PERFORMANCE CHARACTERISTICS OF CONTROL MOMENT GYRO SYSTEMS FOR MANNED ORBITAL LABORATORIES

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INTRODUCTION

The stringent requirements imposed by the research program for a manned orbital laboratory are directly related to those for the majority of long-term manned space missions; and hence an optimum solution to the manned orbital laboratory control problem can be used to define system concepts and control techniques for other complex manned space flights. Accurate laboratory pointing for long periods of time and during tracking operations impose unique problems on the attitude control system. The present analysis, therefore, is concerned with a detailed evaluation of the use of control moment gyros for the experimental and operational tasks for a manned orbital laboratory.

MANNED ORBITAL LABORATORY CONCEPT

Before considering the actual control system performance, let us briefly review the vehicle characteristics for a typical manned orbital laboratory and outline its mission in order to define the stabilization and control requirements. The concept shown in figure 1 is basically a zero gravity laboratory with a lifetime of 1 to 5 years, and will be utilized in an extensive study of the environmental phenomena affecting manned missions. This laboratory is designed to sustain a crew of six men and employs a short-radius centrifuge for crew conditioning in its "zero-g" environment. Power for the laboratory will be derived from solar cell arrays which must be continuously alined normal to the solar radiation.

The laboratory moments of inertia are: 100,000 slug-ft^2 about the roll axis; 170,000 slug-ft^2 about the pitch axis; and 200,000 slug-ft^2 about the yaw axis. Addition of several Apollo logistics spacecraft to the basic laboratory increases the moments of inertia to approximately four times these values and creates a maximum product of inertia of 42,000 slug-ft^2.

LABORATORY EXPERIMENTAL MISSION

A typical laboratory experimental program has been reviewed to determine the interface requirements with the stability and control system in terms of orientation, attitude and rate accuracy, and operational functions. Although

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many experiments require no particular laboratory orientation or stabilization, the analysis indicates that three basic modes of laboratory stabilization are necessary. The first is a fine attitude hold in an essentially fixed orientation such as in a stellar, inertial, or solar reference. The second requires slewing of the laboratory at fixed rates while accurately maintaining a reference such as the local vertical or the orbital velocity vector. The third mode of stabilization consists of slewing the laboratory at variable rates in order to accurately track a target either on the surface of the earth or in another orbital plane.

The degree of attitude stabilization accuracy required by the experimental program is shown in figure 2. This chart shows the number of experiments as a function of the attitude pointing accuracy associated with each. These pointing accuracies are required during both laboratory slewing and inertial attitude holds.

The laboratory is capable of performing 87 percent of the experimental program with a pointing accuracy of 0.1° and 92 percent with an accuracy of 0.01°.

The rate stabilization requirements of the experimental program are summarized in figure 3. This figure shows the number of experiments requiring a particular level of angular rate accuracy. Approximately 81 percent of these requirements are satisfied by a rate accuracy of 0.01° per second. Both the attitude and rate accuracies are obtainable under the worst-case external disturbances.

DISTURBANCES

The primary disturbance torques acting on the laboratory are aerodynamic and gravity gradient torques, centrifuge operation, gyro desaturation, and crew motions. The aerodynamic moments and gravity gradients are cyclic at the orbit rate and double the orbit rate, respectively. However, the use of high control gains enables the momentum system to see these disturbances as essentially constant torques. Centrifuge operation creates two types of disturbances. The first is a constant torque during spin-up and spin-down; and the second is a sinusoidal moment caused by unbalance of the centrifuge unit. Desaturation of the control moment gyros and crew motions represent impulsive torque inputs. The disturbances acting on the laboratory and the accuracies required by the mission size the momentum storage system and determine the system characteristics.

GYROSCOPIC CONTROL SYSTEM

Proper selection of the momentum storage system configuration and response characteristics thus enhances the ability of the laboratory to perform complex experimental missions while most economically using laboratory resources such as weight, power, and fuel.

An extensive evaluation and optimization of momentum storage system weight, power consumption, and reliability for a manned orbital laboratory has been performed. The three most promising system concepts from this study have been further analyzed in a detailed simulation to define their overall performance in specific laboratory missions with the actual disturbance environment. These configurations are illustrated in figures 4 to 6.

The first momentum storage concept, shown in figure 4, consists of a set of single gimbaled twin control moment gyros providing control torques about the laboratory roll axis and a set of double gimbaled twin CMG's producing control torques for the pitch and yaw axes. The total system weight is 562 pounds, the average power consumption is 112 watts, and total volume is 43 cubic feet. This sizing is based directly on the momentum requirements imposed by the laboratory disturbance environment and is approximately the same for all three systems.

The second momentum storage configuration considered is illustrated in figure 5, and consists of a set of single gimbaled twin control moment gyros producing control torques about the laboratory roll axis and one double gimbaled CMG providing control for the laboratory pitch and yaw axes. The third control moment gyro concept is shown in figure 6. This configuration consists of a set of double gimbaled twin CMG's providing control torques for the laboratory pitch and roll axes and another set of double gimbaled twin CMG's to control the laboratory yaw and roll axes.

The objectives of this analysis are to determine any differences or advantages in the performance of these three control system configurations in accomplishing the laboratory missions. The cross-coupling effects internal to the control system will vary with system wheel configuration. It has been shown that the use of high control gains will effectively eliminate the inertial cross coupling in the laboratory motion. This system comparison will determine if this technique will also eliminate the internal coupling effects in the momentum storage system.

CONTROL LAWS

To attain high reliability and simple system mechanization, a rate plus displacement control law has been selected for the momentum storage system control. Figure 7 shows this basic control law for one vehicle axis. The control torque produced about that axis is simply the control gain weighted sum of the laboratory angular rate $\dot{\theta}$, and attitude error θ. Since most of the disturbance torque inputs to the laboratory are either cyclic or constant, a disturbance torque of the form

$$M = A \sin \omega t + B$$

has been substituted into the single-axis equation of motion along with the control law expression. The solution of this expression for the steady-state case yields a maximum angular error

$$\theta_m = \frac{A}{I\left(\frac{K_2}{I} - \omega^2\right)} \sin \omega t + \frac{B}{K_2}$$

where I is the laboratory moment of inertia about the axis in question. It can be seen that, for cyclic disturbances such as aerodynamic moments and gravity gradients whose frequencies are not on the same order as the control system response frequency, the resulting error is simply a standoff error which is cyclic at the disturbance frequency. The maximum attitude error possible in this case is simply the sum of the maximum error due to cyclic disturbances and the error due to constant torque inputs. The expression is

$$\theta_m = \frac{A + B}{K_2}$$

and represents a highly conservative estimation of the maximum error. The maximum permissible steady-state attitude may correspondingly be held to any accuracy desired simply by adjusting the system displacement gain. Although this is the expected result for a rate plus displacement control law, it is not sufficient to insure vehicle stability in all modes of laboratory operation with the system nonlinearities.

