Magnetic Docking Aid for Orbiter to ISS Docking

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Abstract

The present docking system for the Orbiter uses mechanical capture latches that are actuated by contact forces. The forces are generated when the two approaching masses collide at the docking mechanism. There is always a trade-off between having high enough momentum to effect capture and low enough momentum to avoid structural overload or unacceptable angular displacements. The use of the present docking system includes a contact thrusting maneuver that causes high docking loads to be induced into Space Station.

A magnetic docking aid has been developed to reduce the loads during docking. The magnetic docking aid is comprised of two extendible booms that are attached adjacent to the docking structure with electromagnets attached on the end of each boom. On the mating vehicle, two steel plates are attached. As the Orbiter approaches Space Station, the booms are extended, and the magnets attach to the steel plates on the mating vehicle. The capture latches on the docking system are actuated (without thrusting), by slowly driving the extendible booms to the stowed position, thus reacting the load into the booms. This results in a docking event that has lower loads induced into Space Station structure.

This method also greatly simplifies the Station berthing tasks, since the Shuttle Remote Manipulation System (SRMS) arm need only place the element to be berthed on the magnets (no load required), rather than firing the Reaction Control System (RCS) jets to provide the required force for capture latch actuation.

The Magnetic Docking Aid was developed and undergone development testing on a six degree-of- freedom (6 DOF) system at JSC.

Introduction

The present docking system, based on the early Russian version of the Apollo-Soyuz electro-mechanical docking mechanism, has been successfully used to dock the Space Shuttle Orbiter to the Russian Space Station Mir. A similar docking system will be used to dock to the International Space Station (ISS). The docking mechanism is located on the top of the external airlock in the Orbiter payload bay (Figure 1). Figure 2 shows the overall view of the magnetic docking aid installation on the docking system. The docking mechanism consists of the capture compliance and attenuation system, the capture latch system, the extend retract system, the structural latching system, and the separation system. The system provides the guide, capture ring with 6 DOF for capture compliance and attenuation stroke, and it is made up of a series of ball screws and interconnecting differentials to achieve the 6 DOF. The guide and capture rings are suspended by three sets of ball screws and nut combinations,

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equally spaced around the ring. The screws are linked at the guide ring with an interconnecting gear to provide coordinated roll and translation motions of the capture ring. The ball nut pairs are kinematically linked together at the base and attached to a universal joint. Each ball nut pair provides a torque input to the differential mechanism. The three interconnecting differentials ensure dependent movement of ball nut pairs to provide coordinated pitch-yaw motion of the capture ring. The three springs and three dampers, geared into the ball screw rotation, provide roll and shear motion damping, and their two differential centering springs and three high energy dampers provide pitch and yaw motion damping. Three additional springs reduce the impact shock loading to the differentials. Final output from the differentials, connecting to the spring, is "slip clutched" for axial force load limiting. The docking mechanism is shown schematically in Figure 3, and Figure 4 shows one set of ball screws and differentials.

The docking mechanism uses mechanical capture latches that are actuated by contact forces, generated when the two approaching masses collide at the docking mechanism. There is always a trade-off between having high enough momentum to effect capture and low enough momentum to avoid structural overload or unacceptable angular displacements. On the first visit to Russia, it was very clear that the capture ring was extremely stiff in shear or lateral motion. Subsequent test verified that the characteristics of the docking mechanism were unacceptable, and it would not allow the planned docking with the Space Shuttle by simply impacting at the docking mechanism. An operational method was developed, such that thrusting the nose of the Orbiter just at contact would make the ring comply without moving the Shuttle Orbiter and would achieve capture most of the time. However, the loads were rather high. It is precisely this reason that the concept of using a magnetic docking aid was invented. An extendible boom mechanism is attached to the side of the docking mechanism at the airlock interface, whereby it is extended with electro-magnetic power . The astronaut would perform the docking as he would normally, except that he would simply press an actuator, instead of thrusting the Shuttle, thus slowly withdrawing both the extendible boom mechanism and the magnet, which had been attached to the opposite side. This action then gently pulls the two vehicles into compliance with the mechanism, without creating high loads. This paper describes the integration of well-known devices into a system in such a fashion as to greatly minimize the induced docking loads.

Magnetic Docking Aid Description

The magnetic docking aid is implemented with a minimum of additional hardware. The following components are added to the existing docking hardware:

- Two extendible booms that are attached on the airlock support structure, next to the active half of the docking mechanism in the Orbiter payload bay. Figure 5 shows the location of these booms. The extendible booms used in the development testing are bi-stem actuators, manufactured by Astro Aerospace Corp. In the stowed position, the stems are coiled on two opposing spools in the base of the boom. The boom is deployed and retracted with a DC motor, which drives the spools to extend and retract the stems. Electromagnets are

mounted on the end of each boom. The electromagnets are powered by cables that are coiled on the outside of the booms and easily extend when the booms are deployed.

* The mating steel plates are mounted on brackets next to the passive half of the docking mechanism on the ISS Pressurized Mating Adapter (PMA). Figure 6 shows the location of the steel plates.

* The control switches for the magnetic docking aid are mounted in the docking system control panel, located in the aft flight deck panel.

* The Orbiter docking approach, with the current docking targets and the current contact conditions, is used for docking with the magnetic docking aid, except no post contact thrusting is required.

Docking with the magnetic docking aid is accomplished with the following sequence:

1. As the Orbiter approaches Space Station, the booms are extended to a distance such that the magnets contact and attach to the steel plates on the mating vehicle when the petals on the active and passive capture rings are nested. Any relative motion, either closing or laterally, will only cause low loads, since the extendible boom will backdrive to give low compression loads and will deform easily (low lateral stiffness) for lateral motion.

