DYNAMICS AND CONTROL OF DETUMBLING A DISABLED

SPACECRAFT DURING RESCUE OPERATIONS

(Summary Final Report on NASA Grant NGR 39-009-210)

by

Marshall H. Kaplan

Associate Professor of Aerospace Engineering

Astronautics Research Report

No. 73-10

Department of Aerospace Engineering

The Pennsylvania State University

University Park, Pennsylvania

September 1973

ABSTRACT

Results of a two-year research effort at The Pennsylvania

State University (NASA NGR 39-009-210) on dynamics and control of

detumbling a disabled spacecraft during rescue operations are

summarized. Answers to several basic questions about associated

techniques and hardware requirements were obtained. Specifically,

efforts have included development of operational procedures, conceptual

design of remotely controlled modules, feasibility of internal

moving mass for stabilization, and optimal techniques for minimum-

time detumbling. Results have been documented in several reports

and publications.

TABLE OF CONTENTS

1. INTRODUCTION

NASA Grant NGR 39-009-210 was awarded on June 1, 1971 for the purpose of studying dynamics and control aspects of detumbling a disabled spacecraft during rescue operations. The grant expired on July 31, 1973. Answers to several basic questions related to external and internal detumbling were obtained. Specific problem areas were identified, and mission requirements and constraints were formulated for the purpose of developing operational sequences and conceptual hardware designs. Work has been well documented, and associated publications are listed in Section 3. For detailed technical discussions refer to these documents.

The primary objective of the study was to develop technology related to detumbling a large passive spacecraft for the purpose of rescuing the crew. Efforts have included development of operational procedures, conceptual design of remotely controlled modules, feasibility of internal moving mass for stabilization, and optimal techniques for minimum-time detumbling. Although emphasis has changed since the original statement of work was written, the most critical and timely aspects have been considered.

A preliminary design of an unmanned module for automatic dock and detumble (MADD) has been carried out. Extensive analyses on dynamics and controls problems has been completed. These include synthesis of a continuously throttable position control system and an initial design of an attitude control system. A movable mass control system to convert tumbling motion of a spacecraft into simple spin has been devised. The equations of motion of a rigid spacecraft

with attached control mass have been formulated. Such a control system may increase or decrease the system energy to its maximum or minimum state. In the latter case stability and a low spin rate result. A control law relating mass motions to vehicle motions was selected based on Lyapunov stability theory. For a selected spacecraft and realistic initial conditions, it was shown that a movable mass device is capable of decreasing the kinetic energy of the system and establishing a simple spin state about the axis of maximum inertia within a short time interval, thus, demonstrating feasibility of the concept. In addition, optimization techniques have been employed to generate displacement profiles for the general problem of a tumbling asymmetrical body.

Several graduate students have participated in this work. To date, one master of science thesis and one Ph.D. dissertation have been written on the study problems and solutions. One other thesis in this area is still being completed.

2. SUMMARY OF TECHNICAL ACHIEVEMENTS

In the operation of future manned space vehicles there is always a finite probability that an accident will occur which results in uncontrolled tumbling of a spacecraft. The process of detumbling such a vehicle may represent a major part of the rescue operation if crewmen cannot evacuate while tumbling. Hard docking by a manned rescue craft is not possible because of complex maneuvers which would probably require excessive accelerations and fuel usage. In addition, the rescue crew would be exposed to an extremely hazardous environment since the tumbling vehicle may be larger than the rescue craft.

Therefore, elimination of tumbling motion presents a very difficult problem which must be resolved to fulfill a complete space rescue capability.

The most general type of passive attitude motion is referred to as "tumbling". All three orthogonal components of angular velocity may be large, and there is no preferred axis of rotation. Since no spacecraft is absolutely rigid, tumbling motion will tend toward steady spin due to energy dissipation. However, large bodies such as manned space bases have relatively low dissipation rates and may require many days or weeks to passively stabilize at a constant spin rate about a single axis. If this state were reached, despinning is somewhat easier than detumbling. Two philosophies were employed to consider promising methods of implementing attitude control; torque application from outside and built-in autonomous devices. The first category includes the use of fluid jets from a shuttle orbiter and a small automated thruster package to track and dock with the tumbling craft. Internal devices include self-contained, acceleration-activated mechanisms which may vary the moments of inertia or apply thrust with time in order to stabilize motion to steady spin or eliminate all angular momentum.

2.1 The Nature of Tumbling

Angular momentum states have been classified according to motion and missions in which such states are likely to occur. Simple spin is angular motion about a single body axis and is usually associated with passive attitude stabilization and the steady state of initially perturbed or tumbling bodies. Tumbling occurs immediately after a significant attitude perturbation, but eventually decays into simple

spin. The nature of 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 formulated by Poinsot. The "Poinsot ellipsoid"
illustrated in Figure 1 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, as shown. Attitude motion can then be described as
the Poinsot ellipsoid rolling without slip on an inertially fixed
plane with its center at a fixed distance from this plane. If the body
is symmetric, the geometric interpretation is simpler and is illustrated
in Figure 2. 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 coincides with the angular momentum vector. The common cone
element coincides with the angular velocity vector.

Tumbling is the immediate result of a significant attitude per-
turbation to an uncontrolled vehicle with little or no initial spin.
This situation is coupled with continuous angular motion of all three
principal body axes, i.e., no inertially oriented axis exists. Crew-
men trapped inside such a vehicle could not easily escape and may not
even be able to move about due to the changing nature and magnitudes
of accelerations. This kind of attitude motion makes rescue very
difficult. In general, elimination of angular motion of a large body
is a complicated process, because it must be done either from a non-
tumbling frame outside the body or by a possibly massive internal
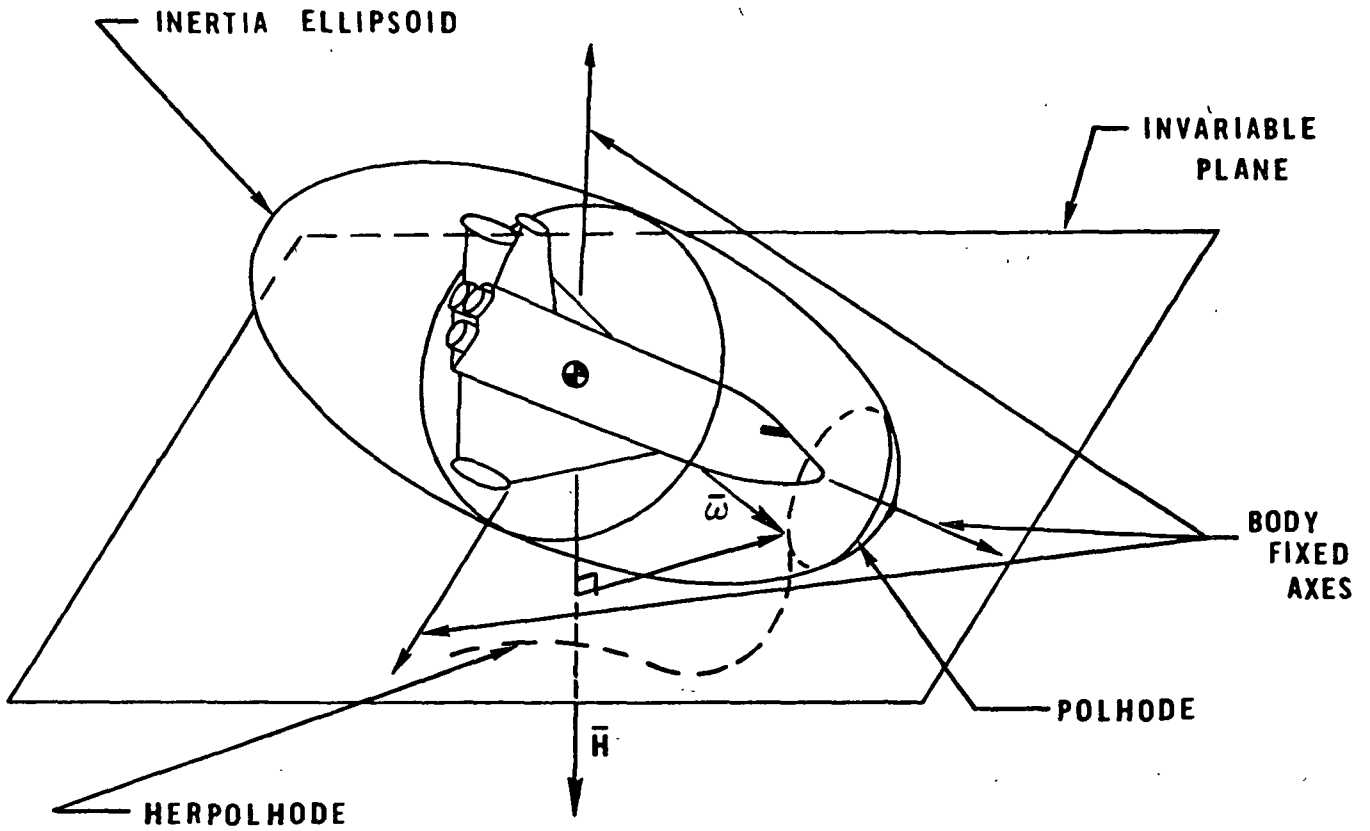device which may only stabilize the motion to steady spin. (Publication 3)

