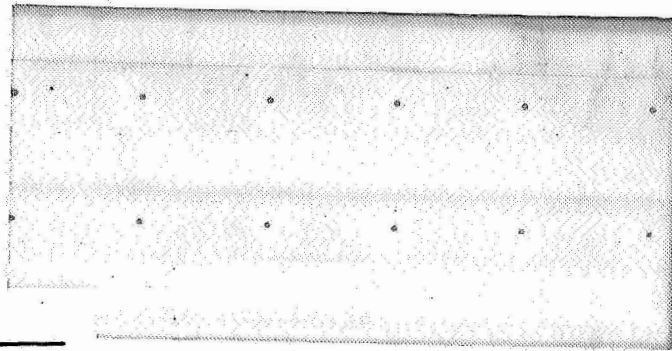
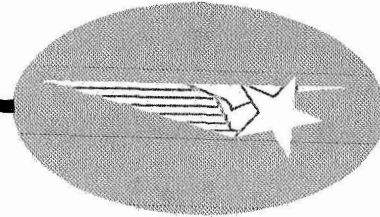


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SUNNYVALE, CALIFORNIA

OWS AUXILIARY ATTITUDE CONTROL
SYSTEM REQUIREMENTS

Augmentation Task No. 30

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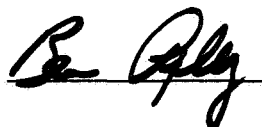
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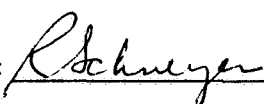
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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CONTENTS

	Page
ILLUSTRATIONS	iii
TABLES	iv
INTRODUCTION	1
STATEMENT OF THE PROBLEM	1
SEQUENCE OF EVENTS	2
CONTROL IMPULSE REQUIREMENTS	6
MODEL	6
COORDINATE SYSTEM	7
VEHICLE CONFIGURATION DATA	9
GENERAL EQUATIONS	11
AXIAL DOCKING	11
RADIAL DOCKING	20
RENDEZVOUS	25
GRAVITY GRADIENT	28
AERODYNAMIC TORQUES	30
UNCONTROLLED MOTION	32
SUMMARY OF AAP-1 THROUGH -4 CONTROL IMPULSE REQUIREMENTS	37

ILLUSTRATIONS

Figure		Page
1	Cluster A Flight Sequence	3
2	Coordinate System	8
3	CSM-OWS Mass Center, Point of Impact and Initial Velocity	13
4	CSM-OWS/LM/ATM Mass Center, Point of Impact and Impact Velocity	17
5	LM/ATM-OWS Mass Center, Point of Impact and Impact Velocity	21
6	Deadband Motion	26
7	Dynamic Pressure Variations	31
8	Uncontrolled Motion or OWS With Gravity Gradient and Aerodynamic Torques	34

TABLES

Table		Page
1	Sequence of Events for Flights of Cluster A	4
2	Sequence of Events After Life Limit of IU	5
3	Cluster Moments of Inertia	9
4	OWS Control Impulse Required	38

Task 30

OWS AUXILIARY ATTITUDE CONTROL SYSTEM REQUIREMENTS

INTRODUCTION

The object of this report is to make an initial estimate of the control system impulse requirements and to analyze the motion during "storage" when the OWS is presumably uncontrolled.

The Cluster A group of vehicles comprises the first four or five launches of the AAP vehicles. (The nominal plan calls for four launches but provision is made for a re-supply flight, AAP-3A, if the need arises.) In each case the booster will put up either a CSM, OWS, or LM/ATM. The first two launches will put an OWS and a CSM into orbit separately. The CSM will then rendezvous with the OWS. Since the S-IVB has not been designed for extended on-orbit operation, it has become necessary to design a control system to stabilize and control the OWS during docking operations.

Following completion of the mission, the CSM undocks and returns the crew to earth leaving the OWS "stored" in orbit. When the next launch occurs, the auxiliary control system must again stabilize and control the OWS throughout the rendezvous and docking operations. Since the OWS may be "stored" in orbit up to six months the overall lifetime of the auxiliary control system may be one to two years. However, the operational periods may total only a few hours.

STATEMENT OF THE PROBLEM

The S-IVB operating as an OWS must be stabilized during docking periods. Following docking and during storage (on orbit), it has no specific control requirements. After docking it is assumed that the CSM will provide control, and during storage it is required only that the OWS should not tumble. Since the normal S-IVB control requirements

are met during ascent by gimbaling the engine and during 7 hr of orbital operations by the life-limited (ablative thrusters) APS, a control system must be designed explicitly for the OWS on-orbit control requirements. The explicit requirements are:

- Angular Displacement 10 deg each axis
- Angular Rate 0.1 deg/sec each axis
- Nominal Attitude for Rendezvous gravity gradient stabilized ± 20 deg
to the vertical but uncontrolled
about the vertical
- Orbital Storage must not tumble
- Lifetime 1 to 2 yr
- Operational Time not specified but on the order of
hours

The docking conditions themselves are specified to be:

- Closing Rate 0.5 ft/sec nominal; 1 ft/sec maximum
- Lateral Rate 0.5 ft/sec
- Lateral Displacement 0 to 1 ft

SEQUENCE OF EVENTS

The sequence of flights for Cluster A is shown in Fig. 1. The OWS is placed into orbit by the AAP. Subsequent flights put up either a CSM or an LM/ATM. Following AAP-4 the OWS must be left in the stored condition, i. e., MDA down-gravity gradient stabilized. The intervals between flights (-2 and -3A for example) are not specified at this time but may be 3 to 6 mo - leading to an overall time of operation of 1 to 2 yr. The sequence of events, matching up with the flight schedule of Fig. 1, is listed in Table 1.

An assumption made in preparing Table 1 was that whenever the CSM is docked to the OWS it will meet all control requirements.

The AAP-4 S-IVB that launches the LM/ATM should also use an auxiliary control system to allow rendezvous and docking of the CSM after the IU has reached its life limit. These events are shown in Table 2.

