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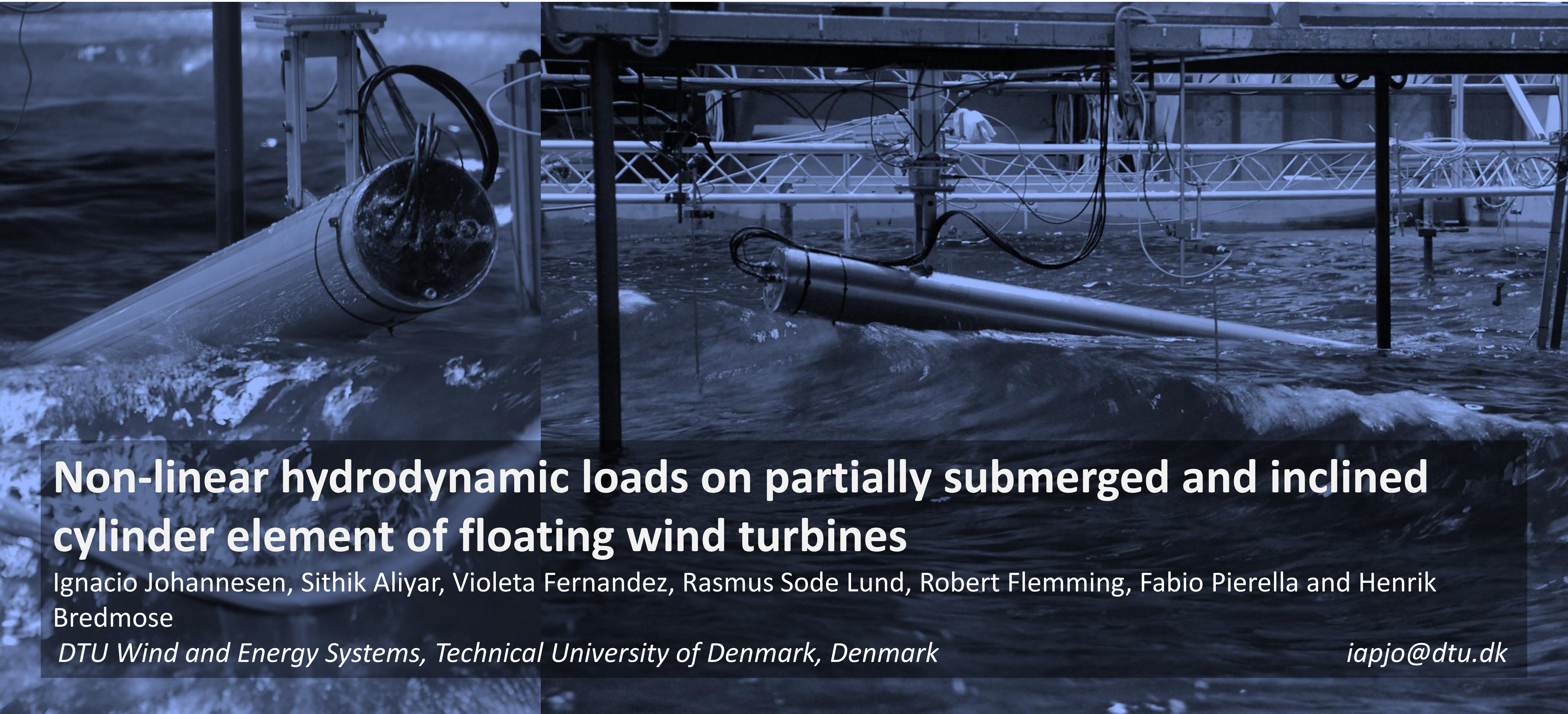
FloatLab (2023-2027)



Non-linear hydrodynamic loads on partially submerged and inclined cylinder element of floating wind turbines

Ignacio Johannesen, Sithik Aliyar, Violeta Fernandez, Rasmus Sode Lund, Robert Flemming, Fabio Pierella and Henrik Bredmose

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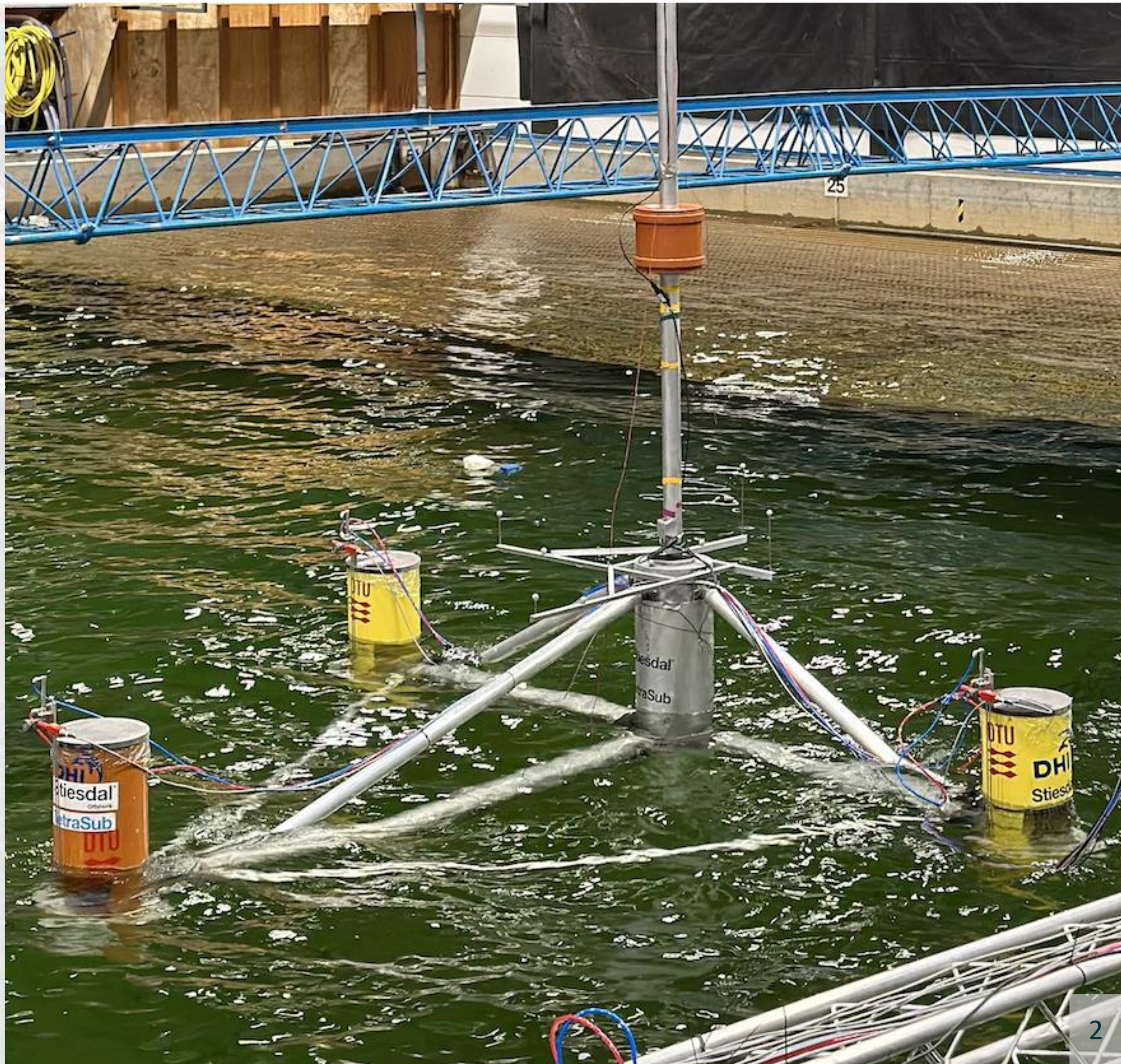
Experimental campaign context

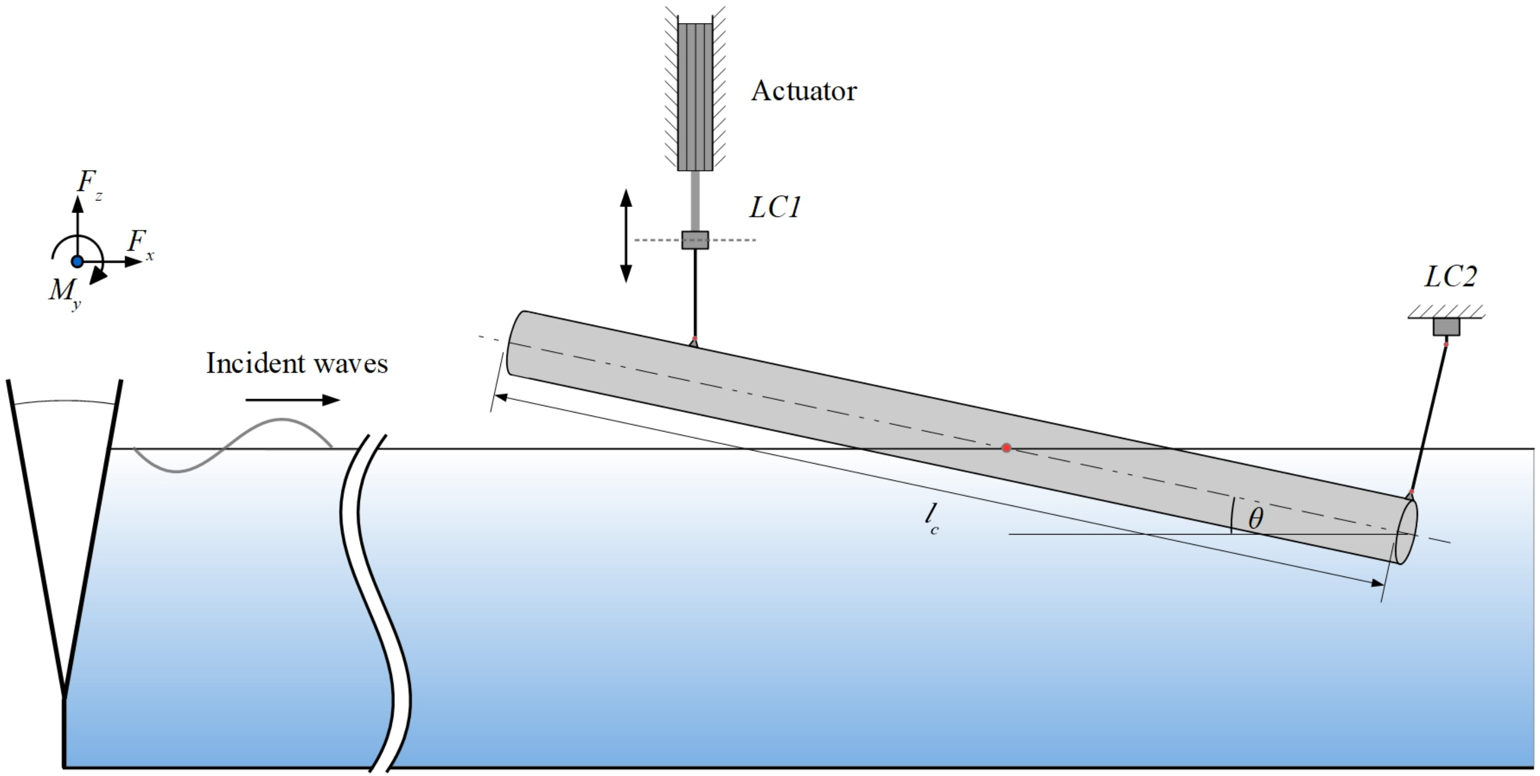
- Substructures of modern Floating Wind Turbines (FWT) are often assembled from cylindrical elements, i.e., the TetraSub (Stiesdal Offshore) or the Brunel concept (Fred Olsen).
- These elements are subject to strong non-linear loads that traditionally are described by radiation-diffraction forces and Morison-integrated drag terms.
- This experimental campaign aims to represent a cylindrical components of a FWT sub-structure.
- The main objective is to have a better understanding about the load components on these common structural elements. With an emphasis on high order contribution to the total force, originated on the wave and motion interaction.



Experimental setup

Conducted at a scale of 1:40, at DHI wave basin (20 by 30 m long and 3 m deep), Hørsholm, Denmark .

Different environmental loads were applied to the cylinder, including; wave only, motion only and both simultaneously.



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Results overview

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Regular oscillatory load	Irregular/ stochastic oscillatory loads	High order interaction loads components
↓ Basic Harmonic separation approach	↓ Harmonic separation methodology	↓ Averaging methodology

Complexity and load order →

Basic Harmonic separation approach

Regular oscillatory loads

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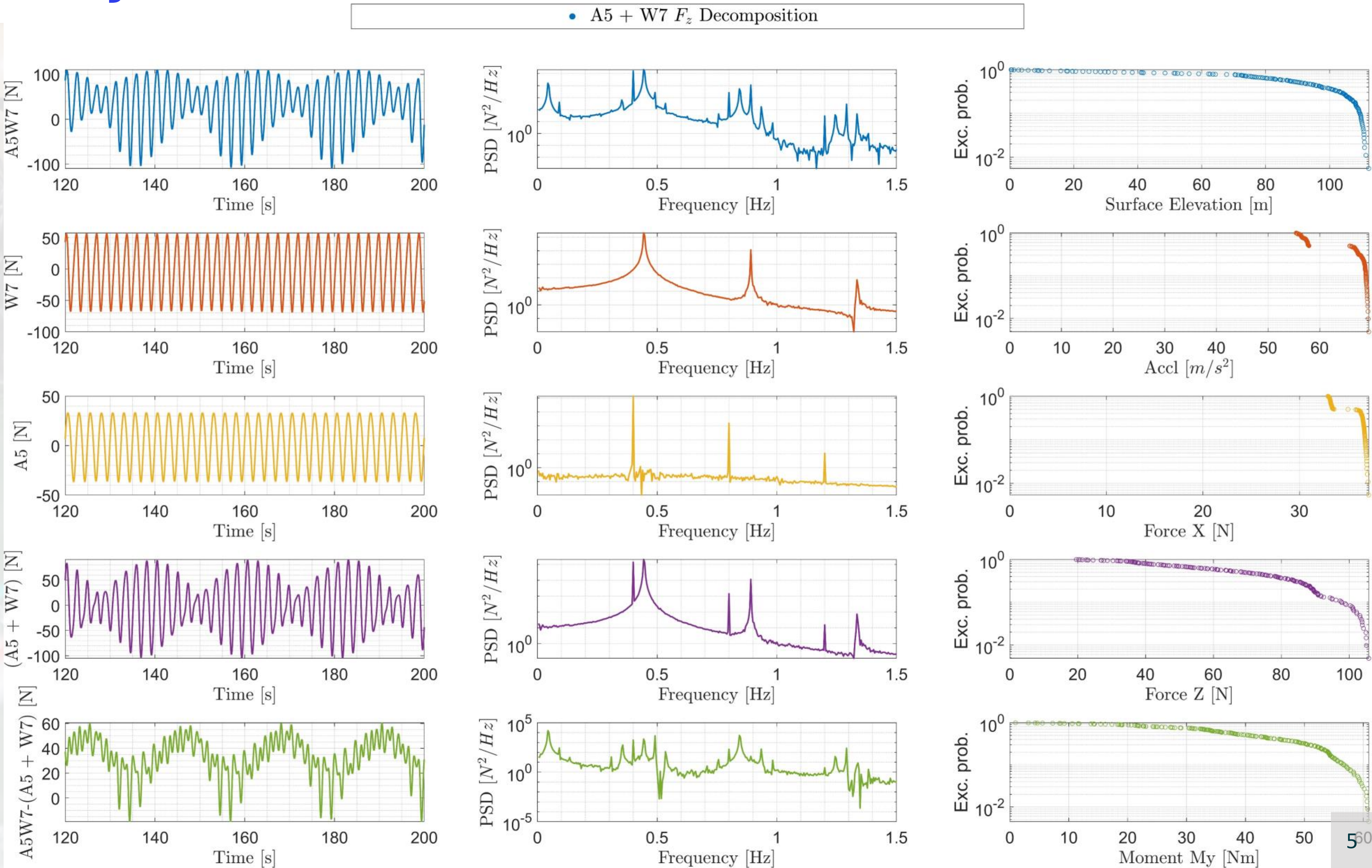
Load cases	Phase	Hs/H [m]	Wave freq. [Hz]
	Model scale		
Irregular waves	0, 90, 180, 270	0,218	0,445
Regular waves	0, 180	0,218	0,445
Focus waves	0, 180	0,218	0,445

