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CFD Analysis based on the SPHERES Tether Slosh mission

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The present document summarizes results of the CFD analysis base on SPHERES TETHER SLOSH mission on the ISS in the frame of an executive summary.

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1. Introduction

SPHERES TETHER SLOSH combines fluid dynamics equipment with robotic capabilities aboard the International Space Station ISS to investigate automated strategies for steering passive cargo. A liquid-filled tank is maneuvered inside the ISS by two Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES). The two satellites are attached to a passive sloshing tank by Kevlar tethers. The satellites maneuver the passive tank both with open loop guidance as well as in closed loop control. A better understanding on how to deorbit e.g. a stranded satellite is goal of the experiment. Furthermore the data is used to benchmark Computational Fluid Dynamics (CFD) which may be used for future mission analysis. The experiment was performed both with a fluid filled tank as well as with a rigid body tank of the same mass and inertia. This allows better understanding the impact of the sloshing liquid.

The following picture shows the basic test setup of the SPHERES TETHER SLOSH experiment during in-orbit operation. The liquid is shown in green which is water with food coloring.

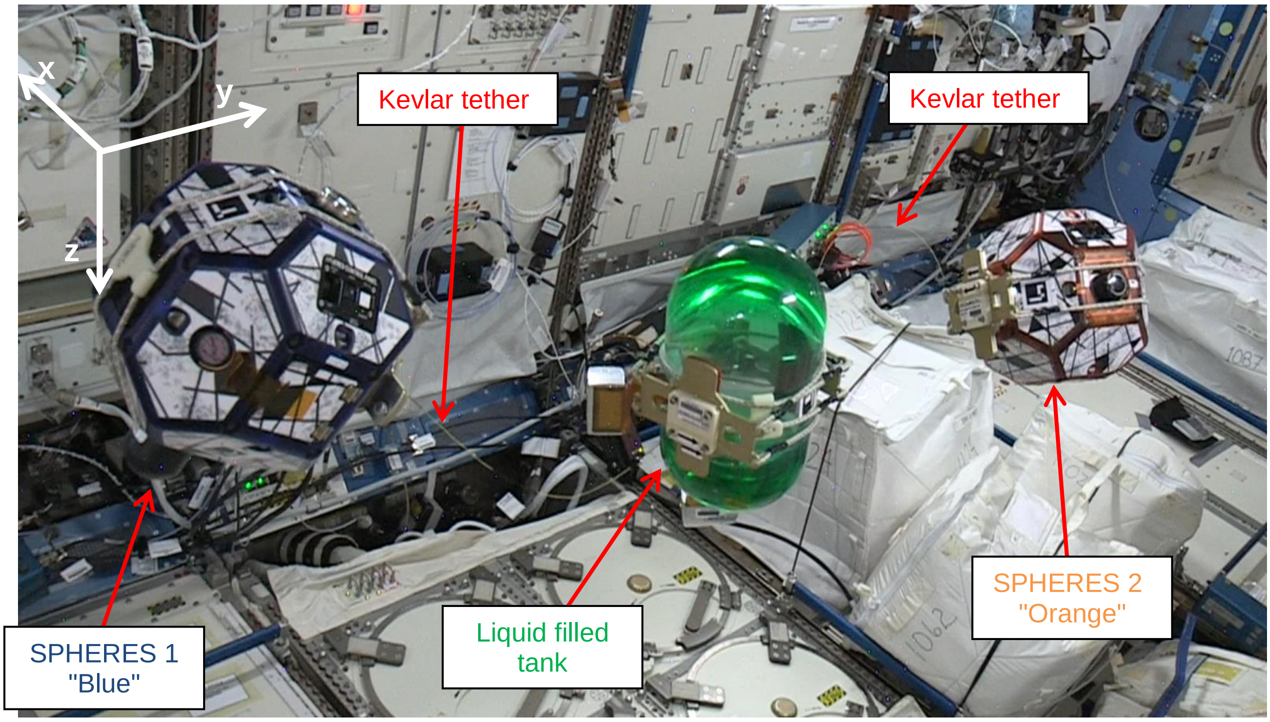


Figure 1: SPHERES TETHER SLOSH Experiment during in-orbit operation [RD 1]

In total four test runs were carried out:

- 1st session (January 17th 2018) – 8 successful tests
- 2nd session (April 4th 2018) – 6 successful tests
- 3rd session (September 29th 2018) – 17 successful tests
- 4th session (October 18th 2018) – 14 successful tests

The tests required major support from the astronauts. Except for the 2nd session there were always two astronauts present. Figure 2 shows astronaut Alexander Gerst manually disturbing the liquid filled tank, to be repositioned by the two SPHERES.

