

How orcas capture seals resting on ice floes

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1 **How killer whales capture seals resting on ice floes**

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11 Flow around a submerged cylinder near a free surface reveals that adjusting the Froude
12 number and gap ratio influences the underwater jet pattern, vortex shedding frequency,
13 and free-surface deformation. The jet typically separates near the wave trough, leading
14 to localized vorticity concentration and breaking waves that dissipate wake energy. In
15 Antarctic waters, Type B killer whales employ a linear formation to generate a deep and
16 smooth depression wave, breaking sea ice and washing seals from ice floes. Noting that
17 killer whales raise their heads and swing their tails downward when approaching ice,
18 we posit that this pitched posture enhances the tail-induced depression wave. This study
19 investigates the wave-generating hydrodynamics using a towing tank and Particle Image
20 Velocimetry. A scaled model with an elliptical body and rotatable wedge-shaped tail was
21 tested under Froude similarity. Experiments covered towing speeds of 0.3 to 0.7 m s⁻¹,
22 combining different body pitch angles (10°/0°/-10°) and tail angles (30°/0°/-30°), at
23 chord-based Reynolds numbers from 17 030 to 40 506. Four wake regimes are identified:
24 small-scale vortex impingement induced by capillary waves; extensive wave breaking due
25 to flow separation at the trough; smooth depression wave caused by downward advection
26 of wake vortices and jet attachment; and large-scale vortex impingement generated by
27 wake vortex perturbations. Results indicate that the posture with an upward-pitched body
28 and downward-swept tail produced the most pronounced depression wave at 0.7 m s⁻¹.
29 The jet attached successively to the curved dorsal surface and the wave trough via the
30 Coandă effect, suppressing flow separation and wave breaking at the trough. The strong
31 jet maintained a low-potential-energy state in the trough. The depression wave caused
32 large ice floes to flip and fracture through cantilever bending, while smaller ice floes were
33 overwashed. The present findings—using a jet to reattach to a deformed free surface for
34 wake optimization—suggest a novel flow-control strategy for objects near the free surface.

35 1. Introduction

36 The killer whale (*Orcinus orca*), the largest species in the family Delphinidae, can reach
37 a body length of 6 to 9 m (Bester *et al.* 2017). Its natural distribution spans a wide range
38 from the Arctic to the Antarctic waters (Blanc & Martínez-Rincón 2023). Orcas exhibit
39 complex group behaviors and possess remarkable environmental adaptability (Baird &
40 Dill 1996; Jefferson *et al.* 1991; Reisinger *et al.* 2015). As apex predators in the ocean,
41 they occupy a unique ecological niche (Pitman *et al.* 2001; Blanc & Martínez-Rincón
42 2023; Pancaldi *et al.* 2024; Orellana-Vásquez *et al.* 2025). In Antarctic regions, Type B
43 orcas primarily prey on seals, with local populations displaying striking social behaviors
44 (Guinet *et al.* 2007; Reisinger *et al.* 2015). They hunt cooperatively, employing strategies
45 such as wave-washing waves by rapid swimming to dislodge seals from ice floes (Smith
46 *et al.* 1981; Visser *et al.* 2008). The Weddell seal (*Leptonychotes weddellii*) and crabeater
47 seal (*Lobodon carcinophagus*) are primary prey of the Type B orcas (You *et al.* 2019).
48 These seals predominantly inhabit flat, low-density first-year ice floes in the circumpolar
49 Antarctic region, which are more accessible due to their regular shape and ease of climbing
50 (Pitman & Durban 2012; Bester *et al.* 2017). They rely on these ice floes for breeding,
51 rearing pups, and evading orca predation (Ackley *et al.* 2003). The predator-prey dynamics
52 between orcas and seals largely revolve around sea ice interactions. Their highly intelligent
53 behaviors may provide insights for human applications.

