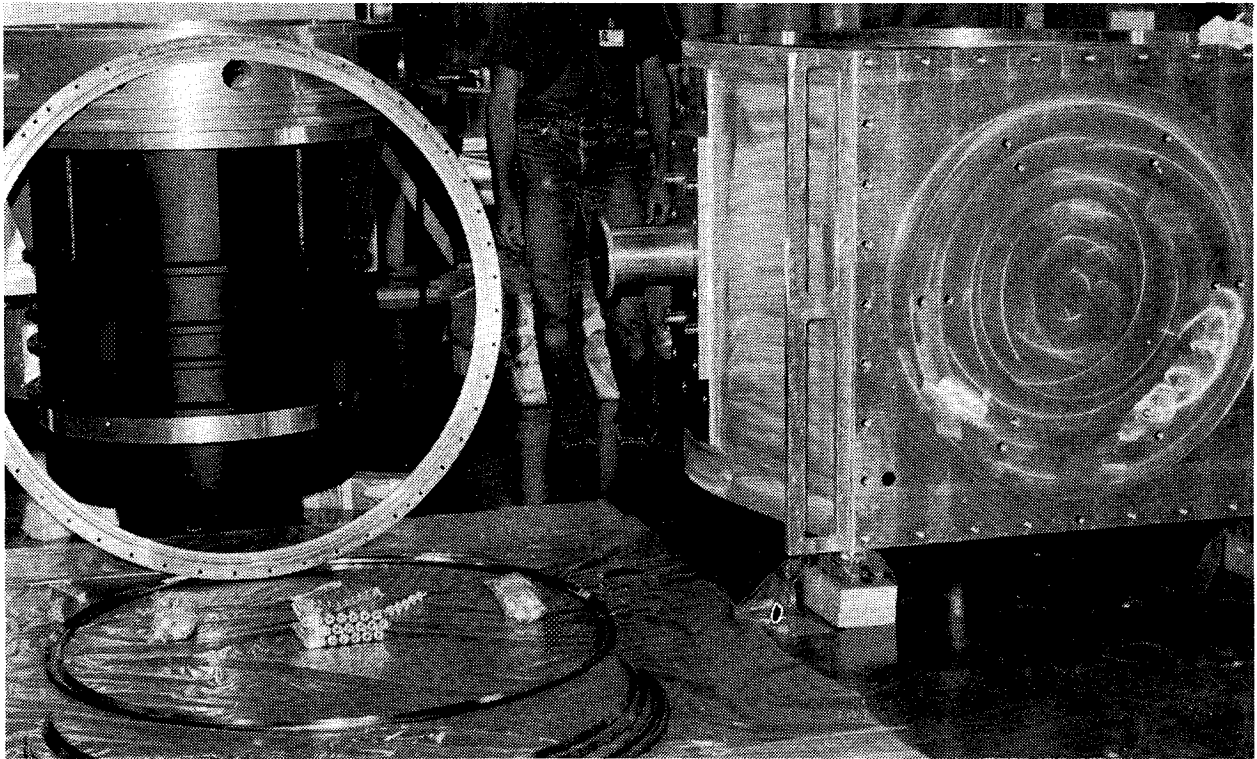


Figure 4. Spin Axis Shaft, Housing, and Bearing Components

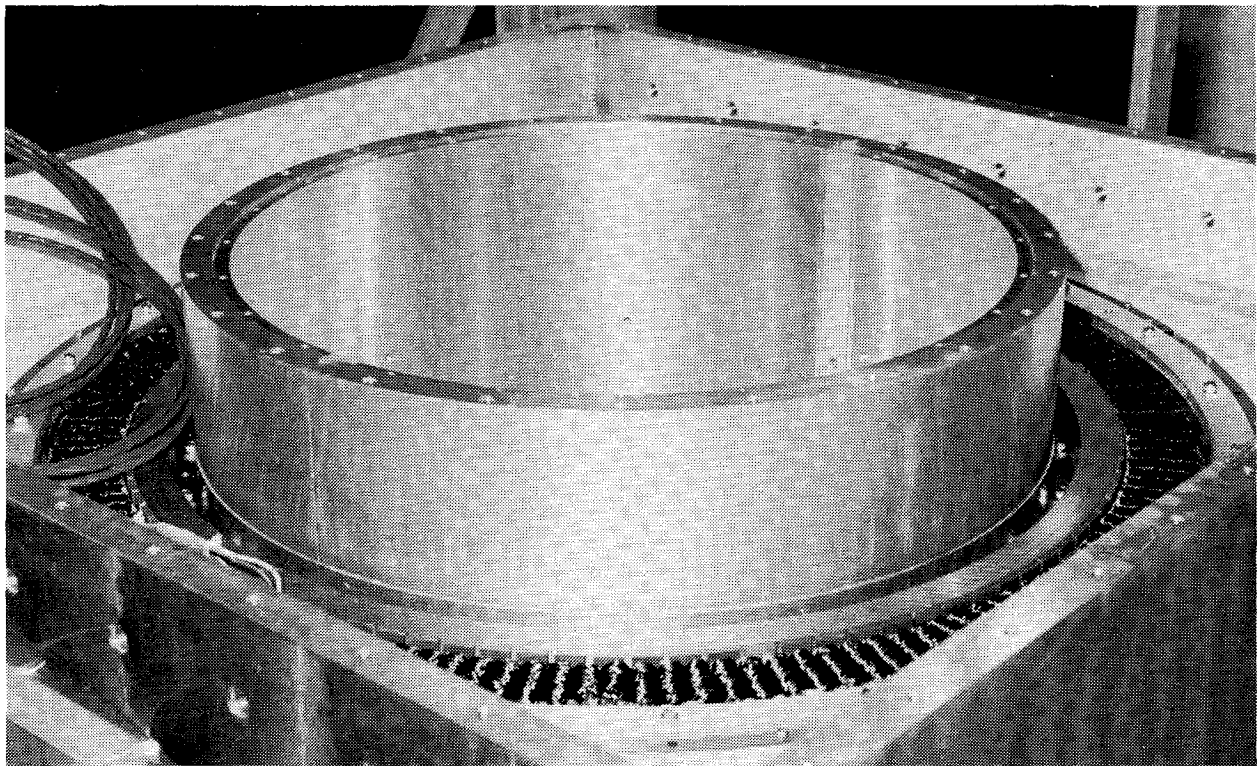


Figure 5. Tilt Axis Assembly with AC Brushless Motor Uncovered

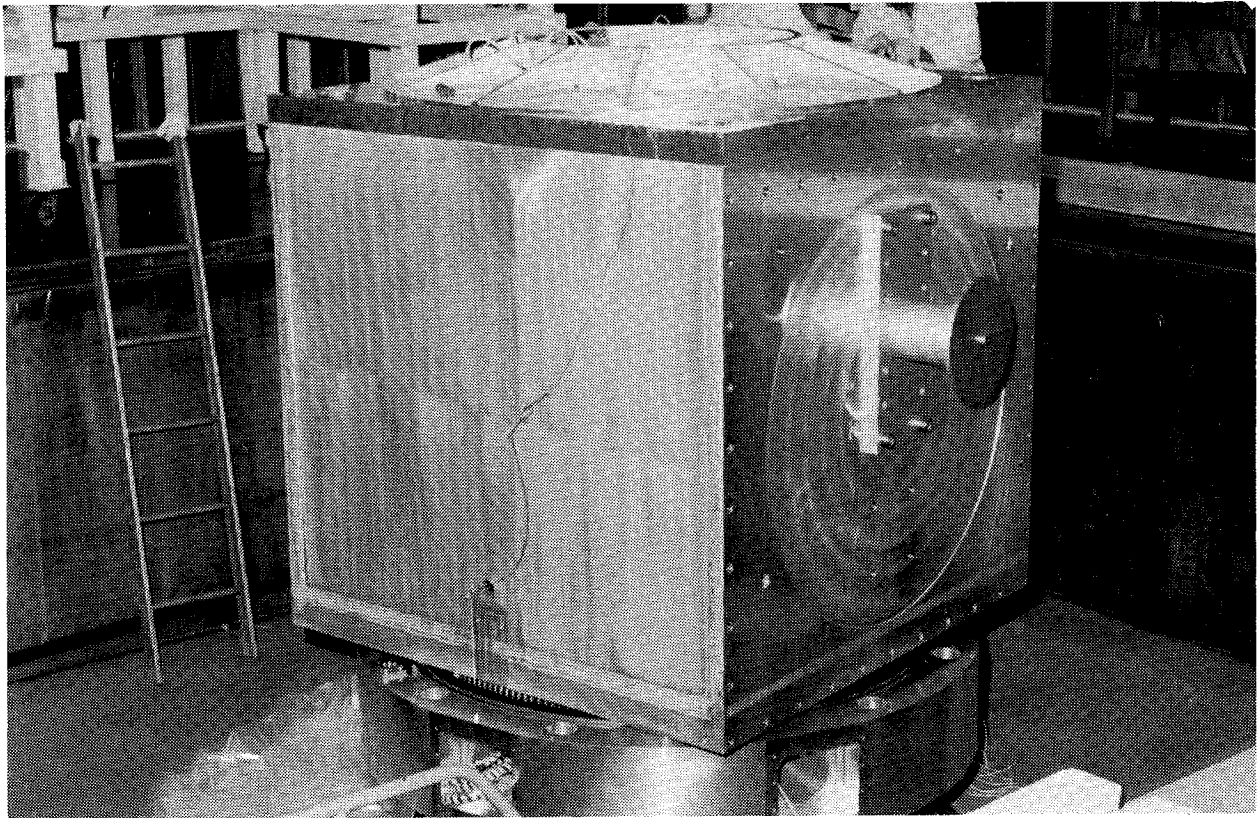


Figure 6. Completed Tilt Axis Assembly

information is received from the resolver on each axis to electronically commutate the motor.

IMPORTANT DESIGN CONSIDERATIONS

Structural Stiffness vs. Solar Source Shadowing

An important compromise inherent in developing the motion simulator was the structural stiffness versus the solar source shadowing. A large structure is the most effective way to support the payload, but this interferes with the solar simulation beam. This interference, or shadowing, can be minimized only by reducing the structure's cross-sectional area, which results in lower stiffness. A smaller and more compliant structure has lower resonances, which may be excited by fluid flow in the shrouds or vibrations in the mounting platform. In addition, low simulator structural resonances may couple the satellite structural resonances and make it more difficult to compensate the axes control systems resulting in a low gain/low bandwidth servo loop. Finding an acceptable compromise to this problem is further complicated by the asymmetry of the "L" shaped configuration and the cantilevered satellite mass.

It should be noted that a major contributor to solar source shadowing is the spin axis assembly. However, its diameter is determined by the space requirements for the satellite instrumentation (slip ring, MUX and connectors). Thus, the diameter of the spin axis shaft and housing was fixed prior to completing the FEM analysis.