2. The capture ring is extended simultaneously while the extendible booms are being retracted.

3. The latches on the docking system capture ring are then engaged (without post contact thrusting), by reacting the load into the extendible booms in tension. The load required to actuate the capture latches is approximately 156 N (35 lb) and is totally reacted by the extendible boom magnets (not by accelerating the structural mass). The need for continuing dynamic analysis, year after year, is eliminated because the latches are activated statically and the loads are internally reacted.

4. Once the capture latches are engaged, the power to the electromagnets is turned off, and the booms are retracted.

5. The remaining portion of the docking is the same as the current docking sequence. The capture ring is driven to the retracted position, thus pulling the Orbiter and space station together, actuating the structural latches, compressing the seals, and forming the structural attachment to complete the docking sequence. This results in a docking event that has lower loads into the Space Station structure.

The magnetic docking aid greatly simplifies the ISS berthing tasks as well. The SRMS arm is used to place the element to be berthed near the berthing interface. The magnets, on the end of the extended booms, attach to the steel plates on the mating interface. The booms are then retracted (with the SRMS in an inactive mode), thus enabling berthing without the need for firing the RCS jets to provide the required force for capture latch actuation.

Docking Loads Using the Magnetic Docking Aid

Docking loads were computed for the magnetic docking aid system by using the Ring-Finger Docking Dynamics simulation (RFDD), developed by personnel in the Structures and Mechanics Division of NASA-JSC.

There are 4 major components to the docking loads analysis:
1. Statistical initial contact conditions model
2. RFDD simulation using the Androgynous Peripheral Assembling System (APAS)
3. ISS elastic-body modal analysis/critical structural loads model
4. SRMS/APAS/SRMS berthing model for two ISS stage assembly events

The statistical contact model, describing contact conditions, hardware mounting errors, and the time delay of the post-contact thrust firing initiation, are used to generate the initial contact condition for docking (typically 200 to 300 cases are generated for the Monte Carlo statistical loads analysis approach).

The RFDD simulation, using the APAS dynamic docking mechanism simulation model, is used to calculate system capture performance and interface loads. The APAS docking mechanism analysis model used in this study was developed by NASA personnel. The APAS docking mechanism model was verified through correlation with the 6-DOF test conducted in Moscow.

The ISS elastic-body/structural loads model is used to calculate docking interface loads and critical internal structural loads throughout the space station.

APAS Docking Mechanism Simulation Model

A high-fidelity simulation model of the APAS docking mechanism has been developed by Johnson Space Center. The APAS is the most mechanically complicated docking mechanism simulated by Johnson Space Center to the present. Figure 3 shows a schematic view of the APAS. Previous major JSC-modeled docking mechanisms included:
1. Apollo Ring and Cone docking mechanism — a USA Apollo design concept similar to APAS
2. Apollo Probe/Drogue docking mechanism
3. The USA-designed and manufactured docking mechanism for the Apollo/Soyuz Test Project
4. USA-designed Orbiter/SSF docking mechanisms.

The mechanism math model simulates the significant dynamic and kinematic characteristics of the docking mechanism, including the following:
- Ball-screw actuator/shock attenuators.
- Interconnecting gear train between ball-screw pairs at the guide ring.

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- Interconnecting gears and torque-rods between ball-screw pairs at the base.
- 3 interconnected differential and centering springs mechanisms.
- 3 lateral, motion-limiting spring mechanisms and rate dampers.
- Preloaded, axial motion spring mechanism at the output of the differentials for connection to the slip clutch/motor drive mechanism.
- Clutch/motor drive mechanism.
- Time-delayed, post-capture activated rotational dampers.
- Capture latch load vector depression resistance.
- Docking interface capture latch tolerance criteria.
- Ball-screw and differential mechanism-constrained dynamics.
- APAS friction, flexibility, and hysteresis characteristics.
- Contact dynamics between the internal petal guides/rings, including sliding friction.
- Orbiter and ISS rigid-body mass properties and geometry.
- Orbiter RCS Post Contact Thrust (PCT) capture latch maneuver.
- Fully coupled APAS/docking vehicle elastic response dynamics (for both Orbiter and ISS).

Correlation of the RFDD Simulation Model with Test Data

The RFDD simulation model was fully correlated with the 6 DOF test in Moscow for capture latching performance and interface loads. This correlation included developmental docking hardware at nominal temperature and qualification hardware at nominal -30°C and -50°C. The correlation is excellent for the total test program. Typical correlation results are shown in Figures 7 and 8.

Figure 7 shows the correlation between RFDD simulation results and the 6 DOF Qual. hardware test number 1.5 results. This test simulated a closing velocity of 3 cm/s (0.1 fps), an Orbiter yaw of 4°, and a PCT delay of 2.0 seconds after initial contact. Figure 8 shows the correlation between RFDD simulation results and the 6 DOF Phase 2A -50°C test data results. This test simulated a post contact thrust firing before contact with a resulting closing velocity of 15 cm/s (0.5 fps) at initial contact. The fully correlated RFDD simulation was then modified to simulate the Magnetic Docking Aid system and used to develop system characteristics for the Magnetic Docking Aid concept.