	Phase	Amplitude [m]	Frequency [Hz]
Harmonic FOM	0, 180	0,10	0,25
		0,08	0,4
Stochastic FOM	0, 180	-	0,445



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Basic Harmonic separation approach

Regular oscillatory loads

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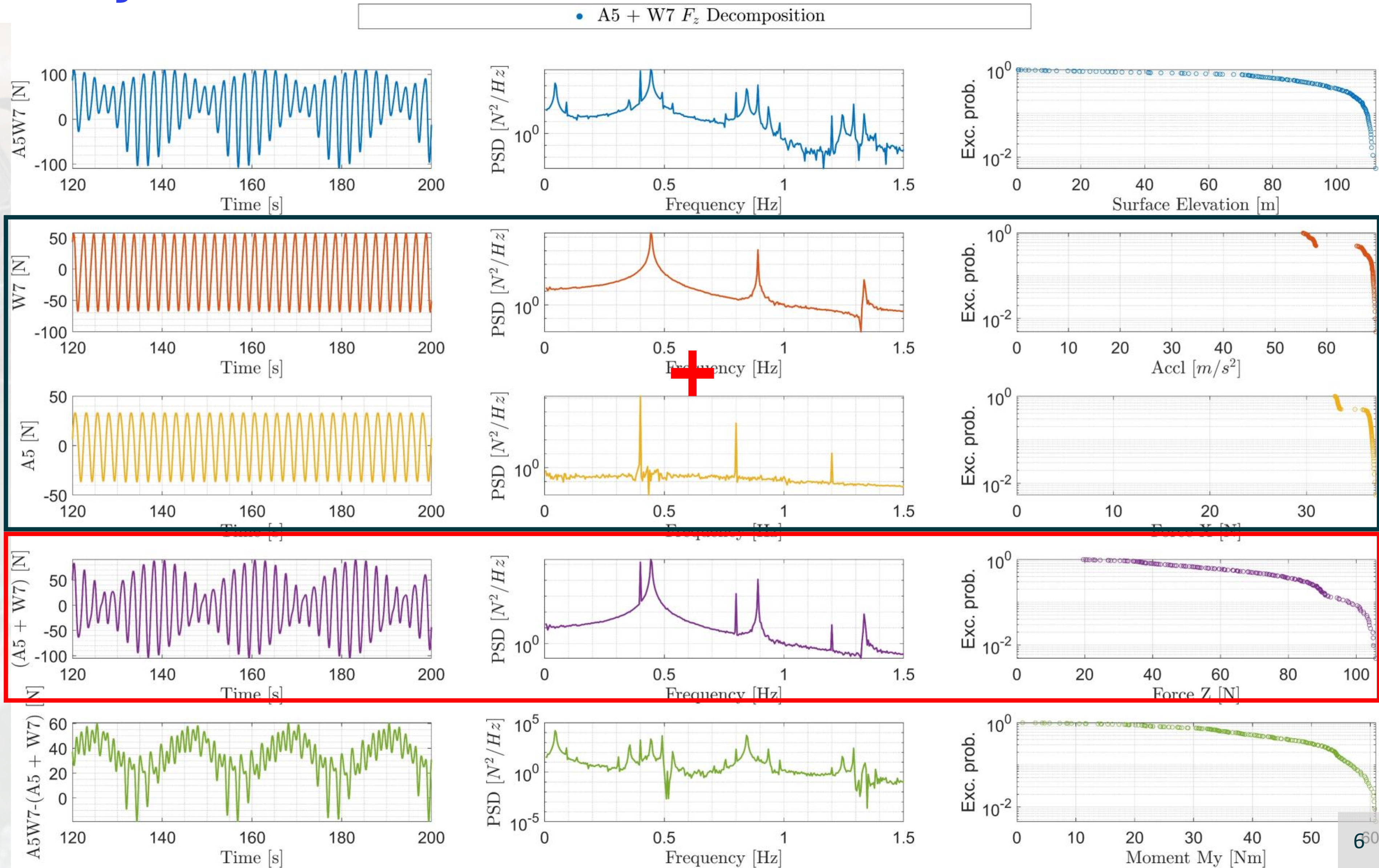

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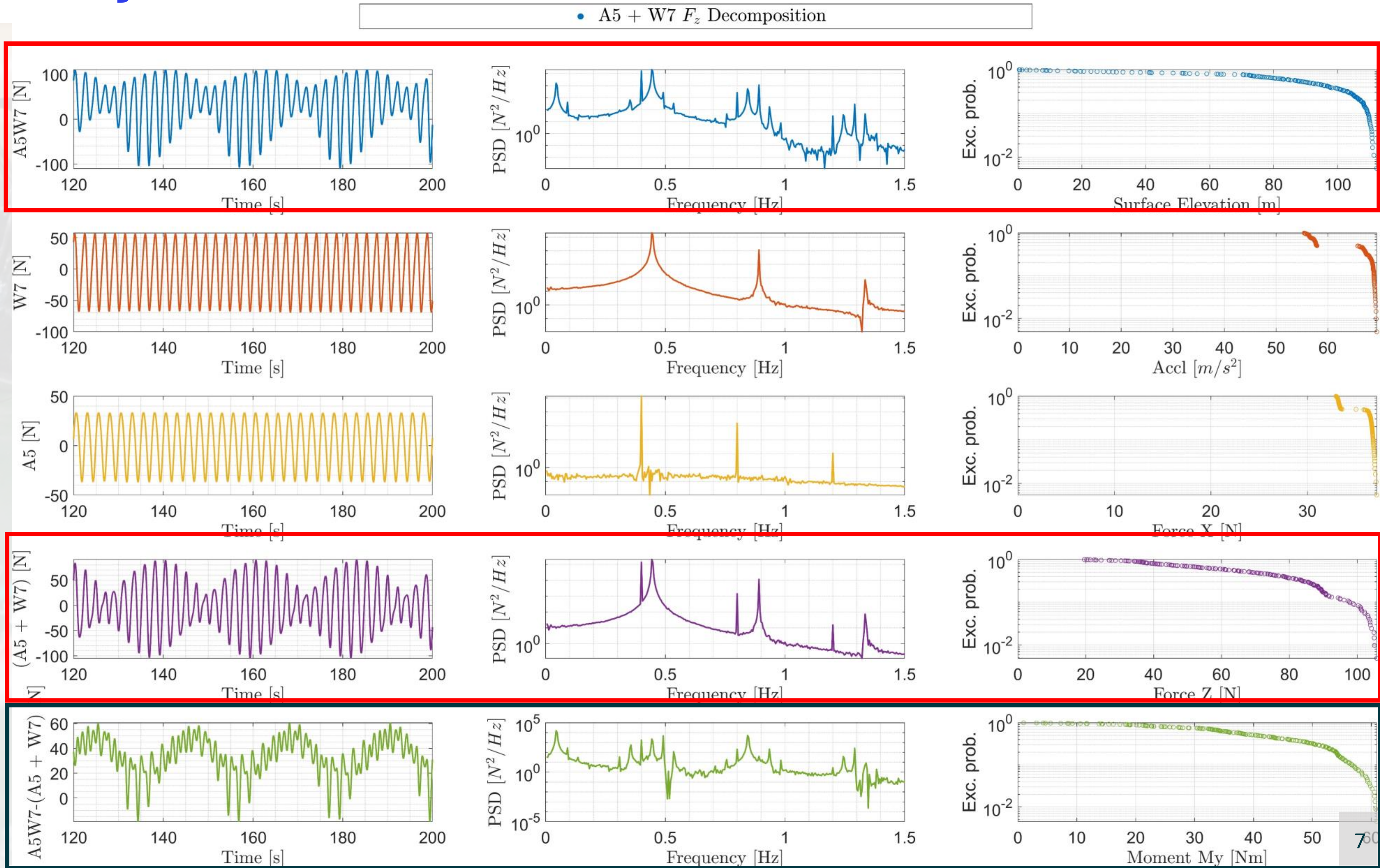
Basic Harmonic separation approach

Regular oscillatory loads



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All the non-linear wave-motion interaction terms

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Basic Harmonic separation approach

Regular oscillatory loads

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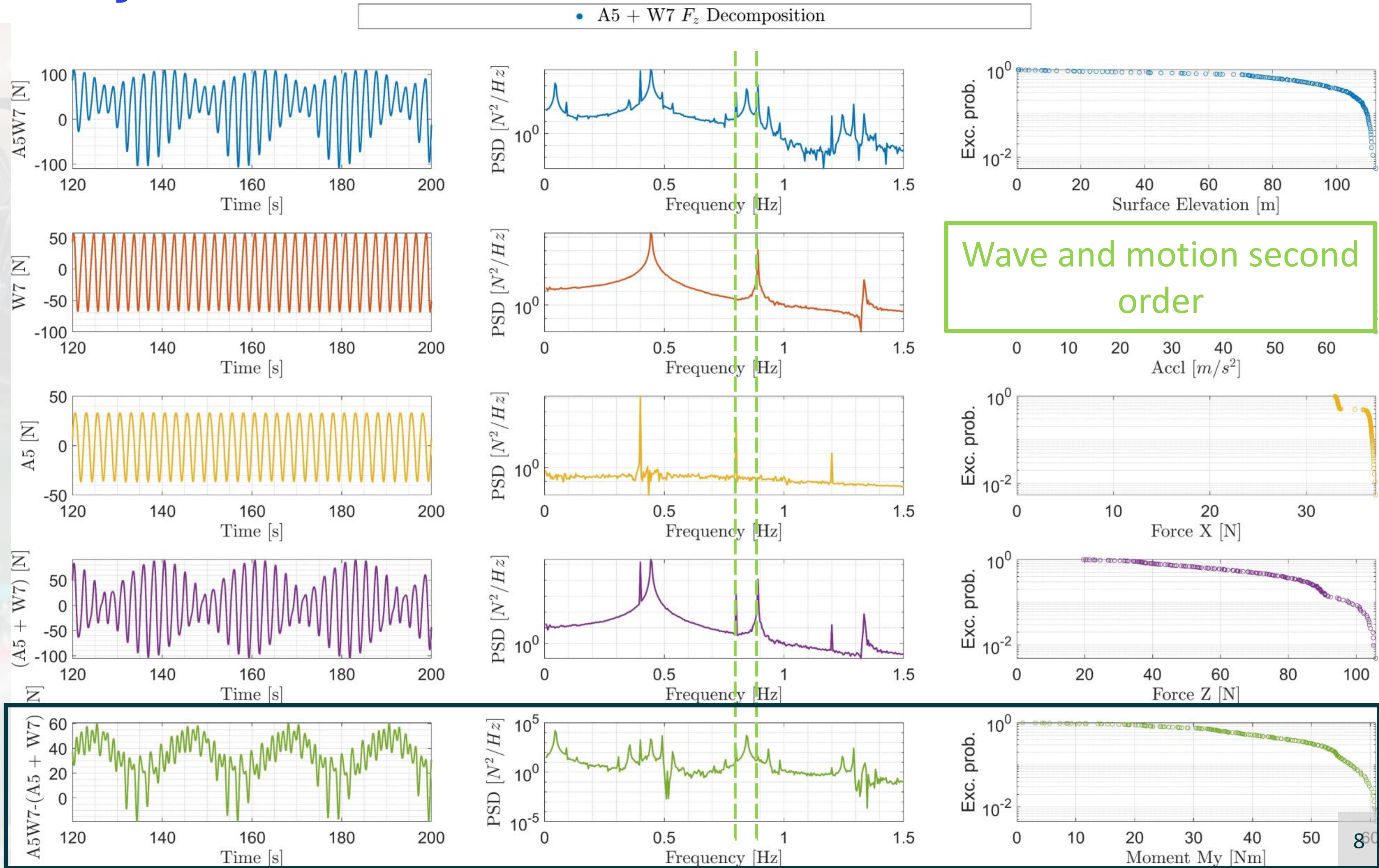

Wave and motion second order

All the non-linear wave-motion interaction terms

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Basic Harmonic separation approach