JET CONTROL

Before discussing the nonlinearities in system operation, it is of interest to look at the problem of maintaining accurate pointing and smooth laboratory operation with the attitude jet system. For a limit cycle type operation about an attitude reference, the fuel consumption per axis, shown in figure 8, may be expressed as

$$\dot{F} = \frac{\left(\int T \, dt\right)^2}{2\theta I l I_{sp}}$$

where $\int T \, dt$ is the total impulse imparted per jet pulse, I is the laboratory moment of inertia, l is the reaction jet moment arm, and θ is the required attitude accuracy. For the laboratory reaction jet system, typical characteristics using minimum jet pulse widths of 50 milliseconds yield

$$\dot{F} = \frac{0.0382}{\theta} \frac{lb}{hr}$$

for all three laboratory axes. The maximum angular rates during such an operation are 0.0172° per second.

From the above expression, the reaction jet fuel required to maintain pointing of 0.1° under no disturbances is 21.9 pounds per hour and to maintain 0.01° requires 219 pounds per hour. The fuel required to counteract the cyclic external laboratory disturbances must be added to this figure and averages about 700 pounds per month. The foregoing analysis has clearly shown that in order to carry out an extensive experimental mission requiring stringent accuracies, reaction jets of the size required to adequately control the laboratory require excessive amounts of fuel in providing very fine pointing or very low angular rate requirements. Adequate pointing control may be provided by equipping the laboratory with very low-impulse jets but this is somewhat unrealistic since a momentum storage system is required to counteract cyclic disturbances.

SYSTEM MECHANIZATION

Having established the method by which pointing accuracy is obtained with momentum storage systems from an analytical standpoint, the actual mechanization of the system must be considered and its effect on the laboratory performance must be determined. In practice, there are two basic methods of providing control torques with gyroscopic devices. The first is to actually apply the required torques to the gyro gimbals and allow them to precess and exert reaction torques on the laboratory which are equal and opposite to the applied torques. This method can effectively eliminate the cross-coupling effects internal to the system. The second actuation scheme involves commanding a precession rate of the gimbals in the proper direction to produce the desired control torques on the laboratory. This method provides much lower torque thresholds but does not compensate for internal cross-coupling effects inherent in gyro systems. One of the objectives of the present study is to determine the extent of these internal coupling effects by comparing the two actuation methods.

Actual laboratory operations such as maneuvering and tracking missions make other gyro system operational constraints such as maximum output torques or maximum gimbal rates important to laboratory performance. The effects of stored angular momentum within the system and of laboratory products of inertia must also be determined.

One of the first problems of note in the simulation is that initiating gyro desaturation every time the gimbal stops are reached does not allow the momentum storage capacity to be fully utilized. It was found that this continuous gyro unloading led to unnecessary desaturations during maneuvers, tracking operations, and many missions requiring stored momentum. Therefore, a selective logic was developed which is shown in general form for one axis in figure 2. Once the gimbal saturation is detected, the logic determines the sign of the ratio of the required control torque signal and gimbal angle. If this sign is favorable, the gimbal is held on the stops and no desaturation is necessary. If this sign is unfavorable, the sign of the ratio of laboratory angular rate and attitude error is checked. A favorable sign of this ratio holds the gimbal on the stops and the opposite sign initiates proper desaturation by determining the sign of the gimbal angle. The addition of these two simple interrogations eliminates unnecessary desaturations and utilizes the full momentum storage capacity during all operations.

RESULTS

Although most of the problems outlined have been studied by preliminary and approximate means, it was felt that a detailed, exact analysis was required in order to obtain accurate quantitative performance data for actual laboratory operations. All system mechanization constraints such as torque limits and gimbal stops and all laboratory disturbances were simulated in the laboratory equations of motion to isolate their primary effects on momentum storage system performance. In general, the results of this simulation are in agreement with the conclusions of preliminary work and many of the assumptions of these analyses have been verified.

One of the most interesting and possibly the most important finding is the fact that, from a mission performance standpoint, no significant difference or real advantage has been found in the operation of the three momentum storage configurations considered. This indicates that the use of high control gains eliminates the effects of internal coupling in system operation and that equal control response can be provided with any configuration. This is an important factor because it allows momentum storage configurations to be selected almost solely by considerations such as weight, power consumption, and reliability, if the angular momentum capacity of each system is sized for the expected laboratory disturbance profile.

The use of high control gains has also been found to eliminate the inertial coupling between the laboratory axes. For all operations considered the results coincide with those obtained with single-axis closed form solutions. This means that the accuracies and performance of missions which do not involve system saturation or torque limiting may be determined by closed form solutions and applied directly to all three axes. Coupling effects due to relatively large products of inertia or principal axis shifts have also been found to have a negligible effect on system operation.

The disturbances created by the operation of an onboard centrifuge are easily compensated for by the momentum storage system. Very precise pointing may be maintained during the spin-up and spin-down torquing operations of a centrifuge by two methods. The first is to provide the torque measured on the centrifuge unit as a feedback into the control loop. The second involves on-off actuation using the signs of the basic rate plus displacement control laws. Both methods essentially eliminate the laboratory errors during centrifuge spin-up. The cyclic torques due to centrifuge unbalance were found to be above the control natural frequencies and do not affect the laboratory or momentum storage system operation.

The on-off actuation scheme which commands maximum torques determined by the sign of the basic rate plus displacement control laws was applied to all laboratory operations to determine whether such a scheme could improve the performance of the momentum storage system. The results indicate that, with on-off actuation, the momentum storage system is capable of holding the laboratory to essentially any accuracy level which can be provided by the laboratory sensors. The resulting operation of this scheme takes the form of a limit cycle identical to reaction jet operation. No stability problems have become apparent with this scheme and it is effective for all disturbances except impulsive inputs such as crew motion and docking impacts which may have to be restricted during some experiments. This technique has great significance since it enables the laboratory to meet any accuracy requirements imposed by the experimental program.

Another important result of the simulation is the fact that the laboratory may be maneuvered fairly rapidly through large angles using only the momentum storage system. Figure 10 shows laboratory maneuvers of 40° about the pitch and roll axes accomplished entirely by the momentum storage system. The final attitude is acquired to within 0.1° in about 4 minutes. Note that inertial coupling into the yaw axis creates a maximum error of about 7°. Performance for the on-off actuation scheme is the same except that the yaw coupling is eliminated. The ability to maneuver the laboratory with the momentum storage system is greatly enhanced by the selective desaturation logic.

