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A MODULAR DOCKING MECHANISM
FOR
IN-ORBIT ASSEMBLY AND SPACECRAFT SERVICING

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INTRODUCTION

As space operations become accepted as "normal" business enterprises, two requirements tend to dominate any future technological developments:

- systems are required to be reliable over a long period of time, either by their inherent reliability, or by means of scheduled maintenance.

and

- future space technology developments need to be cost-effective to warrant their incorporation.

Rendezvous and Docking (RVD) technology, being a prerequisite for advanced space operations, is a typical example of this technology development. Since the RVD process is not only mission critical but also contains the risk of damage to the in-situ space investment, its technology has to be highly reliable. But it must also satisfy the other criterion, of being available at reasonable cost, so that the benefits of in-orbit assembly and servicing can be realized.

The above requirements are passed on to the subsystems comprising the RVD system. This paper is about one of them, the Docking Mechanism Subsystem (DMS) developed during an ESA sponsored contract.

DOCKING MECHANISM CONCEPTS

The various docking mechanism concepts which have flown (e.g., Gemini, Apollo, Soyus/Saljut) were of the "impulse", or "impact", type where the kinetic energy of the active chaser spacecraft was used to trigger, or actuate, the docking mechanism. This was possible because the spacecraft involved were (more or less) rigid and rugged bodies and because their centres of gravity were aligned.

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For future space missions, however, such as large, flexible, and locally fragile platforms, it is very desirable to adopt non-impact docking techniques to avoid the risk of damage, and to make use of self-actuated, and re-usable, docking mechanisms.

Non-impact docking systems can be sub-divided into two categories where, following the close rendezvous of the two satellites, they are brought together into intimate contact either by means of the Docking Mechanism via an extended probe, or by active control of the AOCS of one of the spacecraft. This bringing together is known as "Closure", and the two means of achieving it are referred to in the following as "DMS controlled closure" (DMS-CC) and "AOCS controlled closure" (AOCS-CC). These two closure techniques differ in the operations which are needed, and in the make-up of their constituent components. Table 1 gives an overview of the operations associated with each category. Figure 1 illustrates the two different docking mechanisms implied.

It is clear that, in principle, AOCS controlled closure can result in a simpler mechanism, in that the boom is not needed, nor are the necessarily complex grapple and actuator mechanisms. However, this is at the expense of a greater demand on the AOCS and the need for short range docking sensors. A very major advantage accrues, however: that is the possibility of using a very simple structural docking interface which is compatible with adoption as a "standard" interface.

REQUIREMENTS

The general requirements for the DMS are based on typical European scenarios for automated RVD missions, where the spacecraft are unmanned and 3-axis-stabilized. These missions require a high flexibility and modularity in the DMS concept. Further, to protect the higher investment in orbit it is desirable to ensure that only passive parts of the DMS are located on the more "permanent" spacecraft.

Safety requirements become, in fact, design drivers, and Table 2 gives typical requirements with which the DMS must comply. Latch performance requirements derived to contain a number of alternative missions are given in Table 3, and the range of satellite parameters is given in Table 4. Finally the DMS is required to support certain operational strategies; these are shown in Table 5.

Notable among these requirements is the requirement that, regardless of the failure, it should be possible to separate the two spacecraft in order not to prejudice a further attempt at RVD. The DMS therefore not only needs to be reversible, it must have back-up systems which ensure complete release.

DOCKING MECHANISM DESIGN

THE LATCH

If the technique of AOCS controlled closure is adopted, the mechanical components needed in the DMS are reduced to latches and connectors and their (passive) interfaces. The design task, for latching, assumes a close maneuver of the Chaser Spacecraft up to the target, to within about 60 mm in the longitudinal axis and about ±40 mm in the lateral axis. The role of the AOCS may thereafter be passive, or it may assist in the docking process.

Although the end result is very simple, considerable thought was given to different latch interfaces. Various forms of interface can be envisaged, which lend themselves to passive guidance at the time of final closure. However, as the geometry of the interface is made more complex, so too are the artificially induced requirements on the latch itself, and the design freedom of the latch designer is inhibited.

The latch interface chosen, termed the "cruciform concept", is shown in Figure 2. The structural interface itself is a round bar, radially stiff, but with some axial compliance and with rotational freedom.

The latch is required to perform three fundamental functions:

- Capture and alignment of the Handle
- Absorption and partial storage of residual (small) kinetic energy
- Provision of structural joint (Table 2)

Elements of the chosen latch design are given as an exploded view in Figure 3, and the method by which it operates is outlined in Figure 4. Should at any time the latch jam, a pyrotechnic device collapses the linkage, enabling the clamp to retract under action of a spring. The structural joint can, however, be maintained by two of the remaining three latches. (The cruciform concept is tolerant to failure of two out of the four latches.)

The selected linkage for the latch is shown in Figure 5. Here points C, D and G are fixed points. Link No. 1 (D-A) represents the crank and α_1 the input crank angle. Link No. 3 (B-E) represents the pretension spring. Link No. 5 (F-G) represents the claw, with ${}_5$ the output claw angle.

Based on this layout, with the following dimensions, Figures 6 to 8 give the latch performance parameters, based on the following dimensions:

D-A = 31.50 mm
A-B = 32.48 mm
C-E = 82.10 mm
F-G = 30.00 mm

1 START = 130°
1 END = 76.9°
5 START = 186°
5 END = 60°

LATCH DESIGN TESTING

In order to gain some insight into the latch performance, testing has been performed on a single latch, and Figure 9 shows the test setup used. Two massive blocks (160 kg each) onto which the handle and latch assemblies were mounted, were supported on air bearings and made to approach each other at varying rates and alignments, simulating a constant AOCS thrust. Interactive forces were measured using a piezoelectric transducer mounted between the latch and the base. Figure 10a shows a typical behaviour during such a test with an initial lateral misalignment of 60 mm. Several bounces against the reception element are shown prior to claw engagement. Figure 10b shows a capture with the same approach velocity (15 mm/sec), but with no misalignment.

