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FACILITY FORM 602

N66 34672	1
(ACCESSION NUMBER)	(THRU)
42	
(PAGES)	(CODE)
CR 77223	11
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

TRW SYSTEMS

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) $2.00

Microfiche (MF) .50

ff 653 July 65

RQ-36435

2313-6007-KU000

A SINGLE-AXIS SPACE SIMULATOR FOR TESTING THE OGO ATTITUDE CONTROL SYSTEM

By

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2313-6007-KU000

July 1963

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ABSTRACT

In order to test the operation of the OGO attitude control system, a single-axis wire-suspended space simulator has been developed at STL. This provides, for a single axis of control, those properties of space which affect control system performance - negligible restoring torque and negligible coulomb and viscous friction about the axis of control. The control system equipment is mounted on the simulator and its performance under space conditions observed and evaluated.

This paper describes the design and performance details of the simulator, the procedures used in its calibration, and the type of tests that can be performed with it.

The single-axis simulator described in this report is not intended to do the work of the three-axis, air-bearing simulator, but rather to complement in the development testing program. The single-axis simulator cannot test interaction among the three axes of control, or the three-dimensional acquisition sequence. For testing of each axis independently, however, it offers an inexpensive test bed requiring no lengthy adjustment and calibration procedures, with accuracy at least equal to that of the air-bearing simulator.

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ILLUSTRATIONS

I. INTRODUCTION

During the development of the OGO attitude control system, it was felt that some technique was necessary to check out experimentally the operation and logic of the system during the various modes of operation. This testing was to be divided into two categories: (1) testing of a single axis at a time, and (2) three-axis testing on an air-bearing simulator to explore interaction among the three axes.

Although the three-axis testing can give more complete data, there were several reasons why it was considered advisable to include also a single-axis test program. (1) It is convenient to have single-axis data to analyze that it is unaffected by interactions of the other two axes. (2) An initial analysis of simulator techniques showed that more accurate results could be obtained with less set-up time with single-axis testing than with a three-axis simulator. (3) To get information from a three-axis air-bearing table, telemetry is necessary, whereas other techniques can be used with a single-axis simulator.

The single-axis test program was developed not only to demonstrate the adequacy of the control system logic, during the different modes of operation, but to also obtain quantitative control system data such as limit cycle period, overshoot obtained during an eclipse or noon turn, and limit cycle deadband.

To successfully achieve these goals, the single-axis table must provide an environment that has all those characteristics of outer space that affect the operation of the attitude control system. This means that, about its axis of rotation, the simulator must have negligible restraining torque, and negligible coulomb and viscous friction. It should be capable of rotating any number of revolutions in either direction. There must be sufficient room on the simulator for mounting the attitude control system components for a single axis, and its moment of inertia about the control axis must be adjustable so that the vehicle moment of inertia may be either duplicated or scaled. Vacuum, solar radiation, and other such space conditions of a similar nature, do not have to be duplicated for this type of testing. These affect the reliability of the control system components, but have a negligible effect on system performance parameters.

II. SCHEMES FOR SPACE SIMULATION

Several different techniques for building such a single-degree-of-freedom test bed were investigated. Each of these schemes is discussed briefly below.

1. Knife-edge Table - This design consists of a platform for mounting the control system, batteries, etc., underneath which is attached a horizontal knife-edge bearing. This knife-edge supports the weight of the table and provides the table axis of rotation. Knife-edge bearings are used extensively in materials testing machines, and, as a result, good design data is available. This type of construction was used at STL for early attitude control experiments. (See Reference 2 and Figure 1.)

The construction of this type of simulator is fairly simple except that the knife edges must be finished to very close tolerances and be accurately aligned. There is no spring force from a knife edge, but they do have a considerable amount of inherent friction which cannot be eliminated. Another disadvantage is that this type of platform, with the axis of rotation horizontal, must be accurately balanced both horizontally and vertically, so that the cg is located on the axis of rotation. Otherwise, the force of gravity acting upon the cg would give an unbalance torque to the table. Its angular freedom is definitely limited - probably to ±45 degrees or less.

2. Table Supported by Flexural Pivot - This type of device would have its axis of rotation horizontal, as on the knife-edge table. Its pivot would be a set of thin metal leaves which flex to allow limited motion. They would have no friction (except for that in the flexing metal) but would have a spring constant. Over a small range of angular movement, this spring force could be cancelled by proper vertical location of the cg. Besides the balancing that would have to be done in two planes, this technique is also handicapped by a very limited angular movement.

3. Air-bearing Supported Table - A hydrostatic air-bearing, either spherical or cylindrical, could be used to support a single-axis simulator. With the axis of rotation placed vertically, there would be no balancing problem. Friction of such a bearing could be considered essentially zero. "Turbine torque," an unknown quantity, might cause an unwanted steady state torque. The biggest disadvantage would be the complexity and cost of the air-bearing assembly itself.

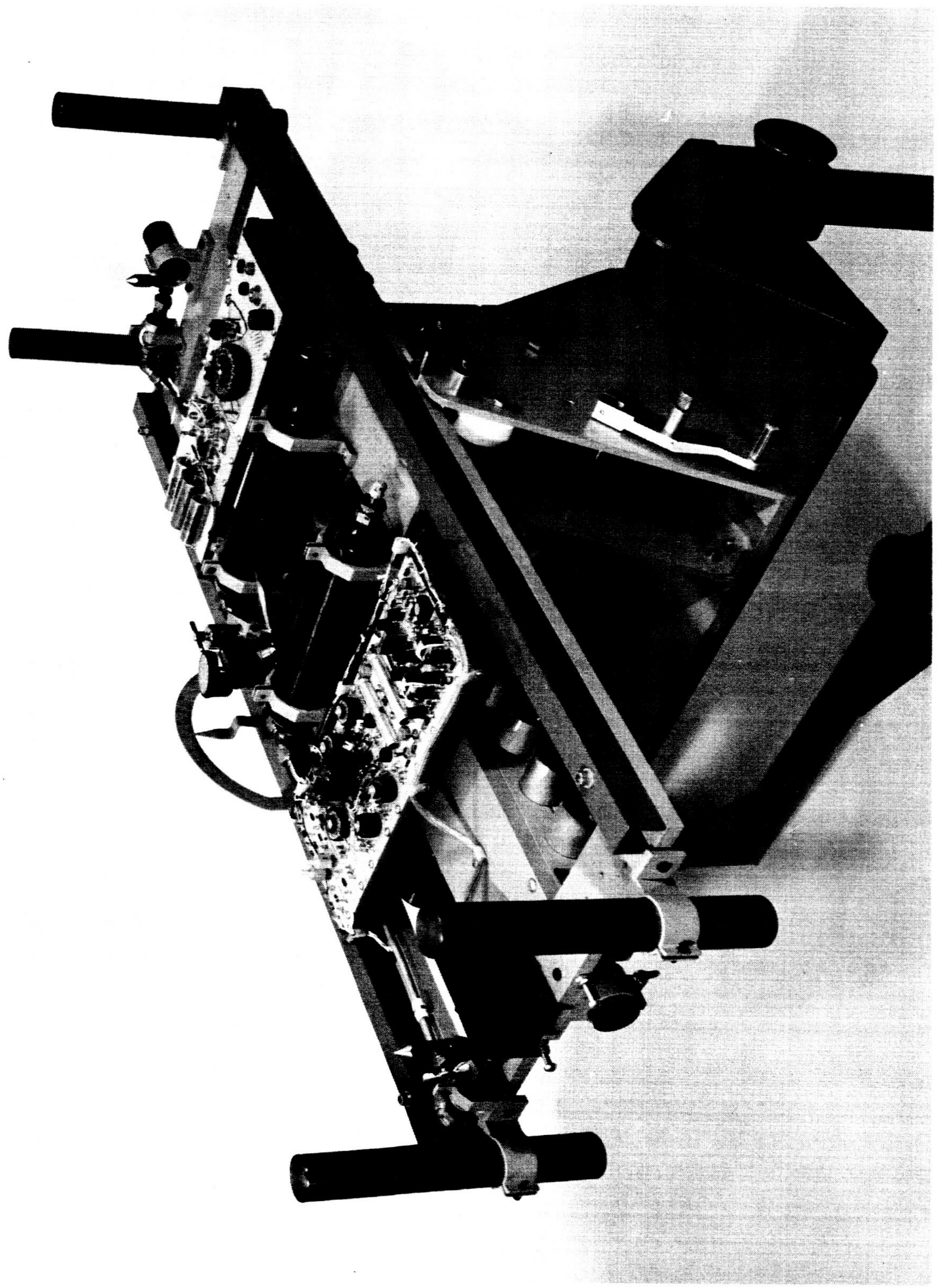


Figure 1. Knife-Edge Single Axis Simulator

4. Wire-Suspended Table - Wire-suspended tables being used for testing control systems were observed several years ago at both G. E. and Aerojet, and are described in Carl Grubin's memorandum (see Reference 1). This type of simulator has the advantages of low cost, no friction (except for the minute friction of a wire being deformed in torsion), and a spring constant that can be made extremely small by proper design. One of the problems observed at both G. E. and Aerojet was a side-to-side motion which tended to build up as the control system operated over a period of time. However, they were using gas jets which gave a torque of several ft.-lbs., while a scaled OGO system would have only 0.036 ft.-lb. This low value should eliminate side sway as an important handicap in our testing program.

