General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Modeling Spacecraft Fuel Slosh at Embry-Riddle Aeronautical University

By Keith Schlee, Analex Corporation

Shortly after it reached orbit in August 1969, NASA's spin-stabilized Applications Technology Satellite 5 (ATS5) began to wobble, sending the spacecraft into an unplanned flat spin and crippling the mission. It was later found that this event was caused by excessive fuel slosh, creating a long-standing concern about this phenomenon.

Spinning is a well-established method for stabilizing a spacecraft or launch vehicle upper stage with a minimum of hardware, complexity, and expense. Fuel slosh reduces the rotational kinetic energy of a spinning space vehicle, leading to a growing *nutation* (wobble) that can undermine its gyroscopic stability. As the ATS5 mission demonstrated, failure to understand the effect of fuel slosh can have serious consequences.

As a NASA-sponsored Graduate Student Research Program Fellow, I worked with researchers, engineers, and analysts at Embry-Riddle Aeronautical University and NASA's Expendable Launch Vehicles Division to investigate this effect. NASA's research into the effects of fuel slosh includes modeling the response in full-sized tanks using equipment such as the Spinning Slosh Test Rig (SSTR), located at Southwest Research Institute (SwRI) in San Antonio, Texas. NASA and SwRI engineers analyze data taken from SSTR runs and hand-derive equations of motion to identify model parameters and characterize the sloshing motion.

With guidance from my faculty advisor, Dr. Sathya Gangadharan, and NASA flight controls analysts James Sudermann and Charles Walker, I set out to automate this parameter identification process by building a simple experimental setup to model free-surface slosh in a spherical tank. We modeled this setup with Simulink and SimMechanics and used Simulink Parameter Estimation to identify the model parameters.

Evaluating Parameter Estimation Approaches

For years, NASA engineers have used simple mechanical analogs, such as pendulums and rotors, to model fuel slosh and estimate space vehicle nutation. Identifying model parameters that accurately represent the sloshing dynamics is one of the most difficult yet most important steps in this approach.

My research at Embry-Riddle focused on modeling free-surface slosh using a pendulum analog. Identifiable parameters include the pendulum's length, mass, hinge spring constant, and hinge damping coefficient. Currently, the identification of mechanical analog parameters is a labor-intensive trial-and-error process in which engineers hand-derive the equations of motion, evaluate them, and compare the results with experimental data gathered from physical experiments like the SSTR. Even in the best of circumstances, designing, constructing, and hand-deriving the first sets of data from these experiments can take six months or longer.

My colleagues and I knew that establishing a robust automated parameter estimation process would not only save time and effort during the hand-calculation phase, it would also allow analysts and engineers to evaluate different tank configurations early in the design phase and eliminate potential problems before the first component was built. Tank configurations include on-axis spinners, off-axis spinners, lateral slosh on a first stage tank, and tanks with propellant management devices (PMDs) such as diaphragms and baffles. To keep the experiment simple yet prove the concept, we decided to model lateral slosh using a spherical tank with no PMDs.

The project can be divided into three broad phases. The first evaluated the effectiveness and accuracy of the automated process by comparing the results from measurements from a simple mechanical pendulum experiment undergoing lateral motion. The second replaced this pendulum with a liquid-filled tank undergoing the same lateral motion, where the identical pendulum-based SimMechanics model would verify the validity of the analog. The third phase involves increasing the complexity of the model by incorporating the effects of a diaphragm into the simulation. This approach will ultimately enable the fast, accurate, and reliable determination of slosh model parameters for actual space missions.

