Simulation and Testing of a Double-Gimballed Momentum Wheel Stabilization System for Communication Satellites

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A double-gimballed momentum wheel stabilization system designed for a synchronous communications satellite is described and the results of hybrid and air bearing tests performed with this system are presented. The control system was designed to operate in the solar torque environment while maintaining accurate beam pointing. A prototype attitude control system was assembled, and integrated system tests were performed. System testing was performed on assembled equipment to match measureable response characteristics against those theoretically predicted. Two types of tests were performed, hybrid tests in which the assembled control system equipment was coupled to an analog computer that simulated vehicle dynamics and certain hardware components, and air bearing tests in which the complete control system was assembled and dynamically tested on a three axis air bearing table. The hybrid and air bearing tests verified the compatibility of the equipment interfaces and demonstrated the functional operation of an orbital stabilization system suitable for synchronous altitude communication satellites. Special procedures were developed during the testing for performance testing of similar momentum exchange control systems on air bearings. The cross checks between test data and analytic simulation reinforced confidence in the mathematical modelling used in the preliminary design analysis.

Introduction

THE double-gimballed momentum wheel stabilization system represents one of several satellite control systems being developed for high performance communication satellites. At present, spin stabilization is prominently used for synchronous satellites. Interest in three axis stabilization is principally due to the need for accommodation of power requirements over a kilowatt and expected simpler system integration of larger spacecraft.[1] Momentum systems have been configured in a variety of ways to achieve long life attitude control. A tradeoff of possible attitude control systems including configurations using three orthogonal reaction wheels, a fixed axis momentum wheel, single- and double-gimballed momentum wheels is discussed in Ref. 2. A double-gimballed wheel system has the feature of accurate three axis control with only two axes of attitude sensing and the possibility of low over-all weight implementation with relatively moderate size and power consumption. A theoretical analysis of this system is given in Refs. 3 and 4. An alternate synthesis for such a system is given in Ref. 5. The present paper deals primarily with the simulation and air bearing testing of a double-gimballed wheel system.

Basic System Description

The basic elements of the attitude stabilization subsystem are a vertical sensor, control electronics, and a variable speed momentum wheel in a two-degree-of-freedom suspension with linear actuators for positioning the wheel. The direction of the local vertical is determined by an infrared Earth sensor which generates signals proportional to the pitch and roll attitude of the spacecraft. The attitude signals are processed by the attitude control electronics and are then used to control the speed of the momentum wheel and the direction of its spin axis. Changes in the wheel's angular momentum vector produce reaction torques on the spacecraft which restore the spacecraft to the desired attitude.

The angular momentum of the spacecraft system is stored in the wheel, with the exception of the angular momentum of the vehicle pitching at orbit rate. Inertially fixed torques acting on the vehicle result in a net change of the total angular momentum of the spacecraft. The change in total angular momentum is absorbed by the wheel system until momentum saturation is reached. External impulse is required periodically to desaturate the momentum storage system. Stationkeeping thrusters also could accomplish the required desaturation. A functional block diagram of a three axis momentum storage controller is shown in Fig. 1. This concept is mechanized by using a variable speed wheel in a two-degree-of-freedom suspension. The pitch controller uses the reaction characteristics of the momentum wheel. Wheel torque is commanded as a combination of pitch attitude, derived attitude rate, and integral of attitude signals. The system band pass or basic natural frequency is of the order of 0.01 Hz which is comparable to that of the roll channel.

The roll and yaw channels are fundamentally cross coupled. The basic stability is provided by the bias momentum which gives the inertial stability characteristics of a spinner to the three axis stabilized spacecraft dynamics. A signal consisting of roll attitude plus derived rate provides the compensated control signal in terms of required torque. The signal is purposely cross coupled into the yaw channel to provide appropriate rate stabilization of the slow gyrocompass dynamics. Rather than generating torque directly, these signals are integrated to produce a commanded momentum whose time rates of change are the desired torques. In order to eliminate the disturbance effects of residual momentum in the spacecraft frame of reference, decoupling terms with gains equal to the nominal orbit rate are introduced between the two integrators. These gains transfer momentum between the vehicle axes as the spacecraft rotates at orbit rate. A final decoupling term positions the bias momentum about the roll axis equal to the roll angle which effectively cancels nutation interactions with the spacecraft dynamics.

