

mass ratio for initial eccentricities of 0.02, 0.06, and 0.1 with a perigee altitude of 110 miles.

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## Orbital Docking Dynamics

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A docking configuration and docking sequence are described for accomplishing an orbital refueling mission. The docking configuration consists essentially of matched conical surfaces, on the docking vehicles, and a latching device. A mathematical model for studying the collision dynamics is presented, and the effects of guidance errors, attitude errors, and various structural parameters on docking performance are discussed. Requirements for attitude control also are included. It is concluded that the proposed docking configuration is feasible and will accommodate reasonable system errors.

### Introduction

THE first orbital docking missions will be performed in order to develop techniques and establish operational procedures as well as to accomplish logistic operations between orbiting vehicles. A typical docking mission will consist presumably of ground tracking to establish ephemerides of the target satellite, launch and ascent guidance of the chaser vehicle to an orbit "nearby" that of the target, terminal or rendezvous guidance to bring the chaser near the target, a docking maneuver to connect the vehicles, and finally a transfer of material from the chaser vehicle to the target. A subsequent disengagement of the vehicles also may be desirable. Of these various phases, all but docking and material transfer have been studied to some degree, and accounts of these studies appear in the literature. This probably can be attributed to the fact that these two phases simply occur later in the natural sequence of events leading to sustained orbital operations. Docking and material transfer tech-

niques must be developed, however, before an integrated system for orbital operation can be designed.

This paper is concerned primarily with the dynamics of a docking collision between vehicles of particular specifications and the accompanying attitude control problem. To place these subjects in their proper context and perspective, the docking assembly is introduced first and the docking sequence summarized. The model used to study the docking collision then is described and the assumptions and parameters used in the collision study are presented. The results of this study and the attendant control requirements then are discussed.

### Docking Description

The docking configuration described below represents a possible design for accomplishing a refueling operation. The configuration (Fig. 1) consists of matched conical docking surfaces on the target and chaser (tanker) vehicles, a shock absorber system around the rim of the target cone, and a latching mechanism located near the vertex of this cone. The docking surface of the target is attached by a compliant system of structural members enabling the surface to yield to the forces of collision. During the docking maneuver the docking surfaces will contact and move into near spatial coincidence, triggering the spring loaded latching mechanism into place. The latching mechanism is spring loaded both transversely and radially so that it not only secures the nose of the chaser vehicle but also tends to bring the vehicles into closer contact. The geometrical placement of the latching mechanism and the shock absorber is such that the chaser rim will contact the shock absorbers at almost the same time the latching device is triggered. The combined effect of the highly damped absorbers and the stabilizing axial force exerted by the latching mechanism will reduce the relative velocities of the vehicles. The latching mechanism finally is drawn into the target vehicle hydraulically and the vehicles securely fastened by additional fittings located at the vertices of the docking cones.

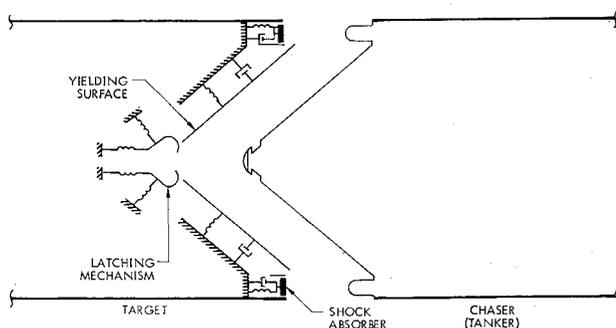


Fig. 1 Schematic cross section of docking assembly

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Table 1 Basic parameter values and parameters ranges