Phase 1: A Simple Mechanical Model

Free-surface slosh has a well-defined resonant frequency where the liquid starts to oscillate with great turbulence over a narrow frequency range. The pendulum represents the free-surface wave. The rest of the liquid is essentially at rest, or fixed. To verify and validate our approach, we constructed a simple one-degree-of-freedom pendulum experiment that simulates this phenomenon (Figure 1).
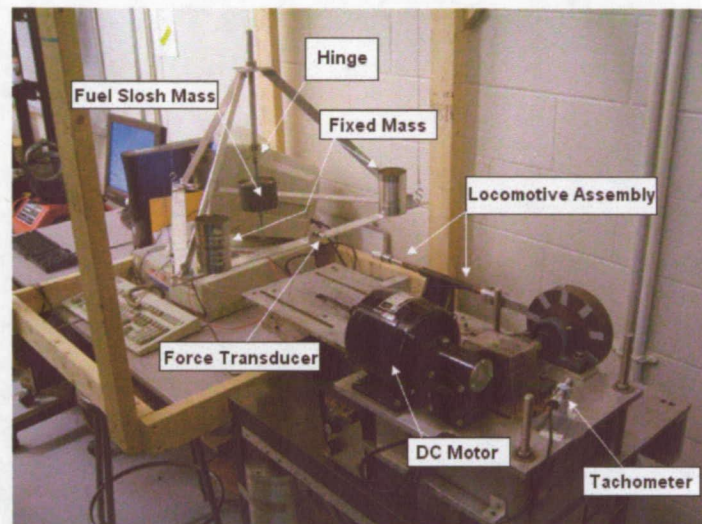

Figure 1: Mechanical analog of lateral free-surface fuel slosh.

To derive the initial pendulum properties for the experiment and simulation, we used *Fuel Slosh in Asymmetrical Tank Software*, a program written in the late 1990s at SwRI by Dr. Franklin Dodge. Nicknamed the "SLOSH code", this program predicts the natural frequency and damping properties of the fuel tank and creates a pendulum analog equivalent. Properties such as tank shape, liquid kinematic viscosity, and liquid fill level are provided as input to the program, which calculates the corresponding

pendulum properties including pendulum mass, pendulum length, and fixed mass. We then ran the experiment at various frequencies using a DC motor connected to a locomotive arm assembly. We measured force as a function of time at a sampling rate of 100 Hz and filtered the force data using Signal Processing Toolbox.

