Propellant Sloshing Modelling for AOCS Design and Analysis during Satellite De-Orbiting

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Introduction

Problem Statement

- End-of-life disposal of satellites is a common requirement to avoid space debris
- Propellant needed for de-orbiting is excited during maneuvers
  - ➢ Sloshing motion inside the partially filled tank
  - ➢ Disturbance forces and torques
- Modelling of disturbances via semi-empirical formulas [1] is difficult for non-simple tank geometries

Approach

- Sloshing modelling by excitation tests done with numerical simulation
- Implementation of derived mechanical sloshing models in an AOCS environment for controller design, tuning and stability analysis
- Example mission: MetOp-SG satellite:
  - Satellite mass: 3837 kg
  - Tank: Airbus OST 22/5
  - Hydrazine mass: 350 kg
  - Filling ratio: 40.2 %
  - Thrust level: 325 N

Picture taken from [2]

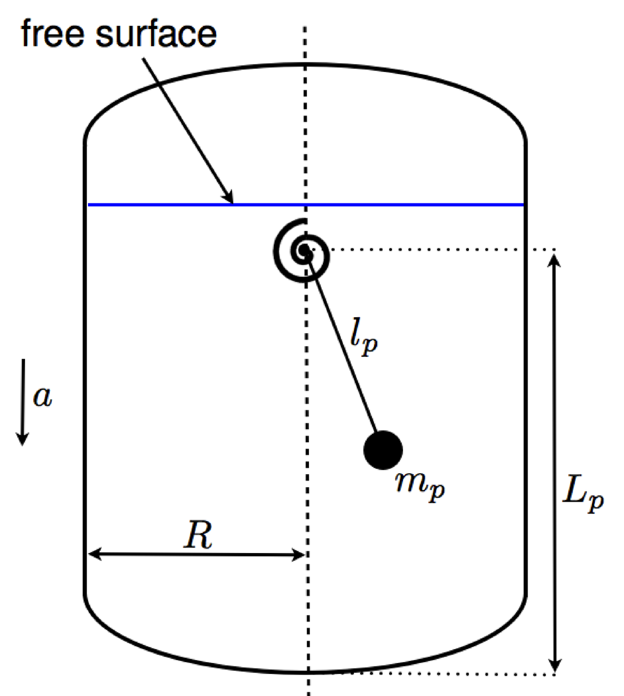
Sloshing Modelling

Sloshing Regime Identification

- Bond number given by

$$Bo = \frac{\rho \cdot a \cdot R^2}{\sigma} = 447$$

  - ➢ Gravitational forces are dominant
  - ➢ Surface tension effects can be neglected
  - ➢ Steady-state high-g lateral sloshing investigated, transient neglected



Representative Analytical Sloshing Model

- Considering small variations around the steady-state-position under high-g
  - ➢ Linear lateral sloshing
  - ➢ Dynamics described by representative linear pendulum model [1], e.g. force

$$F_s(t) = F_0 \cdot e^{-\gamma \omega_s t} \cdot \cos(\omega_0 t)$$

System Identification

- Perform numerical simulations (experimental approach [3])
  - Laterally sinusoidally excite tank with $\omega_0 \ll \omega_s$
  - Quick-stop tank when liquid free-surface reached its maximum height
  - Force & torque response used to calculate the sloshing model parameters

$$m_p = \frac{F_s}{A_0}\left(\frac{1}{\omega_0^2} - \frac{1}{\omega_s^2}\right) \qquad l_p = \frac{a}{\omega_s^2} \qquad L_p = \frac{M_s}{F_s}$$

$$\omega_{s,j} = \frac{2\pi}{t_{F_s^{max,j}} - t_{F_s^{max,j-1}}} \qquad \gamma_j = \frac{\Lambda_j}{\sqrt{(2\pi)^2 + \Lambda_j^2}} \qquad \Lambda_j = \ln\left(\frac{F_s^{max,j}}{F_s^{max,j+1}}\right)$$

Numerical Method

- Propellant dynamics: Incompressible Navier-Stokes equations in ALE formulation

$$\frac{\partial \mathbf{u}}{\partial t}\Big|_{x_r} + \mathbf{c} \cdot \nabla \mathbf{u} - \nabla \cdot \boldsymbol{\sigma}(\mathbf{u}, p) = \mathbf{b} \qquad \boldsymbol{\sigma}(\mathbf{u}, p) = -p\mathbf{I} + 2\nu \boldsymbol{\epsilon}(\mathbf{u})$$

$$\nabla \cdot \mathbf{u} = 0 \qquad \boldsymbol{\epsilon}(\mathbf{u}) = \tfrac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^{\mathrm{T}})$$