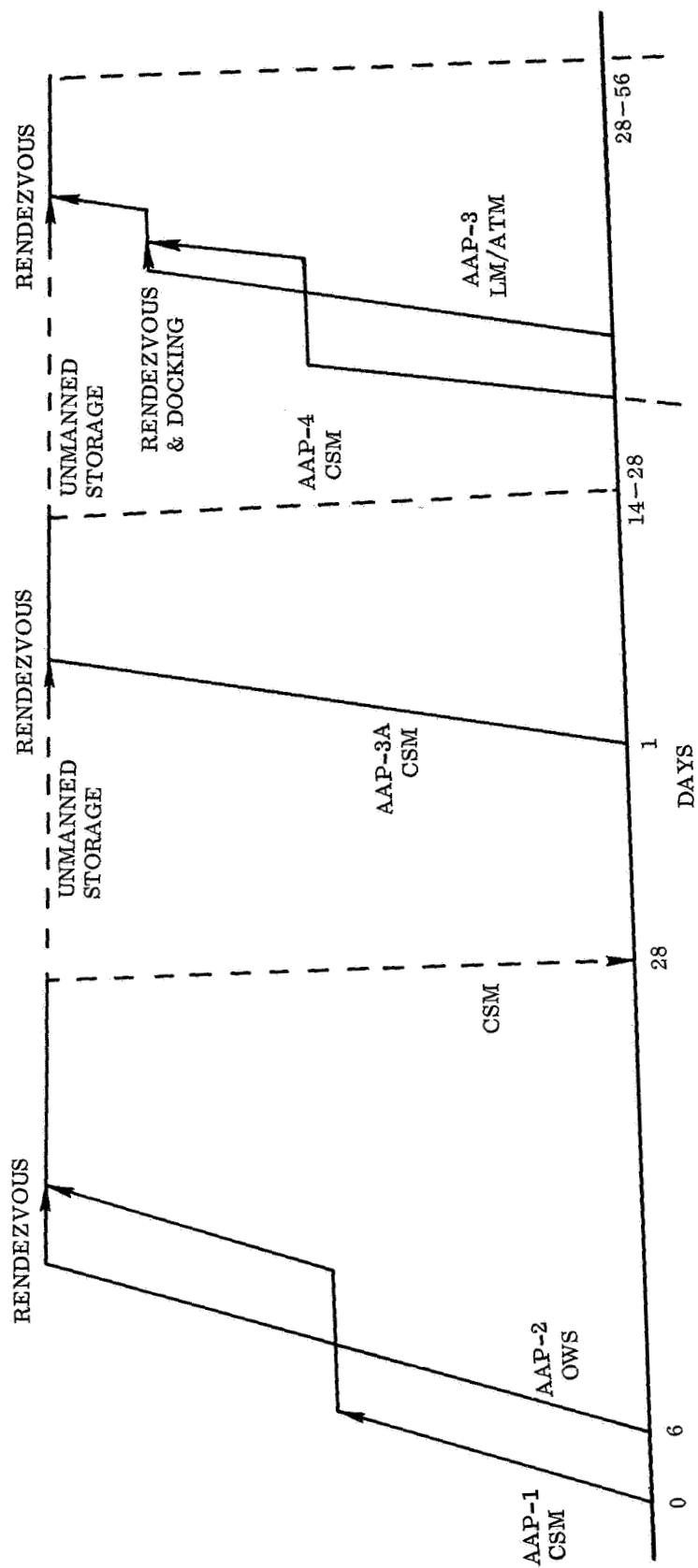


Fig. 1 Cluster A Flight Sequence

Table 1

SEQUENCE OF EVENTS FOR FLIGHTS OF CLUSTER A

<u>Event</u>	<u>Maneuver</u>	<u>Time of Event</u>	<u>Duration of Operation</u>	<u>Operational Requirement</u>
1	Insert S-IVB-OWS (AAP-2) in gravity gradient stabilized position, MDA down	Before IU loses power (7-1/2 hr)	-	Use IU with S-IVB APS
2	Maintain gravity-gradient position during CSM rendezvous	7.5 to 48 hr after AAP-2 launch	-	System must maintain pitch and yaw within ± 20 deg of the local vertical and can allow random roll attitude
3	Stabilize OWS after one successful and one missed docking attempt by CSM	-	1/4 orbit allowed	Rate stabilization only. OWS angular rates must be less than 0.1 deg/sec about each axis
4	Reacquire gravity-gradient stabilized position after CSM undocking	End of 28-day mission	-	Vehicle must be left in storage so that MDA points toward the earth; vehicle is not allowed to tumble
5	Maintain gravity-gradient stabilized position for CSM revisit rendezvous	7.5 to 48 hr		System must maintain pitch and yaw within ± 20 deg and can allow random roll.
6	Stabilize OWS after one successful and one missed attempt by revisiting CSM	-	1/4 orbit	Rate stabilization only. 0.1 deg sec about all axes required. Not needed if CMG's are operating.
7	(Repeat of event 4)			

Table 1 (Cont.)

<u>Event</u>	<u>Maneuver</u>	<u>Time of Event</u>	<u>Duration of Operation</u>	<u>Operational Requirement</u>
8	Maintain gravity-gradient stabilized position during CSM & LM/ATM rendezvous	7.5 to 48 hr	-	System must maintain pitch and yaw within ± 20 deg of the local vertical; random roll is acceptable (attitude)
9	Restabilize OWS after two docking attempts by LM/ATM	-	1/4 orbit after each attempt	System must remove docking disturbances from one unsuccessful docking attempt and one successful docking attempt to prepare for CSM docking; rate stabilization is 0.1 deg/sec about each axis
10	Stabilize OWS after one successful and one missed docking attempt by CSM	-	1/4 orbit	Rate stabilization 0.1 deg/sec about each axis
11	(Repeat of event 4)			

Table 2

SEQUENCE OF EVENTS AFTER LIFE LIMIT OF IU

<u>Event</u>	<u>Maneuver</u>	<u>Time of Event</u>	<u>Duration of Operation</u>	<u>Operational Requirement</u>
1	Maintain gravity-gradient position during CSM rendezvous	7.5 to 48 hr	-	System must maintain pitch and yaw within ± 20 deg of the local vertical and can allow random roll
2	Stabilize AAP-4 after one successful and one missed docking attempt by CSM	-	1/4 orbit required	Rate stabilization only AAP-4 angular rates must be less than 0.1 deg/sec about any axis

CONTROL IMPULSE REQUIREMENTS

The control impulse requirements are determined by three following activities:

- Docking disturbances, including missed docking attempts and undocking
- Control during rendezvous preparatory to docking
- Prevention of tumbling during storage (if there were no significant disturbances during storage, this requirement would be zero. It is included here for completeness.)

MODEL

Both bodies (CSM and OWS) are assumed to have the same orbital velocity and the relative motion between them assigned to the closing velocity of the CSM. As the CSM docks, the impact results in a disturbance to the OWS – both translationally and rotationally. We are concerned here only with the rotational motion. While there may occur some "bouncing" or "rebounding" before the two bodies are locked together, such motion is not assumed. It is assumed that the moment the two bodies contact, they are rigidly held together as one and may then be considered to be a rigid body. Thus, insofar as analysis of the motion arising from the docking is concerned, the mass center to which the equations of motion must be referred to is that of the composite body (the CSM-OWS). For example, the angular momentum of the system, both before and after docking, is computed with respect to this mass center.

Since the control requirements during docking do not require any particular attitude to be held but, rather, a rate not to be exceeded, the control impulse required is literally that needed to cancel the disturbance impulse. Thus, to obtain a good estimate of the required control impulse conventional control system phenomena such as damping, deadband, overshoot, etc., do not have to be considered at this time.

Using this model the computations to determine required control impulse are simple and conservative. Using the maximum permissible rates of closure, and the maximum moment arms permissible, the moment of momentum about each control axis

is computed. Then, using available control moment arms, the impulse required to cancel the change of momentum is determined. The sum for all three axes represents the control impulse required for a single, successful docking. A missed docking is accounted for by assuming, quite conservatively, that in the rebounding the initial conditions of the docking body (CSM, etc.) are restored. Thus, a missed docking is taken to require exactly twice the impulse of a successful docking.

COORDINATE SYSTEM

The coordinate used is shown in Fig. 2. The NASA convention being used for this problem places the X axis along the vehicle centerline, pointed toward the earth. The Y-Z plane contain the orbit velocity vector.

Rotation about the X axis is defined as roll and herein will be denoted by ϕ . The control requirements permit ϕ to have any value. Rotations about Y are defined as pitch and are denoted by θ . Rotations about Z are defined as yaw and are denoted by ψ . θ and ψ are required to be within a ± 20 deg cone about the vertical during docking.

Since all dimensional data are available in terms of Saturn station numbers, the coordinate system is located at the control point (located in the S-IVB engine area), taken to be

$$X = 1225 \text{ in.}$$

$$Y = Z = 0$$

$$\bar{R}_C = \text{a vector from the control point to the mass center}$$

$$\bar{R}_i = \text{a vector from the control point to the point of impact of the docking body}$$

By definition, the moment arm of the disturbing, i.e., the docking impulse, is $\bar{R}_i - \bar{R}_C$. The disturbing moment of momentum is $(\bar{R}_i - \bar{R}_C) \times m \bar{V}$ where $\bar{V}$ is the relative velocity of the docking body.

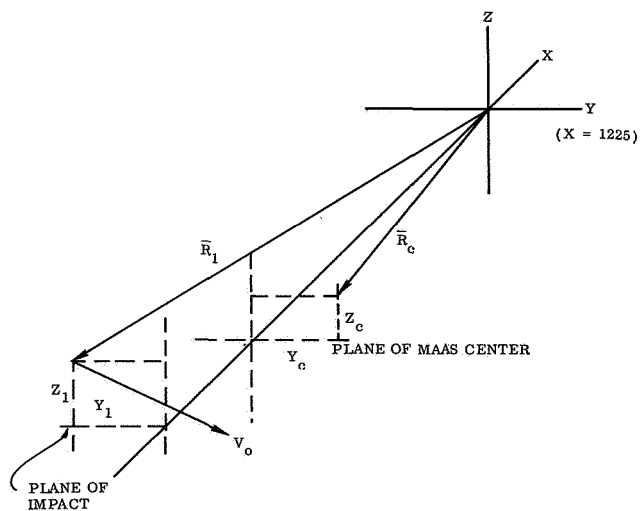
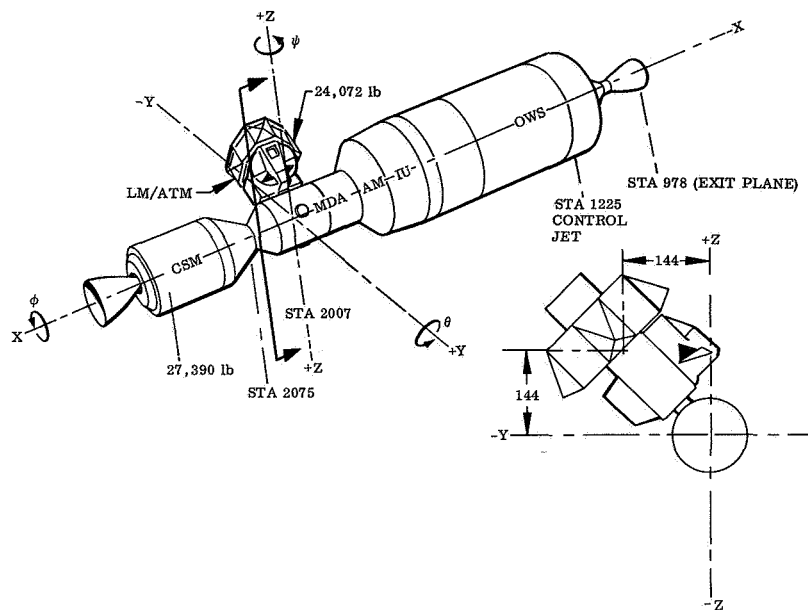


Fig. 2 Coordinate System

VEHICLE CONFIGURATION DATA

The nominal mass center, moments of inertia, and principal axes of inertia of the configuration considered herein are listed in Table 3.