A compromise solution was developed with ANSYS* 4.2B, a finite element modeling

*Trademark of Swanson Analysis Systems.

(FEM) software package. The design goal was a MS with its lowest resonance at 7 Hz and a minimum cross sectional area shadowing the solar beam. As a secondary goal, the overall weight was to be as low as possible.

The final FEM meets these requirements. This half symmetric model is constructed of shell and beam elements (structural walls, fasteners, etc.), spring elements (bearings), and point mass elements (payload and non-structural components). The satellite is modeled at the intersection of axes as a 3000 kg mass and its corresponding inertia. Finally, two important assumptions for this analysis are that the satellite and mounting stand have very high stiffness.

Figure 7 is an ANSYS plot of the lowest predicted mode shape and frequency, and clearly shows the "up and down" vibration of the satellite and its associated 7.44 Hz frequency. To achieve this result several decisions were made. The bearings are a cross roller wire race configuration with a 48-inch pitch diameter. This type of bearing has excellent stiffness using modest preload and low friction. In addition, cross roller bearings are self-preloading which, in conjunction with the split races, makes them less sensitive to temperature changes. Aluminum is the structural material, not stainless steel, because it allows thicker walls to be used while achieving the equivalent mass and sectional stiffness properties. This characteristic allows aluminum to avoid the buckling problems of stainless steel

