



# Nonlinear Propellant Slosh Damping Testing, Analysis, and Implementation for Launch Vehicle Flight Controls

## Part 1: Testing, Analysis and Model Development

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## Part 2: Flight Controls Implementation

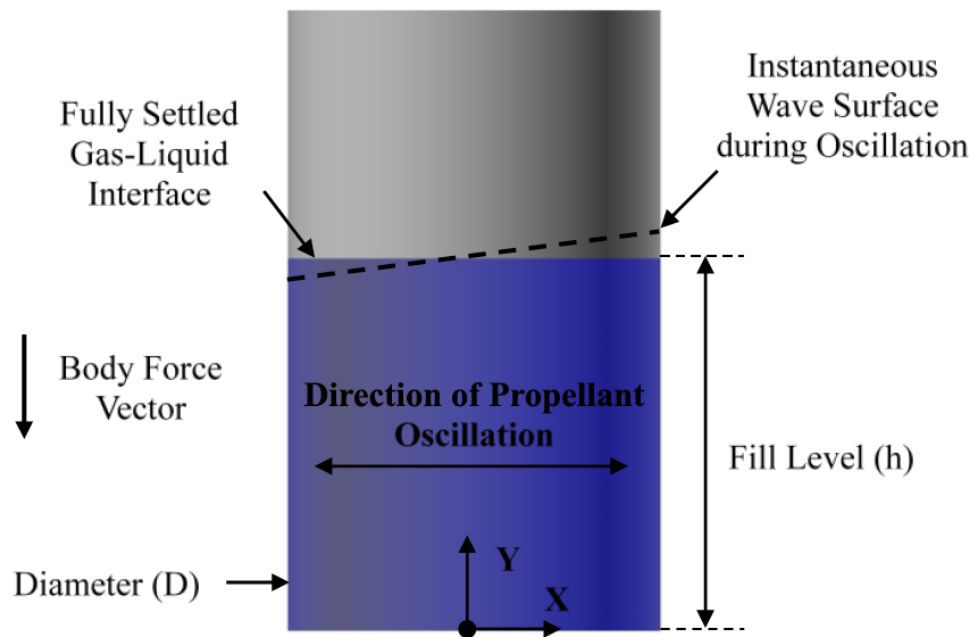
John Ottander, GuideTech

*Separate  
Presentation*

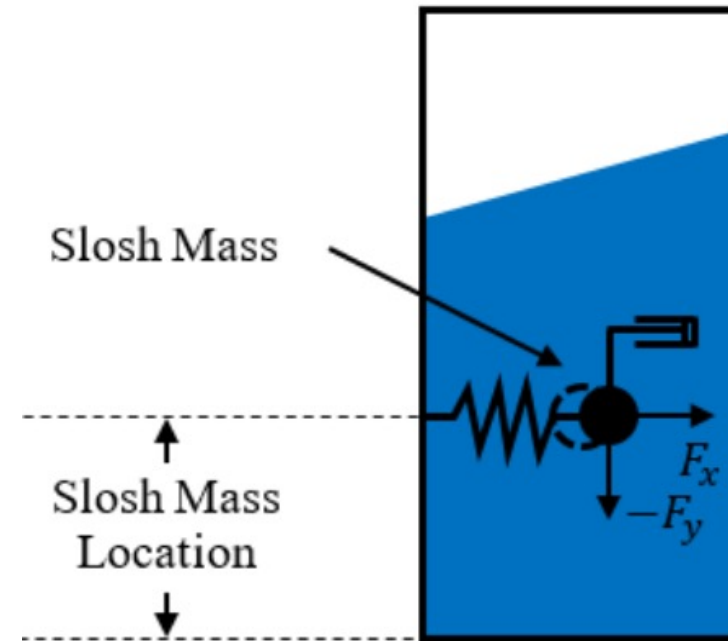


# Background

- Launch vehicle dynamics models / simulations used for GN&C applications typically employ simple mechanical models of lateral propellant slosh
- Slosh mass, spring stiffness, damping, and slosh location typically assumed to be constant for a given liquid fill level



Lateral liquid slosh in a Cylindrical Tank



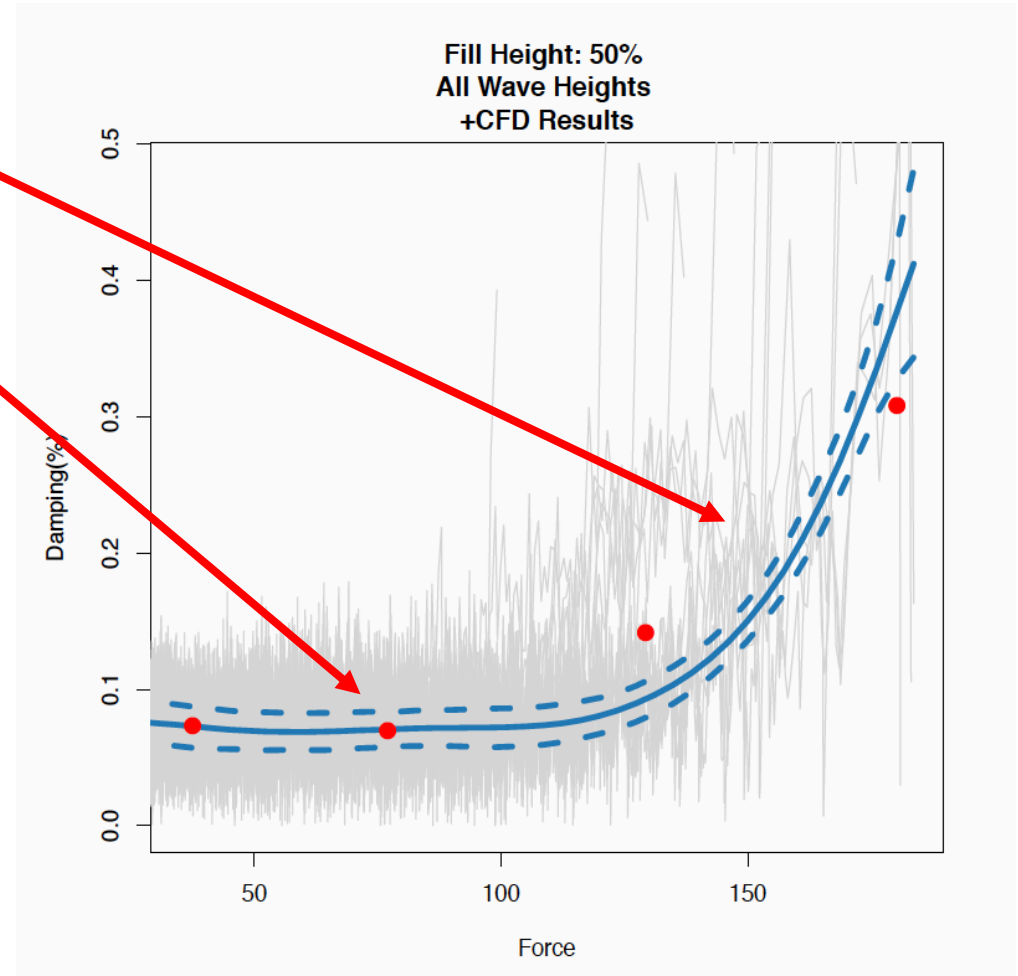
Simple Mechanical Model of Lateral Slosh  
(Spring-Mass-Damper Model)



# Motivation

- Propellant slosh damping increases with wave amplitude (force)
- Traditional flight control stability analysis computations for launch vehicles employ a linear model of slosh dynamics
- Use of linear damping models can lead to an overly-conservative approach for treating propellant slosh, which can result in
  - larger tank damping requirement that drives the baffle design
  - unnecessary loss of vehicle performance (and/or robustness in other areas)
  - unwarranted flight control certification issues

## Example: Smooth Wall Propellant Tank



**Goal of NESC Assessment: Proactively develop nonlinear slosh damping models for potential use by the Space Launch System (SLS) Program**



# Introduction

- The NASA Engineering and Safety Center (NESC) and Space Launch System (SLS) Program completed a multi-year study on launch vehicle propellant slosh

## Nonlinear Slosh Damping Testing and Analysis for Launch Vehicle Propellant Tanks

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Propellant tank slosh damping models for launch vehicle ascent analysis typically employ linear models for bare-wall damping, or assume a single, low-amplitude wave height for baffled configurations. A higher fidelity damping model would incorporate nonlinear effects to increase damping as slosh wave amplitude increases. This paper provides an overview of a technical assessment performed by the NASA Engineering and Safety Center (NESC) to evaluate lateral slosh damping as a function of lateral force (or wave) amplitude for multiple tank configurations. The increased fidelity of nonlinear slosh damping models, if leveraged, has the potential to reduce over-conservatism associated with the use of linear slosh damping models. This can provide design flexibility to enhance launch vehicle flight control performance, reduce baffle design requirements and/or increase robustness in targeted areas such as control-structure interaction during ascent.

### I. Introduction

Propellant tank slosh damping models are typically linear for bare-wall damping, or assume a single, low-amplitude wave height for baffled configurations. A higher fidelity damping model would incorporate nonlinear

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Ref: T. VanZwieten, J. Brodnick, S. Reese, M. Ruth, B. Marsell, R. Parks, "Nonlinear Slosh Damping Testing and Analysis for Launch Vehicle Propellant Tanks," AIAA SciTech, AIAA 2020-2050, 2020.

Ref 2: J. Ottander, R. Hall, J. Powers, "Practical Methodology for the Inclusion of Nonlinear Slosh Damping in the Stability Analysis of Liquid-propelled Space Vehicles", AIAA SciTech, AIAA 2018-2097, 2018.

## • Part 1: Testing, Analysis and Model Development

- Goal: Develop propellant slosh damping models with quantified uncertainty for multiple tank configurations (bare and baffled)
- Also investigated slosh frequency and slosh mass variability with wave amplitude, damping regimes associated with flow physics, use of wave amplitude as an independent variable, influence of initial conditions, etc.
- NESC Final Report is 500+ pages; peer reviewed.
- Presentation summarizes the scope of the work completed and outlines the process followed for test, data analysis, and computational fluid dynamics (CFD).