54 Early observations by Smith *et al.* (1981) documented orcas hunting a solitary crabeater
55 seal. After assessing the hunting environment, a pod of seven orcas generated a powerful
56 wave through coordinated swimming, tilting the ice floe at a steep angle and dislodging
57 the seal into the water, where it drowned. This study qualitatively described the dynamic
58 interplay between ice floes, waves, and orca behaviors. Visser *et al.* (2008) recorded
59 six hunting events, detailing how orcas employed wave-washing to destabilize seals and
60 fracture ice surfaces. However, these studies lacked deeper physical insights into wave
61 generation mechanisms. Pitman & Durban (2012) provided a detailed account of wave-
62 washing behavior. Prior to wave generation, subtle convex waves formed near the orcas'
63 heads, while deeper concave waves emerged near their tails. The tight pod formation of
64 orcas exerts notable effects on the free surface via synchronized locomotion and caudal
65 fin-induced water displacement, suggesting the potential existence of underlying vital
66 physical mechanisms. You *et al.* (2019) employed computational fluid dynamics (CFD)
67 and recirculating flume tank experiments to investigate the wavelength and wave height
68 generated by an elliptical cross-section model of a false orca under varying swimming
69 speeds and depths. Their findings indicated that effective hunting waves are produced at
70 speeds $\geq 3 \text{ m s}^{-1}$ and depths of 0.4 to 1.1 m. However, their model oversimplified the
71 dynamics by neglecting the influence of swimming attitude and the coupled effects of
72 generated waves on ice floes (Fish 1998; Boutin *et al.* 2018).

73 Our observations of orca predation originate from some documentary films or open
74 resources, e.g., *Frozen Planet* (Episode 1, BBC) and *Our Oceans* (Episode 5, Netflix).
75 The documentaries use the terms 'crack' (26:20, *Frozen Planet*) and 'dismantle' (44:00,
76 *Our Oceans*) to describe wave-induced damage to ice floes. Orcas employ fluid-structure
77 interaction to first fracture the ice before encircling their prey. We observed that groups
78 of orcas swim rapidly toward ice floes, generating a depression wave within seconds on
79 otherwise calm water, right behind the pod. The wave height increases with swimming
80 distance while maintaining a width slightly greater than the pod's formation. Based on
81 our observations, orcas appear to deliberately raise their heads during hunting. While the
82 full purpose of this behavior remains unclear, such as for improved visibility or breathing,

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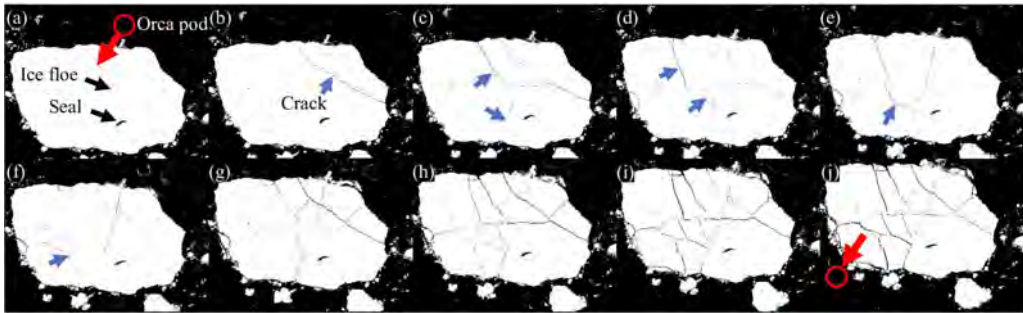


Figure 1. The time-sequenced panels illustrate crack propagation during the ice-breaking process, with an interval of approximately one second between adjacent frames. Red arrows indicate the pod's swimming direction, and red circles mark the orcas' positions. The blue arrows indicate newly formed cracks. Images were extracted from *Our Oceans* (Episode 5, 43:33 to 43:40), a documentary produced by Netflix.

83 we posited that this posture, combined with rhythmic downward tail slaps, may enhance
84 wave-generation efficiency.