The results of the testing confirmed in general the performance of the latch, and gave valuable guidance to the modelling of the latch for RVD simulation purposes. Testing also indicated that some detailed improvements were necessary in the configuration of the spring energy absorber - for example, the addition of a damper. This damper could either be a conventional passive damper (velocity proportional), or an active damper where the interactive forces are measured and the claw is controlled appropriately.

THE CONNECTOR MECHANISM

It soon became apparent that the requirement for achieving electrical and fluid connection within the DMS could become a design driver on the latches, not just with the precision of latching required, but also with the forces which the latches should withstand. The forces required to mate and de-mate connectors, particularly for the fluid connectors, were relatively high, and in order to maintain modularity of design, keeping the latch development independent of connector development, it was decided to provide a self-powered, self-reacting mechanism to achieve connection. This mechanism is still undergoing development, and will not be reported here. However Table 6 shows typical connector mechanism requirements.

STANDARD DOCKING INTERFACE

With a growing number of satellites in orbit, and a growing capability of direct intervention by means of vehicles designed to dock with them, it is particularly interesting to develop usable and commercially viable standard docking interfaces.

The latch design described has certainly some attributes to its credit, but it is not the only latch design that can be found which interfaces with the simple handle. Indeed this latch has co-existed with a latch of totally different concept which is also being considered as an alternative design. This possibility arises from the classic simplicity of the handle. The handle is light (0.4 kg) and the design freedom offered to the latch means that it is not therefore necessary to purchase the latch always from the same supplier.

The handle may be in a number of alternative configurations, e.g., 3 instead of 4, and located at different diameters without invalidating the essential of the standard, or the principles of operation of the DMS. Four such "handles" were chosen as the interface for the design presented in this paper, over the more conventional alternative of a 3-handle configuration for kinematic reasons because of the added security against failure during latching. In addition, aided by the inherent self-centering capability of the latch/handle combination, the concept is also suitable for the so-called androgenous DMS, where active parts are placed on both sides of the interface to allow initiation of separation by either satellite. In this configuration the location of the latches is alternated between the spacecraft, i.e., latches 1 and 3 on spacecraft 1 and latches 2 and 4 on spacecraft 2 (see fig. 11). However in this concept the release security is compromised if the command link fails.

CONCLUSION

A Docking Mechanism concept has been described which is suitable for use with autonomous docking systems. The central feature of using simple cylindrical handles on one side and a type of prism seating on the other is offered as a practical method of achieving a standardized structural interface without freezing continued development of the latches, either technically or commercially.

The main emphasis in future Docking Mechanism concepts will probably be in two directions:

- The first is towards a very simple Docking Mechanism, involving mainly the latch mechanism to achieve a structural link
- the second is towards a sophisticated Docking Mechanism, where the latch mechanism is designed for non-rigid spacecraft and the achievement of very low dynamic interactions between spacecraft during the docking process.

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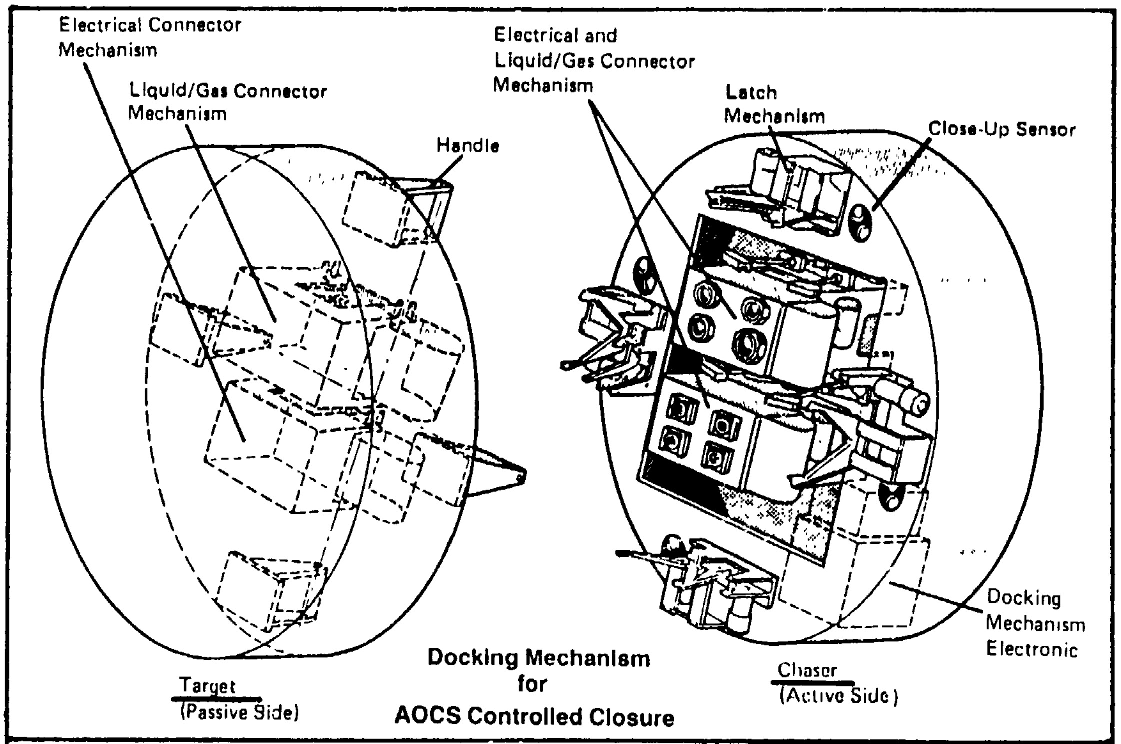
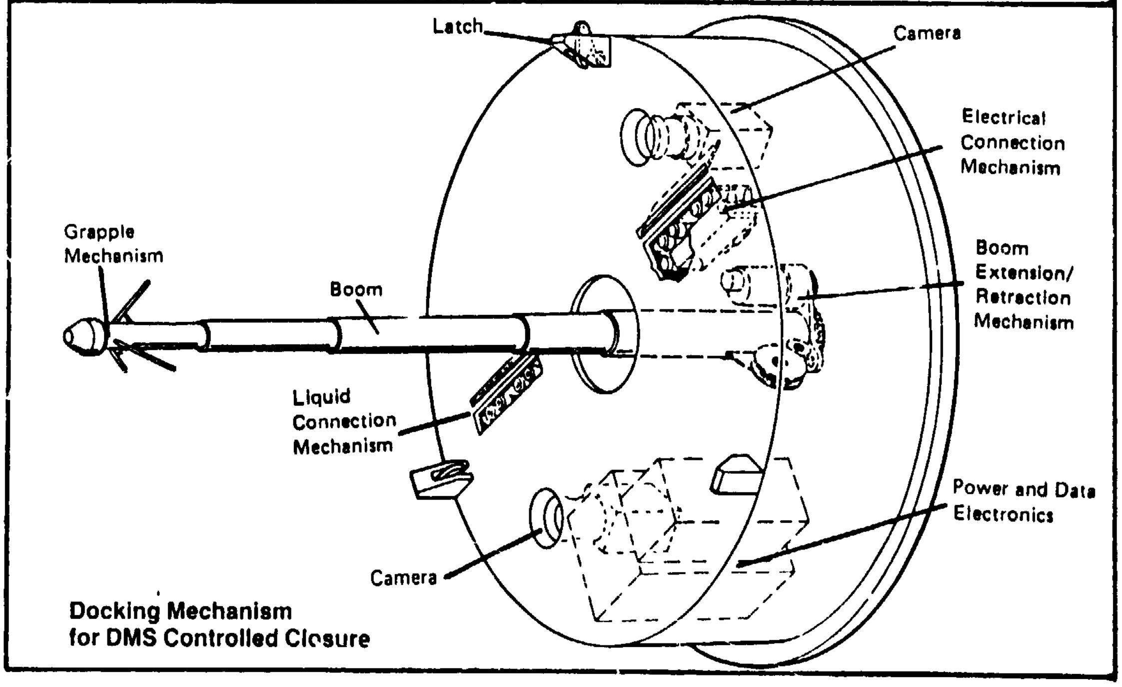