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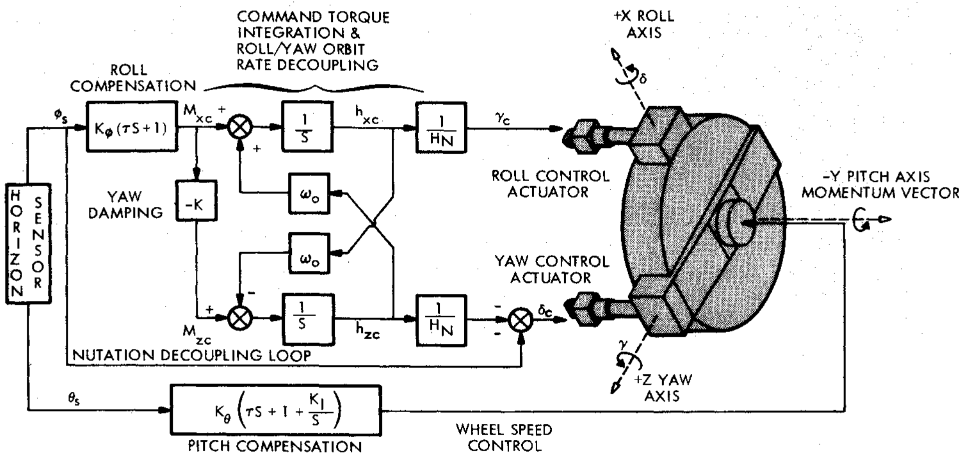

Fig. 1 Functional block diagram of double-gimballed wheel attitude control system.

Hybrid Test Setup

The attitude control system (ACS) testing was separated into two phases, static and dynamic. Frequency response measurements were considered part of the static test phase. The dynamic test phase was defined to include only those tests which were made with the control loop closed. During the ACS static tests, the mechanical and electrical interfaces scale factors, power requirements and operational sequences of the system and its components were verified. Such items as the mechanical alignment of the horizon sensor, momentum wheel, and linear actuators were checked along with the electrical parameters of the system. Subsequent to the static testing, the development ACS was subjected to dynamic systems tests which were divided into two parts, hybrid tests with an analog computer and real time air bearing tests.

Analog computer tie-in tests of the hardware were conducted first. This testing resulted in the collection of a significant quantity of transient response data for later comparison with scientific simulation data. The test philosophy of the hybrid test was to establish a series of scientific simulation responses and compare these results with tests using various combinations of actual hardware elements culminating in a closed loop using the digital electronics, the linear actuators, dual gimbal, and the wheel motor system all operating together. In these tests, the vehicle, horizon sensor, and wheel dynamics were simulated in an analog computer.

The final system tests were run on an air bearing fixture with all physical equipment and no external simulation. The fixture balanced on the air bearing had a torque environment as close to orbiting conditions as could reasonably be attained in a lab. The vehicle pitch axis was aligned to the Earth's spin vector, and the physical dynamics of the momentum wheel controller interacted with the synchronous Earth rate on the nearly frictionless platform. The air bearing tests were a series of attitude response transients to initial conditions and calibrated disturbance torques applied to the balanced fixture. These transients were then "matched" by computer simulation and demonstrated close correlation of physical and theoretical performance.

Hybrid Test Results

The pitch and roll-yaw channels were tested separately on the hybrid computer taking advantage of the independence of their dynamics for small angle motions. This approach allowed a systematic introduction of the hardware with the simulator so that the effects of each element's contribution to the system performance could be ascertained independently. Through the system of interconnecting switches, combinations of equipment could be incorporated into the closed loop dynamics. The torques that would generate the simulated motion in the simulation had to be derived. The wheel speed rate of change corresponding to the pitch control torque was derived from differentiating filtered pulse tachometer signals. These signals are operationally only used for read out and desaturation control. The pulse signals had to be smoothed before interfacing with the analog simulator dynamics. Unfortunately, the lags introduced by this smoothing process contributed a notable destabilizing effect in the closed loop pitch dynamics. The filtering dynamics present only for interfacing in the hybrid tests were equivalent to an approximate first-order 5 sec time constant.

