OBSIdian

On-Board System Identification for Uncertainty Modelling & Characterization

AO/1-9509/18/NL/GLC

Final Presentation

Agenda

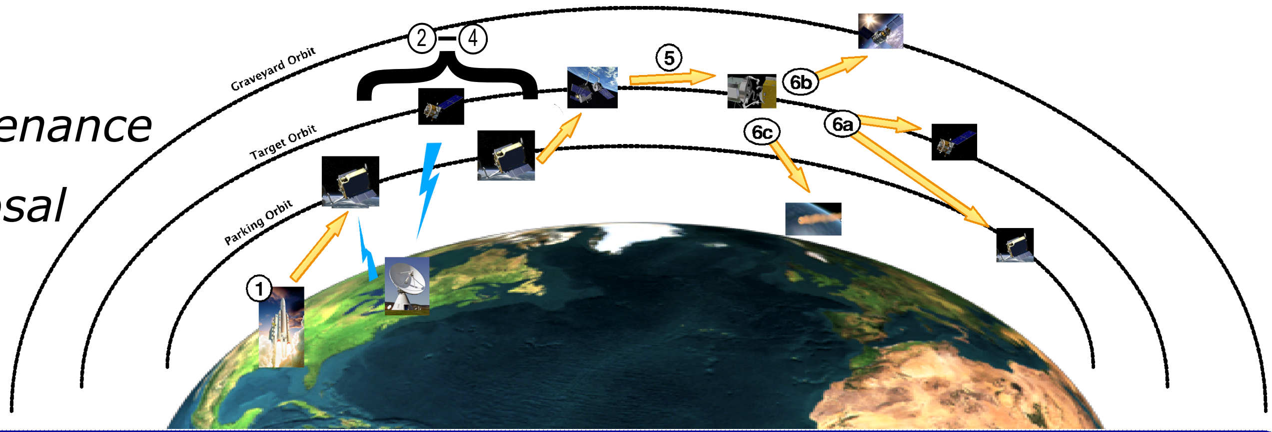
- 09.30 – 09.35 Welcome
- 09.35 – 09.48 Introduction
- 09.48 – 10.48 Benchmark Problems
- 10.48 – 10.58 Break
- 10.58 – 11.26 Study Cases
- 11.26 – 11.35 SYSID Detailed Design – 3D SC1
- 11.35 – 11.45 Sensitivity, Robustness, Sampling Considerations
- 11.45 – 11.48 Project Output Exploitation
- 11.48 – 11.51 Conclusions
- 11.51 – 11.53 Managerial
- 11.53 – 12.30 Discussion

Introduction

Problem Statement (1/5)

❑ *OOS Chaser-Target berthing-type mission*

- *Launch of Servicing satellite (Chaser)*
- *Phasing with Client (Target)*
- *Far Rendezvous sequence/ Homing*
- *Forced Motion/ Closing and Inspection*
- *Final Approach – Capture – Stabilisation – Docking*
- *OOS tasks*
  - *Orbital assembly*
  - *Satellite repair/ maintenance*
  - *Debris handling/ disposal*



Problem Statement (2/5)

- *Chaser and/ or Target parameters may be* ***unknown*** *or* ***uncertain***
  - Fuel consumption changes the sloshing model parameters
  - Temperature changes affects the flexible appendages modal parameters
  - Grasping of Target may result in uncertain change of system inertial parameters
  - Completely unknown Target parameters

Problem Statement (3/5)

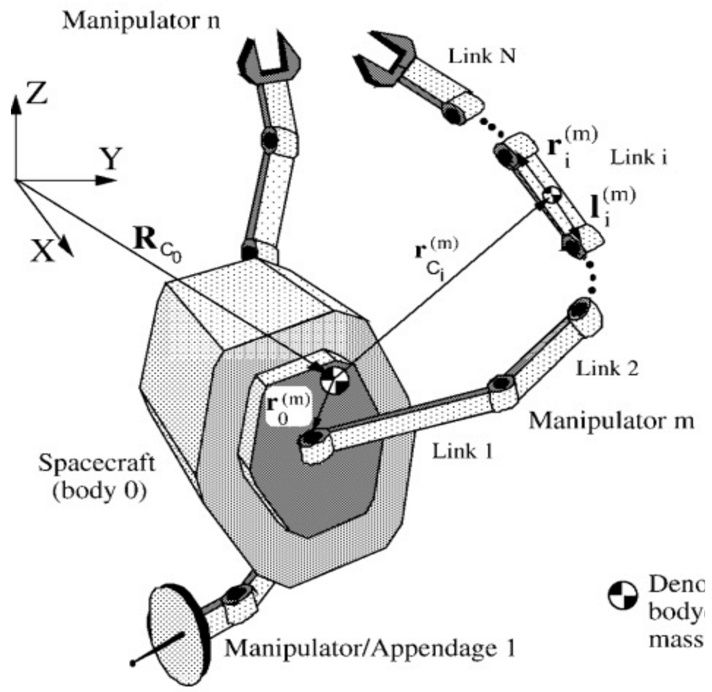
❑ *Parameter change/ uncertainty may be beyond the capabilities of a robust controller to cope with*

- Recalibration of the controller parameters

- Updated parameter estimates by means of a System Identification (SYSID) process

Problem Statement (4/5)

- *Berthing-type OOS mission can be achieved using a **Space Manipulator System** (SMS)*
  - Accurate control of the berthing fixture and the captured Target
  - Complex system
  - We opted to work with an SMS, but results are general
  - Uncertainty types considered:
    - System inertial parameters
    - Fuel sloshing model parameters
    - Flexible appendage modal parameters



Problem Statement (5/5)

- *Inspection and Forced Motion stage (off-line PI)*
  - Chaser subsystems parameters (inertial/ flexible)
  - Chaser fuel sloshing
- *Capture – Mating/ OOS tasks stage (on-/ off-line PI)*
  - Target subsystems parameters (inertial/ flexible)
  - Target fuel sloshing
- *Level of realism vs. Complexity*
- *Not everything can be "unknown"*

OBSIdian Framework

Step 1 — SYSID Bibliography Research

- Identify pros and cons of the various existing Algorithms
- For Nodal and Modal parametric SYSID

Step 2 — Benchmark Problems Simulations

- Each Benchmark Problem (BP) considers only a single uncertainty type
- Novel Methods for implementing SYSID Algorithms
- Trade-off of the various SYSID Algorithms performance, based on simplified, planar BP cases

Step 3 — Benchmark Problems Experiments

- Performed on the consortium experimental facilities
- Significant insight on the developed Methods and selected Algorithms, is gained

Step 4 — Study Cases

- Each Study Case (SC) considers all types of uncertainty simultaneously
- Developed SYSID schemes capabilities and limitations are identified

Benchmark Problems Considered

Benchmark Problem 1 (BP1A)	Benchmark Problem 1 (BP1B)	Benchmark Problem 2 (BP2)	Benchmark Problem 3A (BP3A)	Benchmark Problem 3B (BP3B)
Identification of inertial parameters (no sloshing, no flexibilities)	**Identification of inertial parameters** (no sloshing, no flexibilities)	**Identification of sloshing model parameters** (known satellite, no flexibilities)	**Identification of appendages modal parameters** (known satellite, no sloshing)	**Identification of appendages modal parameters** (known satellite, no sloshing)
Experimental Identification Excitation is user's choice	**Experimental Identification** Excitation is user's choice	**Experimental Identification** Excitation is user's choice	**Experimental Identification** Excitation is user's choice	**Operational Identification** Excitation by the task
Non-recursive SYSID (Parametric Identification Algorithm)	**Non-recursive SYSID** (Parametric Identification Algorithm)	**Non-recursive SYSID** (Parametric Identification Algorithm)	**Non-recursive SYSID** (EMA)	**Recursive SYSID** (OMA)
Model 2D free-floating space robot (manipulator joints actuated only)	**Model** 2D free-flying space robot (active manipulator, thrusters and RWs)	**Model** 2D satellite and 2D sloshing models	**Model** 2D flexible appendage on hub	**Model** 2D flexible appendage on hub

Study Cases Considered

Study Case 1 (SC1)		Study Case 2 (SC2)	
Full System Identification i.e., identification of inertial parameters, sloshing parameters, and modal parameters of flexible appendages simultaneously (to the extent possible)			
Phase 1 Motion before capture		**Phase 2** Motion after rigid capture-during berthing	
Experimental Identification Excitation is user's choice		**Operational Identification** Excitation by the task	
Non-recursive SYSID (Parametric Identification Method for lumped models + EMA for continuous models)		**Recursive SYSID** (Parametric Identification Method for lumped models + OMA for continuous models)	
3D Simulation	2D Experiments	3D Simulation	2D Experiments

SYSID Algorithms (1/5)

- Types of SYSID approaches

  - **White-box** Models and SYSID
    - Both *Physical Laws and Model Structure are known*
    - e.g., system dynamics equations of motion
  - **Grey-box** Models and SYSID
    - *Physical Laws are known*, while *Model Structure is partially unknown*
    - e.g., linear models, LPV models etc. of a nonlinear system
  - **Black-box** SYSID
    - Both *Physical Laws and Model Structure are unknown*
    - More a “curve-fitting” describing the input-output system behaviour

SYSID Algorithms (2/5)

- More than 50 Parametric, Non-parametric and Modal SYSID Algorithms were considered
  - Based on their basic characteristics, many were discarded outright

- 15 Parametric, 2 Non-Parametric and 19 Modal SYSID Algorithms were considered further
  - Trade-off analysis, based on a detailed study of each algorithm's characteristics

SYSID Algorithms (3/5)

- 4 Parametric and 5 Modal SYSID Algorithms chosen as appropriate candidates for a final trade-off

  - Parametric SYSID Algorithms: UKF, IV, PEM, TLS

  - Modal Analysis Algorithms: FSDD, RFP, LSCE, SSI-COV, SSI-DATA

SYSID Algorithms (4/5)

- Trade-off to be based on Performance Metrics

  - Computational Effort: FLOPS and Big-O Notation
  - Relative % error: Parametric error with respect to "true" value
  - Convergence rate also was initially considered but is valid for recursive SYSID only

SYSID Algorithms (5/5)

- SYSID Parametric Algorithms must be applied on equations that characterize the system
  - Equations of motion
  - Energy balance
  - Angular momentum conservation (when applicable)
  - Transfer function (when applicable)

- Choice of appropriate equation is not trivial
  - Constitutes the SYSID scheme Method
  - Results in the required Regressor Formulation

- Different SYSID Algorithms (regressor-based or not)
  - Constitutes the SYSID scheme Algorithm

Benchmark Problems

Basic Considerations (1/4)

- Sensors
  - IMU
  - Motor encoders
  - Flexible appendage accelerometers
  - Sun- Star-trackers (for full scale system) or PhaseSpace MoCap system (for SRE)
  - Realistic noise models employed
- Actuators
  - Joint motors
  - Reaction wheels
  - Thrusters

Basic Considerations (2/4)

❑ Signal Conditioning

- Low – pass filters applied: ‘designfilt’ MATLAB function
    - Pass dominant system dynamics, & filter noise, to the extent possible
    - First order low-pass Infinite Impulse Response (IIR)
    - Filter cut-off frequencies chosen using signal FFT’s
    - Cut-off frequencies values depend on sensor

Basic Considerations (3/4)

Planar Full-scale System Models (simulations)

- ❑ Final trade-off of the chosen SYSID Algorithms
- ❑ Insight on the SYSID Algorithms requirements
- ❑ Develop appropriate Methods to apply the chosen Algorithms

Planar Experiments (scaled-down consortium facilities)

- ❑ Significant insight on the SYSID Algorithms and developed Methods requirements, capabilities and limitations

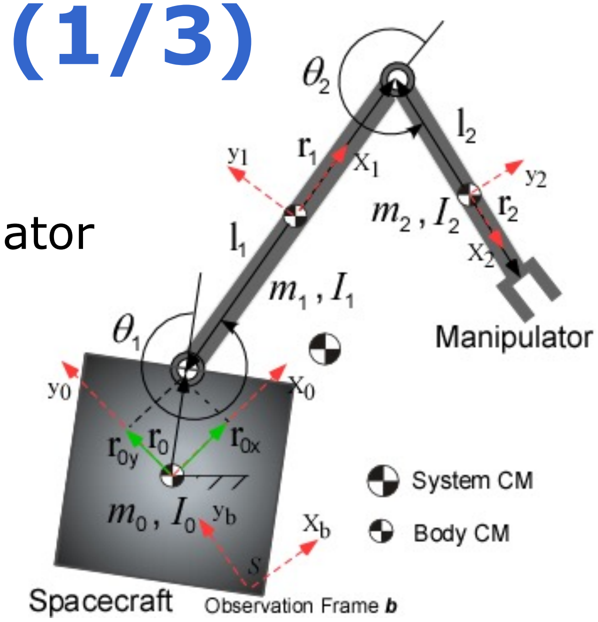
Basic Considerations (4/4)

Experimental Setups Models (simulated experiments)

Simulated experiments performed with the aim to:

- Validate the developed Analytical Models
- Design of excitation signal to be used for the h/w experiment
- Gain knowledge on the behaviour of the experimental set-up (limitations, sources of error, etc.) and on the SYSID algorithm
- Validate the Experimentally Identified Models, using Analytical and/ or SimScape models

BP1: Full-scale planar system (1/3)



Model

2D Space Manipulator System (SMS) with a single manipulator

Modelling Assumptions

- Rigid S/C and manipulator

SMS operational modes

- Free-floating mode (**BP1A**): Only manipulator joints actuated
- Free-flying mode (**BP1B**): Manipulator joints actuated, S/C thrusters and reaction wheels active

Goal

Estimation of SMS inertial parameters (combination sets)

- Full reconstruction of free-floating dynamics (BP1A) or of free-flying dynamics (BP1B)

BP1: Full-scale planar system (2/3)

BP1A Methods and Algorithms

- TLS on regressor formulation of angular momentum conservation (M1-TLS)
- TLS on regressor formulation of equations of motion (M2-TLS)
- IV on regressor formulation of angular momentum conservation (M1-IV)
- IV on regressor formulation of equations of motion (M2-IV)
- PEM
- UKF

Trade-off Analysis Result

The best algorithm and method combination for **BP1A** is M1-TLS.

- Max Rel. Error: 1.19%
- RMS Rel. Error: 0.48%

BP1: Full-scale planar system (3/3)

BP1B Methods and Algorithms

- TLS on regressor formulation of equations of motion (M1-TLS)
- TLS on regressor formulation of energy balance equation (M2-TLS)
- IV on regressor formulation of equations of motion (M1-IV)
- IV on regressor formulation of angular momentum conservation (M2-IV)
- PEM
- UKF

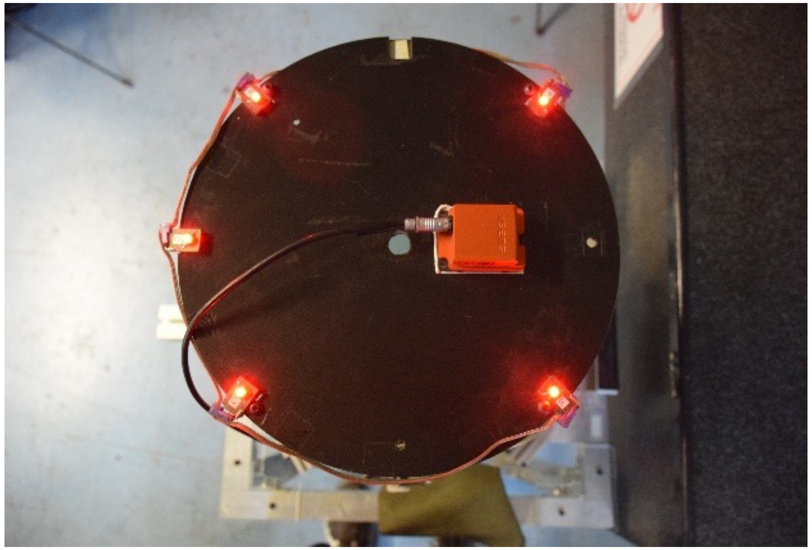
Trade-off Analysis Results

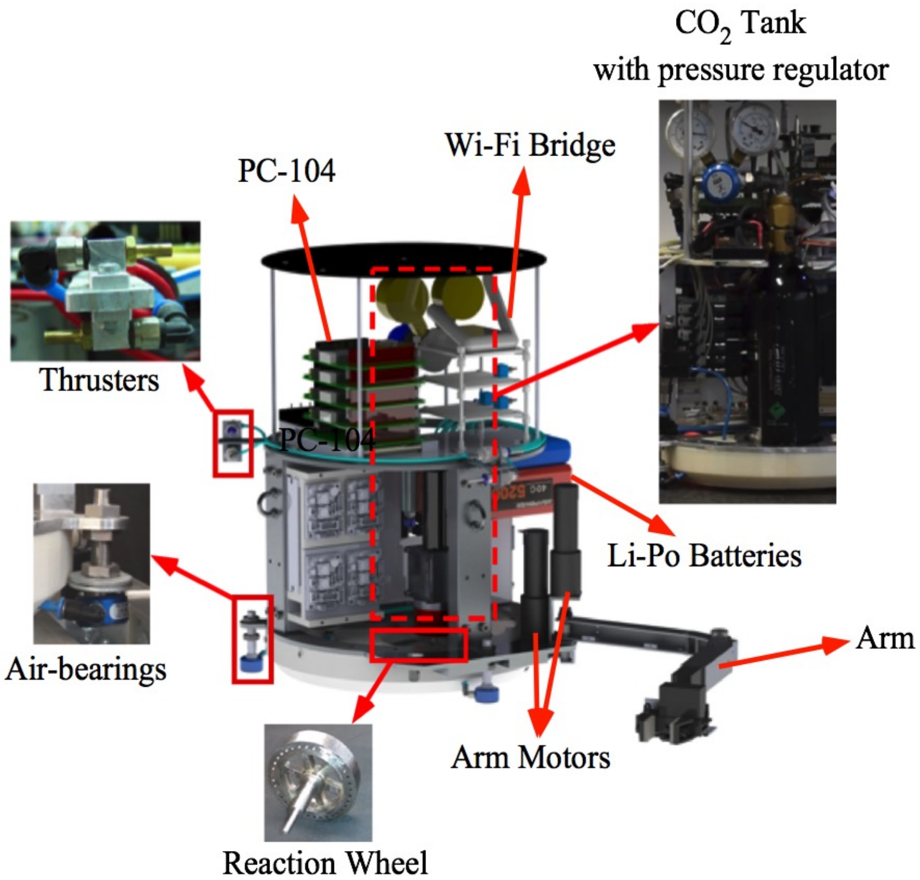
The best algorithm and method combination for BP1B is M2-TLS.

- Max Rel. Error: 2.63%
- RMS Rel. Error: 1.10%

Thus, the best algorithm **for *both* BP1A and BP1B** is **TLS**.

BP1: Experimental Facility & Model (1/4)

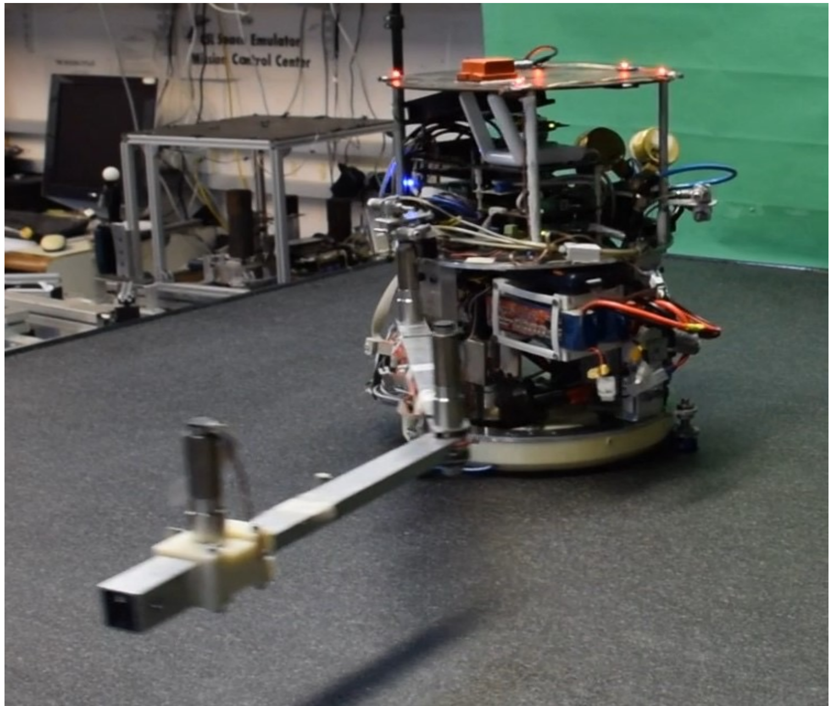




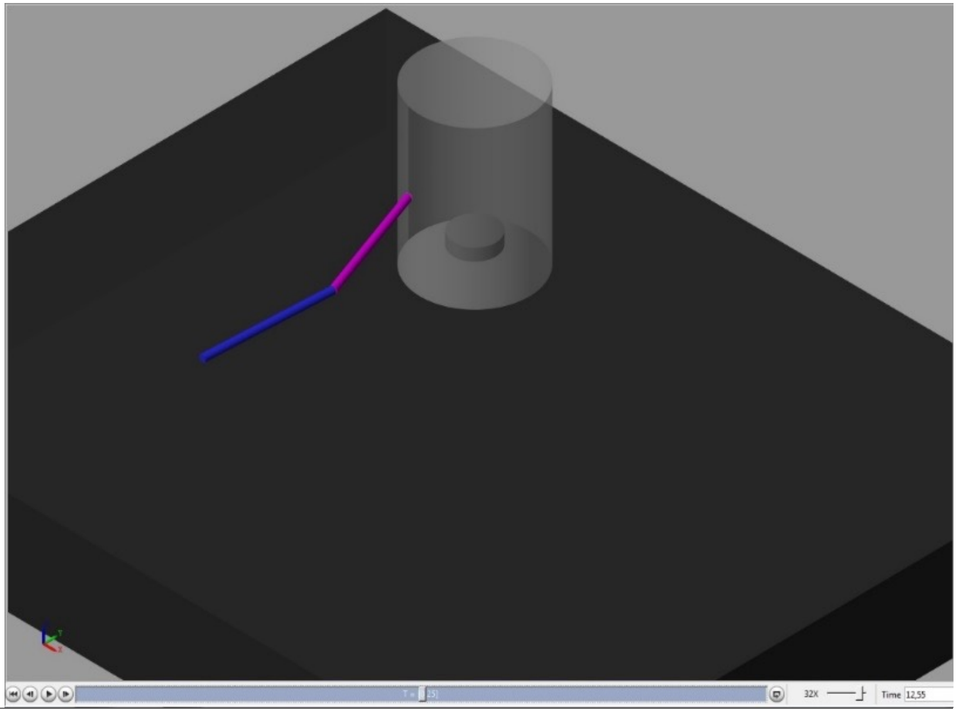
Component	Mass	Notes
Robotic System w/o Manipulator	14 kg	N/A
Robotic System w/t Manipulator	15 kg	N/A
Empty plastic Tank	500 g	N/A
Solar Panel	440 g	N/A
CO_2 Tank (empty) CO_2 Tank (full)	800 g 1500 g	Pressure: 7 bar

BP1: Experimental Facility & Model (2/4)

- Inertial parameters in accordance with those of Cepheus
- Sensors and actuators in accordance with Cepheus



Cepheus

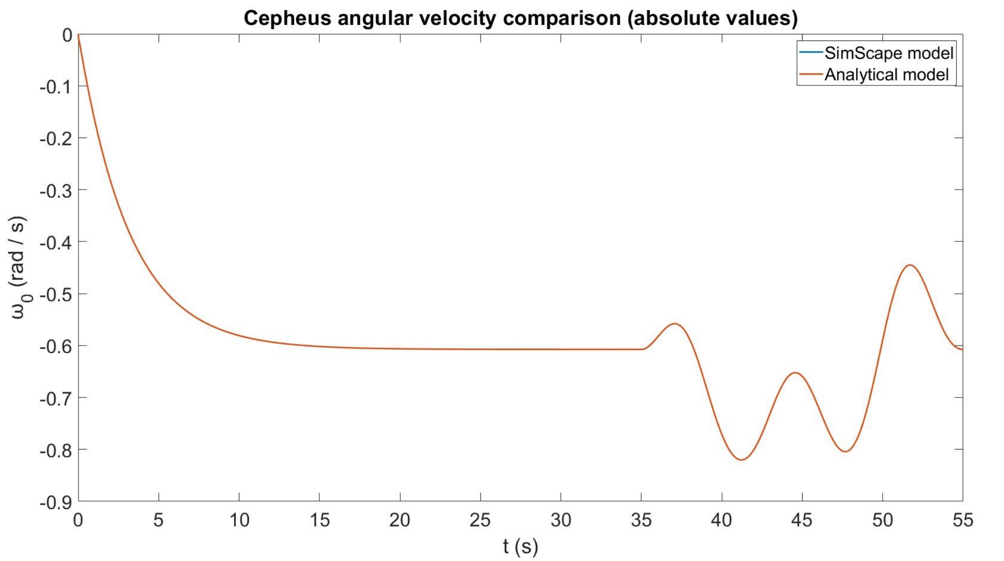


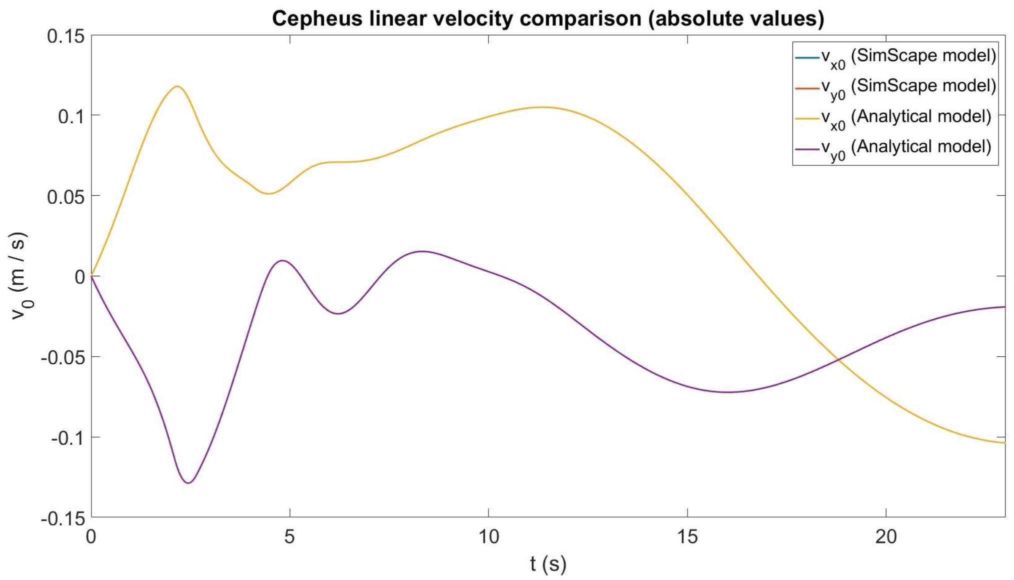
SimScape

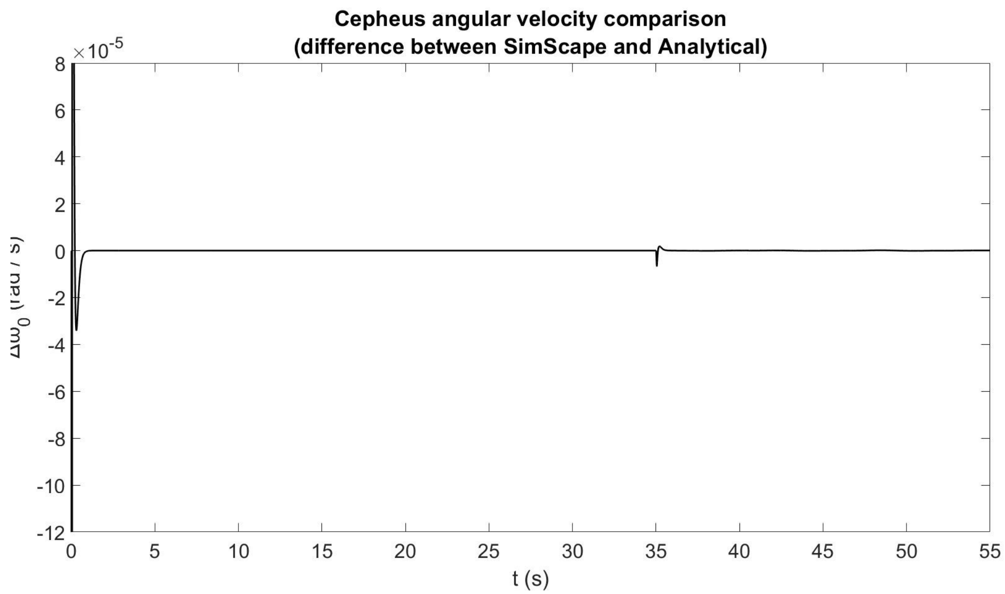
BP1: Experimental Facility & Model (3/4)