- Slip Dirichlet/Neumann boundary condition prescribed at tank wall

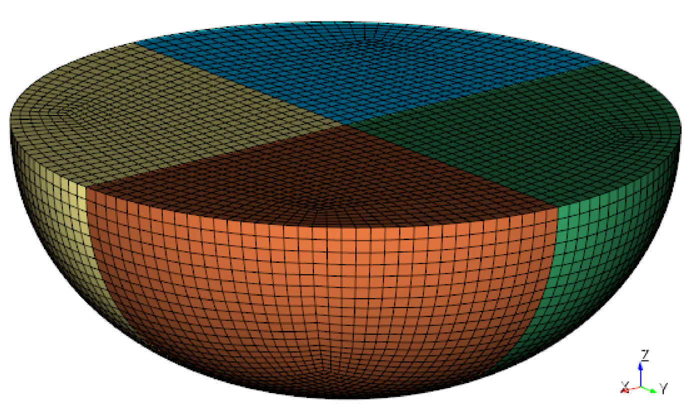
$$\mathbf{n} \cdot \mathbf{u} = 0$$

$$\mathbf{t} \cdot \boldsymbol{\sigma}(\mathbf{u}, p) \cdot \mathbf{n} = \mathbf{b} \cdot \boldsymbol{\sigma}(\mathbf{u}, p) \cdot \mathbf{n} = 0$$

- BC-free boundary condition [4] to avoid spurious velocities at curved boundary
- Liquid free-surface $\mathbf{u} - \mathbf{u}^r = 0$
- Discretization: • Space: Residual-based stabilized finite element method with linearly interpolated hexahedral elements
  • Time: Backward-Euler time-integration scheme
- Resulting non-linear problem solved with partitioned approach [5]

Numerical Simulations

- Tank subjected to vertical acceleration ($9.52e^{-2}$ m/s^2) & sinusoidal horizontal acceleration ($2e^{-3}$ m/s^2, 200s)
- Finite element mesh: • 46,656 elements
  • 348,439 DOFs
- Simulation time: 200s (0.01s time step)



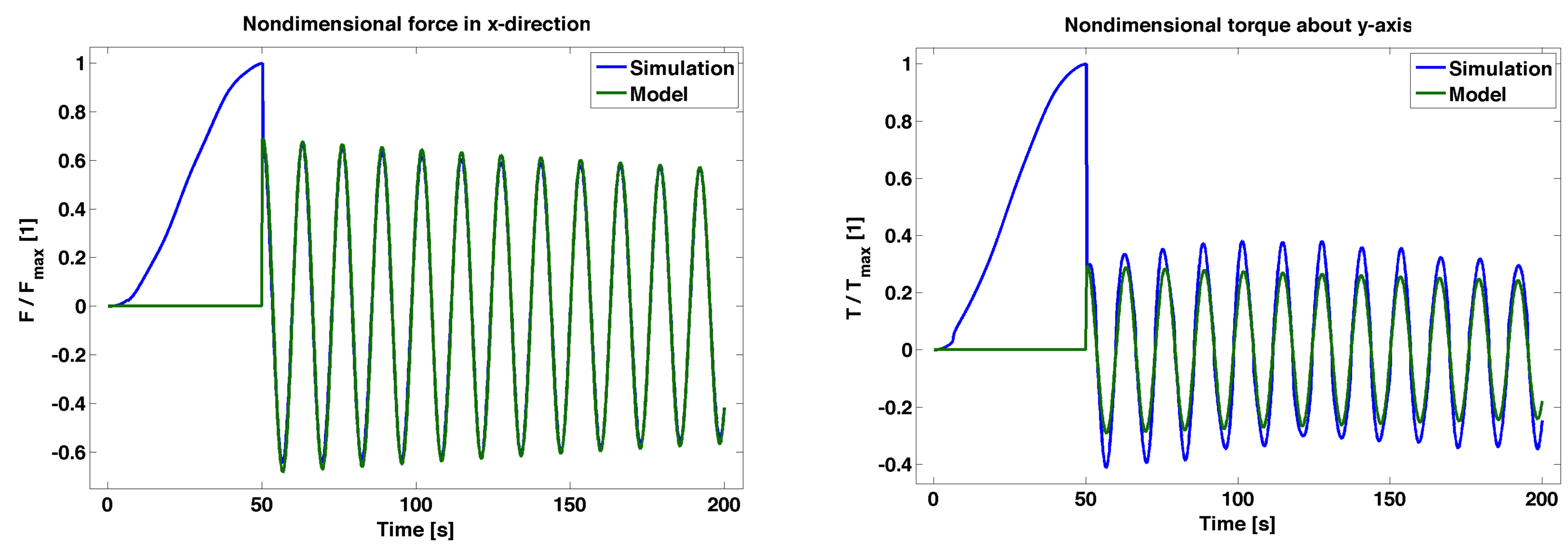
Sloshing Modelling (Cont'd)

Results and Comparison

- Sloshing model parameters derived from simulation vs. semi-empirical formula (combination of cylindrical and spherical tank shapes)