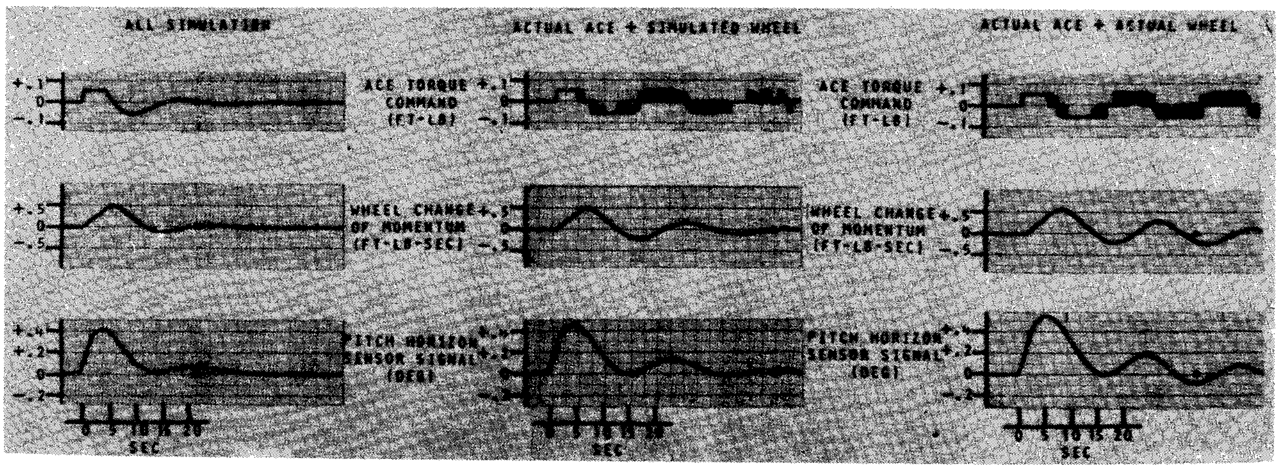

Fig. 2 Hybrid test transient response to pitch angle initial condition.

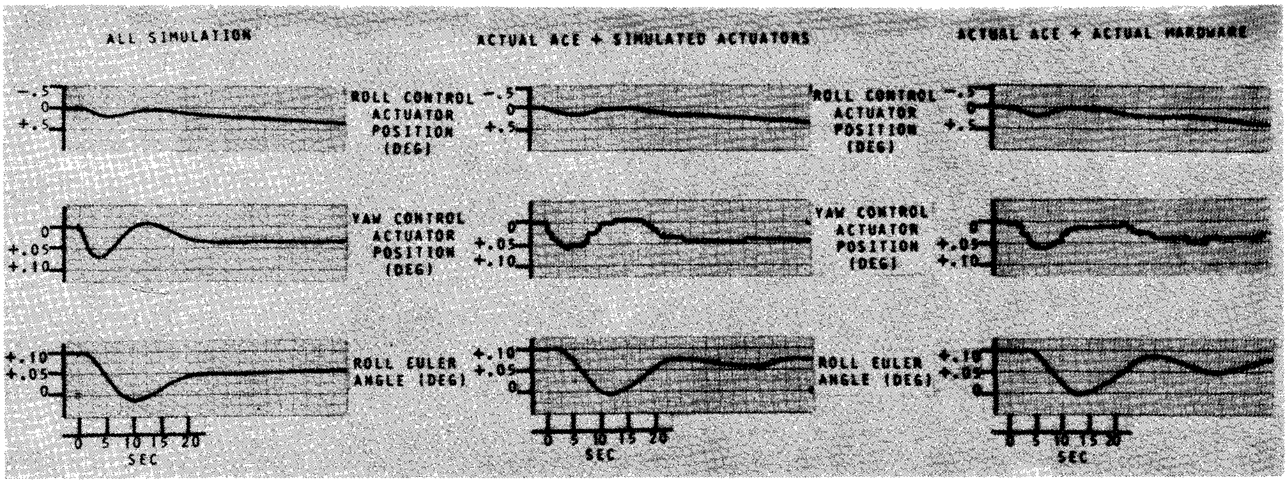

Fig. 3 Hybrid test transient response to roll angle initial condition.

