University of Trento
Università degli Studi di Padova
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European Commission
E.T.PACK-F

Experimental test and numerical validation for evaluating the dynamics of the In-Line Damper for the E.T.PACK-F project

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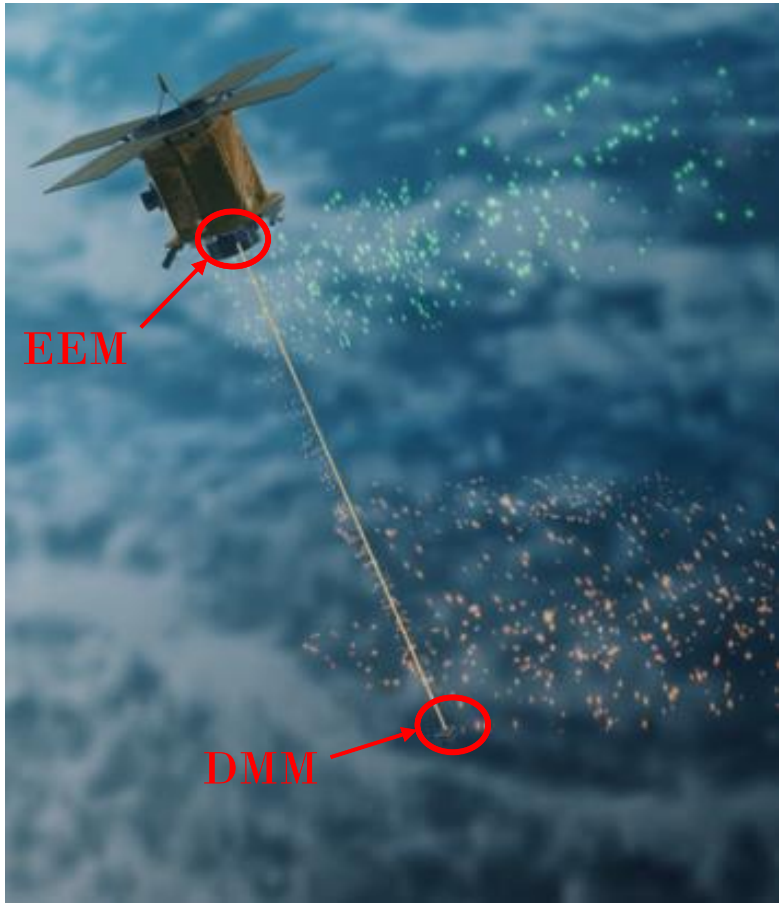
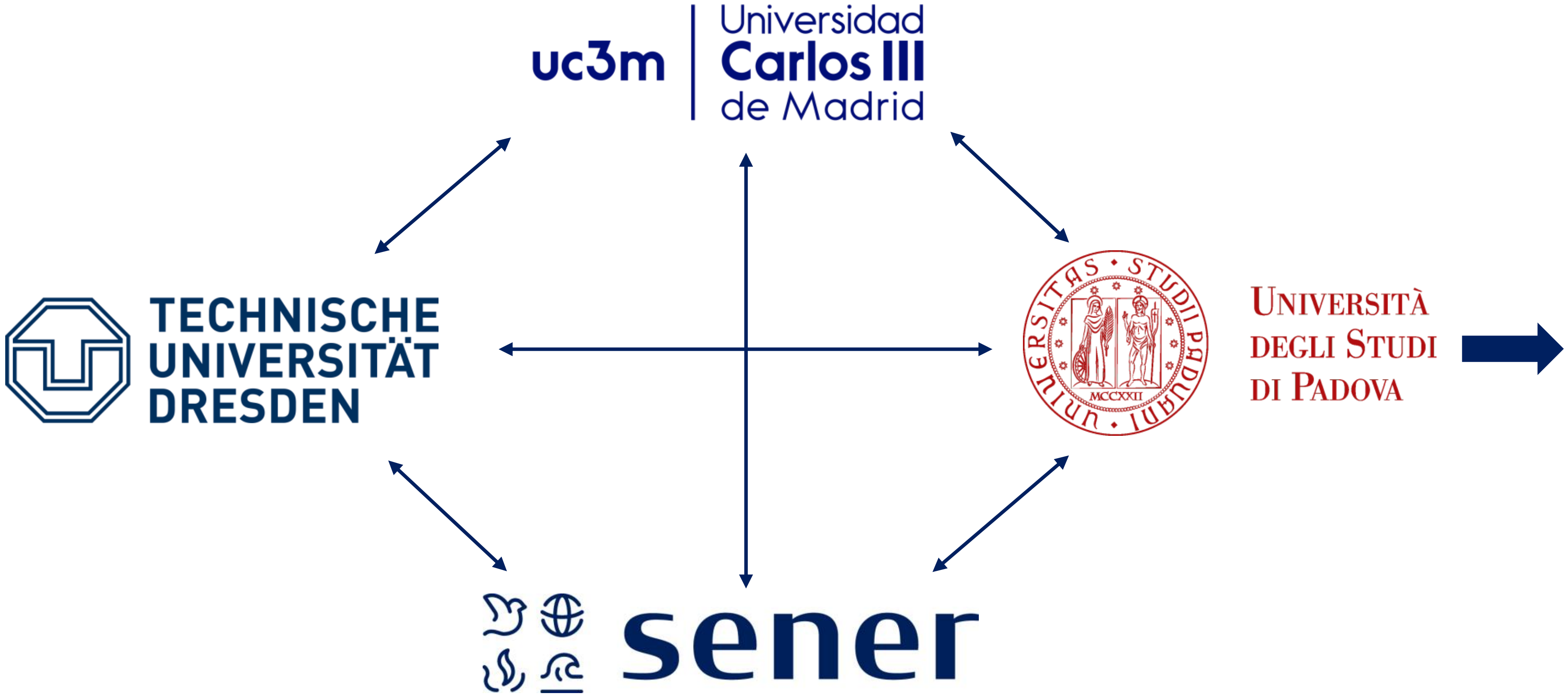
1. E.T.PACK-F project



From E.T.PACK-F website

- E.T.PACK-F is a project funded by the European Innovation Council (EIC).
- The project aims to build a Deorbit Kit that uses the Electrodynamic Tether (EDT) technology for decreasing the orbital altitude of a EOL satellite, where the kit is mounted.
- The kit consists of two module, one for accommodating the deployment mechanism of the tether (DMM) and the other for accommodating the electron emitter (EEM).

1. E.T.PACK-F project



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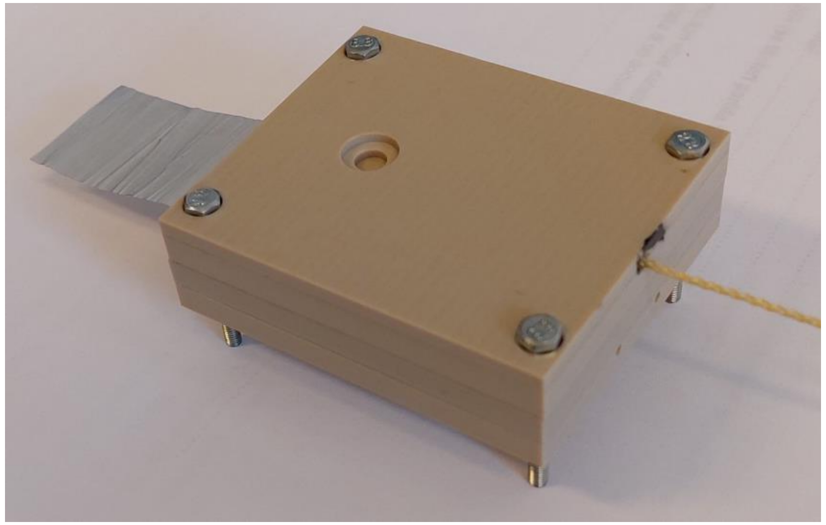
- Andrea Valmorbida
- Giovanni Anese
- Alice Brunello
- Samantha Salmistraro
- Sebastiano Chiodini
- Giacomo Colombatti
- Prof. Enrico Lorenzini

2. The In-Line Damper

- The In-Line Damper is a patented device, design and developed at the University of Padova.