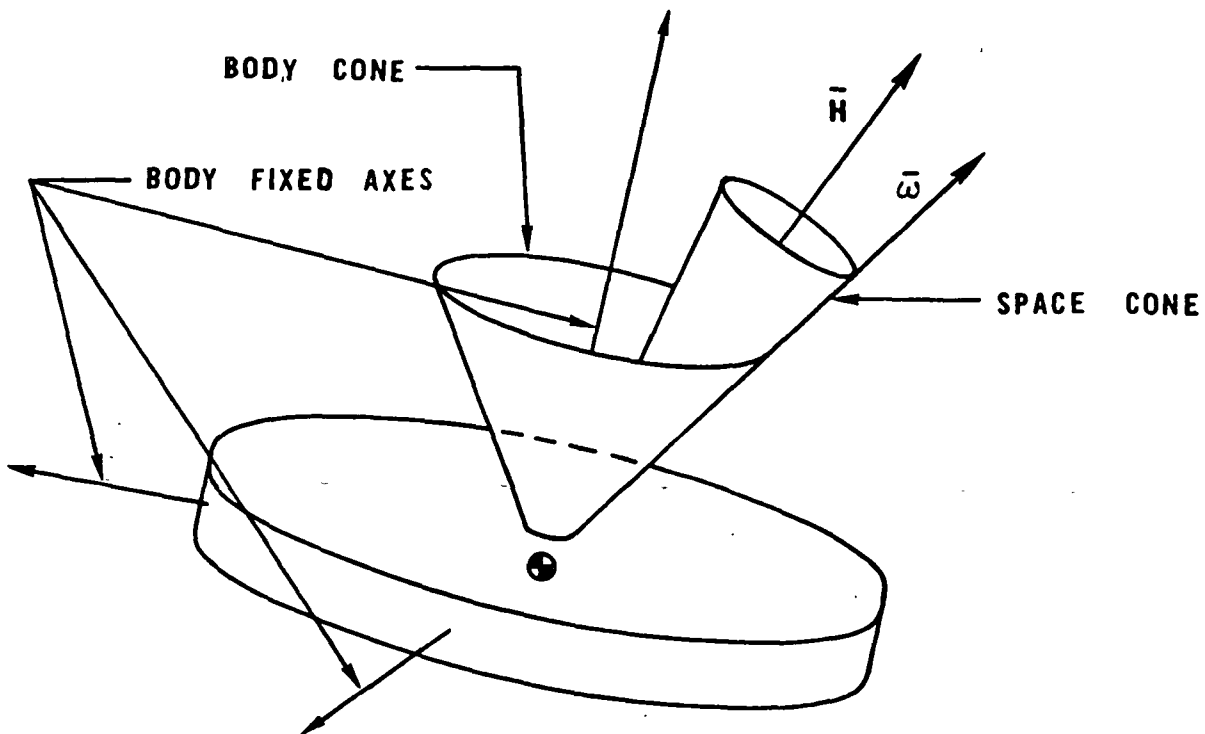Figure 1. Geometric Interpretation of General Attitude Motion

Figure 2. Geometric Interpretation of Axial Body Motion

2.2 Examples of Tumbling Situations

In order to determine the requirements for a device or concept to detumble a large spacecraft some assumptions must be adopted about the causes of tumbling and calculations made to determine resulting maximum rates of tumble. An analysis of realistically determined situations was made with selected spacecraft which are thought to represent future mission hardware. Primary expected causes of tumbling associated with loss of control are vehicle-vehicle collisions, escaping atmosphere, pressure vessel rupture, runaway attitude thruster, and hard-over gimbal during a main engine firing.

