Berthing Load Analysis between Space Manipulator and Berthing Mechanism during On-orbit Assembly Operation

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Abstract
This paper describes berthing load analysis between Space Station Remote Manipulator System (SSRMS) and Japanese Experiment Module (JEM) berthing mechanisms during Flight 2J/A, the third flight of JEM, to assemble Exposed Facility (EF) and Exposed Section (ES). The berthing operation is one of the challenging tasks to perform the on-orbit assembly because unknown and imprecise locations between the berthing interfaces may create a force-fighting situation. It happens when SSRMS is accidentally braked while the mechanism continues to retract EF or ES attached to the manipulator. One of the worst cases found at the berthing load analysis is that exceedance of limit force or torque might happen with the tiny angular misalignment between the berthing interfaces. The solution candidates are identified at EF and ES berthing mechanisms respectively based on the preliminary load analysis results to avoid or mitigate the force-fighting situation.

1. Introduction
Construction of the international space station (ISS) is approaching the final phase. Japanese Experiment Module (JEM), called “Kibo,” will be carried by three Shuttle flights and attached to ISS by 2009 shown in Figure 1. During Flight 2J/A: the third flight of JEM, JEM unique berthing mechanisms will play key roles to assemble Exposed Facility (EF) and Exposed Section (ES). They are named as EF Berthing Mechanism (EFBM) shown in Figure 2 and Equipment Exchange Unit (EEU) shown in Figure 3. Space Station Remote Manipulator System (SSRMS) handles EF and ES to Ready to Latch (RTL) position and then EFBM and EEU start jointing EF and ES respectively.

The main robotic task required for JEM on-orbit assembly consists of the following two steps. In the first step, SSRMS extracts the massive payload, i.e. EF or ES, from the shuttle cargo bay and then transfers it to a well-defined ISS pre-berthing position. These sequences of the operation are exactly determined and confirmed in advance, so only an inter-vehicular activity (IVA) crew member is needed to perform the first step. In the second step, SSRMS moves the payload to the RTL position where the berthing interface points at the payload are within the capture envelop, and the berthing mechanism retracts the berthing points. The second step typically requires two IVA and two EVA crew members. The first IVA operates the manipulator and the second operates the berthing mechanism, while two EVAs guide and navigate the payload to the RTL positions. This paper concentrates on the second step.

The berthing operation is one of challenging task to perform on-orbit assembly because unknown and imprecise locations between berthing interfaces may create a force-fighting situation. It happens when the manipulator is accidentally braked while the mechanism continues to retract the berthing payload attached to the manipulator. This paper describes requirements of force fighting avoidance and berthing load analysis between SSRMS and JEM berthing mechanisms, EFBM and EEU, to assemble EF and ES.

Figure 1 Japanese Experiment Module (JEM)
2. Manipulator and Berthing Mechanism

The large space manipulators used for assembling and operating ISS are a 17m-long 7-degrees-of-freedom (DOF) manipulator SSRMS developed by the Canadian Space Agency (CSA) and a 10m-long 6-DOF manipulator JEM Remote Manipulator System (JEMRMS) Main Arm developed by the Japan Aerospace Exploration Agency (JAXA) shown in Figure 4. These large space manipulators are used to handle and position the large and massive assembled payload. Because the manipulators with long length arm employ high-gear-ratio, high-stiffness and high-brake-torque joints, the manipulator tip stiffness depending on the posture though is relatively soft in translation and hard in orientation. SSRMS has relatively high angular stiffness and high brake torque compared to JEMRMS.

The various berthing mechanisms have been designed and developed in ISS to meet the versatile requirements. EFBM, developed by JAXA, is a unique mechanism jointing EF to Pressurized Module (PM) not only structurally but also electrically and hydraulically in an exposed environment. The EFBM consists of an active half attached to the PM and a passive half attached to the EF. The active half has four latches to capture the passive half shown in Figure 5. The capture envelope, designed within 75mm lateral (o-p) and 1.5deg (o-p), is large enough for manipulator to position the pre-berthing location. During the capture phase, the mechanism retracts the passive half and aligns it by guide vanes and guide pins/sockets. A force-fighting situation might occur at the capture phase when SSRMS becomes safing. In the fully berthed position at the end of the capture phase, the misalignment will be less than 1mm and 0.2deg in each axis. During structure phase after the capture phase, the four bolts on the active half are driven as structural latches to ensure structural connection. The umbilical latches are then driven to provide electrical and fluid mating at the final sequences of EFBM operation.

EEU developed also by JAXA, is a unique mechanism jointing ES or JEM standard payloads to EF in an exposed environment. The EEU consists of EFU and PIU. The twelve EFUs are equipped to the EF while one PIU is equipped at each payload such as ES or JEM standard payload. EFU has three latches to capture the PIU. The capture envelope, designed within 1.2deg-roll (o-p) and 1.6deg-wobble (o-p), is large enough for manipulator to position. During the berthing operation, a force-fighting might happen when EFU retracts and aligns PIU using latching arm and V-shape-guide. At the final phase of the berthing, all connectors including power, signal as well as fluid are mated.