## • Part 2: Flight Controls Motivation and Implementation

- Method for inclusion of nonlinear slosh damping model in launch vehicle flight control stability analysis



# Approach

## Computational Fluid Dynamics (CFD)

- **Cylindrical tanks** (3 sizes; scalability study)
- **EUS LOx tank** (1/5 scale)
- **SLS CS LOx Tank** (1/7.6 scale)
- **Baffled cylinder**

## Data analysis

### Comparison of Results

- Compared with SP-106 & Miles Equation
- CFD/Test comparison resulted in testing modifications in some instances

## Testing

- **EUS LOx Tank** (1/5 scale)
- **SLS CS LOx Tank** (1/7.6 scale)
- **Baffled configurations** (multiple)

## Data analysis

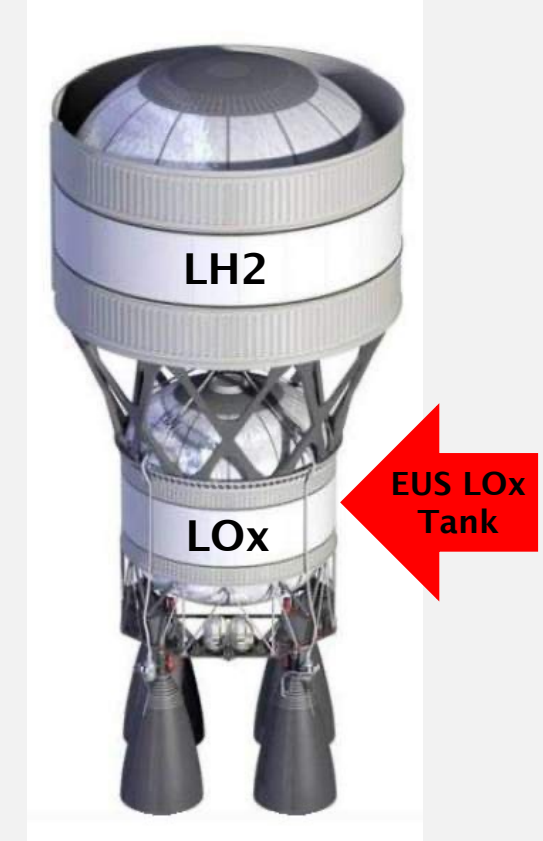
- Statistician included from the onset of the activity (influenced testing)

CONDUCTED INDEPENDENTLY

## Space Launch System (SLS) Block 1



## Exploration Upper Stage (Point of Departure)



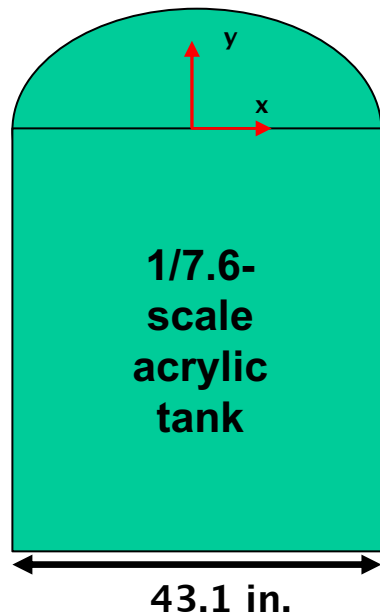
- **Data used to support nonlinear model development for additional tanks**
- **Nonlinear models used for SLS Flight Controls Design (analysis techniques developed by SLS Program)**



# Tank Configurations Analyzed (Bare Wall)

## Cylindrical tanks (three sizes; bare tank)

- CFD analysis; emphasis on evaluating scalability

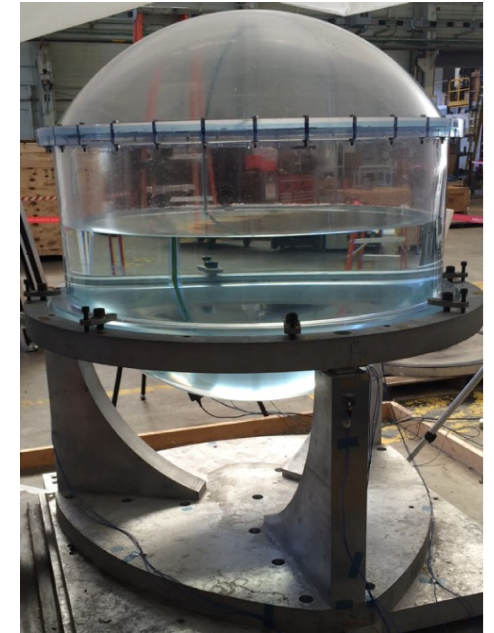


### Bare Wall SLS CS LOx Tank

- CFD, subscale testing & analysis
- Slosh damping GP models and UQ delivered

### Bare Wall EUS LOx Tank

- CFD (subscale with water/air; full scale with LOx/He)
- Sub-scale testing & analysis
- Slosh damping GP models and UQ delivered

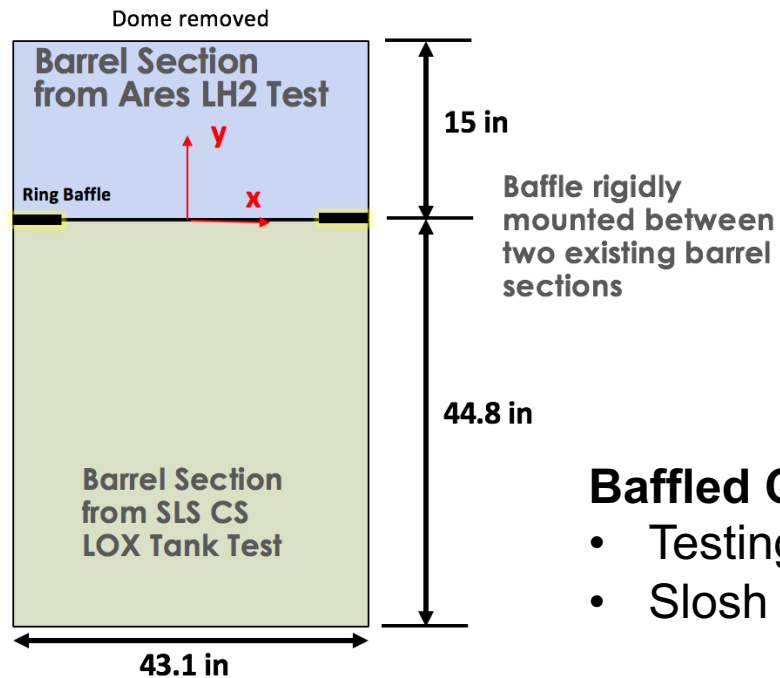




# Tank Configurations Analyzed (Baffled)

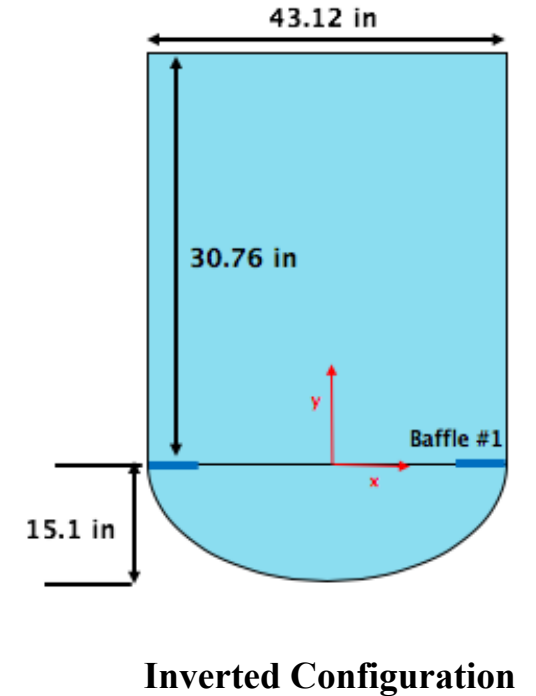
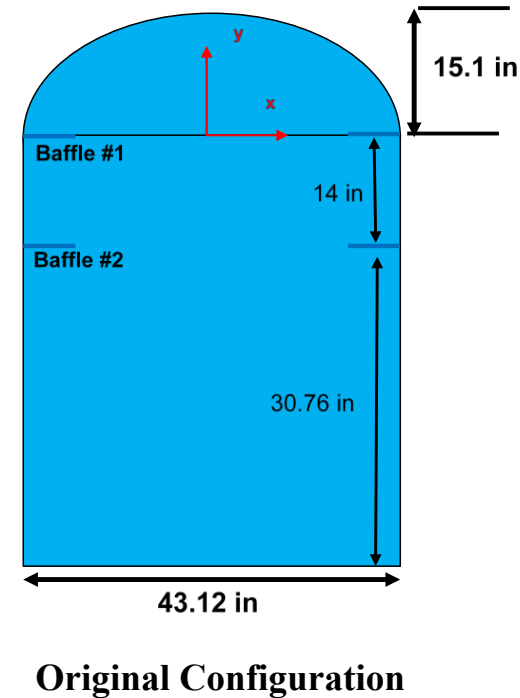
## Baffled SLS CS LOx Tank (Original & Inverted)

- CFD, subscale testing & analysis
- Slosh damping GP models and UQ



## Baffled Cylindrical Tank

- Testing & analysis
- Slosh damping GP models and UQ





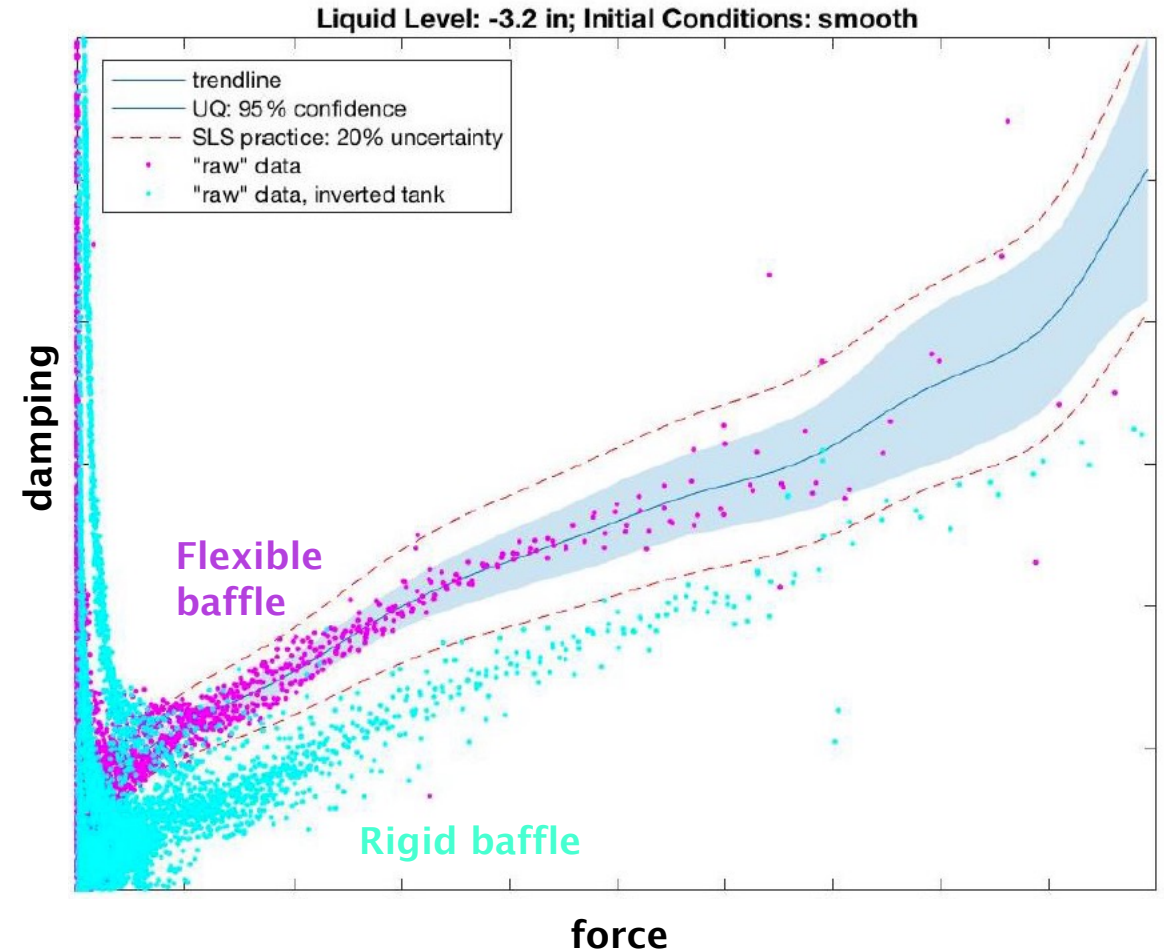
## Sample Findings

### Slosh with Baffles

Baffle flexibility can have a substantial impact on measured damping results:

- Test results from above a single barrel-section baffle showed good agreement with the Miles Equation. However, this result was misleading because of increased damping due to baffle flexibility.

The Miles Equation over-predicted the damping for all fill heights and wave amplitudes evaluated using a cylindrical tank with a rigidly cantilevered baffle.