- Model response comparisons
  - Analytical vs. Simscape
  - with the same excitation
- Responses identical =>

analytical Cepheus model verified







BP1: Experimental Facility & Model (4/4)

- BP1A **Method** based on System Angular Momentum Conservation

$$\mathbf{Y}\left(\dot{\theta}_1,\dot{\theta}_2,\theta_1,\theta_2,{}^0\omega_{0z}\right)\mathbf{a} = \mathrm{h}_{cm}$$

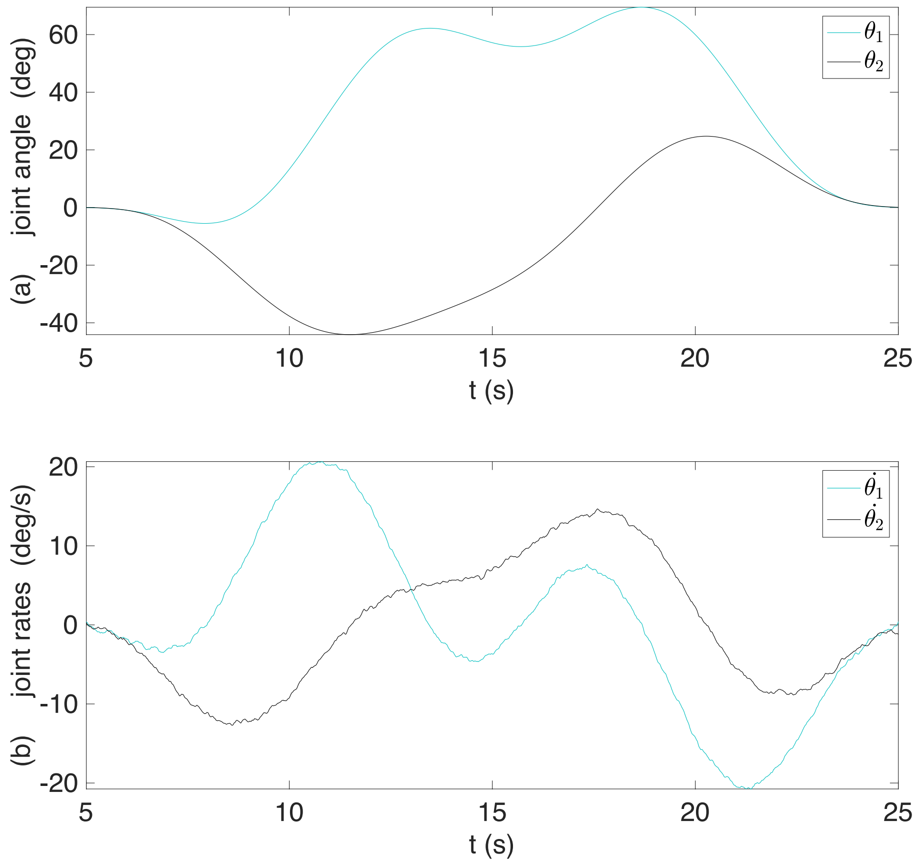
- BP1B **Method** based on System Energy Balance

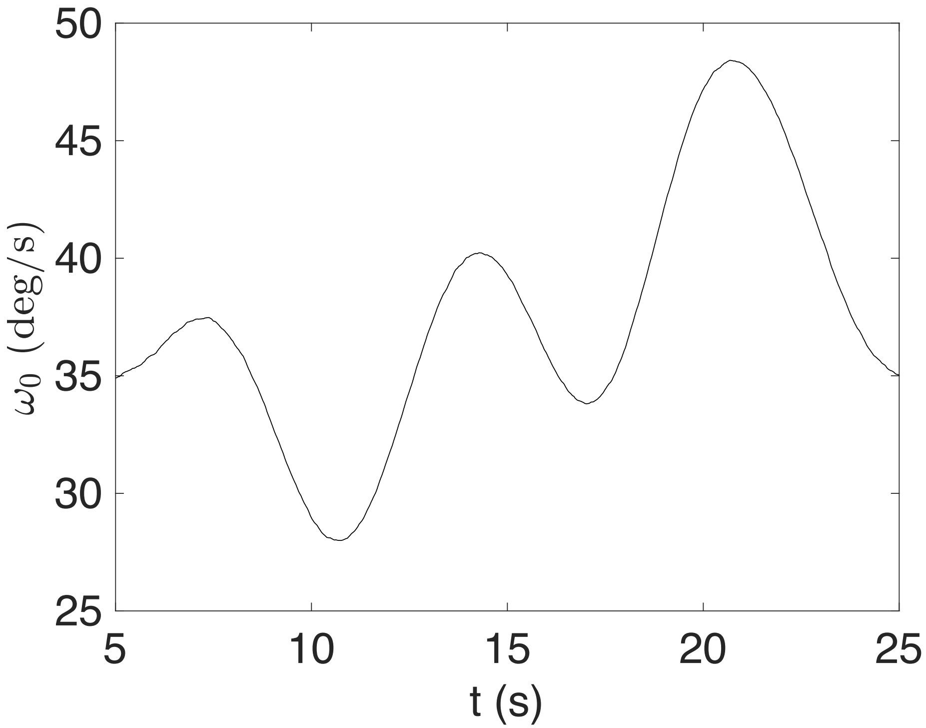
$$\mathbf{Y}\left(\dot{\theta}_1,\dot{\theta}_2,\theta_1,\theta_2,{}^0\omega_{0z}\right)\mathbf{a} = b$$

SYSID Measurements Required	Sensor	Unit
S/C angular velocity	IMU	rad/s
S/C linear velocity	Computed	m/s^2
Manipulator joint angles	Motor encoders	rad
Manipulator joint rates	Computed	rad/s

BP1A: Excitation & simulated response

- **RW** PI Control on $\dot{\theta}_{rw,des} = 150\ rad/s = 1432.4\ rpm$
- **Manipulator** PD control on $\theta_{i,des}$ -> Fourier series: coefficients obtained by minimizing regressor matrix condition number



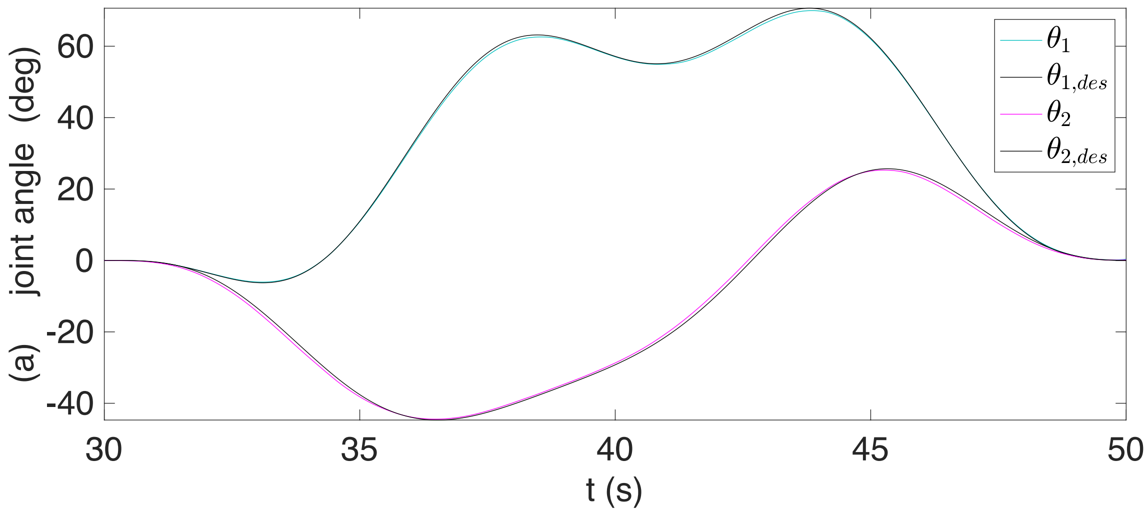


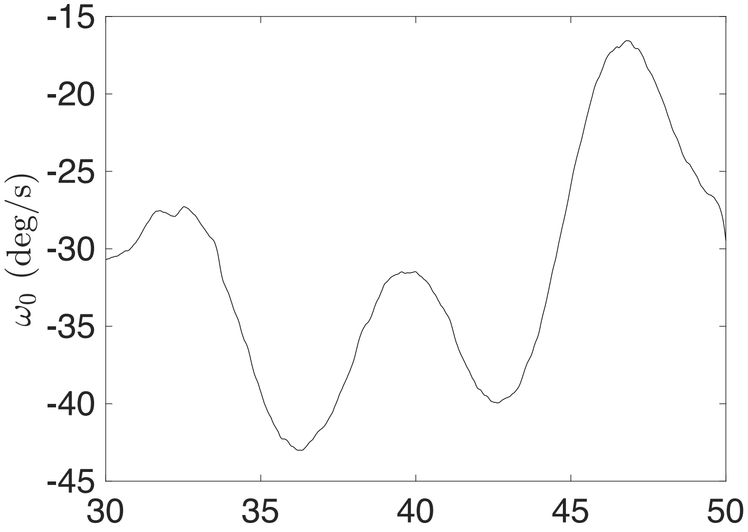
BP1A: SYSID Results (simulation)

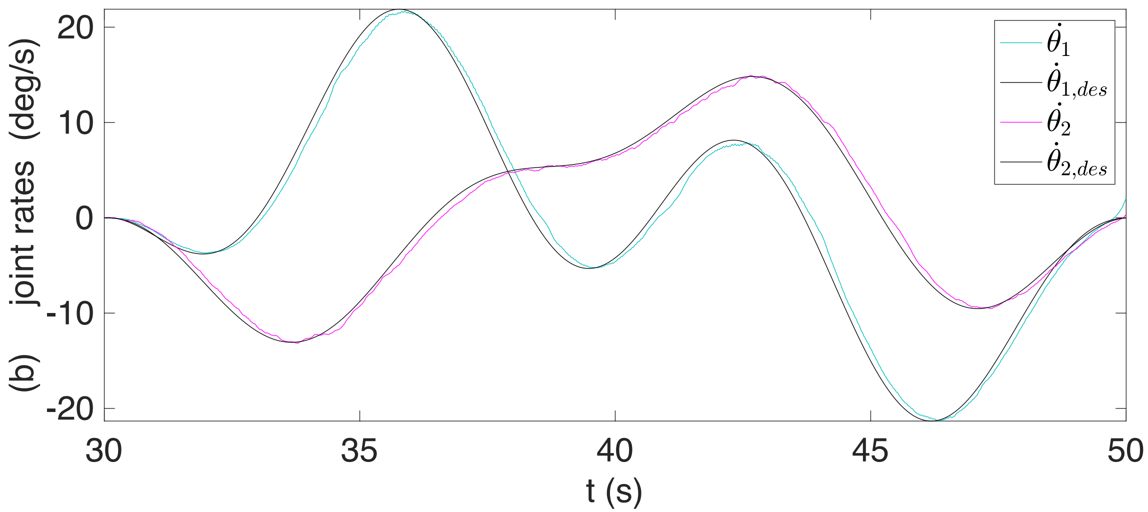
Parametric SYSID by TLS (Algorithm) on Angular Momentum Conservation (Method)

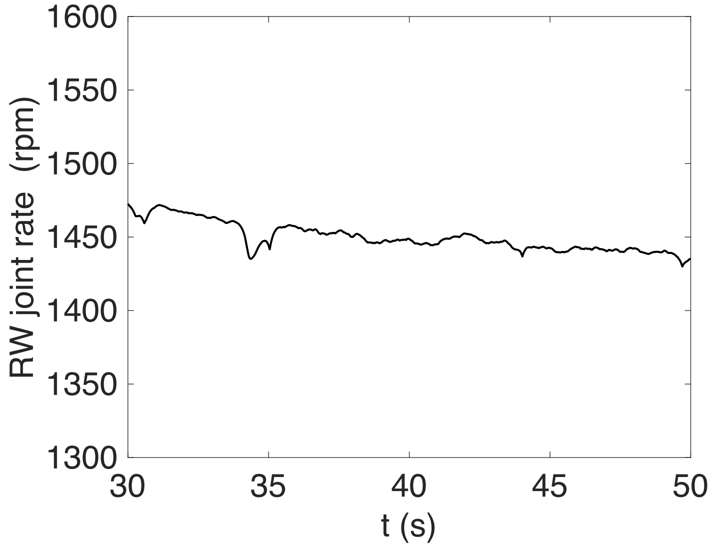
Parameter	True Value	Estimated Value	Relative error (%)
a_1	0.041	0.038	**5.819**
a_2	0.014	0.014	2.57
a_3	0	-0.0008	-
a_4	0	-0.0001	-
a_5	0.200	0.202	0.779
a_6	0.033	0.033	0.107
a_7	0.087	0.089	2.498
a_8	0.025	0.024	1.703

BP1A: Excitation & experimental response









BP1A: SYSID Results (experiment)

Parameter	Estimated Value
a_1	0.030
a_2	0.024
a_3	-0.032
a_4	0.044
a_5	0.248
a_6	0.015
a_7	0.09
a_8	0.109

- The "true" system parameters can be obtained by the system detailed CAD drawings
- Discrepancies do exist between the CAD and the real system
- It is more appropriate that the validity of the identified model to be evaluated using the validation strategy described next

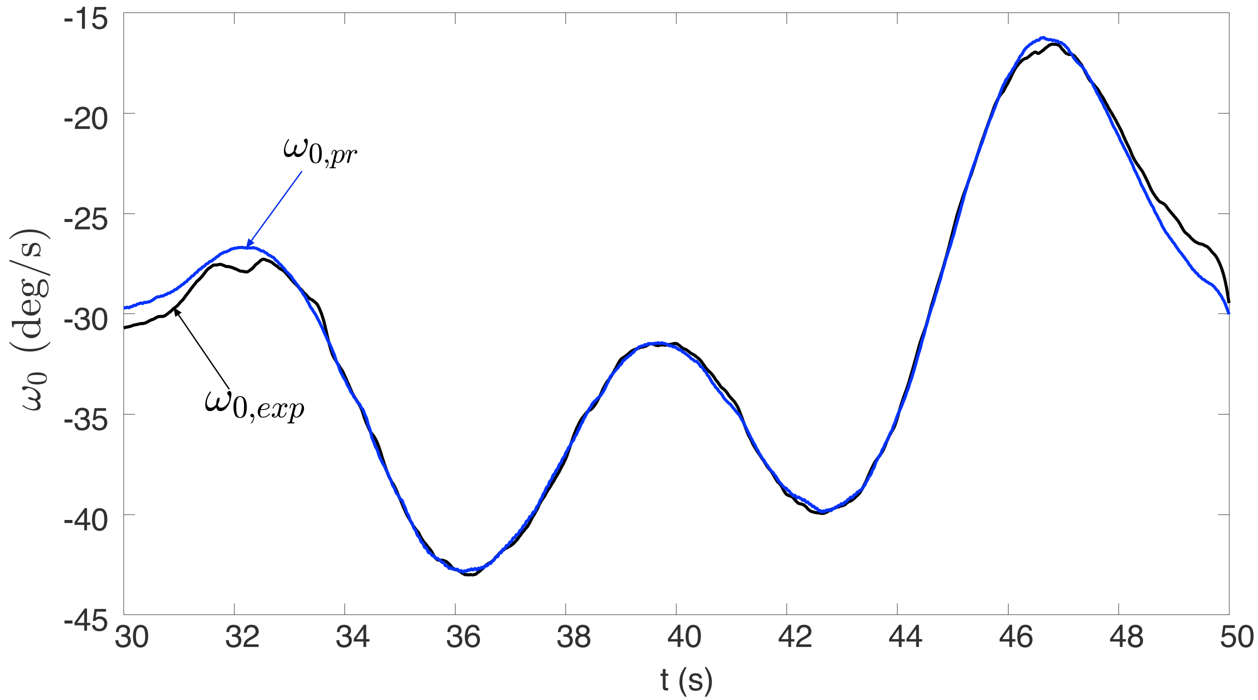
BP1A: Modelling Validation

- Identification Experiment: Experimental vs. Simulated Setup
  - Same excitation
  - Qualitative comparison: $\omega_{0,\exp}$ vs. $\omega_{0,pr} = D^{-1}\left(-I_{rw}\,\dot{\theta}_{rw} - \mathbf{D}_q\,\dot{\boldsymbol{\theta}}\right)$

- Simulated model is based on identified values

- **Very good match**

- The identified parameters can be used to reconstruct the system motion



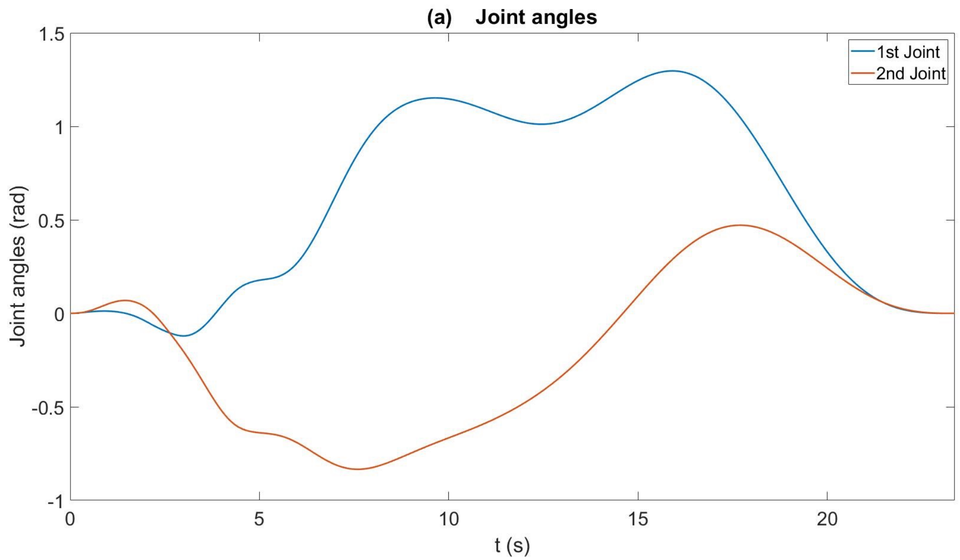
BP1A: Discussion

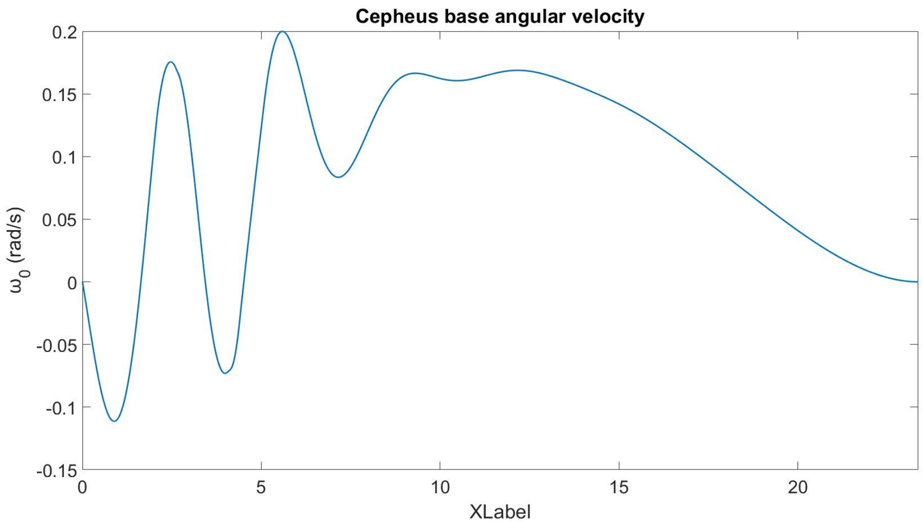
- Simulated data: Parametric SYSID (Agular Momentum & TLS)
  - Results within (or marginally outside in a single case) the acceptable relative error margin of 5%
  - The execution of the BP1A simulated experiment is deemed as **successful**
- Experimental data: Parametric SYSID (Agular Momentum & TLS)
  - Though some parameter clusters were identified acceptably, others were identified with somewhat large relative errors
  - However, system reconstruction based on the identified parameters with the experimental data, was successful
  - Simulated identified system response matching the experimental system response very well

BP1B: Excitation & simulated response

- Coordinated model-based PD control for Cepheus base position and attitude, and manipulator configuration

    - Cepheus position desired trajectory: sinusoidal in x-y plane
    - Cepheus attitude desired trajectory: 5th order polynomial
    - Desired joint-angles trajectory: Fourier series



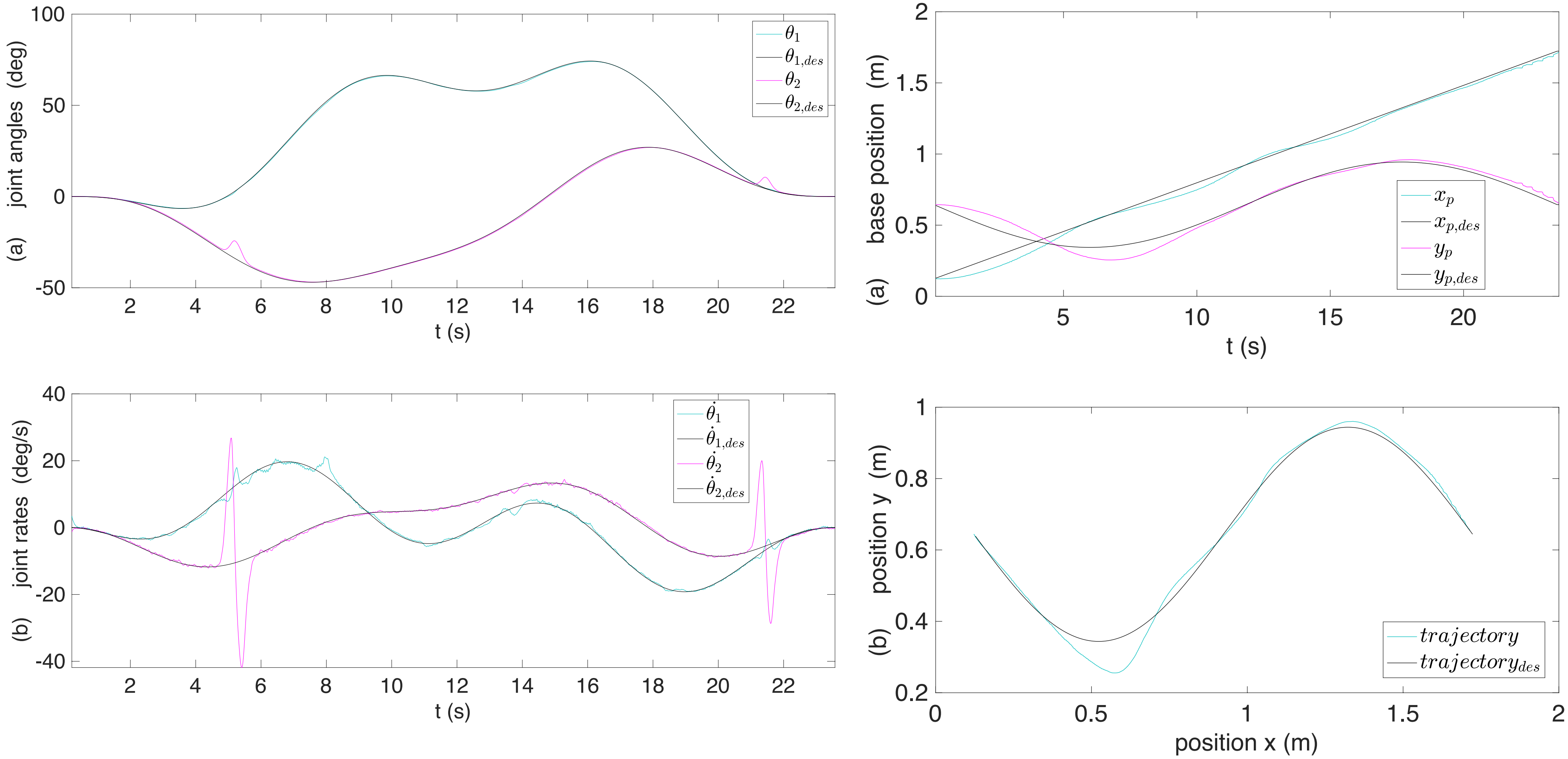


BP1B: SYSID Results (simulation)

Parametric SYSID by TLS (Algorithm), Energy Balance Equation (Method)

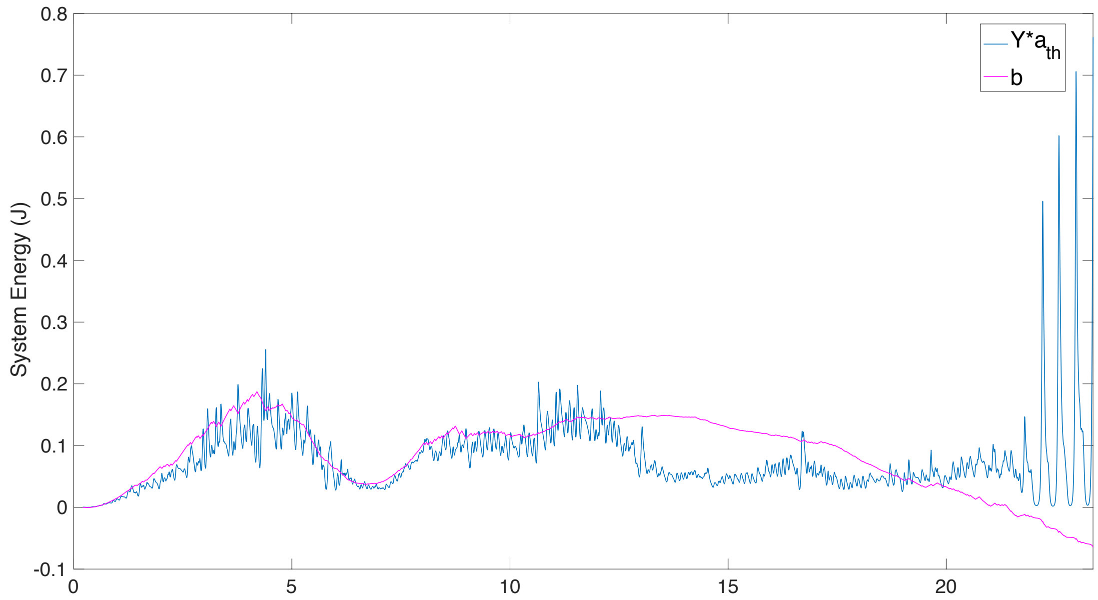
Parameter	True Value	Estimated Value	Relative error (%)
a_1	13.828	13.983	1.1213
a_2	2.1385	2.1734	1.6301
a_3	0	-0.074213	-
a_4	0.26194	0.25793	1.5325
a_5	0.093208	0.076095	**18.361**
a_6	0.90348	0.97262	7.6527
a_7	0.034487	0.046775	**35.631**
a_8	0.091739	0.087453	4.6718
a_9	0.025426	0.019914	**21.678**

BP1B: Excitation & experimental response



BP1B: SYSID Results (experiment)

- The "true" system parameters can be obtained by the system detailed CAD drawings
- Results with data from the first 12s.



