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Galileo Dual-Spin Attitude and Articulation Control System

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Galileo, the first outer-planet explorer to be configured as a dual spinner, will conduct intensive investigation of Jupiter's atmosphere, satellites, and magnetosphere. The exacting mission, coupled with the inherently complex spin and flexible body dynamics of the vehicle, demands careful design of the Galileo Attitude and Articulation Control System (AACS). A brief overview of the Galileo mission and spacecraft is presented, followed by a detailed discussion on the mechanization of the AACS and the many factors that influence its design. Included are discussions on attitude determination and control, high-gain antenna pointing, science scan platform pointing, nutation damping, wobble compensation, spin and despin control, and propellant migration and boom flexibility effects.

Introduction

THE principal objective of the Galileo mission to Jupiter is to conduct intensive investigations of Jupiter's atmosphere, satellites, and magnetosphere. A probe will be released into the Jovian atmosphere to measure its temperature, pressure, chemical composition, physical state, radiation, and atmosphere circulation. The chemical composition and physical state of several Jovian satellites will be measured and the major processes occurring on their surface identified. The magnetic properties of the satellites will also be measured to characterize the manner in which they perturb the Jovian magnetosphere. Investigation of the magnetosphere will include both time and space measurements of the absolute energy spectra and charged particle distribution. Visible light imaging equipment will be used to further examine the Jovian atmosphere and will provide high-quality pictures of the planet and satellites. Galileo is scheduled for launch in January 1982, with Jupiter encounter occurring in mid-1985. It will be the first planetary spacecraft to be launched from the Space Shuttle, and the first to use the Inertial Upper State (IUS) boost vehicle.

The Galileo spacecraft, unlike previous outer planet explorers, will be configured as a dual spinner to accommodate both inertial and rotating science platforms. Although dual spinners are commonplace today in Earth orbiting applications, designing one to perform deep space exploration is not as straightforward as one might first believe. The Galileo mission is very complex, requiring many trajectory correction and orbit trim maneuvers (TCM and OTM), accurate probe delivery, an orbit deflection maneuver (ODM) after probe delivery, a 60-minute orbit insertion burn (JOI), a perijove raise maneuver (PJR), and up to 11 Jovian satellite encounters. The vehicle itself is also quite dynamically complex. It has articulated members on both the spin and despin sections, long flexible booms on the spin section, and a significant proportion of propellant mass to spacecraft mass and hence large deviations in spacecraft inertia properties over the life of the mission. The elaborate mission, together with the inherent complexity of a spinning vehicle, gives rise to a rather sophisticated dual-spin Attitude and Articulation Control System (AACS).

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The purpose of this paper is to familiarize the reader with the Galileo AACS. A brief overview of the Galileo mission and spacecraft is presented, followed by detailed discussions on the mechanization of the AACS and the many factors that influenced its design. Topics to be discussed include the following: 1) spacecraft attitude determination and control, 2) high-gain antenna (HGA) pointing, 3) science scan platform pointing control, 4) wobble compensation using radioisotope thermoelectric generator (RTG) booms, 5) passive and active nutation damping, 6) spacecraft spin control and platform despin control, and 7) boom flexibility and propellant migration effects.

Mission Description

The Galileo mission is scheduled for launch from the Space Shuttle in early 1982. This unusually favorable launch opportunity permits both the probe and orbiter mission to be carried out with a single launch using a three-stage IUS boost vehicle. The first two stages of the boost vehicle are three-axis stabilized using thrust vector and rocket control systems; the third stage is spin stabilized at 70 rpm with no active control. At the end of the IUS injection phase, the third-stage IUS plus spacecraft are spun down to approximately 1 rpm for boom deployment. Immediately following boom deployment, the IUS is jettisoned. The spacecraft then performs the initial acquisition and goes into transit cruise. About three months after launch, Galileo will make a close (250 km) flyby of Mars to gain speed for the long (644,000,000 km) trip to Jupiter. The transit time to Jupiter is about 3½ years, with probe entry and JOI occurring in July 1985. Once the spacecraft is placed into orbit, the satellite tour begins. The tour will last until March 1987, the nominal end of mission. The mission time line is shown in Fig. 1.