In parallel with the experiment, we built a model of the four major subsystems (Figure 2). NASA recommended Simulink and SimMechanics for this work because they use these products for their own modeling efforts.
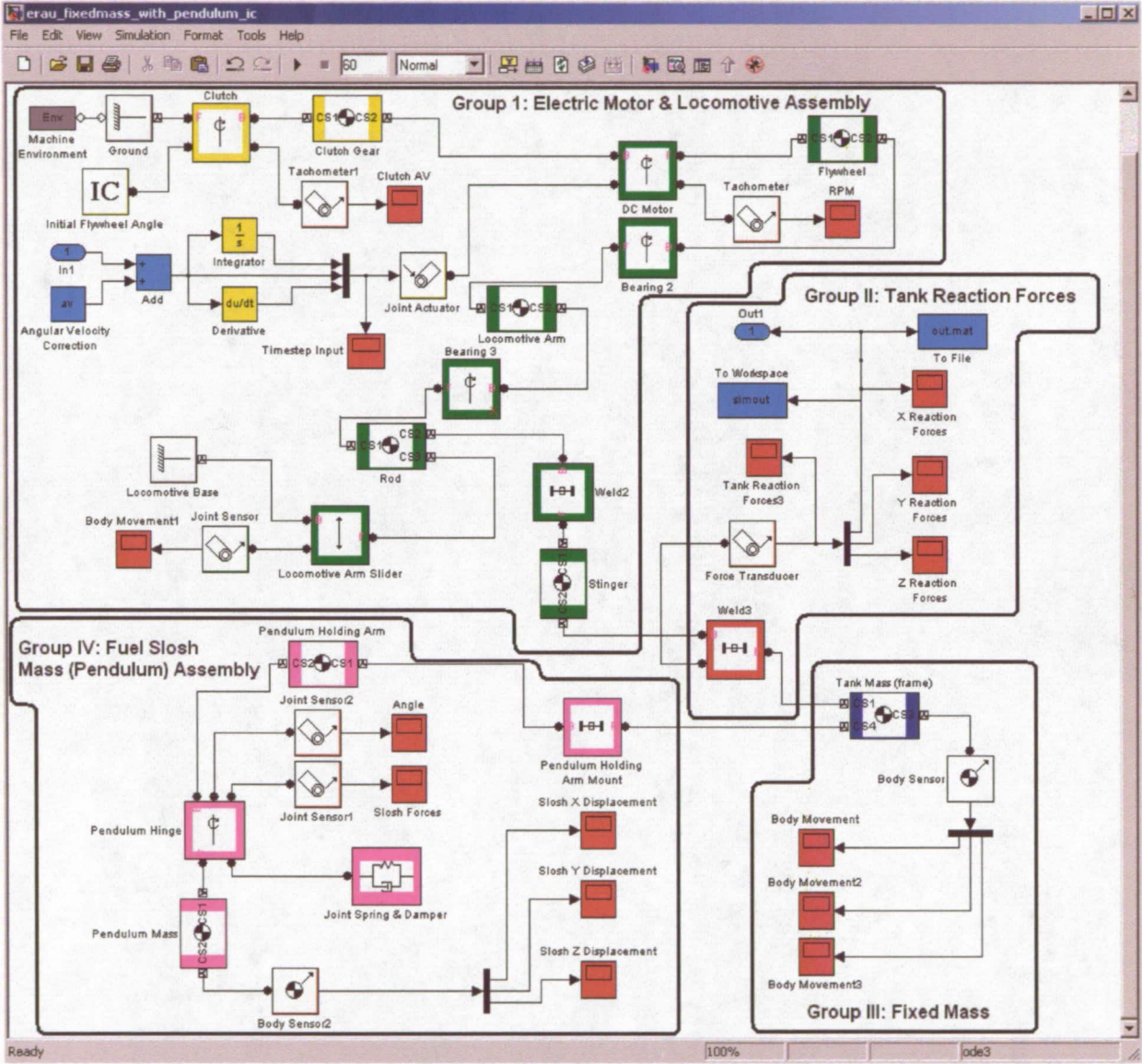

Figure 2: Simulink and SimMechanics model of the pendulum mechanical analog.

We then used Simulink Parameter Estimation to match the response of the Simulink model to the measured outputs of the physical system. Simulink Parameter Estimation automatically identified an optimal set of parameters, including pendulum length and mass, which tuned the model to match its real-world counterpart. Once the parameters were identified, we could use the model to *predict* the dynamics of the physical system for various motor speeds.

3

One benefit of using Simulink Parameter Estimation is that it produces plots of "measured versus simulated" responses in real time, enabling you to visualize the estimation process. Once the parameters converge and stabilize, you can either terminate the estimation or let it iterate until it converges to a predefined stopping criterion, as defined by the chosen optimization algorithm. The estimation can also be terminated if the plots indicate that the parameters are converging towards unreasonable values or if they diverge towards their maximum or minimum limits.