Figure 6 and 7 show the typical configuration of EF and ES assembly by SSRMS respectively.
3. Berthing sequences for manipulator

The assembly operation by SSRMS requires IVA crew members for most sequences, while the berthing operation requires IVA and EVA cooperation. During EF or ES handling, IVA operators can watch the telemetry and video camera views. During the approach to the capture envelop of berthing mechanism, IVA and EVA cooperation begins. The EVA crew member guides and navigates the passive half of EFBM or PIU, and the IVA crew member positions EF or ES. The EVA crew member ensures the position of EF or ES and reports RTL status when it is within the capture envelop of EFBM or EEU. This EVA based berthing is called EVA-GCA (Guidance Control Approach).

In the next phase of EF or ES capturing, the IVA crew member sets the SSRMS mode to limp and another IVA crew member starts retracting the EFBM or EEU. During retraction, the retraction force should be large enough to overcome SSRMS limp resistance. In this nominal sequence of operations, force fighting situation will not occur.

The force fighting situation occurs during capture when the SSRMS is safed. As soon as the SSRMS control processor receives an emergency stop command, each joint enters the brake state and maintains the current position. When the mechanism retracts EF or ES during SSRMS safing, the driving mechanism and braked manipulator pull each other and force fighting occurs. Force fighting may cause structural damage at a weak point within the structure.

4. Safety requirements and its workaround

ISS requested that hazards or potential hazards be visible. The hazard should first be eliminated during the design phase. If it cannot be eliminated, hazard avoidance with fault-tolerant design is applied.

If the hazard is classified as catastrophic, the system must be tolerant to two faults, two miss-operations, or combinations of these two. A catastrophic hazard is defined as one that may cause loss of the shuttle or ISS, or injury to crew members. Force fighting is categorized as catastrophic hazard due to possibility to float EF or ES and to induce collision with ISS. As this hazard cause cannot be eliminated, safety requires two fault-tolerances which are equivalent to provide three independent controls. Hazard control candidates for avoiding the force-fighting situation are described below.

A. Control by Manipulator

When the manipulator enters the limp mode with no failure, the manipulator is back-driven to follow the motion of berthing mechanism. This control can be counted as one of the three controls.

Mechanical constraints cause force fighting situation after SSRMS safing. By de-rigidizing the end-effector LEE during berthing EF or ES, mechanical constraints are relaxed. If the grapple points are still kept hold and not released, this control of de-rigidization would be promising candidates for avoiding force fighting. The further analysis is required for performance purposes as well as safety purpose which might induce other hazard causes such as releasing EF or ES.

Using JEMRMS instead of SSRMS could be another control to avoid force fighting, because JEMRMS brake is not as strong as SSRMS one.
JEMRMS brake will slip before damaging the hardware in mechanical loop. However using JEMRMS changes the whole story of ISS assembly in terms of responsibility, mission priority, operational resource and so on. Therefore it will be the final resort.

**B. Berthing Mechanism Accommodation**

If the berthing mechanism has force/torque limits during retraction, it might avoid force fighting. The slowed latching operation may also be considered to mitigate force fighting. These options are relatively easy during the design phase but difficult to implement after the hardware is manufactured and tested.

Another control is to stop the berthing mechanism when SSRMS enters the safe mode. Triggering the safing event sends the command to turn off the power of the mechanism and stop the mechanism. If the mechanism is turned off within the allowable time before the load builds up, this can be counted as one of the three hazard controls.

Marking on berthing mechanism will reduce misalignment to mitigate the force fighting situation. The EVA-GCA marking was not required for the original EFBM, however it is requested to significantly reduce initial misalignment. According to the crew evaluation using graphical simulator, 0.6 deg wobble with the marking is achieved from 1.5 deg wobble without the marking. EEU has also modified the width of the marking from the original to reduce the roll misalignment.

**C. IVA Crew**

An IVA crew member can stop the mechanism when the SSRMS is braked. However, the SSRMS operator is far from the mechanism operator, and voice communication may take 30sec for the worst case to answer via the voice loop system. It could be counted as one of the three controls if allowable time is more than 30 seconds.

**5. Berthing load analysis**

**5.1 Contact model**

The validity of the above hazard controls depends on not only the berthing load but also the time to build up the load after safing SSRMS. The time to the maximum allowable load can identify the worst cases and estimate the allowable time to stop EFBM or EEU.

To simulate the berthing load, the contact models of both EFBM and EEU have been developed. The contact model calculates the force and torque at the contact points based on geometrical constraints and structural stiffness in hardware. The three-dimensional shape in the model determines whether contact parts interact with each others.