- Its main purpose is to reduce the oscillation on the tether induced by the Lorentz force during separation of the modules and then deorbiting.

- It is attached to the tether from one side, and to the EEM through a Kevlar cable and an electrical connection on the other side.

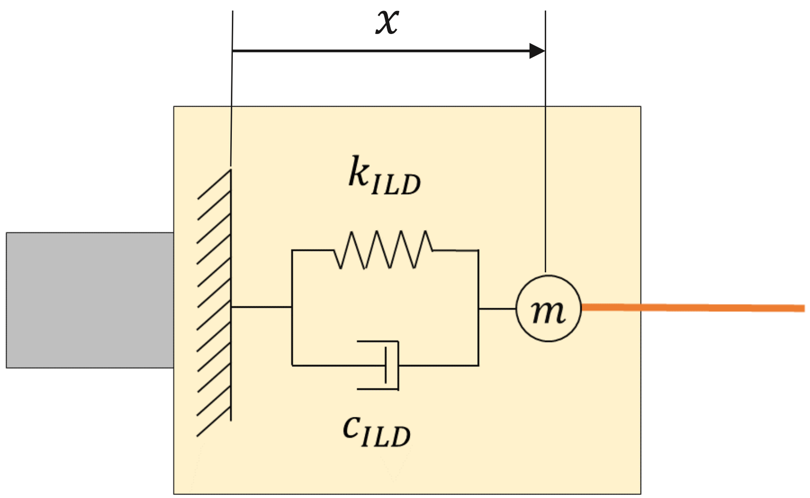


2. The In-Line Damper

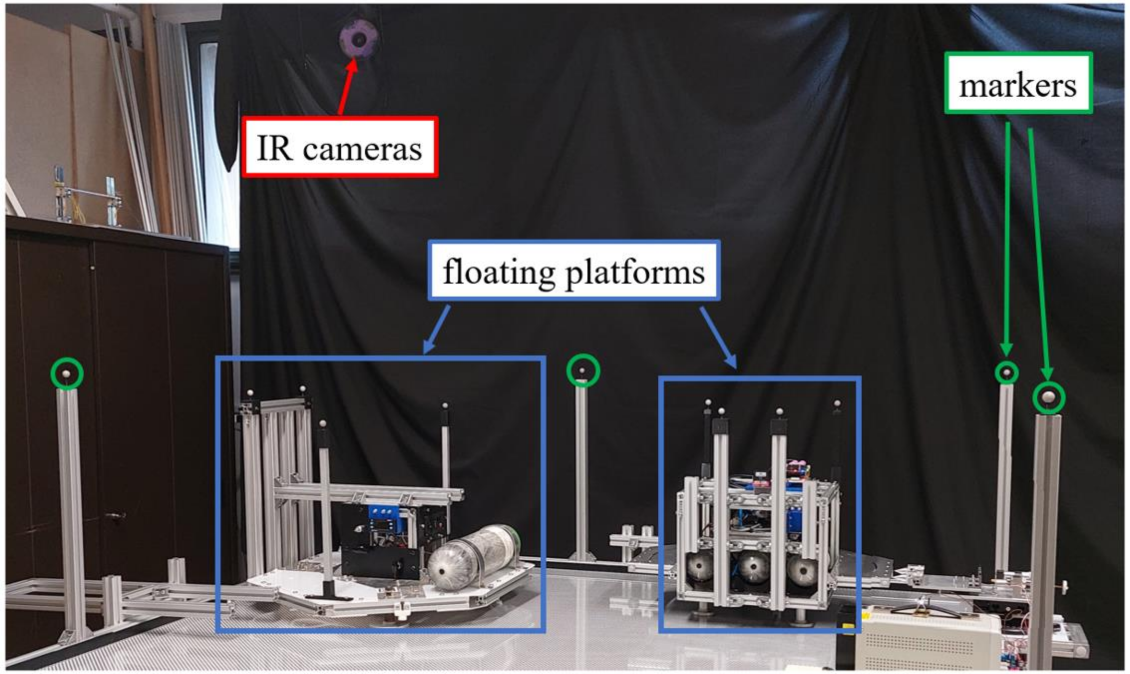
- It works as a mass-spring-damper system, therefore the equation for describing the dynamics is:

$$F = m\ddot{x} = c_{ILD}\,\dot{x} + k_{ILD}(\dot{x})\,x$$

- Its dynamics has a strong impact during the separation of the two modules, therefore an experimental campaign was necessary to assess its behavior.



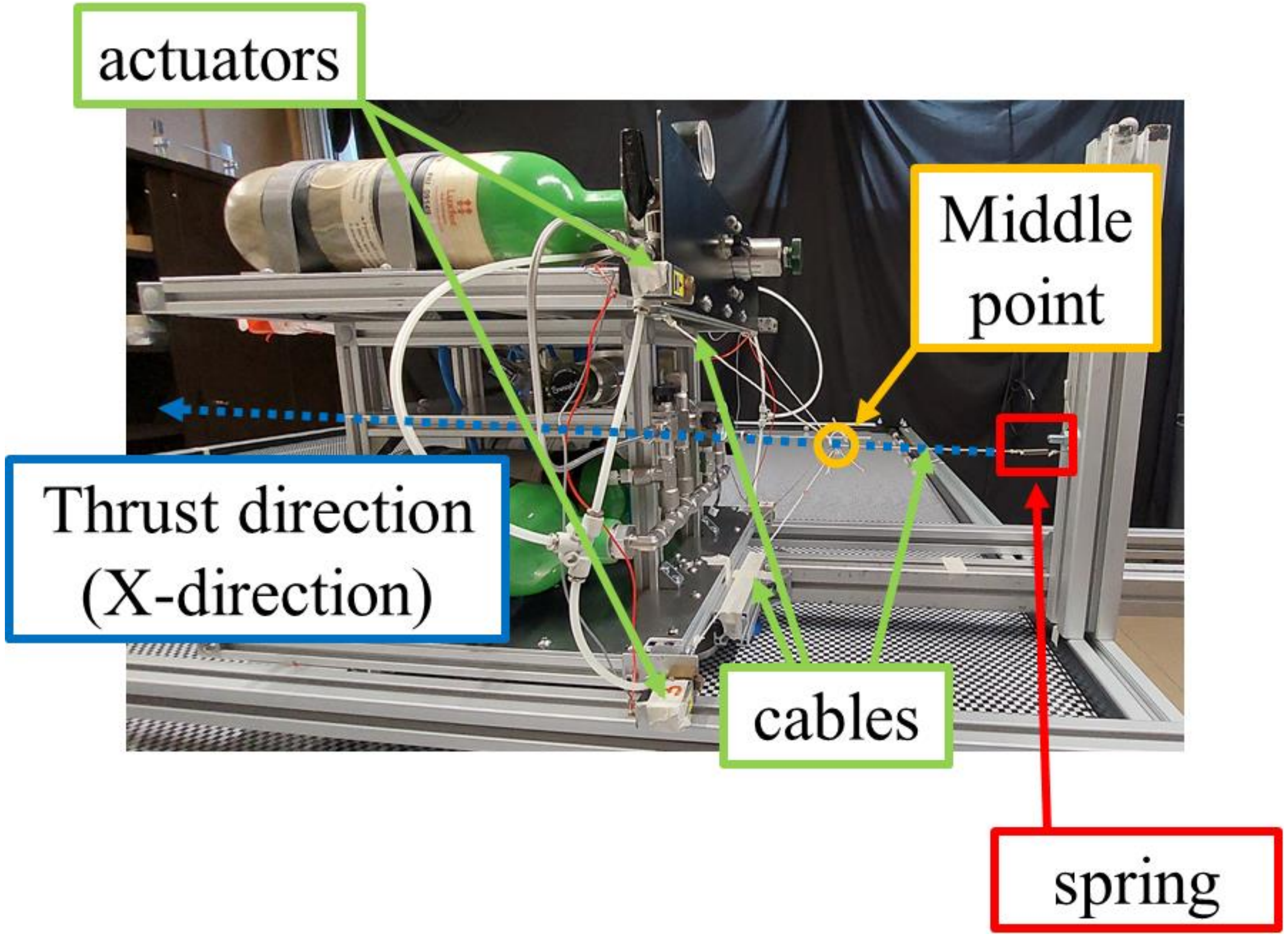
3. Experimental setup and tests



- For the test it is used the SPARTANS facility at the University of Padova.
- Only the small platform is used to emulate the EEM module.

