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DYNAMIC ANALYSIS OF APOLLO-SALYUT/SOYUZ DOCKING

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ABSTRACT

The use of a docking-system computer program in analyzing the dynamic environment produced by two impacting spacecraft and the attitude control systems is discussed in this report. Performance studies have been conducted to determine the mechanism load and capture sensitivity to parametric changes in the initial impact conditions. As indicated by the studies, capture latching is most sensitive to vehicle angular-alinement errors and is least sensitive to lateral-miss error. As proved by load-sensitivity studies, peak loads acting on the Apollo spacecraft are considerably lower than the Apollo design-limit loads.

INTRODUCTION

International cooperation in space exploration has resulted in the possibility of an international rendezvous and docking mission (IRDM). The proposed IRDM will be flown by a modified American Apollo command and service module (CSM) and a modified Soviet Soyuz space vehicle. A docking module (DM) will be attached to the CSM to serve as an airlock for crew interchange and as an adapter section for mounting the international docking mechanism (IDM) (fig. 1). The Soyuz space vehicle will be fitted with a geometrically compatible docking mechanism. An important purpose of the IRDM is to validate physically the docking-mechanism design for use on future spacecraft, such as the American space shuttle. To ensure that the IRDM will be performed successfully, a digital-computer simulation of the docking dynamics has been developed. The use of the computer program in supporting the design and development of the docking system is discussed in this report.

The IDM design information used in the studies presented herein was furnished by William K. Creasy, Larry P. Ratcliff, and Thomas O. Ross of the NASA Manned Spacecraft Center.

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SYMBOLS

A_c	effective working area of attenuator piston
A_o	area of attenuator orifice (fig. 5)
c	coefficient of discharge for attenuator orifice
E	energy absorbed by stroking attenuators
F_a	resultant axial force of attenuator
F_{d_i}	viscous damping force for ith attenuator
F_f	attenuator-stroking friction magnitude
F_s	attenuator spring load (fig. 4)
L	initial lateral misalinement[a]
V	initial axial closing velocity[a]
V_{s_i}	stroking velocity of ith attenuator
W	initial lateral velocity[a]
θ	initial pitch-yaw angular alinement[a]
ρ	damping-fluid density
ϕ	initial roll misalinement[a]
Ω	initial angular velocity[a]

DESIGN CRITERIA

The design of the docking hardware has been directed toward satisfying performance requirements and geometry constraints. The basic performance requirements of the IDM are to capture-latch the docking vehicles, to attenuate and to limit the relative translational and rotational excursions at the docking interface, to aline the docking

[a]Measured relative to the target-body coordinate system.

vehicles, to draw the vehicles together, to connect structurally and to seal the interface, and to undock and to separate the vehicles. The IDM must be capable of satisfactory performance using the following set of docking-interface initial-impact criteria.

1.	Axial closing velocity, m/sec	0.05 to 0.3
2.	Lateral velocity, m/sec	±0.1
3.	Lateral alinement, m	±0.3
4.	Pitch-yaw angular alinement, deg	±7
5.	Roll alinement, deg	±7
6.	Angular velocities, deg/sec	1

Geometrically, the IDM must provide an 800-millimeter-diameter (31.49 inch) clear passageway and must fit within the launch shroud of the Salyut spacecraft.

INTERNATIONAL DOCKING MECHANISM

The IDM is a completely androgynous system, assuming that the mechanism on one of the spacecraft is fully retracted and passive (fig. 2). The active IDM consists of a guide ring, three guides, three capture latches, three body-mounted latches, six attenuators, eight structural ring latches, and a cable-retraction system. During a docking attempt, the active IDM guides intermesh with the passive IDM guides, creating a centering effect. If the impact energy is sufficient, the attenuator geometry of the active IDM will comply, allowing the spring-loaded capture latches of the active IDM to latch the body-mounted latches of the passive IDM. The relative kinetic energy, remaining after capture-latch, is nulled by the six attenuators. The stored energy in the attenuator springs returns the IDM to the initial configuration, facilitating alinement between the docking vehicles. Initiation of the cable-retraction mechanism draws the vehicles together, engaging the structural latches and rigidifying the docking interface.