Maximum torques applied were 10 pounds about the roll axis and 20 pounds about the pitch and yaw axes. Doubling these torque levels does not significantly affect the maneuver operation. Products of inertia and external disturbances have also been found to have little effect on the ability of the momentum storage system to maneuver the laboratory.

However, when the control gains are increased to a certain level, the system operation seems to lose stability, as shown in figure 11. Note that in addition to the loss in damping on the pitch and roll axes the system becomes saturated on the yaw axis. Single axis maneuvers have shown that this is not a coupling phenomenon, but rather seems to be due to saturation of the rate feedback loop. The on-off actuation scheme shows an identical loss in stability at this point.

Using the same rate plus displacement control law to command gimbal rates rather than direct torques on the gimbals considerably improves the system stability as shown in figure 12. The loss of stability for certain system gains and the stabilizing effect of the gimbal rate command need more investigation, however.

Although the momentum storage system is not capable of providing laboratory rates required for all slewing operations, its performance is relatively unchanged during such missions. Even the presence of stored angular momentum which must be transferred from axis to axis as the vehicle slews has little effect on tracking accuracy if on-off actuation is used. One consideration which does require extensive investigation is the problem of accurately providing the variable slewing rates required by some tracking missions.

CONCLUSIONS

The performance of momentum storage systems for manned orbital laboratories has been determined in a detailed simulation. The analysis has confirmed the value of such systems and has defined many system mechanization characteristics such as selective desaturation logic, on-off actuation, and gimbal rate command which enhance the laboratory's performance during complex operational and experimental missions. The present analysis was not able to simulate all the operational characteristics of momentum storage devices. It has shown, however, that an experimental verification of the characteristics of such systems is required before a control concept capable of accurately performing the complex manned orbital laboratory mission can be defined.

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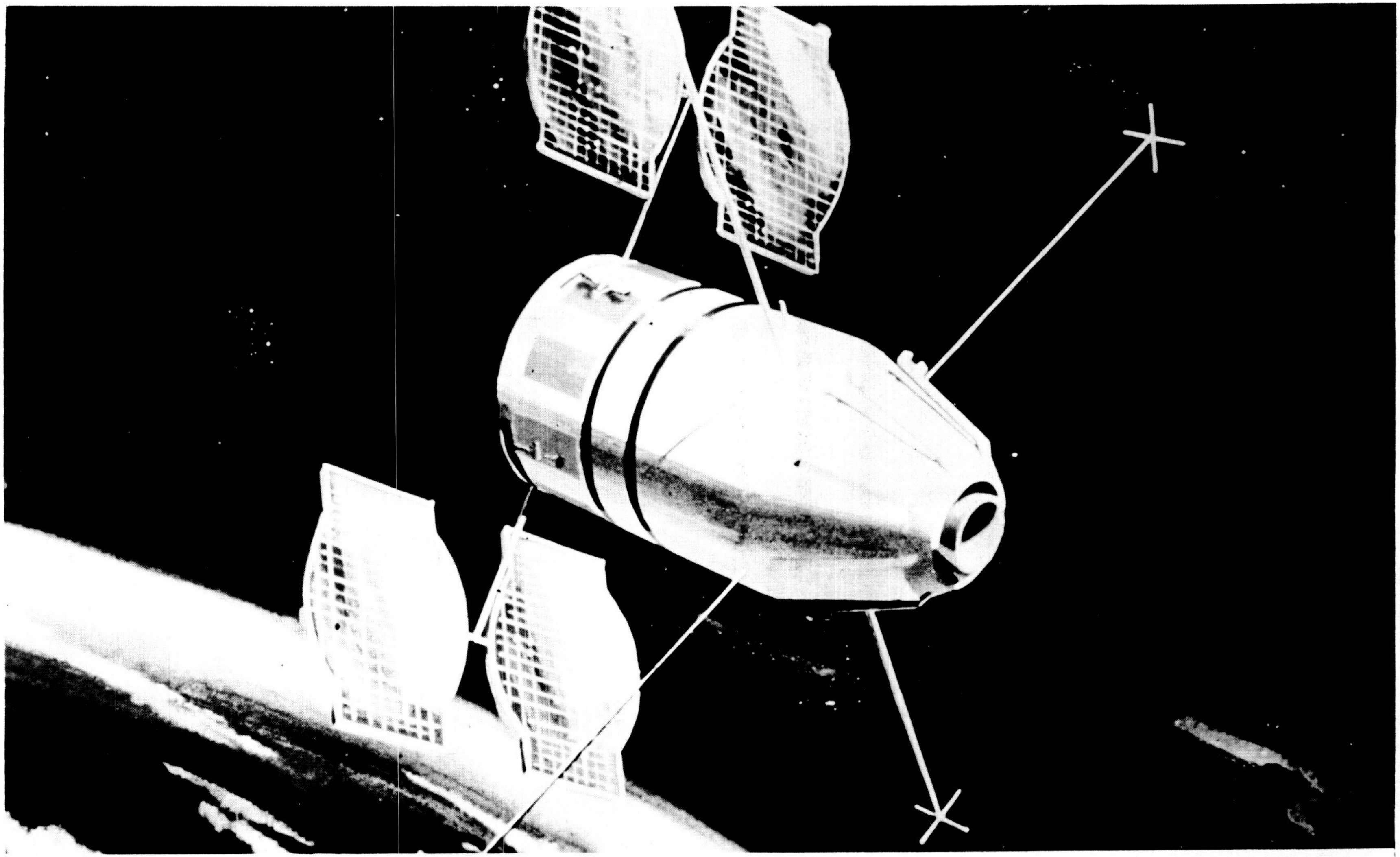

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Figure 1.- Artist concept of a manned orbital laboratory.

