University of Strathclyde Glasgow

Improved FOWT support structure design through Instantaneous Centre of Rotation identification

EERA DeepWind

Katarzyna Patryniak[1], Maurizio Collu[1], Jason Jonkman[2], Matt Hall[1], Garrett Barter[1], Daniel Zalkind[1], Andrea Coraddu[3], Hector del Pozo Gonzalez

[1] Univ. of Strathclyde, [2] NREL, [3] TU Delft

January 17, 2024

The concept of Centre of Rotation

- What point/axis does a Floating Offshore Wind Turbine rotate (pitch) around?

The concept of Centre of Rotation

- What point/axis does a Floating Offshore Wind Turbine rotate (pitch) around?
- Common misconceptions in literature & practice

The concept of Centre of Rotation

- What point/axis does a Floating Offshore Wind Turbine rotate (pitch) around?
- Common misconceptions in literature & practice
- It depends!

The concept of Centre of Rotation

- What point/axis does a Floating Offshore Wind Turbine rotate (pitch) around?
- Common misconceptions in literature & practice
- It depends!
- Implications: design for reduced aero/mooring loads variability, asymmetric design, etc.

Methodology

How to (numerically) identify the Instantaneous Centre of Rotation of FOWT?

Instantaneous Centre of Rotation (ICR)

Definition

- Point of zero (translational) velocity at a given **instant** in time
- Intersection of normals to velocity vectors
- Depends on instantaneous load distribution

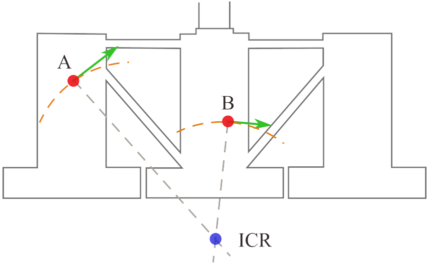
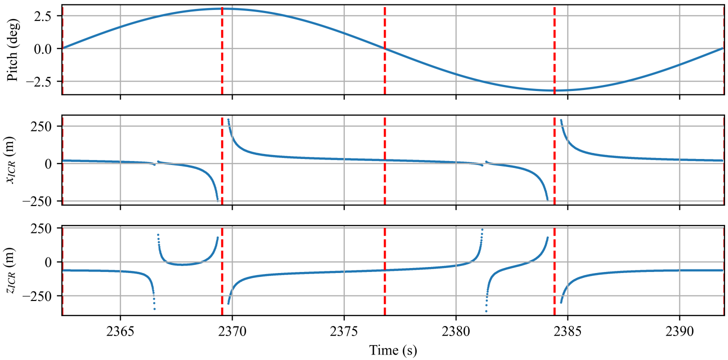


Figure: Construction of ICR

Instantaneous Centre of Rotation (ICR)

Example numerical result - time domain



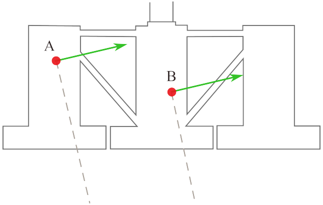


Figure: Construction of ICR

Figure: The ICR in regular waves in the time domain (OpenFAST)

Instantaneous Centre of Rotation (ICR)

Example numerical result - distribution

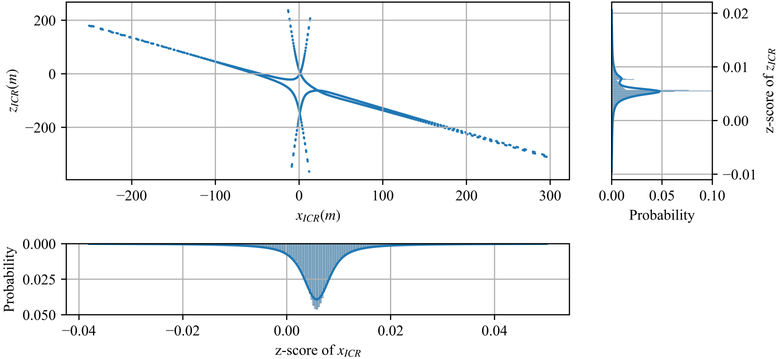


Figure: The ICR of FOWT simulated in regular waves - distribution of coordinates

Presentation order

1. Sensitivity of ICR to environmental loading

Presentation order

1. Sensitivity of ICR to environmental loading

2. Sensitivity of ICR to design variables

Presentation order

1. Sensitivity of ICR to environmental loading
2. Sensitivity of ICR to design variables
3. Case study (impact of ICR on FOWT responses)

University of Strathclyde Glasgow

Sensitivity to environmental loading

How does ICR change with changing environmental conditions?