COMPUTER SIMULATION

To ensure that the IDM is capable of performing the tasks satisfactorily, an all-digital three-dimensional simulation of the IDM dynamics has been developed. Referred to as the ring-finger docking-dynamics program (RFDD), the computer program simulates the dynamic environments produced by the interaction of the guide-ring docking systems during collision, by the use of the automatic attitude control systems, and by the use of astronaut translational-control inputs.

Simulated forces produced by the interaction of the docking system are classified as guide-ring-interaction forces, capture-latching forces, and attenuator forces. In the simulation, the guides and guide ring are considered to be linear elastic members.

During a docking attempt, the guide edges of the active and passive IDM interfere geometrically. At each interference point, the interference distance is determined, enabling the computation of the elastic loads. The interaction load is assumed to be normal to the contact edges. The active IDM guides can contact and force the passive IDM guides and guide ring; the passive IDM guides can do likewise. Relative motion between the DM interface and the active guide ring causes the attenuators to stroke.

The attenuators attach to the DM and guide ring (fig. 3). The force in an attenuator is simulated in the RFDD as a function of the instantaneous stroke and velocity. The force is divided into three components: spring force (F_s), damping force (F_{d_i}), and seal friction force (F_f).

$$F_a = F_{d_i} + F_s + F_f\left(\frac{V_{s_i}}{\left|V_{s_i}\right|}\right) \tag{1}$$

A typical spring force-stroke function is illustrated in figure 4. The curve represents a preload of 44.5 newtons (10 pounds), a pneumatic spring in compression, and a nonlinear equivalent structural spring in tension. The damping force F_{d_i} is given as

$$F_{d_i} = \frac{\rho A_c 3}{2}\left(\frac{V_{s_i}}{cA_o}\right)^2 \tag{2}$$

where ρ, A_c, V_{s_i}, A_o, and c are fluid density, attenuator-piston-cylinder area, attenuator velocity, orifice area, and coefficient of discharge. The orifice area is given as a function of attenuator stroke (fig. 5). It is assumed that the seal friction force is constant and that it opposes the stroking motion. In addition to orifice damping, the attenuators contain a pressure regulator to limit maximum dynamic loads in regions of extremely small orifice area.

The capture latches are simulated in the RFDD as elastic restraints at the geometric-latch locations shown in figure 3. Once the capture latch engages the body-mounted latch, a latch restraint is enforced during an attempted docking. The capture latches develop tension loads normal to the plane of the interface.

CAPTURE-LATCHING DYNAMICS OF THE INTERNATIONAL DOCKING MECHANISM

The compliance motion necessary to capture-latch the IDM can be visualized as four simultaneous motions consisting of relative translation parallel to the interface that centers the docking systems, relative roll indexing of the two systems, axial translation toward capture latch, and relative pitch-yaw rotation that alines the interfaces. Generally, the vehicle dynamics resulting from the impact forces result in the first three types of interface motion. The vehicle-interface motions reduce the amount of IDM attenuator compliance and lower the amount of resulting attenuator energy absorption; however, the resulting relative pitch-yaw rotational motion of the docking vehicles usually is divergent from the desired rotational motion of alining the docking interfaces. The undesirable rotational motion and the initial pitch-yaw rotational error must be compensated for by stroking of the supporting attenuators. This stroking absorbs a significant amount of the kinetic energy needed for capture-latching.

