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UNEXPECTED CONTROL STRUCTURE INTERACTION ON INTERNATIONAL SPACE STATION

On June 23, 2011, the International Space Station (ISS) was performing a routine 180 degree yaw maneuver in support of a Russian vehicle docking when the on board Russian Segment (RS) software unexpectedly declared two attitude thrusters failed and switched thruster configurations in response to unanticipated ISS dynamic motion. Flight data analysis after the maneuver indicated that higher than predicted structural loads had been induced at various locations on the United States (U.S.) segment of the ISS. Further analysis revealed that the attitude control system was firing thrusters in response to both structural flex and rigid body rates, which resonated the structure and caused high loads and fatigue cycles. It was later determined that the thruster themselves were healthy. The RS software logic, which was intended to react to thruster failures, had instead been heavily influenced by interaction between the control system and structural flex.

This paper will discuss the technical aspects of the control structure interaction problem that led to the RS control system firing thrusters in response to structural flex, the factors that led to insufficient preflight analysis of the thruster firings, and the ramifications the event had on the ISS. An immediate consequence included limiting which thrusters could be used for attitude control. This complicated the planning of on-orbit thruster events and necessitated the use of suboptimal thruster configurations that increased propellant usage and caused thruster lifetime usage concerns. In addition to the technical aspects of the problem, the team dynamics and communication shortcomings that led to such an event happening in an environment where extensive analysis is performed in support of human space flight will also be examined. Finally, the technical solution will be presented, which required a multidisciplinary effort between the U.S. and Russian control system engineers and loads and dynamics structural engineers to develop and implement an extensive modification in the RS software logic for ISS attitude control thruster firings.

THE INTERNATIONAL SPACE STATION

INTRODUCTION

The International Space Station (ISS) is a highly complex ~450,000 kg laboratory in low Earth orbit. It consists of solar arrays, radiators, and a main truss that supports these components and pressurized modules. Other components include robotic arms, docked crew vehicles, berthed cargo vehicles, and external stowage pallets. Several of these components are highlighted in Figure 1.

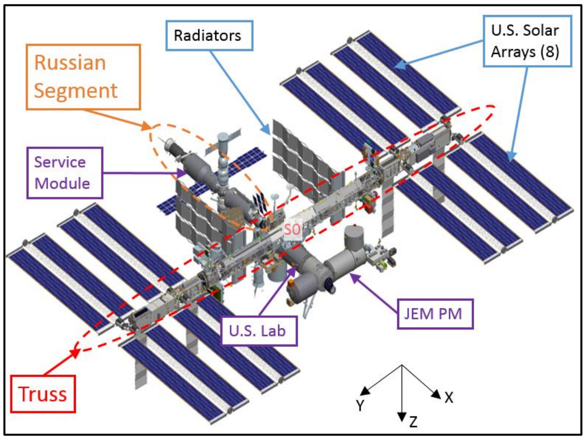


Figure 1 – International Space Station in 2011

The control system for ISS is shared between the U.S. and Russian segments. The Russian Segment (RS) provides thruster control for maneuvering to and holding attitudes required for a variety of on-orbit events, including cargo and crew vehicle approach and departure. The U.S. segment attitude control is responsible for non-propulsive attitude control, which is used during quiescent, non-maneuvering, operations.

JUNE 23, 2011

THE MANEUVER

On June 23, 2011 (Day 174/2011), the ISS was performing a routine 180-degree maneuver to the docking attitude of the 43P Progress cargo vehicle using RS thrusters. Service Module thrusters were used for pitch and yaw control, and Progress on DC1 nadir thrusters were used for roll control, as depicted in Figure 2. The thrusters and vectors are shown in Figure 3.

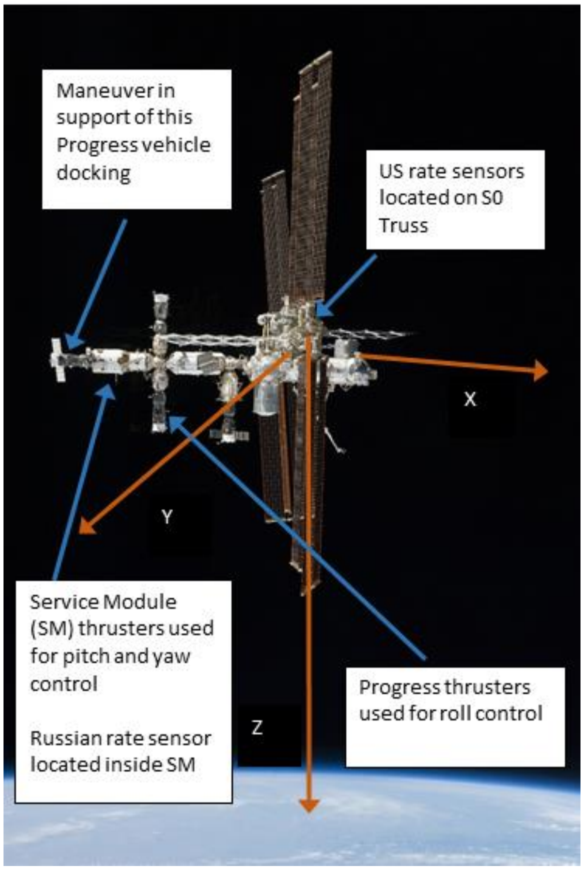


Figure 2 – ISS Thruster Configuration for Day 174

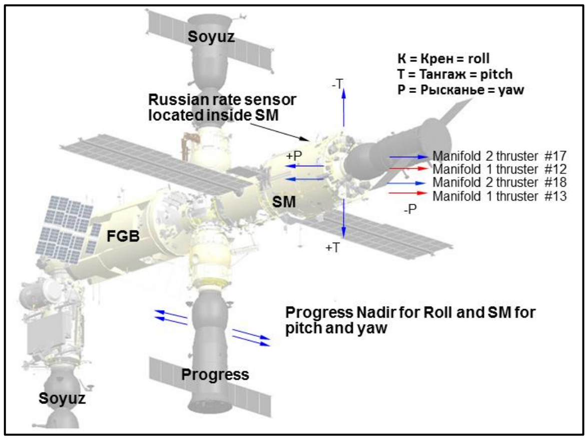


Figure 3 – Thruster Configuration for Maneuver

During the maneuver, the RS software declared certain thrusters failed and switched to alternate thrusters. This was not typical behavior. Nevertheless, the maneuver did complete as planned, achieving the desired 180 degree yaw.

This maneuver resonated the structure, causing high loads and fatigue cycles. The event was clearly visible in ISS sensor data. As an example, the accelerations measured by the Space Acceleration Measure System (SAMS) accelerometer sensor in the Japanese Experiment Module (JEM) are shown in Figure 4. The location of this sensor on the ISS is denoted in Figure 5.