# CFD Analysis

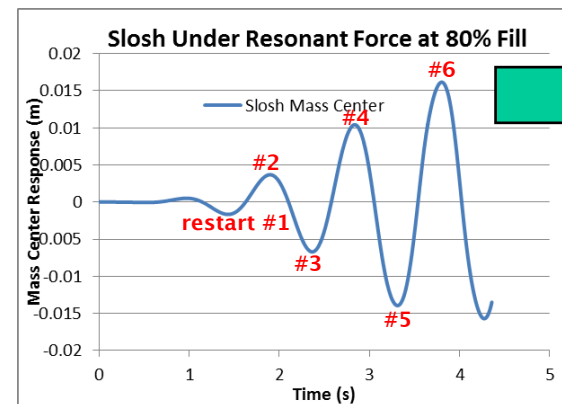
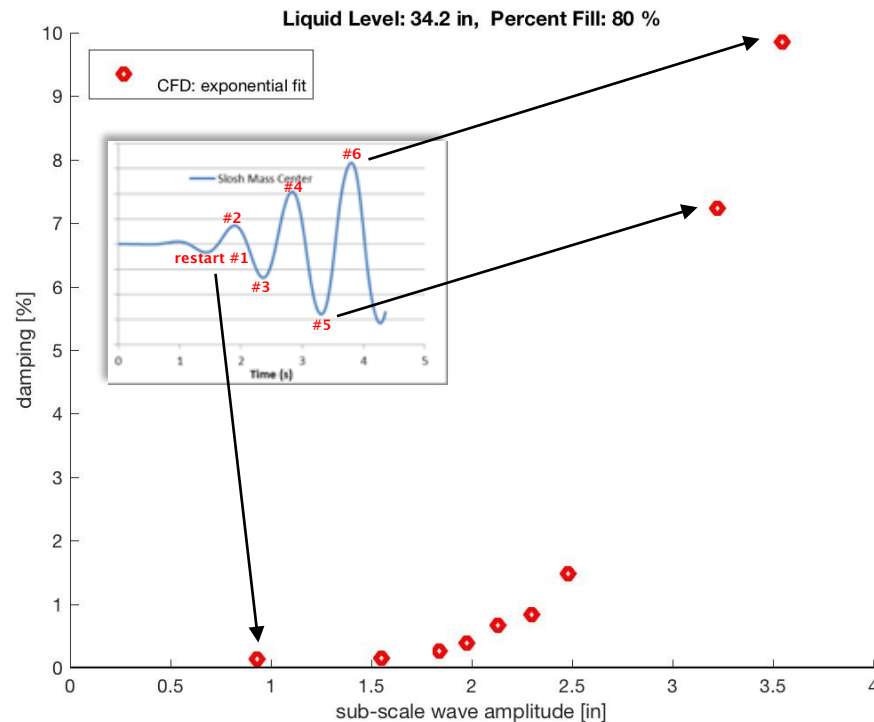
## Key Contributors:

Jacob Brodnick/MSFC ER42 (ESSSA/Jacobs)

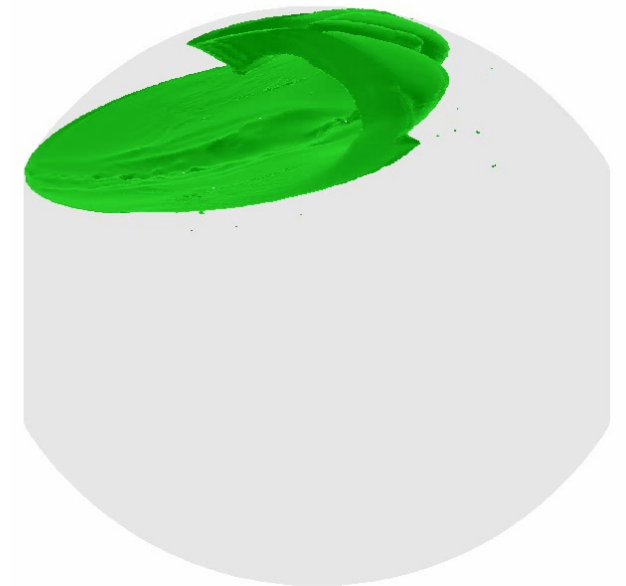
H.Q. Yang/MSFC ER42 (ESSSA/Jacobs)

- CFD predictions determined in advance of the test
  - Full range of forces not analyzed – windows selected to reduce run time
  - Damping results evaluated across each analysis window
- Useful for aiding in physical interpretation of results, identifying sensitivities that could skew test data, and understanding CFD accuracy for alternate tank configurations where test data may not be available

## Sample CFD Result



## CFD Results for Modeled 1/5-scale EUS Tank (~10% damping)



*Slosh amplitude increased using a smooth forcing function near the slosh natural frequency.*



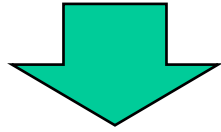
# Testing Conducted at Each Liquid Fill Level

## Key Contributors:

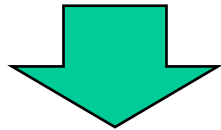
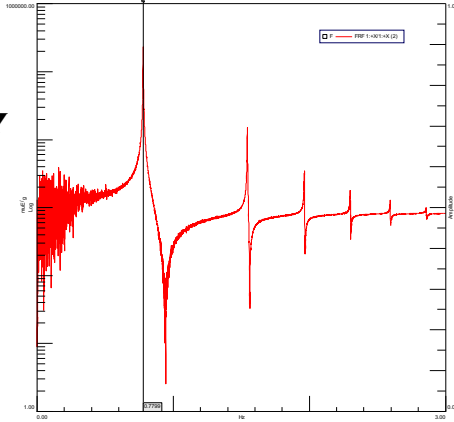
- MSFC ET40: Rusty Parks, Marlon Holt, Alex McCool
- MSFC EV31: Dan Lazor

## Random tests – one test/liquid level

- *Input:* Random, low-amplitude force (0.1-3 Hz)



### FREQUENCY RESPONSE FUNCTION

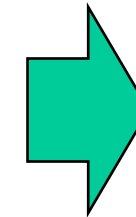
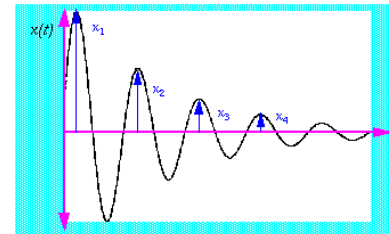


- *Result:*
  - Slosh frequency (low amplitude)
  - Damping (low amplitude)
  - Slosh mass

## Free decay tests – multiple tests/liquid level

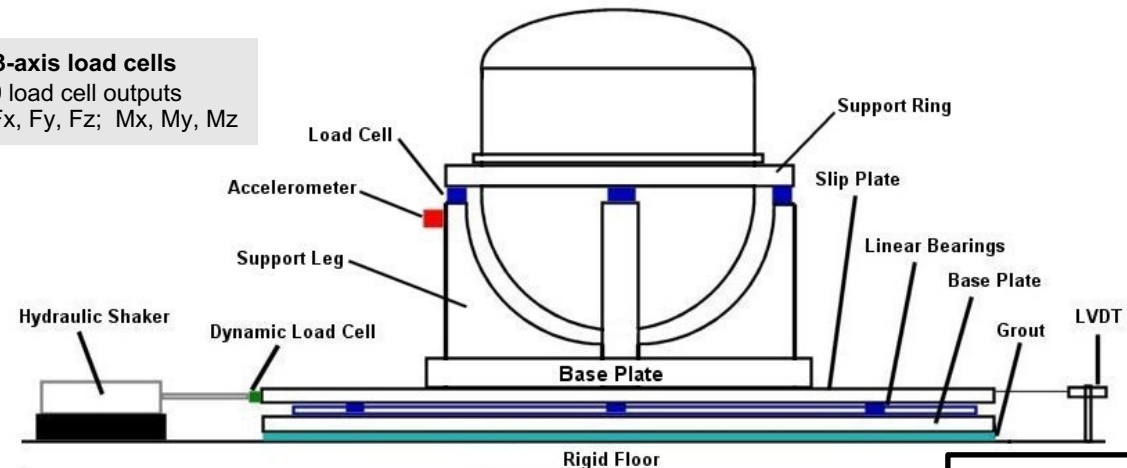
- Sinusoidal forcing functions applied by hydraulic shaker
  - Amplitude increased
  - When desired wave height is reached, forcing is terminated
- Slip plate held constant; forces measured as slosh wave decays

### FORCE VS. TIME



Damping  
(as a function of force amplitude)

3 x 3-axis load cells  
⇒ 9 load cell outputs  
⇒  $F_x, F_y, F_z; M_x, M_y, M_z$



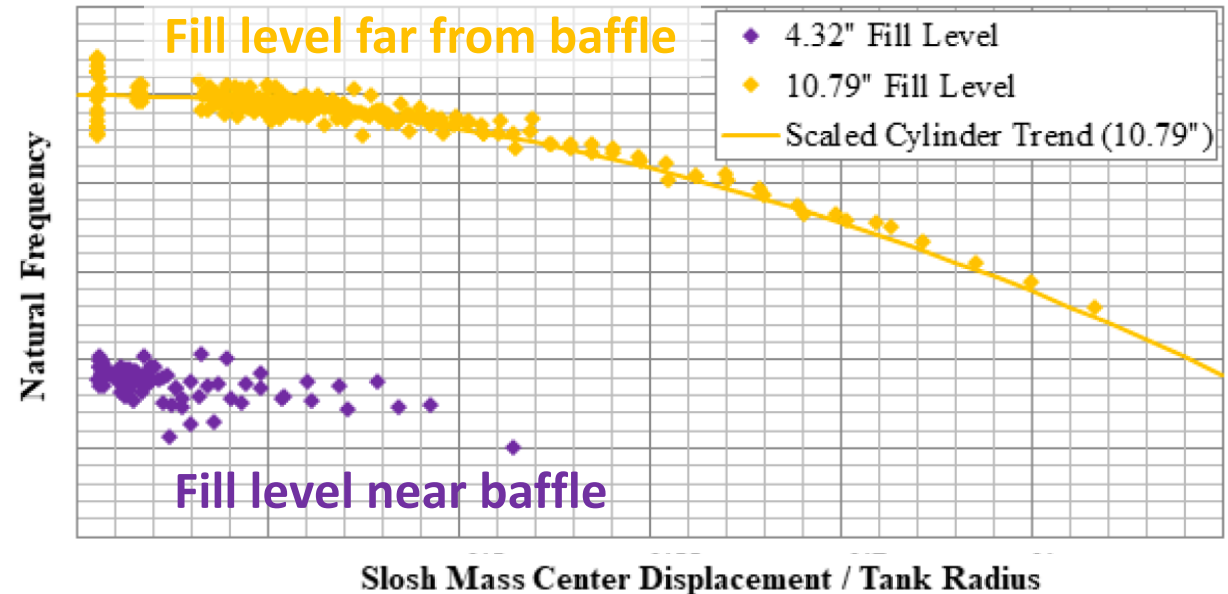
Linear variable differential transformer (LVDT)  
⇒ Tank position



## Sample Findings

**Slosh frequency and slosh mass decrease with increased wave amplitude.**

- Slosh frequency decreased in excess of 5% for large slosh wave amplitudes (i.e., wave amplitudes reaching about 25% of the tank radius).
- Frequency variation can cause the slosh wave to limit cycle as force amplitude increases in support of high-amplitude free-decay testing.



Apply the forcing function at a lower frequency (e.g., 95% of the natural frequency) when attempting to excite high-amplitude sloshing motion.

Consider incorporating amplitude-dependent frequency and mass variations or additional asymmetric uncertainty into the slosh model if the launch vehicle propellant tanks are expected to experience large wave amplitudes.