IDEALIZED CASE

The following idealized case illustrates the attenuator-design problem of accommodating the required compliance with little energy absorption or storage. The IRDM vehicles contact at a minimum closing velocity (0.05 m/sec) and maximum pitch-yaw interface angular misalinement (7°). For this case, the available kinetic energy is 11.1 joules. Assuming that one pair of attenuators actively comply to accommodate the misalinement, the average force F_a in the attenuators must not exceed 52 newtons (12 pounds), or the 11.1 joules of relative kinetic energy will be absorbed before the IDM rings are in position to capture-latch. The attenuator preload must be at least twice as large as the seal friction to overcome the seal breakout force and to aline the vehicles after capture-latch. Even if the damping force is neglected and it is assumed that the attenuators resist compliance with a constant force equal to the preload and seal friction, the resulting bounding values for the preload and seal friction are extremely small: 34.6 newtons (8 pounds) and 17.3 newtons (4 pounds).

RESULTS

Attenuator Optimization

Analytical capture-performance studies of the IDM, in which the varying nature of F_a is taken into account, were conducted with parametric variation in the components of F_a. As indicated by the studies, an improvement in capture performance can be achieved if the seal-friction and spring preload are lowered from the initial design estimates. As a result, the seal friction and attenuator-spring preload requirements were reduced to 22.25 newtons (5 pounds) and 44.5 newtons (10 pounds). Although still in excess of the 52-newton (12 pound) minimum requirement cited for the earlier sample, the total of these values was considered to be as low as is practical. Alternate attenuator designs to reduce the axial stiffness have been rejected because of complexity and corresponding reliability problems. Within practical design constraints, the design of the IDM has evolved in order to optimize the overall capture performance.

Capture-Latching Sensitivity Studies

Digital-computer simulations of the IRDM have been conducted to determine capture-latching sensitivity to parametric changes of the initial contact conditions. The results of the study are presented in figures 6 to 8. In the study, capture-latching capability was investigated as a function of parametric variations in axial closing velocity and state-position-error parameters. Reduction in axial closing velocity reduces capture-latching capability because the relative kinetic energy required for compliance of the active IDM is reduced as a function of the square of the axial closing velocity. Also, increases in state-position error reduce capture capability because the active IDM must comply more to achieve capture latching.

Axial velocity V and miss distance L were varied parametrically; the remaining state parameters W, θ, Ω, and ϕ initially were set equal to zero (fig. 6). As indicated by the results, the capture-latching performance of the IDM is insensitive to miss distance within the range of allowable axial velocity. Little relative kinetic energy is dissipated by the attenuators because the vehicle motion following impact alines the interface. In the IRDM, the moment arm to the center of mass of each vehicle is large, permitting small lateral forces at the docking interface to rotate the vehicles into alinement.

Axial velocity V and roll misalinement ϕ were varied parametrically; the remaining state parameters, W, θ, Ω, and L initially were set equal to zero (fig. 7). As demonstrated by the results, the IDM is sensitive to relative roll misalinements when the axial velocity V is small. Two factors influence the sensitivity: the attitude control system and the small rotational-moment arm about the centerline of the vehicle. The CSM attitude control system maintains the initial relative-roll error, forcing the IDM to rotate and to stroke the attenuators. In addition, the small rotational-moment arm about the centerline of the vehicle decreases the amount of natural relative-roll motion induced by impact. This decrease forces the IDM to comply in roll by stroking the attenuators.

Axial velocity V and relative pitch-yaw rotational error θ were varied parametrically; the remaining state parameters W, Ω, ϕ, and L initially were set equal to zero (fig. 8). As indicated by the results, the capture-latching performance of the IDM is sensitive to θ when the axial velocity is small. These results are in agreement with the previous discussion on attenuator-compliance requirements for pitch-yaw misalinements.

Addition of state-velocity error, radial-velocity state parameter W, and angular-rate state parameter Ω will reduce the given IDM capture performance because the attenuator system must attenuate the relative motion induced at the interface by these parameters.

CONCLUDING REMARKS

The early development of a digital-computer simulation of the IDM has been a valuable tool in the design of the IDM. Use of the program to study the sensitivity of impact loads and capture performance to variations in design parameters has resulted in a simple reliable design that has known performance characteristics. As demonstrated by the performance studies, the IDM capture capability is most sensitive to vehicle angular-alinement errors when the axial closing velocity is near the minimum criteria value and is least sensitive to lateral-miss error for all values of axial closing velocity.

