NASA TECHNICAL NOTE

NASA TN D-6197

C.1

NASA TN D-6197

A SCALING TECHNIQUE FOR AIR-BEARING SIMULATION OF PRECISION POINTING SYSTEMS

by Gordon F. Bullock and Frederick R. Morrell

Langley Research Center
Hampton, Va. 23365

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1971

1. Report No. NASA TN D-6197	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A SCALING TECHNIQUE FOR AIR-BEARING SIMULATION OF PRECISION POINTING SYSTEMS		5. Report Date April 1971
		6. Performing Organization Code
7. Author(s) Gordon F. Bullock and Frederick R. Morrell		8. Performing Organization Report No. L-7532
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 125-19-25-02
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A scaling technique which can be used to simplify the laboratory simulation of the precision pointing system for a large space telescope is presented for the single-axis case. It is shown that the dynamic response of the scaled and unscaled control systems can be maintained the same by suitable scaling of the vehicle inertia, disturbance torque, and the attitude rate and position loops. The control system for the telescope consists of a single-axis, twin-rotor control moment gyroscope as the momentum exchange device, and a high-gain position loop including a star sensor. Experimental results from an air-bearing simulation of the pitch-axis precision pointing system for three different scale factors demonstrate the validity of the scaling technique.

17. Key Words (Suggested by Author(s)) Control-moment gyro; Telescope attitude stabilization; Simulation techniques for precision pointing system		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 17	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

A SCALING TECHNIQUE FOR AIR-BEARING SIMULATION OF PRECISION POINTING SYSTEMS

By Gordon F. Bullock and Frederick R. Morrell
Langley Research Center

SUMMARY

A scaling technique which can be used to simplify the laboratory simulation of the precision pointing system for a large space telescope is presented for the single-axis case. It is shown that the dynamic response of the scaled and unscaled control systems can be maintained the same by suitable scaling of the vehicle inertia, disturbance torque, and the attitude rate and position loops. The control system for the telescope consists of a single-axis, twin-rotor control moment gyroscope as the momentum exchange device, and a high-gain position loop including a star sensor. Experimental results from an air-bearing simulation of the pitch-axis precision pointing system for three different scale factors demonstrate the validity of the scaling technique.

INTRODUCTION

To evaluate the precision pointing capability of a large space telescope, a vehicle-control simulation was designed to study stability, error, and response of the system. Because of very large moments of inertia about its axes and the small environmental disturbance torques exerted upon the telescope, scaling techniques other than conventional are required for a laboratory simulation. Using conventional scaling techniques would require the disturbance torque to body inertia ratio to be maintained. In the large space telescope this requirement would cause the scaled disturbance torques to be in a range where simulator disturbances due to unbalance, turbine torques, and air currents in the room would cause excessive errors. The simulator would have to be stabilized to approximately 48.5 nrad (0.01 arc sec), which is beyond the state of the art in simulation today. For this type of problem, an error-scaling technique is described which results in a change on the torque scaling and on the disturbance torque to body inertia ratio. The features of this scaling technique are (1) the dynamic frequency response of the scaled system is the same as that of the unscaled system and (2) the inputs to the control actuator are unscaled and allow the use of full-scale hardware in the simulation.

