Investigating the Impact of Non-Dimensional Fluid Properties on Violent Sloshing

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Industrial CFD Research Group
University of Cape Town

- University of Cape Town
  - South Africa's oldest university
  - Formally established as a university in 1918
  - Africa's leading research institutions
- Industrial CFD Research Group
  - Based at Dept. of Mechanical Engineering at the University of Cape Town.
  - 15 full time staff and students
  - Development of Industrial Strength Elemental CFD Software
  - South African Research Chair in Industrial CFD
  - Long standing relationship with Airbus

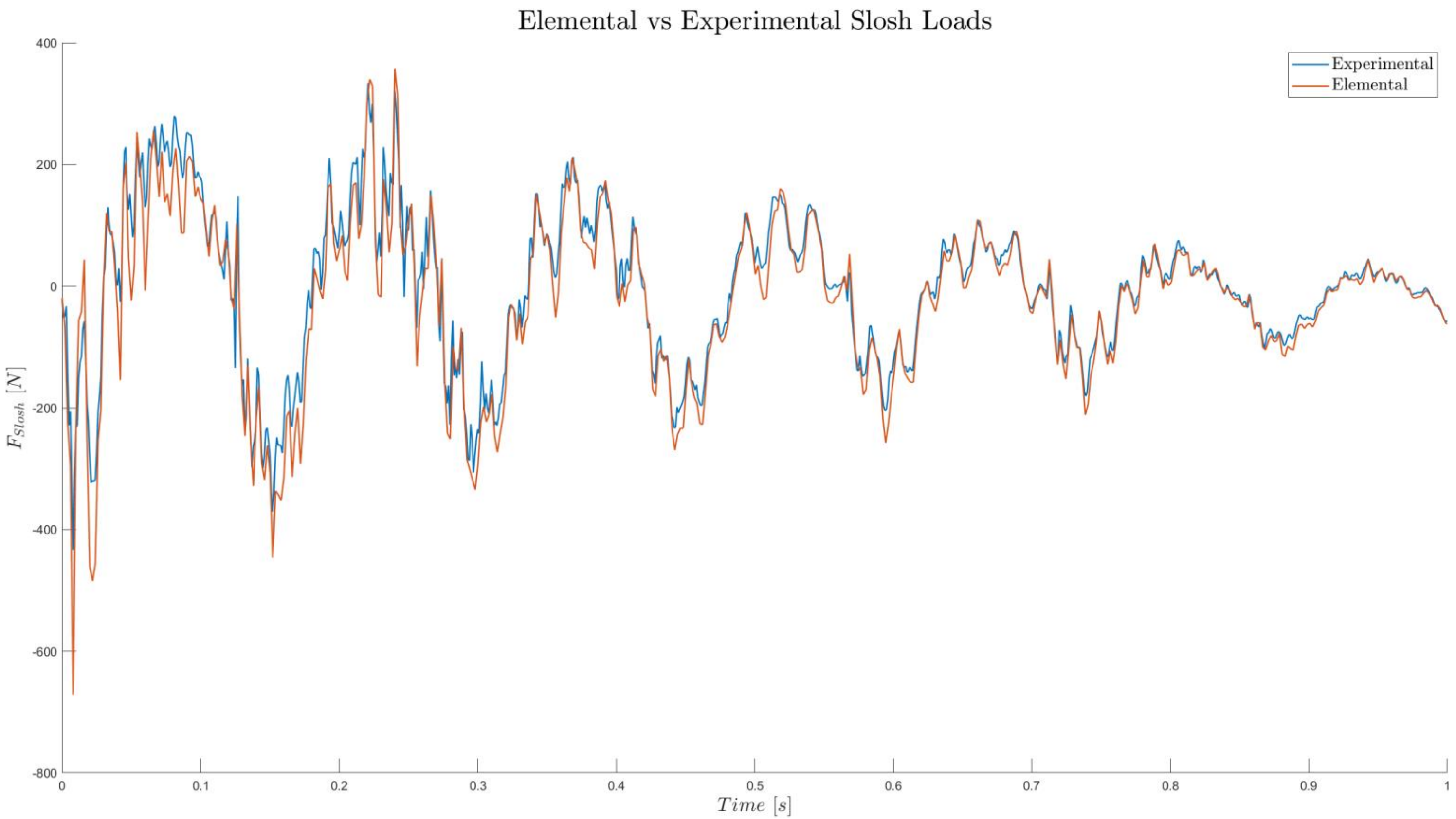
Overview

1. Introduction
2. Non-dimensional Analysis for Vertical FSI Induced Slosh
3. Sloshing Energy Budget
4. Selection of Non-Dimensional Properties of interest
5. Sensitivity Study for Selected Non-Dimensional Properties
6. Conclusions

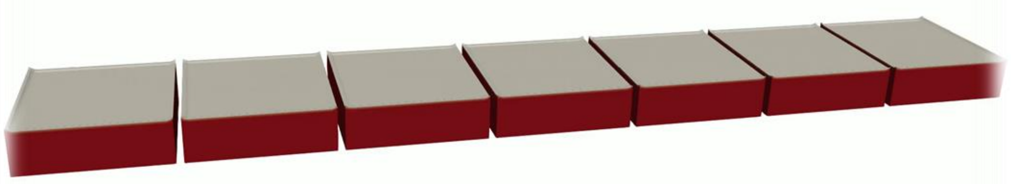
Introduction

- Evaluation of Violent Slosh due to vertical excitation and study of slosh damping
- Scale Prototype models utilized to provide insight into large scale systems
  - Current standard practice is to employ Froude scaling.
  - Froude Scaling has weaknesses in describing this type of physics.
- Towards Non-Dimensionalisation
  - A proposed method for the non-dimensional study of an FSI System Fluid Damping
    - Isolation of fluid specific properties
  - Investigate several non-dimensional groups and investigate their impact
- Utilize high fidelity CFD in order to perform sensitivity study of selected non-dimensional groups
  - Enables unrealistic scaling impossible in the real world
  - Utilizing *Elemental*® VoF code
  - Validated against Protospace Experiment

SLOWD Protospace Simulation



2D Protospace Simulation	
Structured Vertex Centred Finite Volume Mesh	
Element Count	94500
$\Delta x \approx \Delta y$	$0.67mm$
CPU Count	18
Wall Time	$3 - 2{:}30{:}00$
$\|\epsilon_{Force}\|_2$	1.22%



Employing *Elemental*® VoF CFD

- 2nd Order accurate temporal integration
- 2nd Order surface tension model
- Weakly incompressible gas formulation

Non-Dimensional Analysis

- Given the additional dimensionless geometric quantities, contact angle, damp definition
  - $\tilde{A} = \frac{l}{h}$ Tank aspect ratio
  - $\tilde{F} = \frac{\eta_0}{l}$ Liquid fill ratio
  - $\tilde{Y}_0 = \frac{y_0}{h}$ Initial deflection of the system
  - θ Fluid Contact Angle
  - $\xi = \xi_d + \Delta\xi_s$ Total damping is sum of structural and fluid damping
- The fluid damping can be expressed as:

$$\Delta\xi_s = f(\overbrace{\bar{\rho}, Re, Fr, Bo, \theta,}^{\text{Sloshing Flow}} \quad \overbrace{\bar{m}, \bar{\omega}, \xi_d,}^{\text{FSI}} \quad \overbrace{\tilde{A}, \tilde{F}, \tilde{Y}_0}^{\text{Geometric}})$$