The modeling is an important part of the simulation. The parameters used in the contact model originate from the design and the hardware performance testing. These contact models have been tuned up and verified by referring to ground test data.

**5.2 Analysis Conditions**

When the manipulator enters braked mode during the berthing load simulation, all the seven or six DOF joints are assumed to be locked and will not move until the brake slips. When the manipulator is locked at each joint, it is modeled as tip stiffness matrix for safing simulation. On the other hand, when it is slipped at several joints, it is modeled as not only the tip stiffness matrix but also the modified limp mode with limited torque at each joint. The SSRMS limp is less than 290N, 265Nm at the tip.

The most sensitive parts to the load in the manipulators are end-effector and grapple fixture which are the interface between manipulator and payload. The allowable torques on the grapple fixtures are 949Nm in torsion and 1627Nm in bending. The sensitive parts to EFBM are the force of the tip latching arm (4200N), while those to EEU are the misalignment at the final phase during the connector mating (1deg or less). The allowable time to stop EFBM or EEU is determined when the sensitive parts exceed the limit force or alignment.

The simulation parameters include payload property, initial conditions as well as safing time. EF and ES is 3.8 and 2.7 ton payload respectively assumed to be rigid body. The initial conditions are selected from the edge of the capture envelop.

There are so many combinations of the parameters that it is unfeasible to simulate all combination cases. The strategy to find the worst case is based on the phenomena where higher velocity in the limp mode correlates the faster time to rise up the load in the safe
mode. Therefore the manipulator switches the braked mode from the limp mode when the berthing velocity becomes the highest.

5.3 EF Berthing by SSRMS

The initial misalignments cases selected are 43 for limp mode analysis. At least either pitch, yaw or roll is set to plus or minus 1.5 deg at the edges of the EFBM capture envelop. To find the safing time (i.e. switching time from the limp to the brake), peak velocity in either axial, lateral, wobble or roll direction is picked during the limp mode analysis. 172 safing cases have been selected and simulated using EFBM contact model and SSRMS tip stiffness matrix.

Figure 9 shows the safing simulation results. There are 60 cases for grapple fixture force limit exceedance (rectangulars). 51 cases are hit the motor current limiter (trianglse) before hitting grapple fixtures. 4 cases are hit the capture latch tip force (circles) exceedance. When safing time is after 42 sec (i.e. at the end of mating), it is likely that the load exceeds the limit force of the grapple fixture within or less than 10 sec. The worst cases are about 3 seconds to rising load for EFBM to achieve allowable force or moments at the grapple points.

The EFBM power may not be turned off fast enough to avoid the force fighting, so alternate solutions such as de-rigidization of LEE may be necessary. Using JEMRMS might be technically possible as shown in the next section also.

5.4 EF Berthing by JEMRMS

The initial misalignments cases selected are 43 for limp mode analysis as the same as SSRMS selection. To find the safing time, peak velocity in either axial, lateral, wobble or roll direction are picked at the limp mode analysis. About 215 safing cases have been selected and simulated using EFBM contact model and JEMRMS tip stiffness matrix.

There are no cases for exceedance of the grapple fixture force limit due to the slipping joint brake. Only 60 cases exceed the force of the latching arm as shown in Figure 10. However, it is easily avoided as it takes about 50-60 sec to reach the limit.

5.5 ES Berthing by SSRMS

The initial misalignments cases selected are 30 for limp mode analysis. 1.6 deg-wobble or 1.2 deg-roll is set to plus or minus at the edges or its outside of the EEU capture envelop. To find the safing time, peak distance or velocity in wobble or roll direction are picked at the limp mode analysis. About 45 safing cases have been selected and simulated using EEU contact model and SSRMS tip stiffness matrix.

There are quite a few cases at grapple fixture force limit exceedance. The worst cases are around 30 seconds to rising load to achieve allowable force or moments at the grapple points. The solution could be the stop EEU by command and IVA crew voice communication. For the misalignments for connector mating, further analysis is needed.
6. Conclusions

Force fighting occurs when the manipulator is accidentally braked while the mechanism continues to retract the berthing payload attached to the manipulator. A numerical simulation of the berthing operation was performed under carefully selected conditions using a contact model to understand the force-fighting mechanism. According to the EFBM simulation, the load build-up is so quick that turning off the power of EFBM may not be a solution for avoiding force fighting. On the other hand, EEU load build-up is so relatively slow that it takes about 30sec. The stop command and IVA crew voice communication to stop the mechanism could be one of hazard control.

One of the worst cases found at the load analysis is that exceedance of limit force or torque might happen with the tiny angular misalignment between berthed planes. The solution candidates are identified at EF and ES berthing mechanisms respectively based on the preliminary load analysis results to avoid or mitigate the force fighting situation.

7. References