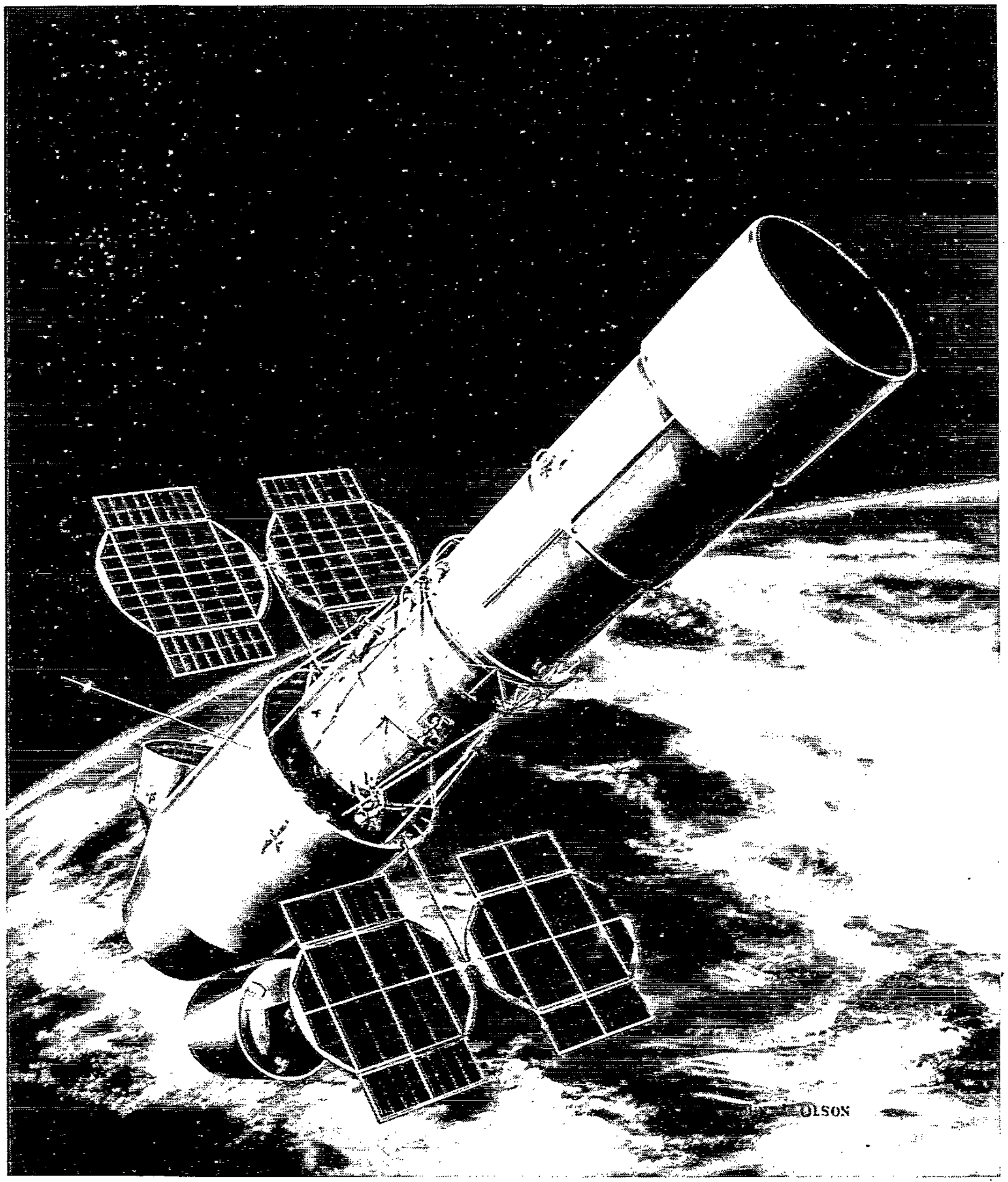
SYMBOLS

D	gyro damping, N-m/(rad/sec) (ft-lb/(rad/sec))
H	angular momentum of control moment gyro rotor, N-m-sec (ft-lb-sec)
I_g	control moment gyro gimbal inertia, kg-m^2 (slug-ft^2)
I_m	inertia as seen by control moment gyro servomotor, kg-m^2 (slug-ft^2)
I_v	telescope pitch axis moment of inertia, kg-m^2 (slug-ft^2)
K_s	sensor gain, volts/rad
k	inertial scale factor, nondimensional
N	gear ratio
s	Laplacian operator, sec^{-1}
T_c	control torque, N-m (ft-lb)
T_d	disturbance torque, N-m (ft-lb)
T_m	torque motor output, N-m
α	control moment gyro gimbal angle, rad
θ_v	telescope pitch axis attitude, rad
τ_s	sensor time constant, sec

Dots over symbols indicate derivatives with respect to time.

VEHICLE DESCRIPTION

NASA Langley Research Center has examined some of the requirements associated with the design and operation of a large space telescope (refs. 1 to 4), an artist's conception of which is shown in figure 1. The telescope under investigation is a 3-meter (120-inch) Cassegrain type that uses control moment gyros (CMG) as control actuators and a reaction control jet system for desaturation. In a 402-km (250-statute-mile)



L-70-1570

Figure 1.- An artist's conception of a soft gimbaled telescope.

circular orbit the maximum disturbance torque exerted on the telescope is due primarily to gravity gradient. For the telescope configuration chosen, this torque is approximately 0.298 N-m (0.22 ft-lb). The control system in its most stringent requirement must stabilize the telescope to better than 48.5 nrad (0.01 arc sec). The vehicle moments of inertia about its pitch and yaw axes are approximately 180 000 kg-m^2 (1.33×10^5 slug-ft^2) and approximately 28 000 kg-m^2 (2.07×10^4 slug-ft^2) about the roll axis. The representative attitude control system investigated uses twin-rotor, single-degree-of-freedom control moment gyros as torque sources, with each rotor of the pair having an angular momentum H of 407 N-m-sec (300 ft-lb-sec), a gimbal inertia I_g of 0.203 kg-m^2 (0.15 slug-ft^2) and damping D of 0.854 N-m/(rad/sec) (0.63 ft-lb/(rad/sec)).

CONTROL SYSTEM DESCRIPTION

A simplified block diagram of the pitch-axis attitude control system of the telescope is shown in figure 2. The single-axis rigid-body equation of motion of the telescope is (ref. 5)

$$I_V \ddot{\theta}_V = T_d - 2H\dot{\alpha} \cos \alpha \tag{1}$$

A disturbance torque T_d acting on the telescope inertia I_V produces changes in the telescope rate $\dot{\theta}_V$ and attitude θ_V. This telescope rate is detected by the CMG gimbals through the gyroscopic cross-coupling torque. The telescope attitude is determined by the star sensor which transmits an error signal to the CMG gimbals. The error signal controls a torque motor to drive the CMG gimbals; this signal changes the CMG momentum vector which generates a control torque T_c opposite to the disturbance torque. Analog computer studies (refs. 3, 4, and 6) have shown that a high loop gain is necessary to stabilize the telescope to 48.5 nrad (0.01 arc sec). Furthermore, these studies showed that nonlinearities in the CMG result in undesirable limit cycle operation. To check the validity of the assumptions made in the computer studies, a single-axis air-bearing simulation of the attitude control system was designed. By using conventional scaling techniques, the problems associated with the large telescope moments of inertia and the small disturbance torques were immediately apparent. If conventional scaling techniques were used, the disturbance torque to body inertia ratio would be maintained. A simulation of the pitch-axis attitude control system, a simulator inertia of 40.7 kg-m^2 (30 slug-ft^2) being assumed, would require the disturbance torque to be

$$T_d(\text{simulator}) = T_d(\text{telescope}) \frac{I_V(\text{simulator})}{I_V(\text{telescope})} = 0.298 \, \frac{40.7}{1.81 \times 10^5} = 67 \ \mu\text{N-m} \ \ (0.0095 \text{ in-oz}) \tag{2}$$

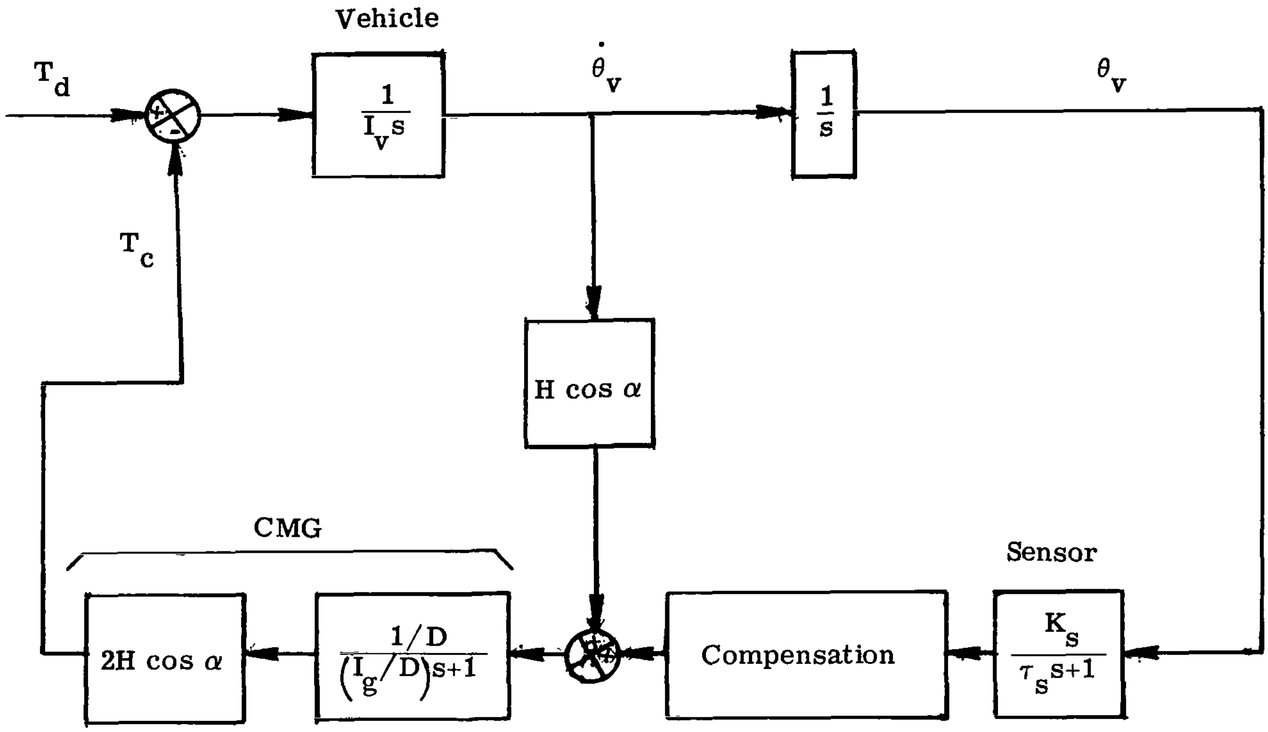


Figure 2.- Block diagram of single-axis telescope attitude control system.