# Sample Test Matrix

## Smooth-wall Tank

Matrix for Test and CFD Analysis

| % Fill (approx.) | Liquid Level (in.) | No. of ICs | Target Slosh Height (peak-to-peak) for Free Decay (in.) | CFD ? |
|------------------|--------------------|------------|---------------------------------------------------------|-------|
| 95               | 40.2               | 7          | 1, 2, 4, 6                                              |       |
| 90               | 38.2               | 14         | 1, 2, 4, 6, 10                                          | X     |
| 85               | 36.2               | 10         | 2, 4, 8, 12, 16                                         |       |
| 80               | 34.2               | 8          | 1, 3, 6, 9                                              | X     |
| 75               | 32.2               | 12         | 2, 4, 8, 12, 16, 20                                     |       |
| 70               | 30.2               | 8          | 4, 8, 12, 16                                            | X     |
| 65               | 28.2               | 10         | 2, 4, 8, 12, 16                                         |       |
| 60               | 26.2               | 12         | 1, 2, 4, 8, 12, 16                                      | X     |
| 55               | 24.2               | 14         | 2, 4, 8, 12, 16, 20, 24                                 |       |
| 50               | 21.1               | 18         | 2, 10, 16, 18, 20, 24                                   | X     |
| 45               | 18                 | 12         | 2, 4, 8, 12, 16, 20                                     | X     |
| 40               | 16                 | 12         | 2, 4, 8, 12, 16, 20                                     |       |
| 30               | 12                 | 12         | 2, 4, 8, 12, 16, 20                                     |       |
| 20               | 8                  | 12         | 2, 4, 8, 12, 16, 20                                     |       |
| 10               | 4                  | 10         | 1, 4, 8, 12, 16                                         | X     |

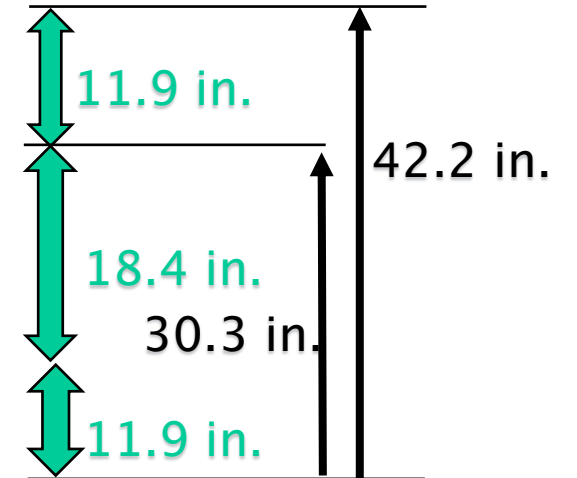
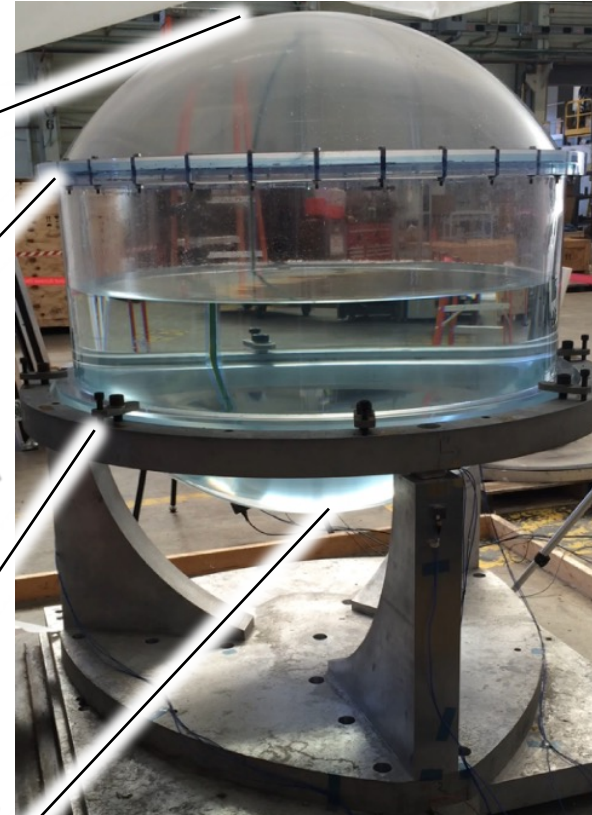
15 Fill Levels

171 Free Decay Runs

Upper dome

Barrel section

Lower dome



Tank Dimensions:  
Height: 42.2 in.  
Diameter: 43.1 in.

### Free decay tests performed at multiple initial wave amplitudes

- Linear (small wave amplitude) region:
  - Forcing function applied at  $\omega_n$
  - Results should be consistent with SP-106
- Nonlinear region: forcing function applied at  $\sim 0.95 * \omega_n$ 
  - Primary objective: quantify damping at higher amplitudes

### Repeated free decay tests at same initial wave amplitude

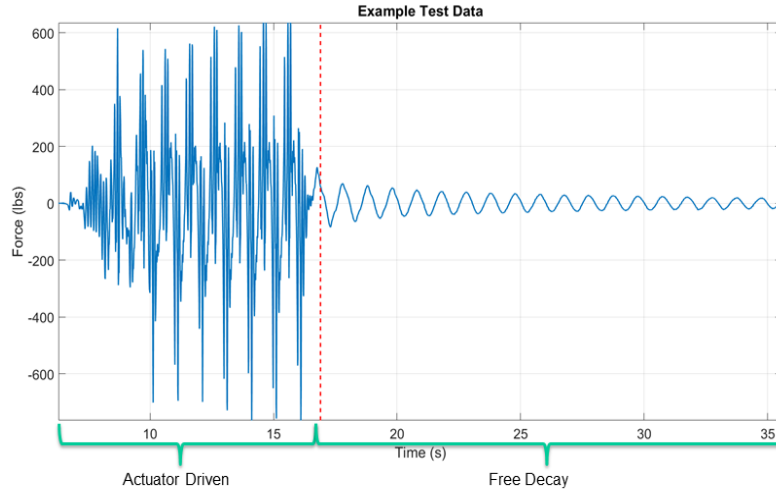
- Understand repeatability; decrease statistical uncertainty



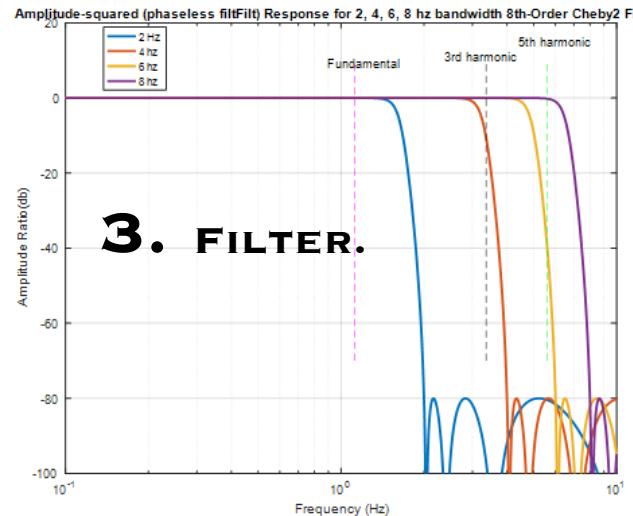
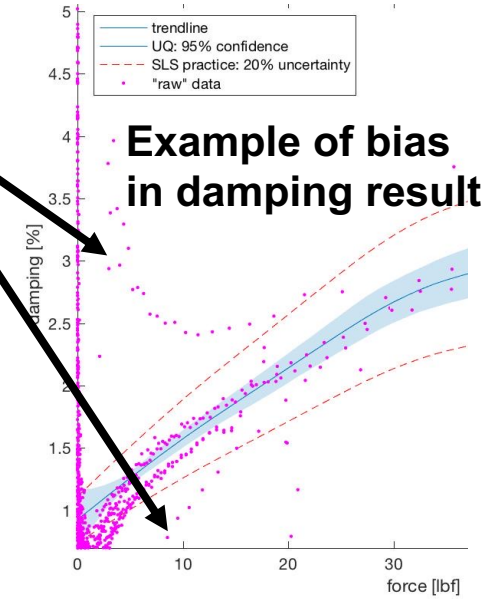
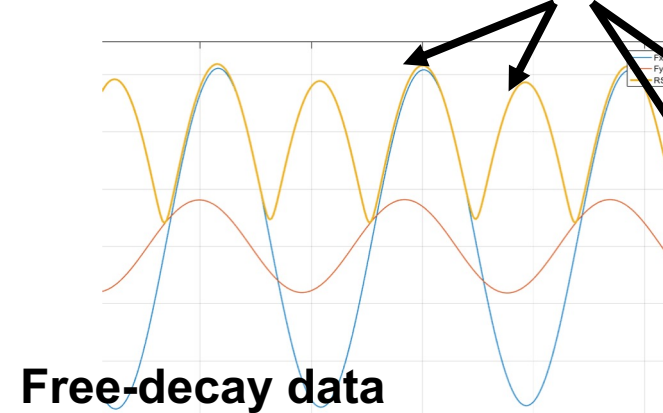
# Analysis of Raw Free-decay Data

**Key Contributors:**  
Brandon Marsell (KSC LSP)  
Mike Ruth (Northrop Grumman)

## 1. REMOVE FORCED RESPONSE FROM RAW TEST DATA.



## 2. REMOVE BIAS.

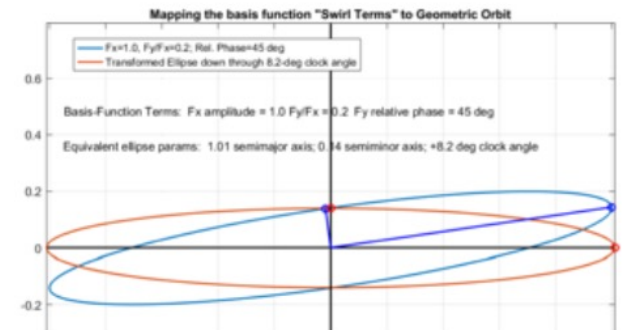


## 4. CALCULATE DAMPING VS. FORCE USING APPROACH (I) AND/OR (II)\*

(I) ROOT SUM SQUARE (RSS), THEN LOG DECREMENT OF EVERY PEAK

$$\zeta = \frac{1}{\pi} \ln \left( \frac{\text{peak amplitude of oscillation}}{\text{peak amplitude of oscillation one half cycle later}} \right)$$

(II) BASIS FUNCTION METHOD – OPTIMIZES PARAMETER SELECTION FOR BEST-FIT ACROSS SPECIFIED WINDOW

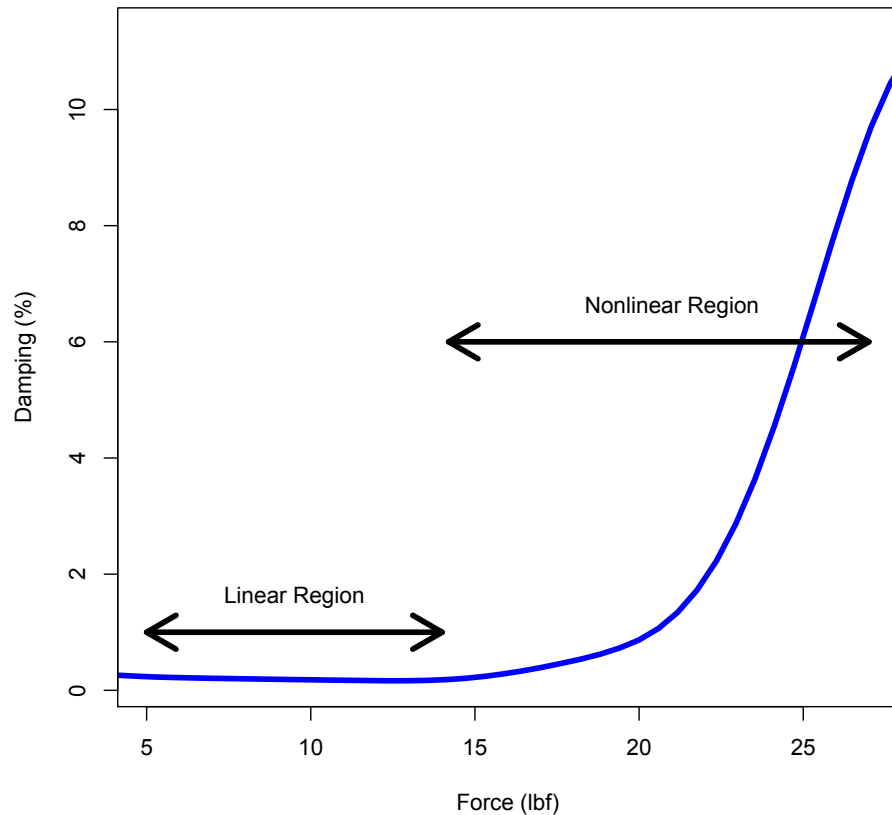


\*Basis function method favored when significant rotational motion exists.