Environmental conditions - test matrix

Table: Impact of varied environmental conditions on the ICR - conditions considered.

	Wind			Waves			Current
Group (-)	Type (-)	V_s (m/s)	TI (-)	Type (-)	H_s (m)	T_p (s)	V_c (m/s)
A	-	-	-	Reg	1.87	5-125	-
B	-	-	-	Reg	1.87	7.47	-
C	-	-	-	JONSWAP	1.87	7.47	-
D	Steady	3-25	-	Reg	1.87	7.47	-
E	Turbulent	11.4	0.1-0.3	Reg	1.87	7.47	-
F	-	-	-	Reg	1.87	7.47	0.5-1.2
G	Turbulent	11.4	0.17	JONSWAP	1.87	7.47	0.85

Effect of (regular) wave period

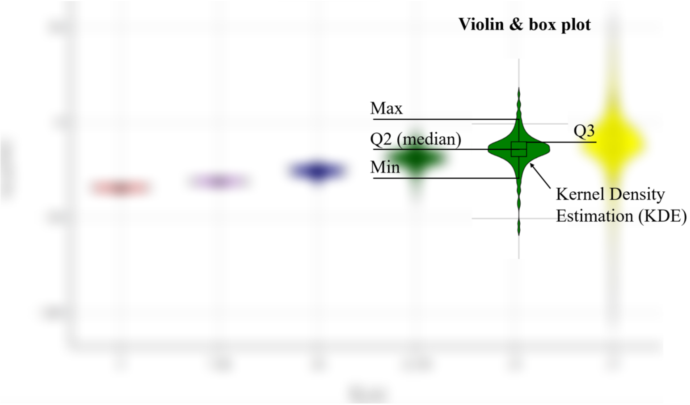


Figure: The ICR of FOWT simulated in regular waves - distribution of z coordinate

Effect of (regular) wave period

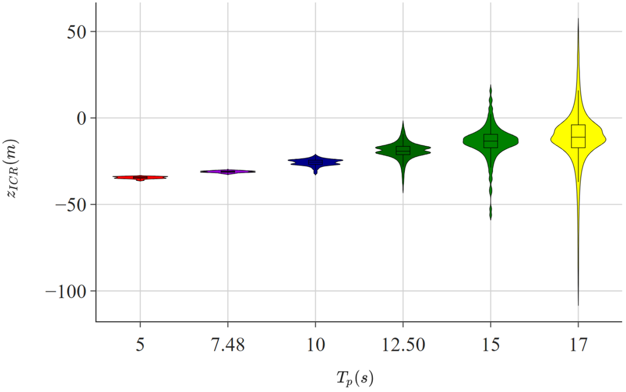


Figure: The ICR of FOWT simulated in regular waves - distribution of z coordinate

- Near-normal distribution of z_{ICR}
- The higher the period (lower frequency), the wider the distribution
- Mean of z_{ICR} gets closer to zero