Parameter	Value from CAD	TLS Estimated Value Fmax=0.6N	TLS Estimated Value Fmax=0.42N
a_1	13.83	23.73	16.90
a_2	2.14	4.75	3.39
a_3	0.00	-5.95	-4.38
a_4	0.26	3.33	2.20
a_5	0.09	-1.25	-0.83
a_6	0.91	5.74	4.33
a_7	0.03	0.36	0.27
a_8	0.09	0.37	0.25
a_9	0.03	-0.56	-0.39

BP1B: Modelling Validation

- Modelling for BP1B validated already in BP1A, except for the thrusters
  - Each thruster-valve pair has been calibrated and tested, using a high-quality ATI force/torque sensor
  - Thruster forces follow the command given
  - In prolonged use and when many of them fire simultaneously, their thrust may be reduced
- Modelling validation for BP1B is complete, except for thruster action consideration

BP1B: Discussion

- Simulated data: Parametric SYSID (Energy Balance & TLS)
  - Most of the results within the acceptable relative error margin of 5%, or close to it (7.6%)
  - Three results with larger relative errors of 18.4%, 21.7% and 35.6%
  - Limitations in excitation and sensors result in marginal SNR

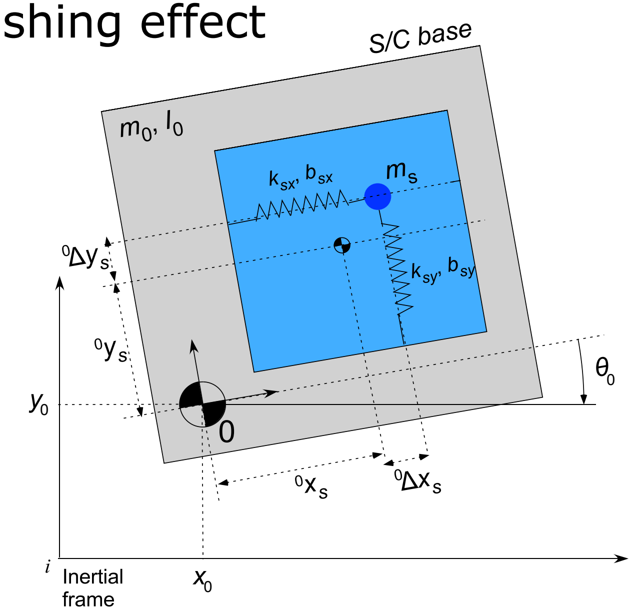
- Experimental data: Parametric SYSID (Energy Balance & TLS)
  - Most parameter clusters identified with large relative errors
  - Low SNR, comparison with CAD “true” values, and inaccurate knowledge of the excitation force, are the main reasons

BP2: Full-scale Planar System (1/5)

Model

2D Spacecraft (S/C) with mechanical equivalent model to represent sloshing effect

- **Sloshing Model**: mass-spring-damper to represent sloshing effect
- Sloshing parameters "true" values based on CFD model



Assumptions

- S/C inertial parameters assumed known
- S/C states are measurable

Main challenge

- Sloshing parameters need to be identified in the presence of unmeasured states
- Sloshing states are not measurable

Additional challenge: Lack of existing methodologies

BP2: Full-scale Planar System (2/5)

Goal

Develop a method that overcomes the challenges and identifies the sloshing parameters

Contribution

Development of novel methods M1, M2, M3 based on regressor formulation

Design of sloshing SYSID Experiment

- Developed methods M1, M2, M3 eliminate the need for unmeasurable sloshing states
- In this presentation, focus on M2
- Pure translational motion of the system enables the elimination

BP2: Full-scale Planar System (3/5)

- Framework of novel method **M2**

Step 1

System Equations of motion - Set I

- Contains all sloshing parameters
  -> Selected as **SYSID equations**

Contains the S/C **measurable** states!

- Contains the unmeasurable sloshing states!

Step 2

Transfer function formulation

- Pure translational motion allows this formulation!
  (Nonlinear System -> Linear System)
- Elimination of the unmeasurable sloshing states!
- Contains all sloshing parameters
- Contains only S/C **measurable** states!

Step 3

Conversion to time domain and double integration

Step 4

Regressor Formulation

$$\mathbf{Y}_s \boldsymbol{\alpha}_s = b_s$$

BP2: Full-scale Planar System (4/5)

BP2 Methods and Algorithms

- TLS on regressor formulation-method M1 (M1-TLS)
- TLS on regressor formulation-method M2 (M2-TLS)
- TLS on regressor formulation-method M3 (M3-TLS)
- IV on regressor formulation-method M1 (M1- IV)
- IV on regressor formulation-method M2 (M2-IV)
- IV on regressor formulation-method M3 (M3- IV)
- UKF
- PEM

Trade-off Analysis Results

The best algorithm and method combination for BP2 is **M2-TLS**.

- Max Rel. Error: 3.09%
- RMS Rel. Error: 2.59%

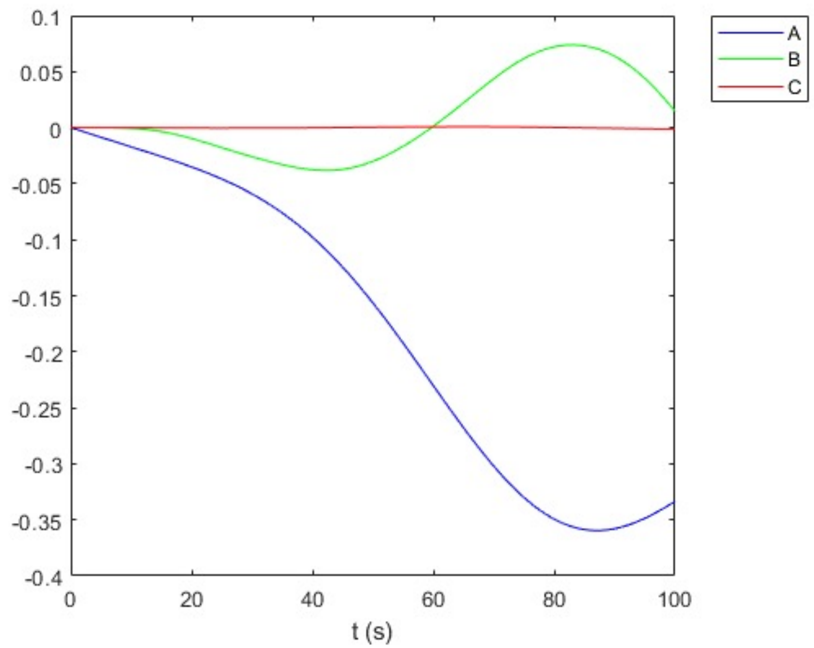
BP2: Sensitivity Analysis

- If e is the difference between the response of a system based on the identified parameters and the response of the system with the "true" parameters, then

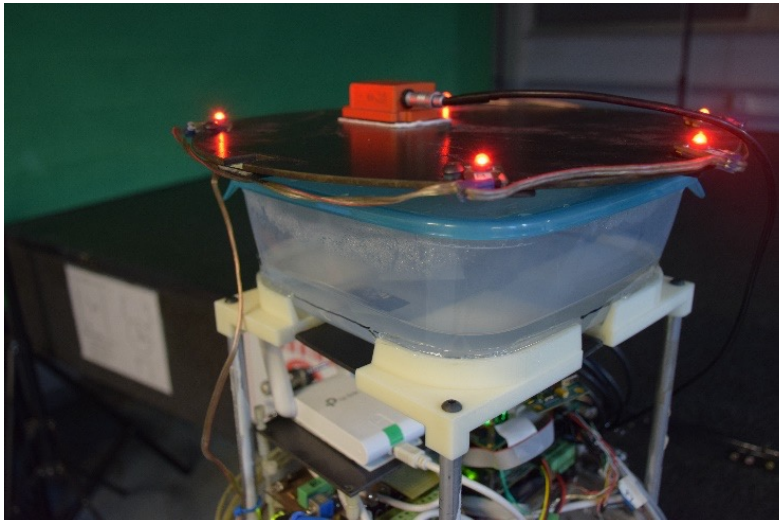
$$e = {}^{0}x_{0}(t, m_{s}, k_{sx}, b_{sx}) - {}^{0}x_{0}(t, \overline{m}_{s}, \overline{k}_{sx}, \overline{b}_{sx})$$
$$= A(t)\varepsilon_{m} + B(t)\varepsilon_{k} + C(t)\varepsilon_{b}$$

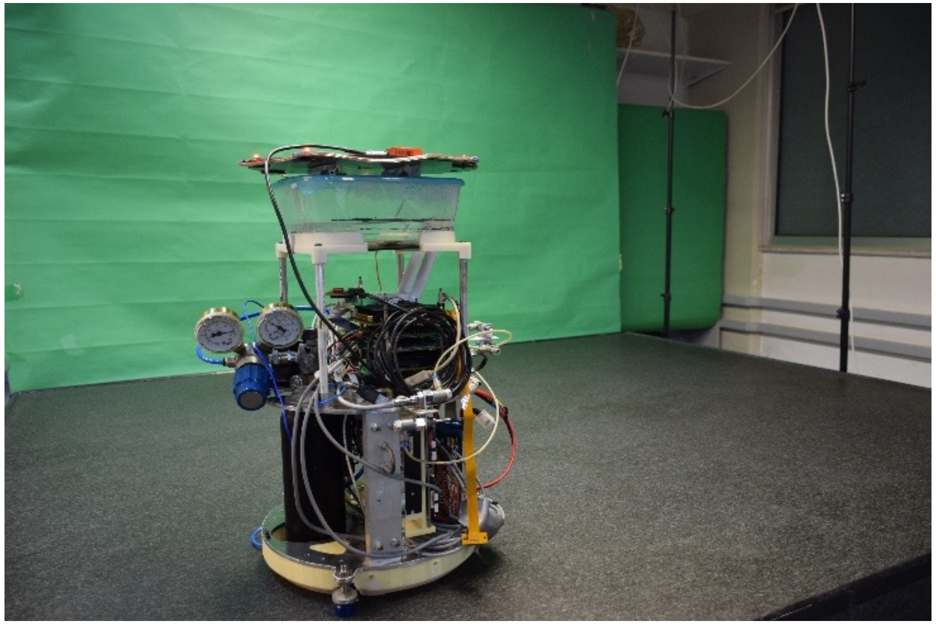
where $\varepsilon_{m_s}, \varepsilon_{k}, \varepsilon_{b}$ are the relative errors of the identified sloshing parameters m_s, k_{sx}, b_{sx} respectively, and A(t), B(t) and C(t) are time-dependent coefficients

- Coefficient C(t), has negligible effect



BP2: Experimental Facility & Model (1/3)



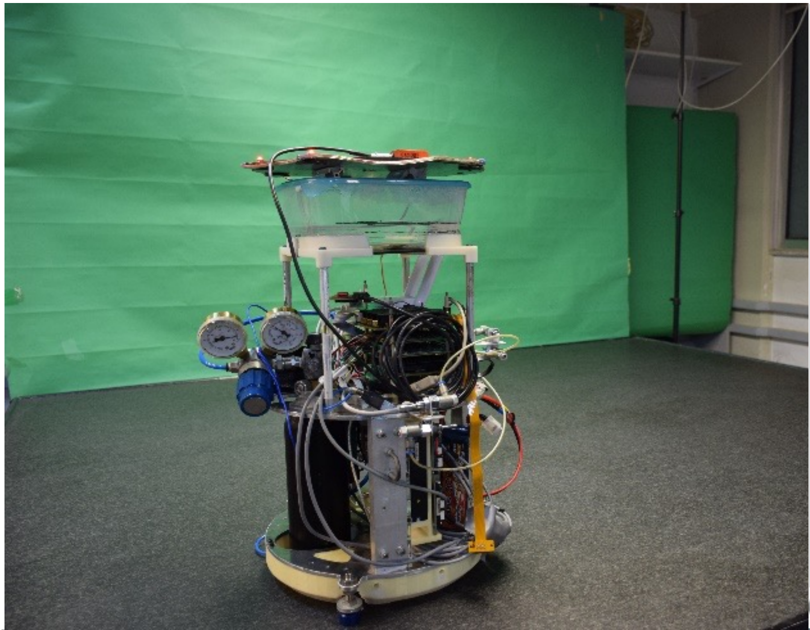


- ❑ **No manipulator**

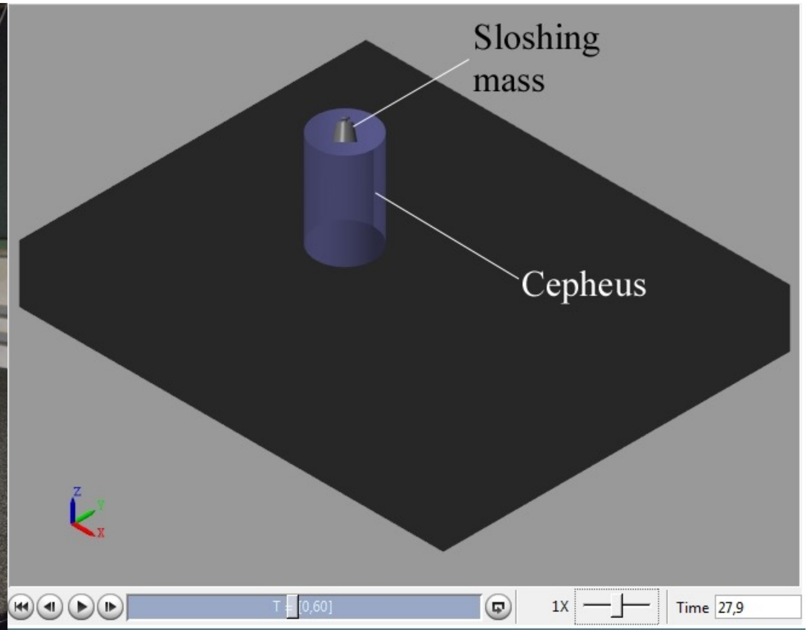
Component	Mass	Notes
Robotic System w/o Manipulator	14 kg	N/A
Robotic System w/t Manipulator	15 kg	N/A
Empty plastic Tank	500 g	N/A
"Fuel" (water)	800 g	N/A
CO_2 Tank (empty) **CO_2 Tank (full)**	800 g 1500 g	Working pressure: 7 bar

BP2: Experimental Facility & Model (2/3)

- Inertial parameters, sensors and actuators: those of Cepheus
- Mass-spring-damper parameters in accordance with CFD model



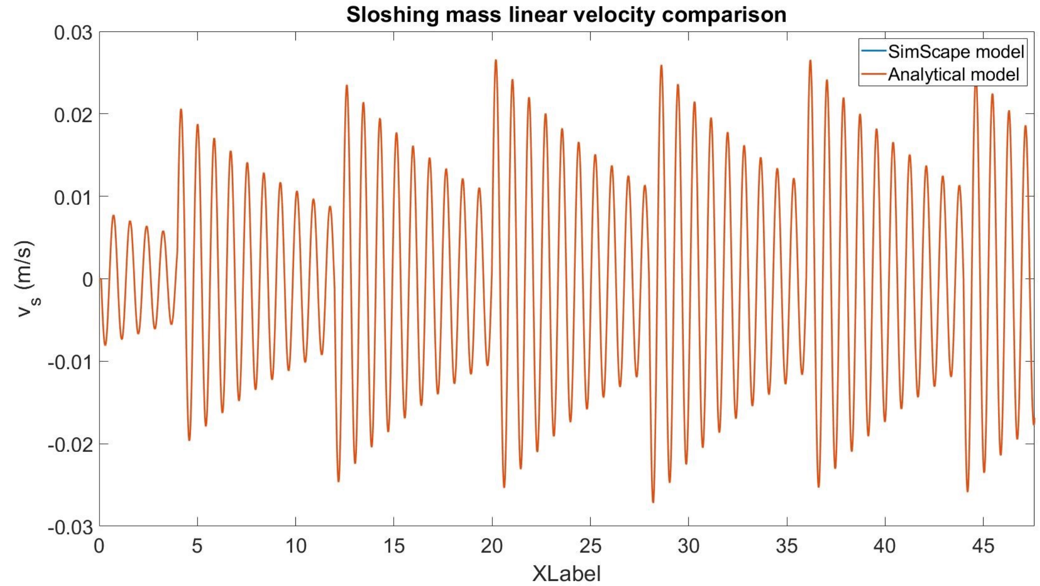
Cepheus

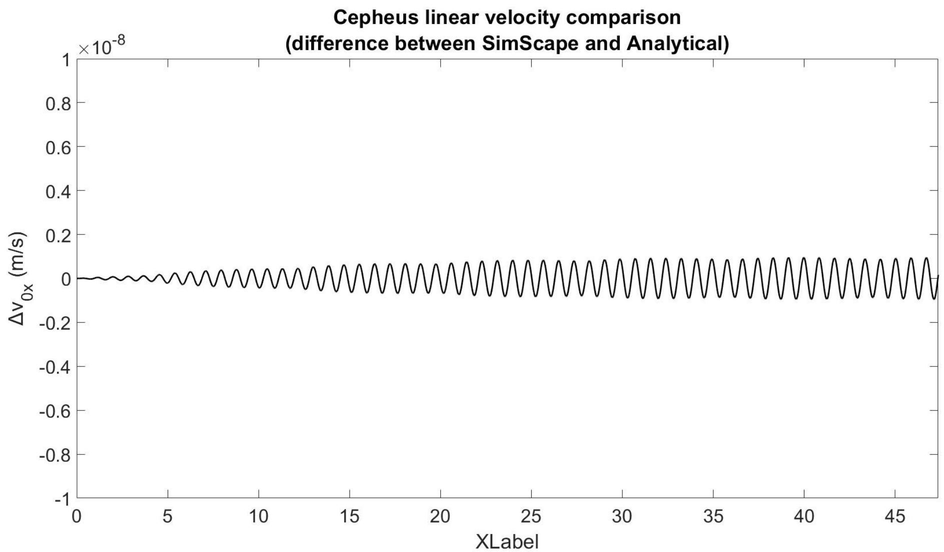


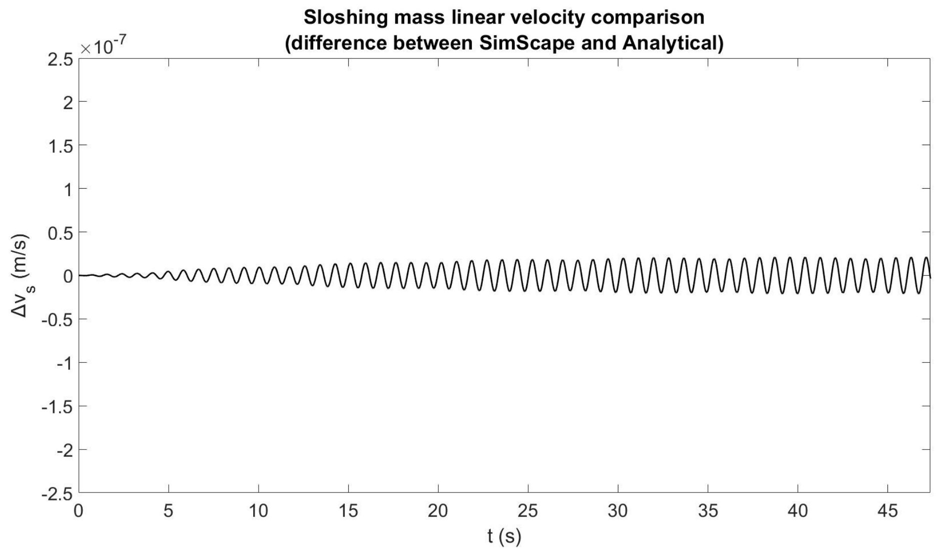
SimScape

BP2: Experimental Facility & Model (3/3)

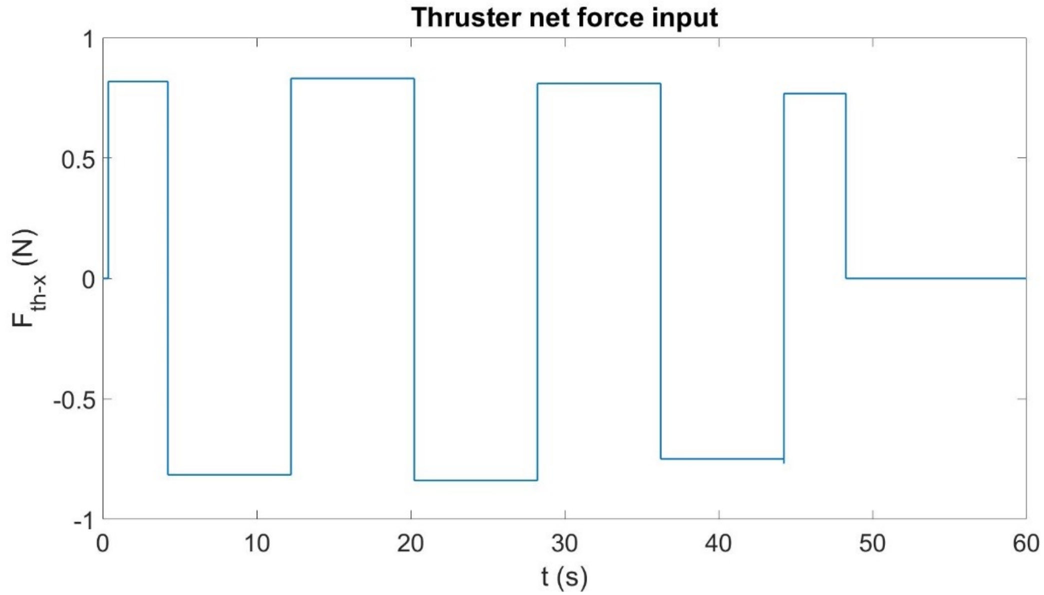
- Compared model response of
  - Analytical vs. Simscape
  - Same excitation
- Responses identical=> analytical model verified

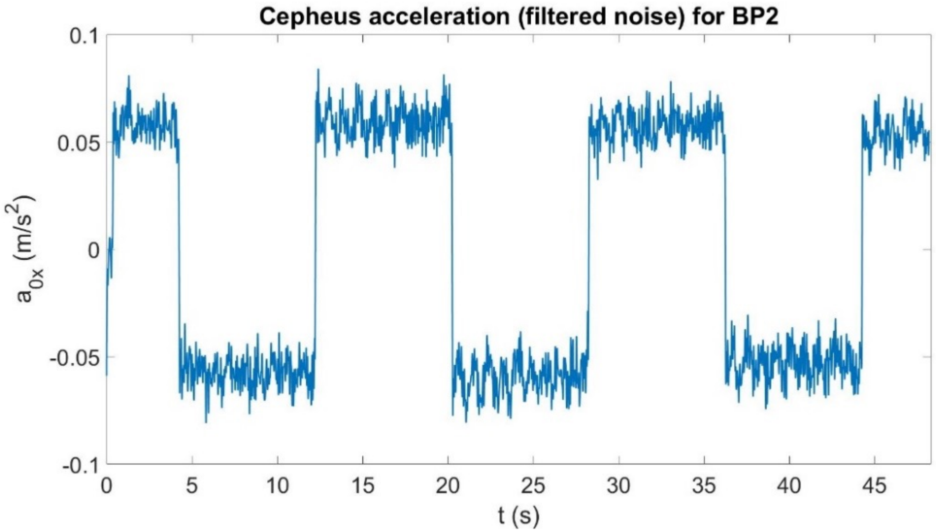


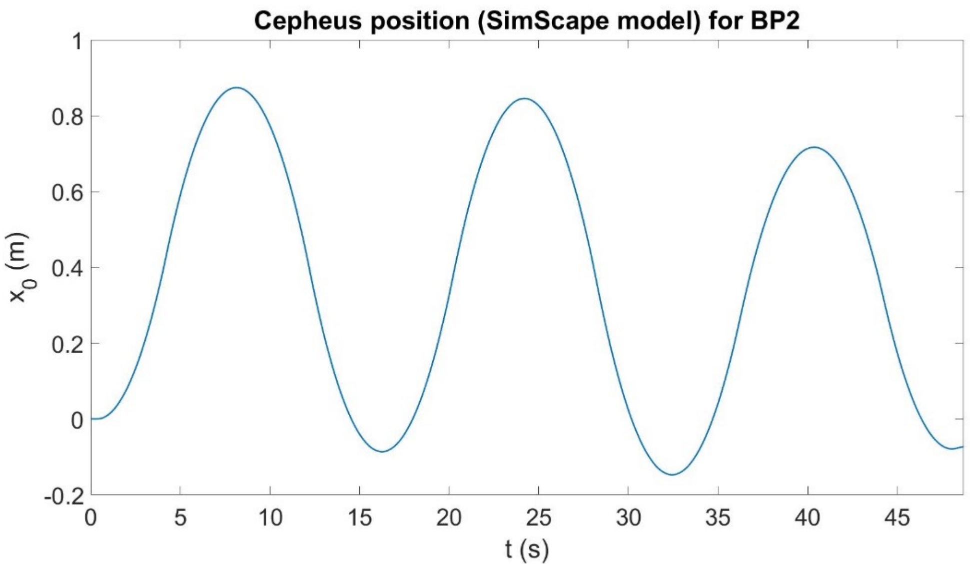


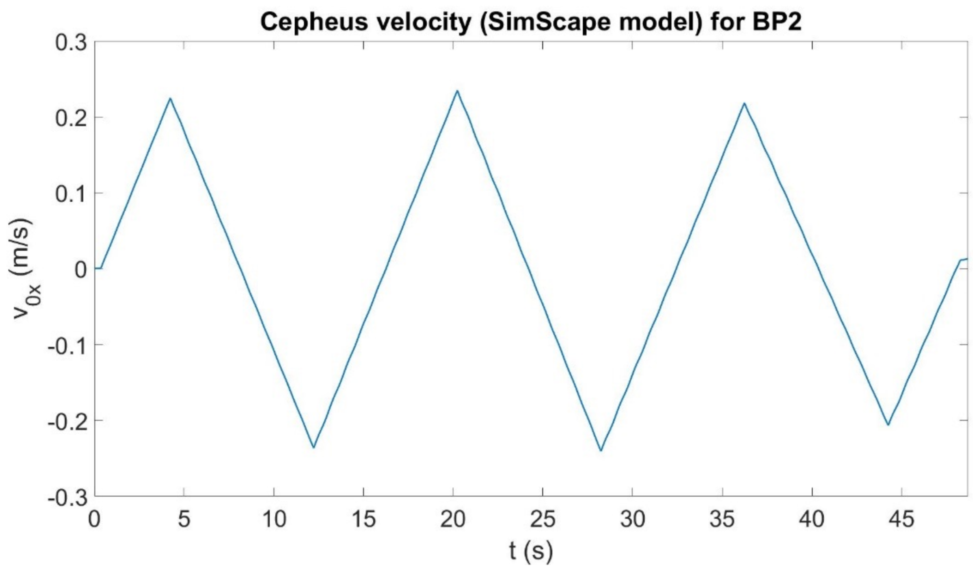


BP2: Excitation & simulated response







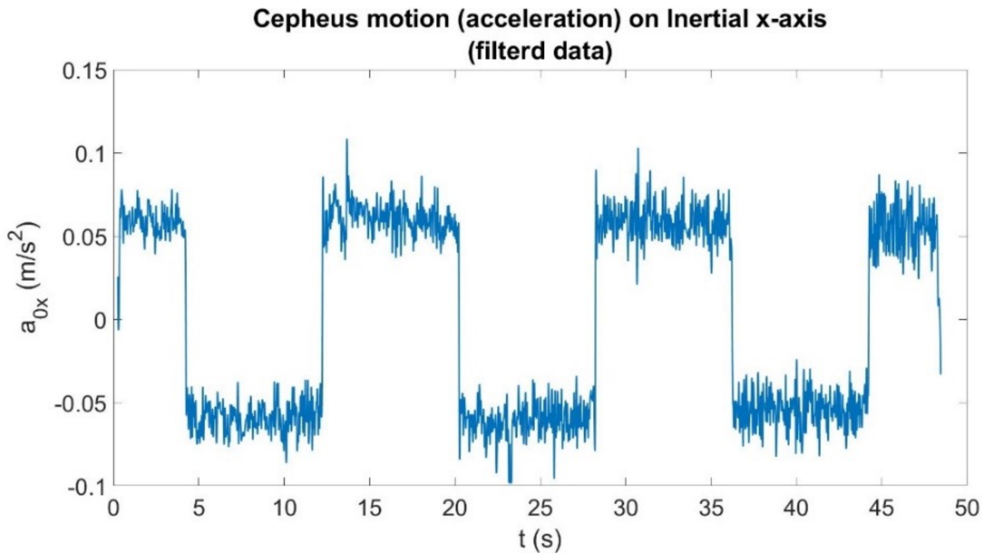


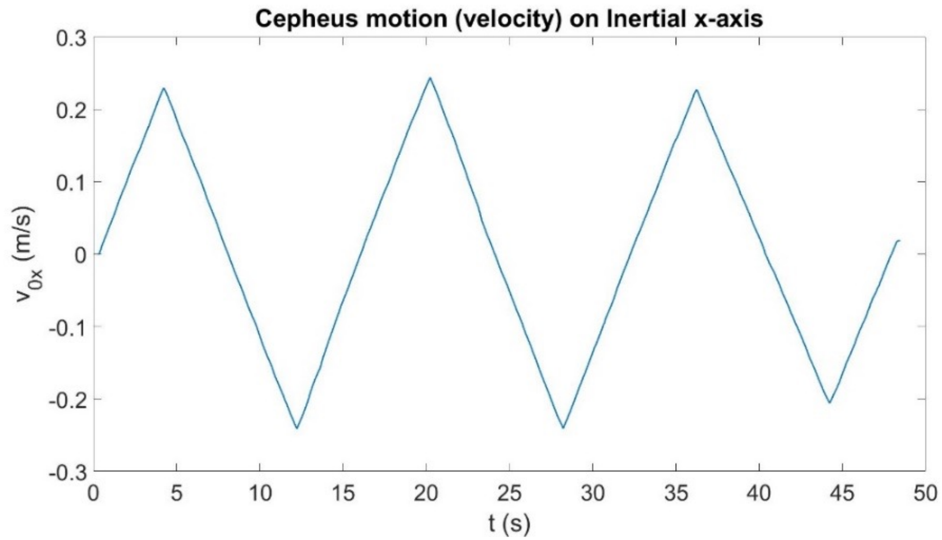
BP2: SYSID Results (simulation)

