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Comparative study on dynamic response of offshore wind turbine with monopile and spar considering ice-structure interaction

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RAVE
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1. Background
2. Ice loads and ice failure mechanism
3. Ice-structure interaction model and simulation procedure
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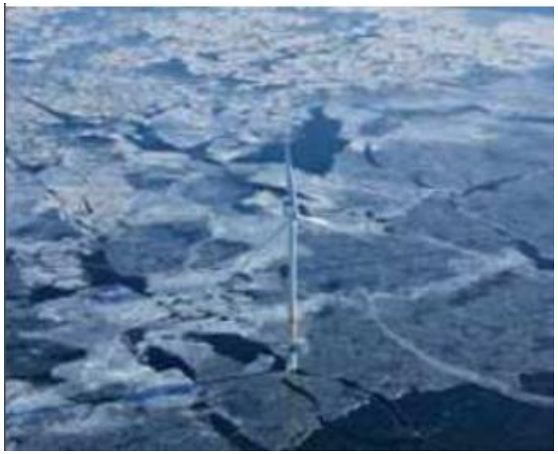
Background

- ✓ Offshore wind energy is an attractive technology for renewable energy
- ✓ Development of the offshore wind has great potential
- ✓ Big challenge to deploy OWT at sub-arctic areas, such as Great Lakes, Baltic Sea, Bohai Bay

Great Lakes



Baltic Sea

Bohai Bay

Background

- ✓ Ice loads introduces the most significant uncertainty for structural design in arctic/sub-arctic regions
  - Icing on the blade
  - Drifting ice acting on the support structure
- ✓ Ice can cause a wind energy project to lose up to 10% of production

Icing on the blade

(Northern Baltic Sea, Feb. 2011)

Drifting ice

Motivation

- ✓ Assessing local ice condition
- ✓ Understanding the ice failure mechanism
- ✓ Determine extreme response or fatigue damage of offshore wind turbine

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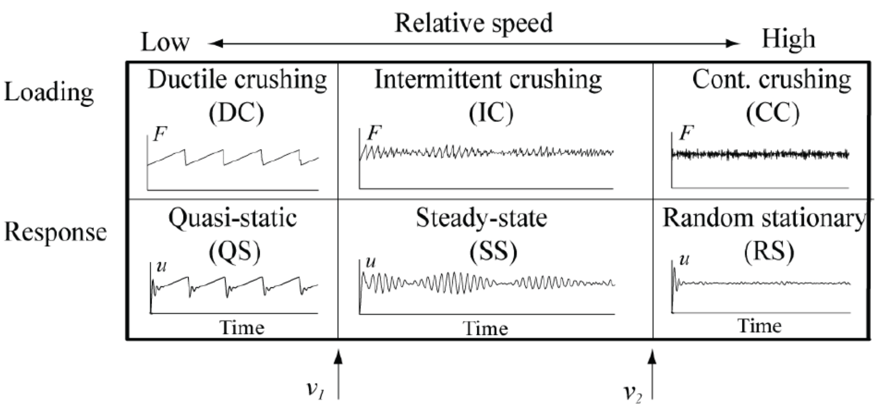
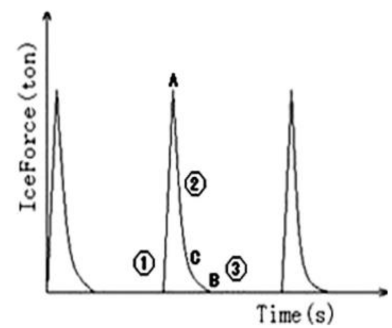
Investigate the ice-structure interaction using a numerical model for a wind turbine in Baltic Sea

Ice failure mechanism for level ice

Crushing failure (vertical structure)



Bending failure (conical structure)