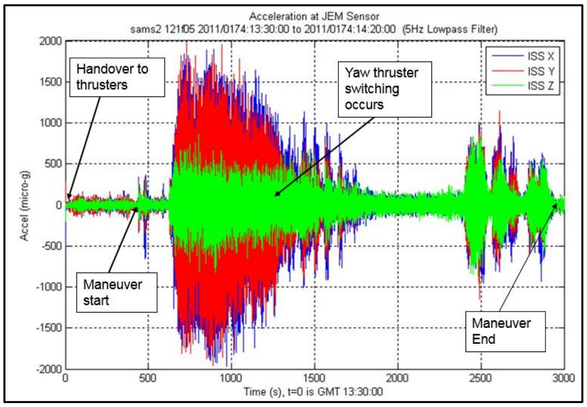


Figure 4 – Acceleration Measured at JEM

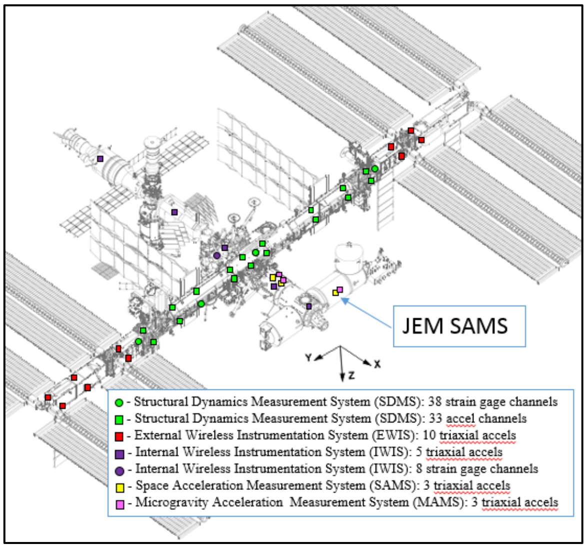


Figure 5 – ISS Sensor Locations

The region of high acceleration, which lasted for over 10 minutes, was not predicted by pre-flight analysis. A review of historical on-orbit SAMS accelerometer data later showed that this was not the first time that this type of structural response had occurred. High acceleration events had occurred during at least a dozen large Russian maneuvers since December of 2009. The June 23, 2011 event was the most severe. It demonstrated that the structural risks due to ISS thruster firings were higher than previously believed.

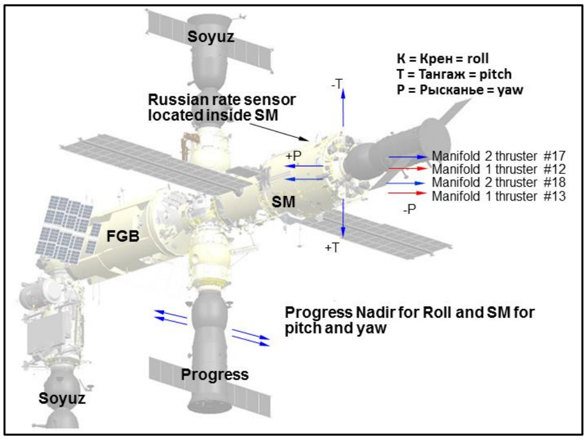
RS THRUSTER FIRING CONSTRAINT LOGIC

The RS software logic that controlled thruster on times during this maneuver implemented a delay time structure. The thrusters could fire for as long as needed, but once they turned off, there was a minimum delay required before they would be allowed to fire again. The minimum delay times were set to 3-1-1 seconds (roll-pitch-yaw). The controller logic provided no limit on thruster on-times and no limit on firing repetitions.

This 3-1-1 minimum delay time control system logic was not new to space stations. Not only had it been in use since the beginning of the ISS, it had been used for the Russian MIR Station as well. There had been no demonstrated issues with the control methodology until Day 174.

RS THRUSTER FAILURE DETECTION LOGIC

RS software has logic to monitor the expected attitude rates following each thruster firing compared to the measured attitude rates. If the difference between the expected and measured rates exceeds a threshold, the software declares thrusters failed and reconfigures to use alternate thrusters. The Russian rate sensor is located in the Service Module. During this particular yaw maneuver, RS software declared two SM positive yaw thrusters on manifold 2 (thrusters #18 and #19) failed. The SM controller automatically switched over to the redundant positive yaw thrusters on backup manifold 1 (#12 and #13) and completed the maneuver and docking operations. The thrust vectors are shown in Figure 3.



Several days after the maneuver, the thrusters were tested and determined to be healthy. This indicated that the declaration of the yaw thrusters as failed was due to yaw rates measured by the rate sensor not comparing well to expected rates. The rate sensor itself was healthy, meaning that the rates it was sensing were real rates. The ISS had experienced notable flex dynamics in addition to the rigid body dynamics inherent to the maneuver.

Figure 6 shows the unfiltered rates as measured by the Russian rate sensor in the SM. Notice that the rates measured for the yaw axis were much larger and noisier than roll and pitch rates.

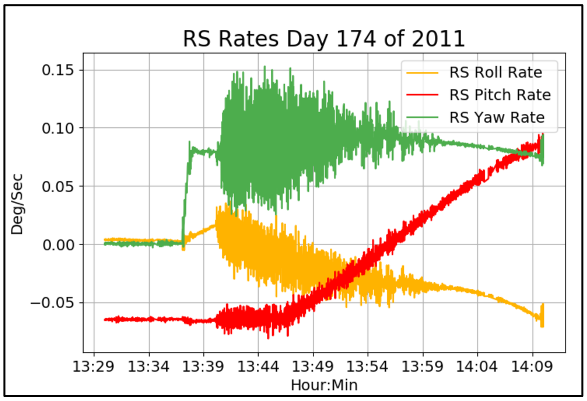


Figure 6 – Measured Rate on RS in deg/sec

USE OF ON-ORBIT ACCELERATION DATA

The high acceleration levels during the maneuver were captured by both of the continuous acceleration data streaming systems on ISS: the Space Acceleration Measure System (SAMS) and the Microgravity Acceleration Measurement System (MAMS). These systems collect data continuously at multiple sensor locations in the pressurized modules. The locations are shown in Figure 5. The resonant event was clearly visible on all of the SAMS and MAMS on-orbit accelerometers. Figure 7 shows the accelerations measured in the JEM during the Day 174 event. The long bright red signature towards the bottom center of the figure indicates that high accelerations were detected for a prolonged period of time at very low frequencies.

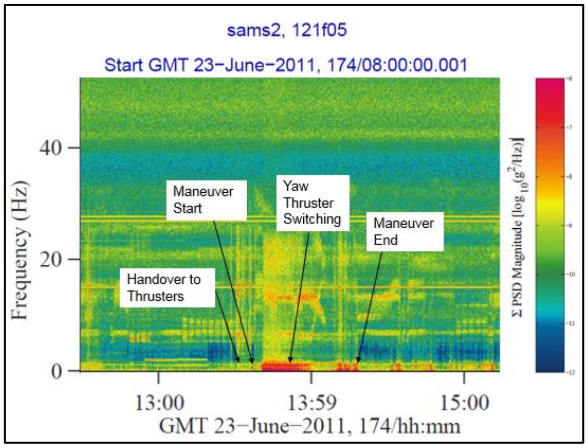


Figure 7 – Power Spectral Density (PSD) Spectrogram using SAMS Sensor in JEM

The Power Spectral Density (PSD) of the on-orbit accelerations in the JEM during the resonant period showed that the structural frequency excitation was greatest at 0.12 and 0.272 Hz, as shown in Figure 8.

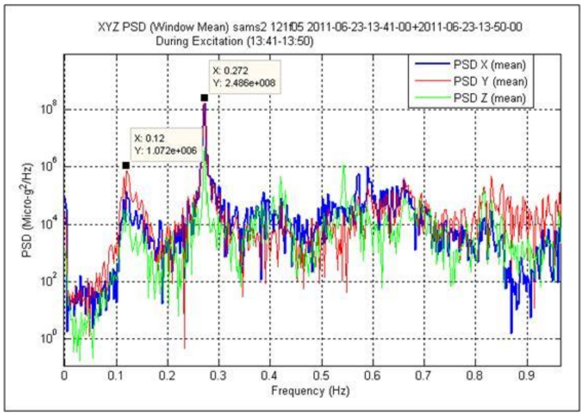


Figure 8 – PSD of Structural Frequency Excitation using SAMS Data

Measured on-orbit data from the SAMS accelerometers was critical to the investigation and reconstruction of the event. The data showed that the frequency content of the ISS response was at the same frequency as two predicted global ISS modes of

0.27 Hz and 0.12 Hz on the day of the event, which elevated the rates and structural loads. The SAMS data allowed the Loads & Dynamics (L&D) team to correlate the analytical event reconstruction to on-orbit measurements.

ANALYSIS OF THRUSTER FIRING DATA

On July 29, 2011, the Russian Guidance, Navigation, and Control (GNC) team provided the as-flown jet firing history for the June 23, 2011 event to the U.S. teams. The PSD of the as-flown jet firing history during the resonance is shown in Figure 9.