- Testing of Sloshing Flow and Frequency ratio ($\bar{\omega}$)
  - Impossible to isolate and test properties individually through real-world experiments

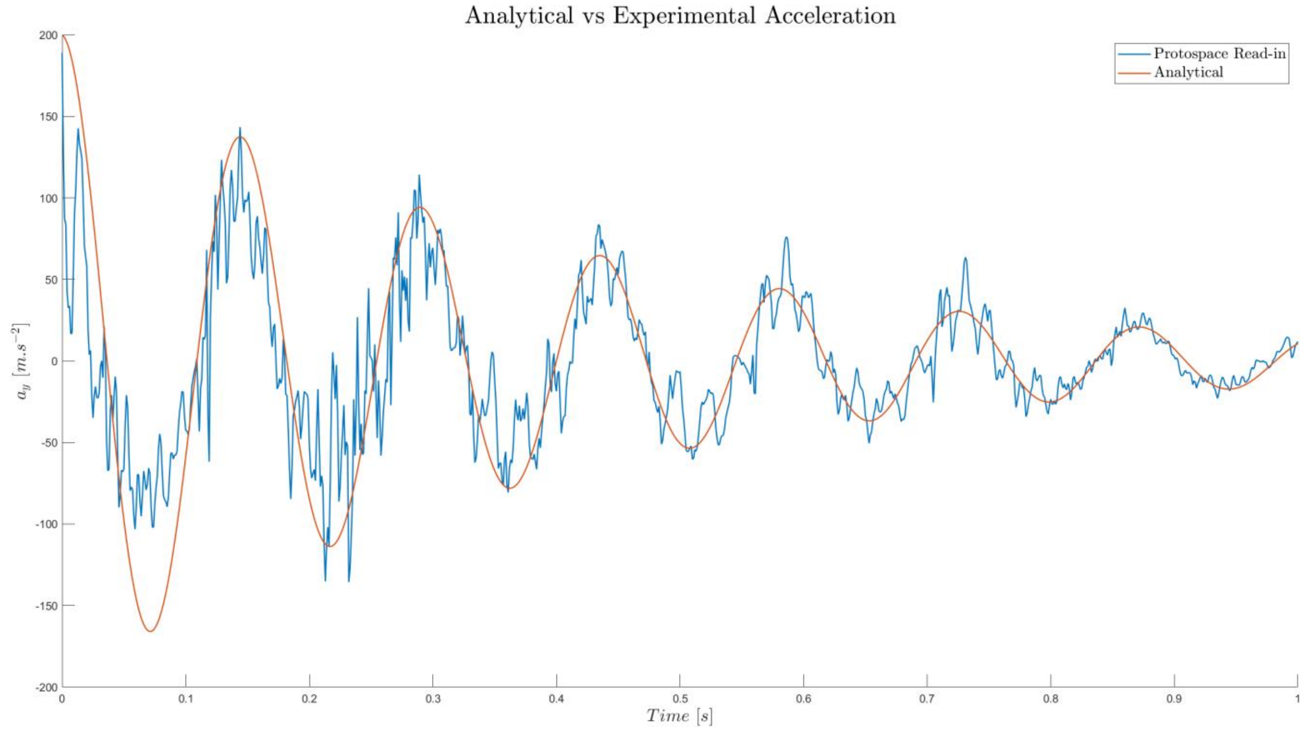
SLOWD Protospace Analytical Excitation

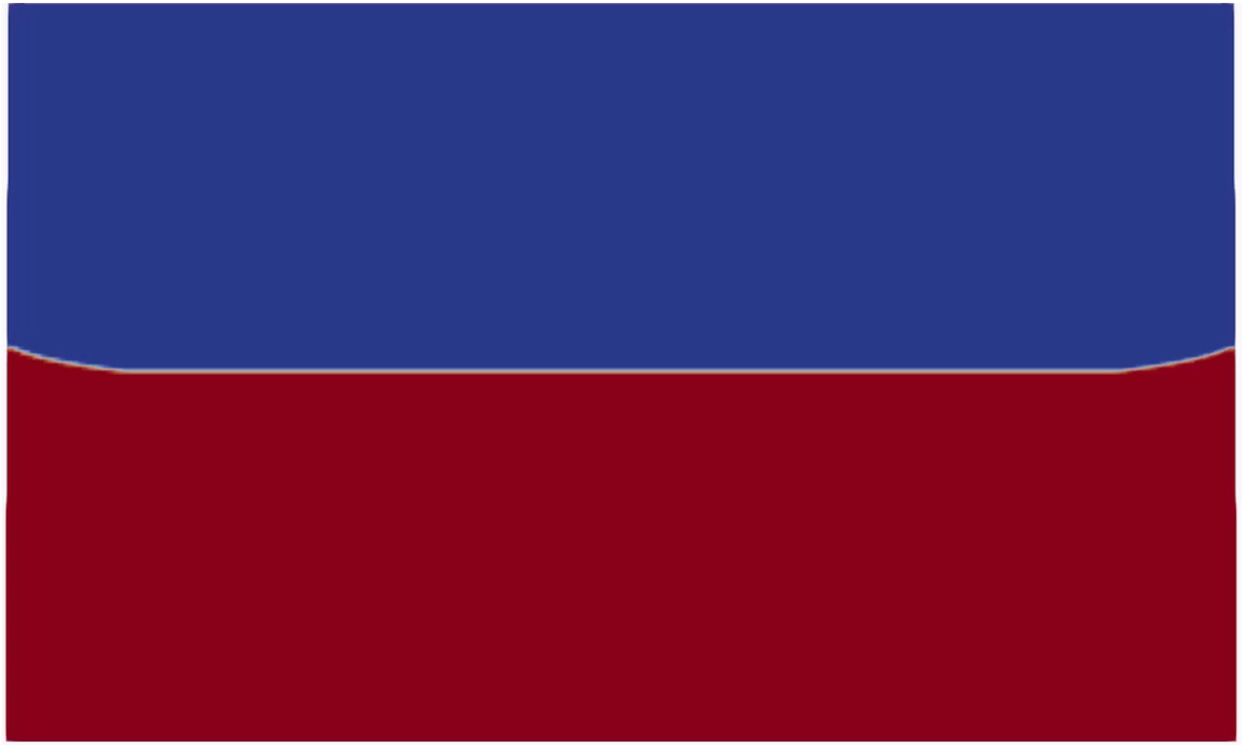
- In order to reduce uncertainty within the SLOWD Protospace experiment
  - An analytical damped sinusoidal acceleration signal is fitted to preserve the natural frequency and damping

$\omega = 2\pi f$ & $\lambda = -\xi\omega$

$a(t) = -a_0 . e^{\lambda t} . cos(\omega t)$

$Mode$	$\boldsymbol{f}\ [\boldsymbol{Hz}]$	$\boldsymbol{\xi}\ [\boldsymbol{Hz}]$	$\boldsymbol{a_0}\ [\boldsymbol{m.s^{-1}}]$
1	7	0.06	200