Case 1	Case 2	Parameter ranges
$V_{x0} = 120$ in./sec	$V_{x0} = 120$ in./sec	$60$ in./sec. $\leq V_{x0} \leq 140$ in./sec
$\theta_{20} = +2^\circ$	$\theta_{20} = -2^\circ$	$-5^\circ \leq \theta_{20} \leq +5^\circ$
$y_{20} = +10$ in.	$y_{20} = +10$ in.	$0$ in. $\leq y_{20} \leq +20$ in.
$\delta = 20^\circ$	$\delta = 30^\circ$	$15^\circ \leq \delta \leq 40^\circ$
$k = 4000$ lb/in.	$k = 4000$ lb/in.	$1000$ lb/in. $\leq k \leq 8000$ lb/sec
$\beta = 20 \frac{\text{lb-sec}}{\text{in.}}$	$\beta = 100 \frac{\text{lb-sec}}{\text{in.}}$	$1 \frac{\text{lb-sec}}{\text{in.}} \leq \beta \leq 100 \frac{\text{lb-sec}}{\text{in.}}$
$\mu = 0.1$	$\mu = 0.2$	$0.1 \leq \mu \leq 0.9$

where

$V_{x0}$  = closing velocity ( $V_{x0}$  is parallel to target roll axis)  
 $\theta_{20}$  = chaser attitude angle (measured with respect to direction of  $V_{x0}$ )  
 $y_{20}$  = lateral miss  
 $\delta$  = cone angle

$k$  = compliance of target docking surface support structure  
 $\beta$  = damping in target docking surface structure  
 $\mu$  = coefficient of Coulomb friction between docking surfaces

During the terminal guidance or active homing phase of the docking mission both vehicles are attitude controlled in yaw and pitch to align their respective roll axes with the relative position vector. In addition, the roll attitude reference for each is derived externally and nominally the same. At the end of the active homing period, which occurs at a relatively short range, all attitude control channels for both vehicles are placed on gyro reference. The vehicles then coast to a collision with fixed attitude, and docking occurs as just described. Any attitude errors induced by the collision ultimately are removed by the attitude control system, and the combined vehicles are returned to the target attitude reference.

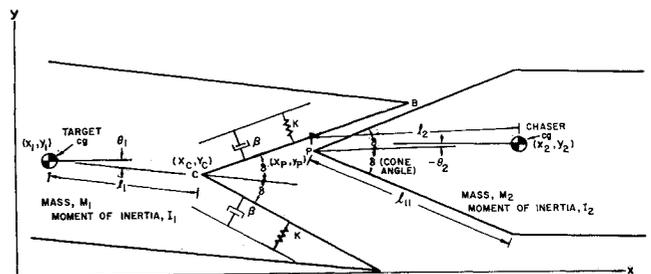


Fig. 2 Two-dimensional model used in docking dynamic simulation

**Mathematical Model**

The two-dimensional model and coordinate system used to study the dynamics of the docking collision are shown in Fig. 2. The details of the latching mechanism and shock absorbers were omitted since the primary concern of this initial study was to examine the feasibility of the conical surface configuration for docking purposes. The attitude control torques were omitted since they prove to be insignificant in comparison to the torques generated by the docking collision with the closing rates that were considered.

**Docking Parameters**

The parameters varied in the collision study (see Figs. 2 and 3) were closing rate, lateral miss, attitude misalignment, cone angle, structural compliance, structural damping, and coefficient of Coulomb friction between the docking surfaces. The moments of inertia, the masses of the vehicles, and the common vehicle radius were held fixed during the study. The attitude misalignment of the target and the component of closing velocity normal to the target roll axis were assumed to be negligible.† The equations of motion‡ were sufficiently complex and the number of parameters sufficiently large to make impractical a strictly analytical study. Hence, an analog computer was used to solve the equations and obtain data on the dynamics of the docking collision.

The collision study results must be prefaced with a few remarks as to the methods of parameter variation and interpretation which were used. In order to limit reasonably

† It should be noted that this approach clearly limits the generality of the study. By placing the parameters in a dimensionless form and by considering more parameters as variables, the scope of the study could have been enlarged. Hence, this work must be regarded as a feasibility study rather than as a parameter analysis.

‡ This paper is a condensation of Ref. 3. The equations of motion used are given in an Appendix of Ref. 3.

