NASA TECHNICAL NOTE

NASA TN D-3843

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NASA TN D-3843

EXPERIMENTAL SIMULATION OF A REACTION JET DAMPING AND ATTITUDE CONTROL SYSTEM FOR A SPINNING BODY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1967

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EXPERIMENTAL SIMULATION OF A REACTION JET DAMPING AND ATTITUDE CONTROL SYSTEM FOR A SPINNING BODY*

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SUMMARY

An experimental simulation of an on-off reaction jet damping and attitude control system for spinning bodies has been conducted. The control system derives torques from the thrust generated by four pneumatic jets equally spaced on the periphery of the simulator. Command signals are derived from rate gyros and sun sensors, and the jets operate when the signals have exceeded a preselected dead band. This system then provides the necessary torques for damping the wobbling motion when a mass shift occurs and the capability to control body attitude for bodies having the inertia distribution of a flat disk or rod shaped configuration.

INTRODUCTION

If a spacecraft requires artificial gravity, rotation of the vehicle may be desired. Many disturbances can now be imposed on the vehicle from normal operating activities of the crew. Kurzhals and Keckler, in reference 1, investigated the dynamics of a rotating space station under transient and steady-state excitations. Here it was shown that an adverse wobbling motion would result from such excitations. An on-off jet system that could control these undesirable motions has been theoretically investigated in reference 2. The present experimental investigation applies the control logic proposed in reference 2 to a rod and a disk configuration. Because of mechanical limitations of the air bearing simulator, the spacecraft inertia and control torque level of reference 2 could not be reproduced exactly. The experimental simulation should, however, establish the feasibility of an on-off jet system for wobble damping and attitude control.

The capability of an on-off control system to minimize spacecraft wobble motions produced by crew movements and to eliminate initial attitude errors was determined.

*The information presented herein includes material presented in a thesis entitled "An On-Off Jet System for Stability and Control of a Spinning Spacecraft," submitted by John G. Shearin in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering, Virginia Polytechnic Institute, Blacksburg, Virginia, April 1965.

To simulate crew movements or a mass shift a pair of weights was moved out of the plane of rotation. Thus, the principal axes shifted and the simulator became dynamically unbalanced.

SYMBOLS

I	inplane moment of inertia, I_X or I_Y, slug-foot^2 (kilogram-meter^2)
I_Z	spin moment of inertia, slug-foot^2 (kilogram-meter^2)
I_{XZ}	product of inertia in XZ body plane, slug-foot^2 (kilogram-meter^2)
M	moment, foot-pounds (newton-meters)
X,Y,Z	body axes used for analysis with Z-axis selected as spin axis
α,β	angular position, degrees (see fig. 4)
Ω	angular velocity, radians per second

Subscripts:

b	body
d	damping
I	intermediate (position of the body axes through an angle α and/or β)

DESCRIPTION OF EXPERIMENTAL CONTROL SYSTEM AND SIMULATOR

The control torques used to stabilize the simulated space station were generated by four pneumatic jets which were equally spaced about the simulator's periphery. Rate and attitude error signals, sensed by rate gyros and sun sensors, caused the jets to operate when these signals exceed the preselected dead band. Figure 1 shows a block diagram of the control logic that was used. At first, the simulator is only rate stabilized; hence, its spin axis can depart from the sun line. If the simulator exceeds the attitude dead band, the attitude system becomes active and the attitude error is reduced. When the attitude error is below the (attitude) limit the (attitude) system is turned off and the simulator is again only rate stabilized. Thus, the process repeats itself. This control logic is developed in reference 2.

Four potentiometers are used to provide accurate adjustment of the rate and attitude dead bands. The potentiometers adjust the overall signal amplification and inversely adjust the signal dead band.

The simulator used in this experiment is (rigidly) constructed of aluminum and mounted on a 6-in. (15.24 cm) spherical air bearing. The air bearing mount gives the simulator, or table, three degrees of freedom, with the spin axis having unlimited freedom, whereas the two-body axes X and Y are restricted to approximately $\pm 20^{\circ}$ of deflection. The attitude of the table is sensed by four photoconductive units, which are illuminated by an artificial sun (fig. 2) and give a voltage indication of any angular deviation. The heat from the sun source caused no noticeable effects on the attitude sensors. Two rate gyros are employed to measure the rate of change of attitude and yield a voltage proportional to the direction and magnitude of the rate of change to be produced. These gyros have a range of ± 20 deg/sec and a hysteresis limit of 0.001 of full scale. The voltages from the gyros are amplified and connected to a four-channel pen recorder. Two channels are connected to the sun sensors, and the remaining two are connected to the rate gyros.

To simulate a mass unbalance or to cause a change in the product of inertia, two movable weights (fig. 3) are mounted on opposite sides of the table; they move in opposite directions parallel to the axis of rotation, thereby keeping the table statically balanced.

The desired spin rate of the simulator was obtained by means of a small spin-up motor mounted overhead on a retractable arm as shown in figure 3. Spin jets were placed on the simulator periphery to maintain this spin rate for short durations. The simulator has the characteristics of a large manned spinning space station with the inertia ratio of 0.756 and 1.17 (disk and rod). The simulator approximately represents the physical and disturbance parameters of the example space station used in reference 2. The characteristics of the simulator are given in the following table:

Characteristic	Disk	Rod
Weight, lb (kg)	321.6 (145.8)	386.0 (175.1)
Inertia ratio, $I_X/I_Z = I_Y/I_Z$	0.756	1.17
Spin inertia, I_Z, slug-ft^2 (kg-m^2)	11.45 (15.52)	12.15 (16.47)
Spin rate, Ω_Z, rpm	18	18
Maximum product of inertia, I_{XZ}, slug-ft^2 (kg-m^2)	0.122 (0.165)	0.122 (0.165)
Maximum attitude setting, deg	10	5, 10
Control moment, M, ft-lb (N-m)	0.16 (0.2169)	0.16 (0.2169)

RESULTS AND DISCUSSION

The ability of an on-off control system to stabilize and reorient a spinning spacecraft after being disturbed by a static product of inertia change and/or an attitude error has been investigated experimentally. The results for the controlled spacecraft are given by time histories of body angles α and β, which correspond to V and -W of reference 2, respectively. These angles are shown in figure 4. The simulator used for this investigation could represent a thin disk or a rod configuration.