Energy Budget

- Impact of selected non-dimensional numbers completed by means of
  - Vertical excitation of $0.06m \times 0.1m$ Protospace compartment, employing 15040 Element mesh
- Fluid damping metric captured by E_{Defor}
- Calculated Normalized Energy and Forces
  - Energy normalized by the maximum potential energy

$$E_{Normalized} = \frac{E_{Simulation}}{|E_p|}$$

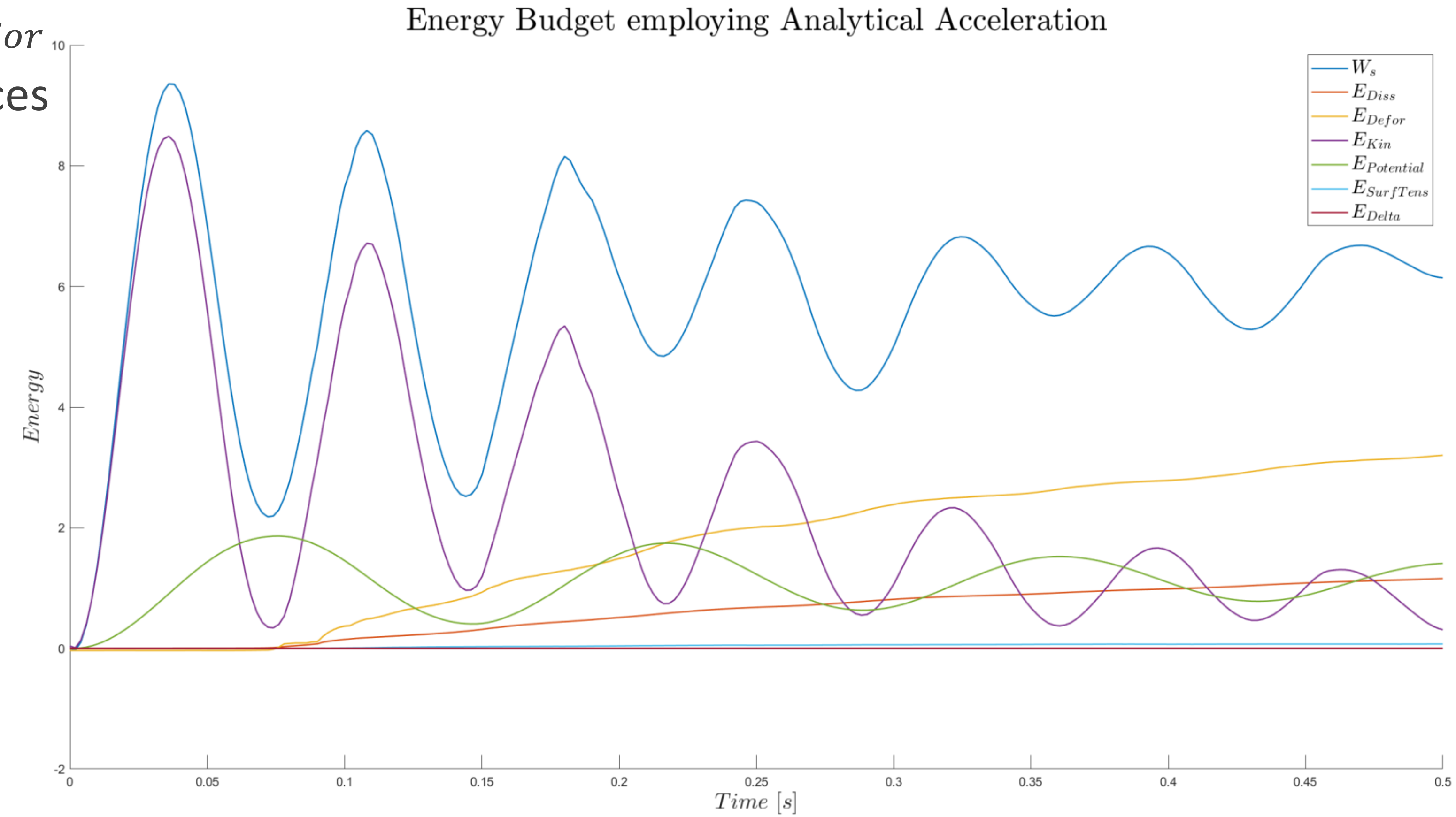
Where $E_p = m_{total} \times 9.81 \times h$

$$\mathrm{h} = \left|\frac{a_0}{(\lambda^2-\omega^2)^2+(2\lambda\omega)^2}(\lambda^2-\omega^2)\right|$$