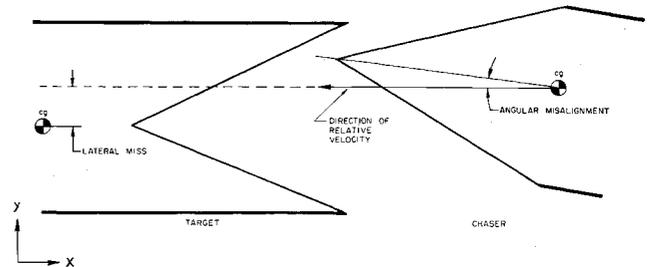


Fig. 3 Geometrical parameters

the number of computer solutions and at the same time obtain data showing the effect of each of the parameters, two basic sets of parameters were selected, and each of the parameters varied from its nominal value while the remaining parameters were held fixed. The basic parameter values, and parameter values and parameter ranges are shown in Table 1. The relative vehicle positions for case 1 with no attitude control are shown pictorially in Fig. 4.

In addition to selecting the parameters in the manner described, it was necessary to select a criterion for evaluating the relative performance of the docking configuration. The criterion chosen was projection of the longitudinal distance between the vertices of the target and chaser cones when the relative velocity became zero. The distance is termed penetration depth and is illustrated in Fig. 5. As ensuing figures will show, penetration depth may be negative, indicating that the chaser nose reached a point beyond the vertex of the target cone. Since the latching mechanism presumably will be activated before the chaser nose reaches this vertex, a negative penetration depth is interpreted as indicating a satisfactory docking performance.

**Collision Study Results**

The results of the collision study are presented in terms of the effect of each of the docking parameters on penetration depth.

**Lateral Miss**

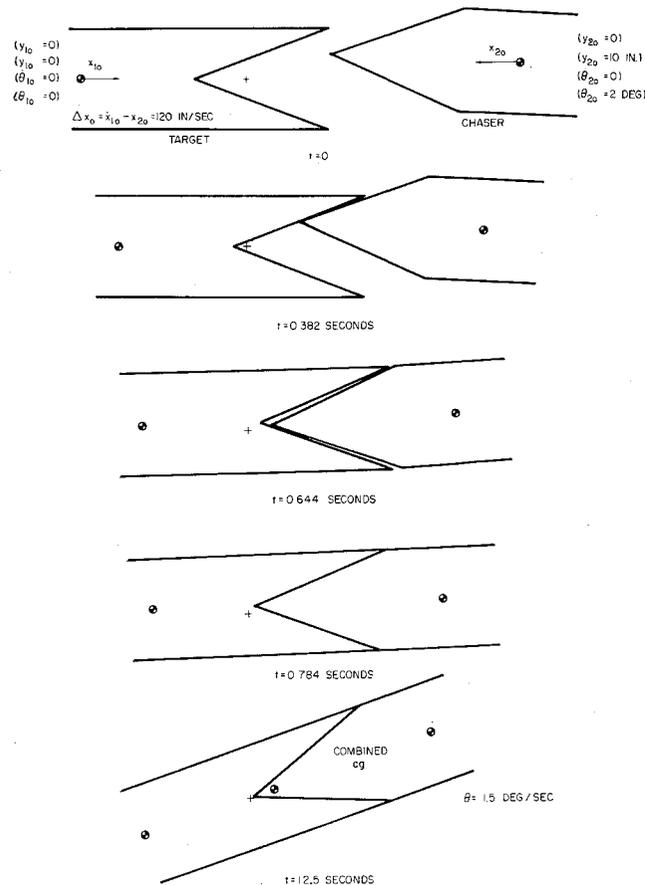
Lateral miss does not appear to be a significant factor in determining penetration depth. The results indicate that the vehicle will dock for miss distances up to 20 in., with a penetration depth of -0.8 and -1.9 in. for cases 1 and 2, respectively, provided the angular misalignment allows the nose of the chaser vehicle to fall inside the docking area (face of the target cone). The lateral miss does prove to be an important parameter in determining the control torques necessary to assure recovery from docking transients.

**Attitude Misalignment**

Penetration depth is relatively insensitive to chaser misalignment up to  $\pm 5^\circ$ . There are some associated geometrical effects such as the change in distance between c.g.'s at initial impact and change in moment arms at initial impact which causes the variations in the curves of Fig. 6. These variations are considered to be of minor importance.