The testing of the control system was performed at a spin rate of 18 rpm. Initially the control system was caged and controlled by an automatic programer. The programer held the control system inoperative until the simulator had obtained the desirable spin speed and the retractable arm had been retracted. The sequence of the programer was controlled by mechanically adjusting the cams within the programer. The simulator was dynamically balanced so that there were negligible initial body rates. This balance was achieved by adding small weights at various positions until the measured body rates were practically zero. The body rates were also measured to see if any disturbances were created by the decoupling of the spin-up device.

The test results of the simulator in the disk configuration and rod configuration are presented in figures 5 to 7 and figures 8 and 9, respectively. The dashed line in these figures indicates where the control system was actuated by the programer. Figure 5 is the time histories of the simulator body angles and body rates resulting from a static product of inertia change. The weights used to produce the dynamic unbalance were initially set in their displaced position. These weights of 2.83 lbm (1.2836 kg) each moved a distance of 6.25 in. (15.875 cm) parallel to the simulator's spin axis, causing a product of inertia of 0.122 slug-ft^2 (0.165 kg-m^2). After displacing these weights the simulator's static balance was rechecked and the simulator was then spun up. Once the desirable spin speed had been obtained the spin-up device was retracted and the sun source was turned on. The simulator was then uncontrolled until the preset programer uncaged the control system. This sequence of events was the same for all tests performed. The left-hand portion of figure 5 represents the uncontrolled response of the simulator. The controlled part of the time histories shows the effect of the control system when used for rate damping only, with damping moments of $M_{d,X} = M_{d,Y} = 0.16$ ft-lb (0.2169 N-m). This damping yields a small residual coning motion of the simulator, which corresponds to steady spin about the new principal Z-axis.

The on-off control system can also be used for only attitude control when precession torques are needed. The system then utilizes the control sequence given in the description of the control system. To experimentally simulate a 10° attitude error, the simulated sun was moved along an arc, having a 4-ft (1.2192 m) radius and centered at the model center of gravity. This setup can be seen in figure 3. After the simulator had obtained the desirable spin rate, it was released and allowed to capture the simulated sun. The results of this test are shown in figure 6. After the first 10 sec of uncontrolled body motion the on-off control system was uncaged. Using a control torque of $M_{d,X} = M_{d,Y} = 0.16$ ft-lb (0.2169 N-m) the resulting motion was a steady precession of the model to the preselected dead band of 0.25° occurring in approximately 44 sec.

Thus far the control system has been used for controlling a body rate or an attitude error. The response of the control system to a combined static product of inertia and an attitude error is presented in figure 7. The weights were initially placed in this displaced position to simulate the static product of inertia and the simulated sun was moved to the appropriate position to cause an attitude error of 10°. Using the same control torque as before, the oscillation of the body rates Ω_X and Ω_Y are damped to a dead band of 0.005 rad/sec in 25 sec. The rate Ω_Y is damped about a constant rate of 0.04 rad/sec which is due to the shift of the principal axis. The simulator is then precessed to within the prechosen attitude dead band of 3.5°. The attitude dead band must be chosen to be greater than the maximum expected body-reference rotation angle of the principal axes of inertia to avoid excessive limit cycling of the control system. However, the rate error dead band can be chosen arbitrarily and is restricted only by the minimum jet pulse.

Test results at an inertia ratio of 1.17 (rod shape) with an initial attitude error of 10° are shown in figure 8. With the use of the same test procedure and control torque as that used for figure 6, the control system precessed the simulator to within the selected 2° dead band of the sun line in approximately 38 sec. No attempt was made to vary the dead band amplitude in attitude control in order to minimize fuel consumption. It is likely that an optimum system would use a variable dead band incorporated in the sensor configuration.

A test similar to that of figure 7 (static product of inertia and an attitude error of 5°) was made at an inertia ratio of 1.17 (rod shape). The results of this test are presented in figure 9. Upon actuation of the control jets, the oscillations of the body rates are damped in approximately 40 sec with the spacecraft spinning about its maximum axis of inertia. The desired angular position of the spacecraft was also achieved in approximately 40 sec. Again the attitude dead band (3.5°) was chosen to be larger than the maximum executed body-reference rotation angle of the principal axis to avoid excessive limit cycling of the control system.

CONCLUDING REMARKS

The experimental simulation of a jet damping and attitude control system for spinning bodies indicates that the on-off system is capable of damping the wobbling motions of the vehicle and of reorienting the vehicle to within specified limits. Results show that the system can be used to provide nutation damping, attitude control, and combined damping and attitude control for bodies having the inertia distribution of a flat disk or rod configuration.

Rate damping to a dead band of 0.005 rad/sec was achieved when a specified mass shift occurred in both configurations, and pure attitude control to a steady spin about a principal axis was obtained for the disk and rod configuration.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 26, 1966,
125-19-03-10-23.

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2. Kurzhals, Peter R.; and Shearin, John G.: An On-Off Control System for a Rotating Manned Spacecraft. NASA TN D-2726, 1965.

