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DESIGN AND DEVELOPMENT OF 2,000 KG LINEAR SHAKER PLATFORM FOR SPACECRAFT PROPELLANT TANK SLOSH BEHAVIOR VALIDATION AND RESEARCH

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ABSTRACT:

The Aerospace Systems And Propulsion (ASAP) laboratory at Florida Institute of Technology has developed a linear shaker platform with capacity of sinusoidal slosh excitation of propellant tanks of up to 2,000 kg (kilogram) at a rate of 1.5 Hz (Hertz) and 15 inches of total travel. The rig is used for flight validation of spacecraft propellant tanks to frequency response, as well as to create a research platform to further investigate slosh behavior inside said tanks. The size of the platform allows to mount spherical or pill-shaped tanks, with sizes of over 50 inches in diameter and up to 100 inches in height. It consists in a steel tube table, running on parallel rails rigidly attached to a foundation concrete block, also acting as a damper. The table is excited using two parallel roller lead screws, directly driven by synchronous electric servomotors in a system with virtually no backlash. The design covers mechanical, electrical and safety aspects of the machine development.

1. INTRODUCTION

Flight certification of spacecraft propellant tanks includes thorough slosh testing to assess the reliability of the tank structure and internal components, such as Liquid Acquisition Devices (LADs). Orbital-ATK, as the main global supplier of spacecraft tanks [1], in partnership with the Aerospace Systems And Propulsion laboratory at Florida Institute of Technology have developed a 2,000 kg (kilogram) total capacity linear stage with the purpose of slosh testing the largest series of tanks to unprecedented excitation levels: a maximum of 2,000 kg of total oscillating mass at a frequency of 1.5 Hz (Hertz) and a double amplitude of 15 inches.

Orbital-ATK manufactures tanks of sizes up to the 50+ inches in diameter, and up to 100 inches tall. Shapes vary from fully spherical tanks to pill-shaped tanks. They can use diaphragm-type LADs or surface-tension based Propellant Management Devices (PMDs). Designs have become increasingly complex over time, and maintaining low material mass leads to using extremely thin metallic parts that maintain their shape under zero-gravity conditions, but could be harmed by motion while transportation, on the launch pad or general handling under earth gravity. This type of research is of particular interest to the teams at Orbital-ATK and Florida Tech ASAP, and the work to date can be observed in references [2], [3], [4], [5] and [6]. Endurance certification of these components achieved by is subjecting test items to extreme conditions, provided by the linear stage detailed through this paper.

Being installed at the Florida Tech Center for Advanced Manufacturing and Innovative Design in Palm Bay, Florida, at the heart of the Space Coast, this linear stage becomes an extremely valuable resource to continuing slosh research, as well as flight component certification.

The stage is currently in its delivery stage, beginning testing in May 2016.

2. MECHANICAL DESIGN

Based on the requirements of 2,000 kg moving mass with a sinusoidal excitation of 1.5 Hz at a double amplitude of 15 inches, the maximum driving force is calculated at the point of maximum acceleration, that being the peak points of the sinusoid, as shown in Eq. (1-4)

$$a_{max} = 2\,(DA)\,\pi^2\,f^2 \qquad (1)$$

$$a_{max} = 55.45\,\frac{ft}{s^2}\,(\sim 16.9\,\frac{m}{s^2}) \qquad (2)$$

$$m = 4{,}409\,lbs\,(\sim 2{,}000\,kg) \qquad (3)$$

$$F = m\,a_{max} = 7{,}608\,lbf\,(\sim 33{,}843\,N) \qquad (4)$$

Where DA = Double Amplitude and f = excitation frequency.

A dual leadscrew mechanism is chosen, driven directly by two electric servomotors, giving a rigid coupling between them and virtually eliminating backlash and play, issues that are consequence of using any mechanical intermediate steps such as gear reductions. This system also provides the flexibility of programming any motion profile, without being constrained by mechanically generating a sinusoid, thus opening the possibility of using any motion profile.

The design approach taken is shown in Figure 1, where a 50 inch spherical tank is mounted on its tooling, bolted down to the machine main frame providing the excitation.

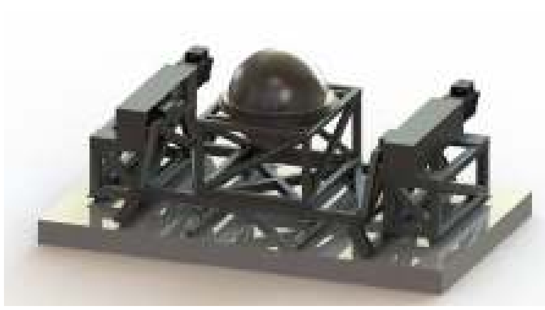

Figure 1. Conceptual 3D model of linear stage, with mockup tank and tooling mounted on it.