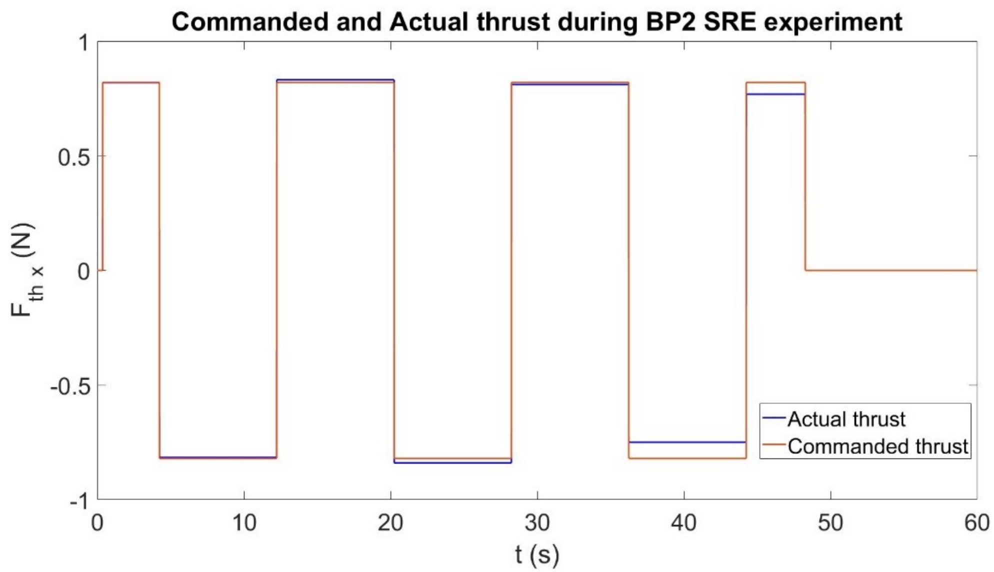
Parametric SYSID: TLS (Algorithm), System Transfer Function (Method)

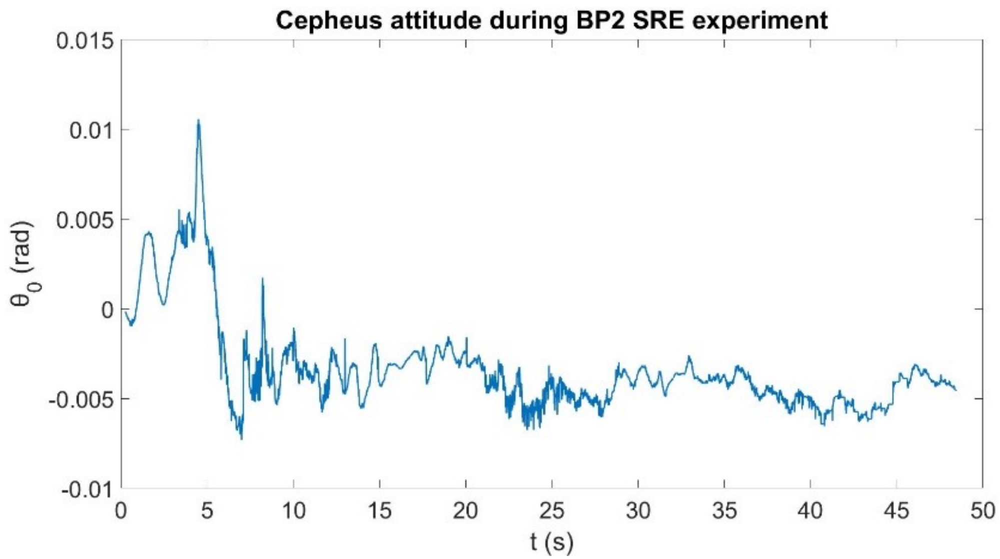
Parameter	True Value	Estimated Value	Relative error (%)
k_s (N/m)	33.2156	13.6968	2.27
b_s (N*s/m)	0.1336	-115.56	-
m_s (kg)	0.650	1.183	**8.59**

BP2: Excitation & experimental response







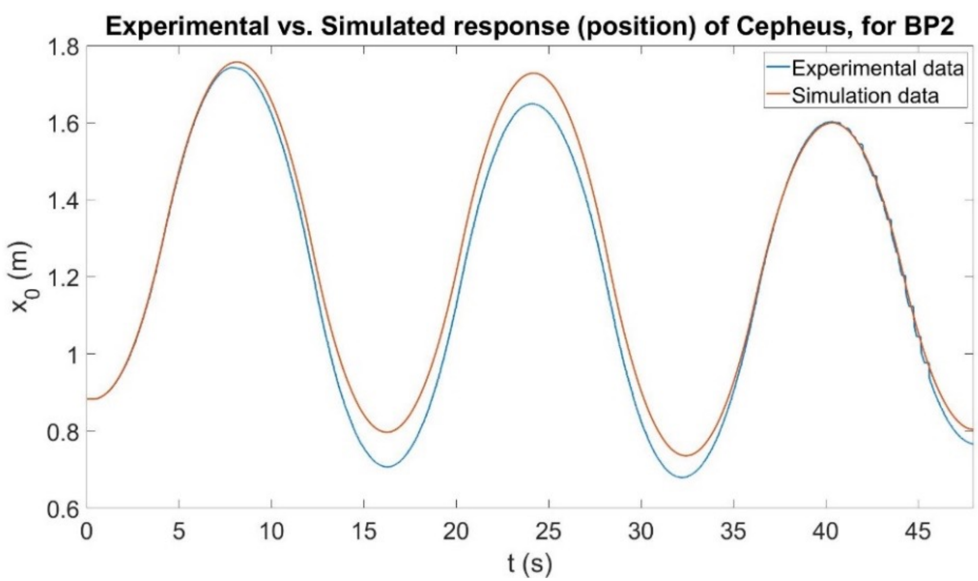


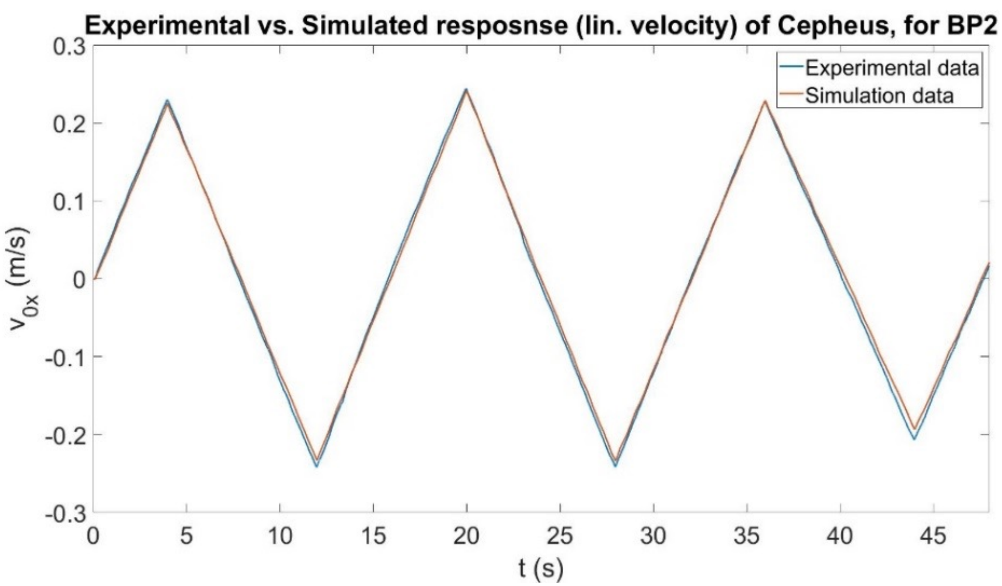
BP2: SYSID Results (experiment)

Parameter	"True" Value	Estimated Value	Relative error (%)
m_s (kg)	0.650	0.402	**20.32**
k_s (N/m)	33.2156	13.44	**10.32**
b_s (N/m/s)	0.1336	-46.17	-

BP2: Modelling Validation

- Identification Experiment: Experimental vs. Simulated Setup
  - Same excitation
  - Qualitative comparison
- Simulated model based on identified values
- **Very good match**





BP2: Discussion

- Simulated data: Parametric SYSID (TF Method & TLS)
  - Damping coefficient not adequately identified (expected), while the other two sloshing model parameters are identified with relative errors within or close to the 5% margin
  - The execution of the BP2 simulated experiment is deemed as successful
- Experimental data: Parametric SYSID (TF Method & TLS)
  - Identified sloshing mass and stiffness of the sloshing model are meaningful but errors outside the 5% limit
  - “True” values are obtained by CFD model and fitting on a mass-spring-damper model
  - Sloshing mass excitation is close to the acceleration noise levels -> difficult to decipher from noise

BP3: Full-scale Planar System (1/2)

2D Model

- Rotating rigid hub with a flexible appendage mounted on a fixed revolute joint
- Appendage deflection as a function of the modal shapes

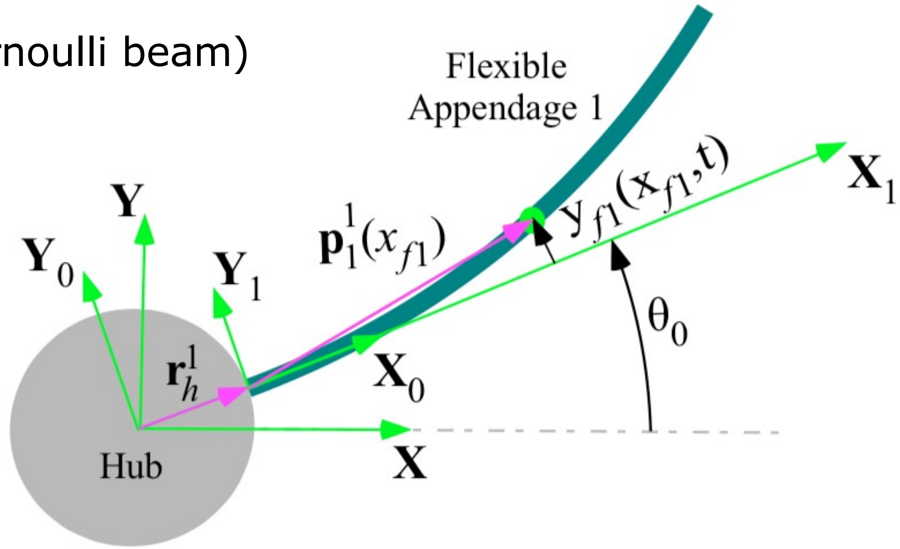
Modelling Assumptions

- Hub Model: Rigid body
- Flexible appendage: Continuous model (Euler-Bernoulli beam)

Goal

Estimation of modal parameters of the appendage

- Natural frequencies
- Damping ratios
- Mode shapes



Cases

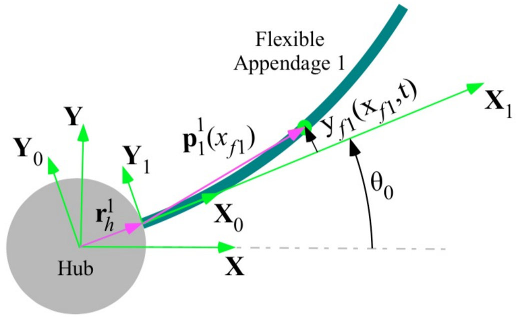
- Experimental Modal Analysis (BP3A): chirp and rectangular signals selected as inputs
- Operational Modal Analysis (BP3B): specific operational task selected

BP3: Full-scale Planar System (2/2)

Design of SYSID Experiment

Input

torque applied by the hub's motor



Measurements

Acceleration of 10 equally spaced points along the appendage

Experimental Modal Analysis

or

Operational Modal Analysis

Algorithms evaluated

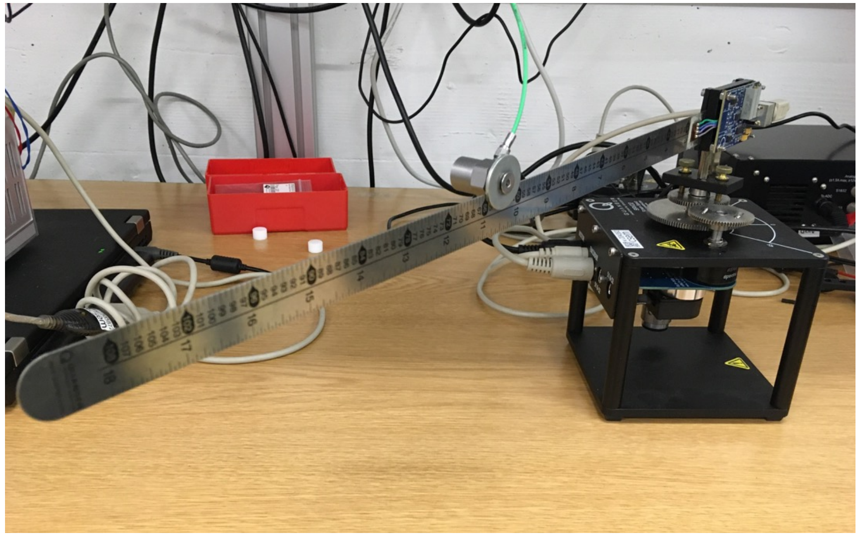
- LSCE
- RFP
- FSDD
- SSI-COV
- SSI-DATA

Trade-off Analysis Results

The best algorithm for BP3 is **SSI-COV**, for both EMA and OMA cases.

- Rectangular input signal yields better results than chip signal
- Relative errors for all modal parameters are quite low
  - Max Rel. Error in Natural Frequencies: 0.02%
  - Max Rel. Error in Damping Ratios: 0.01%
  - MAC Value: 1

BP3: Experimental Facility & Model (1/4)

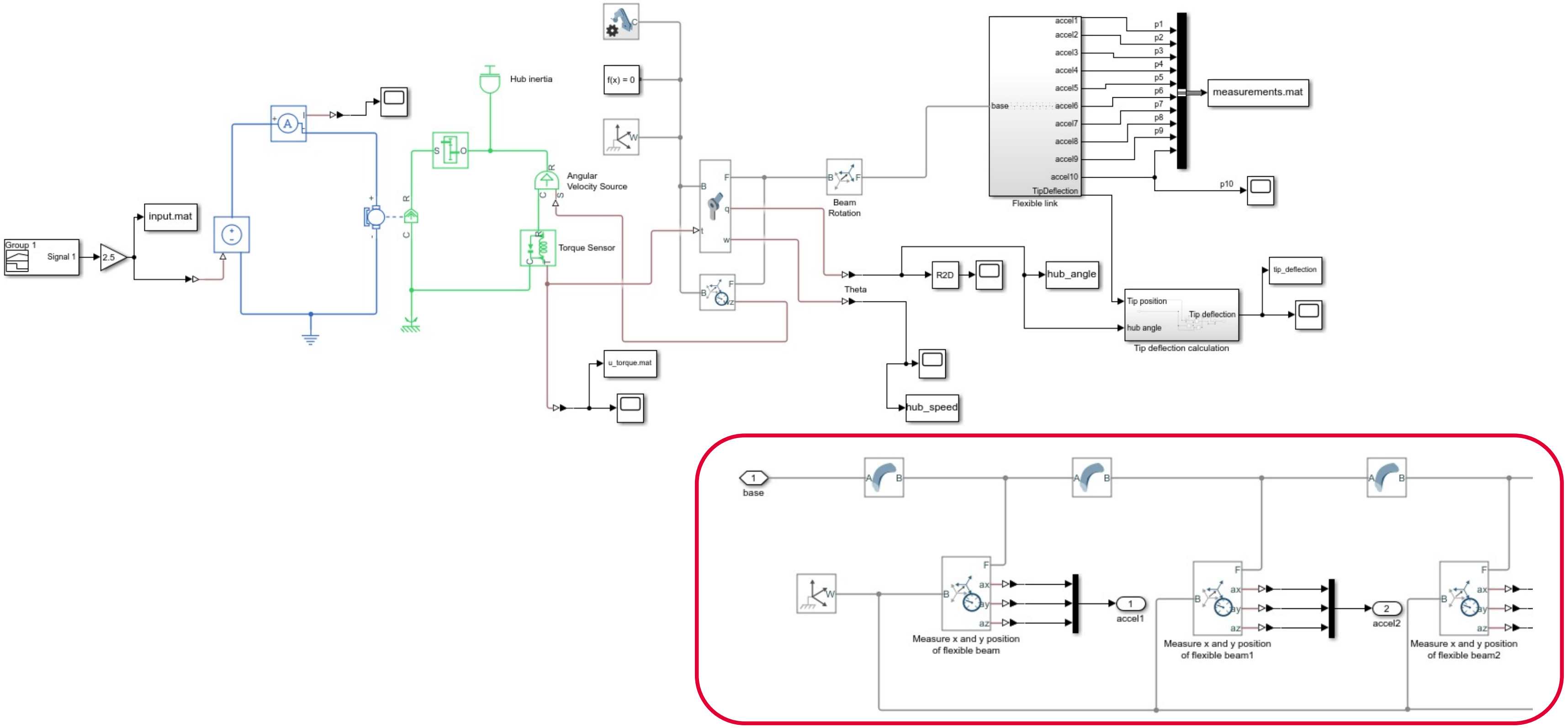


Characteristics	Quanser flexible link
Length	40 cm
Height	2.1 cm
Thickness	0.09 cm
Flexible link mass	69.7 g
Young's modulus	193 GPa
Density (stainless steel)	7850 kg/m^3

SYSID Measurements Required	Sensor	Unit
Hub attitude	Hub motor encoder	rad
Linear accel. of points on flexible appendage	Accelero meters	m/s^2

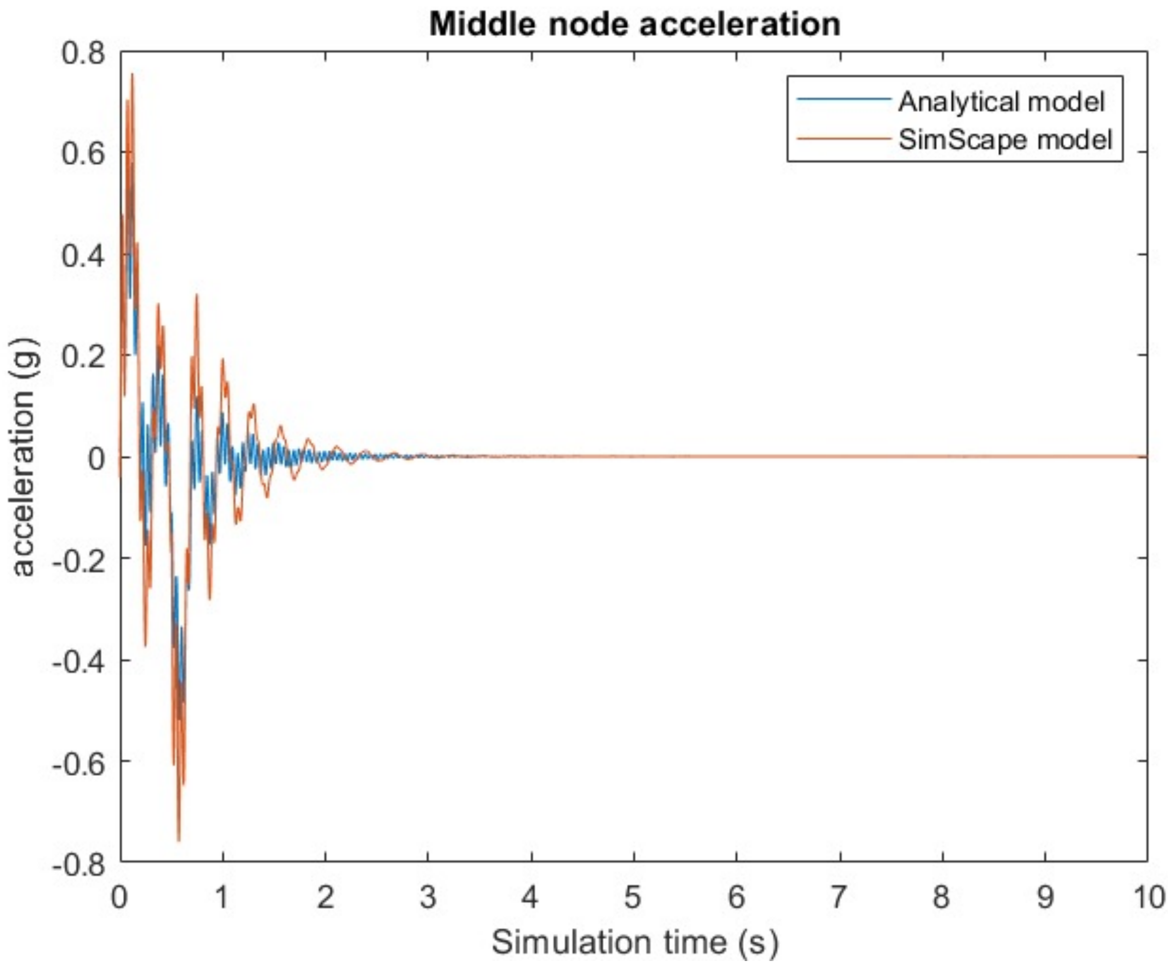
BP3: Experimental Facility & Model (2/4)

- SimScape model: succession of 10 flexible beams, with acceleration measurements between them
  - Inertial parameters, sensors, and actuators by Quanser



BP3: Experimental Facility & Model (3/4)

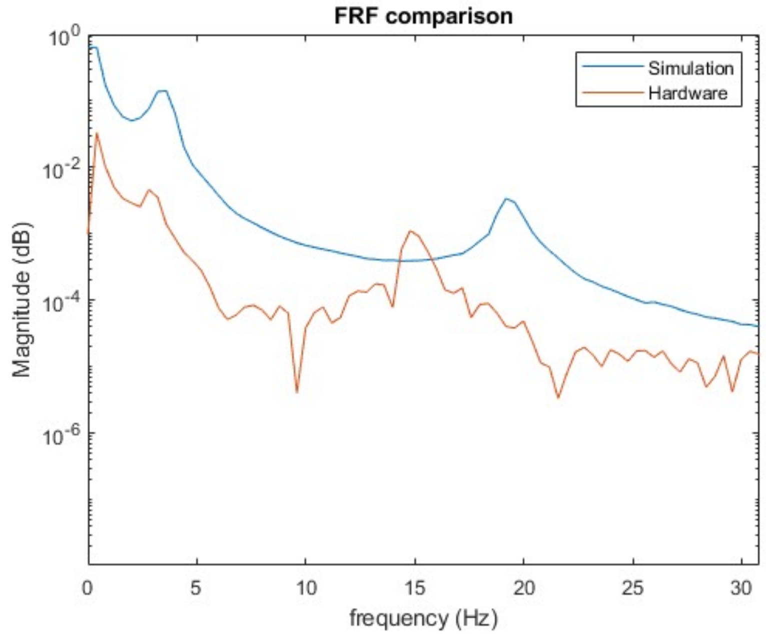
- Compared model response of
  - Analytical vs. Simscape
  - same excitation
- Responses very close=> analytical model verified

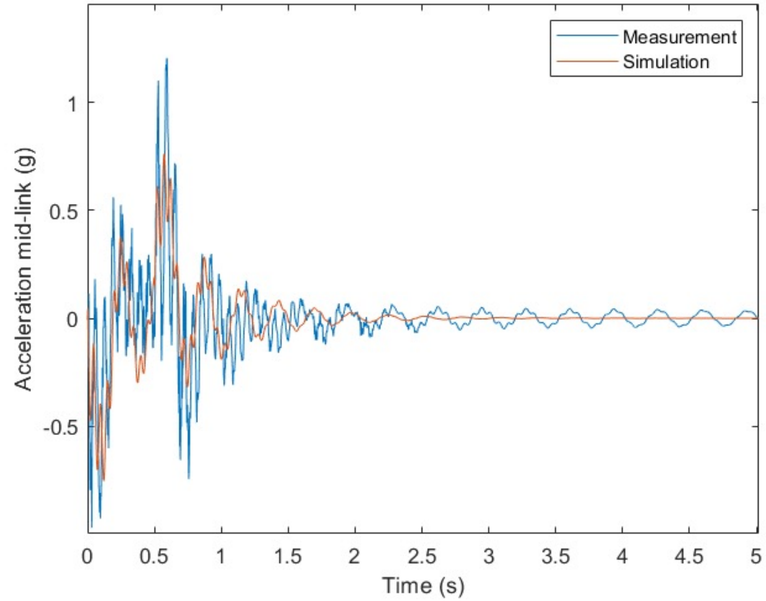


BP3: Experimental Facility & Model (4/4)

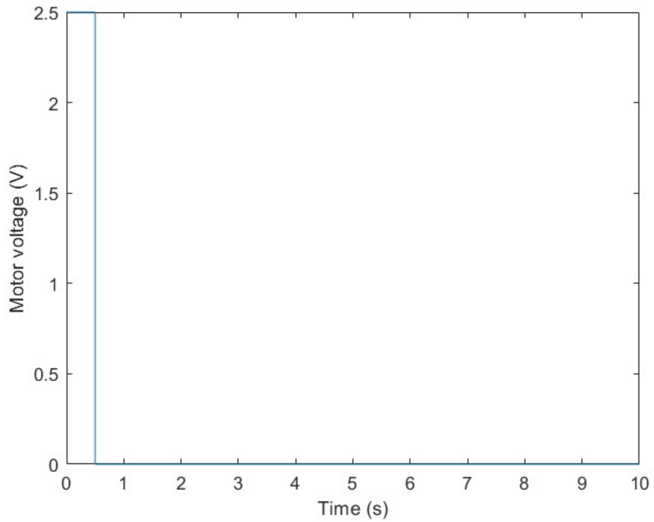
❑ Modelling Validation

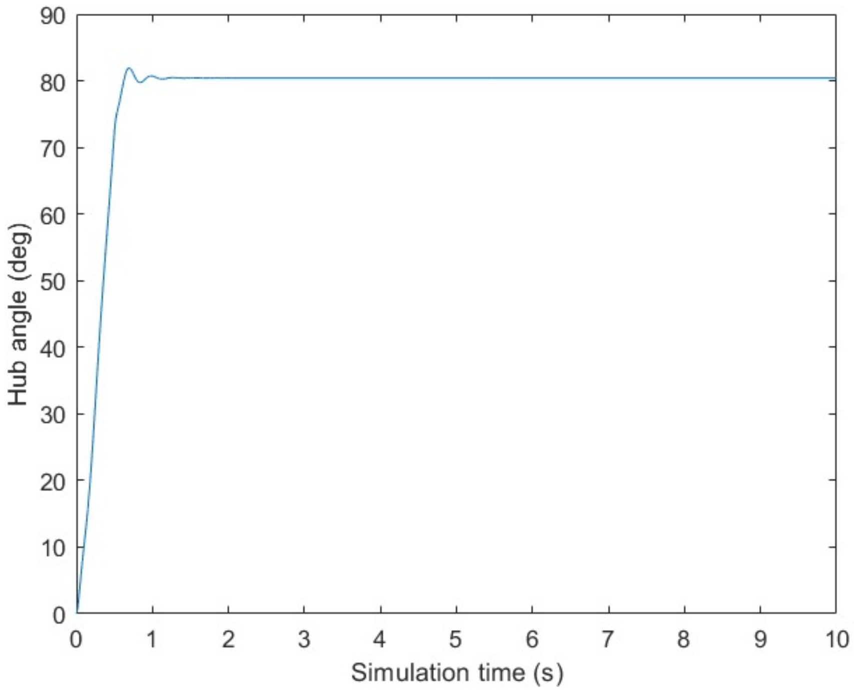
- Identification Experiment: Experimental vs. Simulated Setup
  - Same excitation
  - Qualitative comparison
- Simulated model used CAD values
- Modelling validated
- Some discrepancies exist due to:
  - Damping modelling limitations
  - Intrinsic H/W-S/W differences