Phase 2: Moving to a Liquid-Filled Tank

In this phase, we replaced the pendulum assembly with an eight-inch sphere filled with dyed water (Figure 3). Water is a widely used substitute for hazardous propellants like hydrazine because it has similar physical properties, such as density and viscosity. We used these properties in the SLOSH code to identify the initial pendulum characteristics.
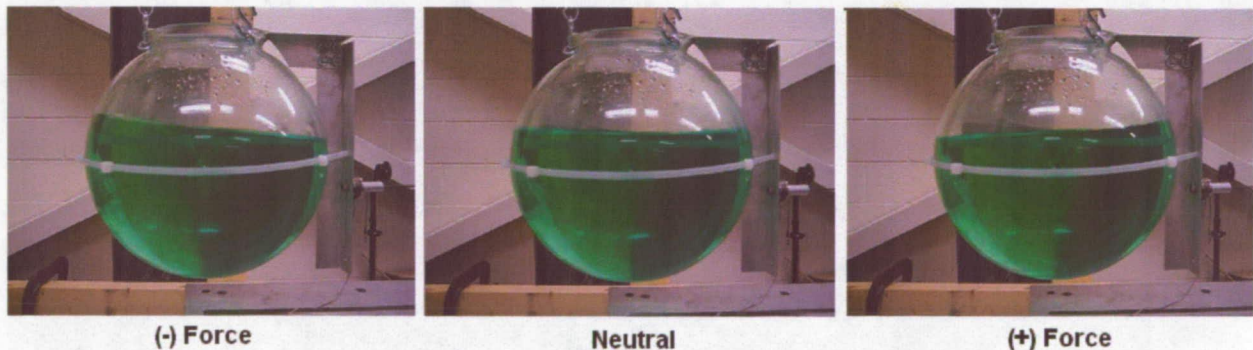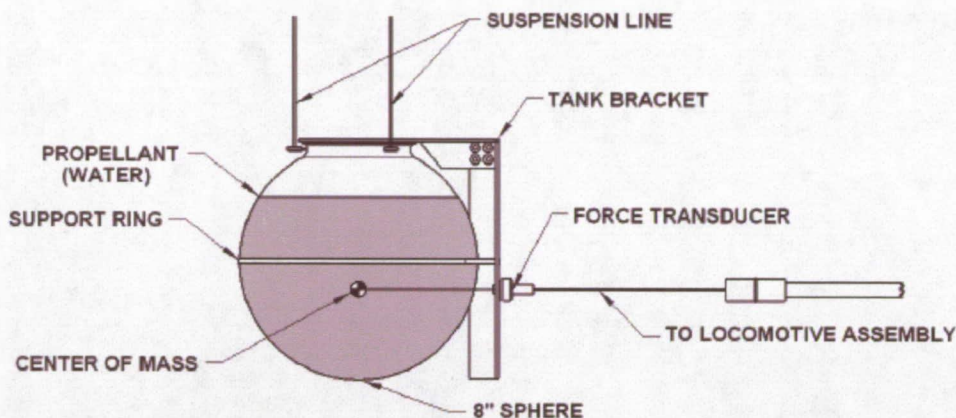

Figure 3. A water-filled tank undergoes lateral slosh that is simulated using a pendulum.

For the liquid-filled tank, we again measured force at 100 Hz and used this data as input for parameter estimation. We then used our pendulum model without modification and re-ran the same parameter estimation process. We tested fill levels ranging from 60% to 80% and found that the SLOSH code predicts the natural frequency of the liquid to within 3%. The natural frequency dictates the corresponding pendulum length based on simple pendulum equations of motion. For example, at a 60% fill level, both the measured and predicted natural frequencies are approximately 2.10 Hz.

Figure 4 illustrates the response of the tank over a 30-second test where the liquid is initially at rest and instantaneously brought to a forced frequency of about 1.95 Hz. The beats, or "humps," represent the

4

difference between the natural and the forced frequency. This small difference, only 0.15 Hz, corresponds to a beat of roughly 6.5 seconds, which is close to that indicated in the figure. Figure 4 also shows the simulation response obtained after using Simulink Parameter Estimation. We found that Simulink Parameter Estimation does a very good job of estimating this data, especially the phase and frequency parameters.