This value of disturbance is approaching the limit of what can be reasonably achieved on a good air-bearing simulator and represents the maximum allowable disturbance torque. Furthermore, pointing errors of less than 48.5 nrad (0.01 arc sec) must be detected. It is doubtful that either of these requirements can be met in a room subject to even small temperature gradients and air motion. Even if the other requirements could be met, the CMG unit is a pure torque device and does not lend itself readily to torque scaling without affecting its nonlinear characteristics. These nonlinearities are one of the principal reasons for performing the hardware simulations and should be retained. These considerations led to the conclusion that the attitude control system for a 3-meter diffraction-limited telescope could not be readily simulated in the laboratory to 48.5 nrad (0.01 arc sec) by using conventional scaling techniques.

Scaling Technique

A simplified block diagram shown in figure 3 describes an error-scaling technique which alleviates these problems and allows the attitude control system to be simulated. The block diagram is for the same basic control system as shown in figure 2, but, in this case, the disturbance torque to body inertia ratio has been changed. The vehicle moment of inertia I_V has been decreased by a factor k and the disturbance torque T_d has

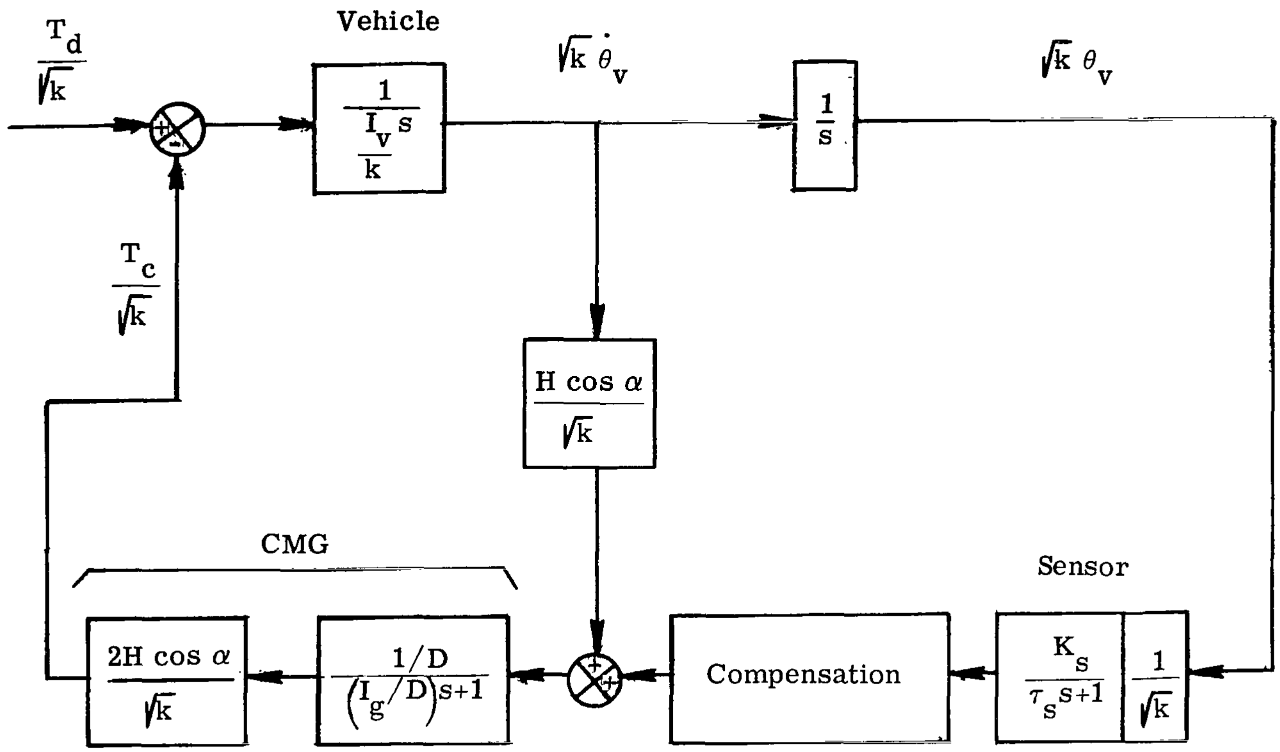


Figure 3.- Block diagram of scaled single-axis telescope attitude control system.

been reduced by the factor $\sqrt{k}$; thus, the telescope rate and position are scaled up by $\sqrt{k}$. The scaled single-axis vehicle equation of motion is

$$\left(\frac{I_v}{k}\right)\left(\sqrt{k}\,\ddot{\theta}_v\right) = \left(\frac{T_d}{\sqrt{k}}\right) - \left(\frac{2H}{\sqrt{k}}\right)\dot{\alpha}\cos\alpha \tag{3}$$

The factor k is chosen so that the vehicle moment of inertia is reduced to values that can be easily implemented in the laboratory and yet keep the disturbance torque high with respect to noise sources such as simulator torques and air currents in the room. In this scaling technique it is important that the star sensor detects unscaled star image motions if actual hardware is to be used in the simulation. This requirement can be attained by changing the focal length of the star-sensor objective optics so that the size and motion of the star image on the focal plane would be the same as that in the unscaled telescope. This optical scaling is represented by the $1/\sqrt{k}$ gain reduction in the attitude sensor shown in figure 3, and results in a sensor output that is the same as that in the unscaled telescope. Thus the sensor gain becomes

$$\text{Sensor output} = \left(\sqrt{k}\,\theta_v\right)\left(\frac{1}{\sqrt{k}}\ \text{Sensor gain}\right) \tag{4}$$

The angular momentum H of the gyro rotors has been decreased by the $\sqrt{k}$. This decrease compensates for the increase in telescope rate $\dot{\theta}_V$ since

$$\left(\sqrt{k}\,\dot{\theta}_V\right)\left(\frac{H}{\sqrt{k}}\right)\cos\alpha = H\dot{\theta}_V \cos\alpha \tag{5}$$

which is the same as that in the unscaled telescope. This condition in conjunction with the sensor modification renders all the inputs to the CMG unscaled; therefore, the CMG gimbal rate and angle are identical to those in the full-sized telescope. The control torque T_c from the CMG is reduced by $\sqrt{k}$ since the momentum H is reduced. This procedure yields the correct reaction torque to counter the scaled disturbance torque.