The wire suspended table was finally chosen because of its good features (including low cost) and its lack of major handicaps. In order to keep the table a practical size, it was decided to scale the inertia of the table down by a factor of 20 from the OGO inertia. None of the design details of the G. E. or the Aerojet simulators were used, since a simulator was wanted that would be optimum for the OGO test program.

Using this type of platform, the following are the items that will theoretically cause a deviation from the pure space environment. The significance of each of these on test results is discussed later under "Design Details."

a. Torque of wire support

b. Side sway of platform - as induced by air current, gas jet imbalance, or releasing of the platform from its support.

c. Extraneous torque from air currents.

d. Air damping

e. Inaccuracies introduced by the scaling of inertia, torque, etc.

III. DESIGN DETAILS

A. General Construction

The single-axis simulator consists basically of a plywood disc supported from the ceiling by a special cable 9 ft. long, with a servo system capable of rotating the top cable support to match the angular position of the plywood disc and thereby eliminate cable twist. Underneath the plywood table there is a steel support structure, padded with sponge rubber, which can be raised by a hydraulic piston to take the weight of the table off the support cable when no testing is underway. Figure 2 shows the general construction of the simulator.

The table itself is a piece of plywood 4 ft. in diameter by 1 inch thick, with the periphery marked in degrees so that its angular position can be seen at any time by means of a pointer. Approximately 200 lbs. of weight are attached to the underside of the table around the periphery to raise its moment of inertia to the desired level. On the surface of the table are mounted two gas receivers, batteries, and a complete control system for one axis. Components are placed symmetrically on the table, insofar as possible, so that it will remain well balanced. Four rods connect the plywood table to the lower cable clamp.

B. System Scaling

The simulator could have been built full size; i.e., with the same inertia as the yaw axis of the OGO vehicle. It was felt, however, that this would result in a structure too large and unwieldy to be practical. Since the simulator was being built for developmental testing - to check out the logic of the system rather than to test flight hardware, there should be no reason for not scaling down the table inertia, so long as it was compensated for by proper modification of the attitude control system. A scale factor of 1/20 was finally decided upon.

With the moment of inertia of the table 1/20 that of the yaw axis of OGO, there are two basic approaches that might be considered for running valid control systems tests: (1) Using a control system that is basically full size, with vehicle torque levels and momentum storage capability, and

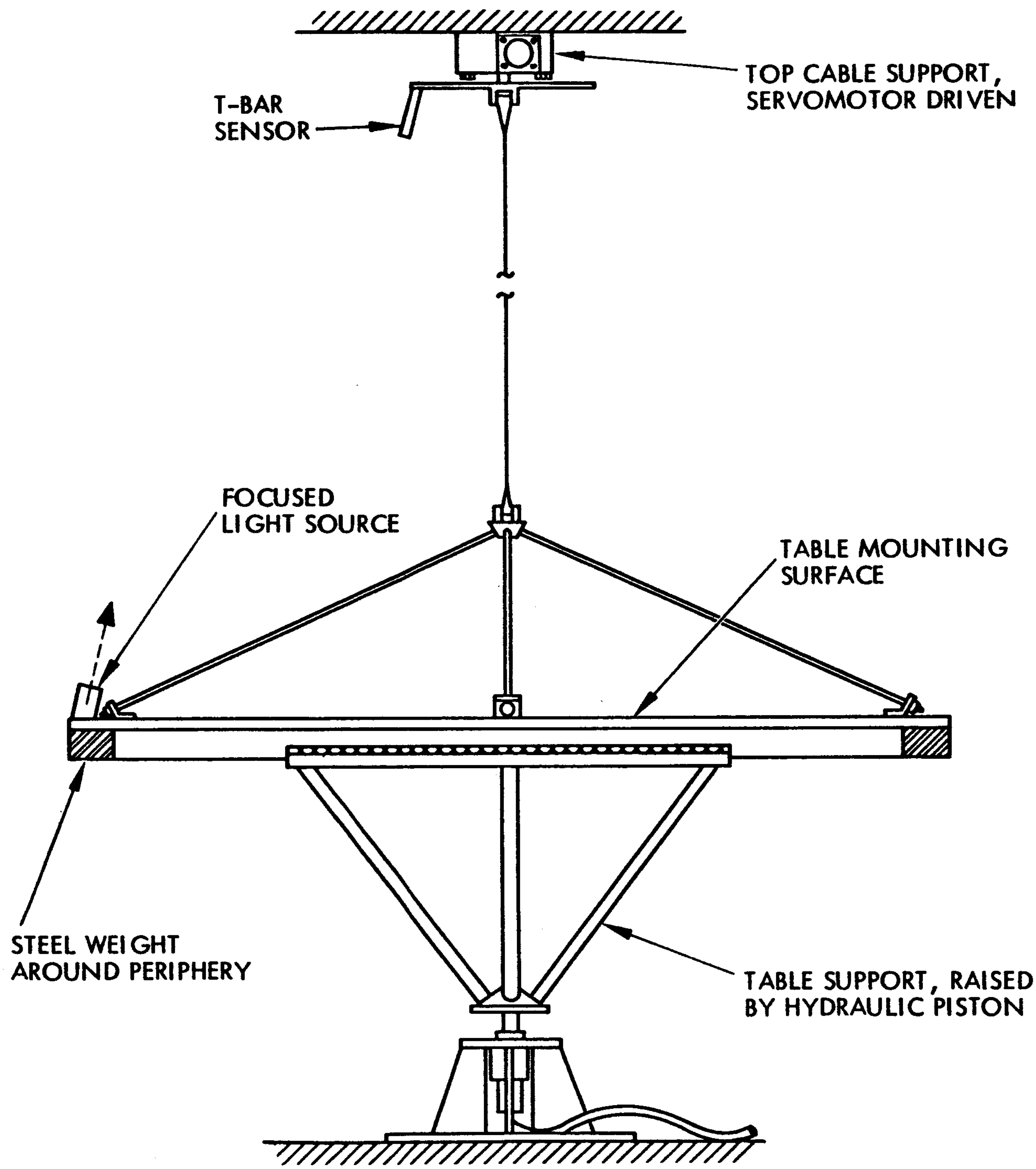
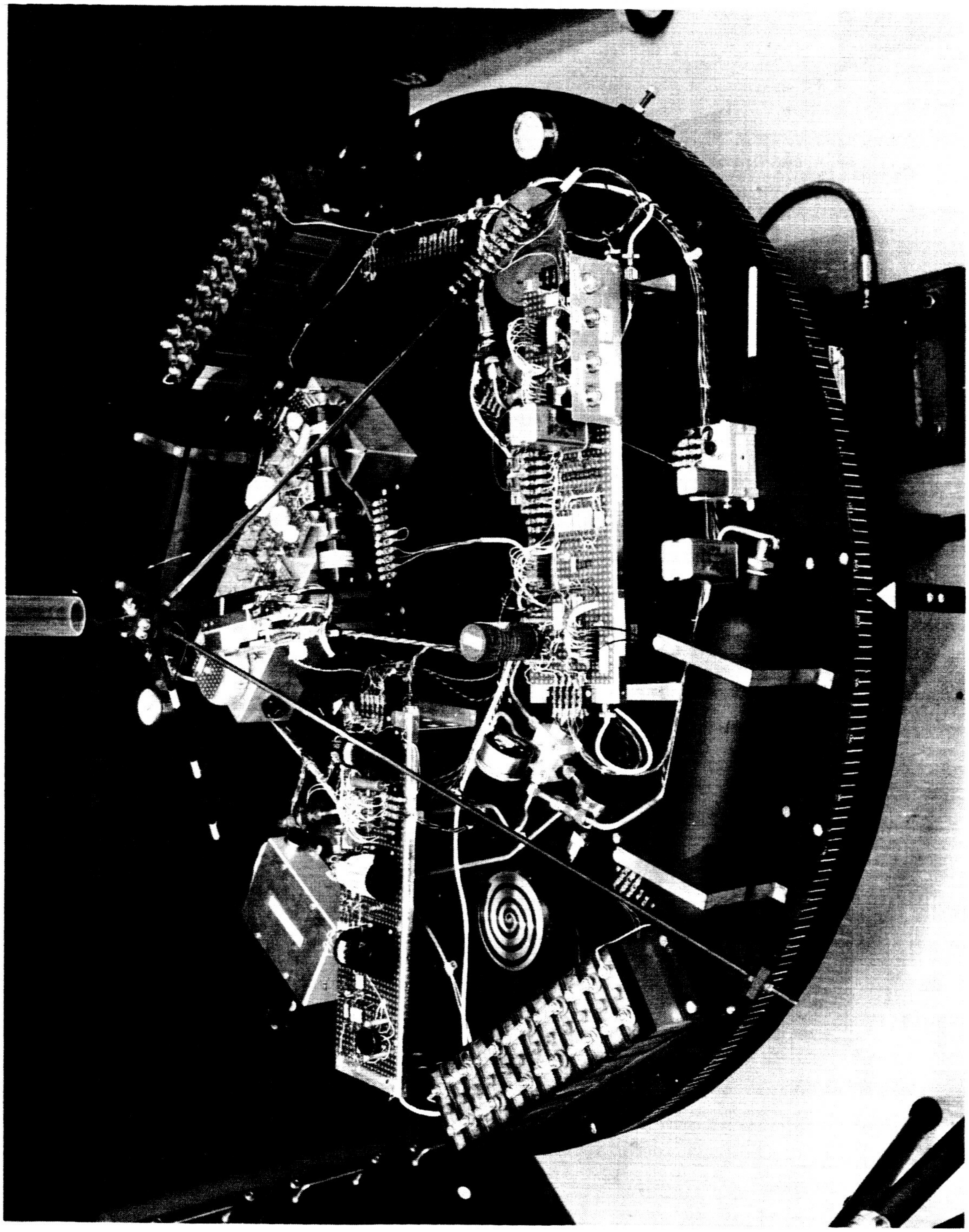