Four configurations were selected based on a recent North American Rockwell study. These are the modular space station, small space vehicle, Mark II orbiter, and generation 1 orbiter. Configurations are shown in Figure 3. Mass and moments of inertia were calculated for each vehicle and are listed in Table 1. Collisions between all combinations of these vehicles were considered, except Mark II- generation 1 orbiter encounters. Such mishaps were assumed to occur during docking operations with a relative velocity of 1.5 m/sec with misalignment of 4 deg in angle and 0.61 m in displacement in addition to an angular vehicle rotation rate of 0.1 deg/sec. Impact parameter values were assumed and energy methods of analysis were used to determine resulting tumbling rates. The escaping atmosphere situation was assumed for the modular space station and small space vehicle. Pressure wall perforation could result from meteorite penetration, internal explosion, etc. The effect on attitude is similar to that of a reaction jet as the inside atmosphere escapes into space. Worst cases were assumed with respect to puncture location and thrust produced.
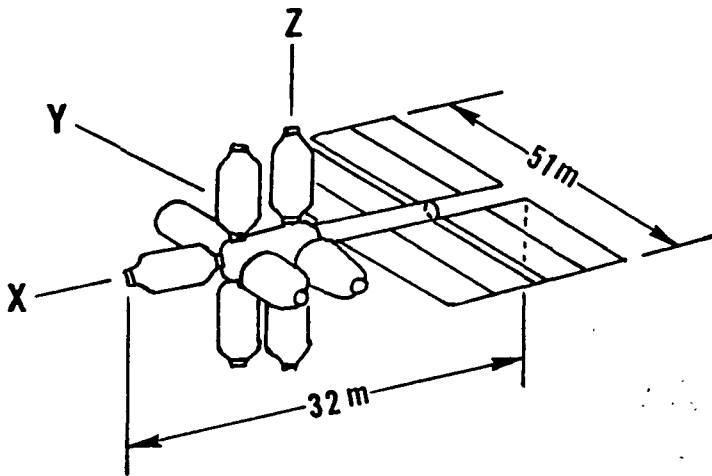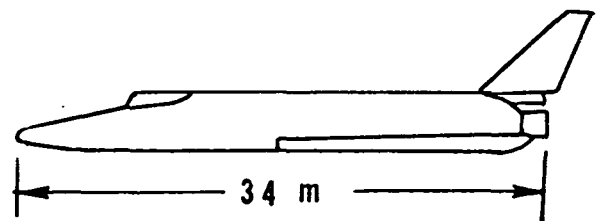
Modular Space Station
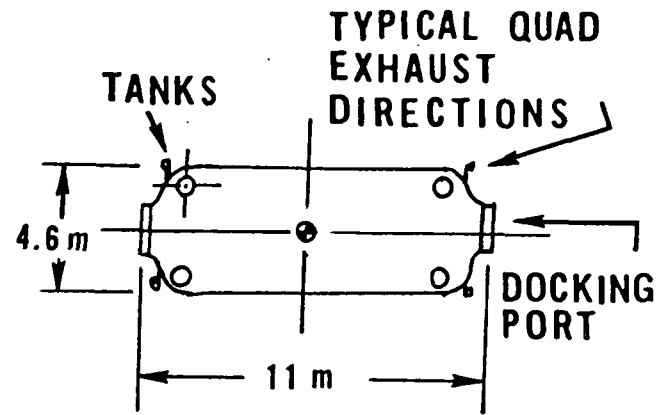
Small Space Vehicle
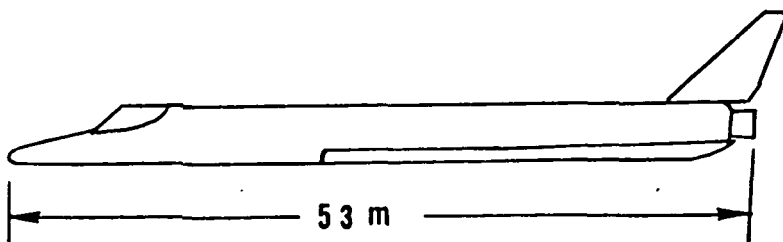
Mark II Orbiter

Generation 1 Orbiter

Figure 3. Configurations Considered in Tumbling Analysis

Escape of fluids from tanks into space will have similar results to those of an escaping atmosphere. A single tank was assumed ruptured for each configuration studied. Worst case conditions prevailed, e.g., contents escaped in one direction producing thrust with a large moment arm about the center of mass. Since only the two orbiter configurations have steerable main rockets, the hard over gimbal situation applied to them exclusively. Two thrusters on each vehicle were assumed fixed at maximum gimbal angle and fired for 15 sec. The final tumble-producing situation is concerned with a malfunctioning attitude thruster which is assumed to thrust for one minute. (Publication 1)

Table 1 Mass Properties of Configurations Considered

		Modular Space Station	Small Space Vehicle	Mark II Orbiter	Generation 1 Orbiter
Mass (Kg)		100,000	11,400	138,000	81,000
Moments of Inertia $(Kg\text{-}m^2)$	I_{XX}	0.636×10^7	0.298×10^5	3.4×10^6	0.993×10^6
	I_{YY}	0.664×10^7	1.34×10^5	24.8×10^6	8.14×10^6
	I_{ZZ}	0.515×10^7	1.34×10^5	28.3×10^6	8.50×10^6
Products of Inertia $(Kg\text{-}m^2)$	I_{XY}	0.19×10^6	0	-1.22×10^4	0
	I_{XZ}	0.785×10^4	0	3.59×10^5	0
	I_{YZ}	0.176×10^4	0	0.271×10^4	0

Results of worst case situations are summarized in Table 2. It must be stressed that the values of angular rates appearing in this Table represent only the initial motion at the end of application of perturbing torque. Since the X, Y, and Z axes do not generally coincide with the principal body axes (motion about the maximum and minimum principal axes is stable for a rigid body) these spin modes will become tumbling modes within a few revolutions of the vehicle. Some of the results are given as ranges of angular rates because of parameter uncertainties in the analysis. In general, one could conclude that angular rates could be expected up to about 9.0 RPM for the large vehicles and up to about 14.7 RPM for the small space vehicle. The escaping atmosphere situation for this last vehicle is considered a catastrophic one, because a spin rate of 52 RPM would probably result in massive structural failure. Therefore, rescue from this spacecraft would be neither possible nor necessary. A few cases could not be analyzed due to a lack of data on configuration dimensions and layout details. However, all cases in which rescue is possible appear to be limited to initial angular rates of less than 10 RPM or 60 deg/sec for large vehicles and less than 15 RPM or 90 deg/sec for the small vehicle.

2.3 Operational Considerations

In general orbital rescue missions may be divided into three phases: 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 this phase involves detumbling a large, manned vehicle before evacuation and repairs can take place.

Table 2 Summary of Maximum Initial Tumbling Rates

	Modular Space Station	Small Space Vehicle	Mark II Orbiter	Generation 1 Orbiter
Collisons	$\omega_X=0.6-2.1$RPM	$\omega_Y=4.7-14.7$RPM $\omega_Z=4.7-14.7$RPM	$\omega_Y=0.3-1.09$RPM	$\omega_Y=0.5-1.45$RPM
Escaping Atmosphere	$\omega_Z=8.9$RPM	$\omega_Y=52$RPM $\omega_Z=52$RPM	I.D.	I.D.
Escaping Fluids	0.4-4.0RPM	I.D.	I.D.	I.D.
Hard Over Gimbal	Does Not Apply	Does Not Apply	1 - 2RPM	1 - 2RPM
Malfunctioning Thruster	.03RPM	$\omega_Y=0.5-4.0$RPM	0.5-4.0RPM	I.D.

I.D. = INSUFFICIENT DATA TO ANALYZE

The sequence of rescue operations depends on the type of control to be used. Two techniques are being considered: application of controlling torques from outside and stabilization by autonomous internal devices.

External application of torque can be done by either a programmed fluid jet or thruster package which maneuvers and docks with the disabled vehicle if tumble rates are not too high. Operationally the rescue craft "parks" at an optimal position with respect to the tumbling vehicle. If a fluid jet is used the jet must impinge the structure such that angular momentum is decreased. This requires careful aiming and variation of jet intensity with time. Improper application could increase tumbling and cause structural damage. If an automated detumbling package is used it must maneuver to an anticipated rendezvous point on the disabled vehicle and then track the intended docking position while maneuvering in to make a "hard-dock." After this is accomplished, thrusters on this device apply a sequence of torques to the vehicle. This may be done optimally to use a minimum of fuel or time to detumble the craft.