Docking Mechanism for AOCS Controlled Closure



Docking Mechanism for DMS Controlled Closure

FIGURE 1: DMS AND AOCS CONTROLLED CLOSURE CONCEPTS

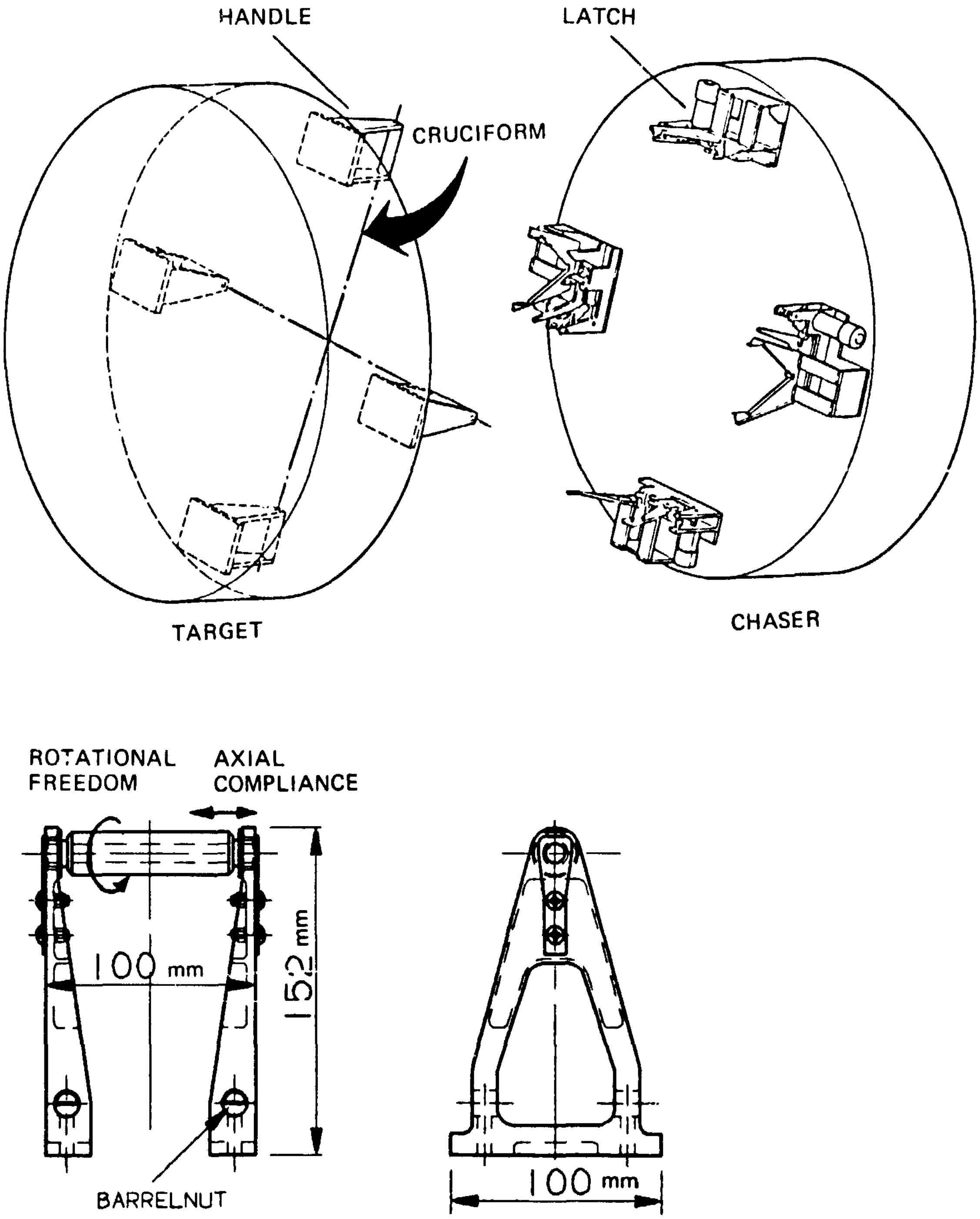


FIGURE 2: THE CRUCIFORM CONCEPT AND ITS BASIC ELEMENTS

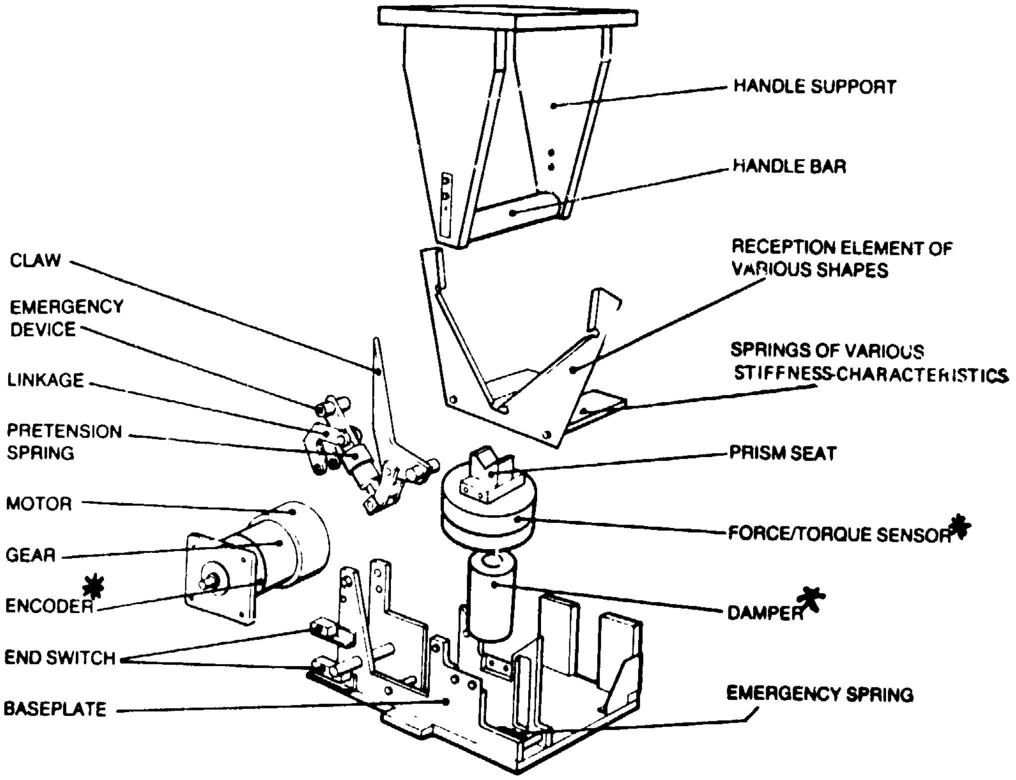


FIGURE 3: BASIC ELEMENTS AND POSSIBLE ADDITIONAL ELEMENTS* OF THE LATCHING MECHANISM

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FIGURE 4a shows the reception positons of latch and handle, which do not necessarily involve immediately a real mechanical contact, but which give the final initiation command for the latch actuator.

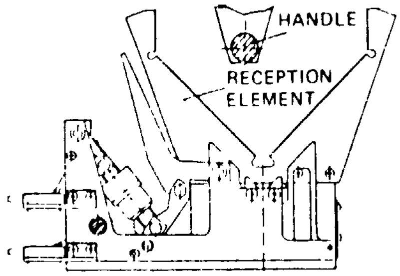