**Closing Rate**

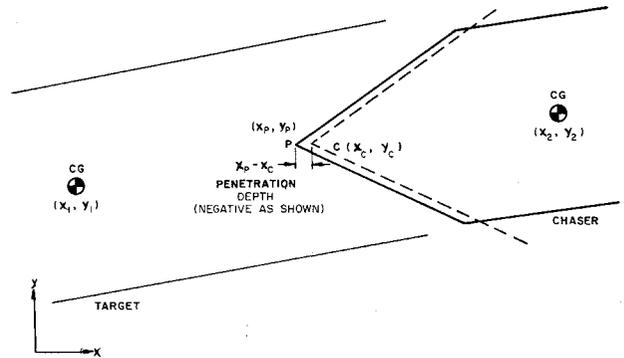
Closing rate effects penetration depth in an almost linear manner as shown in Fig. 7. As the closing velocity is reduced by successive collisions, the ratio of viscous (damping) force to compression force also decreases. At penetration, the closing velocity is such that the compression force dominates and the remaining kinetic energy is approximately equal to the energy transferred into the potential energy of spring compression upon penetration. This potential energy is proportional to the square of the displacement and the linear relation follows. This line of reasoning holds only if the relative phase of the vehicular motions is almost independent of initial docking velocity. Examination of the data shows this to be true.



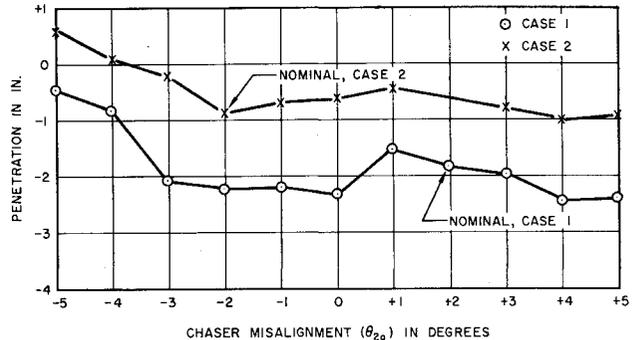
**Fig. 4** Relative motion of vehicles with no attitude control; case 1, 20° cone

**Cone Angle**

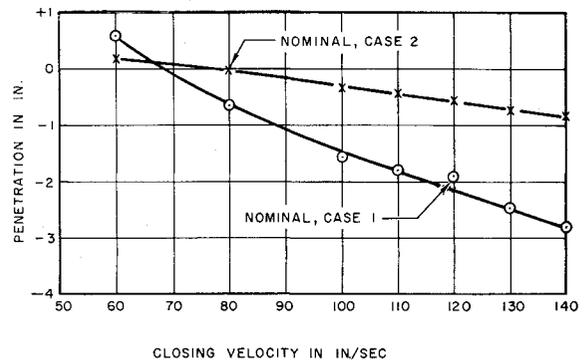
As indicated in Table 1 the cone angle  $\delta$  was varied between  $15^\circ$  and  $40^\circ$  in the simulation. For angles in this range, the effect of cone angle on docking ability was less than anticipated. Figure 8 shows the variation in penetration depth with cone angle. It can be seen that penetration occurs for cone angles from  $15^\circ$  to about  $35^\circ$ . It should be noted that the proportionality constant in the linear relation between closing rate and penetration depth will vary with cone angle.