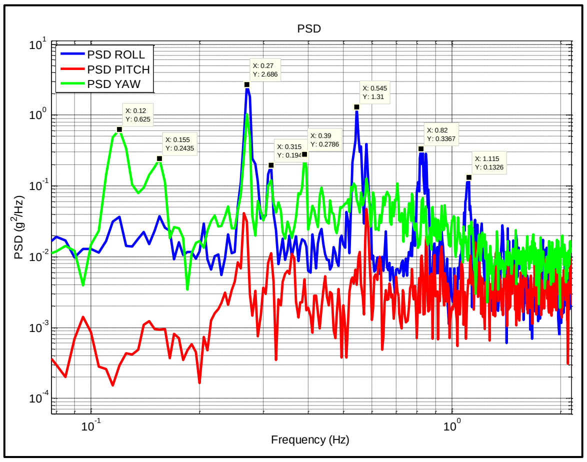


Figure 9 – PSD of As-Flown Jet Firings

The U.S. L&D team used this data to reconstruct the structural loads on ISS by applying the thruster force time histories to a structural finite element model of the ISS configuration at the time of the event. The model used for the reconstruction had a first global mode at 0.1216 Hz and another key mode at 0.2760 Hz. Modal damping of 1% was applied to all modes.

The analytical accelerations calculated using the as-flown jet firing history matched on-orbit SAMS acceleration data very well. PSD plots of the excitation in the JEM during the maneuver, both analytical and measured, are shown in Figure 10.

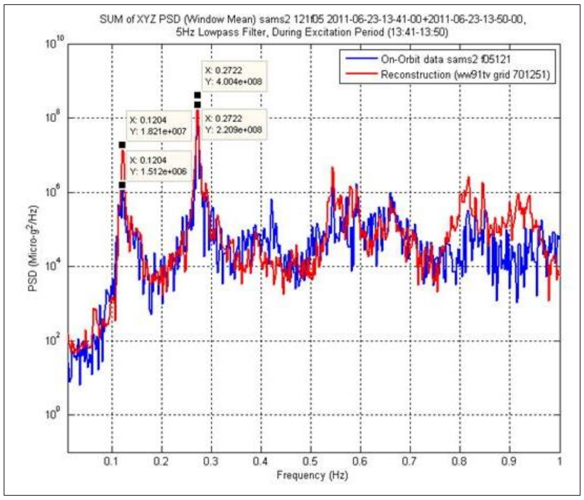


Figure 10 – PSD of JEM SAMS Data Compared to Reconstructed Data

Good correlation between the measured and analytical reconstructed acceleration time histories was observed. This demonstrated that the analytical structural finite element model of the ISS represented the on-orbit ISS configuration well. The good correlation between the as-flown reconstruction and the measured SAMS accelerometer data from the JEM was clearly illustrated early on in the excitation for the ISS Y-direction, as shown in Figure 11.

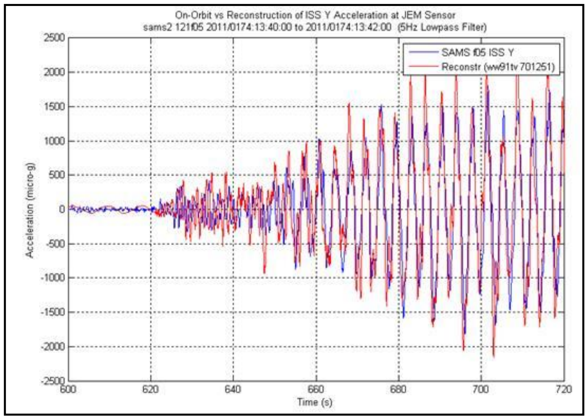


Figure 11 – On Orbit vs. Reconstruction of ISS Y Acceleration

A very good frequency match was observed midway through the excitation period as well, as shown in Figure 12.

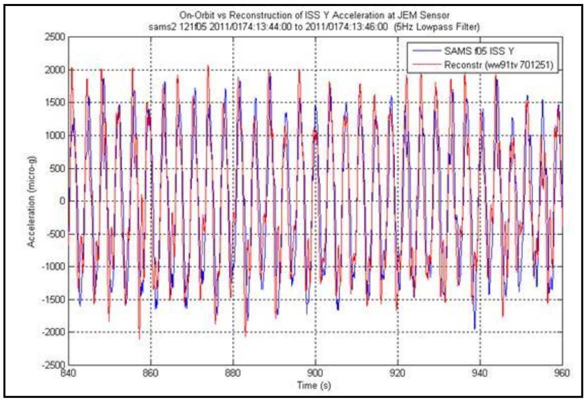


Figure 12 – On Orbit vs. Reconstruction of ISS Y Acceleration

The resonance started to deconstruct before the thruster failure annunciated, as shown in Figure 13.

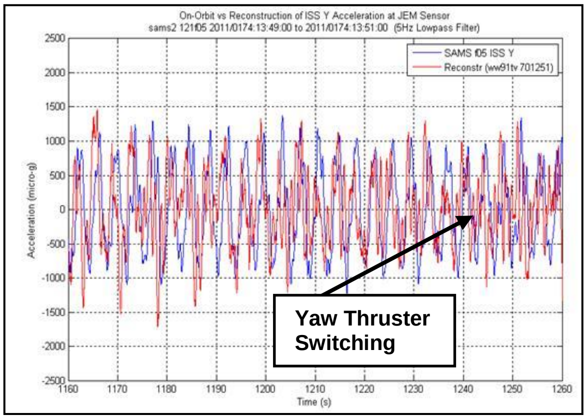


Figure 13 – On Orbit vs. Reconstruction of ISS Y Acceleration

U.S. GNC SIMULATIONS

The U.S. GNC team analyzed the on orbit thruster firing data and compared it to their U.S. simulations of the RS GNC system. Simulations were performed with both rigid model representations of the ISS structure and ISS flexible structural models that contained information regarding the ISS structural mode shapes and frequencies. These flex models were provided to the U.S. GNC team by the U.S. L&D team.

The U.S. GNC team provided its first simulation of the event to the U.S. L&D team on August 15, 2011. Unlike the as-flown jet firing analysis, analytical accelerations derived from the U.S. GNC thruster firing simulation of the maneuver did not match the measured on-orbit accelerations well. The simulation did not capture the observed resonance sufficiently for the loads analysis. Thus, the loads were being under-predicted. Furthermore, the loads previously calculated pre-flight using U.S. GNC inputs did not envelope this on-orbit event.

Enveloped loads from the new GNC simulations set of 97 (96 flex, 1 rigid) cases that were generated a month later (September 19, 2011) better matched the peak loads for Day 174. Even so, only one of the 97 cases resulted in similar load levels. These new GNC simulations also corrected an error in the previous GNC simulations that had held roll and pitch near zero for the yaw maneuver, when in fact the RS logic on orbit allowed roll and yaw to vary. This will be discussed further in a later section.

Figure 14 shows the yaw firing PSD functions for the flight data, a rigid simulation, and one of the 96 flex simulations.

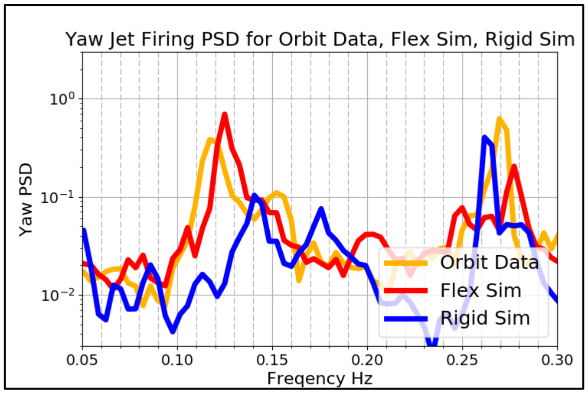


Figure 14 – Flight Data Yaw Thruster Firing PSD Compared to Rigid and Flex Simulation Data

Notice that only the flex simulation recreates the thruster firings at the 0.12 Hz frequency while the rigid simulation does not, suggesting that the 0.12 Hz yaw firings were largely in response to structural flex dynamics, not rigid body dynamics. This means that the 0.12 Hz yaw firings were largely in response to the dynamic flex motion of the ISS. In contrast, the 0.27 Hz frequency content in the yaw firings is in both the flight data and the rigid body simulation data, indicating that the 0.27 Hz yaw firings were largely in response to rigid body dynamics.