Figure 2: Astronaut Alexander Gerst disturbing the slosh tank (in green) with his finger during the fourth test session on October 18th 2018.

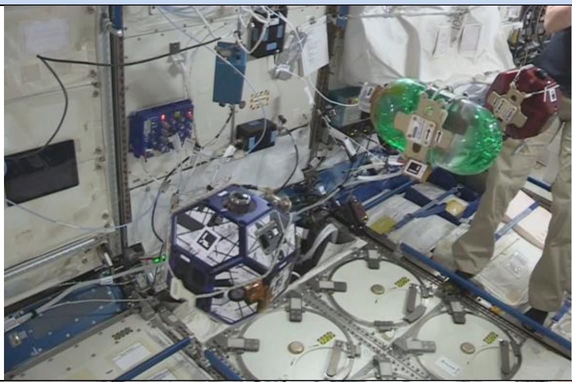
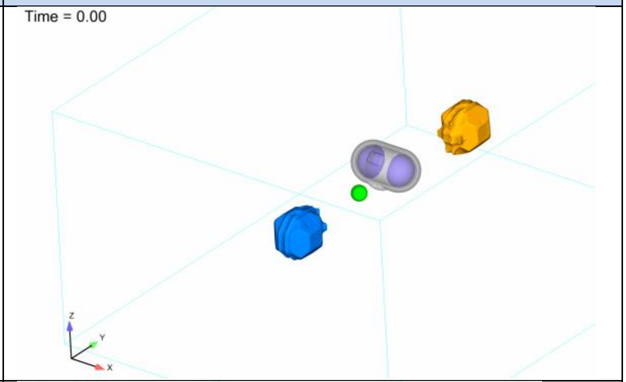
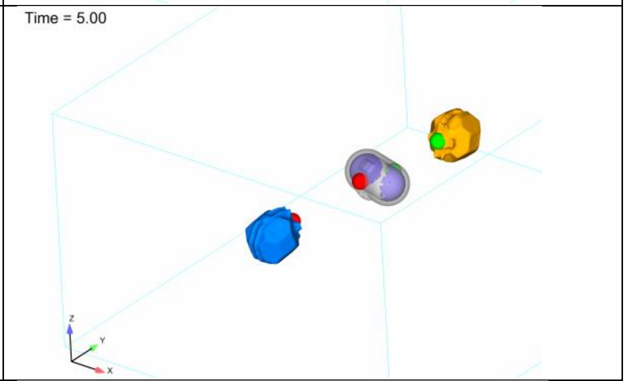
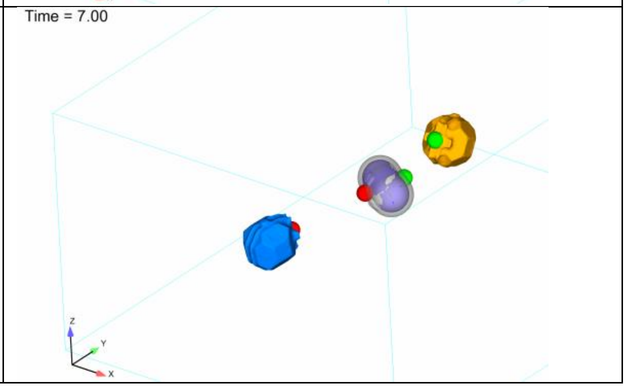
In total 45 successful test runs were carried out during the four sessions.

The SPHERES Tether Slosh payload development and on-orbit execution on ISS was solely funded through industry investment, led by Airbus DS Space Systems, Inc. in Houston, Texas, U.S.A. ISS resources were sponsored via the ISS National Lab.

The ESA sponsored/funded CFD analysis as reported here have been developed based on achieved measurements from the SPHERES Tether Slosh payload.

2. Flight results

The present chapter displays two selected test runs concerning a linear tow experiment from Session #3. Among other these test cases were selected for further benchmarking with CFD. The following graph shows a qualitative comparison between experiment result (left) and CFD analysis (right).

