CWPT Open Water Demonstration
DE-EE0008097.0000
Budget Period 1

Task 2.4.2 Scaled Prototype Tank Testing

Overview of Device Behavior in Different Sea States and Monochromatic Waves

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Variables & Definition

Variables and Constants

Variable	Description	Unit
W	Width	m
L	Length	m
T	Thickness	m
V	Displaced Water Volume by Absorber	m^3
hOp	Operating depth; Vertical distance between mean water line and top of absorber body	m
Alpha	Mooring angle between mooring line/PTO tether and horizontal tank floor	Deg
C	Target PTO Damping Coefficient	Ns/m
K	Target Spring Coefficient	N/m
H	Tank water depth	m
Hs	Significant Wave Height	m
Tp	Dominant Wave Period	s
Te	Energy Period	S
omega	Wave Direction measured in a positive rotation coordinates defined in this document	Deg

Further Conventions

CalWave is using the following convention for the positioning and orientation of the global coordinate system. This convention is equal to the most common convention used in Naval Architecture and specifically in wave energy conversion related research & development:

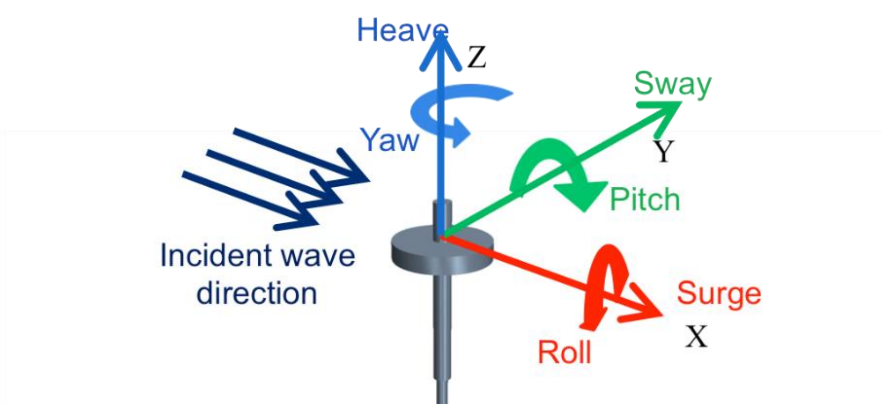


Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

INTRODUCTION

The objective of the project is to advance the Technology Readiness Level (TRL) of the Wave Energy Converter (WEC) developed by CalWave Wave Power Technologies Inc (CalWave) through advanced numerical simulations, dynamic hardware tests, and ultimately a scaled open water demonstration deployment while continuing to exceed DOE's target ACE threshold of 3m/M$. The outcomes of Budget Period 1 will be a detailed design of the scaled demonstration unit and bench testing of the critical hardware components. In Budget Period 2, the key outcomes will be deployment and operation of the demonstration unit at an open water site which replicates full scale ocean conditions, and performance and load measurements will be used to validate the high techno-economic performance (ACE) of the device full scale device, as measured by the "Average Climate Capture Width per Characteristic Capital Cost" (ACE) metric defined for the Wave Energy Prize.

CalWave sought to conduct experimental tank testing of scaled prototype units early on in the design process to obtain a first estimation of device performance for sea states of importance and to perform system identification/PTO tests. These experimental tests primarily aim to assess the wave to structure conversion efficiency and device behavior. Moreover, distinct model parameters of high interest were experimentally tested to validate numerical device modeling and optimization.

1 LIR DEEP OCEAN BASIN RUN-TABLE SUMMARY

The following Table 1 includes an overview of all cases that were run during the Lir Wave Tank tests. Each Run has a unique RunID that will be referred to in the specific post processing topics. The device with a unique label, incident wave parameter, PTO parameter, operating depth and PTO gain is listed. Additionally, the file name is listed for clear assignment of runs to data files. A total of 109 runs were performed and recorded with a total runtime of approximately 19 hours of recoded device data.

For a description of the prototype, experimental setup, sensor and calibrations as well as the (passive) PTO control strategy the reader is referred to the documentation of the Lir Wave Tank Test plan, submitted to MHK-DR as well as PMC at the beginning of Mar. 2018.

Although irregular wave cases used to ACE assessment were run during the tank testing, the focus of this tank testing was not to optimize performance in these runs but rather to perform baseline system ID and device behavior. Thus, irregular wave cases used for ACE assessment (Wave Energy Prize Wave Cases IWS1 – IWS6) were sometimes only run once to fill the matrix for a very preliminary assessment of the nominator in the ACE calculation.

CalWave X20 - RunTable - Cork

Run ID	Time		Device	Waves					PTO #1		PTO #2		PTO #3		PTO#4		DataFile	hOp - FS	PTO Gain [N]	Note
-	Day	TimeStamp	ID	Spectrum	Dir (°)	Tp	Hs	Gain	Damping c	Restoring Force k	Damping c	Restoring Force k	Damping c	Restoring Force k	Damping c	Restoring Force k	-	[m]		-
#1	19-Jan	4:18 PM	#X20-A	N/A	0°	N/A	N/A	1	NON	NON	NON	NON	NON	NON	NON	NON	001_Cork	2.06	NON	Lowered BasinFloor
#2			#X20-A	N/A	0°	N/A	N/A	1	NON	NON	NON	NON	NON	NON	NON	NON	002_Cork	2.06	NON	Submerge Device
#3			#X20-A	N/A	0°	N/A	N/A	1	NON	NON	NON	NON	NON	NON	NON	NON	003_Cork	2.06	NON	Sinusoidal Excitation
#4	22-Jan	4:03 PM	#X20-A	N/A	0°	N/A	N/A	1	1500	NON	1500	NON	1500	NON	1500	NON	004_Cork	-0.06	NON	Submerge, hold in position, reference position analysis
#5		4:53 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	005_Cork	-5.96	NON	Initial Position for run #6
#6		4:53 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	006_Cork	-5.96	NON	continuation of 5
#7		5:11 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	007_Cork	-3.12	NON	Baseline Working principle
#8		5:46 PM	#X20-A	IWS1	0°	1.63	0.117	1	1000	3250	1000	3250	1000	3250	1000	3250	008_Cork	-6.04	NON	IWS 1 10 meters submerged
#9	23-Jan	11:55 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	009_Cork	-5.96	NON	PID Loop Tuning
#10		12:06 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	010_Cork	-5.96	NON	PID Loop Tuning
#11		12:23 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	011_Cork	-5.96	NON	PID Loop Tuning
#12		12:27 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	012_Cork	-5.96	NON	PID Loop Tuning
#13		12:37 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	013_Cork	-5.96	NON	PID Loop Tuning
#14		2:10 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	014_Cork	-5.96	NON	PID Loop Tuning
#15			#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	015_Cork	-5.96	NON	Updated Drive
#16		4:18 PM	#X20-A	NON	0°	NON	NON	1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	FexcPPTO1	016_Cork	-5.96	20	Pink Noise Testcase (qualitative)
#17	24-Jan	3:02 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	017_Cork	-6.04	NON	Baseline
#18		3:30 PM	#X20-A	IWS1	0°	1.63	0.117	1	1000	3250	1000	3250	1000	3250	1000	3250	018_Cork	-6.04	NON	IWS with new PID Loop Tuning
#19		3:58 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	019_Cork	-4.64	75	System ID: Pink Noise PTO, No waves
#20		4:30 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	020_Cork	-4.80	112.5	System ID: Pink Noise PTO, No waves
#21		4:50 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	021_Cork	-4.80	112.5	System ID: Pink Noise PTO, No waves
#22		5:09 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	PPTO_In1_01	022_Cork	-4.82	131.5	System ID: Pink Noise PTO, No waves
#23		5:34 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	023_Cork	-3.22	NON	IWS 2
#24	25-Jan	10:57 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	024_Cork	-5.96	NON	Baseline
#25		-	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	025_Cork	-5.96	0.5	2Input SID - Gain 05 - Experiment1 - 10mDepth
#26		11:29 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	026_Cork	-6.00	0.5	2Input SID - Gain 05 - Experiment2 - 10mDepth
#27		12:01 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	027_Cork	-6.00	0.5	2Input SID - Gain 05 - Experiment3 - 10mDepth
#28		2:14 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	028_Cork	-5.90	0.5	2Input SID - Gain 05 - Experiment4 - 10mDepth
#29		3:22 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	029_Cork	-6.02	0.75	2Input SID - Gain 0.75 - Experiment1 - 10mDepth
#30		3:41 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	030_Cork	-6.02	0.75	2Input SID - Gain 0.75 - Experiment2 - 10mDepth
#31		4:12 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	031_Cork	-6.02	0.75	2Input SID - Gain 0.75 - Experiment3 - 10mDepth
#32		5:12 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	032_Cork	-2.94	0.5	2Input SID - Gain 0.75 - Experiment1 - 7.12 mDepth
#33		5:30 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	033_Cork	-2.94	0.5	2Input SID - Gain 0.75 - Experiment2 - 7.12 mDepth
#34		5:47 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	034_Cork	-2.94	0.5	2Input SID - Gain 0.75 - Experiment2 - 7.12 mDepth
#35	26-Jan	9:56 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	035_Cork	-6.04	NON	Baseline
#36		-	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	036_Cork	-6.16	0.05	2Input SID - Gain 05 - Experiment1 - 10mDepth
#37		10:48 AM	#X20-A	IWS1	0°	1.63	0.117	1	1000	3250	1000	3250	1000	3250	1000	3250	037_Cork	-2.84	NON	IWS1
#38		11:09 AM	#X20-A	IWS2	0°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	038_Cork	-2.84	NON	IWS2
#39		11:40 AM	#X20-A	IWS4	0°	2.84	0.103	1	750	2250	750	2250	750	2250	750	2250	039_Cork	-2.84	NON	IWS4
#40		12:03 PM	#X20-A	IWS1	0°	1.63	0.117	1	1000	2750	1000	2750	1000	2750	1000	2750	040_Cork	-2.84	NON	IWS1
#41		12:24 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	1750	1000	1750	1000	1750	1000	1750	041_Cork	-2.78	NON	IWS2
#42		1:49 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	1750	1000	1750	1000	1750	1000	1750	042_Cork	-2.76	NON	IWS2
#43		2:23 AM	#X20-A	IWS4	0°	2.84	0.103	1	750	1750	750	1750	750	1750	750	1750	043_Cork	-2.68	NON	IWS4
#44		2:50 AM	#X20-A	IWS1	0°	1.63	0.117	1	500	3250	500	3250	500	3250	500	3250	044_Cork	-2.66	NON	IWS1
#45		3:07 PM	#X20-A	IWS2	0°	2.2	0.132	1	500	2250	500	2250	500	2250	500	2250	045_Cork	-2.66	NON	IWS2
#46		3:37 PM	#X20-A	IWS4	0°	2.84	0.103	1	750	2250	750	2250	750	2250	750	2250	046_Cork	-2.66	NON	IWS4
#47		4:16 PM	#X20-A	IWS1	0°	2.84	0.103	1	1000	3250	1000	3250	1000	3250	1000	3250	047_Cork	-0.94	NON	IWS1
#48		4:44 PM	#X20-A	IWS1	0°	2.84	0.103	1	1000	3250	1000	3250	1000	3250	1000	3250	048_Cork	-5.02	NON	IWS1
#49		5:05 PM	#X20-A	IWS2	0°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	049_Cork	-5.02	NON	IWS2
#50		5:29 PM	#X20-A	IWS4	0°	2.84	0.103	1	750	2250	750	2250	750	2250	750	2250	050_Cork	-5.02	NON	IWS4

Table 1: Lir Deep Ocean Basin Runtable

#51	29-Jan	9:31 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	051_Cork	-6.00	NON	Swapped Mooring Loadcells due to failure
#52		5:34 PM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	052_Cork	-6.02	NON	Baseline
#53		5:54 PM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	053_Cork	-6.02	0.005 m	PinkPTO; Position Controlled; 5cm Amplitude
#54	30-Jan	9:51 AM	#X20-A	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	054_Cork	-5.90	NON	Baseline
#55		10:07 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	055_Cork	-5.90	0.05 m	Voltage limited to +/-1 V; Run was good, Desired Position a
#56		10:14 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	056_Cork	-5.90	0.05 m	NO DATA Acquisition started
#57		10:31 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	057_Cork	-6.04	0.025 m	2 Input SID - Gain 0.025m - Experiment 1 - 5m depth
#58		10:56 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	058_Cork	-6.14	0.025 m	2 Input SID - Gain 0.025m - Experiment 2 - 5m depth
#59		11:20 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	059_Cork	-6.06	0.04 m	2 Input SID - Gain 0.04 m - Experiment 1 - 5m depth
#60		11:41 AM	#X20-A	NON	0°	NON	NON	1	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	060_Cork	-6.10	0.04 m	2 Input SID - Gain 0.04 m - Experiment 2 - 5m depth
#61		12:50 PM	#X20-A	PinkWaves1	0°	-	33%	0.33	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	061_Cork	-6.10	0.025 m	3 Input SID - Gain 0.025 m - Experiment 1 - 5 m depth
#62		1:57 PM	#X20-A	PinkWaves2	0°	-	33%	0.33	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	062_Cork	-5.94	0.025 m	3 Input SID - Gain 0.025 m - Experiment 2 - 5 m depth
#63		2:26 PM	#X20-A	PinkWaves3	0°	-	33%	0.33	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	063_Cork	-6.00	0.025 m	3 Input SID - Gain 0.025 m - Experiment 2 - 5 m depth
#64		2:59 PM	#X20-A	IWS6	0°	3.69	0.163	1	500	1000	500	1000	500	1000	500	1000	064_Cork	-6.80	NON	IWS6
#65		3:19 PM	#X20-A	IWS6	0°	3.69	0.163	1	500	1000	500	1000	500	1000	500	1000	065_Cork	-4.80	NON	IWS6
#66		3:39 PM	#X20-A	IWS5	0°	3.41	0.19272	0.66	1000	2000	1000	2000	1000	2000	1000	2000	066_Cork	-9.82	NON	IWS 5, Closed Hatch, 66%
#67		4:16 PM	#X20-A	CWS1	0°	1.25	0.063	1	500	3000	3000	3000	3000	3000	3000	3000	067_Cork	-2.78	NON	WETS CWS1
#68		4:45 PM	#X20-A	CWS1	0°	1.25	0.063	1	500	3000	3000	3000	3000	3000	3000	3000	068_Cork	-1.70	NON	WETS CWS1
#69		5:12 PM	#X20-A	CWS3	0°	1.92	0.175	1	1000	2750	2750	2750	2750	2750	2750	2750	069_Cork	-5.00	NON	SETS Bulls Eye
#70	31-Jan	12:07 PM	#X20-P	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	070_Cork	-5.96	NON	Baseline
#71		1:30 PM	#X20-P	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	071_Cork	-6.02	NON	Baseline
#72		1:46 PM	#X20-P	M3S80	0°	2.0	0.08	1	2000	2000	2000	2000	2000	2000	2000	2000	072_Cork	-6.02	NON	Baseline
#73		2:03 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	073_Cork	-6.90	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment1
#74		2:36 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	074_Cork	-6.90	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment2
#75		2:36 PM	#X20-P	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	075_Cork	-6.98	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment1
#76		3:20 PM	#X20-P	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	076_Cork	-6.98	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment2
#77		3:45 PM	#X20-P	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	077_Cork	-6.96	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment3
#78		4:11 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	078_Cork	-7.04	56.5N	2 Input SID - MISO - Gain 56.5N - Experiment1
#79		4:37 PM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	079_Cork	-6.96	56.5N	2 Input SID - MISO - Gain 56.5N - Experiment2
#80		4:56 PM	#X20-P	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	080_Cork	-7.02	37.5N	3 Input SID - MISO - Gain 37.5N - Wave Gain Higher - Exper
#81		5:13 PM	#X20-P	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	081_Cork	-6.96	37.5N	3 Input SID - MISO - Gain 37.5N - Wave Gain Higher - Exper
#82		5:37 PM	#X20-P	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	082_Cork	-7.02	37.5N	3 Input SID - MISO - Gain 37.5N - Wave Gain Higher - Exper
#83	1-Feb	10:18 AM	#X20-P	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	083_Cork	-5.96	NON	Baseline
#84		10:28 AM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	084_Cork	-4.04	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment1 - 4m depth
#85		10:28 AM	#X20-P	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	085_Cork	-4.02	37.5N	2 Input SID - MISO - Gain 37.5N - Experiment2 - 4m depth
#86		11:07 AM	#X20-P	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	086_Cork	-4.02	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment1
#87		11:30 AM	#X20-P	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	087_Cork	-4.04	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment2
#88		11:46 AM	#X20-P	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	088_Cork	-3.98	37.5N	3 Input SID - MISO - Gain 37.5N - Experiment3
#89		12:15 PM	#X20-P	IWS2	20°	1.7	0.05	1	1000	2250	1000	2250	1000	2250	1000	2250	089_Cork	-5.02	NON	Angeled Wave Case IWS 2 (equivalent to 70 Degree and 20
#90		1:30 AM	#X20-P	CWS3	0°	1.92	0.175	1	1000	2750	2750	2750	2750	2750	2750	2750	090_Cork	-5.02	NON	SETS Bulls Eye
#91		1:54 PM	#X20-P	CWS3	0°	1.92	0.175	1	1000	2750	2750	2750	2750	2750	2750	2750	091_Cork	-5.06	NON	SETS Bulls Eye
#92		3:43 PM	#X20-PS	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	092_Cork	-6.08	NON	Baseline Open Hatch
#93		3:57 PM	#X20-PS	NON	0°	NON	NON	0	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	093_Cork	-6.90	25N	2 Input SID - MISO - Gain 25N - Experiment1 - 7m depth
#94		4:15 PM	#X20-PS	NON	0°	NON	NON	0	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	094_Cork	-6.98	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#95		4:35 PM	#X20-PS	PinkWaves1	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	PPTO_In2_01	095_Cork	-7.04	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#96		4:53 PM	#X20-PS	PinkWaves2	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	PPTO_In2_02	096_Cork	-7.04	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#97		5:15 PM	#X20-PS	PinkWaves3	0°	NON	Peak: 15cm 6 of 15		PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	PPTO_In2_03	097_Cork	-7.04	25N	2 Input SID - MISO - Gain 25N - Experiment2 - 7m depth
#98		5:40 PM	#X20-PS	IWS3	0°	2.58	0.268	1	1000	3500	1000	3500	1000	3500	1000	3500	098_Cork	-10.06	NON	IWS3, Open Hatch, Survival Mode, Detuned PTO
#99	2-Feb	9:46 AM	#X20-PS	M2S80	0°	1.7	0.05	1	2000	2000	2000	2000	2000	2000	2000	2000	099_Cork	-6.00	NON	Baseline
#100		9:55 AM	#X20-PS	IWS2	20°	2.2	0.132	1	1000	2250	1000	2250	1000	2250	1000	2250	100_Cork	-5.00	NON	IWS2 Comparison Hatch open/close 20 Deg
#101		10:17 AM	#X20-PS	IWS5	0°	3.41	0.292	1	1000	3000	1000	3000	1000	3000	1000	3000	101_Cork	-6.04	NON	IWS 5, Open Hatch, Full gain
#102		10:43 AM	#X20-PS	M3S80	0°	2.0	0.08	1	see pattern	see pattern	see pattern	see pattern	see pattern	see pattern	see pattern	see pattern	102_Cork	-5.02	NON	PTO Tuning
#103		11:51 AM	#X30-S	M3S80	0°	1.370	0.0365	1	725	888	725	888	725	888	725	888	103_Cork	-6	NON	Baseline Case 1:30
#104		12:04 AM	#X30-S	Ex2	0°	2.2329	0.39	1	360	1500	360	1500	360	1500	360	1500	104_Cork	-10	NON	Survival Case, 25% Hatch opening, 10 meters hop
#105		12:21 PM	#X30-S	Ex2	0°	2.2329	0.39	1	360	1500	360	1500	360	1500	360	1500	105_Cork	-15	NON	Survival Case, 25% Hatch opening, 15 meters hop
#106		2:05 PM	#X30-S	Ex2	0°	2.2329	0.39	1	360	1500	360	1500	360	1500	360	1500	106_Cork	-10	NON	Survival Case, 25% Hatch opening, 10 meters hop, MinLineT
#107		2:13 PM	#X30-S	IWS2	0°	1.7963	0.088	1	360	1000	360	1000	360	1000	360	1000	107_Cork	0	NON	IWS Case 2 , 25% Hatch opening, Device on Surface, MinLin
#108		2:30 PM	#X30-S	IWS2	0°	1.7963	0.088	1	360	1000	360	1000	360	1000	360	1000	108_Cork	-4	NON	IWS Case 2 , 25% Hatch opening, -4m hop, PTO 2 slack,
#109		2:41 PM	#X30-S	Waves continued to run on purpose				1	360	1000	360	1000	360	1000	360	1000	108_Cork	-4	NON	IWS Case 2 , 25% Hatch opening, -4m hop, PTO 2 slack,

2. Test Objectives

CalWave experimentally tested a 1:20 scaled prototype and a 1:30 scaled prototype of their single body wave energy conversion technology for a total duration of 15 working days at the LiR National Test Facility.

For nearly all of the below mentioned test objectives the 1:20 scaled prototype was used, resulting in a smaller signal to noise ratio and a more representative scale for viscous effects. Whenever the capabilities of the basin/wave maker are reached (e.g. survivability tests) the device was swapped to a 1:30 scale device.

The following test objectives were performed in the Lir DOB basin:

2.1 PTO Integration and Controllability (Included in this report)

- Anticipated Scale: 1:20 Scale
- Test PTO behavior and stability for a static WEC setup in the basin. The capability of the PTO to winch mooring/PTO line in and out, to submerge the absorber body and bring and holt it at its static equilibrium position and to effectively change the operating depth hOp is tested.
- For a static setup with pretension in the mooring/PTO tether lines (entirely submerged absorber body) the behavior in case of a power loss/PTO software failure is tested to minimize risks/threads of malfunctions during test cases with waves running.
- For a static setup, the behavior of the wrapping of the PTO tether around the PTO drum is tested. Although the line should wrap in a single layer any risk and threats from deviation of this is assessed before running test cases with waves running.
- For a static setup or for a single PTO setup without device connected to the PTO, the PTO is disturbed with a single push/pull. Although the PTO should not get excited in a resonant behavior and rather converge to its set equilibrium position, these tests act as a risk mitigation test and validate a stable PTO behavior. Potential tuning of software settings will accommodate these tests.
- For a static setup or a single PTO setup without the device connected to the PTO the PTO characteristic values such as damping or restoring force coefficient are changed on-line. Accuracy in setting these device parameters should be evaluated and response of the PTO closed control loop assessed for stability and response accuracy.
- For a static setup or a single PTO setup without the device connected to the PTO the PTO function of maintaining a minimum line tension is tested.

2.2 Basic Working Principle Verification (Included in this report)

- Anticipated Scale: 1:20 Scale

- For hydrostatic tests and validation of total device buoyancy, respectively pretension in mooring tethers the device in a specified configuration is submerged and tether forces are measured. The operating depth is changed using all four PTO units. Balancing of the tether forces and correction of the absorber level is tested. These tests verify that a specific initial equilibrium setup can be obtained for each wave case.

- Basic working principles of the combined PTO/device setup is tested using small monochromatic wave excitation with small wave heights and mild periods. PTO settings are chosen to be in a mean range of damping / restoring force coefficients. General device behavior is checked, and it is ensured that all PTO units work in the same way; the mooring pulleys behave in the desired way and no obvious threats or risks are identified.

- For a full setup of the absorber body connected to all PTO units the device stability is checked by exciting the absorber body (e.g. push or pull) while no waves are running.

2.3 System Identification Tests (SID) (Subject to Task 2.2 Holistic Control Dev.)

- Anticipated Scale: 1:20 Scale

- Estimation of radiation Frequency Response Function (FRF) using oscillation tests

- Forced oscillation experiments are run in calm water (wave damping mode on wave makers) to obtain a model of the intrinsic device impedance. A pink noise (Inverse frequency signal) is used to excite all PTO units either in phase (1 DOF) or with different uncorrelated pink noise signals (3 or full 6 DOF). Although, the PTO units cannot excite the absorber body in both directions (it is not possible to push on a tether), the positive buoyancy force can effectively be used to "excite" the absorber in the upwards motion. Hence, it must be ensured that the tether tension in the time realization fed to the PTO units never exceeds the PTO pretension.

- For identification of wave excitation characteristics of the device, forced oscillation experiments in presence of waves will be conducted. PTO forces, absorber velocities and wave elevation are measured. Additionally, hull pressure on the absorber body will be measured, allowing for correlation of device behavior and hull pressure fur further system identification.

2.4 Preliminary Performance Evaluation (Included in this report)

- Anticipated Scale: 1:20 Scale

- To compare the device performance in the Wave Energy Prize Metric using the ACE metric, for baseline performance evaluation 6 irregular, 0 Degree incident wave cases are tested. The six wave cases follow exactly the WEP metric and results obtained from these tests can be directly used to compare performance against the CalWave concept used during the 1:20 scale US Wave Energy Prize tests. Tests are performed with WEC/PTO target parameters from numerical simulations and deviations from these to check for optimality of parameters.

- To obtain a first estimate of device performance at specific target locations (e.g. Hawaii) the device's performance in energy extraction will be assessed for specific irregular sea stated.

2.5 WEC Survivability Testing (Subject to Task 2.2 Holistic Control Dev.)

- Anticipated Scale: 1:30 Scale

- To assess the device behavior in severe sea and in extreme wave cases, the 1:30 scale device is used with survival mode enabled.

- To define upper limits of survival cases, the 100-year return wave contour plot for the SETS test side in Oregon, US is used. Multiple cases are defined on that 100-year return contour and wave cases in the basin are tuned to reproduce these sea states until limits of the wave maker/basin are reached.

3. Wave Cases & Calibration

To facilitate a realistic scaled wave environment for the various test objectives, different monochromatic, operating irregular waves states (IWS and CWS), as well as extreme waves were defined prior to testing. Additionally, for System Identification purposes pink noise signals were derived as a time signal for the wavemakers.

To avoid damage of the prototype/setup, for some of the extreme wave and pink noise cases during testing, the wavemaker gain is increased stepwise until the targeted magnitude of the spectrum is reached.

3.1 Monochromatic Waves (MWS)

Monochromatic waves were solely used for basic working principle verification. The M2S80 case was used as a reoccurring baseline case to test the experimental setup in the same device configuration at the beginning of every testing day to ensure consistency of device settings and the physical setup.

Table 2: Monochromatic Waves for basic working principle validation. M2S80 was used as a daily reoccurring baseline case.