Spacecraft Description

The Galileo spacecraft is a dual spinner with an overall mass of approximately 1900 kg; of this amount, 850 kg is oxidizer and fuel. The transverse axis of inertia at the beginning of the mission is 2500 kg-m^2; the rotor inertia about its spin axis is 3500 kg-m^2. Thus the vehicle has an oblate inertia distribution and is inherently stable; that is, all energy-dissipating mechanisms on the spin or despin sections enhance nutational convergence. The nominal cruise configuration of Galileo is illustrated in Fig. 2.

Spin Section

As can be observed in Fig. 2, the spin section or rotor is the more massive of the two spacecraft sections (1500 kg vs 400 kg). The rotor is comprised of the following major components: 1) retropropulsion module (RPM), 2) octangular

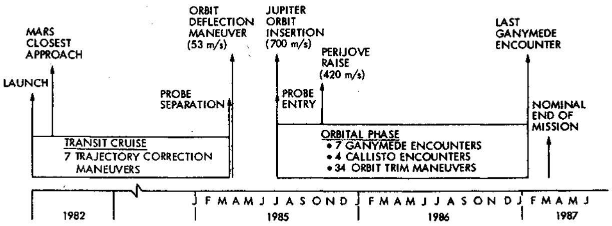

Fig. 1 Galileo mission sequence.

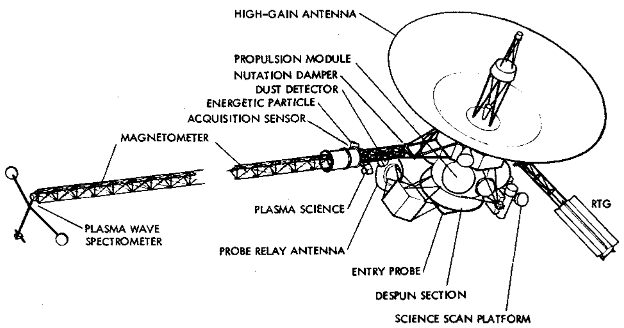

Fig. 2 Galileo spacecraft.

equipment bay, 3) 11-m magnetometer boom, 4) two articulated booms with RTG's, 5) 4.8-m furlable high-gain antenna, 6) low-gain antenna, 7) V-slit star scanner, 8) spin bearing assembly, and 9) acquisition sensors.

The Federal Republic of Germany, in a cooperative agreement with NASA, is providing the RPM, which is a bipropellant system using MMH as fuel and N_2O_4 as oxidizer. The fuel and oxidizer are contained in two tanks, both of which are manifolded and diametrically opposed. The fact that the tanks are manifolded gives rise to an interesting wobble phenomenon which will be discussed later.

The main engine has a 400-N thrust capability and is mounted at the base of the despin bearing assembly with the feed lines routed down the center of the bearing (see Fig. 3). It will be used for the three large ΔV maneuvers: ODM, JOI, and PJR.

Spacecraft attitude correction maneuvers, HGA pointing, spin maintenance, commanded turns, and TCM's are accomplished using two clusters of 10-N thrusters. The location of the thrusters is shown in Fig. 3.

Despin Section

Shown in Fig. 2 is the arrangement of the despin section or stator. Mounted on it are two equipment bays, the scan science platform, the atmospheric entry probe, and the probe relay antenna. Although the stator is asymmetric, it is balanced about the spacecraft bearing axis to minimize dynamic coupling.

The probe relay antenna is rigidly attached to the side of the equipment bays. Probe tracking is performed by slowly rotating the platform about the bearing axis to follow the probe's trajectory. The probe itself weighs 250 kg and contains six of the sixteen experiments to be flown on the mission.