  - Forces normalized by initial force

$$F_{Normalized} = \frac{F_{Simulation}}{|F_0|}$$

Where $\mathrm{F_0} = (\mathrm{a_0}+9.81) \times m_{total}$

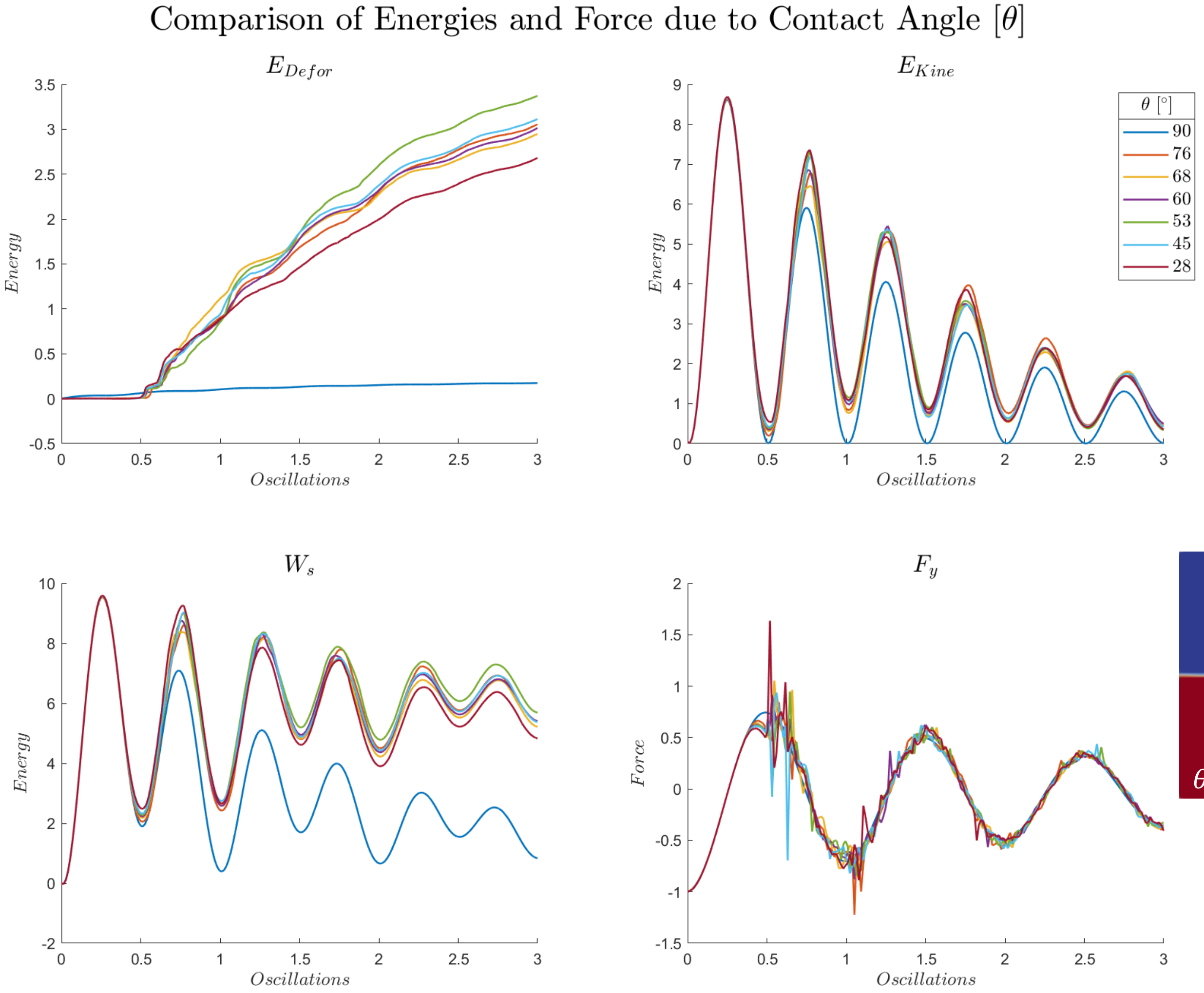


Non-dimensional Analysis Testing Procedure

- Influence of Π groups evaluated by means of modifying specific fluid parameters
  - ρ_{ratio}: Fluid density (ρ)
  - Re: Fluid viscosity (μ_l)
  - Bo: Surface Tension (γ)
  - θ: Contact angle
  - ω_{ratio}: Excitation frequency (f)
- Required values identified allow for the reaction of Full-Scale properties
  - Required properties all lay within tested scaling range
  - Exception is γ due to small meniscus
    - Meniscus of $0.2mm$ required

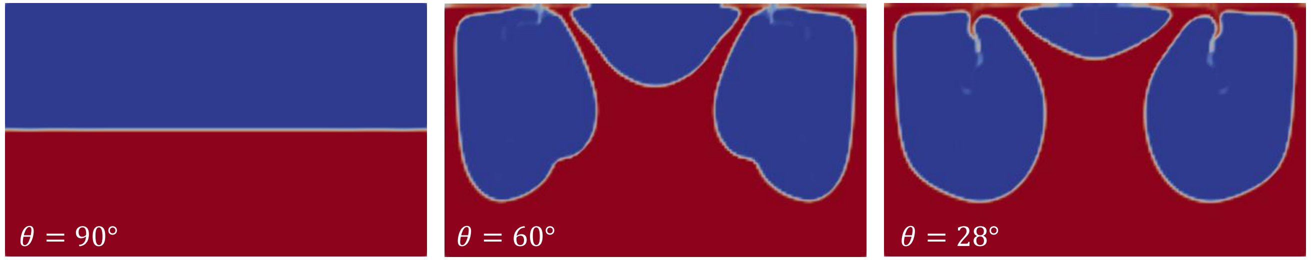
		Protospace	Minimum	Maximum	Required
θ	$[°]$	60	28	90	–
μ_l	$[Pa.s]$	9.77×10^{-4}	0.0	1.95×10^{-3}	1.68×10^{-3}
ρ	$[kg.m^{-3}]$	998	249	1745	750
γ	$[N.m^{-1}]$	0.072	0.0525	0.3675	1.6×10^{-3}
f	$[Hz]$	7	1.5	10	3.35

Contact Angle



Comparison of L_2 Norms against $\theta = 60°$

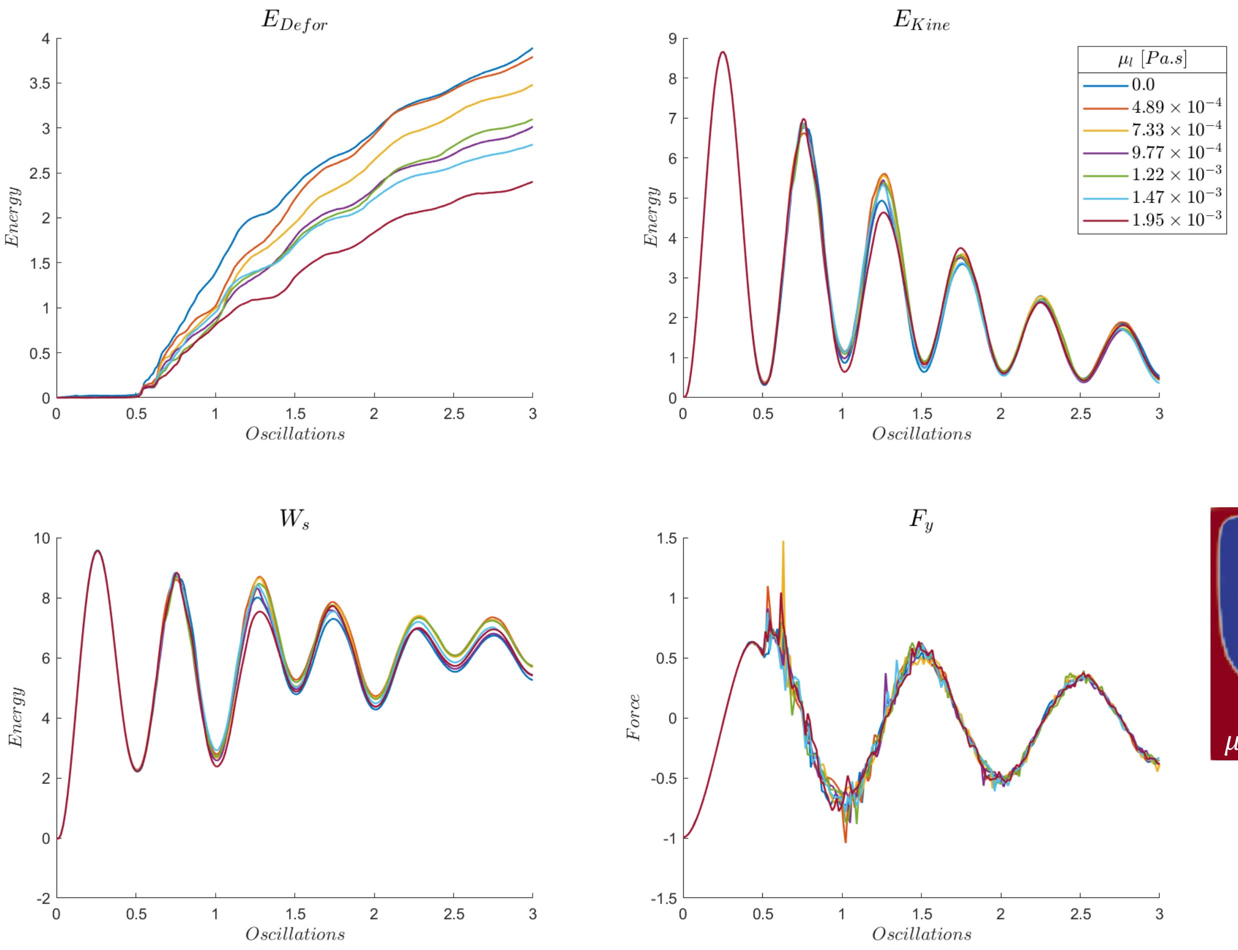
θ [°]	$\left\|\epsilon_{E_{Defor}}\right\|_2$ [%]	$\left\|\epsilon_{E_{Kine}}\right\|_2$ [%]	$\left\|\epsilon_{W_s}\right\|_2$ [%]	$\left\|\epsilon_{F_y}\right\|_2$ [%]
90	27.81	3.62	14.25	4.24
76	1.04	1.10	0.96	4.48
68	1.77	0.77	0.75	4.33
53	4.01	0.74	1.80	5.00
45	1.28	0.78	0.81	6.27
28	4.46	1.20	2.16	6.01