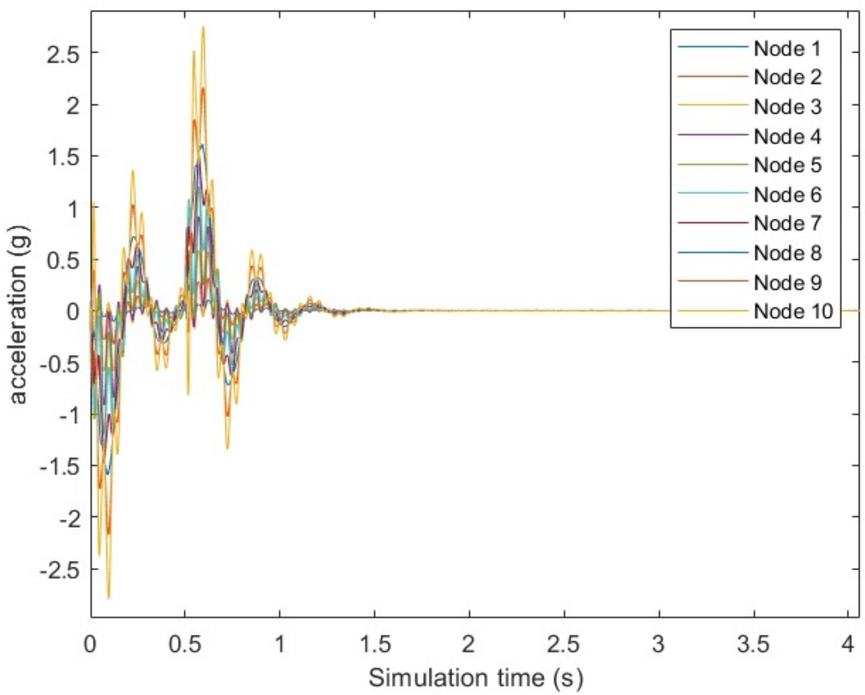




BP3A: Excitation & simulated response







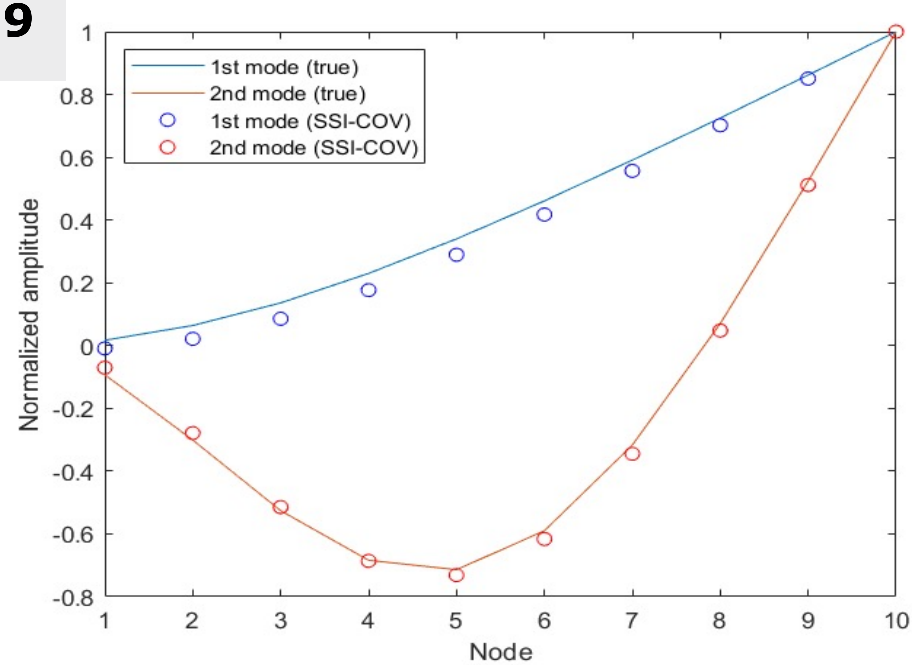
BP3A: SYSID Results (simulation)

Modal Analysis by SSI-COV

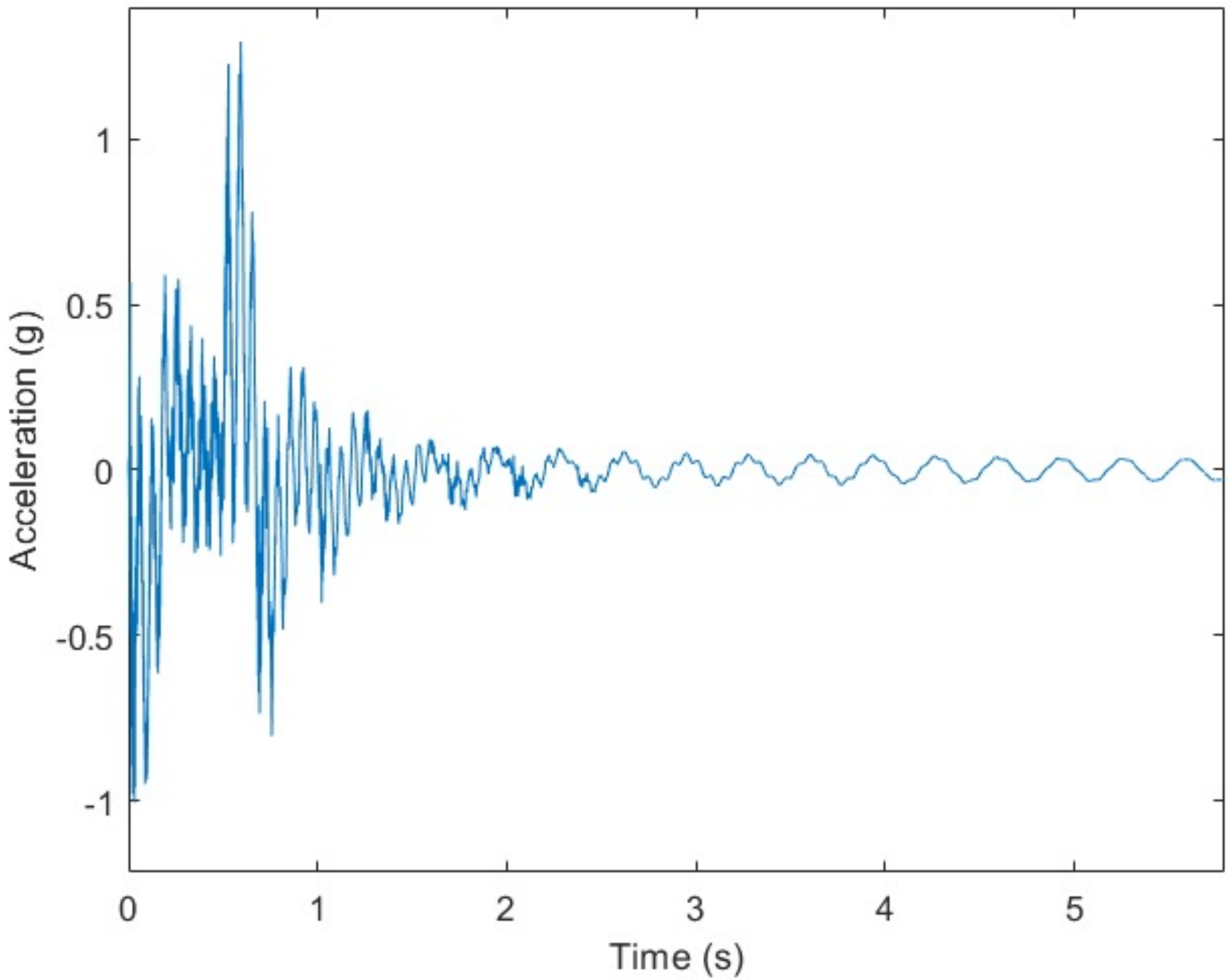
- Spurious modes linked to the excitation, may be detected
- Power spectral density function used to determine the correct modes

Parameter	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
True values	33.3	20.68	0.061	0.010
Rel. Error (%)	**8.67**	-0.23	-11.04	**58.39**

Mode	MAC value [-]
1st	0.9954
2nd	0.9989



BP3A: Experimental response



BP3A: SYSID Results (experimental)

Accelerometer at x/L = 0.5

Parameters	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
Simulated model	3.62	20.63	0.053	0.016
Hardware	2.98	15.21	0.051	0.014
Relative Error (%)	-17.68	**-26.72**	-3.77	**-12.50**

BP3A: Discussion (1/2)

❑ Simulated data: Modal Analysis (SSI-COV)

- The natural frequencies considered as identified correctly by the SSI-COV algorithm (max relative error a bit outside the acceptable limit of 5% (i.e., 8.67%))

- The first damping ratio identified better than the second one (-11.04% vs. 58.39%)

    - 2nd damping ratio true value is very small (only 0.010)

- The physical system and its SimScape implementation do not match perfectly

- The execution of the BP3A simulated experiment is deemed as successful (at least in terms of the natural frequencies)

BP3A: Discussion (2/2)

- Experimental data: Modal Analysis (SSI-COV)

- The accelerometer directly influences the flexible link dynamics
  - Due to link additional mass, its two natural frequencies shifted lower

- Accelerometer position affects the results

Accelerometer at x/L = 0.75

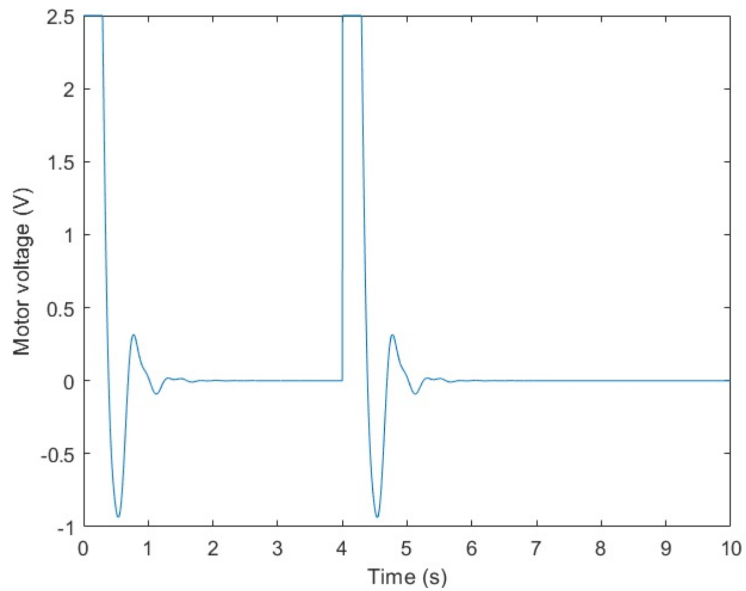
Parameters	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
Simulated model	3.62	20.63	0.053	0.016
Hardware	3.80	20.15	0.071	0.026
Relative Error (%)	4.97	-2.32	33.96	62.50

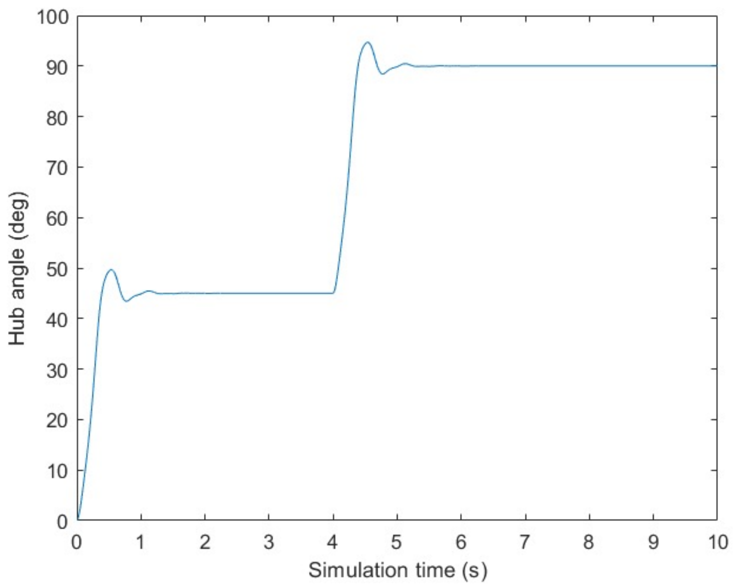
Accelerometer at x/L = 0.25

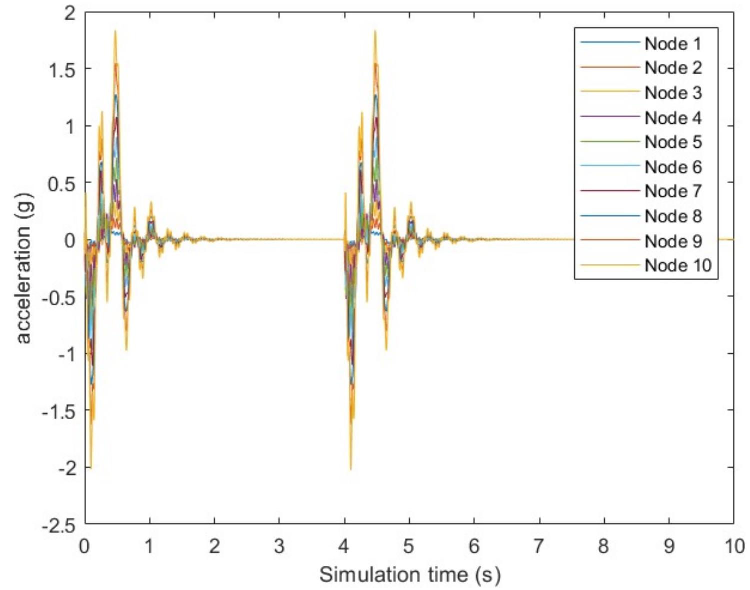
Parameters	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
Simulated model	3.62	20.63	0.053	0.016
Hardware	3.15	17.99	0.059	0.013
Relative Error (%)	-12.98	-12.80	11.32	-18.75

BP3B: Excitation & simulated response

- Operational scenario
  - The hub rotates to reach two angle positions (i.e., 45° and 90°), as fast as possible.
  - Quanser system limitations observed



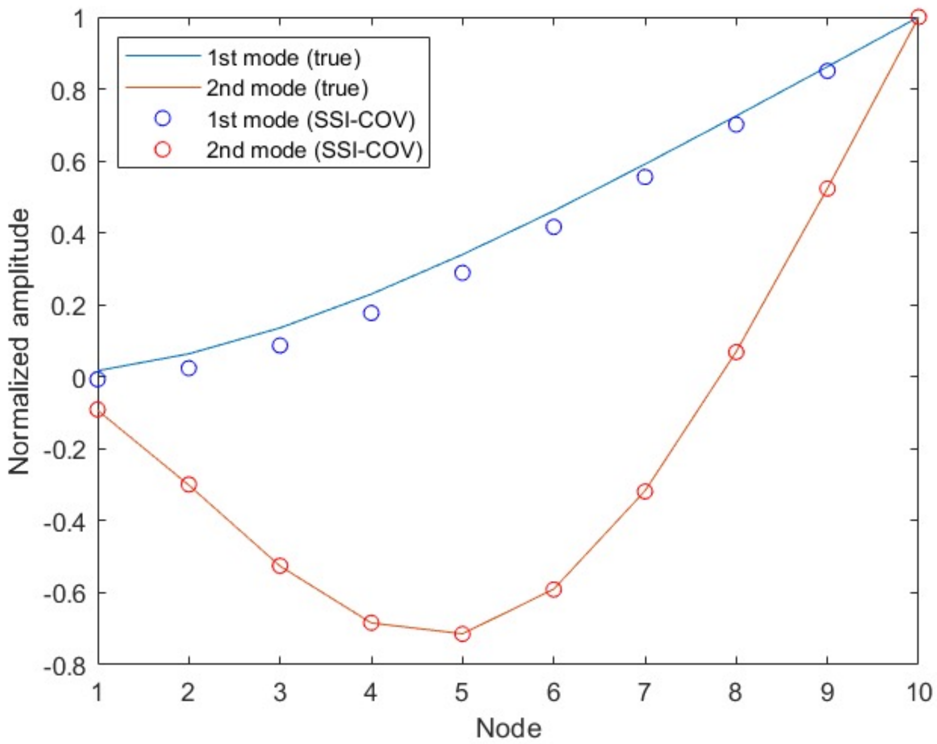




BP3B: SYSID Results (simulation)

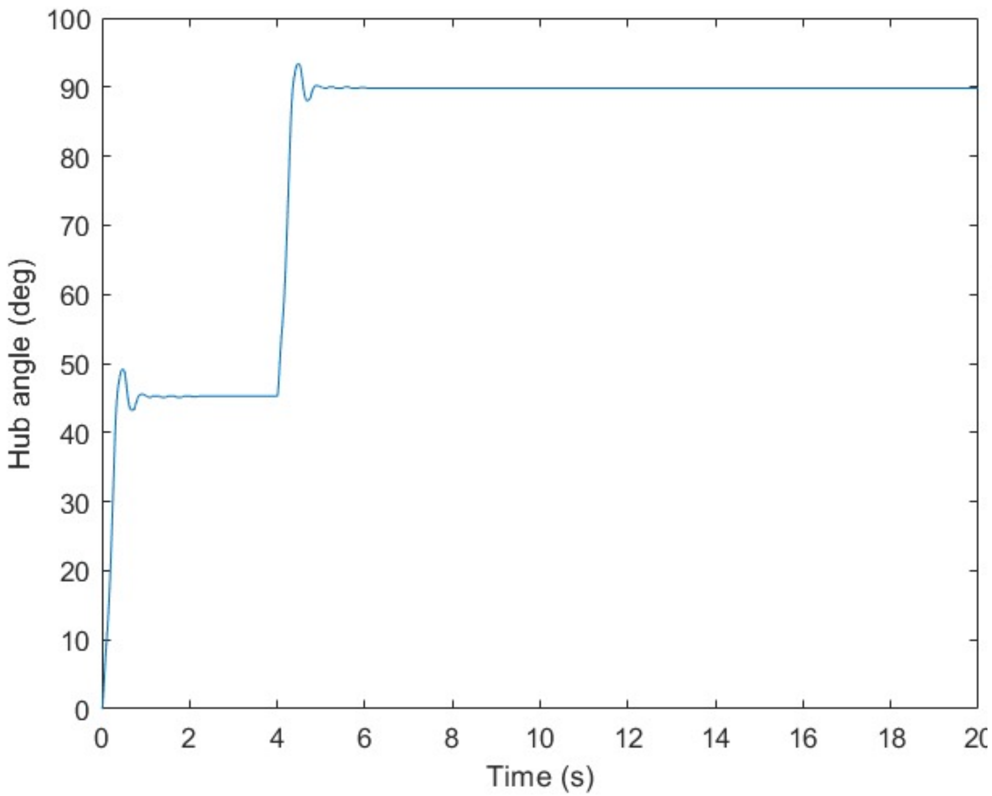
Modal Analysis by RSSI-COV

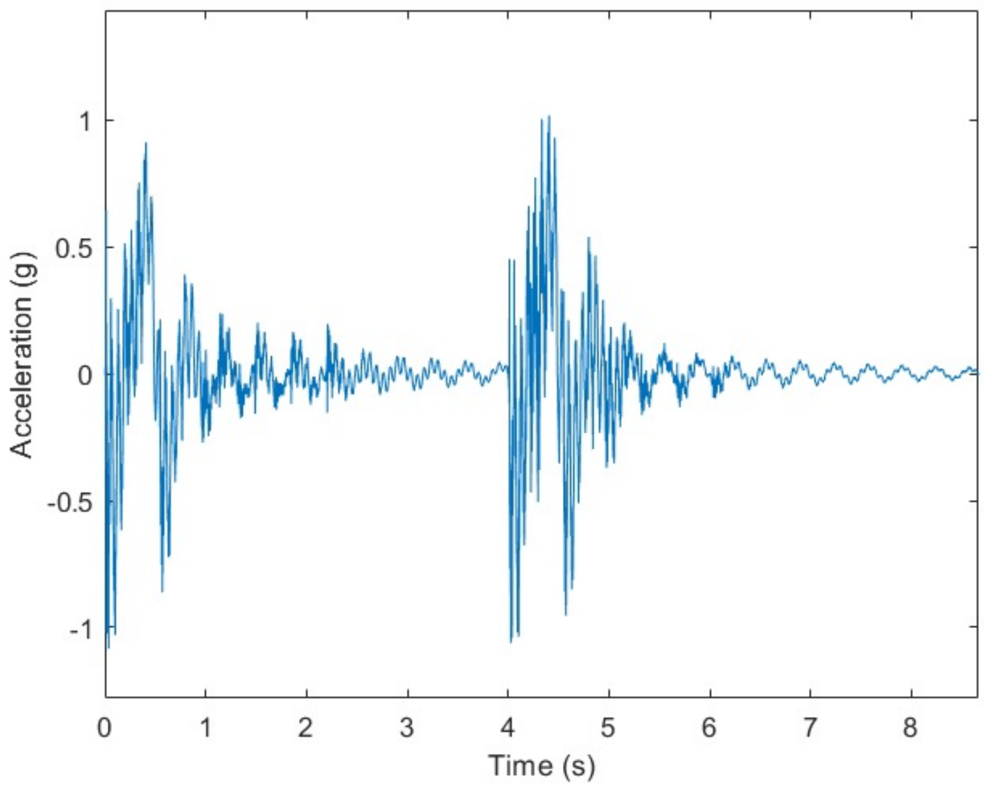
Parameter	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
True values	33.3	20.68	0.061	0.010
Rel. Error (%)	**8.35**	-3.40	**-63.05**	59.88



Mode	MAC value [-]
1st	0.9965
2nd	0.9999

BP3B: Experimental response





BP3B: SYSID Results (experimental data)

Accelerometer at x/L = 0.5

Parameters	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
Simulated model	3.61	19.98	0.098	0.016
Hardware	3.73	15.09	0.064	0.021
Relative Error (%)	3.32	**-24.47**	**-34.69**	31.25

BP3B: Discussion (1/2)

- Simulated data: Modal Analysis (RSSI-COV)
  - The natural frequencies considered as identified correctly by the RSSI-COV algorithm (max relative error a bit outside the acceptable limit of 5% (i.e., 8.35%))
  - Both damping ratios are identified with relatively high relative errors (63.05% - 58.39%)
    - Both damping ratios true values are quite small (0.06 - 0.01)
  - The physical system and its Simscape implementation do not match perfectly
  - The execution of the BP3B simulated experiment is deemed as successful (at least in terms of the natural frequencies)

BP3B: Discussion (2/2)

- Experimental data: Modal Analysis (RSSI-COV)

- The accelerometer directly influences the flexible link dynamics
  - Due to link additional mass, its two natural frequencies shifted lower

- Accelerometer position affects the results

Accelerometer at x/L = 0.75

Parameters	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
Simulated model	3.61	19.98	0.098	0.016
Hardware	3.07	19.85	0.095	0.017
Relative Error(%)	-14.96	-0.65	-3.06	6.25

Accelerometer at x/L = 0.25

Parameters	f_{n1} (Hz)	f_{n2} (Hz)	ζ_{n1} (-)	ζ_{n2} (-)
Simulated model	3.61	19.98	0.098	0.016
Hardware	3.40	15.72	0.057	0.021
Relative Error(%)	-5.82	-21.32	-41.84	31.25

Discussion on BP1 Experiments

- The SYSID with the BP1A simulated data is deemed as **successful**

- The SYSID with the BP1A experimental data is deemed as **partially successful**
  - However, system reconstruction based on identified parameters, was successful

- The SYSID with the BP1B simulated data is deemed as **partially successful**
  - Inadequate SNR

- The SYSID with the BP1B experimental data is deemed as **unsuccessful**
  - Main reasons: Low SNR, comparison with CAD "true" values, and inaccurate knowledge of the excitation force

Discussion on BP2 Experiments

- The SYSID with the BP2 simulated data is deemed as **successful**
- The SYSID with the BP2 experimental data is deemed as **partially successful**
  - Accurate estimation of excitation forces resulted in meaningful (if not acceptable) results
  - However,
    - "True" values were obtained by CFD model and fitting on a mass-spring-damper model
    - Sloshing mass *excitation* is close to the acceleration noise levels -> difficult to decipher from noise.

Discussion on BP3 Experiments

- The SYSID with the BP3 simulated data is deemed as **successful** (at least in terms of the natural frequencies)
  - Model and Simscape implementation do not match perfectly

- The SYSID with the BP3 experimental data is deemed as **partially successful** (depends on accelerometer position)
  - The accelerometer directly influences flexible link dynamics
  - Due to additional mass, natural frequencies shifted lower

Study Cases

Basic Considerations (1/2)

Full-scale Planar System Models (simulations)

- Insight on the SYSID Algorithms requirements
- Develop appropriate Methods to apply the chosen Algorithms

Scaled-down Planar Experiments (consortium facilities)

- Significant insight on the SYSID Algorithms and developed Methods requirements, capabilities and limitations

Basic Considerations (2/2)

Scaled-down Planar Experiments (simulations)

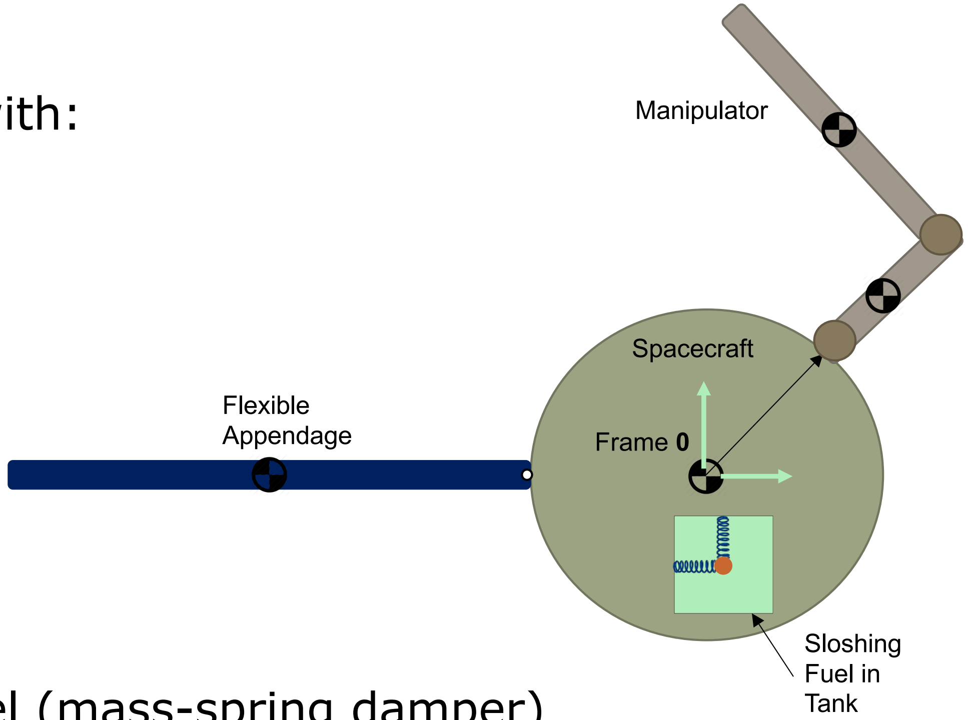
- Validate the developed Analytical Models
- Design of excitation signal to be used for the h/w experiment
- Gain knowledge on the behaviour of the experimental set-up (limitations, sources of error, etc.) and on the SYSID algorithm
- Validate the experimentally Identified Models, using Analytical and/ or SimScape models

Full-scale Spatial (3D) System Models (simulations)

SC1: Full-scale Planar System (1/7)

2D System

- Manipulator equipped chaser S/C with:
  - a fuel tank
  - a flexible appendage



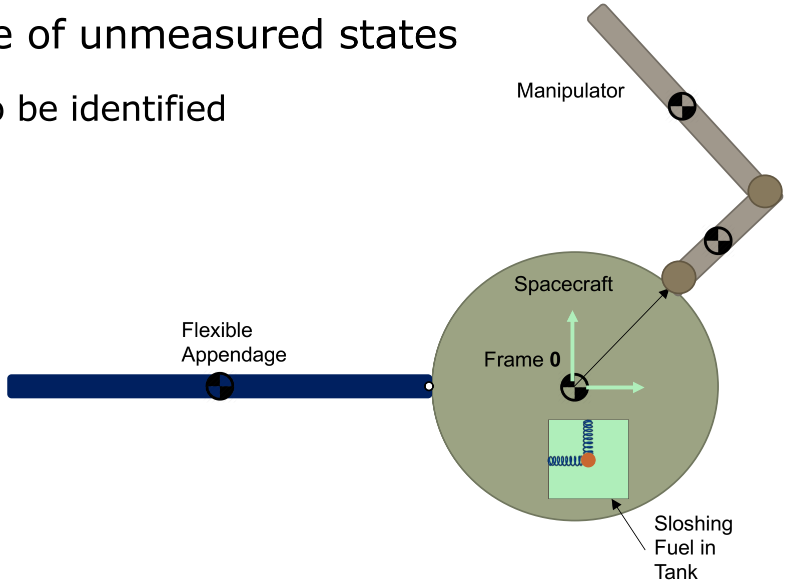
Modelling Assumptions

- S/C Model: Rigid body
- Fuel Sloshing Model: Lumped model (mass-spring damper)
- Flexible appendage: Continuous model (Euler-Bernoulli beam)

