Dynamic Stiffness of Nylon Ropes under Harmonic and Stochastic Loading: Experimental Characterisation and Modelling

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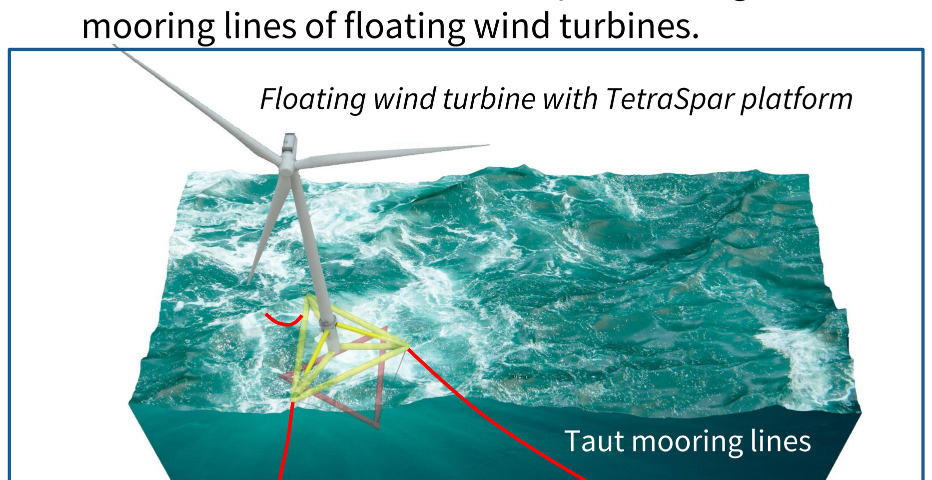
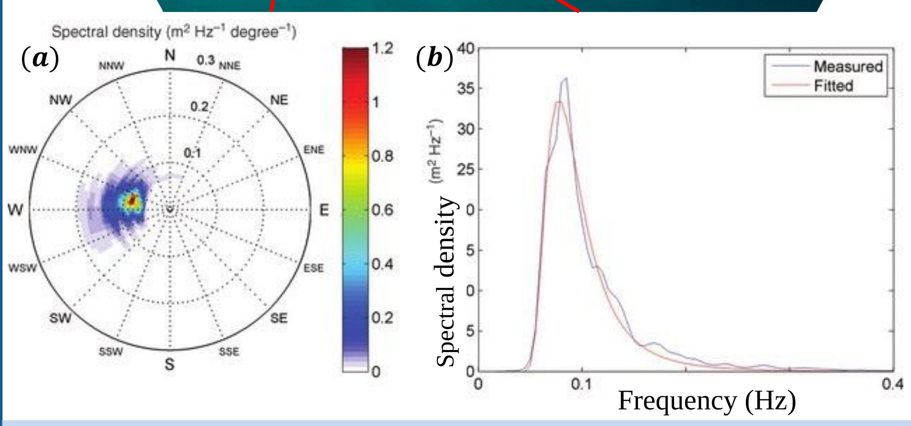
Background

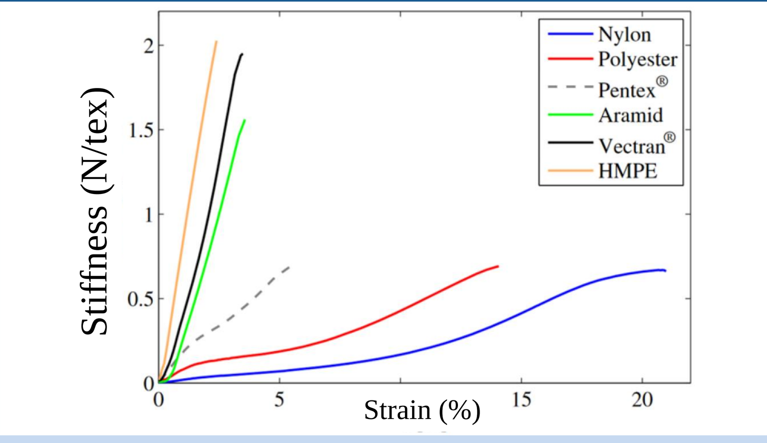
- Marine conditions induce complex loading on mooring lines of floating wind turbines.