The subassemblies are shown in Figure 2 and named:

- Main Frame, providing the supporting structure for the test article, with a loading area of 90 inches x 59 inches (2.28 m x 1.49 m)
- Transmission Systems, in charge of generating the driving forces. One on each side of the main frame
- Side Frames, providing support to each of the transmission systems.
- Two Linear Guides, where the main frame slides. These withstand the vertical forces generated by the weight and excitation forces, as well as side forces generated by the liquid sloshing expected by these tests.
- A Support Frame, embedded into a concrete slab to provide vibration isolation from the building and enough mass to withstand the large excitation forces.

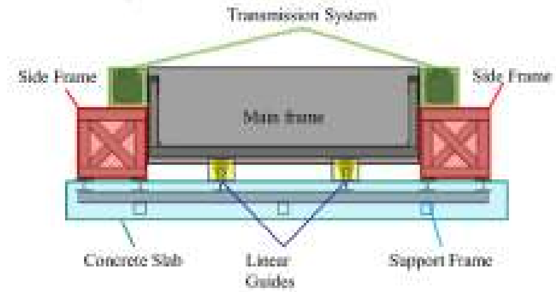

Figure 2. Subassemblies nomenclature. Motion is perpendicular to the page.

2.1. Main Frame

The main frame is built out of rectangular and square steel tubing, hot rolled per A513, material ASTM A36, with a minimum yield strength of 36,000 PSI and a fatigue limit of 29,000 PSI. As shown in Figure 3, multiple finite element simulations including static and modal analyses were performed and the design iterated resulting in:

- Frame built with 4 inch x3 inch x3/16 inch tubing, with top reinforcement plates (1/4 inch) for rivet nut installation.
- Minimum safety factor (maximum excitation, maximum load): 4.0
- Minimum natural frequency 31.2 Hz (first mode), an order of magnitude larger than the excitation frequency.

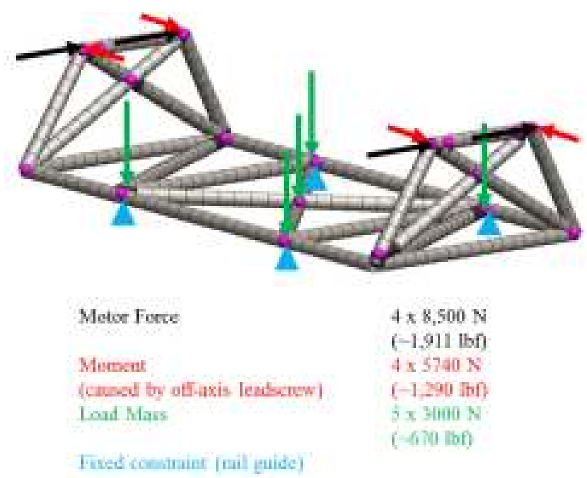

Figure 3. Main Frame loading conditions

1/2 inch – 13 threads per inch rivet nuts are installed in a grid-following bolt pattern, with a maximum pull-out strength of 4,480 pounds force (~20 kN) each, depicted in Figure 4.

The final dimensions of the main frame were determined through iterative design, taking into account the offset loading explained in section 2.7.

Figure 4. Main Frame anchoring

2.2. Side Frame

Side frames were designed and calculated using the same procedure of the main frame, as shown in Figure 5, yielding:

- Frame built with 4 inch x4 inch x3/16 inch tubing.
- Minimum safety factor (maximum excitation, maximum load): 23
- Minimum natural frequency 285 Hz (first mode), two orders of magnitude larger than the excitation frequency.

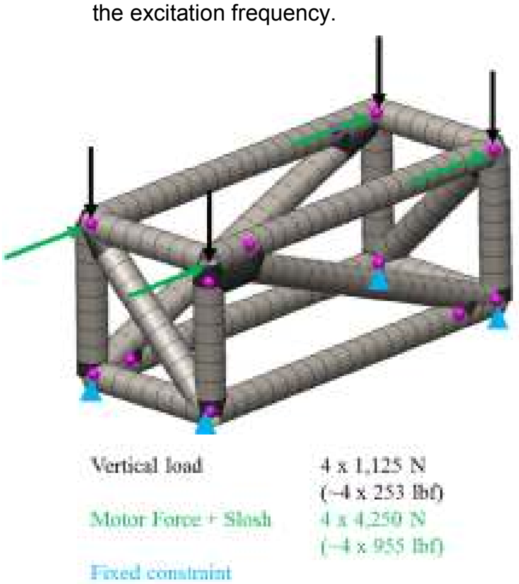

Figure 5. Side Frame loading conditions

2.3. Transmission System

The transmission system is sketched in Figure 6 and composed of:

- Electric motor: Siemens 1PH8 synchronous servomotor, 100 hp.
- Coupling: keyless dual-conical bellows-type coupling, supplied by R+W America.
- Leadscrew with nut, with a 64mm diameter and 36mm pitch, SRF series by SKF.
- Thrust bearing FLRBU7 for leadscrew (SKF).
- Spherical end bearing (SKF).