Figure 15 shows the PSDs for the roll thruster firings. Like the yaw firings, the 0.27 Hz frequency firings are in the flight data and the rigid simulation data. Since these firings are present in the rigid body simulation, they are largely due to rigid body dynamics.

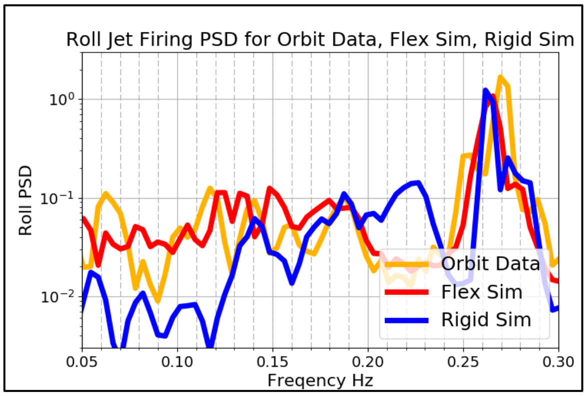


Figure 15 – Flight Data Roll Thruster Firing PSD Compared to Rigid and Flex Simulation Data

Figure 16 shows the co-plot of the PSDs of the Russian Segment unfiltered yaw rate, on orbit yaw jet firings, and the accelerations in the ISS Y-direction as measured by SAMS accelerometer in the JEM (121f05). The plot is scaled to focus on the time period when the resonance occurred, which was the time period from 13:40 to 13:50. Notice that the rate sensor data, thruster firing data, and accelerometer data are well aligned for the 0.12 Hz yaw firings as well as the 0.27 Hz firings. Notice that there are also firings at 0.14-0.16 Hz, but that the rate sensor and accelerometer data do not align well with those firings. There are rigid body yaw firings at 0.14 Hz from Figure 14, but without a structural mode at 0.14 Hz, the structure, rate sensor, and thruster firings do not sync well with each other.

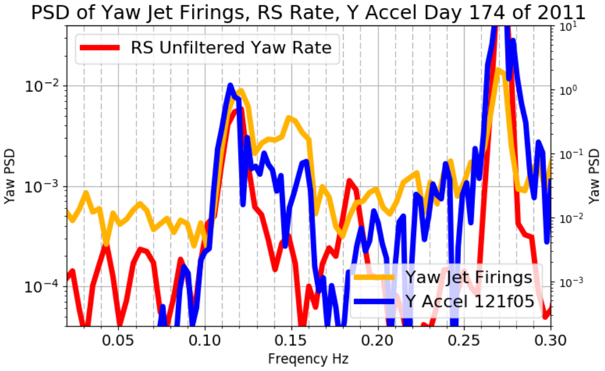


Figure 16 – Co-plot of PSD of Yaw Thruster Firings, Yaw Rate, and Accelerometer Data from 121f05

STRUCTURAL IMPLICATIONS OF DAY 174 EVENT

The L&D analysis showed that the ISS response and high structural loads were predominantly driven by the SM yaw firings. The load levels dropped by only 10% when all of the roll firings were removed from the as-flown reconstruction analysis.

Yaw firings in the as-flown jet firing histories occurred in "clusters" of one to four relatively small pulse width firings near the minimum delay time. These clusters occurred every 8 to 9 seconds, which is equivalent to a single 1.2 second firing every 8 to 9 seconds, or approximately 0.12 Hz. This resulted in the sustained excitation of the 0.12 Hz ISS structural mode. The clusters are visible in Figure 17. Note that the start of each cluster is generally aligned with the peak response of the Module to Truss Structure (MTS) Strut #2 axial load, a key structural location on the ISS.

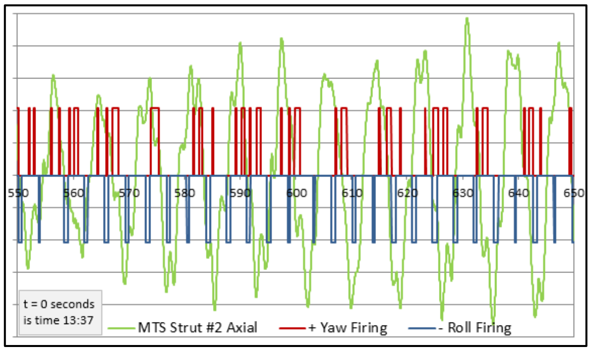


Figure 17 – Co-plot of Thruster Firings and MTS Strut #2 Axial Load during 0.12 Hz Excitation

This type of resonance was not reflected in the pre-flight attitude control loads analysis performed by the U.S. L&D team. As a result, the Day 174 loads on orbit were often 25% higher than existing pre-flight attitude control loads.

The first global ISS mode was a twisting mode of the ISS truss relative to the pressurized modules, as shown in Figure 18. The motion is predominantly in the ISS X-Y plane. It has been referred to as "the scissor mode", as the truss and pressurized modules pivot with respect to one another about a central connection point, like a pair of scissors. This mode can be easily excited by the SM yaw thrusters, which fire almost entirely in the ISS-Y direction. For the ISS configuration at the time of the event, the modal frequency of this first global mode was 0.12 Hz.

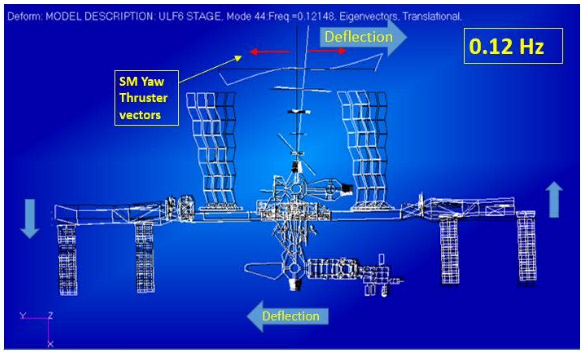


Figure 18 – 0.12 Hz Global ISS Mode

Excitation of the 0.12 Hz mode results in increased loading on the 10 MTS struts, which are the structural elements that connect the pressurized modules to the truss segment at the "scissor" pivot point. The locations of the MTS struts are shown in Figure 19 and Figure 20.

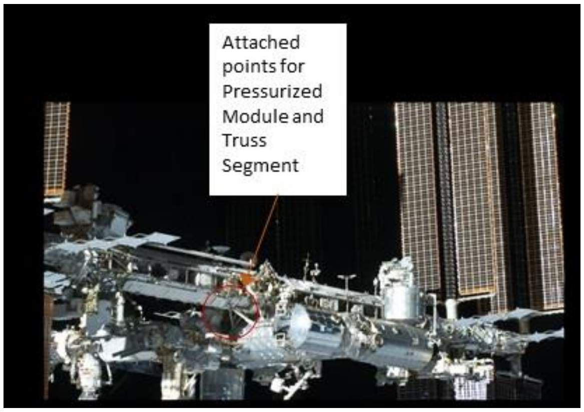


Figure 19 – Attach Point for Pressurized Modules and Truss Segment (MTS Struts)

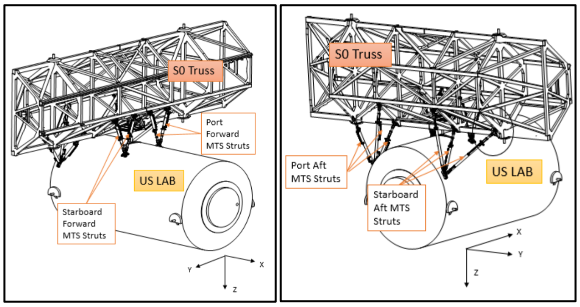


Figure 20 – Schematic of MTS Struts Connecting S0 Truss to Lab

The induced loads in several MTS strut were higher than the pre-flight verification limit. High loads of concern were calculated at several ISS locations, including the MTS struts, the Node1 to Lab interface, Thermal Radiator Rotary Joints (TRRJ), and truss interfaces. The resonance of the 0.12 Hz mode was largely due to thruster firings in response to ISS structural flex.

