Motion Simulator Facility for Spacecraft Attitude Control Evaluation

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TO be completely meaningful, the development program for a spacecraft attitude control system (ACS) should include demonstrations of attitude acquisition from specified initial conditions, static pointing accuracy under anticipated disturbances, dynamic accuracy under specified commands, control response time, and control stability under changing vehicle dynamics. The effects of nonlinearities and cross-couplings in the control equipment and in the controlled vehicle should be identified in such a development program. A facility that can perform these functions and be used for these purposes is shown in Fig. 1. Its focal point is a three-axis motion simulator (TAMS) utilizing gas bearings for support and d.c. torque motors for direct driving on all 3 axes.

These essential components of a typical ACS and of the TAMS facility are shown in a simplified block diagram of Fig. 2. The test vehicle to which the components are attached, is mounted on the platform on the inner axis of the motion simulator. Sensors are oriented on the test vehicle so as to be aligned with their respective simulators as required by governing control laws. Output signals from the various sensors are supplied to the on-board computational electronics.

Actual torquing devices are generally not used with the packages under test because their torque output is too small to have any significant effect on the d.c. torque motor output of the simulator. A hybrid computer that is a part of the facility is mechanized to receive the torque-required signals from the on-board electronics. It calculates the effect upon the spacecraft (i.e., rate and position) considering such physical parameters as inertia, solar pressure area, vehicle and mounting flexibilities, etc. Since the TAMS gimbal axes do not remain orthogonal as motions occur, matrix equations have been developed relating the gimbal, control, and reference axes coordinate systems. The computer provides this transformation so that the outputs of the facility computer are the angles that must be assumed by the gimbals of the motion simulator.

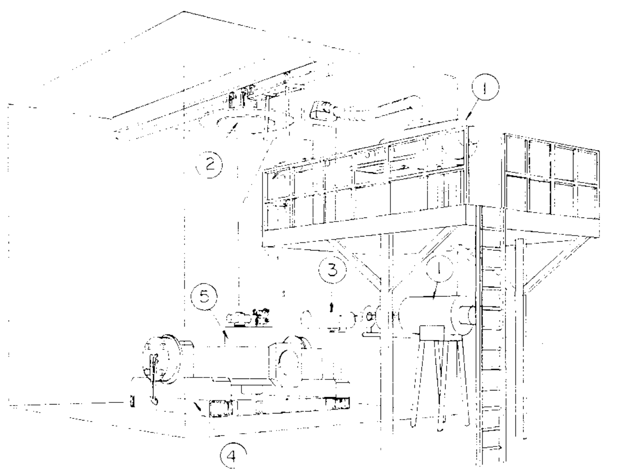

Fig. 1 Motion simulator facility pictorial. 1—Sun simulator, 2—Earth simulator, 3—star simulator, 4—motion simulator, 5—test vehicle.

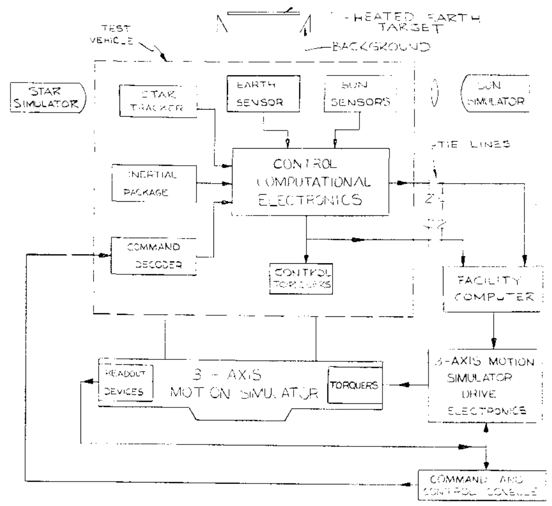

Fig. 2 Over-all control evaluation block diagram

Components utilized in this control system testing may be in practically any form or stage of development. Typically, the first demonstration of a control system could utilize early configurations of sensors, electronics in compact breadboard form and simulated torquing devices. In some cases, certain of the sensors or control elements may not be available but only their performance requirements identified. Then, the facility computer could be programed to provide synthesized components having the appropriate operational characteristics.

Three-Axis Motion Simulator

The TAMS (Figs. 3 and 4) was designed and built by the Fecker Systems Div., Owens-Illinois Inc., Pittsburgh, Pa., for the General Electric Co. It provides rates from 0.0001°/sec to 1200°/sec for the inner axis and 0.0001°/sec to 20°/sec for the two other axes; extremely smooth performance near the zero rate operation with rate variations as low as 0.01%. The three axes meet within a sphere of 0.003 in. with an orthogonality of better than 2 arc sec. The instrument weight is 21,800 lb and its greatest dimension is 14 ft.