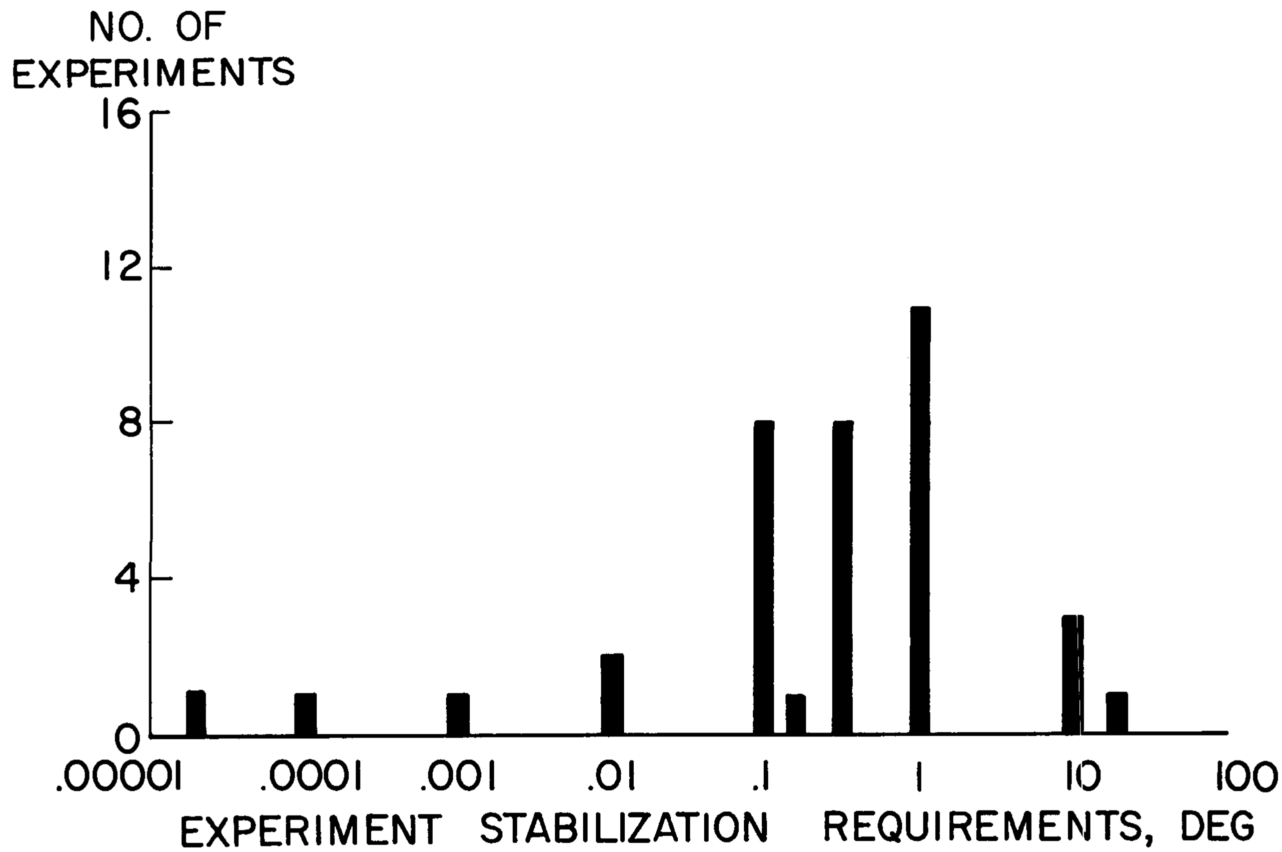

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Figure 2.- Experiment pointing accuracy and history requirements degrees.

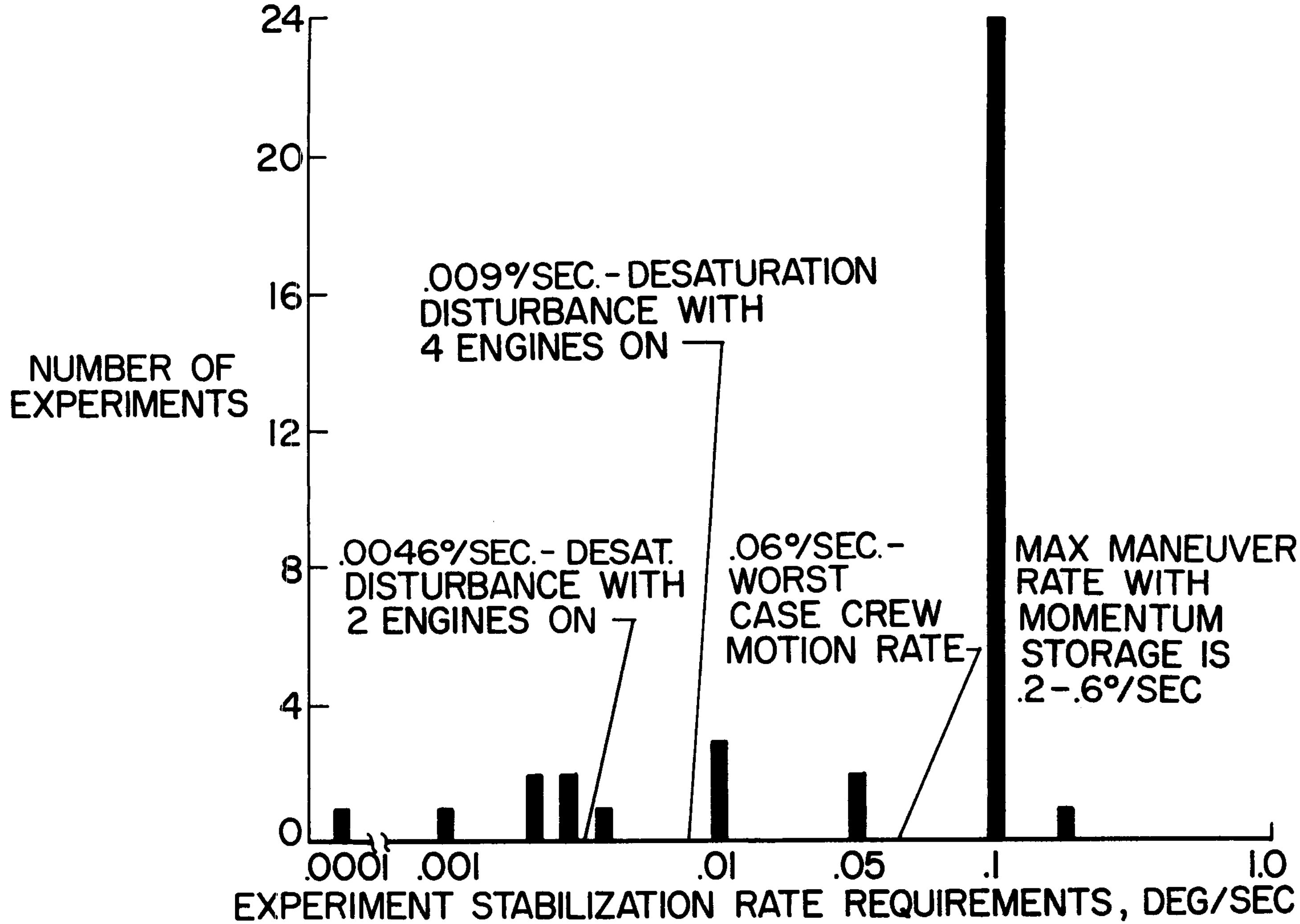

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Figure 3.- Experiment stabilization rate requirements.