Before application of torque or initiation of maneuvering to dock, it is necessary to determine the components of tumbling and angular momentum. Since the disabled vehicle is passive (assuming no autonomous devices were placed in this spacecraft for the specific purpose of measuring angular rates and/or stabilizing the vehicle) this determination must be done from the rescue craft. Such measurements are difficult to make, because angular components vary continuously with time in the general case. Three components of angular velocity are required simultaneously to obtain the direction and magnitude of angular momentum if the vehicle moments of inertia are known. Otherwise, extensive

measurements are required. This latter situation is very likely to be the case if an explosion or loss of propellant has taken place. Techniques which employ visual observations, radar scanning, and laser reflectors in conjunction with onboard computers are likely candidates for these measurements. Special passive reflectors may be required on the disabled vehicle, but these are small, simple devices which can be mounted before launching all manned vehicles. (Publication 3)

2.4 Automated External Detumbling Module

Since the expected tumbling rates for large vehicles are relatively low, a small maneuverable thruster package deployed from the rescue craft could rendezvous and dock with the disabled vehicle while tumbling. A Module for Automatic Dock and Detumble (MADD) could perform an orbital transfer from the shuttle in order to track and dock at a preselected point on the distressed craft. Once docked MADD could apply torques by firing its thrusters to detumble the passive vehicle. This could be done in a minimum time or fuel sequence.

Design of a MADD type spacecraft is influenced by mission objectives and systems constraints. It must maneuver to, dock with, and detumble a large vehicle with limited fuel, and it must be adaptable to varying situations. Size is constrained by cargo bay dimensions of the rescue craft and to some extent geometry of the disabled vehicle. A preliminary configuration for MADD is shown in Figure 4. This version is designed to use an existing docking port on the disabled vehicle, although, there are some situations in which this is not possible or desirable. Other types of attachment devices may be adapted for those cases. All subsystems are contained within the octagonal structure and
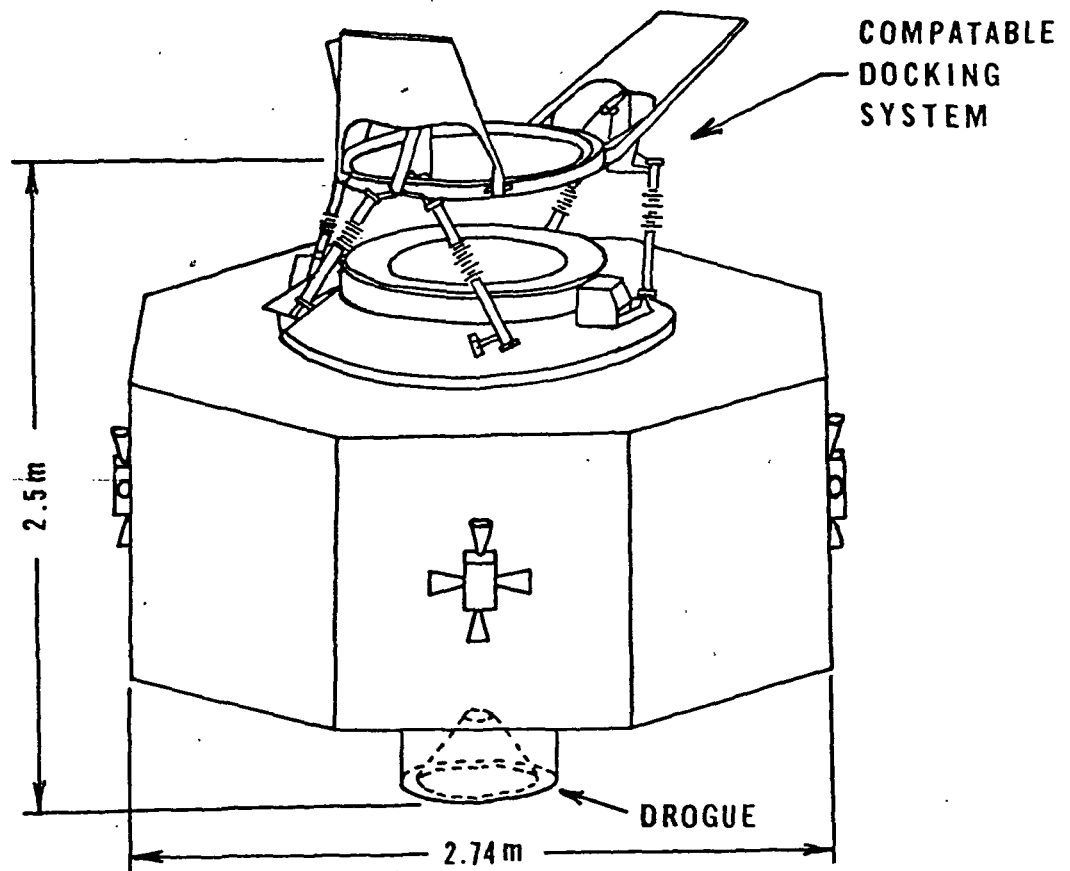
Figure 4. Details of MADD Configuration

include control electronics, attitude control gyros, command and tele-metry, propulsion, power, and various sensors.

The control system has three basic operating modes: transfer, dock, and detumble. During transfer from the rescue craft this system maintains attitude and reorients MADD just before entering the docking mode in which tumble tracking and attachment take place. As soon as hard docking is accomplished the detumble mode is initiated. During this last phase gyro controllers are locked and rate gyros are used for attitude reference. A single propulsion system will satisfy the require-ments for transfer, detumble, and momentum dumping. Thrust profiles during tracking and detumbling phases are computed by an onboard computer based on measurements from sensors and those taken immediately upon com-pletion of docking. Optimal sequences are generated in order to detumble in minimum time with limited thrust when time is a critical factor.

