Satellite Attitude Dynamics and Control in the Presence of Environmental Torques—A Brief Survey

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Introduction

MOTION of a spacecraft presents two dynamical aspects of interest. The most obvious one is the trajectory traced by its center of mass which is governed by the classical Keplerian relations. However, spacecraft are not point masses as Kepler assumed in the analysis of planetary bodies. They have finite size and hence inertia. Thus a satellite, while negotiating a trajectory, may execute rotational motion about its center of mass, commonly referred to as libration.

There are numerous situations of practical importance, such as communications, scanning of cloud cover for weather forecasting, survey of Earth resources, scientific and military observations, and so on, where it is desirable to maintain a satellite in a fixed orientation with respect to the Earth. Unfortunately, even though a spacecraft may be precisely oriented at launch, it tends to deviate from this preferred orientation under the influence of environmental forces (solar radiation pressure, interaction with the Earth's gravitational and magnetic fields, and, if the spacecraft happens to be close to the Earth, free molecular reaction forces), internal changes, and coupling of attitude dynamics with the orbital and flexural mechanics. This leads to undesirable librational motion which must be controlled for successful completion of a given mission.

A wide range of attitude control concepts has been proposed over the years and several have found practical application. Broadly speaking, they may be classified as active, passive, and semipassive procedures. The active systems use energy available onboard the satellite. The passive and semipassive systems, on the other hand, exploit the environmental forces for stabilization and control.

In the earlier days of space exploration, satellites tended to be relatively small, mechanically simple, and essentially rigid. However, this is no longer true for a modern spacecraft, which may carry large flexible solar panels to meet the ever-increasing demand on electrical power to operate onboard instrumentation, scientific experiments, and communications systems. For example, the Canada/USA Communications Technical Satellite (CTS/Hermes), launched in early 1976, carried two solar panels, approximately 1.14×7.32 m each, to generate 1.2 kW. In fact, proposed L-SAT communications satellite of the European Space Agency (ESA), scheduled to be launched in the mid-1980s, will have two solar panels, extending to 33 m, to generate approximately 7 kW. With this trend toward larger spacecraft, further emphasized by proposed gigantic Space Operations Centers (SOC) and Satellite Solar Power Stations (SSPS), passive and semipassive librational control procedures appear to be more promising.

Over the past 25 years, several hundred papers have appeared which deal with the subject of attitude dynamics of satellites in the presence of environmental effects and on their utilizations for attitude stabilization and control. This paper presents a rather concise and hence necessarily incomplete survey of some of the more relevant papers available in open literature. It reviews the following aspects:

1) modeling of environmental forces acting on satellites;
2) effect of environmental disturbances on satellite attitude dynamics;
3) use of the gravity-gradient, solar radiation pressure, aerodynamic forces, and magnetic field for passive and semipassive librational control of satellites; and
4) flexible spacecraft and environment.

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The early work on the subject and related topics is reviewed by Roberson,[1,2] Frye and Stearns,[3] Singer,[4] Ergin,[5] Gerlach,[6] Debra,[7] Beletsky,[8] Fischell,[9] Hughes,[10] Sabroff,[11] Mesch,[12] Shrivastava et al.,[13] and many others. Shrivastava et al.[14] have reviewed at length various facets of attitude control systems. A relatively recent survey by Shrivastava[15] deals with the effects of solar radiation pressure and atmosphere on librational response and its semipassive control. Since the 1960s, problems faced by spacecraft with flexible appendages[16] have started to receive more attention. The literature on the subject is reviewed by Likins and Bouvier,[17] Hughes,[18] and Modi.[19] The importance and complexity of the subject becomes apparent from the fact that during the last 6-7 years, annual symposia and special sessions devoted to the dynamics and control of flexible spacecraft have become common features at aerospace conferences. Reference 20 presents a collection of abstracts of recent work on large, flexible systems.

The presence of environmental forces significantly affects the orbital motion of satellites. Trajectories of the near-Earth satellites are substantially changed by the atmosphere and the Earth's equatorial ablateness, while for the geostationary satellites, the Earth's equatorial ellipticity, the solar radiation pressure, and the attraction due to the sun and moon are the main sources of orbital perturbations. A vast amount of literature on these aspects is available. Some of the important studies on lifetime estimation of the near-Earth satellites and on orbital perturbation and stationkeeping of geostationary satellites were reviewed by King-Hele[21] and Shrivastava,[22] respectively. The interaction of spacecraft and environment in the form of electrical charging, magnetization, heating, and so on, is the subject of a recent book,[23] which contains a number of excellent review articles. In view of this, the present paper is confined only to the topics mentioned earlier. With over 1000 published papers, reports, and theses directly related to the limited scope of this paper, only a small fraction of them are reviewed here for conciseness.