Regular oscillatory loads

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Load cases	Phase	Hs/H [m]	Wave freq. [Hz]
		Model scale	
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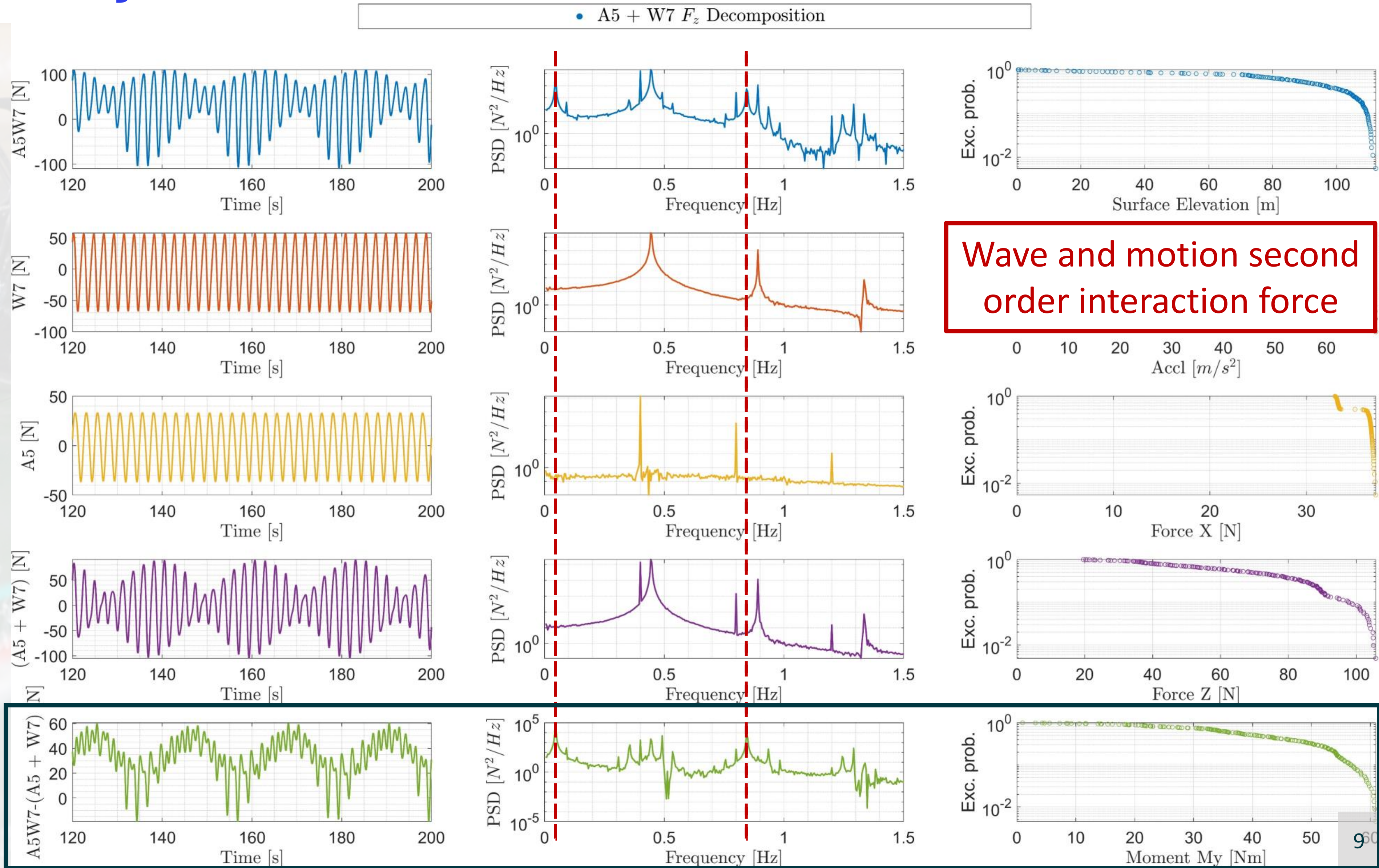

Wave and motion second order interaction force

All the non-linear wave-motion interaction terms

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Basic Harmonic separation approach

Regular oscillatory loads

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Load cases	Phase	Hs/H [m]	Wave freq. [Hz]
	Model scale		
Irregular waves	0, 90, 180, 270	0,218	0,445
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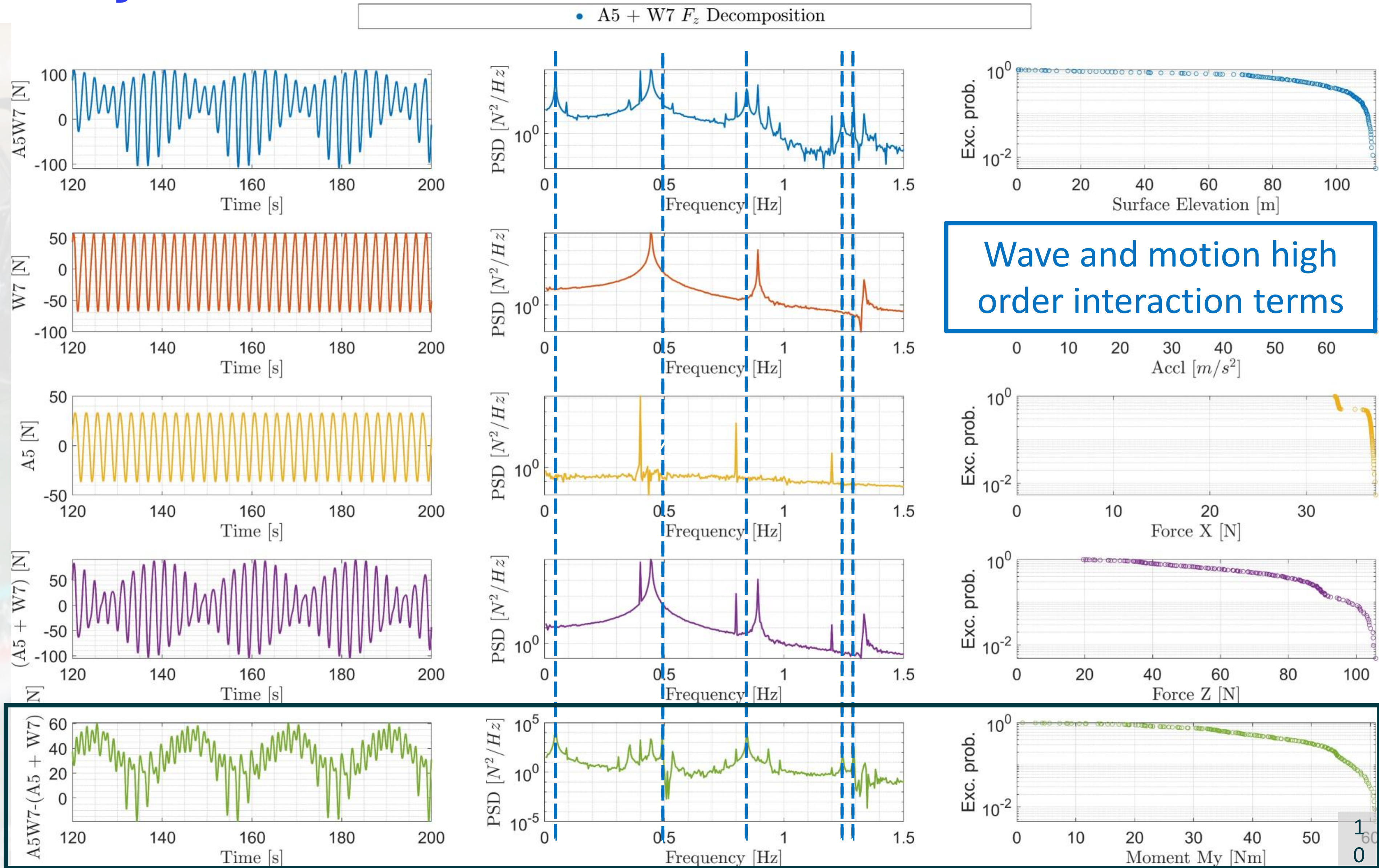

Wave and motion high order interaction terms

All the non-linear wave-motion interaction terms

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Spectral environmental loads as input

Load cases	Phase	Hs/H [m]	Wave freq. [Hz]
	Model scale		
Irregular waves	0, 90, 180, 270	0,218	0,445
Regular waves	0, 180	0,218	0,445
Focus waves	0, 180	0,218	0,445
	Phase	Amplitude [m]	Frequency [Hz]
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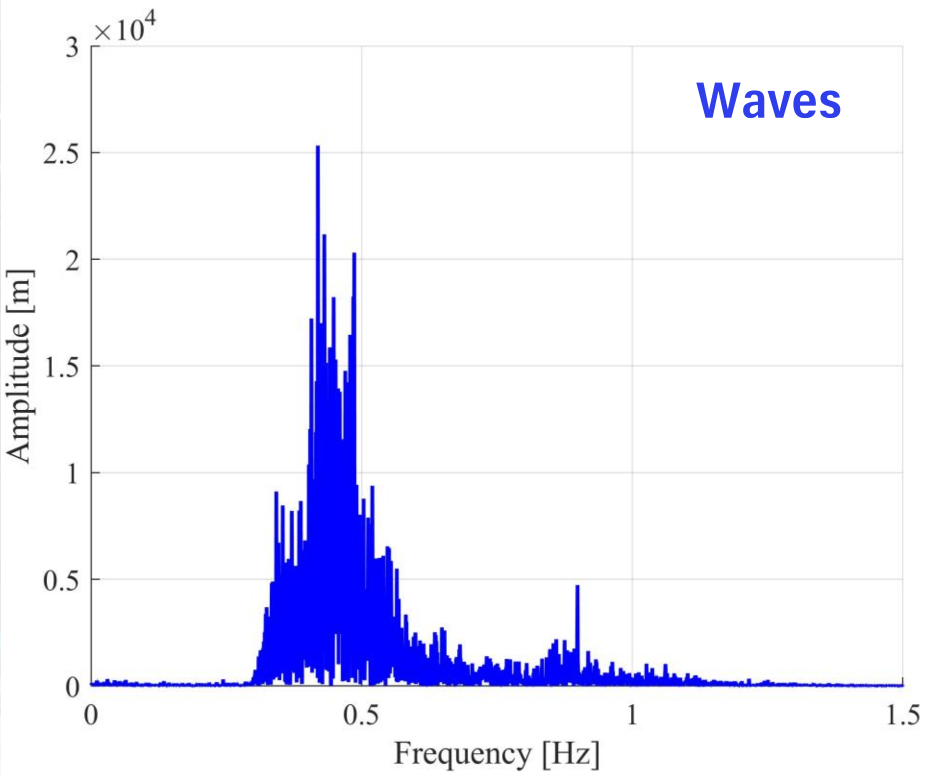
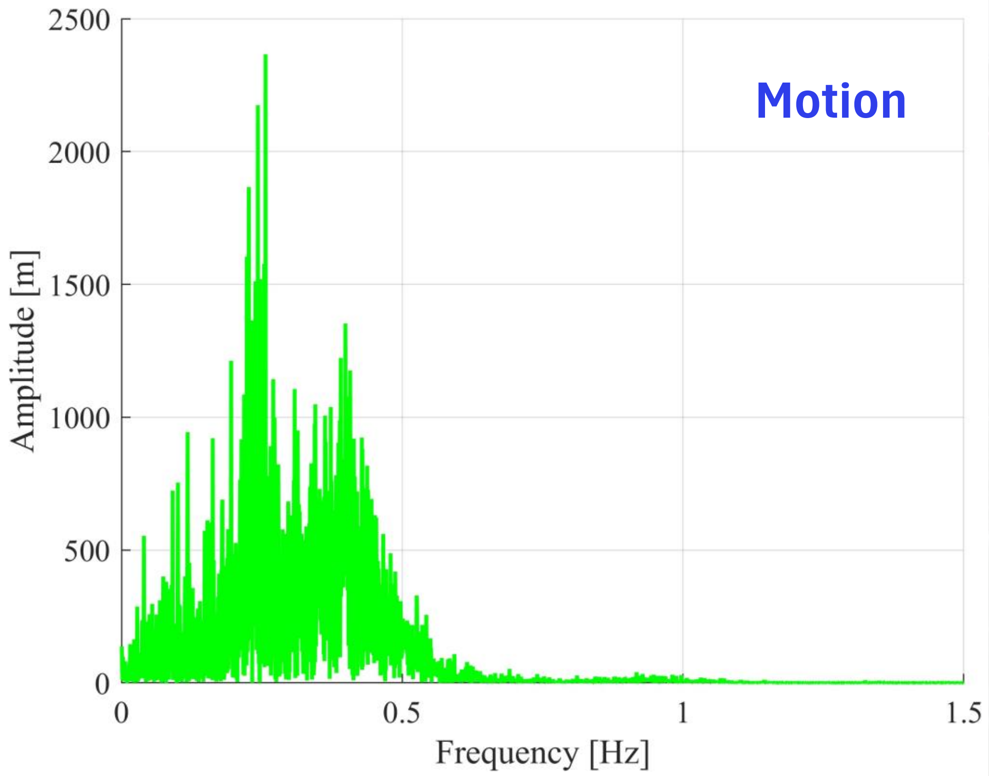
		0,08	0,4
Stochastic FOM	0, 180	-	0,445





Spectral environmental loads as input

Load cases	Phase	Hs/H [m]	Wave freq. [Hz]
	Model scale		
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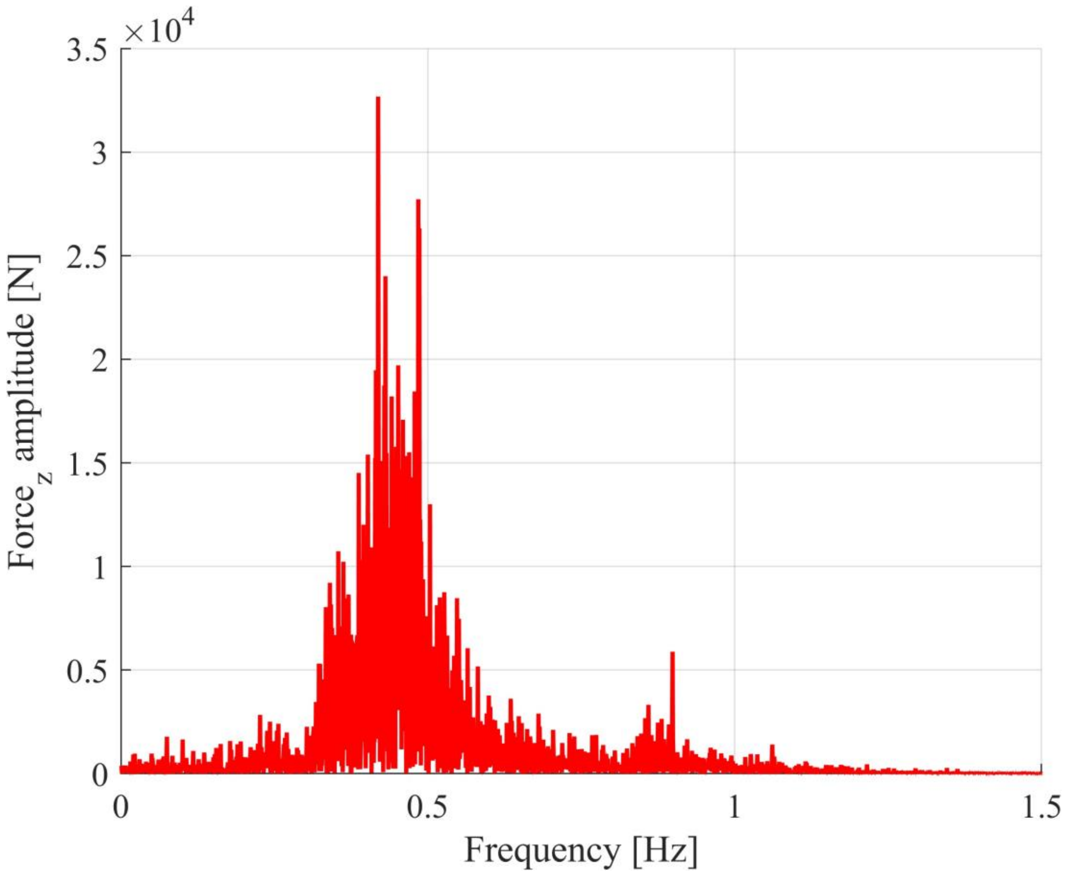

Generate complex responses where the addition and subtraction method it is not possible

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Spectral environmental loads as input

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Harmonic separation methodology

Why?