Figure 2. Single-axis Space Simulation Platform



Single Axis Simulator Table, with OGO Yaw Control
System Mounted

scaling time (using the proper ratio between test time and actual system operation time) to interpret results; (2) Reducing torque sources and angular momentum storage capability to 1/20 flight values, to match the inertia ratio between the table and OGO, and evaluating the actions of the system directly, with no scaling of time or other modification required.

The scaling of time would allow experiments to be done more quickly, and would allow the flight pneumatic system and reaction wheel assembly to be used. An attempt to scale time would, however, introduce problems that would be difficult to solve. For example, if it were assumed that one second of testing time was equivalent to 10 seconds of system operation, then the time constant of the solenoid valves would need to be reduced by a factor of 10, if the results were to be meaningful. This is highly unlikely, since one of the criteria used in selecting solenoid valves for the OGO pneumatic system was that they have as small a time constant as possible. Based primarily on this drawback, it was decided to use the other technique - the reduction of torque sources and momentum storage capability.

The torque output of the pneumatic jets is reduced by a combination of reducing the regulated pressure, using small diameter nozzles, and reducing the moment arm of the nozzles. A small induction motor having a torque-speed curve with the proper shape, but 1/20 the torque of the flight assembly, is used for driving the reaction wheel. The reaction wheel itself is a flywheel sized so that at maximum motor speed its angular momentum is 1/20 that of the flight value. These are the only system changes required; all the electronic assemblies contain actual flight circuitry.

C. Support Cable Design

The main requirements for the support cable are (1) it must have as low a value of torsional stiffness as possible, (2) it must be practical to build and assemble, (3) it must have long life. In addition to these requirements, it would be advantageous for the cable to be capable of carrying a number of electrical signals from the table without additional wiring.

The cable, as designed, consists of 10 parallel bands of Elgiloy, each band measuring 0.050 x 0.003 inches in cross section (See Figure 3). Elgiloy is a special stainless alloy developed by the Elgin Watch Company primarily for watch mainsprings. It has a yield strength in tension of 280,000 psi, an ultimate of 368,000 psi, with excellent fatigue and notch resistance characteristics. All 10 bands are clamped together at each end, with 0.002 inch thick brass shims in the clamps to keep them separated. The clamps are specially designed so that the clamping pressure reduces slowly along their length to zero at the ends. This avoids the high-stress concentration that would occur if the clamping pressure were high right to the end of the clamp.

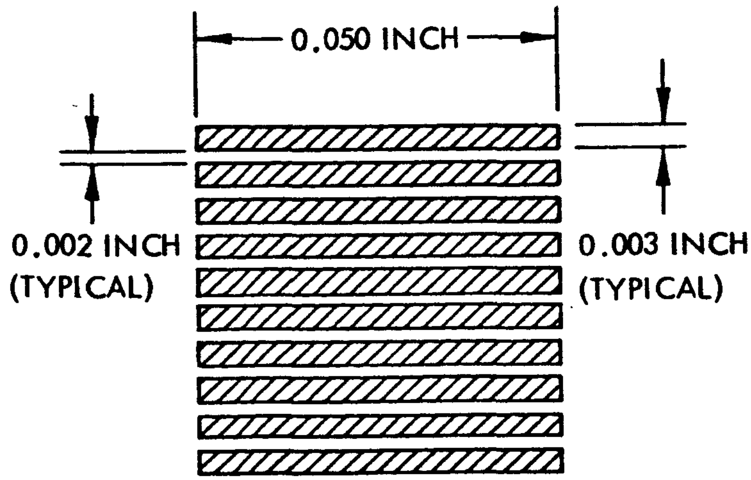


Figure 3. Cross Section of Suspension Cable

With a table weight of 300 lbs., the bands are stressed at 200,000 psi. This causes the cable to stretch approximately 3/4 inch.

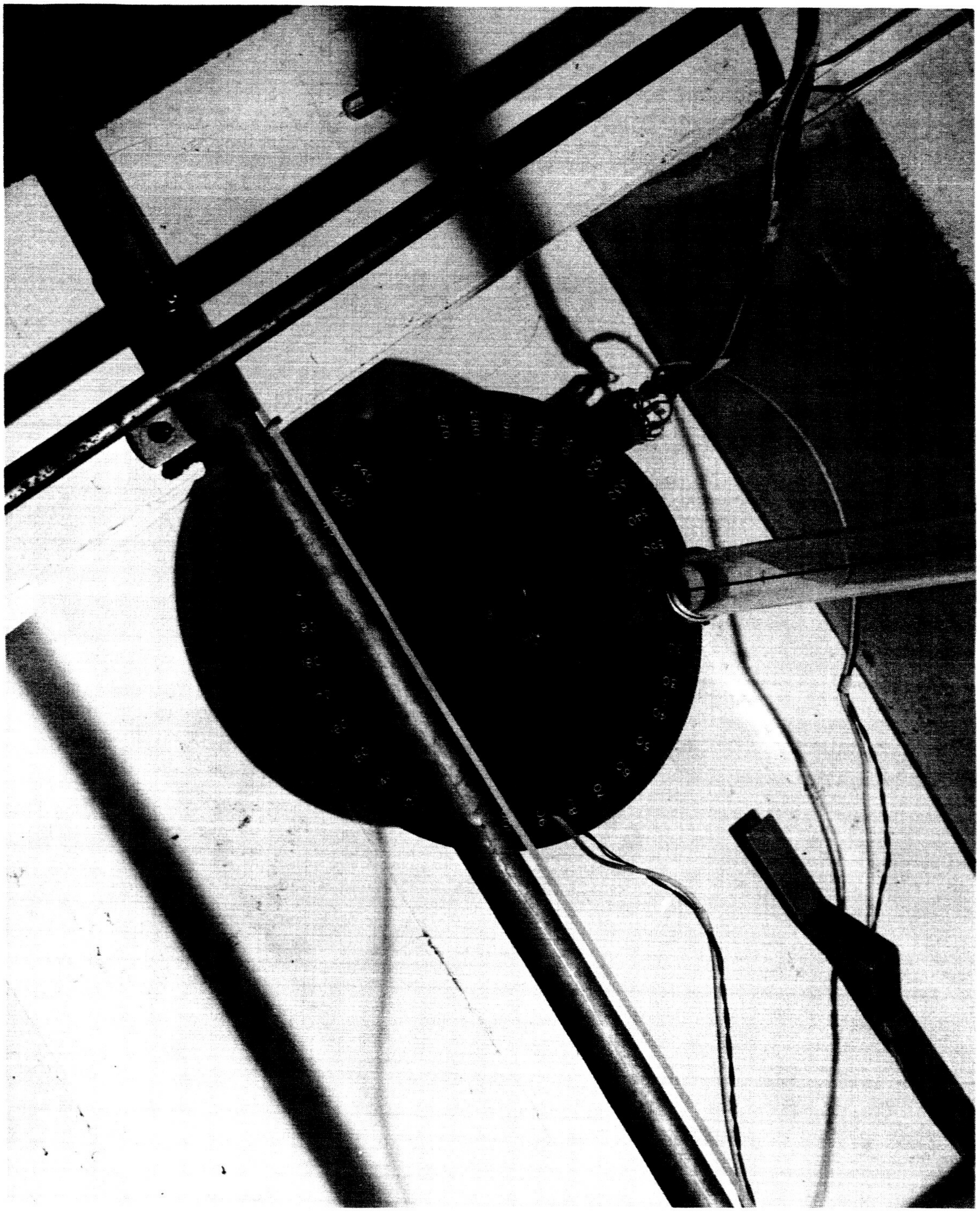
The cable stiffness has been measured to be approximately 0.0033 in.-lb/radian by the technique described under "Calibration Procedures." The exact stiffness is a function of table weight. An analysis of the cable stiffness is given in the Appendix. It should be noted that a piece of piano wire with the same cross-sectional area has a stiffness approximately 12 times as great as this cable.