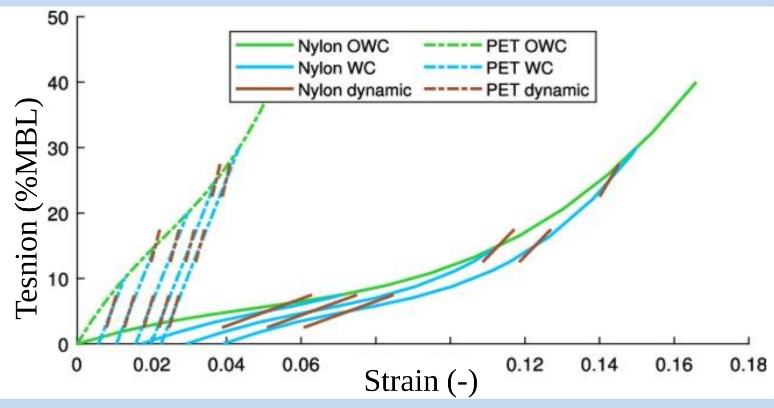


Example of spectra recorded by a waverider buoy at EMEC. a) Direction spectra b) Comparison with a fitted JONSWAP model [1]

- Nylon ropes offer a lower stiffness than steel and polyester but are highly non linear and difficult to predict.

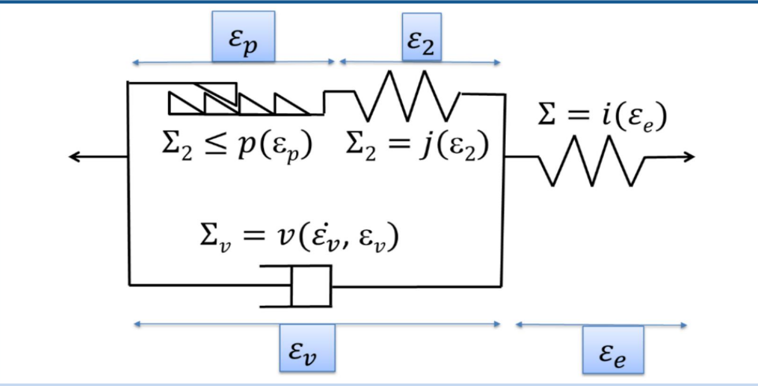


Comparison of tenacity for different polymer fibers [2]



Syrope model for nylon and polyester [3]

- A reliable stiffness model is needed to provide better predictions of line tensions and platform motion.



Modified "Spring-Dashpot" model for nylon ropes [4]

Wibner et al., 2003 : $K_{rd} = \alpha.Lm + \beta$

Casey et al., 2000 : $K_{rd} = \alpha.Lm + \beta.\mathcal{E}a + \gamma$

Chaplin et al., 1992 : $K_{rd} = \alpha.Lm + \beta.La + \gamma.\log(P) + \delta$

Liu et al., 2014 : $K_{rd} = \alpha.Lm - \beta.La - \gamma.e^{-kN} + \delta$

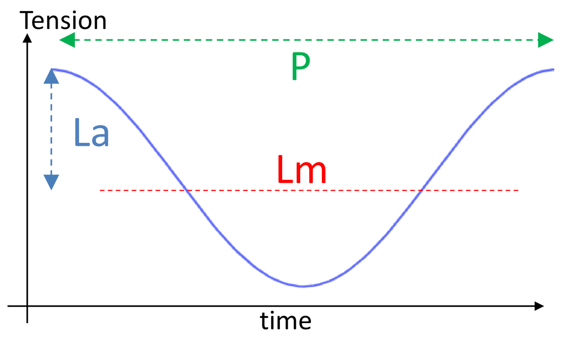
Pham et al., 2019 : $K_{rd} = \alpha.Lm - \beta.La - \gamma$ ◄
(Inspired by the work of Huntley, 2016 [5])

Examples of proposed phenomenological models of stiffness for polymer ropes

Hypothesis

- Stiffness primarily depends on mean load and load amplitude [5, 6]
  - *We chose the bilinear model from Pham et al. [7]*
- Stiffness is much less dependent on frequency within the representative spectrum of marine mooring lines [7]
- Stiffness is strongly influenced by water [8]