The open-loop frequency response for the telescope control system is obtained from figure 2 as

$$\frac{2HK_s}{2H^2 s\left(\frac{I_V I_g}{2H^2}s^2 + \frac{I_V D}{2H^2}s + 1\right)(\tau_s s + 1)} \tag{6}$$

The closed-loop frequency response is

$$\frac{\theta_V}{T_d} = \frac{D\left(\frac{I_g}{D}s + 1\right)(\tau_s s + 1)}{2H^2 s\left(\frac{I_V I_g}{2H^2}s^2 + \frac{I_V D}{2H^2}s + 1\right)(\tau_s s + 1) + 2HK_s} \tag{7}$$

where the CMG gimbals have been assumed to be 0° and no compensation terms have been included in the expressions. Similarly, the scaled open-loop frequency response is found from figure 3 to be

$$\frac{\frac{2H}{\sqrt{k}}\,\frac{K_s}{\sqrt{k}}}{\frac{2H^2}{k}\,s\left[\left(\frac{I_V I_g/k}{2H^2/k}\right)s^2 + \left(\frac{I_V D/k}{2H^2/k}\right)s + 1\right](\tau_s s + 1)} \tag{8}$$

The scaled closed-loop frequency response is

$$\frac{\sqrt{k}\,\theta_V}{T_d/\sqrt{k}} = \frac{D\left(\frac{I_g}{D}s + 1\right)(\tau_s s + 1)}{\frac{2H^2 s}{k}\left[\left(\frac{I_V I_g/k}{2H^2/k}\right)s^2 + \left(\frac{I_V D/k}{2H^2/k}\right)s + 1\right](\tau_s s + 1) + \frac{2H}{\sqrt{k}}\,\frac{K_s}{\sqrt{k}}} \tag{9}$$

It can be seen from equations (6) and (8) and equations (7) and (9) that the dynamic responses of the scaled and unscaled vehicle would be the same.

In figure 3 it can be seen that the inputs to the control moment gyros are unscaled; this condition makes it possible to use control flight hardware in the simulation by suitable adjustment of the CMG rotor speed. Since inputs to the attitude control system components are identical to those for the real case, the nonlinearities in these components will enter the simulation correctly.

To obtain experimental data to verify the scaling technique, laboratory simulations were made at different moments of inertia or values of k and with a known gimbal friction nonlinearity. If the scaling technique is valid, the limit cycle frequency for the different runs should be the same. The telescope rate and attitude should be increased in magnitude by $\sqrt{k}$ whereas the gyro gimbal rate and torque motor output should remain identical in all runs. The equipment used in the simulation runs is described in the following sections.

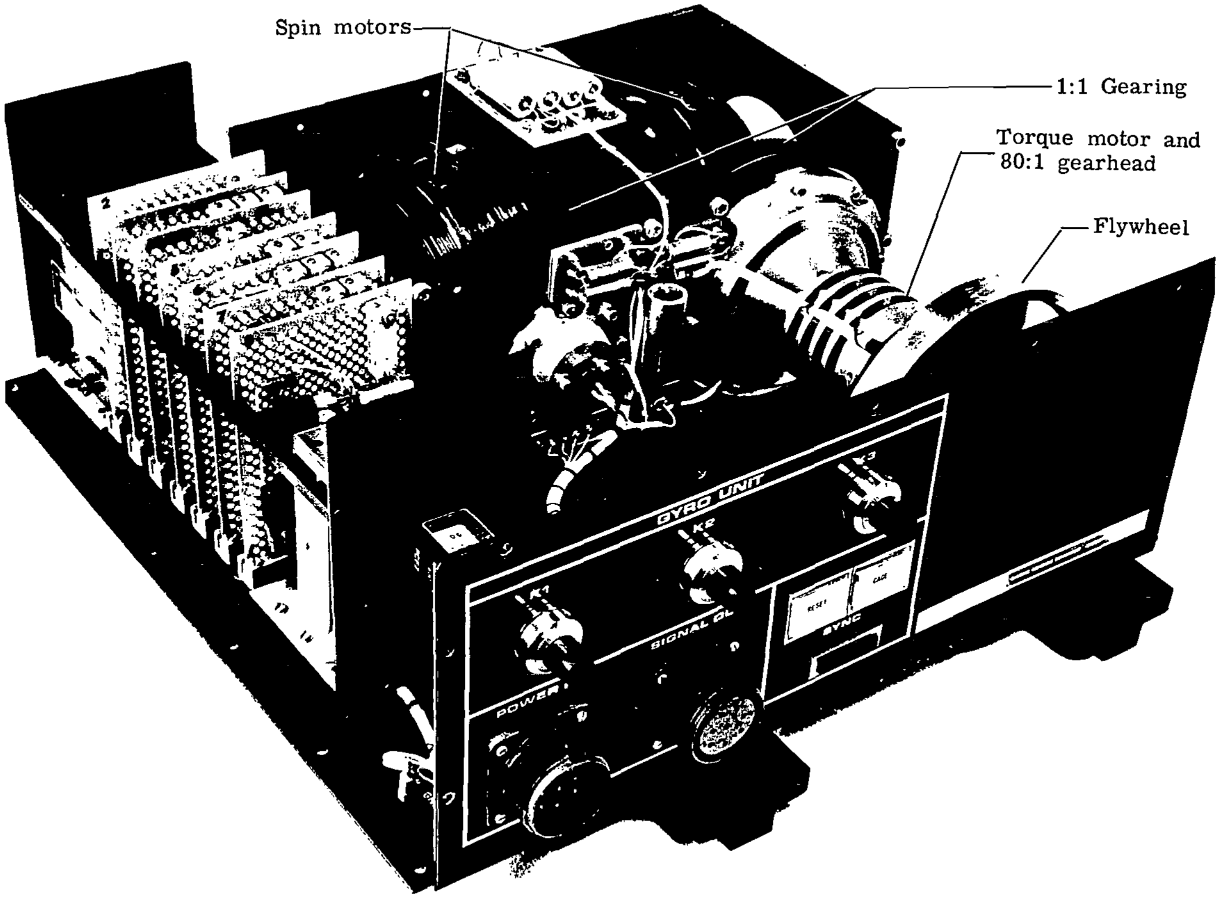
Control Moment Gyro

The control moment gyro, a photograph of which is shown in figure 4 and in block diagram form in figure 5, is the twin-rotor, single-degree-of-freedom type. This CMG was designed and built as a research tool with provisions made to vary the gimbal inertia and gyro damping. The effective gimbal inertia can be varied between 0.1357 and 0.2714 kg-m^2 (0.1 and 0.2 slug-ft^2). Gyro damping can be varied between 0.61 and 1.22 N-m/(rad/sec) (0.45 and 0.9 ft-lb/(rad/sec)).

