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Paper Session II-B - STS-74 SRMS- Assisted Docking of Docking Module Demonstrates ISS Assembly Technique

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STS-74 SRMS-Assisted Docking of Docking Module Demonstrates ISS Assembly Technique

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Abstract

Space station assembly was demonstrated, albeit on a smaller scale, on STS-74. This experience provided confidence in the ISS Flight 2A assembly method, in which Node 1 will be attached to the Orbiter Docking System (ODS) via SRMS-assisted (Shuttle Remote Manipulator System) docking; then the FGB will be attached to Node 1 in a similar fashion. For the Space Shuttle STS-74 mission, a means of attaching the passive Docking Module (DM) to the ODS was required. The SRMS was used to position and hold the DM above the ODS, while the downfiring Reaction Control System (RCS) thrusters were used to effect the docking. This type of operation had never been attempted with the SRMS before, so a comprehensive dynamic analysis of this operation was performed. A non real-time flex dynamics simulation program was developed to provide the capture statistics, structural loads, and dynamics for this operation. An automated Monte-Carlo approach was used to cover the envelope of expected initial docking conditions. The study showed that the STS-74 DM could be reliably installed on the ODS via SRMS-assisted docking and that the resulting structural loads were acceptable. Post-flight comparisons of the simulation vs. flight data showed that the simulation provided an accurate representation of the system.

Foreword

In order to save the expense of building new hardware, the Shuttle Remote Manipulator System (SRMS) was relied upon to dock passive payloads to the Space Shuttle Orbiter. This approach violated many assumptions about how the SRMS should be used. Because of the technical risk involved, a new analytical capability had to be built in a short time to assess the feasibility of this operation. Commercially-available software tools were utilized to build this initial capability. While workable procedures and feasibility were being established, a robust analysis capability using optimized tools and an automated probabilistic approach was developed. As a result, the feasibility analysis required for early decisions was available in time to meet the flight schedule. Engineering and Mission Operations personnel worked as a team, each bringing their specialized skills and knowledge together to solve a unique problem. Because of this approach, verification of the tool and the final analysis, including contingency scenarios, were completed in time to support the flight.

Background

The US Space Shuttle will dock to the Russian Mir Space Station numerous times during the next few years as a part of a cooperative space effort between the United States and Russia. For the first docking mission, STS-71, the Shuttle docked at the end of the Mir's Kristall module. Prior to docking, the Kristall module had to be reoriented by a manipulator arm to provide more favorable

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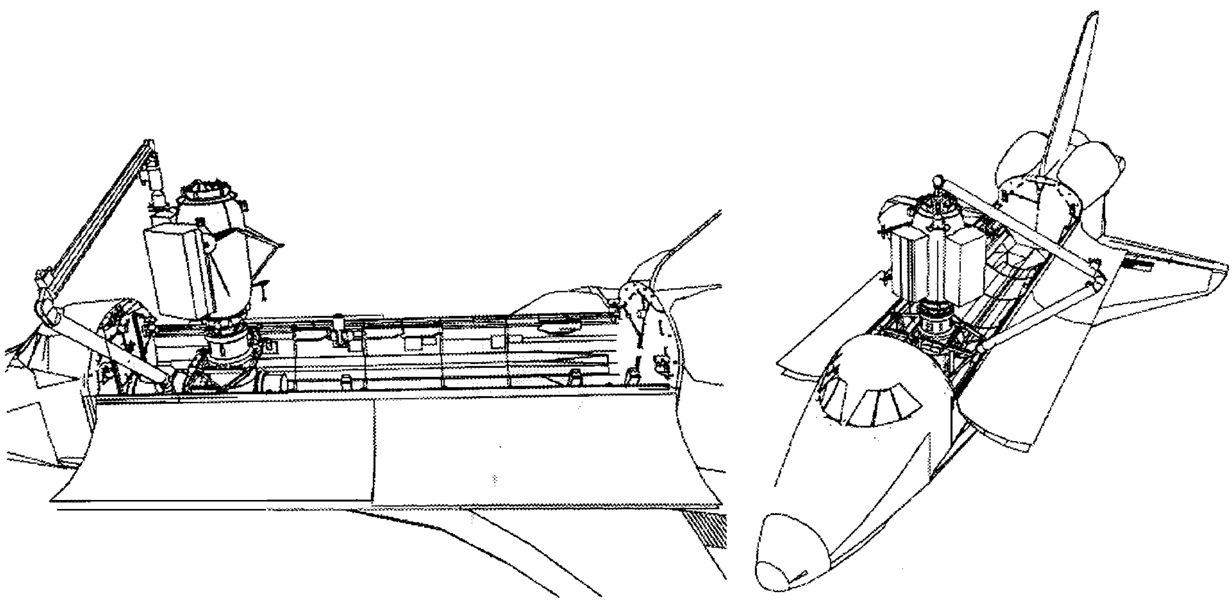
docking conditions. The limited life of this manipulator arm and other factors led to a different docking configuration for the following flights. For these flights, the Orbiter will dock to an extension tunnel, the Docking Module (DM), which was delivered to Mir by the Space Shuttle.