Session #3 Linear tow test (2018_08_09_15_23_23_P527_T2)		
Time [s]	ISS Experiment	CFD analysis
99		
104		
106		

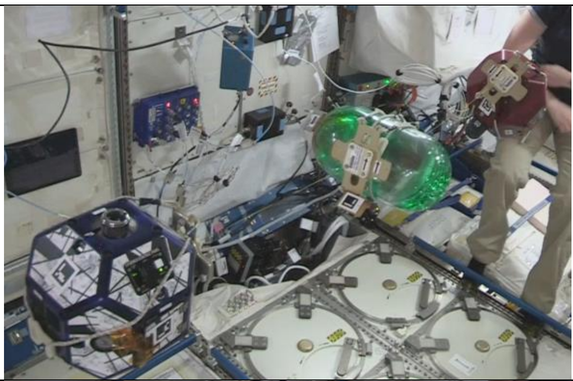
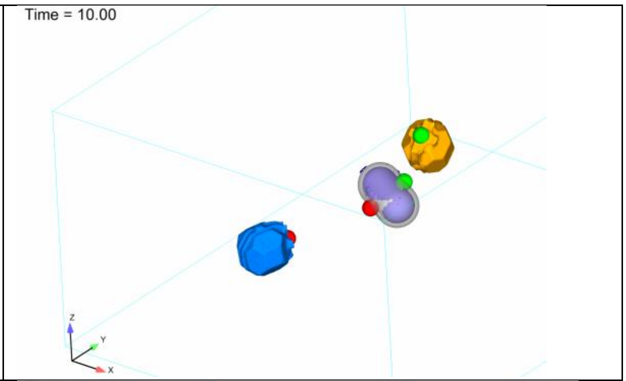
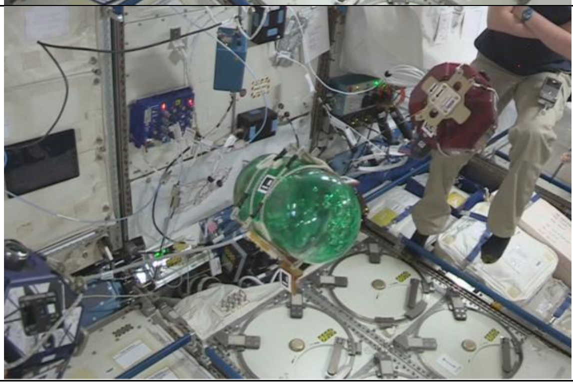
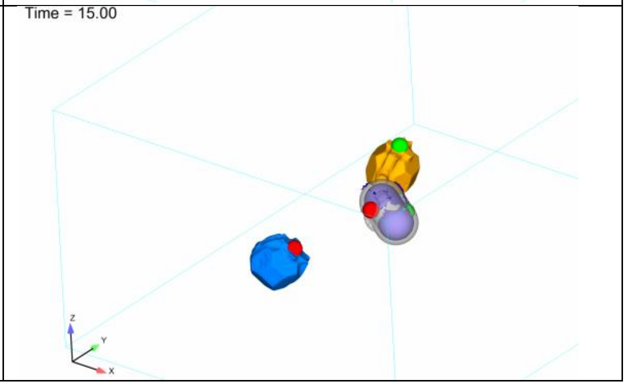
109		
114		

Figure 3: Comparison between ISS experiment and CFD - Session #3 linear tow test with liquid tank (2018_08_09_15_23_23_P527_T2). Both experiment and CFD results are plotted at the same times. The CFD analysis starts at t = 99s.

The corresponding thrust forces and moments are plotted in the following figures.