- $\theta = 90°$ solution shows influence of Rayleigh-Taylor instabilities
  - Meniscus definition critical in vertical sloshing systems
- Low effect on the system energies $\|\epsilon_E\|_2 < 5\%$

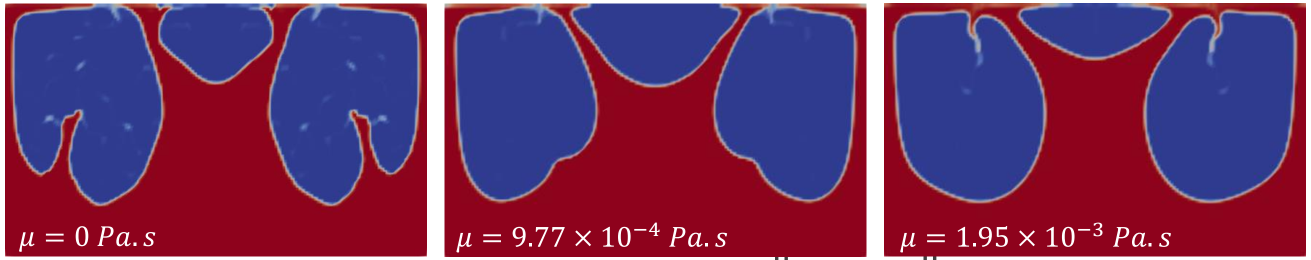
Reynolds Number

Comparison of Energies and Force due to Liquid Viscocity $[\mu_l]$



Comparison of L_2 Norms against $\mu_l = 9.77 \times 10^{-4} Pa.s$

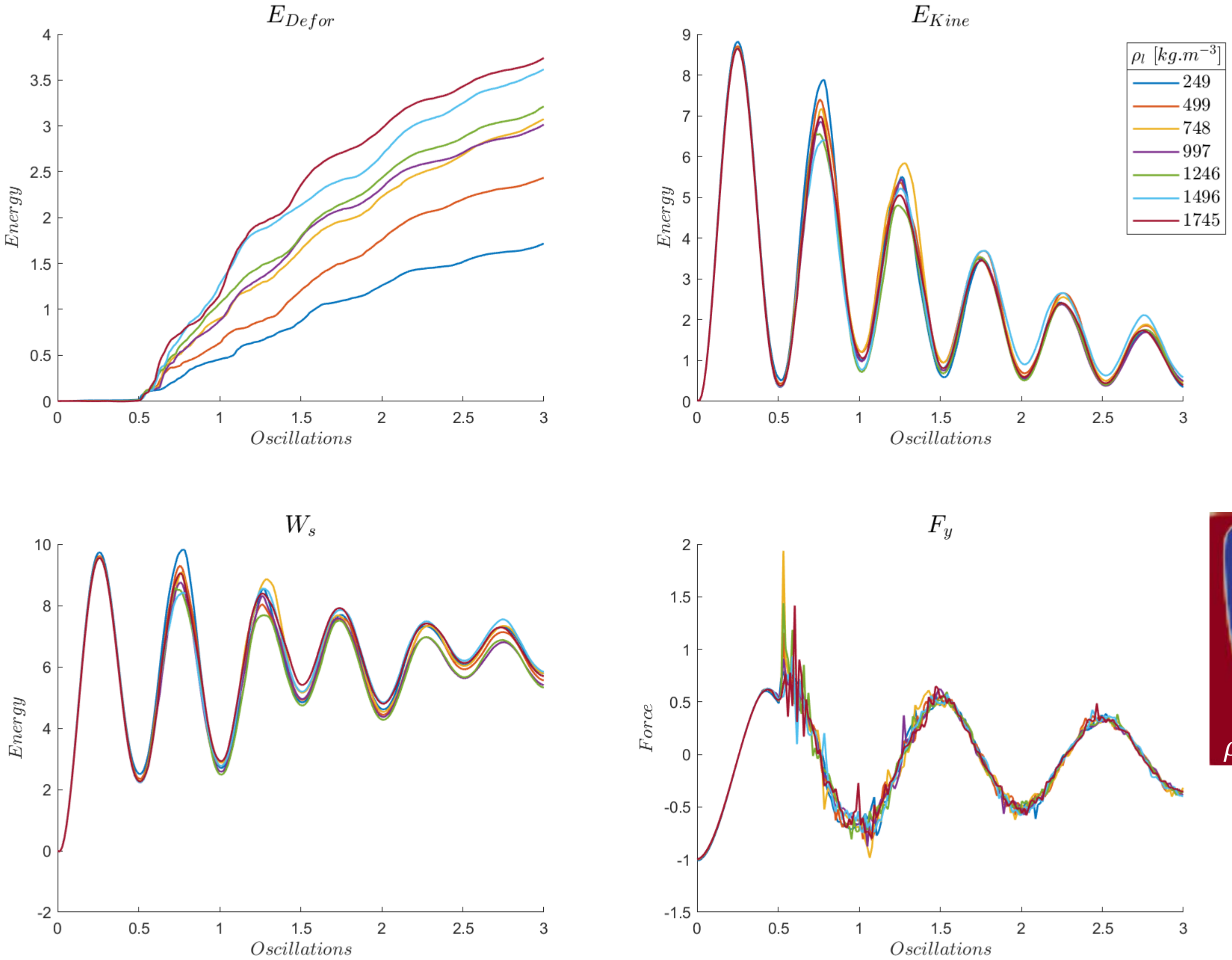
μ_l $[Pa.s]$	$\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{E_{Kine}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{W_s} \right\Vert_2$ [%]	$\left\Vert \epsilon_{F_y} \right\Vert_2$ [%]
0.0	10.43	1.01	0.94	3.74
$\mathbf{4.89 \times 10^{-4}}$	8.84	0.98	1.95	3.78
$\mathbf{7.33 \times 10^{-4}}$	5.06	0.72	1.58	4.91
$\mathbf{1.22 \times 10^{-3}}$	1.09	0.85	1.63	4.15
$\mathbf{1.47 \times 10^{-3}}$	1.84	0.59	1.04	3.33
$\mathbf{1.95 \times 10^{-3}}$	7.19	1.34	1.15	4.20