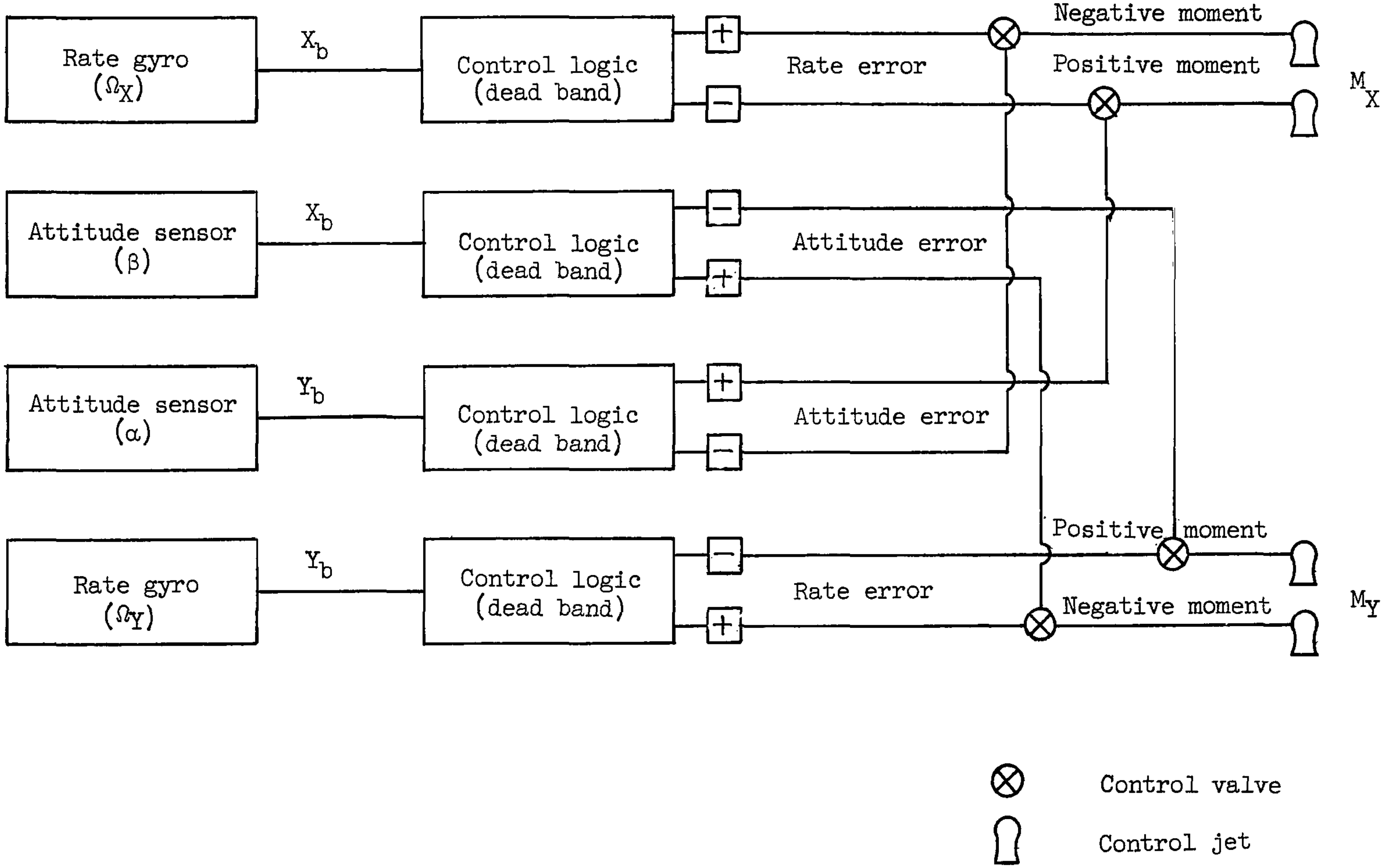

Figure 1.- Block diagram of control logic.