Introduction

For the Space Shuttle STS-74 mission, a means of attaching the passive DM to the ODS (Orbiter Docking System) was required. Since the DM was not a free-flying vehicle, a means of attaching it to the Orbiter, other than standard docking, was required. The SRMS was used to position and hold the DM above the ODS (Figure 1), while the downfiring Reaction Control System (RCS) thrusters were used to effect the docking. This type of operation had never been attempted with the SRMS before, so a comprehensive dynamic analysis of this operation was performed. The purposes of this study were to: 1) determine the feasibility of using the SRMS to attach the STS-74 DM to the Orbiter Docking System (ODS) in the Shuttle bay, 2) provide data to allow selection of the best method for performing this operation, and 3) assess RMS dynamics and loads for these operations.

Figure 1: STS-74 DM Installation



Applicability to ISS Assembly

The DM installation on STS-74 provided confidence in the ISS Flight 2A assembly method, in which Node 1 will be attached to the Orbiter Docking System (ODS) via SRMS-assisted docking (Figure 2); then the FGB will be attached to Node 1 in a similar fashion (Figure 3). This assembly method is unique to Flight 2A since the FGB -to-Node 1 connection requires a US/Russian interface. The Russian APAS interface was designed to dock free-flying vehicles and requires large forces between the two vehicles in order to force alignment and capture. The interface between all other US pressurized elements, the Common Berthing Mechanism (CBM) was designed specifically for US space station assembly via the SSRMS (Space Station Remote Manipulator System) and does not require significant interface forces to be applied, as the SSRMS performs the alignment.

Figure 2: Node 1 Installation

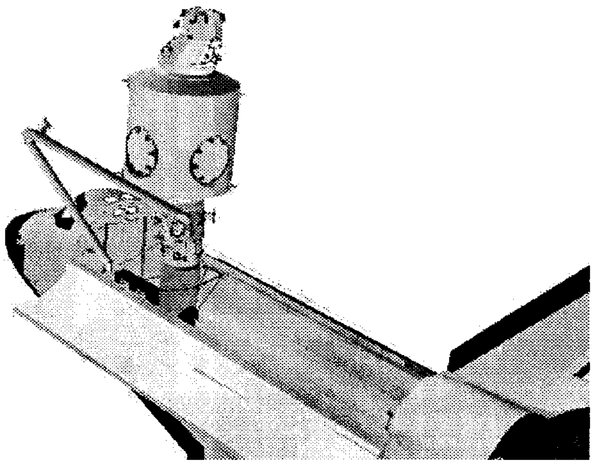
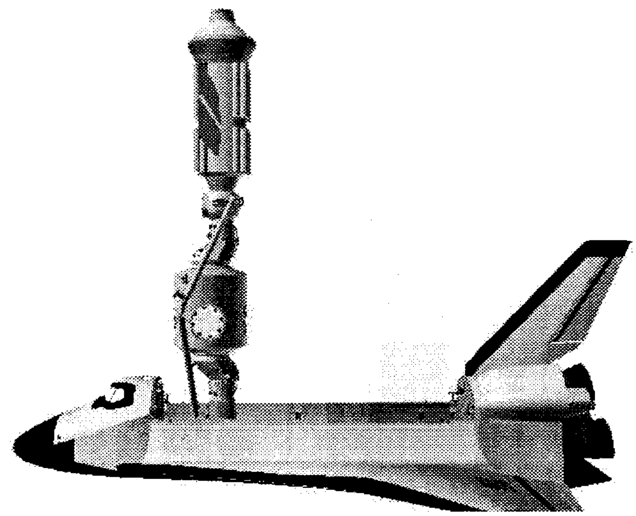