An attempt was made to build the support cable so that it could also carry data from the table during a test. For this purpose, each band was individually lacquered before assembly, so that it could carry an electrical signal without shorting. This technique would have been successful except for one difficulty. The three insulating materials that were tried for spacers between the bands in the clamps - mylar, tracing paper, and scotch tape - would all slip under load. Metal spacers were found to cut through the lacquer and short the bands together.

Due to lack of manpower, no further development work has been done on this insulated cable. The technique is definitely feasible, however, and will work if time is spent to complete the development. Much tedious work is required for assembling each cable, so this development goes slowly. In the meantime, signals can be taken from the table through very small wires, such as varnish-insulated No. 40, hung loosely next to the support cable. Wires of such small cross section add very little torque to the table, especially if they are connected to the top support so that the servo minimizes their twisting.

The cable design was arrived at from an attempt to minimize its torsional stiffness. A group of wires not touching has less torsional stiffness than a single wire of the same strength, since stiffness is proportional to the fourth power of the diameter (for round wires), while load capacity is proportional to the second power of the diameter. The reason bands are used rather than wires with a round cross-section is that a thin band has much lower torsional stiffness than a round wire of the same cross-sectional area. Another advantage of the band suspension is that 10 bands are easier to clamp together than 10 round wires. A further discussion of the cable is found in the Appendix.

The torsional stiffness of the support cable is inversely proportional to its length, so as long a cable as possible was planned. For the laboratory area available for this project, however, a 9 ft. long cable was the longest that could be accommodated.



Top Cable Support, Servomotor Driven

D. Controls for Adjusting the External Torque Applied to the Platform

The only way that an external torque (simulating vehicle disturbances) can be applied to the table (other than the very small unwanted torques from air currents and air damping) is by twisting of the support cable. To allow this twist to be controlled, the top cable clamp is attached to a servomotor-driven gearbox which is bolted to the ceiling. A disc marked in degrees and a pointer show the angular position of the top clamp which, when compared to the table position, gives the angle of twist.

The servomotor has two basic controls: (1) A manual control which allows the cable mount to be moved in either direction at variable rates of rotation, and (2) A servo control which allows the top cable mount to be slaved to the table itself so that the two rotate together. The servo control allows the table to be moved to any angular position during a test with the external torque remaining zero. It is also possible to put an offset into this servo system so that a constant torque bias can be held on the system regardless of its angular position. Use of the manual control makes it possible to vary the external torque applied to the table during the course of an actual test.

Servo Design

Figure 4 is a schematic diagram of the cable support servo and manual control. A two-watt bulb is attached to the table, mounted inside a flashlight reflector so that the light will be focused into a strong beam. This beam is seen by a simple T-bar light sensor attached to the top cable mount. The T-bar consists of two Clairex CL603 Photoconductive cells separated by a shadow bar (See Figure 6). Any relative angular displacement between the reference light and the sensor results in unequal illumination of the two photocells, causing an error signal for the servo system.

The servo block diagram is shown in Figure 5. In addition to the T-bar light sensor described above, the servo incorporates a size 18 servomotor with tachometer, a McIntosh 60-watt audio amplifier, and a special gearbox with a reduction of 200:1 achieved by a single pair of spiroid gears. An analysis of this servo system is given in the Appendix.

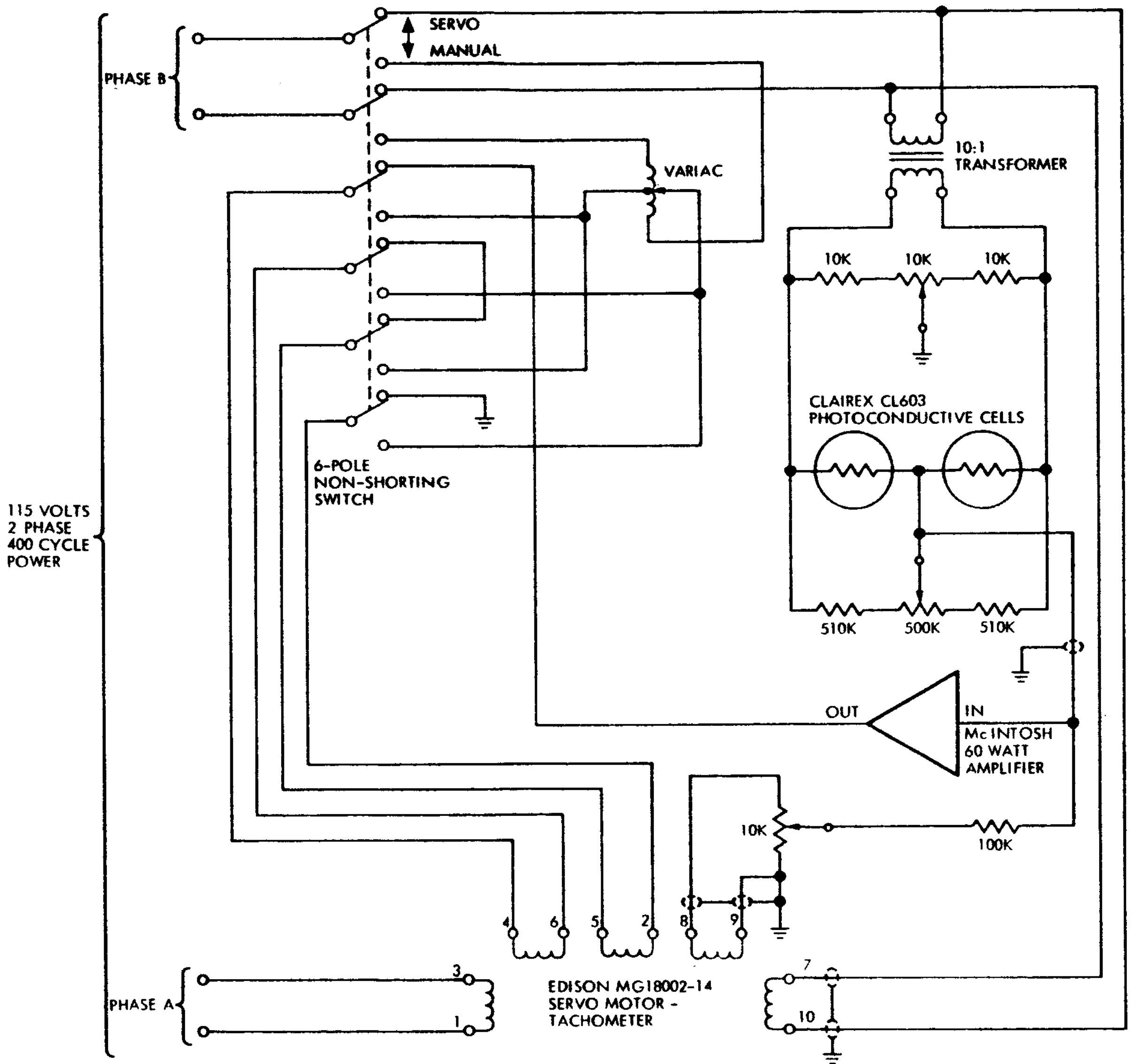


Figure 4. Schematic - Control for Top Cable Support Drive, Single-Axis Space Simulation Platform