The operational procedure for the use of MADD consists of deploy-ing the module, transfer to a rendezvous point, tracking a docking port, hard docking, and detumbling. Before initiating this sequence, the rescue craft crew must determine the angular momentum and physical state of the disabled vehicle. An optimum parking position is selected for the rescue craft based on visual observation advantage, propellant requirements for maintaining this position, and possible transfer paths for MADD. Figure 5 shows a situation requiring a minimum propellant requirement for the rescue craft. Both vehicles share the same orbit but remain separated along the flight path. Once a stand-off situation is established, MADD is deployed from the cargo bay and the transfer phase begins. A general transfer profile is illustrated in Figure 6. Direct observation of MADD is possible from the rescue craft during the
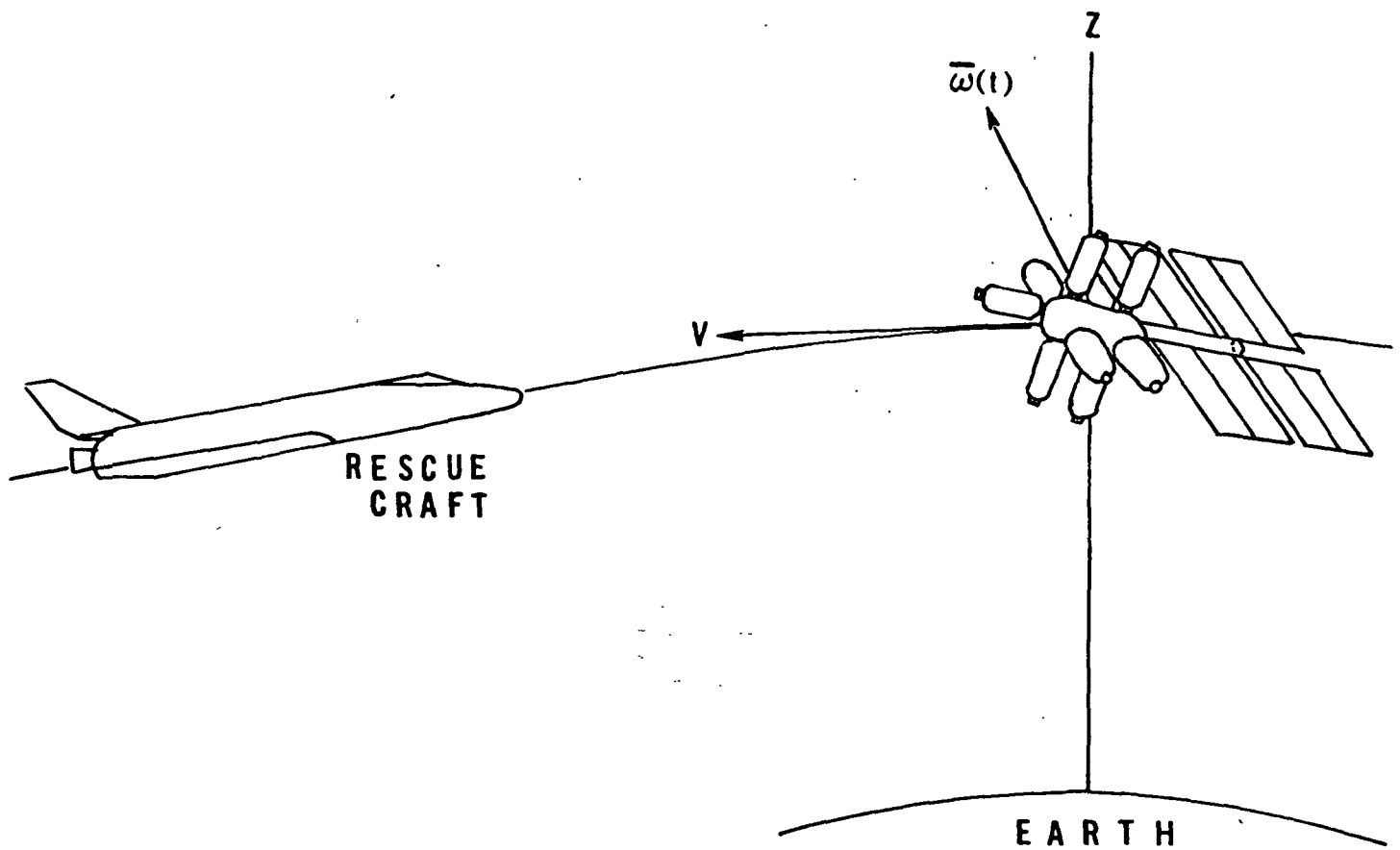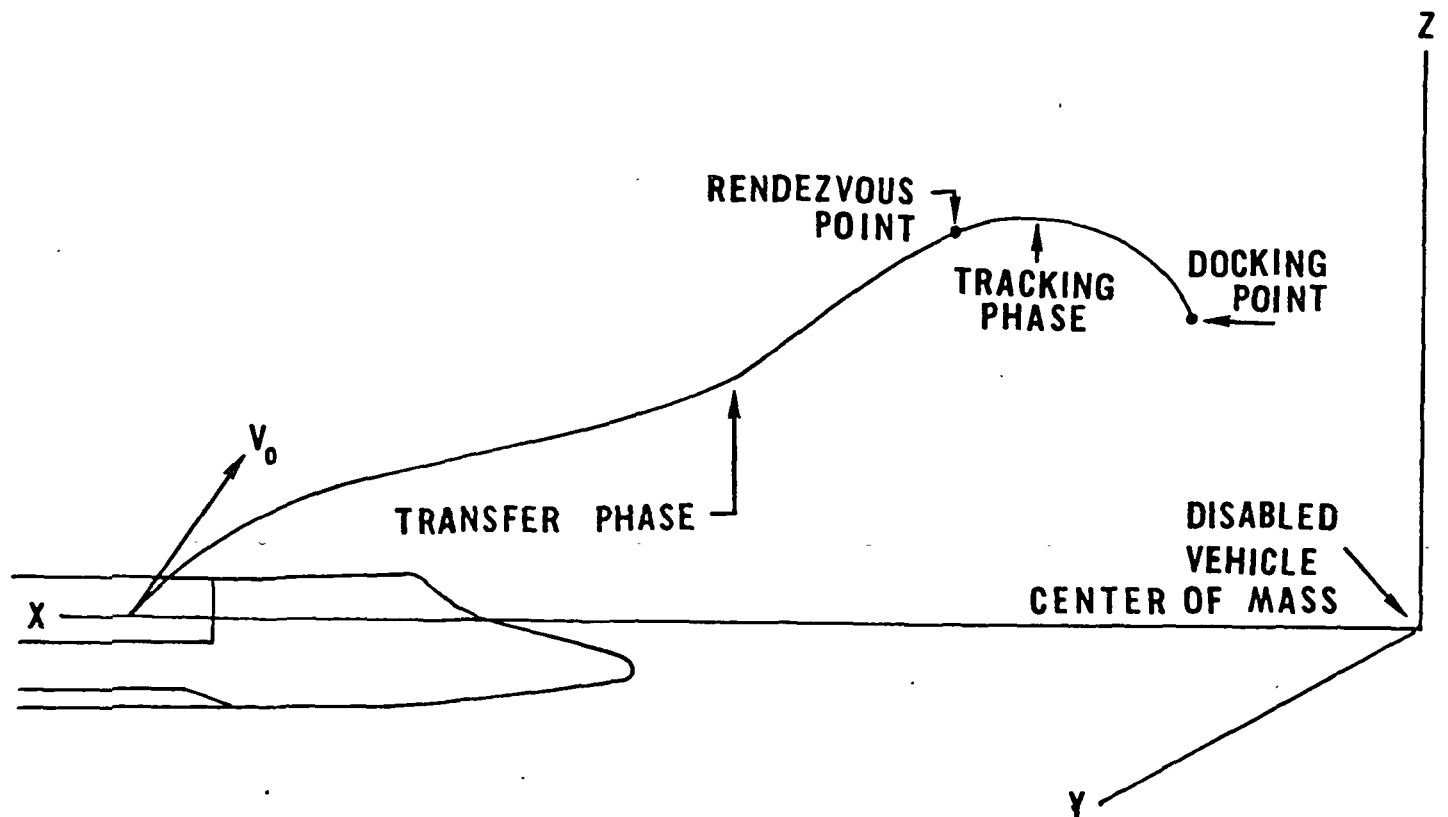
Figure 5. Example of Stand-Off Situation

Figure 6. Typical Transfer Trajectory for MADD

transfer phase. However, during tracking and docking radio and visual contact may be lost intermittently due to occultation. The rendezvous point can be selected such that the velocity of MADD at this point will coincide with the velocity of the disabled vehicle reference point. This will eliminate the need for a terminal maneuver by MADD before the tracking phase begins. The rendezvous point should typically be about 3 meters from the docking port. MADD thrusters begin firing to maintain and then reduce its distance to this port. Passive docking aids may be required around the port for sensing relative position, orientation, and velocity. This permits proper alignment during closure and docking. The process is continued until capture latches are secured. After detumbling crew evacuation takes place. (Publications 3 and 5)

2.5 Optimal Detumbling with Thrusters

The minimum time optimal detumbling of a distressed space vehicle can be divided into the following categories: constraint on the magnitude of the control moment vector and constraint on the magnitude of each component of this vector. The general problem of detumbling considered here is to bring all three components of angular velocity to zero in minimum time. The first constraint category can be handled with relative ease. The appropriate analysis was applied to an example case. A collision between a modular space station and a Mark II orbiter was assumed with a resulting tumble of the space station. Principal axis angular velocity components at commencement of external thrust application by MADD were taken as 1.150, 1.750 and -0.445 RPM about the 1, 2 and 3 principal axes, respectively. These values represent a good test situation for the optimization technique used. These components were brought to zero in about 7 minutes with a control torque magnitude of

3,390 N-m. Figure 7 shows a time history of the principal axis angular velocities during application of the optimum control moment. Figure 8 gives a time history of the body fixed thrusts required at point X = 3.9m, Y = 0.89m and Z = 18.3m to give the necessary 3,390 N-m moment directed opposite to the angular momentum vector. (Publications 2, 3, and 5)

The second type of constraint presents more difficulty in determining the optimum minimum time control moment sequence. In this case, the analysis is not as easily accomplished, and the control moment vector is not simply directed opposite to the angular momentum vector.