DISCUSSION

J. W. James:

Because this docking-mechanism configuration can be installed identically on any spacecraft, is it generally believed that this may be the last new docking mechanism to be designed?

Schliesing:

A primary purpose of the Apollo/Soyuz Test Project is to validate the design concept for possible use on advanced missions. This, of course, leaves open the possibility of using other docking mechanism configurations. In addition, the NASA is studying the feasibility of using manipulator systems to dock and to handle cargo.

J. E. Price:

Complexity is often a product of overly optimistic and an overabundance of design requirements. In establishing the requirements for the docking mechanism, how have you limited the number of basic functions to something that is manageable.

Schliesing:

The requirements presented for the docking mechanism were limited to only those that are related to dynamic analysis, namely performance and impact criteria. The overall design requirements are much more numerous.

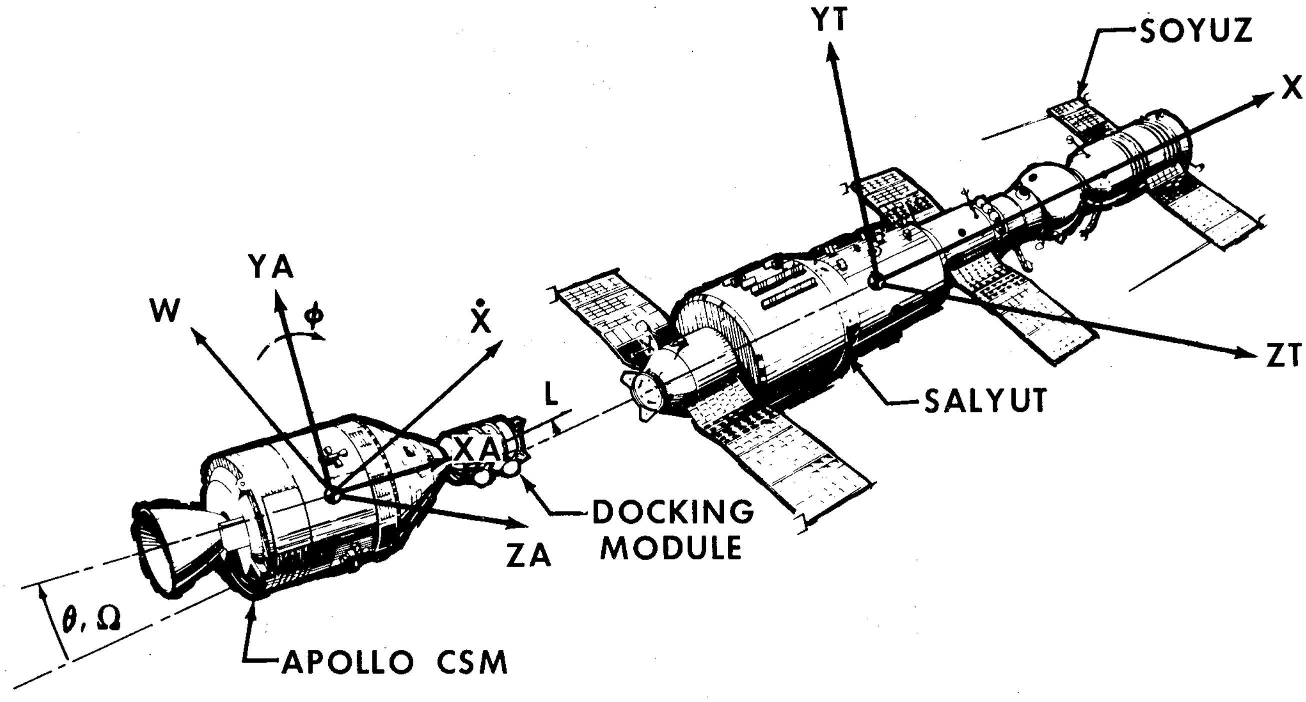

Figure 1. - Apollo-Salyut rendezvous and docking test mission.