Effect of (regular) wave period

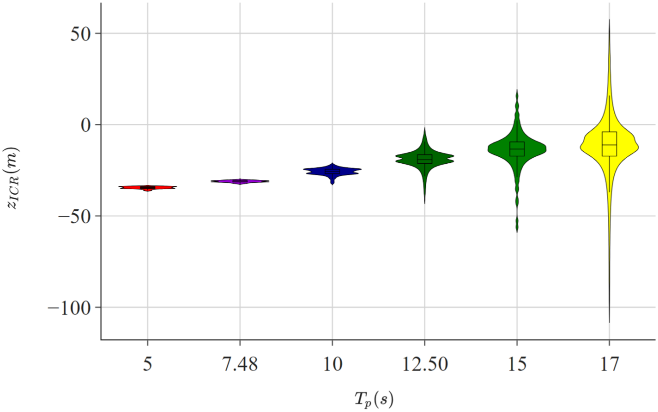


Figure: The ICR of FOWT simulated in regular waves

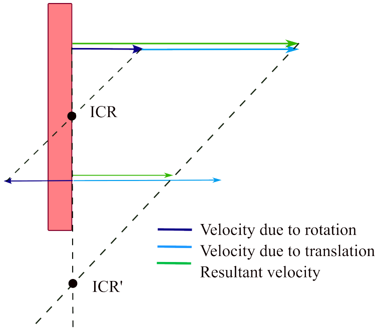


Figure: Transl. velocity effect

Effect of (steady) wind speed

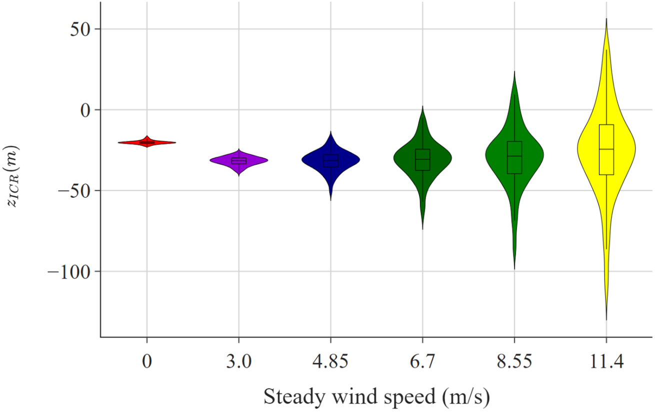


Figure: The ICR of FOWT in regular waves and steady wind - distribution of z coordinate

- The higher the wind speed, the wider the distribution
- non-monotonic median and mean

Effect of turbulence intensity

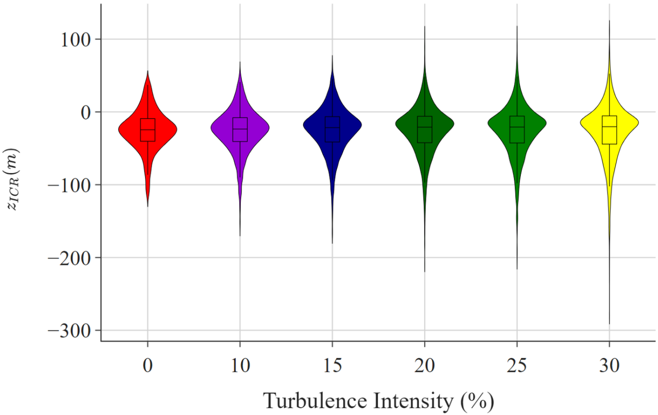


Figure: The ICR of FOWT in regular waves and turbulent wind - distribution of z coordinate

- No effect

Effect of current speed

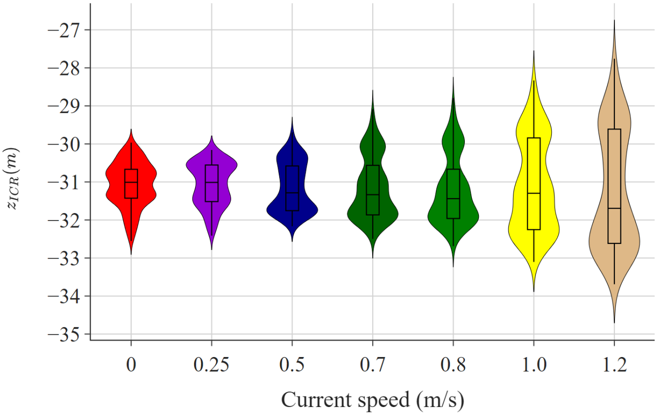


Figure: The ICR of FOWT in regular waves and current - distribution of z coordinate