The 0.27 Hz global mode is characterized by a bending of the pressurized modules about the ISS-Z axis, as well as some motion of the main truss, as shown in Figure 21. This mode can be easily excited by the SM yaw thrusters as well. The resonance of the 0.27 Hz mode was primarily due to rigid body dynamics and not structural flex. Although this mode resulted in loading of key primary interfaces and the MTS struts, the majority of the load was driven by the 0.12 Hz mode.

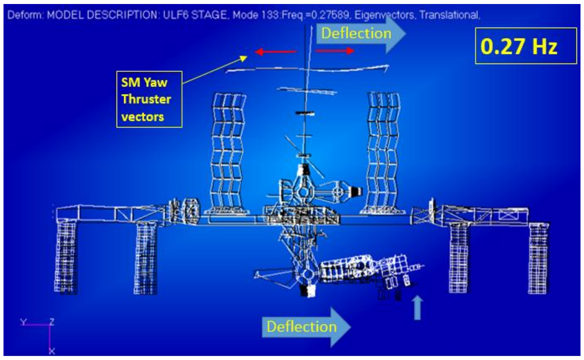


Figure 21 – 0.27 Hz Global ISS Mode

The delay time sweeps in Figure 22 illustrate the general ISS structural response to SM yaw thruster firings at varying frequencies. The plot shows the peak load/limit ratio across the ISS verses frequency.

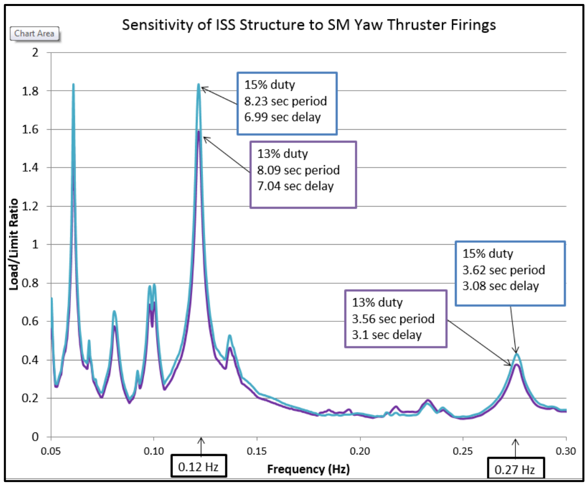


Figure 22 – ISS Structural Sensitivity to Frequency of SM Yaw Thruster Firings

This data was generated with the SM yaw thrusters firing at duty cycles of 15% and 13%, which is close to the thruster firing duty cycle during the on-orbit excitation period.

When the yaw thrusters are fired at the duty cycle of Day 174 such that the frequency is 0.27 Hz, there is a peak, but it is below a ratio of 0.50.

When the yaw thrusters are fired at the duty cycle of Day 174 such that the frequency is 0.12 Hz, there is a huge peak with a ratio between 1.5 and 2.0.

It is clear that excitation of the 0.12 Hz mode by the yaw thrusters drives the loads much more than excitation of the 0.27 Hz mode.

Even more concerning than the magnitude of the structural loads specifically on Day 174 was the fact that on-orbit loads due to thruster firings were not enveloped by the pre-flight analysis load predictions. The L&D team's reconstruction of the Day 174 event showed that the on-orbit thruster firing patterns were different than what was being assumed in pre-flight analysis. The pre-flight analysis had been insufficient.

IMMEDIATE EFFECTS ON OPERATIONS

One of the immediate effects on operations was to limit the use of certain ISS thrusters. Several months after Day 174, the ISS Program pushed to use SM thrusters for roll control rather than Progress thrusters based on recommendations from L&D. The loads induced by SM roll thrusters were much less than the operationally preferred Progress roll thrusters. However, using SM thrusters for roll had several disadvantages. The SM roll thrusters don't have the advantage of the moment arm that the Progress thrusters have, meaning that more propellant is used for an equivalent maneuver. Propellant on ISS is a precious resource, so the additional propellant use was an important impact. Additionally, some of the SM roll thrusters are getting close to their life expectancy with 77% of life used, and ISS is expected to continue to fly until 2024.

The use of thrusters on the visiting vehicles docked to SM aft was limited as well. This included both the Progress mid-ring thrusters and the European Space Agency's Automated Transfer Vehicle (ATV) thrusters. Instead, the SM pitch and yaw thrusters were used for all RS thruster control events. This constraint caused some issues for propellant management, but did not raise a thruster life concern.

After it was confirmed that the pre-flight loads values were under predicting on-orbit loads, an additional 1.25 uncertainty factor was applied to existing loads to compensate for this under prediction. This placed additional constraints on operations, including the allowed U.S. solar array positions during dynamic events, which had implications for power and timelines.

PRE-FLIGHT ANALYSIS OF RS MIN DELAY LOGIC ON ISS

TEAM ROLES

The ISS constantly changes configurations. Some of these changes are due to modules being added or moved, the arrival and departure of cargo and crew vehicles, the rotation of large joints that rotate solar arrays and radiators, and robotic activities. In order to ensure mission success and safe on-orbit operations, both the GNC and L&D teams had been performing continuing and extensive analysis on each ISS configuration since the first assembly mission.

The U.S. and Russian GNC teams both performed analysis of the RS thruster control system. Rocket and Space Corporation Energia (RSC-E) was officially responsible for certification of the RS GNC system. The U.S. analysis of the RS thruster control was an independent assessment and provided inputs to the U.S. L&D team on how to model the RS control system in the structural analysis. The U.S. GNC and RS GNC teams each used their own set of rigid body and structural flex models of the ISS in their analyses. However, the flex models used by U.S. GNC had the additional benefit of being correlated to on-orbit accelerometer data by the U.S. L&D team.

ANALYTICAL METHODOLOGIES BEFORE THE DAY 174 EVENT

During the ISS assembly phase, the U.S. GNC team produced a series of memos for the L&D team to document the RS control system thruster forcing function. The descriptions of the attitude control firings were updates of descriptions originally provided by the Russian specialists in the late 1990's. Parameters included the range of possible thruster on-times and off-times. The data was most applicable to routine and expected attitude control firings. In addition to the memos, the U.S. GNC team provided U.S. L&D with approximately 50 jet firing histories per thruster configuration from rigid body simulations that were representative of various maneuvers the ISS could perform.

The L&D team assessed RS thruster control in pre-flight verification analysis using both synthetic and simulation-based forcing functions to calculate the peak loads on primary ISS structural interfaces and other key locations. The very nature of the preflight analysis assumed that these calculated pre-flight peak loads would envelope any loads induced on-orbit. For each analysis cycle, L&D would build a series of 250 to 400 synthetic forcing function time histories of possible thruster firings based on the equations and parameters in the U.S. GNC memos. Per the preflight verification process, once it was confirmed for each flight that these peak loads were within hardware capability, the use of RS thruster control was approved, including maneuvers up to 0.1 deg/sec rate and thruster firings due to a recovery from Loss of Attitude Control on-orbit.

The Day 174 event loads were significantly higher than the predicted preflight loads, which demonstrated that the behavior of the on-orbit controller was not being captured by the L&D pre-flight analysis.