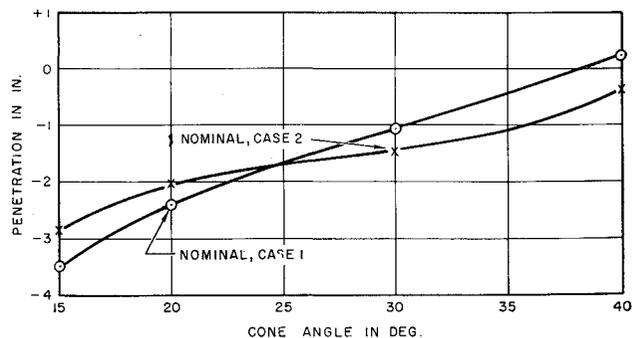
**Fig. 5** Penetration depth



**Fig. 6** Variation in penetration depth with initial chaser misalignment



**Fig. 7** Variation in penetration depth with closing velocity



**Fig. 8** Variation in penetration depth with cone angle

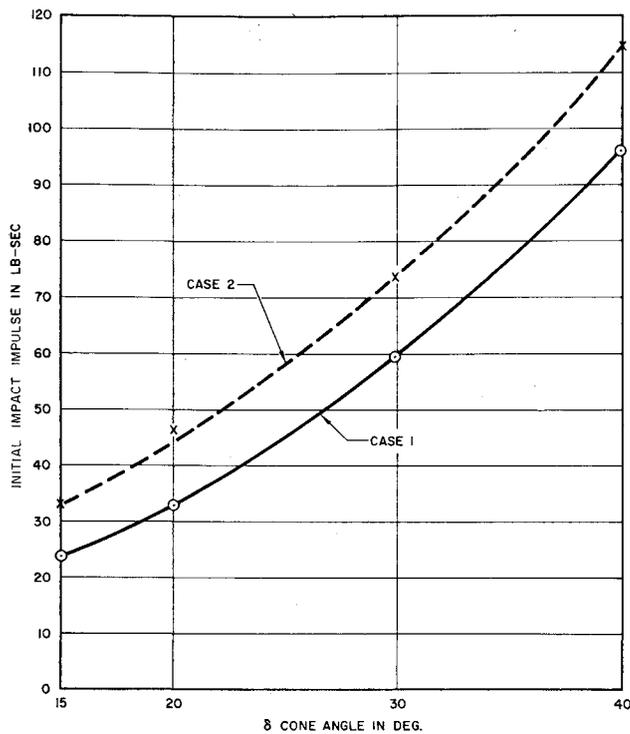


Fig. 9 Variation of initial impact impulse with cone angle

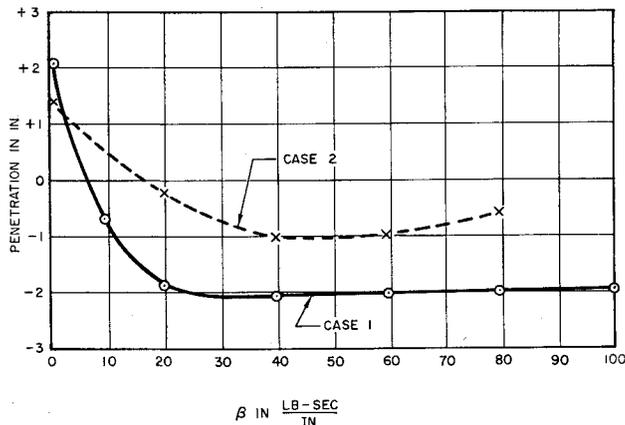


Fig. 10 Variation of penetration depth with damping

The most important influences of cone angle probably lie in the structural area. The impulse generated at initial impact increases with cone angle (Fig. 9) as a consequence of the decreased impulse component acting to produce the angular velocity required to align the docking surfaces.

**Structural Damping and Compliance**

Structural damping and compliance affect the penetration depth as shown in Figs. 10 and 11. The curves indicate an optimum (in the sense of maximum penetration) compliance-damping combination.

The compliance-damping ( $k$ - $\beta$ ) combination in part determines the time history of the impulse type forces. By varying the  $k$ - $\beta$  combination the force time history for impulsive contacts can be varied between the extremes a and c in Fig. 12. Proper choice of compliance and damping would therefore reduce peak forces by producing an impulse shape as shown in b, Fig. 12.

**Coulomb Friction**

The Coulomb friction-penetration depth relation (Fig. 13) is a consequence of 1) an increase in impulse arising from frictional resistance to the rotation required to match the dock-