Mechanical system

The load capacity under the maximum angular range limitation of 360° for the inner axis (at a rate of 200 rpm), ±90° for the middle and outer axes is 300 lb with the center of gravity (c.g.) not higher than 18 in. above the inner axis platform. Weights up to 2000 lb with a c.g. up to 72 in. above the platform can be accomodated with corresponding angular ranges of 360°/5°/5° at spin speeds up to 100 rpm.

The stainless steel, inner axis platform (Fig. 5) is recessed 21 in. into the middle axis gimbal in a 36-in.-diam cavity. Between the inner axis gas and mechanical bearings (adjacent to the angular contact pair of ball bearings) is the 35-ft/lb d.c. drive motor. This configuration provides maximum stiffness and rate stability at a minimum weight. For maximum load carrying capacity and stiffness, the operating pressure of the inner axis is 250 psig.

Connectors for 140 electrical circuits are located on the platform. These circuits are brought from the middle axis to the platform through a separately powered servo driven slip-ring assembly, which is slaved to the table by means

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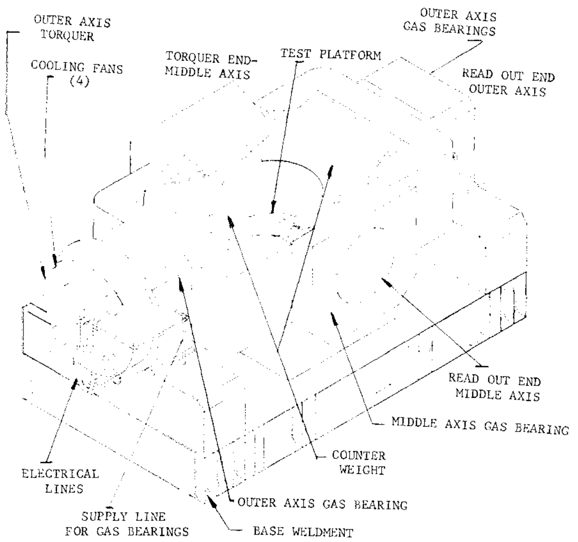

Fig. 3 Three-axis motion simulator design.

of an electromagnetic position sensor. This servo system prevents the transmission of the slip-ring friction and bearing torques to the inner axis drive system. The circuits pass across the middle and outer axes by means of loosely twisted bundles of wires located at the center of rotation of each axis.

The middle axis steel gimbal is supported by two 10-in.-diam gas bearings which operate at 190 psig of dry N_2. The gap between the inner and outer elements of each bearing of 0.0007 in. The outer cylinders of both are suspended in a two-axis system (Fig. 6) which allows a free alignment of the two bearings to the axis of rotation under any load condition without compromising the stiffness and load-carrying capacity of the axis. The bearing on one end of each of these gimbals incorporates a direct drive, d.c. torque motor, while that on the other end is integrated with the readout devices (see Fig. 3). The torque motor for the middle axis is rated at 900 ft/lb. To keep the drive shaft temperatures within the safe limits of 72 ± 20°F, the bore is ribbed, and ambient air is drawn through the bearing shaft at high velocity.

The middle axis gas bearing suspension system is housed in the outer axis aluminum gimbal. The outer axis gimbal has asymmetrical proportions to make a conical field-of-view of 130° at the point of intersection of all three axes possible.

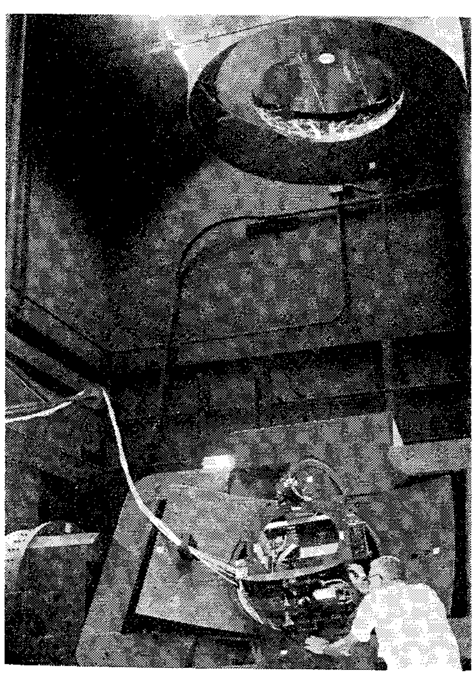

Fig. 4 Three-axis motion simulator with Earth simulator.