Magnetic/Extendible Boom Simulation Model

A model of the extendible boom/magnetic assemblies has been developed and added to the RFDD/APAS docking simulation. The following features have been included in the mathematical simulation model in RFDD:
- Extendible boom and magnet physical characteristics
- Number of extendible booms used

- Extendible boom base and extended magnet positions
- Engagement logic and locking magnet to engagement plate at initial contact
- Extendible boom pull down delay from time of engagement
- Extendible boom retraction to APAS ring capture latching phase
- Magnetic release delay from time of ring capture latch
- Boom and magnet loads characteristics
- Magnet/servo-motor logic and pull down characteristics
- Extendible boom backdrive and tension loads
- Extendible boom beam shear loads.

Point Design Results for the Magnetic Docking Aid System

In Figure 9, the results of three RFDD simulations are plotted on the same curve. Each simulations had the same initial conditions, but the first simulation had no MDAS and used a PCT to effect capture latching, while the other two simulations used the MDAS to effect capture latching. The docking vehicle had a relative twist attitude (Orbiter yaw error) of 4.0° between the vehicles. The dual-boom case, where two booms were assumed to be engaged, resulted in a peak compressive load of 1757 N (395 lb), as compared to the PCT case, which resulted in a peak compressive load of 8585 N (1930 lb). The third case represented one failed boom engagement and one engaged boom, which pulled together at a slower rate with a resulting peak load of 1521 N (342 lb). The tension loads in the booms during the pull down for the dual boom simulation are shown in Figure 10. The tension load for a single pull down boom, assuming the other boom did not engage, is shown in Figure 11. The net pull load of the single boom is slightly less than that of the dual booms, thus resulting in a longer time to capture and release the booms (6.2 seconds vs. 10.8 seconds).

Docking Vehicle Load Relief Using the Magnetic Docking Aid System

A load study without PCT was assumed to be equivalent to using the Magnetic Docking Aid System, since the impact velocity without PCT is the same as when using the Magnetic Docking Aid system. Vehicle loads have been determined for the STS-74 mission, with and without PCT, to understand the load relief of the Magnetic Docking Aid system. The STS-74 mission is very similar to the ISS mission and is a good indicator of benefit. The load cases include the RCS plume flex body dynamics that occur during the approach. The initial contact conditions are based on a Monte Carlo statistical analysis, including 232 load cases generated from the NASA statistical initial contact condition model. These cases were corrected for missing simulator error sources (i.e., thermal deflections and instrument misalignment). The results are given in Table 1, where the Percentage Reduction Using MDAS column shows significant load reduction when using the MDAS.

Design of Magnet/Striker Plate Footprint

A study was conducted to determine the dimensions of the striker plate footprint required for the electromagnets. Supplied by the Rendezvous and Prox-Ops working Group, contact conditions from the 232 cases were used to represent 3-σ initial contact conditions. This data was modified to include thermal distortion and instrument alignment accuracy. The data represents misalignment at first docking hardware contact. This is conservative, since the natural dynamics of conic docking petal contact geometry would reduce the interface misalignment. Magnetic engagement footprints were computed for parametric variation of radius (R) to MDAS from the APAS centerline and height (H) of the magnet. The magnet/striker plate footprint can be interpreted from the plot of magnet position at initial contact (Figure 12). The resulting footprint of 25 cm by 30 cm (10 in by 12 in) is based on data from this figure and accounts for the diameter of the magnet.

Docking Loads Results and Conclusions

Dynamic simulation of the Magnetic Docking Aid system has been conducted for a large range of initial contact conditions. The vehicle interface loads, using the Magnet Docking Aid system, are much smaller than when using the PCT maneuver. Time to capture latch the docking rings is less than 20 seconds. The Magnetic Docking Aid method of capture latching achieves its design goals, thus greatly reducing loads and lifetime concerns throughout the Space Station. The MDAS removes the requirement for PCT by quick magnetic engagement of the ISS and retraction with significant velocity to effect the capture latches. Studies were conducted to determine the system sensitivity if one of the two magnetic booms failed to engage its respective strike plate. It was found that the failure of only one Magnetic Docking Aid did not adversely affect the docking capture latching operations or vehicle dynamics.

Development Testing

A mock-up was designed and built for development testing of the Magnetic Docking Aid. Figure 13 shows the development test hardware setup.

Tests were performed in the structures laboratory at the Johnson Space Center with 4° pitch, 4° roll, and 3.8 cm (1.5 in) lateral misalignment. Various misalignment combinations were performed. The results showed that capture was achieved in all cases using the Magnetic Docking Aid. A test run was performed without the Magnetic Docking Aid, and the hardware did not consistently latch.

Tests were also performed using the 6 DOF facility and STS-71 station/shuttle inertial properties. The initial conditions were 0.1 ft/sec axial velocity, 4.6 cm (1.8 in) lateral misalignment, 3° pitch and 3° roll misalignment. Tests were performed with one and two magnets attached. Positive capture was achieved for the test cases with engaged magnets.

Summary

In summary, the Magnetic Docking Aid has been designed, analyzed, and tested and shown to meet the objective of allowing two large spacecraft to be gently docked, without the characteristically high induced loads.