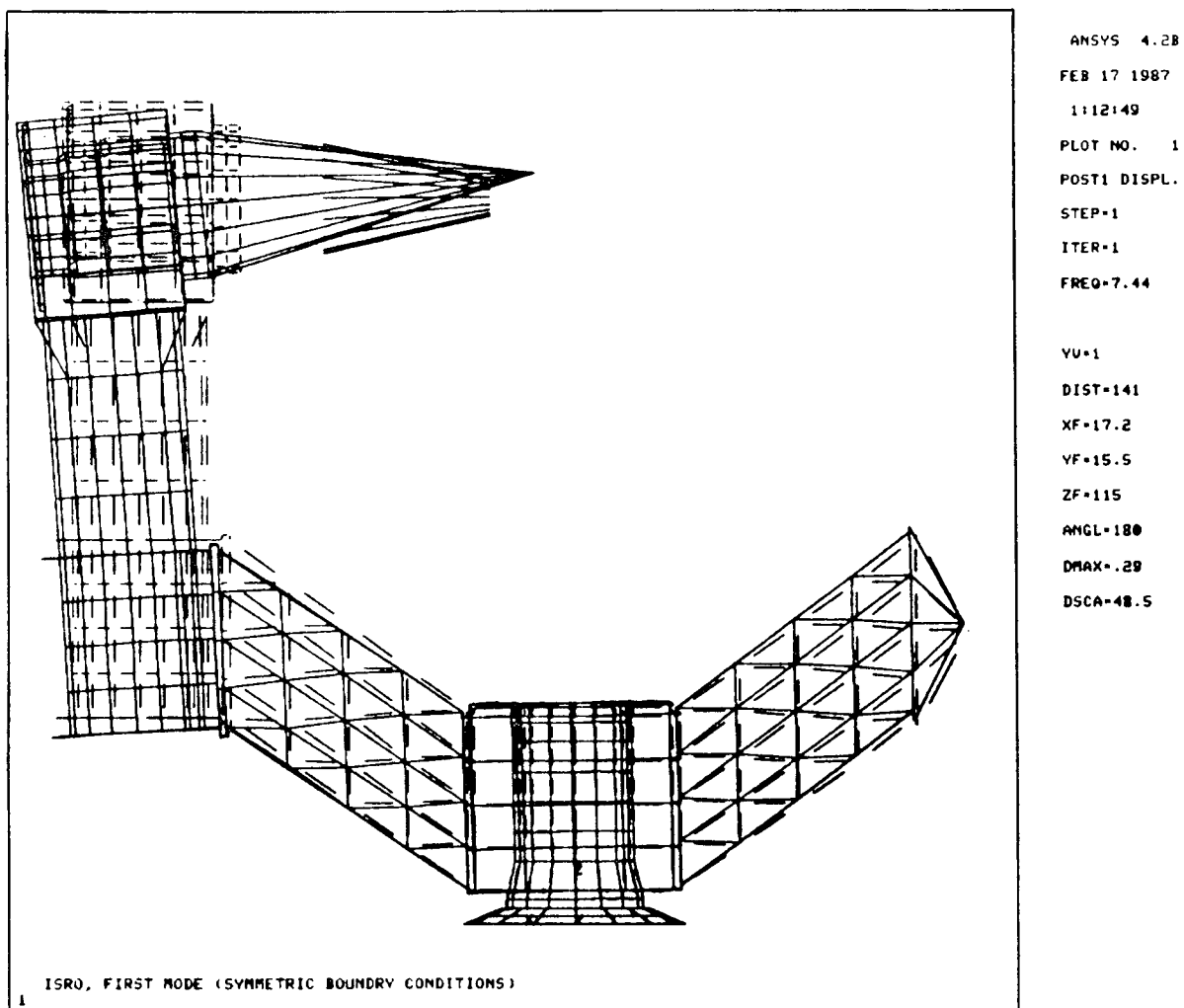


Figure 7. First Mode Symmetric Boundary Conditions

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with fewer stiffeners. In addition, aluminum's high thermal conduction and capacity fit well with a passive cooling scheme, which is discussed in a later section. The upward sloped arms are configured to minimize the unsupported length of the vertical pedestal while meeting the satellite clearance requirements. Finally, the diameter of the pedestal, which shadows the solar beam, is the minimum size that meets the 7 Hz requirement. Figure 8 shows the pedestal and support arms ready for assembly. Figure 9 shows the support arm assembled on tilt axis.

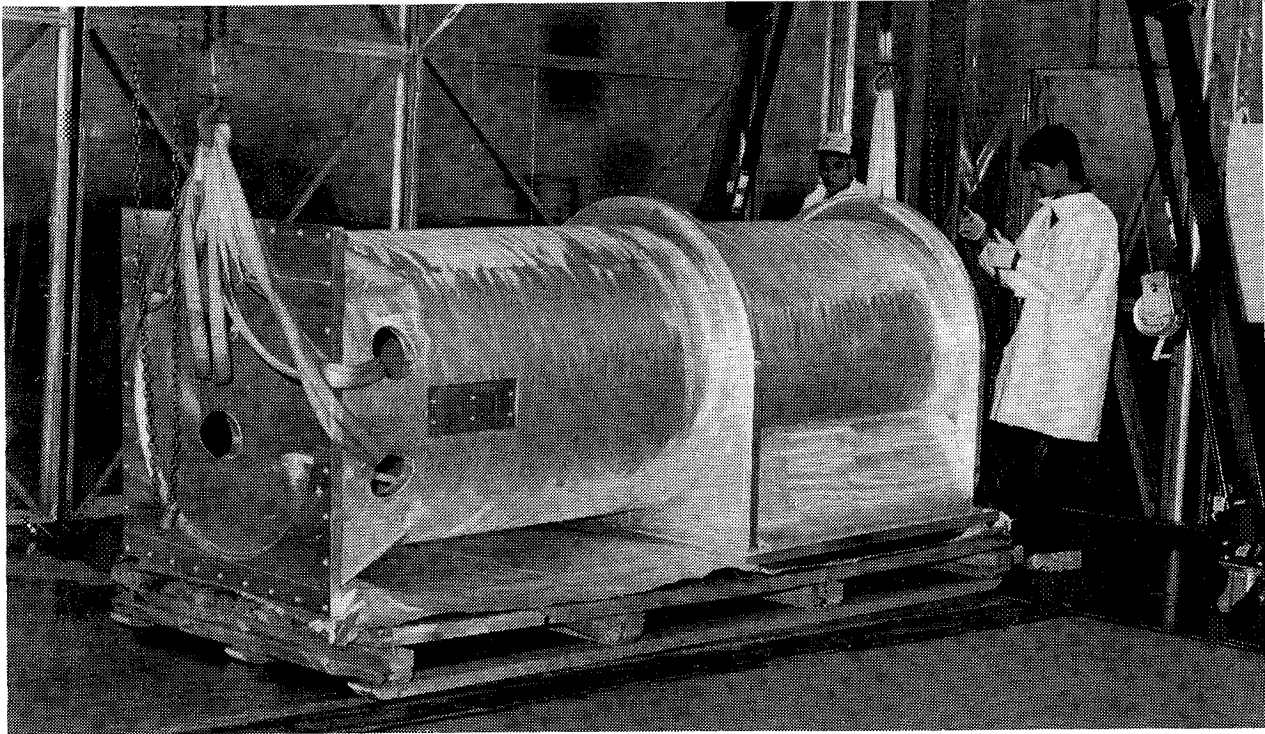


Figure 8. Pedestal Ready for Assembly

Satellite Data Transmission

The two-axis motion simulator provides for the transmission of all of the satellite signals necessary for thermal/vacuum testing. The specifications for these satellite signals are summarized in Table 3.

TABLE 3. SATELLITE DATA TRANSMISSION SPECIFICATIONS

<u>Category</u>	<u>Quantity</u>	<u>Specifications</u>
Single-Shielded Lines	250	100 V at 100 mA
Direct Thermocouple Channels	50	Copper-Constantan
10 Amp Power Channels	10	100V at 10A
5 Amp Power Channels	35	100V at 5A
Co-axial Channels	15	DC to 400 MHz
RF Rotary Joint Channels	2	DC to 8 GHz and 2 to 8 GHz
Multiplexed Thermocouple Channels	640	Copper-Constantan

Satellite signals connect to the MS via a set of vacuum-qualified connectors located at the spin axis shaft. Over 50 connectors are mounted radially on the outside of the shaft. The signals are passed through the continuous rotation spin axis via a

pressurized slip ring assembly. Vacuum feedthroughs are used to interface to the pressurized vessel containing the slip ring. An additional set of connectors is provided at the mounting flange of the spin axis enabling the spin axis to be operated as a stand alone assembly. The satellite signals pass through the limited rotation tilt axis by way of a flexible twist cable. Another set of connectors is mounted at the base of the MS. These connectors are identical to the connectors located at the spin axis mounting flange enabling the same external cables to be used whether testing is performed with the two-axis MS or spin axis by itself.