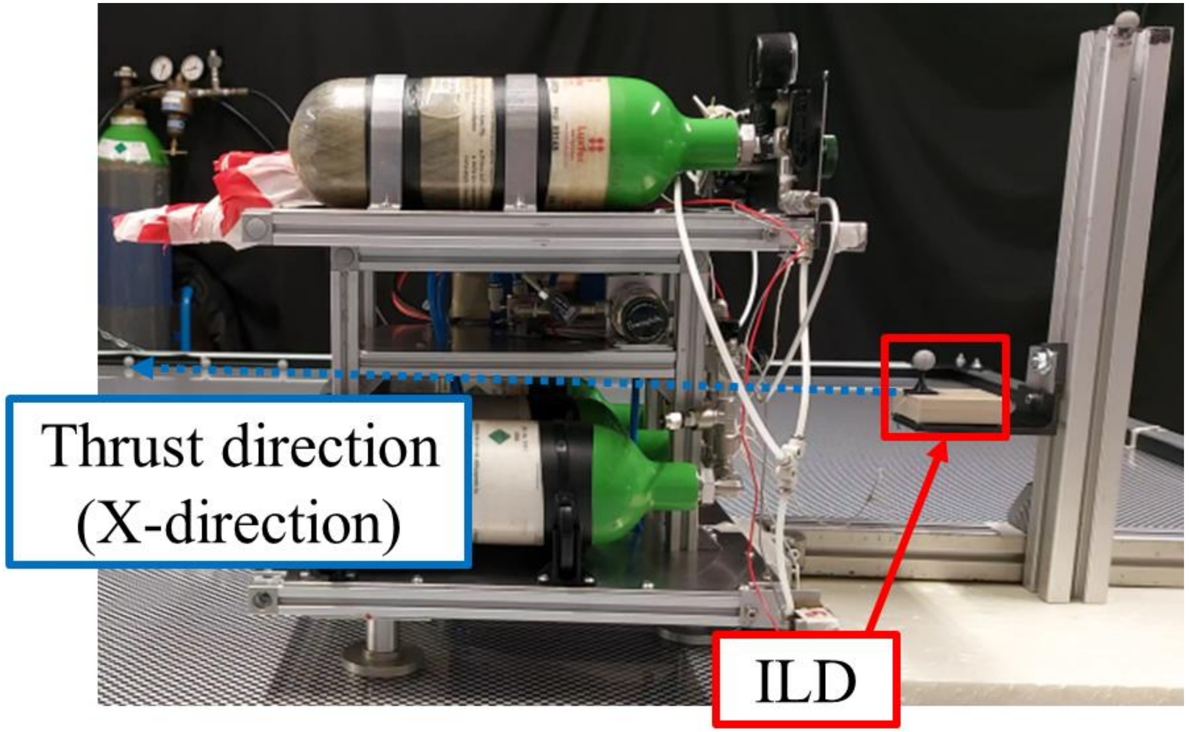
3.2 Thrust tests

- Thrust test is used to determined the thrust force of the actuators.
- A spring with a known elastic constant is connected to the cables linked to the platform.
- The platform is forced to move along the thrust direction for a total time of 40s.

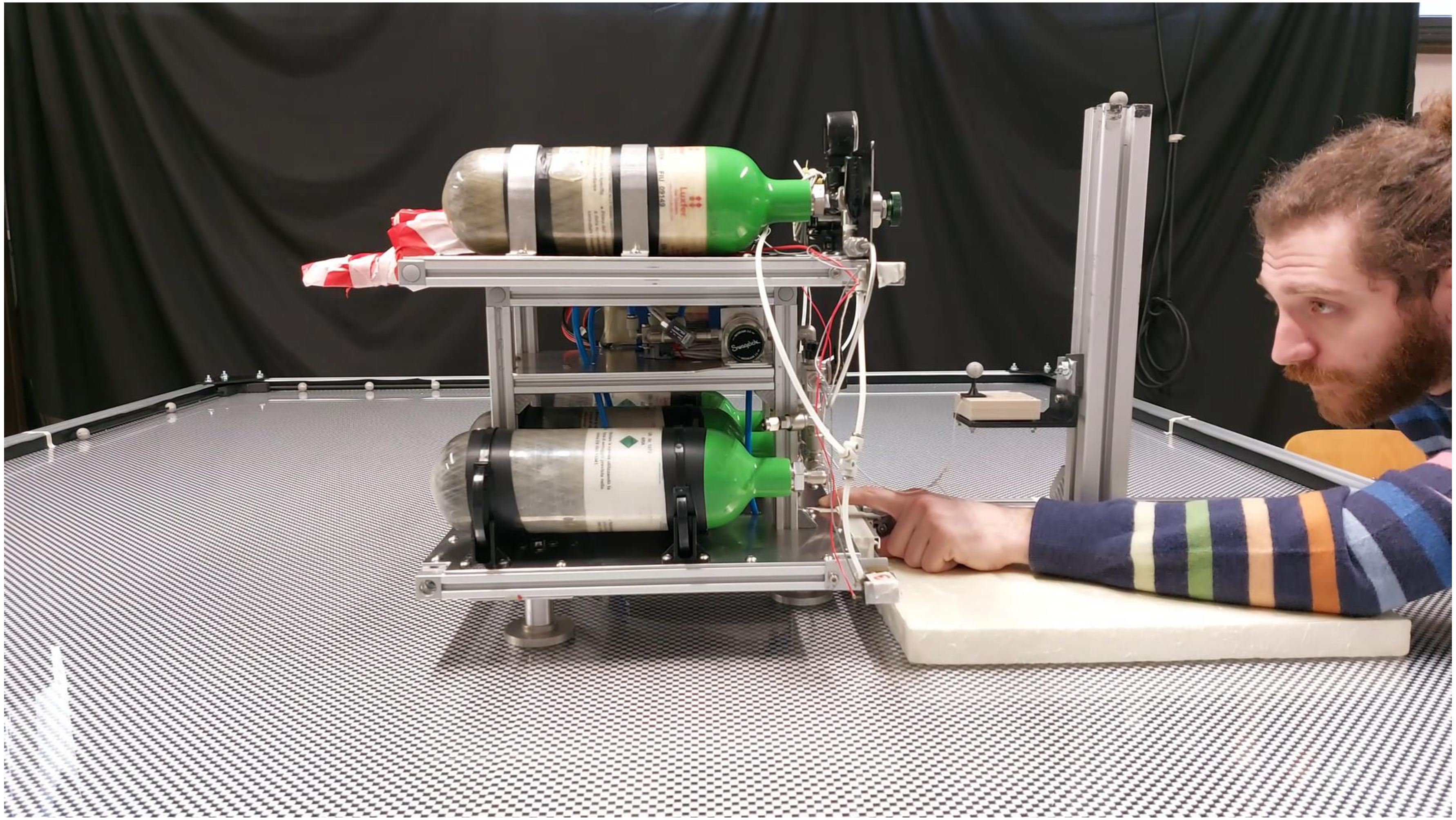


3.3 ILD tests

- ILD tests are used to characterize the elastic and damping coefficient of the ILD.
- At the beginning the cable are in a slack condition.
- The platform is forced to move along the thrust direction for a total time of 10s.