Table 1
Docking Vehicle Load Relief
### Using the Magnetic Docking Aid System (MDAS)

Load Indicator	Load Type	Peak Load Using PCT	Peak LM Using PCT	Reduction Using MDAS
Priroda-BM	Axial	305.80 kg	3.27	-33.7%
Kristal-DM	Bending	463.40 kg	1.08	-61.7%
Kvant SP2	My	32.57 kg-m	3.07	-12.7%
Kvant SP1	Shear	11.50 kg	4.35	-48.9%
HGA	My	72.92 kg-m	1.51	-69.7%
EEU	Shear	15.71 kg	3.18	-31.0%
Kvant SP2	Bending	36.42 kg	2.75	-52.8%
Progress-BM	My	1612.00 kg-m	3.10	-41.5%
Kristal-DM	My	461.29 kg-m	1.08	-68.2%
Kvant-2 SP2	My	113.01 kg-m	3.45	-65.2%
Kristal-DM	My	1927.00 kg-m	2.59	-35.1%

- Critical peak Load Margin (LM) results with and without PCT.
- Loads without PCT represents using the Magnetic Docking Aid
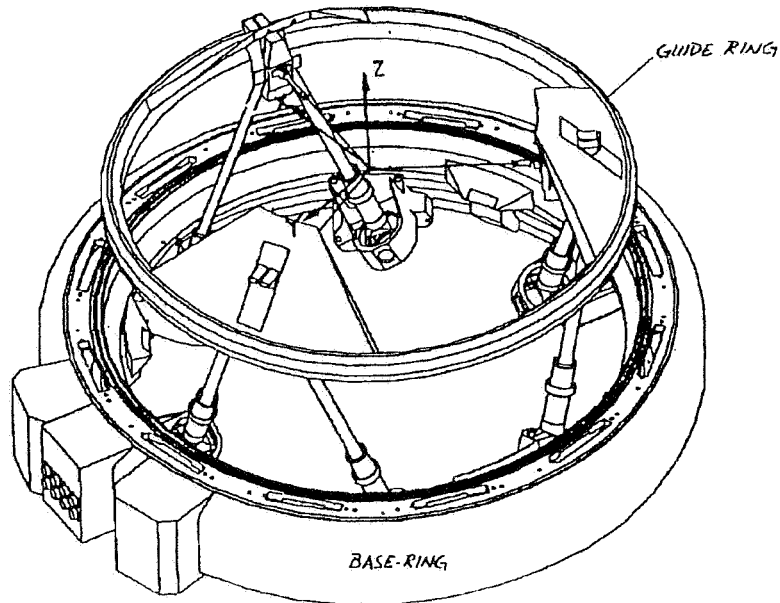
Figure 1   Docking Mechanism
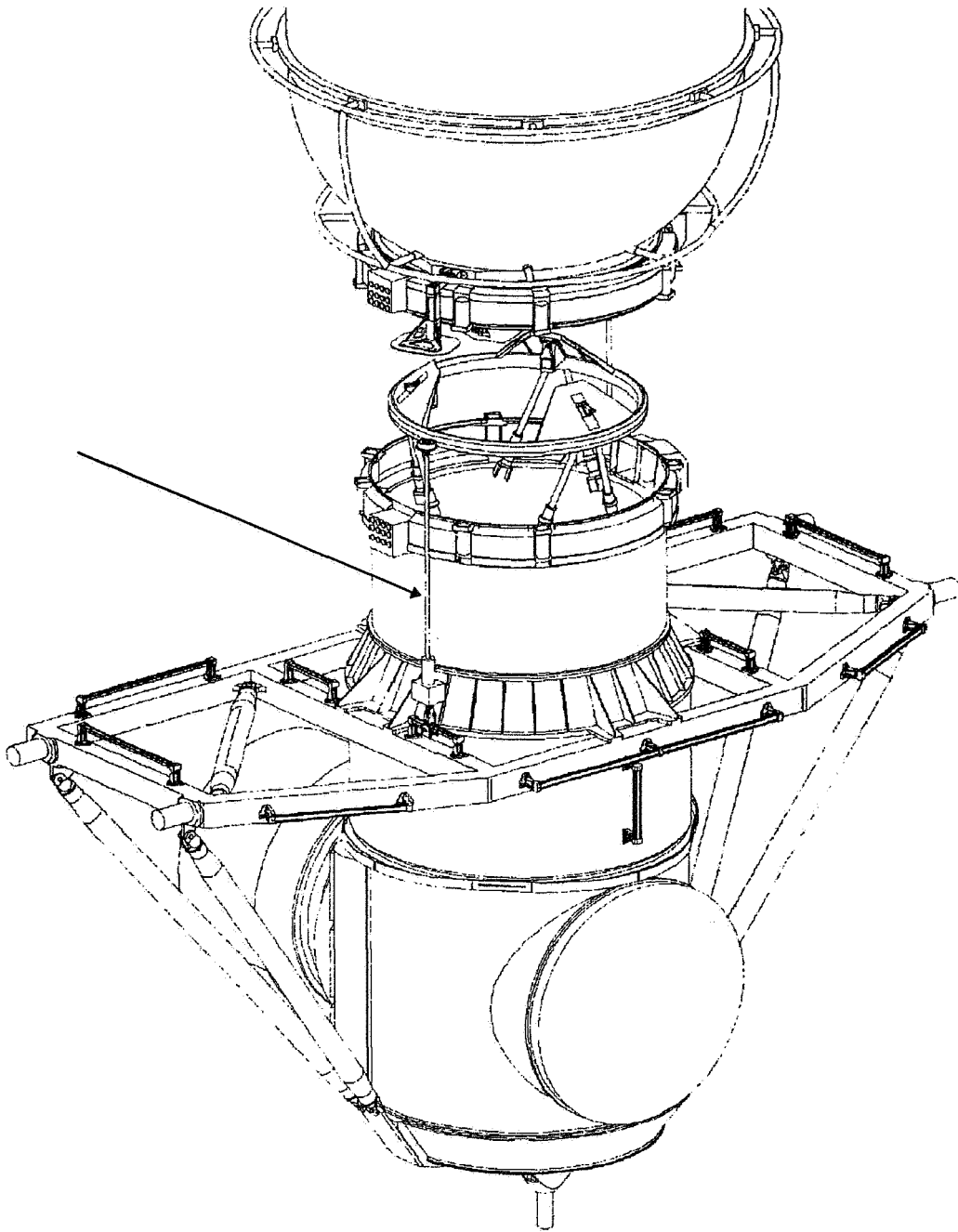
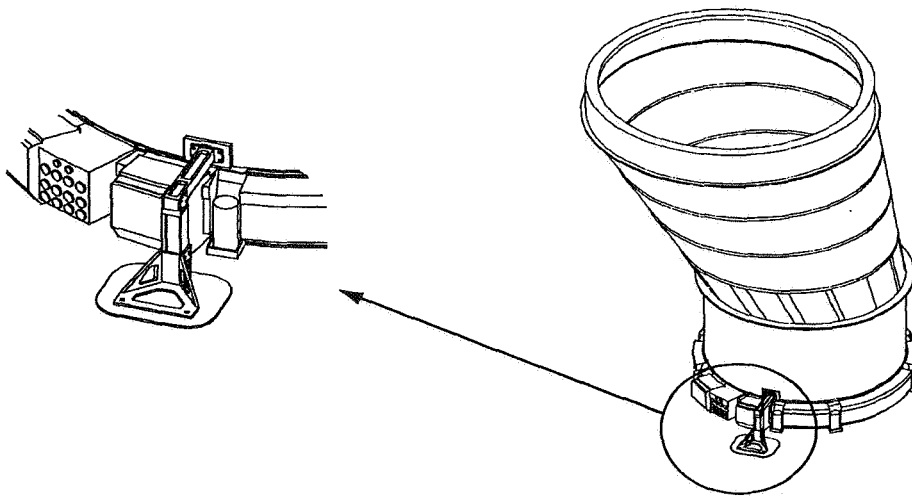**Figure 2 Magnetic Docking Aid Installation on airlock**
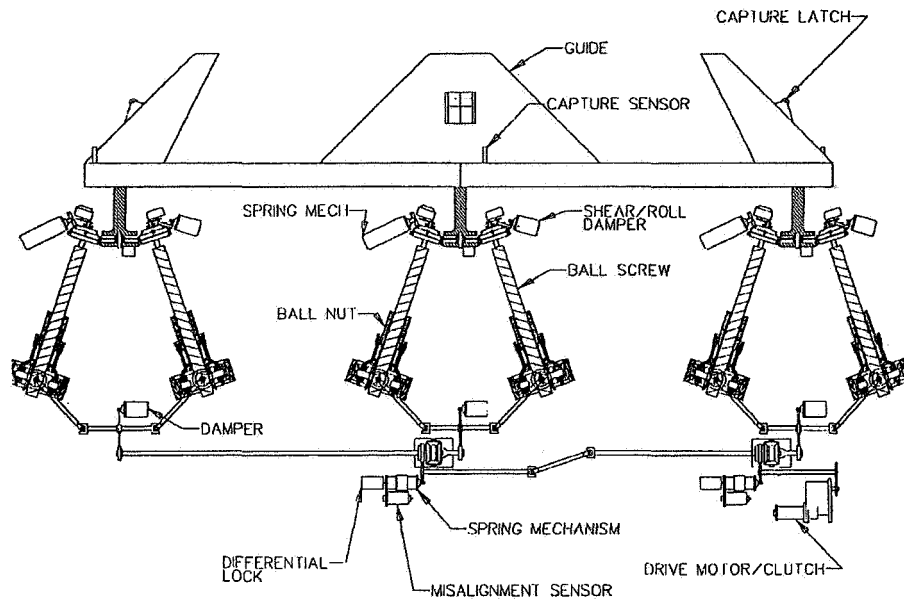
Figure 3 APAS Docking Mechanism Schematic
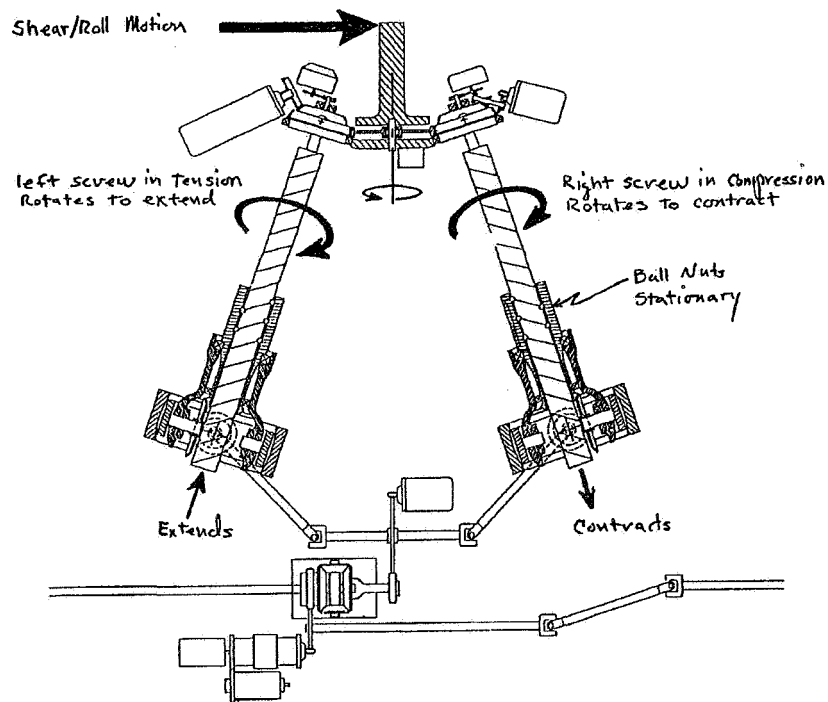
Figure 4 Ball Screw and Differential set
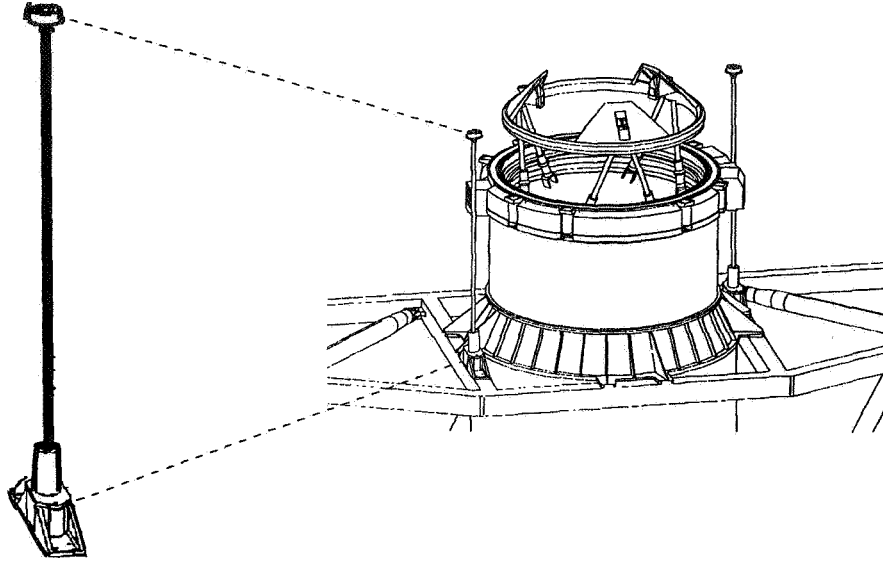
Figure 5   Extendible booms on airlock structure