Monochromatic Waves - Ms80- Parameter Assessment - 1:20 Scale					
#	Monochromatic Waves	Period	wave height	inverse steepness	Incident Direction
	k	T	H	S^{-1}	θ
-	-	[s]	[m]	[--]	[deg]
1	M1S80	1.3	0.035	80	0
2	M2S80	1.7	0.05	80	0
3	M3S80	2.0	0.08	80	0
4	M4S80	2.3	0.11	80	0
5	M5S80	2.7	0.14	80	0
6	M6S80	3.0	0.17	80	0
7	M7S80	3.4	0.21	80	0
Monochromatic Waves - Ms40- Parameter Assessment					
#	Index	Period	wave height	inverse steepness	Incident Direction
	k	T	H	S^{-1}	θ
-		[s]	[m]	[--]	[deg]
8	M1s40	1.3	0.07	40	0
9	M2s40	1.7	0.11	40	0
10	M3s40	2.0	0.16	40	0
11	M4s40	2.3	0.21	40	0
12	M5s40	2.7	0.28	40	0

3.2 Irregular Wave cases (IWS) & Custom Irregular Wave Cases (CWS)

IWS cases were used for baseline performance assessment (ACE) of the device. The wave cases were directly taken from the Wave Energy Prize rules. However, for most of the cases 0 Degree wave heading was used. Additionally, custom irregular wave cases (CWS) were used for a better interpolation across specific JPD diagrams (e.g. Hawaii, or SETS).

Table 3: Irregular Wave Cases (IWS) and Custom Irregular Wave Cases (CWS)

TYPE	#	Tp [s]	Hs [m]	Gamma	Dir	Spread	Te [s]
IWS (Brettschneider)	1	1.63	0.117	1	0	INF	1.4
	2	2.2	0.132	1	0	INF	1.89
	3	2.58	0.268	1	0	INF	2.22
	4	2.84	0.103	1	0	INF	2.44
	5	3.41	0.292	1	0	INF	2.93
	6	3.69	0.163	1	0	INF	3.17
CWS (Custom Wave States)	7	1.25	0.063	1	0	INF	1.1
	8	1.63	0.075	1	0	INF	1.4
	9	1.92	0.175	1	0	INF	1.6
	10	2.3	0.225	1	0	INF	2

For calculation of relative performance (CWR) of the device the incident wave power generated in the Lir basin is of importance. In fact, although the wave maker at the basin were calibrated to match the power spectral density (see Appendix) as good as possible, incident wave power that occurred in the basin deviated from the theoretical calculated power of an ideal Brettschneider spectrum.

The following Table 4 lists the average wave power calculated from the theoretical Brettschneider spectrum, the actual average wave power calculated using an FFT of the wave elevation from 5 wave gages and the relative error between them:

Table 4: Irregular Wave Cases - Incident Wave Power in the Lir Basin

Lir Post Processing - Irregular Wave Cases - Incident Wave Power at Lir Basin			
Case	**Theoretical Wave Power from Brettschneider Spectrum [W/m]**	**Lir Basin Wave Power from FFT of Wave Sensors [W/m]**	**Error [%] (Negative value = less energy in basin wave field)**
IWS 1	9.1391	8.2555	-9.67%
IWS 2	15.7047	14.9779	-4.63%
IWS 3	75.9217	74.1199	-2.37%
IWS 4	12.3446	11.9593	-3.12%
IWS 5	119.1264	114.446	-3.93%
IWS 6	40.169	39.7895	-0.94%
CWS 1	2.0301	1.8878	-7.01%
CWS 2	3.7554	3.4998	-6.81%

CWS 3	24.0882	22.4884	-6.64%
CWS 4	47.7044	45.6876	-4.23%

4. Data Processing and Analysis

4.1 Data Quality

Data quality assurance will be provided on site with first order post processing after each test. Data collection will start before waves are started and continue for at least 1 minute once wave generation stops. This ensures that data captures initial setup condition (e.g. mooring pretension from hydrostatic buoyancy) and transient ramp-up/down effects).

"Raw" data from all sensors are logged including Sensor ID, timestamp, units, and measured values and saved in the LabView "TDMS" format. Sensors measured with other DAQ systems than the NI hardware are saved in an appropriate file format (e.g. text or CSV files).

Motion Tracking Data (3 rotational, 3 translational DOFs) are stored in MATHWORKS Matlab .mat files. Wave Elevation is stored in .txt files with one column for each of the introduced wave gages.

4.2 Synchronization and Measurement procedure

Synchronization of data is straight forward with all data acquired with sensors running on NI hardware / via the main LabView DAQ software as sampling follows the cRIO hardware clock. Synchronization of signals from LiR (e.g. Wave Probes, Motion Tracking) is facilitated using an analog trigger signal.

Measurements are started in the following order:

1. Motion tracking and recording is started
2. Wave probes measuring is started
3. All NI Labview data acquisition is started
4. Wavemaker is started; This triggers a signal
5. Absolute timestamp for all NI Labview DAQ is reset to 0 for synchronization
6. Wave Case is running and waves stop after a specified time
7. Motion tracking recording is stopped manually; Wave probe recording is stopped manually
8. NI Labview DAQ is stopped manually

5. Summary: PTO Integration And Controllability

The prototype PTO units are designed to obtain the largest degree of flexibility in setting PTO parameter, as well as to be able to execute any kind of desired force tracking. To achieve this, an entire electric prototype PTO scheme was chosen. The electric PTO can effectively be used to achieve any kind of PTO behavior and most important for this testing campaign, allows to set any restoring force coefficient k and damping coefficient c with a very high precision. The settings can be changed "on the fly" and no hardware changes are needed. In fact, any kind of PTO behavior based on the feedback measurements, PTO/Tether force, PTO velocity and displacement, can be implemented. Additionally, the PTO can be controlled in such a way, that the device can be submerged to a specific operating depth precisely.

A scheme of the force feedback closed PTO control loop is shown in Figure 2, exemplary shown for a linear spring-damper PTO scheme with an additional F0 offset which respresents the necessary pre-tension of the PTO unit due to the positively buoyant absorber body.

As shown, the PTO control includes a surveilance, if the PTO/Tether tension reaches a certain minimum line tension, respectively a maximum line tension, representative of a maximum generator torque. If one of these max/min tension limits is reached, the PTO control effectively ensures that the tension does not drop below / shoot above the specified value by increasing/decreasing the PTO velocity. This feature is essential to ensure that the PTO tethers never go slack and is envisioned to be implemented in a similar way in a larger scale PTO unit.

For system identification tests it was desired to feed the PTO units with a pink noise signal which was achieved by cutting open the closed loop and feeding a force set point signal representing pink noise excitation.

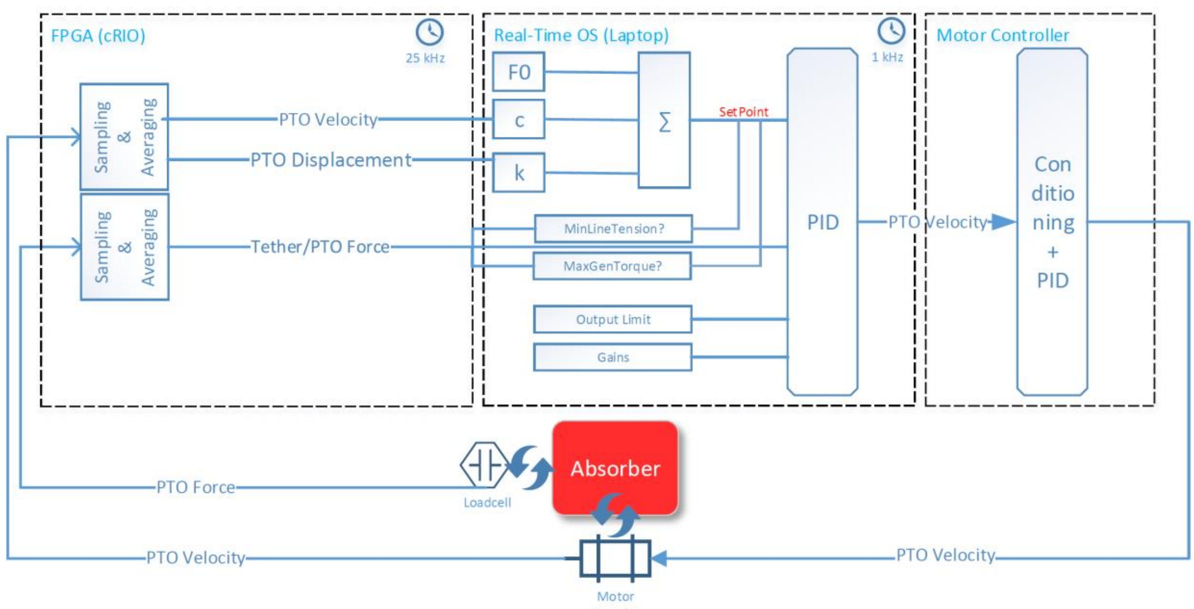


Figure 2: Simple force feedback control of the motor used for tracking any desired set point signal (here, simple linear spring-damper model).

The PID controller in the closed PTO control loop as well as the PID controller inside the motor controller were tuned before the experiments. However, potential re-tuning of the units/control once the prototype is installed in the tank is possible/might be required to achieve a quick and stable response of the PTO units.

The achieved force set point tracking capabilities shows an overall very good behavior. For a random irregular excitation (displacement) of the PTO the force set point and actual tracking signal is compared in Figure 3.

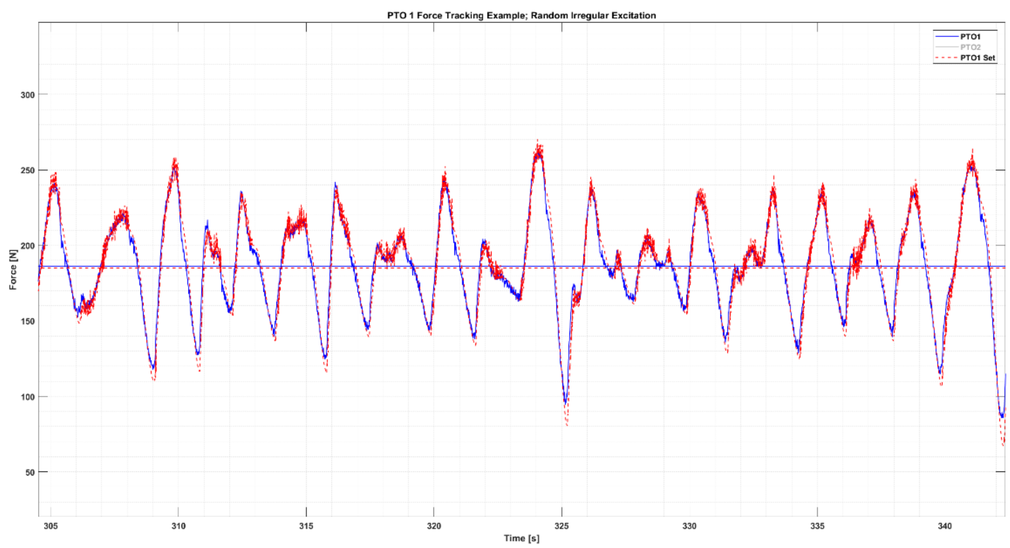


Figure 3: Exemplary Force set point and tracking signal showing a good set point tracking capability of the PTO units. Here, the PTO unit was randomly excited with an irregular signal with a common period and magnitude

A huge advantage of the setup is, that due to the location of the PTO/Tether loadcells directly at the swivel on the absorber body, the closed loop control acounts for any kind of friction in the system. That being said, friction on the PTO winch, friction at the PTO tether pulleys mounted on the basin floor etc are compensated for, to strictly achieve the desired PTO behavior right at the PTO/Tether connection point on the absorber body.

Figure 4 shows the PTO damping force scattered over the PTO velocity measured for a random irregular excitation of the PTO unit. A specific constant damping coefficient (here, 1000 Ns/m) was chosen.

Although the plot show a slight hysteresis around the set point line , the fit of the average actual damping achieved with the PTO units is in very good agreement with the set damping coefficient.

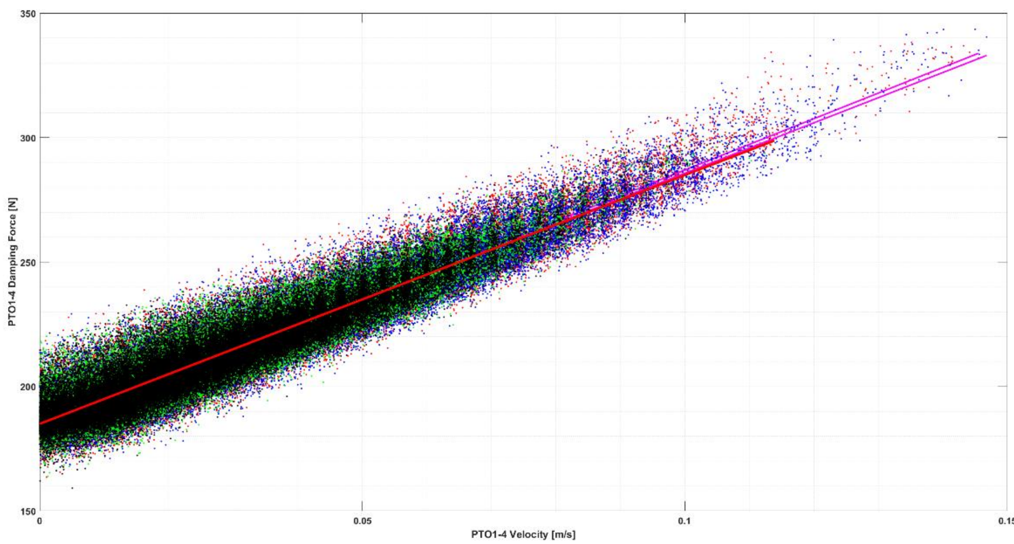


Figure 4: PTO damper force over PTO velocity (damping correlation) plotted for one PTO units which was randomly excited with an irregular pattern of common period and magnitude. The desired force-velocity correlation (damping coefficient of 1000 Ns/m) in red can be very well tracked with the PTO control/system.

6. SUMMARY: BASIC WORKING PRINCIPLE VERIFICATION

The M2S80 monochromatic wave case was used to validate that the system setup, respectively the absorber connected to all four PTO units installed in the wave basin is working. Moreover, the M2S80 case at an operating depth of hOp ~ 0.3m was used as a reoccurring baseline validation case.

This monochromatic wave case was run as the very first wave case on every testing day to validate consistency of the experimental setup. Moreover, the case was run every time a significant modification to the experimental setup was made. The following figures show an overview of one of the baseline monochromatic wave run.

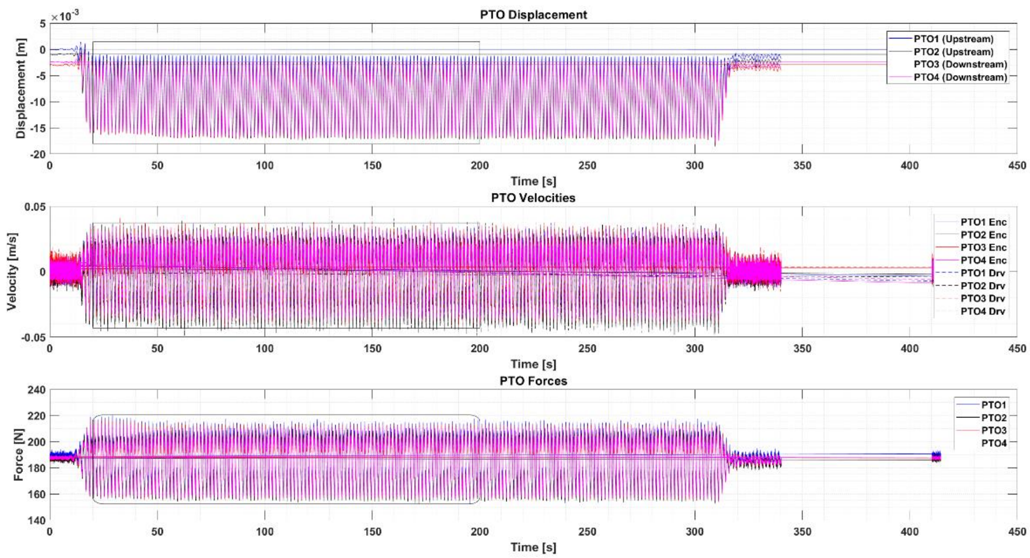


Figure 5: PTO Displacement, Velocities, and Forces for a monochromatic incident wave (M2S80).

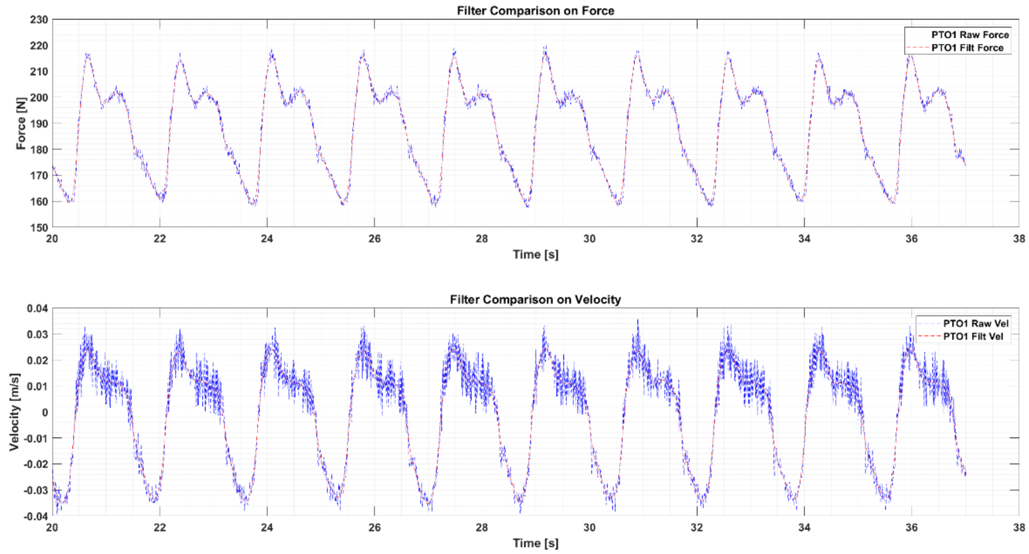


Figure 6: Comparison of raw signal and filtered signal used to smoothen the signal for further post processing for PTO unit 1. Top plot: Force filter; Bottom plot: Velocity filter (M2S80).

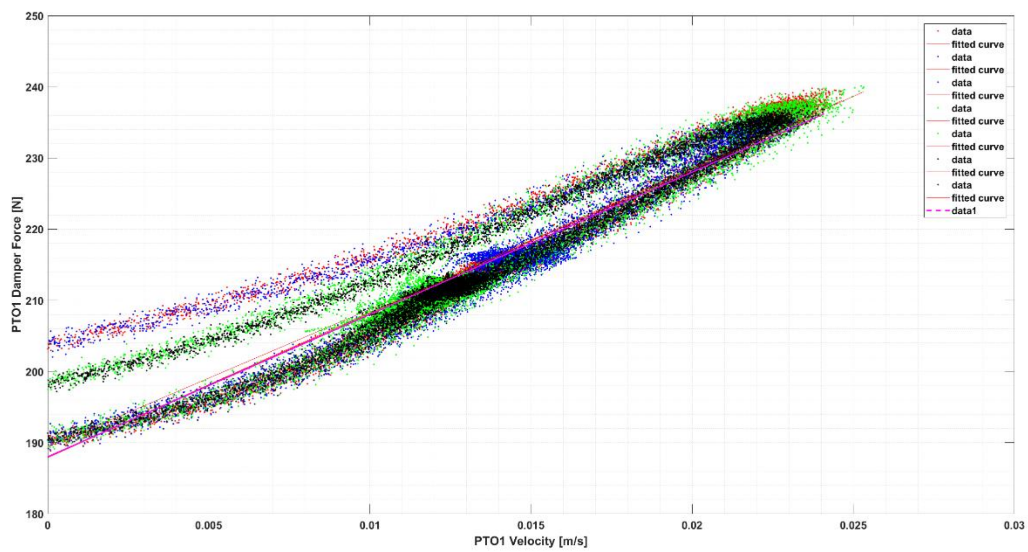


Figure 7: PTO Force over PTO Velocity including a linear fit to derive the experimentally achieved damping coefficient (M2S80).

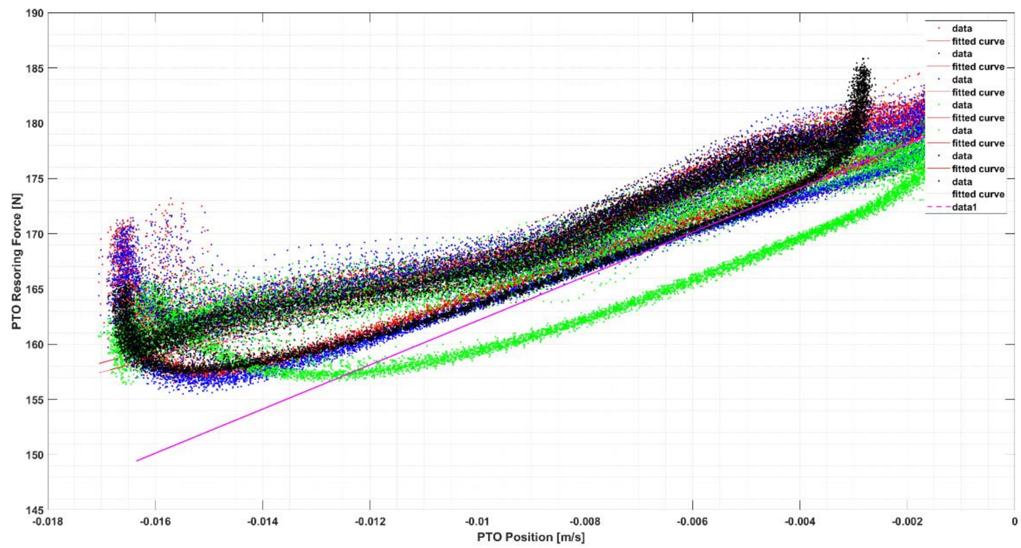


Figure 8: PTO restoring force over PTO velocity including linear fits to derive the experimentally achieved restoring force coefficient (M2S80).

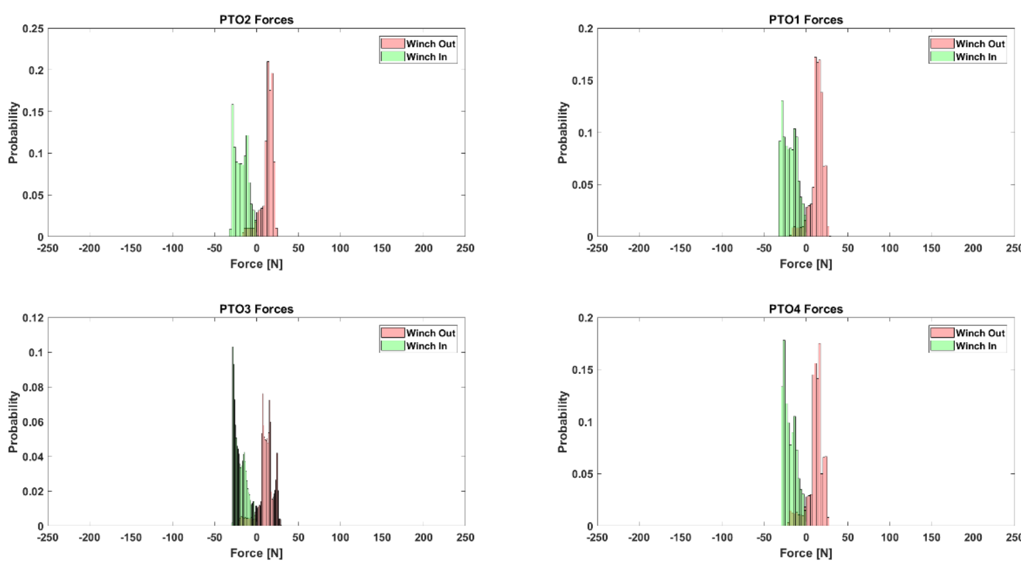


Figure 9: Histogram of dynamic (static buoyancy pre-tension removed) PTO forces for PTO1 - PTO4. The forces are separated in forces occuring during the "winching in" and "winching out" cycle (M2S80).

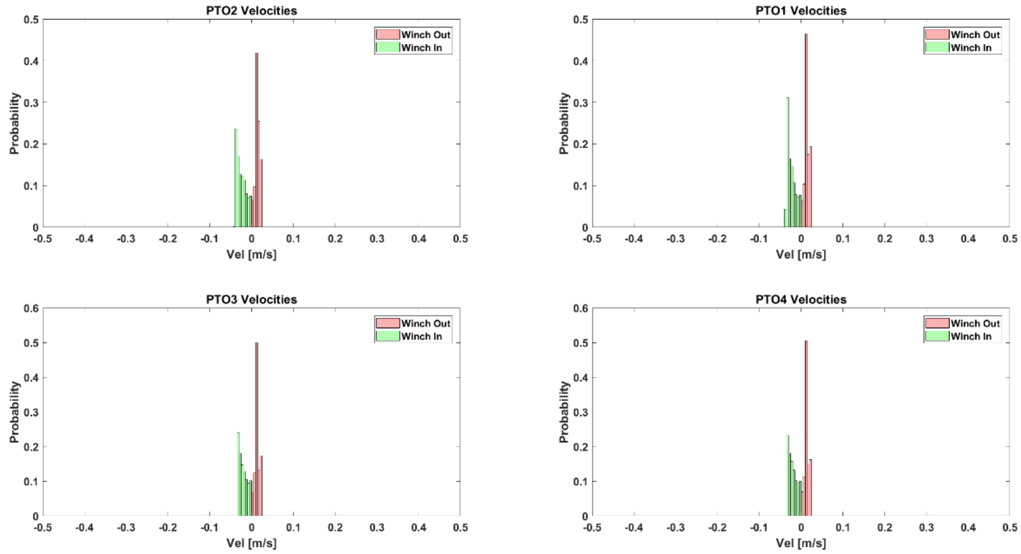


Figure 10: Histogram of PTO velocities for PTO1 - PTO4. The velocities are separated in velocities occurring during the "winching in" and "winching out" cycle (M2S80).