Bilinear Stiffness Law



$Lm^m = \frac{Lm}{m}$ mean load $\left(\frac{N}{tex}\right)$

$La^m = \frac{La}{m}$ amplitude $\left(\frac{N}{tex}\right)$

m : dry linear density (tex)

ρ : density (kg/m^3)

A : section (m^2)

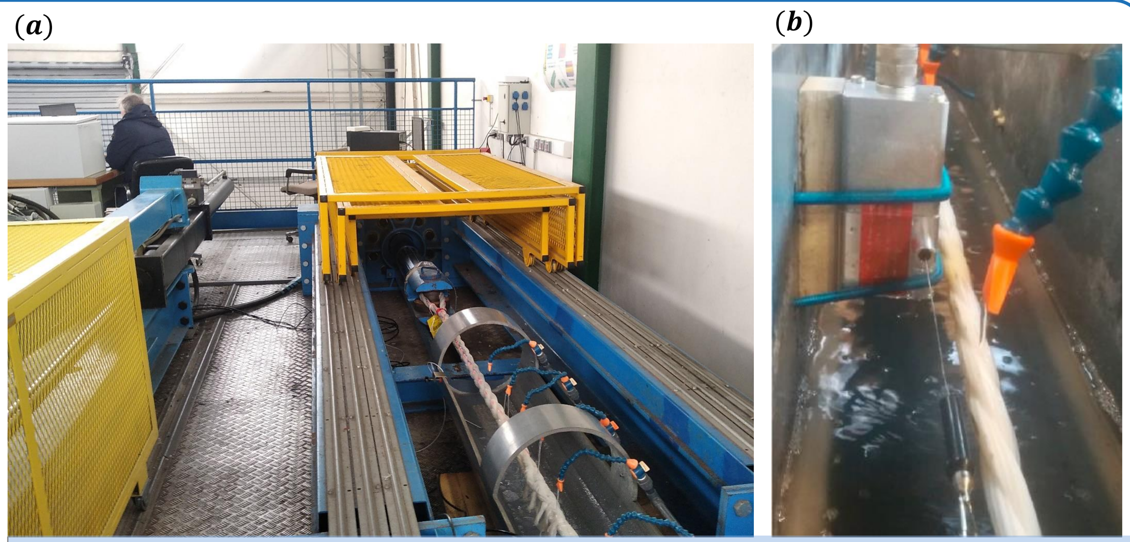
E : Young modulus (N/m^2)

a, b, c: $\left(\frac{N}{tex}\right)$ parameters

$$\frac{E}{\rho}\left(\frac{N}{tex}\right) = \frac{E.A}{m} = a.Lm^m - b.La^m + c$$

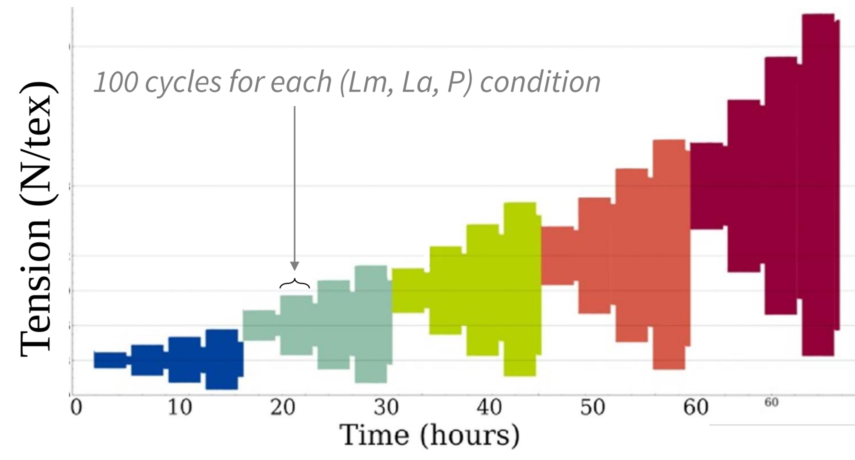
Experimental Setup

- Each test starts with a 'bedding-in' (Weller et al., 2014 [2])
- Sample : nylon subropes (PA6)
  3-strand architecture,
  linear density =120.5 g/m
  immersed during the test [8]
- Stiffness measured by linear regression for each Strain/Tension loop