Table 3

CLUSTER MOMENTS OF INERTIA

CONFIGURATION - 1

OWS, SLA (Folded Back), Airlock, MDA, IU, and Solar Electrical System (Deployed)

- Weight = 48,630 lb

$\bar{X} = 1,547.2$	$I_x = 122,910 \text{ slug-ft}^2$	$I_{xy} = -9,262 \text{ slug-ft}^2$
$\bar{Y} = +4.20$	$I_y = 870,110 \text{ slug-ft}^2$	$I_{xz} = -3,166 \text{ slug-ft}^2$
$\bar{Z} = -3.83$	$I_z = 898,760 \text{ slug-ft}^2$	$I_{yz} = 29 \text{ slug-ft}^2$

- Principal Inertias

$\alpha = -0.71 \text{ deg}$	$I_x = 122,778 \text{ slug-ft}^2$
$\beta = 0.23 \text{ deg}$	$I_y = 870,224 \text{ slug-ft}^2$
$\epsilon = -0.02 \text{ deg}$	$I_z = 898,772 \text{ slug-ft}^2$

CONFIGURATION - 4

Complete Cluster

- Weight = 100,100 lb

$\bar{X} = 1,842.9$	$I_x = 322,000 \text{ slug-ft}^2$	$I_{xy} = -142,626 \text{ slug-ft}^2$
$\bar{Y} = -32.29$	$I_y = 2,948,430 \text{ slug-ft}^2$	$I_{xz} = 116,885 \text{ slug-ft}^2$
$\bar{Z} = 30.99$	$I_z = 2,976,580 \text{ slug-ft}^2$	$I_{yz} = -86,304 \text{ slug-ft}^2$

- Principal Inertias

$\alpha = -3.19 \text{ deg}$	$I_x = 318,634 \text{ slug-ft}^2$
$\beta = -2.62 \text{ deg}$	$I_y = 2,888,338 \text{ slug-ft}^2$
$\epsilon = -40.39 \text{ deg}$	$I_z = 3,049,925 \text{ slug-ft}^2$

Table 3 (Cont.)

CONFIGURATION - 2

Complete Cluster Less CSM

- Weight = 72,710 lb

$\bar{X} = 1,699.4$	$I_x = 296,100 \text{ slug-ft}^2$	$I_{xy} = -246,108 \text{ slug-ft}^2$
$\bar{Y} = -44.86$	$I_y = 1,706,670 \text{ slug-ft}^2$	$I_{xz} = 233,084 \text{ slug-ft}^2$
$\bar{Z} = 45.11$	$I_z = 1,735,940 \text{ slug-ft}^2$	$I_{yz} = -76,116 \text{ slug-ft}^2$

- Principal Inertias

$\alpha = -9.83 \text{ deg}$	$I_x = 215,677 \text{ slug-ft}^2$
$\beta = -9.07 \text{ deg}$	$I_y = 1,723,526 \text{ slug-ft}^2$
$\epsilon = -34.87$	$I_z = 1,799,500 \text{ slug-ft}^2$

CONFIGURATION - 3

Complete Cluster Less LM/ATM

- Weight = 76,020 lb

$\bar{X} = 1,790.9$	$I_x = 138,360 \text{ slug-ft}^2$	$I_{xy} = -17,203 \text{ slug-ft}^2$
$\bar{Y} = 3.10$	$I_y = 2,651,040 \text{ slug-ft}^2$	$I_{xz} = -9,994 \text{ slug-ft}^2$
$\bar{Z} = -4.79$	$I_z = 2,680,900 \text{ slug-ft}^2$	$I_{yz} = 60 \text{ slug-ft}^2$

- $\alpha = -.39 \text{ deg}$ $I_x = 138,201 \text{ slug-ft}^2$
- $\beta = .22 \text{ deg}$ $I_y = 2,651,158 \text{ slug-ft}^2$
- $\epsilon = -.02 \text{ deg}$ $I_z = 2,680,939 \text{ slug-ft}^2$

GENERAL EQUATIONS

The moment of momentum of the docking body is:

$$\bar{H} = (\bar{R}_I - \bar{R}_C) \times m \bar{V} \quad (1)$$

Expanding by components

$$\frac{H_x}{m} = \dot{Z}_O (Z_I - Y_C) - \dot{Y}_O (Z_I - Z_C) \quad (2)$$

$$\frac{H_y}{m} = \dot{X}_O (Z_I - Z_C) - \dot{Z}_O (X_I - X_C)$$

$$H_z = \dot{Y}_O (X_I - X_C) - \dot{X}_O (Y_I - Y_C)$$

where the subscript o indicates the initial value of the velocity.

With respect to $\bar{V}$, two cases of docking arise. Either the docking is axial or radial. If axial, then $\bar{V} = -\bar{i} + \dot{Y}_O \bar{i} + \dot{Z}_O \bar{K}$. If radial, $\bar{V} = \dot{X}_O \bar{i} + 0.707 \bar{i} - 0.707 \bar{K}$. (The radial docking ports are 45 deg to the reference coordinate system – see Fig. 2A.) We consider first the axial case and note that there are two docking situations – CSM-OWS and CSM-OWS/LM/ATM.

AXIAL DOCKING

For axial docking $\dot{X}_O = -1$ ft/sec giving

$$\frac{H_x}{m} = \dot{Z}_O (Y_I - Y_C) - \dot{Y}_O (Z_I - Z_C) \quad (3)$$

$$\frac{H_y}{m} = - (Z_I - Z_c) - \dot{Z}_o (X_I - X_c)$$

$$H_z = \dot{Y}_o (X_I - X_c) + (Y_I - Y_c)$$

Assuming that the longitudinal tolerance on the mass center is negligible in comparison with the absolute value of $(X_I - X_c)$, then the moment of momentum is a function of the lateral values (i.e., Y and Z components) of R_c , R_I , and V_o . Since the lateral displacement of R_I is permitted to be 1 ft in any direction, we will place it diametrically opposite the mass center, after allowing for mass center tolerances, so as to maximize the moment arm. The nominal position of the mass center of the CSM-OWS cluster is (see Fig. 3):

$$X_c = 1791 \quad Y_c = 3.1 \quad Z_c = -4.8 \quad (4)$$

The tolerances on the radial position (Y_c and Z_c) of the mass center have not been specified but discussions with the weight analysts have suggested that 1 percent of the diameter might be reasonable, i.e., 2.60 in. (Presumably this would be a 3σ value.) This value is added on the diameter (see Fig. 3) to give