# GP Models

**IDEALIZED DAMPING CURVE**



Bayesian implementation of GP model is flexible in nature and can model a variety of shapes

- GP features
  - No discontinuities (infinitely differentiable)
  - No parametric form assumed as with a curve fit (flexible)
- Bayesian approach
  - Relies on a pre-established (“prior”) set of smooth functions
  - Capable of combining experimental and computational models (not leveraged for this delivery)
  - Allows for accommodation of full set of uncertainties from multiples sources (not leveraged)

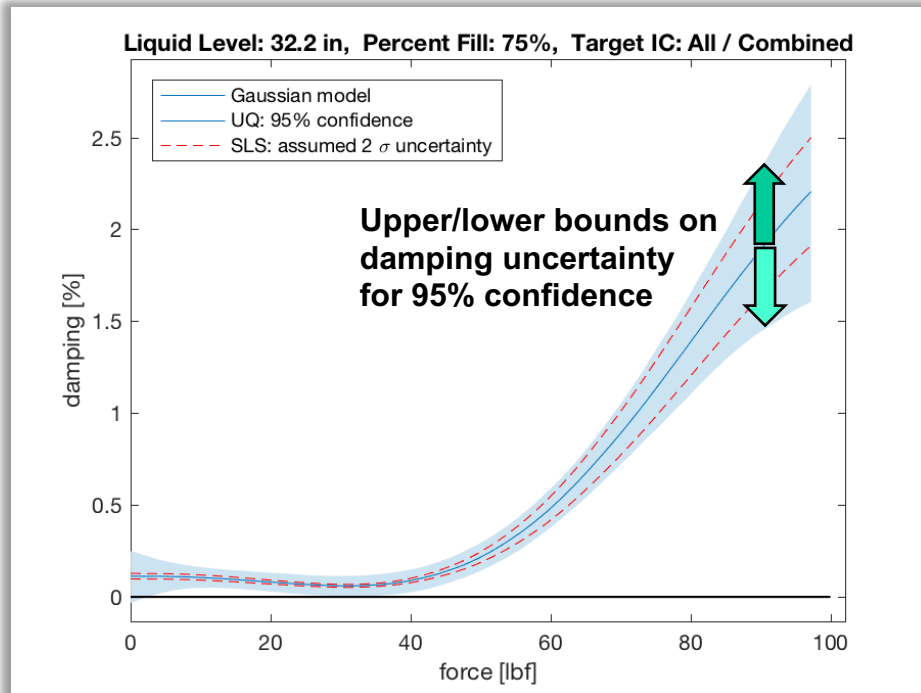
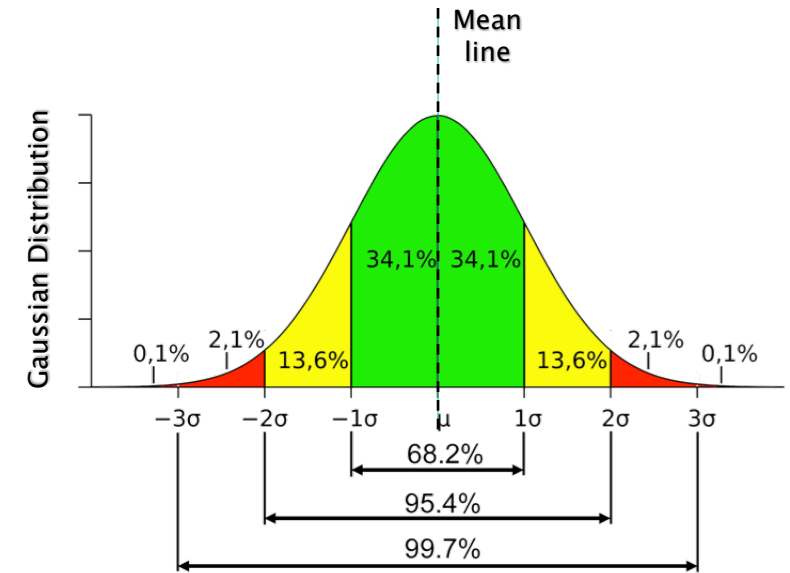
**Key Contributor:**  
Shane Reese (BYU)



# Uncertainty Quantification (UQ)

## UQ definition

- UQ results delivered quantify the run-to-run uncertainty in the mean line (i.e., do we have the correct mean line based on the available data?)
- UQ results are provided for a 95% confidence interval



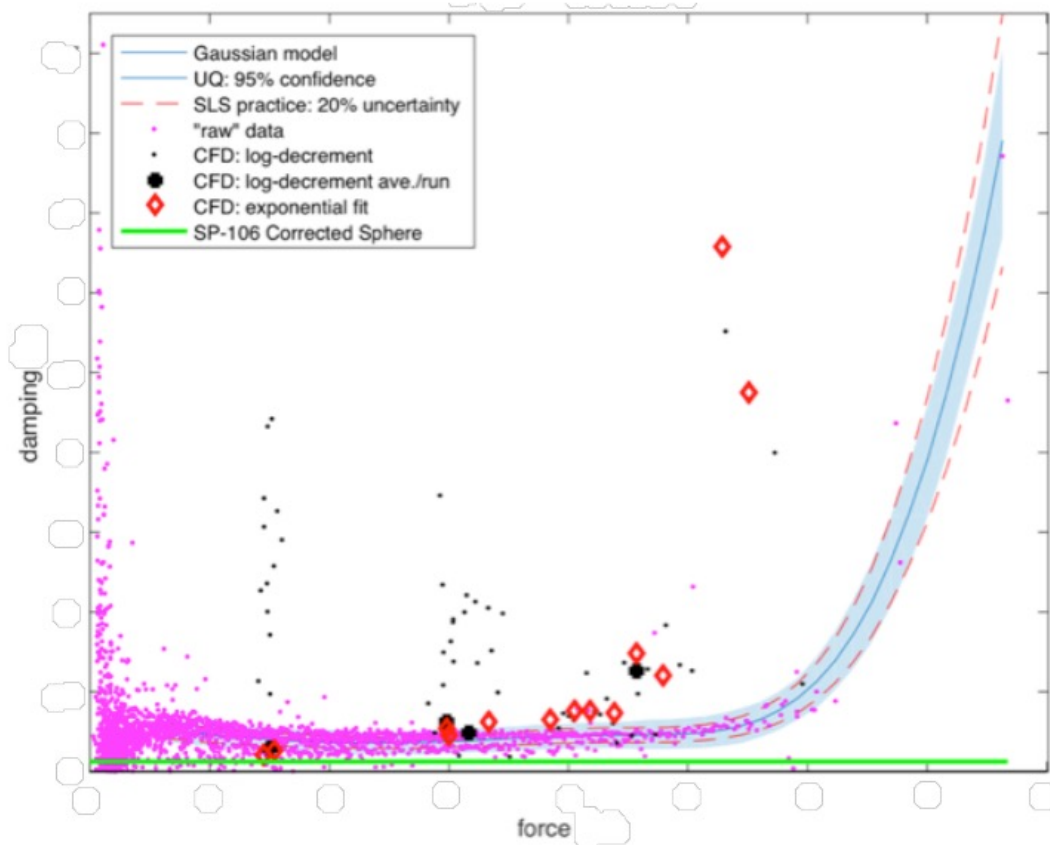
### Key Contributors:

- Shane Reese (BYU)
- Jeff Brouwer (SLS Stages)

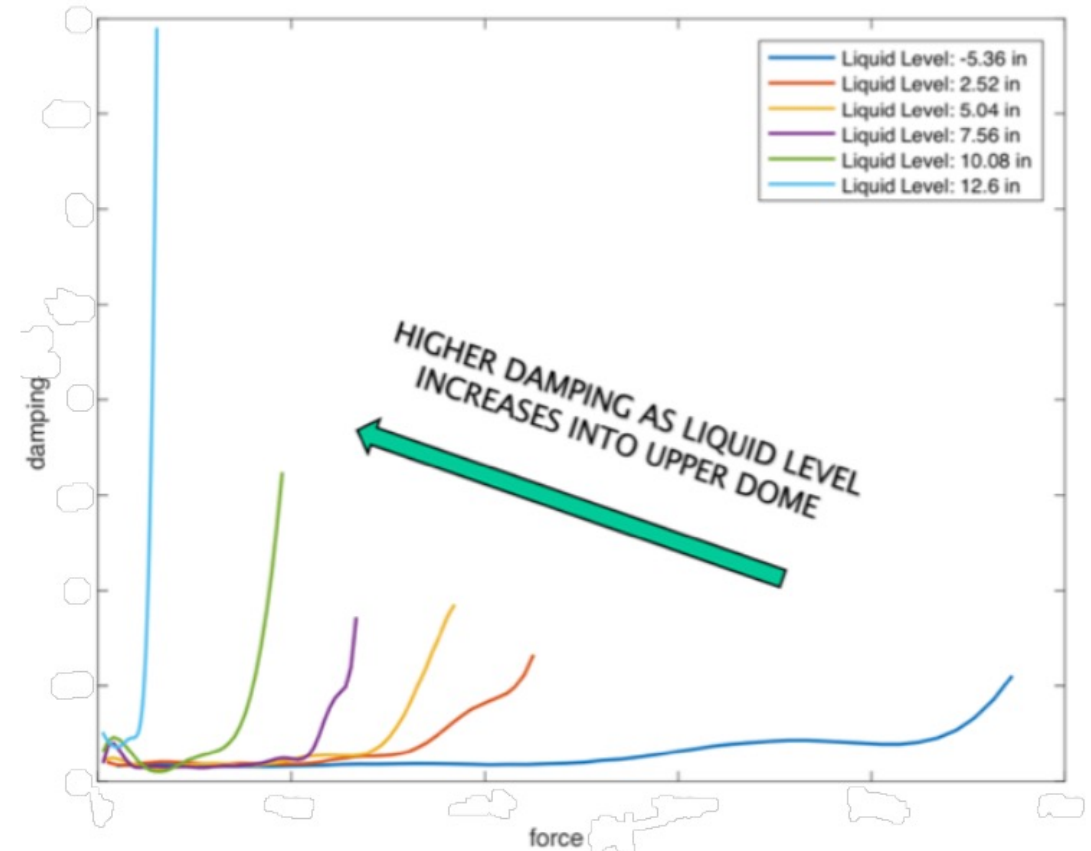
## UQ results contain a subset of slosh uncertainties

- Does not capture systematic errors in the test setup, sensors, or data processing
- Does not capture uncertainties introduced by extrapolating the test results to a flight scenario (i.e., scaling/similarity, fluid properties, multi-axis sloshing, mechanical model simplifying assumptions, etc.)
- Bayesian implementation of GP models supports inclusion of full set of slosh uncertainties (could be incorporated in the future)