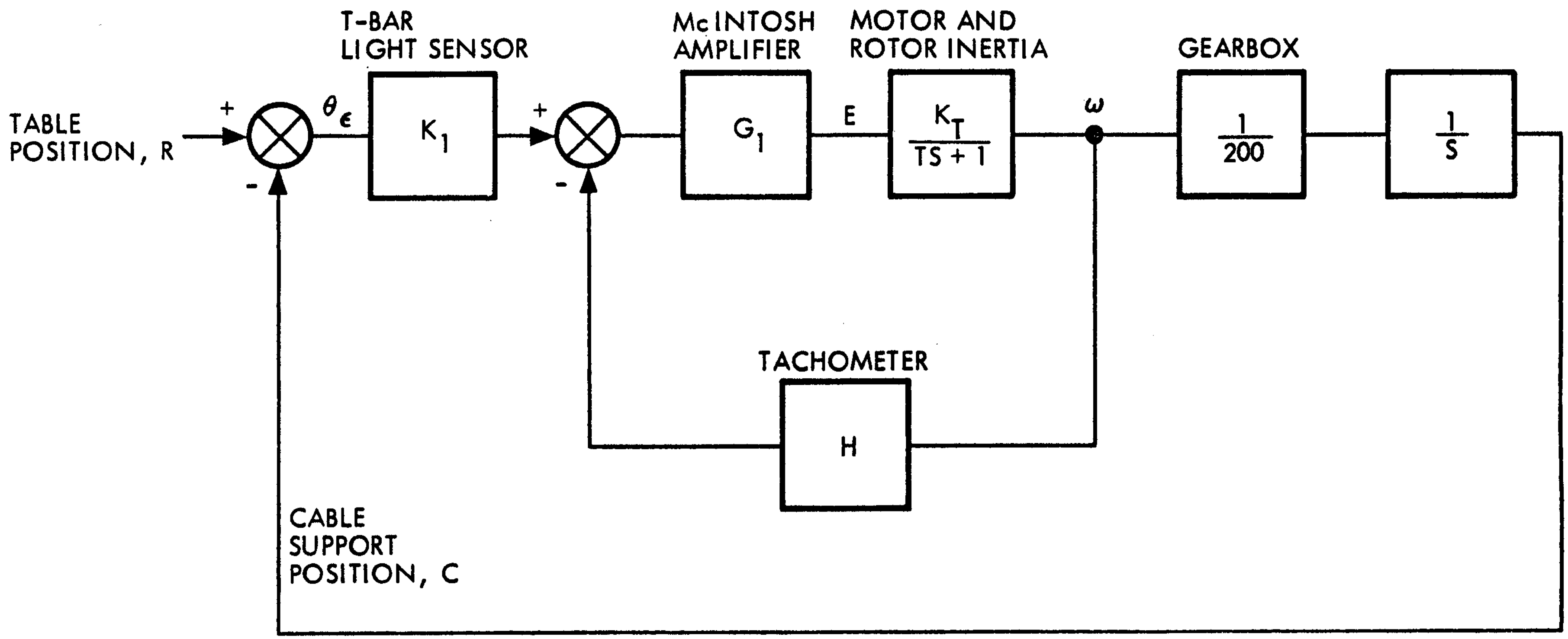


Figure 5. Block Diagram - Servo Control for Top Cable Support, Single-Axis Space Simulation Platform

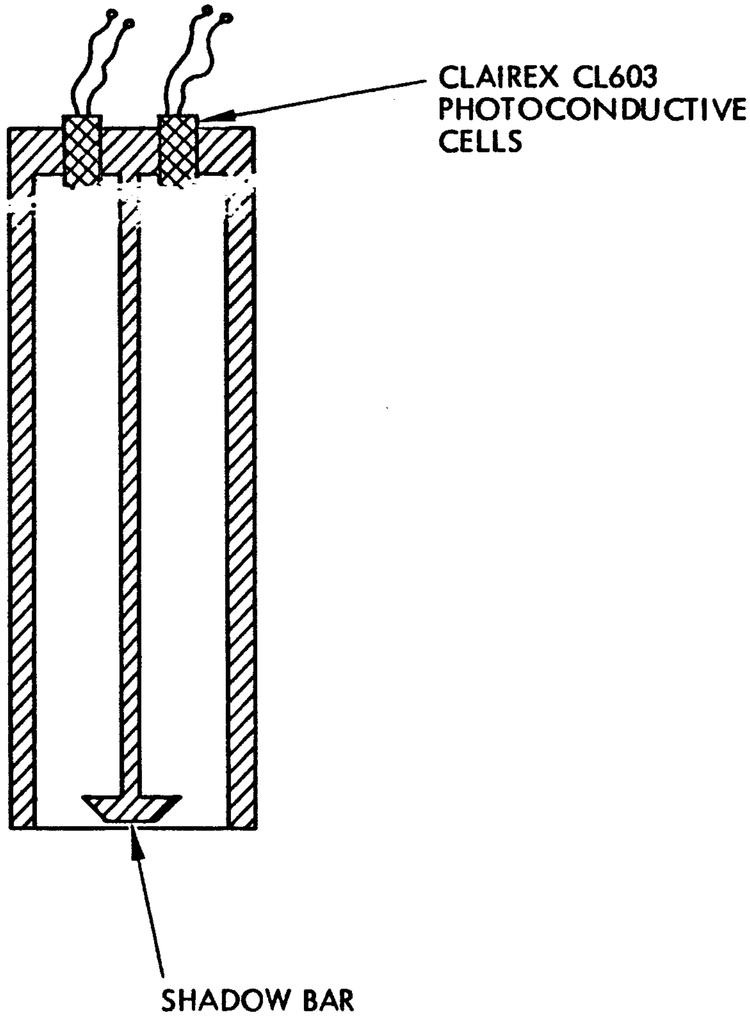


Figure 6. Cross-Section of T-Bar Sensor

E. Inaccuracies Inherent in Simulator Design

1. Torque Transmitted through Suspension Cable - The cable support servo system is capable of keeping the angular position of the top cable support within $\pm 1/4$ degree of the table position. Based on the measured stiffness of the support cable, this tolerance means that torque transmitted through the cable to the table can be kept less than $\pm 1.5 \times 10^{-5}$ in.-lb. during a test. When compared to the torque available from the scaled yaw reaction wheel motor 0.125 in.-lb., it can be seen that this small torque should cause no appreciable error.

2. Side Sway Problems - Use of the table has shown that side sway is not a great problem. There are two undesired modes of sway. The first is the simple pendulum swing about the top support, having a period of oscillation of approximately 3.3 seconds. The second mode is a pendulum action about the lower cable clamp, with a much shorter period.

Side sway can cause (1) a faulty angular position signal from the sun sensor (or horizon scanner) and (2) an oscillation of the cable support servo, as it will follow the movement of the reference light on the table regardless of whether this movement is due to rotation or side sway.

From experience, it has been found that side sway developed during a test will not normally exceed $\pm 1/16$ inch. Using this figure, a quick analysis will show what magnitude of error to expect. If the simulated sun source is placed 10 ft. from the sun sensor, this would cause a maximum position error of $\frac{(0.0625)(57.3)}{120} = 0.0298$ degree. The cable twist induced by this side sway would be $\frac{0.0625\ (57.3)}{22.25} = 0.161$ degree, causing a change in torque transmission through the cable of about 9×10^{-6} in.-lb. Errors of this magnitude would not be seen in a normal test.

3. Extraneous Torque from Air Currents - This factor presents serious problems if personnel are allowed to move near the table during a test, or if any drafts are present. Best results are obtained when tests are run inside a closed room with personnel observing from outside through windows. Any air conditioning in this room should be turned off during testing.

4. Inaccuracies from Scaling - There are no inherent errors from the scaling techniques employed. The error induced will depend only upon the accuracy of the scaling.

5. Air Damping - This factor is very difficult to either calculate or measure for the extremely low angular velocities encountered during a normal test. Very rough calculations, however, indicate that it is not significant.

IV. CALIBRATION PROCEDURES

Before any meaningful tests can be performed with the simulator, it is necessary to go through a series of calibration procedures. Most of the parameters will remain constant, once they are initially set, so that the majority of these operations will need to be performed only once.

The following special equipment is required for calibration.

1. A piece of piano wire, 0.051 dia., with clamps to fit.

   This assembly can replace the normal 10-band cable, being the same length.

2. A solid metal flywheel with a known (by calculation) moment of inertia. It should have a bracket to allow the support cable to be attached at its center.

Fixing the Moment of Inertia

The moment of inertia of the platform is measured by timing its period of torsional oscillation when suspended by the piano wire cable. Before that is done, however, the torsional stiffness of the piano wire must be determined by timing the period of torsional oscillation of the flywheel with known moment of inertia when suspended by this calibration cable. It is not a good idea to use a calculated torsional stiffness of the piano wire because G, the torsional modulus of elasticity for the wire material, may vary somewhat.