- Relatively small effect

Effect of increasing loading complexity

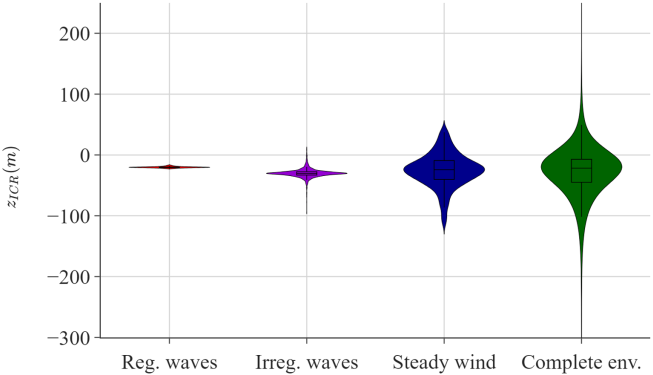


Figure: The ICR of FOWT in normal environment - distribution of z coordinate

- The higher the complexity, the wider the distribution

Effect of increasing loading complexity

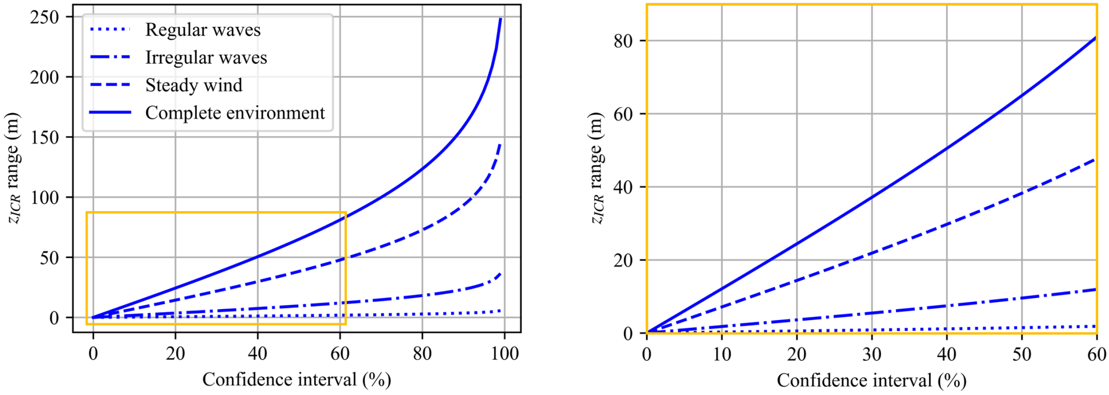


Figure: z_{ICR} range for different confidence intervals

Sensitivity to design features

How to design features influence ICR? I.e., how to "design" for ICR

Floating systems

Main characteristics & design variables

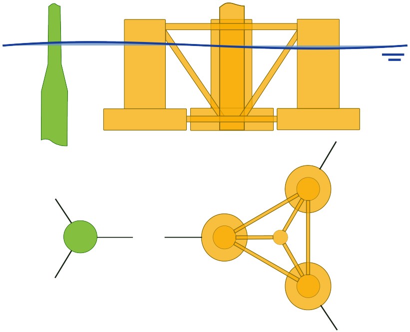


Figure: OC3 spar (left), OC4 semi (right)

Table: Original values of design variables. All values in [m]

	OC3 spar	OC4 semi
Draft	120.0	20.0
Waterline D	6.5	-
Platform CM	-89.92	-13.46
Offset column D	-	12.0
Heave plate D	-	24.0
Line length	902.2	835.5
Fairlead radius	5.2	40.87
Fairlead z	-70.0	-14.0
$E(E(z_{ICR}))$	-29.49	-5.03