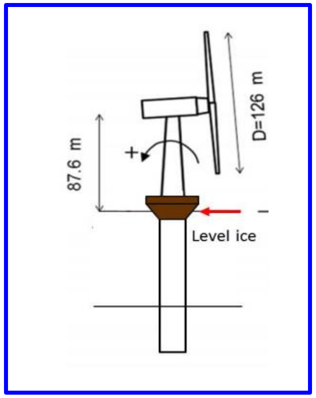
1. Loading
2. Unloading
3. Zero stable force

Focus on the interaction between level ice and OWT with ice-breaking cone

Downward ice-breaking cone

Upward ice-breaking cone

Analysis methods: Coupled Aero-hydro-servo-elastic model

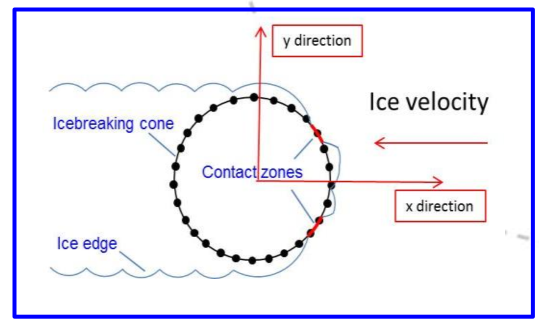


Monopile WT model (HAWC2)

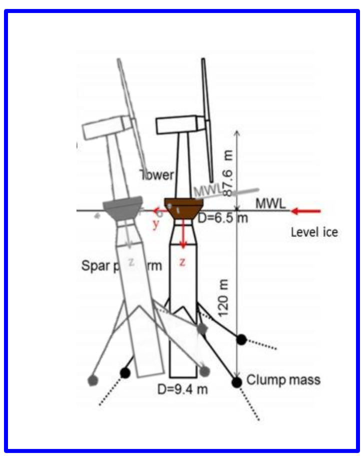
Positions
Velocities

DLL

Force & Moment



Ice-breaking model

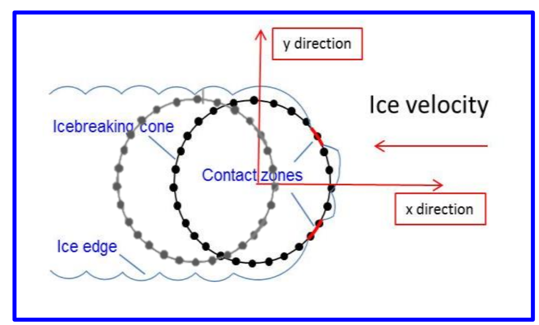


Spar WT model (HAWC2)

Positions
Velocities

DLL

Force & Moment

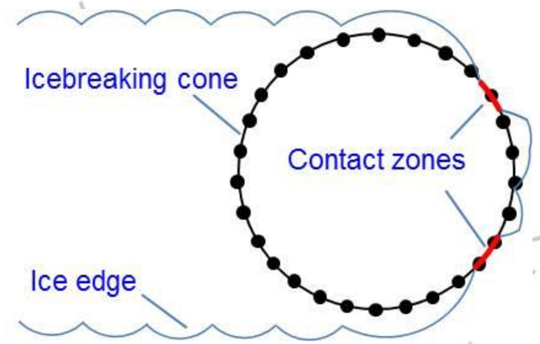


Ice-breaking model

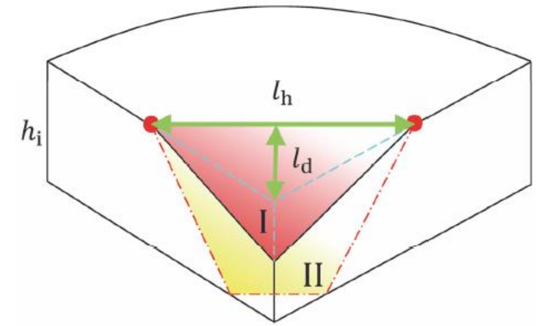
Ice breaking model

1. Contact detection
   - Detecting the overlap between the icebreaking waterline and the ice edge
   - Calculate contact area by

$$A_{cr} = \begin{cases} \frac{1}{2} L_h \frac{L_d}{\cos\varphi}, & L_d \tan\varphi \le h_i (\text{type I}) \\ \frac{1}{2}\left(L_h + L_h \frac{L_d - \frac{h_i}{\cos\varphi}}{L_d} \right), & L_d \tan\varphi > h_i (\text{type II}) \end{cases}$$



2. Contact pressure
   - Local contact pressure $p_{av} = kA_{cr}^{n}$
   - Local crushing force $F_{cr} = p_{av} A_{cr}$
3. The global ice load is obtained by integrating local contact loads all over the contact zones acting on the ice-breaking cone simultaneously.