Galileo Attitude and Articulation Control System

The Galileo AACS is responsible for the following control tasks: spacecraft attitude determination and control, science scan platform articulation and stabilization, wobble compensation, passive and active nutation damping, rotor spin maintenance, platform despin control, spacecraft reorientation, and ΔV control.

Galileo spacecraft attitude control is based on the tendency of the angular momentum of the spinning section to stabilize the spacecraft spin axis in inertial space. Directional changes

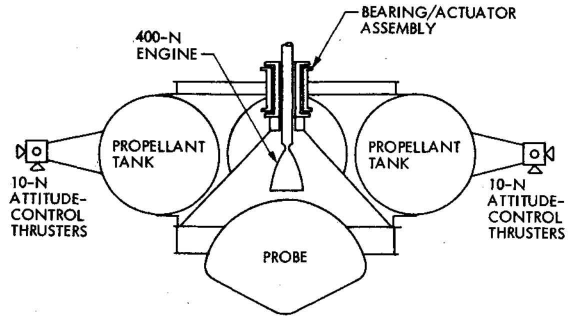

Fig. 3 Retropropulsion module.

of the angular momentum will occur only if momentum is added to the system by external disturbance forces. If the stored momentum is large relative to the integrated effects of the disturbance forces, the directional displacement of the bearing axis will be small, even over a period of days. To compensate for positional drift or to change the attitude of the spacecraft for Earth track or commanded turns, the 10-N thrusters are used. Attitude information for these maneuvers is obtained from the two-axis V-slit star scanner and/or the two dry-tuned rotor gyros. Attitude determination and control are performed on board by the attitude control electronics (ACE) on the spin section. The preliminary HGA pointing accuracy requirement is 3.1 mrad (3σ) in each axis with respect to inertial space.

The Galileo science scan platform is characterized by two degrees of freedom called clock and cone angle. Clock is the angle of the scan platform about the spacecraft spin axis, and cone is the angle from the spin axis. The platform has complete 4π steradian coverage. The two tuned rotor gyros are mounted on the platform to directly provide inertial rate and position information for platform stabilization. The preliminary line-of-sight accuracy requirement is 3.4 mrad (3σ) in each axis; the rate jitter requirement is 20 μrad/s. The control actuators for both axes are brushless dc motors.

Inexact static and dynamic ground balancing and uneven propellant depletion produce bearing axis wobble, i.e., steady-state rotation of the spacecraft bearing axis about the system spin vector. This motion can be greatly reduced by vernier control of the spacecraft inertias. On Galileo, the RTG booms are articulated up or down in planes parallel to the bearing axis to produce products of inertia that effectively cancel the wobble caused by c.m. offsets or products of inertia. The residual wobble angle is expected to be controlled to better than 0.1 mrad. The boom actuators are geared-down stepper motors driving a ballscrew assembly.

In order to achieve a steady-state spin condition with negligible coning motion, a passive bellows nutation damper is mechanized at the hinge of the magnetometer boom. For those periods of the misssion that require nutation damping rates exceeding the capability of the passive damper, active damping will be provided using the scan science platform.

A block diagram of the Galileo AACS appears in Fig. 4. The ACE processor is a 2900-based 16-bit microprocessor with approximately 20 K (16-bit) words of memory. The ACE I/O contains all A/D, D/A, buffering, and drive circuits for communication with and control of the various AACS components and other spacecraft subsystems. The despun control electronics (DEUCE) provides signal multiplexing, conditioning, and buffering for all AACS data communication between the ACE on the rotor and the AACS components (gyros, accelerometers, and cone actuator) on the despin platform.

The spin bearing assembly provides the mechanical and electrical links between the spin and despin sections. It contains power and signal slip rings, relative position encoder, and the despin/clock angle control actuator.