2.6 Automated Internal Stabilizing Devices

A movable-mass control device, which is activated upon initiation of tumble and is autonomous, can convert tumbling motion into simple spin. Such a device would greatly facilitate crew evacuation and final despinning by external means. There have been several other suggestions for using internal devices. Mass expulsion devices require onboard storage of propellants over long periods. Several thrusters would have to be dedicated to this type of system. Thus, such schemes could be complex and massive. Momentum exchange devices could quickly saturate and are difficult to start in a tumbling situation. Passive energy dissipation mechanisms are reliable and simple, but they require long periods of time to reduce kinetic energy if initial rates are low. Of particular concern here is an internal moving mass system which is programmed to quickly stabilize motion about the major principal axis.

The complete equations of motion of a rigid spacecraft with attached control mass have been formulated making no assumptions regarding vehicle symmetry or magnitude of the transverse angular rates. A control law
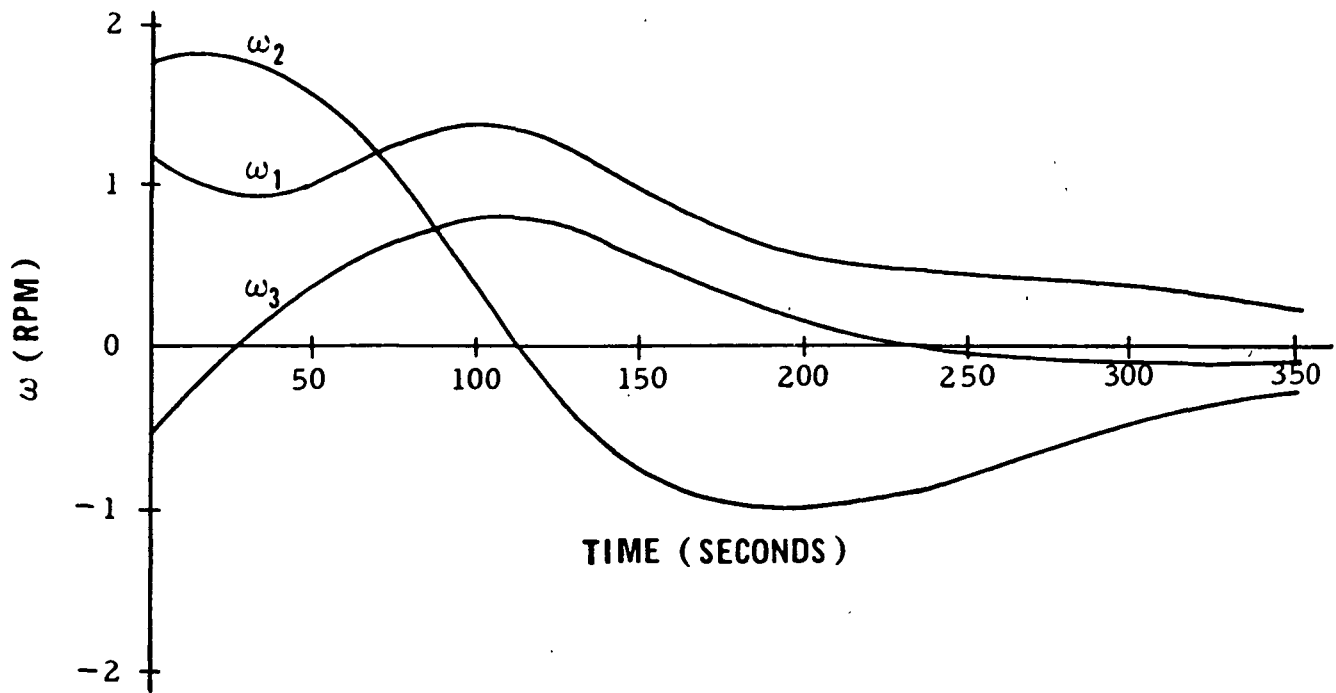
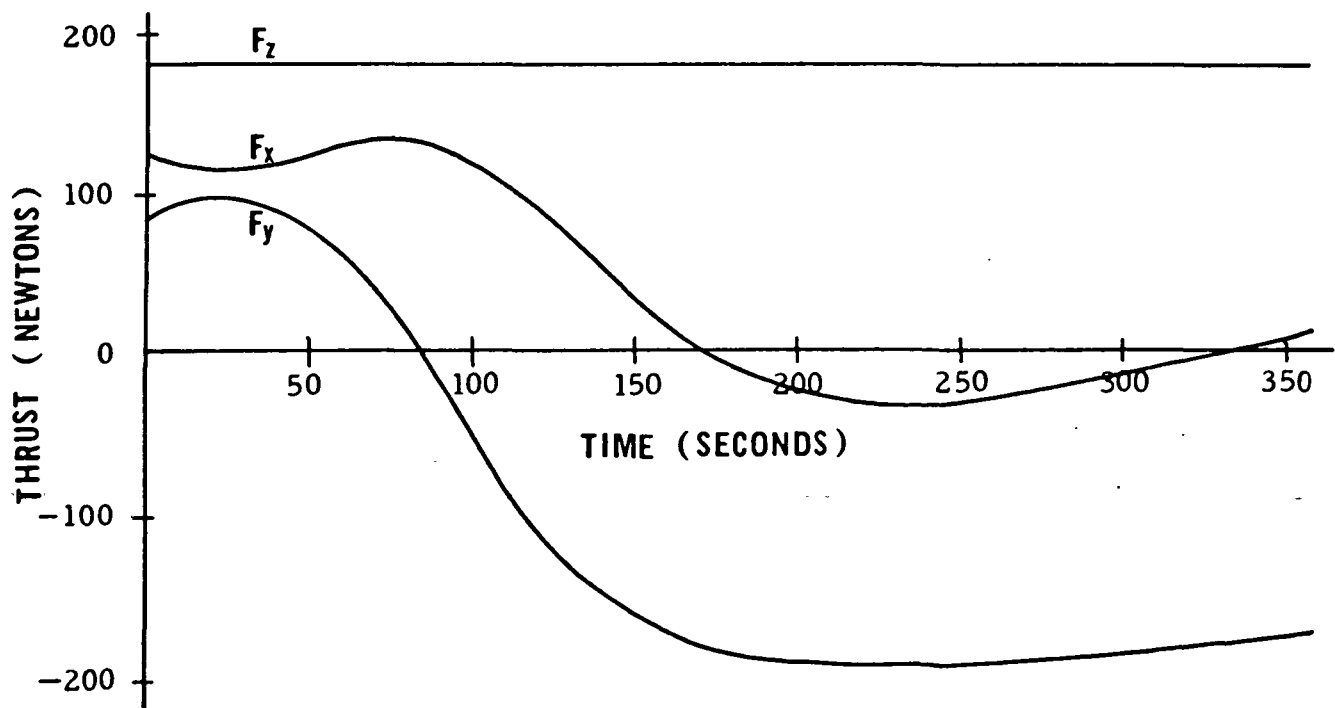Figure 7. Principal Angular Velocities During Detumbling

Figure 8. Body Fixed Thrust Component Profiles During Detumbling

relating control mass motions to vehicle motions was selected based on Liapunov stability theory. A method of determining control system parameter values, based on an estimate of the worst case tumble state has also been developed. For the MSS under previously stated conditions, a movable mass control system is capable of quickly decreasing the kinetic energy of the system to its minimum state, establishing a simple spin about the maximum inertia axis.