FIGURE 4b shows the first mechanical contact. The handle runs against the reception element, which, fixed to the springs, limits the interactive forces by compliance in the axes. The claw is rotated by the actuator for engagement with the handle.

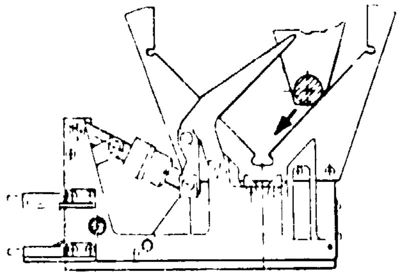

FIGURE 4c shows the handle captured by the claw. The docking process may now be controlled for the minimum dynamic interaction between Chaser and Target. The actuator has to overcome the reaction forces, the spring force and the emergency spring force.

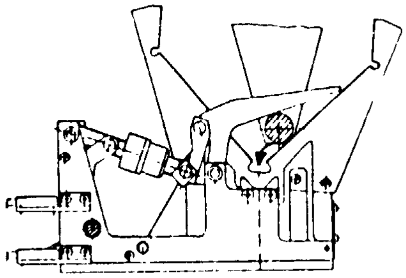

FIGURE 4d shows the final latching position when the handle is forced into the prism seating by the overcenter linkage and loaded pretension spring.

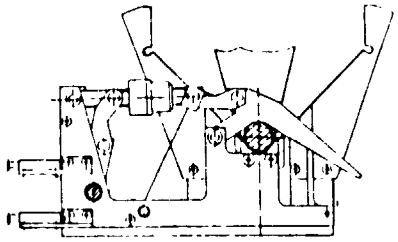

FIGURE 4e shows the emergency undocking when, after disabling a linkage hinge, the chaser is undocked by the spring element.