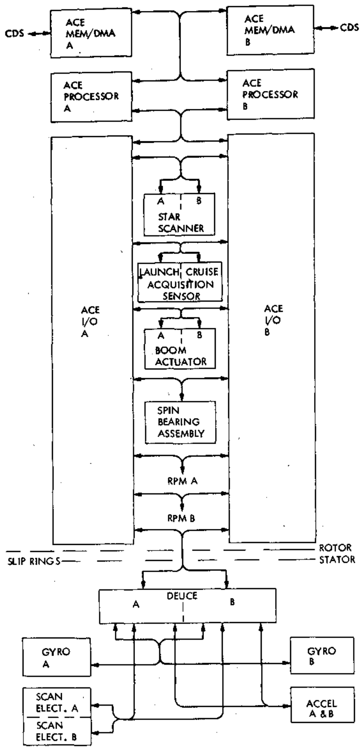

Fig. 4 AACS block diagram.

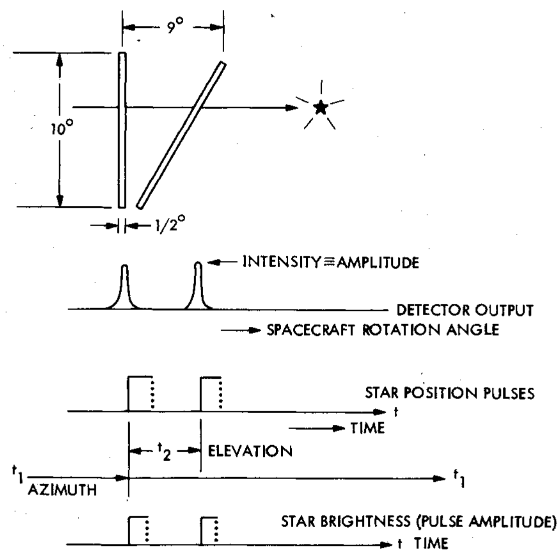

Fig. 5 Basic star scanner operation.

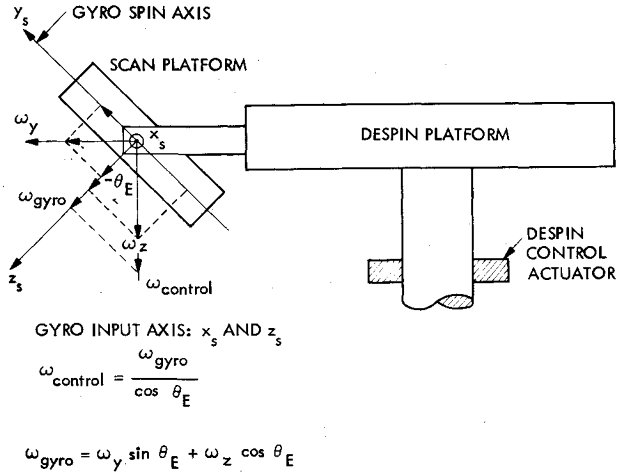

Fig. 6 Scan platform control axes.

The accelerometers are used in conjunction with the 10-N thrusters to provide active nutation control during initial spin down of the spacecraft plus third stage IUS. During this phase of the mission, the combined spacecraft and launch vehicle have a prolate inertia distribution and are nutationally unstable. The accelerometers are also used during all propulsive maneuvers to monitor and control the ΔV.

Attitude Determination and Control

Galileo has two cruise modes: transit cruise and orbital cruise. The two modes are distinguished from one another by their sensor configuration.

During the transit cruise mode, the only source of attitude information is the two-axis V-slit star scanner. The principle of operation of the star scanner is shown in Fig. 5. Since three axes of attitude information are required, multi-star processing is necessary. Galileo will thus be required to carry on board a comprehensive star map. Multi-star processing is a complicated affair, with star identification and star ambiguity being the main problems. There are two types of star ambiguity. One is the uncertainty that arises when adjacent stars have nearly the same intensity; the other is the confusion that occurs when different stars appear in the same slit or both slits at the same time.