WORST CASE THRUSTER FIRING ASSUMPTIONS

Prior to Day 174, the U.S. GNC team believed that the U.S. L&D team was independently evaluating worst case thruster firings at ISS structural mode frequencies. Therefore, the U.S. GNC memos only documented what the U.S. GNC team thought the loads team needed, which was information regarding expected firings, and did not include any direction to perform a frequency sweep or resonant analysis.

Early in the ISS program, the loads team did in fact analyze worst case thruster firings that were aligned with the ISS structural frequencies, but as the ISS grew and the frequencies of global modes decreased, worst case loads could no longer be cleared in pre-flight analysis. It was believed that this analytical approach was extremely conservative and such firings would never occur on-orbit. Thus, the loads analyses of thruster attitude control was modified to focus on more realistic thruster firing patterns and use that data for preflight verification.

This belief of extreme conservatism was largely based on statements made by the U.S. GNC team. Prior to the Day 174 maneuver, the U.S. GNC team produced analyses of RS thruster control with the conclusion stated as "there is no CSI." The U.S. GNC team meant that there was no CSI that caused controllability issues and that the maneuvers completed as desired without excessive propellant use. However, the L&D team interpreted the statement "there is no CSI" as meaning that the thrusters would not fire repeatedly at a global ISS structural frequency such that the structure would be at risk. To further solidify the L&D interpretation, GNC also stated that the worst case thruster firings for the structure would never happen.

From the data and plots in this paper, it is clear that the thrusters could and did fire in response to flex and that ISS had experienced a control structure interaction problem that caused higher than expected loads.

U.S. GNC SIMULATION LOGIC

In addition to the communications issues between the U.S. GNC and L&D teams, the U.S. GNC simulation of the RS maneuver logic did not accurately reflect the roll and pitch deviations occurring during the Day 174 on-orbit maneuver. The original U.S. GNC simulation of the RS controller held the roll and pitch angles near zero degrees during the duration of the yaw maneuver, when in fact in the RS logic allowed the roll and pitch to vary, with roll and pitch both as large as approximately 20 degrees during the maneuver, as shown in Figure 23.

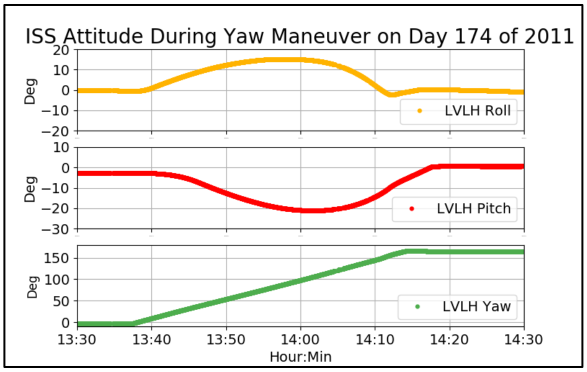


Figure 23 – Roll, PItch, and Yaw during the June 23, 2011 Maneuver

When the ISS roll deviates from zero degrees to nearly 20 degrees, as allowed by the RS maneuver logic, a large gravity gradient torque is experienced by the ISS. The 0.27 Hz roll firings were required on orbit due to the gravity gradient torque on the ISS. Because those firings are not exactly through the center of mass, there is coupling into the yaw channel such that yaw firings at 0.27 Hz were also required. However, the 0.12 Hz yaw firings were largely the result of structural flex, not rigid body dynamics.

The U.S. GNC had been comparing flight data to simulation data for reboosts, but not for maneuvers. After this event, U.S. GNC began comparing flight data to simulation data for maneuvers as well as reboosts to ensure that U.S. simulations were accurately modeling RS thruster firings.

ANALYTICAL METHODOLOGIES AFTER THE DAY 174 EVENT

Soon after the event, the U.S. GNC and U.S. L&D teams adopted new integrated analytical procedures. First, a closed loop process to determine peak structural loads on ISS elements during RS control events was enacted with three basic phases:

(1) L&D would provide an ISS dynamic models to U.S. GN&C
(2) U.S. GNC would perform RS control system simulations and provide jet firing histories back to L&D
(3) L&D would run the jet firing histories on the same model that was provided to GN&C

Since the RS control system was responding to flex motion, the models needed to be the same at each step of the analysis cycle and have the same frequency content.

Second, the number of simulations was increased. Initially, the total number of cases being assessed was typically less than 100 cases per event. In March 2012, the teams suspected the data sets were not large enough to capture the variability inherent in these simulations and loads calculations. A nearly 2,000 case data set was developed to generate a more statistically meaningful set of loads responses for generic maneuvers. A large number of thruster firing time histories are needed because the structural response is quite sensitive to even small changes in the spacing and duration of jet firings when the firing period is near a structural mode. Figure 24 shows the dynamic amplification factor (ratio of peak response of a harmonic input vs response of a static input of same amplitude) for a 1% damped system. For "large" data sets of maneuvers, the peak loads showed exceedances of structural design limits on some interfaces for Progress roll control, which resulted in the operations restriction on Progress roll usage pending event-specific analysis, as mentioned earlier.

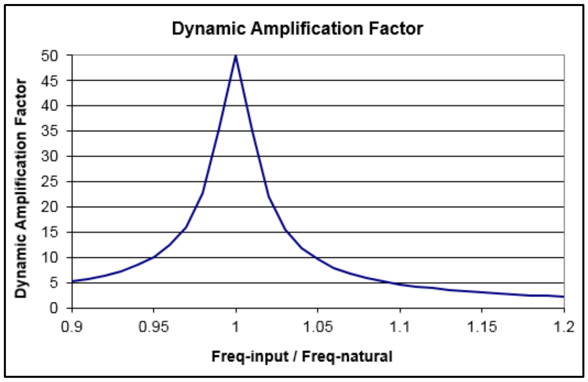


Figure 24 – Illustration of Dynamic Amplification Factor

Third, all of the simulations that were produced after Day 174 used the ISS flex models instead of ISS rigid body models. This was necessary for GNC to capture the full on-orbit behavior.

In the year after the event, the U.S. GNC and U.S. L&D teams worked closely to determine what products were needed from the U.S. GNC team to define RS thruster control. U.S. GNC produced even more flex simulation data for the L&D team to analyze for various maneuvers. Additionally, the memo produced by the U.S. GNC team to document the firing pattern for RS thruster control was extensively modified to include all possible RS thruster patterns. The initial efforts were directed at the only RS controller logic on-orbit, which was the minimum delay logic. The analysis processes continued to transform as the pulse train logic was introduced.

STRUCTURAL RISK MITIGATION: THE PULSE TRAIN

GROWTH OF RISK AWARENESS

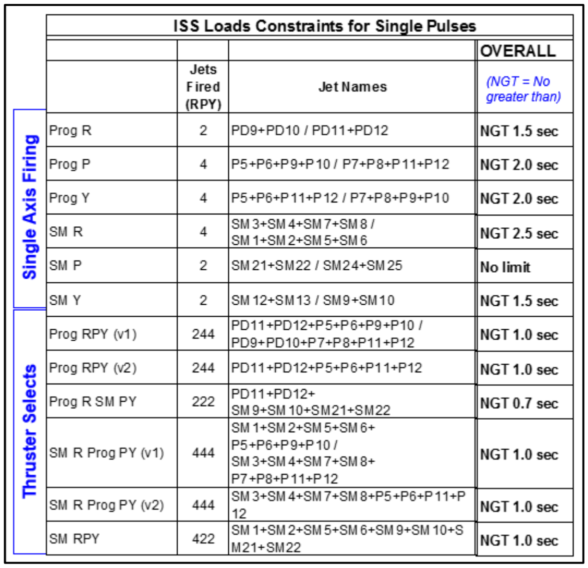
Although Day 174 was the first time that a potential structural overload issue due to thruster firings was demonstrated during an on-orbit event, concerns over the structural risks and confusion over the nature of potential thruster firings were not new.