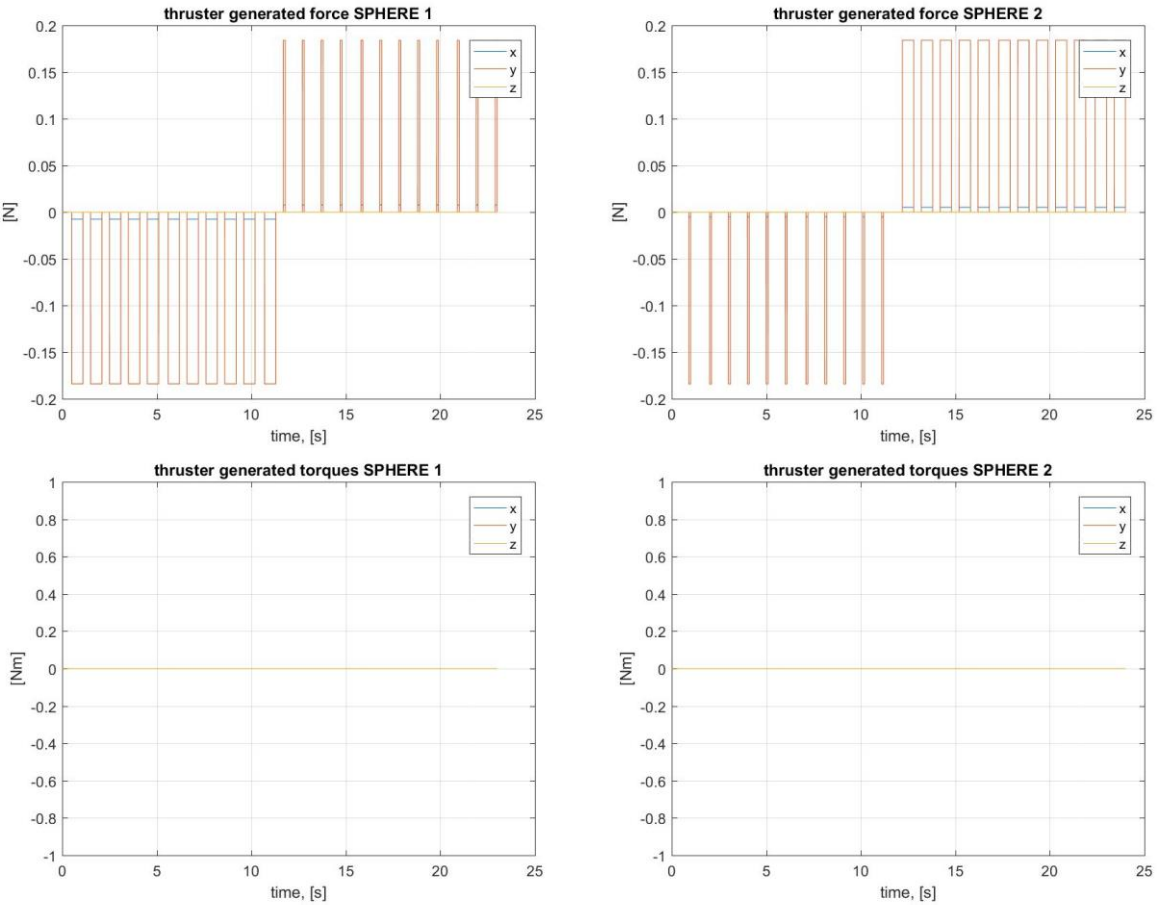


Figure 4: Thruster forces and moments for SPHERES 1 (blue), left, and SPHERES 2 (orange), right - Session #3 linear tow test with liquid tank (2018_08_09_15_23_23_P527_T2).

The first 99 seconds are needed to initialize the position of the two SPHERES. The history plots start at this time with t = 0s corresponding to the initial condition of the CFD simulation. After 99 seconds the linear towing takes place. All torques are then zero. The main thrust is in negative y-direction. The blue SPHERES 1 tows while the orange SPHERES 2 keeps the tension.

It appears that the towing is similar until about 10 seconds after starting the tow. Thereafter the behavior deviates in the CFD simulation. The tank bounces to the side dragging the blue spheres behind. This may be due to the fact that the initial condition of the tank motion is inaccurate assuming a non-moving tank.

A rigid body tank was evaluated in comparison to a liquid filled tank considering a comparable thrust profile