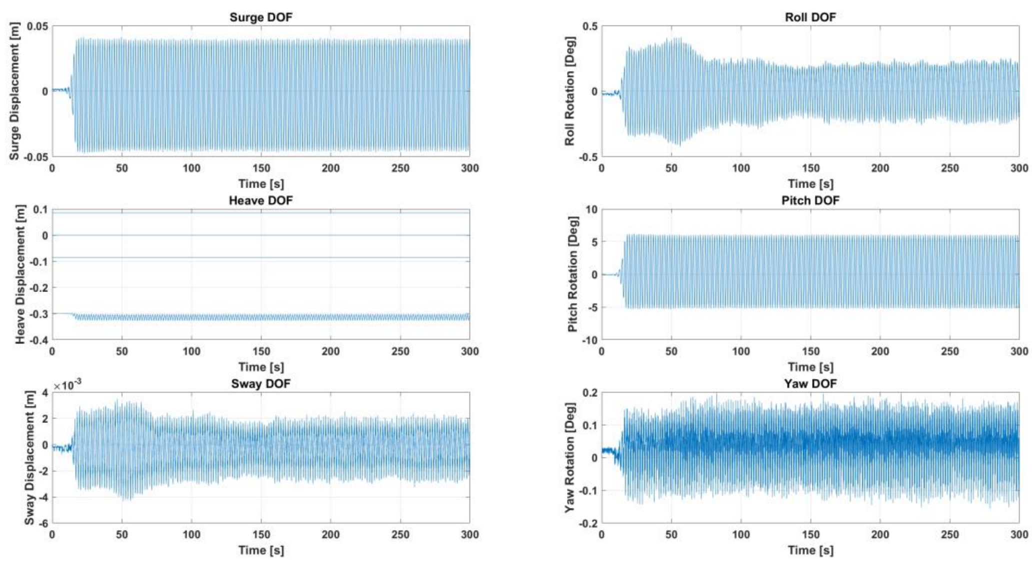


Figure 11: Overview of the absorber motion during a monochromatic wave run. The data validate the assumption, that the absorer is excited primarily in Heave, Surge, and Pitch. (M2S80)

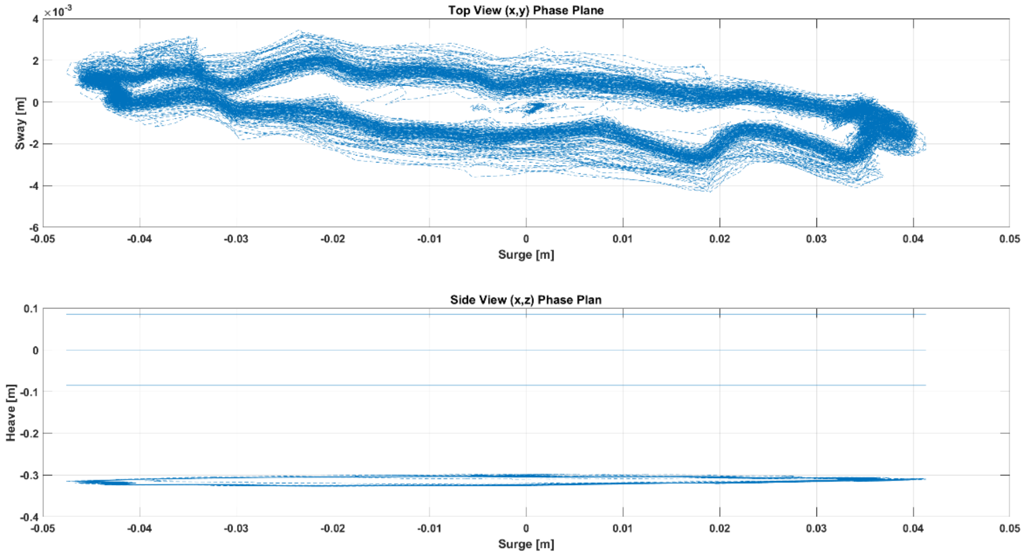


Figure 12: Phase plane plots derived from the absorber motion. Top View phase plane indicates a minor motion in Sway. Bottom View phase plane indicates strong damping in heave DOF und smaller constrain in Surge DOF (M2S80).

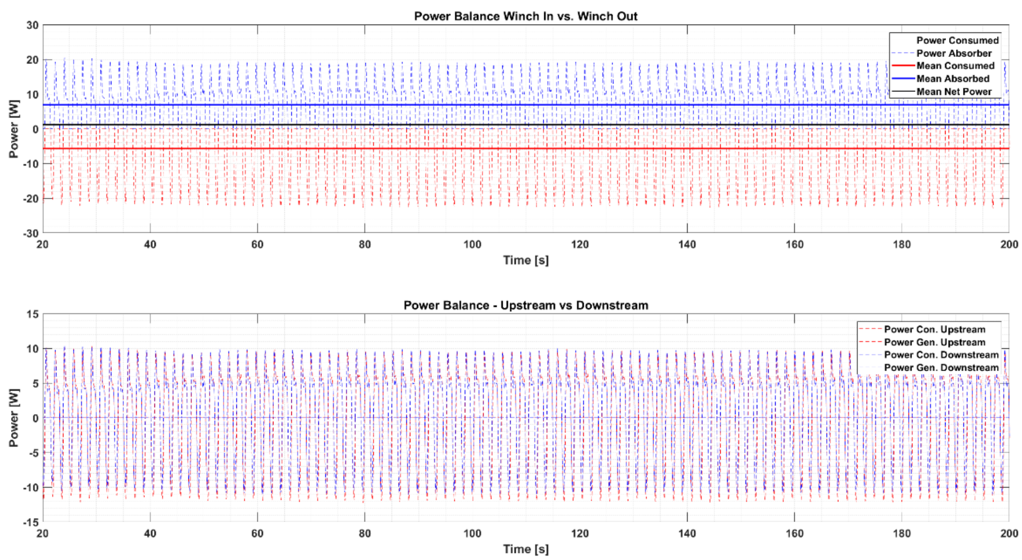


Figure 13: Top plot: Power balance plots for "winch in" vs. "winch out" cycle. Bottom plot: Comparison of power generation/absorption for upstream PTO units vs. downstream PTO units. (M2S80)

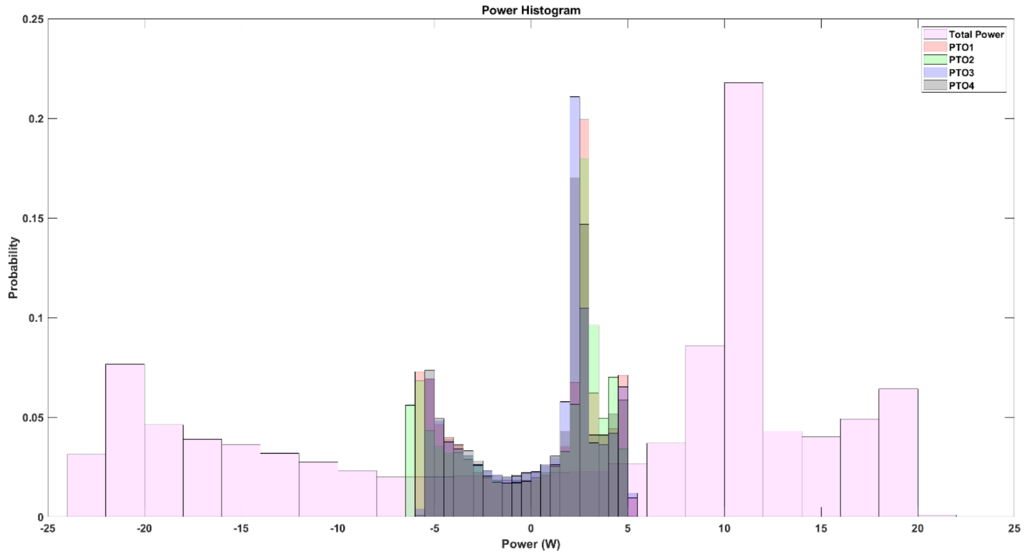


Figure 14: Typical power histogram showing the occurance of different power levels for each PTO unit and for the entire device. (M2S80)

Table 5 shows a summary of monochromatic wave cases run during the prototype testing. The overview shows how consistent the experimental setup was, e.g. when comparing PTO or device power production.

7. Summary: System Identification

Post processing and results of System Identification tests is treated separately under Task 2.2. Holistic Control Development.

Table 5: Monochromatic Wave Case Overview, Reoccurring Baseline Runs

Lir Post Processing - Mono Wave Cases - Reoccuring Baseline Run Overview

Experiment			Wave Information					Device Config		PTO Config				Performance										Misc
Mono Case	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]	Wave Tp [s]	Wave Hs [m]	Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Net Power Up:Downstream	Av. Consumed [W]	Av. Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
2	35	#X20-A	1.000	0.000	1.700	0.050	4.068	-0.302	0%	2000	1463	2000	2040	0.941	1.397	0.674	-7.621	9.959	2.338	0.575	83636.852	11.492	**57.5%**	
2	54	#X20-A	1.000	0.000	1.700	0.050	4.068	-0.295	0%	2000	1450	2000	1984	0.934	1.472	0.634	-7.892	10.297	2.406	0.591	86063.266	11.825	**59.1%**	
2	70	#X20-A	1.000	0.000	1.700	0.050	4.068	-0.298	0%	2000	1467	2000	2039	0.881	1.392	0.633	-7.399	9.672	2.273	0.559	81336.897	11.176	**55.9%**	
2	71	#X20-A	1.000	0.000	1.700	0.050	4.068	-0.301	0%	2000	1458	2000	2039	0.870	1.409	0.618	-7.425	9.704	2.279	0.560	81549.083	11.205	**56.0%**	
2	83	#X20-P	1.000	0.000	1.700	0.050	4.068	-0.298	0%	2000	1462	2000	2023	0.942	1.403	0.671	-7.473	9.818	2.345	0.576	83890.547	11.527	**57.6%**	
2	92	#X20-PS	1.000	0.000	1.700	0.050	4.068	-0.304	20%	2000.000	1424.606	2000.000	2039.456	0.274	0.914	0.300	-5.637	6.825	1.188	0.292	42517.463	5.842	**29.2%**	ull Load Reductio
2	99	#X20-PS	1.000	0.000	1.700	0.050	4.068	-0.300	20%	2000.000	1415.592	2000.000	2032.421	0.196	0.984	0.199	-5.707	6.888	1.181	0.290	42238.789	5.804	**29.0%**	ull Load Reductio
MonoCase	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]	Wave Tp [s]	Wave Hs [m]	Power [W/m]	FS hOp [m]	Config [%]	PTO1.k [N/m]	t PTO.k [N/m]	PTO.c [Ns/m]	t PTO.c [Ns/m]	Power Upstrea	Power Downstr	Power Up:Dow	Power Consum	Power Absorbe	Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
3	72	#X20-P	1	0	2	0.08	12.2532	-0.301	0	2000	1573.244	2000	1954.2233	2.02115	1.9131	1.05648	-9.5782	13.5124	3.93426	0.32108	140756.2	6.42162	32.1%	

Table 6: Overview of tested IWS wave cases.

Lir Post Processing - Irregular Wave Cases - Run Overview

Experiment			Wave Information																					
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]	Wave Tp [s]	Wave Hs [m]	Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Net Power Up:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
1	37	#X20-A	1	0	1.63	0.117	8.2555	-0.142	0	3250	2718.748715	1000	1087.6	1.252992657	1.478111181	84.8%	-9.124	11.855	2.731	0.331	97710.941	6.61645	33.08%	
1	40	#X20-A	1	0	1.63	0.117	8.2555	-0.142	0	2750	2224.508723	1000	1085.3	1.343117201	1.417515642	94.8%	-9.297	12.058	2.761	0.334	98767.403	6.68798	33.44%	
1	44	#X20-A	1	0	1.63	0.117	8.2555	-0.133	0	3250	2683.619705	500	592.1	0.86463882	1.11444398	0.775847719	-10.421	12.401	1.979	0.24	70805.819	4.79458	23.97%	
1	47	#X20-A	1	0	1.63	0.117	8.2555	-0.133	0	3250	2663.686506	1000	1039.1	0.912342276	0.722580436	1.262616908	-7.305	8.940	1.635	0.198	58492.773	3.96081	19.80%	
1	49	#X20-A	1	0	1.63	0.117	8.2555	-0.133	0	3250	2784.050631	1000	1094.0	1.296716607	1.455679883	0.890797917	-9.473	12.225	2.752	0.333	98472.730	6.66803	33.34%	**Used for ACE, NonOpt**
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
2	38	#X20-A	1	0	2.2	0.132	14.9779	-0.142	0	2250	1866.655661	1000	1047.8	2.104910987	1.856160281	1.134013591	-11.550	15.511	3.961	0.264	141715.594	5.28922	26.45%	
2	41	#X20-A	1	0	2.2	0.132	14.9779	-0.139	0	1750	1375.90509	1000	1052.0	1.982086618	1.684641727	1.176562699	-11.193	14.859	3.667	0.245	131184.861	4.89618	24.48%	
2	45	#X20-A	1	0	2.2	0.132	14.9779	-0.133	0	2250	1847.443272	500	557.2	1.421845144	1.38707505	1.025067204	-13.401	16.210	2.809	0.188	100494.984	3.75075	18.75%	
2	49	#X20-A	1	0	2.2	0.132	14.9779	-0.251	0	2250	1882.526172	1000	1043.9	2.168449937	1.82151781	1.190463209	-12.004	15.994	3.990	0.266	142749.426	5.32781	26.64%	**Used for ACE, NonOpt**
2	89	#X20-A	1	-20	2.2	0.132	14.9779	-0.251	0	2250	1925.623677	1000	1027.3	2.185075496	1.945049023	1.123403816	-11.878	16.008	4.130	0.276	147763.827	5.51496	27.57%	**More Power in inc basin spectrum**
2	100	#X20-PS	1	0	2.2	0.132	14.9779	-0.25	0	2250	1883.04153	1000	1051.9	0.909588723	1.228653377	0.740313533	-8.836	10.974	2.138	0.143	76500.075	2.8552	14.28%	Hatch Open Comparison Case
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
3	98	0	1	0	2.58	0.268	74.1199	-0.503	0	3500	3117.678489	1000	1054.3	1.568764142	1.644373264	0.95401949	-11.022	14.235	3.213	0.043	114956.699	0.86701	4.34%	**Used for ACE; Treated as Survival**
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
4	39	#X20-A	1	0	2.84	0.103	11.9593	-0.142	0	2250	1978.348586	750	772.5	1.09287525	1.137997457	0.960349466	-10.730	12.961	2.231	0.187	79814.128	3.73077	18.65%	
4	43	#X20-A	1	0	2.84	0.103	11.9593	-0.134	0	1750	1510.617434	750	770.1	1.123246251	1.106953486	1.014718563	-10.737	12.968	2.230	0.186	79790.051	3.72965	18.65%	
4	46	#X20-A	1	0	2.84	0.103	11.9593	-0.133	0	2250	2008.711233	375	403.5	0.656426663	0.856317462	0.766569283	-12.062	13.574	1.513	0.126	54121.579	2.52982	12.65%	
4	50	#X20-A	1	0	2.84	0.103	11.9593	-0.251	0	2250	2002.737644	750	772.5	1.165448428	1.097662876	1.061754437	-11.078	13.341	2.263	0.189	80967.531	3.78469	18.92%	**Used for ACE, NonOpt**
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
5	66	#X20-A	1	0	3.41	0.292	114.446	-0.491	0	2000	1793.365019	1000	1017.0	2.568617283	2.155024843	1.191920033	-13.925	18.649	4.724	0.041	168998.158	0.82548	4.13%	**Used for ACE; Treated as Survival**
5	101	#X20-PS	1	0	3.41	0.292	114.446	-0.302	0	3000	2714.516655	1000	1036.3	1.574773331	1.659644125	0.948862053	-10.998	14.232	3.234	0.028	115718.037	0.56523	2.83%	Open Hatch
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
6	64	#X20-A	1	0	3.69	0.163	39.7895	-0.34	0	1000	838.6104045	500	518.3	1.73347727	1.545454734	1.121661626	-15.900	19.178	3.279	0.082	117310.638	1.64814	8.24%	
6	65	#X20-A	1	0	3.69	0.163	39.7895	-0.24	0	1000	838.1051036	500	517.6	1.9387101	1.662788	1.165939435	-16.255	19.857	3.601	0.091	128851.113	1.81028	9.05%	**Used for ACE; Treated as Survival**
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
CIWS1	67	#X20-A	1	0	1.25	0.063	1.8878	-0.139	0	3000	2273.329989	500	589.1	0.004240561	0.478219653	0.008867391	-5.161	5.644	0.482	0.256	17261.021	5.11135	25.56%	
CIWS1	68	#X20-A	1	0	1.25	0.063	1.8878	-0.085	0	3000	2252.395785	500	584.3	0.019133026	0.41725107	0.045854948	-4.977	5.413	0.436	0.231	15612.552	4.6232	23.12%	
IWS #	Run ID	Scale / Device	Gamma [-]	Inc. Deg [°]			Wave Power [W/m]	FS hOp [m]	LMM Config [%]	Setpoint PTO1.k [N/m]	Experiment PTO.k [N/m]	Setpoint PTO.c [Ns/m]	Experiment PTO.c [Ns/m]	Av. Net Power Upstream[W]	Av. Net Power Downstream[W]	Upstream:Downstream	Av. Power Consumed [W]	Av. Power Absorbed [W]	Net Power [W]	CW [m]	FS Net Power [W]	FS CW [m]	CWR [%]	Note
CIWS3	69	#X20-A	1	0	1.92	0.175	22.4884	-0.25	0	2750	2426.793693	1000	1060.8	3.361174003	2.832025005	1.186844748	-14.078	20.271	6.193	0.275	221574.624	5.50791	27.54%	**PTO Slipped, Faulty run**
CIWS3	90	#X20-P	1	0	1.92	0.175	22.4884	-0.251	0	2750	2093.772312	1000	849.0	3.314652761	3.015789712	1.099099432	-14.337	20.668	6.330	0.281	226484.795	5.62996	28.15%	
CIWS3	91	#X20-P	1	0	1.92	0.175	22.4884	-0.253	0	2750	1409.801869	1000	739.8004382	2.974075292	2.104556151	1.413160343	-15.5497969	20.62842835	5.078631	0.226	181698.64	4.51667	22.58%	**PTO Slipped, Faulty run**

8. Summary: Primarily Performance Evaluation

To compare the device performance in the Wave Energy Prize Metric using the ACE metric, for baseline performance evaluation 6 irregular, 0 Degree incident wave cases were tested. The six wave cases follow the WEP metric and results obtained from these tests can be directly used to compare performance against the CalWave concept used during the 1:20 scale US Wave Energy Prize tests. Note, that due to the focus on system identification during the experimental prototype tests at Lir, performance of the prototype in the ACE relevant IWS cases was not optimized. While some of the larger IWS wave states were even treated as a survival case to prevent any potential risk of damaging the prototype all IWS 1-6 cases were successfully run.

Table 6 shows a summary of all irregular wave cases (IWS) and custom irregular wave cases (CWS) that were assessed during experimental testing. The table lists experiment IDs, information about the incident wave spectrum, general device configuration parameter, PTO configuration parameter, performance measured in power as well as capture width and capture width ratio. Results highlighted in green can be used to obtain a first estimate of the nominator of ACE.

Moreover, these results allow a first comparison of performance compared to WEP results as shown in Table 7. It is important to mention, that although the CWR for most of the cases decreased compared to CalWave's WEP results the device configuration (single body compared to two body concept) is assumed to be significantly smaller in weight and cost (Single body concept has significantly less weight than even half of the WEP concept).

Table 7: Preliminary comparison of no-optimized, experimentally derived performance to WEP results.

Comparison 1:20 Scale Power Generation [W]			
IWS#	1st Price WEP (1:20 Scale)	CalWave WEP (1:20 Scale)	CalWave (1:20 Scale)
IWS1	1.77	8.12	2.75
IWS2	3.57	14.28	3.99
IWS3	13.80	9.60	3.21
IWS4	2.04	9.80	2.26
IWS5	17.82	21.52	4.72
IWS6	5.73	13.97	3.60
Comparison 1:20 Scale CWR [%]			
IWS	1st Prize WEP (1:20 Scale)	CalWave WEP (1:20 Scale)	CalWave (1:20 Scale)
IWS1	21.28%	34.43%	33.34%
IWS2	25.69%	36.30%	26.64%
IWS3	21.76%	5.34%	4.34%
IWS4	19.47%	33.06%	18.92%
IWS5	14.99%	6.39%	4.13%
IWS6	16.84%	14.48%	9.05%

The following figures show the post processing plots for each of the IWS cases used to assess ACE:

Plot explanation:

Plot #1: Time resolved PTO displacement, PTO velocities, and PTO Forces. Moreover, a time window is shown indicating the time frame used for further post processing.

Plot #2: Comparison of raw signal vs filtered signal. Top plot shows a snippet for qualitative assessment of filtered vs. raw PTO 1 forces. Bottom plot plots the raw PTO1 velocity vs the filtered signal.

Plot #3: PTO damping forces plotted against PTO velocities. From this plot, the damping coefficient c can be derived from the experimental data and compared to the set point. The comparison is plotted for each of the four PTO units.

Plot #4: PTO restoring forces plotted against the PTO stroke/position. From this plot, the restoring force coefficient k can be derived from the experimental data and compared to the set point. The comparison is plotted for each of the four PTO units.

Plot #5: PTO force histogram. Occurrence of dynamic PTO forces sorted into bins of 3N are shown for each PTO unit. The figures indicate how often PTO forces occur and where a force limit/torque limit on the PTO units will be set to reduce maximum PTO loads without significantly affecting performance.

Plot #6: PTO Velocity histogram. Occurrence of PTO velocities sorted into bins of .5 cm/s are shown for each PTO unit. The figures indicate how often PTO velocities occur and where a velocity limit on the PTO units can reduce PTO requirements without significantly affecting performance.

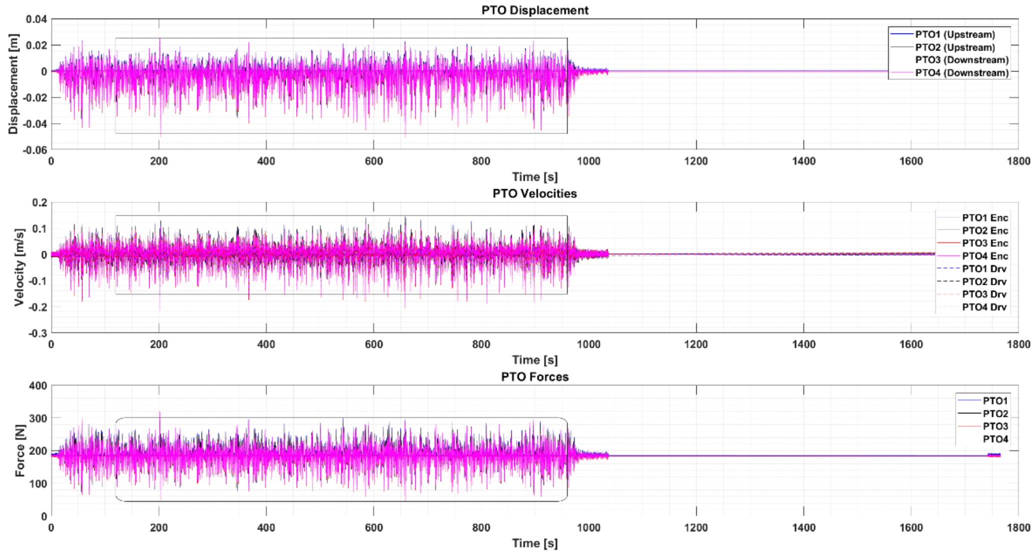
Plot #7: Overview of time resolved absorber displacement derived from the Qualisys motion tracking for each DOF. Left hand side covers the translator motion; Right hand side shows rotational DOFs.

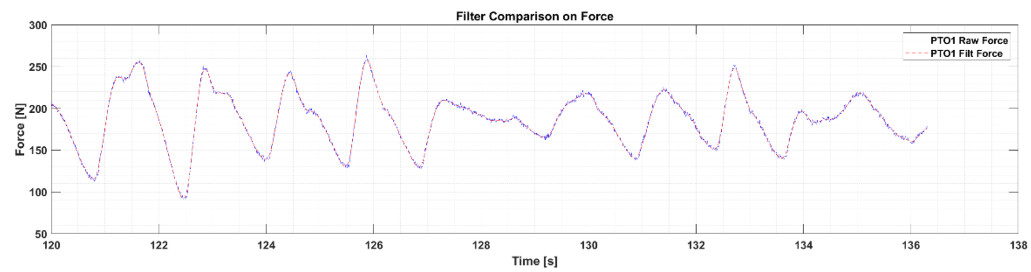
Plot #8: Top view phase plane shows the displacement of the absorber body in Sway DOF against Surge DOF. Plots generally show, that the absorber body is not excited in the sway DOF which was expected for 0° incident waves. Side view phase plane shows the displacement of the absorber body in Heave DOF against Surge DOF. Additionally, a horizontal line is plotted to indicate the SWL and the positive and negative wave height (Hs). Plots generally indicate how strong the motion in Heave is dampened.

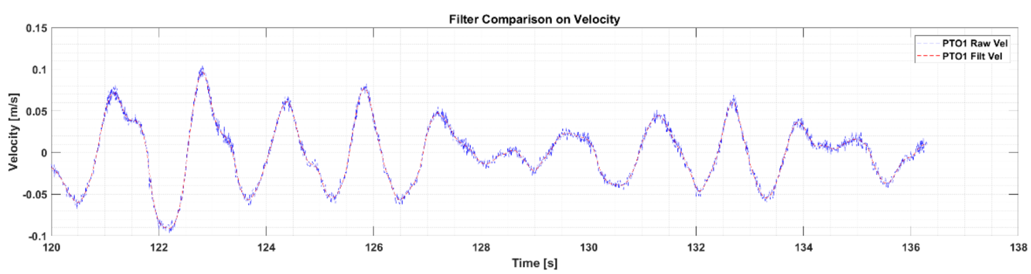
Plot #9: The top plot shows the time resolved balance between generated and consumed power for the entire device. The bottom plot shows the time resolved balance between power generated/consumed for combined upstream PTO units (PTO#1 + PTO#2) vs combined downstream PTO units (PTO#3 + PTO#4).

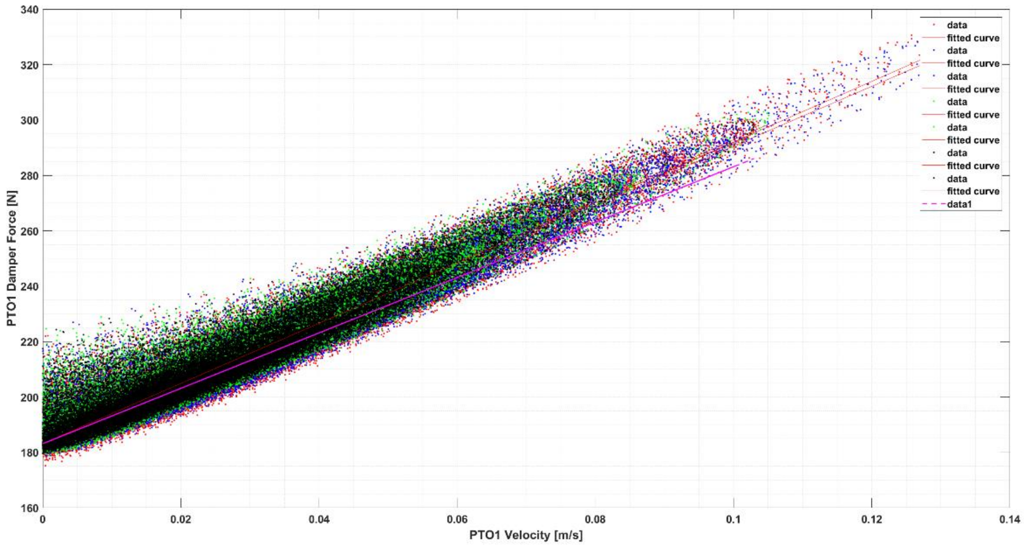
Plot #10: Power histogram: The plot shows the occurrence of individual PTO power generation/consumption and total device power generation/consumption sorted into bins. These plots can be used to derive specifications for the PTO units and to set limits to reduce the PTO specifications/requirements without significantly affecting performance.