Due to spectral overlap of non-linear contributions

Harmonic separation methodology

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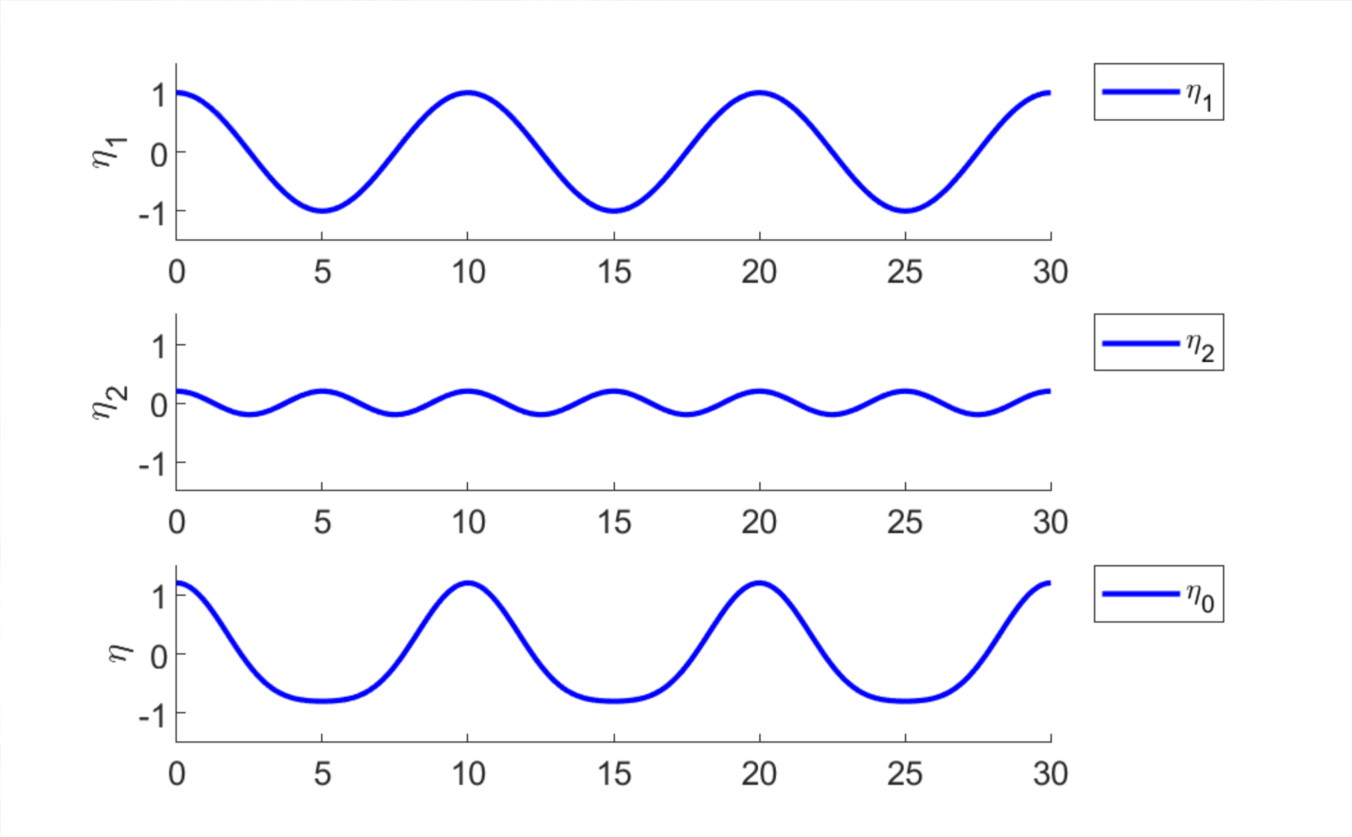

$$\eta_1 = a\cos\omega t$$

$$\eta_2 = c_{11}a^2\cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

Jonathan and Taylor (1997)
Walker, Taylor & Eatock-Taylor (2004)
Fitzgerald et al (2014)

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Harmonic separation methodology

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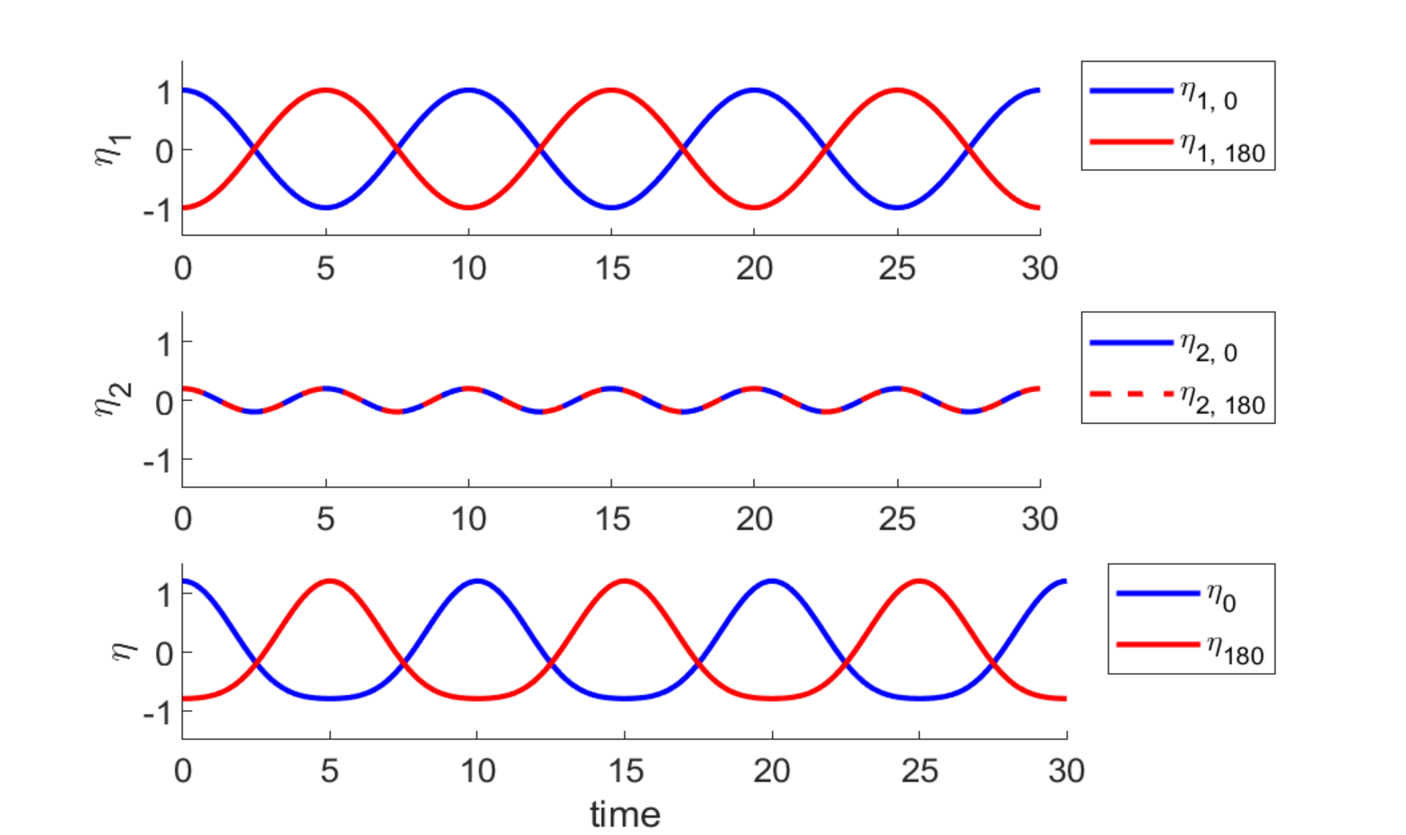

$$\eta_1 = a \cos \omega t$$

$$\eta_2 = c_{11} a^2 \cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

$$\eta_{180} = -\eta_1 + \eta_2$$

$$\eta_{odd} = (\eta_0 - \eta_{180})/2$$

$$\eta_{even} = (\eta_0 + \eta_{180})/2$$

Jonathan and Taylor (1997)
Walker, Taylor & Eatock-Taylor (2004)
Fitzgerald et al (2014)

Harmonic separation methodology

TestCase	Wave	Motion	Quadratic			Cubic				Quartic		
			$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
A	+		+			+						
B	-		+			-						
C		+		+			+					
D		-		+			-					
E	+	+	+	+	+	+	+	+	+	+	+	+
F	+	-	+	+	-	+	-	-	+	-	+	-
G	-	+	+	+	-	-	+	+	-	-	+	-
H	-	-	+	+	+	-	-	-	-	+	+	+

TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E’	E-A-C	0	0	+	0	0	+	+	+	+	+
F’	F-A-D	0	0	-	0	0	-	+	-	+	-
G’	G-B-C	0	0	-	0	0	+	-	-	+	-
H’	H-B-D	0	0	+	0	0	-	-	+	+	+
I”	E’-F’+G’-H’	0	0	0	0	0	4	0	0	0	0
J”	E’-F’-G’+H’	0	0	4	0	0	0	0	4	0	4
K”	E’+F’+G’+H’	0	0	0	0	0	0	0	0	4	0
L”	E’+F’-G’-H’	0	0	0	0	0	0	4	0	0	0

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Harmonic separation methodology

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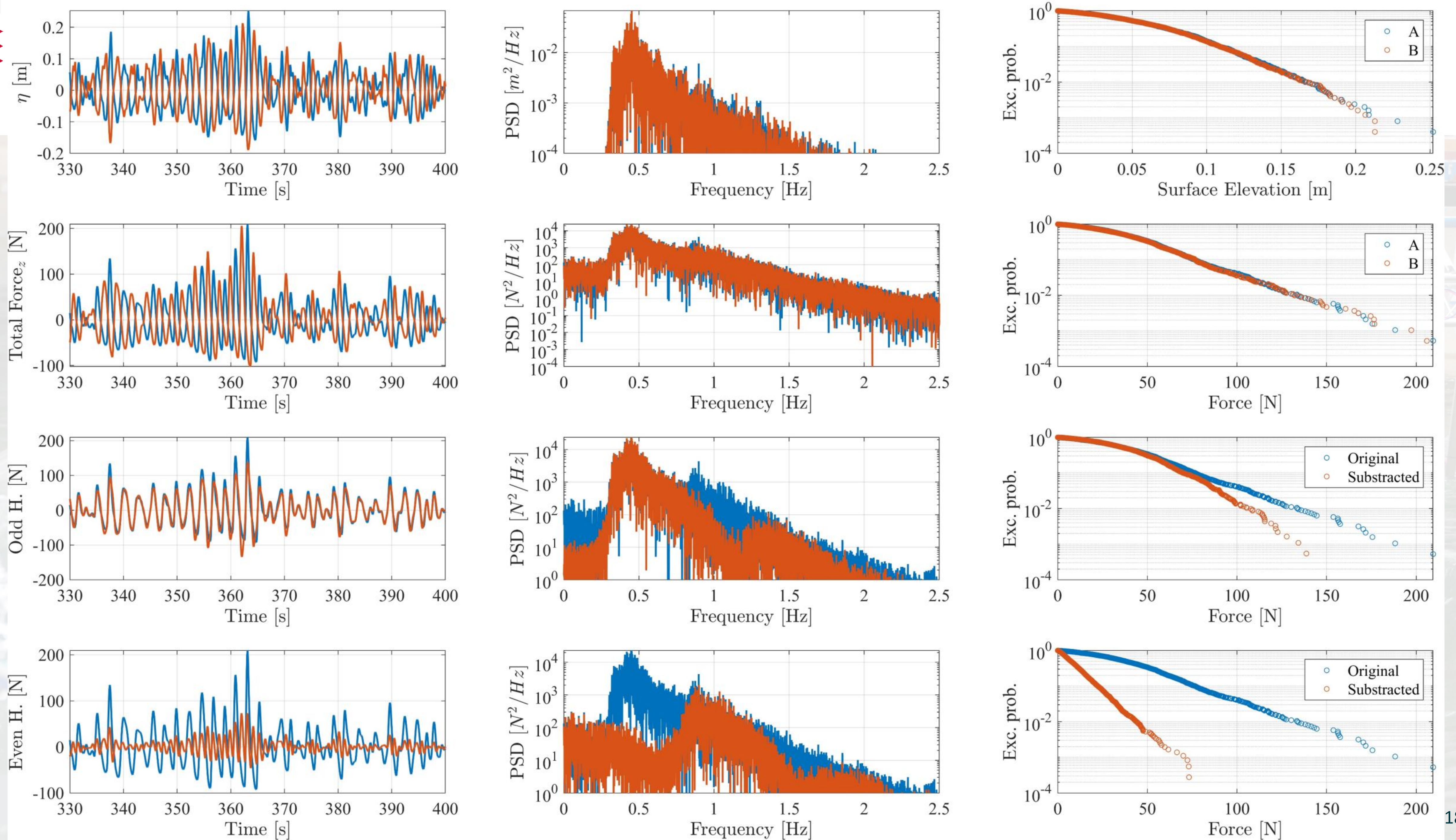
TestCase	Wave	Motion	Quadratic			Cubic				Quartic		
			$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
A	+		+			+						
B	-		+			-						
C		+		+			+					
D		-		+			-					
E	+	+	+	+	+	+	+	+	+	+	+	+
F	+	-	+	+	-	+	-	-	+	-	+	-
G	-	+	+	+	-	-	+	+	-	-	+	-
H	-	-	+	+	+	-	-	-	-	+	+	+

TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E’	E-A-C	0	0	+	0	0	+	+	+	+	+
F’	F-A-D	0	0	-	0	0	-	+	-	+	-
G’	G-B-C	0	0	-	0	0	+	-	-	+	-
H’	H-B-D	0	0	+	0	0	-	-	+	+	+
I”	E’-F’+G’-H’	0	0	0	0	0	4	0	0	0	0
J”	E’-F’-G’+H’	0	0	4	0	0	0	0	4	0	4
K”	E’+F’+G’+H’	0	0	0	0	0	0	0	0	4	0
L”	E’+F’-G’-H’	0	0	0	0	0	0	4	0	0	0