The main objective is to help initiate researchers in this exciting field as well as to provide designers, working under tight time schedules, a quick source of information relevant to their projects.

Modeling of Environmental Forces and Torques

The sources of environmental effects on satellite attitude dynamics are many. They include: gravity gradient; rarefied atmosphere; solar radiation pressure; Earth's magnetic field; Earth's albedo and reflected radiations; micrometeorite impacts; cosmic dust; and so on. Of these, the first four being dominant and deterministic have received much attention. The Earth's albedo and reflected radiation can become significant for large near-Earth satellites.[24] The last two and other less significant causes are random in nature and stochastic approaches have been applied to study their influence. They are not considered here.

A number of papers deal with the modeling of environmental torques. Most of them consider rigid spacecraft of simple geometry.[4] Roberson,[25] Nidey,[26] Carrol,[27] Raymond,[28] and Kane and Johansen[29] among others provide a thorough analysis of gravity-gradient and centrifugal forces acting on a rigid satellite of an arbitrary shape. Neglecting higher-order terms, the gravity-gradient torque can be expressed as

$$\bar{T}_G = 3[(I_3 - I_2)mn\bar{i} + (I_1 - I_3)\ell n j + (I_2 - I_1)\ell m\bar{k}]\dot{\theta}^2/(1 + e\cos\theta) \quad (1)$$

where

θ = true anomaly
e = orbital eccentricity
I_1, I_2, I_3 = principal moments of inertia
ℓ, m, n = direction cosines of the Earth-satellite line with respect to the principal body axes

It is apparent that the torque vanishes[29] if 1) any two direction cosines are zero; 2) all the moments of inertia are equal; or 3) two of the moments of inertia are equal and one direction cosine is zero.

For altitudes up to 800 km, aerodynamic forces can significantly alter the attitude dynamics of satellites. For low perigee orbits, the aerodynamic torque is generally the most dominant environmental source of disturbance.[30] Wiggins,[30] Evans,[31] Singer,[4] Hughes,[10] Karr and Yen,[32] Tidwell,[33] and van Woerkom[34] have modeled the aerodynamic torque on satellites of different shapes. It can be expressed as

$$\bar{T}_A = \bar{\epsilon} \times \bar{F}_A \quad (2)$$

where $\bar{\epsilon}$ is the position vector of the center of pressure with respect to the center of mass of the satellite. The precise determination of $\bar{F}$ is a bit involved. However, it can be closely approximated by

$$\bar{F}_A = 0.5\rho_a V^2 A C_D \quad (3)$$

where

ρ_a = atmospheric density
V = velocity of the satellite relative to the atmosphere
A = characteristic area
C_D = drag coefficient

The difficulties arise due to very large variations in ρ with the height, relative position of the sun, season, solar activity, and local currents.[21] For accuracy, one also has to account for the atmospheric rotation and oblateness of the Earth.[8]

The solar radiation pressure exerted by the incident rays on a surface due to the transfer of momentum from the photons is small (10^{-5} N/m^2, perfectly reflecting body). However, with the present trends toward large, lightweight space systems, it can be the dominant source of attitude and orbital perturbations, especially for the geostationary spacecraft. The force due to the solar radiation on an elemental area, dA, can be written as[24]

$$\bar{F}_S = (S/C)\,|\cos\xi|\,\{(1 - \Upsilon - \rho)\bar{n} + 2\rho\cos\xi\bar{p}\}\,\mathrm{d}A \quad (4)$$

where

$\cos\xi = \bar{n}\cdot\bar{p}$
$\bar{n}$ = unit vector normal to the surface
$\bar{p}$ = direction of the incident ray
S = solar constant
C = speed of light
τ, ρ = transmissibility and reflectivity of the surface, respectively

For different geometries of satellites the solar radiation pressure torque is modeled by several authors.[14,24,30,31,33,35-39] The presence of the Earth's shadow, secondary reflections, and degradation of satellite surface with time complicate the model.