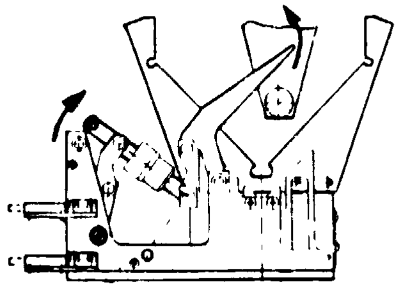

FIGURE 4. OPERATIONAL SEQUENCE OF LATCH FOR DOCKING AND EMERGENCY UNDOCKING

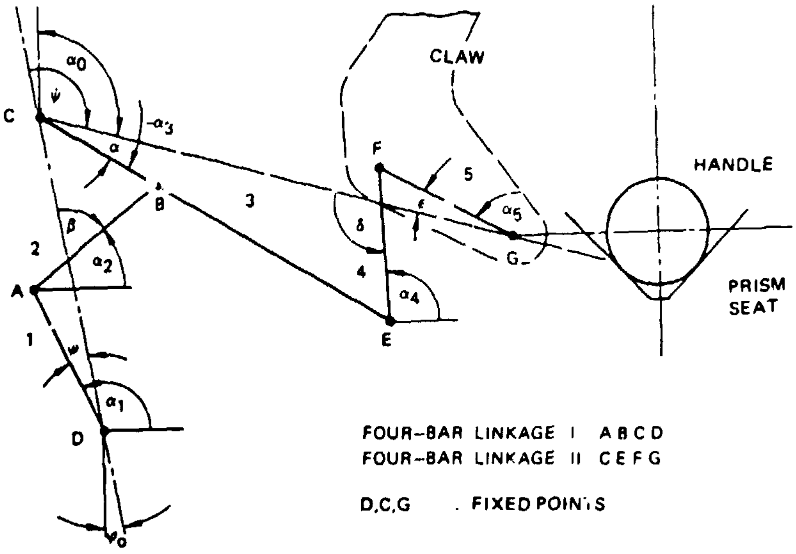

FIGURE 5: LATCH LINKAGE IN 2x4-BAR LINKAGE LAYOUT

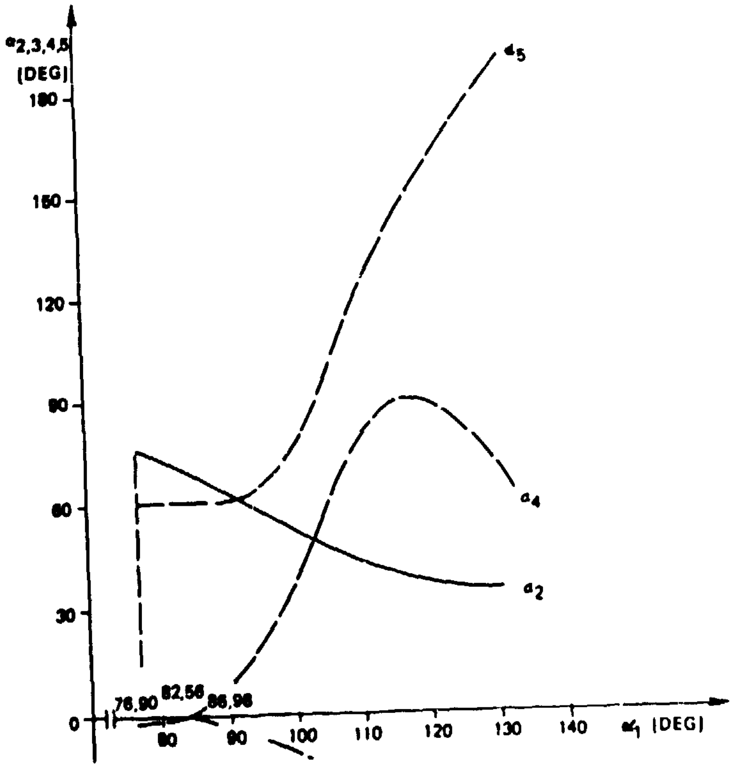

FIGURE 6: INPUT LINKAGE ANGLE (α_1) VERSUS OUTPUT LINKAGE ANGLE (α_5)

