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on

Investigation of Technical Problems Related to Retrieval of Uncooperative Orbiting Objects

NASA Grant NGR 39-009-162

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INTRODUCTION

The subject grant (NGR 39-009-162) on technical problems related to the retrieval of uncooperative orbiting objects has now progressed to the end of the original grant period of two years. During the past six months further publications have been communicated to the scientific community and a one-year renewal grant obtained. This extension permits expansion of the program to include problems related to deployment of payloads into high altitude orbits. A discussion of the general problem of docking with a object possessing angular momentum was presented at the 22nd Congress of the International Astronautical Federation, Brussels, September 1971. A new high-altitude payload deployment technique was introduced at the AIAA Guidance Control and Flight Mechanics Conference, Hofstra University, August 1971. This work became part of the extension and an updated article on this work will appear in the Journal of Spacecraft and Rockets in 1972.

ACCOMPLISHMENTS

During the latter half of 1971 an extension grant was proposed and received in the form of a one-year renewal beginning January 1, 1972. This extension permits expansion and continuation of the work areas in the original grant. Included will be fuel and time optimal transfer trajectories between the shuttle and a target to be retrieved, and deployment of payloads into high altitude orbits. The statement of work is included as Appendix A. Three graduate students will be supported on a half-time basis with the principal investigator participating quarter-time.

In September 1971 the principal investigator attended the 22nd Congress of the International Astronautical Federation, Brussels, Belgium, and a paper entitled, "The Problem of Docking with a Passive Orbiting Object Which Possesses Angular Momentum," was presented. This manuscript, included here as Appendix B, will appear soon in Astronautical Research 1971, Proceedings of the 22nd I.A.F. Congress.

Prior to receiving this extension grant some preliminary work on high altitude deployment of payloads was carried out and the results presented as Paper No. 71-953 at the AIAA Guidance, Control and Flight Mechanics Conference, Hofstra University, August 1971. The paper, entitled, "Attitude Dynamics and Control of an Apogee Motor Assembly with Paired Satellites," has since been revised and updated to be published in the Journal of Spacecraft and Rockets in 1972. This new manuscript is included as Appendix C.

The problem of optimal transfer of the retrieval package from the shuttle to the target is receiving concentrated attention. Out-of-the-plane maneuvers are required for terminal spin axis alignment. The problem is characterized as a nonlinear boundary value problem with a terminal constraint on approach direction. A discussion of current status and method of attack is presented in Appendix D.

Prior to initiation of final approach-to-target maneuvers the spin axis and direction must be identified. One method considered was the "optical strobe," (see Appendix D of the Third Semi-Annual Progress Report, July 1971) a prism arrangement which produces a stationary image of a rotating object when viewed along its spin axis. It was hoped that a demonstration of this device could be carried out. An experiment had been planned to cover three points of interest: misalignment effects, lighting requirements, and accuracy attainable. Since the apparatus used for testing was borrowed, modifications to the arrangement were kept to a minimum to avoid damage to the prisms. This, in addition to elaborate equipment requirements, made meaningful testing impractical. Associated equipment and personnel are presently beyond the scope of the present study, and results are only of secondary interest at this stage. Therefore, this effort has been discontinued, and resources are being directed toward primary objectives.

FUTURE TASKS

Work will continue on the two primary tasks of optimal transfer trajectories and high attitude deployment. Qualitative results are expected on the former problem by mid-1972 and on the latter task by the end of this year. Progress is expected as outlined in Appendix D for the optimal transfer problem. The work reported in Appendix C on high attitude deployment will be continued in order to resolve the question of ambiguity in axis pointing direction. At least two Master of Science theses will result from this effort, in addition to related reports, papers, and presentations.

APPENDIX A

EXTENSION GRANT STATEMENT OF WORK

1 January 1972 to 31 December 1972

A primary mission of the space shuttle system is to deploy and retrieve satellites in earth orbit. The associated technology must be developed well before shuttle applications become practical. Although the current research grant has yielded an initial understanding of retrieval problems and solutions, there remains a great deal of work to be done in developing technology for satellite deployment and retrieval.

The next phase of work will be concerned with continuing current research on the calculation of fuel and time optimal transfer trajectories between shuttle and target, as well as the determination of optimum stand-off positions for the shuttle orbiter. Since many satellites are placed in high orbits, such as synchronous, it would be extremely desirable to retrieve and repair many of these if it proves economically feasible. Furthermore, the technology of deployment of such payloads from the shuttle is closely related to retrieval technology. Thus, deployment of payloads into high altitude orbits will also be included. The AMAPS technique will be further developed for practical application to high altitude payload deployment. This extension of work into deployment of payloads should yield general technology useful to primary shuttle applications.

APPENDIX B

THE PROBLEM OF DOCKING WITH A PASSIVE ORBITING OBJECT WHICH POSSESSES ANGULAR MOMENTUM

by

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The Problem of Docking with a Passive Orbiting Object Which Possesses Angular Momentum*

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Abstract

The problem of docking with a passive orbiting object which is either spinning or tumbling has recently developed interest for several reasons. Retrieval and repair of spent satellites will be technically feasible and economically desirable with the advent of the space shuttle system. Manned space stations will be circling the globe within a few years; thus, indicating that elimination of at least part of the space debris may be imperative to insure safety from collisions. Many of the discarded items are spinning and have a wide variety of shapes and sizes. Furthermore, if a collision or other mishap should occur, a manned vehicle may become uncontrolled and enter a tumbling mode of attitude motion. In order to rescue the crew or repair the spacecraft, this tumbling must be controlled and eliminated. Many studies have been carried out to formulate rescue schemes and requirements, develop uncooperative rendezvous techniques, and investigate satellite manipulation via remote operators. However, several specific problems related to docking with objects possessing angular momentum have not previously been considered and require new technology for solution. Techniques for retrieving uncooperative spinning objects are presented. A conceptual spacecraft for remotely despinning and retrieving debris of moderate size is discussed in depth. In addition, the more complex problems of detumbling a large vehicle are described. Specific aspects of rescue from such a vehicle are presented, although a general solution has not yet been formulated. The major objective is to identify the particularly important problems of docking with a spinning or tumbling object and present the current status of some promising solutions.

1. Introduction

During the past 14 years man has placed in excess of 5,200 objects into terrestrial, lunar, and solar orbits.[1] Of these, more than 2,300 are currently in orbits about the earth. There are only a few hundred operational

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satellites among all the terrestrial captives, with the remainder consisting of launch vehicle upper stages, payload fairings, and other components associated with spacecraft insertions. Although the average number density of objects is negligible, most are confined to just a few popular orbits, e.g., synchronous and low, inclined orbits. In the near-future manned space stations will be orbiting the earth as well as an increasing number of unmanned satellites and debris.

Many orbiting objects possess angular momentum in the form of steady spin or tumbling because of stabilization mode, attitude jet failure, collision, etc. Tumbling motion will always dissipate into steady spin due to energy absorption resulting from structural flexibility, propellant sloshing, and nutation dampers. Due to the increasing probability of collision, retrieval or elimination of many discarded items is becoming an urgent concern with regard to success of future orbital missions and restoration of repairable satellites. A significant problem arising in missions dealing with passive objects such as satellites and disabled space bases is docking with a target which possesses angular momentum. In the case of a discarded satellite, steady spin can be expected if angular momentum is present, because a minimum energy state is assumed to have been reached. However, a disabled station requires immediate attention and cannot be left to dissipate tumbling motion into steady spin. Unfortunately, tumble is the general result of a major uncorrected attitude disturbance resulting from control system failure, collision, or explosion.

A considerable amount of information is available in the literature on handling passive, non-spinning objects.[2] Limited work has been done with capturing targets of moderate size using a modified Apollo command and service module.[3] A preliminary analysis to determine the causes of tumbling and resulting acceleration components has recently been carried out.[4] Thus, properties of bodies possessing angular momentum are well known, but promising capture and control techniques for spinning objects and tumbling space bases have not previously been studied in depth. The work presented here deals primarily with docking problems associated with these two situations. Of particular concern are techniques and devices for eliminating angular momentum, capturing spinning objects of moderate size, and rescuing the crew of a tumbling space vehicle. Dynamics and control aspects of a device for retrieving spinning objects are presented in detail. This remotely controlled vehicle may be used in conjunction with the space shuttle system.[5] Finally, attitude dynamics and control of tumbling motion are also discussed in reference to the problem of rescue from a disabled space base and other manned vehicles.

2. Classification of Angular Momentum States

For the purpose of defining docking problems associated with objects having angular momentum, attitude motion can be classified into three categories: simple spin, nutation, and general tumbling. Simple spin is defined as the case in which the angular velocity and momentum vectors are colinear, and motion is assumed to be about the principal body axis only. Nutation is defined as a perturbed state of steady spin in which the transverse components of angular velocity are small. Thus, the deviation of motion from simple spin is only slight, allowing considerable simplification of the equations of motion. Finally, the general case of attitude motion is referred to as "tumbling," since transverse components of angular velocity may be large and there is no preferred axis of rotation.

General torque-free tumbling motion of rigid bodies has been well established and may be described analytically or geometrically. For an unsymmetrical body the equations of motion are non-linear and cannot be solved without difficulty. A geometrical interpretation has been established by Poinsot.[6] In fact, the "Poinsot ellipsoid" represents the locus of all possible values of angular velocity of the body which satisfy the constant kinetic energy condition. This imaginary ellipsoid is fixed to the body and moves with it. Attitude motion can then be described as the Poinsot ellipsoid rolling on an inertially fixed plane with its center at a fixed distance from this plane. If the body is symmetric, the geometric interpretation of motion is much simpler. A "body cone" whose apex is at the center of mass and is fixed to the body rolls on an inertially fixed "space cone" whose axis is the angular momentum vector. The common cone element is colinear with the angular velocity vector.

Classification of angular momentum states is associated with the types of missions in which docking with passive objects is required. Simple spin is usually associated with retrieval of old satellites and other orbiting items of interest. Nutation may arise in capturing a spinning object if the target is accidently perturbed by the retrieval package. Tumbling may arise in connection with space rescue operations involving large manned space vehicles which have suffered a loss of attitude control. Problems of docking during retrieval and rescue are discussed in detail below.

3. Operational Aspects of Orbital Retrieval

Of primary concern here is the retrieval of unmanned payloads which can be stored in the shuttle cargo bay, e.g., weather and scientific data collecting satellites. Such satellites and existing orbiting objects do not necessarily incorporate docking provisions, and possibly spin in such a passive state that docking equipment cannot be used. It is assumed that objects to be retrieved are spinning about their major principal axes of inertia. This is the state attained after a period of time in which kinetic energy has been dissipated by liquid sloshing, elastic deformation of structural members, or nutation dampers. For objects of the size considered here, the time required to reach a stable state is, at most, of the order of weeks, after significant attitude disturbances have stopped. However, large objects which are tumbling may require several months to passively dissipate enough energy to reach a stable spin state. Techniques used for spinning bodies would not be directly applicable to rescue from a tumbling vehicle, primarily because tumbling motion does not have an inertially oriented spin axis associated with it, which is assumed in normal retrieval operations.

Since the most economical means of reaching an object in a low orbit for retrieval, repair, or elimination will be by using the space shuttle, many aspects of the operational sequence assume a man will be controlling the events and maneuvers. Automatic control systems are assumed whenever practical, but the nature of such missions requires the ability of a man to make decisions and perform functions which are prohibitive in an automated mode because of the inherent uncertainties involved. Missions to high altitude orbits would require very similar maneuvers. However, shuttle performance is expected to limit it to low altitude orbital missions and an orbit-to-orbit vehicle may also be required for high altitude retrieval.

The initial task in a retrieval sequence is considered to be locating and identifying the object upon arrival in its predetermined vicinity. The size and shape of the search area will greatly influence the method of search and identification, and time to search. Furthermore, a successful rendezvous requires extreme accuracy in orbit determination. A non-cooperative radar rendezvous system is considered to be available using current technology. It is understood that the accuracy of orbit determination by ground tracking will permit the shuttle to be guided very close to the target object. In fact, the search region within which the target is predicted to be located is assumed to be a cone with a 4 mile (6.4 km) diameter, 5 miles (8 km) long (1σ), up to a possible 12 mile (19.3 km) diameter, 15 miles (24 km) long (3σ), with the shuttle at the apex.[5] A non-cooperative radar rendezvous should have a system range of at least 35 miles (56 km) with range accuracy of about 1 percent and angular accuracy of 2 milliradians (3σ). Once in the search cone the system can automatically scan the region and should detect an object within minutes.

One possible method of identification upon initial acquisition of an object employs a television camera guided by the radar tracking system. A zoom lens can be used to receive an image with limited resolution. If the object is spinning a "frozen" scene television display can be produced. This is equivalent to using an electronic strobe, except the picture is "flashed" on a storage tube. The image can be held or reinforced at the spin rate of the object. However, the degree of resolution is somewhat uncertain with such a system. To determine the dynamic state and physical condition of a spinning body with assured accuracy and image quality, an optical or electronic strobe is very effective once the shuttle is within a few hundred feet of the target.[5]

After locating and identifying the object, orbital maneuvers are executed to approach and acquire a stand-off position relative to the target. If the object is not spinning or has some minimal spin rate and is of acceptable size, a direct docking may be attempted. Otherwise, the shuttle must maintain a stand-off or parking position while the retrieval package is deployed to eliminate angular momentum and capture the target. Objects which are too large for retrieval are not considered reusable. In many cases it is desirable to simply eliminate such large pieces of "space junk" from orbit. To accomplish this a remotely fired retro-pack could be attached to an object after despinning. Of course, this device would reenter with the object and would not be reusable. Furthermore, large objects, such as empty upper stages and payload fairings, in low orbits decay rapidly due to pronounced drag effects.