$$r_{Mc} = 2.6 + \sqrt{3.1^2 + 4.8^2} = 8.3 \text{ in.} \quad (5)$$

$$\alpha = \tan^{-1} 3.8/4.8 = 32.8 \text{ deg} \quad (6)$$

Thus, the effective position of the mass center is

$$Y_{c_{EFF}} = 8.3 \sin 32.8 \text{ deg} = 4.5 \text{ in.} \quad (7)$$

$$Z_{c_{EFF}} = 8.3 \cos 32.8 \text{ deg} = -6.97 \text{ in.}$$

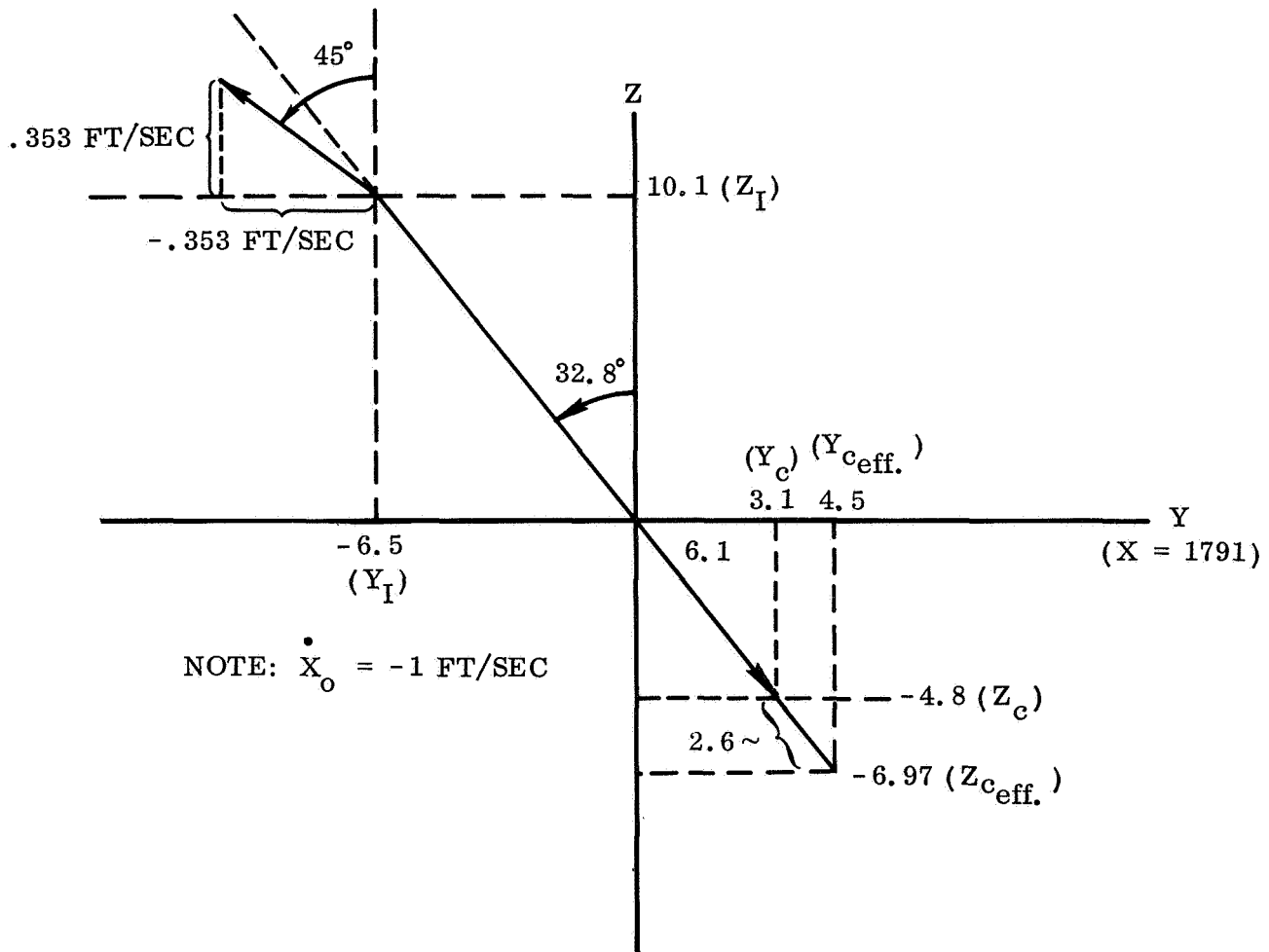


Fig. 3 CSM-OWS Mass Center, Point of Impact and Initial Velocity

Placing the point of impact diametrically opposite gives

$$Y_I = - 12 \sin 32.8 \text{ deg} = - 6.5 \text{ in.} \quad (8)$$

$$Z_I = 12 \cos 32.8 \text{ deg} = 10.1$$

$$X_I = 2075$$

Substituting these values into Eq. (3)

$$\frac{H_x}{m} = 11 \dot{Z}_O - 17 \dot{Y}_O \quad (9)$$

$$\frac{H_y}{m} = - 17 - 284 \dot{Z}_O$$

$$\frac{H_z}{m} = 284 \dot{Y}_O - 11$$

By trial and error the absolute value of the moment of momentum was found to be a maximum for the lateral velocity at an angle of 135 deg (See Fig. 3) giving

$$\dot{Y}_O = -0.5 \sin 135 = -0.353 \text{ ft/sec} \quad (10)$$

$$\dot{Z}_O = 0.5 \cos 135 \text{ deg} = 0.353 \text{ ft/sec}$$

Substituting these values into Eq. (9)

$$\frac{H_x}{m} = 2 \frac{\text{ft-in.}}{\text{sec}} \quad (11)$$

$$\frac{H_y}{m} = -117 \frac{\text{ft-in.}}{\text{sec}}$$

$$\frac{H_z}{m} = -111 \frac{\text{ft-in.}}{\text{sec}}$$

The mass of the CSM is 850 lb-sec²/ft. Ignoring polarity we have

$$H_x = 1700 \text{ in.-lb-sec} \quad (12)$$

$$H_y = 99,500 \text{ in.-lb-sec}$$

$$H_z = 94,500 \text{ in.-lb-sec}$$

Equation (12) represents the disturbance angular momentum that the auxiliary control system must cancel. At this time the control system is assumed to be located in the S-IVB engine area — station 1225 is assumed. This station gives a (1791-1225) = 566 in. pitch and yaw moment arm. The roll control jets are assumed to lie near the edge of the vehicle to maximize the roll moment arm — a radius of 125 in. is assumed. Using these control moment arms the control impulse required is

$$I_x = \frac{1700}{250} = 6.8 \text{ lb-sec} \quad (13)$$

$$I_y = \frac{99,500}{566} = 176 \text{ lb-sec}$$

$$I_z = \frac{94,500}{566} = \underline{167 \text{ lb-sec}}$$

$$I_c = 350 \text{ lb-sec}$$

Without attempting to analyze a missed docking in detail, it is assumed that the net effect would be to restore the CSM to its initial condition excepting that its velocity vector is reversed. Thus, under this assumption, a missed docking will require twice the impulse that a successful docking requires. In other words, the CSM must first be brought to a halt, then accelerated again in the opposite direction. The total control impulse for one successful and one unsuccessful docking is

$$I_{c_{TOTAL}} = 350 + 2 \times 350 = 1050 \text{ lb-sec} \quad (14)$$

The foregoing accounts for the CSM-OWS axial docking case. A second axial case arises when the CSM docks to the OWS-LM/ATM combination. The foregoing analysis applies directly except for the numerical values.

For the CSM-OWS-LM/ATM Configuration (see Fig. 4)