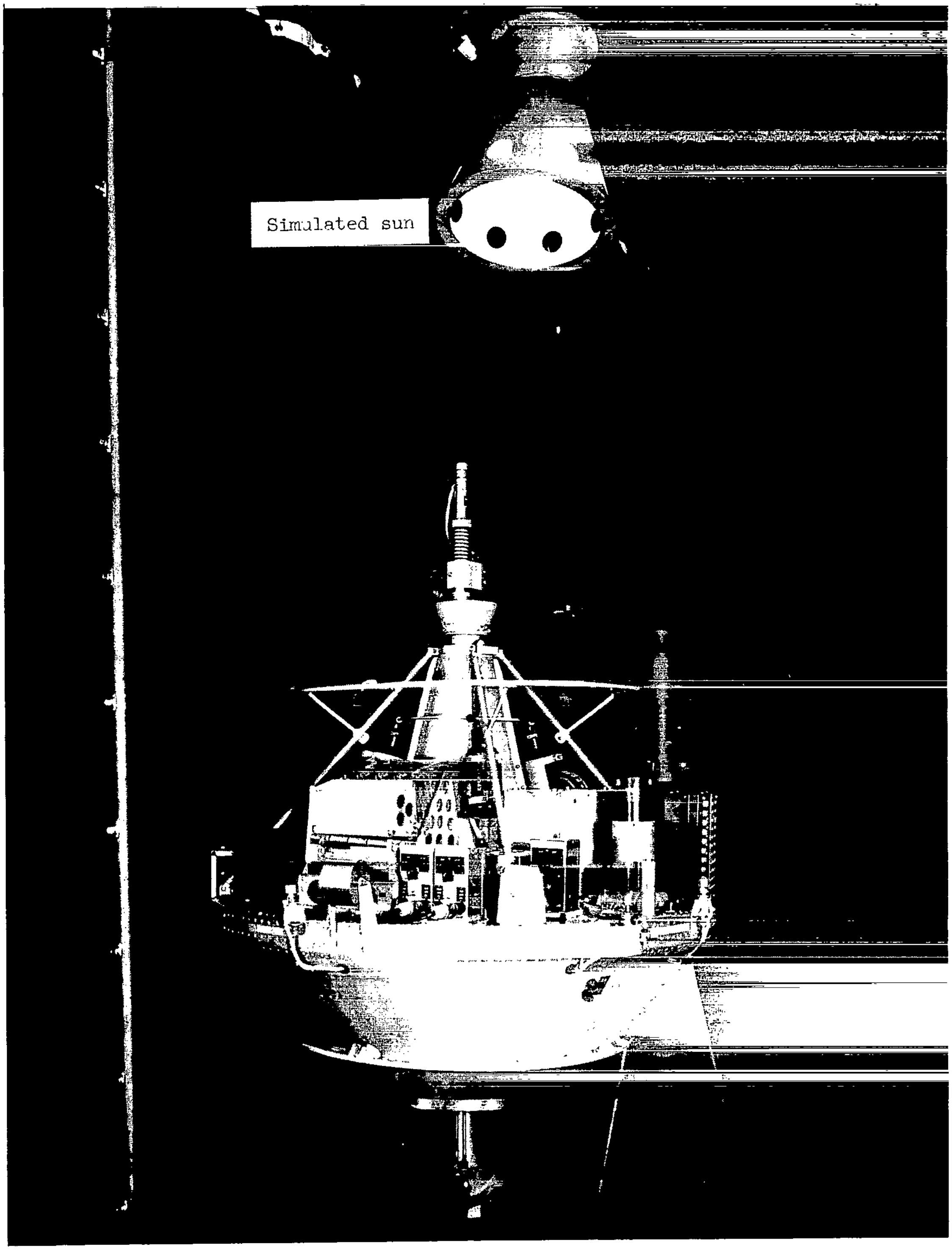

Figure 2.- Photograph of simulated sun. L-65-1398.1

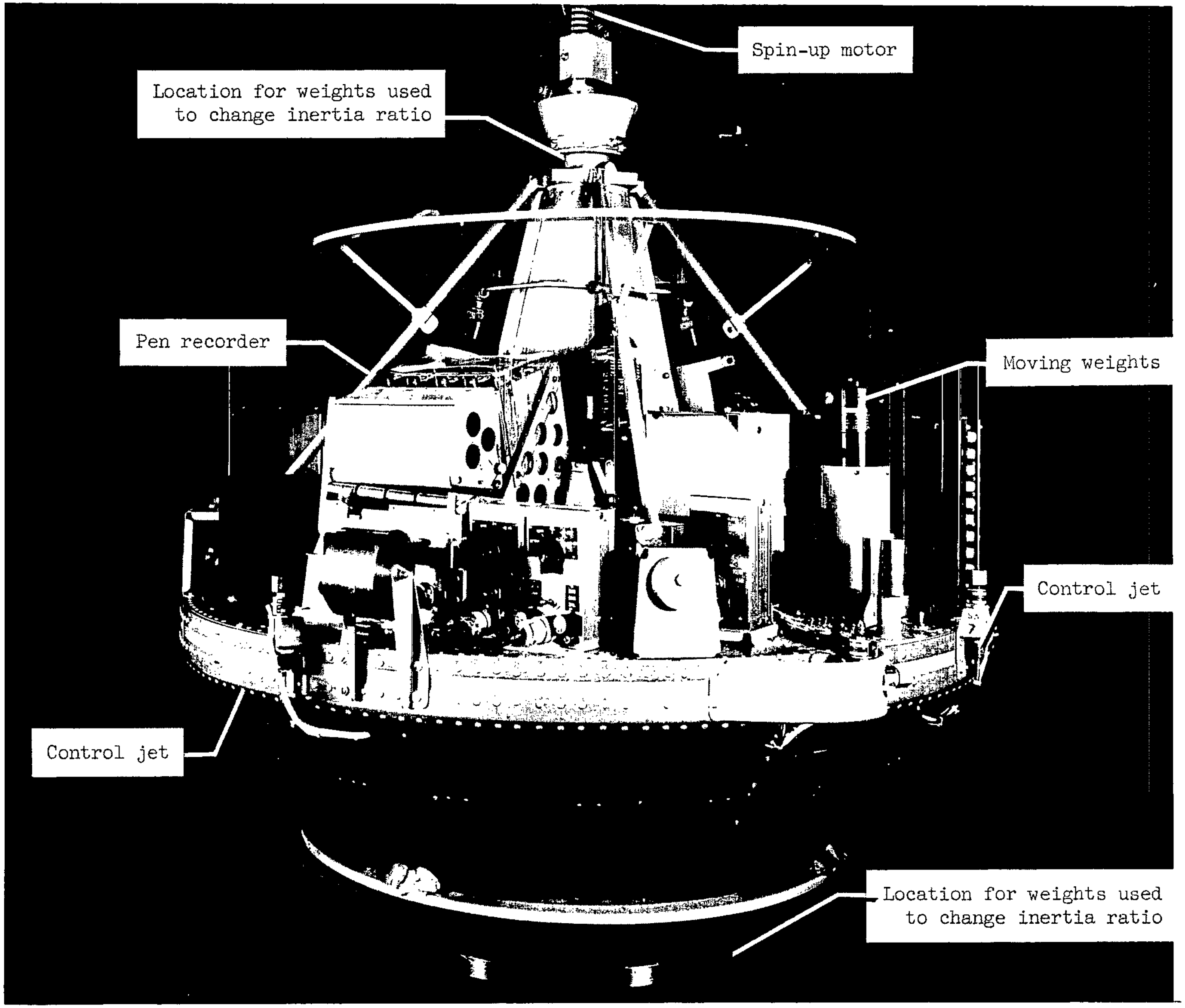

Figure 3.- Photograph of inertial simulator.