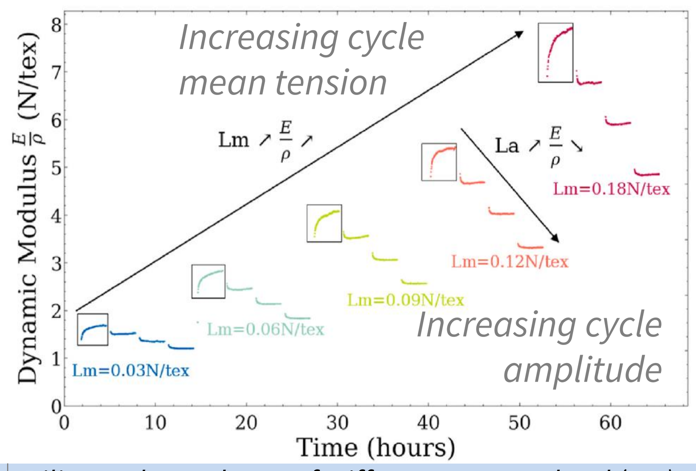


a) 100 tons traction bench in the SMASH lab at IFREMER – Brest (France)
b) Wire extensiometer and spray system that keeps the sample wet

Stiffness Measure in Harmonic Conditions

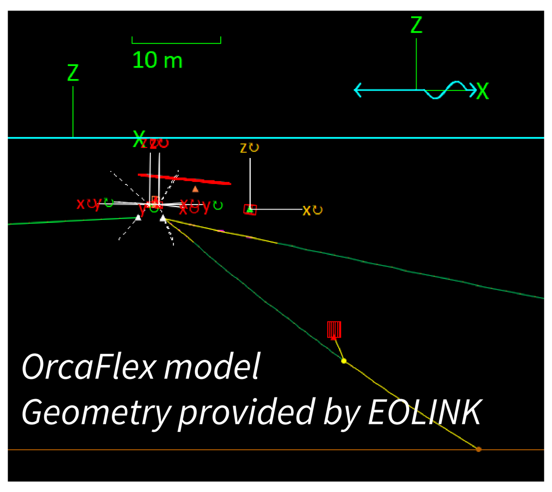


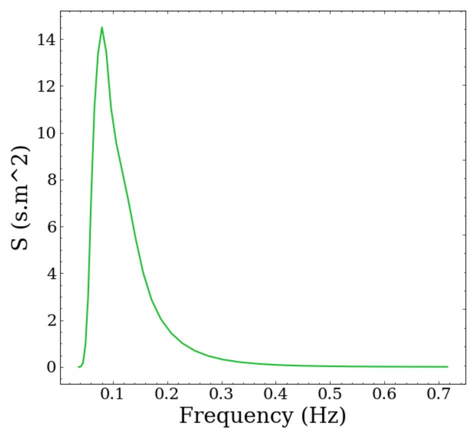
100 load cycles for different (Lm, La) values. Stiffness is measured with linear regression over the last 5 cycles



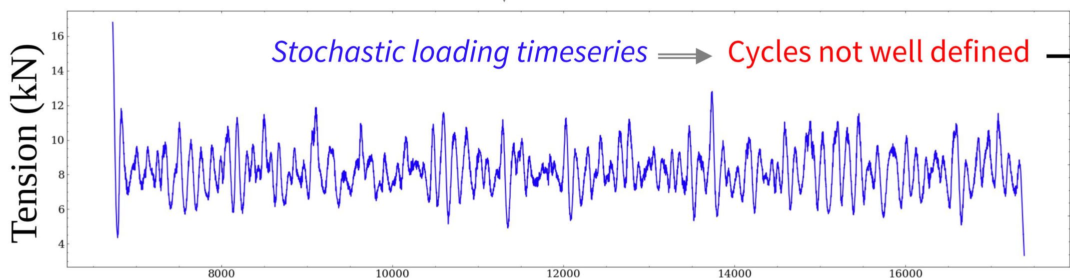
Bilinear dependency of stiffness on mean load (Lm) and load amplitude (La) in regular cyclic conditions [9]