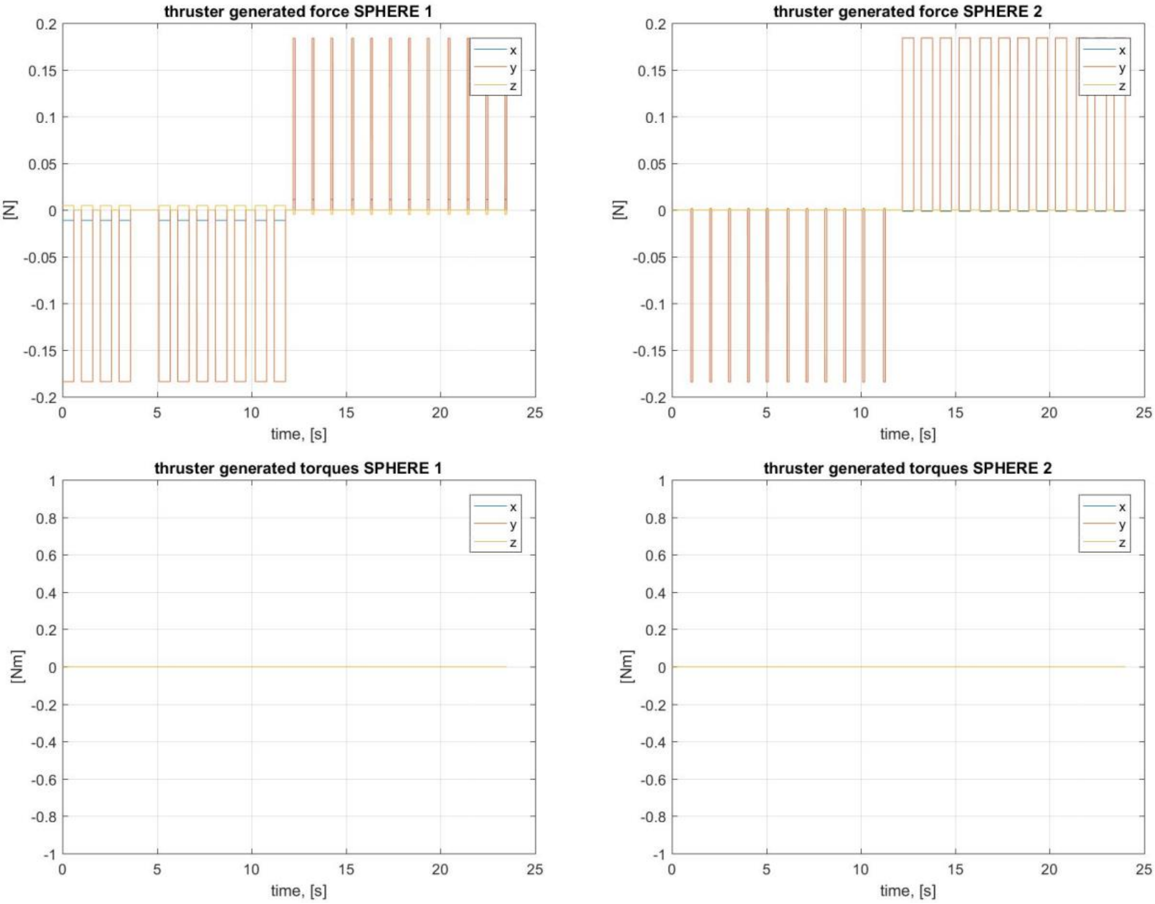
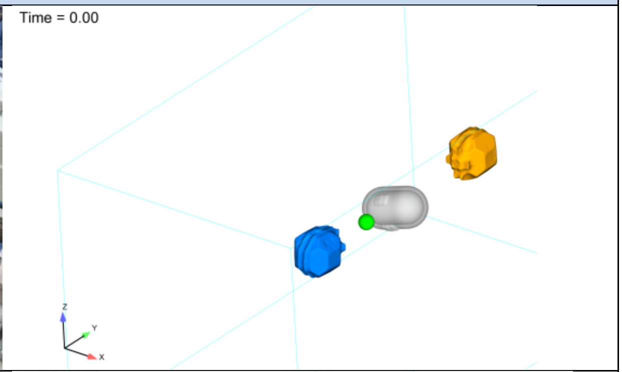
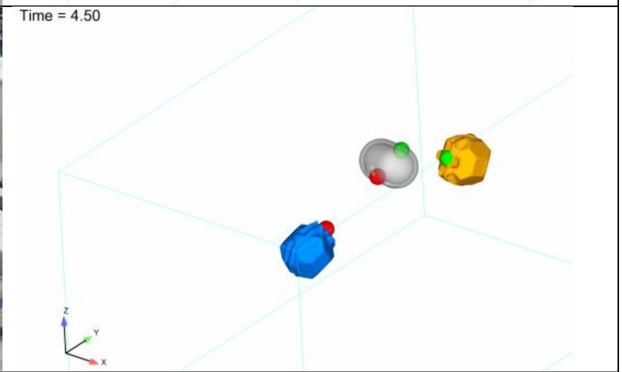
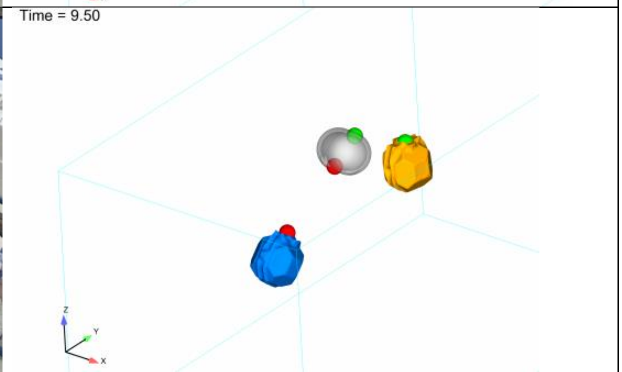
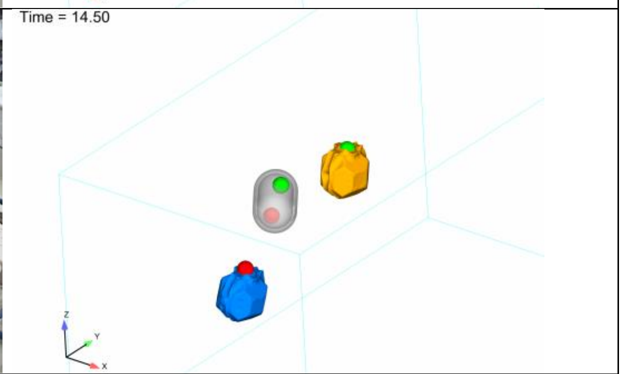