L-65-1397.1

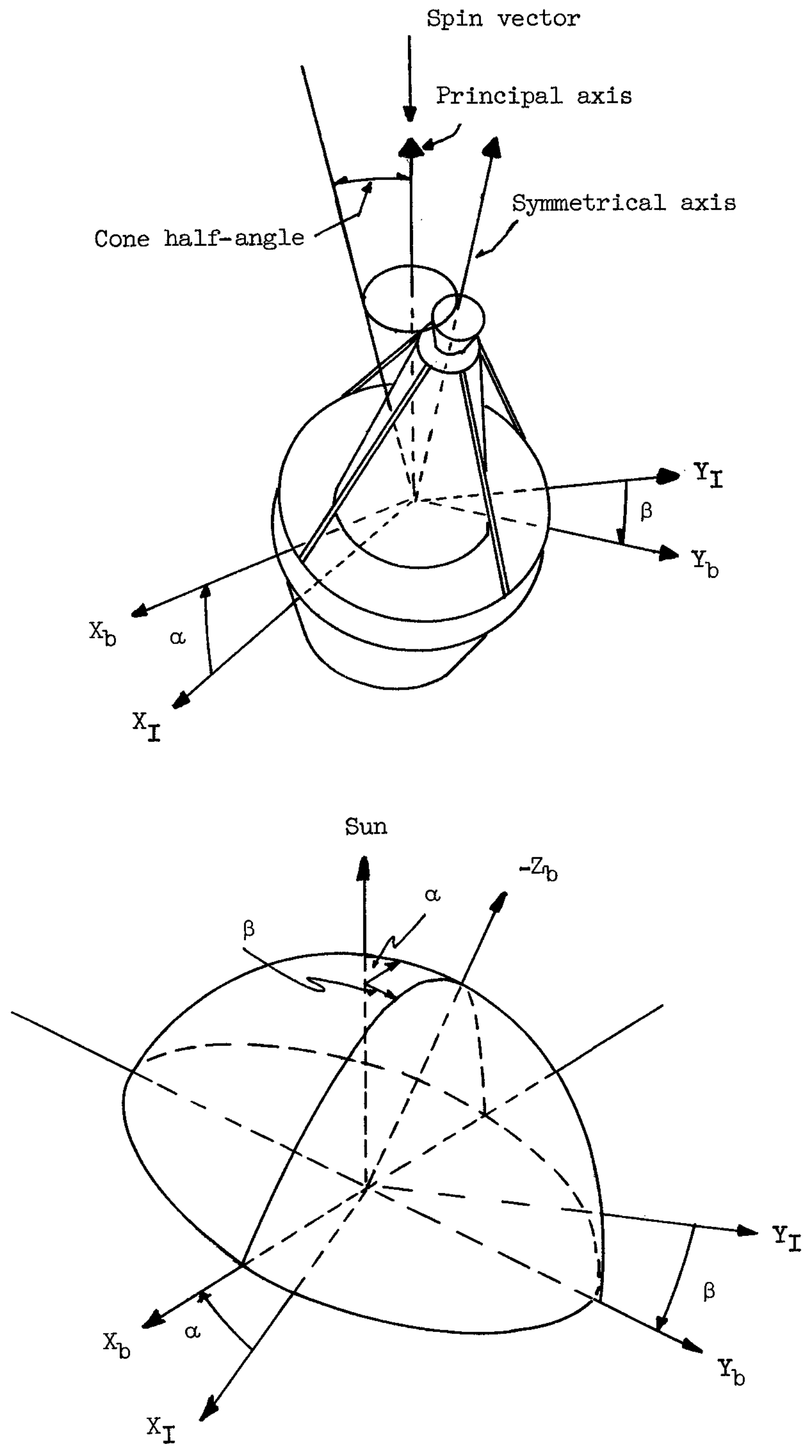

Figure 4.- Orientation of experimental body axes with respect to space fixed axes.