Figure 6.   Steel plate mounting on PMA for ISS

Test Correlation (Qual,P2): Nominal Temperature
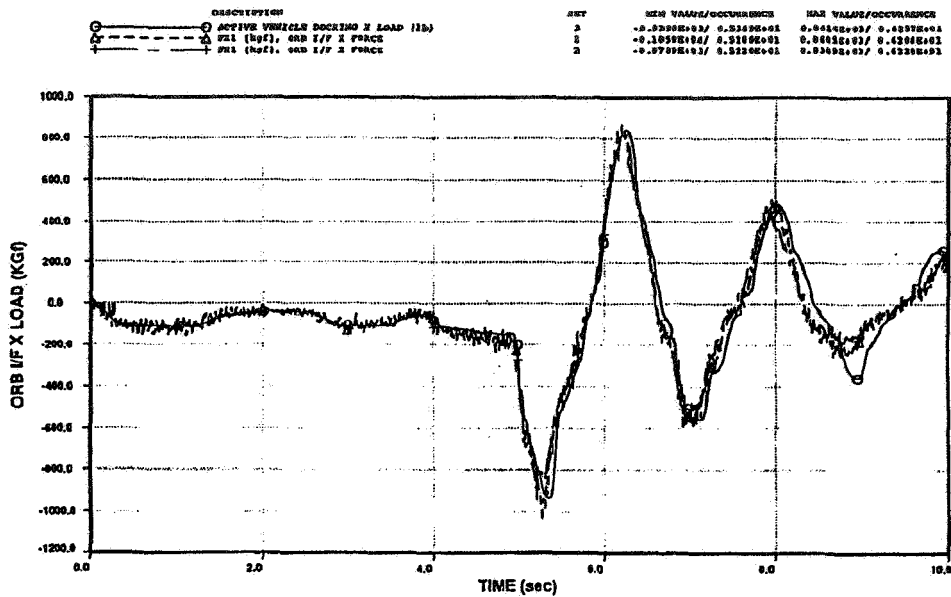APAS Q1M1, testing case tc1_5, qual1.5-nom.dat

**Figure 7. RFDD Math Model/ Qual 1.5 Test Data Correlation
(IC's: PCT at 2.s, Vz=0.1 ,Yaw=4 degrees)**

Test Correlation (PHASE 2A,P2): -50c temperture
APAS Q1M1, testing case tc17_1a, qual17.1a-50c.dat
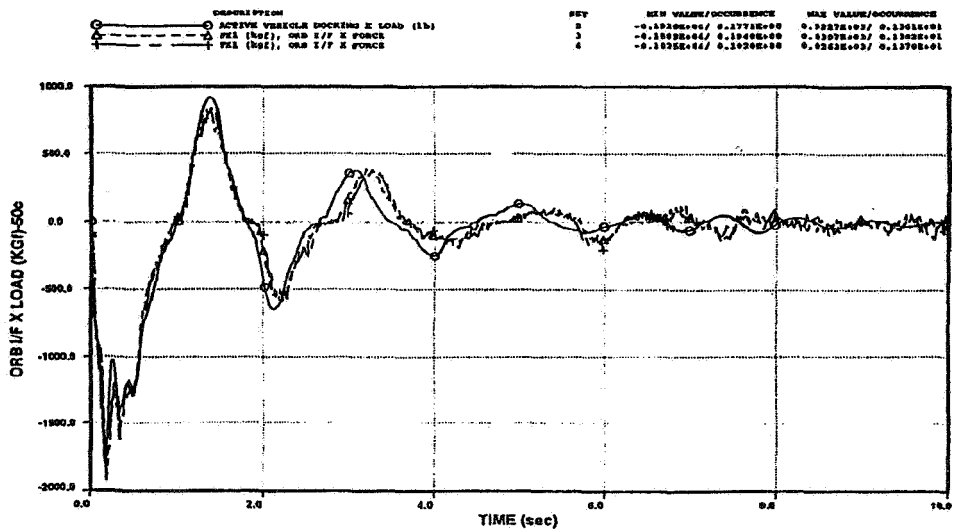
**Figure 8. RFDD Math Model/ Phase 2A -50 degrees c Test Data Correlation
(IC's: PCT before contact, Vz=0.5)**

