# EXPERIMENTAL STUDY OF THE DAMPING EFFECTS ON A SDOF SLOSHING TANK

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POLITÉCNICA
UNIVERSIDAD POLITÉCNICA DE MADRID

SLOWD

# OUTLINE

1. Introduction

2. Experimental methodology

3. Sloshing force calculation procedure

4. Results

5. Conclusions

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815044.

# THE SLOWD PROJECT

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# AIM & OBJECTIVES

Understand sloshing-induced damping by means of SDOF experiments

1. Confirm that fluid presence adds an extra damping to the system
2. Define an experimental methodology to derive the vertical sloshing force
3. Gain insight on the nature of this force and how it affects the damping of the system
4. Identify and quantify the sources of energy dissipation in the problem
5. Test a numerical model using the experimental results as input

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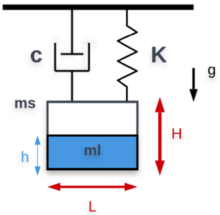
# Experimental methodology

Which magnitudes does the dissipated power depend on?




Length: $H$

Time: $\sqrt{m/K} = 1/w_0$

Mass: $\rho_f H^3$

$$W^{disp} = f(\rho_f, \rho_a, \mu_f, \mu_a, h, g, K, c, H, L, y_0, m_s, t, \sigma)$$

$$\frac{W^{disp}}{mH^2 w_0^3} = f(\frac{\rho_a}{\rho_f}, Re, \frac{\mu_a}{\mu_f}, f = \frac{h}{H}, Fr, \frac{K}{mw_0^2}, \frac{c}{mw_0}, \frac{L}{H}, r = \frac{m_l}{m_s}, tw_0, We)$$

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# FROUDE SCALING

$$Fr = \sqrt{\frac{Ng}{w_0^2 H}} \quad \text{and} \quad 1:5 \text{ scale}$$

| | Wing (W) | Scaled SDOF Experiment |
|---|---|---|
| $f_0$ [Hz] | 3 | 6.56 |
| $H$ [m] | 0.3 | 0.06 |
| $L$ [m] | 3.5 | 0.1 |
| $m_l$ [kg] | 350 | 0.18 |
| $m_s$ [kg] | 5000 | 2.06 |

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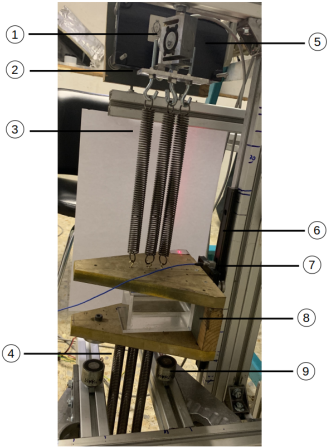
# EXPERIMENTAL SETUP




1. Load cell
2. Metallic plate
3. Upper set of springs
4. Lower set of springs
5. Laser sensor
6. Mechanical guide
7. Accelerometer
8. Tank and C-shaped wooden structure
9. Release mechanism: pair of solenoids

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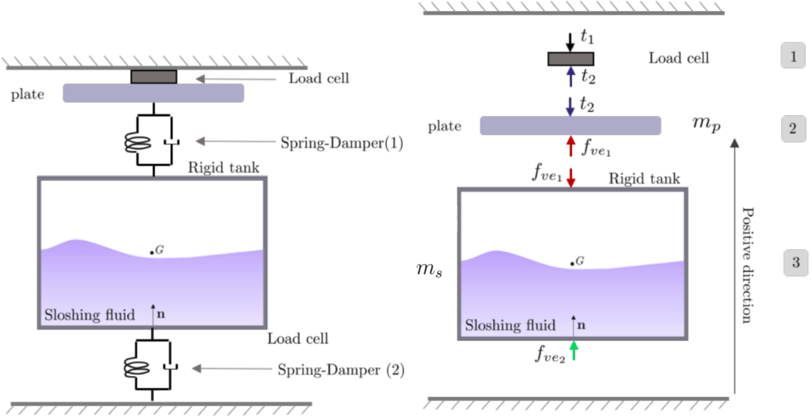
# Sloshing force calculation procedure

# FORCE BALANCE

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# EXPERIMENTAL SLOSHING FORCE