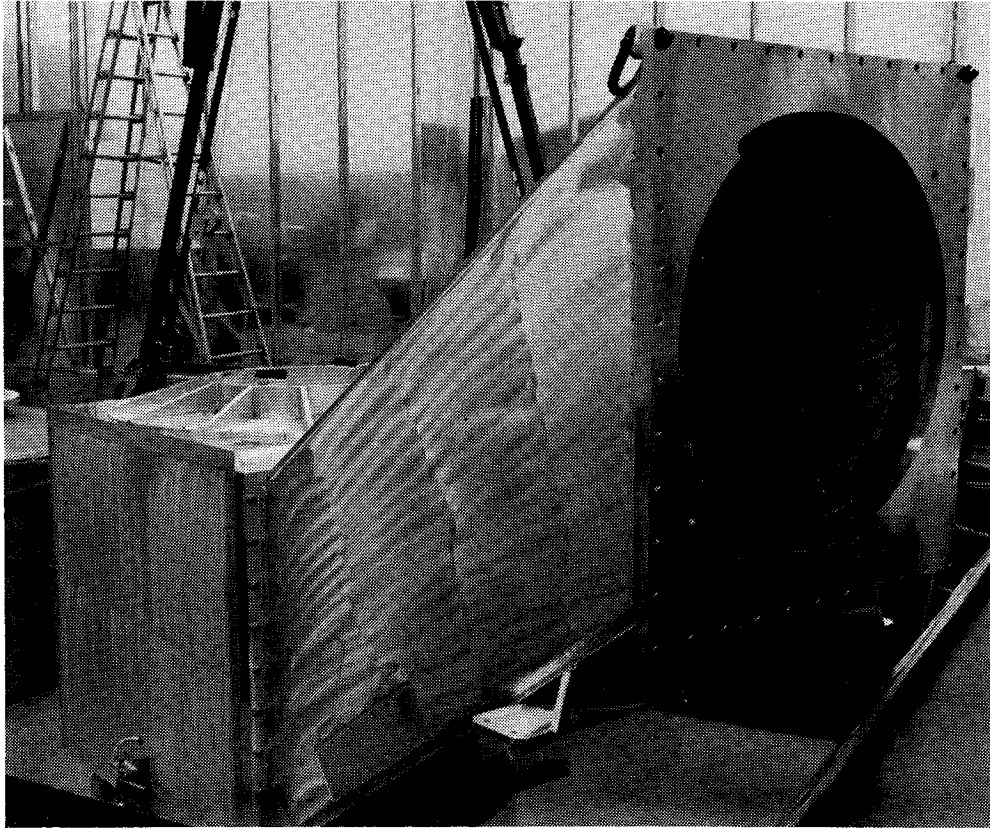


Figure 9. Support Arm Assembled on Tilt Axis

The key components of the satellite data transmission system are the slip ring and thermocouple multiplexer. Both are manufactured to CGC's specifications by outside vendors. This slip ring is shown in Figure 10 and has over 500 lines. This large number of lines requires a dual concentric drum configuration to fit within the spin axis shaft. Silver-teflon* brushes and silver rings are fully compatible with both pressurized and vacuum operation. This feature allows slip ring operation, at low voltages, if the module seal fails. Finally, a two channel high frequency rotary joint is nested inside the slip ring.

The thermocouple multiplexing system (MUX) transmits 640 channels of temperature information using only a few slip ring circuits. The analog thermocouple signals are converted and combined into a digital signal inside the spin axis shaft. This digital information is transmitted, using the slip ring, to a receiver in the console and is available through an RS-232 computer interface. This method eliminates measurement errors introduced by the thermo-electric junctions of the connectors, rings, brushes, and solder joints.

*Trademark of Dupont

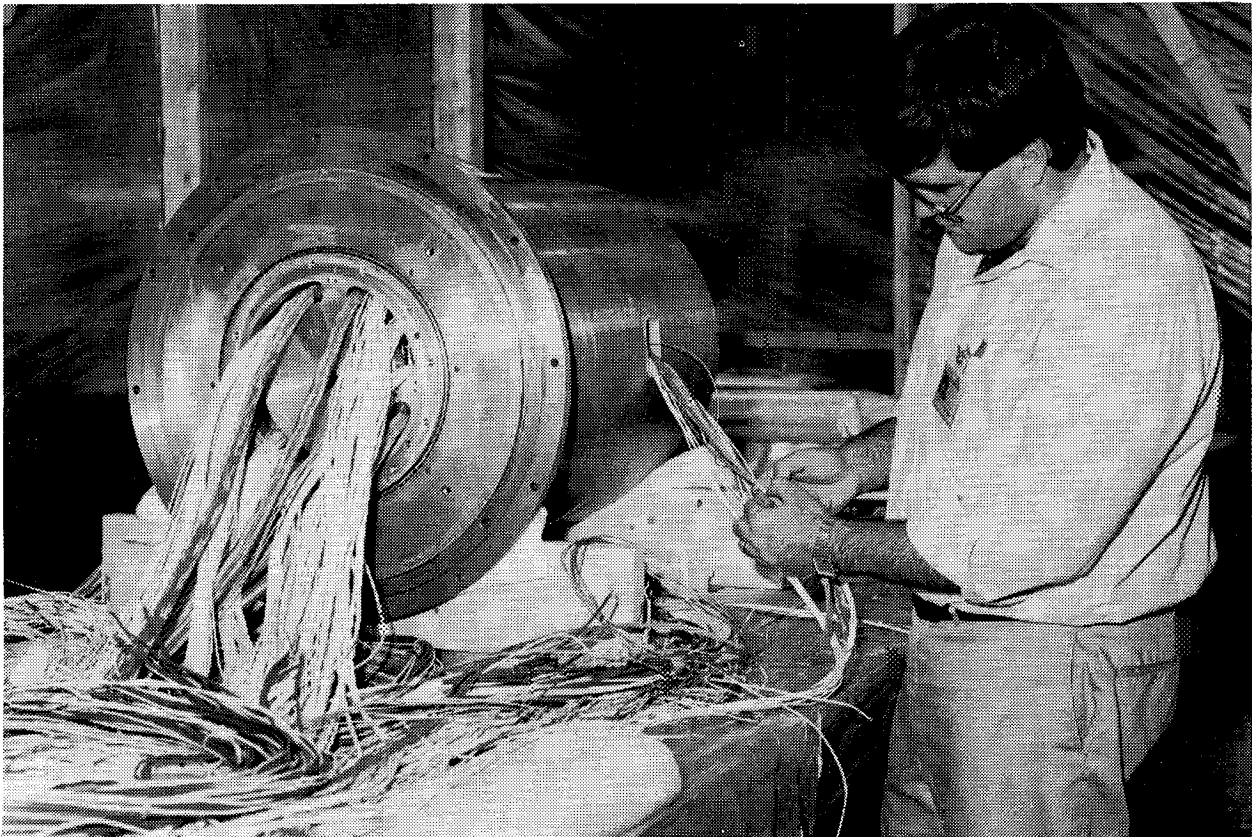


Figure 10. Picture of Slip Ring Assembly

Outgassing and Leak Rates

Low outgassing and low leak rates are important requirements for successful thermal/vacuum testing. Excessive amounts of outgassing and leakage will prevent the chamber from reaching its required pressure of 5×10^{-5} millibar. In addition, the escaped material contaminates the satellite, optics, and chamber. No quantitative specification is given for total MS outgassing because of the inherent measurement difficulties. To limit outgassing, an alternative contamination control plan, devised in consultation with the vacuum system engineer, is used. Rather than specifying the total outgassing rate, it is controlled by specifying the MS design configuration, materials selected, and the manufacturing processes used. In contrast, the slip ring leak rate can be measured directly and is limited to less than 5×10^{-5} , millibar liter/second.

Outgassing

These steps are taken to limit outgassing:

- All welds, bolted joints, and interfaces are vented to avoid virtual leaks. This is achieved by proper placement and interruption of weld beads, tapping holes through, and using vented screws.
- Castings are not used to avoid the porosity and corresponding virtual leakage which results when the chamber pressure is cycled.
- Where possible, all surface finishes meet 63 RMS which limits absorption and facilitates cleaning.