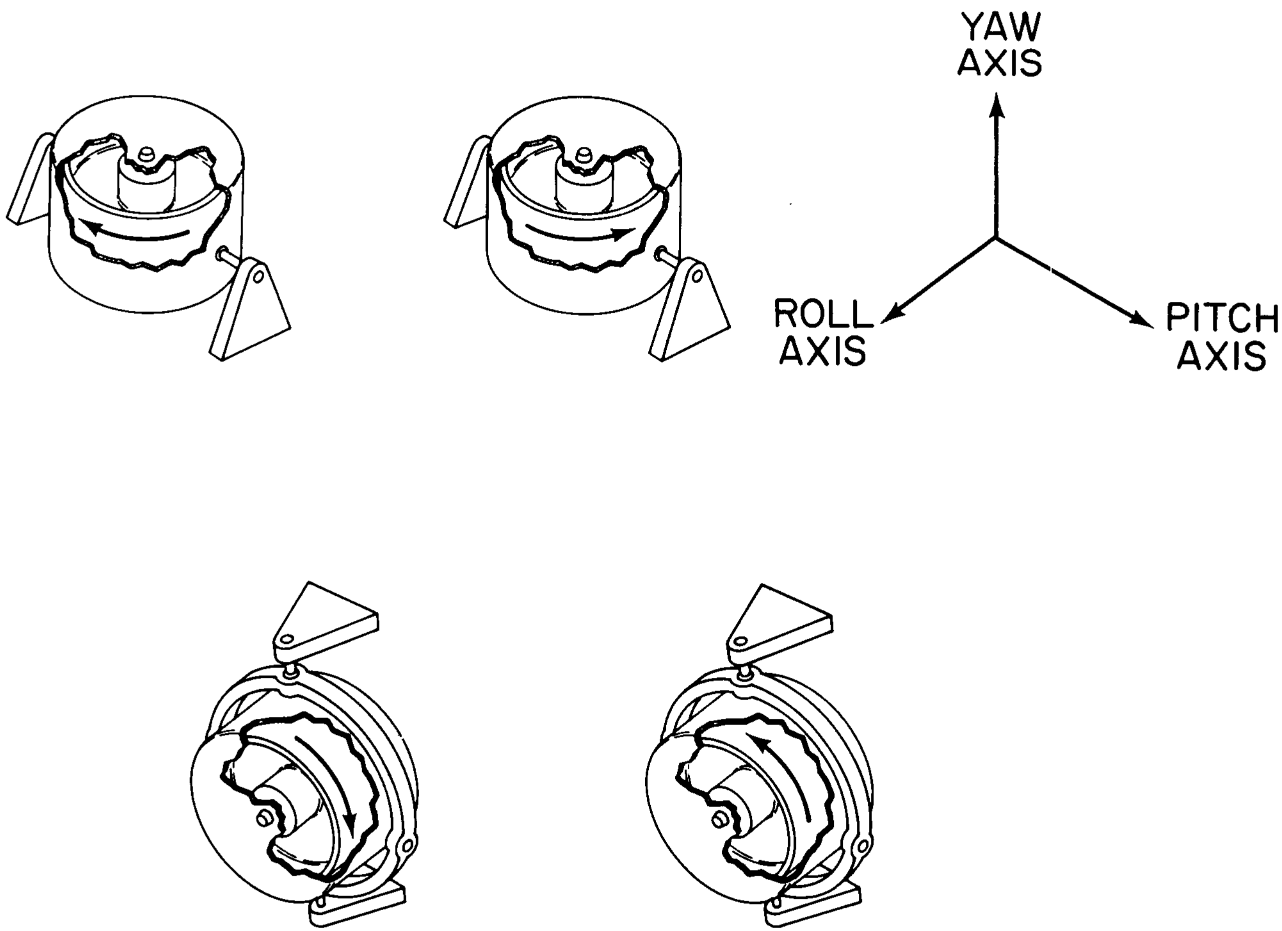

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Figure 4.- Control concept I.

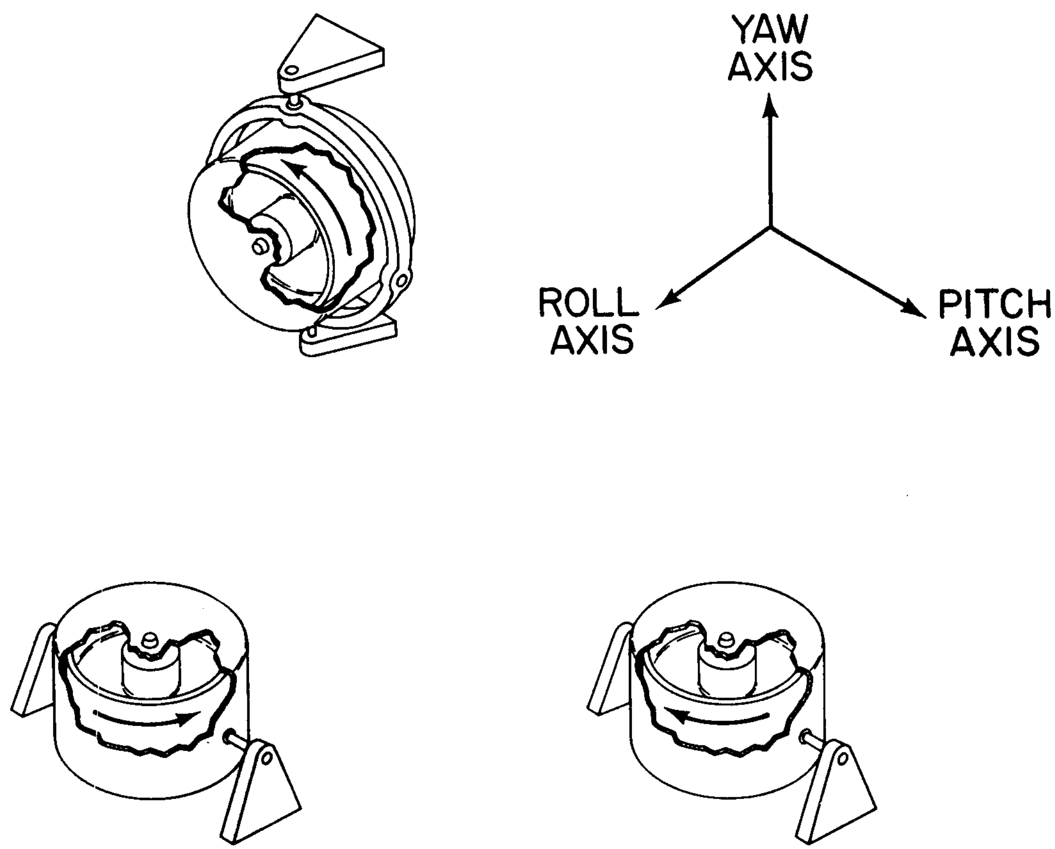

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Figure 5.- Control concept II.