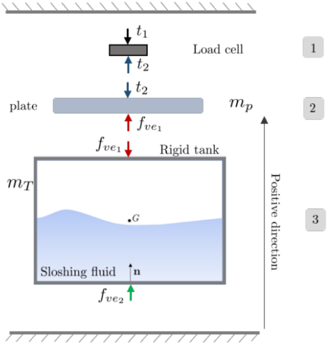
Applying Newton's second law to bodies 1, 2 and 3:

$$t_1 = t_2 \equiv t$$

$$0 = f_{ve1} - t - \underbrace{(m_p + \frac{m_k}{2})g}_{t_0}$$

$$(m_s + m_k)\frac{d^2y}{dt^2} = F_{slosh} - 2(t - t_0)$$

$$F_{slosh} = m_s \underbrace{\frac{d^2y}{dt^2}}_{\text{Accelerometer}} + \underbrace{T_{LC}}_{\text{Load cell}}$$

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# SEMI-EMPIRICAL SLOSHING FORCE

Applying Newton's second law to body 3 and modelling the damping force involved in the problem:

$$\underbrace{m_s \frac{d^2y}{dt^2}}_{\text{Accelerometer}} + \underbrace{F_D}_{\text{Damping force model}} + \underbrace{Ky}_{\text{Laser}} = F_{slosh}$$

$$m_s \frac{d^2y}{dt^2} + \underbrace{B_0 sign(\frac{dy}{dt})}_{\text{Dry friction}} + \underbrace{B_{1d} \frac{dy}{dt}}_{\text{Viscous friction}} + Ky = F_{slosh}$$

$B_0$ and $B_{1d}$ coefficients come from a Least-Squares fitting analysis.

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# Results

# THE EXPERIMENT

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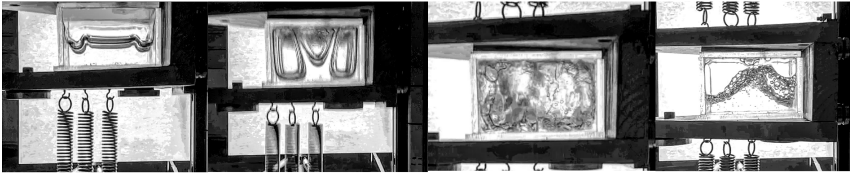

(1) Ripple travels horizontally

(2) Rayleigh-Taylor instability & first impact

(3) Turbulent chaotic regime

(4) Standing wave regime

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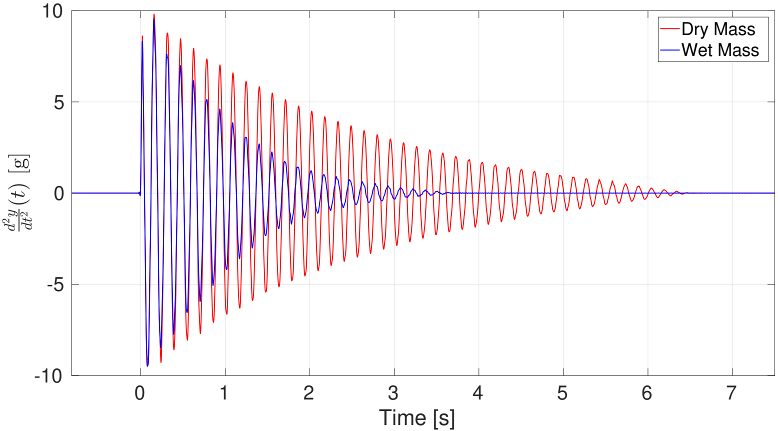
# ACCELERATION MEASUREMENTS

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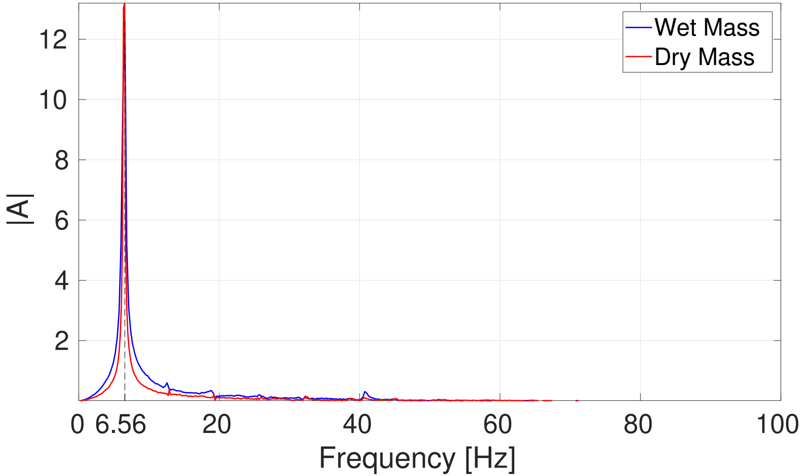
# FREQUENCY STUDY