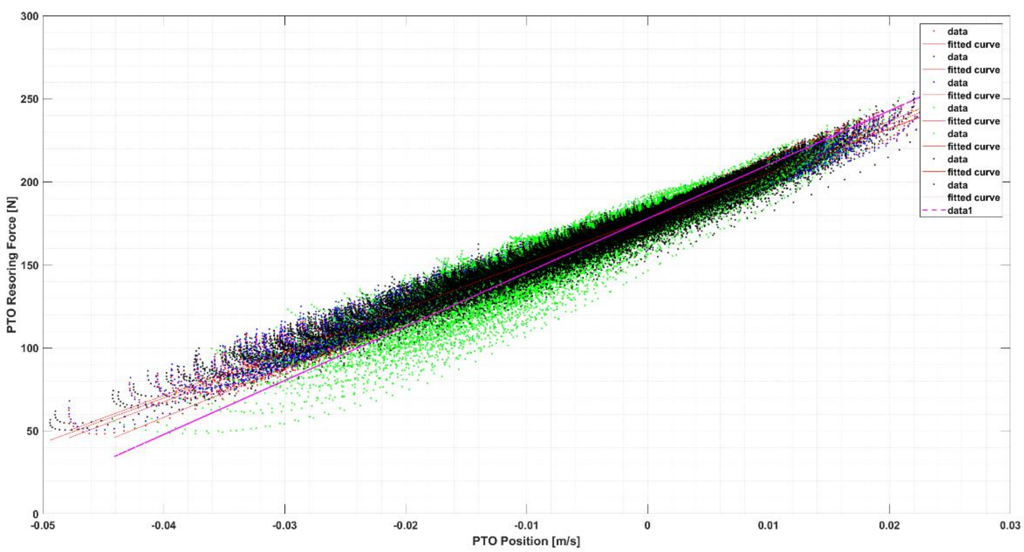
IWS 1

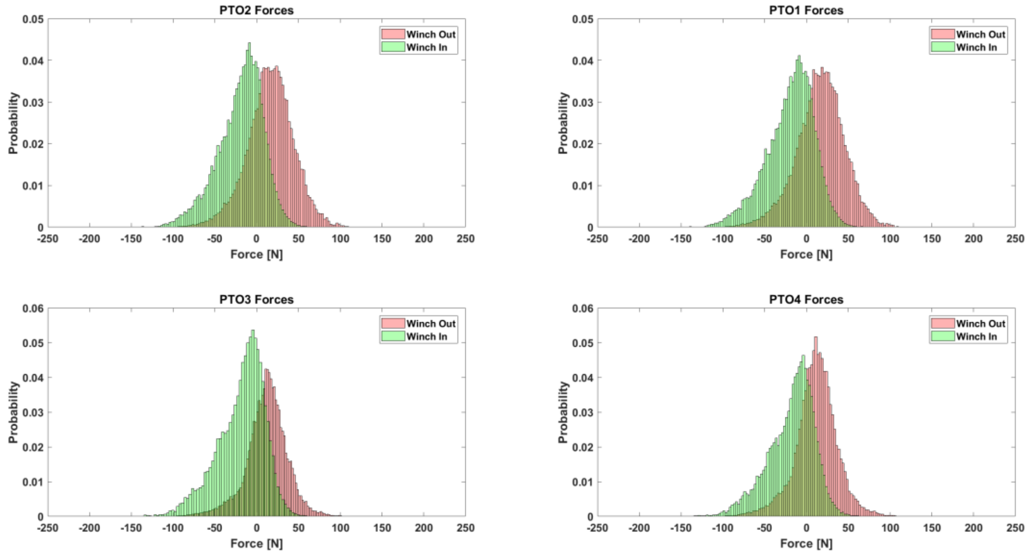

PTO Displacement
Displacement [m]
Time [s]
PTO1 (Upstream)
PTO2 (Upstream)
PTO3 (Downstream)
PTO4 (Downstream)
PTO Velocities
Velocity [m/s]
Time [s]
PTO1 Enc
PTO2 Enc
PTO3 Enc
PTO4 Enc
PTO1 Drv
PTO2 Drv
PTO3 Drv
PTO4 Drv
PTO Forces
Force [N]
Time [s]
PTO1
PTO2
PTO3
PTO4

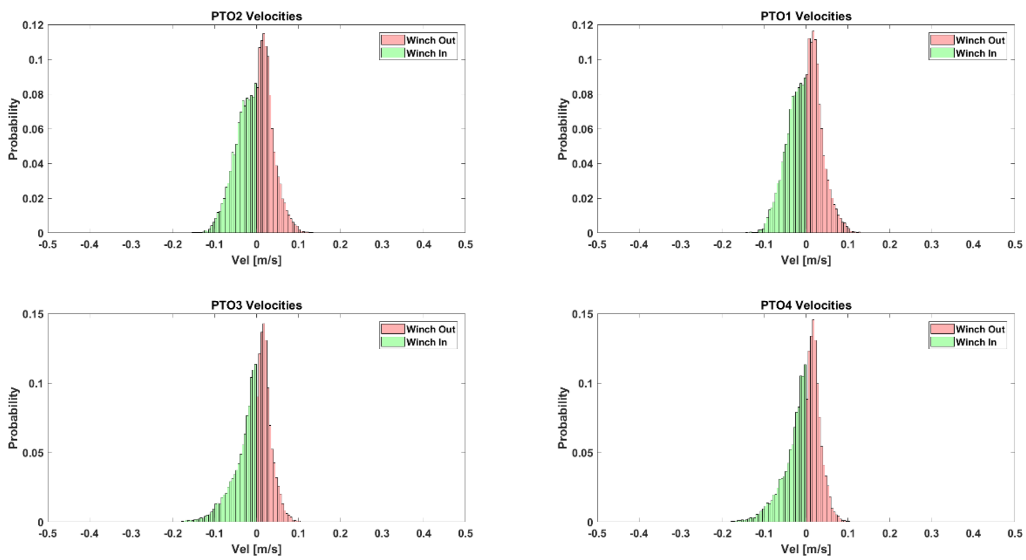

Filter Comparison on Force
Force [N]
Time [s]
PTO1 Raw Force
PTO1 Filt Force

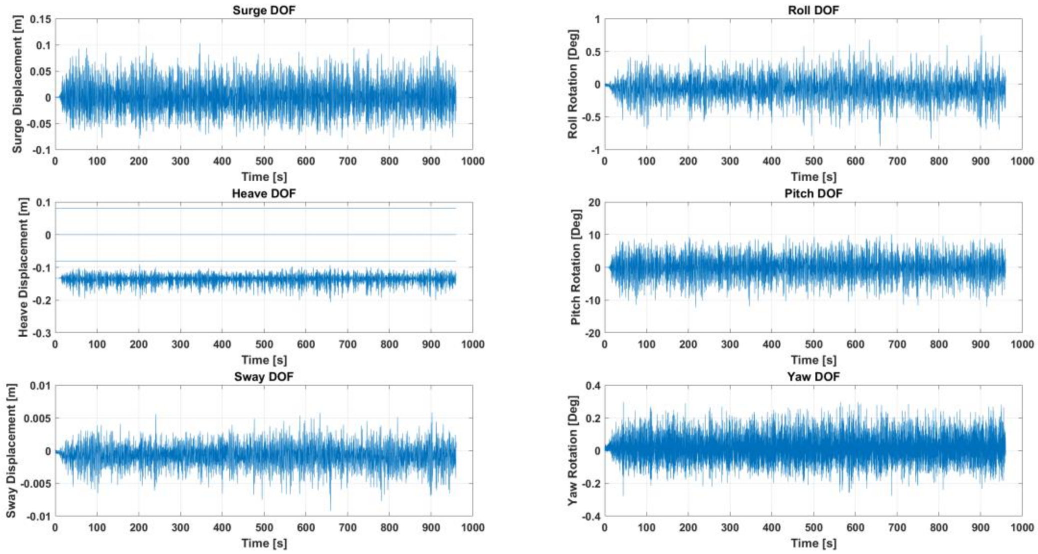

Filter Comparison on Velocity
Velocity [m/s]
Time [s]
PTO1 Raw Vel
PTO1 Filt Vel

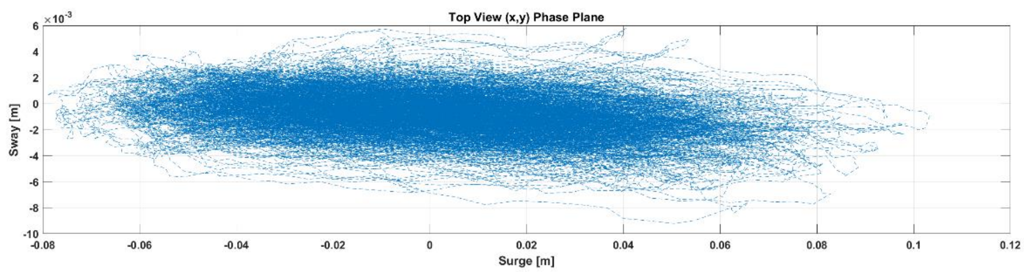

PTO1 Damper Force [N]
PTO1 Velocity [m/s]
data
fitted curve
data1

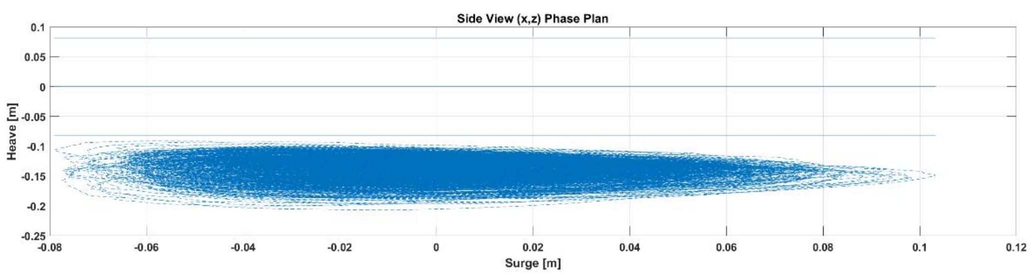

PTO Resoring Force [N]
PTO Position [m/s]
data
fitted curve
data1

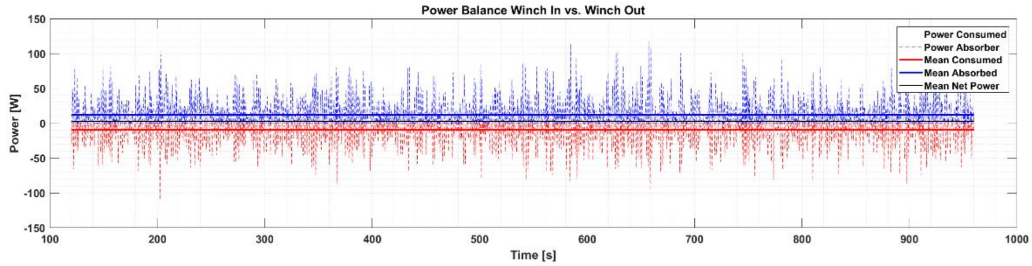

PTO2 Forces
PTO1 Forces
PTO3 Forces
PTO4 Forces
Winch Out
Winch In
Probability
Force [N]

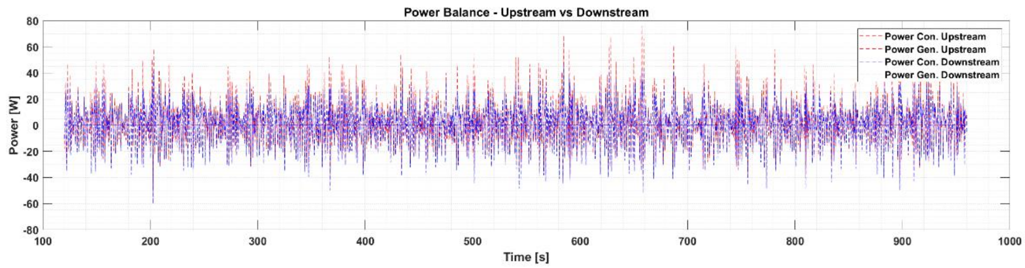

PTO2 Velocities
PTO1 Velocities
PTO3 Velocities
PTO4 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

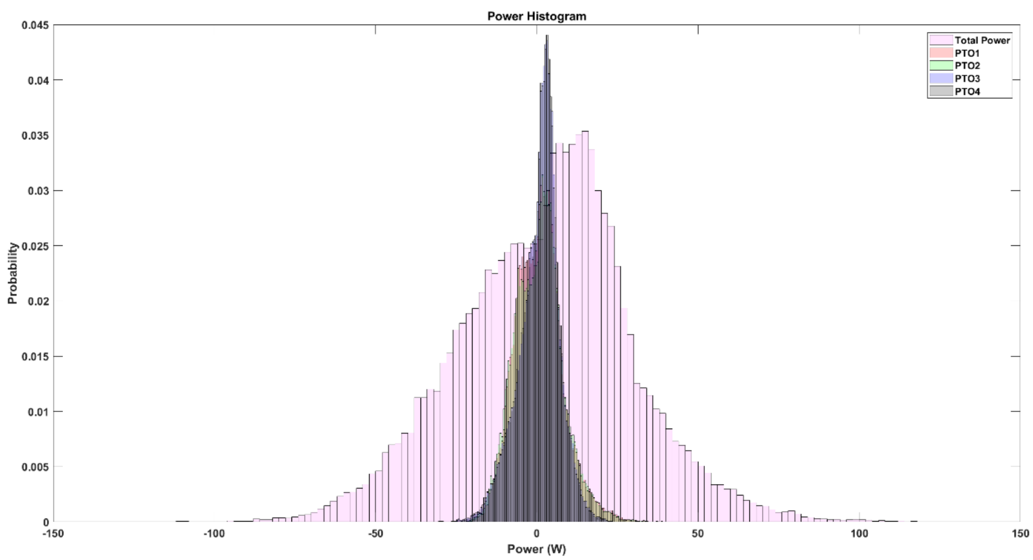

Surge DOF
Surge Displacement [m]
Time [s]
Roll DOF
Roll Rotation [Deg]
Time [s]
Heave DOF
Heave Displacement [m]
Time [s]
Pitch DOF
Pitch Rotation [Deg]
Time [s]
Sway DOF
Sway Displacement [m]
Time [s]
Yaw DOF
Yaw Rotation [Deg]
Time [s]


Top View (x,y) Phase Plane
Sway [m]
Surge [m]

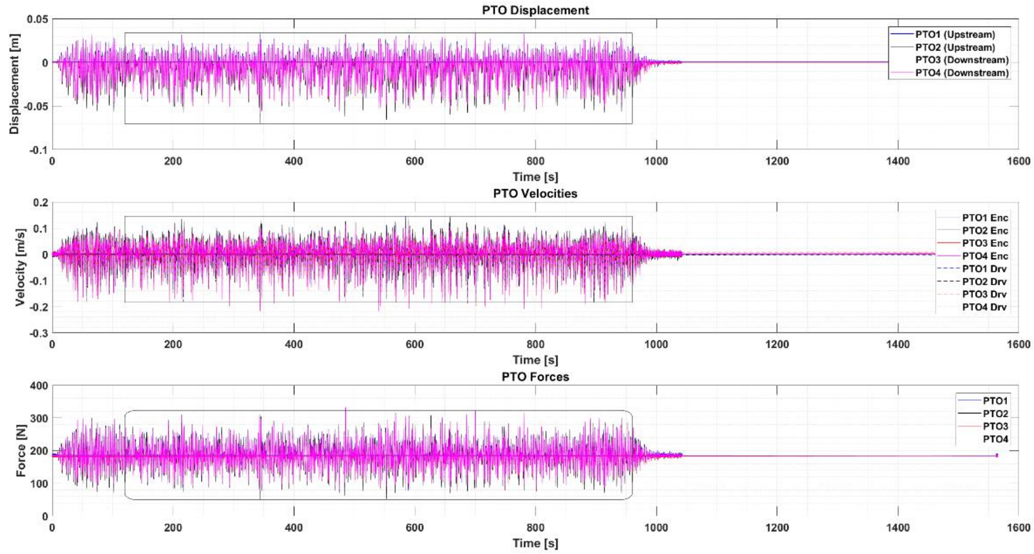

Side View (x,z) Phase Plan
Heave [m]
Surge [m]

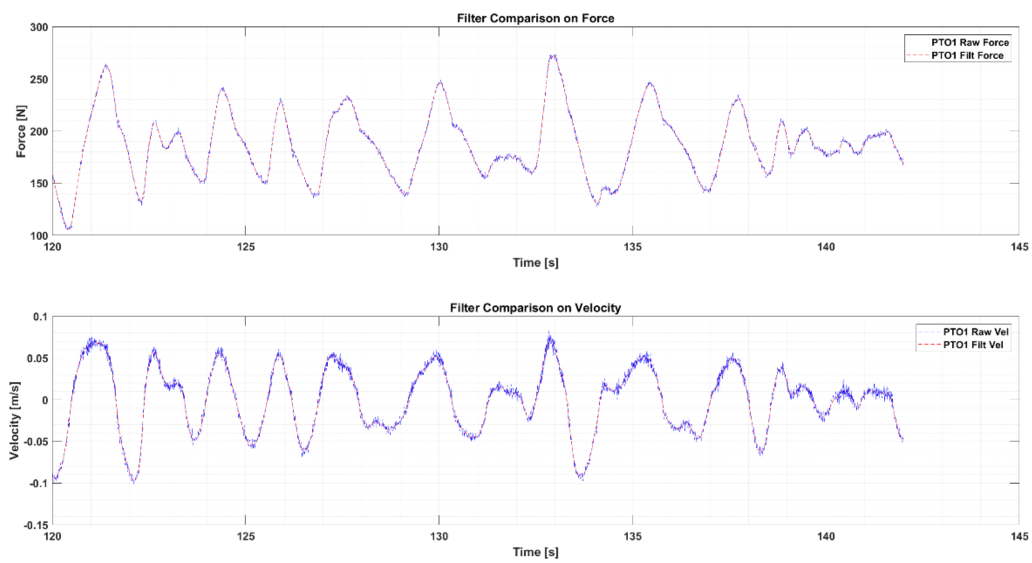

Power Balance Winch In vs. Winch Out
Power Consumed
Power Absorber
Mean Consumed
Mean Absorbed
Mean Net Power
Power [W]
Time [s]

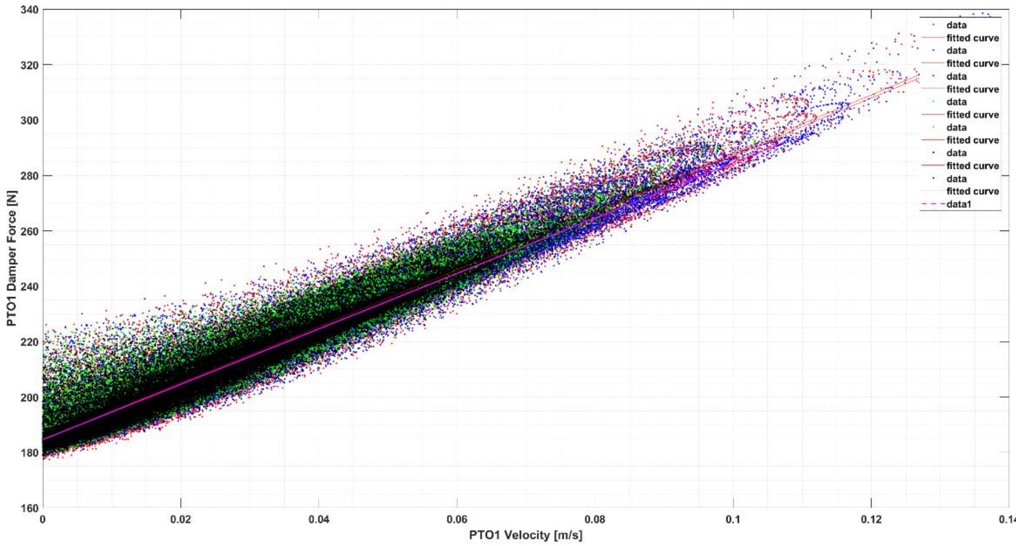

Power Balance - Upstream vs Downstream
Power Con. Upstream
Power Gen. Upstream
Power Con. Downstream
Power Gen. Downstream
Power [W]
Time [s]

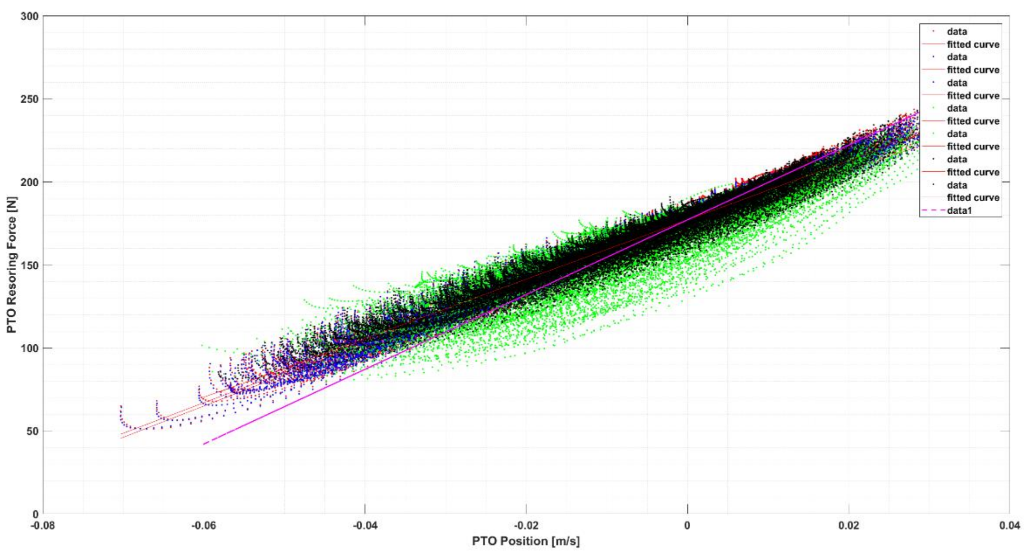

Power Histogram
Total Power
PTO1
PTO2
PTO3
PTO4
Probability
Power (W)

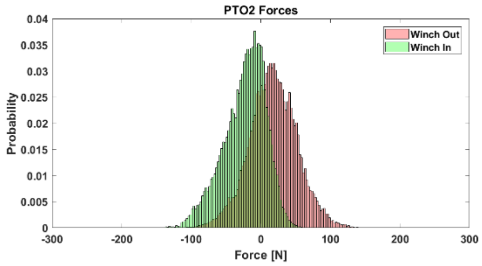
IWS2

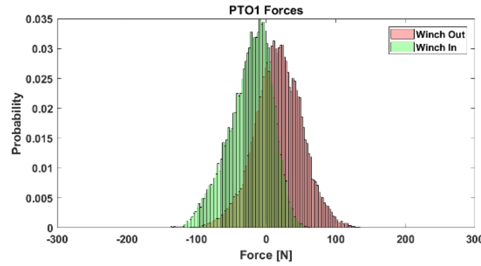

PTO Displacement
Displacement [m]
Time [s]
PTO1 (Upstream)
PTO2 (Upstream)
PTO3 (Downstream)
PTO4 (Downstream)
PTO Velocities
Velocity [m/s]
Time [s]
PTO1 Enc
PTO2 Enc
PTO3 Enc
PTO4 Enc
PTO1 Drv
PTO2 Drv
PTO3 Drv
PTO4 Drv
PTO Forces
Force [N]
Time [s]
PTO1
PTO2
PTO3
PTO4

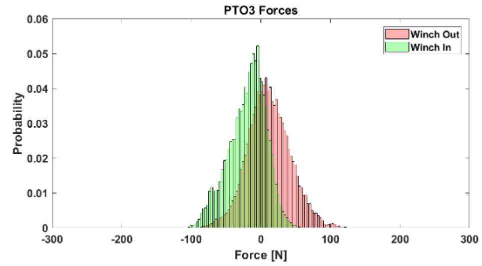

Filter Comparison on Force
Force [N]
Time [s]
PTO1 Raw Force
PTO1 Filt Force
Filter Comparison on Velocity
Velocity [m/s]
Time [s]
PTO1 Raw Vel
PTO1 Filt Vel

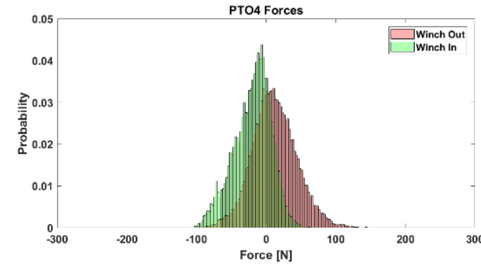

PTO1 Damper Force [N]
PTO1 Velocity [m/s]
data
fitted curve
data1

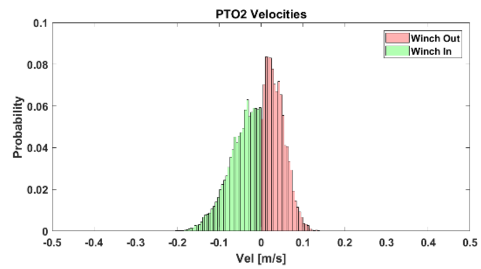

PTO Resoring Force [N]
PTO Position [m/s]
data
fitted curve
data1

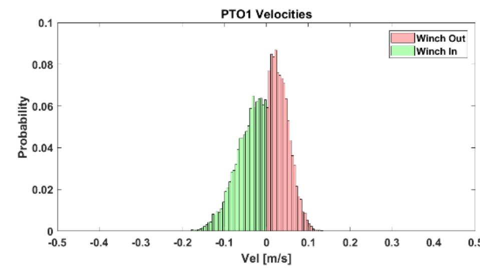

PTO2 Forces
Winch Out
Winch In
Probability
Force [N]

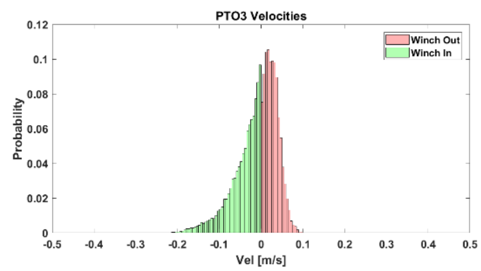

PTO1 Forces
Winch Out
Winch In
Probability
Force [N]

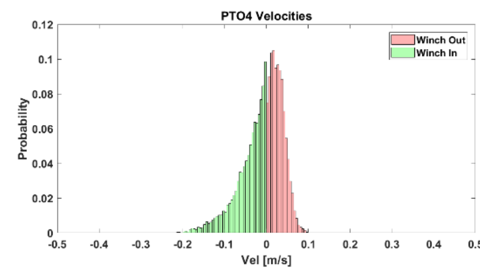

PTO3 Forces
Winch Out
Winch In
Probability
Force [N]