Single variable sensitivity

OC3 spar & OC4 semi

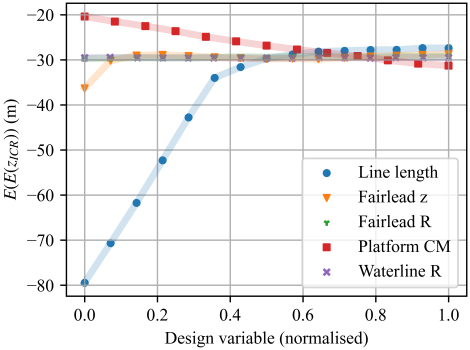


Figure: Sensitivity of z_{ICR} to spar variables

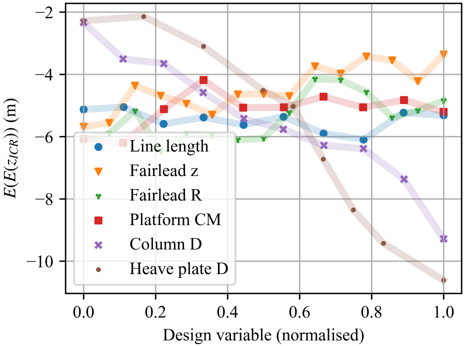


Figure: Sensitivity of z_{ICR} to semi variables

Single variable sensitivity

Spearman correlation coefficient

$$r_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

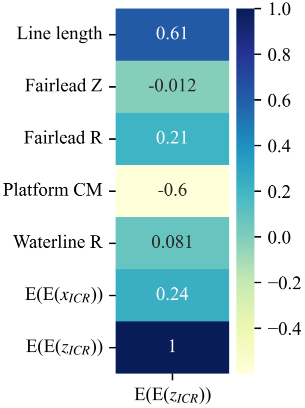


Figure: Sensitivity matrix: ICR and design variables - OC3 spar

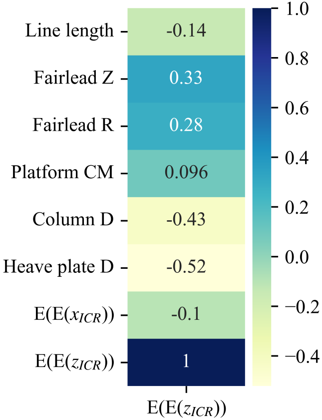


Figure: Sensitivity matrix: ICR and design variables - OC4 semi

Single variable sensitivity

Spearman correlation coefficient

$$r_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

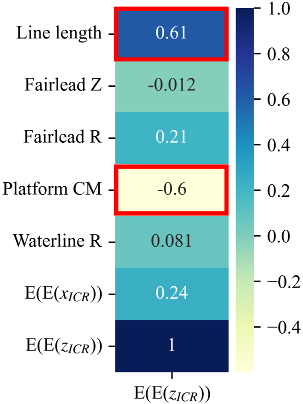


Figure: Sensitivity matrix: ICR and design variables - OC3 spar

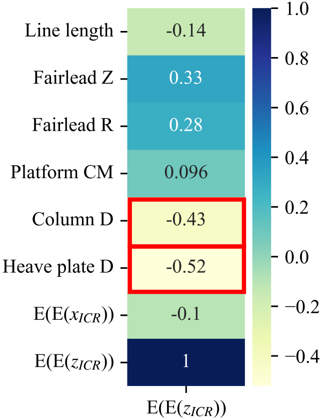


Figure: Sensitivity matrix: ICR and design variables - OC4 semi

Full factorial design

Two most significant variables

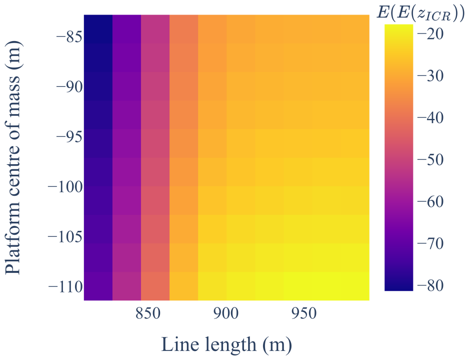


Figure: Design space - OC3 spar. Dominance of line length effect

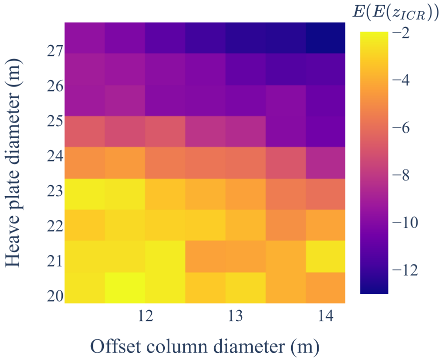


Figure: Design space - OC4 semi. Smaller members lead to higher z_{ICR}

University of Strathclyde Glasgow

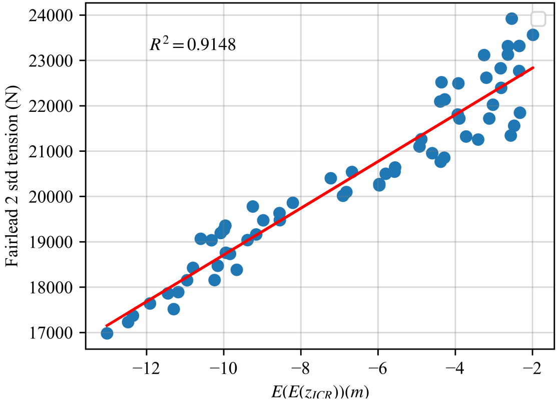
Case study

So what? How to use the knowledge of ICR

Case study

OC4 semi – effect of ICR on mooring tension

Figure: Standard deviation of tension vs $E(E(z_{ICR}))$ - OC4 semi



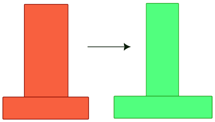
- Standard deviation of tension drives mooring line fatigue
- High correlation with $E(E(z_{ICR}))$
- Adjust design variables to lower $E(E(z_{ICR}))$

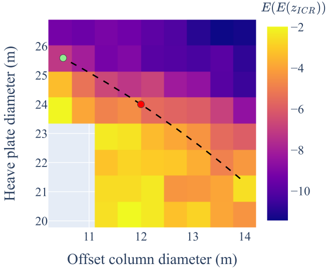
Case study

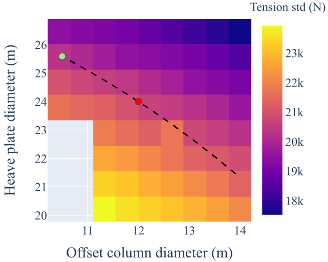
OC4 semi – setup

Change the column and heave plate diameters to shift $E(E(z_{ICR}))$ towards the fairlead ($z = -14m$) and reduce mooring tension amplitude.

