Magnetic Torquers for Momentum Desaturation of Space Station Control Moment Gyros

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Theme

WHEN control moment gyros (CMG's) are used to stabilize and control the attitude of a space station, an auxiliary torquing system must also be included to prevent saturation of the CMG's. The auxiliary torquing system can employ mass ejecting thrusters, gravity-gradient torquers, solar pressure torquers, or torques generated by interaction of three mutually perpendicular current carrying coils with the Earth's magnetic field. This paper presents the results of studies which employed an electromagnetic actuation system for the momentum desaturation of control moment gyros and compares it to the alternate approaches.

Content

The theory of the electromagnetic actuation system has been previously developed in several papers and contract reports[1] by these authors and many others. In general, a set of three mutually perpendicular electromagnetic actuators or coils are driven with a current which is proportional to the cross product of the unwanted momentum vector and the Earth's magnetic field vector ($\bar{I} = \bar{M} \times \bar{B}$). The resultant space station control torque then is the cross product of the coil current vector and the Earth's magnetic field vector ($\bar{T} = \bar{I} \times \bar{B}$). The resultant control law which is mechanized to implement the electromagnetic actuation system is of the form: $\bar{T} = \bar{M} \times \bar{B} \times \bar{B}/B^2$. To mechanize this control law three mutually perpendicular coils, a three axis magnetometer, cross product multiplication and signal processing electronics in addition to a means of measuring the unwanted momentum are required. With control moment gyros, the gimbal angle deflections represent the components of unwanted momentum.

The physical characteristics of the electromagnetic actuators have been determined as a function of CMG size, space station size, and orbital altitude and inclination over wide ranges of these independent variables.[1] The power required by the electromagnetic actuators is taken into account by including the power supply weight in the total electromagnetic actuation weight. The changes in the magnitude of the solar pressure, gravity gradient, and aerodynamic torques as a function of space station size were incorporated as was the coupling feedback effect of the electromagnetic actuators on attitude control system performance. The method of analysis employed for the development of these data was the generation and operation of a digital computer program which simulated the attitude controlled orbiting vehicle, the disturbances, the Earth's magnetic field, and all the elements of both the CMG and electromagnetic control systems.

In a comparison with other means of CMG momentum unloading it was determined that the electromagnetic actuation system is the most feasible for a large space vehicle. The electromagnetic method is seen to be a better choice than a system of thrusters, which is typical of the approaches to momentum desturation that can be seriously considered at this time. This choice rests largely on the higher reliability of the electromagnetic system, which includes only simple static devices (a magnetometer, a signal processor, and three coils). Thruster systems typically include a number of solenoid valves, nozzles, high-pressure tanks and lines and pressure reducers, or fuel heaters and pressure transducers. In addition, the electromagnetic system does not depend on a fixed fuel supply or a convenient fuel resupply rate and is more adaptable to the environment of disturbance torques which store momentum and to the mission life or resupply schedule. The electromagnetic approach is much lighter than the simplest thruster systems with low specific impulse and weighs approximately the same as more sophisticated techniques with higher specific impulses. Thrusters for desaturating momentum would have to be rated at a few millipounds thrust in order to avoid significant disturbances to the CMG system. Therefore, it is not likely that a reaction jet system which may or may not be on board for coarse attitude maneuvers could be used satisfactorily as a CMG momentum desaturating device.

For space vehicle sizes considered in this study (diameters of 10–15 ft and lengths in the range 12 to 60 ft), the weights for iron-core and air-core magnetic torquers are approximately equal. However, iron-core torquers are slim cylinders that can be made as short as 3 ft with only a minor increase in weight; the three torquers can be separated and mounted in any convenient location. For reasonable weight efficiency, the air-core torquers would be thin coils wrapped around the outside of the spacecraft.

As an example, the weight of a magnetic system for a 40,000-lb vehicle (12 ft in diameter and 36 ft long) in a 200-naut mile circular orbit inclined at 30° to the equator is 200 lb, including a 1 lb/w power supply. This figure results from a pessimistic assumption regarding the size of the aerodynamic disturbance torque, which would otherwise saturate the CMG system and which is the dominant influence on the magnetic system at low altitudes. At 300 naut miles, the electromagnetic system weight is down by a factor of four.

The parametric performance and weight study covered ranges of 100 to 1000 naut mile altitude, 0° to 90° orbit inclination to the equator, and spacecraft sizes as just stated.[1] For the purpose of determining disturbance torques and simulating the CMG system, it was assumed that the vehicle was oriented with its longitudinal axis (z) generally vertical and another axis (y) normal to the orbit plane. However, operation of the magnetic momentum desaturation system is not limited to this orientation. Center of mass offsets along the longitudinal axis of the cylindrical vehicle were assumed to develop aerodynamic and solar radiation torques. It was further assumed that the longitudinal axis was actually oriented 1° from the vertical, producing a steady gravity gradient torque in addition to the constant aerodynamic torque.

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CMG rotor momenta of 1000 ft-lb-sec for each of two double-gimballed gyros and 500 ft-lb-sec for each of two single-gimballed units were assumed for the example case of a 12-ft-diam, 36-ft-long, 40,000-lb spacecraft. For other spacecraft sizes in the parametric study, the CMG rotor momenta were assumed to be scaled up or down from this base level in proportion to the vehicle moments of inertia.