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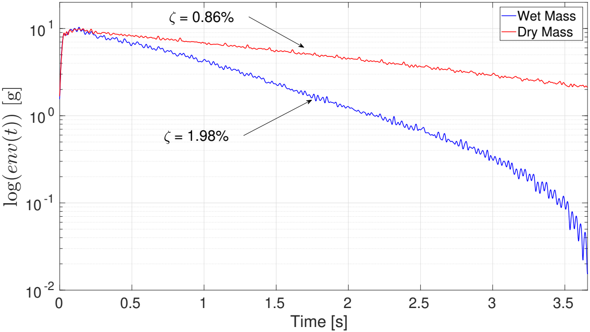
# ENVELOPE STUDY




| | Number of peaks | $t_d$ [s] | $\xi$ [1/s] | $\zeta$ [%] |
|---|---|---|---|---|
| Dry mass experiment | 80 | 6.48 | 0.35 | 0.86 |
| Wet mass experiment | 42 | 3.7 | 0.82 | 1.98 |

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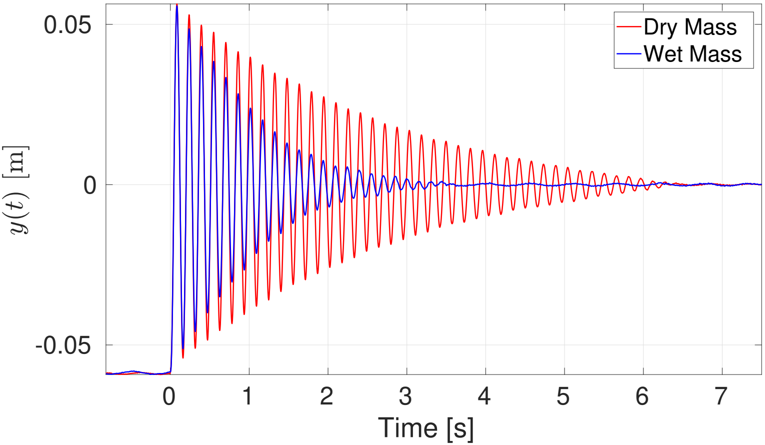
# POSITION MEASUREMENTS

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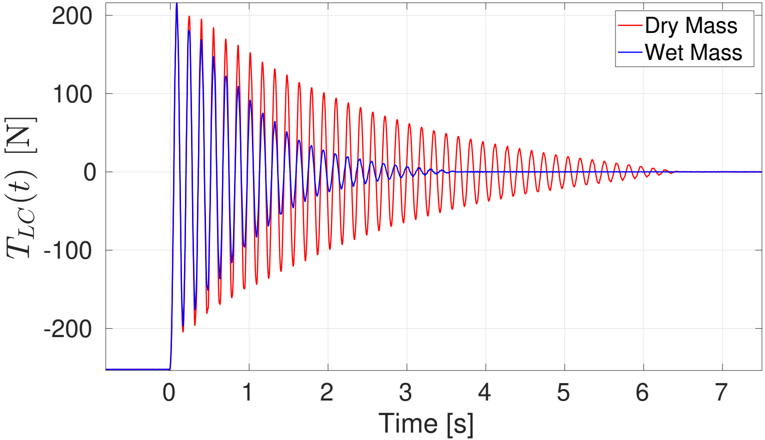
# LOAD CELL MEASUREMENTS

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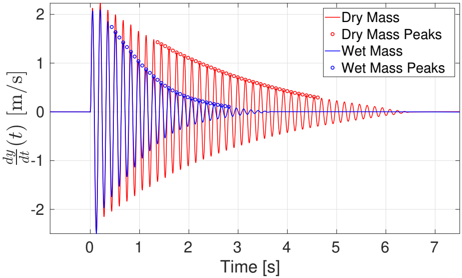
# VELOCITY INTEGRATION & DAMPING COEFFICIENTS




| | $B_0$ [N] | $B_1$ [kg/s] |
|---|---|---|
| Dry mass experiment | 0.37 | 1.58 |
| Wet mass experiment | 0.4 | 3.66 |