Figure 2 shows three sets of pitch axis runs for identical initial conditions. The first set was done totally with analog simulation, the second with the attitude control electronics (ACE) and simulated wheel dynamics, and the third with the ACE and the hardware wheel with tachometer output to the simulation. The slightly reduced damping of the transient responses is attributed to the degree of filtering necessary to interface the equipment adequately with the simulator. The torque of the wheel drive signal is shown in Fig. 2 as a continuous analog signal for the simulation case. The discontinuous traces of the wheel torque using the attitude control electronics and with wheel hardware are a result of plotting the pulse width modulator output since no continuous trace is generated during modes of operation which use actual hardware. The density of the pulse train is a measure of the torque amplitude in those cases.

Transient responses for roll-yaw are shown in Fig. 3. The interface problem here involved the use of rate circuits to derive the actuator rate of extension or retraction which was used for determining the time rate of change of momentum, or torque, along the simulated vehicle roll and yaw axes. The equivalent 0.05 sec first-order lag introduced with this differentiation had essentially no effect on system performance. Figure 3 gives a comparison of roll-yaw dynamics with all simulation and with ACE and actuator hardware. The slight deterioration of performance of the tests with hardware is again attributed to the lags introduced by the simulation interface equipment and is not present in flight operation.

Figure 3 shows the roll and yaw response of the spacecraft to an initial roll angle of 0.1°. All simulation results are compared with those generated using the hardware linear actuators and digital electronics. The two gimbal actuator positions are shown at the top of the figure. The gamma actuator rotates the wheel about the spacecraft yaw axis. A positive increment of the gamma actuator rotates the bias momentum vector about the yaw axis and generates a positive component of momentum along the spacecraft roll axis. The bias momentum is along the negative pitch axis. The short term roll response is reflected principally in gamma actuator activity. The delta actuator rotates the wheel momentum about the spacecraft roll axis and thus increments the wheel's momentum component on the negative yaw axis for a positive rotation. The activity in this channel is due primarily to the low frequency gyrocompassing dynamics and the roll nutation decoupling loop.

Air Bearing Tests

The air bearing test incorporated the complete attitude control system operating independently and in real time. The subsystem was mounted on a rigid table structure which was supported on an air bearing sphere to permit three degrees of freedom. In addition to the attitude control subsystem, an electrical power system and a telemetry and command subsystem were included on the air bearing table. An attempt was made to mount the components on the table in a symmetrical manner to minimize the effect of inertia cross coupling. The momentum reaction wheel assembly was mounted in the center of the table and the horizon sensor was mounted above it. The complete system including the table was tilted to align the wheel spin axis to the Earth's angular velocity vector. The horizon sensor target was attached to the ceiling at 90° to the table and in line with the horizon sensor. This method of alignment closely simulates orbital operation with the exception of the effects of gravity unbalance and air current disturbances. It was estimated that these disturbances were of the order of 10^{-3} ft-lb during the tests.

The three axis spherical bearing test fixture used in the air bearing subsystem test program is shown schematically in Fig. 4. The basic unit consists of a 10-in.-diam stainless steel sphere suspended in a 120° air bearing pad. The five batteries used for electrical power were rechargeable through the battery control and distribution box from external power supplies. Each source could individually be charged or discharged. Safety features included diode isolation on charging lines with individual circuit breakers mounted on each battery.