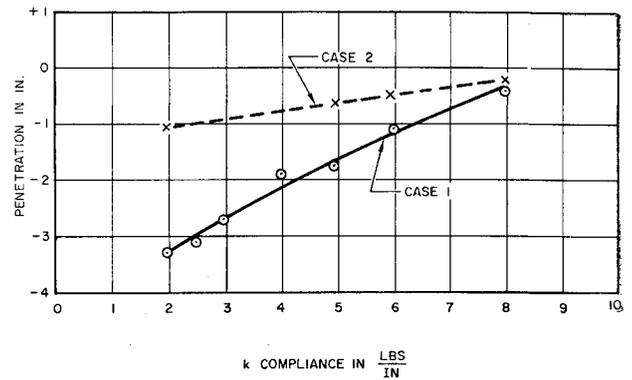


Fig. 11 Variation of penetration depth with compliance

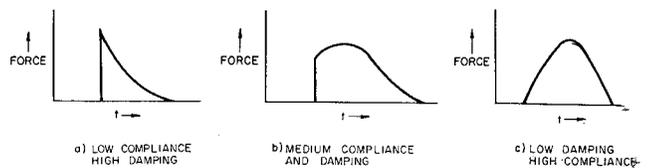


Fig. 12 Force-time histories for three different damping compliance ratios

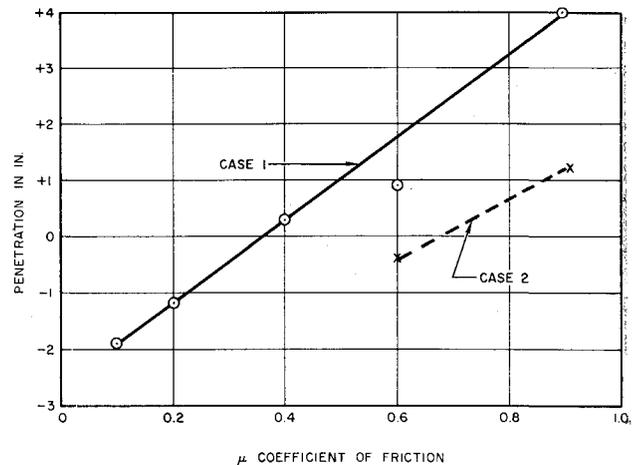


Fig. 13 Variation of penetration depth with friction

ing surfaces, and 2) a variation in closing rate reduction at each contact arising from the rotational effect of friction on the direction of the forces. Closing rate then affects penetration as just discussed. A reasonable upper limit on the friction coefficient appears to be 0.3.

**Attitude Control Discussion**

During the docking period (the time interval between the initial collision and the triggering of the latching mechanism), the vehicles may be subjected to high angular accelerations. The resulting angular velocities may be sufficiently high and the docking period sufficiently short to subject essentially the attitude control gyros to a step input of angular displacement. In addition the angular momentum of the two-vehicle system, which arises from a nonzero lateral miss, is conserved during the collision and results in an angular rate for the combined vehicle at the end of the docking period. The attitude control system must be capable of removing this terminal rate before the gyros lose reference if reacquisition maneuvers are to be avoided.

An upper bound for the angular displacement input during the docking period can be computed by assuming that the centers of gravity (c.g.'s) of the two vehicles continue to move in a straight line during this period. The angular displacements of the target vehicle given by the simulation are shown and compared to this upper bound in Fig. 14. The angular