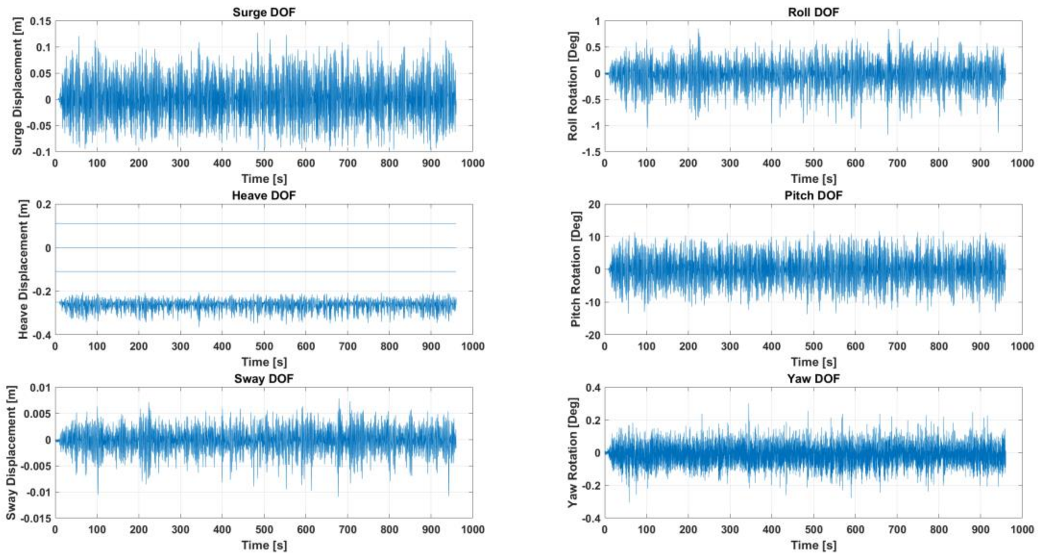

PTO4 Forces
Winch Out
Winch In
Probability
Force [N]

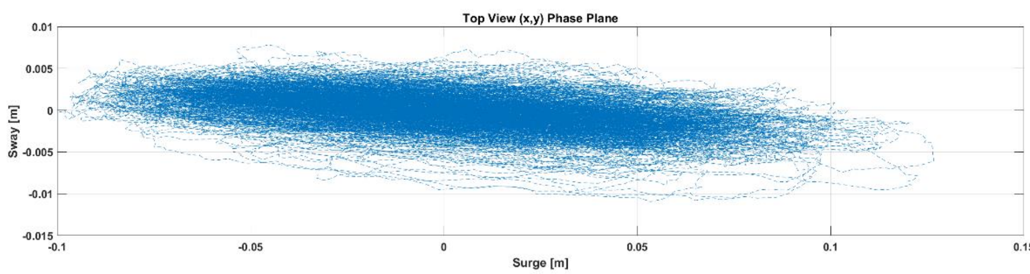

PTO2 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

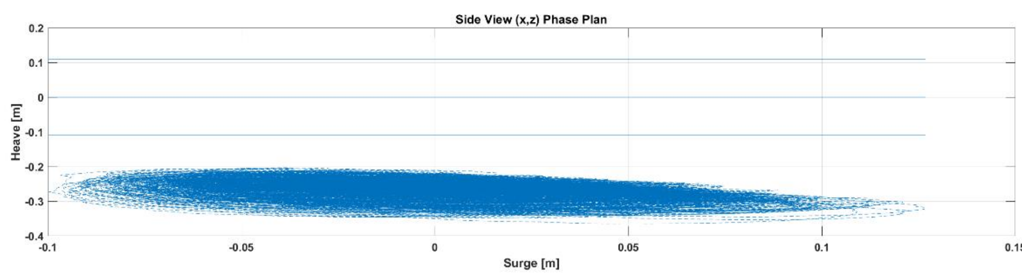

PTO1 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

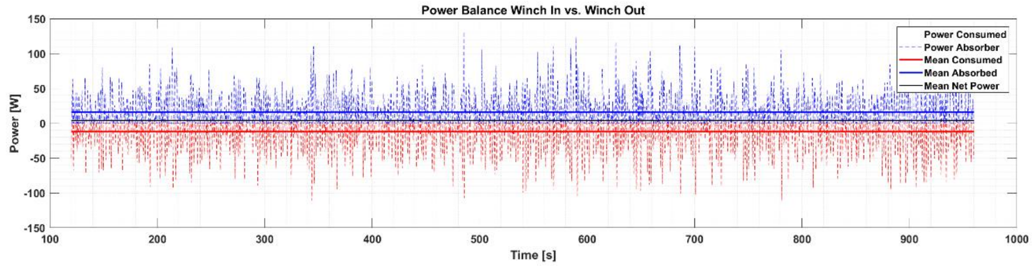

PTO3 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

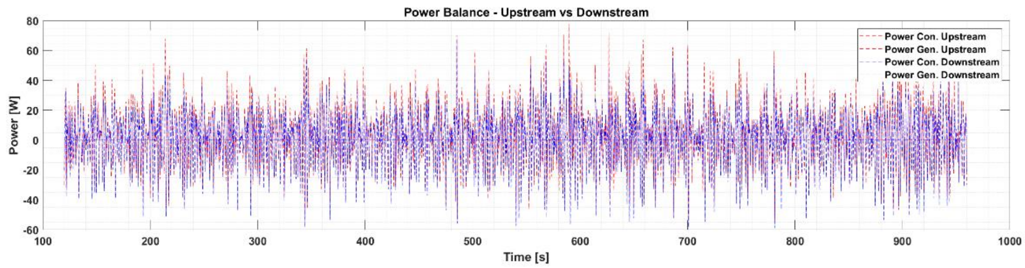

PTO4 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

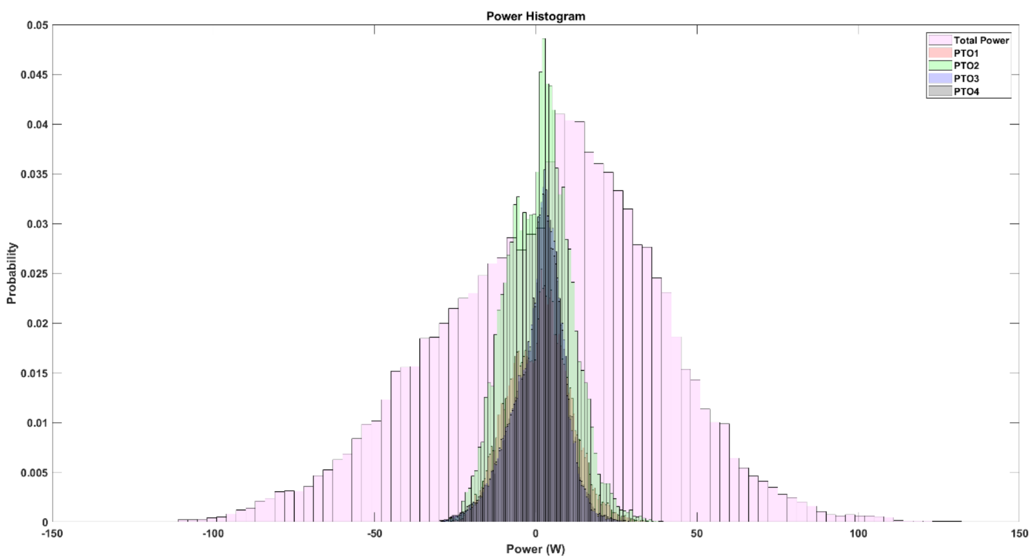

Surge DOF
Surge Displacement [m]
Time [s]
Heave DOF
Heave Displacement [m]
Time [s]
Sway DOF
Sway Displacement [m]
Time [s]
Roll DOF
Roll Rotation [Deg]
Time [s]
Pitch DOF
Pitch Rotation [Deg]
Time [s]
Yaw DOF
Yaw Rotation [Deg]
Time [s]


Top View (x,y) Phase Plane
Sway [m]
Surge [m]

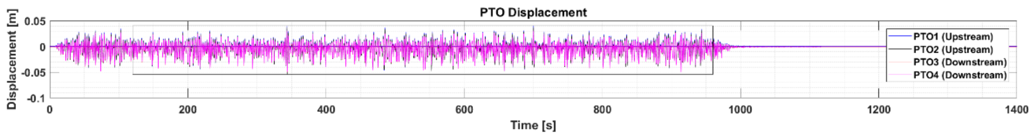

Side View (x,z) Phase Plan
Heave [m]
Surge [m]

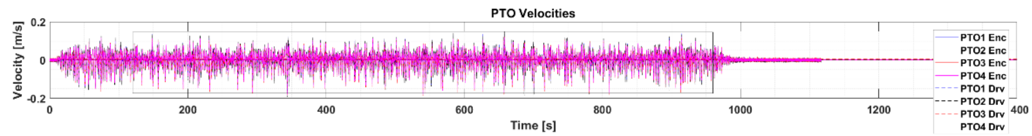

Power Balance Winch In vs. Winch Out
Power Consumed
Power Absorber
Mean Consumed
Mean Absorbed
Mean Net Power
Power [W]
Time [s]

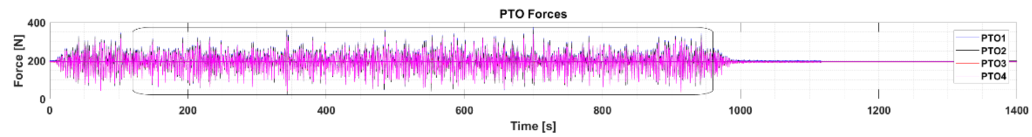

Power Balance - Upstream vs Downstream
Power Con. Upstream
Power Gen. Upstream
Power Con. Downstream
Power Gen. Downstream
Power [W]
Time [s]

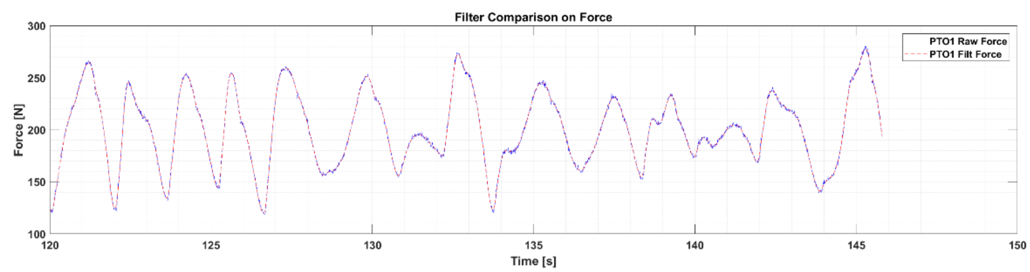

Power Histogram
Total Power
PTO1
PTO2
PTO3
PTO4
Probability
Power (W)

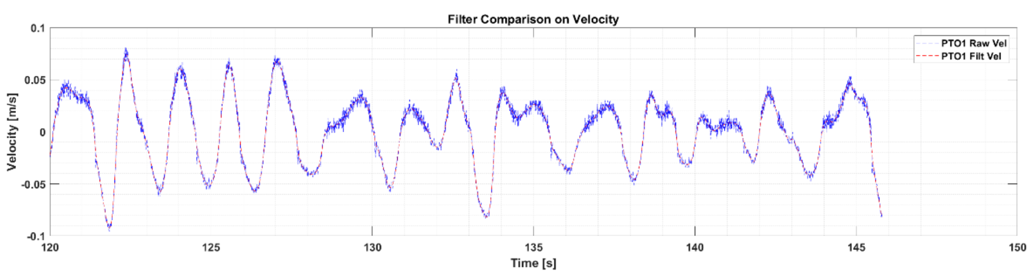
IWS3

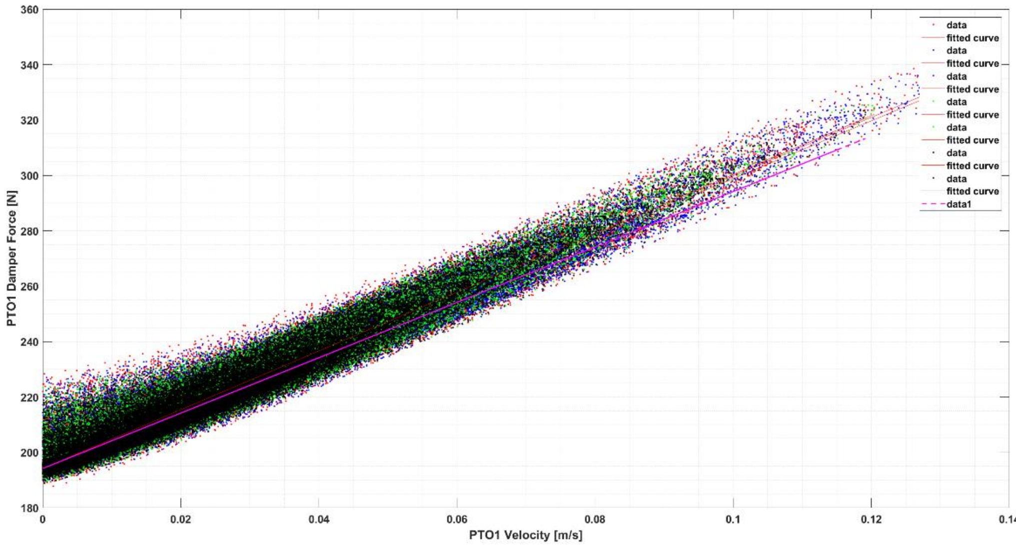

PTO Displacement
Displacement [m]
Time [s]
PTO1 (Upstream)
PTO2 (Upstream)
PTO3 (Downstream)
PTO4 (Downstream)

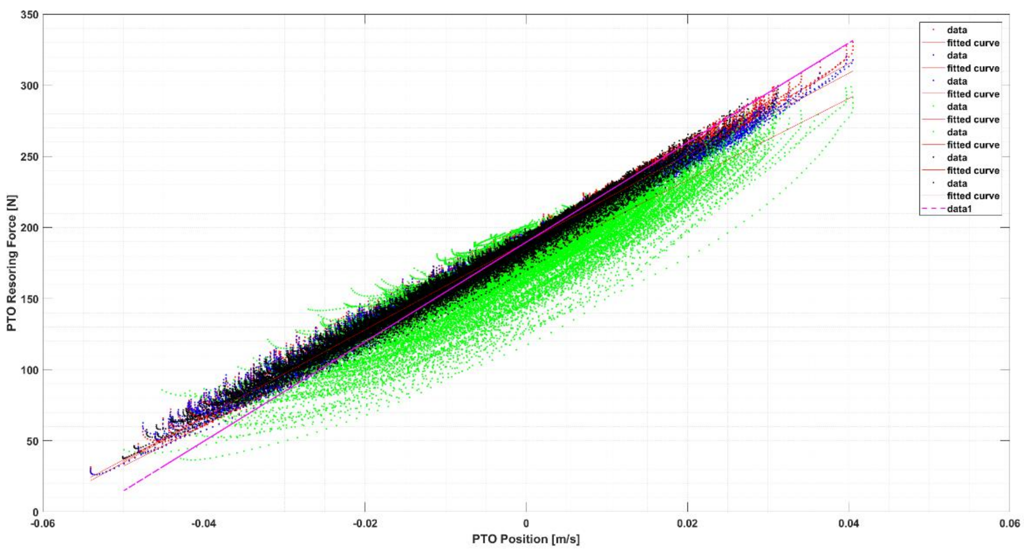

PTO Velocities
Velocity [m/s]
Time [s]
PTO1 Enc
PTO2 Enc
PTO3 Enc
PTO4 Enc
PTO1 Drv
PTO2 Drv
PTO3 Drv
PTO4 Drv

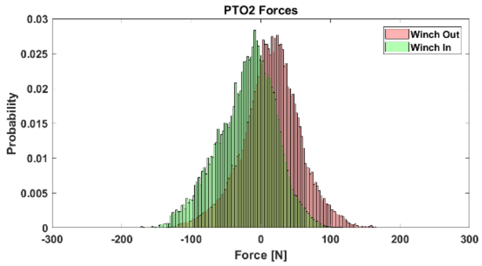

PTO Forces
Force [N]
Time [s]
PTO1
PTO2
PTO3
PTO4

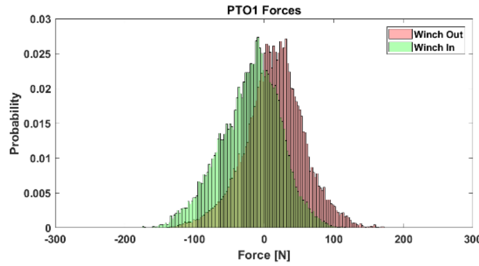

Filter Comparison on Force
Force [N]
Time [s]
PTO1 Raw Force
PTO1 Filt Force

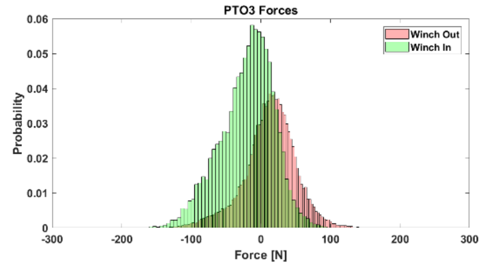

Filter Comparison on Velocity
Velocity [m/s]
Time [s]
PTO1 Raw Vel
PTO1 Filt Vel

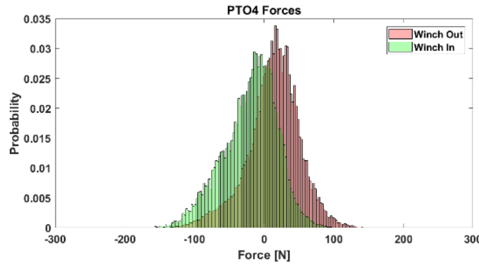

PTO1 Damper Force [N]
PTO1 Velocity [m/s]
data
fitted curve
data1

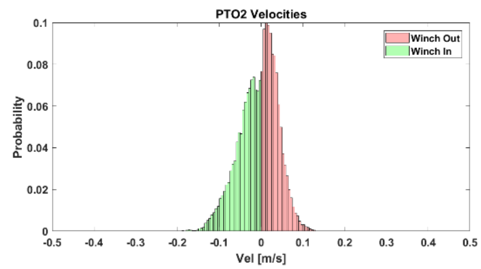

PTO Resoring Force [N]
PTO Position [m/s]
data
fitted curve
data1

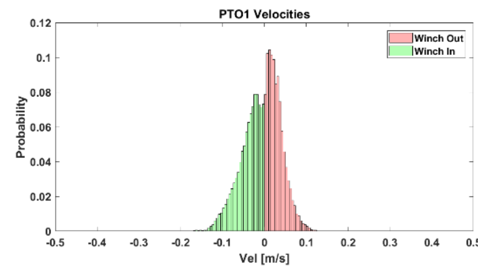

PTO2 Forces
Winch Out
Winch In
Probability
Force [N]

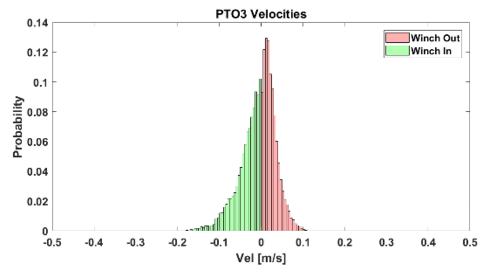

PTO1 Forces
Winch Out
Winch In
Probability
Force [N]

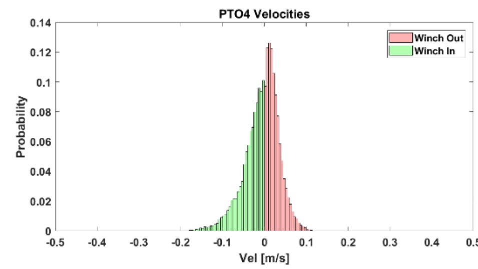

PTO3 Forces
Winch Out
Winch In
Probability
Force [N]

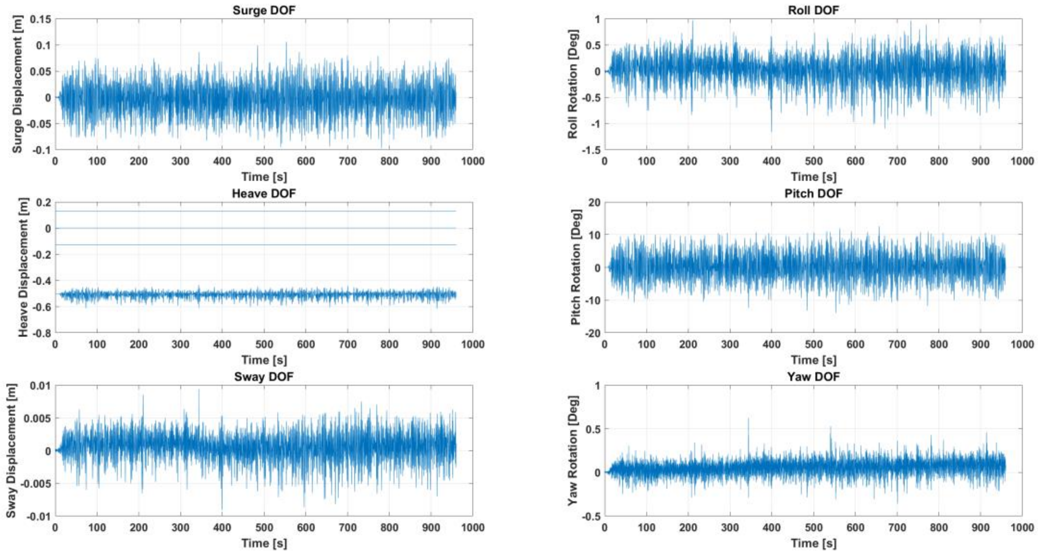

PTO4 Forces
Winch Out
Winch In
Probability
Force [N]

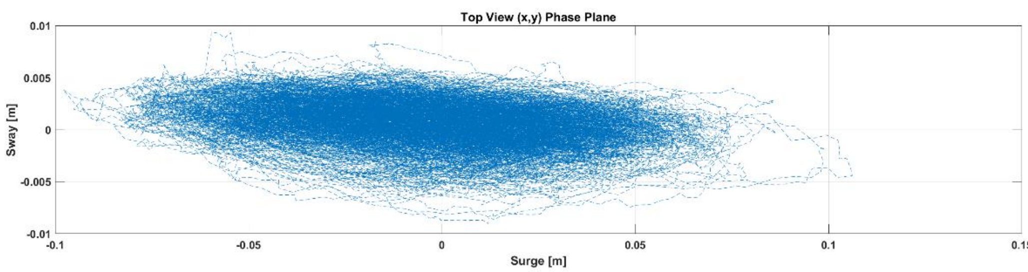

PTO2 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

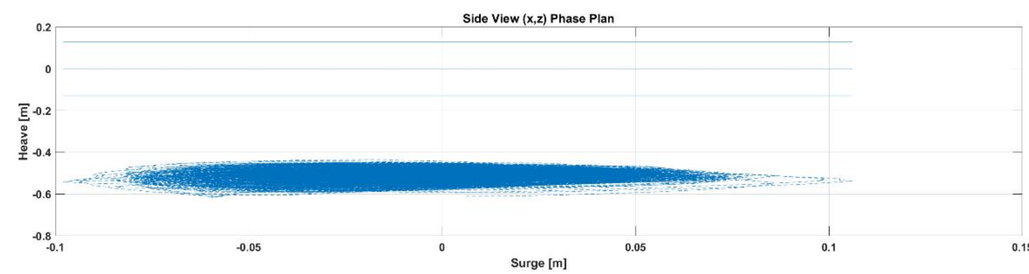

PTO1 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

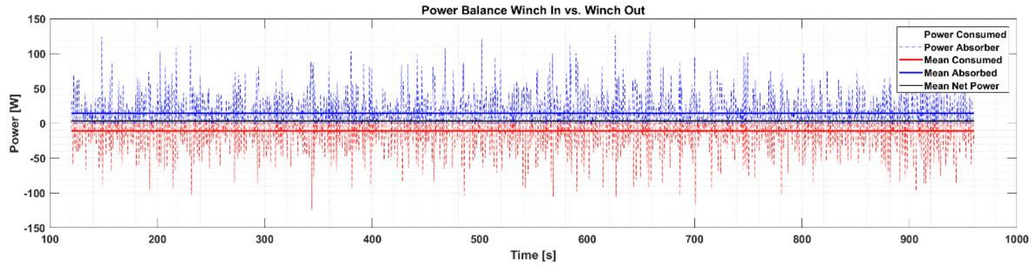

PTO3 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

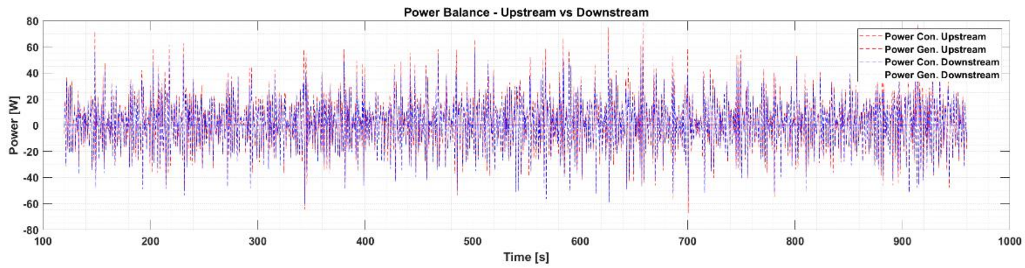

PTO4 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

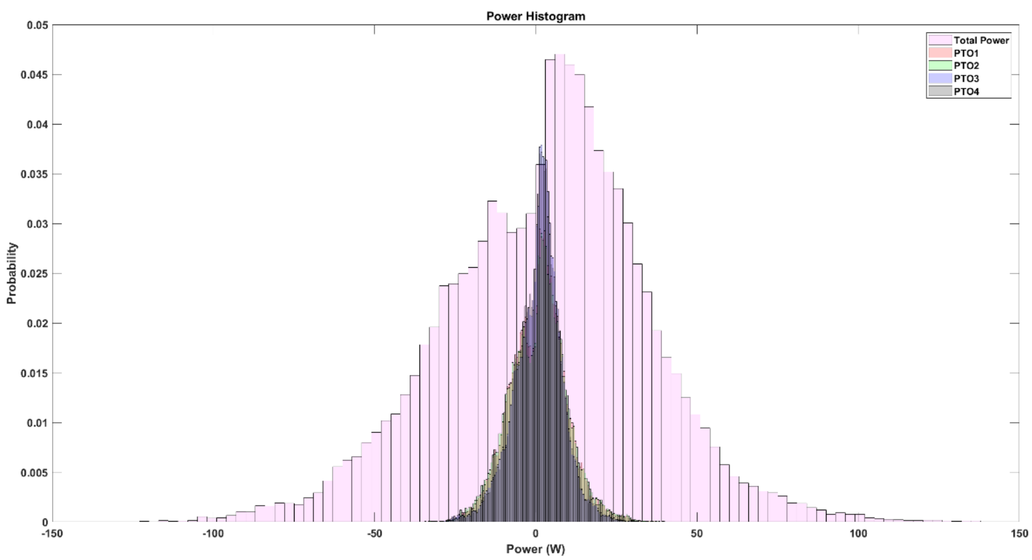

Surge DOF
Surge Displacement [m]
Time [s]
Roll DOF
Roll Rotation [Deg]
Time [s]
Heave DOF
Heave Displacement [m]
Time [s]
Pitch DOF
Pitch Rotation [Deg]
Time [s]
Sway DOF
Sway Displacement [m]
Time [s]
Yaw DOF
Yaw Rotation [Deg]
Time [s]