Once we had perfected a reliable parameter estimation method, we began to investigate the relationships between parameters. Simulink Parameter Estimation makes this very straightforward by giving us the option to de-select parameters and reset their initial values. We found that several parameters are interdependent with one another. That is, we could treat each parameter as a "knob" that can be turned to arrive at an optimized solution similar to that shown in Figure 4. For example, pendulum length need not correspond to the pendulum's un-damped natural frequency. Simulink Parameter Estimation simply adjusts the hinge spring and damping constants to compensate for the difference. These relationships are documented in the pendulum equations. The ability to factor them in is a powerful feature of Simulink Parameter Estimation. It is particularly useful when simulating more complex experiments where the natural frequency cannot be calculated without tremendous effort.
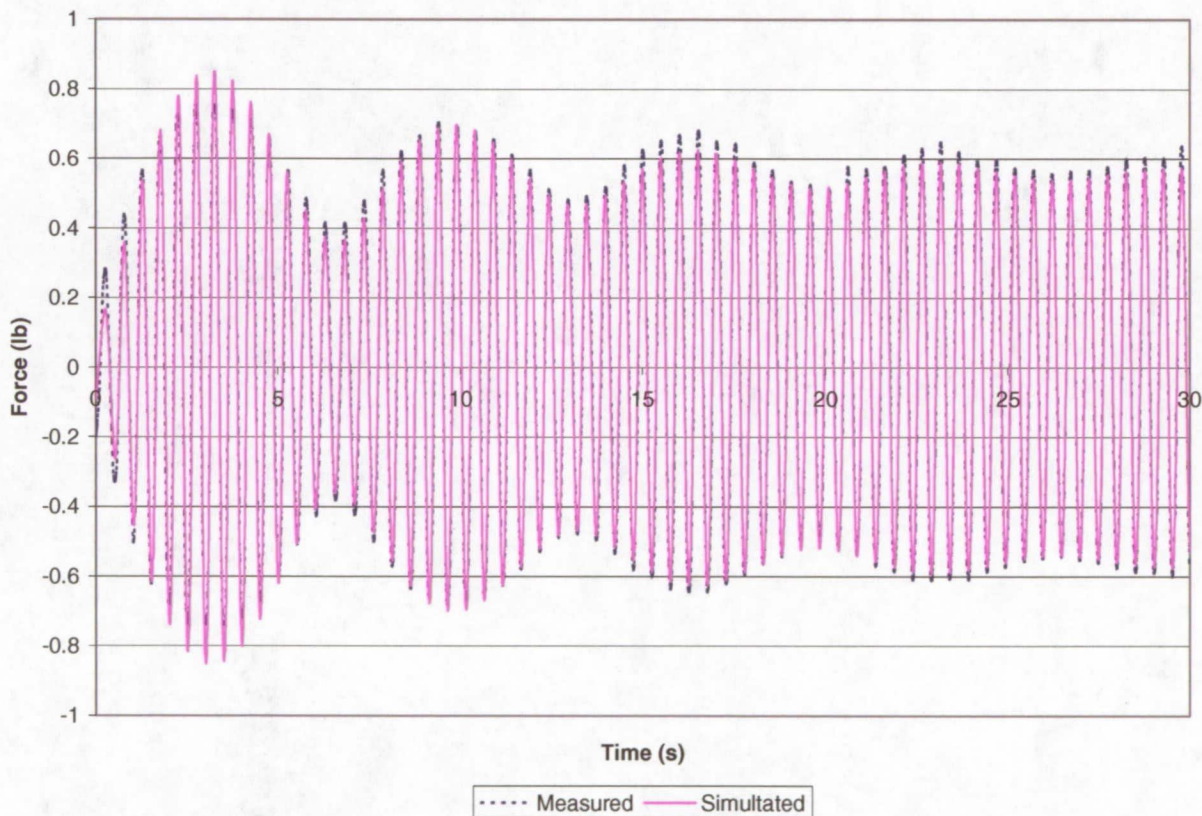

Figure 4. SimMechanics response for sphere at 60% fill at a forced frequency of 1.953 Hz.

Phase 3: Automated Parameter Estimation for Real-World Applications

In a typical spacecraft, the fuel tanks tend to be much more complicated than a simple sphere without any PMDs. Many modern tanks now incorporate PMDs to ensure that thrusters receive a steady, gas-free flow of propellant. While the SLOSH code provides accurate results for free-surface slosh in a tank with no PMDs, it was never designed to handle a tank with a PMD. With SimMechanics, however, it is

5

straightforward to add elements such as a rotor or a sliding mass spring damper. With Simulink Parameter Estimation, we can then quickly determine whether these changes improve the model's ability to accurately reflect real-world dynamics.