An FM/FM telemetry control system was used during the air bearing subsystem test program. This system provided simultaneous transmission of measurement data and command signals between the air bearing table and a stationary receiving subsystem. The telemetered functions were the on/off commands for attitude control electronics, horizon sensor, and the momentum wheel. Additional up-link command functions were pitch and roll attitude bias, bias polarity, and pitch/roll telemetry clock. The transmitted functions from the table were the wheel speed, both actuator positions, and the horizon sensor outputs. The minimum bit count of the horizon sensor digital output was 0.007°; however, the granularity of the telemetry was 0.11°.

Air Bearing Table Balance

Doubtless the most critical item of the air bearing test was the balance of the air bearing table. The maximum torque capability of the attitude control system is 0.1 ft-lb (0.136 N-m) in all three axes, and it was necessary to limit extraneous torques to an order of magnitude below that value.

Measurements were taken of the unbalance of the air bearing table in the zero attitude position caused by the positioning of the momentum wheel by extending and retracting the linear actuators. Counterbalance weights were added to the wheel to reduce the unbalance to acceptable limits.

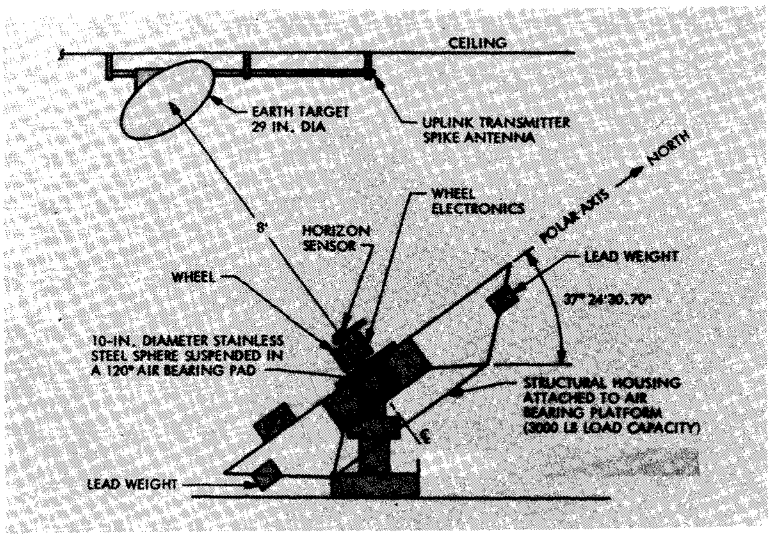

Fig. 4 Side view of air bearing table and test equipment.

During the course of systems alignment and static balance tests, the air bearing table was very slightly pendulous. Table pendulosity was adjusted by adding equal increments of weight to the top of the table at the extremes of the pitch and roll axes. The final pendulosity period was approximately 120 sec. The calculated moment arm between the air bearing center of rotation and the center of mass of the table was about 0.004 in. (0.1 mm).

The pendulosity null alignment appeared to change as a function of time and the table had to be rebalanced each day and sometimes several times during the day. The cause of this was not identified specifically, but the most suspect items were the batteries which could have redistributed their mass as a function of temperature and time and also structural deformation of the table fixture or components. The structural shifts appear the most likely cause of the pendulosity change as the table was blocked in position at the end of each night's run with the air pressure removed. At the beginning of each day, the air pressure was turned on and when the table was unblocked, the balance had changed. The small distance between the air bearing center of rotation and the center of mass of the 2900 lb (1320 kg) table fixture was critical. Very slight bending of the table structure could account for the observed shifts in the center of mass.

The table was released by de-energizing solenoids aligned to the table on stands 90° apart. This method of table release proved very satisfactory for verifying the pendulosity null position and for establishing zero initial rate conditions to the table for test purposes.

Attitude Control System Test Results

The response of the double-gimballed wheel attitude control system was studied on both the air bearing table and on the analog computer. Engineering data from the air bearing tests consisted of recorder traces of the telemetered pitch and roll horizon sensor error signals, both gimbal actuator positions, and momentum wheel speed. Recordings were made of the air bearing response to step position commands, angular momentum impulses, and step torques applied about both the pitch and roll axes.