Figure 5: Thruster forces and moments for SPHERES 1 (blue), left, and SPHERES 2 (orange), right - Session #3 linear tow test with rigid tank (2018_08_09_15_49_33_P527_T2).

Session #3 **Linear tow test (2018_08_09_15_49_33_P527_T2)**		
Time [s]	**ISS Experiment**	**CFD analysis**
44.5		
49		
54		
59		

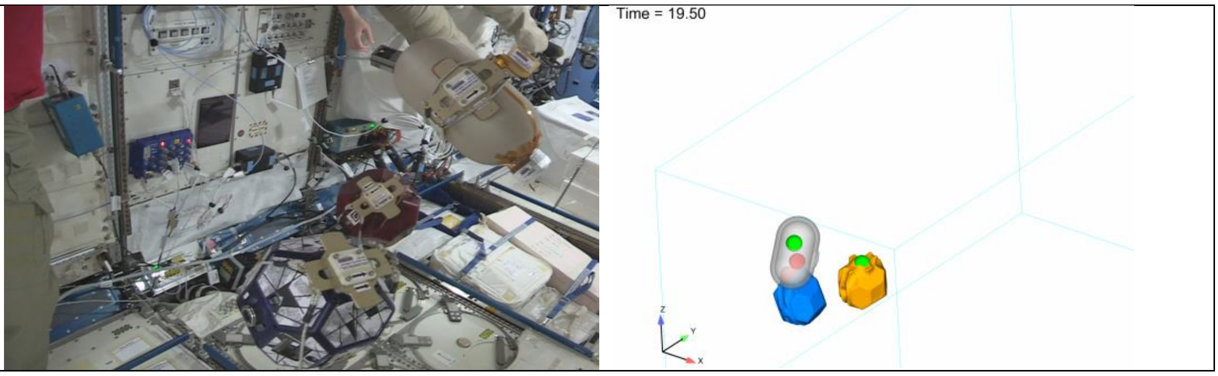
64	

Figure 6: Comparison between ISS experiment and CFD - Session #3 linear tow test with rigid body tank (2018_08_09_15_49_33_P527_T2). Both experiment and CFD results are plotted at the same times. The CFD analysis starts at t = 44.5s.

The scenario is very much driven by the upwards motion of the rigid body satellite which is disturbing the overall motion. The simulation shows a similar behavior in comparison to the experiment. The discrepancies however become larger with time. This underlines the sensitivity of such a system on the initial conditions. The initialization of the SPHERES leads to a significant initial velocity for the rigid body tank which impacts the motion of the three bodies during the towing mission. The moving rigid tank then turns the SPHERES which fly into a deviated direction. The simulations were done in open loop.