The residual permanent magnetism of ferromagnetic materials used in satellite, closed-loop currents in the instrumentation, and eddy currents induced due to the satellite motion in the Earth's magnetic field make it behave as a magnetic dipole. This results in a magnetic torque

$$\bar{T}_m = \bar{M} \times \bar{B} \quad (5)$$

where $\bar{M}$ is the dipole moment of the satellite and $\bar{B}$ the local geomagnetic induction. $\bar{M}$ is generally determined experimentally. The Earth's magnetic field can be specified in a number of ways depending on the purpose and required accuracy of the model. For most applications, it can be approximated as a small magnetic dipole with a strength of 8.06×10^{25} unit-pole-cm (8.06×10^{5} Wb-m) at the center of the Earth whose axis is tilted at an angle of 11.5 deg with respect to the geographical polar axis.[40-44] For a more accurate model, the known magnetic field data at various points in space can be combined together by spherical harmonic expansion using a digital computer.[45] At high altitudes, the field is affected by the sun-spot activity and solar emissions. Using this simple model, many authors have determined the magnetic torque acting on a satellite.[4,9,12,30,33,40-43] Modeling of the torque due to eddy currents on simple symmetrical geometries has also received considerable attention.[33,45-48] In modeling the torque, one should be careful to use appropriate units, otherwise even a sophisticated analysis would lead to incorrect results, as in Refs. 33 and 47.

These models are useful in the dynamical analysis, design of attitude control system, simulation, attitude determination, as well as in the study of the environment itself.

Effect of Environmental Disturbances on Satellite Attitude Dynamics

In general, the environmental forces disturb the satellite attitude which must be controlled. Most of the early satellites were spin-stabilized. Then came the concept of dual-spin. Now the majority of the satellites are three-axis stabilized using momentum exchange devices, reaction jets, and electromagnets. A large number of studies deal with the effect of environmental disturbances on spin, dual-spin, and three-axis stabilized rigid satellites.

The motion of a rigid symmetric spinning satellite in a circular orbit subjected to gravity-gradient and aerodynamic torques, and orbital nodal regression is studied by Beletsky,[8,49,50] analytically as well as numerically. The analytical predictions agree with the motion of Sputnik III. Duboshin[51] has examined stability of spinning satellites subjected to the Earth's gravity-gradient field and shown the opposite behavior of prolate and oblate bodies. For a satellite with spin axis normal to the orbital plane, Thomson[52] has presented a stability criterion using linearized analysis, while Pringle[53] investigated motion in the large employing the Hamiltonian as a Liapounov function. Asymmetry is taken into account by Kane and Shippy[54] applying the Floquet theory. The same approach is applied later by Kane and Barba[55] to study librational motion in the small, for a satellite in an orbit of arbitrary eccentricity. Wallace and Meirovitch[56] applied an asymptotic analysis in conjunction with Liapounov's direct method and constructed stability diagrams in a parametric space. Modi and Neilson[57,58] described roll motion of a spinning satellite in an elliptic orbit using the WKBJ approximation and checked its validity through comparison with the numerical solution. The Floquet theory was extended by the authors to assess stability of periodic solutions of a slowly spinning satellite in the gravity-gradient field and circular or elliptic orbits.[59] Stability in the large was also investigated making use of the concept of integral manifold.[60]

Studies on dual-spin stabilized satellites taking the gravity torque into account are rare but offer, nevertheless, valuable results. Of particular interest is the conclusion by Kane and Mingori[61] that the stability of undamped axisymmetric dual-spin satellites is equivalent to that of the rigid spinning bodies. White and Likins[62] extended the result to a slightly asymmetric system by making use of asymptotic expansions and resonance lines. The contributions of Roberson et al.[63,64] and Yu[65] should also be noted here. They determined equilibrium positions of a single rigid body containing a symmetric, constant speed, fixed-axis rotor, also called a gyrostat, in the presence of gravity forces. Fueschel et al.[66] have discussed the effect of gravity-gradient and atmospheric torques with a pendulum-type nutation damper on the despun part, and determined the transient decay time constant. Longman[67] proved that at a critical spin rate, a dual-spin satellite subjected to the gravity-gradient torque can tumble.

For a three-axis stabilized satellite, the gravity-gradient torque acts as a disturbance unless the configuration of the satellite is such that its maximum moment of inertia axis is perpendicular to the orbit and the minimum moment of inertia axis is along the local vertical. In elliptic orbits, the disturbing effect is more pronounced due to the presence of periodic forcing terms. For satellites with a large difference in the principal moments of inertia the gravity-gradient torque is higher.