A key advantage of using automated parameter estimation is the ability to find solutions to more sophisticated tank configurations without laboriously hand-deriving a model. More complex simulations incorporating novel analogs that may be too complex to derive fully by hand can now be created to take advantage of this method. With the automated approach, the months of work needed to hand-derive accurate models for a given tank has been reduced to a month or less. This acceleration enables engineers to test different models as they work with different tank shapes, mounting configurations, and PMDs.

Ongoing Research

Many of today's expendable launch vehicles, such as the Delta II third stage, still depend on spin for stability. Future manned missions are also likely to depend on spin to provide artificial gravity to counteract the effects of extended weightlessness. Managing fuel slosh will continue to be essential to the success of these missions. Lateral slosh will also continue to be a concern for all launch vehicles that use liquid propellant during their ascent phases.

Today, fuel slosh research continues in several directions. Graduate students at Embry-Riddle are enhancing the model shown in Figure 2 to accommodate tanks with PMDs. At NASA, analysts are developing a SimMechanics model for the upcoming DAWN mission. At SwRI, engineers are conducting a test series with an on-axis SSTR using an identical tank configuration that has flown on the Deep Impact and Pluto New Horizons missions. These experiments will help further validate the SimMechanics-based method for parameter estimation by enabling engineers to compare simulation results with actual flight data.

I am now working for Analex Corporation at Kennedy Space Center and applying the experience gained at Embry-Riddle to real-world problems by modeling the on-axis SSTR at SwRI. The research that my colleagues and I conducted and the techniques learned at Embry-Riddle in building the SimMechanics model has paved the way for these more complex simulations. I have begun introducing engineers at SwRI to this automated estimation method. As these engineers combine their expertise and their facilities adopt the techniques developed and fine-tuned at Embry-Riddle, NASA anticipates substantial reductions in time and cost. More importantly, this approach will enable engineers to minimize the effects of fuel slosh during the preliminary design phase.

REPORT DOCUMENTATION PAGE

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
18/04/2007	Digest Article	01/09/2004 - 18/04/2007

4. TITLE AND SUBTITLE		5a. CONTRACT NUMBER
Modeling Spacecraft Fuel Slosh at Embry-Riddle Aeronautical University		
		5b. GRANT NUMBER
		NNK05EE78H
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
Schlee, Keith L.		
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Embry-Riddle Aeronautical University Department of Mechanical Engineering 600 S. Clyde Morris Blvd. Daytona Beach, FL 32114	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
NASA Launch Services Program: VA-A ATTN: Export Control Representative Kennedy Space Center, FL 32899	
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

No restrictions/limitations.

13. SUPPLEMENTARY NOTES

Digest title: MATLAB Digest

14. ABSTRACT

As a NASA-sponsored GSRP Fellow, I worked with other researchers and analysts at Embry-Riddle Aeronautical University and NASA's ELV Division to investigate the effect of spacecraft fuel slosh. NASA's research into the effects of fuel slosh includes modeling the response in full-sized tanks using equipment such as the Spinning Slosh Test Rig (SSTR), located at Southwest Research Institute (SwRI). NASA and SwRI engineers analyze data taken from SSTR runs and hand-derive equations of motion to identify model parameters and characterize the sloshing motion. With guidance from my faculty advisor, Dr. Sathya Gangadharan, and NASA flight controls analysts James Sudermann and Charles Walker, I set out to automate this parameter identification process by building a simple physical experimental setup to model free surface slosh in a spherical tank with a simple pendulum analog. This setup was then modeled using Simulink and SimMechanics. The Simulink Parameter Estimation Tool was then used to identify the model parameters.

15. SUBJECT TERMS

MATLAB, Simulink Parameter Estimation, SimMechanics, Fuel Slosh

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Keith Schlee
U			UU	6	19b. TELEPHONE NUMBER *(Include area code)* (321) 867-4186