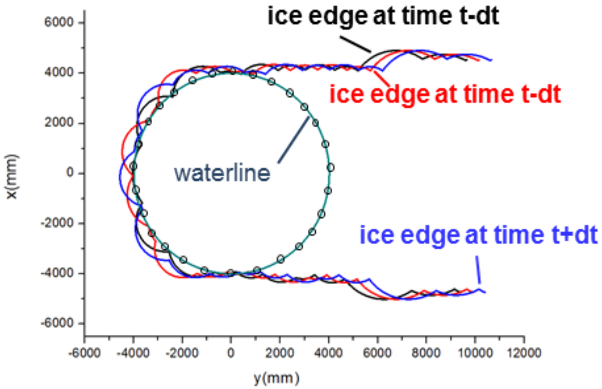
(Xiang, 2014)

Ice breaking model

4. The ice edge was broken according to the dynamic bending failure criterion.

$$P_f = \left(1.65 + 2.47 v_2^{0.4}\right) \sigma_f h_i^2 \left(\frac{\theta_w}{\pi}\right)^2$$

5. Once the ice edge has broken away from the ice sheet, a new ice edge is generated and the next icebreaking cycle begins.



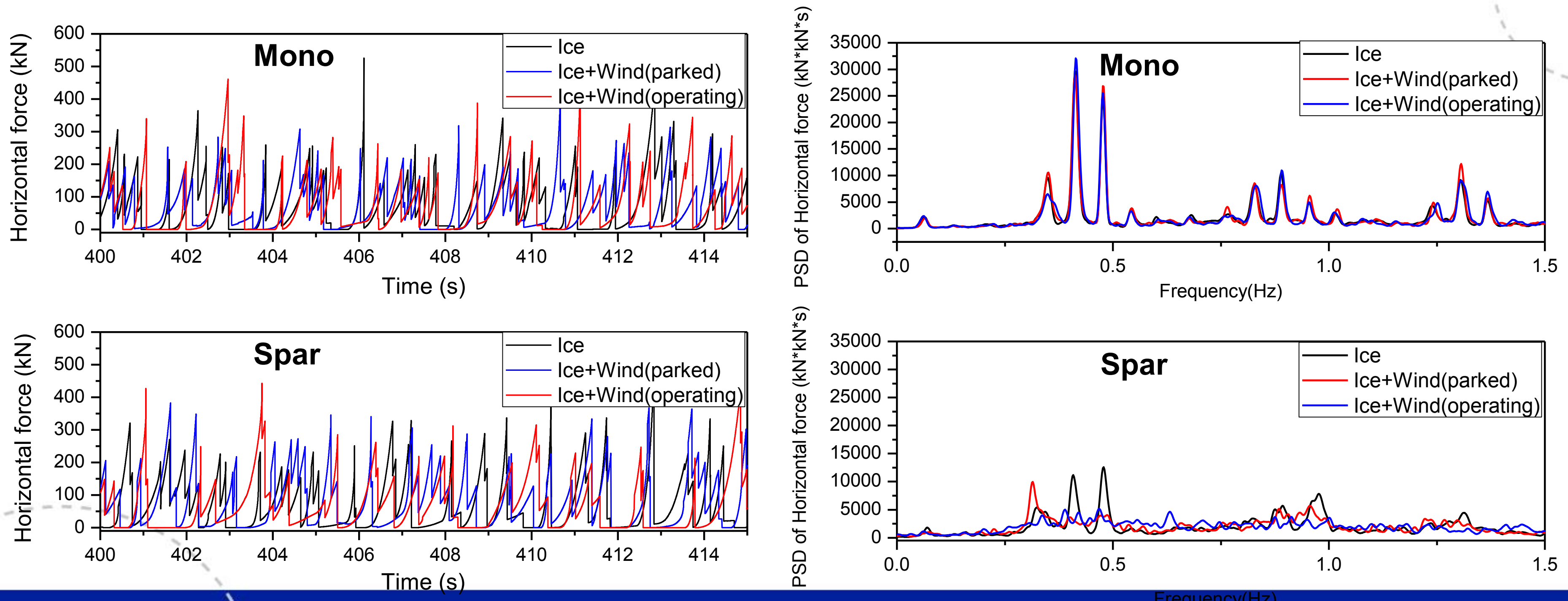
6. The structure motion and icebreaking pattern affect each other simultaneously.