- Large effect on the Deformation energy $\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ up to 11%
- Low effect on the Kinetic energy and System work $\left\Vert \epsilon_{E_{Defor}} \right\Vert_2 \& \left\Vert \epsilon_{W_s} \right\Vert_2$ below 5%

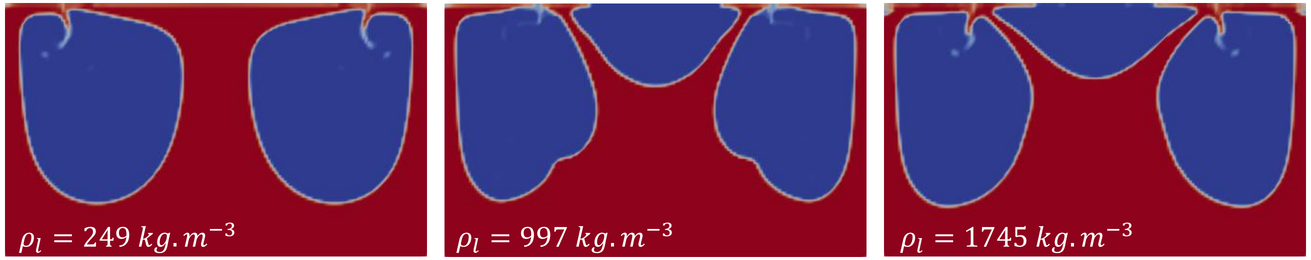
Fluid Density Ratio

Comparison of Energies and Force due to Liquid Density $[\rho_l]$



Comparison of $L_2 Norms$ against $\rho_l = 997 kg.m^{-3}$

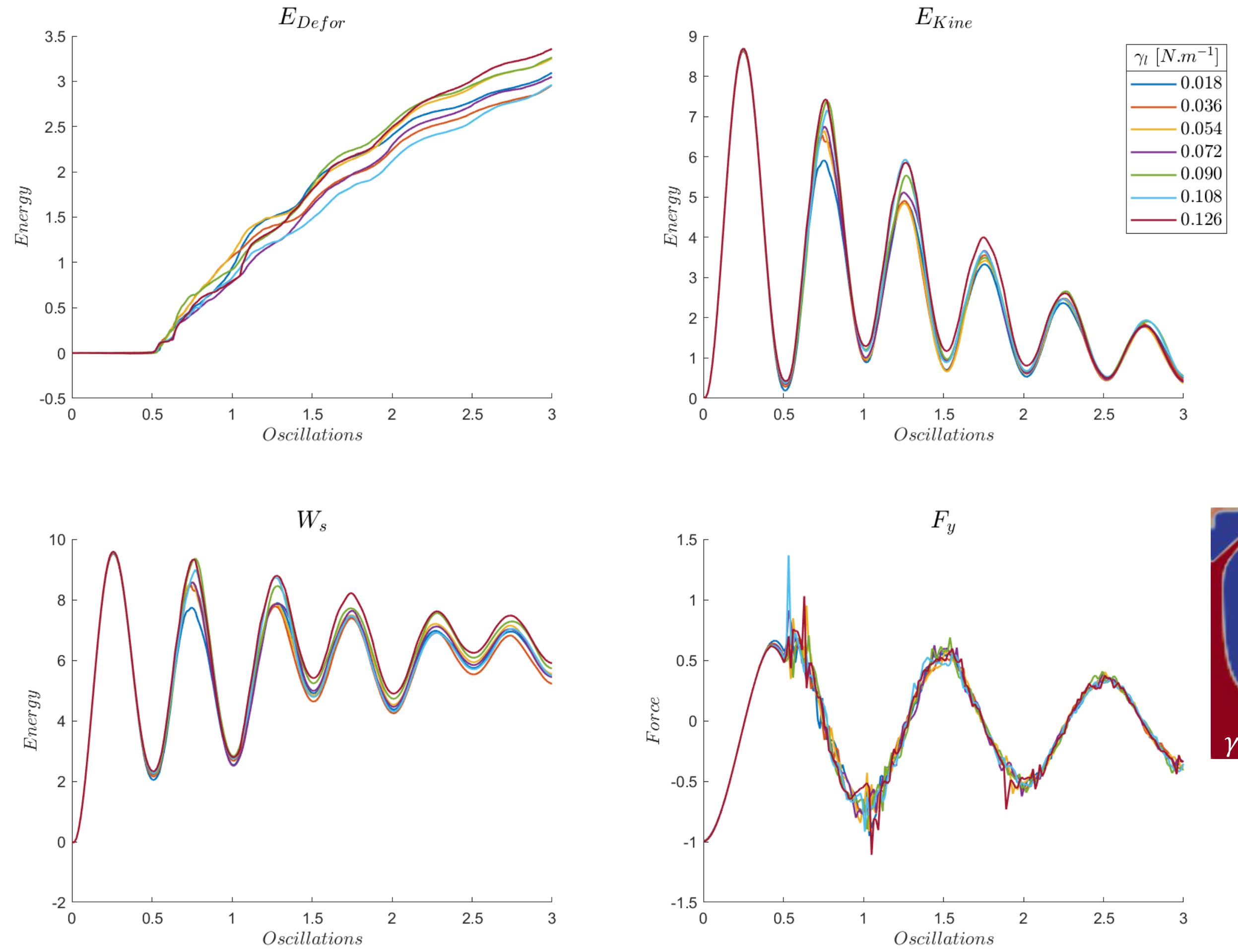
ρ_l $[kg.m^{-3}]$	$\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{E_{Kine}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{W_s} \right\Vert_2$ [%]	$\left\Vert \epsilon_{F_y} \right\Vert_2$ [%]
249	15.67	1.94	2.42	4.10
499	8.09	1.46	1.42	3.48
748	1.31	1.54	1.95	5.77
1246	2.14	1.03	0.95	4.87
1496	7.18	1.45	2.25	4.37
1745	9.83	0.68	2.15	4.84



- Large effect on the Deformation energy $\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ up to 16%
- Low effect on the Kinetic energy and System work $\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ & $\left\Vert \epsilon_{W_s} \right\Vert_2$ below 5%