SC1: Full-scale Planar System (2/7)

Main challenge

- All system parameters to be identified in the presence of unmeasured states
  - Inertial, sloshing, modal parameters of chaser system to be identified
  - Sloshing states are not measurable
  - Modal states are not measurable



Additional challenge

Lack of existing methodologies

Goal

Develop a method that overcomes the challenges and identify all the Chaser's parameters

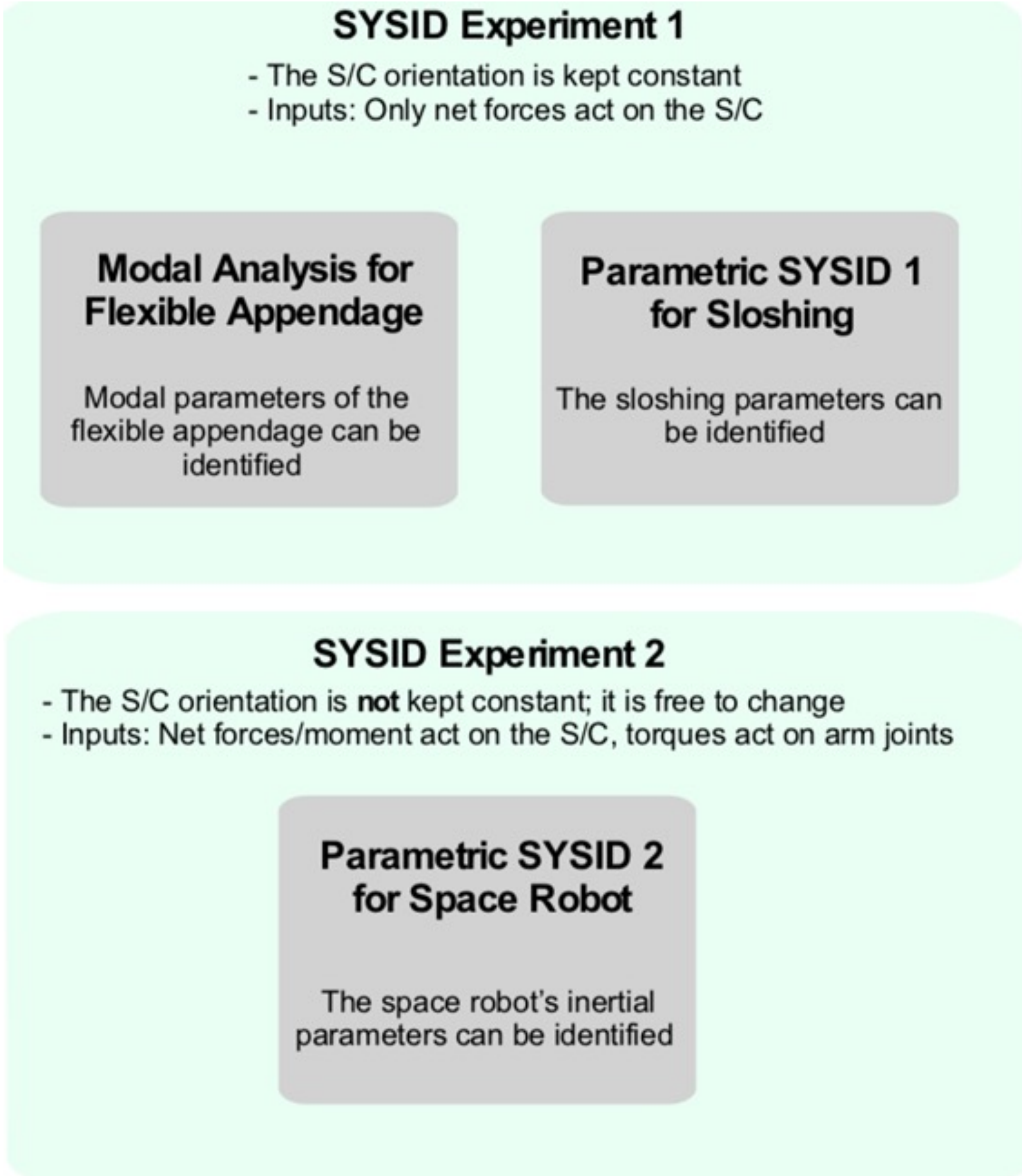
Contribution

Development of a method based on two subsequent experiments (stages)

SC1: Full-scale Planar System (3/7)

Design of SC1 SYSID Experiments:

- Experiment 1
- Experiment 2



SC1: Full-scale Planar System (4/7)

Design of SYSID Experiment 1: Pure translation by applying net forces only

SYSID Experiment 1

- The S/C orientation is kept constant
- Inputs: Only net forces act on the S/C

Modal Analysis for Flexible Appendage

Modal parameters of the flexible appendage can be identified

- Modal parameters identified: natural frequencies, damping ratios, mode shapes
- Measurements of flexible appendage tracked points accelerations
- SSI-COV algorithm used based on the BP3 Trade-off Analysis

SC1: Full-scale Planar System (5/7)

Design of SYSID Experiment 1: Pure translation of S/C, arm locked

SYSID Experiment 1

- The S/C orientation is kept constant
- Inputs: Only net forces act on the S/C

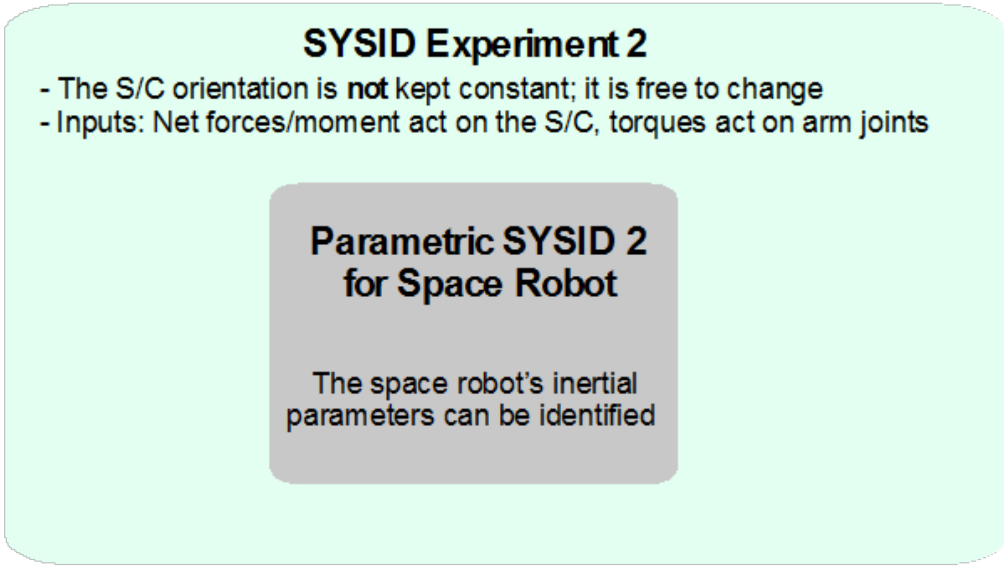
Parametric SYSID 1 for Sloshing

The sloshing parameters can be identified

- Novel Method developed based on transfer function formulation (same framework as BP2-M2)
  - Eliminates unmeasurable sloshing and modal states from SYSID equations
  - Decouples sloshing identification from modal parameters identification
  - Allows for sloshing parameters identification to run in parallel with modal analysis
- TLS algorithm used based on the BP2 Trade-off Analysis.

SC1: Full-scale Planar System (6/7)

Design of SYSID Experiment 2: S/C translation & rotation, arm performs trajectories



- *Excitation similar to BP1B*
- All *Fourier series coefficients* obtained by minimizing regressor matrix condition number

- Method developed, consisting of:
  - A SYSID equation based on *energy balance* (same framework as BP1-M2)
  - An estimator for the unmeasurable sloshing states based on *equations of motion*
  - An estimator for the unmeasurable modal states based on *assumed modes method*
- TLS algorithm used based on the BP1 Trade-off Analysis.

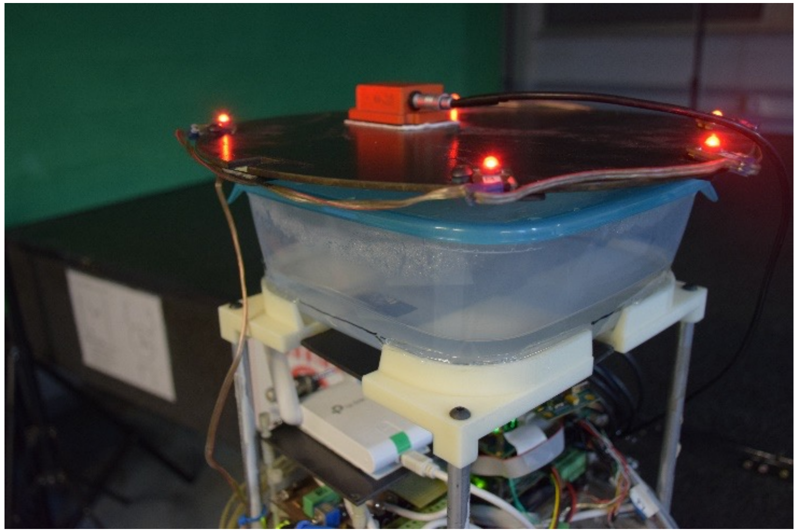
SC1: Full-scale Planar SYSID Results (7/7)

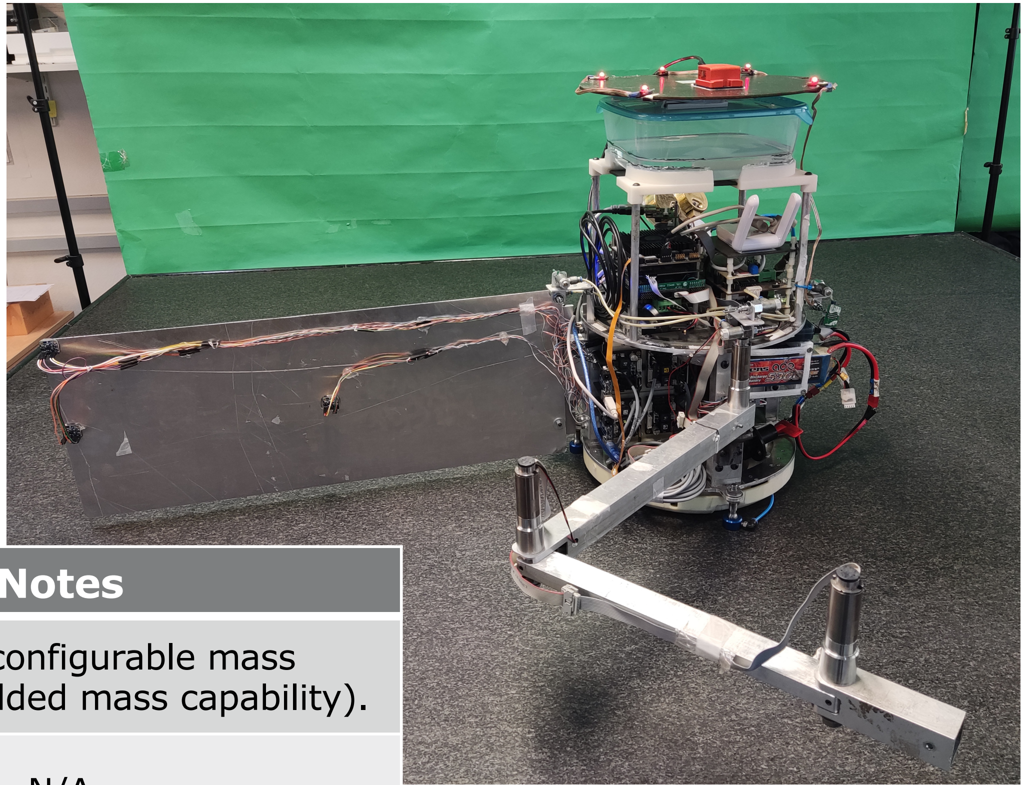
- SYSID in Experiment 1, yields good results in general
  - Relative errors for most modal and parametric SYSID, are low
    - Max Rel. Error in Natural Frequencies (*SSI-COV*): 3.14%
    - Max Rel. Error in Sloshing Estimation (*TLS*): 3.63% (damping excluded)
  - RTLS was tried also, with Max. Rel. Error in Sloshing Estimation: 2.40%
  - Relative errors of estimated sloshing damping coefficients are large; negligible effect on the S/C response prediction (see sensitivity analysis earlier in this presentation)

- SYSID in Experiment 2 yields acceptable identification
  - Max Relative Error in Inertial Estimation: 4.62%

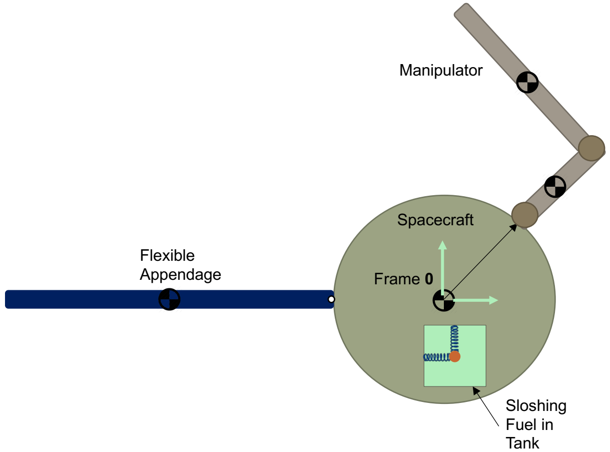
- Thus, SC1 SYSID for both Experiment 1/2, is deemed as *successful*

SC1: Experimental Facility & Model





Component	Mass	Notes
Robotic System w/o Manipulator	13 kg	Cepheus has reconfigurable mass (provision for added mass capability).
Robotic System w/t Manipulator	14 kg	N/A
Empty Plastic Tank	500 g	N/A
Water Emulating Sloshing Fuel	800 g	Based on CFD model, only about 650g of the 800 g are contributing to the sloshing phenomenon.
Solar Panel	440 g	N/A
CO_2 Tank (empty)	900 g	Working pressure: 7 bar
CO_2 Tank (full)	1650 g	



SC1 EXP1: SYSID Results (simulation)

Experiment 1

- **Modal Analysis**

Parameters	SSI-COV	RSSI-COV	SSI-COV	RSSI-COV
Type	Bending	bending	bending	bending
True values (Hz)	1.947		12.200	
Est. value (Hz)	1.946	1.942	12.275	12.254
Rel. Error (%)	**0.049**	**0.222**	**0.614**	**0.447**

- **Parametric (sloshing) SYSID (realistic noise models)**

Param	True Value	Est. Value TLS	Relative error (%)	Est. Value RTLS	Relative error (%)
M	15.117	15.178	**0.4011**	15.2072	**0.5966**
m_s	0.625	4.0178	**542.84**	4.0204	**543.27**
k_s	33.2156	717.3224	--	715.9319	--
b_s	0.1336	3.0551	--	2.3180	--
ρ	0.675	-0.2563	**137.96**	-0.1739	**125.76**

- **Parametric (sloshing) SYSID (increased SNR)**

Relative Error for Parameter	Relative Error (%) from Simulation		
	Lower noise, 3 acc/meters	Lower noise, 7 acc/meters	Noiseless, 3 acc/meters
M	**0.014662**	**0.0095055**	**6.5045e-10**
m_s	**15.026**	**0.52262**	**0.028216**
k_s	**15.294**	**0.73895**	**0.028216**
b_s	**24.451**	**8.6107**	**0.028216**
ρ	**29.036**	**4.5398**	**0.061576**

SC1 EXP2: SYSID Results (simulation)

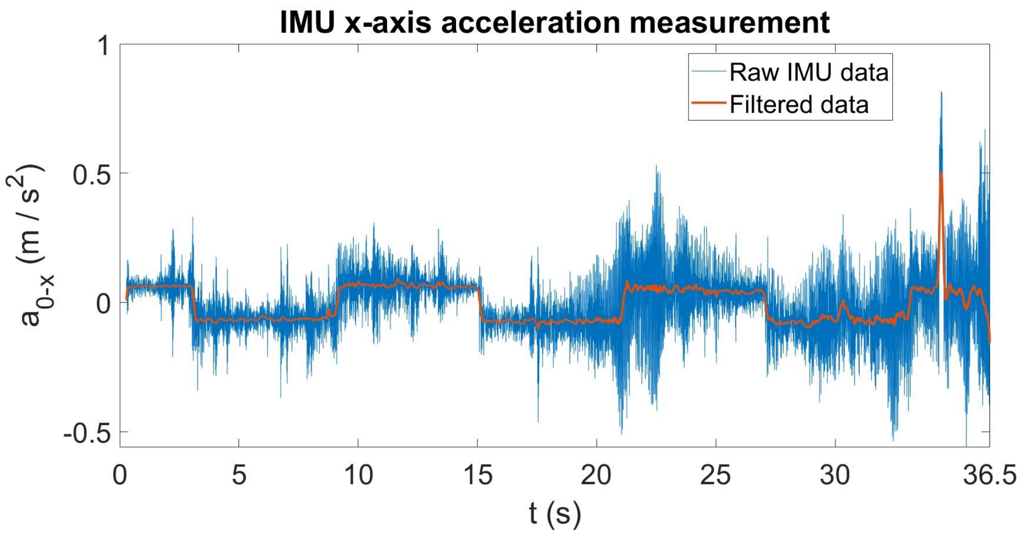
- Experiment 2

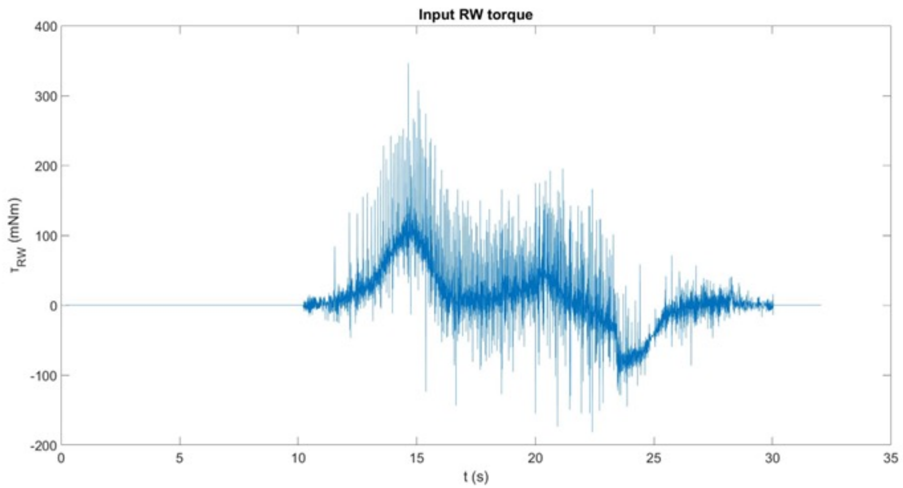
  - **Parametric SYSID (inertial)**

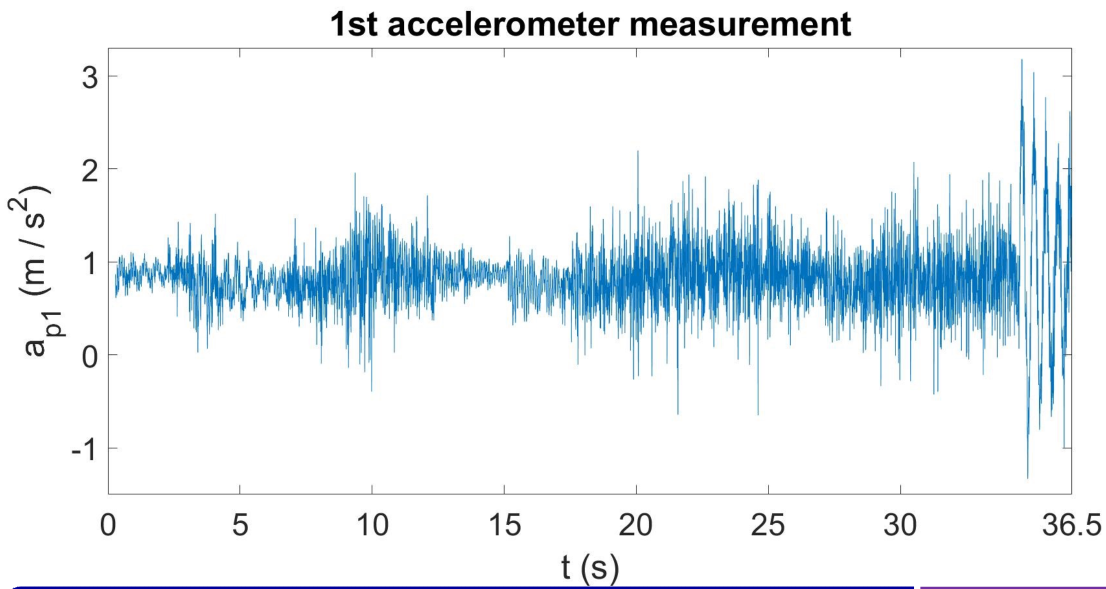
Param	True Val.	Est. Value TLS	Rel. error (%)	Est. Value RTLS	Rel. error (%)	Rel error (%) (lower noise) TLS
a_1	0.424	0.4068	**4.06**	0.4051	**4.45**	**0.97**
a_2	0.13626	0.1366	**0.29**	0.1195	**12.30**	**5.69**
a_3	0.21477	0.2333	**8.65**	0.2496	**16.20**	**0.40**
a_4	0.20152	0.1192	**40.82**	0.0959	**52.41**	**8.30**
a_5	0.26194	0.2360	**9.89**	0.2305	**11.99**	**6.13**
a_6	0.03933	0.0841	**113.7**	0.0807	**105.1**	**2.96**
a_7	0.09321	0.1502	**61.11**	0.1531	**64.30**	**3.59**
a_8	0.03569	0.0653	**83.04**	0.0660	**84.97**	**4.84**
a_9	0.05626	0.0645	**14.73**	0.0715	**27.07**	**4.55**
a_{10}	0.0127	0.0017	**86.40**	-0.0002	**101.5**	**8.08**
a_{10}	0.02002	0.0386	**92.70**	0.0407	**103.1**	**7.94**
a_{12}	0.02442	0.0262	**7.30**	0.0308	**26.35**	**4.00**

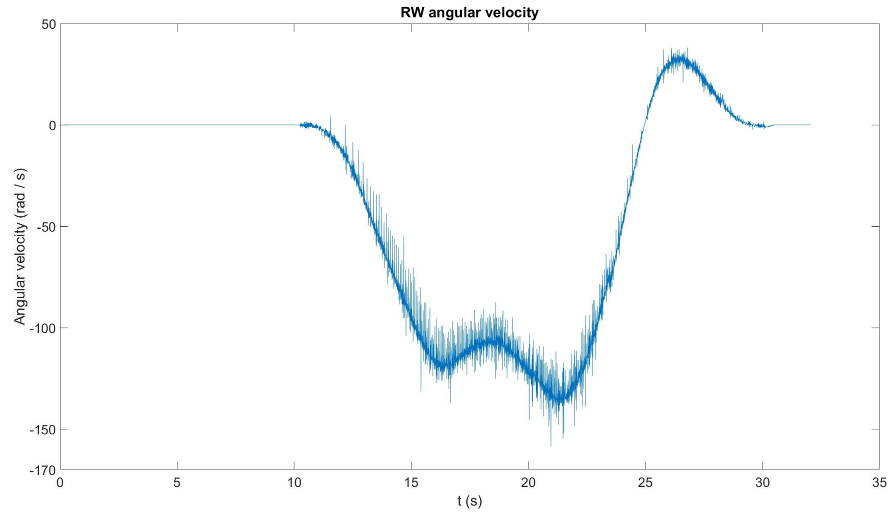
- Estimators used for unmeasurable quantities

SC1: Experimental response









SC1 EXP1&2: SYSID Results (experimental)

- **Experiment 1**

Modal Analysis

Parameters	SSI-COV	RSSI-COV	SSI-COV	RSSI-COV
Type	bending	bending	bending	bending
True values	1.947 (Hz)		12.200 (Hz)	
Estimated value	2.271 (Hz)	2.265 (Hz)	11.62 (Hz)	11.566 (Hz)
Rel. Error (%)	**-16.85**	**-16.33**	**4.73**	**5.19**

Parametric (sloshing) SYSID

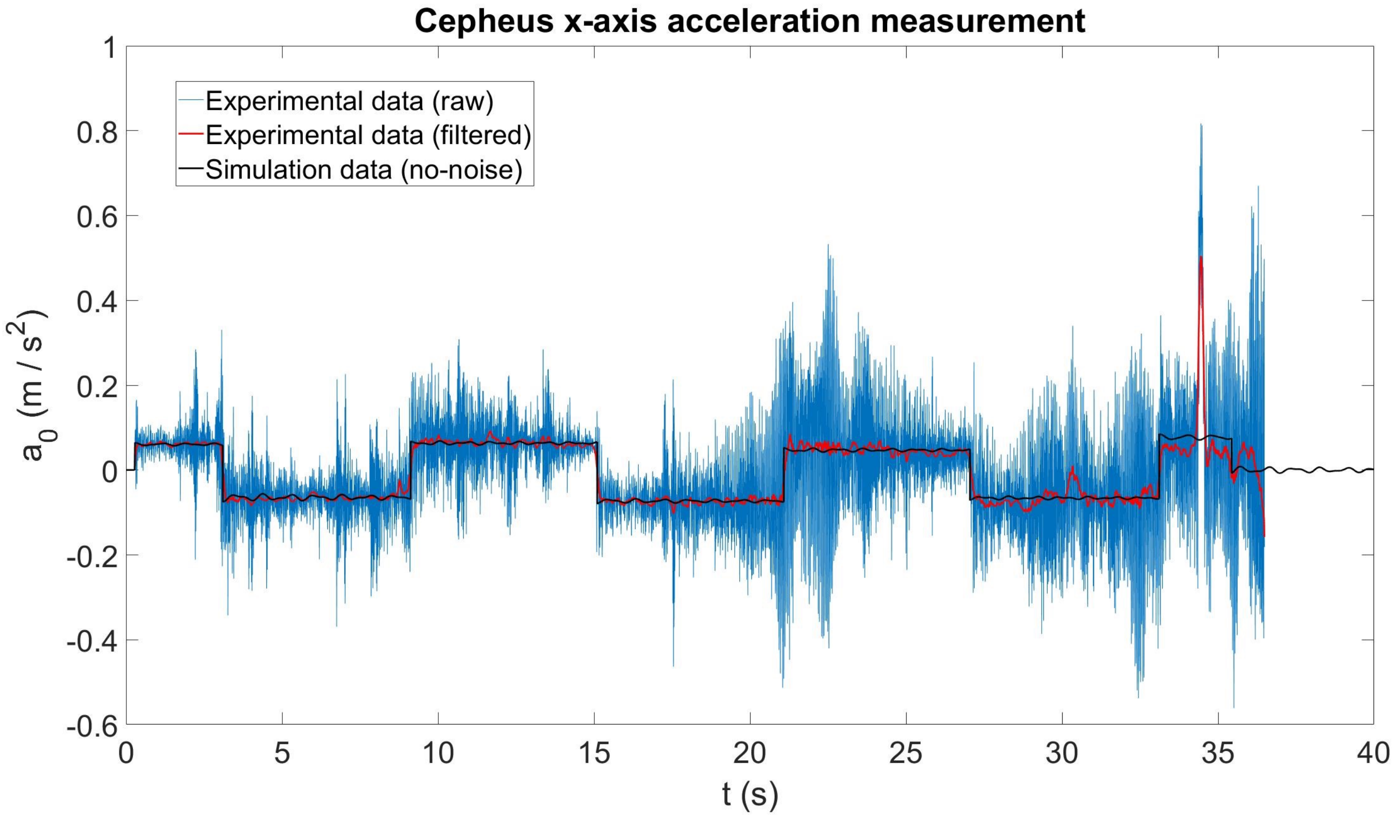
Parameter	True Value	Estimated Value TLS	Relative error (%)	Estimated Value RTLS	Relative error (%)
M	15.117	11.7012	**22.596**	12.09	**20.027**
m_s	0.625	-8.1245	**--**	-10.655	**--**
k_s	33.2156	0.3339	**98.977**	1.5275	**95.401**
b_s	0.1336	-7.3121	**--**	-15.879	**--**
ρ	0.675	0.7711	**14.232**	0.7856	**16.391**