The orbital cruise mode uses both star scanner and the tuned rotor gyros on the scan platform. In this mode the observability of the spacecraft is greatly enhanced by using the gyros to directly measure the rates and positions of all three spacecraft axes. The star scanner is used in similar fashion as before, except that in this mode, its output is used to determine and update gyro drift. During encounter phases of the mission when star occultations occur, attitude determination will rely entirely on the gyro data. Obviously this cannot be done for long periods of time since gyro drift will become significant.

High-gain antenna correction maneuvers and spacecraft reorientations are accomplished by momentum precession using the 10-N thrusters. There are several momentum precession techniques that can be used; each has its own advantages and disadvantages. The simplest one is to rotate $\bar{H}$, the angular momentum vector, directly to the target using one thruster burn and then to wait for the precession to dampen. If nutation damping time constants are prohibitively long, there are more complicated schemes available whereby $\bar{H}$ can be rotated and the nutation dampened in the time of one spin revolution. For a detailed discussion on the subject, the reader is referred to Ref. 1. The maneuver scheme that will be used on Galileo has not yet been determined.

Despin/Scan Clock Angle Control Loop

The despin/scan clock angle controller is responsible for despinning and positioning (clock angle control) of the despin section. Three sensors are used: a star scanner, which provides the inertial reference for clock; a two-axis tuned rotor gyro mounted on the scan platform, which provides clock rate and position between star scans; and a position encoder between the spin and despin sections.

To keep the clock angle of the despin platform fixed or despun in inertial space, the relative position between the spin and despin section is checked with each star scan and an appropriate error signal developed to drive the despin motor to reposition or despin the platform. Since the star scanner output is available only periodically (once every 20 s using one star and a spin rate of 3 rpm), the bandwidth of this loop is quite low. If it is only necessary to keep the platform despun, the bandwidth is sufficient; however, during scan science pointing sequences, higher bandwidth is required to minimize the rate stability or jitter. Hence, the despin loop is supplemented with the gyro during scan pointing to continuously provide platform rate and position between star scans. The position update with each star scan is used to compensate for gyro drift. Use of the scan-mounted gyro to provide the despin platform rate is not as straightforward as it might first appear. Whenever the scan platform is pointing out of the transverse plane, the sensor axis and the control axis are no longer collinear; hence, a transformation of the control information is required. As shown in Fig. 6, ω_c, the control rate, can be expressed as

$$\omega_c = \omega_g / \cos\theta_E \tag{1}$$

where ω_g is the gyro output and θ_E is the cone angle. The gyro output ω_g can be further expressed as

$$\omega_g = \omega_y \sin\theta_E + \omega_z \cos\theta_E \tag{2}$$

where ω_y is the transverse rate of the spacecraft about the y axis, and ω_z is the spin rate of the despin section. Substituting Eq. (1) into Eq. (2) yields

$$\omega_c = \omega_y \tan\theta_E + \omega_z \tag{3}$$

Equation (3) illustrates an interesting point. If the clock controller is to minimize motion about z_s, the scan platform z axis, ω_z must be made equal to $-\omega_y \tan\theta_E$ by properly driving the bearing actuator. Therefore, during scan pointing, the clock controller does not endeavor to hold the despin platform fixed or despun in inertial space, but rather, it drives the platform in a cyclic fashion to compensate the components of spacecraft transverse rate that are being experienced by the scan platform. As the platform approches 90 deg, a gimbal lock condition is encountered and the torque required goes to infinity. The effective cone range for clock control is expected to be on the order of ±70-80 deg. The limiting factors are the torque capability of the despin motor and the inertia of the despin section about the spin axis. Scan pointing outside the effective range will be accomplished in a body pointing mode; i.e., the scan platform is positioned and held fixed relative to the spacecraft, which is inertially pointed. Pointing degradation will occur since any motion experience by the spacecraft is also experienced by the scan platform. Complete operation of the despin/scan clock angle controller is illustrated in Fig. 7. The control law will be a form of proportional-plus-integral control. Integral control is required to offset the friction in the despin bearing.