3.3 ILD tests



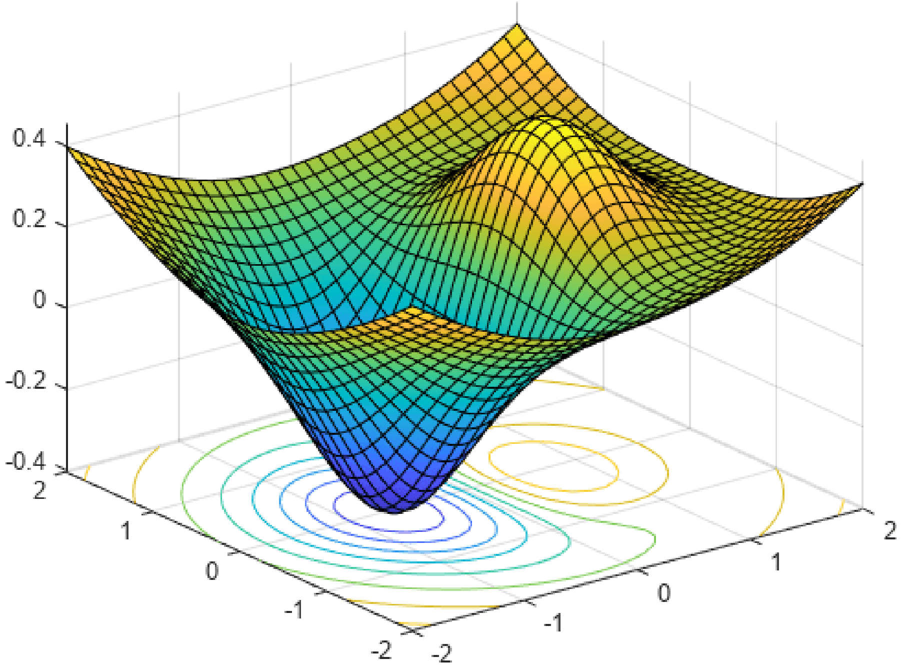
4. Model tuning

- MATLAB™ based algorithm is used for tuning the mathematical models used to describes the platform dynamics.

- The algorithm minimize a cost function that is the Sum of Squared Residuals (SSR)

$$SSR = \sum_{i=1}^{N} (y_i - \hat{y}_i)^2$$

- For comparing each test, in the results are shown the maximum value of the residuals and their mean.



Courtesy of MATLAB™ website

4.1 Thrust test tuning

- A one-dimensional equation is used to describe the dynamics of the motion.

$$x(t)_{ramp} = x_0 + \frac{F_0}{k}\left[1 - e^{-\zeta\omega_n t}\left(\cos(\omega_s t) + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin(\omega_s t)\right)\right]$$
$$+\frac{F_1}{k}\left\{t - \frac{2\zeta}{\omega_n}\left[1 - e^{-\zeta\omega_n t}\left(\cos(\omega_s t) - \frac{\zeta^2}{\sqrt{1-\zeta^2}}\sin(\omega_s t)\right)\right]\right\}$$

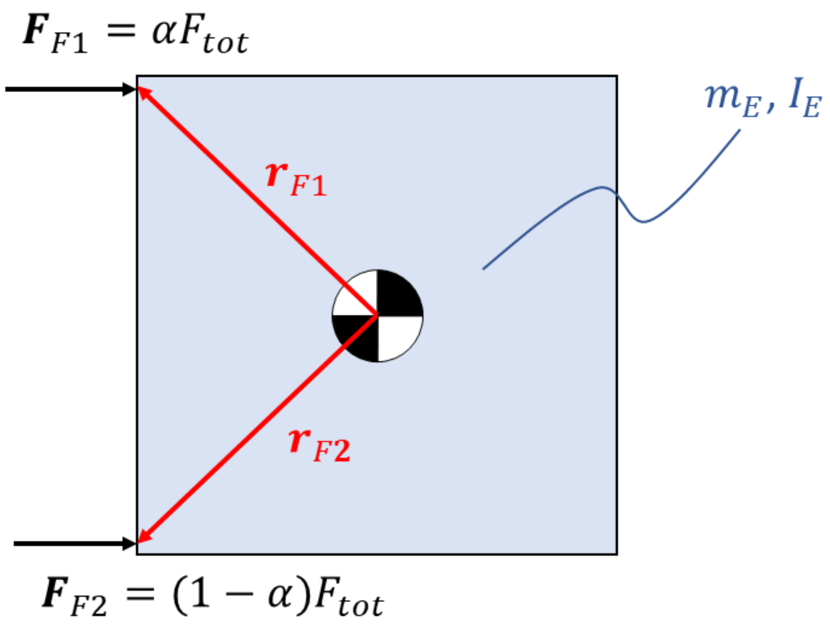
$$\omega_s = \sqrt{1-\zeta^2}\,\omega_n$$

- Force is considered to be linearly increasing as follow:

$$F(t) = F_0 + F_1 t$$

- Force is assumed to increase due to the following motivation:
  1. Mass is assumed to be constant, therefore, instead of changing the mass due to the gas consumption, the force increases.
  2. The Supply Pressure Effect (SPE) increases the pressure on the thruster, while decreasing the pressure on the tank.

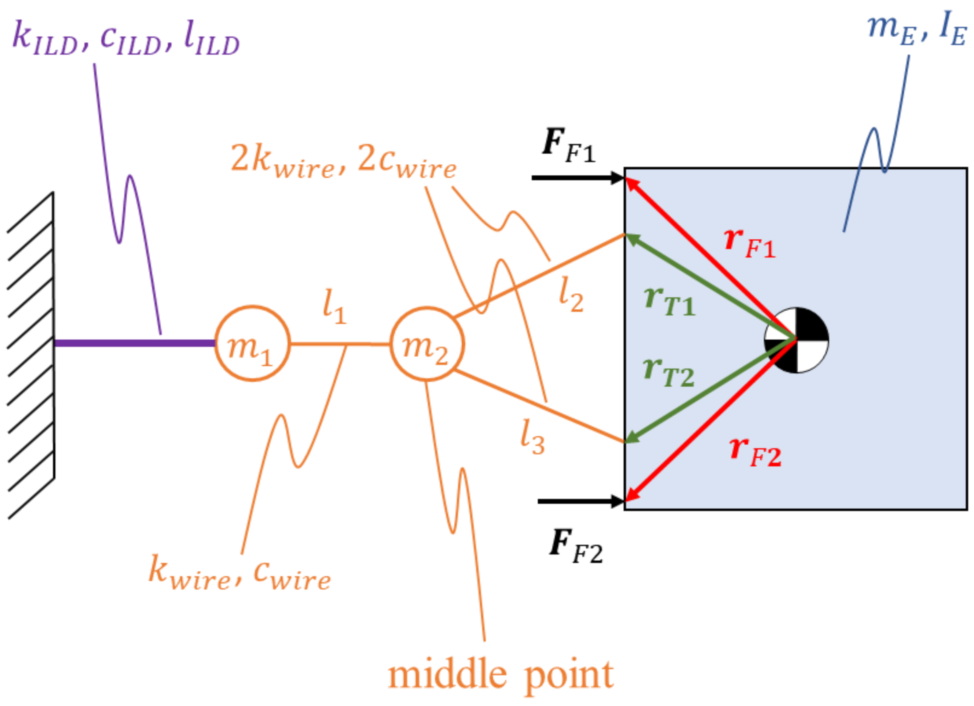
4.2 Initial condition tuning



- Tuning the first seconds of the experimental tests, when the cable are in a slack condition, make it possible to easily reconstruct the initial condition of the ILD tests.

- The mathematical model considered is the 2D dynamic model of a rigid body.