- **Experiment 2**
  - **Estimators used for unmeasurable quantities**
  - **SYSID results not meaningful**

SC1: Modelling Validation (1/2)

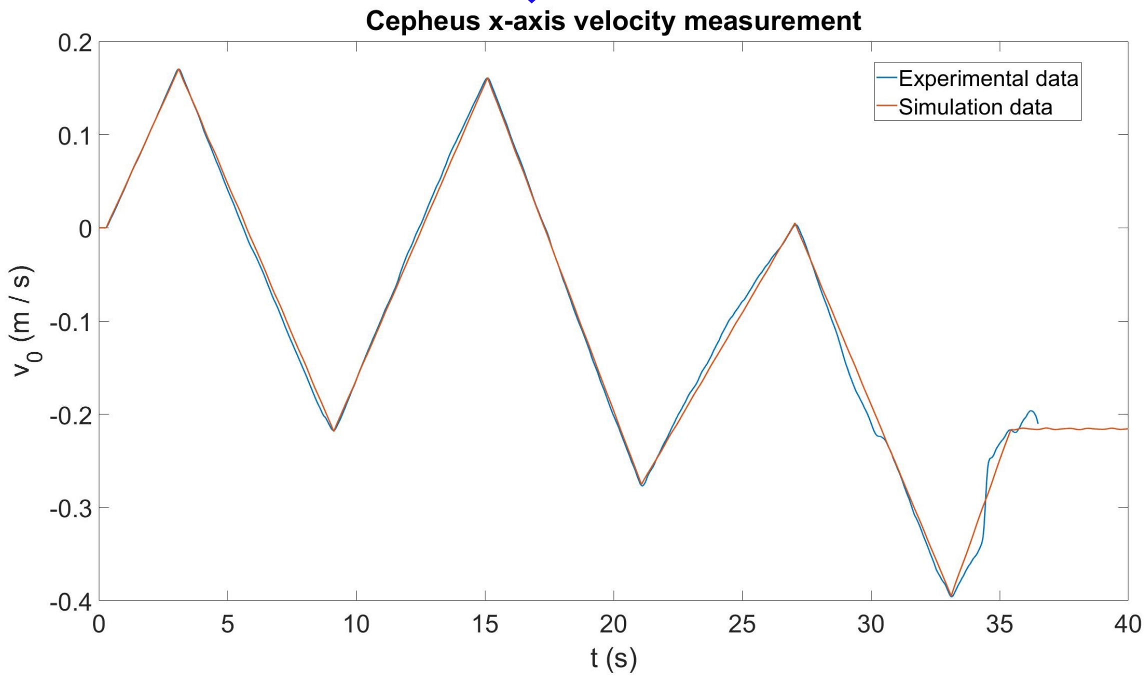
- Identification Experiment: Experimental vs. Simulated Setup
  - Same excitation
  - Qualitative comparison

- **Very good match**

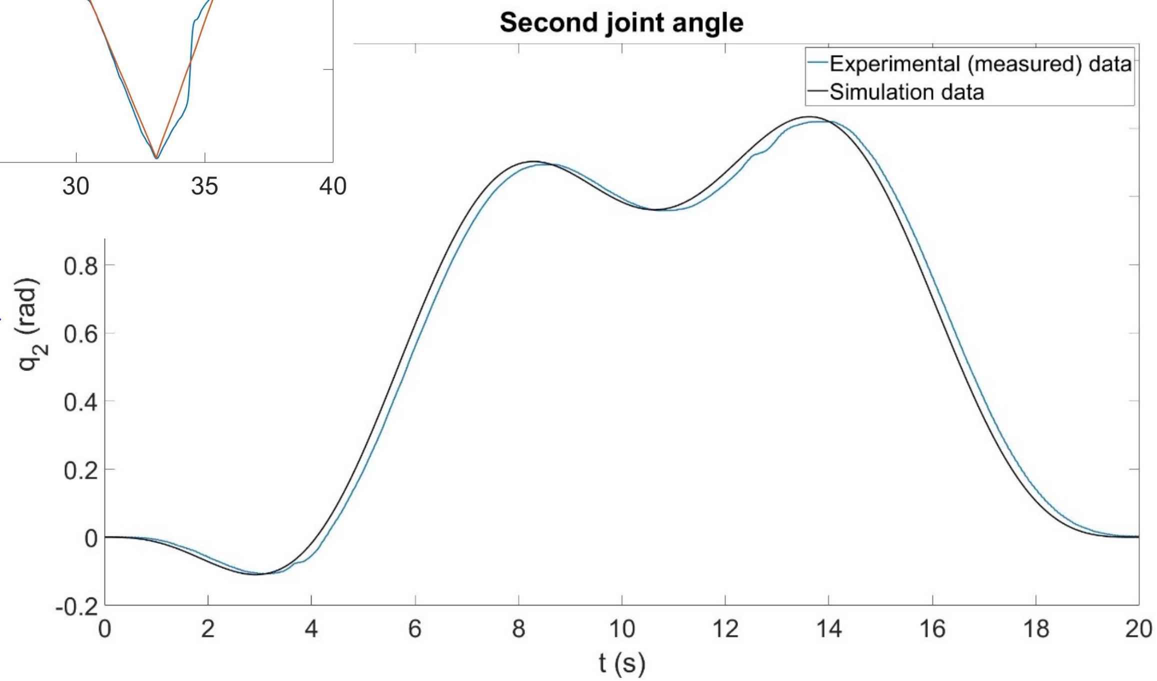


SC1: Modelling Validation (2/2)

- Experiment 1



- Experiment 2



- **Very good match**

SC1: Discussion: Simulated Data

- **Parametric SYSID** with both TLS and RTLS for **SC1** (both Experiment 1 and 2), does not yield meaningful results for several parameters
  - Inadequate SNR is observed
  - *Increasing SNR* (e.g., by lower noise or more accelerometers) leads to significant improvement and good results
- **Modal Analysis** with both SSI-COV and RSSI-COV for **SC1** (Experiment 1), is deemed as **successful** in identifying the first two natural frequencies
- **Recursive** implementations of the Algorithms
  - yield slightly worse results to the non-recursive ones
  - but converge at about halfway through the simulation

SC1: Discussion: Experimental Data (1/2)

- **Parametric SYSID** with both TLS and RTLS for **SC1** (both Experiment 1 and 2), does not yield meaningful results for *most parameters*

  - Experiment 1 is close to BP2, which yielded good results. But “close” is not “the same”:

    - Added mass ⇨ lower max accel. ⇨ lower excitation ⇨ lower SNR

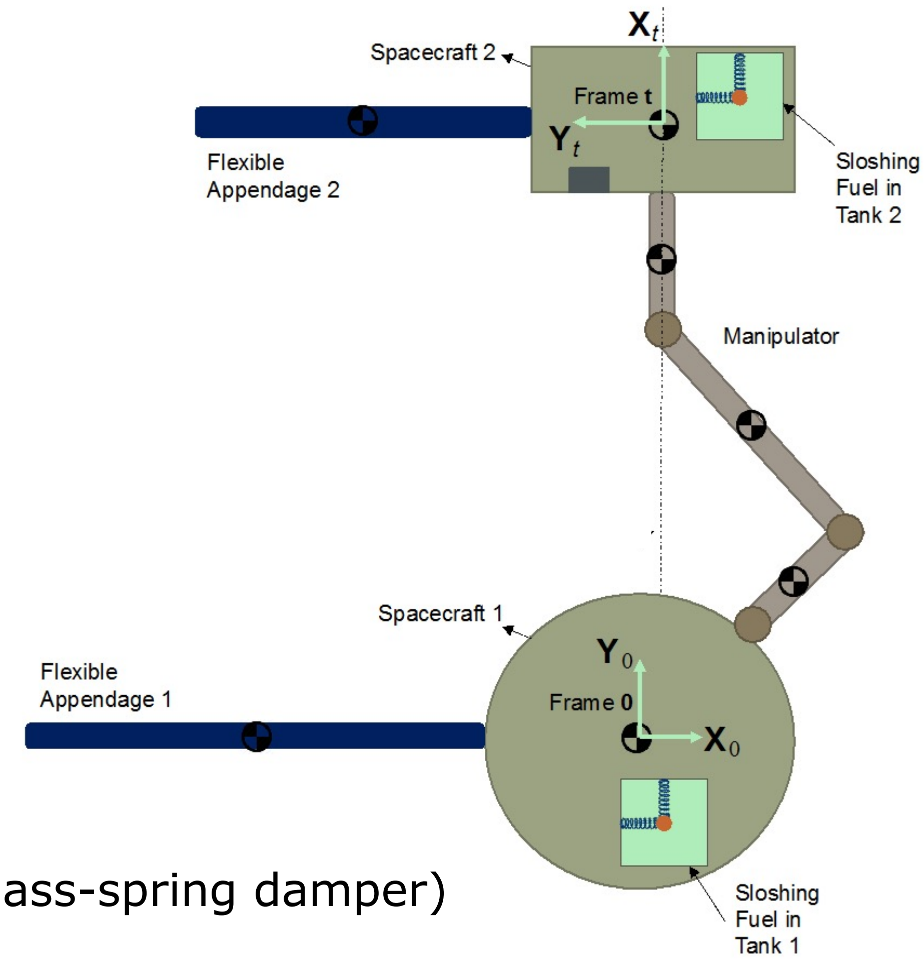
    - Added oscillations from flexible panel, make the excitation force reconstruction more difficult ⇨ again, lower SNR

- **Recursive** implementations (same as in simulation)
  - Yield slightly worse results to the non-recursive ones
  - Converge at about halfway through the simulation

SC1: Discussion: Experimental Data (2/2)

- **Modal Analysis** with both SSI-COV and RSSI-COV for **SC1** (Experiment 1), is deemed as **successful** in identifying the first two *natural frequencies*
  - ID of 2^{nd} bending frequency is good, but ID of 1^{st} one has 16% relative error.
  - However, all Modal Analysis (with data from >10 experiments) yielded a 1^{st} bending frequency of 2 to 2.3 Hz.
  - CAD-FEM models 1^{st} bending frequency of 1.95Hz, used as "true"
  - Possibly the actual 1^{st} bending frequency is 2 - 2.3 Hz, yielding significantly lower error
- Results consistent with the simulated experiment results

SC2: Full-scale Planar System (1/6)



2D System

- Manipulator equipped chaser S/C with:
  - a fuel tank
  - a flexible appendage
- Grasped target S/C with:
  - a fuel tank
  - a flexible appendage

Modelling Assumptions

- S/C Model: Rigid body
- Fuel Sloshing Model: Lumped model (mass-spring damper)
- Flexible appendage: Continuous model (Euler-Bernoulli beam)
- Rigidly grasped Target S/C

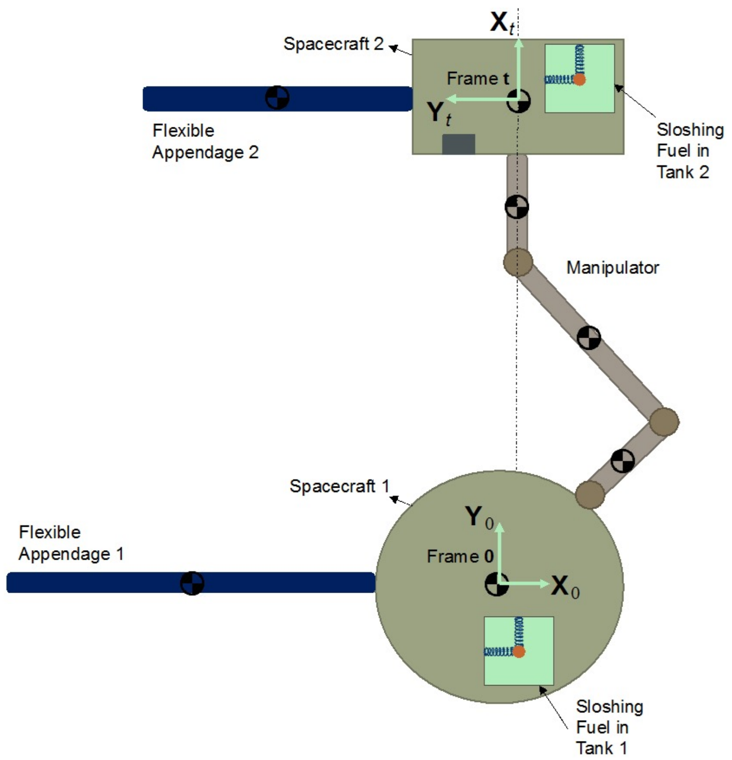
SC2: Full-scale Planar System (2/6)

Main challenge

- All system parameters to be identified in the presence of unmeasurable states
  - Inertial, sloshing, modal parameters of Target system to be identified
  - Sloshing states are not measurable
  - Modal states are not measurable

Additional challenge

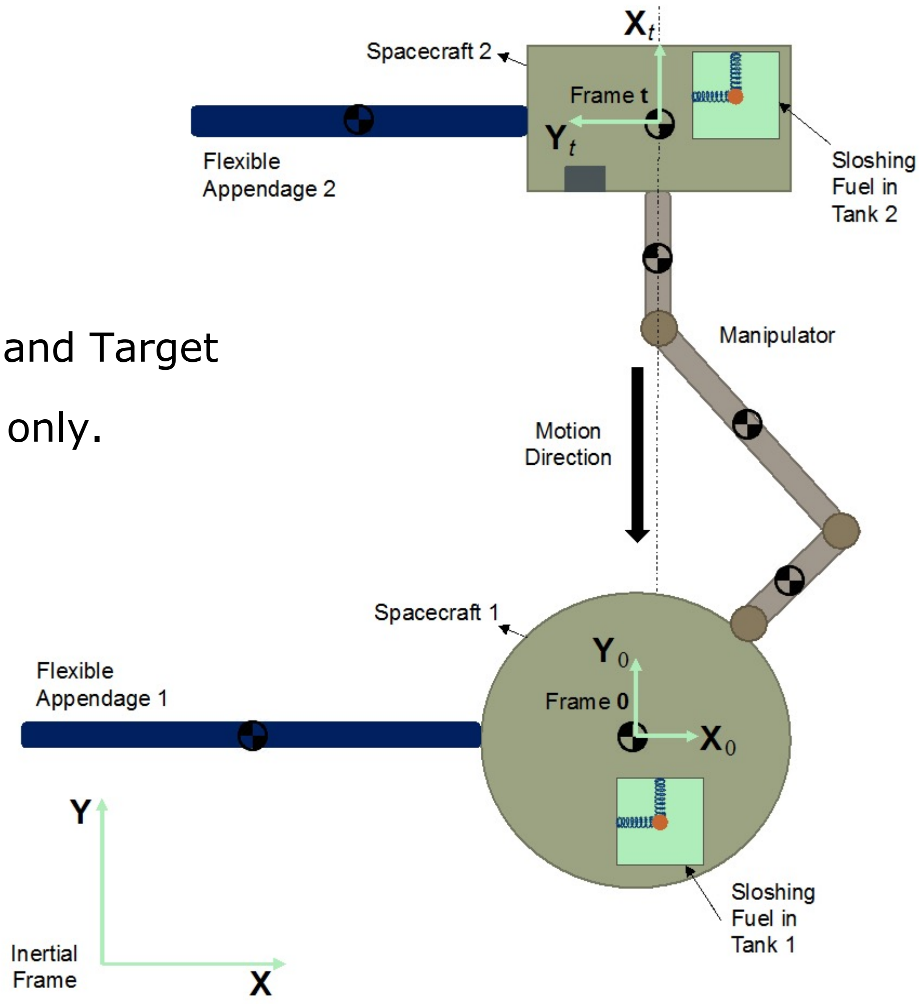
Lack of existing methodologies



SC2: Full-scale Planar System (3/6)

SC2 Task: Berthing

- Requirements
  - Fixed Chaser attitude
  - Constant relative attitude between Chaser and Target
  - Target translation along the inertial **Y**-axis only.
- Control
  - Coordinated control
  - Control in Cartesian space
  - Model-based PD control law



SC2: Full-scale Planar System (4/6)

SYSID during Berthing

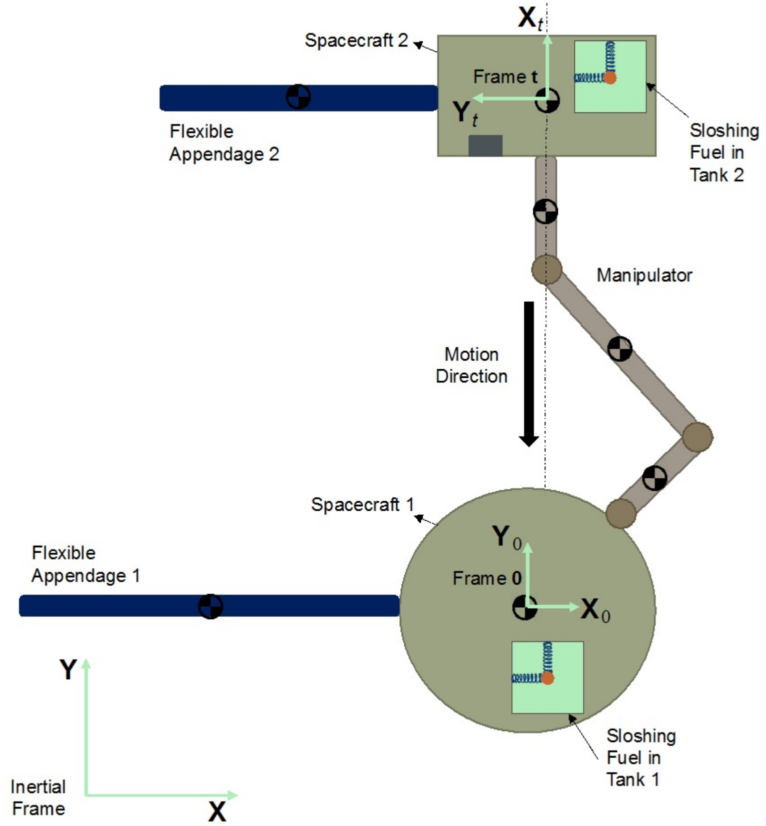
- The Target's S/C orientation is kept constant
- The Target's S/C translates along inertial **Y** axis

Modal Analysis for Flexible Appendage

Modal parameters of the Target's flexible appendage can be identified

Parametric SYSID for Sloshing and Mass

The Target's sloshing parameters and S/C mass can be identified



- Due to the chosen motion, impossible to identify
  - the target S/C's polar moment of inertia
  - the sloshing model parameters on the $\mathbf{Y}_t$–axis

- In the absence of rotation, the Target CoM position is not be identified

SC2: Full-scale Planar System (5/6)

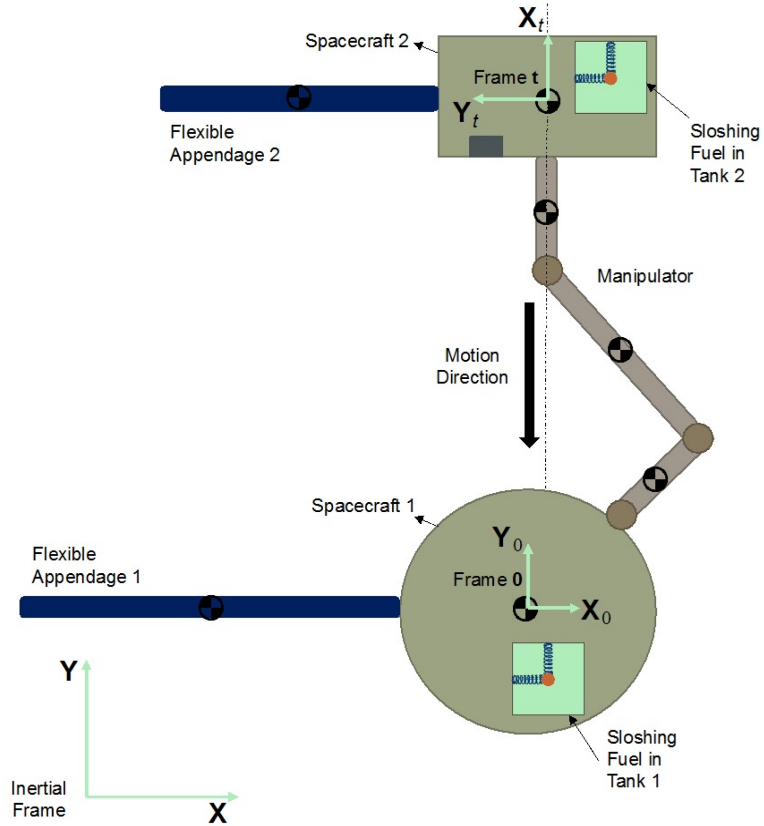
Modal Analysis for Flexible Appendage

SYSID during Berthing

- The Target's S/C orientation is kept constant
- The Target's S/C translates along inertial **Y** axis

Modal Analysis for Flexible Appendage

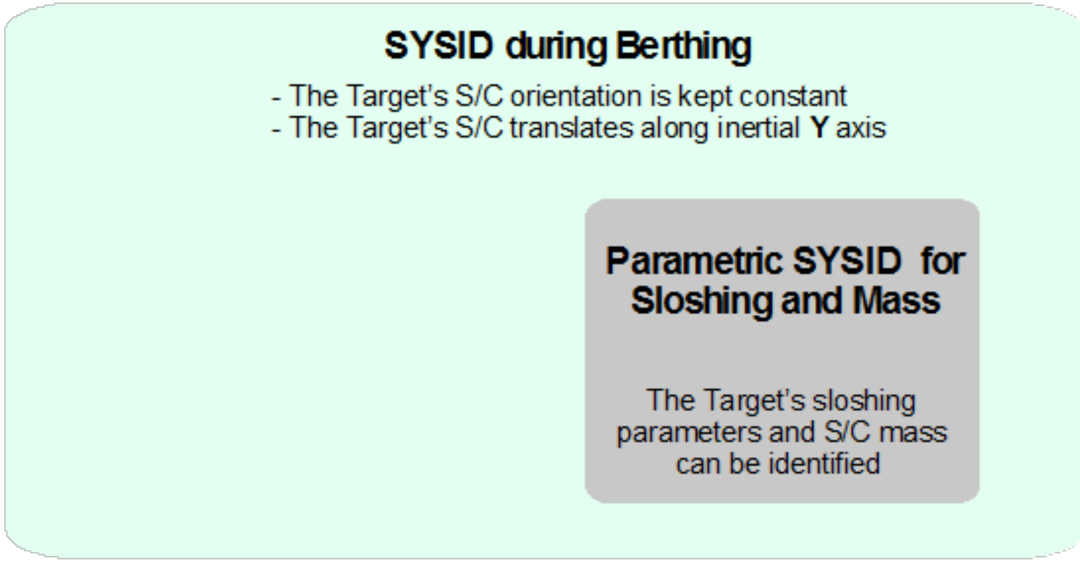
Modal parameters of the Target's flexible appendage can be identified



- Pure translation only in inertial **Y**-axis, by applying net forces only
- Measurements of flexible appendage tracked points accelerations
- Recursive SSI-COV algorithm used based on the BP3 Trade-off Analysis

SC2: Full-scale Planar System (6/6)

Parametric SYSID for sloshing and inertial parameters



- Novel method developed based on transfer function formulation (as in BP2-M2)
  - Eliminates unmeasurable sloshing and modal states from SYSID equations
  - Decouples sloshing identification from modal parameters identification
  - Allows for sloshing and S/C mass identification to run in parallel with modal analysis
- Recursive-TLS (RTLS) algorithm used based on the BP1 Trade-off Analysis

SC2: Discussion on Simulated Data (1/3)

- Modal SYSID yields very good results, within acceptable limits
  - Requires enough measurements, leading to a long operation
  - Manipulator workspace limits result to very slow operation
    - Benefits Modal Analysis
    - But results in very low SNR

- Parametric SYSID yields poor results, due to the low SNR
  - Enhanced trajectory

SC2: Discussion on Simulated Data (2/3)

- Enhanced trajectory case: a two-part trajectory considered
  - **Part 1**: General motion of Target, aligning the S/C berthing fixtures
  - **Part 2**: Pure translation of Target (as the original SC2 motion)
- Even then, SNR is still not adequate
- However, note that lower noise levels result in adequate SNR and very good Parametric SYSID results

SC2: Discussion on Simulated Data (3/3)

- For SYSID, two fundamental requirements must be satisfied:
  - Behaviours due to parameters must be excited
  - Measured quantities of appropriate SNR must be available
- When these requirements are satisfied (e.g., noiseless measurements or exciting enough motion as in SC1), the evaluated/developed methods and algorithms perform successfully
- Else, SYSID results may not be useful

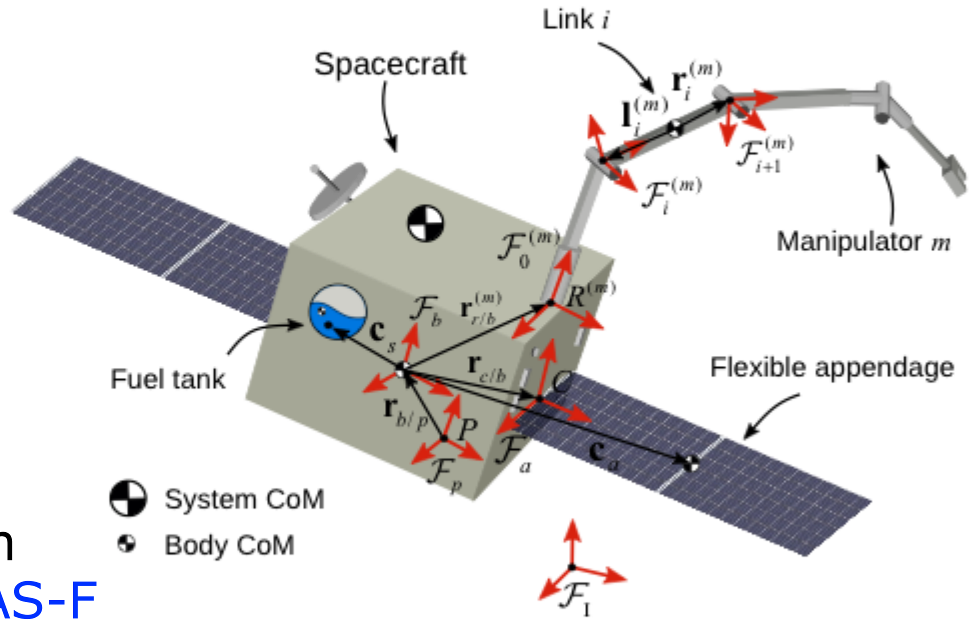
SYSID Detailed Design

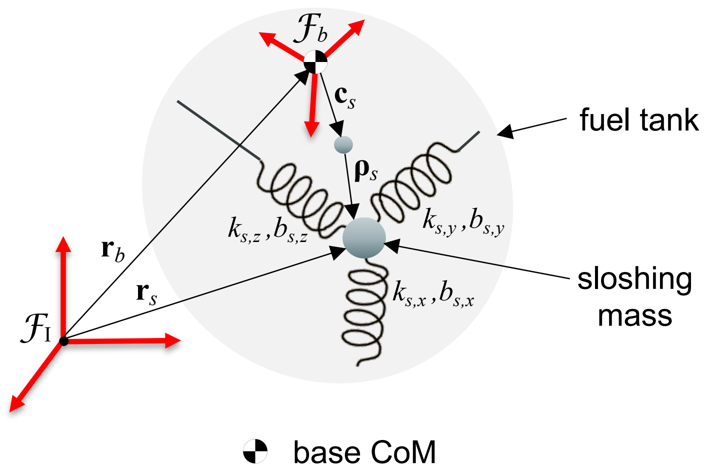
3D Study Case 1

(simulations)