The following equation gives the relationship between the cable stiffness and table moment of inertia for this method of calibration.

$$K = \frac{48\pi^2 J}{T^2}$$

where: K = cable torsional stiffness - in. lb. /rad.

J = table moment of inertia - slug ft. ^{2}

T = period of torsional oscillation - seconds.

Gross changes in "J" of the table can be accomplished by adding or subtracting the large inertia weights bolted to the underside of the platform. The final small changes required for accurate simulation are made by fastening small weights with wood screws to the top periphery of the table. During this final fine adjustment, the table is also balanced so that it will hang level, i.e., perpendicular to the support cable.

Measuring the Torsional Stiffness of the Support Cable

After J, the polar moment of inertia of the table, is fixed at the desired value, the stiffness of the 10-band support cable is found by installing it in place of the piano-wire cable and again measuring the torsional period of oscillation. A check can be made on its linearity by repeating the test at different amplitudes.

Adjusting the Cable Support Servo

This servo slaves the top cable support to the table, so that the two will rotate together. This allows the external torque to the table to remain at a fixed value throughout the testing. In order to be useful, the position of zero cable twist (zero torque transmission through the cable) must be determined. This is best done by observing the free torsional oscillation of the table and determining the center point of this movement. Several oscillations should be observed, since air damping, cable hysteresis, etc., will cause a decrease in amplitude. To set the servo for zero torque, the table is fixed at this angular position by raising the underneath support structure, the "output" wire from the McIntosh amplifier is disconnected so that the top cable support will not rotate, and then the T-bar light sensor manually positioned (with the table reference light on) so that it puts out no unbalance signal. A good check on this adjustment, and also a means of achieving a finer adjustment, is to observe the action of the reaction wheel when the OGO attitude control system is run in a limit cycle.

If there is still torque being transmitted through the cable, a position error will result, and the reaction wheel will eventually build up to its maximum velocity, either clockwise or counter-clockwise. A continuing torque on the table will then cause it to rotate further until the gas jet trigger angle is reached.

For certain tests, it is necessary to maintain an unbalanced torque constant at some value other than zero. To accomplish this, an adjusting procedure similar to that just described is followed. After the zero torque position of the table is found, the top cable support is twisted by the "manual" motor control until it has moved through the proper angle to give the desired torque (based on the measured stiffness of the cable). The output from the McIntosh amplifier is then disconnected, the motor control turned to "servo" and the T-bar signal reduced to zero as before.

Calibrating Gas Jet Torque

The torque of the gas jets can best be calibrated directly, without going through the intermediate step of measuring the nozzle thrust. For this calibration the platform must be supported by the piano wire cable. If the inertia weights are removed, the process will be facilitated. The amount of steady-state twist that the desired torque will induce in the piano wire must be calculated. The equilibrium angle under this torque is then determined as a reference point. The platform is rotated to this angle, and held in place by raising the table support. The gas jets are then turned on and the table support slowly lowered. If the jets cause the wire to be twisted further their torque must be too high, and vice-versa. Adjustments should be made to the regulated nitrogen pressure until the table is at equilibrium at the proper twist angle with the pair of gas jets on. A note should be made of the regulated pressure, since this is the only variable in the system.

Reaction Wheel Assembly

No attempt is made to have the maximum speed of the scaled reaction wheel assemblies the same as that of the flight items. The parameter that must be fixed is the angular momentum at maximum motor rpm. Since the maximum motor speed will vary somewhat with flywheel size, due to windage, bearing friction, etc., the final flywheel inertia must be arrived at through a "cut and try" process.

V. OGO TESTING TECHNIQUES

The OGO attitude control system is designed to keep the vehicle yaw axis pointed toward the center of the earth at all times, and to maintain the proper combination of yaw angle and solar paddle angle so that the sun's rays are always perpendicular to the solar panel collecting surface. The control system also maintains the proper orientation of the OPEP, but no provision has been made for testing this function on the single-axis simulator.

Three sensing systems are used to meet the above requirements: (1) A horizon scanner consisting of four tracking heads which can "see" the edge of the earth. This scanner controls vehicle rotation about its pitch and roll axes. (2) A sun sensor consisting of an RTT (Radiation Tracking Transducer) for fine two-axis control (± 17 degree), and a total of six solar cells which give a coarse position signal for any possible vehicle orientation. The sun sensor controls the vehicle angular position about its yaw axis and the rotation of the solar array. (3) A gyro to sense pitch rate, used only in acquisition.

Gas jets and reaction wheels are used as torquing devices to maintain the proper vehicle attitude. A servomotor and gear train are used to rotate the solar array. The control system is strictly "bang-bang", i.e., no power is applied to the reaction wheel motors until an error of ± 0.4 degrees (± 1 degree for yaw) is reached, and the gas valves are not actuated before an error of ± 1 degree (± 2.5 degrees for yaw). For the solar array, the deadband allowed is ± 0.5 degrees. Lead networks will modify these angular limits when the rates of rotation are other than zero.

In the normal operating mode, the yaw gas jet system is deactivated. The yaw reaction wheel has about five times the momentum storage capability of either the pitch or roll wheel. Since the stored momentum in the yaw wheel is transferred to one or both of the other reaction wheels during each orbit (because the vehicle attitude in inertial space is constantly changing), the necessary gas expulsion to dump momentum is taken care of by the pitch and roll channels.

Although all three axes can be tested on the single-axis simulator, most of the testing being done is for the yaw system. This is because of the importance of the "noon turn" and the "eclipse turn," both of which take place about the yaw axis only.

As a part of the attitude control system for the yaw axis, a simulated solar array shaft is mounted on the table, allowing the sun sensors to rotate as they do on the spacecraft. This feature is important for valid testing, especially in the case of the "eclipse turn" and the "noon turn."

Details of how various tests can be conducted are given below.

A. "Noon Turn"

To accomplish a "noon turn" maneuver, the sun source, located above the table, must be slowly moved from one side of the table to the other, to simulate the case of satellite control when the sun passes overhead (satellite intersecting a line joining the sun and earth). Whenever this happens, the OGO control system circuitry is such that the vehicle will automatically make a 180 degree turn. The advantage of this maneuver, and also of the "eclipse turn," described below, is to prevent the cables to the solar array from wrapping up past a certain point, since no slip rings are provided for these on the spacecraft.

If the sun simulator is some type of uncollimated light bulb, best results will be obtained if there is some means of keeping it pointed directly at the sensor and at the same approximate distance from the sensor throughout the test (so that the sensor will put out a valid signal during the whole operation). This can be done by having the light travel along a special circular track.

B. "Eclipse Turn"

The "eclipse turn" is somewhat easier to conduct on the single-axis table than the "noon turn," since it is not necessary to move the sun simulator during testing.

Two sun sources are required. These are placed above the table, the first source being at a position corresponding to the point where the sun is eclipsed by the earth, and the second at the point where it reappears.

To begin this test sequence, the control system is turned on and allowed to limit cycle with the first sun source only turned on. After the control system is found to be operating normally, the first sun source is turned off. Both lights are left off for a period of time equal to the time the sun would be eclipsed. Then the second sun source is turned on, and the action of the control system observed.

This test can be run, of course, with the sun sources placed to correspond to a satellite position at any distance from the earth.

Since there is no yaw control during the time that the sun is eclipsed, the vehicle can drift to any yaw angle and have various yaw rates in either direction. Therefore, an alternate, and probably more systematic, method of testing the eclipse turn involves using only one sun source, placed at the position corresponding to the end of eclipse. The simulator can be placed at a number of different angles and given different rates to adequately cover the range of possible post-eclipse conditions.

C. Limit Cycle

A limit cycle test is very easy to conduct on the single-axis table. A single sun simulator is used, the control system turned on and its limit cycle action observed. "Momentum dumping" (the expulsion of gas to reduce the reaction wheel speed) is considered a part of the limit cycle operation. It occurs on only the pitch and roll channels, as explained previously.

Important and interesting data can be obtained by varying some of the test parameters.

(a) The angle between the sun's rays and the yaw axis (array angle) can be varied (applies to yaw channel only).

(b) The reaction wheel can be disabled, simulating failure, and gas jets only used (pitch and roll channels only).

(c) The unbalance torque on the table (transmitted through the support cable) can be varied over a wide range.

(d) Control system gains and other parameters can be changed.

VI. TEST RESULTS

Up to this time, testing has been conducted only for the yaw axis. Limit cycle operation and eclipse turns have been observed.

Data was taken with a Sanborn recorder. Yaw reaction wheel power, array drive power, sun sensor mode, and table angular position were the four items recorded during the tests. Figure 7 is a typical curve of control system performance during a post eclipse turn.

A more complete description of this testing program and an interpretation of the results is to be covered in another report.