It is the function of the control law to relate motion of this mass to measurable vehicle parameters such that kinetic energy decreases. A satisfactory control law should not be unnecessarily complicated and should not have excessive power or sensor requirements. It should however, require determination of only measurable vehicle parameters, produce stable responses, and result in a final state of simple spin about the axis of maximum inertia. For the work considered here, the vehicle is assumed to have three distinct principal moments of inertia (asymmetric vehicle). Since initial tumble rates may be large about all three axes, the equations of motion could not be simplified by linearization. However, a limited number of simple cases were identified which permitted development of a suitable control law. Linear mass motion parallel to the axis of maximum inertia was selected. Simulations indicate that the MSS can be brought to stable spin with a 1% movable mass in 2 hours using a displacement amplitude of about 3 meters. Figure 9 illustrates time histories of angular velocity component magnitudes under the influence of this control mass.

Observations concerning the use of such a device included:

1. The mass track should be placed as far as possible from the vehicle center of mass and oriented parallel to the maximum inertia axis.
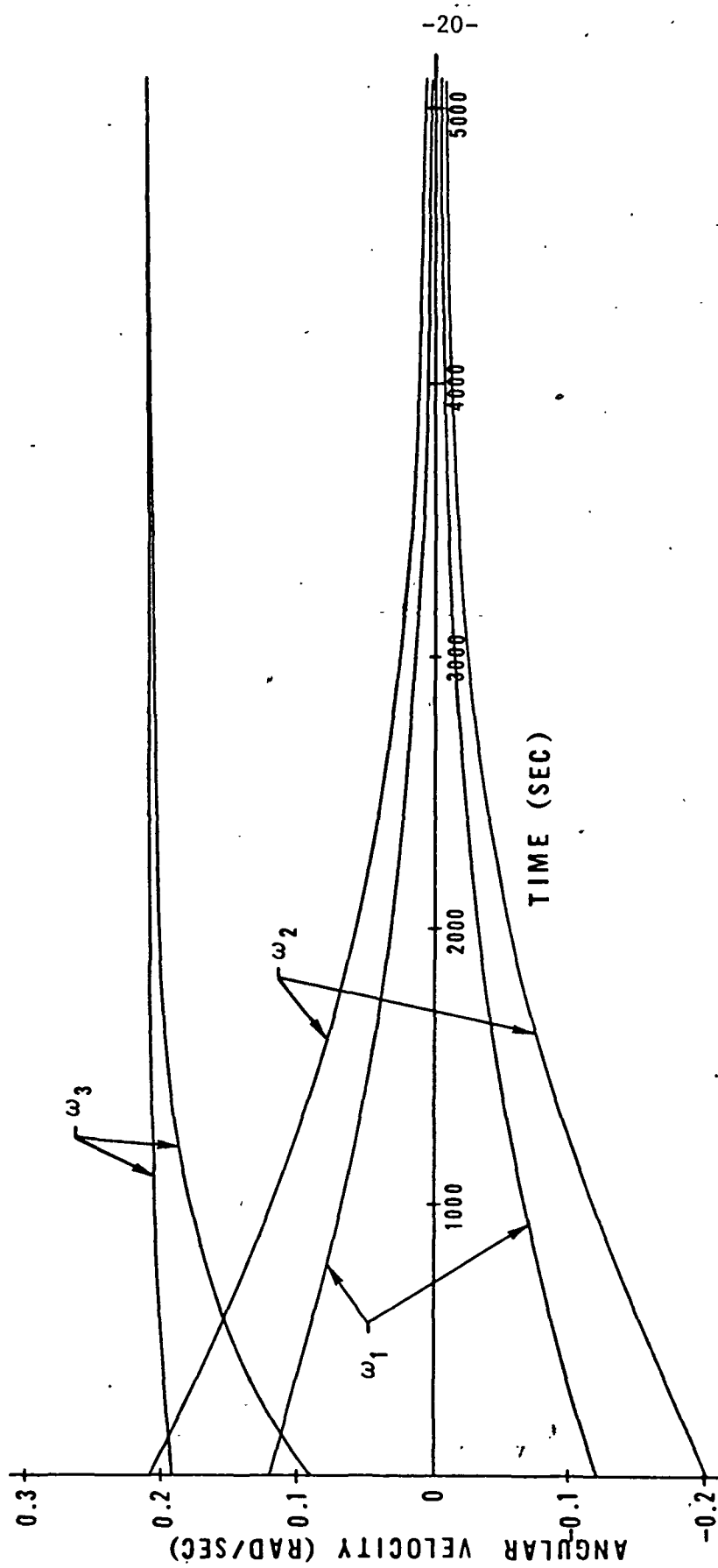
Figure 9. Envelopes of Angular Velocity Component Oscillations