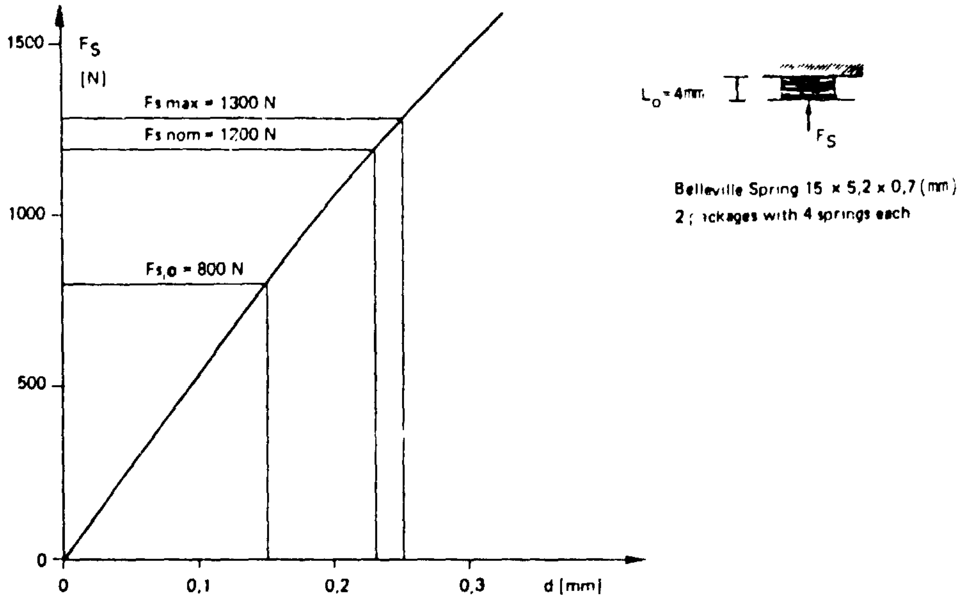

FIGURE 7: CHARACTERISTIC OF PRETENSION SPRING PACKAGE

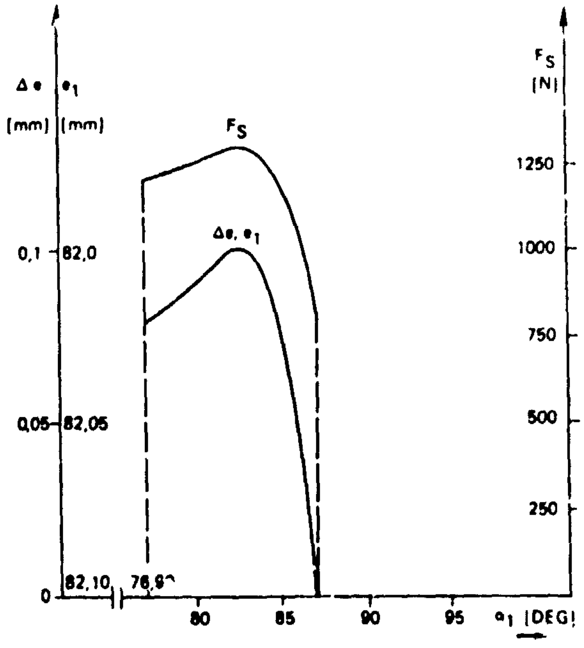

FIGURE 8: LENGTH VARIATION OF LINK 3 AND SPRING FORCE VERSUS CRANK ANGLE

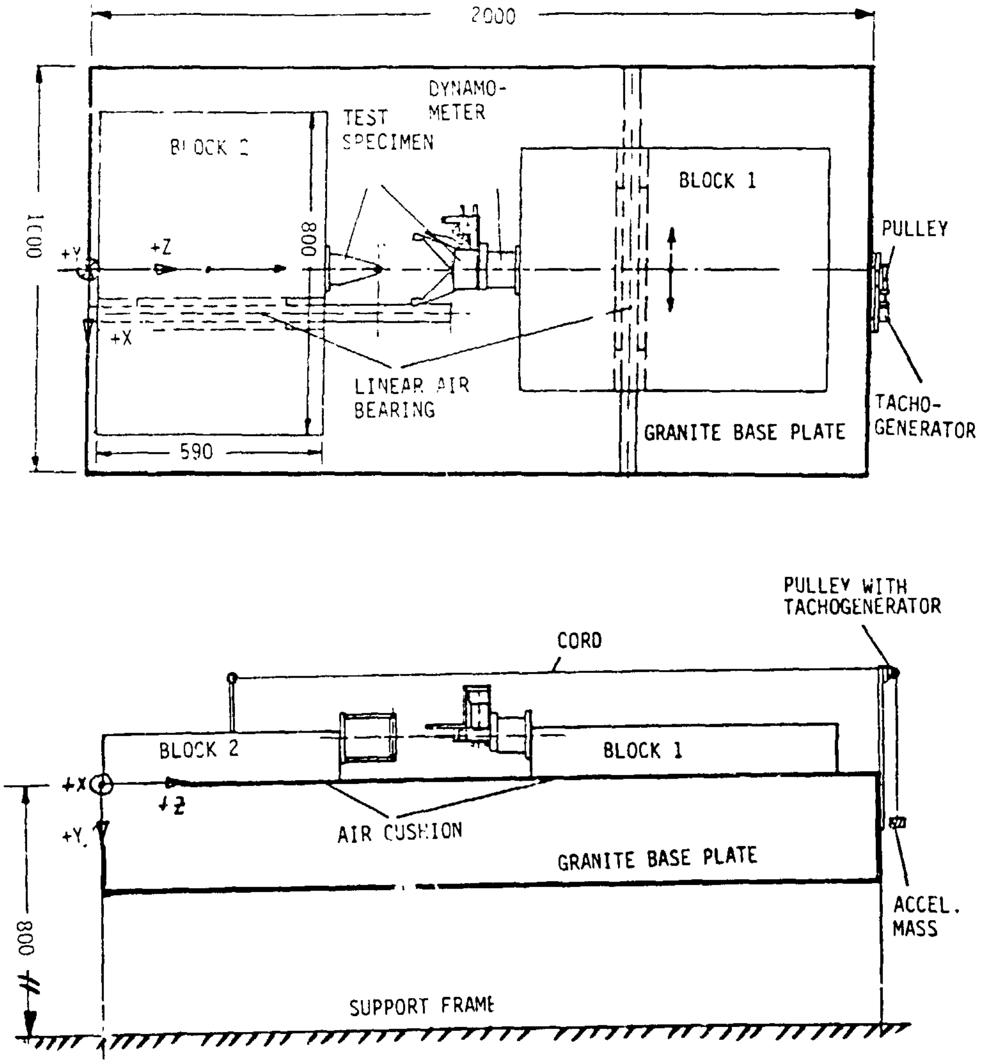

FIGURE 9: AIR BEARING TABLE TEST SETUP TO TEST DOCKING DYNAMIC INTERACTION WITH ONE LATCH ONLY (ALL DIMENSIONS IN mm)