Top View (x,y) Phase Plane
Sway [m]
Surge [m]

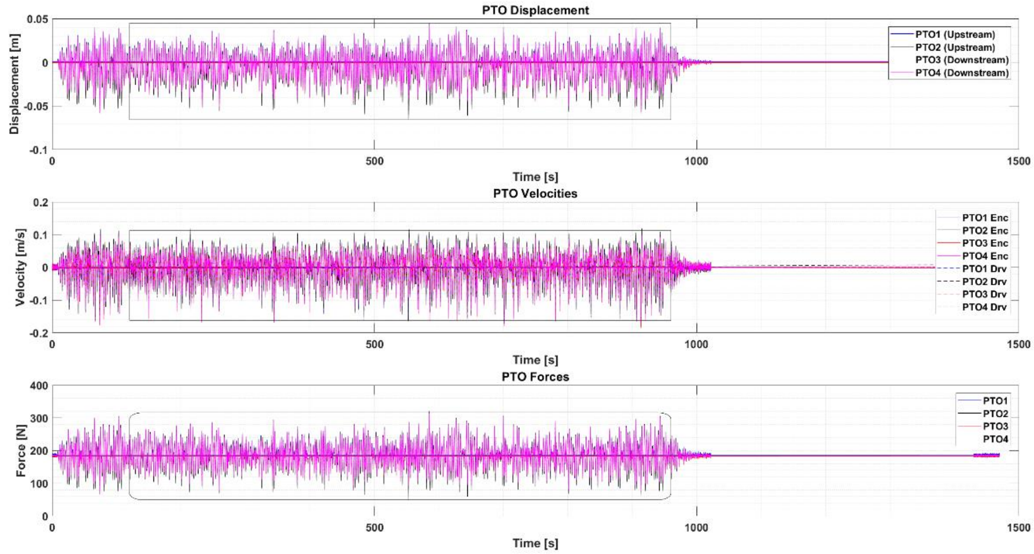

Side View (x,z) Phase Plan
Heave [m]
Surge [m]

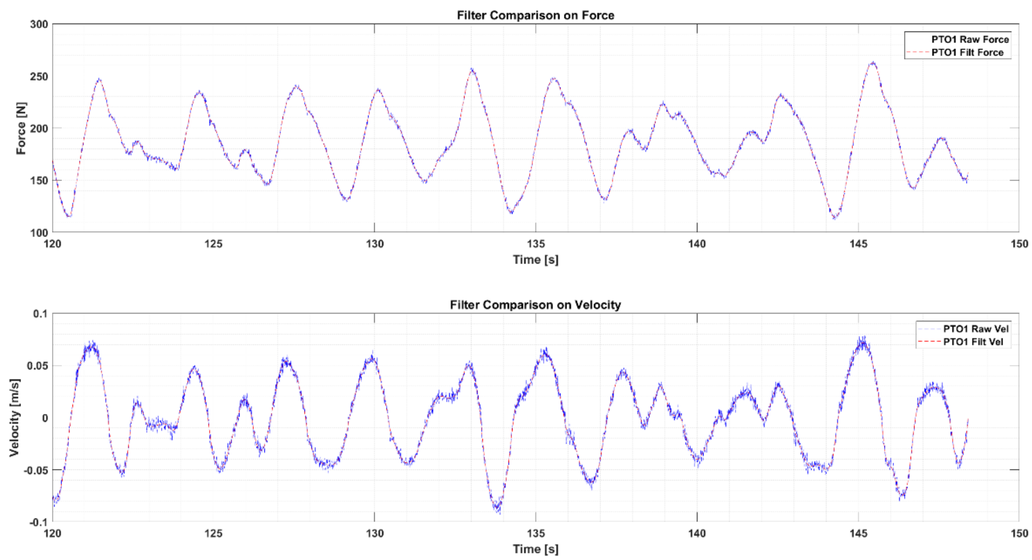

Power Balance Winch In vs. Winch Out
Power Consumed
Power Absorber
Mean Consumed
Mean Absorbed
Mean Net Power
Power [W]
Time [s]

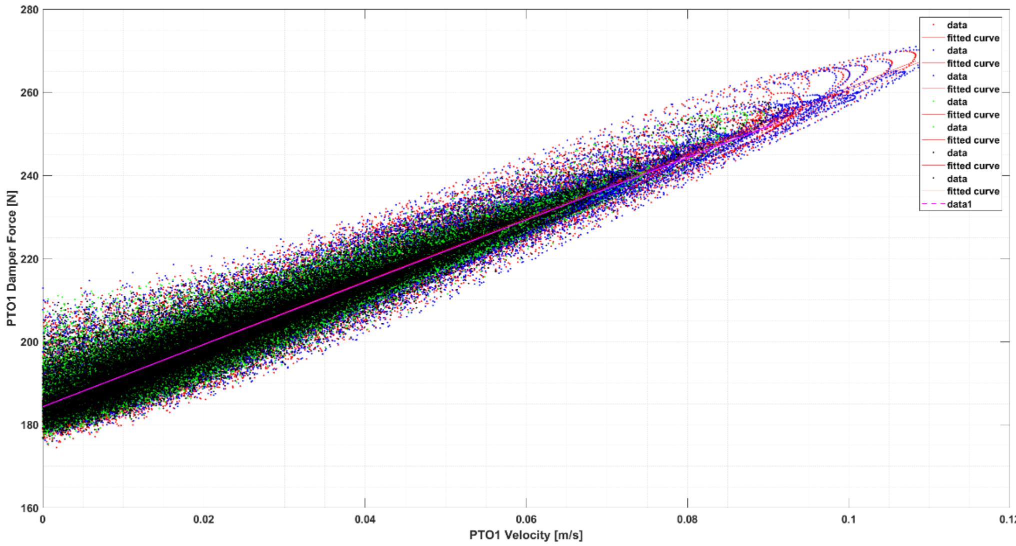

Power Balance - Upstream vs Downstream
Power Con. Upstream
Power Gen. Upstream
Power Con. Downstream
Power Gen. Downstream
Power [W]
Time [s]

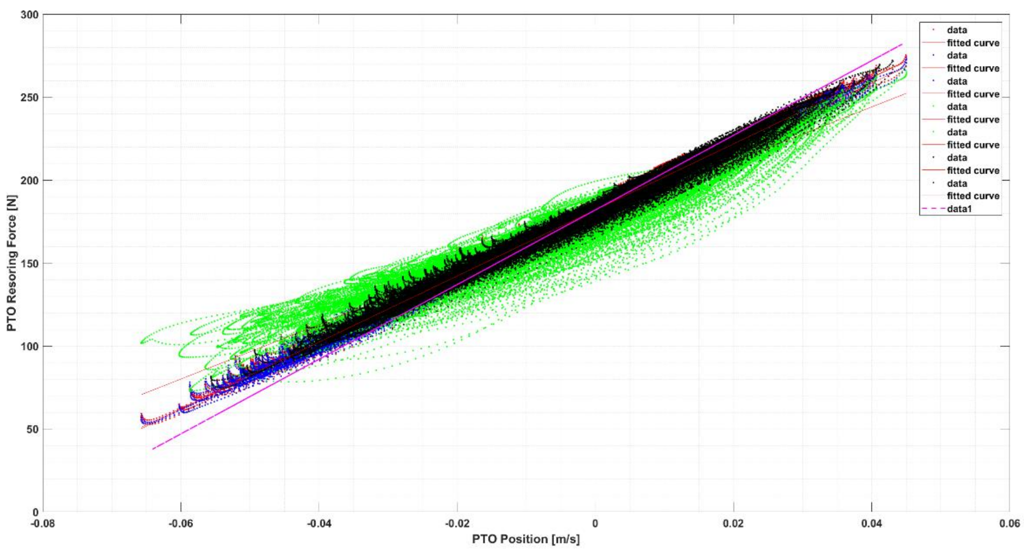

Power Histogram
Total Power
PTO1
PTO2
PTO3
PTO4
Probability
Power (W)

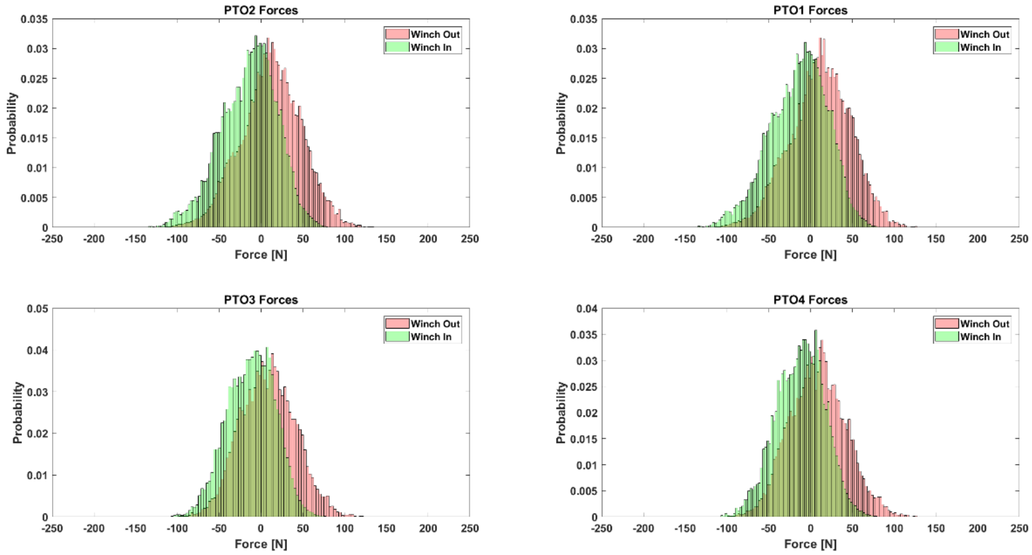
IWS4

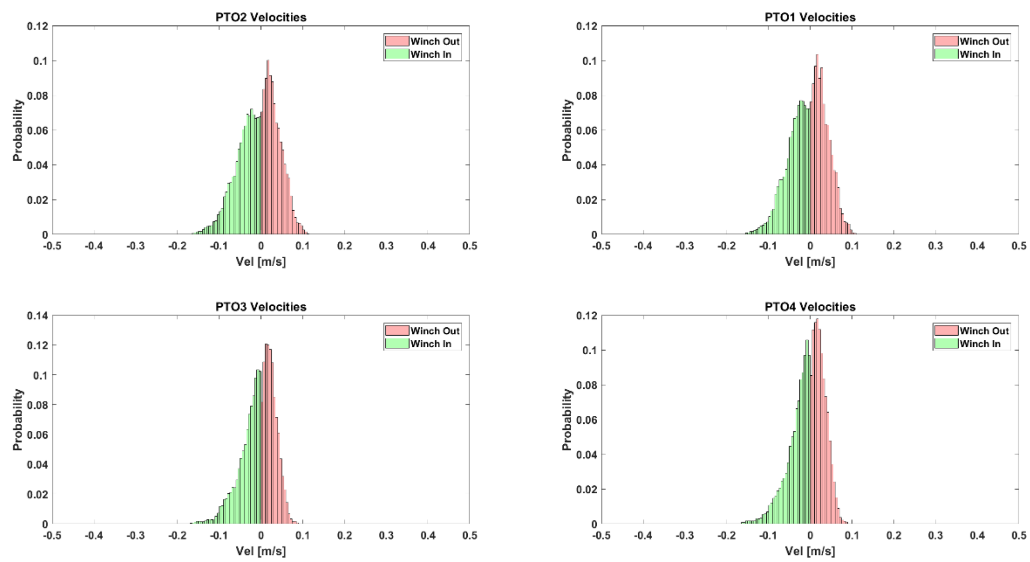

PTO Displacement
Displacement [m]
Time [s]
PTO1 (Upstream)
PTO2 (Upstream)
PTO3 (Downstream)
PTO4 (Downstream)
PTO Velocities
Velocity [m/s]
Time [s]
PTO1 Enc
PTO2 Enc
PTO3 Enc
PTO4 Enc
PTO1 Drv
PTO2 Drv
PTO3 Drv
PTO4 Drv
PTO Forces
Force [N]
Time [s]
PTO1
PTO2
PTO3
PTO4

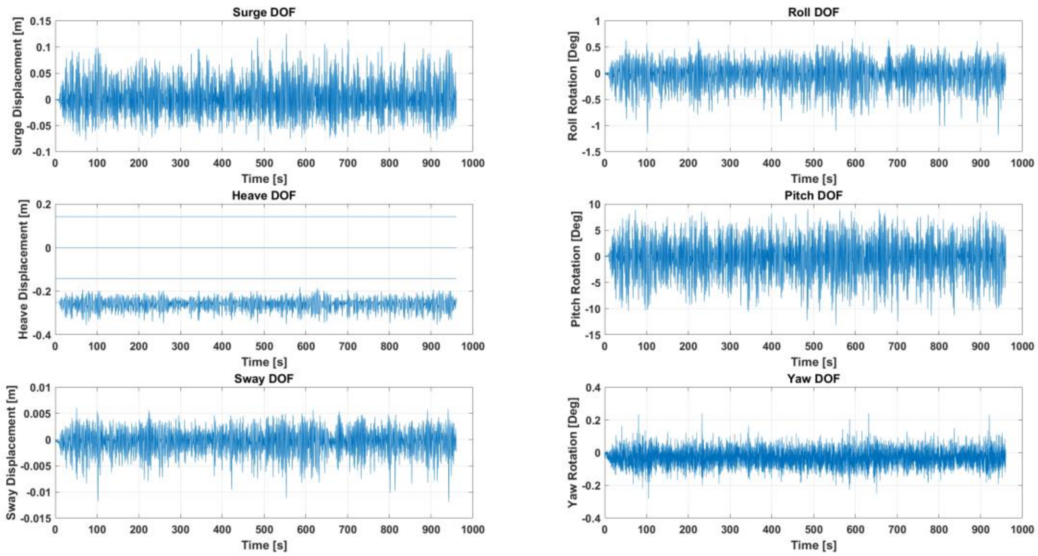

Filter Comparison on Force
Force [N]
Time [s]
PTO1 Raw Force
PTO1 Filt Force
Filter Comparison on Velocity
Velocity [m/s]
Time [s]
PTO1 Raw Vel
PTO1 Filt Vel

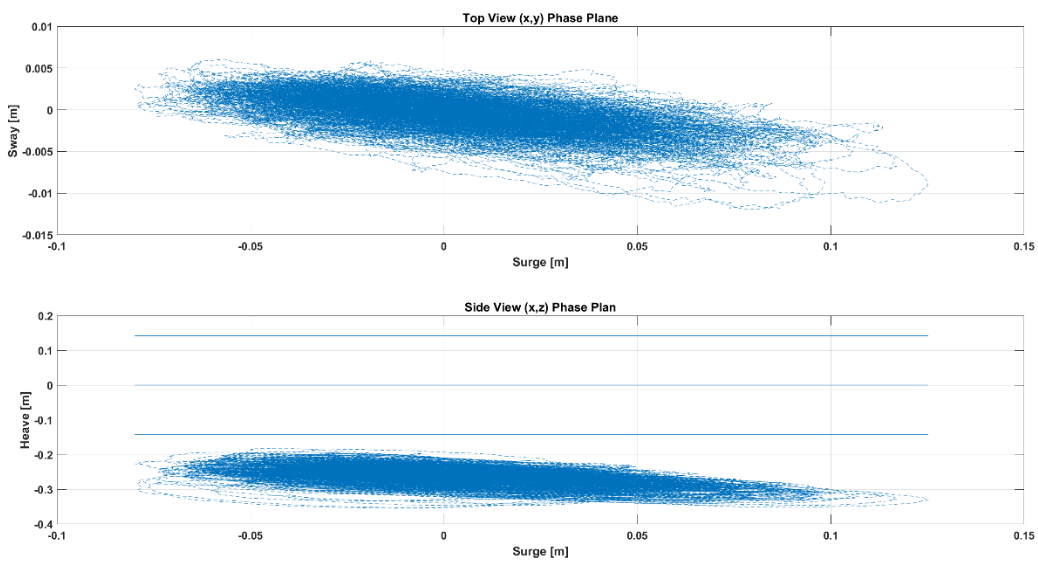

PTO1 Damper Force [N]
PTO1 Velocity [m/s]
data
fitted curve
data1

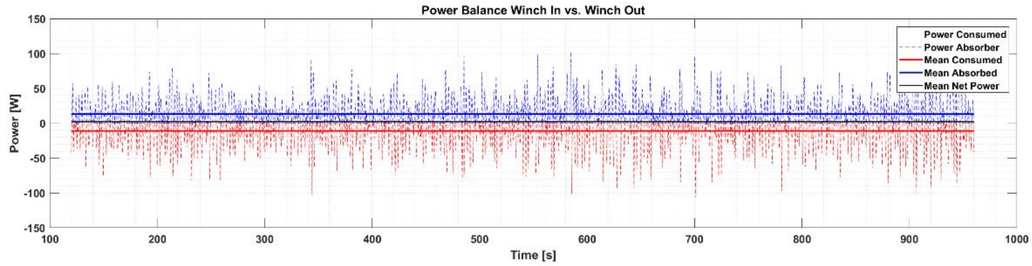

PTO Resoring Force [N]
PTO Position [m/s]
data
fitted curve
data1

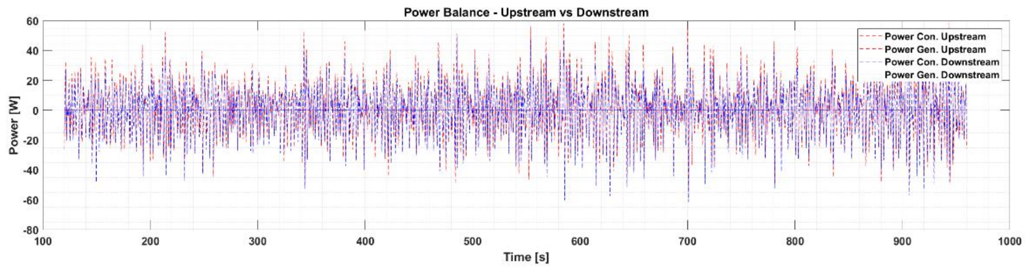

PTO2 Forces
PTO1 Forces
PTO3 Forces
PTO4 Forces
Winch Out
Winch In
Probability
Force [N]

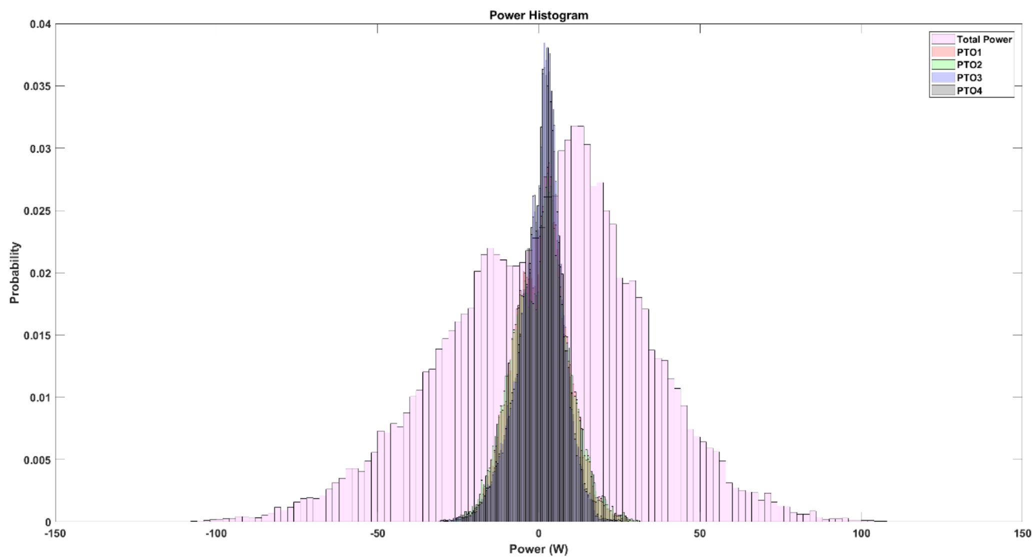

PTO2 Velocities
PTO1 Velocities
PTO3 Velocities
PTO4 Velocities
Winch Out
Winch In
Probability
Vel [m/s]


Surge DOF
Surge Displacement [m]
Time [s]
Roll DOF
Roll Rotation [Deg]
Time [s]
Heave DOF
Heave Displacement [m]
Time [s]
Pitch DOF
Pitch Rotation [Deg]
Time [s]
Sway DOF
Sway Displacement [m]
Time [s]
Yaw DOF
Yaw Rotation [Deg]
Time [s]

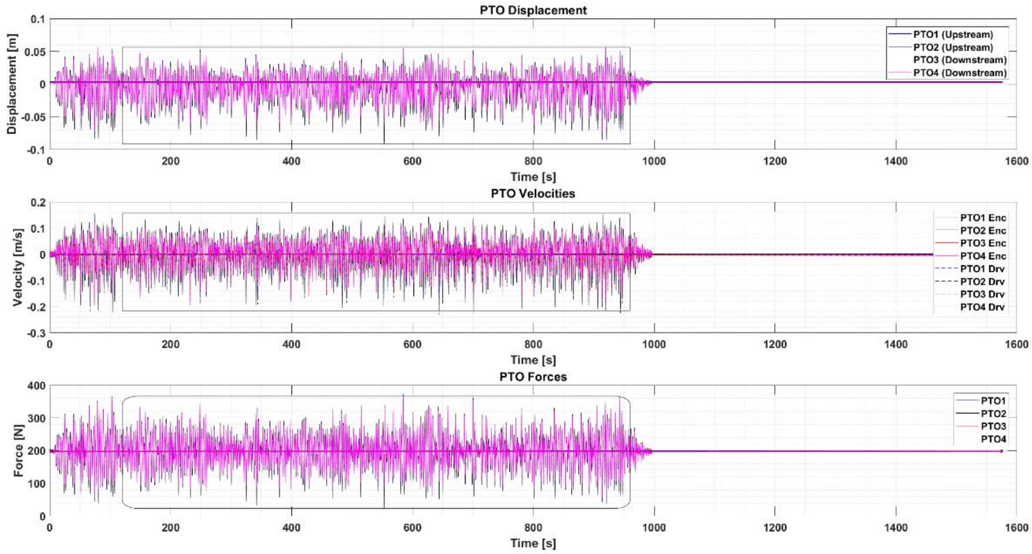

Top View (x,y) Phase Plane
Sway [m]
Surge [m]
Side View (x,z) Phase Plan
Heave [m]
Surge [m]

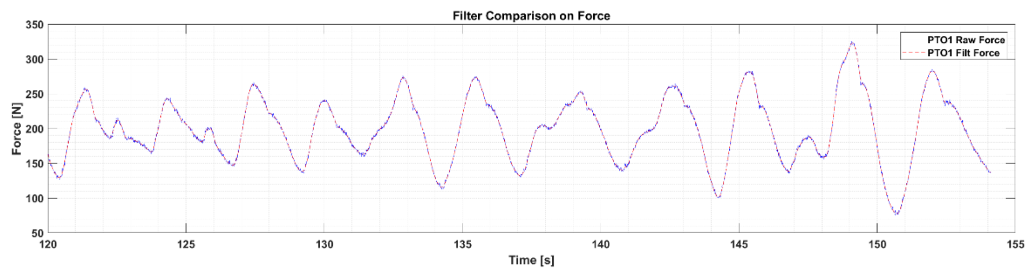

Power Balance Winch In vs. Winch Out
Power Consumed
Power Absorber
Mean Consumed
Mean Absorbed
Mean Net Power
Power [W]
Time [s]

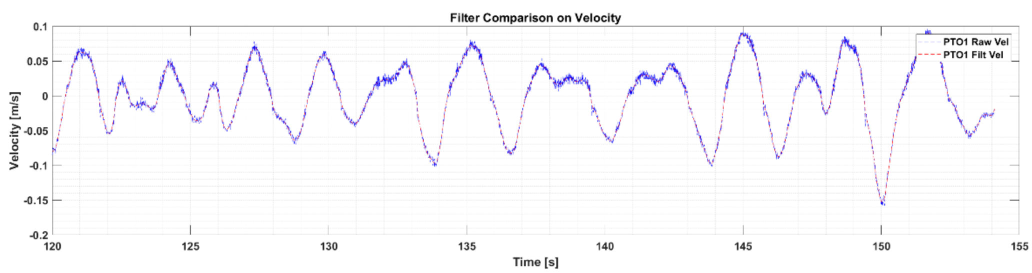

Power Balance - Upstream vs Downstream
Power Con. Upstream
Power Gen. Upstream
Power Con. Downstream
Power Gen. Downstream
Power [W]
Time [s]

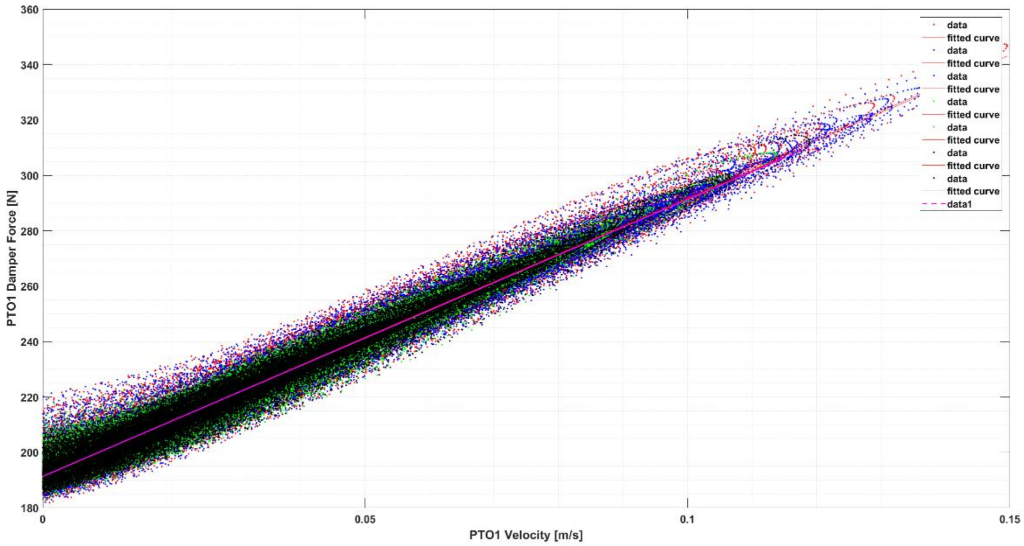

Power Histogram
Total Power
PTO1
PTO2
PTO3
PTO4
Probability
Power (W)