Stiffness Measure in Stochastic Conditions

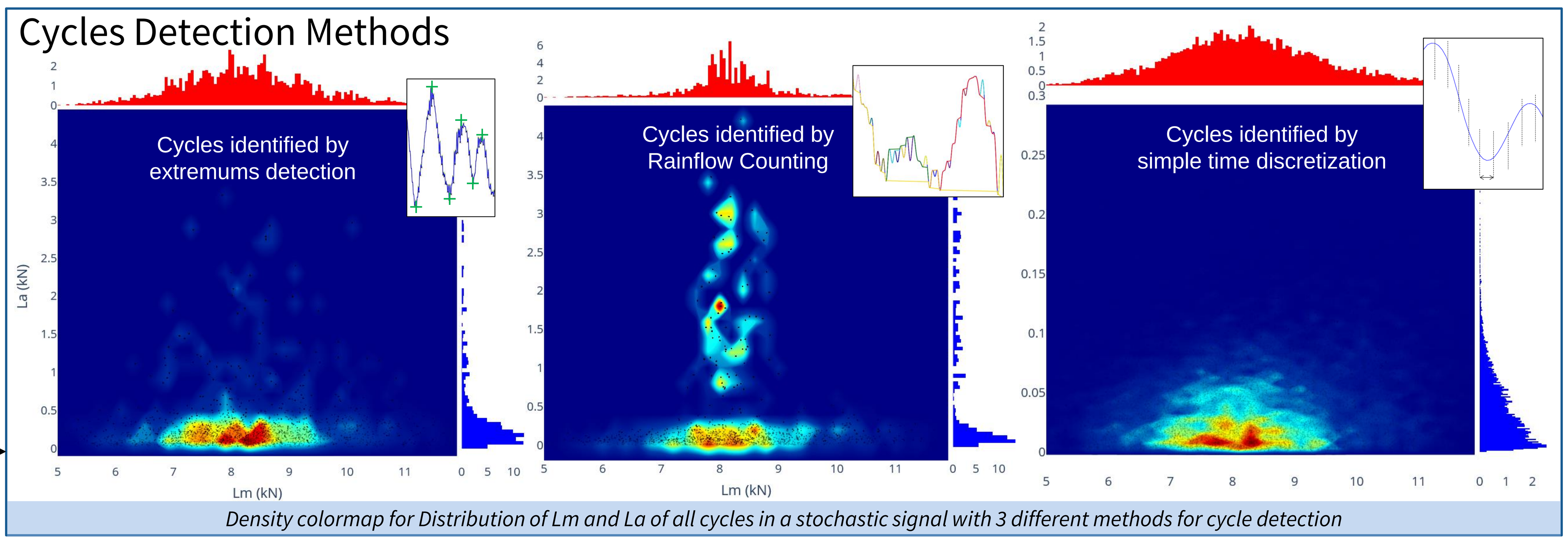




Energy density spectra representative of the SEM-REV test site in the French Atlantic coast



Cycles Detection Methods



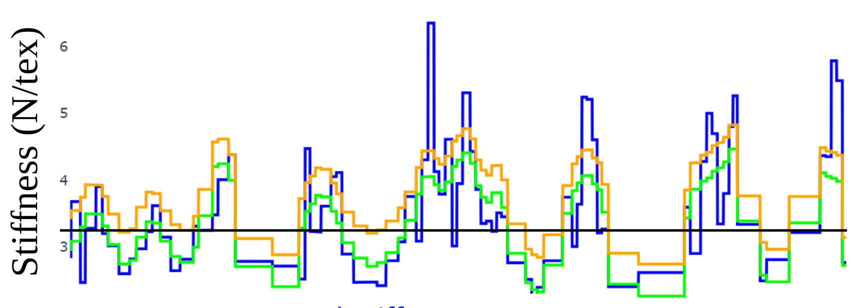
Density colormap for Distribution of Lm and La of all cycles in a stochastic signal with 3 different methods for cycle detection