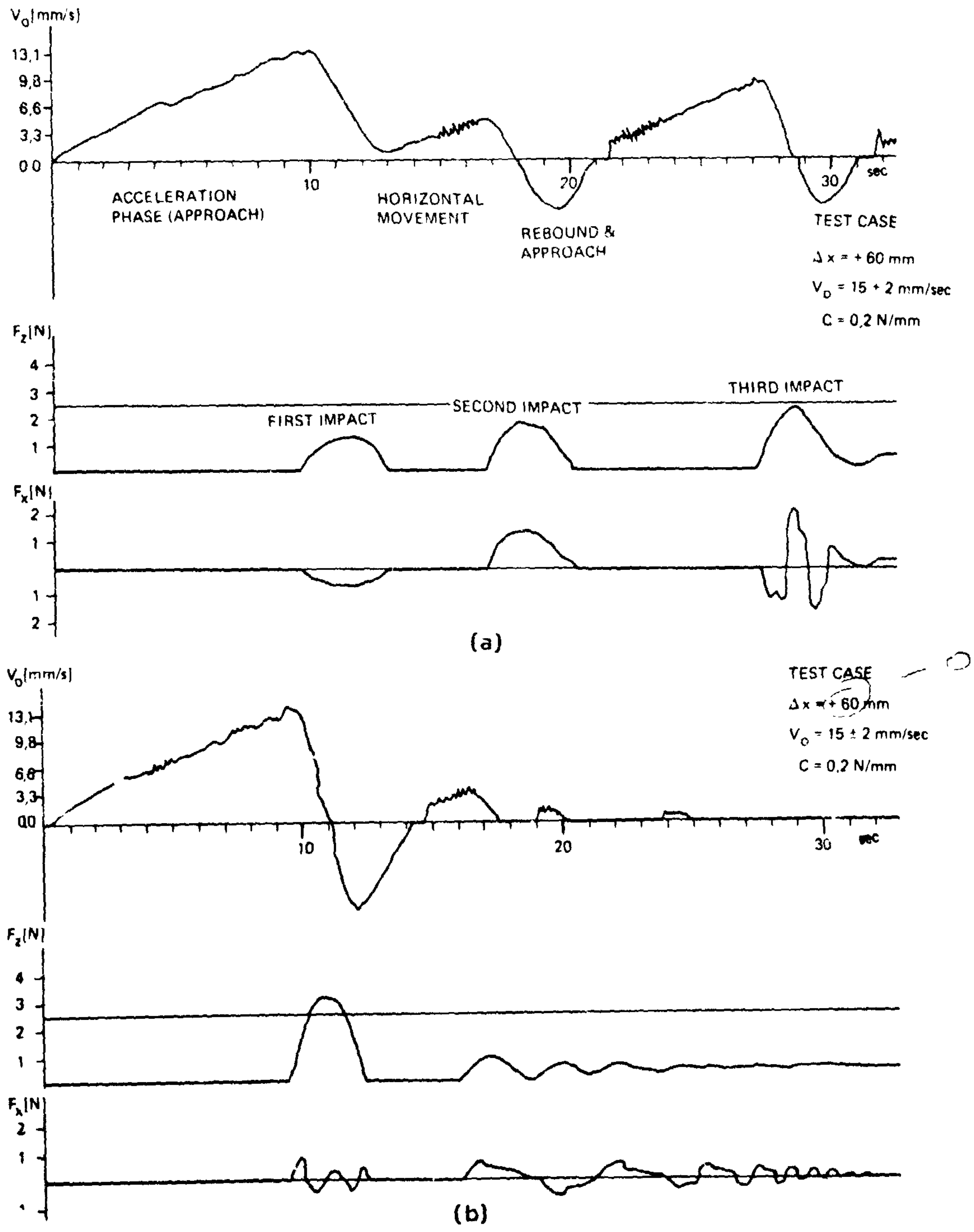

FIGURE 10: DYNAMIC INTERACTION FOR TWO DOCKING CASES WITH CONSTANT AOCS FORCE

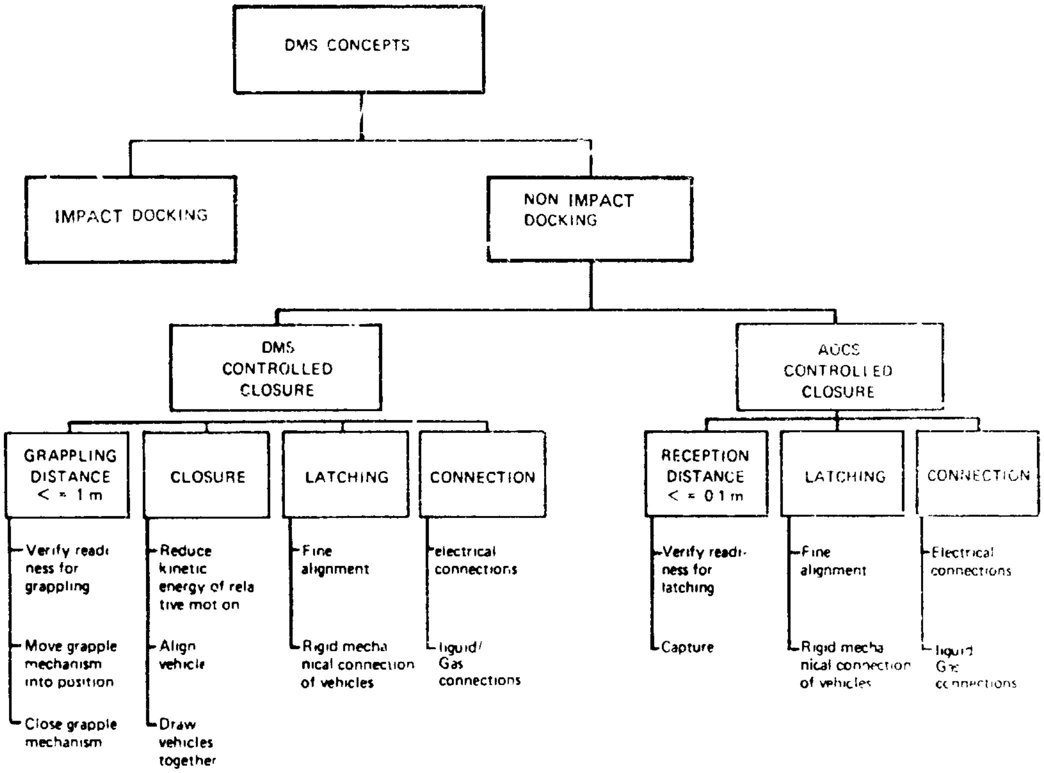

TABLE 1: DOCKING CONCEPTS AND RELATED DOCKING OPERATIONS

General	• The DMS shall not hazard to other equipment or personnel during ground testing. • The DMS shall have no credible single point failure which results in an unsafe condition for either vehicle • The DMS shall make available provisions for docking abortion at any time and satellite release without damage to either satellite. • The DMS shall be protected against false commands. • The DMS shall be designed to a fail-safe, fail-safe standard • The first point of contact shall be grounded.
During Docking	• No damage shall occur to either satellite during docking, nor shall their operational performance be isolated. • It shall be possible to abort docking at any point in the sequence. • The docking operation shall be man supervised.
During Contingency Operations	• It shall be possible, following contingency operations, to re-dock with the same two spacecraft • The DMS shall provide failsafe means for Contingency operations.
During Emergency Operations	• Emergency Operations shall not impair the docking capability of the Target Satellite. • There is no necessity for docking with the same Chaser Satellite following Emergency Operations

TABLE 2: SAFETY REQUIREMENTS

INITIAL SEPARATION CONDITIONS

Parameter	AOCS Controlled Closure
displacement (mm)	$-55 \leq d_{x,s}, d_{ys} \leq +55$ $0 \leq d_{zs} \leq +30$
approach velocity (mm/sec)	$-2.0 \leq v_{xs}, v_{ys} \leq +2.0$ $5 \leq v_{zs} \leq 15$
angular misalignment (deg)	$-0.5 \leq \phi_{xs}, \phi_{ys}, \phi_{zs} \leq +0.5$
rotational speed (deg/sec)	$-0.05 \leq \omega_{xs}, \omega_{ys}, \omega_{zs} \leq +0.05$

LATCHING CHARACTERISTICS

Parameter	Final Conditions at End of Latching
displacement (mm) between both satellites	$-1.0 \leq d_{xe}, d_{ye}, d_{ze} \leq +1.0$
misalignment between both satellites (deg)	$-0.2 \leq \Theta_e, \phi_e, \Psi_e \leq 0.2$
Stiffness axial, lateral forces	$K_x = K_y = K_z \geq 2.2 \cdot 10^6$ N/m
bending, torsional	$C_x = C_y = C_z \geq 12 \cdot 10^3$ Nm/deg

The DMS shall maintain these characteristics while transmitting the following loads across the docking interface:

– axial, lateral forces	$F_x = F_y = F_z \leq 220$ N
– bending, torsional moments	$M_x = M_y = M_z \leq 200$ Nm

TABLE 3: FUNCTIONAL PERFORMANCE REQUIREMENTS