# Sample Results



**Example Nonlinear Damping Data Set  
(single liquid fill level)**



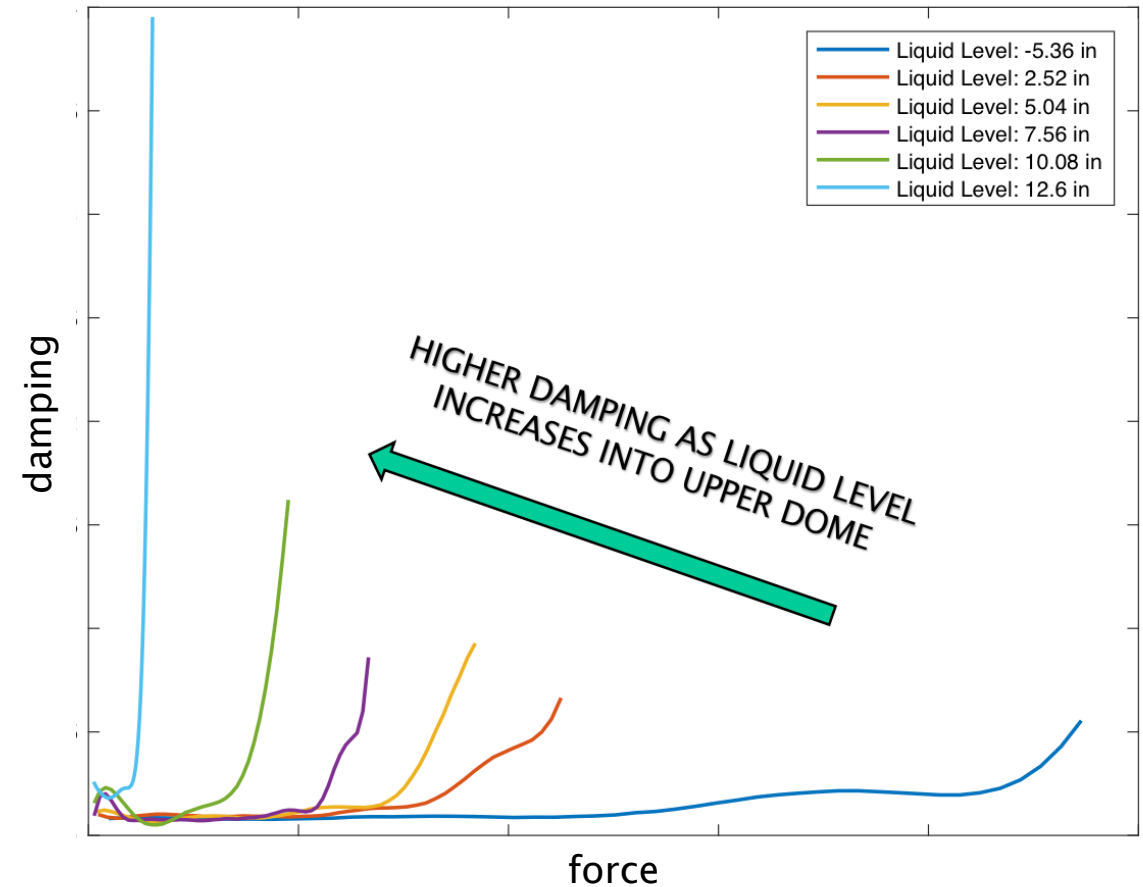
**Nonlinear Damping Model Trends  
(Mean Lines from Multiple Fill Levels)**



## Sample Findings

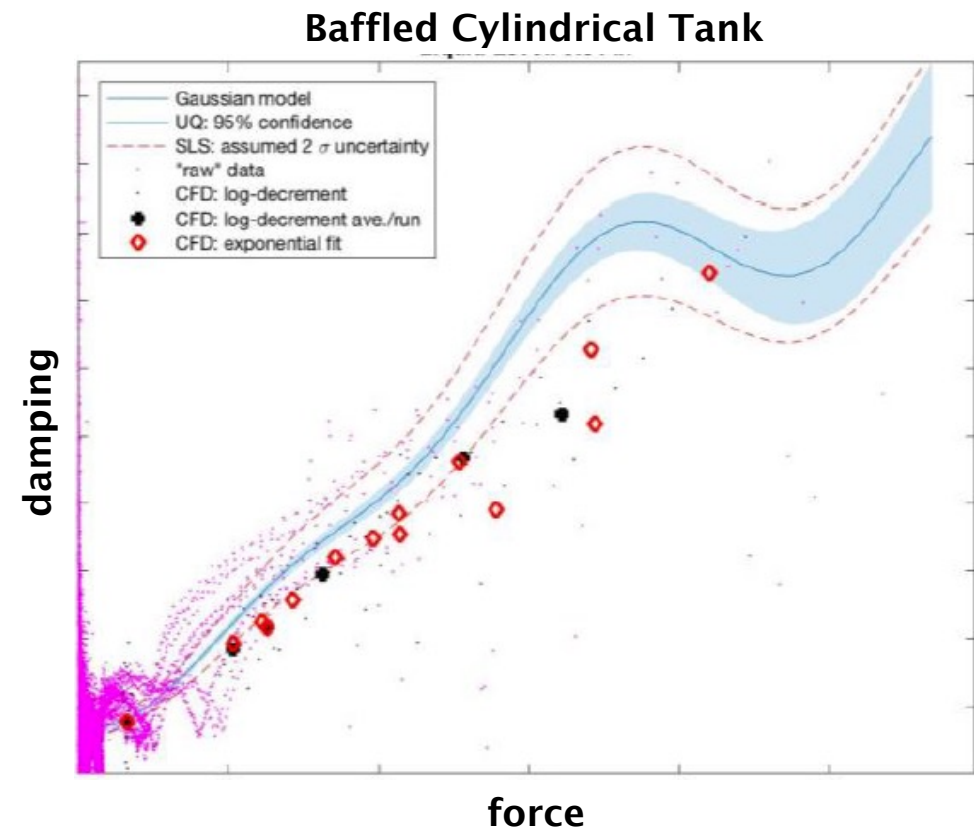
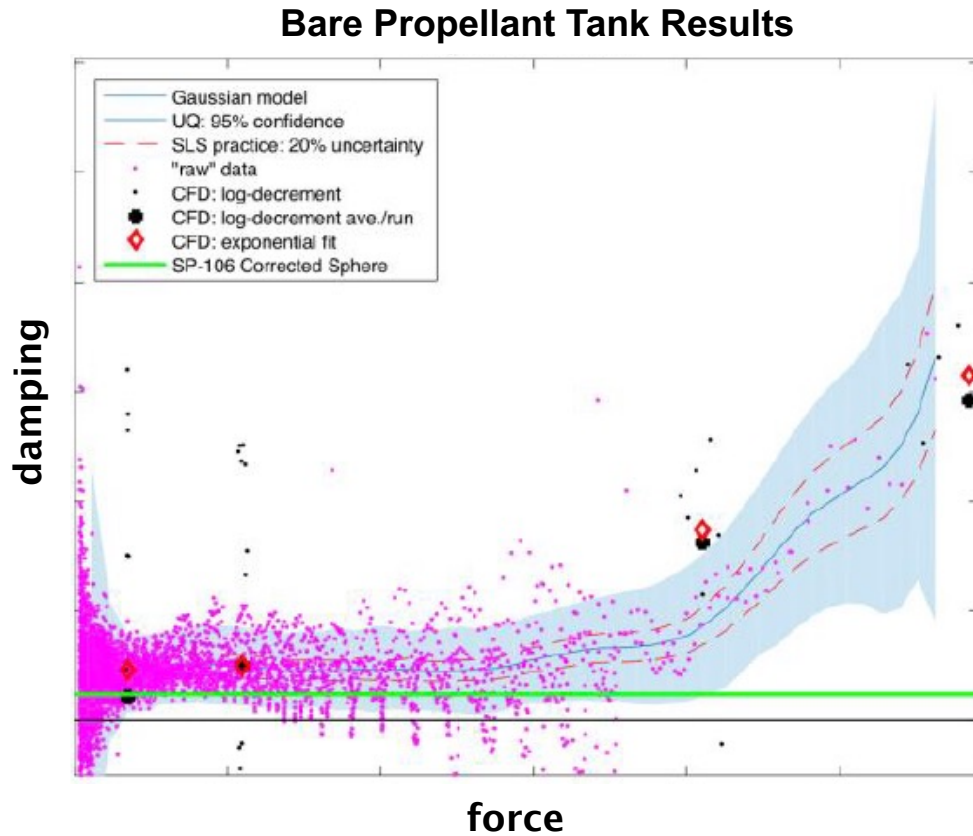
- Transition to the nonlinear damping regime in the subscale bare-wall tank upper dome occurs at decreasing force (wave) amplitudes for increasing fill levels.
- Nonlinear damping models for bare subscale tanks exhibit the most substantial increases in damping in the upper dome and near discontinuities in the tank curvature (i.e., when the slosh wave interacts with the dome/barrel interface).

### Bare Propellant Tank Results



# Sample Findings

## Slosh Rotation during Testing



Modulations in the magnitude of the lateral damping were correlated with slosh rotation.

For slosh testing intended to capture lateral damping, use tanks fabricated with minimal ovality to mitigate data analysis complexity and uncertainty introduced by fluid rotation.



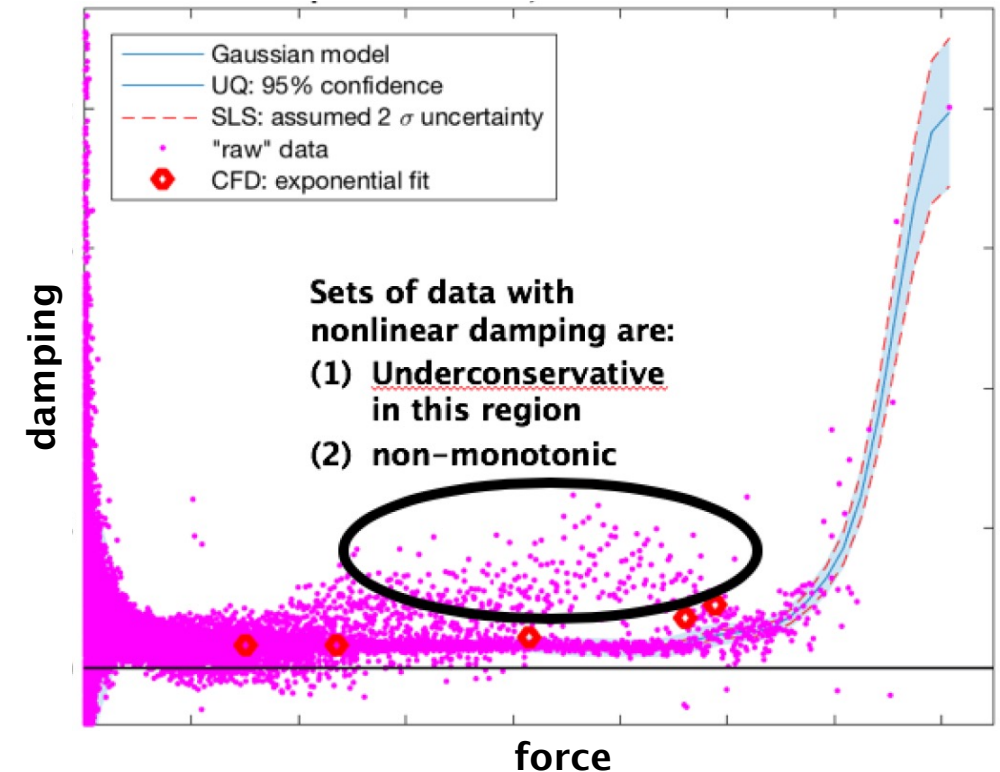
# Sample Observations

## GP Model and UQ

Multiple “families” of damping data were present in the subscale EUS LOx tank, driven by varying initial conditions. Consequently:

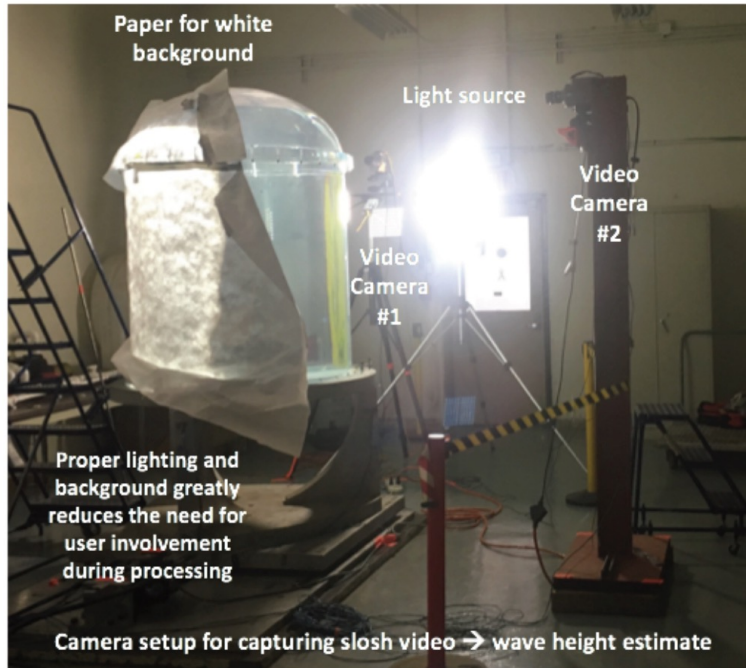
- The lower damping (i.e., conservative) family was employed in these scenarios for defining best-fit curves and reporting results.
- All other tank configurations implemented preprogrammed initial conditions to decrease run-to-run variability.