0° and 180° phase decomposition for η, cases A and B



Inclined cylinder analysis

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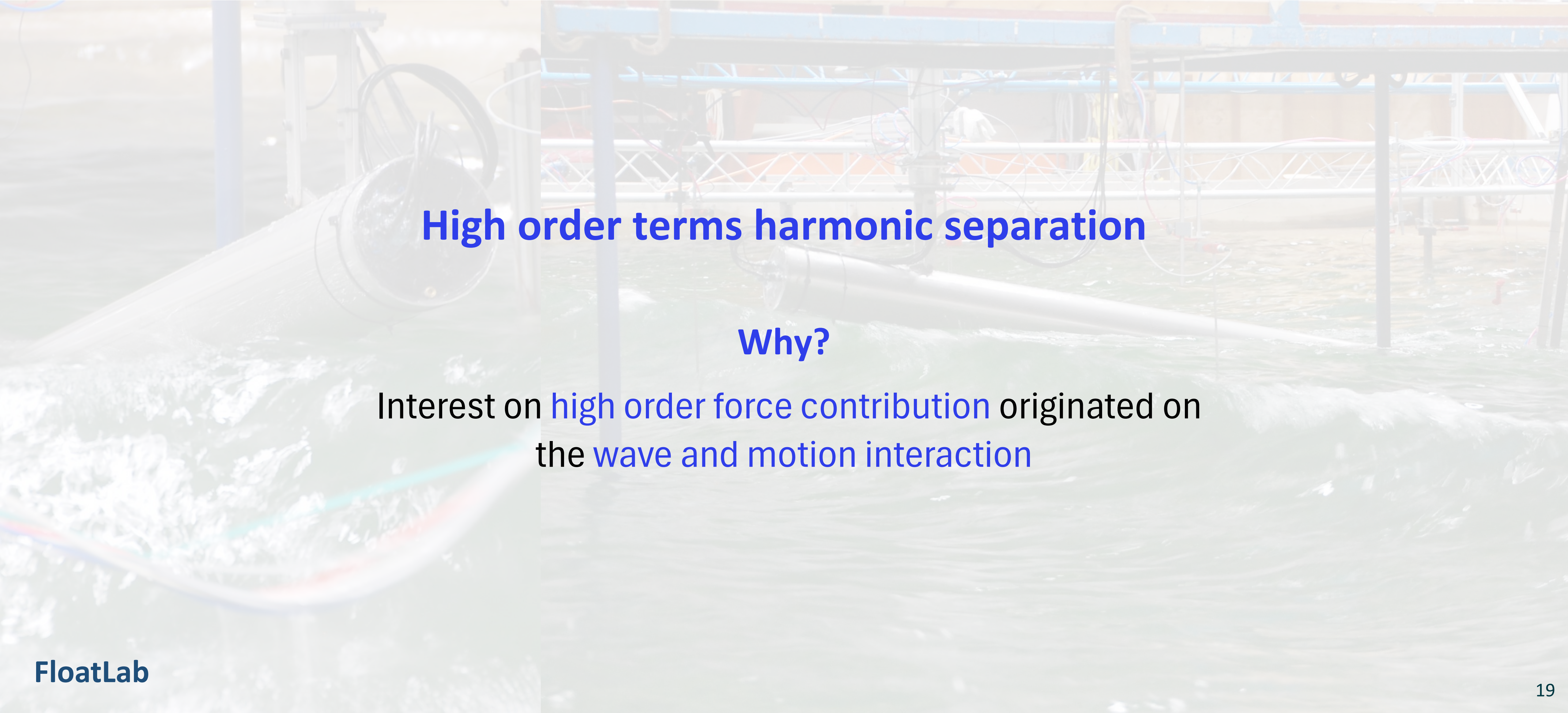


High order terms harmonic separation

Why?

Interest on high order force contribution originated on the wave and motion interaction

Inclined cylinder analysis

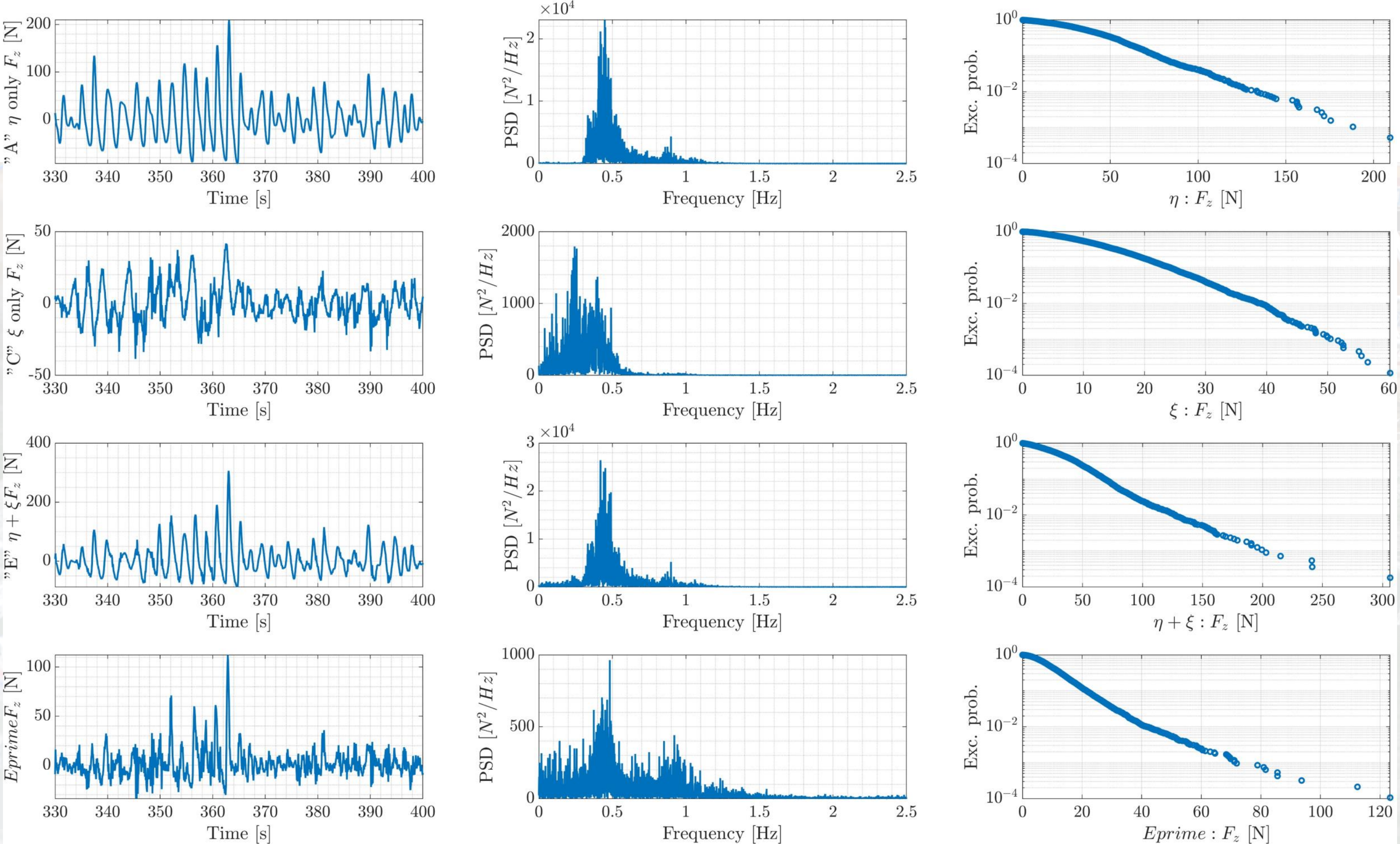
TestCase	Wave	Motion	Quadratic			Cubic				Quartic		
			$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
A	+		+			+						
B	-		+			-						
C		+		+			+					
D		-		+			-					
E	+	+	+	+	+	+	+	+	+	+	+	+
F	+	-	+	+	-	+	-	-	+	-	+	-
G	-	+	+	+	-	-	+	+	-	-	+	-
H	-	-	+	+	+	-	-	-	-	+	+	+

TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E'	E-A-C	0	0	+	0	0	+	+	+	+	+
F'	F-A-D	0	0	-	0	0	-	+	-	+	-
G'	G-B-C	0	0	-	0	0	+	-	-	+	-
H'	H-B-D	0	0	+	0	0	-	-	+	+	+
I"	E'-F'+G'-H'	0	0	0	0	0	4	0	0	0	0
J"	E'-F'-G'+H'	0	0	4	0	0	0	0	4	0	4
K"	E'+F'+G'+H'	0	0	0	0	0	0	0	0	4	0
L"	E'+F'-G'-H'	0	0	0	0	0	0	4	0	0	0

Inclined cylinder analysis

TestCase	Wave	Motion	Quadratic			Cubic				Quartic		
			$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
A	+		+			+						
B	-		+			-						
C		+		+			+					
D		-		+			-					
E	+	+	+	+	+	+	+	+	+	+	+	+
F	+	-	+	+	-	+	-	-	+	-	+	-
G	-	+	+	+	-	-	+	+	-	-	+	-
H	-	-	+	+	+	-	-	-	-	+	+	+

TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E'	E-A-C	0	0	+	0	0	+	+	+	+	+
F'	F-A-D	0	0	-	0	0	-	+	-	+	-
G'	G-B-C	0	0	-	0	0	+	-	-	+	-
H'	H-B-D	0	0	+	0	0	-	-	+	+	+
I"	E'-F'+G'-H'	0	0	0	0	0	4	0	0	0	0
J"	E'-F'-G'+H'	0	0	4	0	0	0	0	4	0	4
K"	E'+F'+G'+H'	0	0	0	0	0	0	0	0	4	0
L"	E'+F'-G'-H'	0	0	0	0	0	0	4	0	0	0

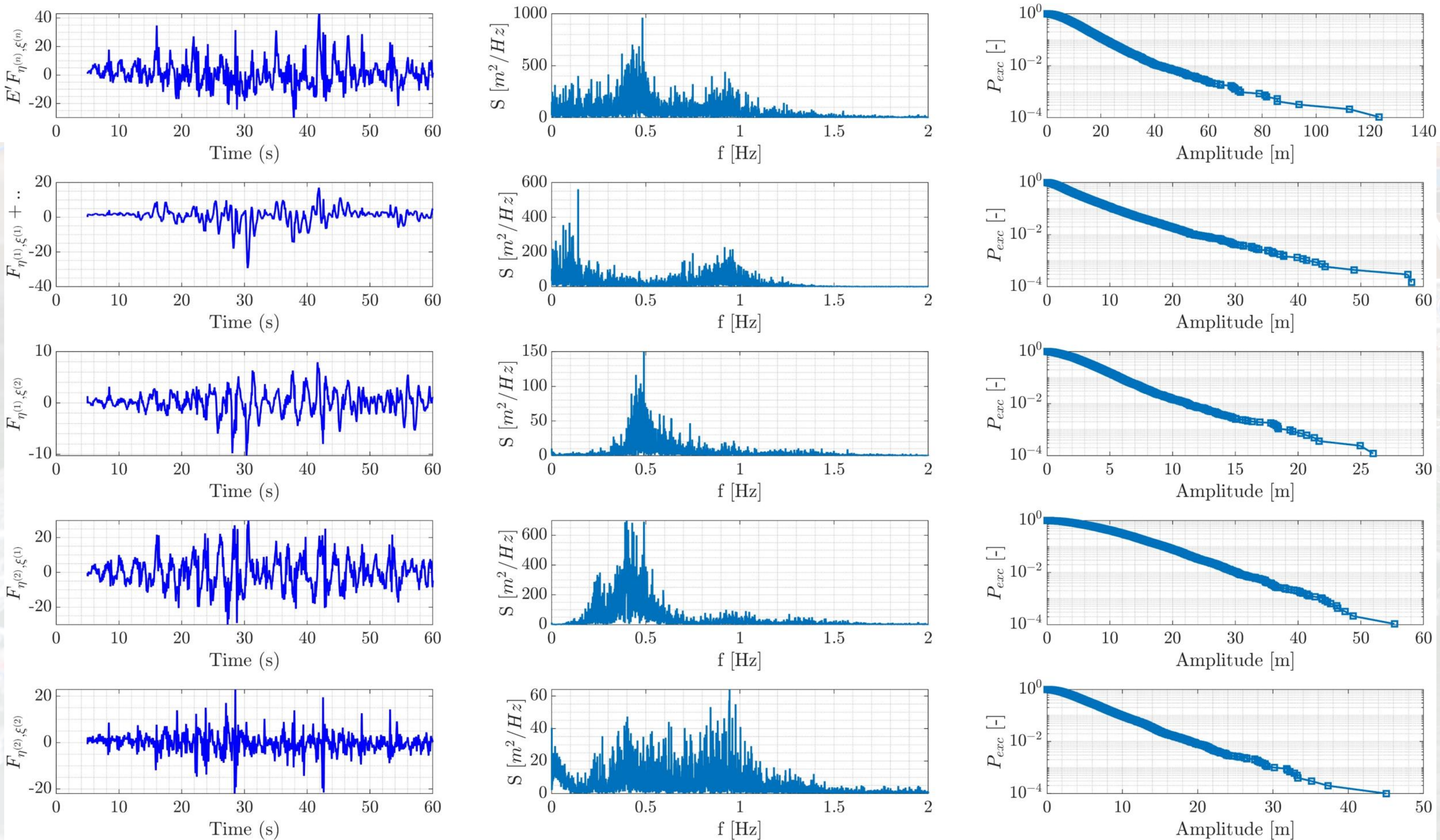

"A" η only F_z [N]
"C" ξ only F_z [N]
"E" $\eta + \xi F_z$ [N]
$Eprime F_z$ [N]
Time [s]
$\times 10^4$
PSD [N^2/Hz]
Frequency [Hz]
Exc. prob.
$\eta : F_z$ [N]
$\xi : F_z$ [N]
$\eta + \xi : F_z$ [N]
$Eprime : F_z$ [N]

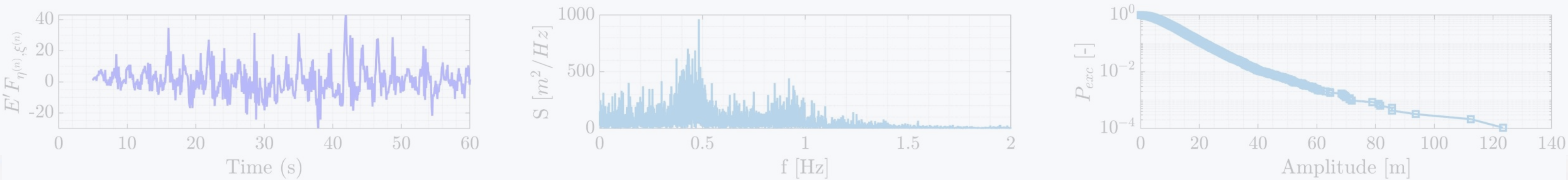
Inclined cylinder analysis

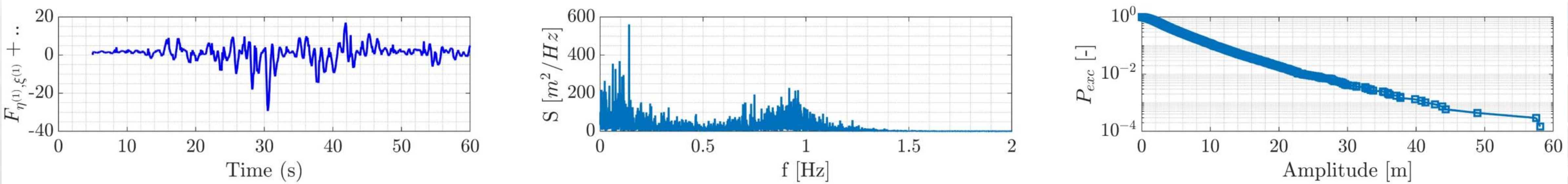
TestCase	Wave	Motion	Quadratic			Cubic				Quartic		
			$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
A	+		+			+						
B	-		+			-						
C		+		+			+					
D		-		+			-					
E	+	+	+	+	+	+	+	+	+	+	+	+
F	+	-	+	+	-	+	-	-	+	-	+	-
G	-	+	+	+	-	-	+	+	-	-	+	-
H	-	-	+	+	+	-	-	-	-	+	+	+