$$X_c = 1843 \quad Y_c = -32 \quad Z_c = 31 \quad (15)$$

As before, adding 2.60 in. on the radius

$$Y_{c_{EFF}} = -33.4 \text{ in.} \quad (16)$$

$$Z_{c_{EFF}} = 32.7 \text{ in.}$$

$$X_c = 1843 \text{ in.}$$

$$\alpha = \tan^{-1} \frac{31}{32} = 136 \text{ deg}$$

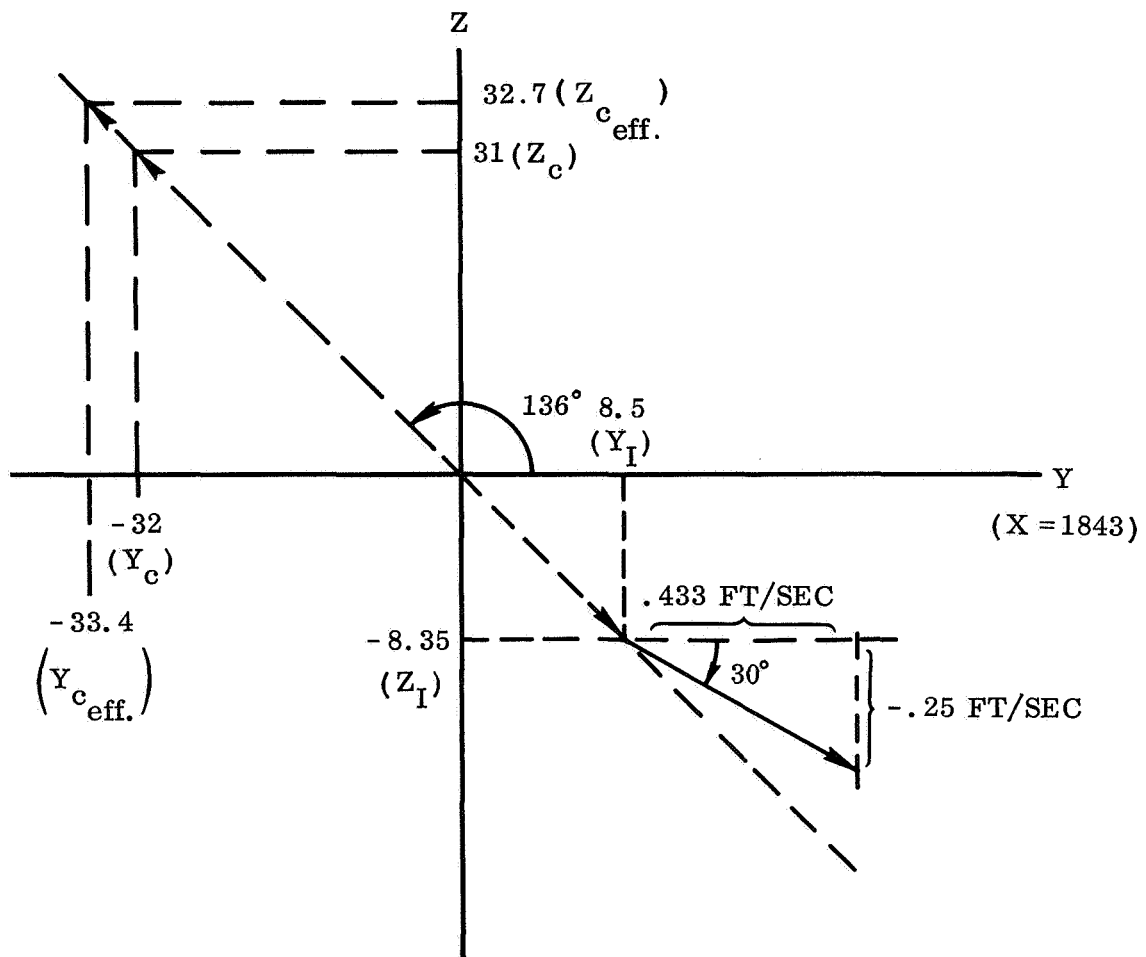


Fig. 4 CSM-OWS/IM/ATM Mass Center, Point of Impact and Impact Velocity

As before, putting the impact point diametrically opposite the mass center

$$Y_I = 12 \cos -44 \text{ deg} = 8.51 \text{ in.} \quad (17)$$

$$Z_I = 12 \sin -44 \text{ deg} = -8.35 \text{ in.}$$

$$X_I = 2075 \text{ in.}$$

Substituting into Eq. (3)

$$\frac{H_x}{m} = 41.9 \dot{Z}_O + 41.1 \dot{Y}_O \quad (18)$$

$$H_y = 41.1 - 232 \dot{Z}_O$$

$$H_z = 232 \dot{Y}_O + 41.9$$

Trial and error shows the absolute value of the moment of momentum to be maximum for the lateral velocity vector at an angle of 330 deg (see Fig. 4) giving

$$\dot{Y}_O = 0.5 \cos 330 \text{ deg} = 0.433 \text{ ft/sec} \quad (19)$$

$$\dot{Z}_O = 0.5 \sin 330 \text{ deg} = 0.25 \text{ ft/sec}$$

Substituting these values into Eq. (18)

$$\frac{H_x}{m} = 10 \frac{\text{ft-in.}}{\text{sec}} \quad (20)$$

$$\frac{H_y}{m} = 99 \frac{\text{ft-in.}}{\text{sec}}$$

$$\frac{H_z}{m} = 142 \frac{\text{ft-in.}}{\text{sec}}$$

For a CSM mass of 850 lb-sec²/ft

$$H_x = 8500 \text{ in.-lb-sec} \quad (21)$$

$$H_y = 84,000 \text{ in.-lb-sec}$$

$$H_z = 121,000 \text{ in.-lb-sec}$$

The roll moment arm remains 250 in. but the pitch and yaw moment arms are (1843-1225) = 618 in. Using these control moment arms the control impulse required is

$$I_x = \frac{8500}{250} \quad 34 \text{ lb-sec} \quad (22)$$

$$I_y = \frac{84,000}{618} \quad 136 \text{ lb-sec}$$

$$I_z = 121,000 = \underline{196 \text{ lb-sec}}$$

$$I_c \quad = 366 \text{ lb-sec}$$

Using the previous assumptions concerning a missed docking, a total control impulse is obtained.

$$I_{c\text{TOTAL}} = 366 + 2 \times 366 = 1098 \text{ lb-sec} \quad (23)$$

RADIAL DOCKING

The radial docking case arises when the LM/ATM docks to the OWS. The radial docking ports are at 45 deg to the coordinate system used herein as is shown in Fig. 5.

With this orientation the docking velocity vector is

$$V_o = \dot{X}_o I + 0.707 \bar{J} - 0.707 \bar{K} \quad (24)$$

Substituting into Eq. (2)

$$\frac{H_x}{m} = -0.707 [Y_I - Y_c + Z_I - Z_c] \quad (25)$$

$$\frac{H_y}{m} = X_o (Z_I - Z_c) + 0.707 (X_I - X_c)$$

$$\frac{H_z}{m} = 0.707 (X_I - X_c) - \dot{X}_o (Y_I - Y_c)$$

With respect to determining the moment arms, two general cases arise. The mass center can be assumed to move radially (as was assumed for axial docking) and the point of impact assumed to move longitudinally (see Fig. 5A). In this case $H_x \equiv 0$ but H_y and H_z will be maximized if X_I moves 12 in. positively. The other case permits the mass center to move tangentially as well as the point of impact. In this case $H_x \neq 0$ but H_y and H_z are not maximized since the permitted lateral displacement is taken in Y and Z . Both cases will be considered. First let the mass center move radially and the lateral displacement of the point of impact of 1 ft be taken in X . The nominal mass center is at

$$X_c = 1699 \quad Y_c = -45 \quad Z_c = 45 \quad (26)$$

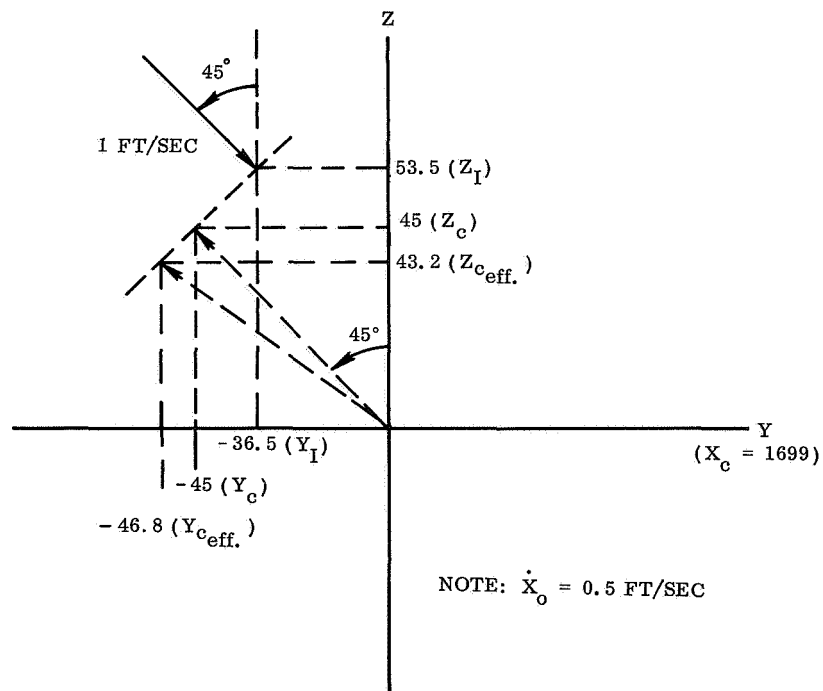
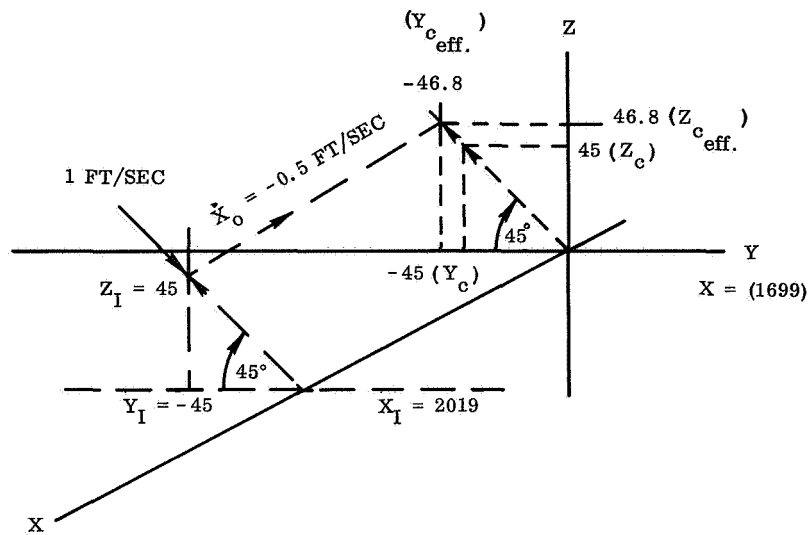