85 The wave propagation speed matches the orcas' swimming velocity. When the wave
86 reaches the ice floe, the initial depression causes the leading edge to tilt toward the wave's
87 center. For a larger ice floe, while the trailing edge remains horizontal, the leading edge
88 experiences gravitational loading that induces bending stresses. Fracture occurs when
89 these stresses exceed the ice's flexural strength. As the wave propagates, the depression
90 continues to act on subsequent sections of the ice floe, producing radial cracks aligned
91 with the wave's direction of travel. Figure 1 presents binarized snapshots showing four
92 orcas fracturing a large ice floe. The primary cracks exhibit a radial pattern relative to the
93 pod's approach direction, as shown in figure 1(j). Squire *et al.* (1995) described parallel
94 fractures along ice shelf edges caused by incident ocean waves, which subsequently break
95 into angular ice floes—a process sharing similarities with orca-induced fracturing, though
96 the pod's narrower wave width likely explains the observed radial cracking. Smaller ice
97 floes resist fracture due to strong inter-crystalline bonding (Mellor 1986) but experience
98 pronounced tilting. The subsequent wave crest then impacts the inclined surface, generating
99 sufficient kinetic energy to wash seals into the water. Currently, critical gaps remain
100 in understanding how orcas generate hunting waves and how these waves mechanically
101 interact with ice floes. The development of flow structures beneath ice floes and their
102 fluid-structure interactions may be more complex than currently understood, warranting
103 further quantitative investigation.

104 Based on the degree of freezing, sea ice can be classified into landfast ice, pack
105 ice, marginal ice zone, pancake ice, nilas, and frazil ice (Squire 2020). The complex
106 relationship between crystallization temperatures of different salts poses challenges in
107 characterizing the mechanical properties of sea ice (Timco & Weeks 2010). During
108 seawater freezing, the incompatibility between ice crystal lattice points and seawater
109 ions results in stratified internal structures and varying microstructures within ice floes
110 (Petrich & Eicken 2017). Under gravitational influence, the intermediate layer of columnar
111 ice formed by the crystallization of free water at low temperatures dominates ice floes,
112 exhibiting characteristic hexagonal patterns in horizontal cross-sections (Petrich & Eicken
113 2009). This intermediate layer profoundly influences the mechanical properties of ice
114 floes. Although environmental factors (e.g., temperature affecting brine volume and pore
115 geometry) and the ice's formation history may alter the material properties of natural
116 sea ice, making comprehensive quantification of internal physical parameters difficult
117 (Petrich & Eicken 2017), the intermediate layer still demonstrates significant directional