Towing the rigid body tank appears to be more chaotic in comparison to the liquid filled tow experiment.

3. Conclusion and Lessons Learned

The SPHERES TETHER SLOSH ISS experiment was concluded with four successful test sessions. In preparation of individual test runs we have attempted to predict several test runs by using CFD analysis, which in several cases allowed us to develop improved test profiles based on previous sessions. It shows that CFD is today able to handle such complex maneuvers including the tether behavior. However the goal of towing in a prescribed direction was qualitatively only managed by the linear tow scenario pulling the three bodies along a straight line. The sloshing liquid was very advantageous in stabilizing the motion of the uncontrolled tank. This indicates that further studies will be necessary in order to assess the amount of damping which is needed to control the system. In general it is increasing the complexity of a mission significantly if the bodies are slowly moving relative to each other. Controlling such a system will be a task for future missions. In any case the ISS is most useful for these missions.

Subsequent CFD analysis based on ISS collected measurements show that, considering for example a deorbitation mission, it is for sure a difficult task to attach a tether to an uncontrolled body. But it is as difficult to tow this body then in a controlled manner when using a tether. In this context the series of SPHERES Tether Slosh experiments can only been seen as a first step into future investigations in this field.

There are many lessons learned from the test runs which shall be summarized in the future enabling a benefit for future missions.

The ISS is an optimum place testing such a complex towing mission. It appeared to be very difficult gaining a proper initial condition, even though the astronauts were placing the two SPHERES and the tank as accurate as they could with the final corrections being done by the SPHERES controller. Future testing may therefore consider a fixed attachment of the three bodies being released before test.

Due to the long time between astronaut release and start of the experiments (in the order of 1 minute) there was a considerable drift in the positions and at the start of the experiment a non-zero velocity. The KALMAN filter was well able to position the SPHERES in space but had no control over the tank. During the first run the KALMAN filter became unstable during tow sequences since the external tether force was not considered and the determined positions of the SPHERES satellites were not correctly determined. An updated version of the KALMAN filter resolved this problem after the first test session although ArianeGroup has no visibility on the updates done on the filter.

There were some inaccuracies with respect to the proper thrust level with some thrusters having reduced thruster performances. It is therefore recommended that, whenever using SPHERES or a follow-on system, to measure the thruster performance before starting the experiment. Generally this should be done as the first task since time is usually running short at the end. So finally we were not able to do this test for the fourth test session leaving some inaccuracies concerning the real forces. In the future a more accurate system would be useful. Also testing the SPHERES thruster performance in a lab enviroonment once the system is back on earth would be beneficial. Presently the orange SPHERES was brought back.

The on-board video system was the most important measurement system used for the tests. This system was not sufficient to observe the detailed behavior of the fluid inside the tank. However to study the global towing behavior this was of no major concern since the comparison with CFD indicates how the liquid behaves. In test session #3 smaller bubbles were visible. Ideally only one large bubble would be present. However this was acceptable.

More driving for future missions will be a better knowledge of the view angle and the dedicated positions of the onboard cameras. The positioning of the cameras was measured by the astronauts, but they are only a rough measurement. These data are necessary in order to determine the position of the bodies using the marker system. Presently only the video system was used which does not allow a quantitative evaluation.

A first study on the evaluation of the marker system was carried out by the University of Braunschweig in the frame of the SPHERES TETHER SLOSH test sessions [RD 2]. Generally it would have been better having more markers on the bodies. At least one marker should always be visible. For future missions this should be considered whenever surfaces do not obscure visibility of e.g. the sloshing liquid. The marker system can be useful for future post evaluation.

The Wisenet acceleration system was applied during the first two test sessions. It was able to detect the moments when the tether is strained and starts to pull. For future evaluations this can also be taken into account. The accuracy of the system was not sufficient to determine the global motion of the rigid body and the liquid filled tank. A system with higher accuracy would be useful for future missions, however this system was readily available within the allocated budget. The system should be able to detect both linear and angular accelerations properly of the tank.

The impact of initial disturbances was underestimated in the predictions since the bodies were never without motion. This however may not be a too unrealistic scenario when intending to tow a non-cooperative body in orbit. Also, in comparison to the predictions, the tethers were never strained at the start of testing. This also leads to increased uncertainties when performing a tow.