Fig. 5 LM/ATM-OWS Mass Center, Point of Impact and Impact Velocity

Allowing for the 2.60 in. tolerance

$$r_c = 2.6 \sqrt{45^2 + 45^2} = 2.6 + 63.5 = 66.1 \text{ in.} \quad (27)$$

$$Y_{c_{\text{EFF}}} = -66.1 \cos 45^\circ = -46.8 \quad Z_{c_{\text{EFF}}} = 66.1 \sin 45^\circ = 46.8$$

$$X_{c_{\text{EFF}}} = 1699$$

The docking port is at the same position as the nominal mass center but we take the permitted 1 ft lateral displacement in X.

$$X_I = 2007 + 12 = 2019 \quad Y_I = -45 \quad Z_I = 45 \quad (28)$$

Substituting Eqs. (27) and (28) in Eq. (25)

$$\frac{H_x}{m} = 0 \quad (29)$$

$$\frac{H_y}{m} = -1.8 \dot{X}_O + 226$$

$$\frac{H_z}{m} = 226 - 1.8 \dot{X}_O$$

The permitted lateral velocity of 0.5 ft/sec will be taken as $\dot{X}_O = -0.5 \text{ ft/sec}$ to maximize H.

$$H_x = 0 \quad \frac{H_y}{m} = \frac{H_z}{m} = 227 \frac{\text{in.-ft}}{\text{sec}} \quad (30)$$

The mass of the LM/ATM is $747 \text{ lb-sec}^2/\text{ft}$

$$H_y = H_z = 170,000 \text{ in.-lb-sec} \quad (31)$$

As before, the roll control moment arm is 250 in. but the pitch and yaw arms is now $(1699-1225) = 474$ in giving a required control impulse of

$$I_x = 0 \quad (32)$$

$$I_y = \frac{170,000}{474} = 359 \text{ lb-sec}$$

$$I_z = \frac{170,000}{474} = \underline{359 \text{ lb-sec}}$$

$$I_c = 718 \text{ lb-sec}$$

As before, take a missed docking as requiring twice the impulse of a successful one.

$$I_{c\text{TOTAL}} = 718 + 2 \times 718 = 2154 \text{ lb-sec} \quad (33)$$

For the alternate case let the mass center move tangentially. To maximize the moment arms let $|Y_c|$ increase and $|Z_c|$ decrease (see Fig. 5B).

$$Y_{c\text{EFF}} = -45 - 2.6 \cos 45 \text{ deg} = -46.8 \text{ in.} \quad (34)$$

$$Z_{c\text{EFF}} = 45 - 2.6 \sin 45 \text{ deg} = 43.2 \text{ in.}$$

$$X_{c\text{EFF}} = 1699 \text{ in.}$$

The point of impact moves in the opposite direction to the mass center movement in order to maximize the moment arms.

$$X_I = 2007 \text{ in.} \quad (35)$$

$$Y_I = -45 + 12 \cos 45 \text{ deg} = -36.5 \text{ in.}$$

$$Z_I = 45 + 12 \sin 45 \text{ deg} = 53.5 \text{ in.}$$

Substituting the foregoing into Eq. (25)

$$\frac{H_x}{m} = -14.6 \frac{\text{in.-ft}}{\text{sec}} \quad (36)$$

$$\frac{H_y}{m} = 10.3 \dot{X}_O + 218$$

$$\frac{H_z}{m} = 218 - 10.3 \dot{X}_O$$

Because of the symmetry in the H_y and H_z , the polarity of $\dot{X}_O$ does not influence the value of the total control impulse required. Take $\dot{X}_O = 0.5 \text{ ft/sec}$.

$$\frac{H_x}{m} = -15 \frac{\text{in.-ft}}{\text{sec}} \quad (37)$$

$$\frac{H_y}{m} = 223 \frac{\text{in.-ft}}{\text{sec}}$$

$$\frac{H_z}{m} = 213 \frac{\text{in.-ft}}{\text{sec}}$$

Using $m = 747 \text{ lb-sec}^2/\text{ft}$

$$H_x = -10,900 \text{ in.-lb-sec} \quad (38)$$

$$H_y = 167,000 \text{ in.-lb-sec}$$

$$H_z = 159,000 \text{ in.-lb-sec}$$

Using a roll moment arm of 250 in. and a pitch-yaw arm of 474 in.

$$I_x = 43.5 \text{ lb-sec} \quad (39)$$

$$I_y = 353 \text{ lb-sec}$$

$$I_z = \underline{336 \text{ lb-sec}}$$

$$I_c = 733 \text{ lb-sec}$$

Allowing for one missed docking

$$I_{c\text{TOTAL}} = 733 + 2 \times 733 = 2199 \text{ lb-sec} \quad (40)$$

Of the two cases the later is the more demanding, but only by about 2 percent suggesting that the control impulse requirements are not sensitive to mass center and point of impact variations.

RENDEZVOUS

To estimate the control impulse requirements during rendezvous, a deadband control system limiting the vehicle to 0.10 deg/sec and ± 20 deg about the vertical will be assumed. Current NASA data indicate that a control force of 50 newtons (about 11.2 lb) will be available. Using the notation shown in Fig. 6 the control impulse per

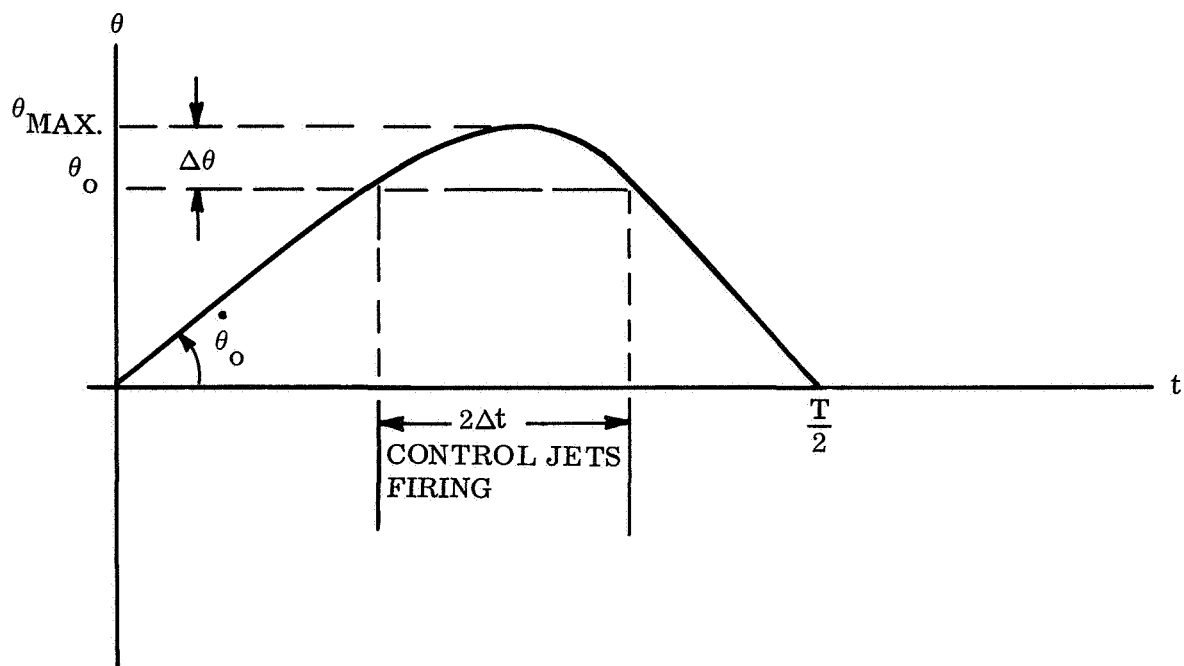


Fig. 6 Deadband Motion

cycle, the period of the steady-state oscillation, the period of control force operation, and the "overshoot" ($\Delta\theta$) are given by

$$I_c = 4 I \dot{\theta}_0 / \ell \quad (41)$$

$$T = 4 (\theta_m + \Delta\theta) / \dot{\theta}_0 \quad (42)$$

$$\Delta t = I \dot{\theta}_0 / F \ell \quad (43)$$

$$\Delta\theta = I \dot{\theta}_0^2 / 2 F \ell \quad (44)$$

For the OWS alone we have

$$\begin{aligned} I &= 880,000 \text{ ft-lb-sec}^2 \\ \ell &= 26.8 \text{ ft} \\ F &= 11.2 \text{ lb} \\ \dot{\theta}_o &= 0.10 \text{ deg/sec (specified)} \\ \theta_m &= 20 \text{ deg (specified)} \end{aligned} \tag{45}$$

For these values we find

$$\begin{aligned} I_o &= 229 \text{ lb-sec/cycle} \\ \Delta\theta &= 0.256 \text{ deg} \\ T &= 815 \text{ sec} = 13.6 \text{ min} \\ \Delta t &= 5.1 \text{ sec} \end{aligned} \tag{46}$$

The period of operation in this mode is unknown at this time. However, it seems likely that it will be found highly desirable to have established successful operation in this mode of control before launch of the docking vehicle. To do this would appear to require initiation of this mode of control at one pass followed by monitoring at the second to be followed by launch of the docking vehicle. This sequence places a minimum of one orbit period, around 94 min, as the duration of this mode. For purposes of estimating control impulse we will assume 2 hr.