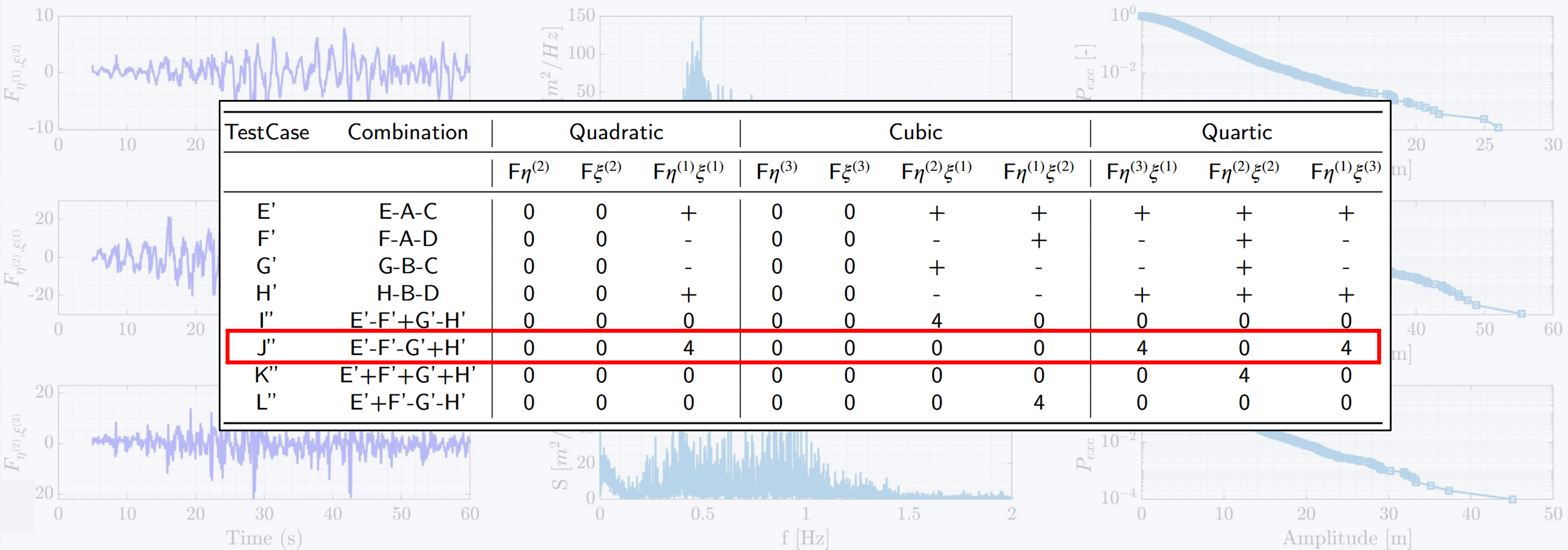
TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E'	E-A-C	0	0	+	0	0	+	+	+	+	+
F'	F-A-D	0	0	-	0	0	-	+	-	+	-
G'	G-B-C	0	0	-	0	0	+	-	-	+	-
H'	H-B-D	0	0	+	0	0	-	-	+	+	+
I"	E'-F'+G'-H'	0	0	0	0	0	4	0	0	0	0
J"	E'-F'-G'+H'	0	0	4	0	0	0	0	4	0	4
K"	E'+F'+G'+H'	0	0	0	0	0	0	0	0	4	0
L"	E'+F'-G'-H'	0	0	0	0	0	0	4	0	0	0

Investigation of Quadrtic, Cubic and Quartic Terms



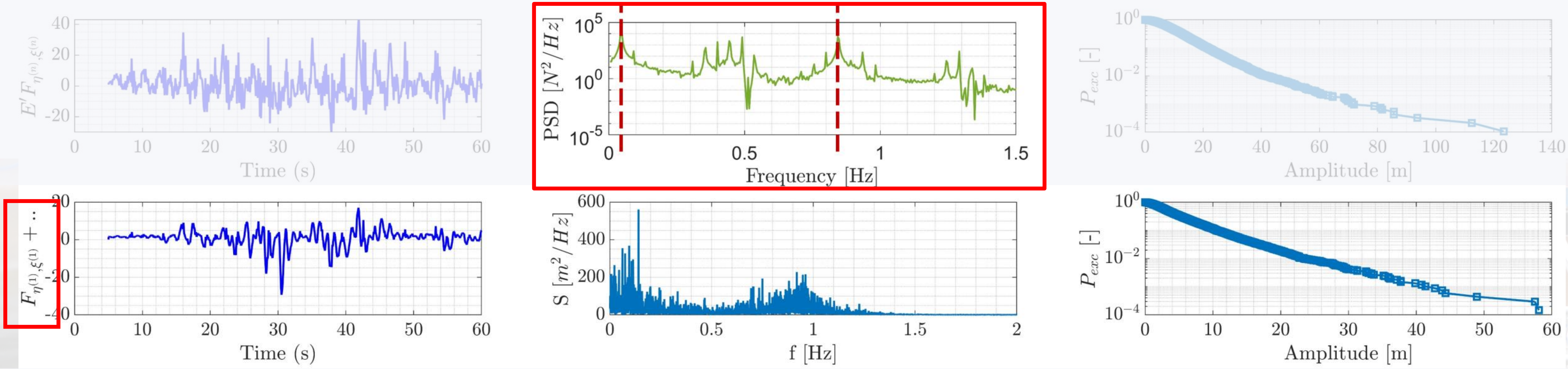


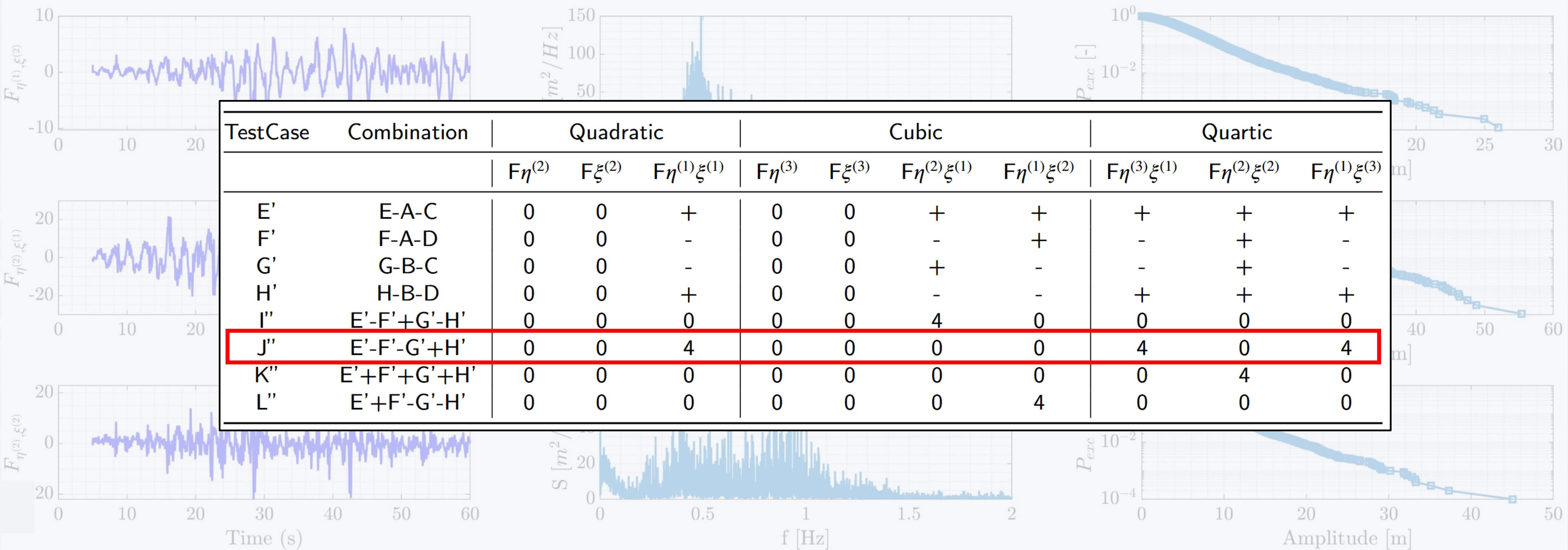




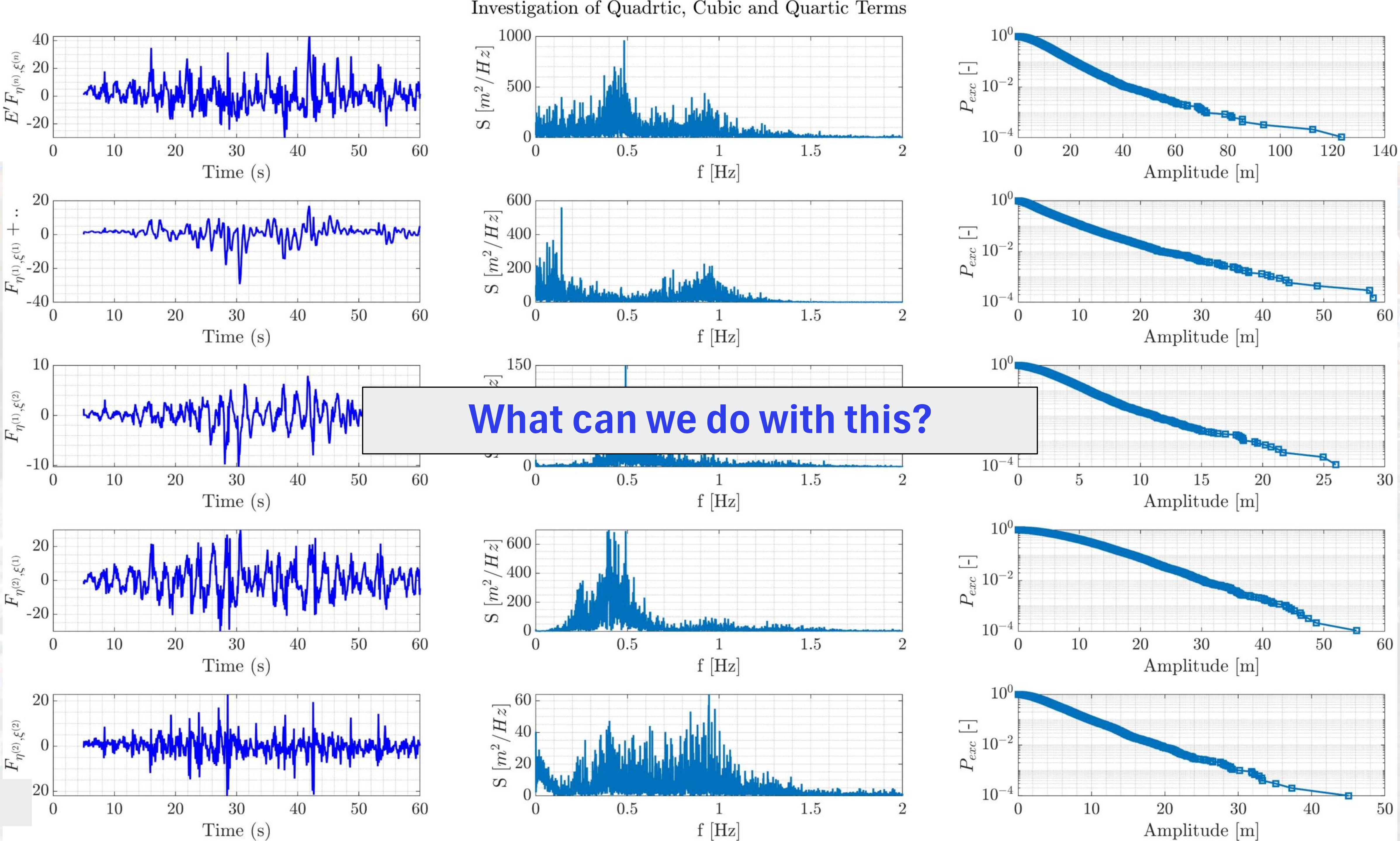
TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E'	E-A-C	0	0	+	0	0	+	+	+	+	+
F'	F-A-D	0	0	-	0	0	-	+	-	+	-
G'	G-B-C	0	0	-	0	0	+	-	-	+	-
H'	H-B-D	0	0	+	0	0	-	-	+	+	+
I''	E'-F'+G'-H'	0	0	0	0	0	4	0	0	0	0
J''	E'-F'-G'+H'	0	0	4	0	0	0	0	4	0	4
K''	E'+F'+G'+H'	0	0	0	0	0	0	0	0	4	0
L''	E'+F'-G'-H'	0	0	0	0	0	0	4	0	0	0