- Fluid presence increases $B_1$
- $B_0$ is similar in both experiments

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# SLOSHING FORCE MODEL

Modelling the wet mass experiment as a mass-spring-damper system:

$$m\frac{d^2y}{dt^2} + B_{1w}\frac{dy}{dt} + B_0\ sign\left(\frac{dy}{dt}\right) + Ky = 0$$

$$(m_s + m_l)\frac{d^2y}{dt^2} + (B_{1s} + B_{1slosh})\frac{dy}{dt} + B_0\ sign\left(\frac{dy}{dt}\right) + Ky = 0$$

$$m_s\frac{d^2y}{dt^2} + B_{1s}\frac{dy}{dt} + Ky = F_{slosh}$$

The sloshing force is composed by an inertial and dissipative term:

$$F_{slosh} = -(\underbrace{m_l\frac{d^2y}{dt^2}}_{\text{Inertial}} + \underbrace{B_{1slosh}\frac{dy}{dt}}_{\text{Dissipative}})$$

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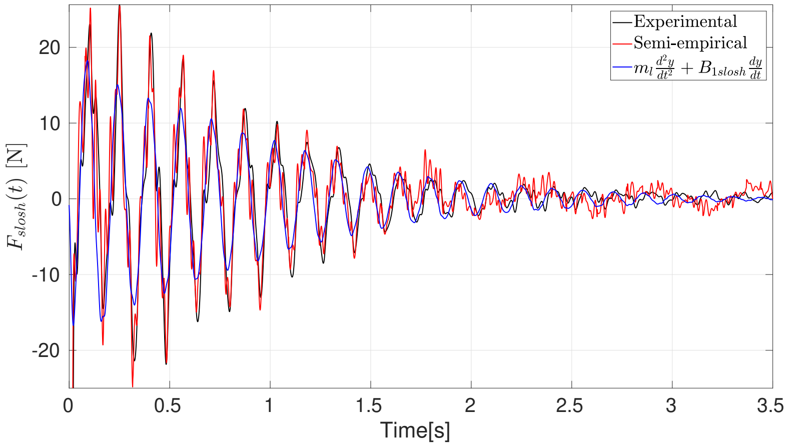
# SLOSHING FORCE

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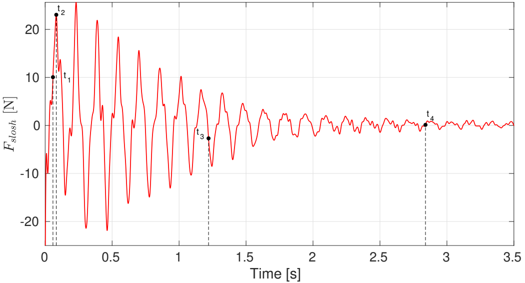
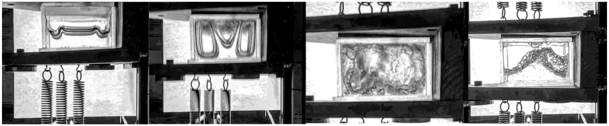
# SLOSHING FORCE VIDEO CORRELATION



(1) (2) (3) (4)

$t_1$ = 0.058 s $t_2$ = 0.083 s $t_3$ = 1.23 s $t_4$ = 2.84 s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# ENERGY DISSIPATION

- The dissipative forces acting in the experiment are $F_{slosh}$ and $F_D = B_0 sign(\frac{dy}{dt}) + B_{1d}\frac{dy}{dt}$
- The energy dissipated by those 2 forces can be computed over the $N$ cycles of the experiment.
- The dissipated energies are normalised with the initial mechanical energy $E_{m0} = \frac{1}{2}K{y_0}^2$

$$\eta_{slosh} = \frac{1}{E_{m0}} \int_N F_{slosh}\, dy \qquad \eta_D = \frac{1}{E_{m0}} \int_N F_D\, dy$$

| | $\eta_D$ [%] | $\eta_{slosh}$ [%] |
|---|---|---|
| Dry mass | 100 | 0 |
| Wet mass | 43.9 | 56.1 |

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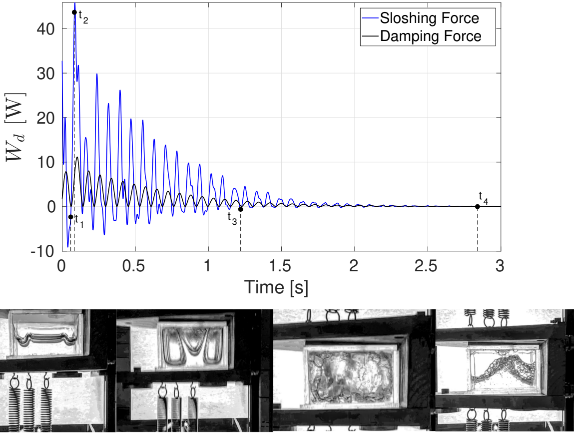
# POWER DISSIPATION