Each rotor has a momentum storage capability of 6.03 N-m-sec (4.45 ft-lb-sec) when driven by a 445-Hz power source. Provisions were made to change the momentum storage capability by varying the frequency of the drive power. The two rotors are mechanically coupled through a 1:1 gearing. A servomotor is used to drive the gimbals through an 80:1 gear head. Stall torque of the servomotor is 0.0102 N-m (1.45 in-oz), a flywheel of 0.001356 kg-m^2 (0.001 slug-ft^2) attached to the servomotor represents the inertia seen by the servomotor. A 0.085 N-m (12 in-oz) negator spring is used on one of the gimbals to take up the backlash in the 1:1 gearing and in the 80:1 gear head.

Star Sensor

The star sensor is the pyramid beam splitter type as shown in figure 6. Light from the star entering the lens is focused on the beam splitter. From the beam splitter the light is directed to the two photomultiplier tubes located on each side of the beam splitter. Angular motion of the star with respect to the sensor will cause more light to be directed to one of the photomultiplier tubes. The outputs of the two photomultiplier tubes are



L-71-532

Figure 4.- Control moment gyro unit.

subtracted to get the error signal. The sensor was designed for an output of 2060 volts per radian, which is the sensor gain required by the model gyro rate loop.

Vehicle Inertia Simulator

The air bearing, which is a three-axis vehicle inertia simulator used in a single-axis configuration, is shown in figure 7 with the CMG and control-system hardware mounted on the payload table. The simulator is supported at the center by a ball-and-socket type of low-friction air bearing and the payload table is mounted on a shaft attached to the ball. A journal air bearing is used to restrict the motions of the simulator to those about its vertical axis. The moment of inertia about the simulator vertical axis represents the pitch axis of the telescope in the simulation. Power and signals to the simulator are channeled through a mercury-bath type of slip-ring assembly.

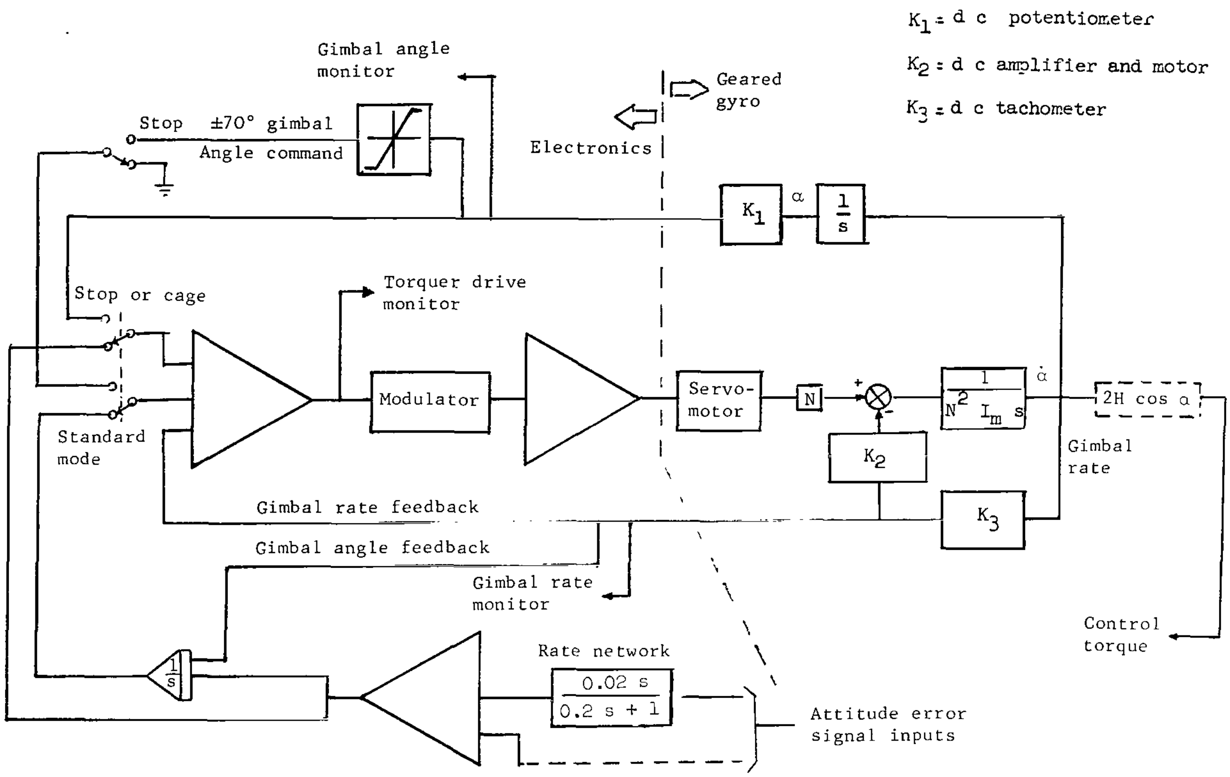


Figure 5.- Block diagram of control moment gyro unit.