It was found that, except for the time discretization, the method of cycle extraction does not strongly influence the identified bilinear model EA = f(Lm, La)

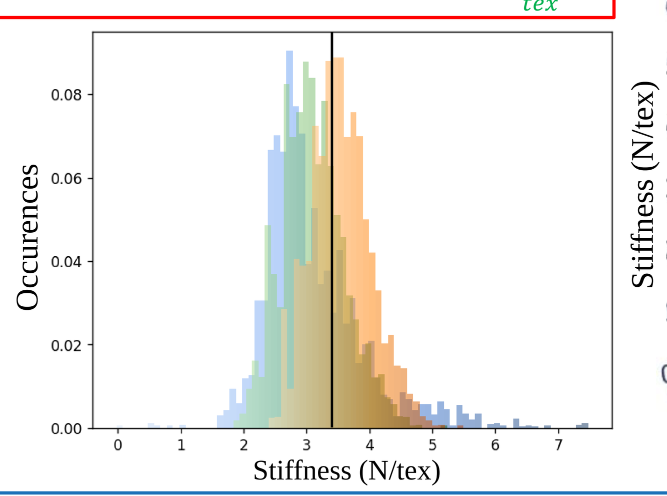
Results

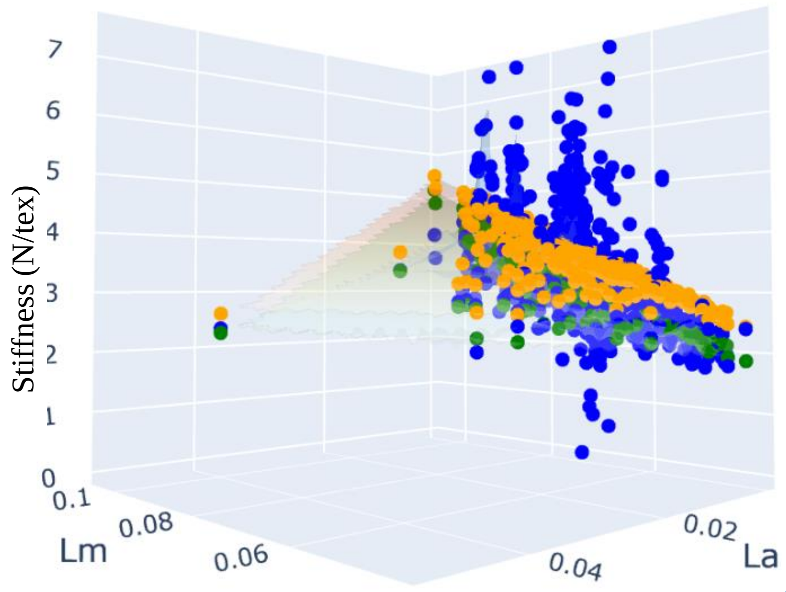
Identified parameters in harmonic conditions: $a = 46.3;\ b = 27.3;\ c = 0.501\,\frac{N}{tex}$ [5]

Identified parameters in stochastic conditions: $a = 52.6;\ b = 25.5;\ c = -0.646\,\frac{N}{tex}$



Measured Stiffness	
Constant mean Stiffness	RMSE = 0.818
Harmonic Bilinear Model	RMSE = 0.784
Stochastic Bilinear Model	RMSE = 0.646





Conclusion and Discussion

- Efficient experimental protocol for identifying model parameters for established stiffness in harmonic conditions.
- Good correlation between the bilinear stiffness model and the experimental measurement of estabilised stiffness: RMSE = 0.12 .
- Identification methods in stochastic conditions can help increase the correlation but not drastically.
- In the future, the sensitivity of the line design, particularly under fatigue conditions, will be analysed with respect to parameter variability.