4.3 ILD test optimization



- For describing the entire ILD tests the model adopted includes the influence of the cables.
- Cables are modeled as a mass-spring damper system when tensioned and no-force when slack.

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5.1 Experimental results

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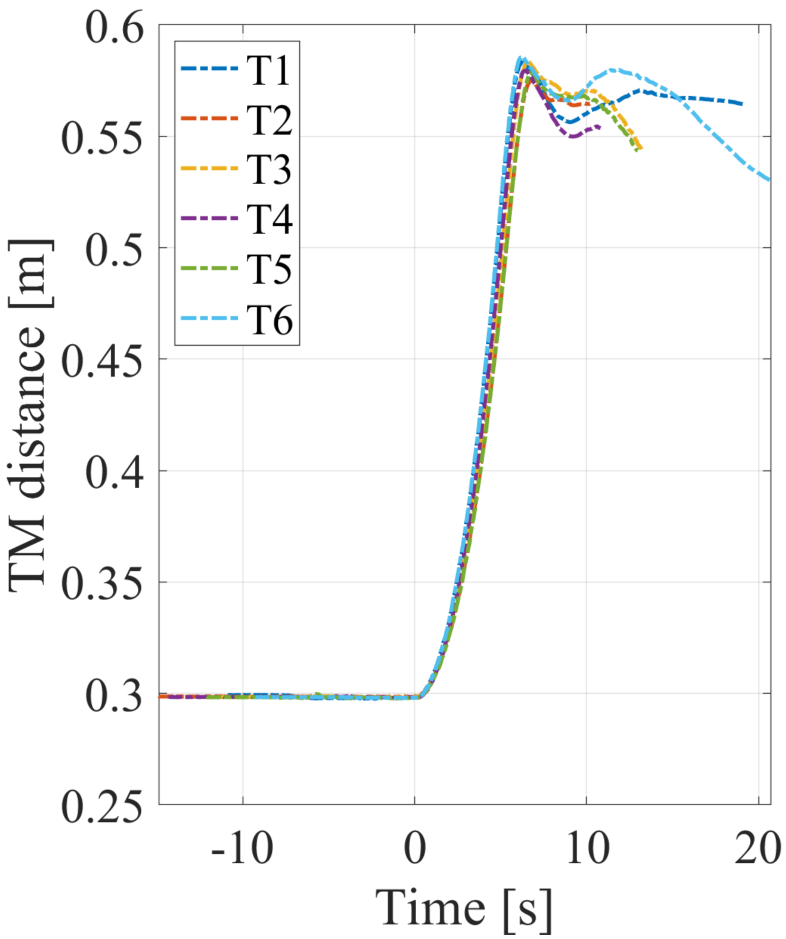
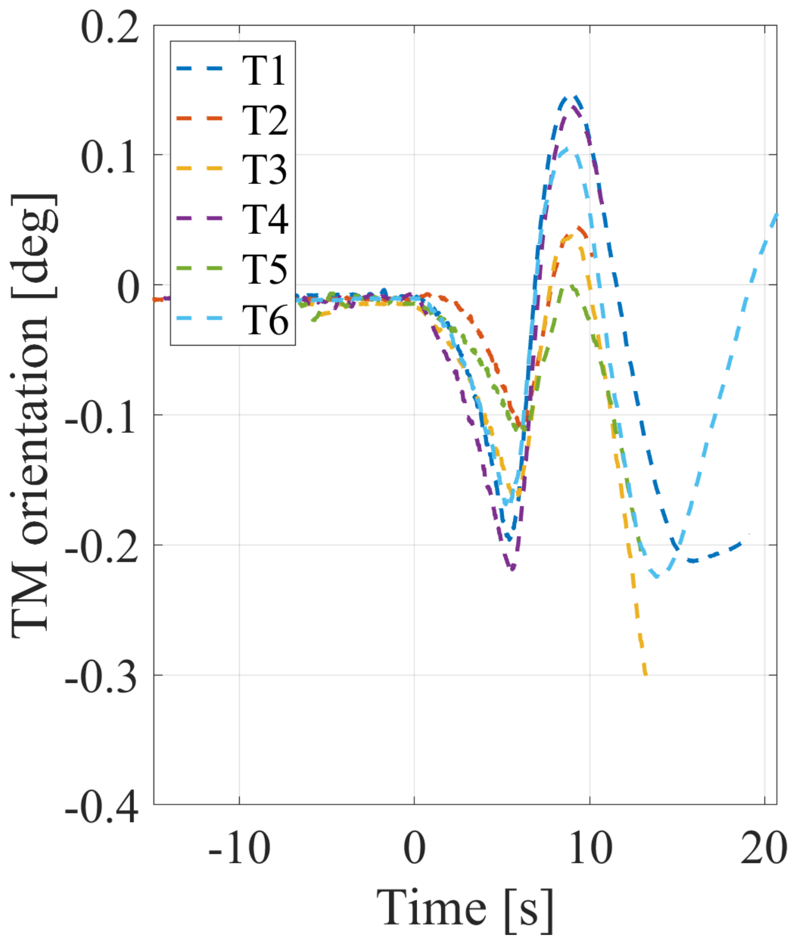
Comparison of the distance of the module during the six tests



Comparison of orientation of the module during the six tests



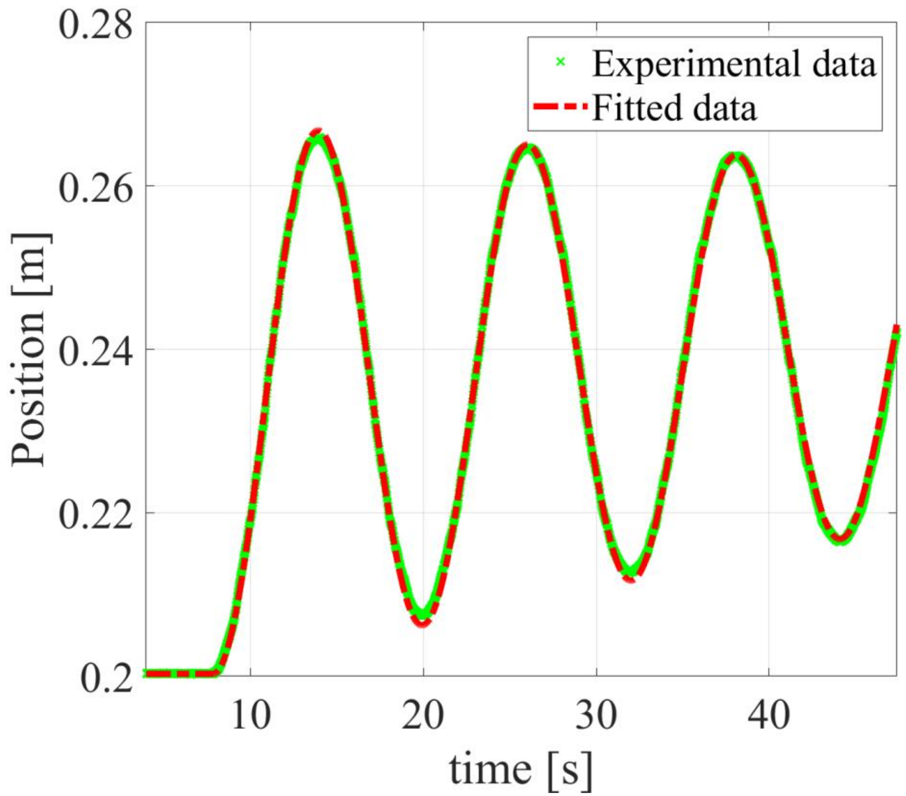
5.2 Thrust test results

- The results show that the parameter F_1 is positive, therefore the force is increasing, as expected.
- $k_{sys} \approx k_{spring}$, hence the stiffness of the system and the dynamic response is dominated by the spring.
- The values obtained for the cable are not representative, hence they are not used for the ILD test tuning.