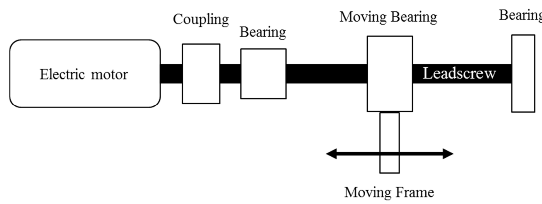

Figure 6. Transmission system diagram

The electric motor and the thrust bearing are bolted to a steel substructure shown in Figure 7, which is welded to the side frame.

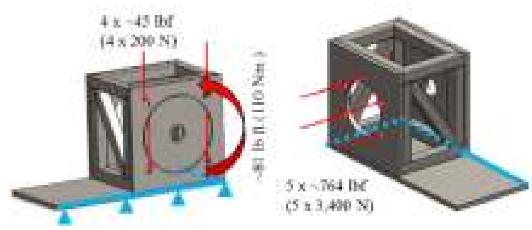

Figure 7. Transmission substructure

2.4. Linear Guides

Linear bearings chosen are SKF LUCT with 50mm rails, for their high load capacity bearings. This allows for a compact, robust design. Linear guides are bolted directly to the support frame beams as shown in Figure 8.

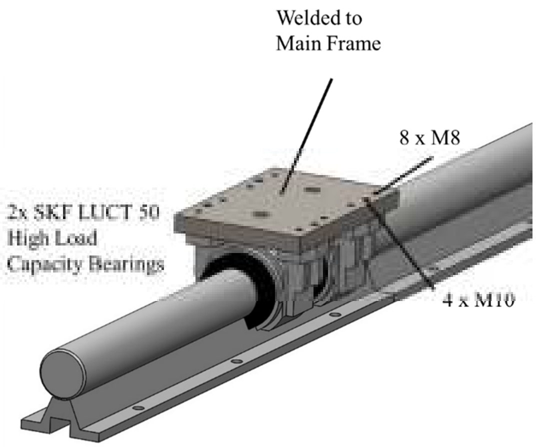

Figure 8. Linear Guides

2.5. Support Frame

Embedded in concrete, a support frame is assembled off of wide angle H beams and construction reinforcement bars. As can be observed in Figure 9, two central H beams precision-machined to a flatness requirement of 0.002 inches in their top surface provide a mounting point for the linear guides. 4 additional beams are used for supporting the side frames. 4 bumper beams are added for passive safety in the vertical direction. All these are embedded in a concrete slab of dimensions 14 ft x 10 ft x 20 in, of a resistance of at least 4000 psi. Also embedded in the concrete are two reinforcement meshes (top and bottom), providing bending resistance, as well as vertical hooks to provide additional vertical constraints, creating a solid piece with a mass of 35,000 lb (15,800 kg). This mass is isolated from the building through the use of 1 inch rubber isolators. To prevent sinking, maximum dynamic loads to the soil are below 500 psi, while the soil is compacted to meet at least twice that resistance (1000 psi).

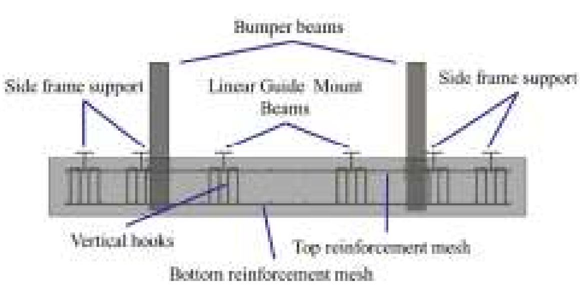

Figure 9. Concrete-embedded support frame section

All these components are invisible to the observer of the machine, since they sit below ground level (Figure 10).