Combined environmental conditions

LC	Conditions		mono	spar
	ice	wind		
LC1	V_i=0.5 m/s h_i=0.4 m	no	LC1_mono	LC1_spar
LC2	no	V_w=18 m/s turbulent	LC2_mono	LC2_spar
LC3	V_i=0.5 m/s h_i=0.4 m	V_w=18 m/s parked	LC3_mono	LC3_spar
LC4	V_i=0.5 m/s h_i=0.4 m	V_w=18 m/s turbulent	LC4_mono	LC4_spar

Comparison——Ice loads

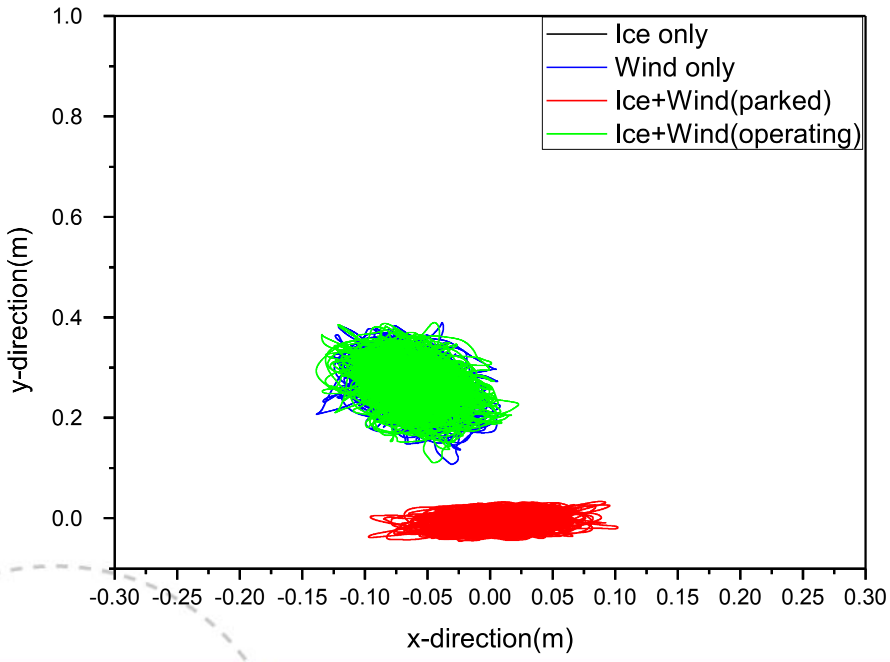
- The ice loads for spar-type FOWT are slightly smaller than the monopile due to large motion of floating wind turbine.
- For the monopile, all the load cases have same ice breaking frequencies because the relative motion of the structure is not significant. At loading frequency of 0.35 Hz, monopile under operating condition experiences smaller ice loads.
- For the spar, ice breaking frequencies shift between different load cases due to large relative motion. Non-simultaneous failure is dominant for spar-WT under operating.