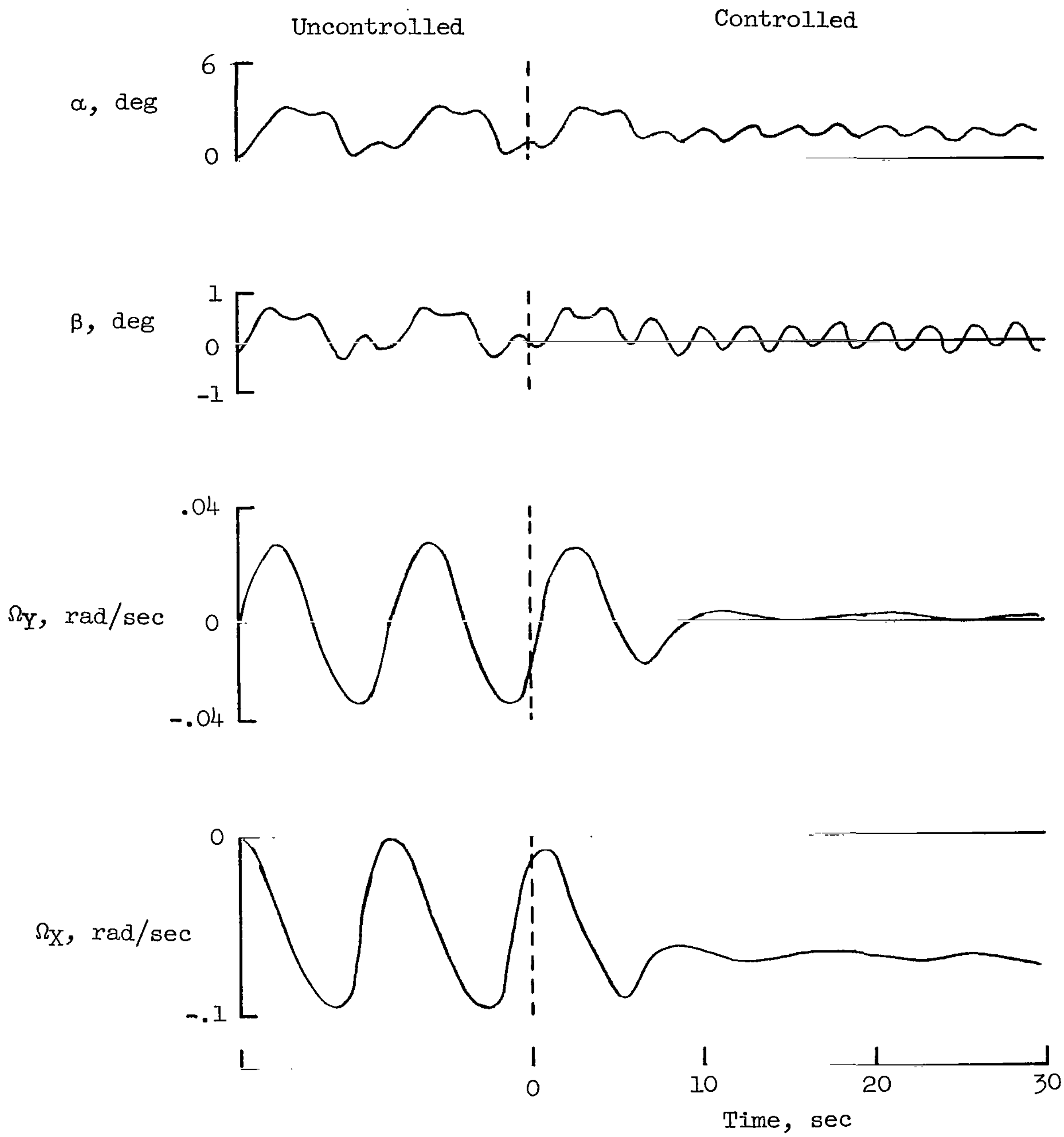

Figure 5.- Motion of a spinning spacecraft with a static product of inertia for a disk configuration. $\frac{I_X}{I_Z} = 0.756$.

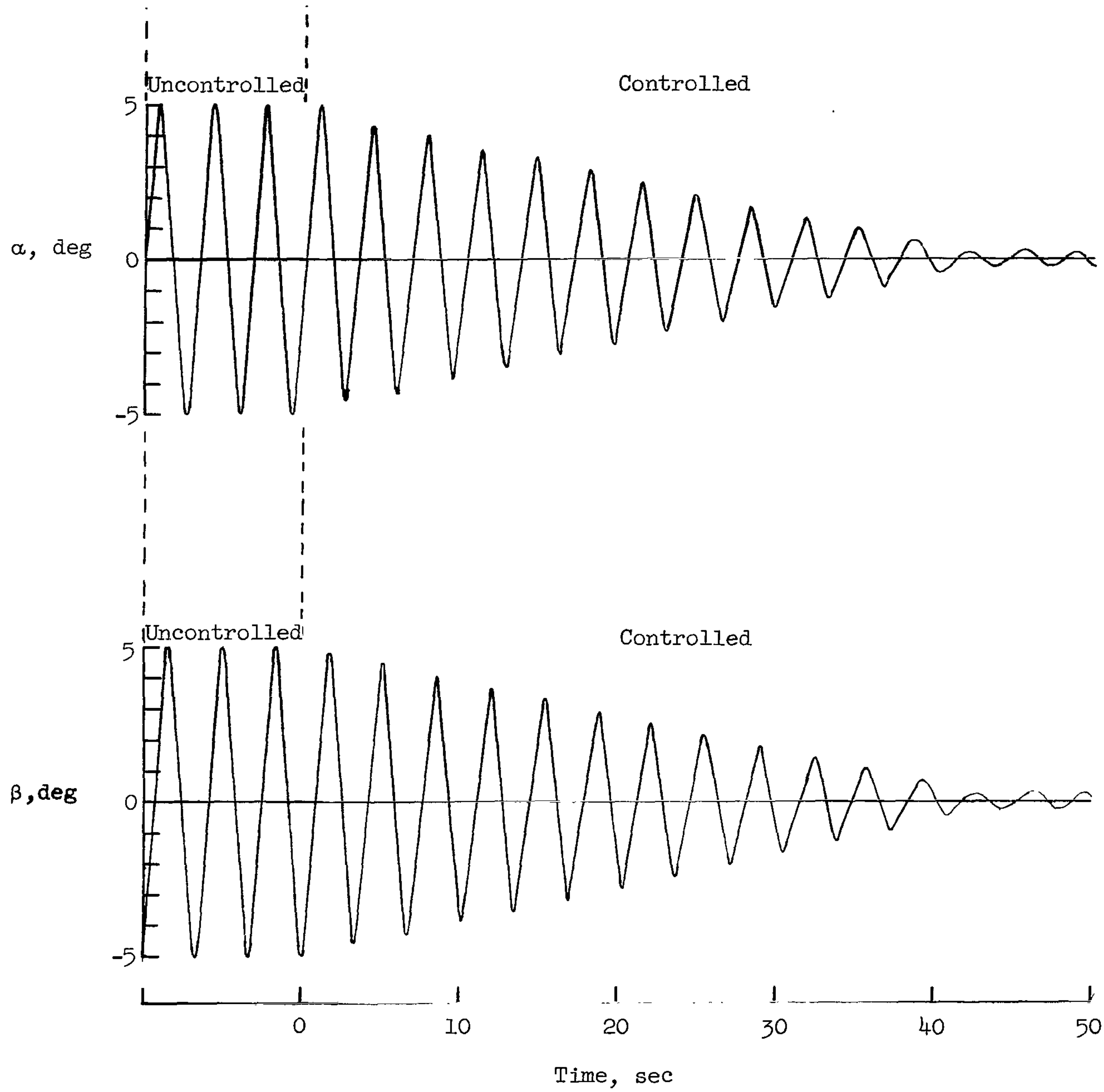

Figure 6.- Motion of spinning spacecraft with an initial attitude error and the rate-attitude controlled jet system for a disk configuration. $\frac{I_X}{I_Z} = 0.756.$