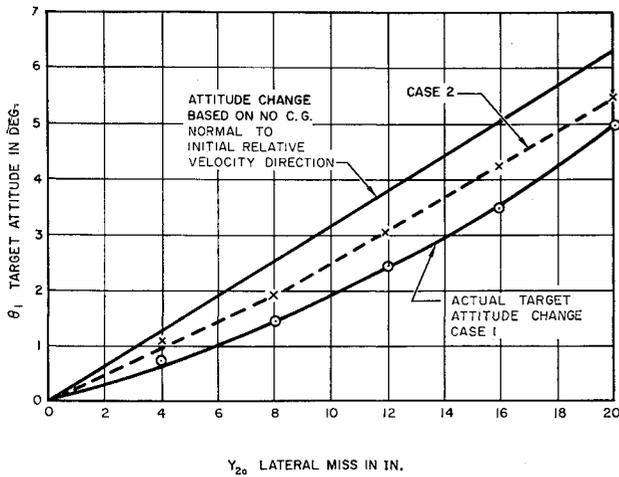


Fig. 14 Variation of accrued target attitude angle with lateral miss

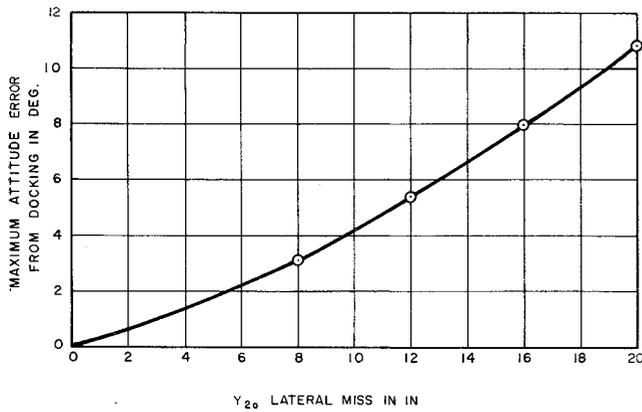


Fig. 15 Variation of maximum attitude transient at docking with lateral miss

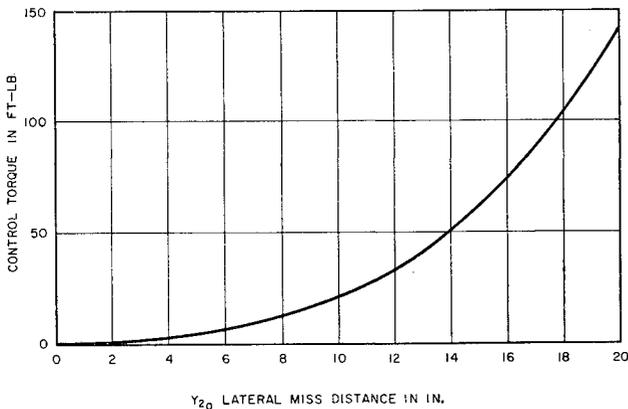


Fig. 16 Variation of control torque required with lateral miss (assumes no loss of reference with 12° gyro)

rate of the combined vehicles may be computed from the fact that angular momentum is conserved. The maximum angular excursion, assuming a specific saturation control torque, can be determined by combining these results. Similarly, it is possible to compute the saturation torque necessary to limit the total angular excursion to a specific value. The results of such calculations are shown graphically in Figs. 15 and 16.

The preceding results specifically apply to rotational motion in the plane defined by the relative velocity vector and rela-

Table 2

Parameter	Effects
Lateral miss	<ol style="list-style-type: none"> <li>1) In conjunction with closing rate, determines attitude control requirements for attitude recovery after docking.</li> <li>2) In conjunction with attitude misalignment, determines whether chaser nose enters docking area.</li> </ol>
Attitude misalignments	See 2 above.
Closing rate	<ol style="list-style-type: none"> <li>1) Low closing rate may not result in match of docking surfaces.</li> <li>2) High closing rate increases structural loads.</li> </ol>
Cone angle	<ol style="list-style-type: none"> <li>1) High cone angle can result in failure to match docking surfaces.</li> <li>2) High cone angle increases forces.</li> <li>3) Low cone angle magnifies effect of attitude misalignment.</li> <li>4) Low cone angle increases length of vehicle resulting in booster vehicle structural and launch difficulties.</li> </ol>
Friction	<ol style="list-style-type: none"> <li>1) Forces increase with increasing friction.</li> <li>2) Docking surfaces will not reach full contact for high values.</li> </ol>

tive position vector at impact. That is, the results apply to a planar model and would be strictly valid in a three-dimensional case only if the plane contained the roll axis of both vehicles. Nevertheless, these results can be used for worst cases for the yaw and pitch control channels, since out-of-plane misalignment of the roll axes would result in a non-zero roll rate but lower pitch and yaw rates.

The relative roll displacement of the vehicles during the docking period is an important factor in the detail structural design. Almost any transfer of material between the two vehicles will require precise roll alignment between the transfer fixtures. In order to determine the post-docking alignment which will be required, an estimate of the maximum roll displacement to be expected during the docking period should be available. An estimate of this displacement can be made based upon the relative roll rate generated at the first impact.

### Conclusions

The main conclusion to be drawn from this study is that a docking assembly using a conical docking surface does provide a means for docking with small attitude alignment and guidance errors. The effectiveness of the assembly is governed by various parameters. Table 2 summarizes the effects of the parameters that were considered. These effects are found to agree with the intuitive notations that prompted selection of the conical configuration.

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