As mentioned earlier, for satellites at an altitude less than 800 km, the rarefied atmosphere is a significant source of attitude perturbations. For low-altitude satellites it can be the most dominant environmental torque. In an early study, Debra[68] has discussed the variation in equilibrium configuration for two gravity-stabilized satellites. Beletsky[49] treats the force as a small perturbing source acting on a rapidly spinning system. Through a linearized analysis, Schrello[69] shows that the aerodynamic torque may exceed the gravity-gradient moment even at altitudes nearing 500 km. The influence of a constant moment acting on a gravity-stabilized system is determined through an infinitesimal analysis by Garber.[70] More directly, Sarychev,[71,72] with a particular reference to Russian satellites, has derived governing equations of motion and determined the necessary and adequate conditions for asymptotic stability of the eigen oscillations which are also caused by the rotating atmosphere. Meirovitch and Wallace[73] established the regions of guaranteed stability for a slowly spinning system with a constant aerodynamic force. For two configurations, the stability of equilibrium positions was studied using Liapounov's direct method. Morozov[74,75] includes the magnetic effects and finds conditions for stability of the steady-state behavior of a gyrostat. Kopnin[76] includes the aerodynamic lift, which is considerably smaller than the drag, in the equations of motion. Johnson[77] has derived an expression for the aerodynamic drag leading to spin decay of the near-Earth rotating satellites. Even a relatively stable dual-spin spacecraft, SAS-A, exhibited susceptibility to atmospheric perturbations.[66,78] Nurre[79] shows that the presence of inertial or geometric asymmetries can result in instability due to interactions with the atmosphere. For an arbitrarily shaped body, Frik[80] finds that if the aerodynamic forces were conservative, at least one stable equilibrium position would exist. For nonconservative forces no stable orientation is possible.

The planar libration of a gravity-stabilized satellite, modeled as a plate in an elliptic orbit and subjected to various radiations and aerodynamic forces is investigated by Flanagan and Modi.[81] A more complete analysis accounting for the transverse motion as well, for a cylindrical satellite moving in an arbitrary orbit and subjected to the gravity-gradient and aerodynamic torques, is presented by Shrivastava and Modi.[82-85] On establishing the stability of equilibrium through infinitesimal as well as Liapounov's direct approach, detailed response and stability studies were carried out.[82] The concept of integral manifold was successfully extended to axisymmetric satellites in circular orbits. Three distinct types of motion corresponding to the fundamental and other periodic solutions was noted. The critical Hamiltonian representing the strength of the maximum permissible disturbances was established through the Floquet theory.[83] An approximate solution in terms of elliptic function was also found using the constant first integral of the system.[84] Under the combined influence of eccentricity and atmosphere, the equilibrium changes continuously and the response gets much more complicated. The stability bounds also shrink very rapidly,[85] putting a severe limitation on the effectiveness of the gravity-gradient moment for stabilization of near-Earth satellites. Continuing his earlier studies Beletsky[86] discusses rotations of the Proton satellite as affected by the atmosphere.

All the studies referred to above are deterministic in their approach and assume a rather simple model for a complex and uncertain phenomenon. Random nature of the disturbance is analyzed by Sheporaitis.[87] A parametric stability region is determined using a stochastic Liapounov function and probability estimates of the convergence to equilibrium position given. Mitchell[88] also has considered satellite response to random disturbances.

The presence of solar radiation pressure has been known for a long time. However, in the early designs of satellites not much attention was paid to its effect. Roberson[89] has estimated its order of magnitude. The attitude and orbit perturbations of Echo, Vanguard, and spinup of Explorer XII, which were later attributed to solar radiation pressure by Bryant,[90] Evans,[31] and Fedor,[91] have emphasized the necessity of a careful consideration of this effect in design and operation of even small satellites. McElvain[35] obtained an analytic expression for the direct solar radiation torque and determined, for two geometries, the change in the satellite's angular momentum necessary to maintain a specified orientation. In a later study,[92] he suggested ways to minimize the solar torque on the gravity-stabilized satellite ATS by optimal balance of surfaces and their characteristics. Karymov[93] has derived equations of librational motion of a sun-orbiting satellite and analyzed the stability of equilibrium along the local vertical. The derivation, however, is needlessly complicated. Clancy and Mitchell[94] have presented a more complete analysis accounting for three major sources of radiations, namely, the sun, the Earth, and reflections from the Earth and its atmosphere. The dynamical behavior of the system is represented as the motion of and about the angular momentum vector. The resulting force expressions, given in an integral form, were evaluated numerically. The computational effort involved was extremely demanding. Whisnant and Anand[95] noticed a possibility of excitation of resonant motion across the orbital plane, due to radiations, for GEOS-II. This was later confirmed through observations.[96] A detailed study of planar librations of a flat plate in an eccentric, ecliptic orbit subjected to the solar, Earth, and Earth-reflected radiations is due to Flanagan and Modi.[24,81,97-99] The closed-form characteristic of the force expressions[25] make them ideally suited for attitude dynamics studies. The response under solar radiation pressure was analyzed using the WKBJ approach. They also obtained altitude bounds where various environmental forces become significant.[81,88,99] The stability was found to shrink rapidly in the presence of orbital eccentricity and environmental forces. Modi and Kumar[100] considered solar radiation pressure acting on a cylindrical satellite. The cross-plane motion in circular orbits was also included in a later study.[101] Modi and Pande[102] looked at the effect of solar radiation pressure on the attitude dynamics of a slowly spinning system and observed that it can be as important as the effect of gravity-gradient and orbital eccentricity. Shrivastava and Hablani[103] presented a simple analysis of coupled librations of a gravity-stabilized satellite in an arbitrary orbit subjected to solar radiation pressure. Useful stability manifolds in parametric space were obtained. As systems become larger and more complex, the effect of solar radiation pressure needs careful attention. This is established in a number of studies related to specific satellites.[37,38] Furthermore, in the design of attitude maneuvers, one may have to account for these disturbances.[104] It is interesting to note the configuration design of the Indian National Satellite (INSAT), which has a solar sail on a long astromast to compensate for the solar radiation pressure acting on the solar panels, which are all located on one side of the satellite.[105] For the proposed solar power satellite,[106] the solar radiation pressure will be a dominating source of orbit and attitude perturbations.