### Example of Multiple “families” of data

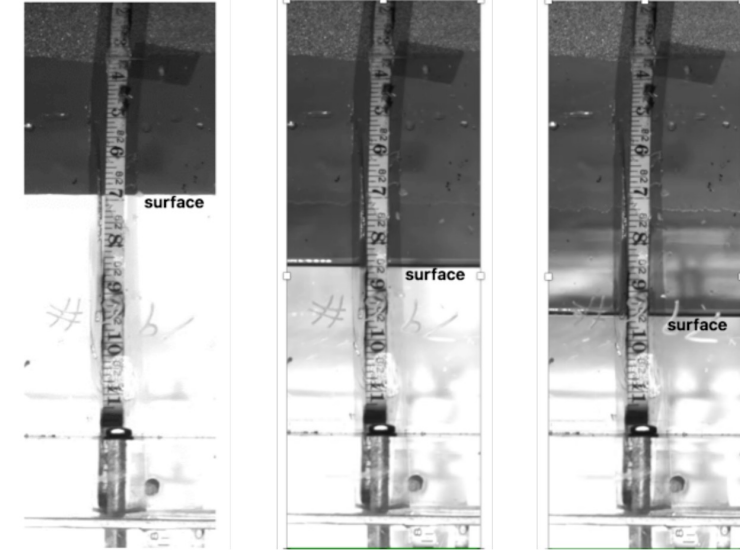
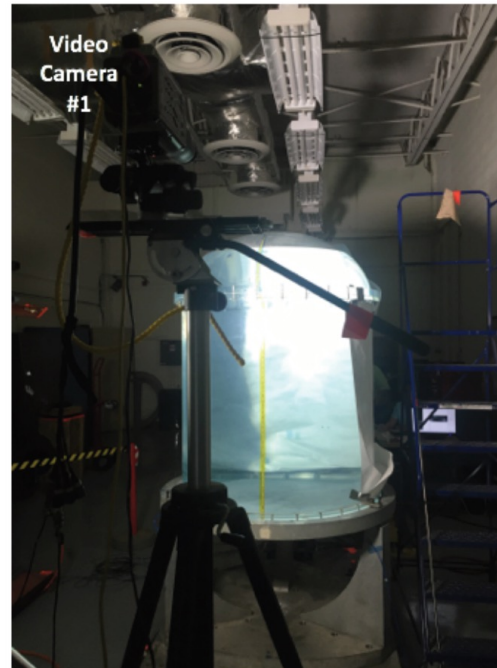




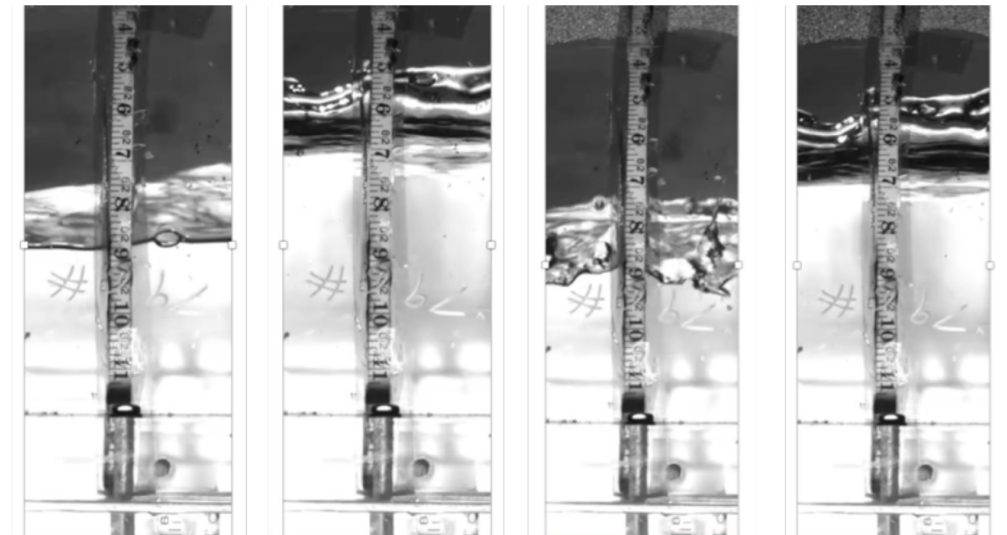
# Video Data Collected to Supplement Force Measurements



Video Camera Setup for Slosh Testing

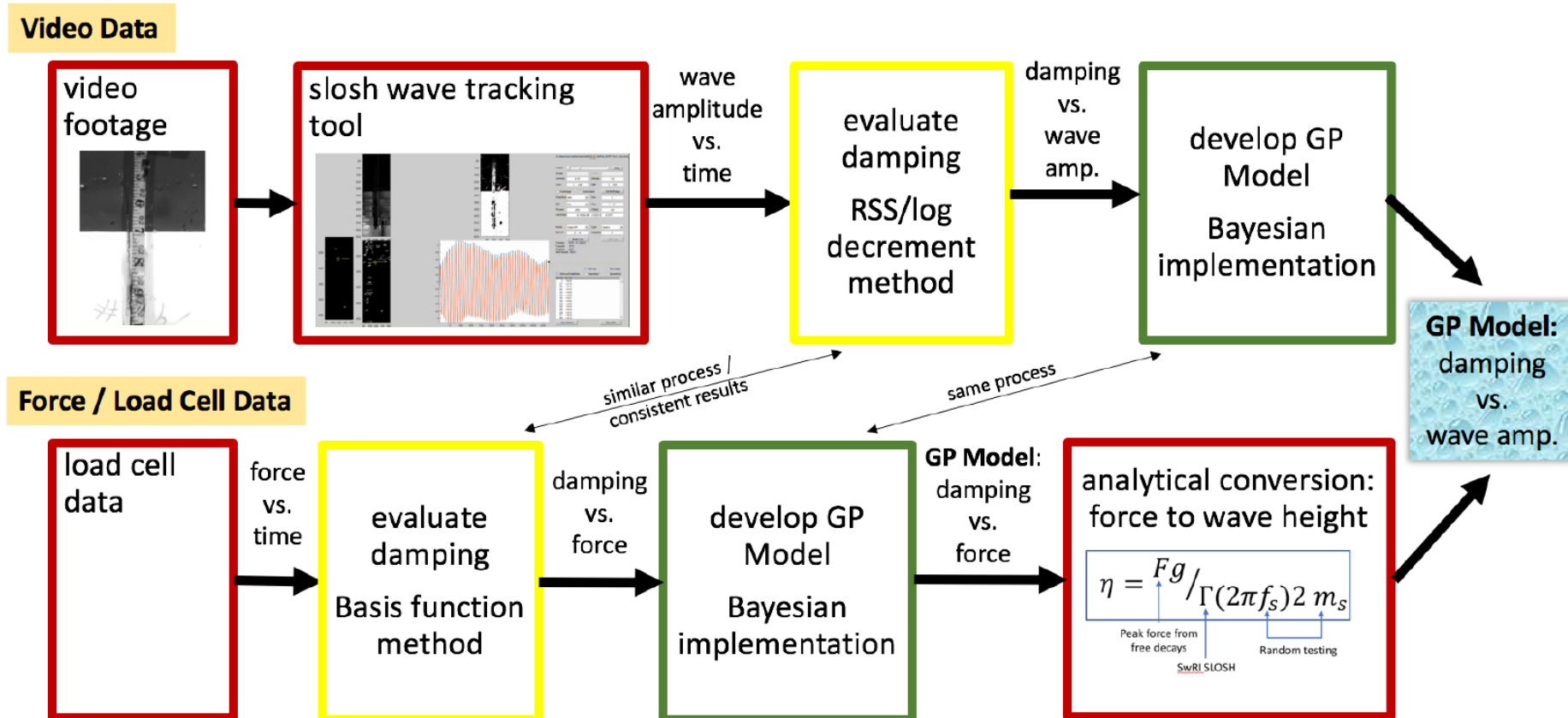


Still frames from video recordings of low (above) and high (below) amplitude waves



# Comparison of Processes for Analyzing Video and Load Cell Data

- Two methods used to estimate the wave amplitude from the indicated test data:
  1. Estimation from video data
  2. Analytical conversion of force measurements to wave amplitude
- GP Models of slosh damping determined using the same process to compare results

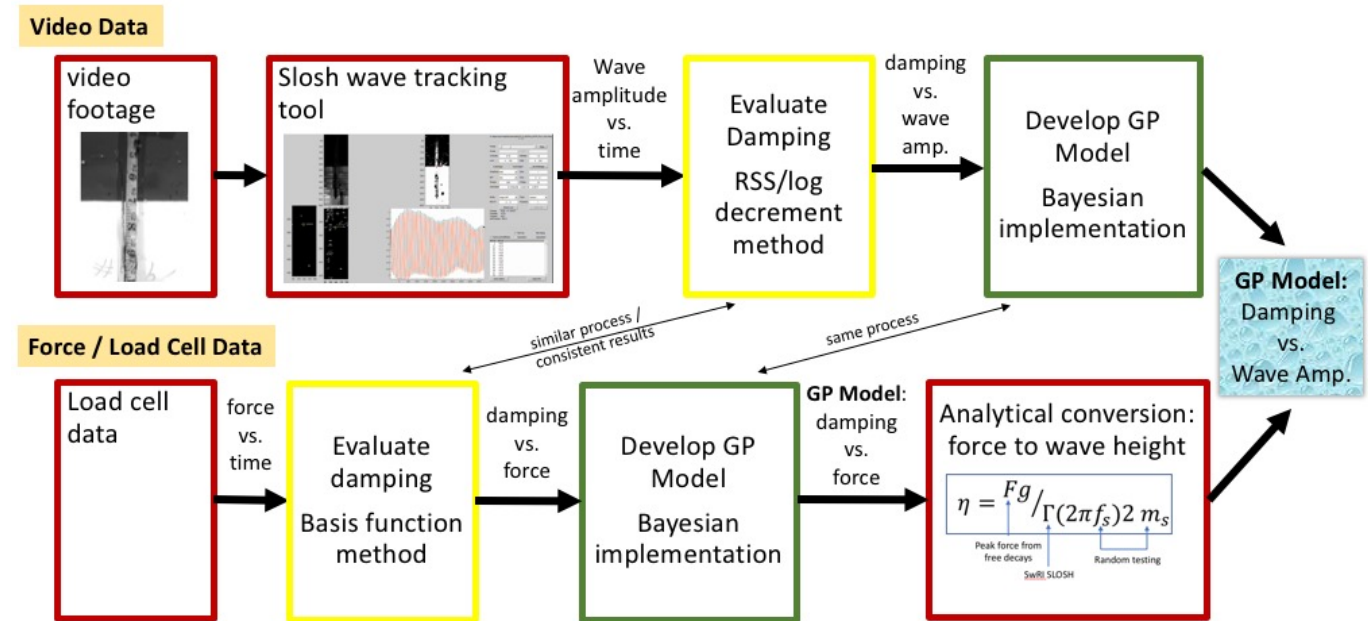


# Sample Findings

## Wave Amplitude as an Independent Variable

Analytical conversion of force to wave amplitude has shortcomings for nonlinear sloshing waves, including:

- It is based on linear theory.
- It requires slosh mass and slosh frequency estimates.
- It requires an estimate for a geometry-specific conversion factor.