	Simulation	semi-empirical
1st sloshing frequency [Hz]	0.0776	0.0775 – 0.0823
Sloshing damping factor [%]	0.27	0.23 – 0.25
Sloshing mass [kg]	216.3	138.1 – 183.3
Pendulum length [m]	0.4005	0.3188 – 0.3935
Pendulum hinge point location [m]	0.5347	0.4282 – 0.4460

- Comparison x-direction force & y-direction torque from simulation & model



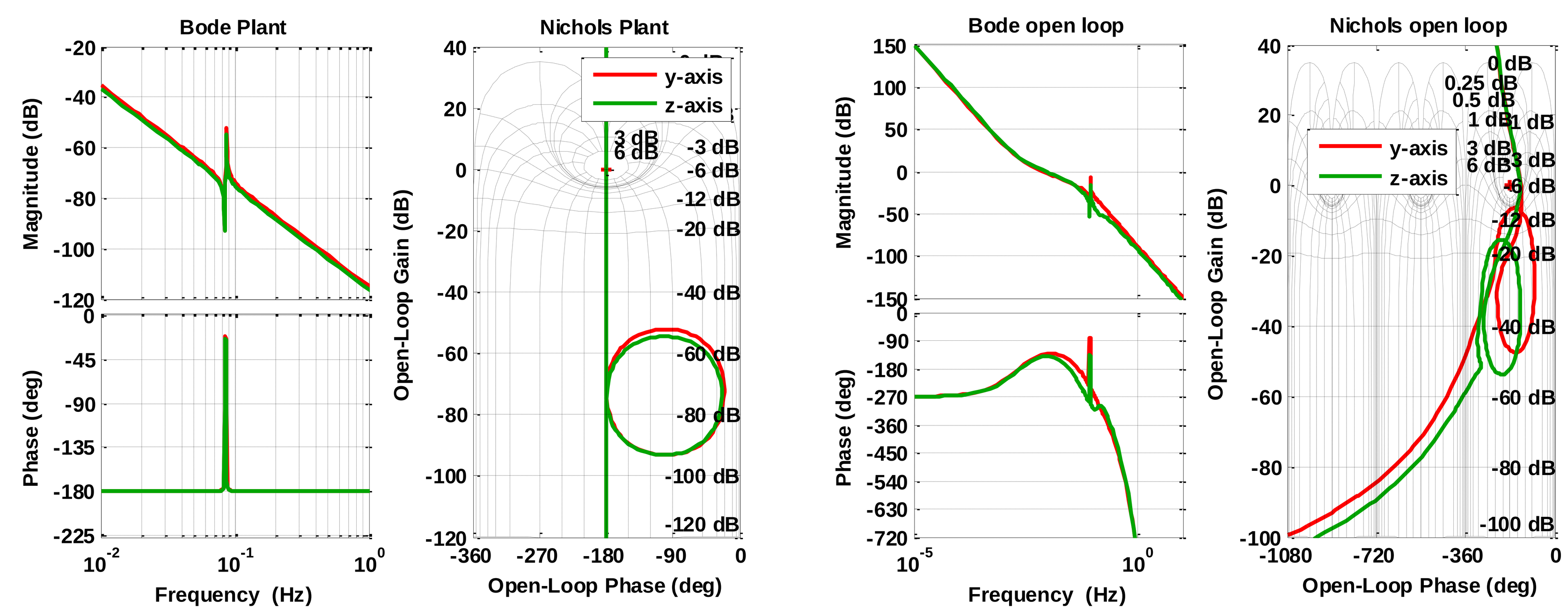
Sloshing Analysis

Sloshing Model for Controller Design and Performance Simulations

- Planar sloshing pendulum model used to include sloshing effect into S/C dynamic model and to derive equations of motion of complete system, including rigid-body part of the satellite, as well as fixed and moving (sloshing) part of the fuel
- Sloshing pendulum model implemented in Airbus Defence and Space standard multi-body dynamics modelling tool and used for controller tuning and analysis as well as for performance simulations in frequency and / or time domain

Controller Design and Analysis

- PID controller augmented with separate 2nd order low pass filter for the rate and the angular branch, followed by a lead/lag filter
- Closed loop bandwidth tuned (i.e. reduced) to cope with the delay mainly due to thruster sampling time (3s) and to stabilize the sloshing mode in Pitch and Yaw achieving sufficient gain margin
- Integral part assures steady-state attitude deviations close to zero, proportional gain is maximized and derivative gain is minimized in order to restrict the transient attitude overshoots
- Soft lead/lag filter applied for y-axis for reduction of first solar array flexible mode since low-pass filter frequency is increased for stabilization of sloshing modes



Conclusions

Process for propellant sloshing modelling during de-orbiting demonstrated:

- MetOp-SG will experience high-g sloshing
- High-g lateral sloshing model derived by use of numerical simulations and compared to semi-empirical models provided in literature
- Successful controller design and tuning under consideration of propellant sloshing and solar array modes

References

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