Standard rendezvous maneuvers are anticipated during approach of the shuttle to the stand-off position. Upon arriving at this position an autopilot will be enlisted to maintain spatial relationship with the target while the attitude control system maintains required orientation. Figure 1 illustrates one possible situation in which the shuttle is positioned along the orbital path of the object. Assuming a despin maneuver is required, the retrieval package must make an orbital transfer from the shuttle to the position of the target such that the axis of this remotely controlled spacecraft is in line with that of the object spin axis. Fine adjustments are to be made after one of the shuttle crewmen checks alignment via a remote bifocal television system on the package. This terminal situation is represented in Figure 2, illustrating the retrieval of OSO 1.

Position of the shuttle and transfer trajectory of the retrieval package during capture operations are very important factors to mission success. An artificial reference frame must be provided the crew in order to remotely perform capture maneuvers and satisfy viewing constraints for continuous communications and observations. In terms of propellant requirements of the shuttle to maintain such a position, the ideal location would be along the orbital path of the target, as shown in Figure 1. Propellant expenditure would be for correcting perturbations only. Excessive fuel would be required to maintain an out-of-plane position; thus, it is assumed that the shuttle will be coplanar with the target during retrieval maneuvers. Final selection of a stand-off position for a given situation will depend on spin axis orientation of the target with respect to the orbital plane.

The transfer trajectory of the retrieval package to the target will, in turn, depend on shuttle position and object spin orientation. In general, this spin axis will not lie in the orbital plane of motion. Therefore, an out-of-plane transfer must be assumed for proper terminal alignment. A minimum of three thrust impulses is required for a transfer time of less

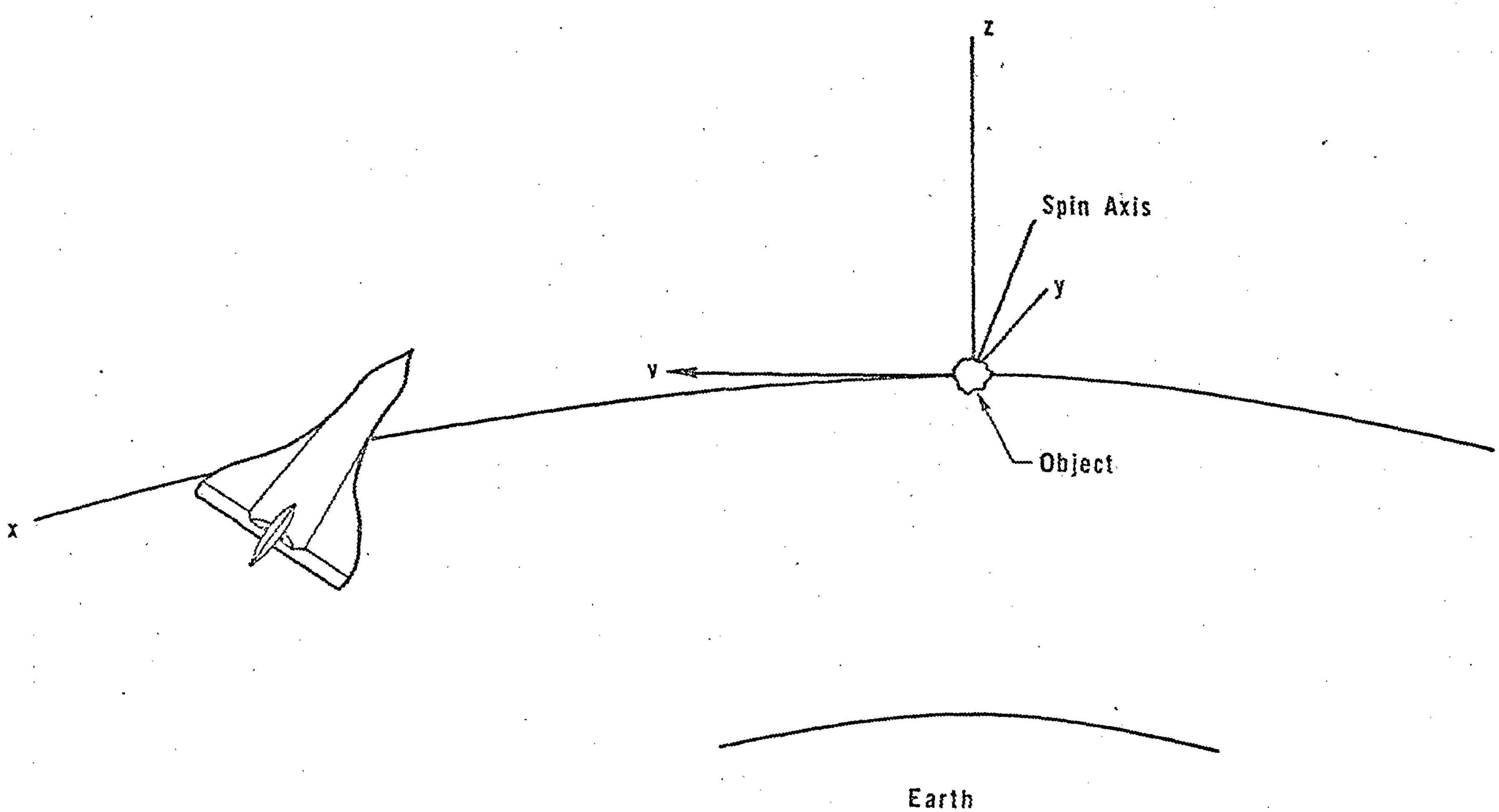


Figure 1 Shuttle/Object Relative Position Nomenclature

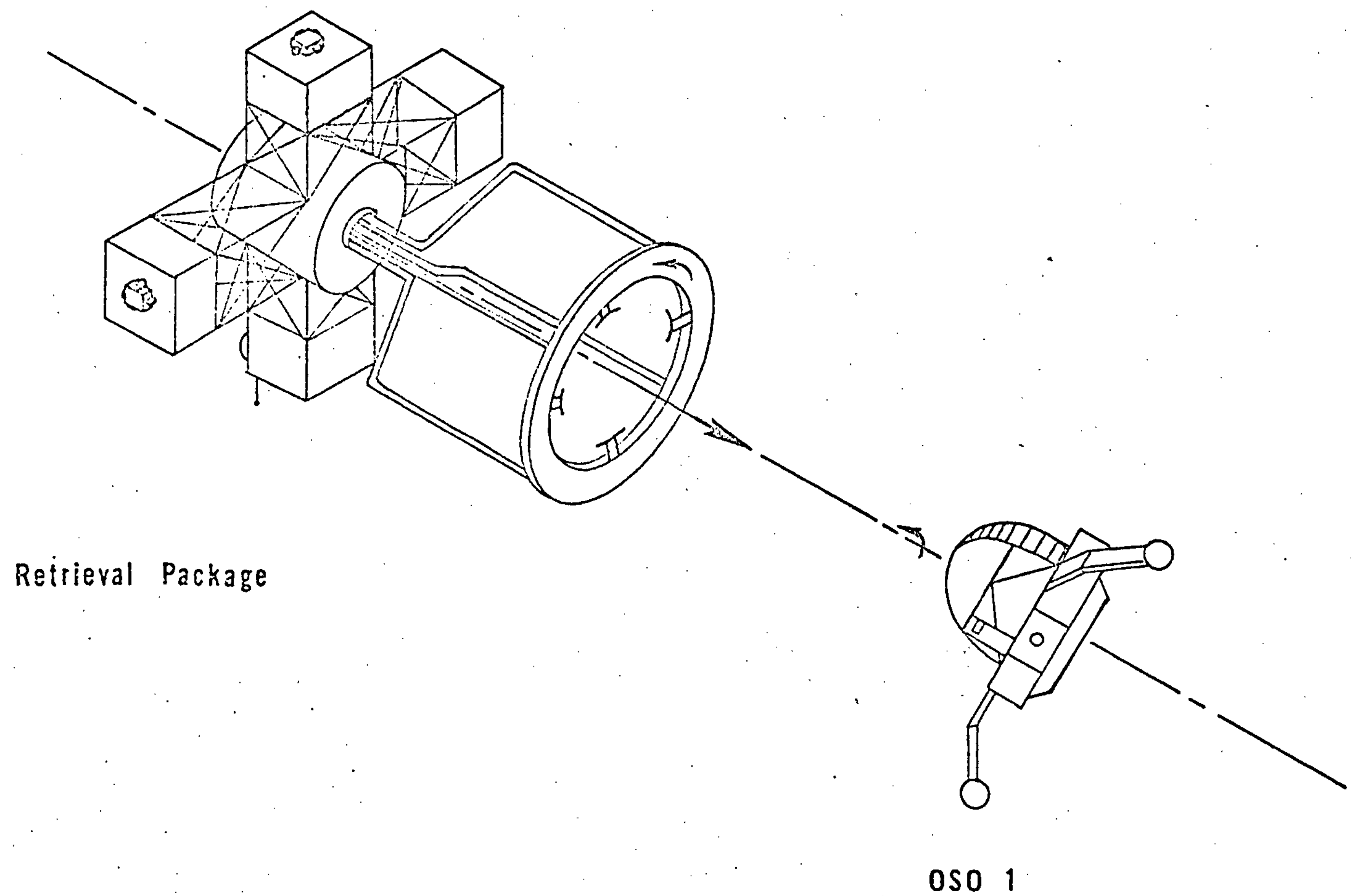


Figure 2 Retrieval Package Aligned with Spin Axis of OSO 1

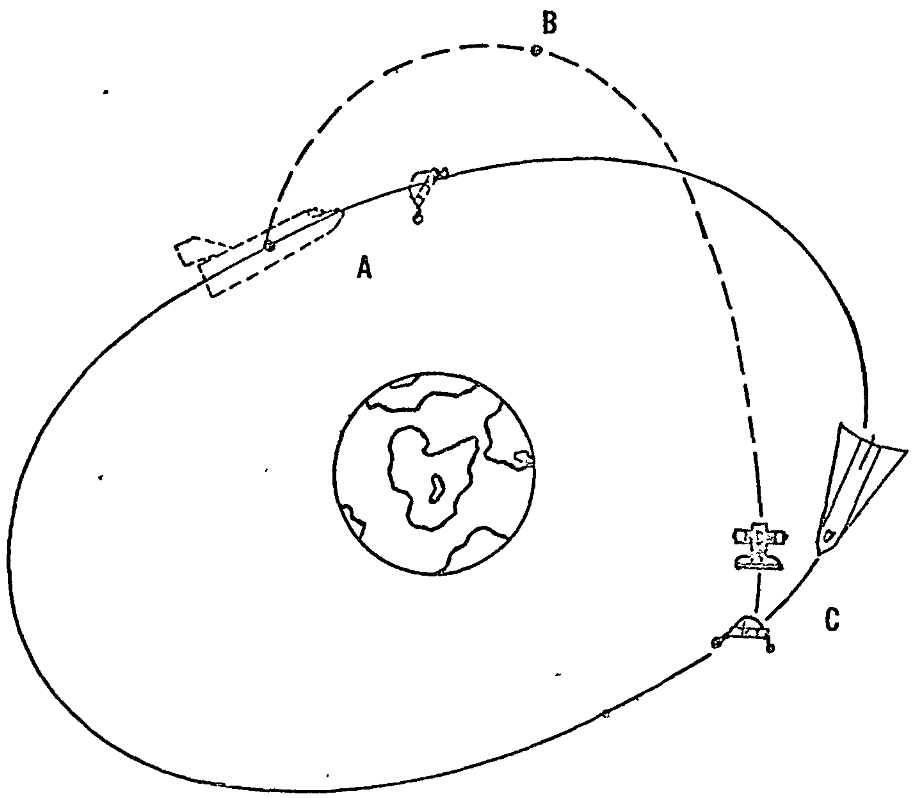
than half an orbital period. If the shuttle is maintained along the orbital path of the target, then initial and final transfer conditions on orbital energy and altitude are identical, but a change in orbital position relative to the object has taken place. A typical transfer sequence is illustrated in Figure 3. At point A the package leaves the orbital plane on a path corresponding to an orbit with a different period. A midcourse thrust at B is necessary to bring the package back to the original plane in less than half a period. The final impulse at C will stop the package, and terminal capture procedures may then commence.

Actual attachment to and despin of the object is carried out by a ring which is aligned with the object spin axis. This ring is spun up to the same angular speed as the target, while the main body of the despin package remains 3-axis oriented in an inertial frame as shown in Figure 2. After the ring is synchronized through the use of an axially mounted television camera, the entire spacecraft is translated along its axis until the ring-plane reaches a position near the center of mass of the object. At that point attachment arms are extended from the ring toward its center. Once the target is secured by these arms, despin is executed while momentum is dumped via attitude jets on the main body of the package. A docking device on this inertially oriented body allows the shuttle to rendezvous and recapture the package with object in hand, and stow it in the cargo bay for return or repair.