Investigation of Quadrtic, Cubic and Quartic Terms





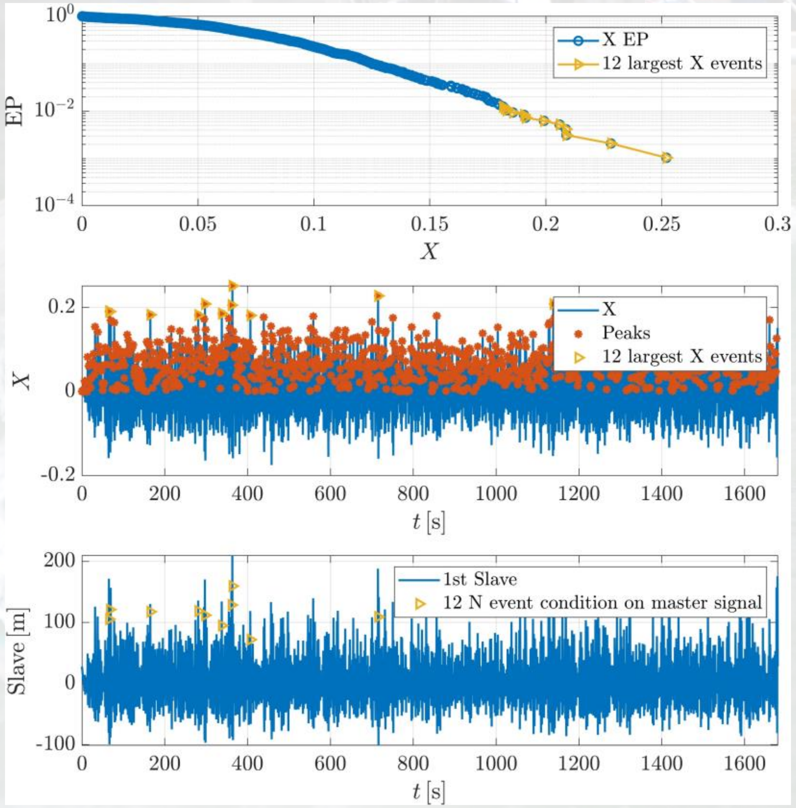
TestCase	Combination	Quadratic			Cubic				Quartic		
		$F\eta^{(2)}$	$F\xi^{(2)}$	$F\eta^{(1)}\xi^{(1)}$	$F\eta^{(3)}$	$F\xi^{(3)}$	$F\eta^{(2)}\xi^{(1)}$	$F\eta^{(1)}\xi^{(2)}$	$F\eta^{(3)}\xi^{(1)}$	$F\eta^{(2)}\xi^{(2)}$	$F\eta^{(1)}\xi^{(3)}$
E'	E-A-C	0	0	+	0	0	+	+	+	+	+
F'	F-A-D	0	0	-	0	0	-	+	-	+	-
G'	G-B-C	0	0	-	0	0	+	-	-	+	-
H'	H-B-D	0	0	+	0	0	-	-	+	+	+
I"	E'-F'+G'-H'	0	0	0	0	0	4	0	0	0	0
J"	E'-F'-G'+H'	0	0	4	0	0	0	0	4	0	4
K"	E'+F'+G'+H'	0	0	0	0	0	0	0	0	4	0
L"	E'+F'-G'-H'	0	0	0	0	0	0	4	0	0	0

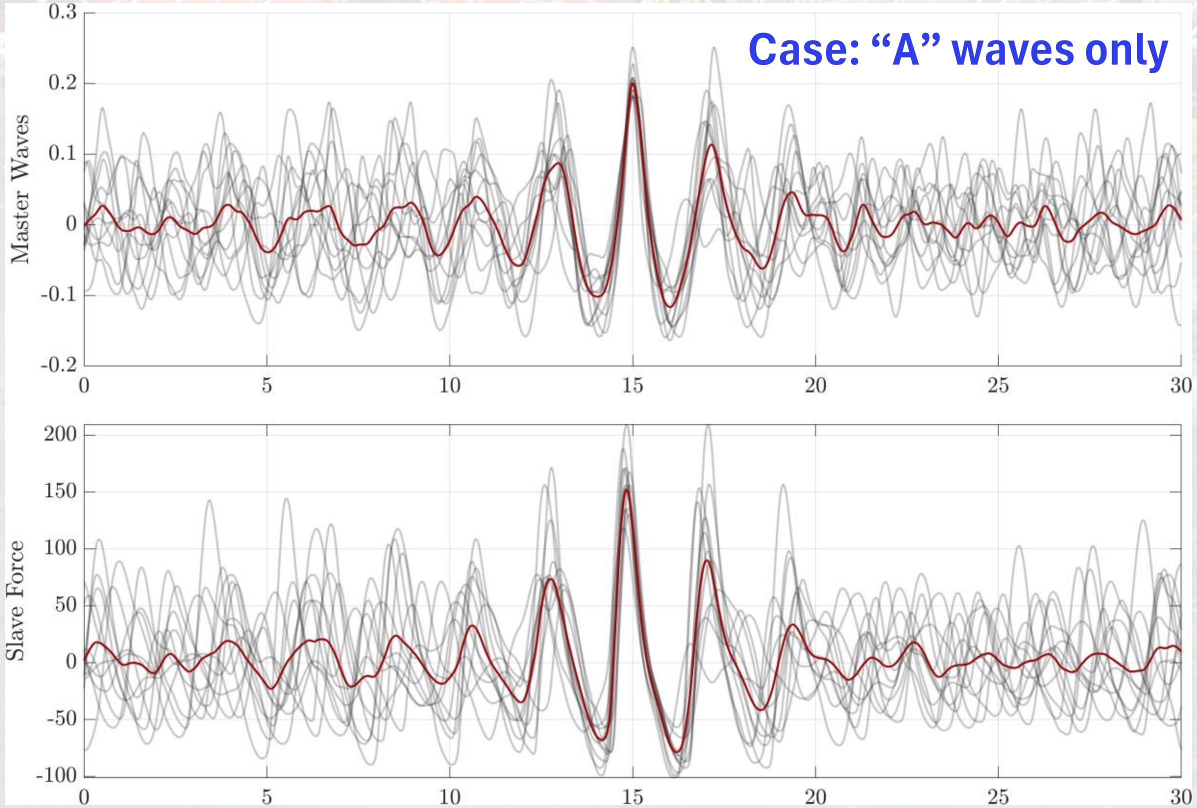


What can we do with this?

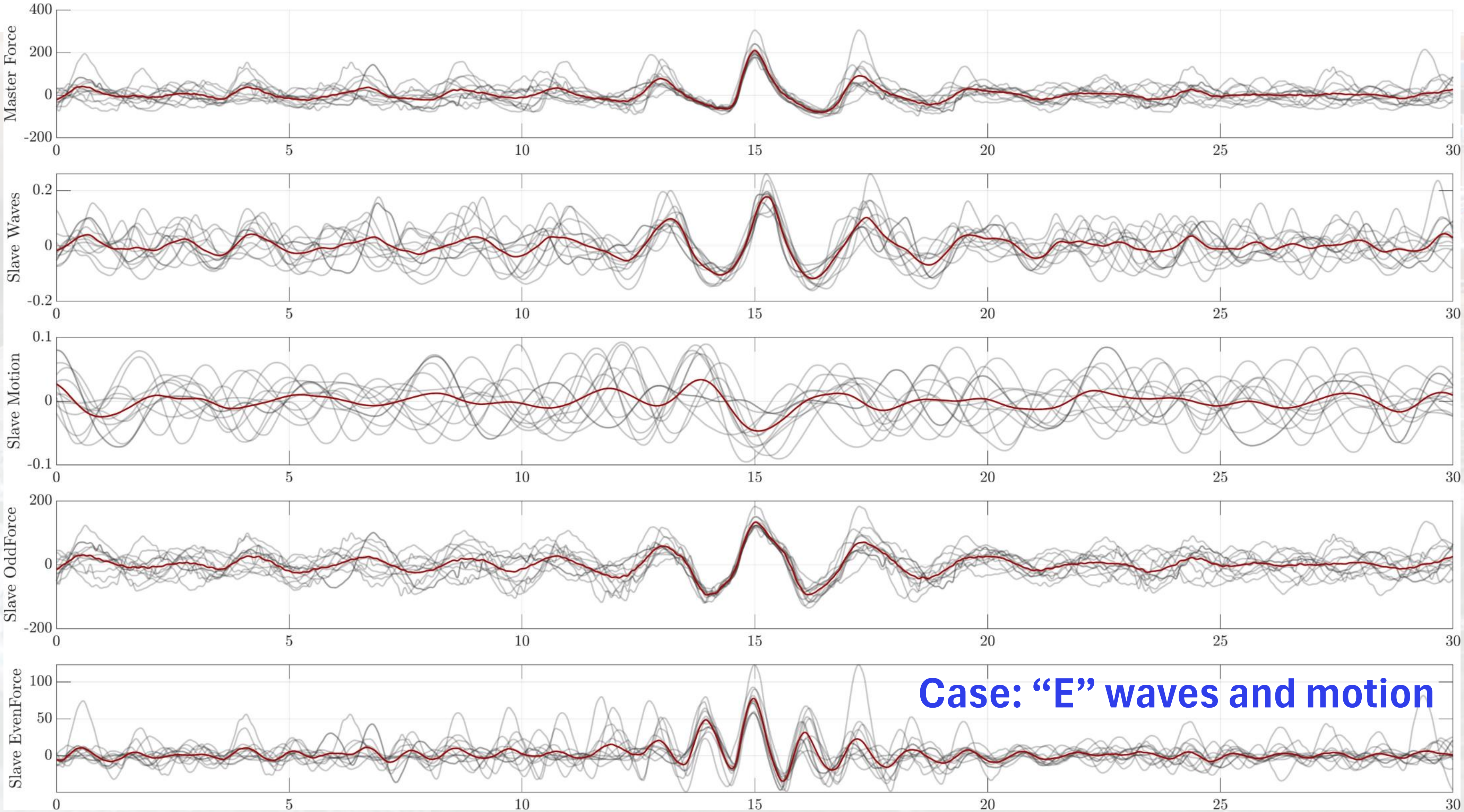
Inclined cylinder analysis

The averaging process identifies the “n” significant “master” events, creating a pre-determined time window for each event, to then overlap and average them over each timestep. This, is then repeated on different co-existing “slave” signals under the time rule of the master signal.