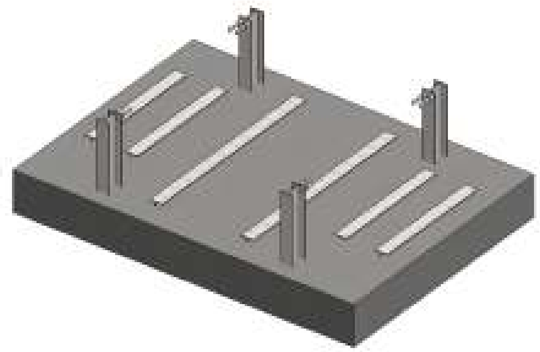

Figure 10. Perspective view of the finished sub-frame

2.6. Part Life Expectancy

All the mechanical components had their expected lifetime as a design factor, with the results of continuous operation summarized in Table 1. The bearings in the electric motors would be the first components to fail at 20,000 hours. All other components exceed that requirement.

Table 1. Main components life expectancy

Component	Minimum Lifetime [Hours/Years]	Reliability [%]	70-day Tests [Tests]
Servomotor	20,000 h (2.28 years)	-	11.9
Leadscrew	26,123 h (3.0 years)	99	15.5
Leadscrew Thrust Bearing	47,942 h (5.47 years)	90	28.5
Linear Bearings	165,870 h (18.9 years)	90	98.7

2.7. Mass Center of Gravity (CG) Offset

All the calculations and determinations for the design process were done based on a range of heights of the center of mass. Minimizing the moment generated by the actuation is a critical task, therefore care must be taken when developing tooling for heavy items.

Optimal loading conditions would consider making the excitation forces coplanar to the center of mass of the entire assembly, as depicted in Figure 11. This translates into nearly zero dynamic vertical loads into the linear bearings, increasing their life expectancy.

Determining the optimal CG placement is a function of the mass to be added to the system, that is tooling (or sub-frame) and tank itself, including its liquid mass. A calculation for this end was created, taking into account variable CG height and variable mass, yielding Figure 12. The blue line in the center represents the optimal loading case: the CG is perfectly collinear to the force actuation. As the CG for a specific mass is changed, or as the mass is changed for a specific setup, it is important to remain as close as possible to the blue center line.

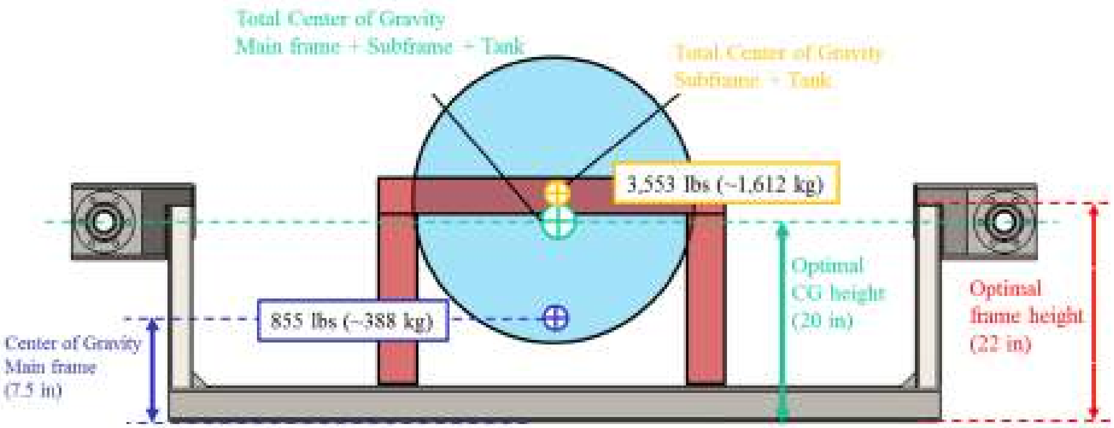

Figure 11. Center of gravity placement

Two cases are illustrated in Figure 12, the red illustrating a worst case scenario with the highest mass and the worst offset, while the green is a realistic scenario. For these cases, the life expectancy of the linear guides is estimated to be 0.41 years and 18.9 years of continuous use, respectively. Figure 12 becomes then a fundamental part of tooling design, targeting the optimal line in every case.