- The primary structure is MIG welded aluminum. Stainless steel is used for some small components. Carbon steel is not used.
- All organic materials used in the MS are evaluated using SP-R-0022A⁽³⁾ criteria for thermal vacuum stability (TVS). Generally all materials have less than 1.0% total weight loss (TWL) and 0.1% volatile condensable material (VCM).
- The bearing grease is a prefluorinated polyether compound with molybdenum disulfide which exceeds SP-R-0022A TVS criteria.
- A vacuum backout is used to clean and precondition the motors, resolvers, tachometers, and MUX prior to assembly.
- The MS components are completely cleaned, prior to assembly, using soap, water, and alcohol. Assembly is completed in a controlled access clean area.

Leakage

The only source of leakage from the MS is the pressurized slip ring assembly. This module is maintained at room ambient pressure, irrespective of the chamber pressure, by a vent line to the atmosphere. The dynamic seal, between the rotating and stationary components, is a permanent magnet ferrofluidic seal which provides extremely low leakage combined with high reliability, and zero maintenance. The electrical feedthroughs are molded epoxy and all static seals are either viton "O" rings or copper gaskets. The final assembly is leak tested to verify hermeticity.

TEMPERATURE CONTROL

Temperature control is a critical requirement for the MS reliability. The safe operating temperature range is 280 to 310 degrees K. Many variables in thermal/vacuum simulation make this temperature range difficult to maintain. The MS produces heat in its motors and bearings. The solar simulation beam shines on the spin axis and pedestal. Small heat fluxes can also occur, via conduction, at the satellite mounting flange and the base support stand. Finally the LN₂ shrouds attached to the chamber walls and mounted to the MS can vary in temperature from 100 degrees K to ambient, causing wide variations in radiant heat transfer.

The traditional solution to this thermal control problem is to place heat exchangers on the MS and pump a thermal exchange fluid through a closed loop at an externally controlled temperature. This method, while effective, has the disadvantage of potential leaks and high operating and maintenance costs.

To avoid these problems, a thermal control system using passive cooling and active reheat was developed. This "semi-passive" system uses conduction links to the LN₂ shrouds, mounted on the MS, to remove heat at a constant rate of approximately 1500 watts. Electric heaters, RTDs, and electronic controllers provide four zones of active reheat control.

A semi-passive thermal control system is possible because of several important MS features. A multilayer insulation blanket, wrapped around the MS exterior, isolates it from LN₂ shroud's and solar beam's radiative thermal loads. The thick walled aluminum structure effectively distributes the cooling and heating loads to minimize temperature gradients. The large thermal mass of the aluminum also ensures that, even when the shrouds provide no cooling, the maximum temperature rise is only one degree K per day. In addition, the interior surfaces of the shafts and housings are coated with a high emissivity paint to increase the thermal radiation coupling between the

rotating and stationary components. This paint combined with the conduction of the bearings minimizes temperature gradients between the rotors and the stators.

The efficiency of the bearings and motors is a critical factor in the success of a semi-passive thermal control system. The bearings generate heat in direct proportion to their friction and the expected value for each axis is less than 500 ft-lbs. Just as important, however, is the ability of the round wire races to flex in their housings. This characteristic ensures that even under high loads, which may cause eccentricities, the bearing friction remains unchanged. Finally, the high efficiency AC servo motors produce only 90 watts of power at their maximum expected duty cycle. Unlike traditional motors with brushes, the heat load is produced in the stationary windings and is easily dissipated into the large diameter housings.

Corona Protection

Since the MS is almost entirely vented to the vacuum environment and since operational scenarios were identified that could drive the environment into a regime where corona might occur; the elimination of corona within the MS was a critical design requirement. The slip ring assembly; which contains the highest risks for arc over, is the only electrical element that is completely sealed. All other electrical elements such as motors, axis rate and position sensors, and connectors are designed to operate within the vacuum environment without arc discharge. The final configuration is a robust, simple design without the need for costly, large rotating seals.

Arc-over₃ is most likely to occur at intermediate pressure (typically between 100 torr and 10^{-3} torr) where the air can become ionized and then be able to pass a high current. The breakdown voltage is directly proportional to the gas pressure and the distance between the electrodes. "Typical" Paschen curves of this phenomena are shown in Figure 11. The curve is a plot of breakdown voltage versus the product of electrode distance and gas pressure. The "work function" parameter; which is a measure of electrical resistance, demonstrates the dependence of the curve on

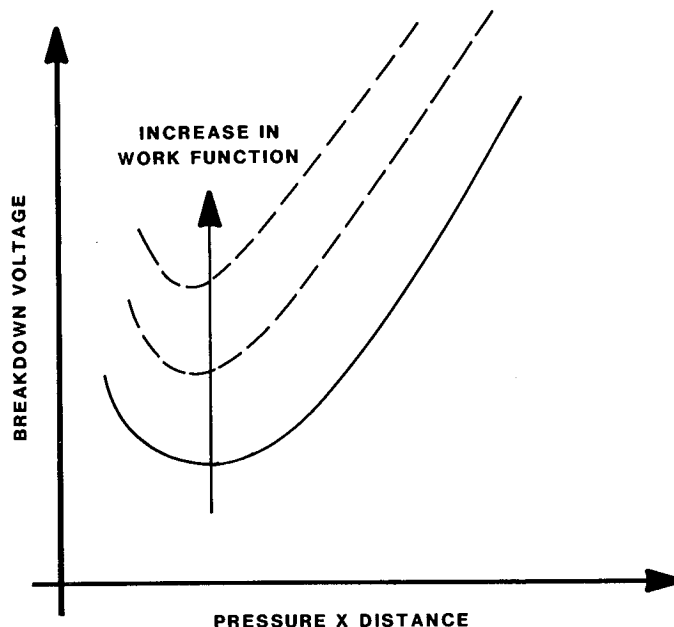


Figure 11.

electrode material and the type of gas used in the system. As an example, the minimum breakdown voltage for silver electrodes in pure helium is approximately 200 volts. Various techniques and designs have been employed throughout the design of the motion simulator to reduce the probability of corona onset.

To the extent possible, the operating voltage of all electrical systems has been set below 200 volts. The thermal control system, axes sensors, and data multiplexer operator well below 200 volts. Only the spin and tilt axes motors operate above this voltage; the motors will intermittently reach a voltage of 300 volts (RMS). The motors are AC synchronous (brushless) motors with permanent magnet fields. This motor design eliminates the need for brushes and commutator which are common to DC motors, or motor slip rings that are common to AC motors with separately excited fields. By eliminating brushes, commutators, and motor slip rings, the most likely sources for arc discharge have been eliminated. The remaining elements in the system that have potential for arc-over are the motor wiring, cables, connectors, and terminations. Techniques have been described in the literature (1), (2) that have been used to eliminate corona; the electrical design of the MS follows these techniques, e.g.,

- Cables and connector with large differences of potential are kept segregated.
- All cables and motor external wires are Teflon insulated.
- Grounded shields are used over the insulation of high voltage cables.
- Exposed conductors at the interface of connection receptacles and plugs are eliminated.
- Connections are vented to eliminate trapped gas.

Corona onset is best described as a statistical phenomena. To prevent the occurrence of corona, the most likely conditions for its existence must be eliminated. Every attempt has been made to accomplish that in the design of the MS.

Precision Motion Control

The motion control techniques utilized on the MS were originally developed for the inertial guidance test industry. The instrumentation is configured in the CGC Modular Precision Angular Control System (MPACS) and provides a closed-loop, multi-mode servo system for each axis.