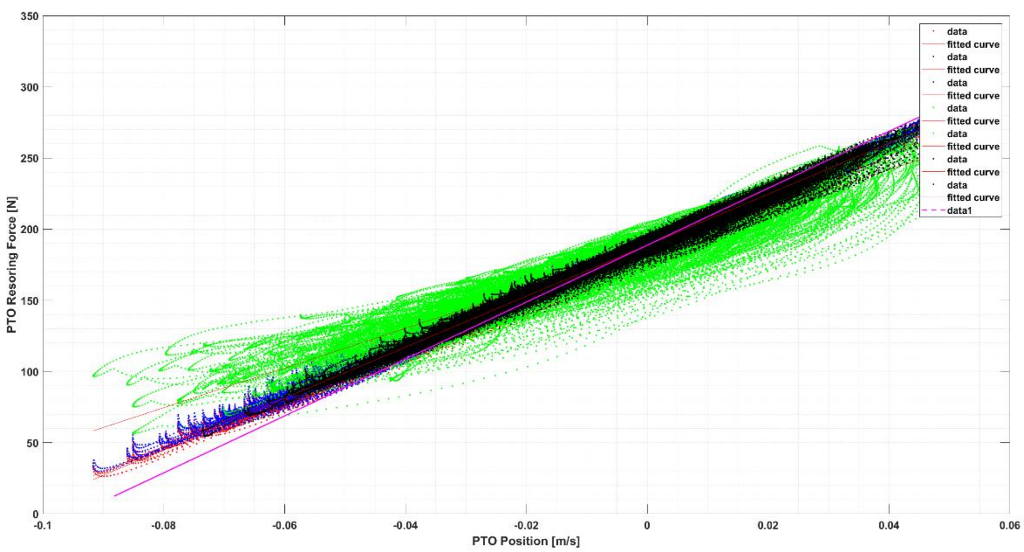
IWS5

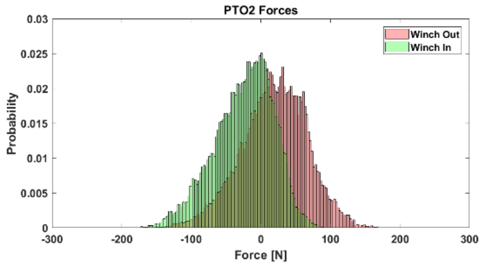

PTO Displacement
Displacement [m]
Time [s]
PTO1 (Upstream)
PTO2 (Upstream)
PTO3 (Downstream)
PTO4 (Downstream)
PTO Velocities
Velocity [m/s]
Time [s]
PTO1 Enc
PTO2 Enc
PTO3 Enc
PTO4 Enc
PTO1 Drv
PTO2 Drv
PTO3 Drv
PTO4 Drv
PTO Forces
Force [N]
Time [s]
PTO1
PTO2
PTO3
PTO4

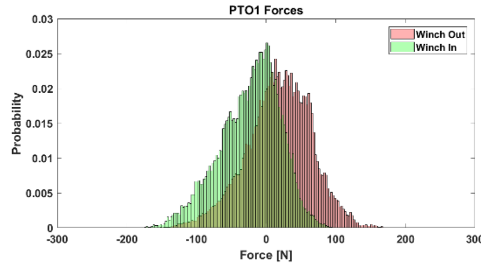

Filter Comparison on Force
Force [N]
Time [s]
PTO1 Raw Force
PTO1 Filt Force

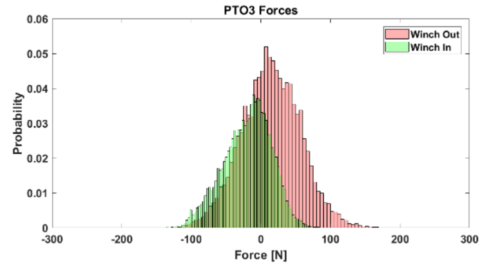

Filter Comparison on Velocity
Velocity [m/s]
Time [s]
PTO1 Raw Vel
PTO1 Filt Vel

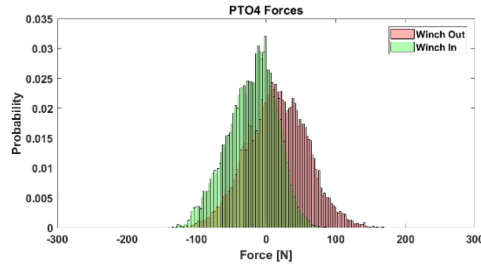

PTO1 Damper Force [N]
PTO1 Velocity [m/s]
data
fitted curve
data1

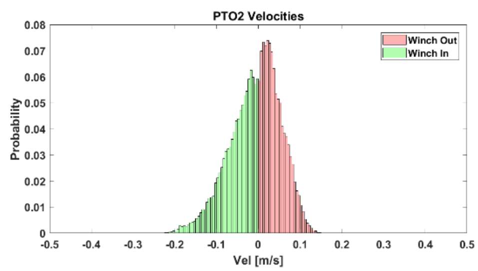

PTO Resoring Force [N]
PTO Position [m/s]
data
fitted curve
data1

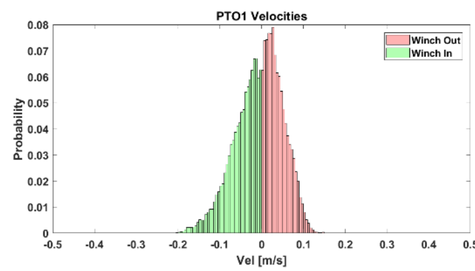

PTO2 Forces
Winch Out
Winch In
Probability
Force [N]

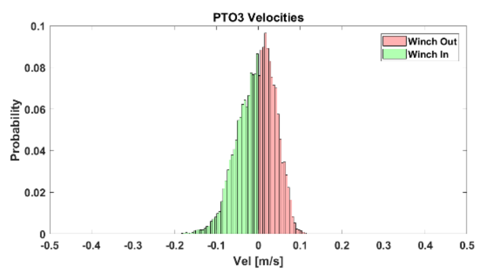

PTO1 Forces
Winch Out
Winch In
Probability
Force [N]

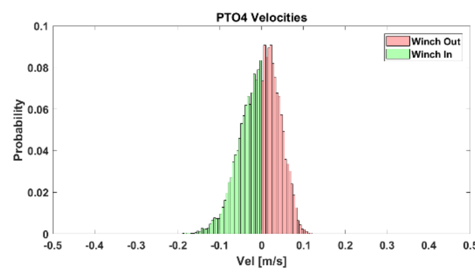

PTO3 Forces
Winch Out
Winch In
Probability
Force [N]

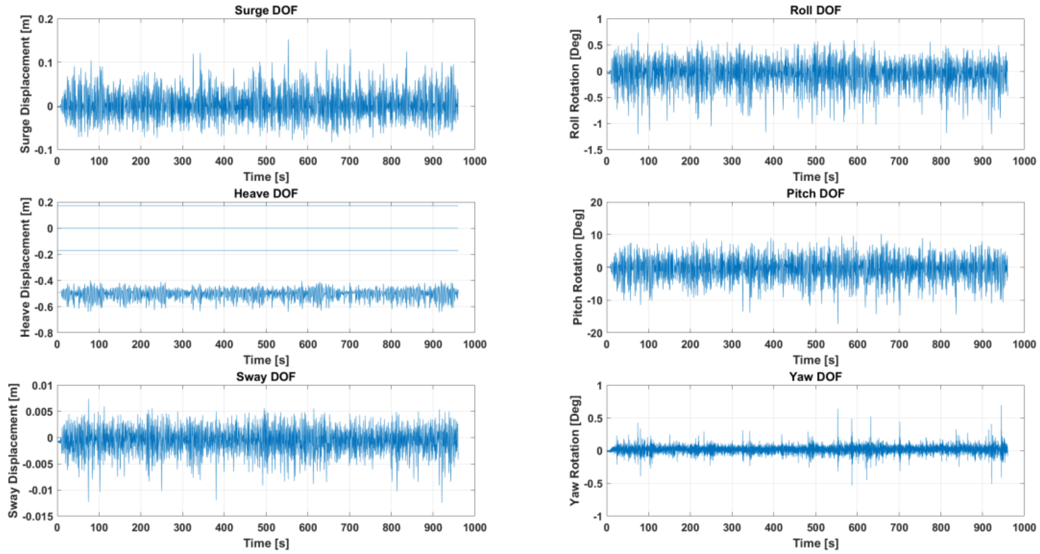

PTO4 Forces
Winch Out
Winch In
Probability
Force [N]

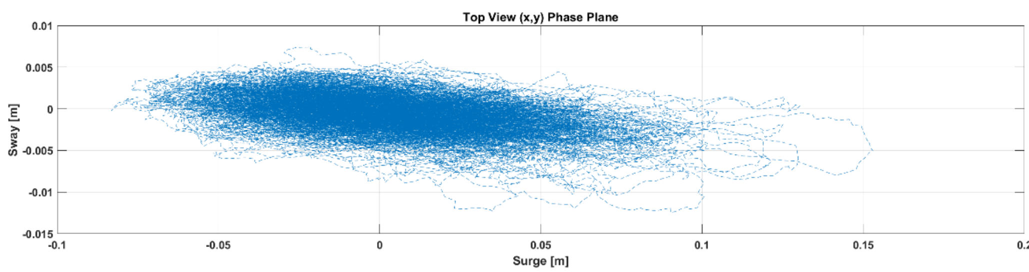

PTO2 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

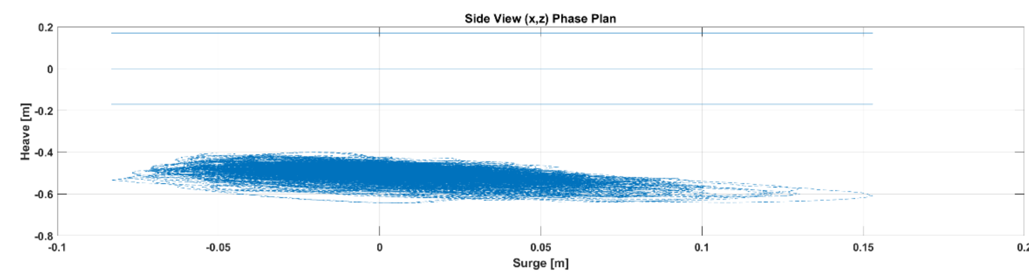

PTO1 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

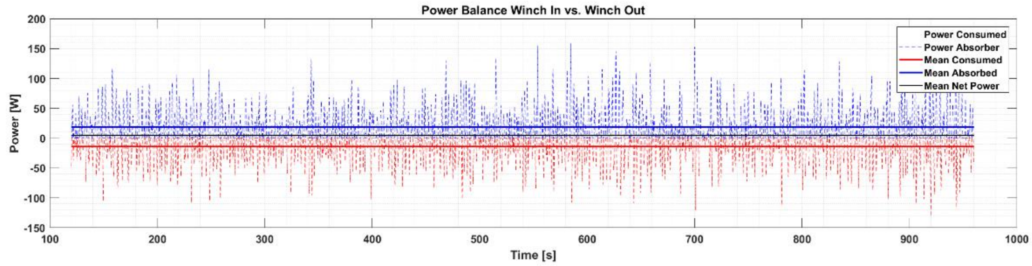

PTO3 Velocities
Winch Out
Winch In
Probability
Vel [m/s]


PTO4 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

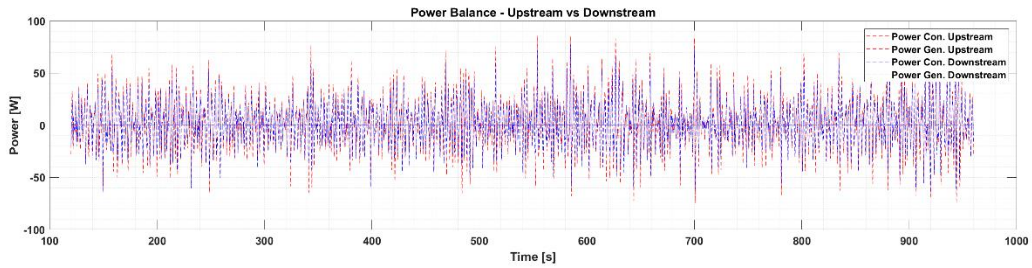

Surge DOF
Surge Displacement [m]
Time [s]
Roll DOF
Roll Rotation [Deg]
Time [s]
Heave DOF
Heave Displacement [m]
Time [s]
Pitch DOF
Pitch Rotation [Deg]
Time [s]
Sway DOF
Sway Displacement [m]
Time [s]
Yaw DOF
Yaw Rotation [Deg]
Time [s]


Top View (x,y) Phase Plane
Sway [m]
Surge [m]

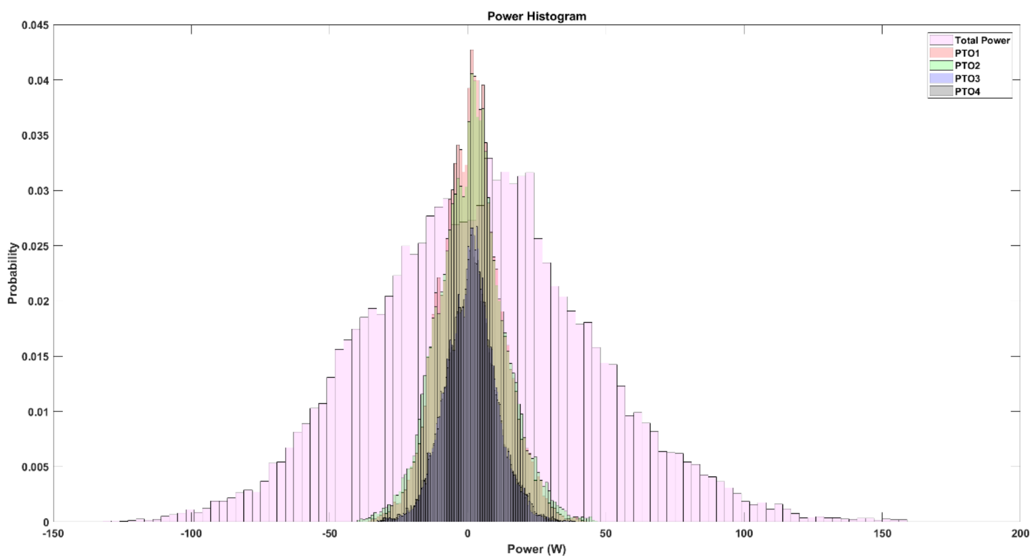

Side View (x,z) Phase Plan
Heave [m]
Surge [m]



Power Balance Winch In vs. Winch Out
Power Consumed
Power Absorber
Mean Consumed
Mean Absorbed
Mean Net Power
Power [W]
Time [s]

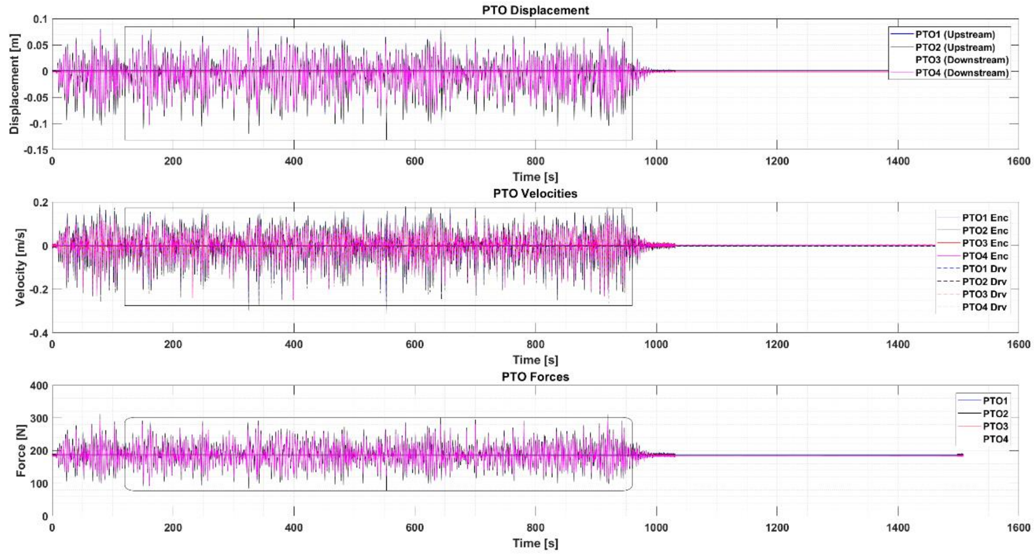


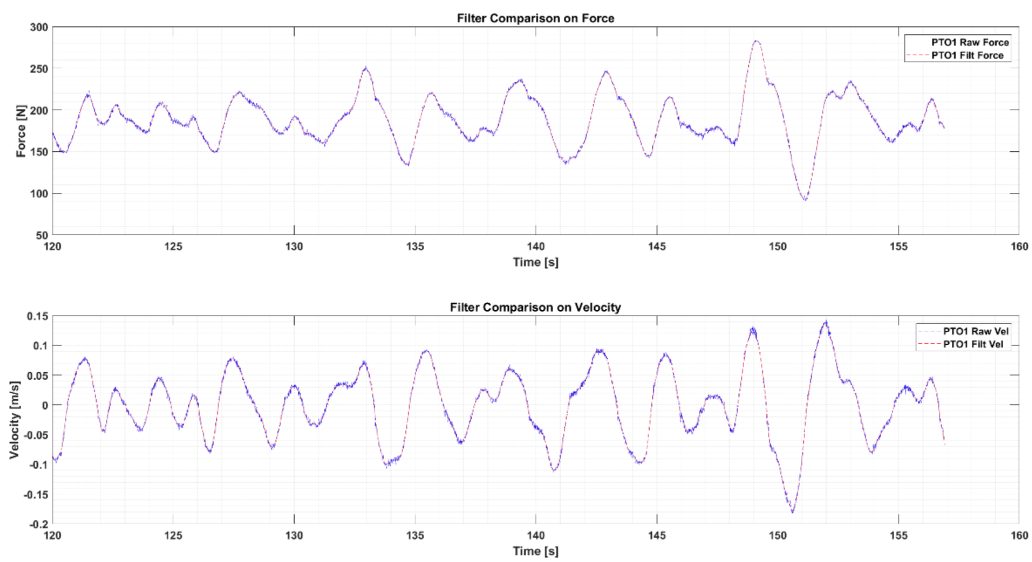
Power Balance - Upstream vs Downstream
Power Con. Upstream
Power Gen. Upstream
Power Con. Downstream
Power Gen. Downstream
Power [W]
Time [s]

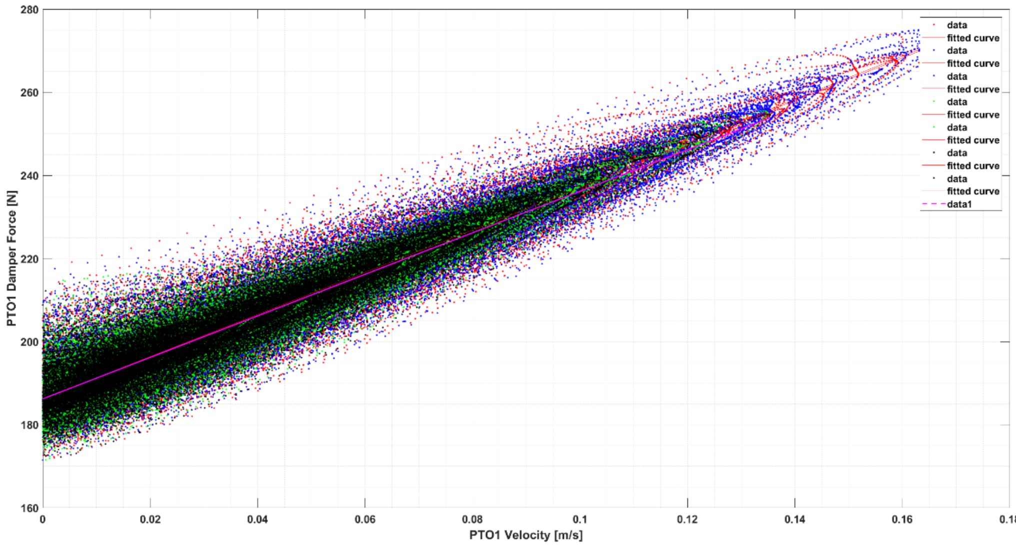


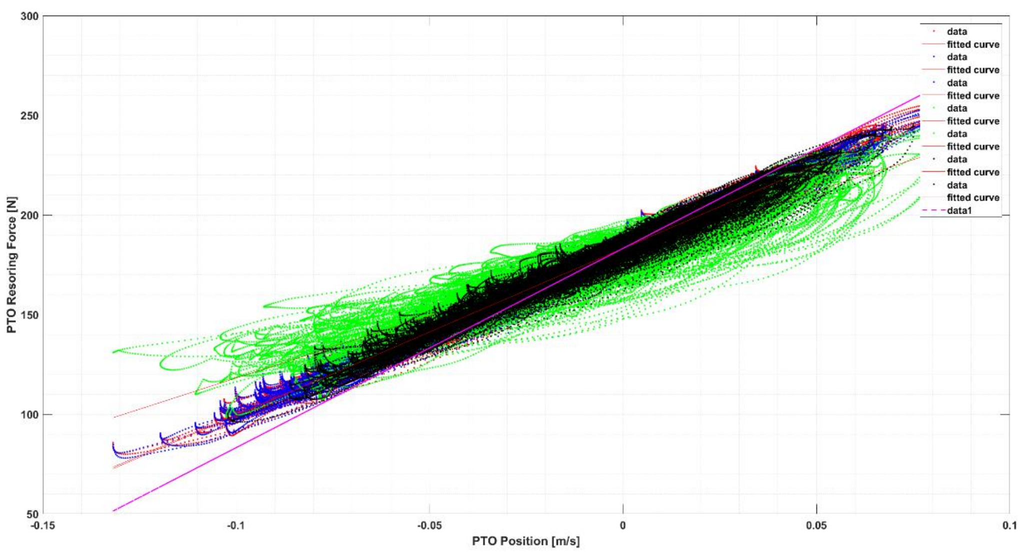
Power Histogram
Total Power
PTO1
PTO2
PTO3
PTO4
Probability
Power (W)

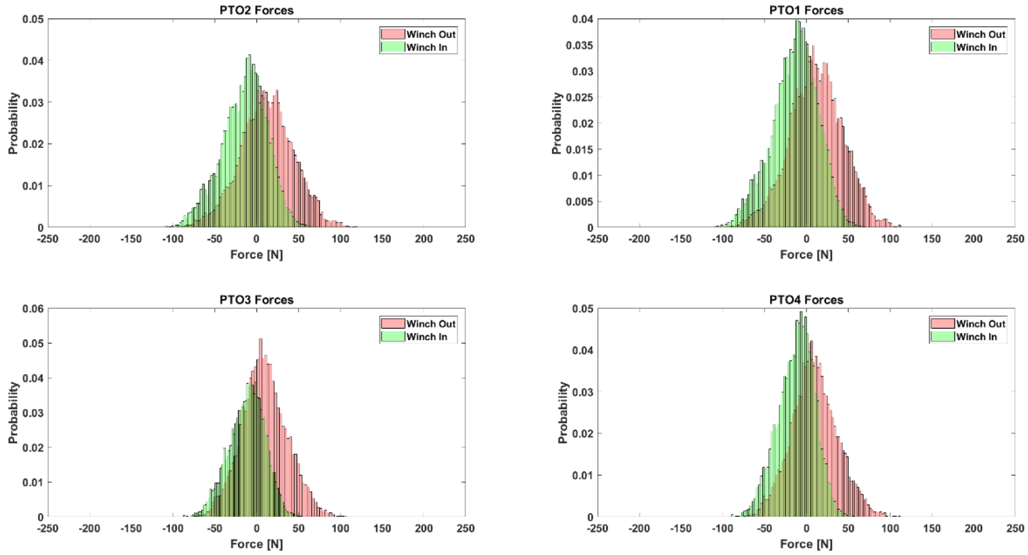
IWS6

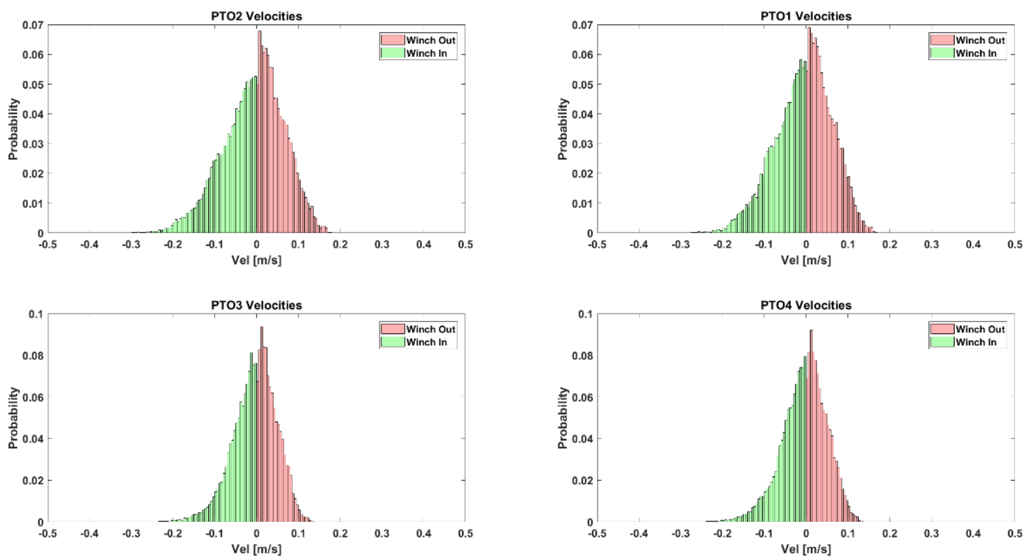

PTO Displacement
Displacement [m]
Time [s]
PTO1 (Upstream)
PTO2 (Upstream)
PTO3 (Downstream)
PTO4 (Downstream)
PTO Velocities
Velocity [m/s]
Time [s]
PTO1 Enc
PTO2 Enc
PTO3 Enc
PTO4 Enc
PTO1 Drv
PTO2 Drv
PTO3 Drv
PTO4 Drv
PTO Forces
Force [N]
Time [s]
PTO1
PTO2
PTO3
PTO4

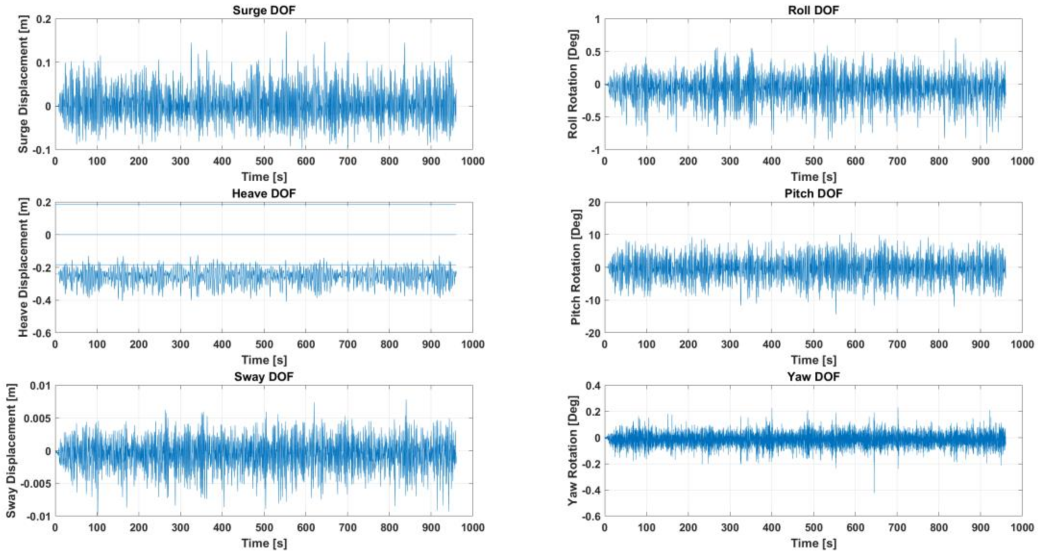

Filter Comparison on Force
Force [N]
Time [s]
PTO1 Raw Force
PTO1 Filt Force
Filter Comparison on Velocity
Velocity [m/s]
Time [s]
PTO1 Raw Vel
PTO1 Filt Vel