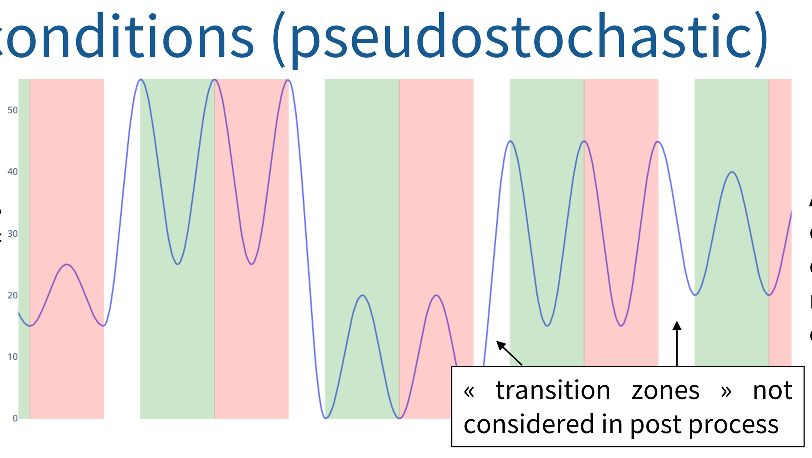
Future Work: Stiffness measure in controlled, randomized cyclic conditions (pseudostochastic)

- Harmonic loading are far from the reality of wave induced loading
- Stochastic loading poses the problem of cycle definition

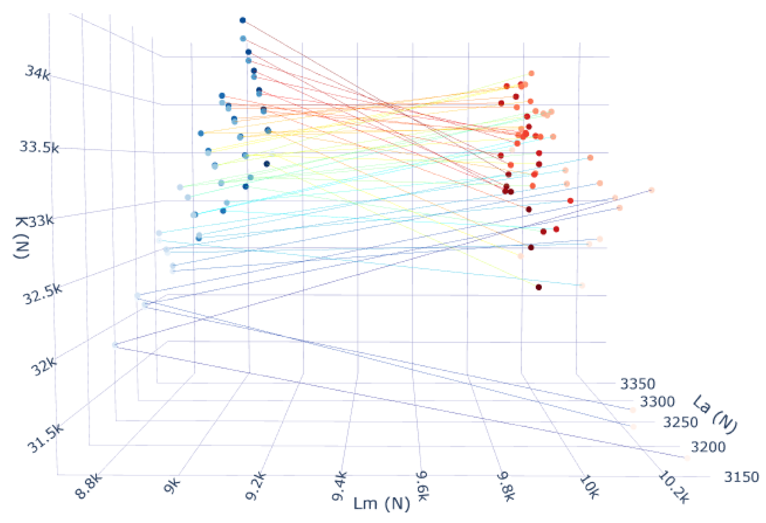
Creation of a loading sequence with well defined harmonic cycles in a stochastic distribution

La \ Lm	10	20	30 %MBL
5			
8			
12 %MBL	Negative tension is taken out		

Building the sequence with each possible pair of different cycle (Lm, La)



Allows observation of the influence of one cycle on the next for all loading cases.



Pseudostochastic protocol showed that previous cycles have a rather weak influence on those following, but it does not give the same set of parameters: to be examined.

[1] Mackay, E., 2012. Resource Assessment for Wave Energy.
[2] Weller, S.D, Davies, P., Vickers, A.W., Johanning, L., 2014. Synthetic rope responses in the context of load history: operational performance.
[3] Sørum, S.H., Fonseca, N., Kent, M., Faria, R.P., 2023. Assessment of nylon versus polyester ropes for mooring of floating wind turbines
[4] Chevillotte, Y., 2020. Characterization of the long-term mechanical behavior and the durability of polyamide mooring ropes for floating wind turbines (PhD Thesis).
[5] Huntley, M.B., 2016. Fatigue and modulus characteristics of wire-lay nylon rope.
[6] Varney, A.S., Taylor, R., Seelig, W., 2013. Evaluation of wire-lay nylon mooring lines in a wave energy device field trial.
[7] Pham, H.-D., 2019. Modélisation et Suivi en Service des Lignes d'Ancrages des Éoliennes Flottantes (PhD Thesis).
[8] Francois, M., Davies, P., Grosjean, F., Legerstee, F., 2010. Modelling fiber rope load elongation properties-Polyester and other fibers.
[9] Thuilliez, H., Davies, P., Cartraud, P., Feuvrie, M., Soulard, T., 2023. Characterization and modelling of the dynamic stiffness of nylon mooring rope for floating wind turbines

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