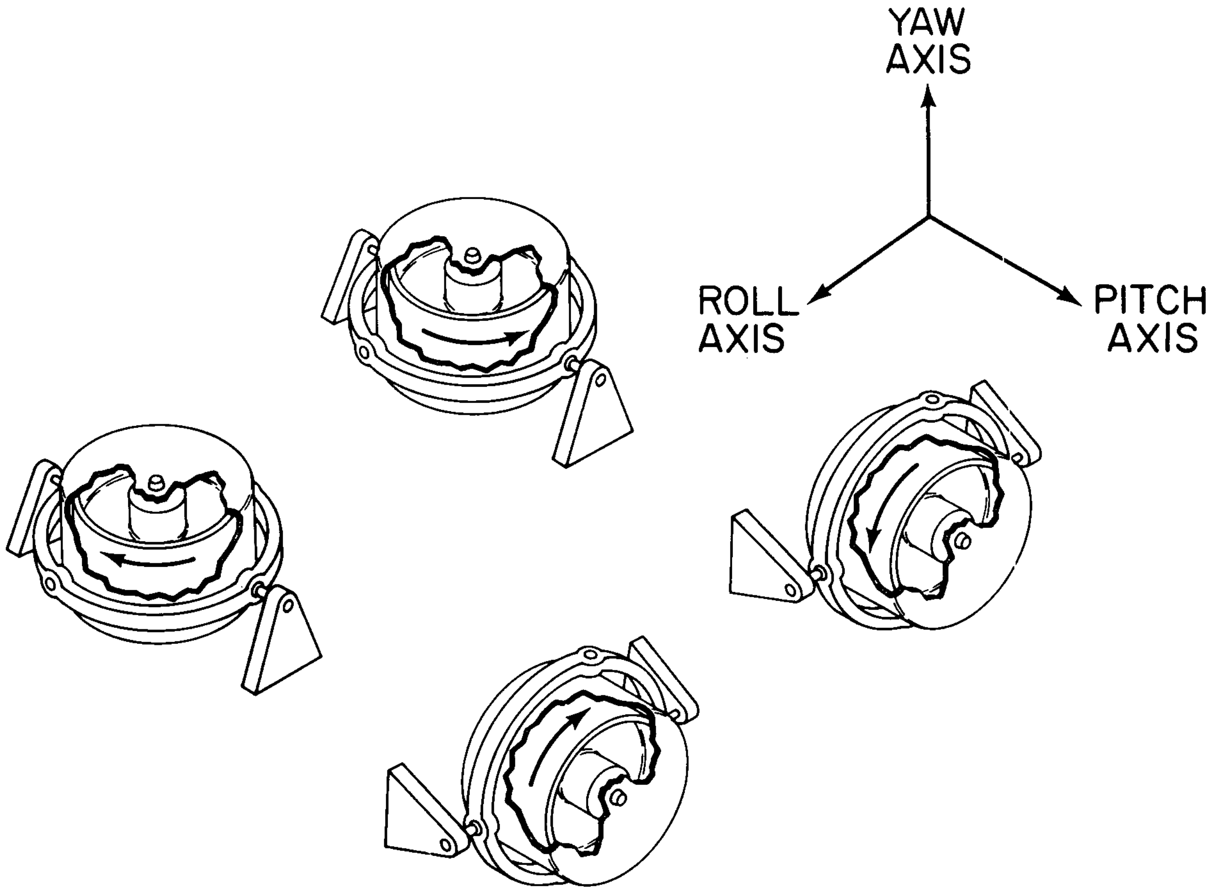

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Figure 6.- Control concept III.

THE CONTROL LAW IS

$$T = K_1\dot{\theta} + K_2\theta$$

FOR A DISTURBANCE TORQUE OF THE FORM

$$M = A \text{ SIN } wt + B$$

SOLUTION OF THE EQUATIONS OF MOTION FOR MAXIMUM ANGULAR ERROR YIELDS

$$\theta_M = \frac{A}{I\left(\frac{K_2}{I} - w^2\right)} \text{ SIN } \omega t + \frac{B}{K_2}$$

FOR $w << \frac{K_2}{I}$

$$\theta_M = \frac{A + B}{K_2}$$

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Figure 7.- Rate plus displacement control.

FOR A JET LIMIT CYCLE, THE FUEL CONSUMPTION RATE IS

$$\dot{F} = \frac{\left[\int T dt\right]^2}{2\theta I l I_{sp}}$$

WHERE

$\int T dt$ = TOTAL IMPULSE PER PULSE

I = LABORATORY MOMENT OF INERTIA

l = MOMENT ARM

θ = REQUIRED ACCURACY IN RADIANS

FOR THE LABORATORY JET SYSTEM

$$\dot{F} = \frac{.0382}{\theta} \quad \frac{LB}{HOUR}$$

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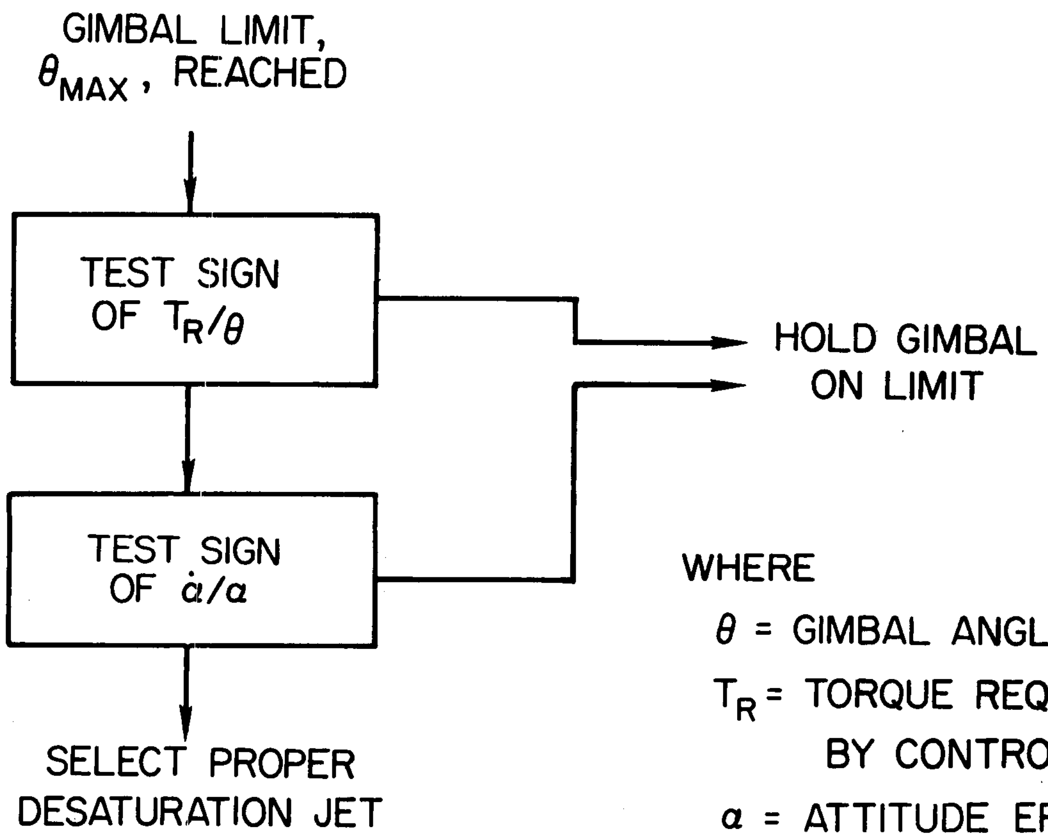
Figure 8.- Jet control.