A large number of studies deal with orbital perturbations due to solar radiation pressure. These are reviewed by Shrivastava.[22] The thermoelastic behavior due to solar radiations is considered in a later section.

Interaction with the Earth's magnetic field is a major source of disturbance for satellites below 1500 km. As the Earth's field varies as the inverse cube of the distance from the center of the Earth, the magnetic torque disturbing the satellite attitude may not be significant at large distances. For three-axis stabilized satellites, the magnetic torque mainly arises from the dipole moment of the satellite and tends to disturb the attitude. Magnetization and demagnetization of the ferromagnetic material onboard led to hysteresis damping while the eddy currents generated in a spin-stabilized satellite result in reduction of the spin. These have been studied by a few investigators, with the major emphasis on the last problem.[4,9,30,33,40-48,74,75,107-110] Cohen and Savet[111] have analyzed the attitude dynamics of a huge electromagnet orbiting around the Earth. They found that it will oscillate about the Earth's local magnetic field with an amplitude determined by the initial misalignment. Even in the case of perfect alignment, an oscillation of a few degrees with respect to the field will take place. The analytical solutions for spin decay due to eddy currents, derived recently by Shrivastava and Shivananda,[48] are of interest. To some extent it is possible to reduce the undesirable influence of the magnetic torque by:

1) minimizing the use of ferromagnetic materials;
2) designing the electrical circuits in a way so as to minimize the dipole moment of the satellite; and
3) reducing the thickness and interrupting continuity of the conducting structural material to minimize eddy currents.

Use of Environmental Forces for Passive and Semipassive Attitude Control of Satellites

From the foregoing it is apparent that the environmental forces play a significant role in the attitude dynamics of satellites. A judicious design of the system can change their role, making them useful for stabilization and control. A vast body of literature is now available on the use of gravity-gradient and magnetic torques to that end. Some attention has also been devoted to the utilization of solar radiation pressure and aerodynamic forces to achieve the same effect.

Gravity Gradient

Gravity-gradient forces the satellite to align its minor axis along the local vertical. This natural tendency makes it ideally suited to the Earth-oriented communications, Earth resources, and meteorological satellites. The simplicity of the system has attracted the attention of the designers from the beginning of the space era. This is apparent from the review papers[1-8,11,13,14] and the proceedings of the two symposia on gravity-gradient systems[112,113] held during the 1960s.

Gravity gradient provides a passive means of stabilization. In elliptic orbits the forced planar librations are always present with the amplitude (in radians) approximately equal to the eccentricity of the orbit. As the difference diminishes and the orbital eccentricity increases, the stability of the system is adversely affected. The pioneering contributions to the subject are due to Klemperer[114] and Baker,[115] who obtained analytic solutions for planar motion. Michelson[116] found the equilibrium orientation, while Beletsky[117] focused the attention on resonance effects for satellites in elliptic orbits. Zlatousov et al.[118] obtained periodic solutions of the planar motion. A comprehensive study of planar libration is due to Modi and Brereton, who employed the concept of integral manifolds and analytical techniques to determine the bounds of stability in the large[119,120] and the periodic solutions.[121,122] They observed that at the critical eccentricity for stability, the only available solution is a periodic one and gravity-gradient stabilization is not possible beyond an orbital eccentricity of 0.35, even for the most stable dumbbell system. For higher eccentricities one may need to introduce a moving mass device.[123]

In an early study, Kane[124] has shown that for a triaxial satellite strong coupling may exist between pitch, roll, and yaw motions. In fact, even resonant motion, leading to instabilities are possible for certain inertia ratios.[125] Bounds of librations are established by Auelmann,[126] Pringle,[127] and Beletsky.[128] A linearized analysis of the near-resonant librations is presented by Hitzl.[129,130] Stability and response of coupled nonlinear librations of an axisymmetric satellite in circular and elliptic orbits are studied by Modi and Shrivastava.[82,85,131,132] The study establishes the importance of the inertia parameter and periodic solutions. It is noted that depending upon the system parameters and disturbances, the satellite may execute regular, "island type," or ergodic motion.