Deployment of payloads which are to be spin stablized can be performed in a similar manner. The retrieval package would extract this payload from the cargo bay, maneuver to a safe position, spin it up, and release it. The shuttle could stand by to check system operation before continuing with the mission.

4. Retrieval Package

The problem of despinning an uncooperative object has been cited as one of primary interest in this study. The decision to propose a separate device for this operation is the result of safety and performance considerations with respect to the shuttle. With a despin package maneuvering about the object at a "safe" distance away from a manned vehicle, the risk of bodily harm from a mishap is minimized. Crewmen on the shuttle can maneuver



Impulse sequence:

A — Initial impulse geometry

B — Midcourse correction

C — Terminal impulse geometry

Figure 3 Typical Three Impulse Transfer Geometry for Retrieval Package a small spacecraft with great ease, especially when aligning the package with the target spin axis.

The despin package is conceived to consist of two major components; tender and despin ring. The tender provides all functions required for orbital transfer and alignment with the target, while the despin ring performs the actual capture of the object. A configuration based on constraints and mission objectives were formulated. The complete spacecraft is illustrated in Figure 2, with tender and despin ring shown in greater detail in Figure 4. Overall size of the despin package is limited by the shuttle cargo bay dimensions, proposed to be 15 feet (4.6 m) in diameter and 60 feet (18.3 m) long. This restricts the ring size and, in turn, limits the size of objects which can be considered for retrieval. The tender is configured to allow maximum applied torque from the reaction control system while permitting large values of inertia about the ring axis. These innovations will minimize propellant requirements and effects of disturbances associated with the despin sequence. Thus, the major dimensions of this main body were selected as 14 x 14 x 8 feet (4.3 x 4.3 x 2.4 m). Compartments in the four arms contain the power system, monopropellant reaction control equipment, and command and telemetry system. The central cylinder houses the ring spin motor, twin-gyro controllers for the attitude control system, a reserve propellant tank, and shuttle docking drogue. The despin ring as conceived here has an inner diameter of 13 feet (3.9 m) and an outer diameter of 14 feet (4.3 m). The four docking arms are assumed to extend inward another foot (0.3 m) when in the retracted position. These arms are independently operated to permit capture of arbitrarily shaped objects and can each extend to 6 feet (1.8 m) in length. Therefore, objects as small as one foot (0.3 m) and as large as 11 feet (3.3 m) in diameter can be handled by the same despin ring. Structural support of this ring is provided by four struts illustrated in Figures 2 and 4.

Attitude and orbit control systems, in conjunction with remote commands from the shuttle, provide maintenance of position and orientation during transfer and docking. Twin-gyro controllers were chosen for momentum exchange and monopropellant reaction jets for momentum dumping. Since the

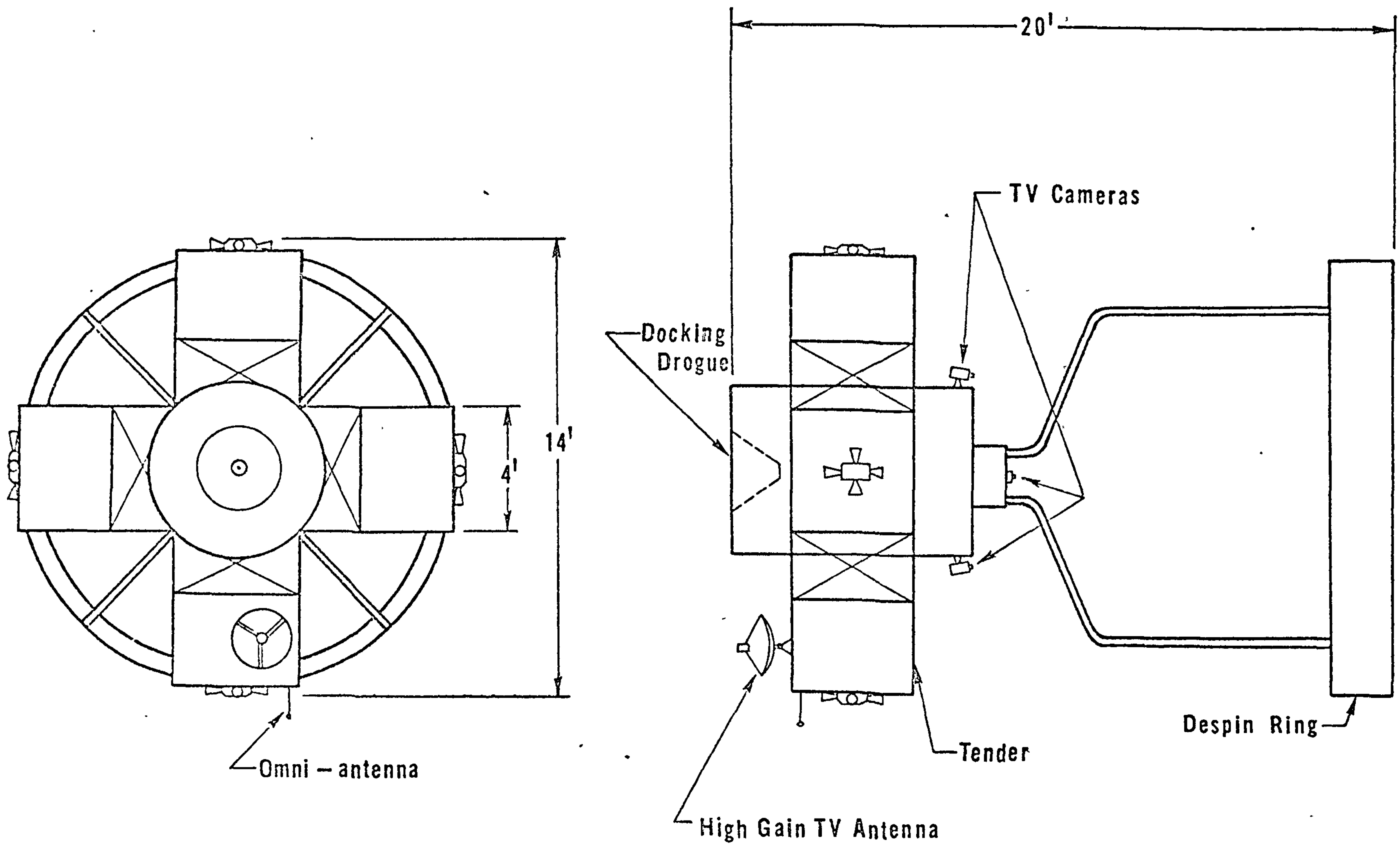


Figure 4 Details of Retrieval Package Configuration

tender is inertially oriented in the attitude maintenance mode there is no first-order cross-coupling. A momentum wheel could be used during ring spin-up and despin to conserve propellant. However, this would introduce more complexity into the system. Furthermore, the reaction jet tanks are easily refillable before each retrieval sequence. This reaction control system also provides thrust impulses for transfer to the target and aligns the package with the target spin axis under commands from the crew. Once the package is aligned, capture should be accomplished in a short period of time. Therefore, relative position drift is very slight during this time interval, and an automated position control system is not required.

The command and telemetry system incorporates television cameras and two antennas, an extendable omnidirectional type for the command and telemetry link, and a high gain directional dish for television transmission. The high gain dish imposes some constraint on the shuttle stand-off position in order to satisfy the viewing requirements for this antenna. One camera is mounted along the ring axis at the center of the support struts, and spins with the ring. This offers a very convenient means of synchronizing ring and target spin rates and provides a check on final alignment. Two other television cameras mounted diametrically opposed on the central cylinder are used for relative position maintenance through bifocal viewing of the target. These cameras will be focused at a given distance from the target which will permit rough alignment and stand-off parking simultaneously. When the angle between the spin axis and the center line of the despin ring is zero, the axes will be aligned. Slight spin desynchronization will cause an apparent rotation of the target about its actual spin axis with frequency equal to the difference between object and ring spin rates. This can be used to make fine adjustments for final synchronization. The despin sequence may then proceed.

The shuttle/package docking apparatus, shown in Figure 5, consists of a folding arm mechanism with probe, docking latches, and tender drogue. The folding arm extends a docking probe to a position which is easily observable by the pilot. The shuttle then maneuvers to the retrieval package, and upon completion of docking, it is deactivated and retracted into the cargo bay.

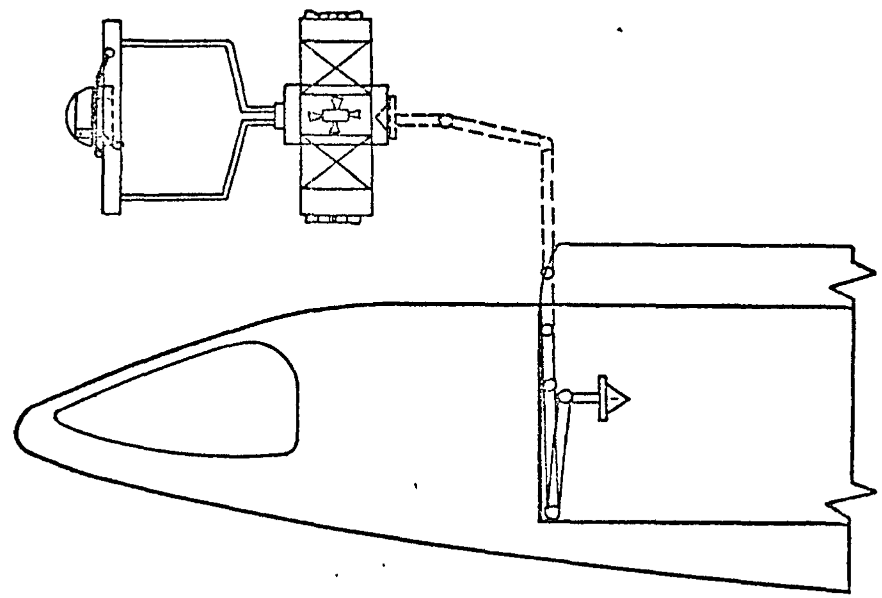


Figure 5 Shuttle/Retrieval Package Docking Arrangement

5. Relative Motion of a Passive Object During Retrieval

During terminal maneuvering and capture operations the retrieval package may perturb the steady spin of the target. The resultant motion must be anticipated in order to determine attitude control requirements of the package. Disturbance torques may result from the despin ring striking an appendage or one capture arm making contact before the others. Such a situation can be considered through the use of the Euler moment equations. As an example, consider the case of a symmetric or near symmetric target,[6]

$$\begin{aligned} A\dot{\omega}_1 &= \tau_1 \\ B\dot{\omega}_2 + \omega_1\omega_3(A-B) &= \tau_2 \\ B\dot{\omega}_3 - \omega_1\omega_2(A-B) &= \tau_3 \end{aligned}$$

where A, B are the principal moments of inertia,

ω_1, ω_2, ω_3 are angular velocity components about the body principal axes,

and τ_1, τ_2, τ_3 are the disturbance torque components.

Solving for transverse accelerations yields

$$\dot{\omega}_2 = \frac{\tau_2}{B} - \omega_1\omega_3 \left(\frac{A-B}{B}\right)$$

$$\dot{\omega}_3 = \frac{\tau_3}{B} + \omega_1\omega_2 \left(\frac{A-B}{B}\right)$$

It is apparent that a disturbance about the axis of symmetry (1-axis) will change the spin rate without affecting spin axis orientation. Nevertheless, such a disturbance torque is highly unlikely since the ring would be synchronized with the target about this axis. There may, however, be disturbances about the transverse principal axes, which would result in simple harmonic oscillation of both ω_2 and ω_3 corresponding to steady precession. The frequency of oscillation would be $(A-B)\omega_1/2\pi B$. Amplitude of motion is proportional to the ratio of disturbance impulse to transverse moment of inertia, i.e., $\int \tau dt / B$. Thus, an observer on the ring spinning at a rate of

ω_1 would see only ω_2 and ω_3 components of angular velocity, i.e., target would appear to wobble without spin.

Disturbances resulting from docking maneuvers are considered to be small and their effects can be handled by a combination of capture arm mechanisms and the retrieval package attitude control system. Furthermore, such disturbing torques can be minimized by observing three procedural suggestions: (1) make axis alignment as accurate as possible, (2) close with target at a very low rate, and (3) capture target about its center of mass, if possible.