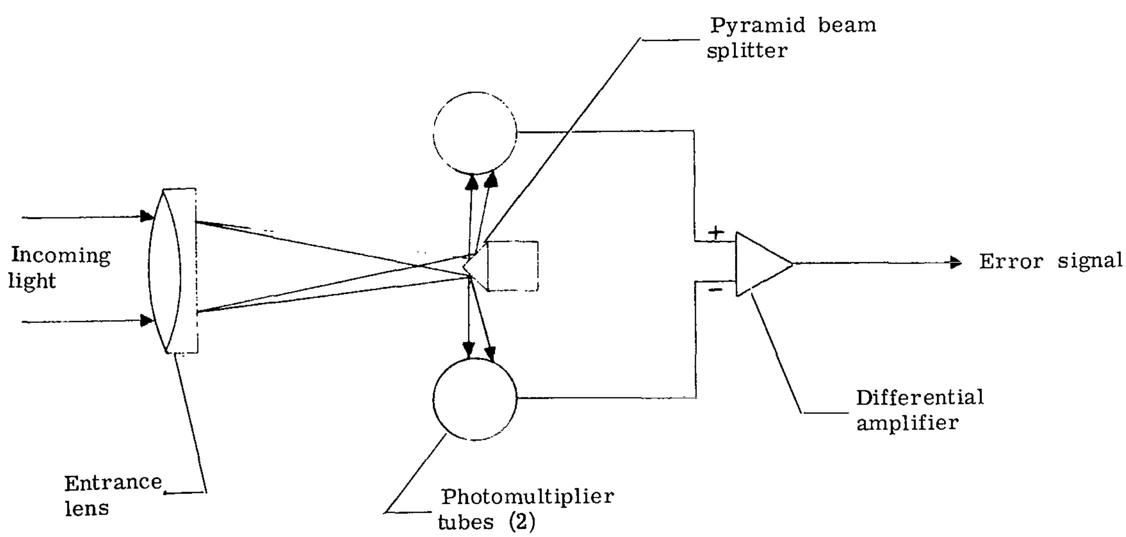
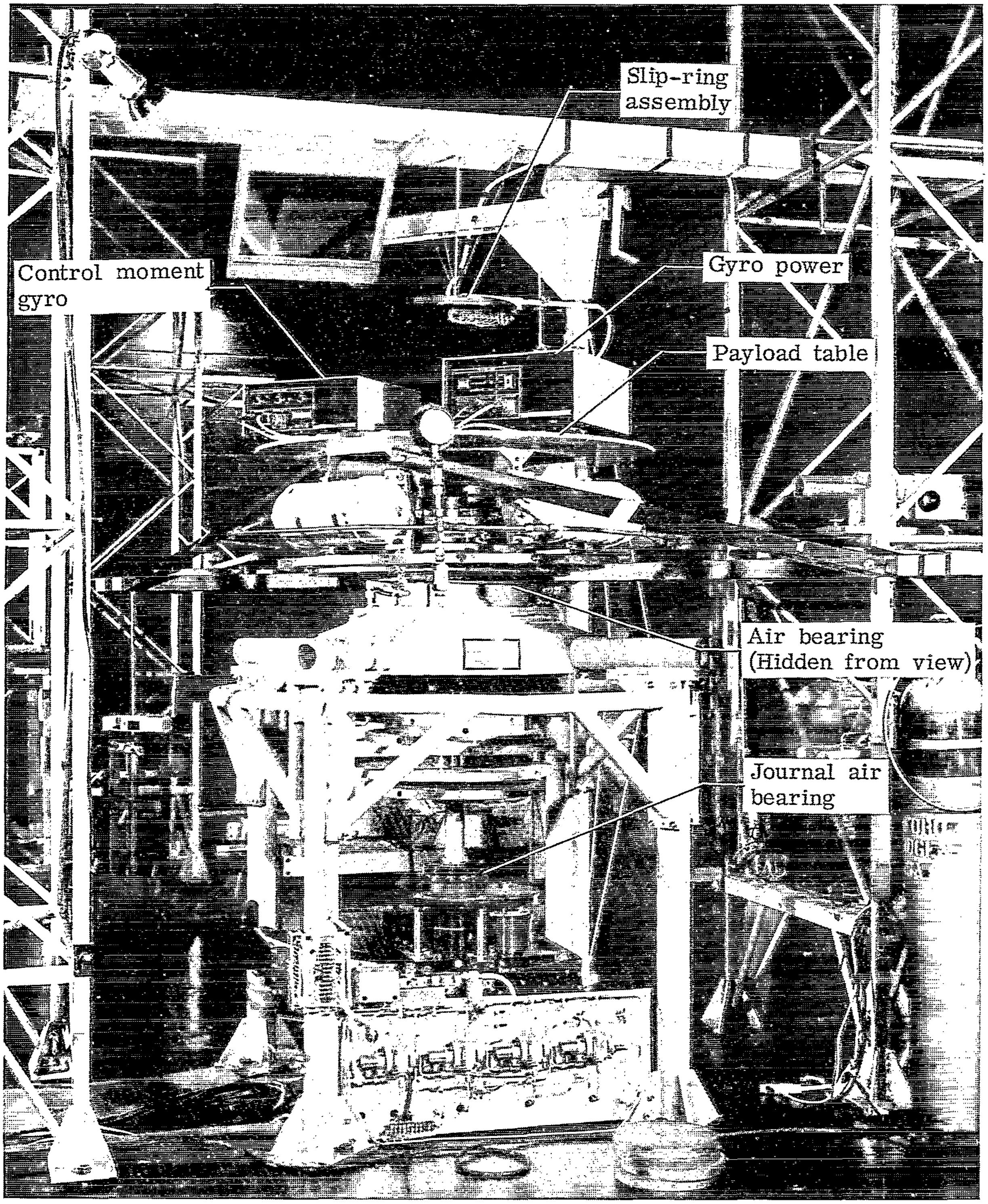


Figure 6.- Pyramid beam-splitter-type star sensor.



L-69-7007.1

Figure 7.- Vehicle inertia simulator with associated equipment.