Figure 3: FGB Installation to Node 1



Development of Analysis Tools

The capability to analyze the dynamics of the integrated APAS/SRMS/payload system did not exist. To meet this need, existing component models were assembled into an integrated simulation. The challenge was to accurately model SRMS behavior when constrained by the APAS interface. This non real-time flex dynamics simulation program[8] was used to provide the capture statistics, structural loads, and dynamics for DM installation. It consisted of the following models:

Test-validated APAS model

Dynamic model of APAS mechanism including:

1. ring petal mass properties
2. three ball-screw assemblies -- ballscrews, cross-shafts, idler gears, and dampers
3. differential assembly -- differential gears, shock springs, and clutches

Docking interface contact model

Models the contact forces between the two docking interfaces. Includes the petals, rings, and the capture latch springs

Flight-validated SRMS model

Dynamic, flexible model of Shuttle RMS (SRMS). Includes:

1. flexible booms and MPM/longeron
2. gearbox with freeplay and non-linear stiffness
3. high-fidelity servo model
4. RMS software model.

The APAS model had been validated against ground-test results. Comparisons with flight data from previous payload deployments were made in order to provide confidence in the SRMS models.

[8] Wu, S., et. al., "Dynamic Simulation of RMS-Assisted Shuttle/Mir Docking", AIAA 36th SDM Conference, April 10-12, 1995, New Orleans, LA

SRMS-assisted docking requires the SRMS to operate in a constrained, closed-chain configuration. The SRMS was, however, designed to maneuver a payload in free space, physically connected back to the Orbiter only through the shoulder. The analysis tools developed over the years to study SRMS dynamics were generally limited to open-chain type formulations and were therefore inappropriate for analysis of the proposed SRMS use.

A new dynamics formulation was required for this task. In the model, the RMS arm is represented by seven flexible links connected in series with single DOF joints. With the Orbiter and Docking Module attached at both ends of the links, the system can be represented by a chain of nine bodies. The equations of motion of the system were derived using a recursive formulation. The component mode method was used in the formulation to represent flexibility of each link. Representing the flexibility of each link independently, rather than at the system level (the usual method used in modeling the SRMS), provides a more accurate solution. This added accuracy is crucial at the docking interface, since a realistic loads assessment is required.

DM Installation Methods Trade Study

Four candidate DM installation methods were studied:

- “Mechanism extension” made use of the APAS extension capability. Immediately after a Mir docking, the APAS active ring petal can be driven out to full extension in order to align the vehicles before APAS retraction. In this scenario, the SRMS holds the DM with the SRMS in Brakes-On mode, then the APAS is driven to full extension. The simulation showed that the APAS would simply push the DM away and the desired alignment would not be achieved.

- “RMS Velocity Mode” uses the SRMS to drive the DM down from a pre-determined stand-off point, providing momentum to effect capture. Relatively high rates were required to effect capture, and at these rates, the SRMS had difficulty maintaining alignment at the interfaces. Also, there were safety concerns since much of the DM travel is essentially unconstrained by the docking interfaces. If the RMS deviated significantly off-course, unwanted contact could occur.