Each axis incorporates "direct drive" concepts to maximize motion performance. Each axis is driven by a direct-coupled AC servo motor and incorporates a DC tachometer velocity transducer, resolver position transducer, and direct-coupled Inductosyn position transducer. Through the use of the shaft-mounted Inductosyn and motor, non-linearities and low frequency resonances associated with other drive systems (e.g., gear drives, belt drives, chain drives, hydraulic drives, etc.) are eliminated. This permits the configuration of high gain, high bandwidth servos to provide accurate motion control.

The Inductosyn position transducer (Figure 12) is utilized in the primary modes of position and velocity control. This device is actually a high-accuracy 360-speed resolver used to measure axis position. The stator of the Inductosyn contains two windings which are mechanically arranged so that the inductive coupling between the SIN winding and the rotor varies sinusoidally over one degree of rotor travel. The coupling for the COS winding varies as the cosine over one degree of rotor travel. These two windings are excited by precision current sources within the MPACS .

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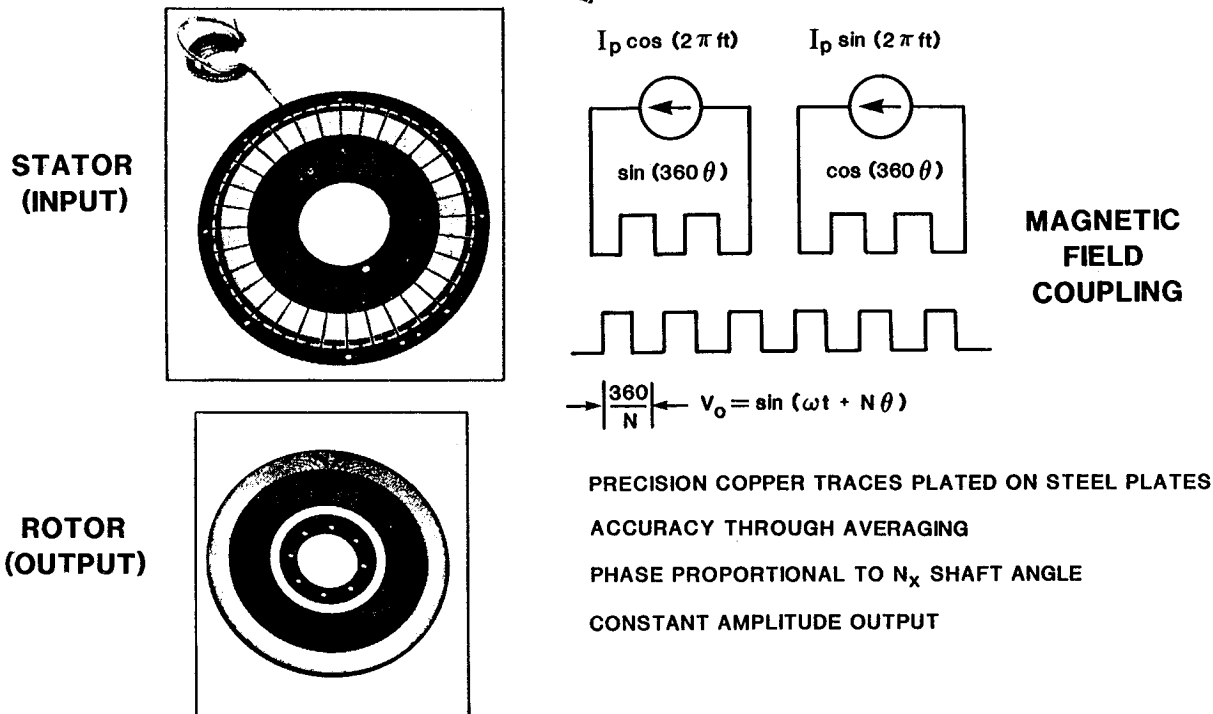


Figure 12. Inductosyn Position Transducer

The amplitudes and phases of these signals are accurately controlled by amplitude and phase servos within the MPACS. The output of the Inductosyn rotor is a constant amplitude sinusoid of frequency "f", whose phase varies through 360 degrees with respect to the sin reference signal for each mechanical degree of axis motion. The resolver mounted on the axis is utilized in the same manner to provide another phase-modulated feedback signal which varies through 360 degrees of phase for each complete ventilation of the axis.

The MPACS instrumentation system receives the feedback signals from the resolver and Inductosyn and converts them to a digital format for use by the encoding and control systems.

Control System

Position Mode (See Figure 13)

The MPACS controls axis motion primarily through the use of a position servo. In the Position control mode, the Inductosyn and resolver feedback signals are utilized to drive the axis to a commanded position input. Analog "low resolution error" (LRE) and "medium resolution error" (MRE) position error signals are generated from the resolver feedback signals. These signals represent the difference between commanded and actual axis positions. An analog "high resolution error" (HRE) signal is generated from the Inductosyn feedback. The Position control mode uses a dual-mode servo control mechanism. A "coarse" position loop responding to the resolver generated MRE signal moves the axis to the vicinity of the terminal position. In this mode, the MRE signal acts as a velocity command to an inner velocity loop using tachometer feedback. A clamping circuit is included to limit this velocity command to a preset value. In this manner, the slew rate between positions may be controlled. When the axis approaches the terminal position, control is transferred from the "coarse" loop to the "fine" position loop utilizing the Inductosyn generated HRE signal. "Bumpless" transfer is accomplished by monitoring the MRE, HRE, and HRE rate.

Transfer to the "fine" loop occurs only when:

- the MRE indicates a position error of less than 0.2 degrees.
- the HRE indicates a position error of less than 0.02 degrees
- The rate of change of the HRE is less than 3 deg/sec

Satisfaction of these tests transfers control to the Type III "fine" position servo. The tachometer velocity loop utilized in the "coarse" loop is eliminated in the "fine" loop. This allows increased stiffness and small signal bandwidth. With this type of control, MS positioning accuracies of 10 arc seconds and repeatabilities of 1 arc second are readily achievable.