The above studies deal with undamped motion of gravity-gradient stabilized satellites. Several types of passive and semipassive dampers have been proposed and used for the same class of spacecraft. Review of the vast body of literature in that area is outside the scope of this paper. From the analytical point of view, however, several contributions should be recognized: Pringle[133] gave several theorems of stability of damped systems; Bainum and Mackison[134] analyzed in detail performance of the DODGE satellite; Modi and Tschann[135] studied the nonlinear behavior of damped systems; and Murphy and Kane[136] derived explicit attitude stability criteria for flexible damped gravity-stabilized systems.

Several satellites, notably GEOS-A, DODGE, and RAE, have successfully demonstrated the effectiveness of the concept. Chobotov[137] has proposed a gravity-stabilized solar power satellite. Gravity-gradient torque can also be employed for momentum desaturation of control moment gyros and reaction wheels.[138] The concept is attractive due to its simplicity, long life, and reliability. The main problem, however, is with the low-accuracy design of an effective damper and high susceptibility to other environmental disturbances mentioned earlier.

Solar Radiation Pressure

The solar radiation pressure generally affects the performance of spacecraft adversely. A judicious design of the system can change its role, making it useful for stabilization and control. Such a possibility was first suggested by Garwin,[139] who proposed "solar-sailing" for interplanetary missions. Though requiring a huge surface, it was shown to take less time than chemical rockets for a journey to a distant planet. It was also thought to be simpler in operation and easier to implement compared to its main competitor, ion propulsion. Sohn[140] suggests the use of a weathervane-type solar attitude stabilizer. Frye and Stearns[3] consider a trailing cone for the purpose. Avoiding rather cumbersome appendages, Newton[141] prefers a satellite to be a big sphere having two types of coatings—one portion reflecting and the other absorbing. The local heating in such a system, however, could create problems. A possibility of increasing the effectiveness of the available force by focusing it through a set of reflecting and collecting mirrors is suggested by Hibbard.[142] Ule[143] has designed and built an array of windmill-type mirrors with corner reflectors that could maintain the axis of rotation sun-oriented and could regulate the spin rate. In absence of damping the effectiveness of all these systems would be limited. Accord and Nicklas[144] evolved a unique passive stabilizer, technically feasible, which could also provide damping, through a thermomechanical phase-lag component. The system, now patented,[145] is said to be better than the conventional ones. Donlin and Randall's model[146] is essentially similar. Mar and Vigneron[147] proposed the use of the shape deformations of a balloon satellite of the type of Echo-II for spinup. Galitiskaya and Kisler[148] analyzed a set of panels for three-axis stabilization and qualitatively established their optimum inclinations for the maximum utilization of the solar pressure. Several theoretical studies,[149-154] carried out at the Massachusetts Institute of Technology, consider the dynamics, generally through linearization, of both spinning and nonspinning, sun-orbiting spacecraft stabilized by the solar radiation pressure. Aside from the conventional dampers, a possibility of using the lag in thermal reradiation from the spacecraft's surface to produce nonconservative torques was investigated. The last of the above studies has presented a workable design of a three-axis controller for a small probe. Dzhumanoliev[155] has analyzed the small oscillations of a sun-pointing spacecraft with two coatings, which resulted in a net control moment. A system of connected bodies to impart damping to a sun-pointing solar stabilizer is suggested by Merrick et al.[156] To maintain spin and axis orientation, Crocker[157] proposed sets of shining and black paddles. The spring-mounted paddles provided a desired change in attitude automatically. A preliminary analysis of the system ignoring the gravity effects and assuming existence of a damper showed promise.

It is recognized that the gravity-oriented systems need damping to be effective. As discussed earlier, they are also susceptible to even small disturbances. Mallach,[158] using a phase-plane analysis and average torques, has considered the use of a solar pressure damper. Modi et al. suggested several semipassive systems involving a controlled change of area, moment arm, or angle of incidence. The first one is a simple velocity-sensitive pitch damper. Its success both in circular and elliptic orbits under large external disturbances[159] has led to the development of a velocity- and position-sensitive controller that could stabilize the satellite in any desired orientation.[160] The difficulties in making area changes through unfurlable material, and so on, in space are overcome by changing the moment arm.[101] This idea was later extended to coupled motion in a circular orbit of an arbitrary inclination.[161]