- “Quasi-static latching” used the SRMS to position the DM at the docking position, then to push the DM into the ODS. Since there is little momentum, this method relied on the ability of the SRMS to provide enough vertical force to complete the alignment and to overcome the resistance of the APAS capture latches. Simulation results indicated that this method was possible, but unreliable.

- “RCS Thrusting(or SRMS-assisted docking)” used the downfiring RCS thrusters to push the Orbiter into the DM. This is similar to Orbiter/Mir docking, except that the DM has only a small fraction of the Orbiter mass, leading to the possibility that the DM would bounce off of the ODS. The SRMS was used to orient and position the DM just above the APAS. The downfiring RCS jets were then fired to provide the energy to force the interfaces together. Some of this energy will be in the form of linear momentum, and rest will continue to force the interfaces together after contact occurs. For alignment to occur, the SRMS joints must be backdriven. Initial results showed this method to be very attractive in that it was reliable and because the interfaces are partially meshed, quite safe from unwanted collisions.

The SRMS uses a rate-controlled feedback control system and has no information on the direction or magnitude of tip forces and torques. It has known instabilities when placed with constrained situation. Concerns regarding constrained behavior and possible SRMS failure modes led to an approach using the SRMS as a passive holding device, rather than using it to provide the force required for APAS capture. RCS Thrusting was selected as the baseline DM installation method.

Capture can be achieved with either Test Mode or Brakes-On. When the brakes are applied, the SRMS is moded to a truly passive state. Test Mode is a "limped-arm" control mode which was designed to allow on-orbit checkout of the SRMS hand-controllers. The SRMS is under active control, but does not have enough control authority to actually move in this mode. Test Mode allows the SRMS joints to move easily, which assists docking, whereas the brakes resist the motion and thereby increase misalignments and reduce velocity at contact. Because of this, Test Mode was selected for the primary method.

Analysis Method

Because the worst-case combinations of misalignments were not known, a Monte-Carlo approach was used to cover the envelope of expected initial docking conditions. Initial docking interface misalignments were based on statistical data from studies performed in a man-in-the-loop simulator. The generation of random initial conditions and the submission of simulation runs were automated in order to provide a consistent and efficient means of generating statistical data on capture performance and structural loads.

Results

The study[9] showed that the STS-74 DM could be reliably installed on the ODS via SRMS-assisted docking. In over a thousand simulations using the final procedures and misalignment envelope, capture was achieved in every case. It was also shown that the dynamic motions and the resulting structural loads were acceptable.

If the SRMS Test Mode had not been available, DM installation could have still been performed by firing the RCS with the joint brakes applied. Since piloting studies showed that the SRMS operator could place the DM quite accurately, Brakes-On simulations showed this method to also be very reliable. Use of the brakes during the RCS firing would increase the arm and grapple point loads, but would also decrease the APAS loads (due to reduced velocity at contact). Reasonable variations in SRMS joint friction levels, both high and low, were shown to have negligible effect on capture success.

Missed-capture dynamics were studied by expanding the misalignment envelope beyond that expected in flight. This study showed that the inherent friction in the joints alone would bring the DM to a halt within one foot of vertical motion after a Test-Mode bounce-off. For a Brakes-On

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[9] "STS-74 Docking Module Installation Dynamics Study Report", S. Ghofranian to B. Brandt, Rockwell IL# ODS-1.4.2.11.1-95-082, July 5, 1995.

case, the DM would simply bounce up and down and recontact the ODS, with the APAS petals still meshed.

Conclusions

On mission STS-74, the DM installation behaved as predicted by the simulation. Post-flight comparisons of the simulation vs. flight data showed that the simulation provided an accurate representation of the system response. Actual SRMS joint angles and motor tachometer rates from flight compared well to the simulation (Figure 4).

Figure 4: Simulation Results Compared to Flight