- Column D: $12.0 \rightarrow 10.5$ m
- Plate D: $24.0 \rightarrow 25.59$ m







Case study

OC4 semi – results

- Volume/frontal area vertical distribution change
- Hydrodynamic load change
- Tension standard deviation driven by both surge motion and ICR

Table: Case study results. Tension: mean over the lines

Response	Original	Modified	Rel. difference
$E(E(z_{ICR}))$ (m)	-5.03	-7.73	53.70%
Surge std (m)	0.11	0.10	-1.48%
Line tension std (N)	1.03E+04	1.01E+04	-1.90%

Conclusions

- **The** centre of rotation does not exist! FOWT pitches about a point which depends on dynamic loading and can only be defined instantaneously

Conclusions

- **The** centre of rotation does not exist! FOWT pitches about a point which depends on dynamic loading and can only be defined instantaneously

- ICR presents near normal distribution which gets wider in more complex environmental conditions

Conclusions

- **The** centre of rotation does not exist! FOWT pitches about a point which depends on dynamic loading and can only be defined instantaneously
- ICR presents near normal distribution which gets wider in more complex environmental conditions
- ICR is most sensitive to design variables that tap into the main stability mechanism of a given floating concept

Conclusions

- **The** centre of rotation does not exist! FOWT pitches about a point which depends on dynamic loading and can only be defined instantaneously
- ICR presents near normal distribution which gets wider in more complex environmental conditions
- ICR is most sensitive to design variables that tap into the main stability mechanism of a given floating concept
- Design variables, ICR, and dynamic responses are highly correlated which complicates the analysis of specific ICR impacts.

Thank you!

Q&A

University of Strathclyde Glasgow