The same system parameters were used in the analog computer simulation of the double gimballed wheel attitude control system. The simulation was divided into two parts, pitch dynamics with wheel speed control and roll/yaw dynamics with gimbal position control.

The analog simulation included rate limits of 0.14°/sec on gimbal actuator motion and a torque limit of 0.1 ft-lb on the momentum wheel torquer. Quantization representing the least significant bit of the horizon sensor output was included in the horizon sensor model to permit small angle limit cycle studies. The horizon sensor model also included a sample and hold circuit with a 1-sec sample interval. The noise filter in each horizon sensor channel was simulated by a first-order lag with a 4-sec time constant. Provisions were also made to include the effects of pendulosity and horizon sensor noise; however, these two features were not used in the simulation runs included in this paper because accurate quantitative information on these parameters was not available at the time.

Data taken during the air bearing tests and analog simulation data were compared for each of the different forms of systems excitation. In general, the two types of data are in very close agreement. The most notable difference occurs because no attempt was made to model the telemetry system in the analog simulation. Consequently, the simulated horizon sensor traces are continuous, whereas the air bearing traces show the effects of telemetry quantization. The remaining small differences are due to such effects as noise, cross axis coupling, small gain variations, and residual pendulosity. The close correspondence between the engineering data from the air bearing tests and the analog simulation data establishes the validity of the math models of the system used in the simulation. This results in a high degree of confidence that the on-orbit operation of the flight model can accurately be predicted using a simulation of the system.

Pitch Angle Command Response

The response of the double gimballed wheel attitude control system to a pitch horizon sensor bias command of 1.9° is presented on the left-hand side of Fig. 5. The engineering data obtained from the analog computer simulation of the system are shown in the upper two traces of pitch horizon sensor error signal and wheel angular momentum. The lower two traces show the same variables, with identical scales, as telemetered during the air bearing test.

Since the horizon sensor target was relatively close to the air bearing table and the horizon sensor was mounted away from the suspension ball, there was a geometrical gain of 1.4 between the vehicle attitude and the angle measured by the horizon sensor. The geometrical gain factor is a function of the distances between the sensor and target to the center of the platform support. Hence the 1.9° command represented a command of 1.35° of vehicle pitch motion. The pitch command passed through the sample and hold circuits and the 4 sec noise filter before being displayed as telemetered horizon sensor output. As the error signal built towards 1.90° the wheel speed control system started operating to remove the error. Consequently, the peak error only reached 1.5° before damping to zero. The angular momentum of the wheel varied by less than 1 ft-lb-sec (1.36 N-m-sec) during the transient before returning to its original value.