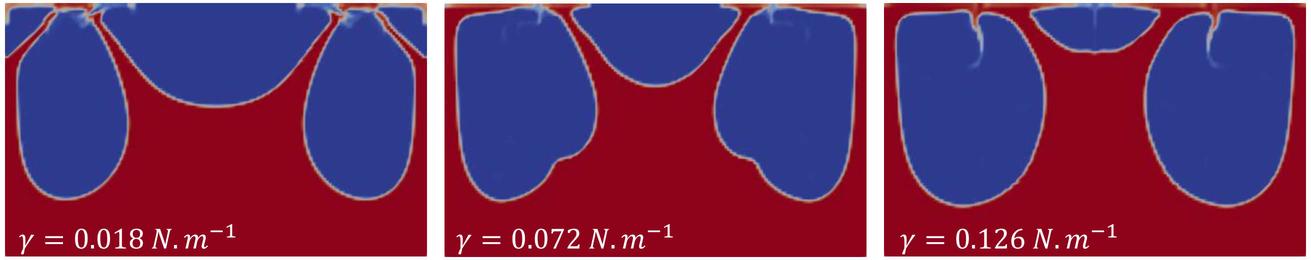
Bond Number

Comparison of Energies and Force due to Liquid Surface Tension $[\gamma]$



Comparison of L_2Norms against $\gamma_l = 0.072 N.m^{-1}$

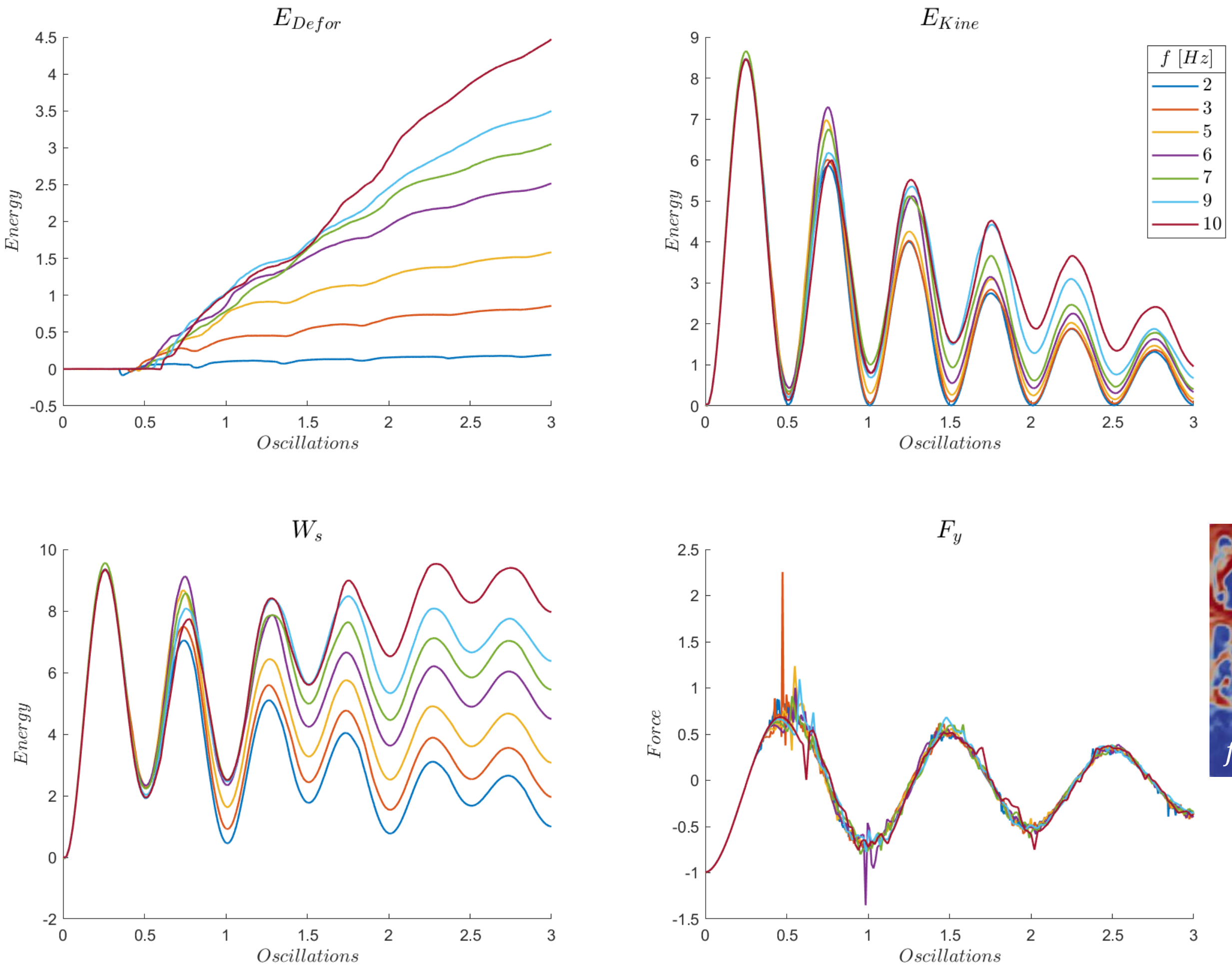
γ_l $[N.m^{-1}]$	$\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{E_{Kine}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{W_s} \right\Vert_2$ [%]	$\left\Vert \epsilon_{F_y} \right\Vert_2$ [%]
0.018	2.65	1.33	1.11	3.81
0.036	2.19	1.03	1.43	3.57
0.054	3.54	1.02	0.95	4.51
0.090	3.47	1.29	1.86	4.13
0.108	2.10	1.40	1.47	3.94
0.126	3.44	1.93	2.69	5.27



- Surface tension has a low effect on the fluid energies $\left\Vert \epsilon_E \right\Vert_2$ below 5%