The asymmetrical shape as well as the one-sided weight of the middle axis torque motor is counterbalanced with structurally-integrated, heavy gimbal sections up to 5 in. in wall thickness. Two 10-in. gas bearings support the outer axis gimbal using the same design principle as on the middle axis. The outer axis bearing suspension system is mounted to the trunnion blocks of the base which is a steel weldment with a three-point leveling arrangement. The electrical and pneumatic inlet connections are located at the 3000 ft/lb drive side of the base. Fans draw cooling air through this torque motor also. Swivel joints for the gas supply line are used to carry the gas across the outer and middle axes of rotation.

Simulation servo system

The system can be operated as a simulator in either an analog or a digital control mode, or in a servo mode in which the table can be slaved to outputs from the package being evaluated. Command inputs for each axis are received from the facility computer and are compared with the axis attitude information to generate error signals for the power amplifier which in turn controls the torque motor to drive the axis so that its rate and position outputs follow the input command. Because of the inherently greater resolution, the digital mode provides the better accuracy.

The extreme smoothness of motion required, combined with the wide bandwidth requirements, precluded the use of a conventionally mechanized position loop control. Potentiometer noise effects or even very small amplitude digital quantizations, along with computer iteration problems, would cause very high instantaneous rate errors. To overcome this problem a unique control technique is utilized that incorporates a wide bandwidth rate loop which is kept drift-free by a narrow bandwidth position loop. The system, therefore, requires both position and rate commands from the facility computer. An angle encoder system for each axis provides a digital output indication of the axis position accurate to ±1 arc second. This output is displayed in binary form and fed to the general purpose computer of the simulator for processing digital position error signals and generating decimal-coded axis attitude information.

The general purpose digital computer is included to a) convert the binary digital angle output from the shaft angle encoder into a binary coded decimal (BCD) form for display, b) process incremental position and time information to generate axis rate information, and c) receive the 23-bit parallel digital position commands in full binary form from an external digital computer, when in the digital mode. The complete command is compared with the position readout from the simulator axis to generate a digital position error signal and a rate command to the position control loop.

Visual readouts are provided for all three axes that have resolutions of 0.0001° for position and 0.0001°/sec for rate data. The same digital data that are used to generate the displays are also converted into analog signals and fed to

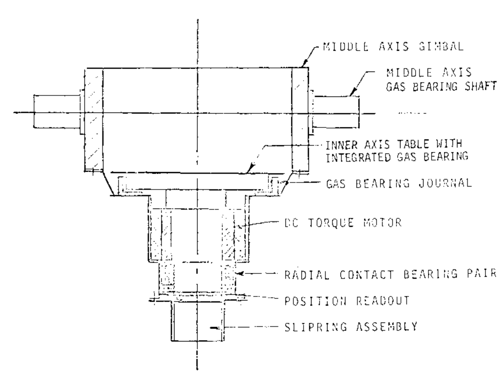

Fig. 5 Inner axis configuration.

the simulation servo system. Six panel-mounted voltmeters are used to read out analog axes position and rate information.

Sensor Stimulation

A high-current, carbon arc lamp with a properly designed lens system is used as the sun simulator to provide a reasonable near-optimum source. For certain spacecraft control modes, sunlight impinging from a nearly vertical direction is required. For this condition a large, front-surface mirror, oriented as shown in Fig. 1, is used to reflect the light from an arc lamp mounted on an elevated platform onto the test vehicle. For other control modes, the sun simulator in the lower position of Fig. 1 may be required. In this location the arc lamp can be more closely coupled to the test package, and a higher intensity light is obtained. The facility is sufficiently versatile to permit other orientations of the solar simulator if appropriate. Solar constants from 0.2 to 1.0 have been obtained with an apparent source size or collimation at the sensor of approximately 0.5°. This type of solar simulation has proven to be quite satisfactory for the control systems evaluated to date.

For many spacecraft missions, Polaris forms an ideal reference for precise pointing maneuvers. The star simulator used in this facility provides a replica of the +2.1 visual magnitude of this star with an F8 spectral characteristic. It consists of a small light source positioned at the focal point of a 15-in.-diam parabolic mirror with a focal length of 40 in. The intensity of the light source can be varied from +6 to −2 magnitude by the selection of the proper neutral density filter for the excitation lamp.