2. The control mass size should be as large as possible, while being consistent with peak force and power limitations.

3. The performance of the control system may be improved through larger mass amplitudes.

Optimizing the control law can bring further improvement in stabilization time with the same control mass and initial conditions. A first-order gradient technique has been used to minimize angular velocity components along the intermediate and minimum inertia axes. This open-loop method permits a wide range of initial guesses for mass position history. Motion of the control mass was assumed to be along a linear track as discussed above. The control variable is taken as mass acceleration with respect to body coordinates. Motion was limited to defined quantities and a penalty function used to insure a given range of positions. Numerical solutions of the optimization equations verify that minimum time detumbling is achieved with the largest permissible movable mass, length of linear track, and positions of the mass on the two coordinates perpendicular to the linear motion. Also, the mass should oscillate, about the zero point, on an axis parallel to the major principal axis. A minimum mass solution was obtained by fixing the time at the largest feasible value. The optimal method permits detumbling in about one-fourth the time when compared to the force control law formulation discussed above. Time histories of angular velocity component magnitudes for this case are shown in Figure 10. Since stabilization may require hours, this reduction in time is very significant. In regard to minimum mass, optimization permits the use of a much smaller mass for detumbling in the same time. This mass reduction is quite substantial since very large masses are required. Use of this control system for
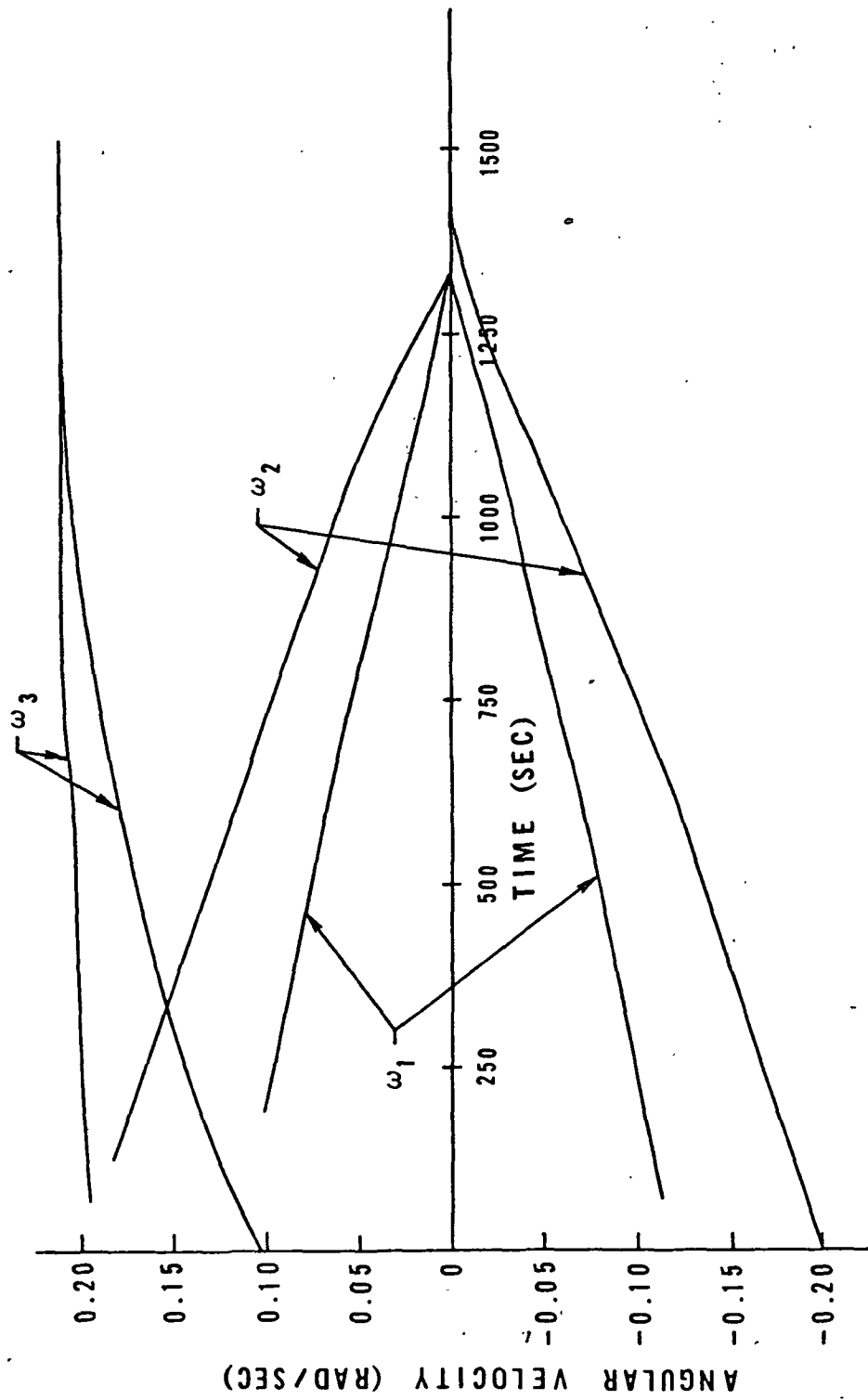
Figure 10. Envelopes of Angular Velocity Component Oscillations for the Optimal Case

actual operations in space is feasible since the velocity and accelera-
tion of the mass, and the power requirement, are low. (Publications 4,
6, 7, and 9)

3. PUBLICATIONS AND RESEARCH REPORTS RESULTING FROM THIS RESEARCH

1. ____, "First Semi-Annual Progress Report on Dynamics and Control of Escape and Rescue from a Tumbling Spacecraft," NASA Grant NGR 39-009-210, December 1971.

2. ____, "Second Semi-Annual Progress Report on Dynamics and Control of Escape and Rescue from a Tumbling Spacecraft," NASA Grant NGR 39-009-210, June 1972.

3. Kaplan, M. H., "Despinning and Detumbling Satellites in Rescue Operations," presented at the 5th Space Rescue Symposium, at the 23rd Congress of the International Astronautical Federation, October 1972. Also to appear in Proceedings of the 5th Space Rescue Symposium, 1973.

4. ____, "Third Semi-Annual Progress Report on Dynamics and Control of Escape and Rescue from a Tumbling Spacecraft," NASA Grant NGR 39-009-210, December 1972.

5. Snow, W. R., Kunciw, B. G., and Kaplan, M. H., "A Module for Automatic Dock and Detumble (MADD) for Orbital Rescue Operations," Astronautics Research Report No. 73-3, Pennsylvania State University, Dept. of Aerospace Engineering, April 1973.

6. Edwards, T. L., "A Movable Mass Control System to Detumble a Disabled Space Vehicle," M.S. Thesis, The Pennsylvania State University, June 1973. Also Astronautics Research Report No. 73-5.

7. Kunciw, B. G., "Optimal Detumbling of a Large Manned Spacecraft Using an Internal Moving Mass," Ph.D. Thesis, The Pennsylvania State University, June 1973. Also Astronautics Research Report No. 73-8.

8. Edwards, T. L. and Kaplan, M. H., "Automatic Spacecraft Detumbling by Internal Mass Motion," submitted to the AIAA Journal, 1973.

9. Kaplan, M. H., "Techniques for Detumbling a Disabled Space Base," to be presented at the 6th Space Rescue and Safety Studies Symposium, Baku, U.S.S.R., October 1973.

10. Kaplan, M. H. and Kunciw, B. G., "Optimal Detumbling of a Large Manned Spacecraft Using an Internal Moving Mass," to be presented at the 6th IFAC Symposium on Automatic Control in Space, Tsakhkadzor, Armenia, August 1974.

4. CONCLUSIONS AND RECOMMENDATIONS

Results of a two-year study of detumbling techniques related to orbital rescue missions indicate that several devices may be candidates for use in future space rescue systems. Both internal and external devices show promise and may be best applied in combinations. Work should be continued to completely formulate automatic control logic associated with tracking and docking of MADD during tumble maneuvers. Optimum combinations of mass motion and external devices for varying situations should be sought. Built-in rescue aids should be developed in conjunction with future space stations. Specific recommendations with regard to future manned spacecraft designs include:

1) Reflectors designed for tumble state determination should be placed strategically about the outside of each vehicle.

2) Each new spacecraft design should be examined for possible inclusion of moving mass and/or passive dissipative devices.

3) Passive sensors for MADD docking alignment should be installed around all docking ports.

4) Realistic tumble rates are expected to be low, permitting the use of small thruster modules such as MADD.

5) Internal autonomous devices are desirable but cannot be expected to completely detumble the vehicle unless they are massive. Thus, outside torque application should be anticipated for future rescue missions.

Future studies should include:

1) Development of MADD units should be considered in depth. New technology will be required for at least the automatic control system and sensors.

2) Hardware components should be developed for use in determining tumbling rates through outside observations.

3) An extensive investigation of the properties of fluid jets into vacuum should be made to determine feasibility and application with respect to applying detumbling torques.

4) Simple and lightweight mechanisms should be sought for use as internal controlling elements to aid in detumbling.