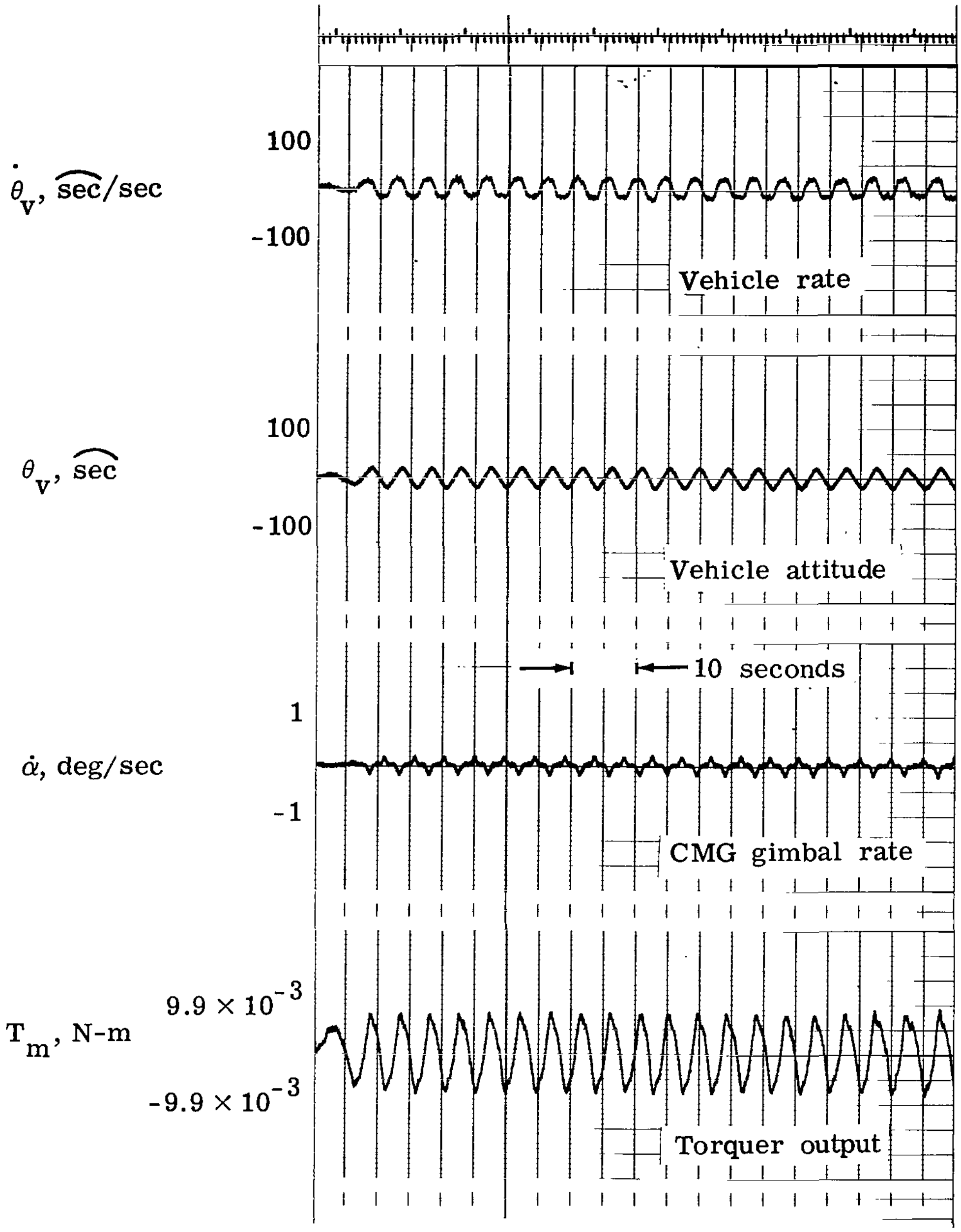
CONTROL SYSTEMS SIMULATIONS

Three simulation runs were made with moments of inertia of 277 kg-m^2 (204 slug-ft^2), 138.3 kg-m^2 (102 slug-ft^2), and 46 kg-m^2 (34 slug-ft^2). In the 277 and 138.3 kg-m^2 runs, moment arms were extended out from the payload table and mass was added to provide the desired moments of inertia.

In the first run the moment of inertia of the simulator was set at 277 kg-m^2 (204 slug-ft^2). The gain in the position loop was set to give a 9.7 μrad (2 arc sec) pointing accuracy with 0.225 N-m (0.166 ft-lb) of disturbance torque on the vehicle. The CMG was driven by 445 Hz power to develop a total momentum of 12.1 N-m-sec (8.9 ft-lb-sec). A mechanical friction was applied to the torque motor flywheel on the motor side of the 80:1 gear head, of 0.0056 N-m (0.8 in-oz). This mechanical friction was sufficient to cause the system to go into limit cycle operation. The results of a run under these conditions are shown in figure 8(a). These results show that the vehicle rate and position peak at ± 97 μrad/sec (± 20 arc sec/sec) and ± 97 μrad (± 20 arc sec), respectively. The gyro gimbal rate peaks at ± 0.0035 radian per second (0.2°/sec). The output of the torque motor reaches ± 0.00846 N-m (1.2 in-oz). The frequency of the limit cycle is approximately 0.218 Hz.

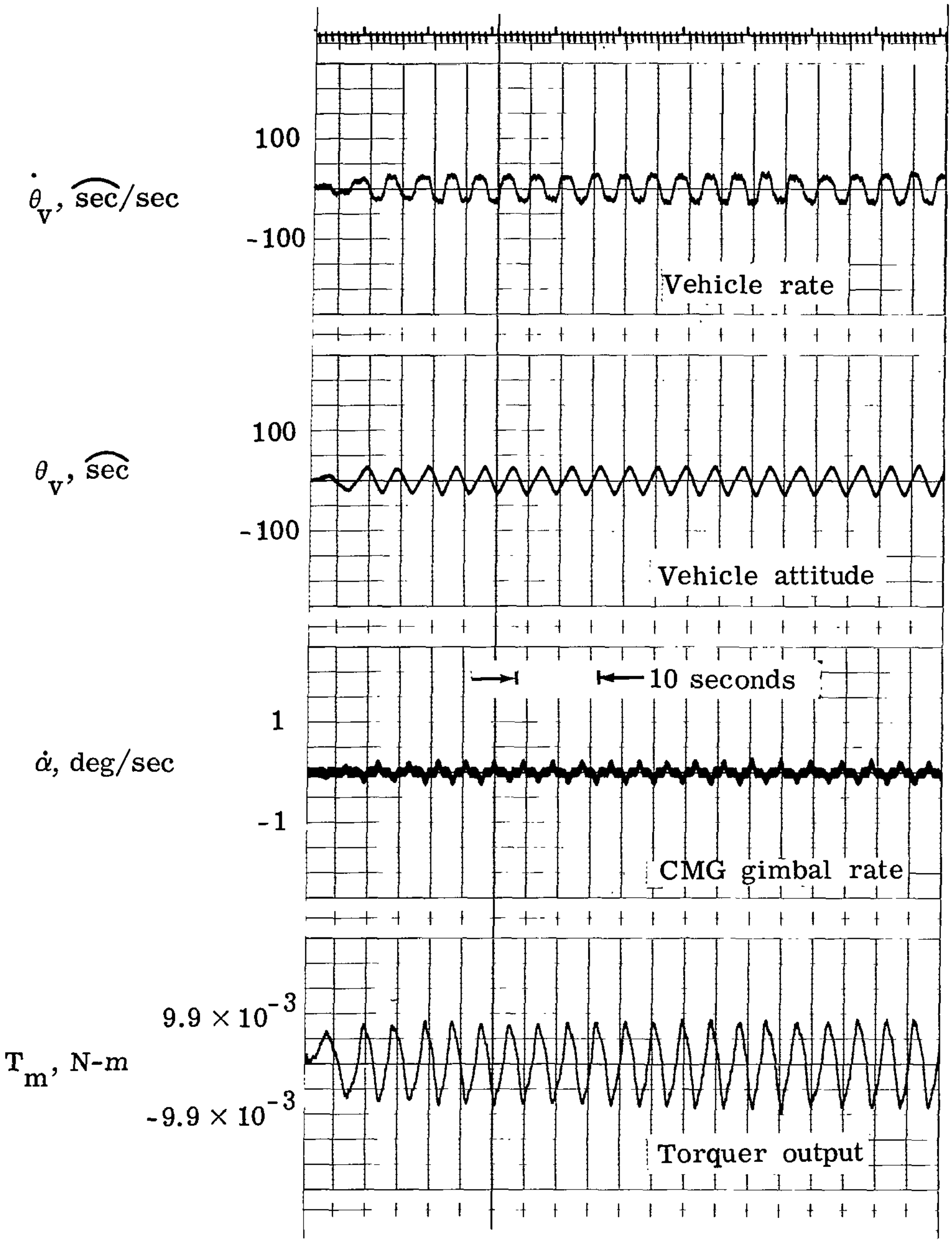
In the second run, shown in figure 8(b), the moment of inertia of the vehicle was reduced from 277 kg-m^2 (204 slug-ft^2) by a factor of 2 to 138.3 kg-m^2 (102 slug-ft^2). The star sensor gain was reduced by the $\sqrt{2}$ instead of physically changing the sensor lens. The drive frequency for the spin motors was reduced by the $\sqrt{2}$ from 445 Hz to 314 Hz lowering the total gyro momentum from 12.1 N-m-sec (8.9 ft-lb-sec) to 8.55 N-m-sec (6.3 ft-lb-sec). The gimbal friction level was kept at the same value. The results of the second run show that the telescope rate and position reached approximately ± 0.131 mrad/sec and 0.131 mrad (27 arc sec), respectively. These values compare well with the predicted values of 0.137 mrad/sec and 0.137 mrad, respectively. The gimbal rate and torque motor outputs remained approximately the same.