# Sample Findings

## Wave Amplitude as an Independent Variable

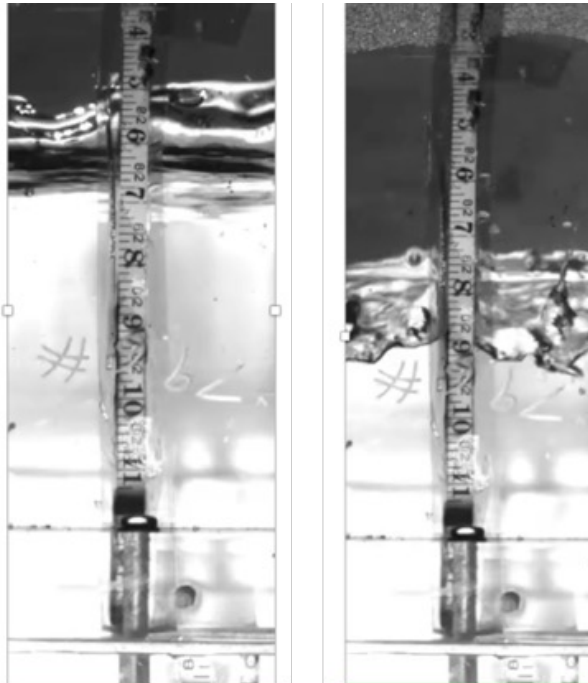
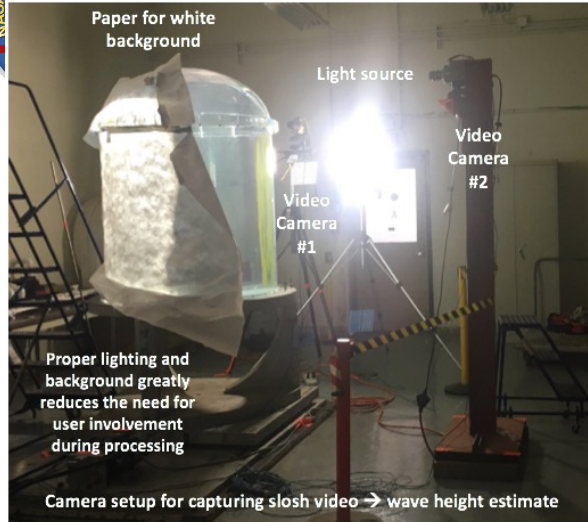
Estimation of wave amplitude from video data captured during this assessment has shortcomings, including when:

- The free surface shape is not a straight line or well defined (e.g., when multiple prevalent liquid modes are present, the dynamics are chaotic due to highly nonlinear wave amplitudes, or there is wave interaction with a baffle).
- The fluid film adheres to the tank interior surface.
- The wave amplitude is obscured due to lighting artifacts.
- The slosh wave is rotating.

Video-derived damping models had lower uncertainty than their force-derived counterparts when fluid motion was simple, and higher uncertainty as the fluid behavior exhibited more nonlinearities and complex surface shapes:

- Other independent variables may exist, but it would take an effort similar in scope to this assessment to determine whether it is a more suitable alternative for the development of slosh damping models.

Consider using force as the independent variable for the nonlinear slosh damping model implementation in place of wave amplitude



Video footage (still frames)



# Conclusion

- Simplified mechanical models of propellant slosh are typically incorporated into launch vehicle dynamics model
  - Higher fidelity slosh damping models may allow for reduce conservatism in flight control design
  - Benefits of incorporating nonlinear slosh into flight control design tools may include reduced need for baffles (reduced mass), improved flight control robustness and performance, etc.
- Process for determining lateral propellant slosh damping as a function of force (wave amplitude) discussed, included
  - Tank configurations included in study
  - CFD analysis process
  - Test setup, instrumentation & approach for conducting tests
  - Analysis process for determination of slosh damping from free decay data
  - Development of Gaussian Process models and uncertainty quantification
  - Video data collection and analysis
- Determination of slosh damping models based on testing, CFD, and statistical analysis was challenging
  - Sample findings from nonlinear slosh damping testing and analysis were discussed as they may be useful for future slosh damping testing and/or model implementation
- Nonlinear slosh damping models developed under NESC assessment through CFD analysis and testing were used by the SLS Program for multiple propellant tanks



# Broad Perspective from NESC Technical Bulletins

National Aeronautics and Space Administration

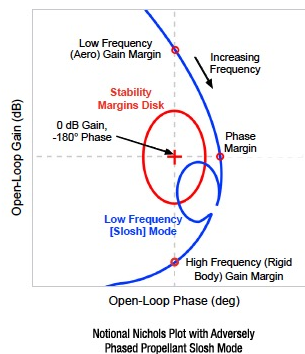
NASA Engineering and Safety Center Technical Bulletin No. 22-05

## Launch Vehicle Flight Control Stability Margin Reduction Considerations

Launch vehicle ascent stability analyses typically rely on a combination of frequency and time domain analyses. Frequency domain analysis uses a sequence of high-fidelity linear models with constant parameters spanning the ascent trajectory. Complementary time domain analysis is performed using high-fidelity, nonlinear 6-DOF simulations. Analyses are typically dispersed to verify robustness to parameter variations by showing the vehicle meets frequency domain stability margin requirements and time domain performance metrics. This Technical Bulletin outlines standard stability margin best practices and provides recommendations for treatment of deviations from industry-standard launch vehicle stability margins due to vehicle flexibility, slosh dynamics, aerodynamics, other offending dynamics, or coupling thereof.

### Stability Margin Best Practices

Current best practices for launch vehicle flight control design target 6 dB/30 degrees undispersed rigid body gain/phase margins and 12 dB amplitude margin for gain-stabilized flexible body modes. Well-characterized fundamental (low-frequency) flexible body modes can potentially be phase-stabilized to maintain 45 degrees of undispersed phase margins. Best practices for dispersed analysis ensure 3 dB/20 degrees on the rigid body gain/phase margin, 6 dB amplitude margin for gain-stabilized flexible body modes, and 30 degrees for phase-stabilized flexible body modes. All relevant dynamics, including engine inertial coupling, bending, and slosh dynamics, are included in the linear plant model and should respect the same stability margin requirements. Due to the nonlinear and uncertain characteristics of propellant slosh modes in the absence of passive damping devices (e.g., ring baffles), analysis beyond that of the standard frequency and time domain analyses may be needed to address the effects of sloshing propellant for bare-walled tanks. Any other vehicle dynamics exhibiting significant nonlinearities or complex coupling, or where the available model representation is of low fidelity and/or not anchored to test data, may similarly necessitate an extended treatment.



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National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 22-06

## Treatment of Slosh Stability Margin Reductions for Human-Rated Launch Vehicles

Slosh dynamics pose a stability concern for human-rated launch vehicles during ascent. Historical perspectives on the treatment of slosh dynamics, newly developed rules of thumb, the utility of flight data, and methods for analyzing and dispositioning slosh instability risks should be considered when linear stability margins are lower than typically accepted for human-rated systems.

### Historical Perspective on Slosh Treatment for Human Space Flight (Ascent)

No conclusive example has been found in Space Shuttle or Saturn Program crewed flight history in which transient negative linear slosh stability margins were permitted. The uncrewed Saturn 1 S-IV had low-to-negative slosh margins, but tank baffles and a slosh deflector were added to gain-stabilize slosh prior to human-rating the S-IVB vehicle. Precedent exists in Saturn and Shuttle to rely on time domain performance metrics to accept reduced slosh margins. Time domain simulations included external forcing functions to quantify impacts (e.g., gimbal oscillations, attitude error, crew acceleration) associated with worst-case slosh excitation due to disturbances (e.g., staging and guidance command transients).

### Slosh Fundamentals

Each slosh mode can be accurately modeled as a linear mass-spring-damper or spherical pendulum with two degrees of freedom. The mechanical model parameters are scheduled as a function of flight condition (e.g., propellant liquid level, acceleration) based on test-correlated analytical and empirical relationships. This mechanical analog provides insight into the basic nature of slosh response. Analysis of fundamental physics involved in sloshing propellants can demonstrate the nature of the slosh response and serve as a foundation for understanding and verifying responses from more complex vehicle simulations. A rule of thumb known as the slosh "danger zone" was established in the Saturn era for a single tank. This zone predicts poor phasing of slosh dynamics will occur when the slosh mode location falls below the center of percussion and above a location near the vehicle center of gravity (CG). An advanced analytical technique was recently developed to determine the propensity for unfavorable phasing with dual-tank sloshing modes that would be undetected by the single-tank danger zone criteria. Slosh interactions with flexible structural dynamics can also impact vehicle stability. Analysts should verify consistency between rules of thumb, linear analyses, nonlinear analyses, and flight data.

### Utility of Flight Data for Slosh Stability Model Validation

Flight data is typically inconclusive regarding slosh stability margins as it may not provide sufficient information to anchor slosh model predictions or validate stability margins. Even when slosh is predicted to be unstable in the frequency domain, slosh instability detection from flight data is elusive due to inadequate excitation and small growth rates. Thus, the lack of observable ascent slosh response is not a demonstration of vehicle stability robustness. Without targeted excitation, sufficient sensing, and dwell time, specific vehicle model response validation (e.g., aero, rigid body, slosh, or flex) is not possible. In-flight response of lightly damped flexible/slosh modes can provide frequency confirmation if sufficient excitation exists, but long dwell

times may be needed to identify slosh gain and phase margins. In contrast to slosh, bending-mode models can typically be verified to higher accuracies because the signatures in flight data tend to be cleaner. In summary, flight experience raises confidence but cannot validate slosh modes or determine stability margins without targeted provisions (e.g., programmed test inputs).

### Methods for Treatment of Low or Negative Slosh Stability Margins

Vehicle stability margins should be reported with the inclusion of all relevant dynamics (i.e., rigid body, slosh, flexible body, and aerodynamics). If slosh stability margins are below industry standards, routine analysis should be augmented by an evaluation of sensitivities and consequences. Targeted sensitivity studies conducted in the frequency and time domains should be designed to analyze the effects of parameter and system variations. In the frequency domain, this can include dispersing the relative slosh frequency in multiple tank scenarios, investigating the effects of flexible body/slosh coupling, evaluating mitigations afforded by nonlinear damping, and computing the time to double. In the time domain, this can include application of a doublet and direct slosh state initialization during stressing flight conditions or periods of instabilities for nominal and worst-case dispersed vehicle parameters. When slosh margin instabilities are present, slosh amplitude doubling times can be compared against the duration of the instability. The purpose is to evaluate opportunities for instability to occur in flight and analyze the relevant indicators (e.g., growth rate/decay, actuator usage, slosh wave

amplitude, crew acceleration, abort margins). Stressing cases of concern can then be evaluated for credibility, probability, and consequences from the perspective of overall vehicle risk. Early in a development program, and for pre-flight certification, it is good practice to automate stressing simulations and incorporate them into the standard analyses to increase design confidence and coverage for effects not otherwise captured even when the linear margins indicate stability.

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Evaluation of mitigations afforded by nonlinear slosh is one of several possible methods for managing low linear slosh stability margins



**Backup**



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