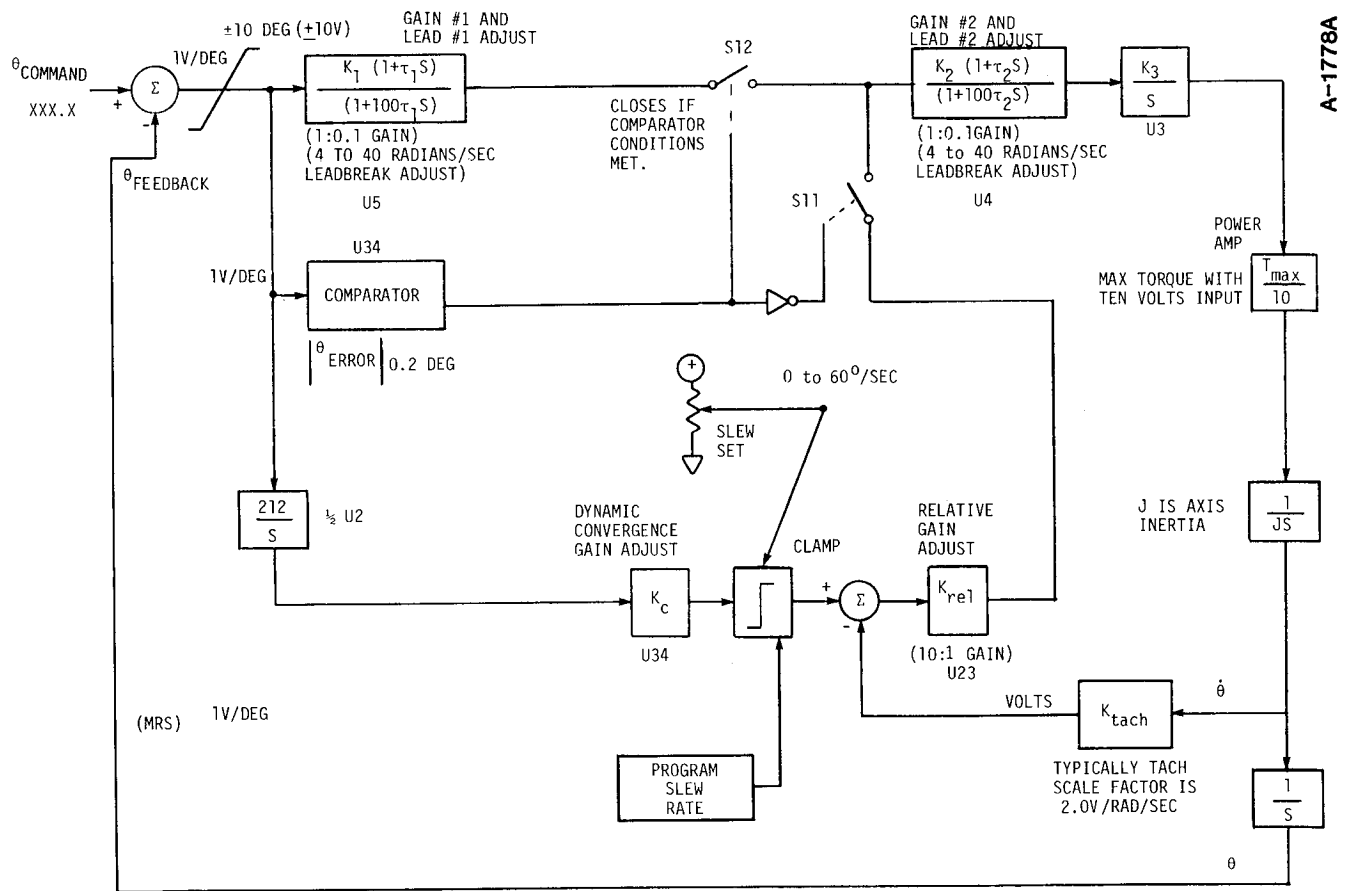


Figure 13. Position Mode Diagram

Precision Rate Mode (See Figure 14)

Axis velocity control is obtained in the Precision Rate mode. This mode is also implemented using the Type III fine position servo detailed in the Position mode description. This implementation provides the generation of highly accurate velocities, and eliminates the "ripple" error inherent in tachometer based velocity loops. In this mode, precision velocities are produced by incrementing the position command at a rate based upon the commanded velocity. The position command is incremented in steps of 0.0001 degrees; hence, an axis velocity of 1 deg/sec requires

10,000 increments per second. Since the position loop is a Type III servo, it is capable of responding to this command with no following error.

The direct-coupled nature of the axis components permits the configuration of high gain, high bandwidth servos. This, in turn, provides the ability to reject disturbance torques due to friction, load imbalance, motor cogging, etc. The result is precision rate performance accurate and stable to 0.0005%. Furthermore, the rate generator producing the position increment pulses is crystal controlled. By synchronizing this crystal oscillator with the timing crystal of the satellite data acquisition system, it is possible to obtain satellite parameter measurements which are fully correlated with axis position.

Encoding System

The digitized, phase-encoded signals from the resolver and the Inductosyn on each axis are utilized by axis encoders within the MPACS to provide real-time axis position readouts. Each encoder contains separate circuits to encode the "coarse" position from the resolver and the "fine" position from the Inductosyn. These outputs are correlated to provide a 7-digit position readout available for visual display or computer interface.

Each encoding circuit is structured as a phase-locked loop. A high-speed digital ring counter is driven by a 0-24 MHz voltage controlled oscillator (VCO). This counter is