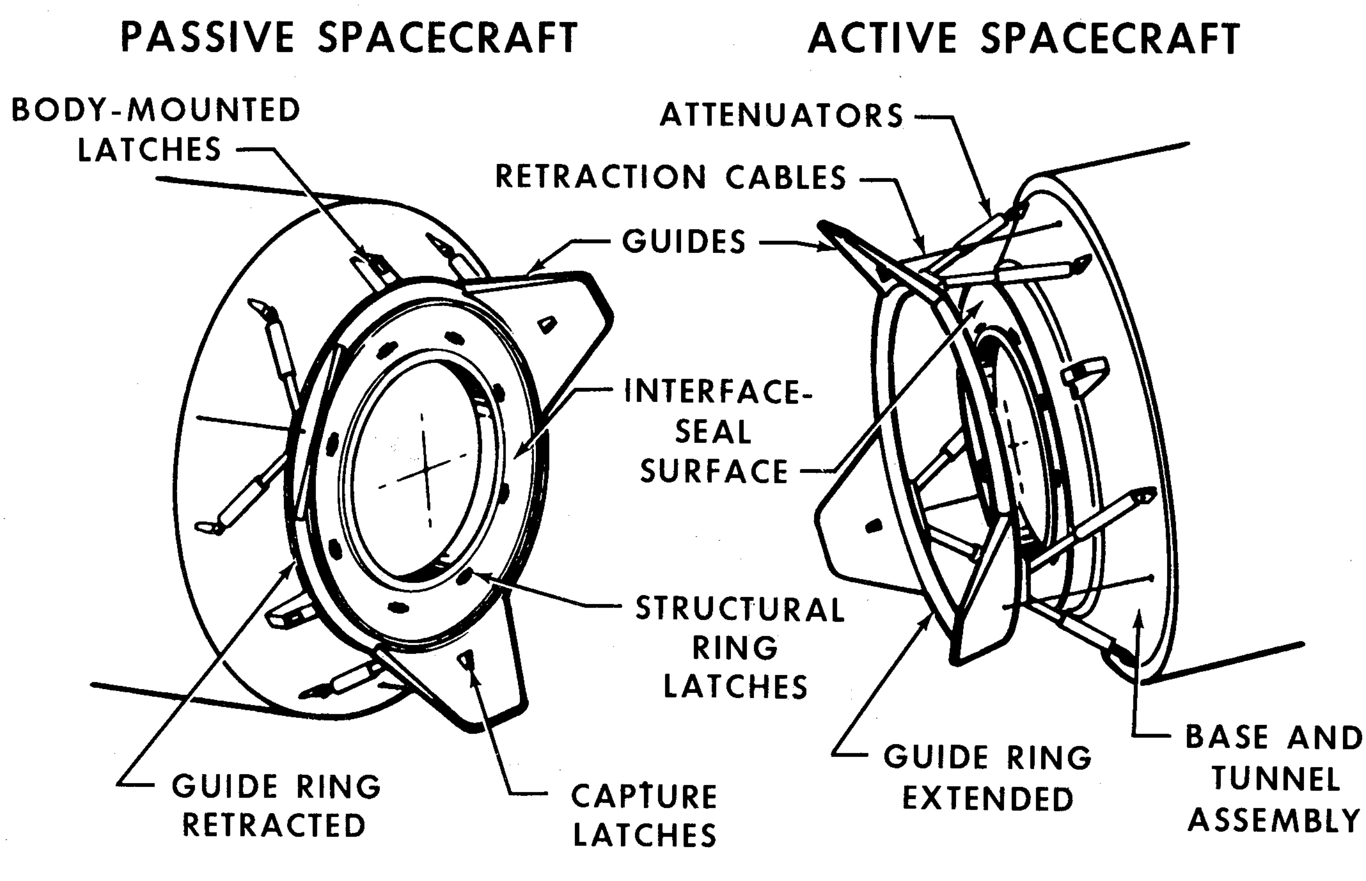

Figure 2. - International docking mechanism.