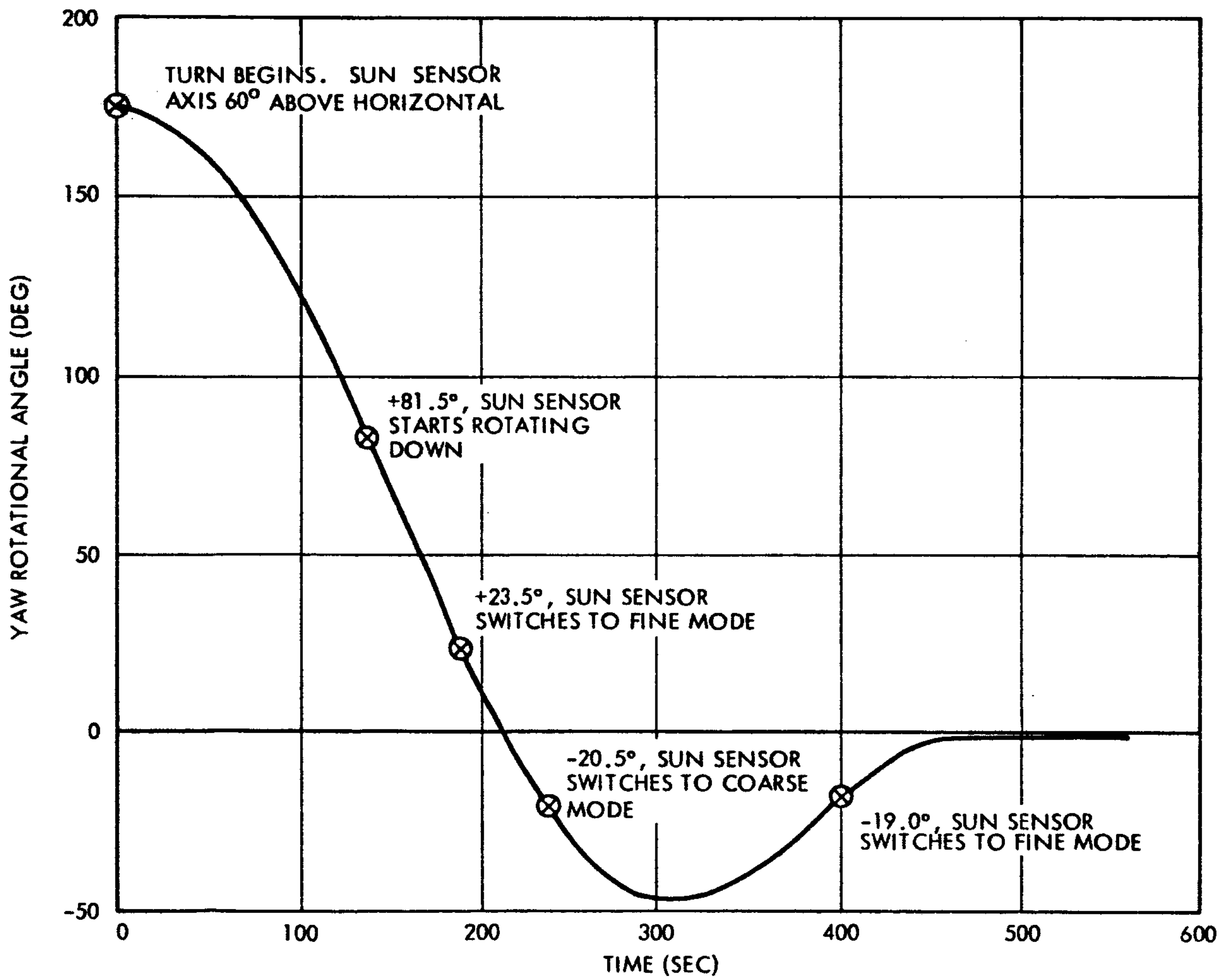


Figure 7. A Typical OGO Post Eclipse Turn as Tested on the Single-Axis Space Simulator

APPENDIX

1. Suspension Cable

Assume: (a) Table weight of 300 lb.

(b) Cable length of 108 inches

(c) Cable working stress of 200, 000 psi

Total cable area needed,

$$A = \frac{300}{200,000}$$

$$= 0.0015 \text{ in.}^2$$

If a single steel wire (with a circular cross-section) is used to support the table, its diameter will need to be:

$$d_i = \sqrt{\frac{(0.0015)(4)}{\pi}}$$

$$= 0.0437 \text{ inch}$$

The stiffness of this wire will be:

$$K_1 = \frac{GI_p}{\ell}$$, with G the torsional modulus, I_p the moment of inertia, and ℓ the length of the wire

$$= \frac{G(0.098\ d^4)}{\ell}$$

$$= \frac{(12 \times 10^6)(0.098)(0.0437)^4}{108}$$

$$= 0.0397 \text{ in.-lb./radian}$$

This stiffness can be reduced by using a number of wires to carry the load. For instance, if 10 wires (circular cross-section) are used,

$$d_2 = \sqrt{\frac{0.00015(4)}{\pi}}$$

$$= 0.0138 \text{ inch}$$

$$K_2 = \frac{(10)\ (12 \times 10^6)\ (0.098)\ (0.0138)^4}{108}$$

$$= 0.00397 \text{ in.-lb./radian}$$

If 10 bands, each 0.050 inch by 0.0030 inch in cross-section, are used, the cable stiffness is reduced still further. The torsional stiffness of a metal band with a high width-to-thickness ratio is given by the following formula (from "Elements of Strength of Materials," by Timoshenko and MacCullough):

$$K = \frac{bc^3G}{3\ell},$$

where c is the thickness, b is the width, and ℓ the length of the band. Therefore, for our cable of 10 bands:

$$K_3 = \frac{(10)\ (0.05)\ (3 \times 10^{-3})^3\ (12 \times 10^6)}{(3)\ (108)}$$

$$= 0.00050 \text{ in.-lb./radian}$$

There is a secondary stiffness effect that must be considered when the primary stiffness (as calculated above) is so small. This is due to the facts that any wires (or bands) not lying exactly on the axis of rotation have a component of their tensile force acting to give a restoring torque to the table when it is rotated. This effect is analyzed fully in Carl Grubin's memorandum (Reference No. 1); the additional spring constant from each wire is given by the equation:

$$K' = \frac{Wr^2}{n\ell}$$

where

$$W = \text{table weight}$$

$$r = \text{distance of wire from the axis of rotation}$$

$$n = \text{number of wires}$$

$$\ell = \text{length of wire}$$

In the case of the 10-band support, an exact calculation of this secondary spring constant is a bit difficult, because it is not immediately obvious what one should consider "r" for each of these thin bands. The action of the bands is rather complex when the cable is rotated, but some simplifying assumptions can be made. Since, for a small angular displacement, the force vector causing the restoring torque can be considered to lie on the major axis of the band cross-section, it would appear most reasonable to assume that "r" is the perpendicular distance between the center of the cable and the major axis of the band cross-section. The following calculation is based on this assumption.

$$K' = 2\left[\frac{W\,(0.0025)^2}{10\,(108)}\right] + 2\left[\frac{W\,(0.0075)^2}{10\,(108)}\right] + 2\left[\frac{W\,(0.0125)^2}{10\,(108)}\right] + \ldots\ldots$$

or

$$K' = \left[\frac{2W}{10\,(108)}\right]\left[(0.0025)^2 + (0.0075)^2 + (0.0125)^2 + (0.0175)^2 + (0.0225)^2\right]$$

$$= (0.00185W)\,(0.00000625 + 0.0000562 + 0.000156 + 0.000306 + 0.000506)$$

$$= 1.90 \times 10^{-6}\ W \text{ in.-lb./radian}$$

For a table weight of 300 lb.,

$$K' = 0.00057 \text{ in.-lb./radian}$$

Adding together the primary and secondary spring constants, we get

$$K_c = 0.00107 \text{ in.-lb./radian}$$

The cable stiffness has been measured to be 0.0033 in.-lb./radian for small angular movements. Since this is about three times the calculated value, it is apparent that either faulty assumptions were made in the analysis, or else there are modes of distortion and/or other factors that were not considered in the analysis. One such factor is the possible touching together of bands. Theoretically, there is a 0.002 inch clearance between each two adjacent bands over the full length of the cable. If they touch, the cable stiffness will be changed. As an extreme example: if all the bands were touching over their full length, and if stiction was high enough so that they were unable to slip during the testing, then the cable would act as a solid piece of wire, with corresponding stiffness.

With a great deal of research and experimentation, a cable could probably be designed and built with a considerably lower spring constant than the present one. For the OGO test program, however, the cable in use meets all requirements.