Ratings of the x, y, and z magnetic torquers have been computed as functions of altitude, orbit inclination, and spacecraft size for two torquer types—long, cylindrical nickel-iron cores wound with aluminum wire (the x, y, and z torquers arranged with longitudinal axes along the vehicle x, y, and z axes, respectively) and large-diameter, air-core torquers. The ratings are expressed in ft-lb/gauss of the perpendicular Earth's field component. The ratings can be summarized, however, by stating only the sum of x, y, and z torquer ratings. This is meaningful because the ratio of torquer weight to torquer rating is essentially constant for a large range of ratings. The most stringent requirements for the magnetic torquing system are found in the low-altitude, low-orbit inclination cases.

Figure 1 shows how the total rating depends on altitude for the 40,000-lb vehicle with an orbit inclination of 30°. Below 300 naut miles, the aerodynamic torque is a very important influence. Above 300 naut miles, two effects oppose each other and produce a rating nearly invariant with altitude. One is the diminishing Earth's field, leading to higher torquer ratings. The other is the diminishing gravity gradient disturbance.

The desaturation capability of the system is approximately a function of $\sin^2 \beta$, where β is the rms value of the angle between the orbit plane and the magnetic equator. This can be explained as follows. First, $\bar{T} = (\bar{M} \times \bar{B}) \times \bar{B}$, and $\bar{T}$ is proportional to B^2. Considering the chief vehicle disturbance torques, pessimistically assumed to lie about the y axis, the Earth's field components of interest are B_x and B_z, those along the vehicle x and z axes. B_x and B_z are functions

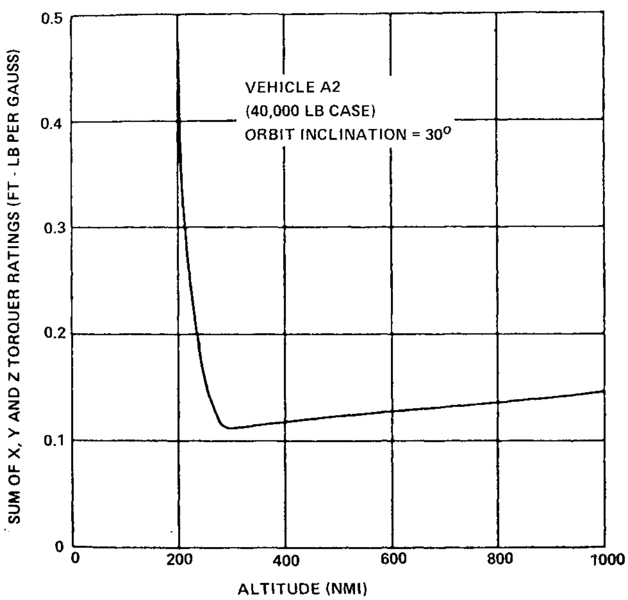

Fig. 1 Torquer ratings vs altitude.

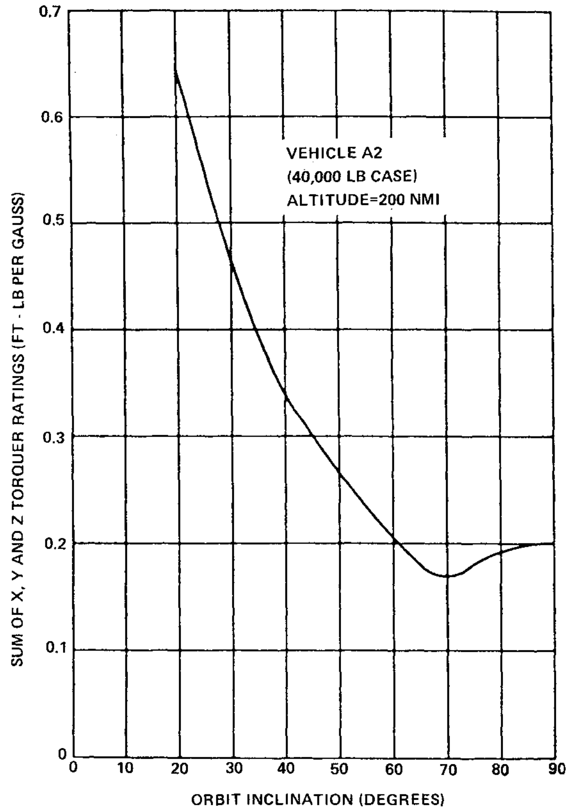

Fig. 2 Torquer ratings vs orbit inclination.

of $\sin \beta$. Hence $|T|$ is proportional to $\sin^2 \beta$. The result is a decrease in required torquer ratings with increasing orbit inclination, as shown in Fig. 2.

It should be remembered that the data below 300 naut miles are based largely on a pessimistic assumption that the center of mass and center of pressure are constantly separated by one-tenth of the spacecraft length.

A family of torquer designs has been calculated,[1] optimizing the total weight of the torquer and its part of a power supply which is assumed to weigh 1 lb/w. Each of the nickel-iron core torquers were assigned lengths equal to the diameter of the spacecraft (six spacecraft sizes were considered). Using the 40,000-lb vehicle as an example, the total iron-cored torquer-power supply weight to rating ratio is 430 lb/ft-lb/gauss.

The momentum desaturation system acts like any other external disturbance in causing CMG system attitude errors. The errors caused by the occasional maximum torques exerted by the magnetic system were found in a computer simulation which included the 40,000-lb satellite at an altitude of 200 naut miles and the CMG system grossly specified earlier. The worst pointing errors were less than 2 arc-sec.

Reference

[1] "Application of Magnetic Torquing for Desaturation of Control Moment Gyros in Space Vehicle Control, Technical Report AFFDL-TR-67-8," Air Force Contract AF33(615)-3602, Feb. 1967, Westinghouse Electric Corp., Baltimore, Md.