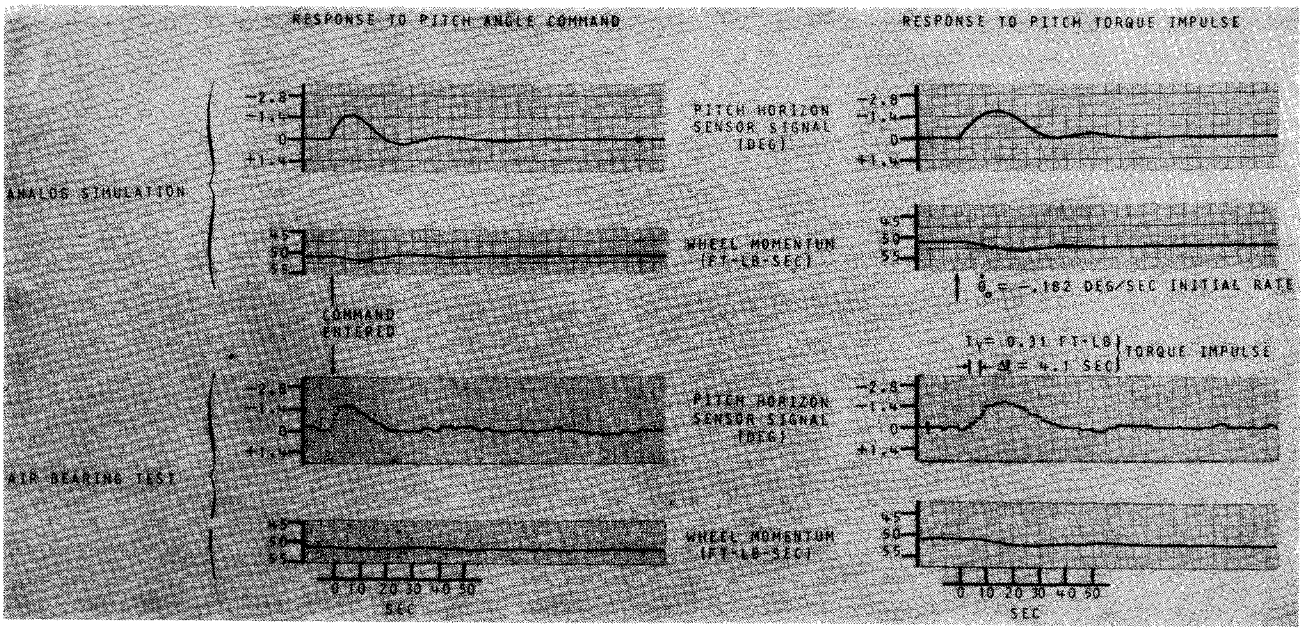

Fig. 5 Air bearing test transient response to pitch excitations.

Pitch Impulse Response

Comparisons of pitch channel impulse response transients are shown on the right-hand side of Fig. 5 with the top two traces showing the simulated results and the bottom two the measured transients. In the air bearing test the impulse was applied by placing a 0.1 lb (46 g) weight on the table for a little over 4 sec. In order to provide a pure pitch torque with no yaw component, it was necessary to apply the force normal to the surface of the inclined air bearing table. This control was accomplished by restraining the weight with a taut cord held parallel to the table so that no yaw displacement or unbalance torque was produced. The pitch axis moment arm from the center of the ball to the point of contact for the weight was about 46 in. These conditions produced a net change of pitch angular momentum of -1.27 ft-lb-sec (-1.72 N-m-sec). This impulse was simulated on the analog computer by applying an initial pitch rate of $-0.18°$/sec. This impulse was sufficient to drive the torque motor into saturation at 0.1 ft-lb. Because of the sample and hold the time lag in the noise filter required approximately $2\frac{1}{2}$ sec to reach saturation. The torquer then remained saturated for approximately 17.5 sec before returning to linear operation. The peak overshoot thus occurred at $2.5+1.27/0.1 = 15.2$ sec and had a displacement of $-1.61°$. During the course of the transient the wheel momentum increased by 1.27 ft-lb-sec in order to store the momentum impulse.

Roll Angle Command Response

The system response to a roll horizon sensor bias command of 0.9° is shown on the left-hand side of Fig. 6. The engineering data obtained from the analog computer simulation of the system is displayed in the top three traces of roll horizon sensor error