Scan Cone Angle Controller

The cone servo loop is similar to that of the clock. The scan platform is gimballed about its c.m. and is driven by a brushless dc torque motor. The desired cone angle is set using a high-resolution encoder. In this loop, the control information is measured directly by the tuned rotor gyro and no transformations are required. Ideally, since the scan platform is mounted about its c.m., no control effort is required to accomplish scan pointing in the presence of vehicle motion; however, because of bearing torque, cable torque, and other nonlinearities, some control effort is required, even in the absence of pointing error. Again, the control law will be a form of proportional-plus-integral control. The block diagram for the loop is shown in Fig. 8.

Spin Control

The spin rate of the spacecraft is maintained by a set of 10-N thrusters that provide torque about the spin axis as required to keep the spin rate within a desired spin rate deadband. Tight control of the spin rate is not required, and the deadband size can be several percent of the nominally selected spin rate. Accurate knowledge of the spin rate is important, however, since the attitude control gains are a function of the angular momentum of the system. The following factors influence the nominal spin rate selection:

1) Resistance to disturbance torques decreases with decreasing spin rate (attitude correction frequency increase).

2) Life of rotation components (bearings, brushes, slip rings) decreases with increasing spin rate.

3) Propellant requirements for the spacecraft reorientation increase with increasing spin rate.

4) Bearing motor torque availability decreases due to back electromotive force (BEMF) as spin rate increases.

5) Required minimum thruster pulse time is relaxed with increasing spin rate.

A block diagram of the spin rate control loop appears in Fig. 9. The sensor for this loop is the star scanner. The spacecraft spin rate is calculated using the angle and time between successive star scans. The calculated spin rate is held constant until the next rate calculation and is compared to the commanded spin rate to form the spin rate error. If the error signal exceeds the desired deadband, it is multiplied by the gain $K_S = \hat{I}_R / \tau$ (where $\hat{I}_R$ is the estimated spin inertia and τ is the thruster torque) to determine the thruster on-time Δt required to bring the spin rate back to the middle of the deadband. How accurately this is done depends on the ac-

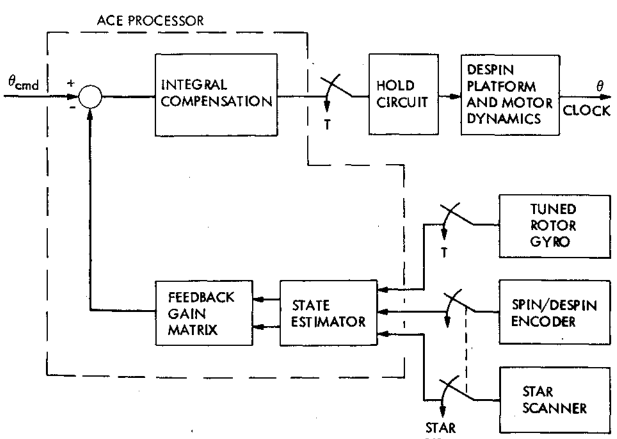

Fig. 7 Despin/scan clock angle control loop.

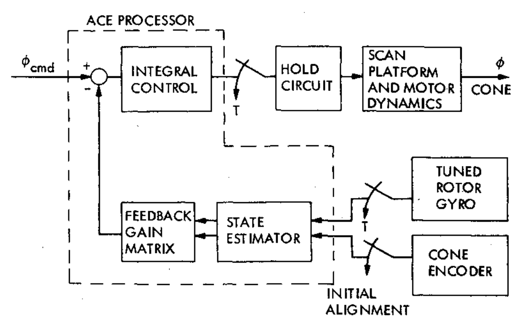

Fig. 8 Cone angle control loop.