6. Attitude Control of the Retrieval Package

In order to determine the feasibility of using a remotely controlled retrieval package for docking with spinning objects, an attitude control system should be synthesized and responses associated with the maneuvers obtained. Twin-gyro controllers were chosen as the momentum exchange devices appropriate for this spacecraft.[7] Selection was based on their inherent advantages, including first-order decoupling and large operational range of gimbal angles. The uncoupled equations of motion for a twin-gyro controlled spacecraft assuming small gimbal angles, δ_x, δ_y, δ_z, are[8]

$$I_x\dot{p} = -2C_z\Omega_z\dot{\delta}_z + L_x$$

$$I_y\dot{q} = -2C_x\Omega_x\dot{\delta}_x + L_y$$

$$I_z\dot{r} = -2C_y\Omega_y\dot{\delta}_y + L_z$$

where I_x, I_y, I_z are the vehicle principal moments of inertia,

p, q, r are the corresponding angular velocity components,

C_x, C_y, C_z and Ω_x, Ω_y, Ω_z are the axial moments of inertia and angular velocities, respectively, of the gyros associated with the three torque units,

and L_x, L_y, L_z are the disturbance torque components. Thus, the x-axis is controlled by the z-gyrotorquer etc. Use of identical gyros on all axes permits further simplification,

$$C = C_x = C_y = C_z$$

$$\Omega = \Omega_x = \Omega_y = \Omega_z.$$

Control equations now differ only in vehicle moments of inertia and disturbance torque components. Thus, the three control systems for the x, y, and z axes are identical except for the system gains which vary with moments of inertia.

Consider the roll (or ring) axis controller, taken as the z-axis here. The rate of change of the gimbal angle δ_y is given by the characteristic equation of a twin-gyro device,[8]

$$2(I_a + A_g)\ddot{\delta}_y + K_f\dot{\delta}_y + K_c K_g \delta_y = - K_c K_B \frac{r_E}{s} + 2C\Omega r$$

where r_E is the roll rate error,

I_a is the sum of transverse gimbal and gearing moments of inertia,

A_g is the transverse rotor moment of inertia,

K_f, K_c are torque-speed and torque-voltage constants, respectively,

and K_g, K_B are input gains of gimbal angle and roll rate error, respectively. Combining this with the roll equation of motion yields the basic control system block diagram given in Ref. 8. The uncompensated system transfer functions are:

(a) Command:

$$\frac{r(s)}{r_c(s)} = \frac{K_o \omega_c^2}{s^3 + 2\xi_c \omega_c s^2 + \omega_c^2 s + K_o \omega_c^2}$$

(b) Disturbance:

$$\frac{r(s)}{L_z(s)} = \frac{s^2 + 2\xi_c \omega_c s + \omega_c^2}{I_z s(s^2 + 2\xi_c \omega_c s + \omega_c^2) + K_o I_z \omega_c^2}$$

(c) Error:

$$\frac{r_E(s)}{r_c(s)} = \frac{s^3 + 2\xi_c \omega_c s^2 + \omega_c^2 s}{s^3 + 2\xi_c \omega_c s^2 + \omega_c^2 s + K_o \omega_c^2}$$

where

$$K_o = \frac{2C\Omega K_B K_c}{4C^2\Omega^2 + I_z K_c K_g}$$

$$\omega_c^{\,2} = \frac{4C^2\Omega^2 + I_z K_c K_g}{2I_z(I_a+A_g)}$$

$$\xi_c = \frac{K_f}{4\omega_c(I_a+A_g)} .$$

With the aid of the final value theorem, steady state response relations are immediately available. All responses to an impulsive input are zero. For a unit step input

$$\left.\frac{r}{r_c}\right|_{ss} = 1.0$$

$$\left.\frac{r}{L_z}\right|_{ss} = \frac{1}{I_z K_o}$$

$$\left.\frac{r_E}{r_c}\right|_{ss} = 0$$

Thus, it is desirable to have system gain K_o as large as possible. The transient response and system stability can be obtained by root locus methods once the values of constants are determined. Some form of compensation may be required to obtain a desirable combination of damping, response time, and steady state values. Furthermore, the spinning ring has a stiffening effect on the control system and must be included in a detailed system synthesis as a momentum device.

7. Despin Ring Control System

Synthesis of a spin control system to maintain synchronization of the despin ring and the target vehicle is considered here. The ring is physically constrained such that motion is possible only about the major principal axis of the package, so the single equation of motion is

$$J_z \dot{\rho} = f_z + L_z$$

where J_z is the ring moment of inertia about the roll axis,

ρ is the angular velocity or spin rate of the ring,

and f_z, L_z are control and disturbance torques about the z-axis, respectively. The control torque is provided by the spin motor and can be expressed as

$$f_z = K_c V_m$$

where K_c is a torque-voltage constant,
and V_m is the input signal to the motor.
Input voltage is proportional to the command spin rate and the spin rate error, i.e.,

$$V_m = K_s \rho_c + K_p \rho_E$$

where $\rho_E = \rho_c - \rho,$

and ρ_c is the commanded spin rate.

The equation of motion in Laplace form then becomes

$$sJ_z \Gamma(s) = K_c K_s \Gamma_c(s) + K_p K_c \Gamma_E(s) + L_z(s).$$

This leads to the control system block diagram shown in Figure 6. Closed-loop transfer functions can be obtained easily;

(a) Command:

$$\frac{\Gamma}{\Gamma_c} = \frac{K_c K_p}{J_z s + K_c K_p}$$

(b) Disturbance:

$$\frac{\Gamma}{L_z} = \frac{1.0}{J_z s + K_c K_p}$$

(c) Error:

$$\frac{\Gamma_E}{\Gamma_c} = \frac{J_z s}{J_z s + K_c K_p}$$

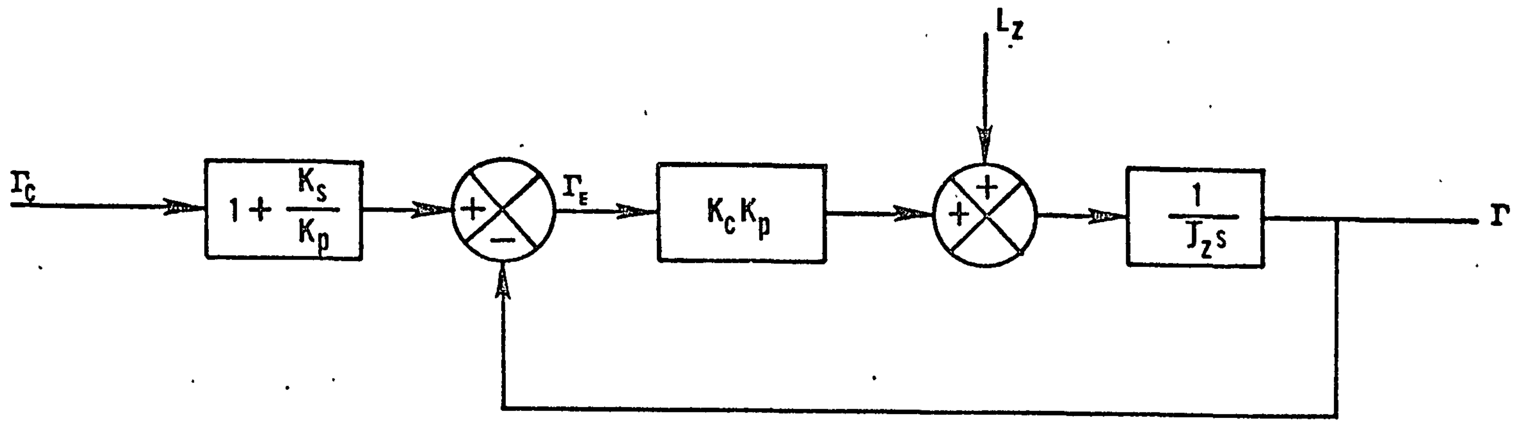


Figure 6 Despin Ring Control System

Steady state responses to unit impulse and step inputs are obtained directly. Response to an impulse is zero in all three cases. A unit step causes the following steady state situation:

$$\left.\frac{\Gamma}{\Gamma_c}\right|_{ss} = 1.0$$

$$\left.\frac{\Gamma}{L_z}\right|_{ss} = \frac{1}{K_c K_p}$$

$$\left.\frac{\Gamma_E}{I_c}\right|_{ss} = 0$$

This indicates that it is desirable to have K_c and K_p as large as possible in order to minimize the disturbance effects.

A root-locus analysis shows that this system is stable for all positive values of $K_c K_p / J_z$. Since this is a first-order system, it has an exponential transient response. Compensation may be required to achieve desired system characteristics.

8. The Tumbling Space Base

In the operation of manned orbiting vehicles there is always the small, but finite, probability that an accident will occur which renders the vehicle disabled. Therefore, an emergency must be anticipated in which evacuation of personnel is required. In general, such space missions may be divided into three phases:[9] rescue alert and rendezvous with the disabled vehicle, rescue operations proper, and return of the rescue vehicle. The second phase is of primary concern here, since a major part of the operation may very well involve detumbling of the uncontrolled spacecraft before escape of the occupants or repair of the control system. Tumbling is the general result of a significant attitude perturbation to an uncontrolled vehicle. This situation is coupled with continuous angular motion of all three principal body axes, i.e., no inertially oriented axis. Of course, a tumbling body would reach a stable spin state after a sufficient amount of energy has been dissipated. However, large bodies such as space stations have relatively low dissipation rates and may require many weeks or months to passively stabilize.

Astronauts trapped in a tumbling spacecraft could not easily escape and may not even be able to move about inside due to the changing nature of accelerations. Therefore, rescue from such a situation represents a very difficult problem and one which could arise as the result of an explosion or collision. Either event would probably cause tumbling and possible loss of attitude control. Preliminary estimates indicate that residual spin rates of the order of 4 rpm may result.[10] It is apparent that spacecraft attitude motion would have to be arrested before rescue operations could be carried out. However, elimination of angular motion of a large tumbling body is complicated, because it must be done from a non-tumbling frame. A "detumbling package" could not move in such a way as to eliminate relative motion, because both the target and detumbling system cannot simultaneously possess the same center of mass location, principal moments of inertia, and angular momentum components.

Although techniques for controlling tumbling motion of a large vehicle have not yet been fully developed, a few promising ideas are worthy of identification. Techniques for reducing tumbling motion must involve either the activation of a momentum transfer device on the disabled vehicle or a tumbling-arrester system on the rescue craft.[10] Examples of momentum transfer devices include a yo-yo or rocket system appropriately located in anticipation of an emergency. Tumbling arrest from a rescue vehicle involves application of torque, even though hard docking does not seem feasible prior to stabilizing the distressed craft. The proper application of a fluid jet eminating from the rescue ship is one promising technique for applying detumbling torque. If spin or tumble can be reduced to a low value, hard docking or grappling may be attempted such that no further damage results.

9. Conclusions

A thorough understanding of the motion of orbiting bodies with angular momentum is essential before attacking the problems of docking with such passive objects. Solutions of these problems are becoming increasingly urgent as progress is made in establishing space bases and developing reusable boosters. Many of these problems have been identified and some solutions offered. Two major conclusions can be drawn:

(a) Spinning objects of moderate size can be retrieved from at least low orbits in a safe manner through the use of a remotely commanded vehicle operated in conjunction with the space shuttle.

(b) A situation in which a large manned space base is in an uncontrolled tumbling mode may result from a mishap or control failure. Rescue from such a vehicle is a very complex operational problem that must be solved to provide complete space rescue capability.

Of course, further efforts will be required to completely establish retrieval and rescue procedures, hardware requirements, and mission profiles. Results could significantly influence future space shuttle designs, operations, and applications.

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APPENDIX C

Attitude Dynamics and Control of an Apogee Motor Assembly with Paired Satellites*

by
Marshall H. Kaplan and Norman M. Beck, Jr.

Abstract

The Apogee Motor Assembly with Paired Satellites (AMAPS) technique takes advantage of a well-known instability of spinning bodies to deploy pairs of satellites into high circular orbits from either a low-orbiting space shuttle or a launch vehicle which performs the apogee transfer injection. A spinning semi-rigid body, free of applied torques and active controls, is stable only when rotating about its axis of maximum moment of inertia, because energy dissipates until a minimum energy state is reached. This principle has been widely used in the passive attitude control of earth satellites and has been disastrous to those who ignored it. In this application the instability associated with rotation about the minor principal axis is used to passively control spin axis reorientation of the payload assembly. An investigation of associated attitude dynamics and energy dissipation processes is reported here. Dissipation is simulated with viscous ring dampers. Approximate and numerical methods for predicting time of spin axis reorientation from minor to major principal axis are reviewed and examples presented.