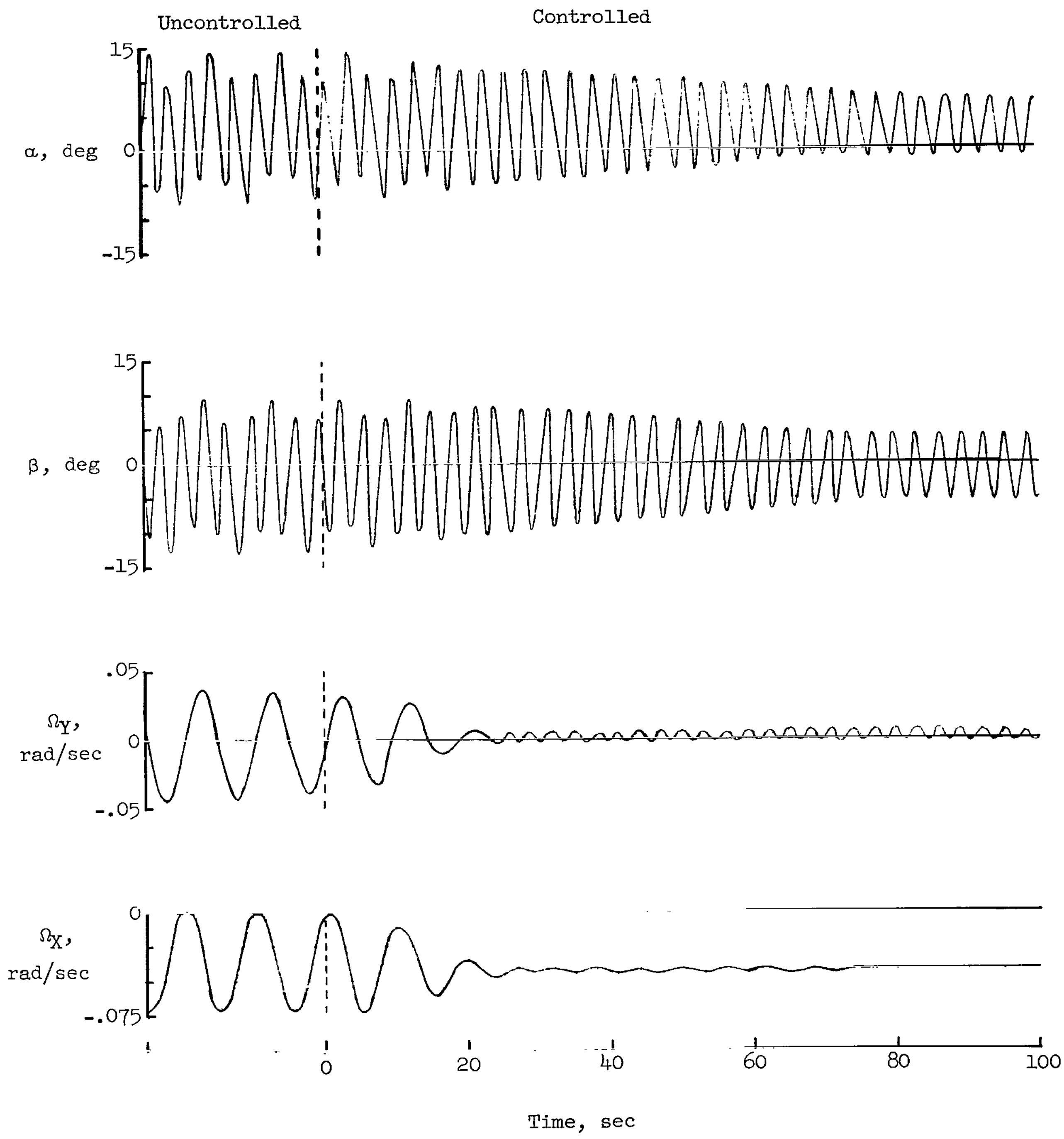

Figure 7.- Motion of spacecraft with an initial attitude error and static product of inertia for a disk configuration. $\frac{I_X}{I_Z} = 0.756$.