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RUSSIAN 6-DOF TESTS (QUAL 1): 19/05 1.5
RCS= 1,SCN=6,T1=2.00,T2=0.16,T3=0.08,T4=1.00,T5=0.08,T6=0.16

ORB I/F X LOAD (lbs)

APDM/Single Boom -342 (lbs)

APDM/Dual Boom -395 (lbs)

APDM/PCT -1930 (lbs)

TIME (SEC)
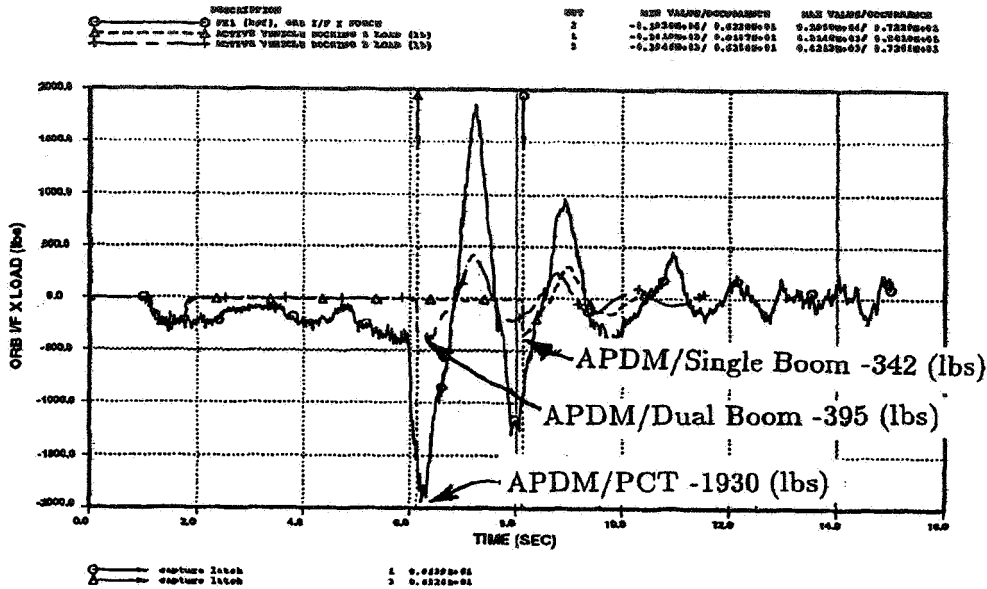
Figure 9. Boom/ Magnet Design Case (Qual 1.5 - nom.dat), Comparison plots between Qual, Single, and Dual Booms

Shuttle/Mir, magload03.dat, apas m1m1.1
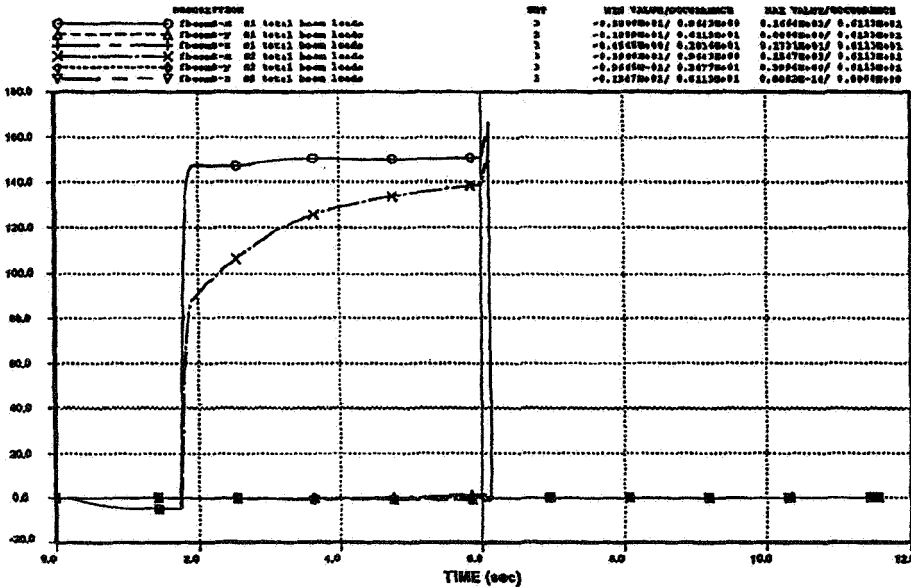Dual Boom, Roll=4, Mis=0, Vel Boom =6ips

TIME (sec)