Parameters	Value
k_{sys}	4.302 ± 0.002 $[N/m]$
c_{sys}	0.327 ± 0.003 $[Ns/m]$
F_1	$(7.09 \pm 0.09) \times 10^{-4}$ $[N/s]$
$mean(Res)$	0.09×10^{-3}
$max(Res)$	1.54×10^{-3}
SSR	0.75×10^{-3}

Parameters	Value
k_{spring}	4.641 ± 0.68 $[N/m]$
c_{spring}	0.360 ± 0.054 $[Ns/m]$
k_{cable_tot}	58.91 ± 109.51 $[N/m]$
c_{cable_tot}	3.452 ± 5.31 $[Ns/m]$

Comparison between experimental and fitted data of the thrust test



5.3 Initial condition results

➢ From the table it can highlighted that:

1. F_{tot} is always different for each test
2. $\alpha > 0.5$
3. $mean(Res)_{T4} = 1.652 \cdot 10^{-3}$

Parameters	T1	T2
t_0 [s]	10.82 ± 0.01	14.88 ± 0.02
F_{tot} [N]	0.277 ± 0.001	0.223 ± 0.002
α	0.551 ± 0.001	0.526 ± 0.001
y_0 [m]	-0.006 ± 0.003	-0.009 ± 0.009
$mean(Res)$	0.05×10^{-3}	0.311×10^{-3}
$max(Res)$	2.65×10^{-3}	4.639×10^{-3}
SSR	0.5×10^{-3}	20.6×10^{-3}
Parameters	T3	T4
t_0 [s]	11.76 ± 0.02	14.30 ± 0.03
F_{tot} [N]	0.242 ± 0.002	0.251 ± 0.004
α	0.553 ± 0.001	0.581 ± 0.001
y_0 [m]	-0.001 ± 0.054	-0.001 ± 0.159
$mean(Res)$	5.347×10^{-3}	1.652×10^{-3}
$max(Res)$	0.805×10^{-3}	9.374×10^{-3}
SSR	163.4×10^{-3}	634.3×10^{-3}
Parameters	T5	T6
t_0 [s]	14.30 ± 0.03	11.76 ± 0.02
F_{tot} [N]	0.251 ± 0.004	0.242 ± 0.002
α	0.581 ± 0.001	0.553 ± 0.001
y_0 [m]	-0.001 ± 0.159	-0.001 ± 0.054
$mean(Res)$	0.385×10^{-3}	0.229×10^{-3}
$max(Res)$	3.916×10^{-3}	2.813×10^{-3}
SSR	34.4×10^{-3}	13.2×10^{-3}

5.4 ILD tests results

- From the results obtained the maximum value of the $mean(Res)_{T4} = 3.24 \cdot 10^{-3}$

- For the ILD, when the estimated stiffness coefficient is high, the damping coefficient is low and vice versa.

- For the cable coefficients other values are used to better describes the dynamics of the motion. This values are within the tolerances of the spring values utilized for the thrust test.

Parameters	Value
k_{cable}	930 $[N/m]$
c_{cable}	2 $[Ns/m]$
k_{spring}	4.322 $[N/m]$
c_{spring}	0.391 $[Ns/m]$

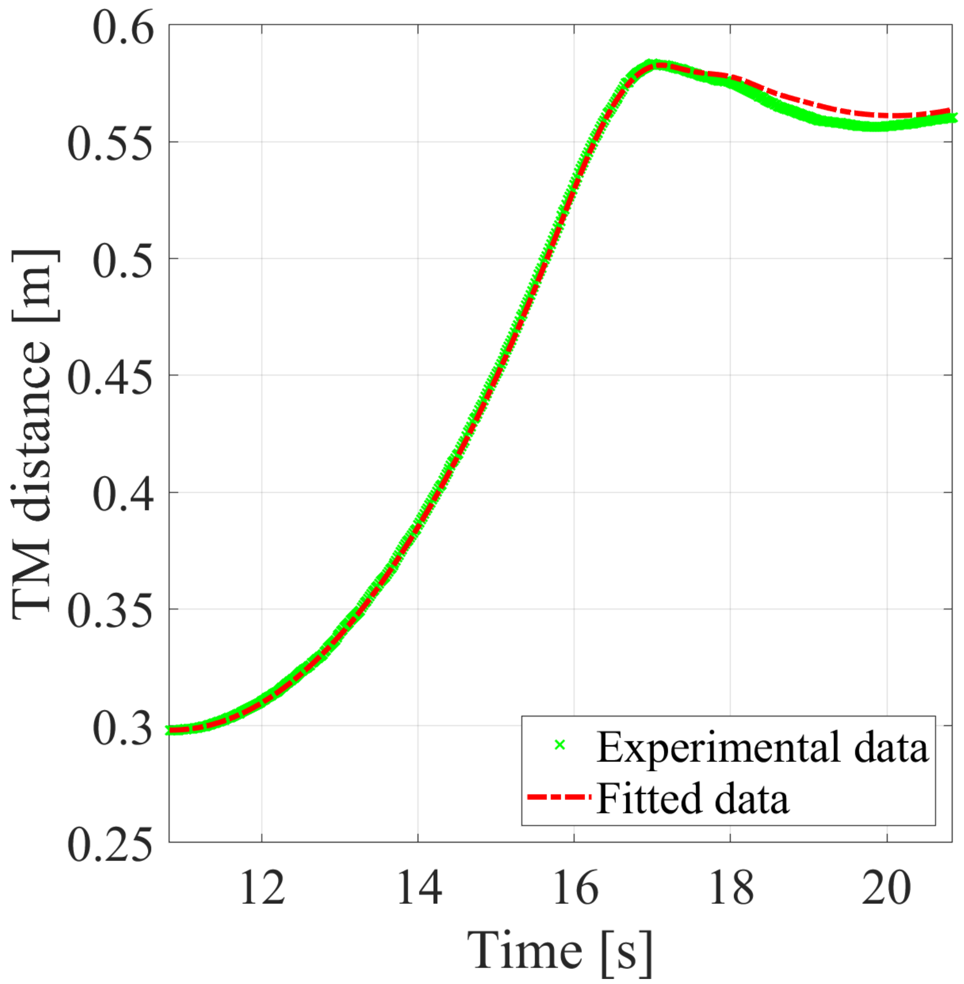
Parameters	T1	T2
k_{ILD} $[N/m]$	27.2 ± 0.5	31.4 ± 0.2
c_{ILD} $[Ns/m]$	2.03 ± 0.32	0.91 ± 0.13
θ_i $[deg]$	1.4 ± 0.1	5.0 ± 0.1
$max(Res)$	0.023	0.019
$mean(Res)$	0.05×10^{-3}	0.28×10^{-3}
SSR	0.5	0.9

Parameters	T3	T4
k_{ILD} $[N/m]$	21.2 ± 1.6	21.8 ± 1.9
c_{ILD} $[Ns/m]$	5.00 ± 1.06	5.00 ± 1.13
θ_i $[deg]$	6.4 ± 0.3	4.3 ± 0.5
$max(Res)$	0.060	0.065
$mean(Res)$	2.83×10^{-3}	3.24×10^{-3}
SSR	15.3	24.