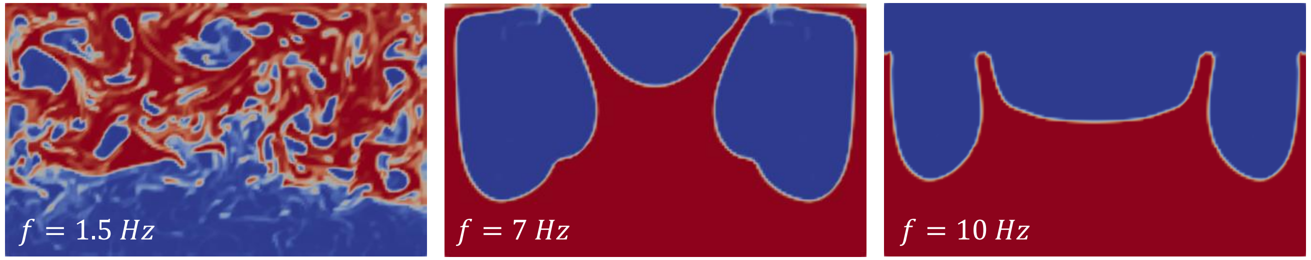
Frequency Ratio

Comparison of Energies and Force due to Excitation Frequency $[f]$



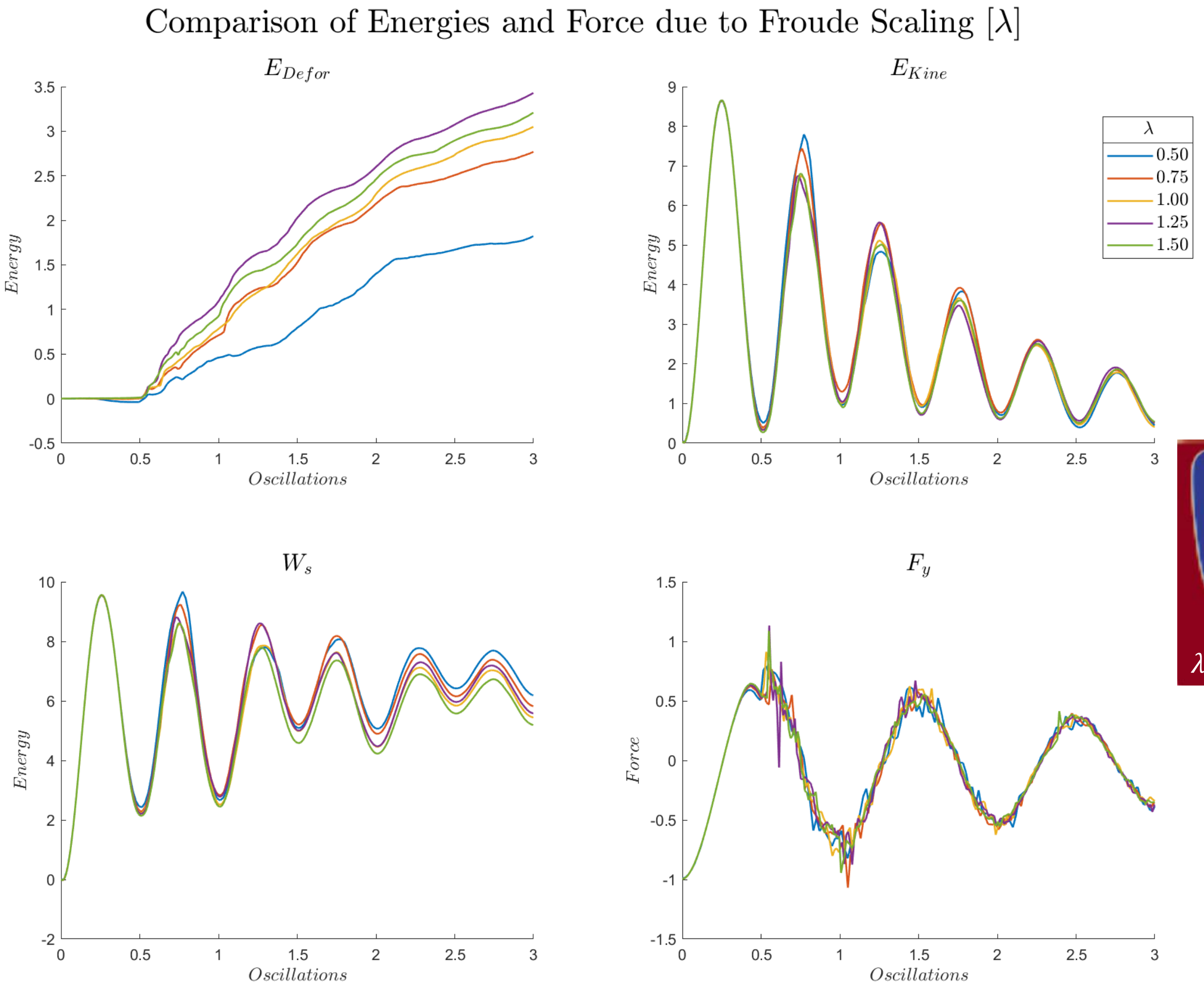
Comparison of L_2 Norms against $f = 7Hz$

f $[Hz]$	$\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{E_{Kine}} \right\Vert_2$ [%]	$\left\Vert \epsilon_{W_s} \right\Vert_2$ [%]	$\left\Vert \epsilon_{F_y} \right\Vert_2$ [%]
1.5	31.43	4.41	17.58	3.80
3.0	23.71	3.98	13.91	5.57
4.5	15.20	3.07	9.27	4.44
6.0	5.26	1.73	3.98	4.46
8.5	4.20	2.83	3.72	4.56
10.0	11.91	4.55	8.74	4.98



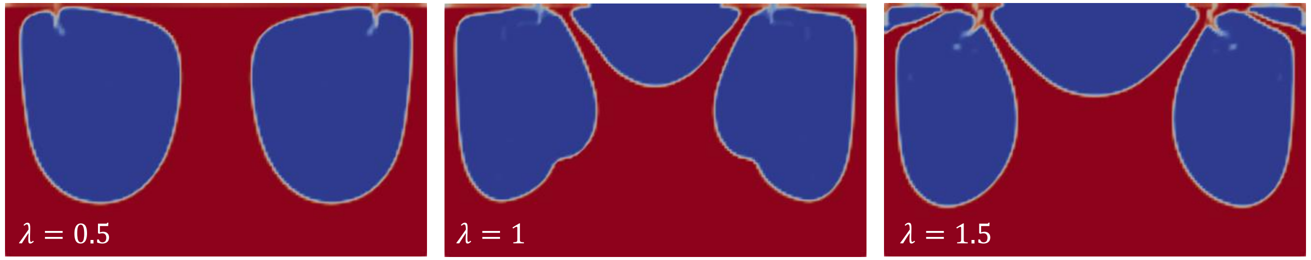
- Frequency of excitation has a large effect on the internal energies of the liquid
  - $\left\Vert \epsilon_{E_{Defor}} \right\Vert_2$ up to 32% $\left\Vert \epsilon_{W_s} \right\Vert_2$ up to 18%

Practical Froude Scaling



Comparison of $L_2 Norms$ against $\lambda = 1$

$\boldsymbol{\lambda}$	$\left\Vert\epsilon_{E_{Defor}}\right\Vert_2$ [%]	$\left\Vert\epsilon_{E_{Kine}}\right\Vert_2$ [%]	$\left\Vert\epsilon_{W_s}\right\Vert_2$ [%]	$\left\Vert\epsilon_{F_y}\right\Vert_2$ [%]
0.5	13.91	1.71	2.97	4.46
0.75	2.43	1.51	2.27	4.59
1.25	5.68	1.05	1.31	4.30
1.5	2.68	0.94	1.44	3.90



- System models realistic Froude scaling.
- Froude Scaling Fluid response similar to density ratio scaling
- Damping changed due to change in $\left\Vert\epsilon_{E_{Deform}}\right\Vert_2$ of up to 14%
- Scaling has low impact on the system net work and kinetic energy $\left\Vert\epsilon_{W_s}\right\Vert_2 \& \left\Vert\epsilon_{E_{Kine}}\right\Vert_2$ of below 3%

Conclusion

1. Low impact of Non-dimensional groups on the normalized net-force slosh loads
   - Energy balance is an integral part of evaluating violent slosh behaviour
2. Importance of surface tension and the meniscus on sloshing is due to prevention of Rayleigh-Taylor Instabilities
   - Meniscus collapse required to initiate free-surface disturbances
   - Does not offer influence on disturbance propagation once collapsed
3. Fluid damping most sensitive to the effects of:
   - Reynolds Number, Density Ratio and Frequency Ratio
   - Frequency ratio has major effect on kinetic energy in comparison against other non-dimensional quantities
4. Effects of Practical Froude Scaling
   - Froude scaling does not scale slosh damping
   - Highlights future considerations for Practical Froude Scaling
5. Future Work
   - Investigation of ideal Froude Scaling where all properties scaled accordingly (Unrealistic fluid properties)
   - Mesh refinement and stretching to reach the required γ value and resulting $0.2mm$ meniscus height
   - Increased Froude Scaling towards the required $\lambda = 5$ to match the scaling of the Protospace

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