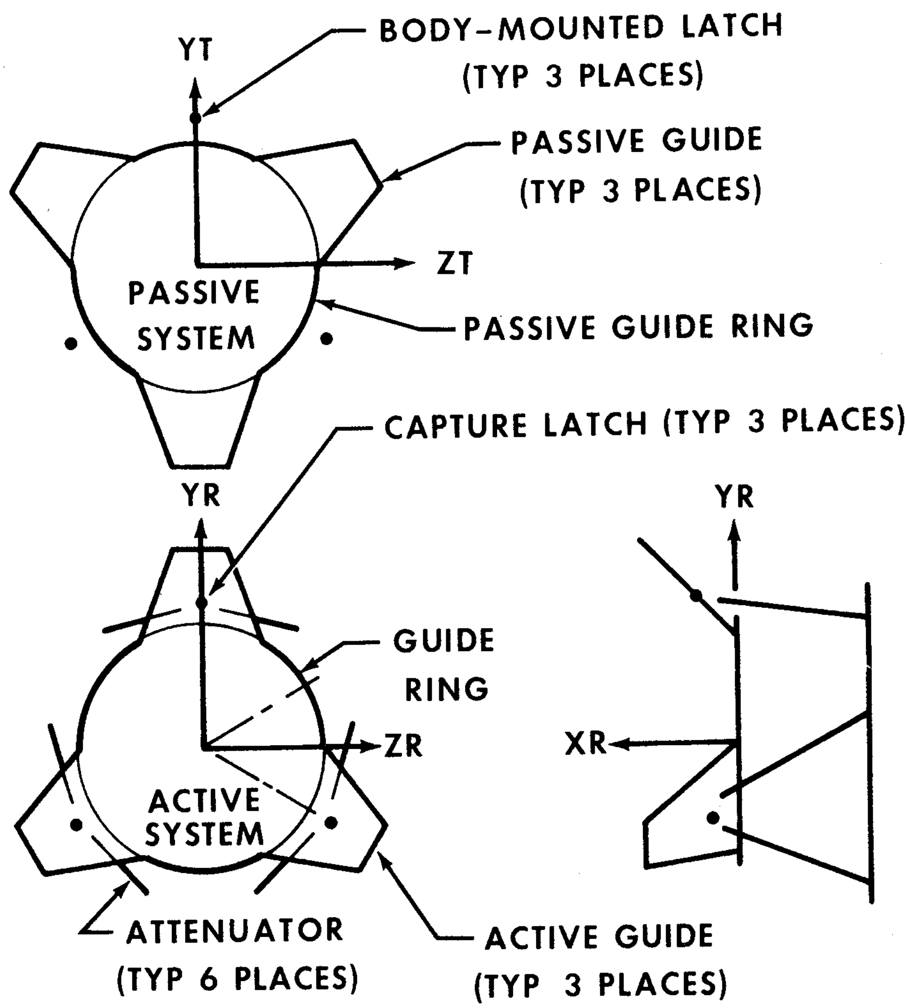

Figure 3. - Schematic of international docking mechanism.