For dual-spin stabilized spacecraft, Modi and Pande[162,163] showed nutation damping and attitude control to be possible through a set of rotatable panels interacting with the solar pressure. A generalized analysis for vehicles in arbitrary orbit was developed. Its application to INTELSAT-IV and Anik-1 showed the transient time to be only one-eighth of an orbit with the steady-state errors completely removed through a modified control function. The system was optimized numerically.[164,165] Pande has also designed an attitude control scheme using the solar radiation pressure for a spin-stabilized system[166] and pitch control of an inertially fixed asymmetric satellite.[167] A scheme for solar pitch control of gravity-stabilized satellites in elliptic orbits is presented by Kumar and Joshi.[168,169] Two different designs of three-axis attitude control for geostationary communication satellites was presented by Stuck.[170] In an earlier study, Shrivastava et al.[171] designed a three-axis solar controller suitable for station-keeping and attitude control of a geostationary satellite. For fine attitude control of an Earth observation satellite, Chretien et al.[172] used a similar concept of asymmetrical rotating solar array.

It may be mentioned that a solar pressure controller has been successfully tested, despite some initial difficulties, on Mariner IV spacecraft.[173] With the present trend toward construction of large space systems, this form of essentially passive stabilization procedure may find itself in vogue.

Aerodynamic Forces

The aerodynamic forces have a substantial influence on the attitude motion of the near-Earth systems. Unlike the solar radiation pressure, the literature on favorable application of aerodynamic forces is rather small. This may be due to the complex nature of the free molecular forces, rotation of atmosphere, and strong dependence of density on height, season, sun-position, and local variations. The lack of a complete understanding of the atmospheric model also adds to the limited effort in their utilization. Yet, the few studies that have been made do show a feasibility of designing an effective aerodynamic attitude controller, which might also add to the life of the near-Earth systems. Such possibilities are indicated qualitatively in the early analyses by Debra and Stearns,[174] Wall,[175] and Schrello.[176] The success of aerodynamic pitch control, with the roll and yaw stabilized by gyros, is exhibited by COSMOS-149.[177] In a model suggested by Hoffer,[178] the gyros were replaced by a set of moving masses. Here the planar librations were reduced by a pair of drag flaps operating in an on-off fashion. This system may be difficult to implement because of the large changes in inertia. Ravindran and Hughes[179] optimized, through linearization, a set of aerodynamic controller paddles for a satellite in a circular orbit. The system provided stabilization along the local horizontal. Using Liapounov criteria, the stability of such a controller was also studied by Flanagan and Rangarajan.[180]

For the general case of nonlinear, coupled motion in an arbitrary orbit, Modi and Shrivastava[85] proposed several schemes of rotatable flaps which use both lift and drag. The velocity-sensitive controller resulted in an effective damping and stabilization of a gravity-gradient system. Later, an aerodynamic controller capable of stabilizing the system about any arbitrary spatial orientation was evolved using a velocity and position-sensitive strategy. Through parametric optimization,[181] the transient time was reduced to less than one-third orbit and the steady-state amplitude (in elliptic orbits) below 1 deg.

Noting the success of solar controllers and realizing the limitations of aerodynamic systems in elliptic orbits, where the usable force may be significant only near the perigee, a simple hybrid controller employing atmospheric forces at lower altitudes and solar pressure at upper levels was developed.[182] The analysis is general enough to be applicable to an aerodynamic, solar, or hybrid system. A modified control relation removes the steady-state errors even for large eccentricities. A similar system for a spinning satellite was also analyzed.[183] In a recent study Pande and Venkatachalam[184] optimized an aerodynamic controller for a spin-stabilized spacecraft minimizing orbital energy loss, control surface excursion, and speed of response.

Magnetic Torque

Use of the Earth's magnetic field for attitude control has received much attention from the beginning of the space era. Systems with permanent magnets; hysteresis dampers; air-cored, current-carrying coils; and ferromagnetic electromagnets have been tested for the control of spin, dual-spin, and three-axis stabilized spacecraft either by themselves or in conjunction with other control actuators. Of the numerous studies on the subject, only a few are referred to here.

Magnetic torquing as a primary mode of attitude stabilization was first suggested by Kamm[185] and White et al.[40] for control of a nonspinning spacecraft about two axes. Fischell[186] analyzed magnetic orientation phenomena for equatorial and polar orbits. He also recommended several passive dampers using highly hysteric rods[187] kept orthogonal to the stabilizing magnet. Chan[188] derived equations of motion including restoring and damping torques, while Mesch[12] formulated the problem accounting for electromagnets. Aiguabella[189] studied the magnetically stabilized ESRO-I. Kammuller[190] analyzed the roll motion of magnetically oriented satellites and found that resonant oscillatory or rotational roll motion at twice the orbital frequency may be induced due to forcing terms. The manifold of resonant roll motion and their dependence on the inertia ratio were discussed leading to an optimal policy for the selection of these parameters to insure stable motion.