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Attitude Dynamics and Control of an Apogee Motor Assembly with Paired Satellites

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Nomenclature

A, B, C	= Principal moments of inertia of the rigid body
D	= Diameter of ring cross-section
f	= Darcy-Wiesbach resistance coefficient
h_x, h_y, h_z	= Components of angular momentum about the body-fixed axes
I_x, I_y, I_z	= Moments of inertia of the fluid slug about the body-fixed axes
N_z	= Moment due to viscous shear in the annular ring
P	= Circumference of the ring cross-section
Q_α	= Generalized torque function
R	= Mean radius of the viscous ring
R_n	= Reynolds number = $RD\dot{\alpha}/\nu$
S	= Cross-sectional area of viscous ring
T	= Rotational kinetic energy
v	= Velocity of the fluid slug relative to the ring

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Index category: Spacecraft Attitude Dynamics and Control

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α, $\dot{\alpha}$	=	Angular position and velocity of fluid slug relative to the ring, respectively
β	=	Angular span of fluid slug in the ring
ν, ρ	=	Kinematic viscosity and density of damper fluid, respectively
τ_o	=	Shear stress
ϕ, θ, ψ	=	Euler angles
ω_o	=	Initial spin rate about Z-direction
ω_x, ω_y, ω_z	=	Components of angular velocity about the body-fixed axes

Introduction

A spinning semi-rigid body, free of applied torques and active controls is stable only when rotating about its axis of maximum moment of inertia. This phenomenon has been widely used advantageously for passive attitude control of earth satellites, but has proven disastrous to those who have ignored it.[1] Explorer I is a classic example of the consequences of such a neglect. After only a few hours into the flight of the first American satellite, radio signals indicated a tumbling motion had developed and was increasing in amplitude in an unstable manner. It was concluded that the four turnstile wire antennae were dissipating energy; thus, causing a transfer of body spin axis from the axis of minimum moment of inertia to a transverse axis.[2] The Apogee Motor Assembly with Paired Satellites (AMAPS) technique uses this instability to passively transform spin axis orientation during deployment of a pair of satellites into high circular orbits from either a low-orbiting space shuttle or a launch vehicle which performs the apogee transfer injection. The use of this technique with a surface-to-orbit shuttle system would eliminate the requirement for an orbit-to-orbit shuttle; thus, permitting the use of relatively simple deployment hardware. Active attitude control beyond apogee transfer injection is not required when the AMAPS scheme is used with a launch vehicle or shuttle. Furthermore, the requirement for built-in apogee kick motors as part of the satellites is eliminated.

Primary objectives of this study are to develop the AMAPS scheme and investigate methods for analytically determining spin axis transfer times for realistic satellite configurations. Energy dissipation is provided by a viscous ring damper mounted on the major axis. Solutions of attitude motion for large-angle reorientation of asymmetric spacecraft are not generally available and must be obtained with approximate or numerical methods. When the axis of maximum moment of inertia is oriented close to the angular momentum direction, linearization is possible and results are available in the literature for such cases.[3] Feasibility of the scheme is discussed and numerical examples are presented.

Operational Schemes

There are two basic configurations with which the AMAPS technique may be associated. When used with a launch vehicle no apogee transfer injection motor is required. Such a scheme is illustrated in Figure 1. Either the upper stage of the booster is spin stabilized, or a spin table is used to spin-up AMAPS about the YY-axis. Immediately after injection into a high altitude transfer orbit the payload attitude is changed so that the momentum vector is reoriented for later apogee firings, and then the release sequence is executed. Since the assembly is stable about its axis of maximum moment of inertia, energy dissipation would result in the transfer

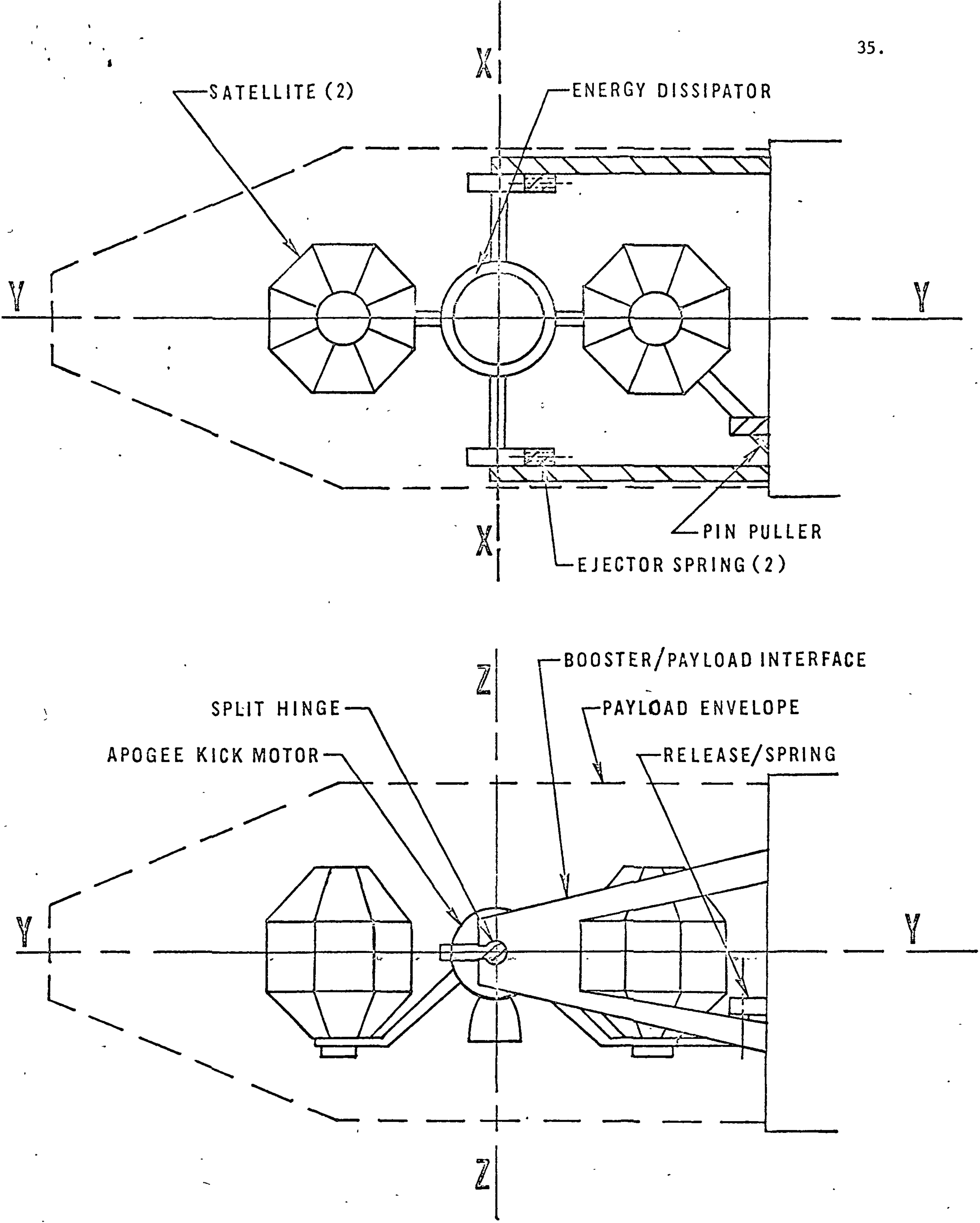


Figure 1. AMAPS Configuration for Launch Vehicle Applications

of spin to the axis of maximum moment of inertia while keeping the direction of the angular momentum vector fixed in inertial space. It is assumed that the ZZ-axis is the body axis of maximum momentum of inertia and YY is the axis of minimum moment of inertia. The ZZ-axis will tend to align itself with the angular momentum direction if the YY-axis is initially perturbed when separated from the launch vehicle, and the assembly has an energy absorber or nutation damper. Figure 1 shows how initial conditions can be achieved in order to start the transfer of the rotation axis as the assembly leaves the launch vehicle. Immediately after injection into apogee transfer by the upper stage, a pin puller device is fired. This allows a spring to start rotational motion about the XX-axis, which induces a perturbation, starting the transfer of rotation axes. When the split hinges line up with the axle flats, springs will push the assembly away from the upper stage, and the payload is then freely precessing. The axially mounted damper shown in Figure 1 will absorb energy in such a way as to transform spin axes. The rate of axis transfer for a given payload is a function of initial spin rate and the energy dissipator configuration. When the assembly has stabilized and is rotating only about the ZZ-axis, then this axis will be parallel to the originial YY-direction, and the assembly will be in the proper orientation for apogee firing. After apogee kick the two satellites can be separated and, if desired, spun-up simultaneously by converting angular momentum of the assembly to the satellites. Spin rate adjustments and positioning around the orbit can be done with individual satellite propulsion systems.

The other basic configuration useful with the AMAPS technique is associated with deployment from a low-orbiting space shuttle. This scheme is illustrated in Figure 2. The payload package consists of two satellites, an apogee kick motor, and an apogee transfer injection motor. This assembly

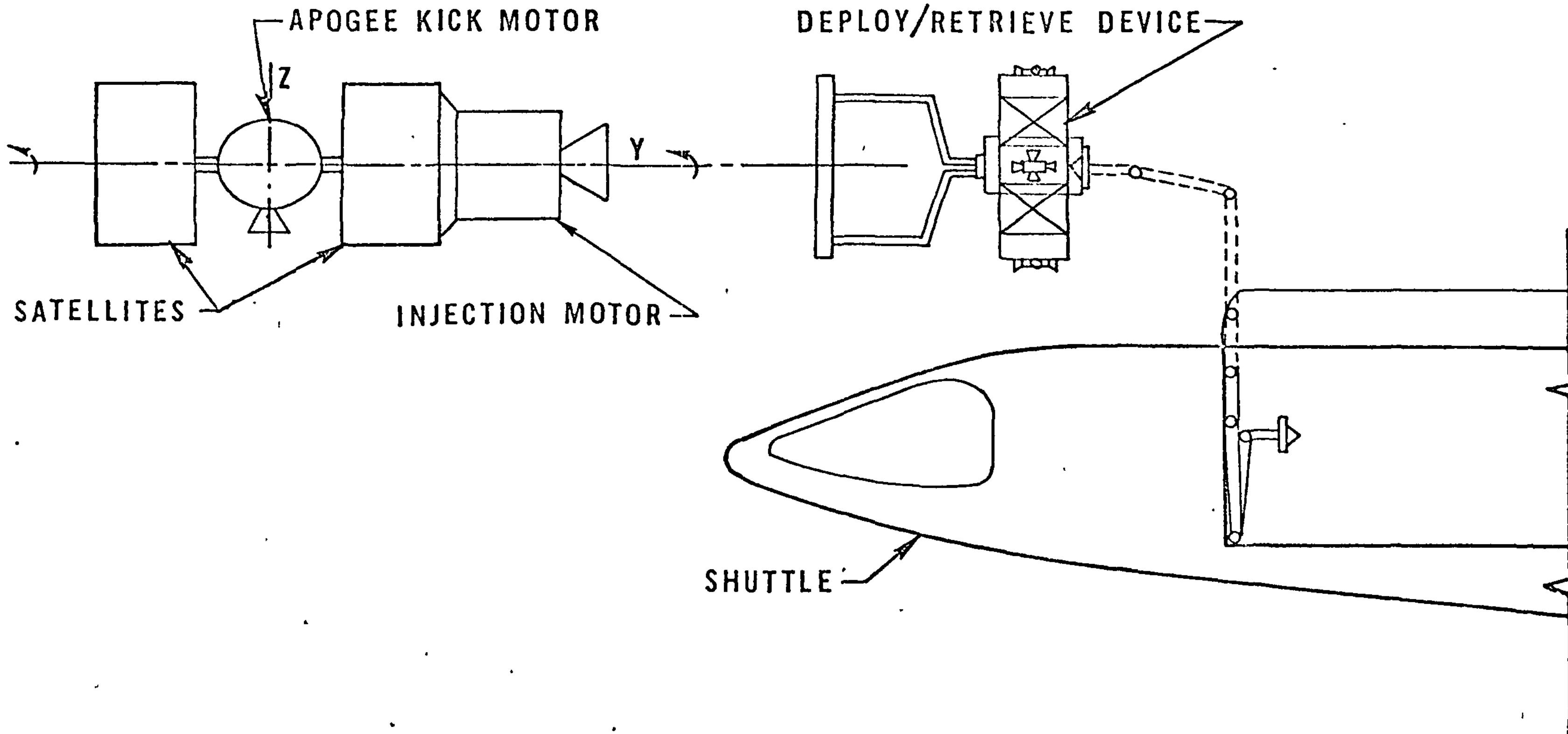
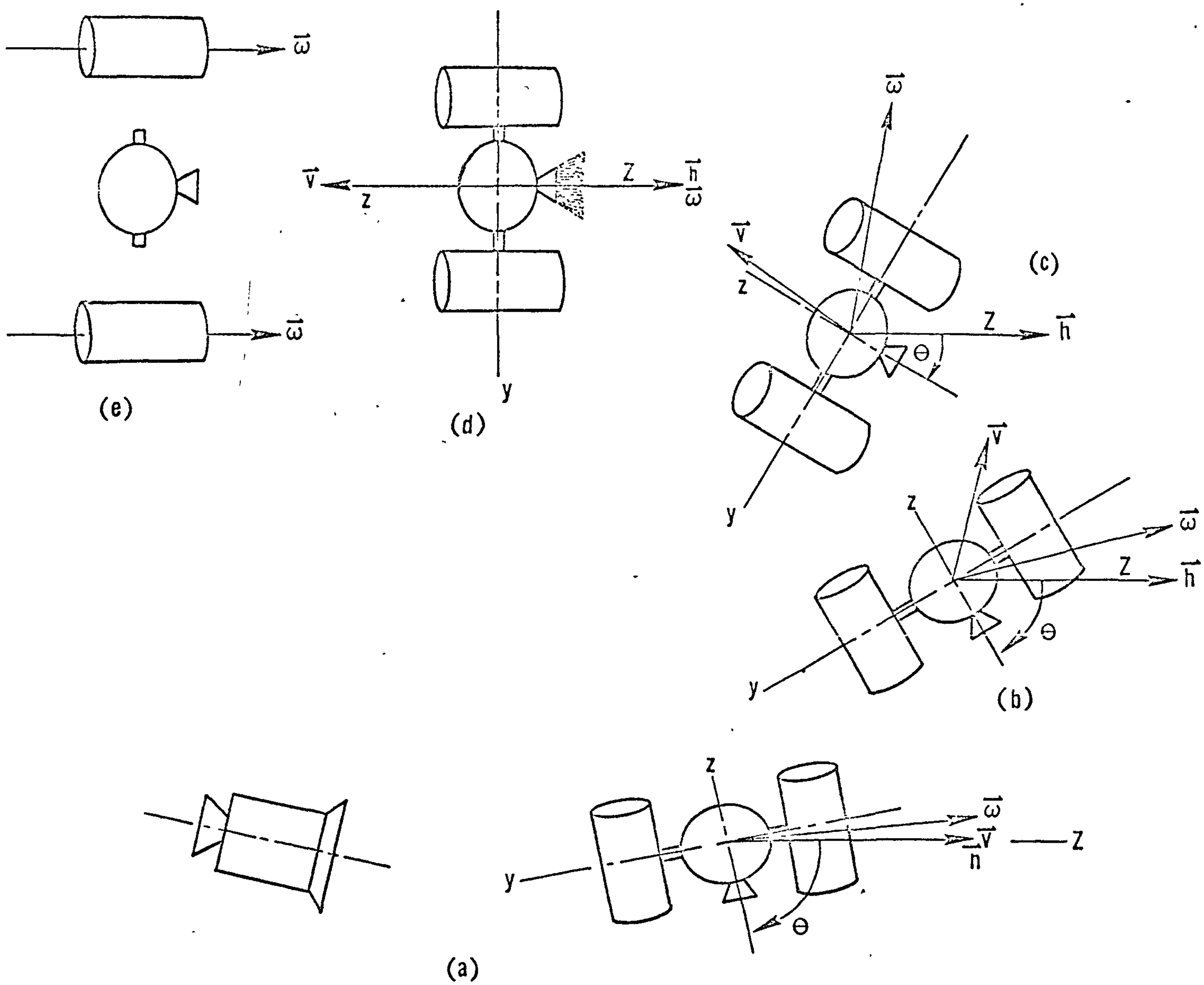