The most straightforward way of towing was the linear tow where all three bodies are kept in a straight line. The force vector which is applied by the tethers on the SPHERES is then close to the SPHERES center of gravity. In consequence there are only low slewing motions changing the SPHERES pointing direction.

The liquid in the tank generally had a positive effect on the mission since the disturbances which were produced by the jerking effect, once the tether is strained, was partially dampened. In conclusion a close consideration of the proper damping has to be considered when doing a tow.

Concerning towing a body it was noticed that the attachment points of the tethers on the tanks was not accurately defined. With respect to the tank center of gravity this may also lead to a momentum which rotates the tank. This may be an important aspect to be considered when a towing mission is performed for deorbiting a body, potentially of arbitrary shape and unknown center of gravity location.

It can be seen that the tethers have certain rigidity. Thus, if the tether is in a loose condition, there is still a residual force acting which pushes the two bodies away from each other. This leads to additional inaccuracies in the motion.

The attachment point of the tethers on the SPHERES satellites is such that the tether's force will generally lead to an additional momentum around the SPHERES satellite's center of gravity. This leads to a change in the pointing direction with respect to SPHERES and finally in a deviated flight direction (if not properly controlled in closed loop). The SPHERES satellites are turning. Under this condition it is understandable that the results of the linear tow scenario are the most reproducible with respect to its flight conditions. In a future application or in a real flight condition it therefore has to be assured that the tether force vector is as much as possible directed towards the SPHERES center of gravity. Otherwise a momentum will be generated which leads to a turning of the satellite. This turning will have to be counterbalanced by a control loop. Generally, if the force vector is not in the direction of the center of gravity it leads to additional disturbance torques which should be prevented. A different attachment concept is therefore preferable, like a cardan mounting (momentum free mounting).

Initially the astronaut had put the three bodies rather steady. But about 1 1/2 to 2 minutes were needed to initialize the system (finding the correct initial position etc.). The tank was drifting significantly during this time. Therefore, if we could have fixed all three bodies before the real test starts, then better results could have been obtained. Also the pointing direction of the three bodies would be clearly defined.

The SPHERES satellites were many years in operation. The status of the SPHERES and a possible degradation of the thruster systems are therefore difficult to evaluate in orbit. Once all SPHERES satellites are deorbited it would be possible to measure the thruster performance on ground in a lab environment in order to obtain more reliable data.

The Wisenet system had an estimated accuracy of ~4 mg noise floor. It was able to detect the occasions when the tether was strained but not the free flying phases. Due to costs and time constraints only the ISS qualified sensors could be used. In the future it would be however of advantage to consider acceleration sensors with higher accuracy. The system should be able to measure both linear accelerations as well as the angular accelerations.

The flight behavior appears to be much more stabilized by introducing a damper into the tether. The stabilization is similar to what is observed with the liquid, both dissipating energy. Therefore it may be an option for future towing experiments to study the effect of a damped tether.

Generally, it can be stated that the SPHERES Tether Slosh experiment allowed significant insight into the dynamics of a sloshing body and it's interactions with the rigid bodies. It became obvious that the system has its limitations; however within the constraints of a limited budget combined with the limitations of an existing system, we were able to achieve significant baseline data collection as an initial input to CFD analysis for benchmarking experiment and numerics.

Based on the post evaluation with CFD it was shown that the flight behavior is much more stabilized by liquid sloshing damping the overall motion. CFD analyses furthermore show that damping may also be introduced directly into the tether dynamics. The stabilization, adding a damping coefficient to the tether, behaves similar to what is observed with the liquid, both dissipating energy. Therefore it may be an option for future towing experiments to study the effect of a damped tether. More detailed assessments concerning the required damping could be done in follow-on CFD analyses.

4. References

[RD 1] Behruzi, P. et al., SPHERES TETHER SLOSH Free Flyer Experiment on ISS, AIAA Propulsion & Energy Conference, Cincinnati, AIAA-2018-4939, 2018.

[RD 2] Hesse, J.-T., R 1832 S SPHERES Tether Slosh ISS experiment – Evaluation and Processing of experimental data and videos, Thesis, Institute of Space Systems, Technische Universität Braunschweig, 2018