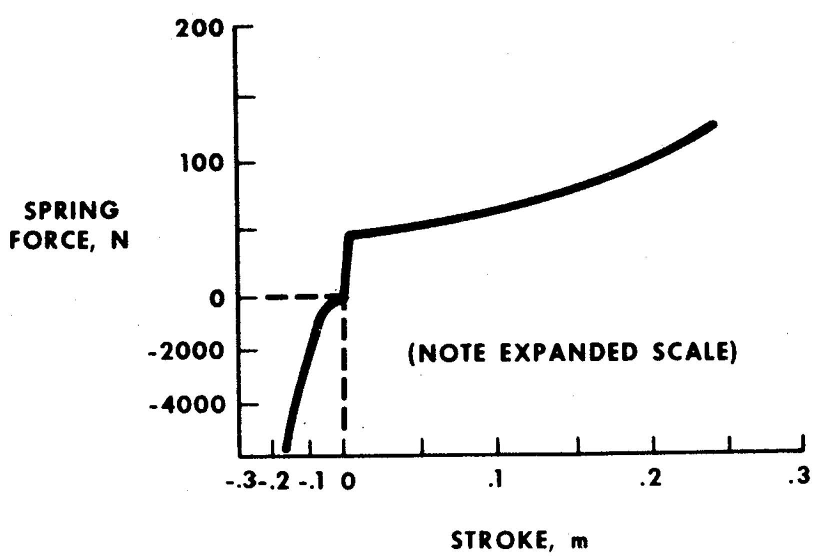

Figure 4. - Attenuator spring force.

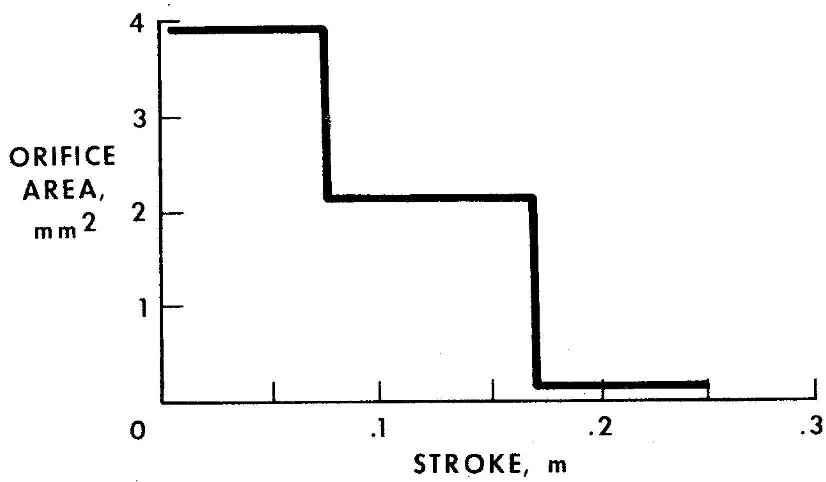

Figure 5. - Attenuator orifice area.

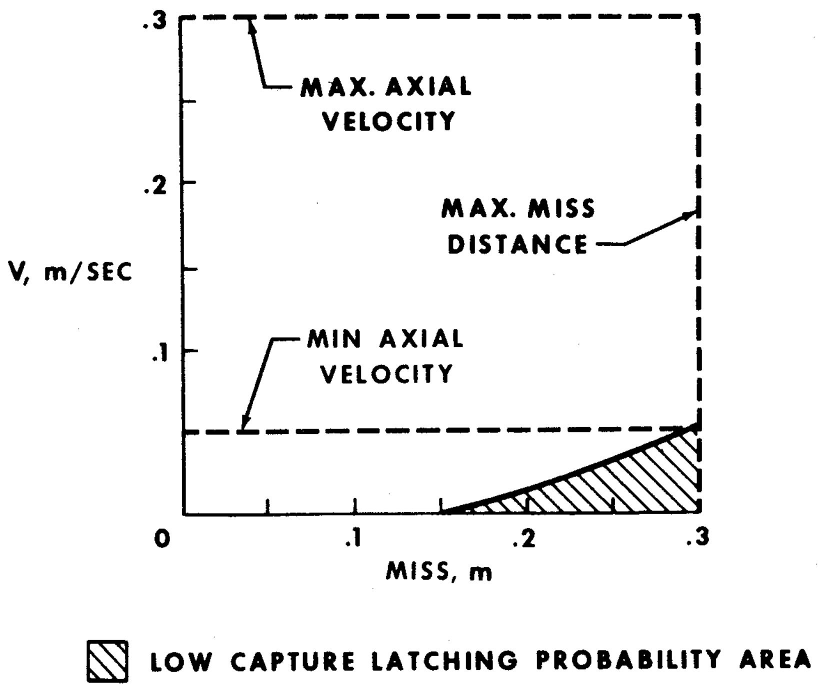

Figure 6. - Axial velocity compared to miss distance.