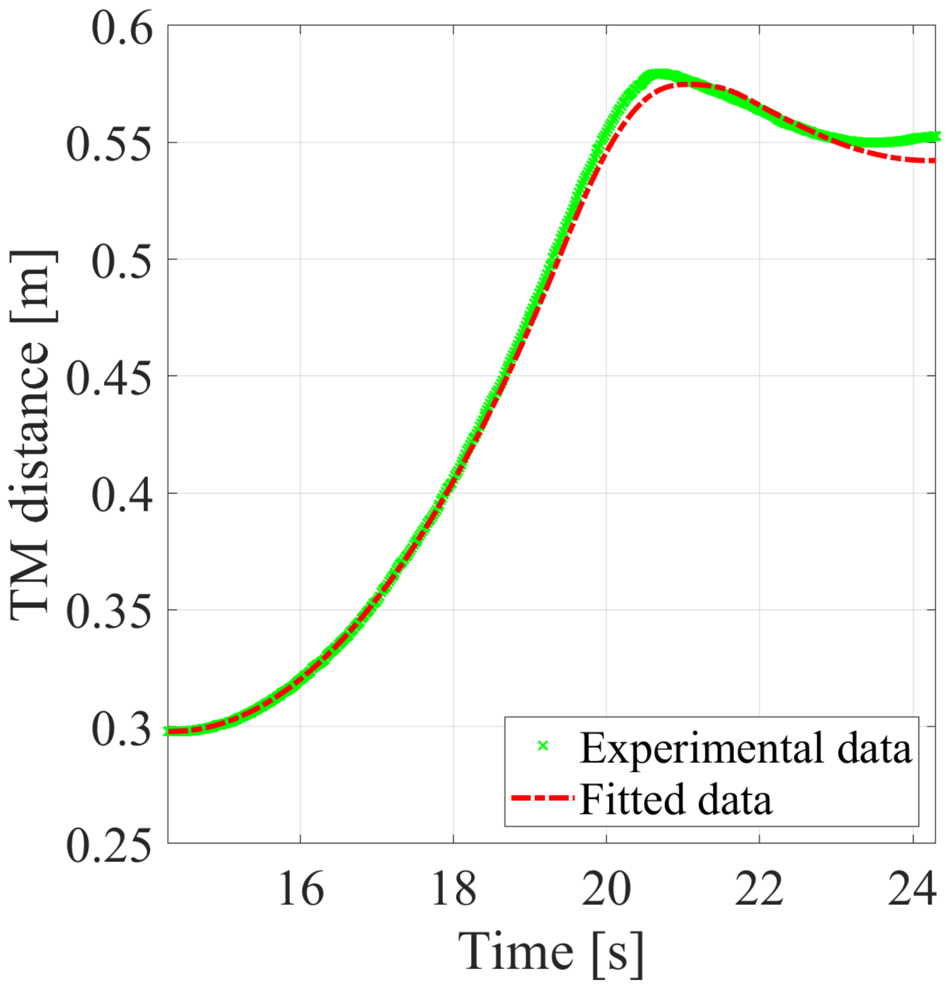
Parameters	T5	T6
k_{ILD} $[N/m]$	28.7 ± 0.4	22.5 ± 0.7
c_{ILD} $[Ns/m]$	1.58 ± 0.29	4.94 ± 0.47
θ_i $[deg]$	7.6 ± 0.1	2.0 ± 0.2
$max(Res)$	0.056	0.039
$mean(Res)$	3.15×10^{-3}	1.44×10^{-3}
SSR	3.6	1.3