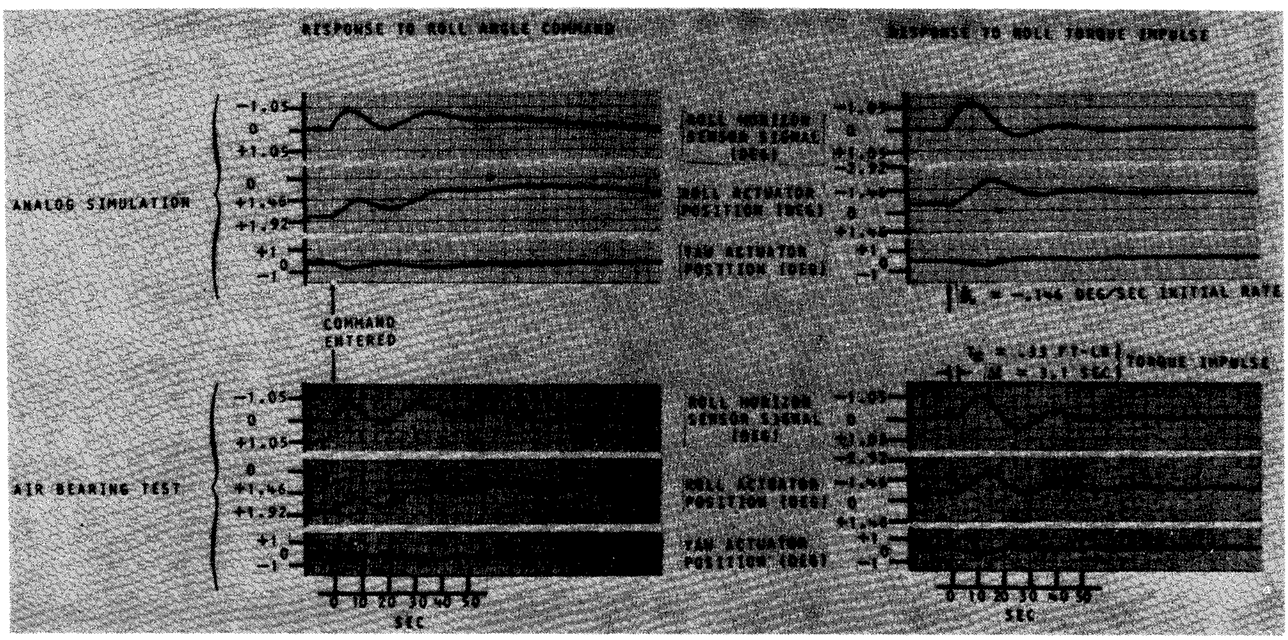

Fig. 6 Air bearing test transient response to roll excitation.

signal, gamma actuator position, and delta actuator position. The bottom three traces show the same variables, with identical scales, as telemetered during the air bearing test.

The corresponding vehicle motion due to the geometrical gain of 1.4 was 0.64°. The filtered roll horizon sensor error signal did not rise immediately to 0.90° because of the sample and hold and the filter lag time constant. As the error signal built up, the gamma actuator went into rate saturation. The filtered error signal was also passed through a one-half gain in the nutation decoupling loop to drive the delta actuator. The nutation motion induced by the 4-sec filter lag and the one-half gain in the nutation decoupling loop were damped out over the course of several cycles.

Roll Impulse Response

The right-hand side of Fig. 6 displays the close correspondence between engineering data taken during the air bearing test and analog computer simulation data of system response to a roll impulse. The roll impulse excitation was applied to the air bearing configuration by placing a 0.07 lb (31 g) weight on the laser grid at the front of the structure for about 3 sec. The horizontal distance from the target grid to the air bearing suspension ball was 57 in. This condition resulted in a decrease of roll momentum of about 1 ft-lb-sec. The roll impulse was simulated on the analog computer by applying an initial roll rate of $-0.15°/\text{sec}$ corresponding to the momentum applied to the 400 slug-ft^2 vehicle inertia.

The negative roll impulse caused a negative roll rate as shown by the initial slope of the roll horizon sensor signal. This rate produced an initial rate on the delta actuator through the nutation decoupling loop. The operation of the main control loop produced an additional delta actuator command in the opposite direction that brought the delta actuator rate to zero in less than one roll time constant (approximately 25 sec).

The gamma actuator was driven by the roll horizon sensor error signal to provide a roll restoring torque. In this case the roll impulse was large enough to drive the gamma actuator rate into saturation during the first segment of the transient. System response was essentially linear after one roll time constant and was dominated by a damped nutation oscillation. This nutation was primarily the result of the 4-sec time constant of the noise filter, although the reduced loop gain particularly through the nutation decoupling loop, also contributed.

Conclusions

The hybrid and air bearing tests established the compatibility of the equipment interfaces and demonstrated the functional operation of an orbital stabilization system suitable for synchronous communication satellites. In the process of performing the tests, special procedures were developed for use of air bearings suitable for performance tests of similar momentum exchange control systems. The operation of the components have been verified individually and as a functional system. The tests proved the feasibility of the double gimballed momentum wheel control system for three axis stabilization of synchronous satellites and the close matching of dynamic motion with predictions reinforces confidence in the theoretical analyses.

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