PARAMETER	CHASER	TARGET
Mass (kg)	$200 \leq m \leq 4000$	$1200 \leq m_p \leq 15000$
Moment of inertia (kg $-m^2$)	$100 \leq J_{XA} \leq 11000$ $100 \leq J_{YA} \leq 11000$ $100 \leq J_{ZA} \leq 8000$	$5000 \leq Jx_p \leq 250000$ $9000 \leq Jy_p \leq 520000$ $12000 \leq Jz_p \leq 600000$
Centre of gravity (m) (relative to DMS)	$0.05 \leq X_{CGA} \leq 0.25$ $0.05 \leq Y_{CGA} \leq 0.25$ $0.75 \leq Z_{CGA} \leq 2.00$	$0.2 \leq X_{CGP} \leq 10.0$ $0.2 \leq Y_{CPG} \leq 4.8$ $0.2 \leq Z_{CPG} \leq 2.5$
Eigenfrequencies (Hz)	$f1 \leq 10$ Hz $f2 \leq 35$ Hz	$0.9 \leq f_{7p} \leq 2.0$ $1.20 \leq f_{8p} \leq 2.0$ $1.25 \leq f_{9p} \leq 2.0$
Flexible appendages and moving parts	TBS	TBS

TABLE 4: PHYSICAL PROPERTIES OF CHASE AND TARGET

Operational Principles: man involvement shall be limited to:

- Supervision of DMS operation
- Interpretation of housekeeping data
- Specially assigned stop/go commands
- Contingency and Emergency control

Operational Modes:

- Permanent docking
- Episodical docking

Nominal Operations Task Structure:

- The DMS shall be checked for docking readiness prior to the initiation of docking
- Nominal operations shall be based on a predetermined operational sequence
- Prior to each sequence and after each sequence go-ahead checks shall assess the status of the docking process and the DMS itself
- The DMS shall provide automatic correction and switch-over commands and/or control of those functions from the ground, according to the mission requirements.

Contingency Operations Task Structure:

- Contingency and Emergency operations shall be initiated when any system of either spacecraft is endangered and safety is no longer guaranteed
- Contingency and Emergency operation shall be initiated by the DMS and/or from the ground, according to the mission requirements

TABLE 5: OPERATIONAL REQUIREMENTS

TRANSFER CAPABILITIES

ELECTRIC

- 2 kW at 50 V
- 1 kW at 28 V
- Low Rate Signal: 100 lines
- High Rate Signal: 100 mb/sec
- Only Parasitic Loads to DMS latches
- Plate Travel < 30 mm
- Emergency Separation Capability
- Separation of Electrical from Liquid/Gas

LIQUID/GAS

- High Pressure Gas
  - 80 kg total at 100 DM^3/H
  - 280 bar initial pressure
- Low Pressure Gas:
  - 100 DM^3 total at 100 DM^3/H
  - 1 bar
- Liquid Connectors:
  - 100 kg of freon 21, 45 bar, 350 K, 360 kg/h, $\Delta_p = 6$ bar
  - 500 kg bipropellant, 20 kg/h

TABLE 6: REQUIREMENTS FOR CONNECTING MECHANISM (TYPICAL)