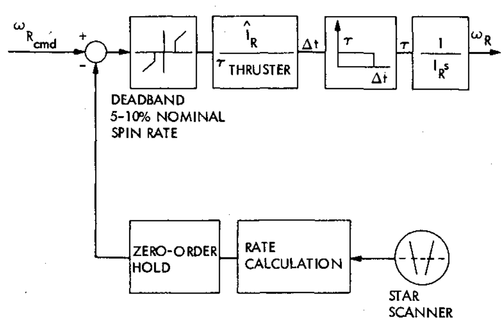

Fig. 9 Spin rate control loop.

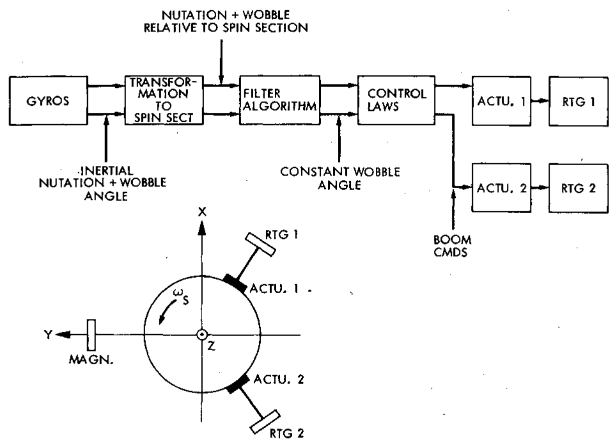

Fig. 10 Wobble controller.

curacy of $\hat{I}_R$, whose magnitude decreases as the mission progresses. This parameter may be periodically updated by ground command or may be calculated on board. Another option is to fix its value at I_R minimum, which will always result in a Δt less than or equal to what is required to achieve the middle of the deadband; this Δt will never burn excess fuel and accuracy will only improve with mission life ($I_R \rightarrow I_{R\min}$).

Wobble Control

Wobble motion resulting from c.m. offsets or products of inertia are a source of attitude errors affecting HGA pointing and angular position knowledge of the fields and particles experiments. Wobble angle is defined as the angle between the bearing axis and the system spin vector. If the transverse inertias are approximtely equal, the wobble angle is constant in magnitude and direction for an observer on the rotor, and the rate of the coning motion is equal to the rotor spin rate ω_R. Given the above assumption, an expression for estimating the wobble angle is

$$\phi_i = (I_{iz} - mrs) / (I_z^R - I_T) \tag{4}$$

where

$i = x$ or y axis
I_{iz} = product of inertia in the x-z or y-z plane
mrs = product resulting from a c.m. offset

with

m = mass of offset
r = radial distance from bearing axis
s = axial distance of the offset from the spacecraft c.m.

Notice in Eq. (4) that a wobble angle resulting from a c.m. offset can be effectively cancelled with a product of inertia and vice versa. Further, the magnitude of the wobble angle is a function of the difference between the transverse and spin inertia. Wobble compensation, then, is accomplished by moving a mass on the spin section in such a way as to create a product of inertia equal and opposite to that causing the wobble. Efficient utilization of spacecraft mass dictates that the mass used to effect the corrective offset be an already existing one. Because the two RTG's are massive and are located more than 3 m radially from the bearing axis, they are a natural selection for the wobble masses. A sufficient range of products of inertia is available by adjusting the angle of the two RTG booms in planes extending through the bearing axis. The boom articulation range necessary to accommodate the entire Galileo mission is expected to be in the order of ±10 deg out of the x-y plane. Good wobble control about both axis is possible since they are separated ~120 deg.

The algorithm used to determine wobble angle, which is constant for an observer on the spin section, depends on whether the wobble sensor is on the spin or despin section. For platform-mounted sensors, it is first necessary to transform the sensor output to the spin coordinates. Once transformed, the signal is filtered to extract the constant (dc) wobble angle component. If the sensor is rotor-mounted, the sensor output is filtered directly. On Galileo, the platform-mounted gyros will be used to sense the wobble about both transverse axes. Given the wobble angle, the required boom position can be calculated and commanded. A block diagram of the wobble controller is shown in Fig. 10. Initial wobble correction will be required shortly after separation; thereafter, it will be required only after large quantities of mass have been expended or a mode change occurs, i.e., after many trajectory correction maneuvers, probe release, orbit insertion or corrections, or changing configuration from all spin to despin, or vice versa.