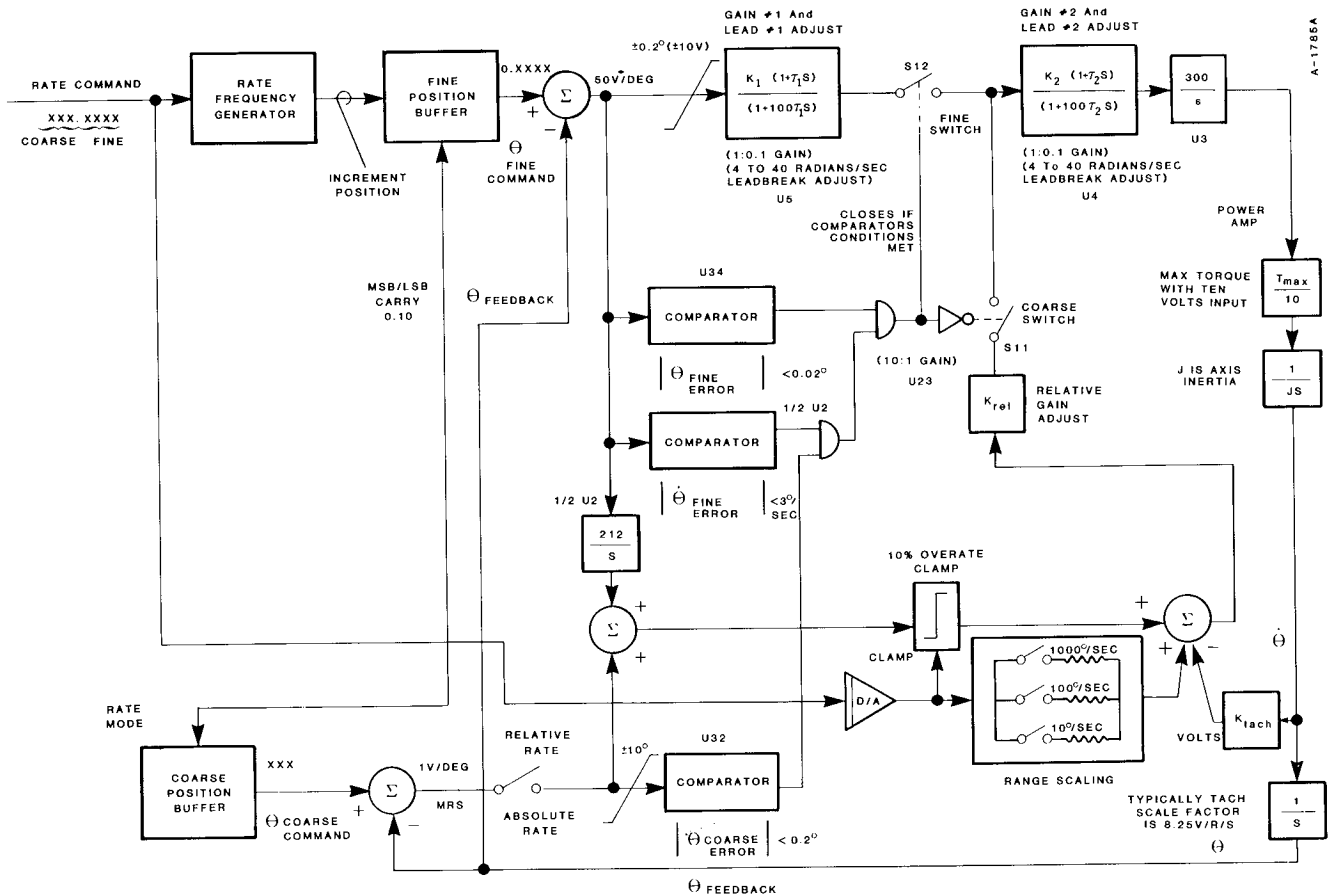


Figure 14. Precision Rate Mode

used to generate a square wave over a complete counter cycle. This square wave is phase-detected, and compared with the square wave signal derived from the phase-encoded Inductosyn feedback. The resulting error signal is compensated and fed as an input to the VCO. The result is a digital ring counter which cycles synchronously with the Inductosyn feedback. The value in this counter at the zero crossing of the sin reference to the Inductosyn is loaded into a second counter. Hence, this value represents the phase shift between the sin reference and the inductosyn feedback which is linearly related to the axis position. The second counter is also clocked by the VCO output; therefore, it tracks axis motion and provides a digital measurement of axis position.

An equivalent circuit processes the resolver feedback in the same manner. The two digital values are combined to form a 7-digit position measurement.

This system is capable of encoding axis positions accurate to 1 arc second, with a resolution of 0.36 arc seconds (0.0001 deg). The use of a Type II servo in the phase-locked loop permits zero tracking error for static positions and constant velocities.

Motor Drive System (Figure 15)

The MS utilizes AC servo motors for axis actuation. These 3-phase permanent magnet motors are driven in a "vector control" mode by high-power pulse width modulation (PWM) amplifiers. These amplifiers operate by measuring the axis position

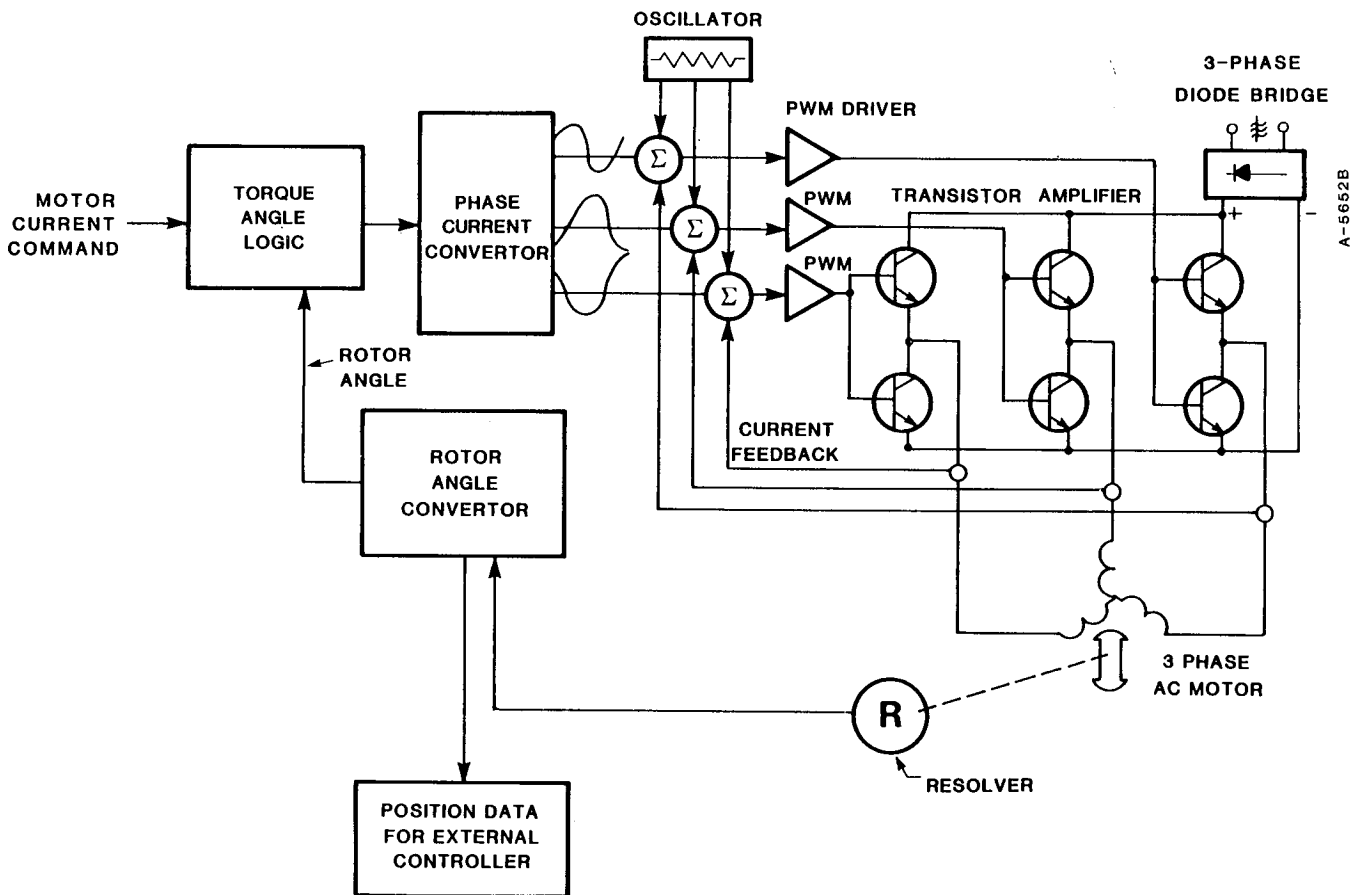


Figure 15. Brushless AC Servo Drive Block Diagram

using a resolver. From this measurement, the drive computes the coordinates of the three-phase sinusoidal motor currents required to produce optimum torque. The magnitude of these currents is then adjusted as a function of the torque command magnitude and direction. This process is repeated continuously within the drive. The result is low torque-ripple brushless motor drive system which responds to torque commands from the servo electronics.

SUMMARY

This two axis motion simulator fully meets all requirements for thermal/vacuum simulation. Large satellites can be tested with minimal solar source shadowing and sufficient structural stiffness to achieve resonances greater than 7 Hz. The motors and transducers are directly coupled devices which eliminates the inherent instabilities of gear drive mechanism. Over 1000 channels are available for satellite data transmission via slip rings and thermocouple multiplexing system. Corona risk is eliminated by using brushless motors, special connectors, and pressurizing the slip ring assembly. Except for the slip ring, the balance of the motion simulator is completely vented. This greatly simplifies the design and manufacturing process and the risk of leakage. Leakage from the slip ring is eliminated using ferrofluidic seals and epoxy feedthroughs. All components exposed to the vacuum meet SP-R-0022A requirements for thermal vacuum stability to limit outgassing. Temperature control is achieved using passive cooling and active reheating which eliminates the need for expensive and unreliable fluid heat exchangers. Precision motion control with arc-second resolution and zero drift is achieved using Inductosyns, MPACS controller, and a pulse width modulated three phase motor amplifier. Motion commands, are accepted manually or using remote computer control. The end result is a two-axis satellite motion simulation system which provides an extremely accurate, flexible, reliable, and cost effective solution for thermal/vacuum space simulation testing.

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