Several investigators have suggested the use of a single magnetic dipole aligned with the spin axis as a possible means of attitude control of a rigid spinning spacecraft. Ergin and Wheeler[191] and Mobley[192] have discussed specific applications of this configuration for keeping the spin axis normal to the orbital plane. Renard[193] suggested a quarter orbit bang-bang control scheme suitable for near-polar orbits to perform spin-axis acquisition and control, which was ground commanded. Wheeler[42] developed an automatic scheme for circular orbits using magnetometers and rate gyros. The difficulty lies in the change of magnetometer reading due to magnetotorquers. Glass[194] has touched upon basic principles for designing the magnetic coils. Tossman[195] was probably the first to consider active nutation damping and despin control. His scheme used passive hysteresis rods. A control law based on the asymptotic stability criterion for the spin-axis and spin-rate control using two dipoles, one along the spin axis and the other normal to it, was suggested by Shigehara.[196] Using a two-coil system, Sorenson[197,198] employs the Kalman filter and derives an optimal control law for a highly eccentric orbit. Collins and Bonello[199] discuss several autonomous magnetic control schemes that provide nutation as well as precessional control. Several satellites including Tiros,[200,201,] LES-4,[202] LES-5,[203] DME-A,[204] RAE,[195] AEROS,[205] HEAO,[206] S^3-A,[207] and Bhaskara[208] have successfully used some of the concepts discussed above.

A number of studies deals with the use of magnetic torquers in conjunction with dual-spin, momentum-biased wheels, reaction wheels, and control moment gyros. The torque is used for control, momentum dumping, or librational damping. Using a single magnetic torquing coil on the despun platform, control of a dual-spin stabilized satellite is proposed by Sonnabend.[209] The concept of STABILITE, a flywheel-stabilized magnetically torqued satellite,[210] uses a magnetic coil with axis normal to the wheel. In a series of recent studies, Alfriend et al.[211-213] have developed several closed-loop magnetic control laws in the presence of momentum bias. The system works in an autonomous mode and the concepts are simple to implement. Equatorial orbits present special problems because torquing capability is always weak along the orbit normal. However, with a judicious design of a wheel with magnetic torque, it can be used even for geosynchronous orbits. LES-5,[203] RCA's SATCOM,[214] and APPLE[215] have proved the validity of this concept. Modi and Pande[216] proposed a hybrid controller using magnetic torque and solar pressure for three-axis nutation damping and attitude control of dual-spin satellites in near-equatorial orbits. It is shown that bang-bang controllers can effectively impart any arbitrary orientation to the satellite. Spencer[217] developed proportional control laws for slewing maneuvers and wheel-speed corrections. Lacombe[218] analyzed the feasibility of magnetic torquing in the case of a single-degree-of-freedom control of large geostationary satellites. Goel and Rajaram[215] designed a closed-loop control scheme which performs both attitude correction and nutation damping for a momentum-biased satellite in near-equatorial orbits.

The use of magnetic torque for momentum dumping of momentum wheels, reaction wheels, and control moment gyros has been a subject of numerous studies. Among the early investigations is the one by McElvain[219] where various methods of momentum dumping such as continuous, optimum intermittent, and nonoptimum intermittent are considered. An optimal momentum dumping scheme with a special reference to Skylab is studied by Levidow and Kranjon.[220] Buckingham and Braumiller[221] considered momentum desaturation of control moment gyros for a space station. Stakem[222] suggested a passive magnetic torquer for momentum dumping while Krishna et al.[223] used two air-core coils to the same end for a reaction control system and applied it to near-Earth satellites.

Environmental Forces and Flexible Spacecraft

Since the past decade there has been a growing trend toward large, lightweight, flexible spacecraft. With the success of the Space Shuttle one may soon see satellites ranging from a few meters to several hundred meters in size. For these satellites the influence of environmental forces will be necessarily significant. Also the high pointing accuracy requirement would dictate careful consideration of the environmental effects. However, unlike the rigid satellites, the literature on the subject is quite sparse.[19] A few studies available have concentrated mainly on the effect of gravity-gradient or the thermoelastic behavior of satellite appendages. There is practically no study dealing with the effect of other environmental forces on a flexible spacecraft or on their utilization for control, even though they may prove to be ideal for attitude and shape control. In general, the analyses of rigid satellites cannot be extended to flexible systems. This is a useful and challenging area for further research.

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