Wobble Amplification[2]

The presence of flexible elements on inertially oblate spinning bodies gives rise to a very interesting wobble phenomenon called wobble amplification. Whenever an elastic deformation occurs, the balance of the spacecraft and hence the axis about which it spins changes. As the spin axis approaches its new equilibrium position, the deformation persists even more, causing the spin axis to move further and creating a potentially unstable condition. It is interesting to note that this only occurs for inertially oblate spinners, which are normally thought of as being inherently stable. For prolate vehicles the elastic deformation will always occur in such a way as to reduce the imbalance, causing the actual spin axis to drift towards the desired geometric spin axis; that is, the flexible members will perform passive balancing to a limited degree.

Of particular interest to Galileo is the flexible interaction that results from propellant migration between manifolded tanks. The tanks are manifolded to ensure equal pressurization and, hence, equal fuel usage during the lift of the mission. It is shown in Ref. 2 that a spacecraft dry imbalance level, which is achieved in the laboratory on a spin balance machine, is amplified by propellant migration so that the in-flight imbalance is larger than would otherwise be expected. Expressions can be developed that will allow one to predict the amplification factor as a function of systems mass properties, tank geometry, and propellant loading. The reader is referred to Ref. 2 for a thorough discussion on the topic.

The sensitive parameters of the fuel tank manifolding problem are z, the distance from the spacecraft c.m. to the transverse plane of the tank centers, and ΔI, the difference of the rotor inertia and the inertia about the transverse axis of interest. For a large z or small ΔI, the stability boundary is approached, and the wobble amplification becomes infinite. Conversely, for small z and large ΔI, the wobble amplification is finite and a stable equilibrium spin condition will exist. Wobble amplification analyses on Galileo have indicated unacceptably small ΔI (50 kg-m^2). As a result, the spacecraft has been reconfigured to increase ΔI to an acceptable level (500 kg-m^2).

Nutation Damping

Passive nutation damping on Galileo is accomplished using a fluid bellows damper of the type flown on the Pioneer Jupiter spacecraft. The nutation damping time constant is expected to be on the order of 10 minutes. There are several times during the mission, however, that may require faster time constants. During these periods the scan platform and cone controller will be used as an active nutation damper. To do this, it is only necessary to hold the platform fixed in cone relative to the spacecraft, using a cone control loop that is sharply resonant with the precession rate as seen by the scan platform. Preliminary simulations have demonstrated active nutation damping time constants in the order of several minutes. Because a high rate of damping is desirable, current consideration is being given to the idea of putting the scan platform in the active damper mode whenever it is not being used for science sequences.

Summary

The Galileo spacecraft, the first to orbit a giant planet, has an entry probe that will plunge deep into Jupiter's atmosphere, measuring the chemistry and structure as it descends, and an orbiting vehicle that will explore near-planet space for two years after probe release. The mission will be launched from the Space Shuttle in early 1982. En route to Jupiter, the spacecraft will make a close flyby of Mars to gain speed for the long trip to Jupiter. Jupiter encounter will occur in mid-1985, with the mission terminating in early 1987.

The Galileo spacecraft is a dual-spin vehicle, providing both inertially stabilized and rotating science platforms. Because the mission is a comprehensive and complex one, there are stringent performance requirements placed on the spacecraft's attitude and articulation control system (AACS). Design of the AACS has been in progress for approximately one year. As a result of this effort, the preliminary AACS design has been developed and is described herein. Some of the unique features of the AACS discussed include on-board attitude determination and control using a single star scanner, inertial stabilization of the science scan platform, on-board wobble compensation, wobble amplification resulting from boom flexibility and propellant migration, and active nutation damping using the scan platform.

Acknowledgment

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