Figure 2 AMAPS Package Leaving Deploy/Retrieve Device

is deployed from the cargo bay and spun up about the Y-axis by a deploy/ retrieve device.[4] The payload package is then separated from this device, and the apogee transfer motor is fired shortly thereafter. This is followed by reorientation with the limited attitude control capability of the injection motor subsystem, and then payload separation and perturbation occur. The apogee transfer and axis transformation sequence is shown schemically in Figure 3.

Discussion of the Problem

The time of transfer of spin axes from the axis of minimum to maximum moment of inertia is a function of energy dissipation rate. This, in turn, depends on the orientation and magnitude of angular momentum for a given AMAPS configuration and absorber. The most accurate approach to determining this time is to simulate the free-body motion with energy dissipation over the time interval of interest. Since the axis transformation time should be less than or equal to the time of transfer to apogee (typically about 5 hours), this situation could be represented by a two point boundary value problem with fixed terminal time. However, the end conditions on orientation are satisfied naturally by the effects of dissipation. Thus, the motion can be conveniently treated as an initial value problem with an inequality constraint on axis transfer time, i.e., axis transfer time $\leq$ transfer to apogee time. Simulation of motion can be appropriately accomplished on a digital computer. However, the large number of iterations leads to practical limitations on the extent of quantitative results obtainable. Therefore, numerical simulations were carried to the point where feasibility of the scheme was satisfied.



Fgiure 3 Deployment Sequence for Shuttle Scheme

Previous research of primary interest to this study is that which is related to fluid loop damper performance. A comparison of viscous and inertial forces acting on the fluid slug will determine whether motion in the ring is laminar or turbulent. The small angle (perturbation of stable spin state) case corresponds to laminar flow, because this situation is associated with high viscous and low inertial forces along the tangential direction. Small angle theory permits the fluid to be modeled as a closed ring, illustrated in Figure 4. Energy is dissipated by cyclic forming and degeneration of surface waves. Fitzgibbon and Smith[3] have developed an energy dissipation function which accounts for this phenomenon. Furthermore, for large angle situations (significant deviation from stable spin about the axis of maximum moment of inertia) they conclude that turbulent flow must be assumed for θ greater than about 0.2 radians. Under these conditions the fluid forms a slug, also illustrated in Figure 4. Motion of the slug with respect to the ring causes energy dissipation through shear stress acting on the wall of the tube, as in elementary pipe flow

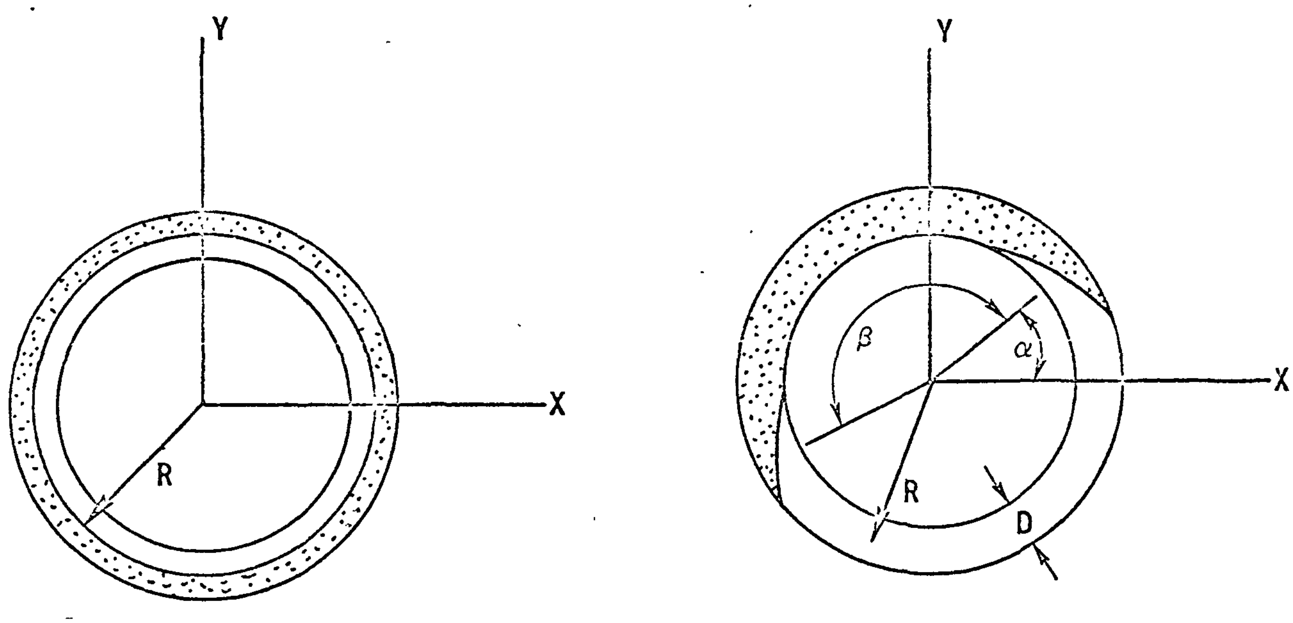
$$\tau_o = \frac{f}{4}\frac{\rho v^2}{2}$$

End effects are of negligible significance. However, the diameter of the cross section is restricted to be small compared with the ring radius in order to simplify integration of the shear stress over the wetted area of the ring. The retarding torque about the ring axis of symmetry becomes

$$N_z = -\tau_o(R^2 P \beta)$$

Therefore, the energy-dissipation rate is

$$\dot{T} = N_z \dot{\alpha} = -\tau_o R^2 P \beta \dot{\alpha}$$



(a) Small angle situation

(b) Large angle situation

Figure 4 Fluid Configurations of Interest

For turbulent flow ($2000 < R_n < 10^5$) in smooth round pipes, the resistance coefficient can be approximated by an empirical relation of Blasius.

$$f = \frac{.316}{R_n^{\frac{1}{4}}}$$

Thus, the energy dissipation rate becomes

$$\dot{T} = - \frac{.316\ \bar{\rho}\ P\ \beta\ R^4}{8\ R_n^{\frac{1}{4}}}\ \dot{\alpha}^3 = - 0.0395\ \frac{\rho\ P\ \beta\ R^{15/4}}{(D/\nu)^{\frac{1}{4}}}\ \dot{\alpha}^{11/4}$$

This analytical formulation yielded good correlation with experiment for a 12° deviation of θ and was used for all values above 10°. As θ is reduced below 10° and approaches approximately 5°, neither large nor small angle theory holds. A realistic model of the fluid in this transition phase is not yet available, because the fluid exhibits both laminar and turbulent properties over varying transition periods. To insure validity of large angle theory, it should be applied only for $\theta \geq 10°$.

A great deal of insight into the problem can be gained by summarizing available and experimental results related to spin axis reorientation. Consider a typical AMAPS configuration with initial spin about its minor axis and θ perturbed away from 90°. The rate of energy dissipation is very low for a considerable period of time, because the average fluid slug velocity is low. As θ decreases below about 75°, this velocity increases on the average; thus, increasing the energy loss rate and further promoting transition of spin axes. In fact, the mean value of θ is a parabolic function of time for large values. The transition processes, as depicted in Figure 5, can be modeled by large angle theory down to about θ = 10°. Below about 5° small angle theory can be applied. Here an exponential decay is caused by

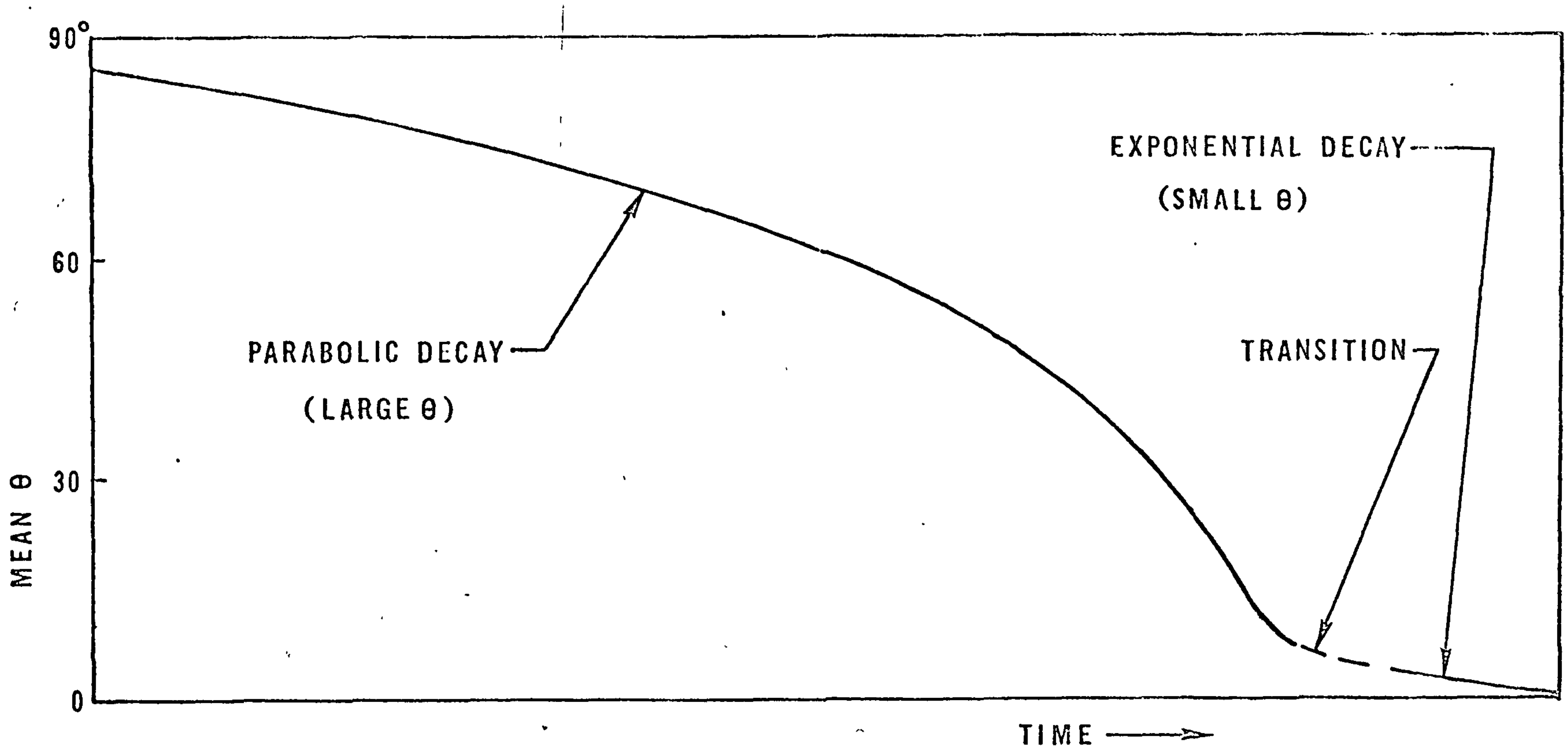


Figure 5. Axis Transformation Phases

the fluid loop. However, this period of time is shortened by added dissipation from vehicle flexibility and liquid sloshing in propellant tanks. Thus, the major portion of time for spin axis transformation is required to reduce the mean value of θ to about 10°.