WHERE

θ = GIMBAL ANGLE

T_R = TORQUE REQUIRED BY CONTROL LAW

α = ATTITUDE ERROR

$\dot{\alpha}$ = LABORATORY ANGULAR RATE

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Figure 9.- Selective desaturation logic.

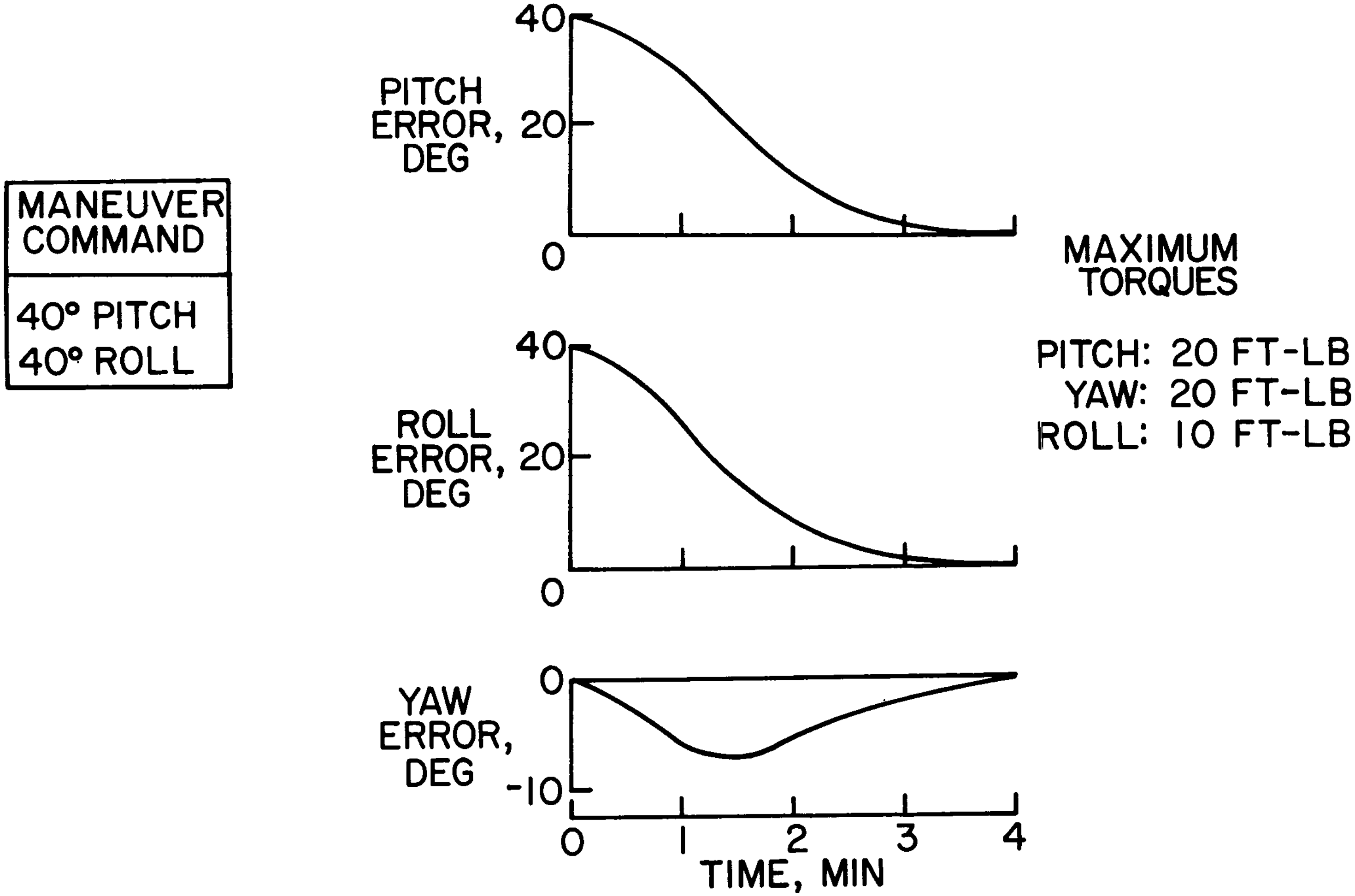

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Figure 10.- Laboratory motion for 40° maneuver commands.