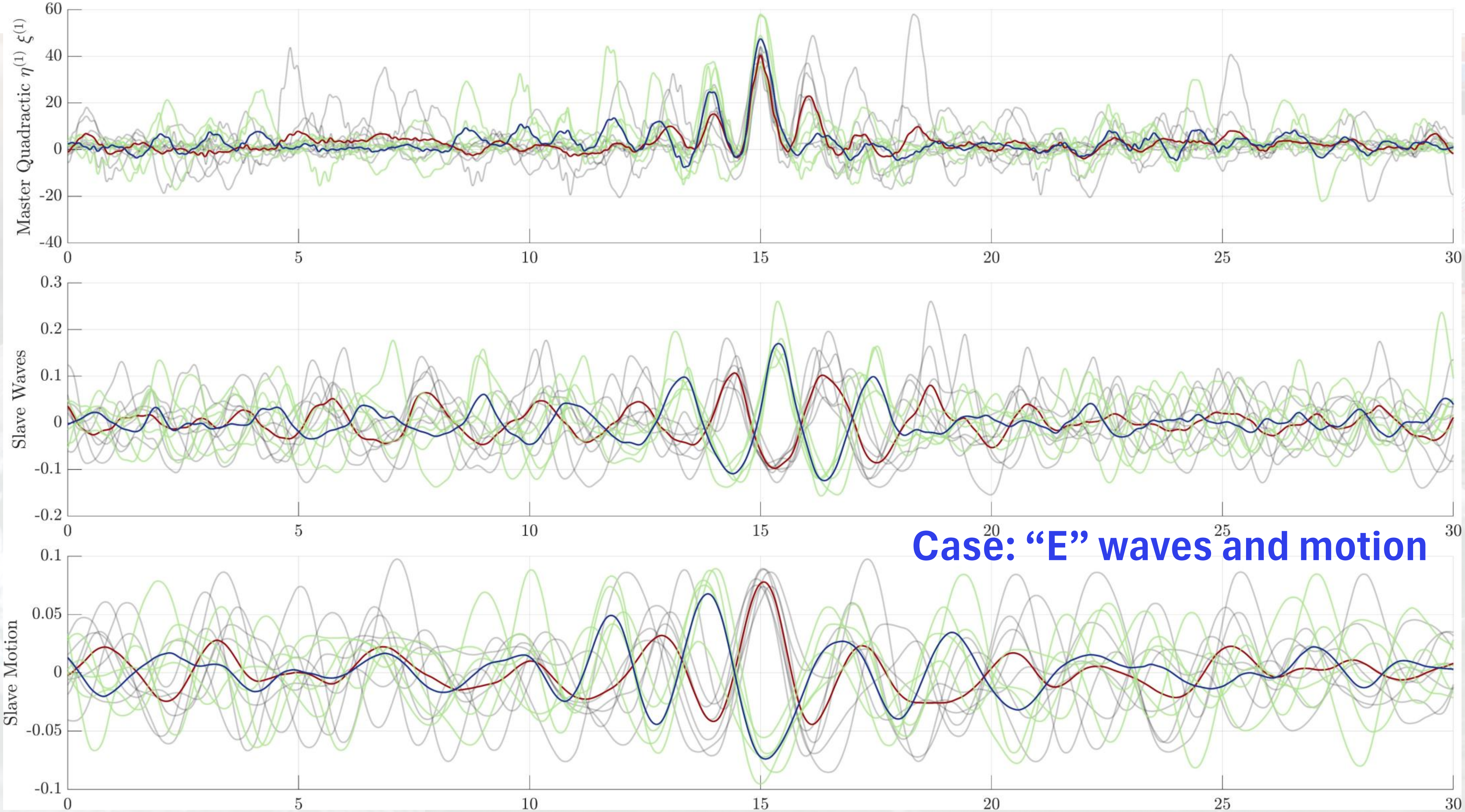


Inclined cylinder analysis



FloatLab

Inclined cylinder analysis

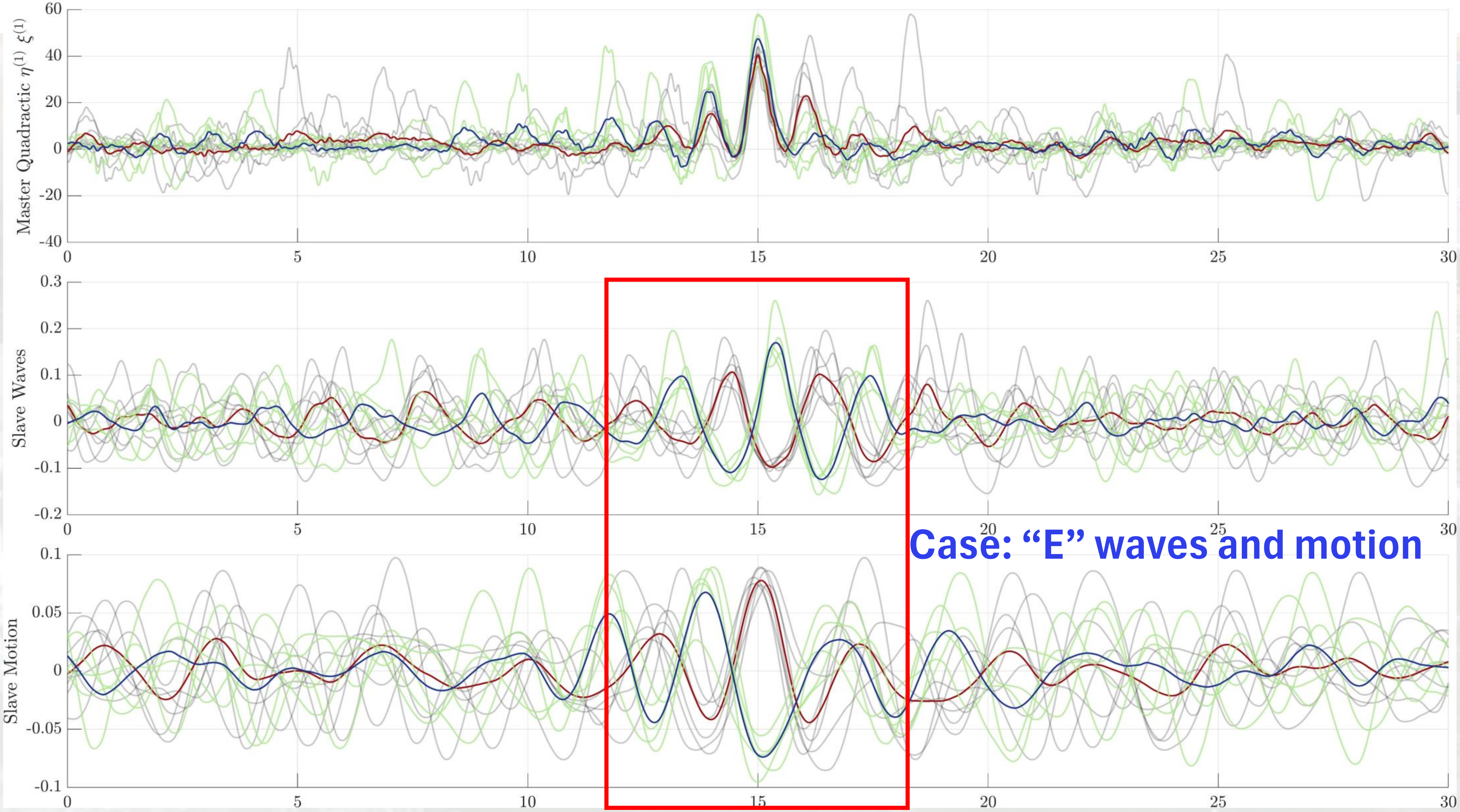


Case: “E” waves and motion

FloatLab

Inclined cylinder analysis

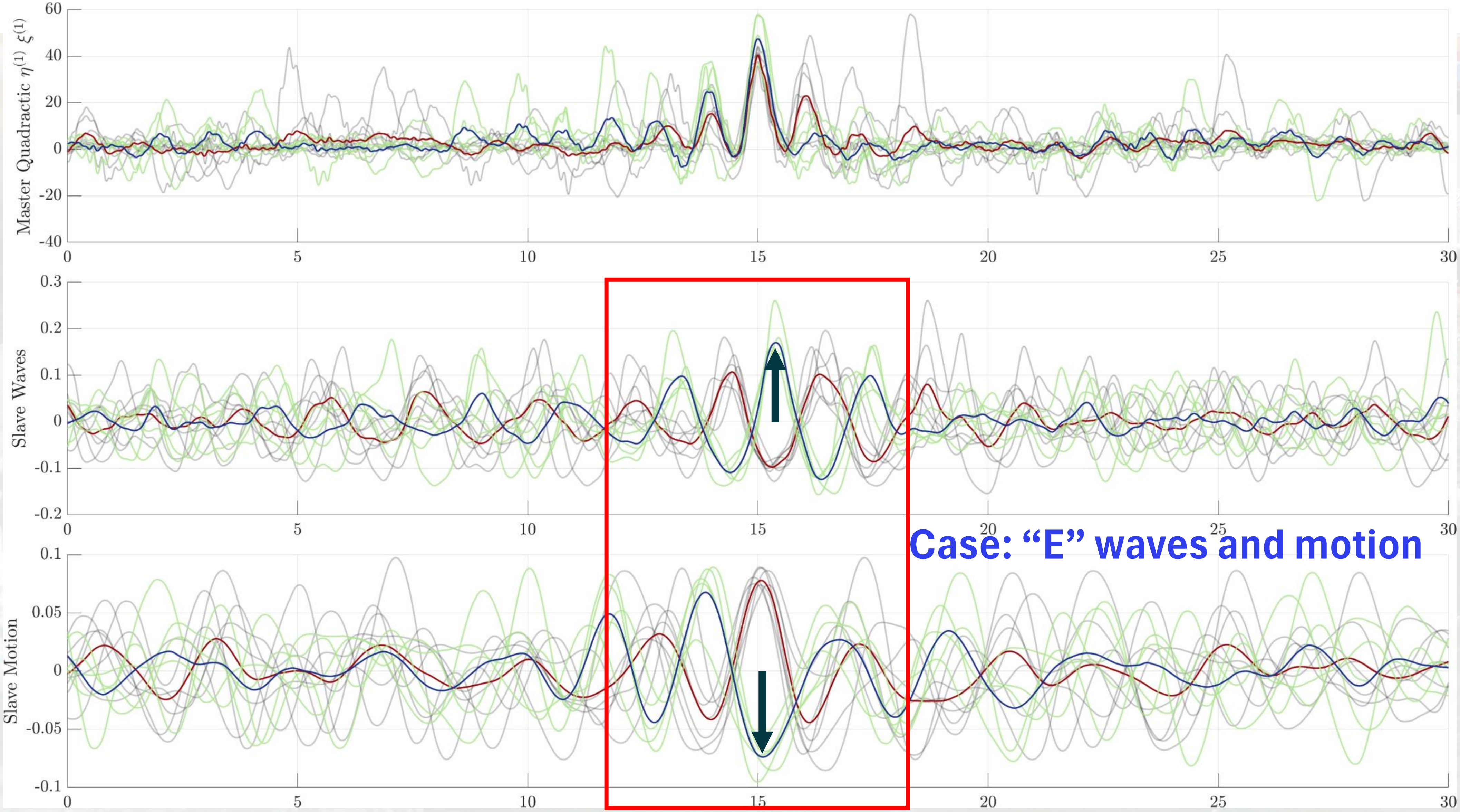
Innovation Fund Denmark



Case: "E" waves and motion

FloatLab

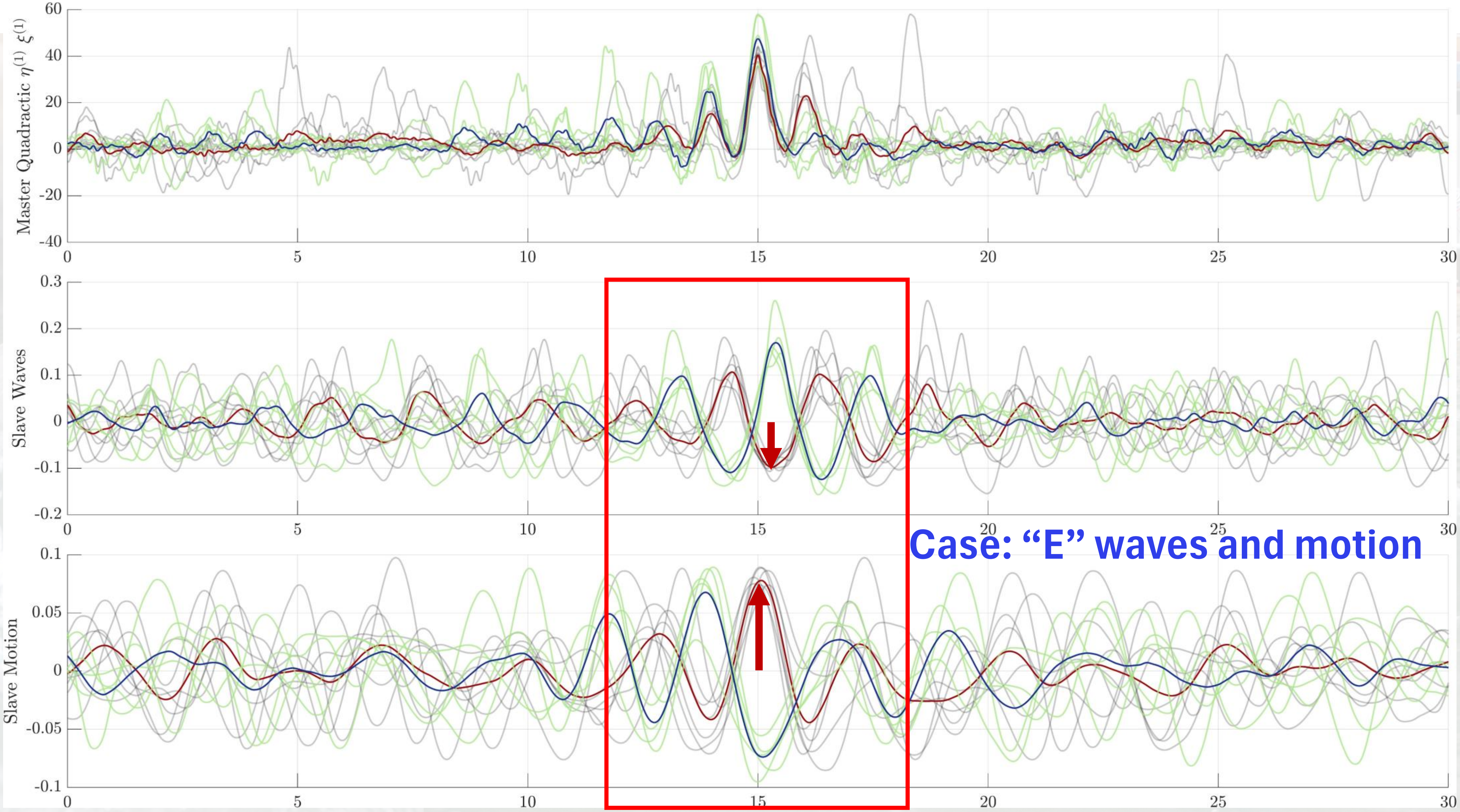
Inclined cylinder analysis



FloatLab

Inclined cylinder analysis

Innovation Fund Denmark

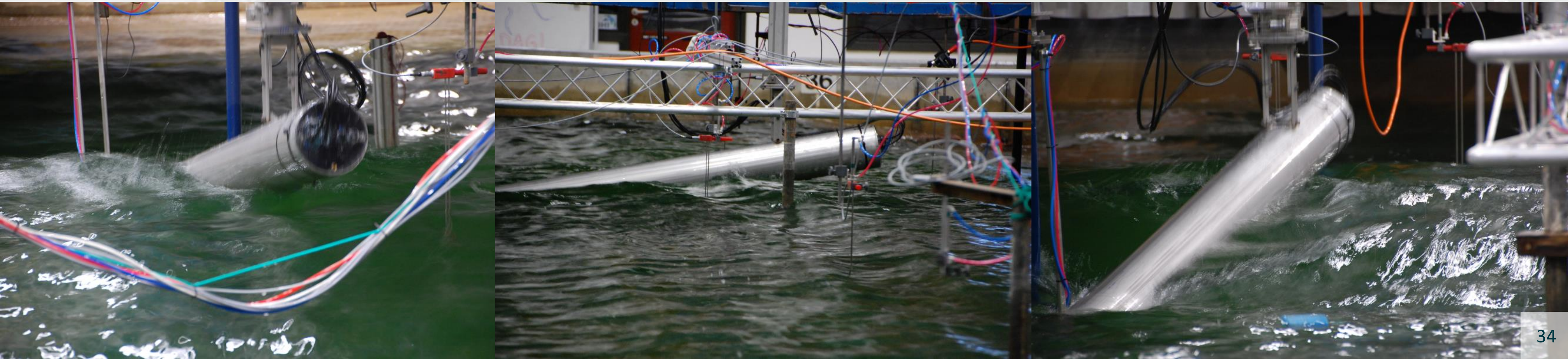


FloatLab

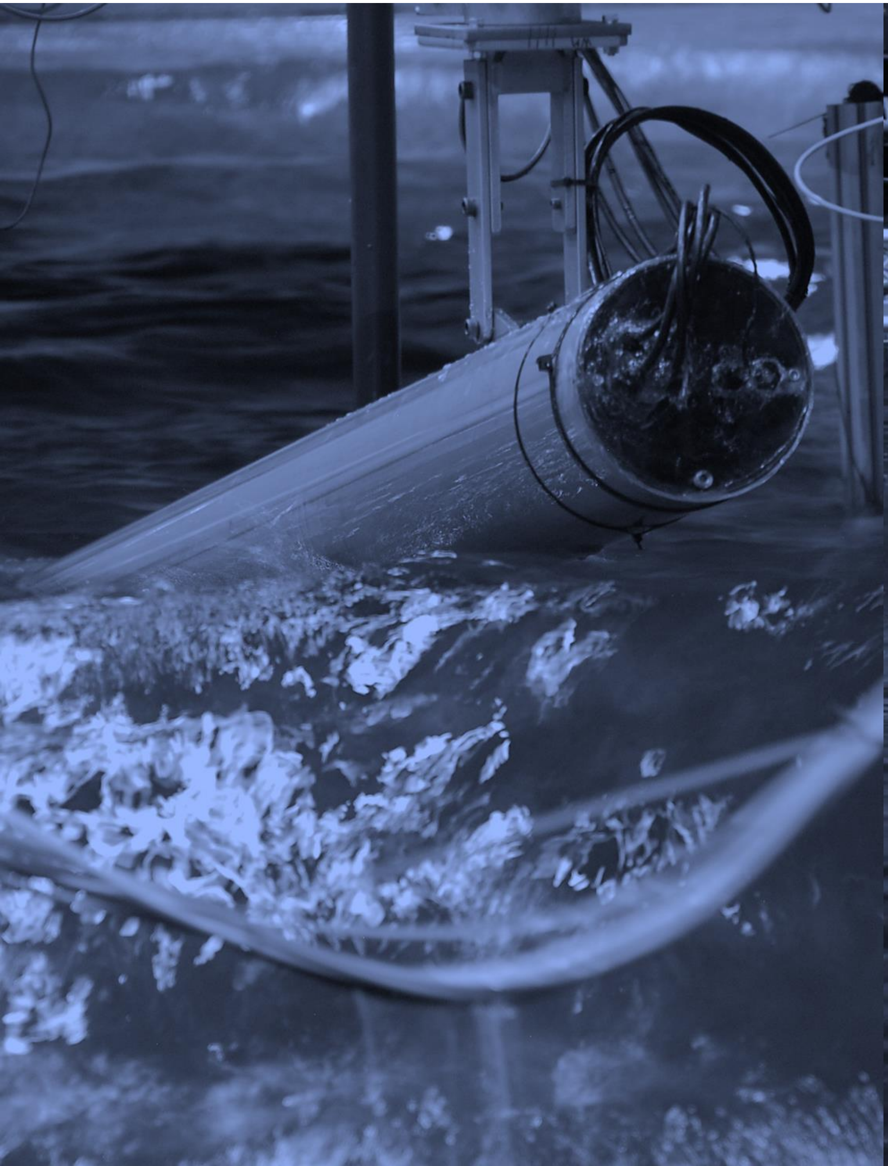
Take aways and future work

- We can successfully identify high order wave-motion interaction forces while averaging can hunt the conditions that develop these forces .
- Cylindrical elements present significant non-linear forces that are originated on the high order wave-motion interaction (up to ≈40% in certain events and cases).

- Force model and respective comparison with identified high order terms
- Make a CFD setup of the case and simulate the identified conditions for high order forces.
- Identification of slamming events and the conditions that develops them.



FloatLab (2023-2027)



Thank you!

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