5.4 ILD tests results

Comparison between experimental and fitted data of the module distance for T1

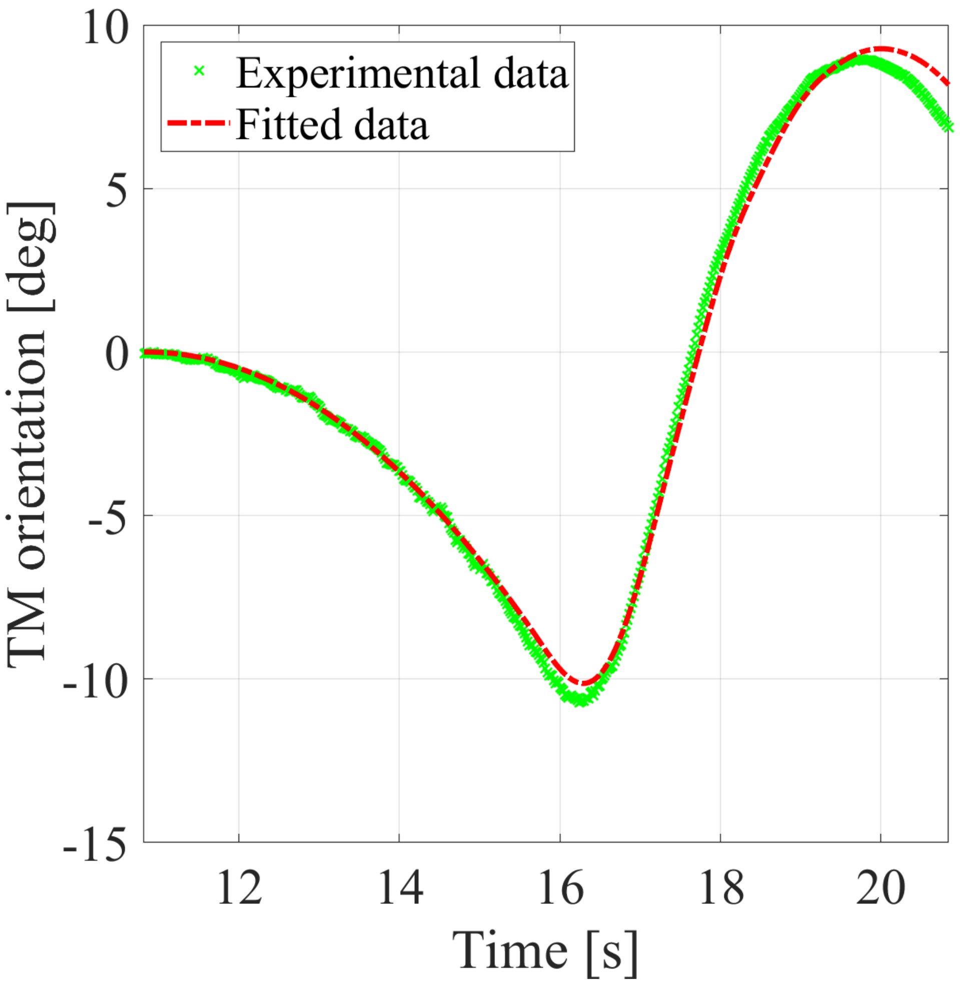


Comparison between experimental and fitted data of the module distance for T4

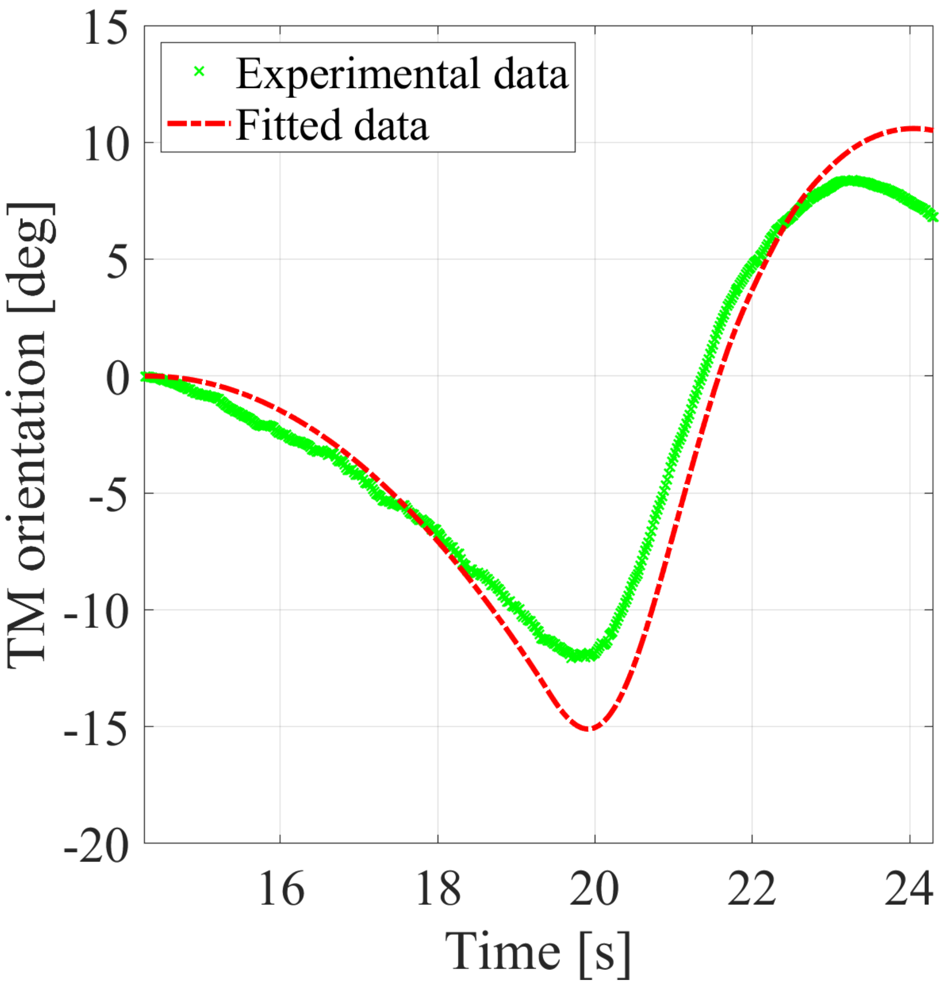


5.4 ILD tests results

Comparison between experimental and fitted data of the module orientation for T1

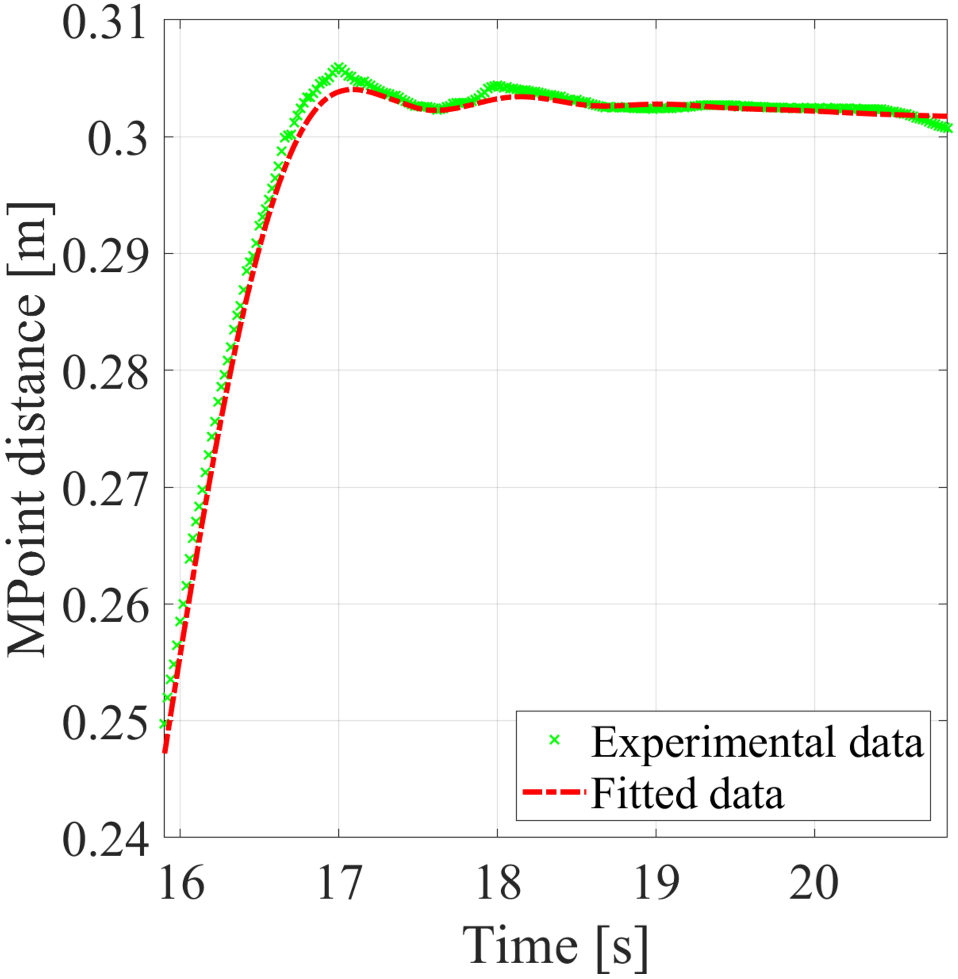


Comparison between experimental and fitted data of the module orientation for T4

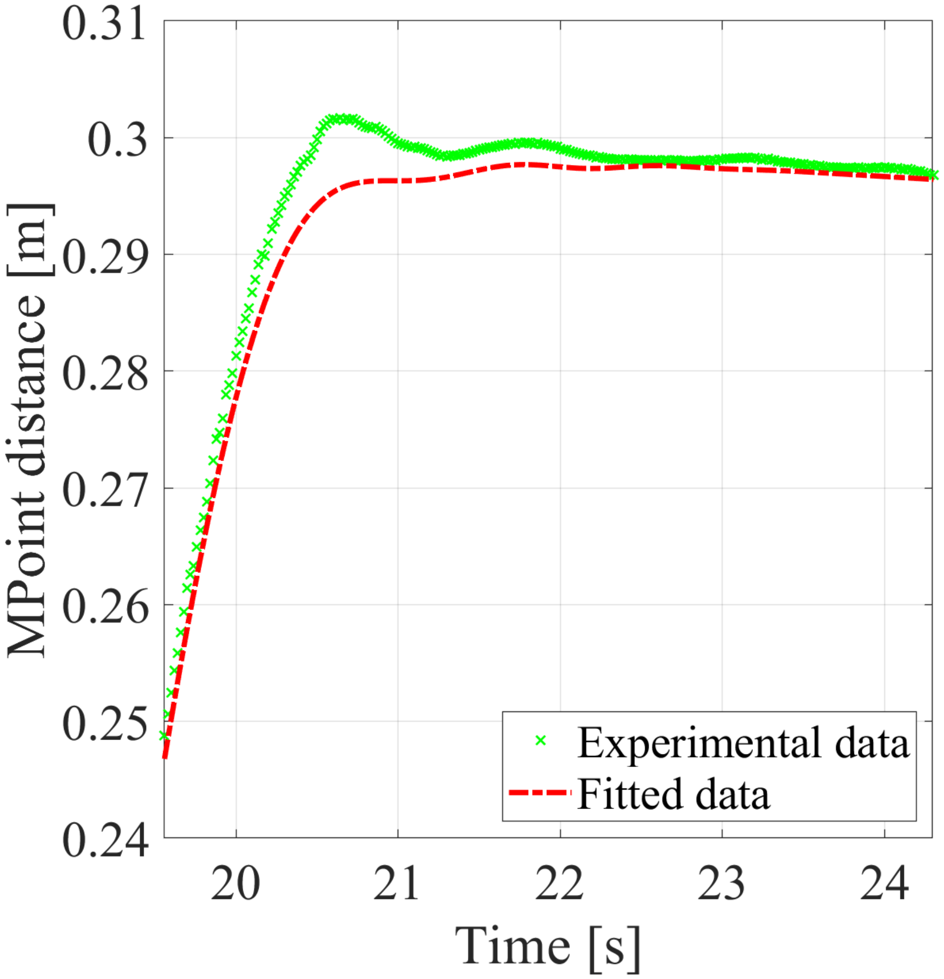


5.4 ILD tests results

Comparison between experimental and fitted data of the middle point distance for T1



Comparison between experimental and fitted data of the middle point distance for T4



6. Conclusions

- The results shown that the 2D mathematical model can correctly describes the experimental results.

- The ILD elastic constant ranges from 21 N/m to 31 N/m, while the damping coefficient ranges from 1 Ns/m to 5 Ns/m.

- Most of the elastic energy is dissipated by the internal friction forces of the ILD

- Future development includes the implementation of an experimental setup to reduce the range of ILD parameters.

Thank you for your attention!

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