Figure 10. Boom Pull Down Loads for Design Case (Dual Boom)
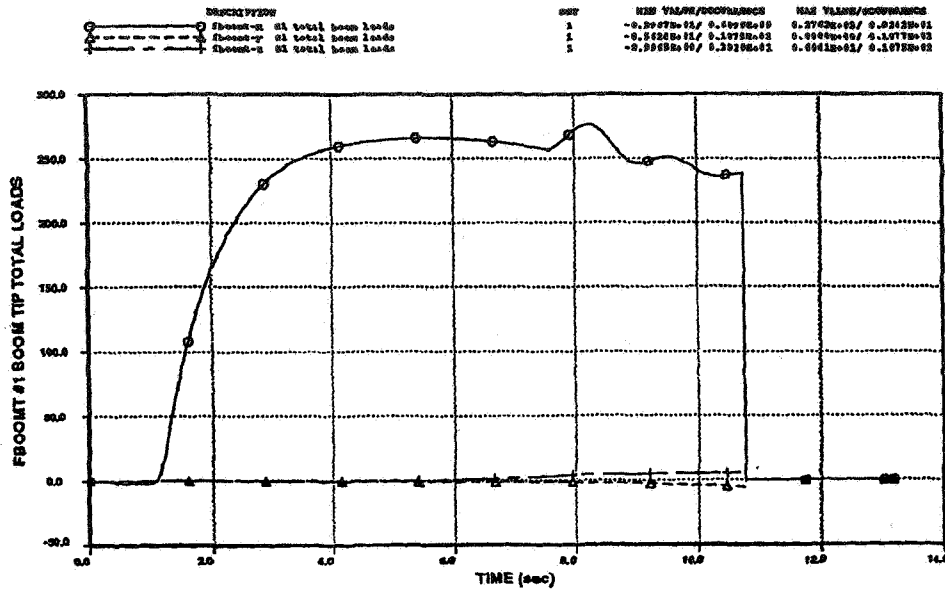
Figure 11. Boom Pull Down Loads for Design Case (Single Boom)
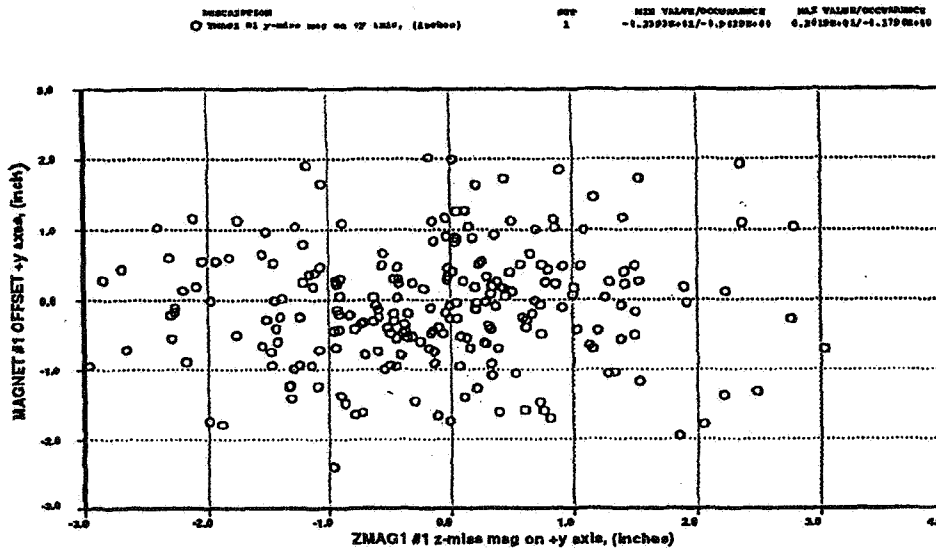
Figure 12. Design of Magnet/ Striker Plate Footprint

VERTICAL
SLIDING
GUIDE

COUNTER
-WEIGHT

12 X 10
STRIKER PL

FULL SCALE
DOCKING
INTERFACE

3.5 DIA
ELECTRO
-MAGNET

EXTENDABLE
BOOM

PITCH-YAW
COMPLYING
MECHANISM

6-DOF
PLATFORM
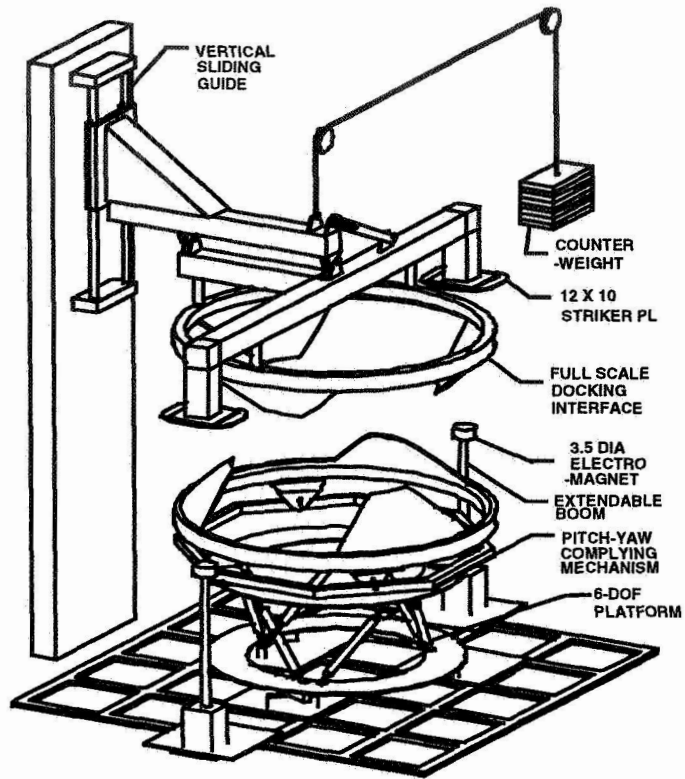
Figure 13 Development Test Hardware Installation