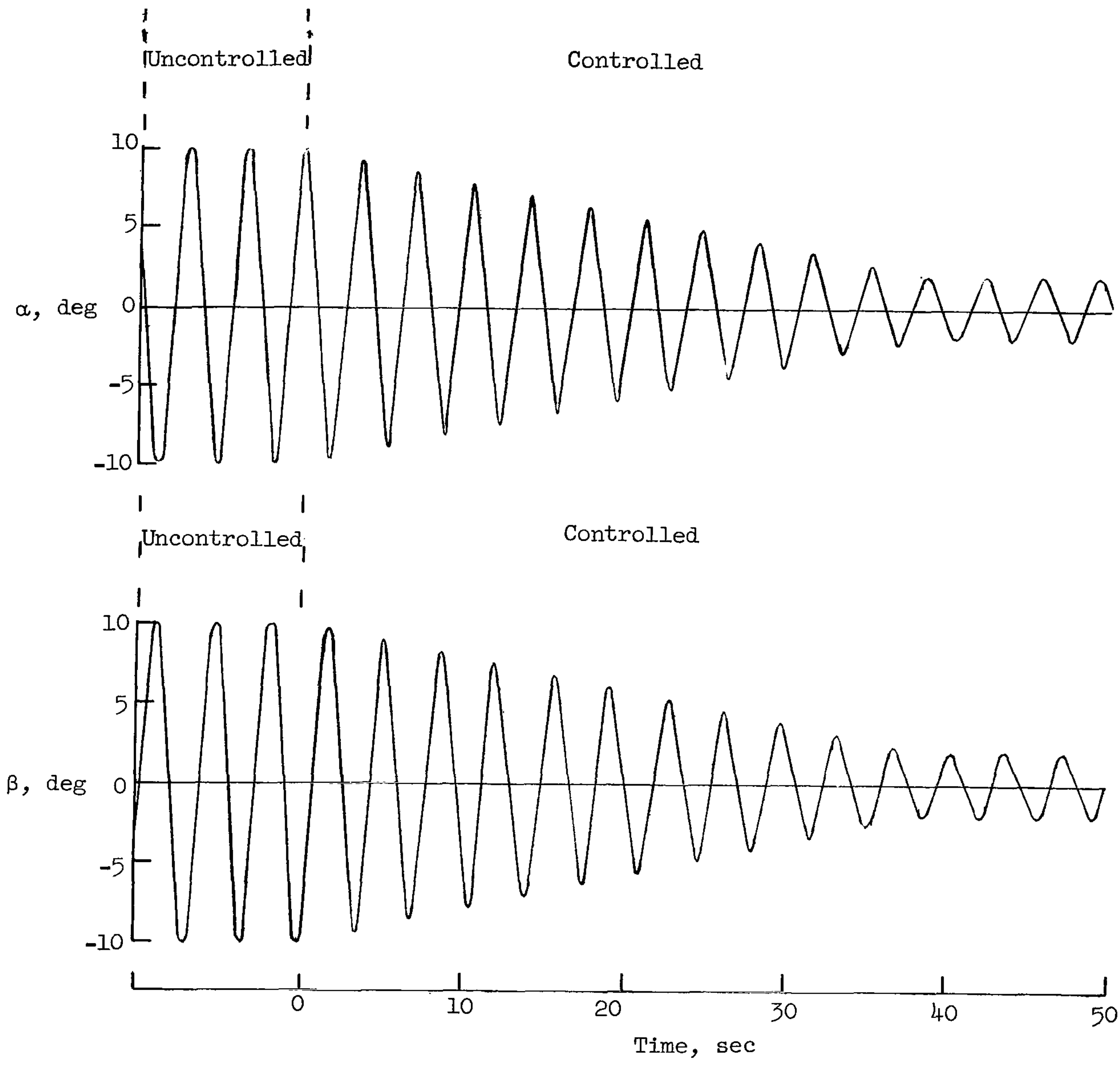

Figure 8.- Motion of spinning spacecraft with an initial attitude error and the rate-attitude controlled jet system for a rod configuration. $\frac{I_X}{I_Z} = 1.17$.

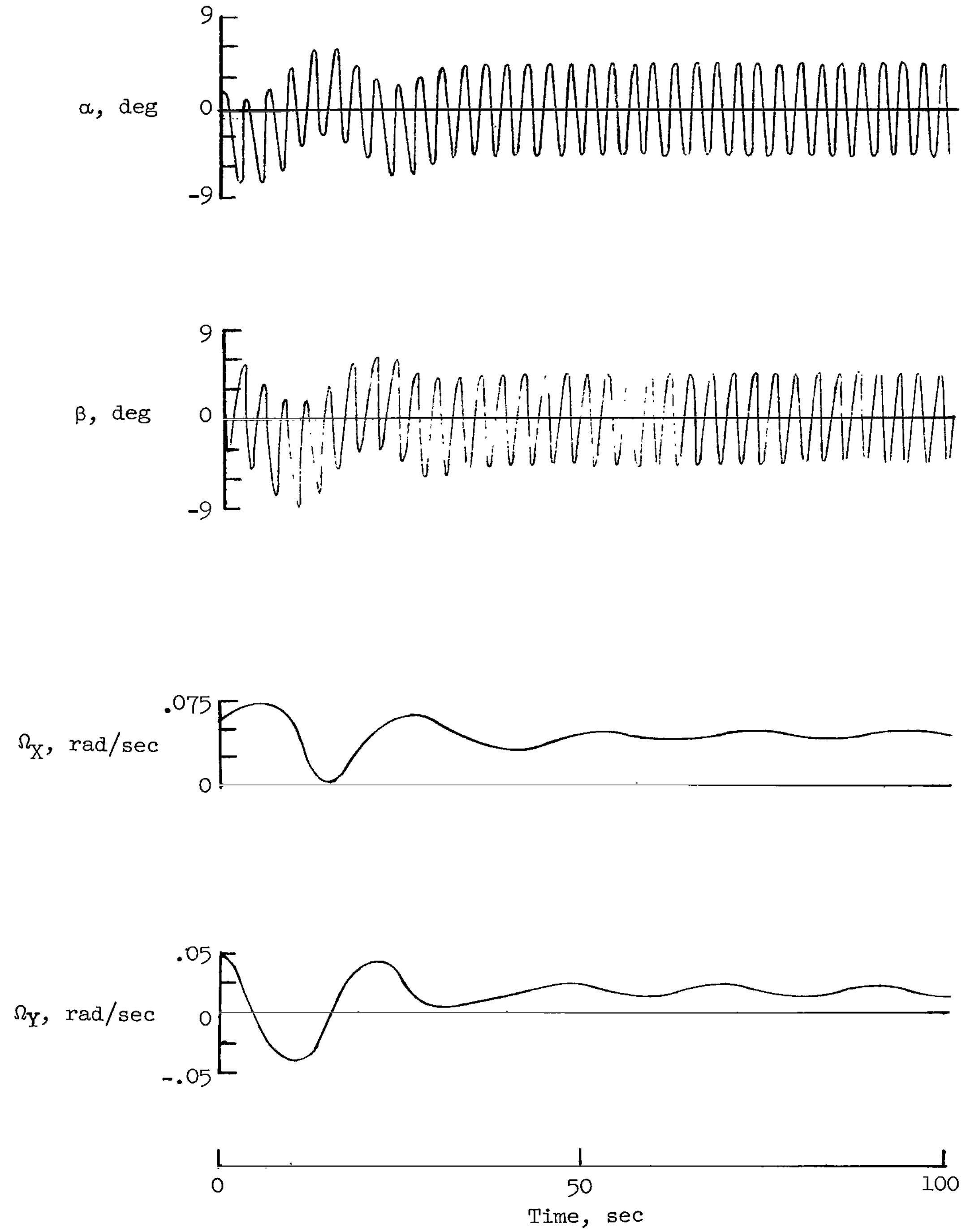

Figure 9.- Motion of spacecraft with an initial attitude error and static product of inertia for a rod configuration. $\frac{I_X}{I_Z} = 1.17$.

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