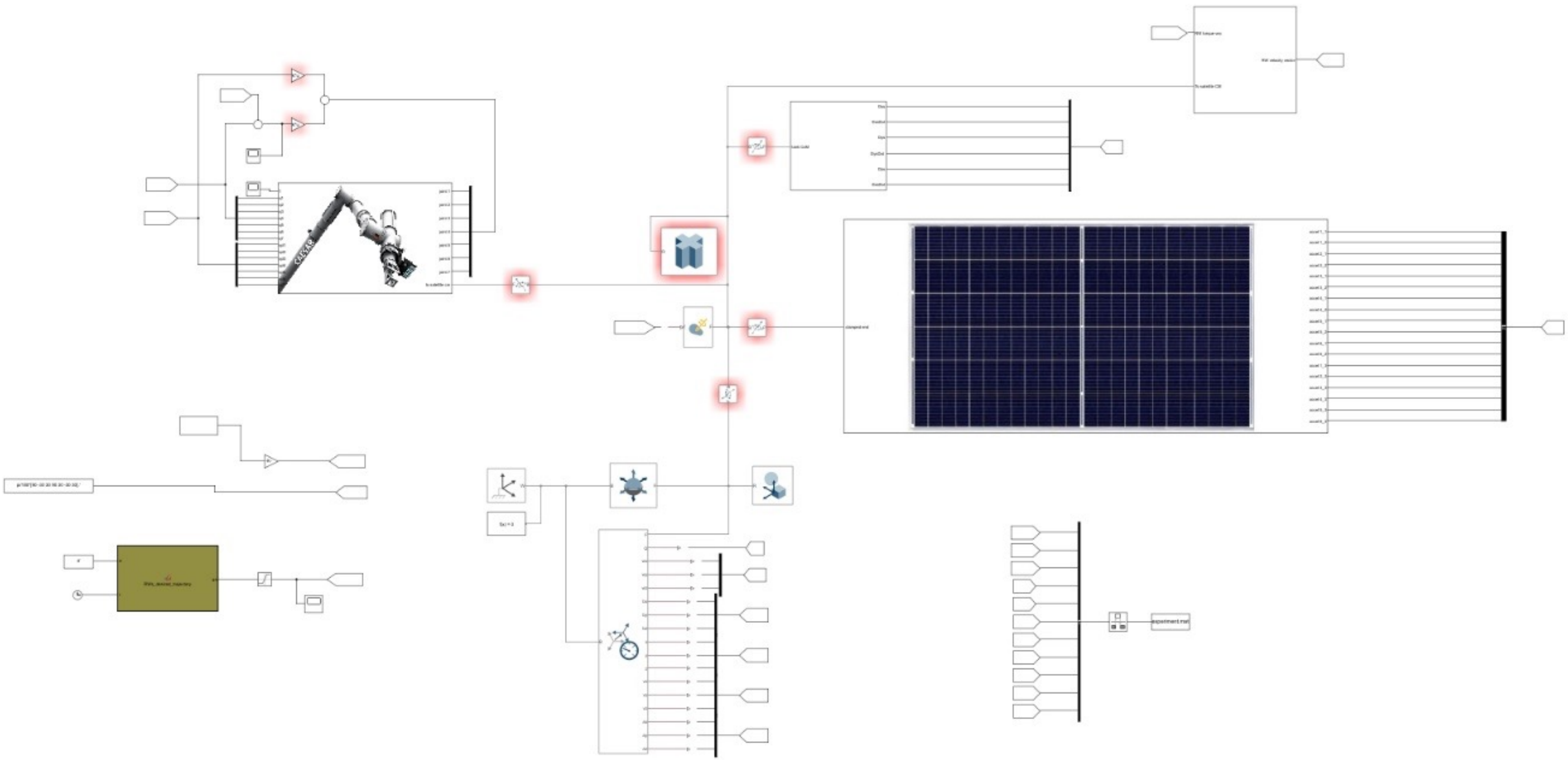
Analytical Full-scale 3D SC1 Model

- SC1 model
  - Quasi-Lagrangian approach
  - System equations of motion
- Structure & Parameters
  - Parameters in accordance with realistic values provided by TAS-F
  - Manipulator based on DLR's CAESAR
  - Sensors and actuators in accordance with actual ones





Simscape Full-scale 3D Model



Sensors and Actuators

❑ Sensors

- IMU
- Sun-tracker/ Star-tracker
- Motor-encoders
- Flexible appendage accelerometers
    - Realistic noise models

❑ Actuators

- Joint motors
- Reaction wheels
- Thrusters

❑ First order low-pass Infinite Impulse Response (IIR)

Method and Algorithm

- 2-stage motion (Experiment 1 & 2)

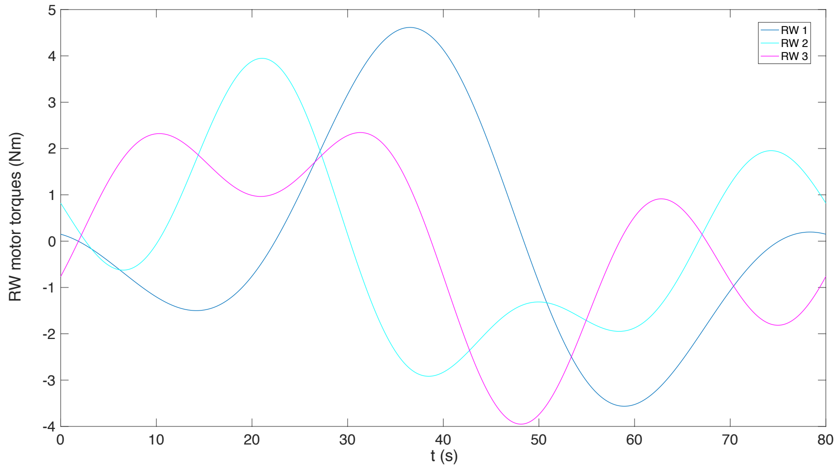
- **Experiment 1**
  - Modal Analysis with SSI-COV
  - Parametric SYSID (sloshing model parameters) with TLS on a Method based on the System Transfer Function
    - Method decouples Parametric SYSID from Modal Analysis

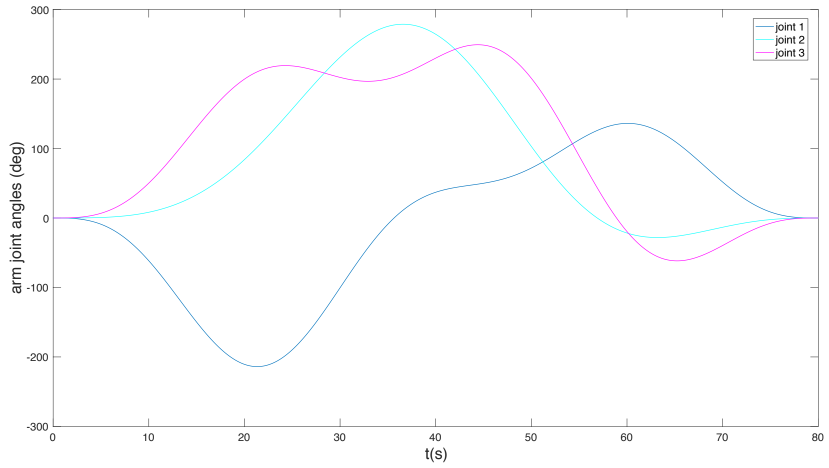
- **Experiment 2**
  - Parametric SYSID (inertial parameters) with TLS on a Method based on the System Energy Balance

- Novel estimators for the unmeasurable quantities

Excitation & simulated response

- **Experiment 1**
  - Thruster forces: consecutive pulses
- **Experiment 2**
  - RW torque input: Truncated Fourier series
  - Manipulator torque inputs: PD controller on desired joint trajectories (truncated Fourier series)
  - All Fourier series coefficients obtained by minimizing regressor matrix condition number





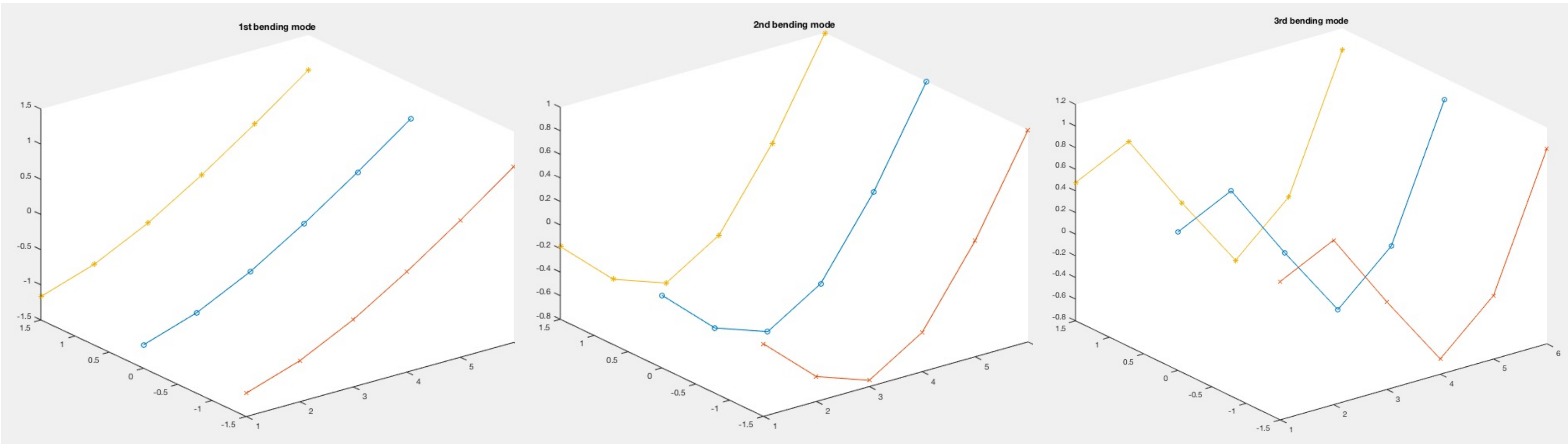
Experiment 1 SYSID Results

Modal Analysis

Parameters	(Hz)	(Hz)	(Hz)
Type	bending	bending	bending
True values	0.046	0.286	0.801
Estimated value	0.046	0.287	0.800
Rel. Error (%)	**0.114**	**0.354**	**0.245**

Parametric (sloshing) SYSID with TLS

Parameter	True Value	Estimated Value	Relative error (%)
M	1023.55	1022.22	**0.129**
m_s	49.6	49.90	**3.41**
$k_{s,x,y,z}$	0.41	0.41	**0.788**
$b_{s,i}$	0.02	-	**-**
ρ	2700	2761.17	**2.266**



Experiment 2 SYSID Results

Parametric (inertial) SYSID

Parameter	True Value	Estimated Value	Relative error (%)
π'_m (1)	235904.27	232816.76	1.31
π'_m (2)	42646.93	42500.42	0.34
π'_m (3)	216860.44	215087.54	0.82
π'_m (4)	-43783.03	-44874.32	-2.49
π'_m (5)	-78364.67	-76945.42	-1.81
π'_m (6)	-16799.40	-17113.4	-1.87
π'_m (7)	-674.38	-695.10	-3.07
π'_m (8)	-3145.80	-3127.54	-0.58
π'_m (9)	-1205.82	-1190.96	-1.23
π'_m (10)	-0.50	-0.53	**-5.83**
π'_m (11)	-1.50	-1.44	-3.85
π'_m (12)	-0.60	-0.62	-4.14
π'_m (13)	837.41	835.22	0.26
π'_m (14)	837.42	837.65	0.03
π'_m (15)	-720.27	-715.63	-0.64
π'_m (16)	720.32	716.36	0.55
π'_m (17)	150.00	149.28	0.48
π'_m (18)	-117.04	-121.40	-3.72
π'_m (19)	117.09	122.08	4.26
π'_m (20)	50.00	51.67	3.34
π'_m (21)	-101157.00	-103746.97	-2.56
π'_m (22)	-471870.00	-466707.79	-1.09
π'_m (23)	-180873.00	-177657.18	-1.78
π'_m (24)	-33719.00	-35920.32	**-6.53**
π'_m (25)	-157290.00	-161684.34	-2.79
π'_m (26)	-60291.00	-61632.43	-2.22
π'_m (27)	7500.00	7586.22	1.15

Discussion on SC1 Full-scale 3D Simulation (1/2)

- **Modal Analysis** with SSI-COV and **Parametric SYSID** with TLS for SC1 (**Experiment 1**), are deemed as **successful** in identifying the first three natural frequencies and the sloshing model parameters, respectively.
  - Identified parameters within the 5% relative error margin

- **Parametric SYSID** with TLS for SC1 (**Experiment 2**), is also deemed as **successful** in identifying the inertial parameters.
  - Two parameter clusters marginally outside the 5% error margin

- For computational reasons, the first three flexible panel bending modes and the first three manipulator DoFs only were used

Discussion on SC1 Full-scale 3D Simulation(2/2)

- Simulations of a full-scale 3D system yield very good results

- Most of the scaled-down SC1 actual and simulated experiments did not!
  - Sensor resolution is not scaled down according to length scale
  - Space-ready sensors (modelled for the full-scale system) are far superior to the available sensors at the SRE
  - Small disturbances existing in the experimental facility do not exist in space
  - Those small disturbances affect the scaled-down systems more significantly

Sensitivity, Robustness, & Sampling Considerations

1. Sensitivity Analysis

(preliminary)

Sensitivity Analysis Examples

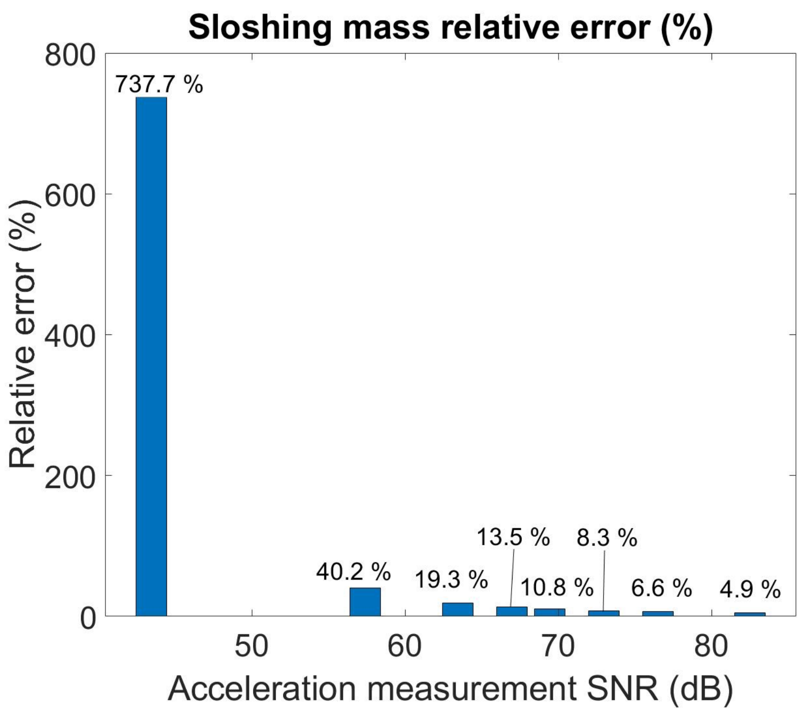
- Identify factors whose variation affects the SYSID process
  - What is the various factors impact on the identification results?
  - Which estimated variables are impacted most?
  - To what extent can a factor be varied before crossing a pre-defined threshold on an estimated variable?

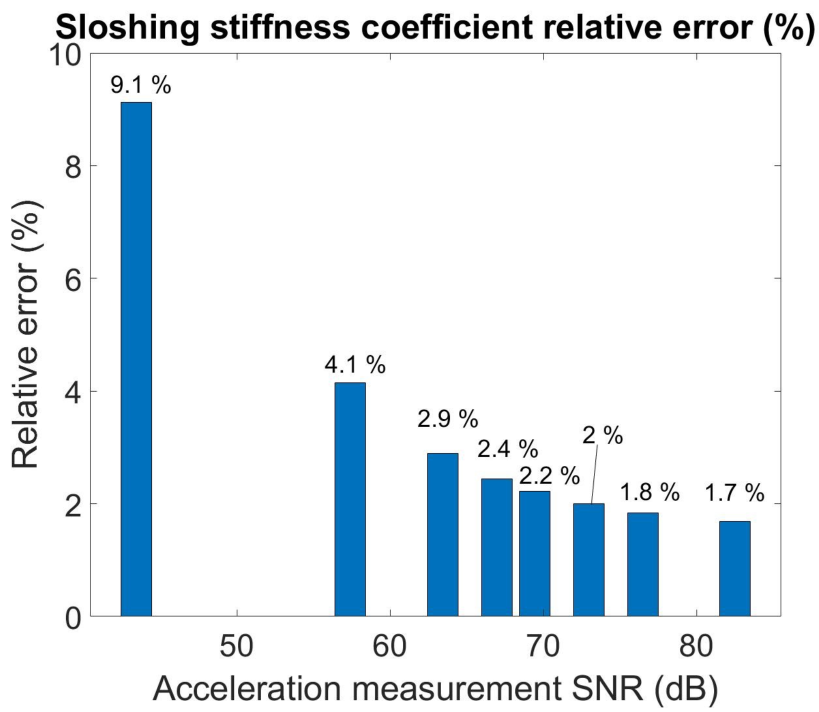
- Parametric SYSID Sensitivity Analysis Illustrative Examples
  - SC2-Exp2: SNR
  - BP1A: Mass ratio of manipulator – S/C

- Modal SYSID Sensitivity Analysis Illustrative Examples
  - BP3: SNR
  - BP3: Hub inertia

Parametric SYSID Sensitivity Analysis (1/2)

- SNR for SC2-Exp2





Parametric SYSID Sensitivity Analysis (2/2)

❑ Manipulator – S/C mass ratio for BP1A

Mass ratio	a_1 error (%)	a_2 error (%)	a_3 error (%)	a_4 error (%)	a_5 error (%)	a_6 error (%)	a_7 error (%)	a_8 error (%)
60	-1.204	-4.458	7.497	12.222	0.073	1.845	1.031	4.509
40	-1.199	-4.443	7.475	12.206	0.072	1.839	1.031	4.481
25.92 (nominal)	-1.192	-4.421	7.457	12.181	0.069	1.830	1.033	4.437
20	-1.187	-4.404	7.443	12.162	0.068	1.823	1.034	4.401
10	-1.165	-4.346	7.401	12.092	0.061	1.795	1.039	4.254
5	-1.133	-4.291	7.380	12.015	0.051	1.752	1.041	4.009

- Nonnegligible but small effect
- Almost all relative errors decrease as the manipulator-to-S/C mass ratio increases

Modal SYSID Sensitivity Analysis

- ❑ SNR for BP3 ⇨ very small increase of errors with SNR variation, after a quite low dB threshold

- ❑ Hub inertia for BP3 ⇨ very small effect

Discussion

- SNR increase leads to a dramatic improvement of SYSID results
- Subsystems mass ratio variations have limited effect
- Future work suggestions
  - Sensitivity Analysis to be run for all BPs and SCs, for those and other Factors
  - Sensitivity Analysis for simultaneous variation of Factors. Monte-Carlo Analysis

2. Robustness Considerations

Robust On-line Capabilities (1/2)

- Robust control of a fundamentally nonlinear system (e.g., space manipulator), is an open research issue
  - Nonlinear robust controllers such as SMC, have known issues (e.g., actuator chattering)
  - NMPC not always convex and computationally expensive
  - Use of LPV, though very good for linearizable systems, is still an open research issue for complex, highly nonlinear systems

Robust On-line Capabilities (2/2)

❑ Lines of attack

- Feedback linearization (model-based control), assisted by a linear robust controller (e.g., $H\infty$)

- Partial linearization due to uncertainty results in "disturbance" term with known bounds, related to the uncertainty statistics

- In operational scenarios and as data are collected during task execution, the uncertainty statistics can be obtained on-line

- Online adaptation of controller parameters

SYSID results statistics

- 100 simulations of BP1A are run with different noise profiles
  - Different seed number on the random number generator

Inertial Parameters Cluster	Mean value	Mean value 95% confidence interval	σ	σ 95% confidence interval
a_1	-26.917	[-26.927, -26.907]	0.0496	[0.0436, 0.0577]
a_2	-9.224	[-9.242, -9.207]	0.0893	[0.0784, 0.1038]
a_3	10.582	[10.553, 10.611]	0.1445	[0.1269, 0.1679]
a_4	3.077	[3.067, 3.087]	0.0504	[0.0443, 0.0586]
a_5	964.646	[964.51, 964.782]	0.6851	[0.6015, 0.7959]
a_6	16.743	[16.731, 16.755]	0.0612	[0.0537, 0.0711]
a_7	44.44	[44.428, 44.452]	0.0597	[0.0524, 0.0694]
a_8	10.933	[10.916, 10.950]	0.0852	[0.0748, 0.0989]

- Statistics for relative errors (%) are also obtained

Computational Impact Preliminary Analysis

- On-line robust controller adaptation requirements using uncertainty statistics derived from a repetitive SYSID process are discussed:
  - in terms of time requirements for the statistics derivation
  - in terms of buffer size

- Additional factors identified
  - CPU available time for the additional computations
  - Additional energy consumed for such computations
  - Closed-loop system stability during robust controller parameter adaptation

3. Sampling Rate Considerations

Parametric SYSID Sampling Rate Considerations

- Non-recursive implementation
  - 2.5 Hz to 66 Hz
  - High sampling rate is not a requirement for SYSID
    - Lower sampling rate improves regressor condition number
    - However, enough data with low sampling rate, leads to prolonged experiments (see 3D SC1)

- Recursive implementation
    - Several measurements at 50Hz per step, but only a few steps to converge
    - Important future work: Trade-off between measurements requirement per step vs. steps required for convergence, considering sampling rate and computational realistic constraints

Modal Analysis Sampling Rate Considerations

- For both SSI-COV and RSSI-COV
  - To be able to:
    - Identify the largest natural frequency considered having significant effect on system motion
    - Distinguish it from identified spurious modes
  - Then, sampling rate must be at least 2 to 3.5 times the natural frequency

Project Output Exploitation

In-Flight Experiments (1/2)

- Identification of inertial parameters using Parametric SYSID with SPHERES-like
  - With varying inertial parameters

- Identification of modal parameters using Modal SYSID with SPHERES-like
  - Simple panels attached in various positions of chassis

- Identification of inertial parameters of a manipulator using Parametric SYSID with a SPHERES-like or Astrobee-like system
  - Use of manipulator with custom made links (variable inertial parameters)
  - Experiments with emphasis in uncertain grasping and manipulation

In-Flight Experiments (2/2)

❑ Full Mated Experiments

- Orbital Express Mission or EROSS-like experiments
- Satellites for these experiments do not need to be of medium/large scale
  → exploit the Newspace trend of small satellites

❑ Components

- 7dof manipulator-equipped Chaser satellite
- Active Target satellite, with varying inertial properties
  (e.g., by use of simple mechanisms).
- Control Room can activate/deactivate subsystems, to allow for different SYSID scenarios

❑ Indicative experiments

- Experiments like SC1 and SC2 (both with Experimental and Operational excitation) can be considered.

ECSS Requirements Guidelines

- Accuracy of the Model Parameters
- Measurement Noise & SNR Improvement
- Experimentation

Conclusions

Conclusions (1/4)

- Linearization of a fundamentally nonlinear system, such as a space manipulator, around an equilibrium point, would result in derived system dynamics valid only close to that point.

- Study of the full nonlinear system was opted

- Analytical models were verified by comparison to Simscape models responses and (when applicable) by comparison to the experimental facilities system responses

Conclusions (2/4)

- Modal analysis is found to be quite successful with SSI-COV and RSSI-COV (except for the damping ratios identification)

- Parametric SYSID with TLS and RTLS is also found to be quite successful (except for the sloshing damping coefficients identification), provided adequate measurements SNR exists

- Recursive implementations of the Algorithms provided similar results than the non-recursive ones (somewhat higher relative errors), but required about half the time to yield these results

Conclusions (3/4)

- It was observed that the SYSID results were affected by four main factors:

  - Accuracy of the model parameters knowledge

    When comparing SYSID results with inaccurate estimations of the actual system parameters, then even perfect SYSID may seem erroneous

  - Signal to Noise Ratio (SNR)

    Solutions: higher excitation (if possible), better sensors, filtering (be careful of the time-shift when online)

  - Sampling Rate

  - Experimental facilities disturbances

Conclusions (4/4)

- Even for a highly-nonlinear, complex system such as a full-scale spatial Space Manipulator System, the SYSID results are quite promising

- For easily linearizable systems (e.g., satellite operating around certain attitude "equilibrium-points"), the results are expected to be at least equally good

- Standardized off-line and especially on-line SYSID can be very useful in enhancing robust control performance in space

- We are not "there" yet, but these initial results are definitely promising, and the goal looks both "doable" and "worth doing"!

Managerial

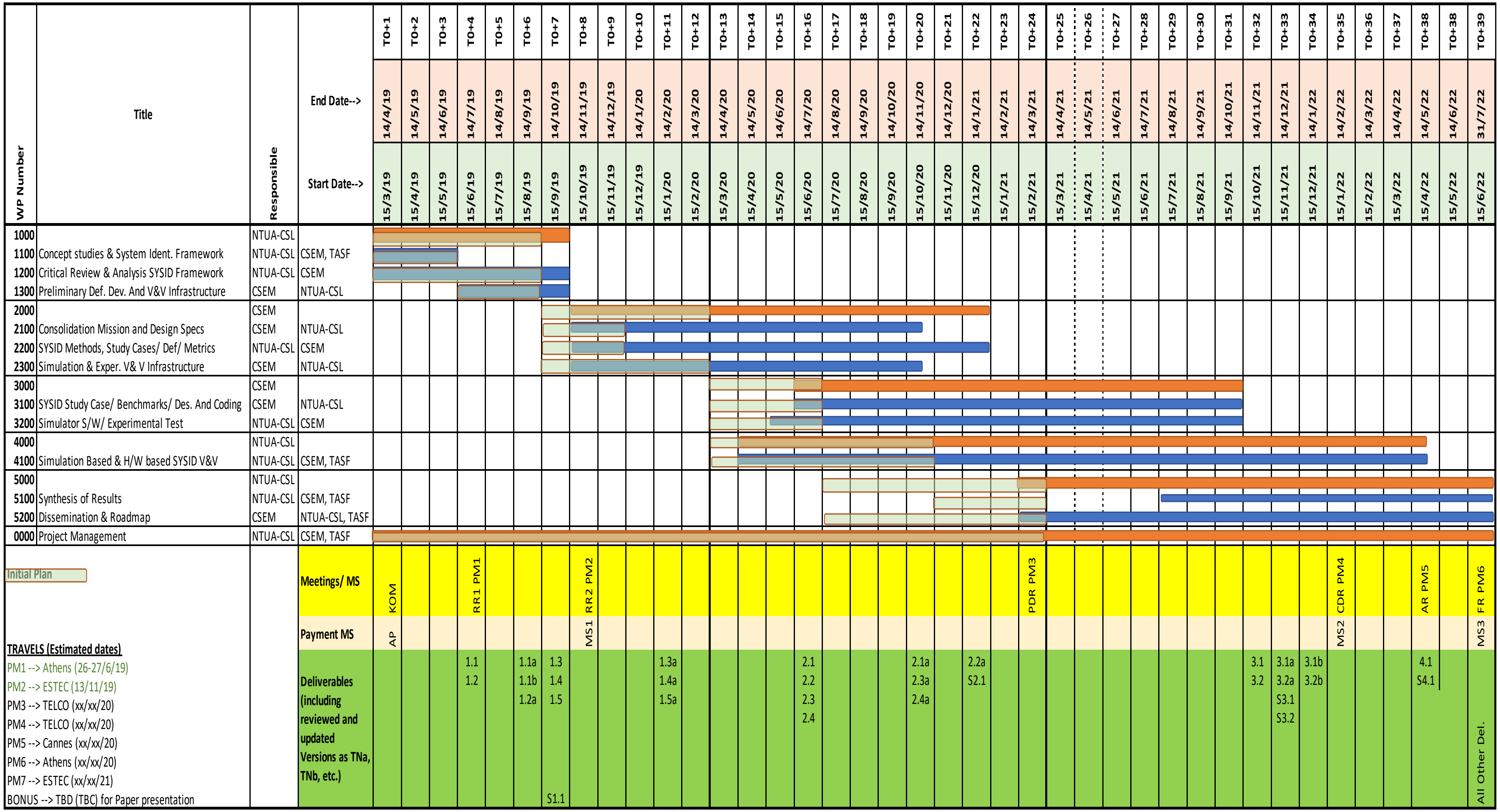
Status

- The project has been completed

- Significant delays due to:
  - Covid-19 lockdowns (force majeure)
  - Technical complexity
  - Certain steps where needed that SoW did not include (CCN has been issued for this reason)

- Deliverables completed

Final Gantt Chart



Thank you