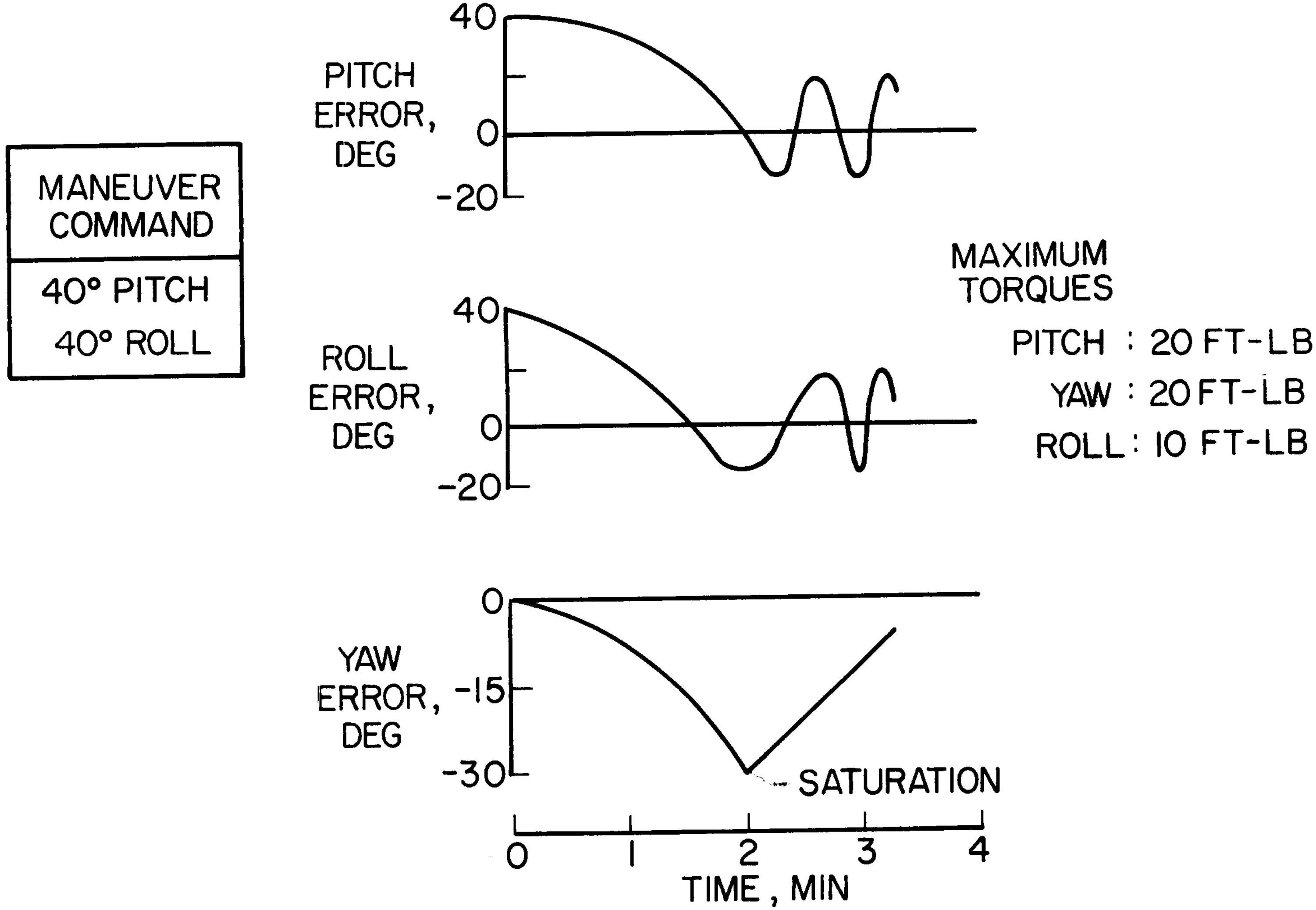

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Figure 11.- Laboratory maneuvers with increased gains.

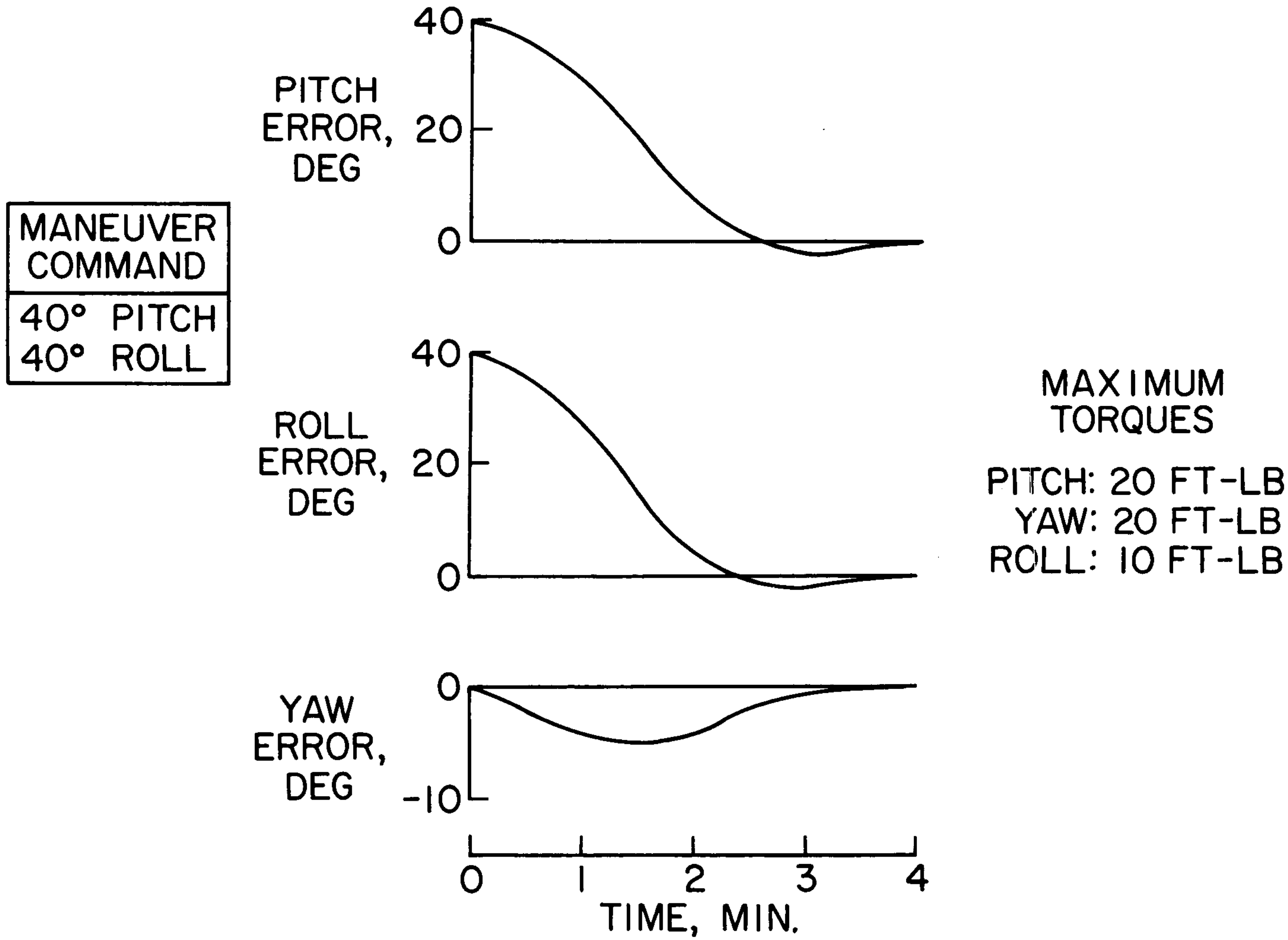

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Figure 12.- Laboratory maneuvers with gimbal rate command and increased gains.

NASA-Langley, 1965