Ignoring any startup transient in 2 hr of operations we have

$$N = \frac{2 \times 3600 \text{ sec}}{814 \text{ sec/cycle}} = 8.83 \text{ cycles} \tag{47}$$

giving

$$I_{c_{TOTAL}} = 229 \frac{\text{lb-sec}}{\text{cycle}} \times 8.83 \text{ cycles} = 2020 \text{ lb-sec} \quad (48)$$

GRAVITY GRADIENT

During storage, the two significant torques acting upon the vehicle are those caused by the gravity gradient and aerodynamic forces. We consider here those caused by the gravity gradient and, in the following section, those caused by aerodynamic forces.

For a vehicle turning at orbit rate, i.e., basically aligned to the local vertical, the torques caused by the gravity gradient are given by (see Fig. 2A)

$$M_x = \frac{K}{2} (I_z - I_y) \sin 2 \theta \sin \phi \quad (49)$$

$$M_y = \frac{K}{2} (I_x - I_z) \sin 2 \theta \cos \phi$$

$$M_z = \frac{K}{2} (I_x - I_y) \sin 2 \phi \cos^2 \theta$$

$$K = \frac{3GM_e}{R_o^3}$$

If the usual small angle approximations are made, Eq. (49) becomes

$$M_x \cong K (I_z - I_y) \theta \phi \cong 0 \quad (50)$$

$$M_y \cong K (I_x - I_z) \theta$$

$$M_z \cong K (I_x - I_y) \phi$$

For the OWS alone

$$I_x = 123,000 \text{ ft-lb-sec}^2 \quad (51)$$

$$I_y = 870,000 \text{ ft-lb-sec}^2$$

$$I_z = 899,000 \text{ ft-lb-sec}^2$$

$$K = 3.88 \times 10^{-6} \frac{1}{\text{sec}^2}$$

Substituting into Eq. (50)

$$M_x \cong 0 \quad (52)$$

$$M_y \cong -2.9 \theta \frac{\text{ft-lb}}{\text{rad}}$$

$$M_z \cong -3.02 \phi \frac{\text{ft-lb}}{\text{rad}}$$

For the OWS/LM/ATM configuration

$$I_x = 296,000 \text{ ft-lb-sec}^2 \quad (53)$$

$$I_y = 1,707,000 \text{ ft-lb-sec}^2$$

$$I_z = 1,736,000 \text{ ft-lb-sec}^2$$

$$M_x \cong 0 \quad (54)$$

$$M_y \cong -5.6 \phi \frac{\text{ft-lb}}{\text{rad}}$$

$$M_Z \cong - 5.5 \theta \frac{\text{ft-lb}}{\text{rad}}$$

Since the moments are negative, the torques are stabilizing in that they tend to hold the vehicle to the vertical. However, the actual motion can only be determined by including both the aerodynamic moments and the initial conditions with which the vehicle is stored in orbit.

AERODYNAMIC TORQUES

The aerodynamic characteristics for the nose-down attitude in orbit are

$$C_N = 26.4 \tag{55}$$

$$X_{cp} = 457 \text{ in. ahead of control point (Station 1225)}$$

$$S = 369 \text{ ft}^2$$

The aerodynamic moment is given by

$$M_{aero} = C_N S (X_{cg} - X_{cp}) q \tag{56}$$

where q = dynamic pressure

Figure 7 shows the variation in dynamic pressure with altitude for day and night conditions for maximum solar activity. Using the day and night extremes and the OWS mass center of $X_{cg} = 1547$ we get

$$M_{aero \min} = 0.22 \text{ ft-lb} \tag{57}$$

$$M_{aero \max} = 0.77 \text{ ft-lb}$$

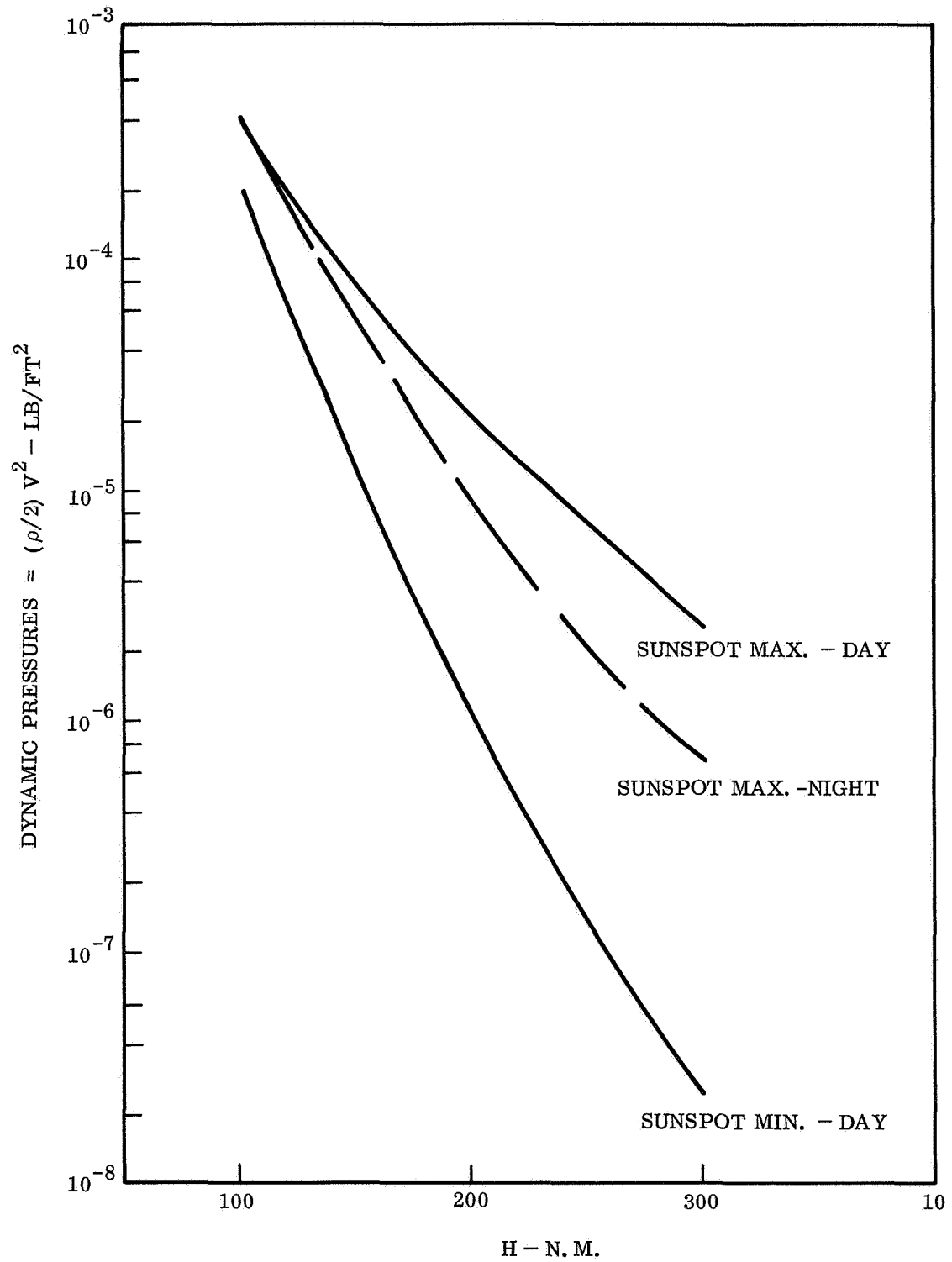


Fig. 7 Dynamic Pressure Variations

It should be noted that these results are essentially the same for the OWS and the OWS-CM/ATM configuration.