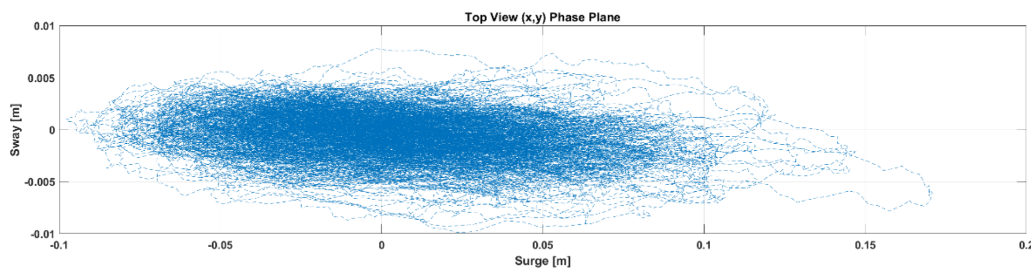

PTO1 Damper Force [N]
PTO1 Velocity [m/s]
data
fitted curve
data1
280
260
240
220
200
180
160
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

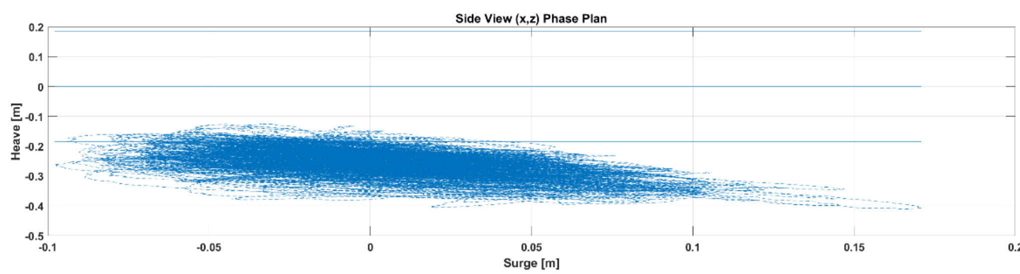

PTO Resoring Force [N]
PTO Position [m/s]
data
fitted curve
data1
300
250
200
150
100
50
-0.15
-0.1
-0.05
0
0.05
0.1

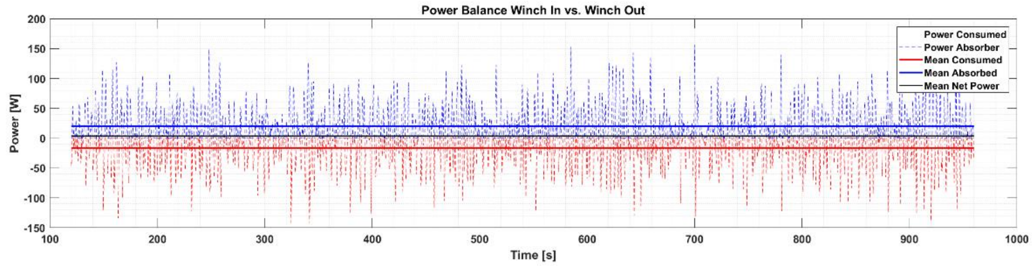

PTO2 Forces
PTO1 Forces
PTO3 Forces
PTO4 Forces
Winch Out
Winch In
Probability
Force [N]

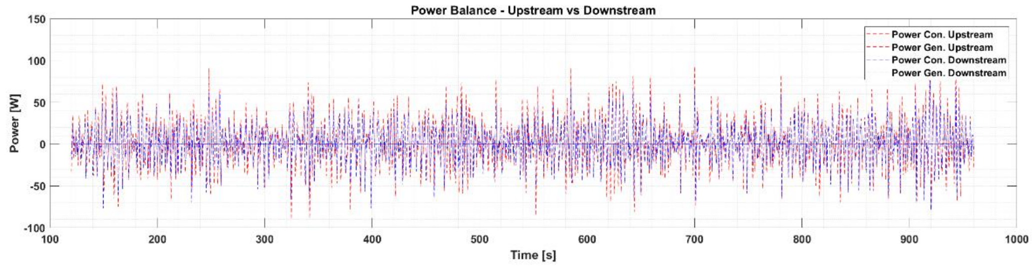

PTO2 Velocities
PTO1 Velocities
PTO3 Velocities
PTO4 Velocities
Winch Out
Winch In
Probability
Vel [m/s]

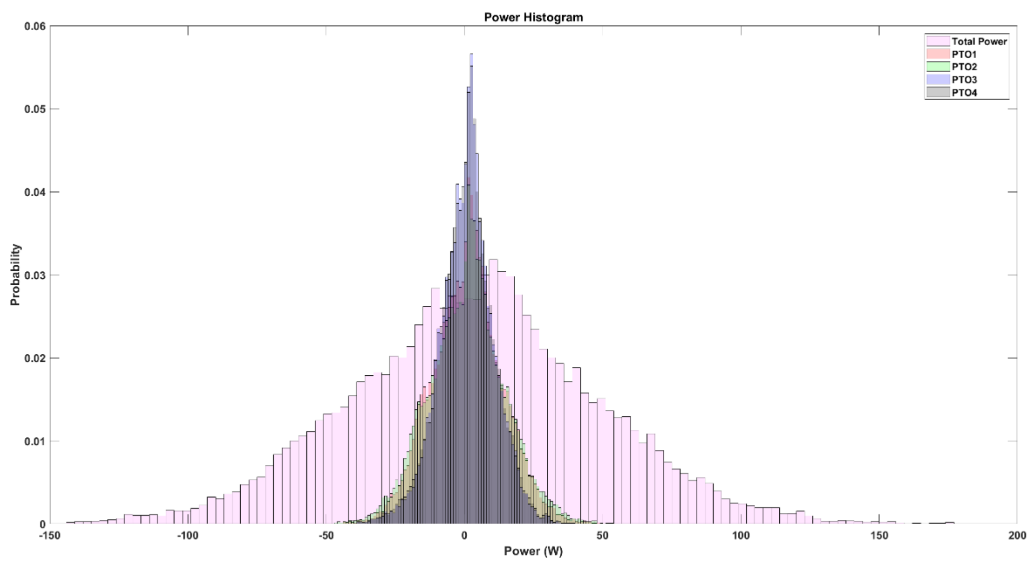

Surge DOF
Surge Displacement [m]
Time [s]
Roll DOF
Roll Rotation [Deg]
Time [s]
Heave DOF
Heave Displacement [m]
Time [s]
Pitch DOF
Pitch Rotation [Deg]
Time [s]
Sway DOF
Sway Displacement [m]
Time [s]
Yaw DOF
Yaw Rotation [Deg]
Time [s]


Top View (x,y) Phase Plane
Sway [m]
Surge [m]

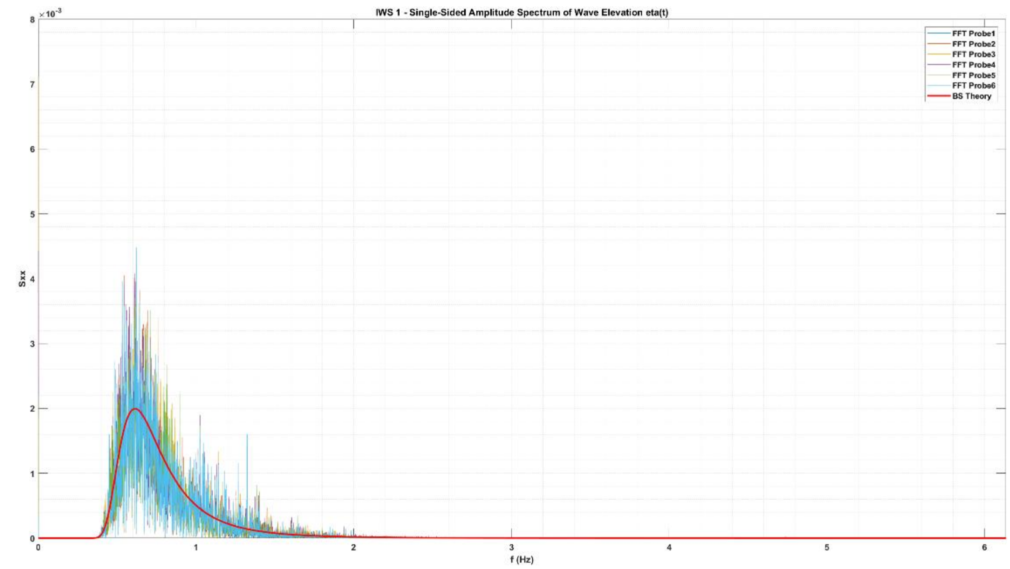

Side View (x,z) Phase Plan
Heave [m]
Surge [m]

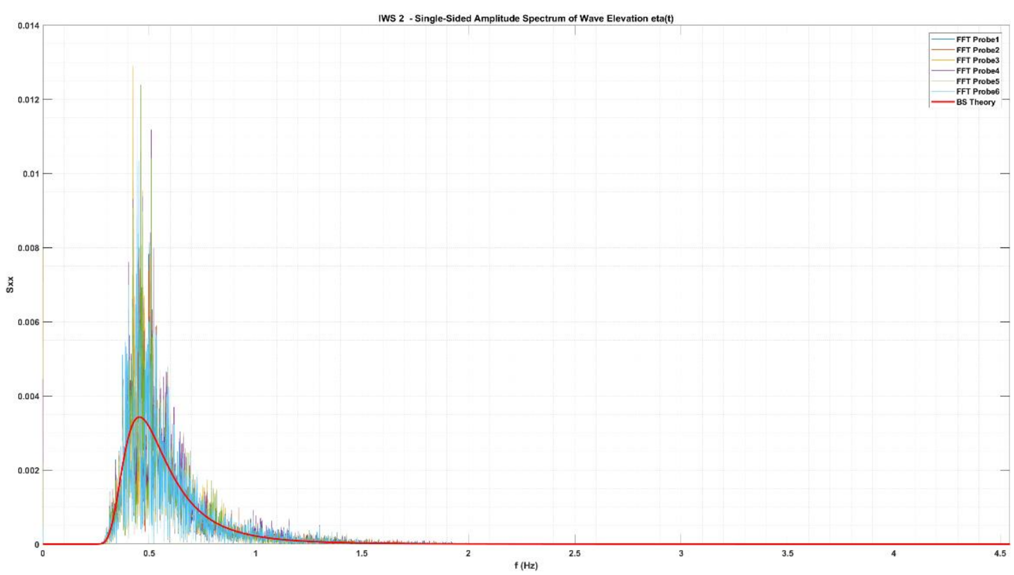

Power Balance Winch In vs. Winch Out
Power Consumed
Power Absorber
Mean Consumed
Mean Absorbed
Mean Net Power
Power [W]
Time [s]

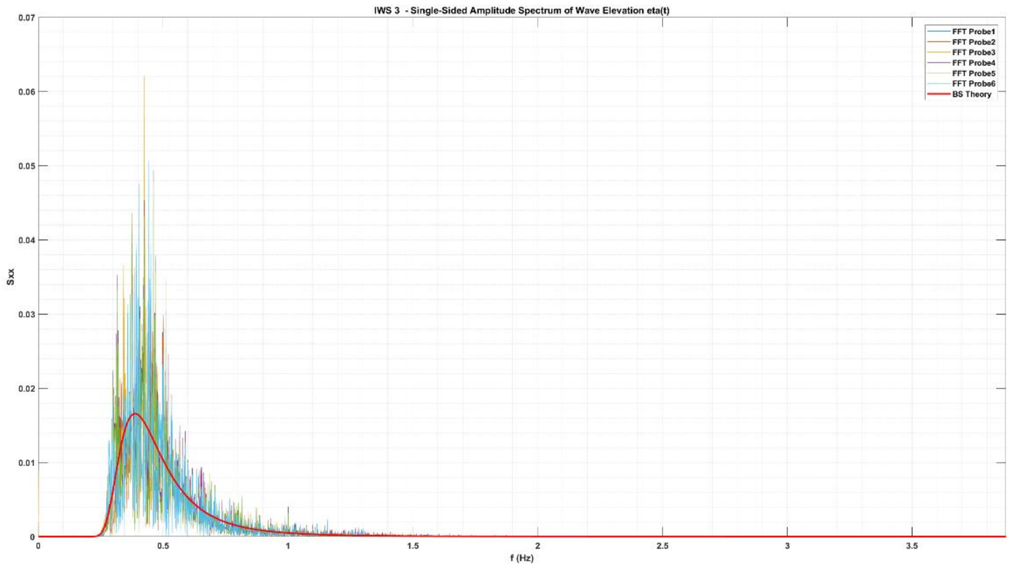

Power Balance - Upstream vs Downstream
Power Con. Upstream
Power Gen. Upstream
Power Con. Downstream
Power Gen. Downstream
Power [W]
Time [s]

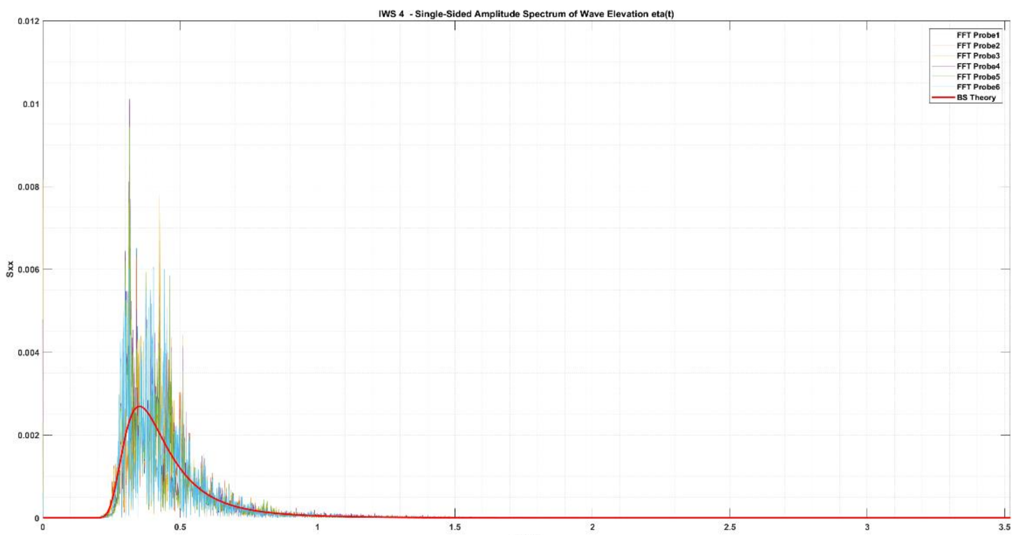

Power Histogram
Total Power
PTO1
PTO2
PTO3
PTO4
Probability
Power (W)

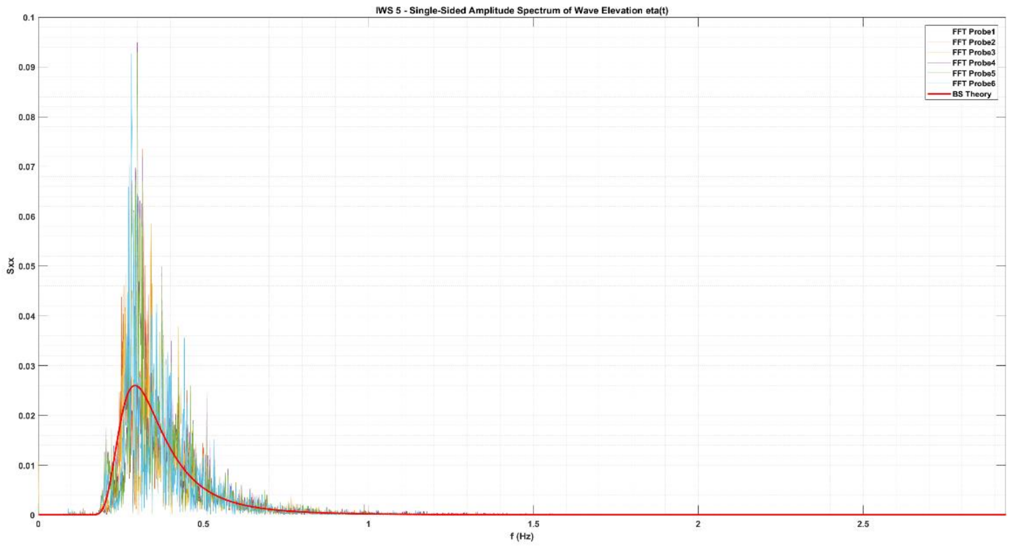
APPENDIX A: WAVE CALIBRATION IRREGULAR WAVES

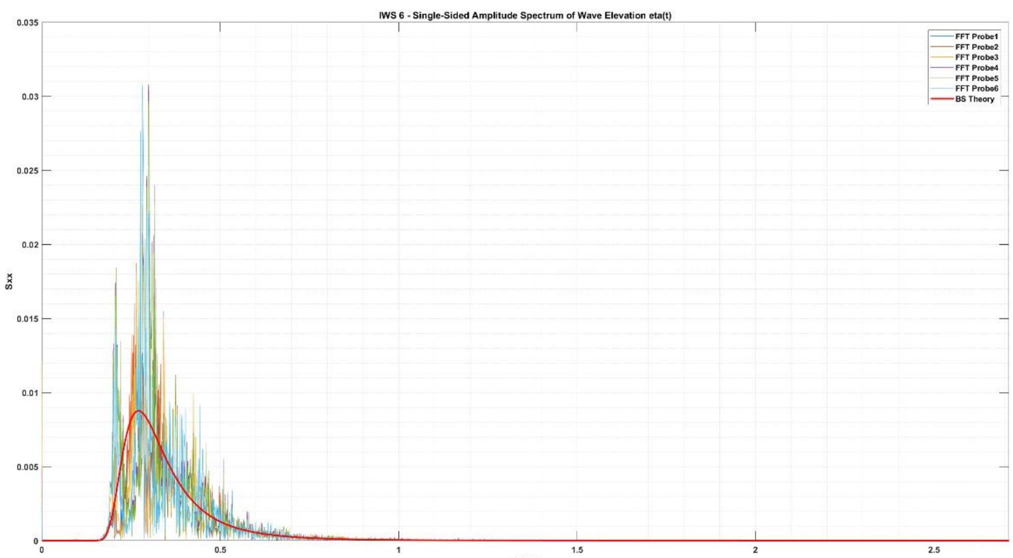


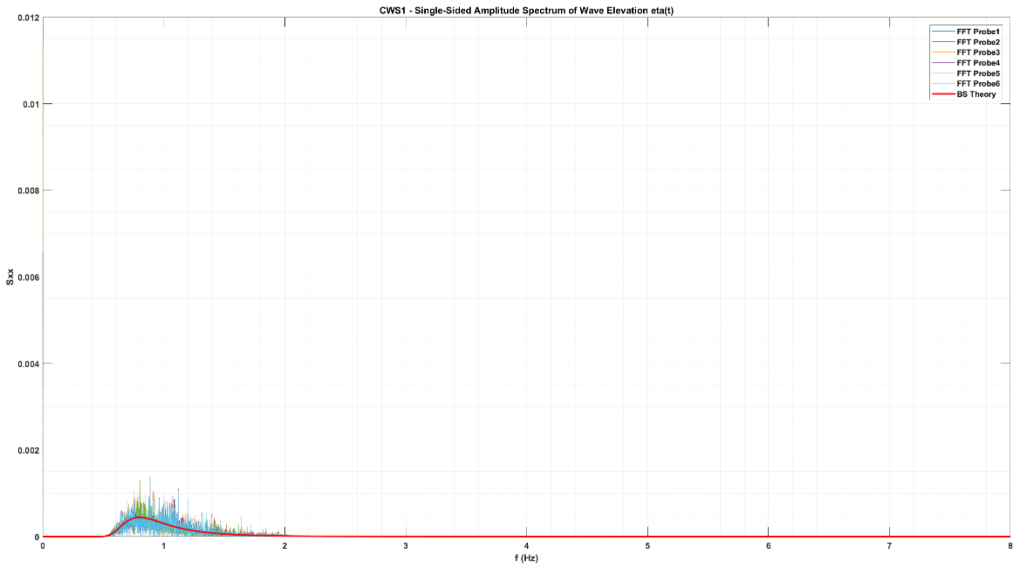


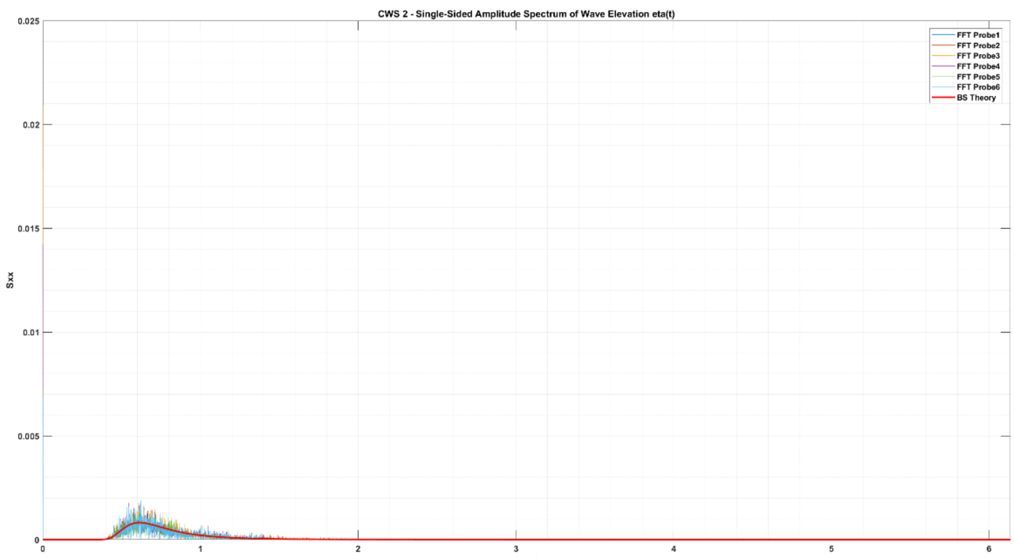

IWS 3 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)

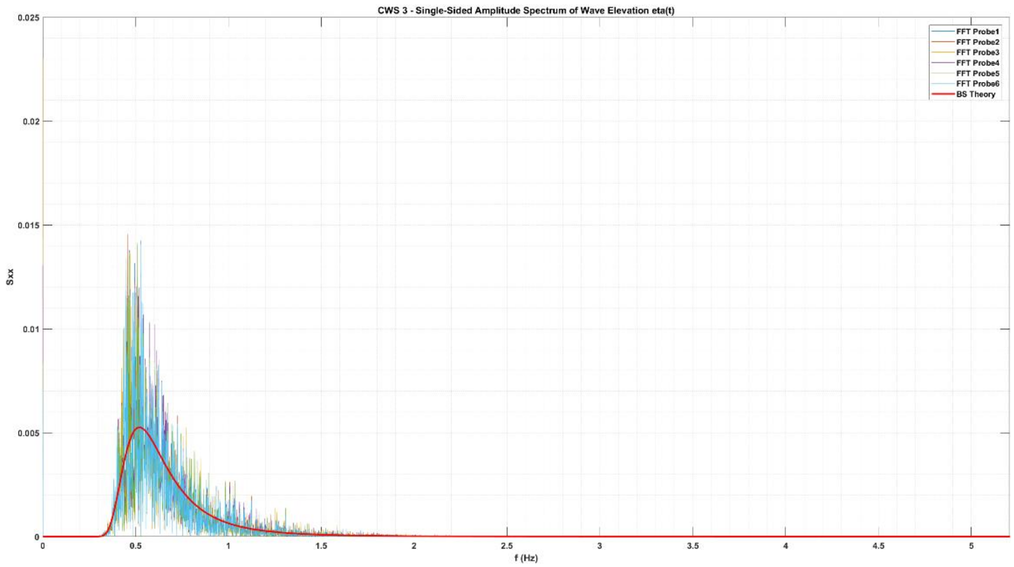

IWS 4 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)

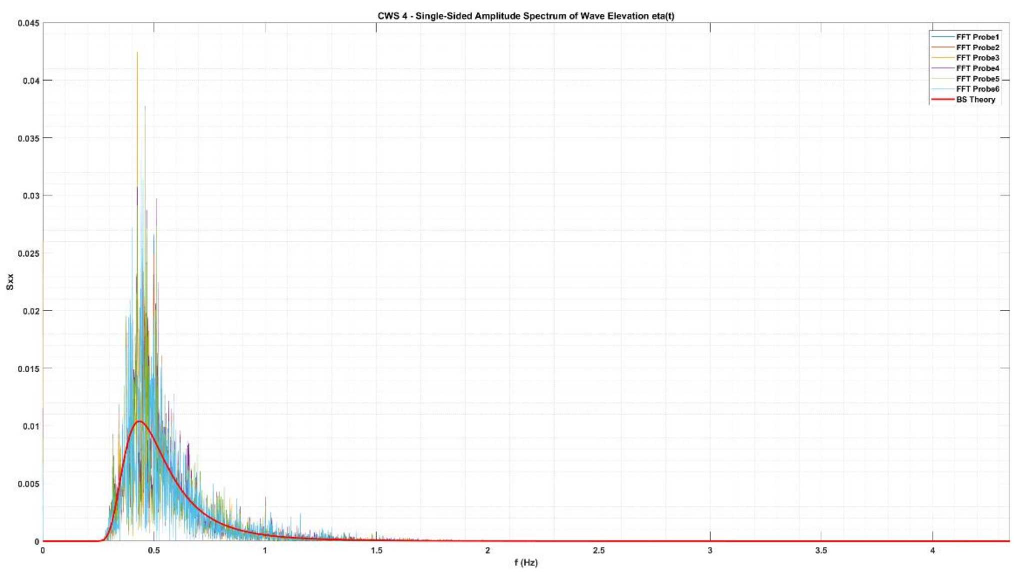

IWS 5 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


IWS 6 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS1 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS 2 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS 3 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)


CWS 4 - Single-Sided Amplitude Spectrum of Wave Elevation eta(t)
FFT Probe1
FFT Probe2
FFT Probe3
FFT Probe4
FFT Probe5
FFT Probe6
BS Theory
Sxx
f (Hz)