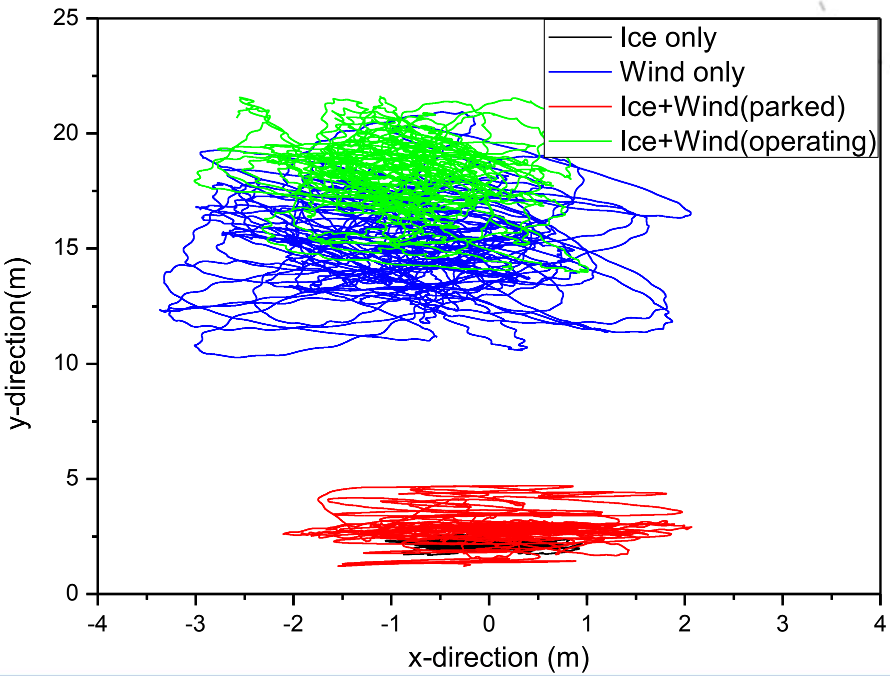
Comparison——Tower top trajectory

- The motion of the spar-WT is significant larger than monopile-WT.
- Wind loads are the main source of the monopile- and spar- WT motion.
- The tower top displacement is smaller when the spar-WT is operated under ice and wind load cases compared with load case of wind only. The interaction of ice and structure could reduce the motion of the spar.

Mono



Spar



Comparison——dynamic response

Fy at MSL (kN)	item	mono	spar
Ice only	mean±std	70±119	20±55
Wind only	mean±std	340±100	617±146
Ice+wind(parked)	mean±std	81±101	43±61
Ice+wind(operating)	mean±std	410±131	655±131

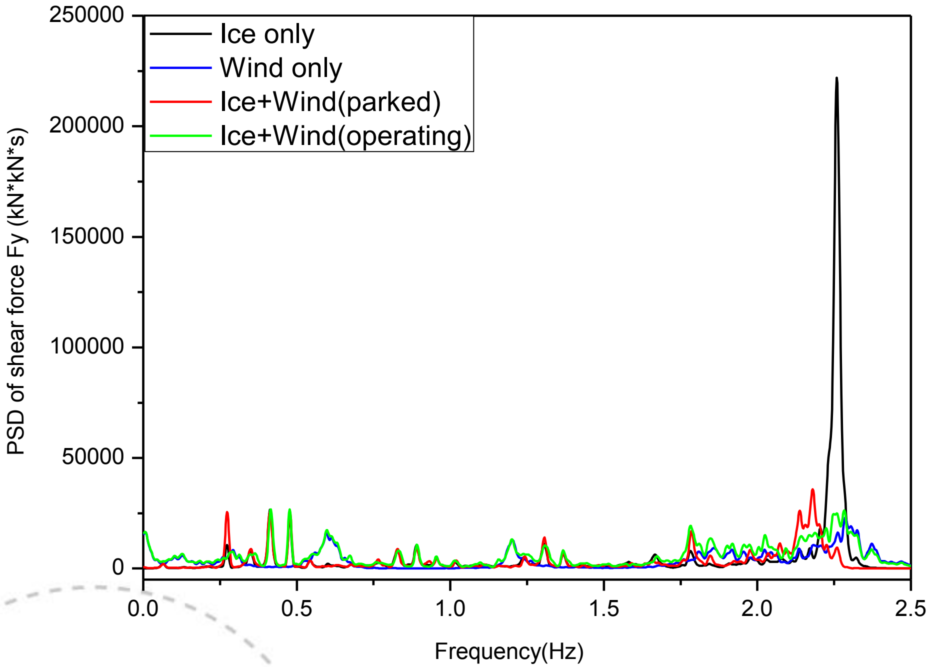
Mx at MSL(kNm)	item	mono	spar
Ice only	mean±std	-1223±1660	-232±3731
Wind only	mean±std	30322±4493	46763±13153
Ice+wind(parked)	mean±std	68±2037	1721±6795
Ice+wind(operating)	mean±std	30574±4532	48954±11580