For the analysis of the following section we will assume that the dynamic pressure varies sinusoidally between the night and day extremes, i.e., $q = q_o + \Delta q \sin wt$ (w is the orbit frequency). Taking the remaining terms of M_{aero} as constants we get ($M_{aero} = A + B \sin wt = 0.495 + 0.275 \sin wt$). (58)

UNCONTROLLED MOTION

During storage it is required only that the vehicle not tumble. Assuming that active control is not required during this mode of operation the vehicle moves under the action of initial conditions, gravity gradient torques, and aerodynamic torques. The equation of motion is

$$I \ddot{\theta} + K\theta = M_{\alpha}(t) \quad (59)$$

where

- θ = the body rotation in pitch or yaw
- K = gravity gradient spring [see Eqs. (52) or (54)]
- $M_{\alpha}(t)$ = aerodynamic moment which is a function of time because of the variation in q as the vehicle proceeds around the orbit from day to night and back
- I = pitch (or yaw) moment of inertia

Assuming that $M(t)$ can be represented as a sinusoidal variation about a nominal level [see Eq. (58)] the solution to Eq. (59) is

$$\theta(t) = \frac{\theta_o}{\omega_n} \left[\left(\frac{\dot{\theta}_o}{\theta_o} \right)^2 + \omega_n^2 \right]^{1/2} \sin(\omega_n t + \Psi) + \frac{A}{I\omega_n^2} (1 - \cos \omega_n t) \quad (60)$$

$$- \frac{B\omega}{I(\omega^2 - \omega_n^2)} \left[\frac{\sin(\omega_n t)}{\omega_n} - \frac{\sin(\omega t)}{\omega} \right]$$

$$\Psi = \tan^{-1} \frac{\omega \theta_o}{\dot{\theta}_o}$$

where

θ_o = initial attitude

$\dot{\theta}_o$ = initial attitude rate

$W_N = K/I$

W = orbit frequency (period $\cong$ 94 min)

A = nominal value of $M_{\alpha}(t) = 0.495$ ft-lb

B = half amplitude of sinusoidal variation of $M_{\alpha}(t) = 0.275$ ft-lb

For the OWS alone we have

$$W_N^2 = \frac{K}{I} \cong \frac{3 \text{ ft-lb/rad}}{9 \times 10^5 \text{ ft-lb-sec}^2} = 3.33 \times 10^{-6} \text{ rad/sec}^2 \quad (61)$$

$$W = 0.0011 \text{ rad/sec}$$

$$A = 0.495 \text{ ft-lb}$$

$$B = 0.275 \text{ ft-lb}$$

Ignoring initial conditions and substituting the foregoing data into Eq. (60)

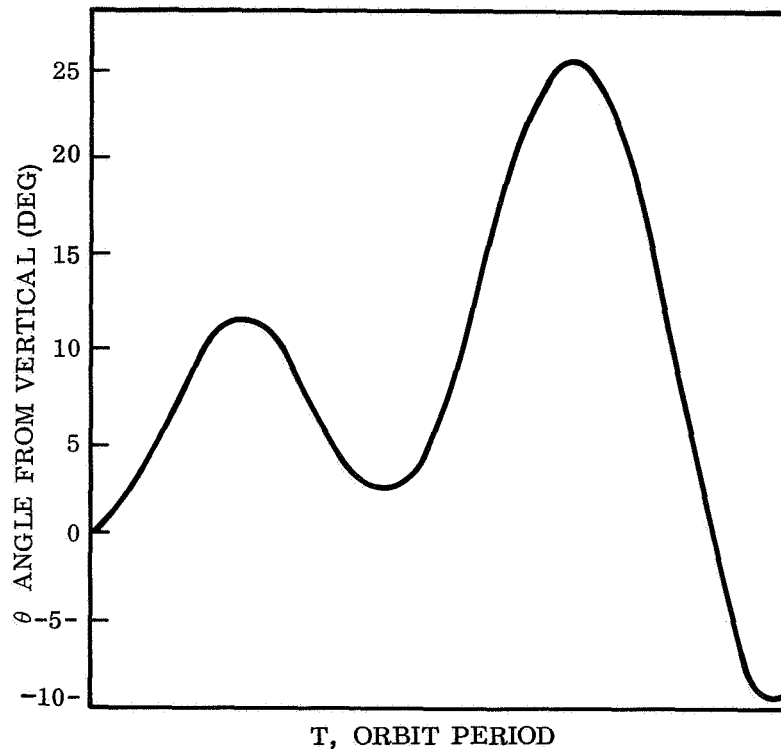


Fig. 8 Uncontrolled Motion of OWS With Gravity Gradient and Aerodynamic Torques

$$\theta(t) = 0.164 (1 - \cos 0.0018t) = 0.145 (\sin 0.00115 - 0.61 \sin 0.0018t) \quad (62)$$

Normalize to the body natural frequency, i. e., let

$$t = \frac{2\pi T}{0.0018} \quad (63)$$

giving

$$\theta(T) = 0.164 (1 - \cos 2\pi T) + 0.145 (0.61 \sin 2\pi T - \sin 3.91T) \quad (64)$$

Repeating for the OWS-LM/ATM configuration

$$\theta(T) = 0.0895 (1 - \cos 2\pi T) + 0.0815 (0.62 \sin 2\pi T - \sin 3.91 T) \quad (65)$$

The OWS alone would appear to reach the larger amplitudes. Equation (64) is shown in Fig. 8 for the first two cycles, i. e. , through $T = 2$.

Figure 8 shows clearly that within one or two orbits (body frequency $\cong$ orbit frequency) the amplitude of Eq. (64) may reach 25 deg. Higher values may be possible for a greater number of orbits.

The third term of Eq. (60) suggests that if $W = W_n$ a resonance phenomena might occur. Rather than analyze this term in its present form we return to Eq. (59) and take the Laplace Transform of this one component of $\theta(s)$ which we denote $\theta_1(s)$.

$$\theta_1(s) = \frac{BW}{I(S^2 + W^2)(S^2 + W_N^2)} \quad (66)$$

If the rigid body frequency (W_N) should be the same as W , the orbit frequency, we obtain

$$\theta_1(s) = \frac{BW}{I(S^2 + W^2)^2} \quad (67)$$

The inverse transform is directly found to be

$$\begin{aligned} \theta_1(t) &= \left(\frac{BW}{I}\right) \frac{\sin wt - wt \cos wt}{2W^3} \\ &= \frac{B}{2IW^2} (\sin wt - wt \cos wt) \end{aligned} \quad (68)$$

Using the data previously listed for the OWS

$$\begin{aligned} \theta_1(t) &= \frac{0.274}{2 \times 9 \times 10^5 (0.00111)^2} (\sin 0.00111t - 0.00111t \cos 0.00111t) \\ &= 0.122 (\sin 0.00111t - 0.00111t \cos 0.00111t) \end{aligned} \quad (69)$$

In 900 sec the amplitude of the second term will equal that of the first; thereafter, the cos term will dominate. At the end of one orbit (94 min = 5,640 sec).

$$\begin{aligned}\theta_1(5640) &= 0.122 (\sin 359 \text{ deg} - 6.27 \cos 359 \text{ deg}) & (70) \\ &= 0.122 (0 - 6.27) = -0.765 \text{ rad} = -43.7 \text{ deg}\end{aligned}$$

Thus, by the end of one orbit the amplitude would reach 44 deg and after two orbits be around 90 deg.

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Table 4
OWS CONTROL IMPULSE REQUIRED

<u>Event</u>	<u>Maneuver</u>	<u>Impulse (lb-sec)</u>
1	Insert S-IVB (AAP-2) in gravity gradient stabilized position – MDA down	0
2	Maintain gravity-gradient position during CSM rendezvous	2, 020
3	Stabilize OWS after one successful and one missed docking attempt by CSM	1, 050
4	Reacquire gravity-gradient stabilized position after CSM undocking	1, 000
5	Maintain gravity-gradient stabilized position for CSM revisit rendezvous	2, 020
6	Stabilize OWS after one successful and one missed attempt by revisiting CSM	1, 050
7	Reacquire gravity-gradient stabilized position after CSM undocking	1, 000
8	Maintain gravity-gradient stabilized position during CSM and LM/ATM rendezvous	2, 020
9	Restabilize OWS after two docking attempts by LM/ATM	2, 199
10	Stabilize OWS after one successful and one missed docking attempt by CSM	1, 098
11	Reacquire gravity-gradient stabilized position after CSM undocking	1, 000
Total		14, 457