In the third run the simulator moment of inertia was lowered by a factor of 6 from 277 to 46 kg-m^2 (204 to 34 slug-ft^2). The position loop gain was reduced by $\sqrt{6}$ by changing the gain of the star sensor. The spin motor drive frequency was lowered by the $\sqrt{6}$ from 445 Hz to 181.5 Hz, and thus the gyro momentum was reduced from 12.1 to 4.93 N-m-sec (8.9 to 3.63 ft-lb-sec). The gimbal friction level was not changed. The results of this run are shown in figure 8(c). The telescope rate and position peak at approximately 0.228 mrad/sec and 0.228 mrad (47 arc sec), respectively. These values are approximately $\sqrt{6}$ times the output for the 277 kg-m^2 case shown in figure 8(a). These results compare favorably with rate and position predicted values of 0.238 mrad/sec and 0.238 mrad, respectively. The traces showing gimbal rate and output of the torque motor



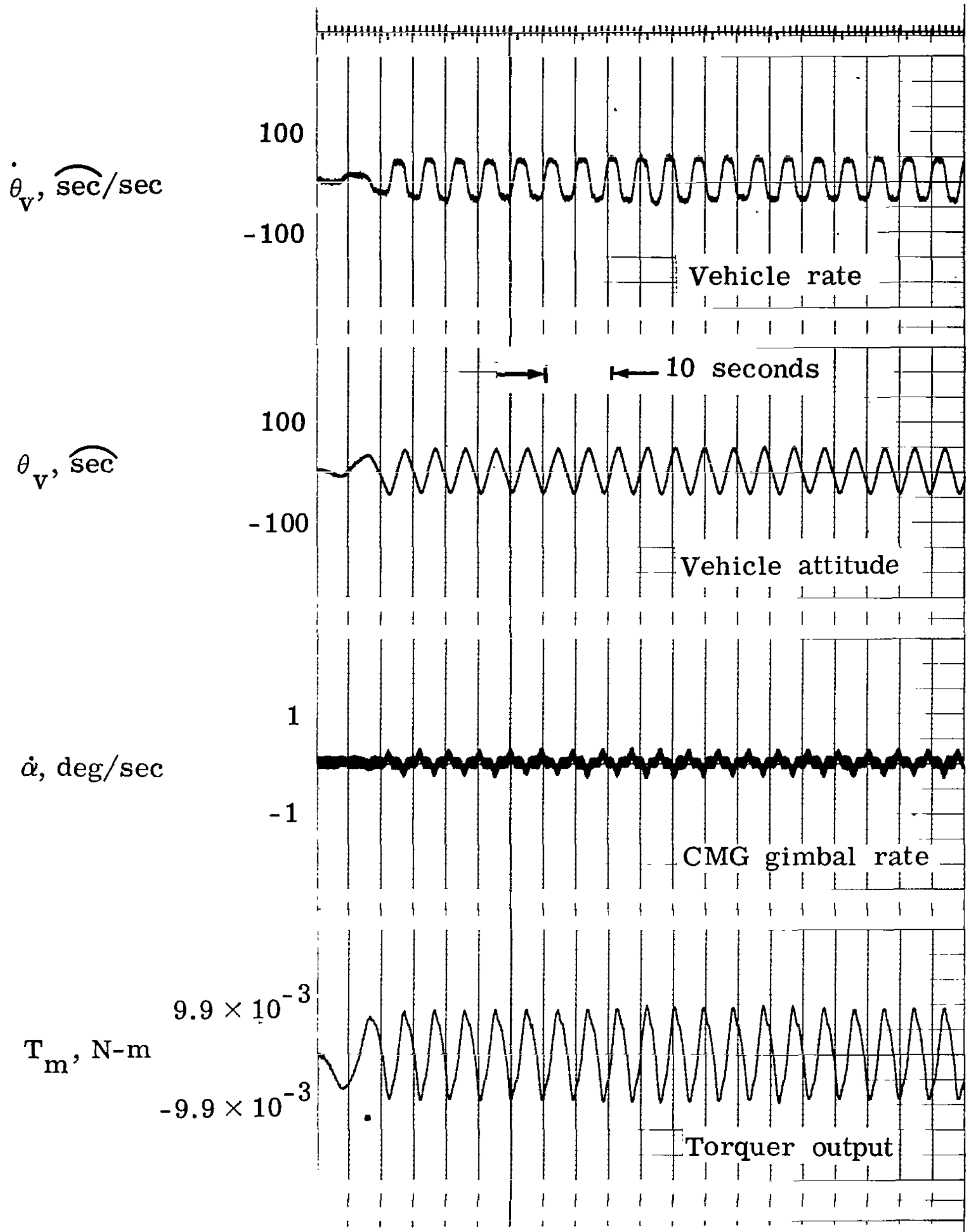
(a) 277 kg-m^2 (204 slug-ft^2).

Figure 8.- Simulation in limit cycle operation.



(b) 138.3 kg-m^2 (102 slug-ft^2).

Figure 8.- Continued.



(c) 46 kg-m^2 (34 slug-ft^2).

Figure 8.- Concluded.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

11U 001 39 51 3DS 71088 00903
AIR FORCE WEAPONS LABORATORY /WLOL/
KIRTLAND AFB, NEW MEXICO 87117

ATT E. LOU BOWMAN, CHIEF,TECH. LIBRARY

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546