* Fy: fore-aft shear force
Mx: fore-aft bending moment

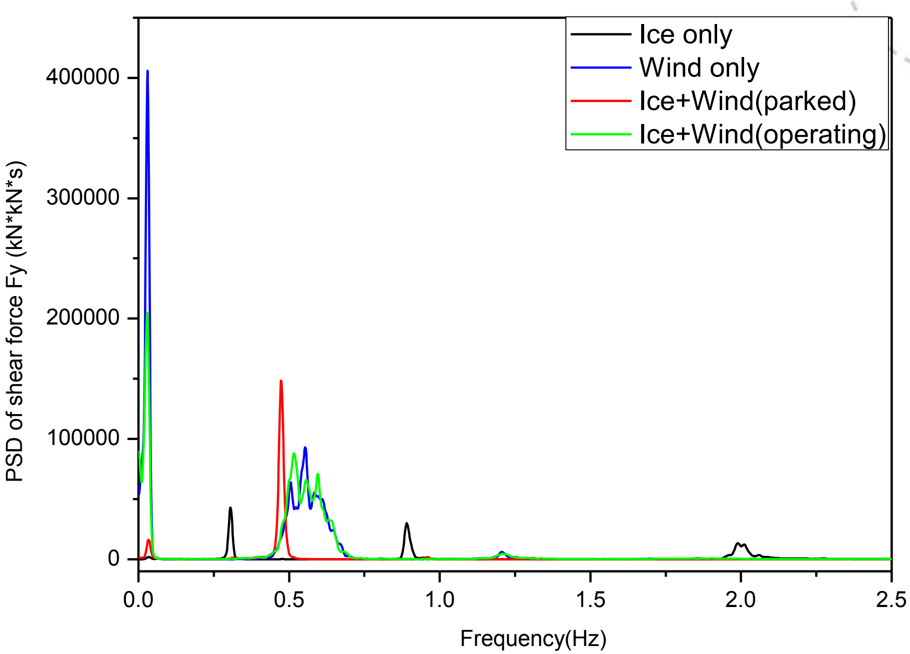
Comparison——dynamic response

- For the monopile, the second tower bending frequency (2.28 Hz) is clearly shown in the response for all the load cases. The response was reduced when the turbine is operating due to the aerodynamic damping.
- For the spar, largest energy content could be identified at platform roll/pitch natural frequencies (0.032Hz). Ice breaking frequency at around 0.5 Hz gives also arise of the response.

Mono



Spar



Conclusion

- A numerical ice-structure interaction model was implemented to aero-hydro-servo-elastic tool, HAWC2, to investigate the ice load effect on offshore wind turbines.
- The ice loads for spar-type FOWT are slightly smaller than the monopile due to large motion of floating wind turbine. Non-simultaneous bending failure is dominant for spar-WT under operating.
- Wind loads are the main source of the monopile- and spar- WT motion.
- The ice breaking frequencies give a large contribution to the dynamic response of the spar-type OWT.

Future work

- Varying ice field (thickness, strenght)
- Data validation against experimental results

Danke!

Thanks for your attention!

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