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# NUMERICAL MODEL

- The experimentally obtained sloshing force can be used as an input to numerically test the following ODE:

$$m_s \frac{d^2 y}{dt^2} + B_0 sign\left(\frac{dy}{dt}\right) + B_{1s}\frac{dy}{dt} + Ky = F_{slosh}$$

- Initial conditions are $y(0) = y_0$ and $\dot{y}(0) = 0$
- Both "Experimental" and "Semi-empirical" sloshing forces are used as input

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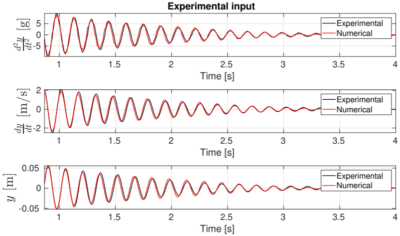
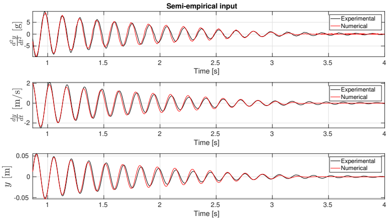
# NUMERICAL MODEL




Acceleration, velocity and position results match the experimental measurements.

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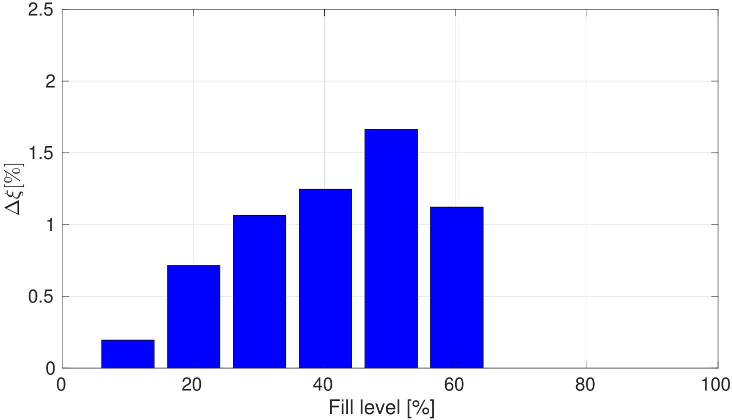
# FILLING LEVEL STUDY

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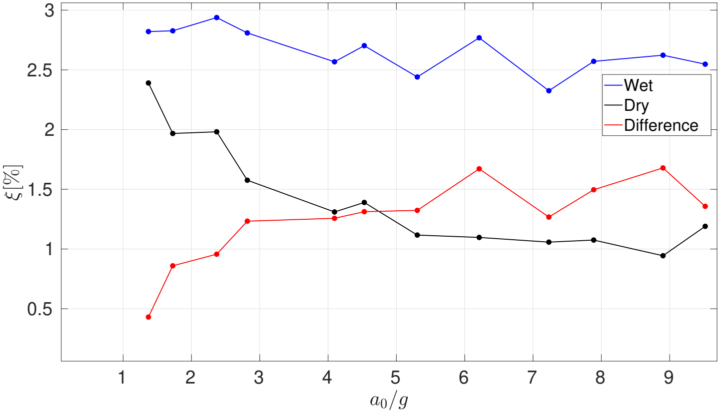
# FROUDE NUMBER STUDY

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# Conclusions

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# CONCLUSIONS

- A low cost 1:5 Froude scaled experimental rig has been built for vertical sloshing study
- The fluid presence increases the viscous damping coefficient $B_1$ when compared to the dry mass experiment
- Two methodologies have been presented to derive the sloshing force acting in the system showing good agreement between them
- The vertical fluid action can be considered as an inertial-dissipative duality

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# CONCLUSIONS

- More than half of the dissipated energy in the wet mass experiment is due to fluid sloshing.
- Liquid to wall impacts are the main source of energy dissipation and the time-shift with the velocity signal is a key element for this dissipation
- Using the sloshing force as an input the problem has been tested numerically displaying good agreement with experimental measurements

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Thank you for your attention