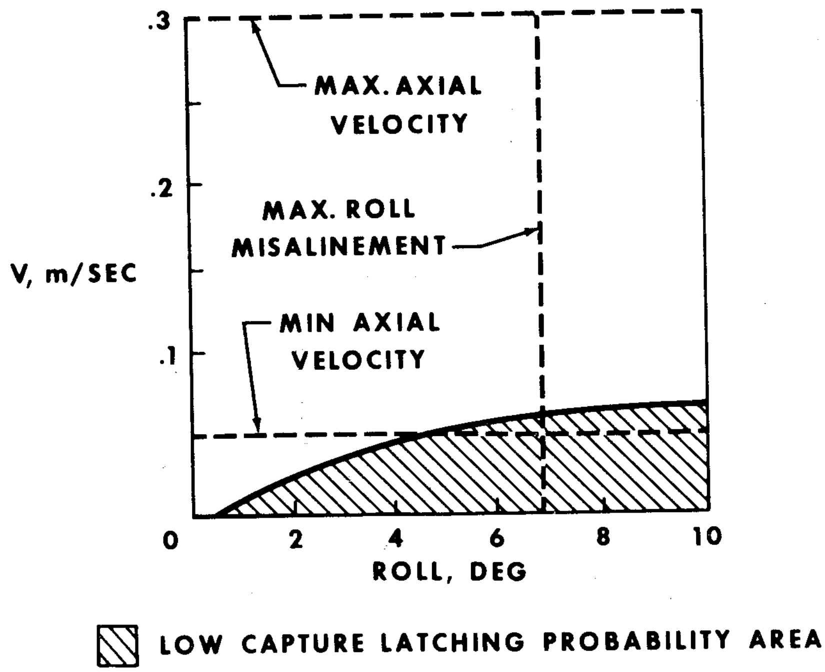

Figure 7. - Axial velocity compared to roll misalinement.

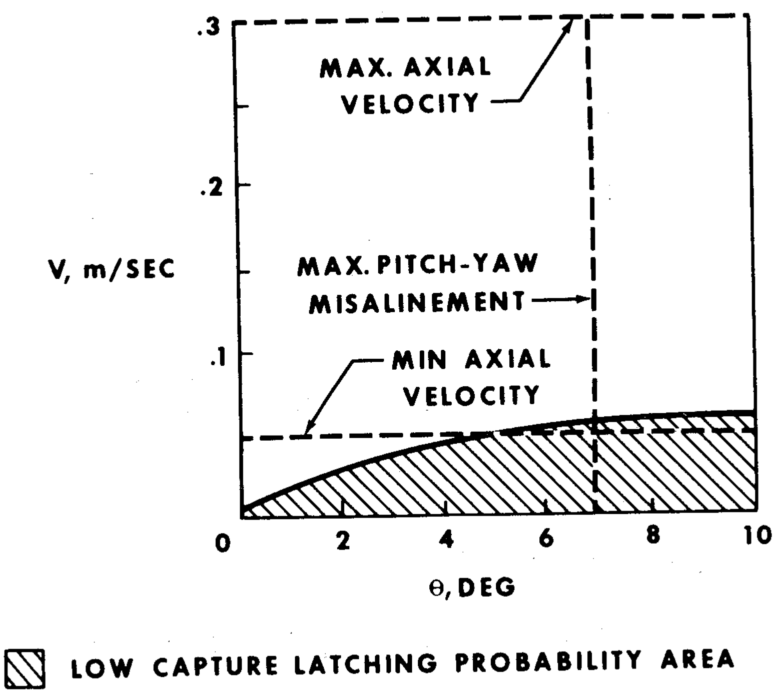

Figure 8. - Axial velocity compared to pitch-yaw misalinement.