The earth simulator (Fig. 7) for this particular control evaluation has been configured to that seen by a spacecraft which is orbiting at synchronous altitude (approximately 20,000 naut miles) where the angle subtended by earth is about 18°. By proper design, other sizes of earth can be simulated if required. The earth sensor used in one control system evaluated, sensed radiation in the 20- to 40-μ infrared band and the simulated target was designed to duplicate the

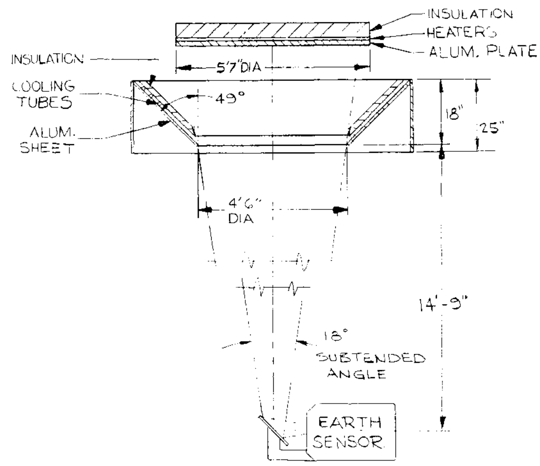

Fig. 7 Earth simulator configuration.

earth's irradiance energy in this band against a deep space background. The background in the simulated earth system is nominally at room temperature. The inner diameter of the background determines the subtended limb of the simulated earth as observed by the sensor. The temperature of the earth target (an aluminum disk with surface heaters bonded to the back side) can be varied up to 360°F. The front side is coated to provide high emissivity. The simulated space background consists of a coated (to provide high emissivity), truncated conical section of aluminum sheet to which a spiral of tubing is bonded. Cooling or heating liquid may be circulated through this tubing. The cone half-angle and length of cylindrical section were selected to prevent single specular reflections of energy radiation from any source in the facility within the space background field-of-view of the sensor.

Summary

Thus, a motion simulator facility is provided which permits simulation of in-orbit flight for attitude control performance demonstration by duplicating spacecraft motion and by simulating reference targets.

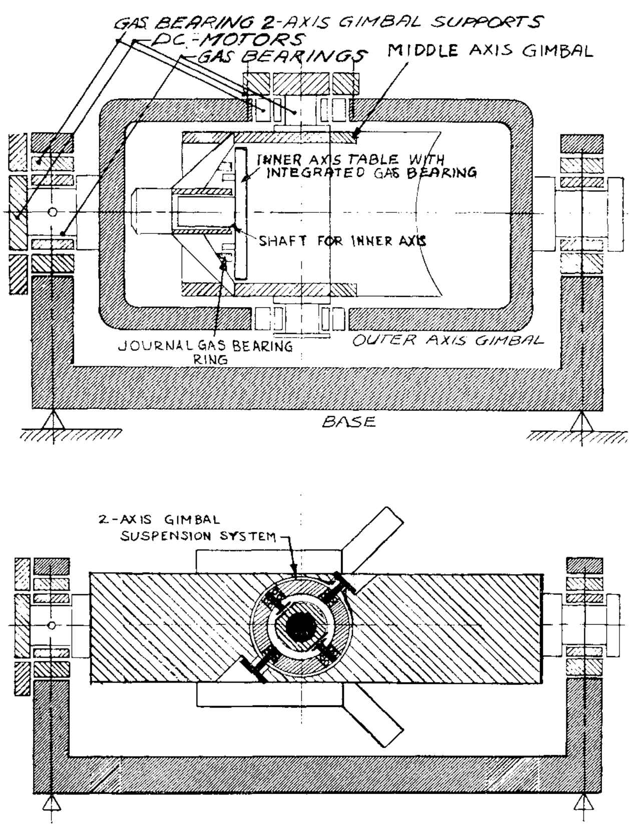

Fig. 6 Gas bearing suspension system.

Influence of Spatial Correlation upon Load Resolution

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Nomenclature

D	=	reference length on bluff body
$l(x,t)$	=	load per unit length at station x and time t
$L(t)$	=	total load over domain at time t
t	=	time
β	=	$(r - s)/D$ = dimensionless spacing variable
γ	=	r/D = dimensionless distance
τ	=	time lag
ω	=	circular frequency
χ	=	correlation length scale, fraction of D
$\Phi(r,s,\omega)$	=	cospectral density relating station s to station r at frequency ω
$\Psi(r,s,\omega)$	=	quad-spectral density relating station s to station r at frequency ω
$\psi_2(r)$	=	spatial variable in $\Phi(r,s,\omega)$ for two-dimensional flow case

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