Before Day 174, it was known that the RS thruster control architecture had no limit on pulse width and no limit on repeated firings and that worst case thruster firings could exceed hardware capability. L&D was aware that ISS primary structure risk existed prior to GMT 174, but believed it to be very low based on multidisciplinary discussions.

Loads issues regarding the effects of ISS thruster attitude control on the U.S. solar arrays had received significant attention. In January 2010, the U.S. L&D team raised concerns regarding thruster plume impingement on the U.S. solar arrays during RS control. The team determined that in certain scenarios the solar array pre-flight load limits could be exceeded with just a few thruster firings. The concerns led the ISS Program to disable the capability to auto handover to RS thrusters whenever the U.S. Solar Arrays were in auto track. While this helped to mitigate the potentially catastrophic loads on the U.S. Solar Arrays, it also impacted existing operational procedures. The constraint did not mitigate the risk of thrusters resonating the primary structure.

Throughout 2010 and 2011, L&D worked to kick start a focused effort to constrain RS control system induced loads on the structure. The team performed several studies to determine the pulse widths and structural frequencies that should be avoided. The single pulse length limits provided to GNC by L&D in March of 2010 are shown in Figure 25. The limited pulse durations in the last column are needed in order to stay below structural limits. Figure 26 shows the frequency sensitivity of two representative ISS configurations provided to GNC by L&D in August of 2010.

It was believed that modification of the RS thruster firing patterns would reduce structural risk and increase the lifetime of ISS structure. Although the importance of balancing these structural concerns with sufficient GNC control authority was the topic of much discussion, the effort was not deemed a high enough priority to make major changes prior to Day 174.



ISS Loads Constraints for Single Pulses

				OVERALL
		Jets Fired (RPY)	Jet Names	(NGT = No greater than)
Single Axis Firing	Prog R	2	PD9+PD10 / PD11+PD12	NGT 1.5 sec
	Prog P	4	P5+P6+P9+P10 / P7+P8+P11+P12	NGT 2.0 sec
	Prog Y	4	P5+P6+P11+P12 / P7+P8+P9+P10	NGT 2.0 sec
	SM R	4	SM3+SM4+SM7+SM8 / SM1+SM2+SM5+SM6	NGT 2.5 sec
	SM P	2	SM21+SM22 / SM24+SM25	No limit
	SM Y	2	SM12+SM13 / SM9+SM10	NGT 1.5 sec
Thruster Selects	Prog RPY (v1)	244	PD11+PD12+P5+P6+P9+P10 / PD9+PD10+P7+P8+P11+P12	NGT 1.0 sec
	Prog RPY (v2)	244	PD11+PD12+P5+P6+P11+P12	NGT 1.0 sec
	Prog R SM PY	222	PD11+PD12+ SM9+SM10+SM21+SM22	NGT 0.7 sec
	SM R Prog PY (v1)	444	SM1+SM2+SM5+SM6+ P5+P6+P9+P10 / SM3+SM4+SM7+SM8+ P7+P8+P11+P12	NGT 1.0 sec
	SM R Prog PY (v2)	444	SM3+SM4+SM7+SM8+P5+P6+P11+P12	NGT 1.0 sec
	SM RPY	422	SM1+SM2+SM5+SM6+SM9+SM10+SM21+SM22	NGT 1.0 sec

Figure 25 – Single Pulse Length Constraints (March 2010 data)

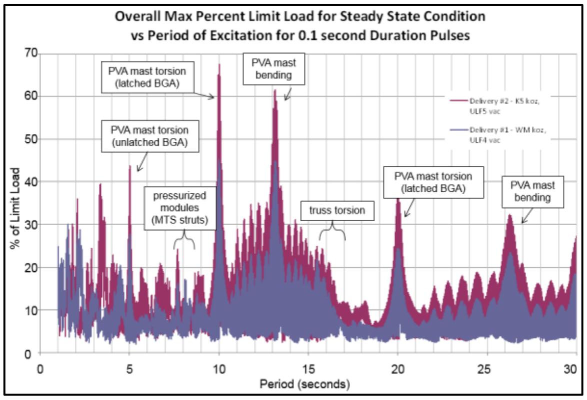


Figure 26 – Frequency Sensitivity of ISS Structure to Thruster Firings (August 2010 data)

EVALUATION OF STRUCTURAL RISK MITIGATION OPTIONS

The nature of the Day 174 event demonstrated that the ISS was at risk for loads even higher than the loads induced on that day. There were no adequate safe guards in the controller software that would prevent thrusters from firing at ISS frequencies, whether the firings were in response to flex or due to other disturbances, like gravity gradients. In order to reduce the risk that future thruster firings would not cause excessive loads on the ISS, several paths were pursued. Ultimately a modification to the RS software was implemented. Before that path was selected, teams evaluated several other options.

One option was to use the U.S. rate sensor located on the S0 truss instead of the RS rate sensor located on the SM. Since the U.S. sensor is much closer to the center of mass, it is less susceptible to dynamic motion and structural flex.

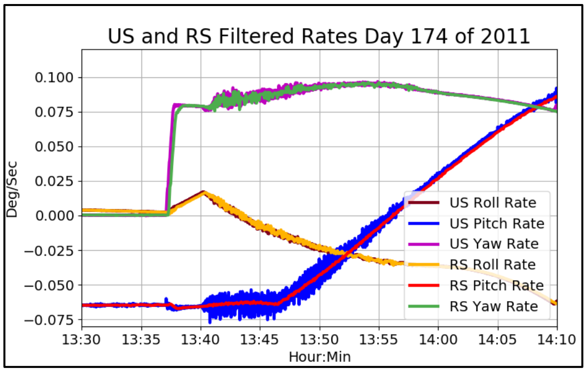


Figure 27 – U.S. and RS Filtered Rate Sensor Output during Day 174 Maneuver

Notice that the U.S. rate sensor data shown in Figure 27 is less noisy for the Day 174 maneuver in yaw, yet noisier in pitch, than the RS rate sensor data. Use of the S0 rate sensor would reduce firings in response to flex, but would not address undesired firings in response to other disturbances. In the end, analysis did not show a consistent overall loads reduction, so this option was not pursued.

Another option was to modify the notch filter in the RS software to better notch out structural frequencies. The existing adaptive filter was designed to seek and filter out suspected structural modes, which would guard against thrusters firing in response to structural flex. L&D identified fixed target frequencies for a proposed fixed notch filter. However, once again, the analysis showed no dependable overall loads reduction with the modified filter, so this option was not pursued.

A third option was to continue using the existing controller logic, but use longer minimum delay times between thruster firings. The RS thruster control was using a 3 second delay in roll and a 1 second delay in pitch and yaw for all maneuvers. Unfortunately, analysis showed that while RS thruster control could avoid first multiple of structural modes by changing the minimum delay times, it could just as easily resonate with second or third multiples of modes. Figure 28 illustrates the loads sensitivity for one thruster configuration at two sets of expected duty cycle percentages. The U.S. GNC team wanted to keep the delay times below 30 seconds in order to maintain sufficient controllability, while the L&D team wanted to raise the delay times beyond 30 seconds to reduce the structural loads.