Analytical Development

Solution of the equations of motion for a rigid body are readily available in the literature. Incorporation of a fluid loop damper about an initially transverse axis of an asymmetric body represents a situation not previously treated analytically with accurate simulation of dynamics. Thus, the equations of motion must be formulated to account for energy dissipation through a viscous mechanism and solved numerically for large values of θ. There are several distinct methods offered in the literature for developing these equations. They include the energy-sink method,[5] discrete parameter model method, and modal model method.[6] The first, as the name infers, assumes dissipation by friction or viscous effects. It is perhaps the easiest to apply but requires approximations that sometimes cannot be rigorously justified and may produce erroneous results. The discrete parameter method employs rigorous forms of the equations of motion which are generally integrated by numerical methods. The modal model method is the most complex of the three. Of these methods the first and second were considered to be suitable for this study, and both are discussed below. However, the discrete parameter method was used in obtaining numerical results in order to insure accuracy and because this technique has proven useful with nutation dampers.[7]

The viscous ring dissipator was chosen because it has no moving mechanical parts, as do pendulum dampers or spring-mass-dashpot systems. Furthermore, such devices have been flight tested for spin axis reorientation with the WRESAT spacecraft.[8] The formulation of dynamics must account for this dissipation mechanism while maintaining constant angular momentum of the system. The following developments satisfy this condition.

Figure 6 shows the set of generalized coordinates used here: ϕ, θ, and ψ. Also, X, Y, Z and x, y, z are initial and body-fixed coordinates, respectively. Note $\dot{\phi}$ is the precession rate and the net value of $\dot{\theta}$ is the induced nutation rate due to dissipation. General assumptions made in the analysis are:

(1) The body is assumed rigid so that energy dissipation due to flexibility is neglected.

(2) The products of inertia of the fluid slug about axes parallel to the body principal axes are small relative to body moments of inertia and their effects can be neglected.

For the energy sink method, the body is assumed to be in force-free motion. During each revolution of ψ a certain amount of energy is lost due to viscous dissipation. This is easily modeled through conservation of angular momentum, i.e., the inertial components of this vector must be constant. This is satisfied for AMAPS when $h_X = h_Y = 0$, and $h_Z = C\ \omega_O$. Very restrictive assumptions must also be made on the relative motion between the fluid slug and ring. For example, Fitzgibbon and Smith[3] assumed $\dot{\alpha} = \dot{\psi}$. Results can be obtained by computing an average $\dot{\psi}$ during a cycle of ψ and obtain the corresponding loss of energy during the interval of that cycle. A plot of $\dot{T}$ vs θ can be obtained, and numerical integration used to generate approximate curves of θ vs t for various situations. However, the validity of assuming $\dot{\alpha} = \dot{\psi}$ is questionable.

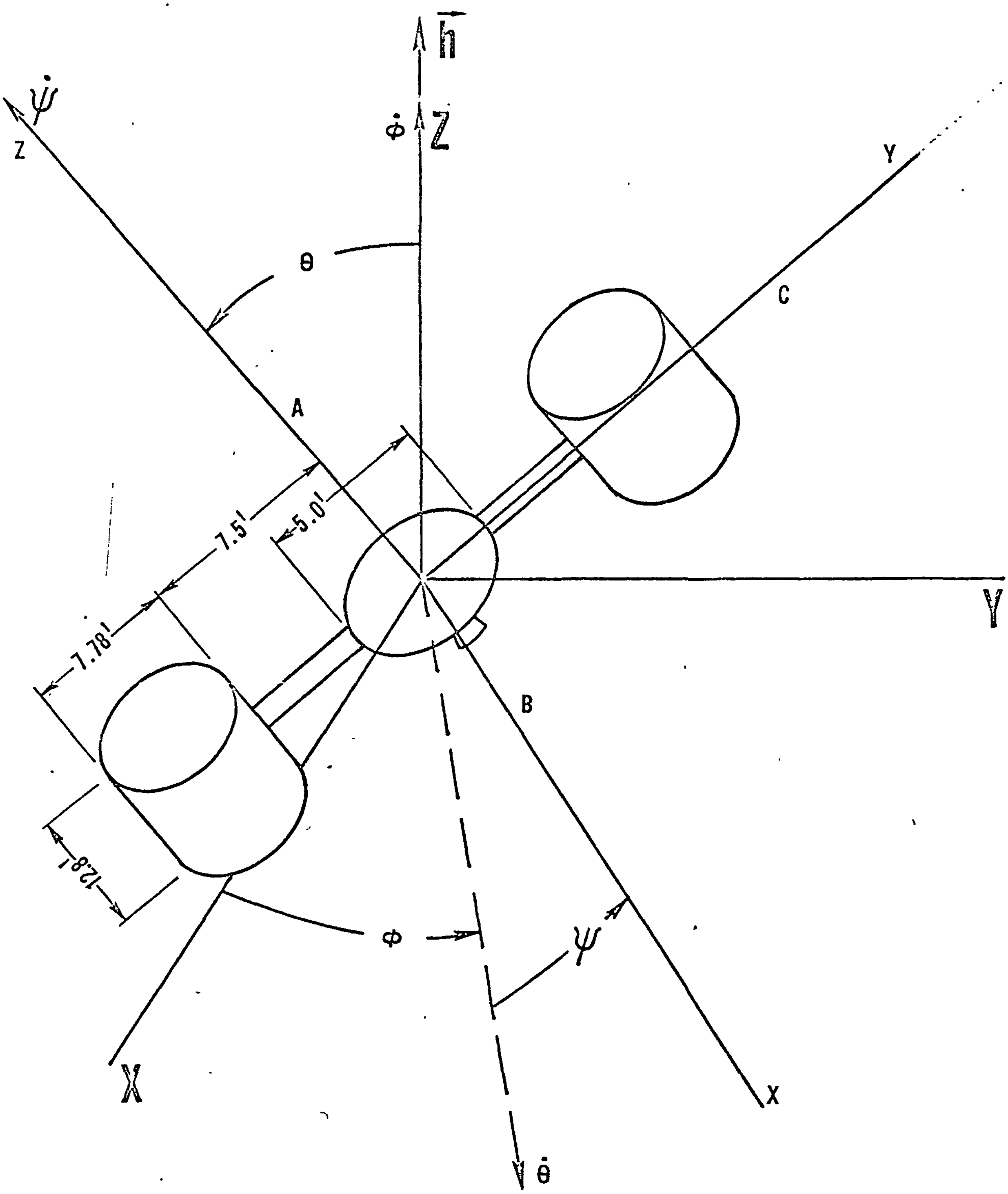


Figure 6. Coordinate System and Numerical Model

The discrete parameter model method uses the rigid body equations of motion to satisfy conservation of angular momentum. These are quickly expressible in the Euler form for principal axes.[9]

$$\dot{h}_x + \omega_y h_z - \omega_z h_y = 0$$

$$\dot{h}_y + \omega_z h_x - \omega_x h_z = 0$$

$$\dot{h}_z + \omega_x h_y - \omega_y h_x = 0$$

Angular momentum components for the complete system are

$$h_x = (B + I_x)\,\omega_x$$

$$h_y = (C + I_y)\,\omega_y$$

$$h_z = A\omega_z + I_z\,(\omega_z + \dot{\alpha})$$

Note that the AMAPS configuration requires that $A > B > C$. Components of angular velocity can be expressed in terms of Euler angles by using standard transformations. To simulate energy dissipation, the fluid slug is modeled separately and as through acted upon by an outside viscous force. Thus, a generalized torque function Q_α can be introduced, and motion of this fluid body relative to the ring can be derived from a Lagrangian formulation,[10] as though it were a rigid body,

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\alpha}}\right) - \frac{\partial T}{\partial \alpha} = Q_\alpha$$

Since Q_α is the retarding torque resulting from viscous shear, it must satisfy $Q_\alpha = N_z$.

This technique could accommodate several such energy absorbers. However, only one annular ring is assumed here. This device is mounted about the body z-axis with its center at the center of mass of the assembly. The rotational kinetic energy of the fluid slug in terms of Euler angles and rates is

$$T = \frac{I_x}{2} (\dot\phi \sin\theta \sin\psi + \dot\theta \cos\psi)^2 + \frac{I_y}{2} (\dot\phi \sin\theta \cos\psi - \dot\theta \sin\psi)^2 +$$

$$\frac{I_z}{2} (\dot\psi + \dot\alpha + \dot\phi \cos\theta)^2$$

Moments of inertia for the fluid slug were taken as

$$I_x = \frac{\rho S\ R^3}{4} [2\beta - \sin 2(\alpha + \beta) + \sin 2\ \alpha]$$

$$I_y = \frac{\rho S\ R^3}{4} [2\beta + \sin 2(\alpha + \beta) - \sin 2\ \alpha]$$

$$I_z = \rho S \beta R^3$$

The equations of motion for a rigid body with viscous energy dissipation become

$$(B + I_x)\ (\ddot\phi \sin\theta \sin\psi + \dot\phi\ \dot\theta \cos\theta \sin\psi + \dot\phi\ \dot\psi \sin\theta \cos\psi$$

$$+ \ddot\theta \cos\psi - \dot\theta\ \dot\psi \sin\psi) + \omega_x\ \dot I_x + \omega_y\ \omega_z\ A$$

$$+ \omega_y\ I_z\ (\omega_z + \dot\alpha) - \omega_z \omega_y\ (C + I_y) = 0$$

$$(C + I_y)\ (\ddot\phi \sin\theta \cos\psi + \dot\phi\dot\theta \cos\theta \cos\psi - \dot\theta\dot\psi \sin\theta \sin\psi$$

$$- \ddot\theta \sin\psi - \dot\theta\dot\psi \cos\psi) + \omega_y\ \dot I_y + \omega_z\ \omega_x\ (B + I_x)$$

$$- \omega_x\ \omega_z\ A - \omega_x\ I_z\ (\omega_z + \dot\alpha) = 0$$

$$A(\ddot{\psi} + \ddot{\phi}\cos\theta - \dot{\phi}\dot{\theta}\sin\theta) + I_z(\ddot{\psi} + \ddot{\phi}\cos\theta - \dot{\phi}\dot{\theta}\sin\theta + \ddot{\alpha})$$

$$+ \omega_x \omega_y (C + I_y) - \omega_y \omega_x (B + I_x) = 0$$

$$I_z(\ddot{\psi} + \ddot{\alpha} + \ddot{\phi}\cos\theta - \dot{\phi}\dot{\theta}\sin\theta) - \frac{\omega_x^2}{2}\frac{\partial I_x}{\partial \alpha} - \frac{\omega_y^2}{2}\frac{\partial I_y}{\partial \alpha} + \frac{0.316\,\rho\,P\,\beta\,R^{15/4}}{8(D/\nu)^{\frac{1}{4}}}\dot{\alpha}^{7/4} = 0$$

The first three equations guarantee conservation of angular momentum while the last one supplies energy dissipation. This method provides greater accuracy, because relative fluid slug motion is not restrictive as in the energy sink formulation.

Discussion of Simulation Results

The discrete parameter model formulation presented above was applied to a numerical example. Integration was carried out for specified accuracy until error accumulation exceeded bound values. The large number of integration steps required to accurately simulate rotational motion severely limits the length of real-time motion simulation. However, results for short-time simulations indicate validity of this modeling method and provide a basis for determining whether or not axis transformation will be completed in the apogee transfer interval.

The large number of physical and dynamic parameters force a limitation on variations of these quantities for meaningful simulations. Consider an assembly consisting of two cylindrical satellites similar in shape and size to Intelsat IV and an ellipsoidal apogee kick motor, as shown in Figure 6. The principal moments of inertia of the assembly are taken as,

$$A = 6{,}920 \text{ lb-ft-sec}^2$$
$$B = 5{,}190 \text{ lb-ft-sec}^2$$
$$C = 1{,}785 \text{ lb-ft-sec}^2$$

For the cases studied, mercury was selected for the viscous fluid, although other fluids can also be used, e.g., silicone. The pertinent physical properties of mercury are

$$\rho = 1.27 \times 10^{-3} \text{ lb-sec}^2/\text{in}^4$$
$$\nu = 1.8 \times 10^{-4} \text{ in}^2/\text{sec}$$

The radius of the fluid loop was limited by several restrictions. In order to guarantee significant damping, R must be at least 3 feet. However, to neglect the products of inertia of the fluid slug when considering the dynamics of the rigid body, R was restricted to a maximum of 4.35 feet. For the cases studied R was taken as 3.26 and 4.35 feet and other parameters were varied for given R. Furthermore, in the analysis of viscous energy dissipation, straight pipe flow was assumed. This leads to the restriction that the cross-sectional radius of the ring must not be greater than 3 percent of the ring radius. In all cases studied the cross-sectional radius was held at 3 percent for maximum damping.

Two different enclosed angles of the fluid slug were considered, β = 1.0 radian and β = 5.0 radians. There was, of course, no limit on initial spin rate. However, as ω_o was increased, real-time simulation was decreased due to associated increases in all other dynamic parameters. This then led to earlier breakdown in accuracy limitations for the simulation. Thus, ω_o was restricted to a maximum of 60 rad/min. Assuming the configuration to be restricted as outlined, parameters which effect energy dissipation and the mean value of the nutation angle θ, were varied as listed in Table 1.