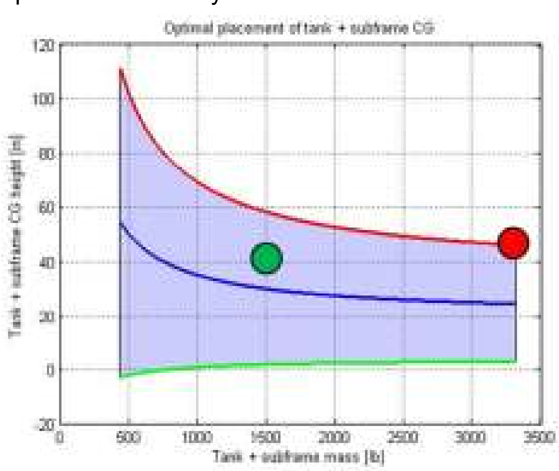

Figure 12. Recommended location of CG. Blue line: Optimal. Green and Red lines: Limit cases

3. ELECTRICAL DESIGN

For the electrical and control design, a complete Siemens system was developed, including in the main cabinet:

- Siemens 1PH8 synchronous servomotors with liquid cooling due to their high torque characteristics.
- Sinamics S120 drive control unit, with:
  - Two motor modules
  - 480 V, 160A Infeed
  - Braking module, connected to an external braking resistor.
- Siemens 24V power supply and Uninterrupted Power Supply module
- Siemens 480 V line reactor, to filter power and protect main components
- Siemens 480V 250A main breaker
- Tower light with buzzers for indication

Control is exerted from a pedestal and a panel. The pedestal has switches for two man operation. The control panel has duplicate switches and a Siemens Human Machine Interface (HMI) touchscreen TP1200 Comfort panel, connected to the Sinamics S120 unit through a PROFINET interface.

Liquid cooling of the motors is provided by means of a Mokon AS-3 3 ton chiller with a remote condenser, to reduce the thermal load inside the building.

Four feet (1.2m) tall Keyence laser barriers with 30 mm resolution prevent breaching into the operation zone. Always-on inductive limit switches monitor the carriage position and have the capability of stopping the control system.

All inputs (buttons, switches, safety devices) and outputs (buzzer, indicator lights) are controlled directly by the onboard Sinamics S120 I/O.

4. SAFETY

Safe operation was taken as part of the design philosophy of the entire machine. 3 layers can be defined to prevent mishaps, and mitigate in case all else fails:

1. Standard Operation Procedures (SOPs):
    a. A fundamental understanding of the machine and its systems is required to begin operation. Only trained personnel can make use of the machinery.
    b. Start-up procedures require at least two people working on site to operate the machine.
2. Active Safety:
    a. Software designed to not allow overshoots or dangerous test situations (checking inputs of mass, amplitude and frequency to not exceed bounds of system).
    b. Control system running on an uninterruptible power supply (UPS), protecting in the event of a power surge or failure.
    c. Emergency Brakes:
        i. ‘Hard’ stops – Dump all energy into breaking resistor. Emergency-Stop buttons pressed (one on pedestal and one on podium).
        ii. ‘Soft’ stop – Gradually reduce and break within ~10 seconds.
        iii. Light sensor barriers in conjunction with audible alarm that the safety barrier has been breached.
    d. Limit Switches (2 sets):
        i. Limit of normal operation – soft stop.
        ii. Limit before bumper impact – wired directly to motor drive inhibits to cut infeed power.
3. Passive Safety: Hydraulic bumpers to absorb all energy and break max load within 2 inches.

5. CONSTRUCTION

The linear stage was decided to be built at Florida Tech facilities in Palm Bay, Florida, near the main campus in Melbourne. For the construction phase which begun in August 2015, the main mechanical parts were built, machined and the installation laid out. The second phase, installation, started with the embedment of the sub-frame in a concrete pad, shown in Figure 13. Central beams were aligned using a custom-made alignment jig and a precision level, allowing the linear guides to be parallel within 0.001in per foot (~0.076mm per meter), ensuring a smooth operation.

Figure 13. Concrete base. Top: sub-frame structure. Bottom: Concrete poured

Currently, the machine is in its final configuration, as shown in Figure 14. Software development and control loop tuning are taking place, setting the machine ready for operation during the month of May 2016.

Figure 14. Final machine configuration, undergoing welding of transmission systems

6. SUMMARY

The design and construction process of a linear stage for slosh research and flight tank certification, capable of exciting a 2,000 kg mass at up to 1.5 Hz and 15 inches of double amplitude was outlined through this paper. Main aspects of the mechanical, electrical and safety design items were presented. Mechanical construction of the machine is finished, with all subsystems in place and working perfectly, now in the process of polishing software details and controller tuning.

7. ACKNOWLEDGEMENTS

The authors wish to thank all the visiting scholars of the ASAP lab for their exhaustive work to bring this project to reality. Undergraduate Students from the Netherlands, Germany and France participated in all stages, from CAD design, engineering calculations, component sourcing and mechanical assembly. This has been a true international collaboration between Florida Tech, Orbital-ATK and universities all over the European Union.

A major thank you also goes to Chris and Elaine Larsen at Larsen Motorsports, as well as their entire crew, who has been extremely helpful and provided invaluable contribution to build this linear stage.

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