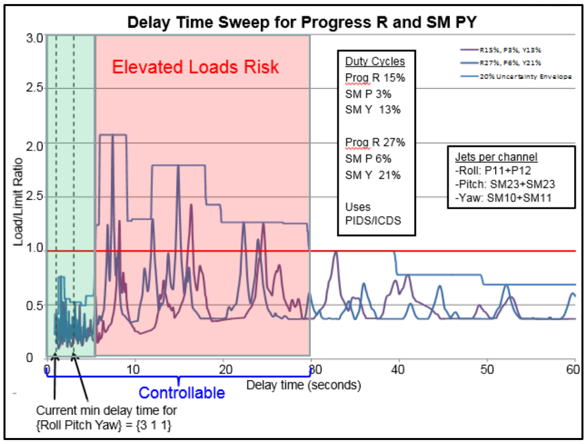


Figure 28 – Loads Evaluation of Controllable Minimum Delay Time Regime

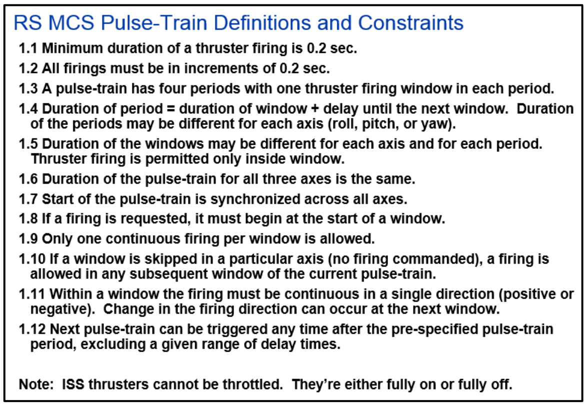
In the end, it was decided that a change in the minimum delay time would not reduce the high loads risk enough while still maintaining sufficient controllability. Efforts were redirected to the design of a new controller logic.

MODIFICATION TO RS SOFTWARE LOGIC

Eventually, the U.S. and RS teams decided jointly that the best option was to modify the RS software to break up the thruster firings. U.S. and RS GNC engineers, in conjunction with L&D team engineers, developed a concept to break up the thruster firings into what was named a Pulse Train. The architecture is defined by up to 24 periods, with each period having a firing window. There are flags to allow or inhibit bi-polar firings and allow or inhibit skipped windows, as well as an exclusion zone where firings are not allowed.

The original joint agreement on the baseline architecture occurred in December of 2011 for the SM 8.05 software.

The SM 8.05 version of the Pulse Train was implemented on-orbit in December of 2012. The rules of the pulse train are outlined in Figure 29. The SM 8.07 version, which was implemented in December of 2013, added the two flags currently on-orbit.



RS MCS Pulse-Train Definitions and Constraints

1.1 Minimum duration of a thruster firing is 0.2 sec.
1.2 All firings must be in increments of 0.2 sec.
1.3 A pulse-train has four periods with one thruster firing window in each period.
1.4 Duration of period = duration of window + delay until the next window. Duration of the periods may be different for each axis (roll, pitch, or yaw).
1.5 Duration of the windows may be different for each axis and for each period. Thruster firing is permitted only inside window.
1.6 Duration of the pulse-train for all three axes is the same.
1.7 Start of the pulse-train is synchronized across all axes.
1.8 If a firing is requested, it must begin at the start of a window.
1.9 Only one continuous firing per window is allowed.
1.10 If a window is skipped in a particular axis (no firing commanded), a firing is allowed in any subsequent window of the current pulse-train.
1.11 Within a window the firing must be continuous in a single direction (positive or negative). Change in the firing direction can occur at the next window.
1.12 Next pulse-train can be triggered any time after the pre-specified pulse-train period, excluding a given range of delay times.

Note: ISS thrusters cannot be throttled. They're either fully on or fully off.

Figure 29 –Description of Pulse Train Architecture

The Pulse Train selected for use on ISS with SM 8.07, called “ptc02”, is represented in Figure 30. It is still in use on-orbit as of the writing of this paper. SM thrusters are used for pitch and yaw. Either the nadir Progress or the SM thrusters are used for roll.

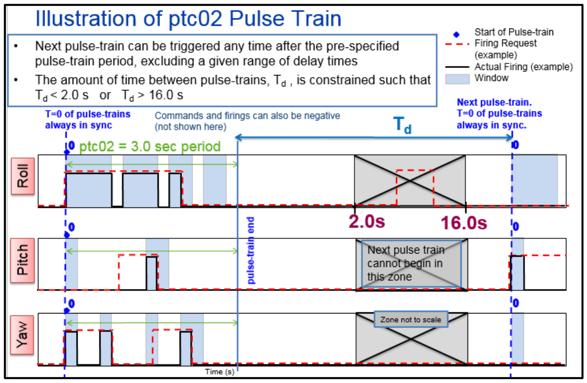
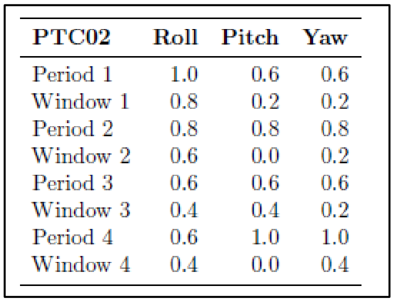


Illustration of ptc02 Pulse Train

- Next pulse-train can be triggered any time after the pre-specified pulse-train period, excluding a given range of delay times
- The amount of time between pulse-trains, T_d , is constrained such that $T_d < 2.0$ s or $T_d > 16.0$ s

Figure 30 – Visualization of the ISS Pulse Train

The total duration of the ptc02 pulse train is 3.0 seconds with duty cycles of 73% roll, 20% pitch, and 33% yaw. The times of the periods and windows, in seconds, is as follows:



PTC02	Roll	Pitch	Yaw
Period 1	1.0	0.6	0.6
Window 1	0.8	0.2	0.2
Period 2	0.8	0.8	0.8
Window 2	0.6	0.0	0.2
Period 3	0.6	0.6	0.6
Window 3	0.4	0.4	0.2
Period 4	0.6	1.0	1.0
Window 4	0.4	0.0	0.4

The exclusion zone is defined such that if a subsequent pulse train does not start within 2 seconds, then it is not allowed to start until 16 seconds have elapsed since the end of the previous pulse train. The primary purpose of the exclusion zone is to avoid large amplitude resonance with the first ISS global mode.

Due to the number of possible thruster firing sequences and number of ISS configurations, it is difficult to determine the theoretical maximum loads for a given controller. Efforts to calculate these values suggest that, with the widely used thruster configuration of Progress Roll SM PY, the theoretical maximum loads using the minimum delay time could be more than 4 times pre-flight design limit loads. With the ptc02 pulse train, the theoretical maximum is much lower at approximately 1.4 times pre-flight design limit loads. The 3-sigma loads for ptc02 were determined during the pre-flight verification analysis to be well within ISS hardware capability.

SUMMARY

The Day 174 event successfully alerted the community to a structural risk posture that was higher than previously believed. Although it is believed that the Day 174 thruster firings were largely in response to structural flex, the exact cause of the firings did not dictate the need for a new RS controller on ISS. Rather the event revealed that the control system could, and did, fire in a way that caused loads higher than those predicted in preflight, regardless of the driver. Furthermore, it was realized that the ISS had been flying at risk of catastrophic structural loads caused by thruster firings, and those loads had the potential to be much higher than those experienced on Day 174. The existing minimum delay controller logic could not prevent such firings.

The multi-disciplinary investigation and issue resolution resulted in a significantly reduced structural risk posture for ISS via the implementation of the Pulse Train logic. It resulted in a more robust pre-flight analysis procedure as well.

The fidelity of the investigation and conclusions were made possible due to the availability of on-orbit accelerometer data in the pressurized elements. Without that data, the accuracy of the model and the reconstruction would have likely been greeted with more skepticism. As has been the case with dozens of other structural health events, the existence of actual on-orbit accelerometer and rate data proved invaluable.

The Day 174 event demonstrated the importance of continuous integration and communication. This includes rigorous definition of terminology and an awareness and acceptance of multiple drivers. In this case, it was discovered that the concept of Controller Structure Interaction was defined differently by different disciplines, teams, and individuals. Also, the cause of the firings was due to both rigid body disturbances and structural flex. At times, the debates regarding the cause of the Day 174 event gave the appearance that it must be one or the other, when it was both. How much each contributed cannot be determined precisely.

The high level of respect and cooperation among the international teams during the pulse train design discussions and implementation is a testament to the importance and success of the ISS Program itself. The teams came together with a common goal and a focus on the issue, willing and eager to contribute to the best programmatic and technical solution. The ISS Program continues to demonstrate the importance and benefits of working together internationally.