2. Cable Support Servo

A block diagram of the servo which allows the top cable support to follow the angular position of the table is shown in Figure 3. An electrical schematic is given in Figure 4. A description of the main servo components has been given earlier in this report.

The servo transfer function is

$$\frac{C}{R} = \frac{K_1 G_1 K_t}{200\tau S^2 + 200S(1 + G_1 K_t H) + K_1 G_1 K_t}$$

To determine the damping coefficient, let

$$\frac{\dfrac{K_1 G_1 K_t}{200\tau}}{S^2 + S\left(\dfrac{1 + G_1 K_t H}{\tau}\right) + \dfrac{K_1 G_1 K_t}{200\tau}} = \frac{K}{S^2 + 2\zeta W_n S + W_n^2}$$

Solving for ζ:

$$\zeta = \left[\frac{1 + G_1 K_t H}{2\tau} \quad \frac{200\tau}{K_1 G_1 K_t}\right]^{1/2}$$

Assuming

$$K_t = 6.51 \frac{\text{rad.}}{\text{volt-sec.}}$$

$$\tau = 4.08 \times 10^{-2} \text{ sec.}$$

$$K_1 = 42.9 \text{ volt/radian}$$

$$H = 0.03 \frac{\text{volt-sec.}}{\text{rad.}} \quad \text{(no amplification of tachometer signal)}$$

$$G_1 = 50$$

We get

$$\zeta = 3.18$$

If no tachometer feedback is used, the transfer function reduces to

$$\frac{C}{R} = \frac{K_1 K_t G_1}{200\tau S^2 + 200S + K_1 G_1 K_t}$$

and

$$\zeta = \frac{1}{\tau} \left[\frac{200\tau}{K_1 G_1 K_t} \right]^{1/2}$$

If all the system parameters are left unchanged, except for the elimination of the tachometer feedback, we find

$$\zeta = 0.593$$

The damping coefficient gives a good indication of the stability of the servo loop. In practice, it has been found that the servo will work satisfactorily with or without tachometer feedback. Without feedback, there is a tendency toward instability if the gain of the McIntosh amplifier is raised much above 50. This is undoubtedly due to gear backlash, which wasn't considered in the linear analysis.

The frequency response of the servo much better than necessary, since the movement of the table is very slow during testing. By experimentation, it has been found that the servo will follow the table within an error band of $\pm 1/4$ degree when tachometer feedback is used and the gain of the McIntosh amplifier is raised to its maximum value (approximately 400). Without tachometer feedback, the gain must be kept at a lower value, and the error band is somewhat greater.

3. <u>Side Sway of Platform</u>

The natural frequency of any side sway present is dependent only upon the length of the wire support. The period of the swing is given by the following equation:

$$\tau = 2\pi\sqrt{\frac{L}{g}}$$
$$= 1.10\sqrt{L}$$

where L is the length of the cable in feet.

The length of the cable is nine feet in its present location.

$$\tau = 1.10\sqrt{9}$$
$$= 3.3 \text{ seconds}$$

It would, therefore, be important that the gas jets not fire during a test regularly at a period of 3.3 seconds or multiples thereof. If this should happen, the side sway could become excessive.

The natural frequency of the pendulum action about the lower cable support is calculated, by the same formula, to give a period of 1.31 sec. In practice, it has been found that this is the mode less likely to be excited.

In calculating the amount of side motion that would be induced by an unbalance in a pair of jets during a momentum dumping operation, it is assumed that the displacement is the steady-state value that is necessary to balance the resultant side force. (Since the period of oscillation of the table is 3.3 seconds and the jets are on approximately 50 seconds in the momentum dumping operation, a steady-state force balance should be reached.)

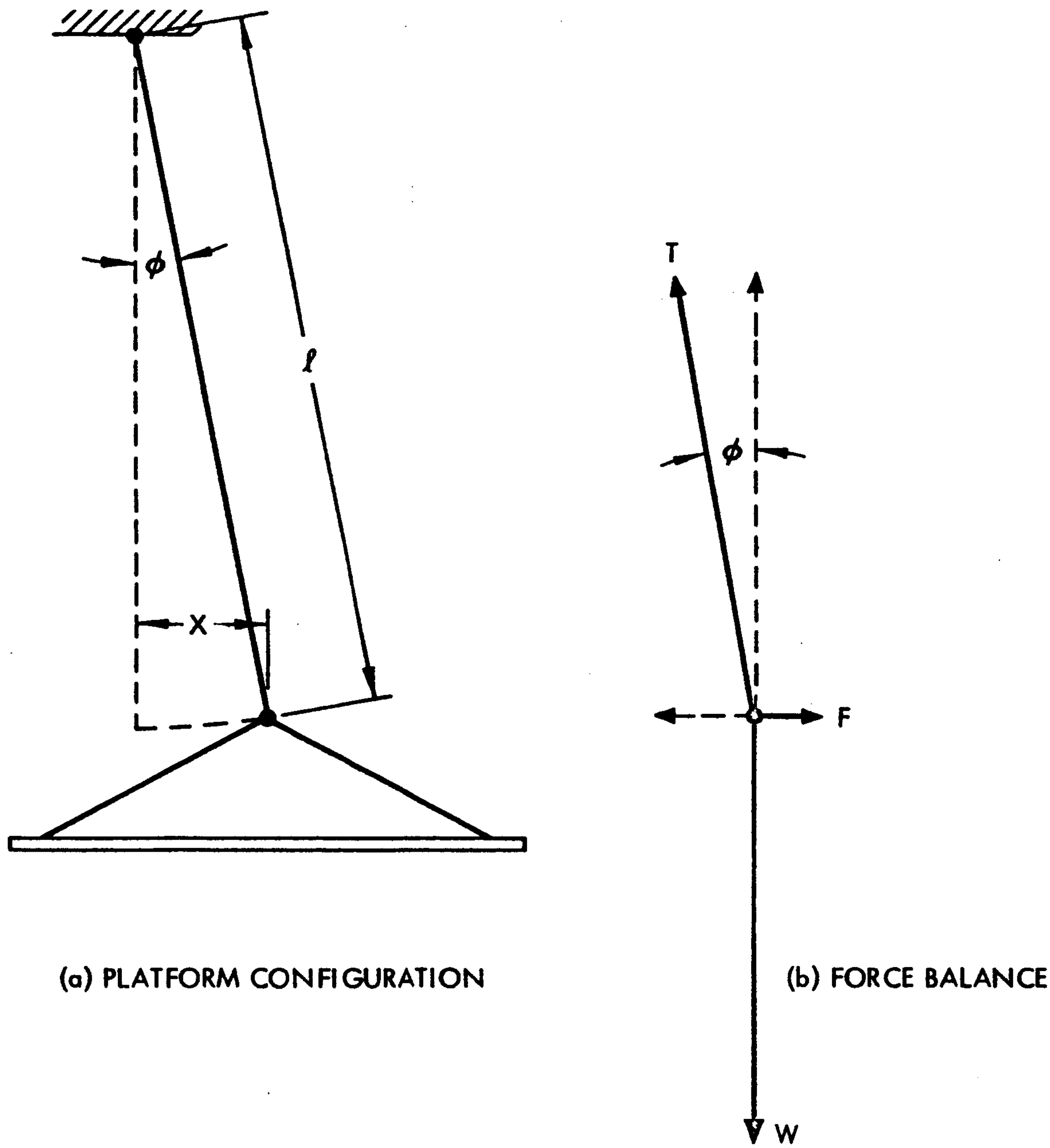


Figure 8. Platform with Lateral Motion from Jet Imbalance During Momentum Dumping

Referring to Figure 8,

$$x \cong \phi \ell$$

$$\tan \phi = \frac{F}{W},$$

$$\text{or } \phi \cong \frac{F}{W} \text{ if } \phi \text{ is small}$$

$$\therefore X \cong \frac{F}{W} \ell$$

Where

X = horizontal displacement of table

F = horizontal unbalanced force from a pair of jets

W = weight of table

ℓ = length of support wire

Assume:

(1) jet unbalance, F, is 0.00035 lb. (5 percent of 0.007 lb.)

(2) ℓ = 108 inches

(3) W = 300 lbs.

$$X = \frac{0.00035}{300} (108)$$

$$= 1.26 \times 10^{-4} \text{ inches}$$

The side motion induced by momentum dumping should be negligible as this movement corresponds to an angular rotation of less than 1×10^{-4} degrees as seen by a light sensor with its light source 10 feet away.

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3. 9313.2-93, "Design of a Single-Axis Platform for Testing of Attitude Control Systems," by N. H. Beachley, 10 April 1961.

4. 9313.2-91, "Program Plan for Construction of a Wire-Suspended, Single-Axis Space Simulation Platform," by N. H. Beachley, 30 March 1961.

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