Table 1

Case variation of simulation parameters

Case	ω_o (rad/min)	R (ft)	β (rad)
A	7.5	3.26	5.0
B	7.5	3.26	1.0
C	5.5	3.26	1.0
D	9.5	4.35	5.0
E	7.5	4.35	5.0
F	20.0	3.26	5.0
G	40.0	3.26	5.0
H	60.0	3.26	5.0
I	20.0	4.35	5.0
J	40.0	4.35	5.0
K	60.0	4.35	5.0

The rate of kinetic energy dissipation is of primary importance. Figure 7 offers curves of energy vs time for two values of ω_o at $\beta = 1.0$ rad. Computations were obtained for 80 minutes of real time for cases B and C. By comparison case B, with greater initial spin, has greater dissipation and loss rate than case C. However, greater initial spin implies more energy must be dissipated. The parameter of interest is the percent of energy dissipated of the total energy to be dissipated in given time. Case B dissipated approximately 32 percent of the

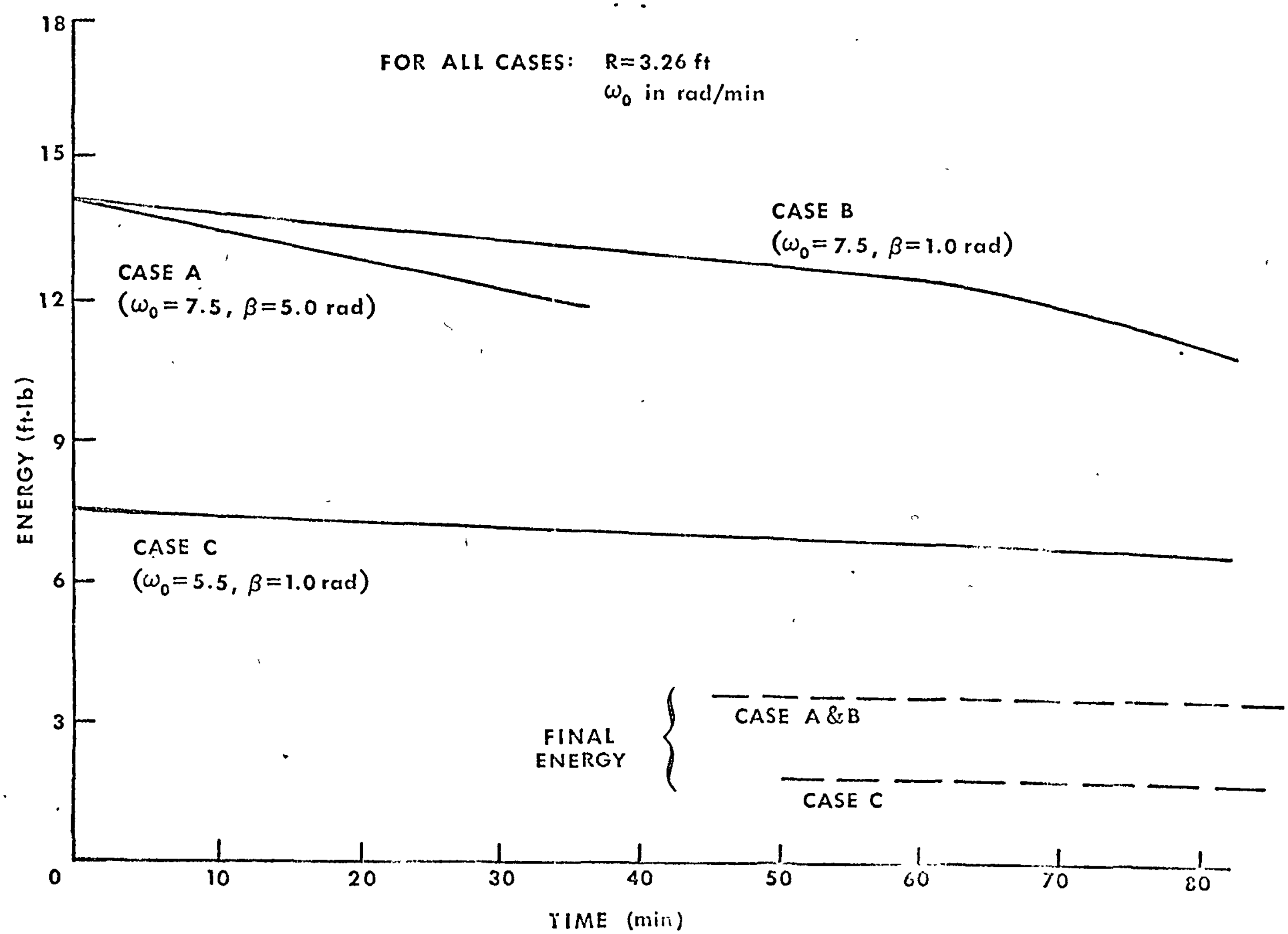


Figure 7. Energy Dissipation Profiles

total energy to be lost while case C dissipated only 8 percent in the same 80 minutes. Case D and E yielded analogous results. Thus, a greater initial spin rate seems to result in faster axis transformation, even though there is more energy to be disspated. This greater rate of loss of kinetic energy for increased ω_0 can be attributed to the increase in dynamic rates. As spin rate increases the average relative velocity of the fluid slug with respect to the ring will also increase, thus, increasing energy dissipation.

The effect of varying the fluid slug size can be considered by comparing the curve of case A for $\beta = 5$ rad with that of case B of Figure 7. Case A has dissipated 13 percent of energy in 30 minutes and extrapolation to 82 minutes indicates it will dissipate about 35 percent. As expected, increasing β results in increased dissipation rates.

Cases F to K were simulated for an equivalent of 30 minutes for initial spin rates of 20, 40, and 60 rad/min. These verify the earlier results, i.e., the rate of energy dissipation increases for increasing initial spin rate. Table 2 shows the percent dissipation of kinetic energy for these six cases. An increase in R also increases the dissipation rate, because the fluid slug length is enlarged with constant β. As initial spin rate is increased, this simulation approaches correlation with Baines[8] for total time to stabilization. For the initial rate of 60 rad/min, a total projected stabilization time would be about 4.5 hours, as compared to 2.5 hours predicted by Baines.

Mean value of the nutation angle θ is illustrated qualitatively in Figure 5. However, due to asymmetry of the body θ is an oscillatory quantity. After initial perturbation it will oscillate with increasing amplitude for some time, because the angular velocity vector is "precessing" from minor to major axes. This unstable oscillation will reach a peak and the envelope of oscillation will slowly start to converge to its final state. Figure 8 shows the general form of the θ envelope with destabilizing and stabilizing modes defined. This form, confirmed by the simulations, points out a problem of major concern. At the peak value of θ, as the destabilizing mode ends, it is possible that the mean value of θ may converge to π, rather than 0. Although this "ambiguity" did not occur for the model studied, it can be the result of other dissipation mechanisms which were not considered. This ambiguity was experienced by ATS-V and results in opposite spin and pointing in the retrofire direction. Resolution of this ambiguity problem must be obtained before practical application of AMAPS is possible.

Table 2

Percent decrease in kinetic energy for various cases during 30 minutes of real time

Case	ω_o (rad/min)	Percent decrease in energy	R (ft)
F	20	37	3.26
G	40	46	3.26
H	60	51	3.26
I	20	40	4.35
J	40	50	4.35
K	60	58	4.35

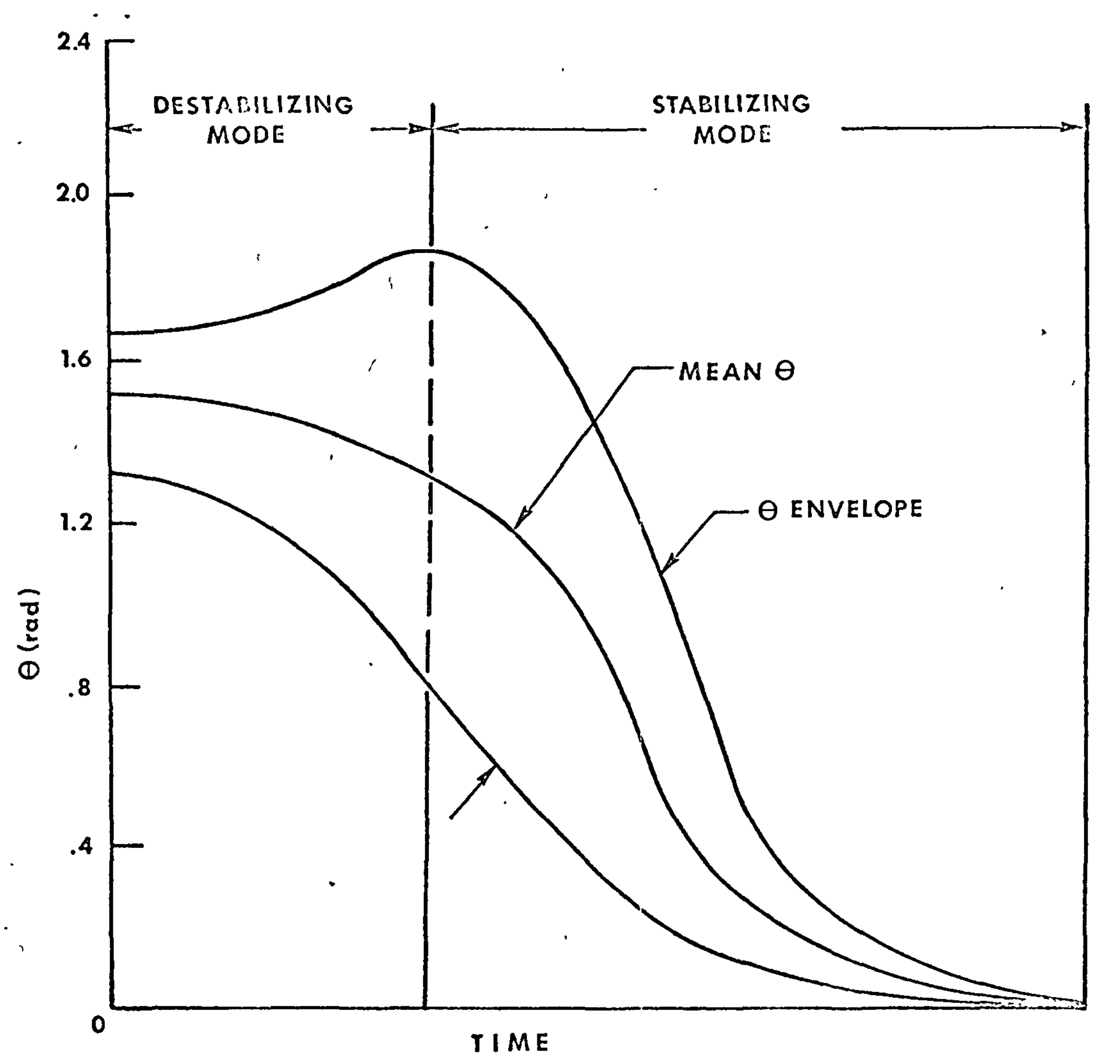


Figure 8. Configuration for θ Envelope of Oscillation

Conclusions

Although operational details have not been worked out, the AMAPS concept seems feasible and should result in significant reduction in deployment hardware and cost in many cases. Quantitative results are limited, but those obtained indicate axis transformation is easily accomplished before the first apogee. Furthermore, the discrete parameter model method seems to perform well for simple dissipation mechanisms.

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APPENDIX D

Optimal Transfer Trajectories

The problem considered is one of optimal transfer of the retrieval package from the space shuttle to a target satellite. The spin axis of the target satellite in general will not lie in the plane of shuttle and target orbits. Therefore, an out-of-plane transfer is required for terminal spin axis alignment. The situation is represented by a nonlinear boundary value problem with a terminal constraint on the approach direction.

During the past six months an investigation was undertaken to determine a suitable technique for computing optimal three-dimensional rendezvous trajectories in terms of minimum fuel and time. A number of methods were studied and it has been concluded that either a conjugate gradient or quasilinearization algorithm will yield valid results within a reasonable amount of computational time. However, because of the sensitivity to poor initial guesses, a quasilinearization procedure would have to be preceeded by a first-order gradient analysis in order to generate good starting values (a good nominal trajectory) to the optimum solutions.

A conjugate-gradient approach tries to combine the advantages of both first and second order gradient methods while eliminating their disadvantages. As the iterations proceed in the conjugate-gradient algorithm, convergence becomes fast near the optimum, unlike a first-order approach, where a poor initial guess will yield good solutions at first, but near the optimum, convergence is slow.

Quasilinearization involves choosing nominal-state-variable functions that satisfy as many of the boundary conditions as possible. The system and influence equations are linearized about the nominal and the resulting linear two-point boundary-value problems are solved accordingly. This method shows good convergence near the optimum solution similar to second-order gradient methods.

The next step will involve actual computation of trajectories using a conjugate-gradient algorithm. Comparisons will be made with results obtained from other methods. From solutions obtained the optimum stand-off position of the shuttle will also be determined.

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