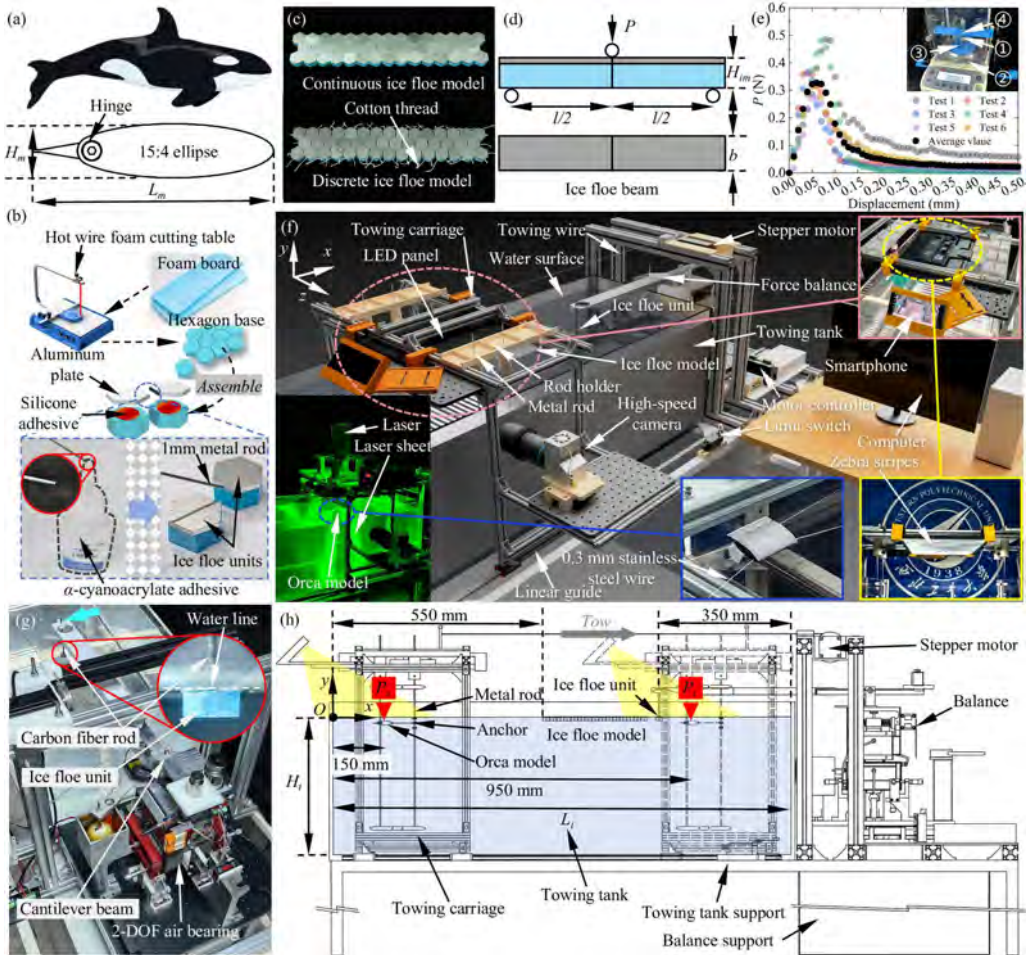


Figure 2. (a) Comparison between real orca morphology and simplified orca model. (b) Fabrication of ice floe unit. (c) The continuous and the discrete ice floe model. (d) Schematic diagram of the three-point bending test for ice floe beams. (e) Three-Point Bending Test. (f) Experimental towing tank and related arrangements. (g) The three-dimensional micro-force measurement balance. (h) The side view of the towing tank clearly illustrates the installation relationships of the measurement devices and multiple critical dimensions. The edge of the upstream water surface in the towing tank is regarded as the geometric origin for describing key locations in the side view.

118 dependence, with elastic characteristics showing anisotropy (Petrich & Eicken 2009). For
 119 instance, tensile strength parallel to the growth direction of columnar ice can be three times
 120 greater than in the perpendicular direction (Timco & Weeks 2010), while deformation
 121 perpendicular to crystal columns is markedly greater than parallel deformation (Wang
 122 1981). Compared to multi-year ice, first-year ice exhibits pronounced anisotropy (Timco
 123 & Weeks 2010). Ocean waves can induce bending in ice layers, forming ice-coupled waves
 124 or flexural-gravity waves (FGWs) that lead to ice fracture (Zemlyak *et al.* 2019; Squire
 125 2020). In open water, FGWs may play a critical role in ice breaking.

126 When the load reaches a specific velocity, the frequency of flexural waves in the ice
127 matches that of surface gravity waves, resulting in coupled FGWs capable of breaking ice
128 (Kheisin 1967). Compared to studies on ice-breaking under impact or moving surface loads,
129 research on FGWs generation by submerged moving objects remains limited (Pogorelova
130 *et al.* 2018). Early experimental validation was provided by Kozin & Onishchuk (1994),
131 demonstrating that submarine-induced FGWs could fracture ice. Pogorelova & Kozin
132 (2011) conducted experiments measuring ice deflection under submarine models at
133 varying submerged depths, water depths, and speeds, finding that reduced water depth
134 increased FGW amplitude. Kozin & Zemlyak (2012) experimentally showed higher wave
135 resistance beneath ice compared to free surfaces. Zemlyak *et al.* (2013) investigated
136 submarine geometry effects, revealing that larger cross-sections improved ice-breaking
137 efficiency. Zemlyak *et al.* (2018) studied length-to-diameter ratios and depth effects,
138 concluding that ratio changes didn't reduce critical velocity (peak fracture occurred at
139 critical speed), though increased ratios decreased wave curvature. Pogorelova *et al.* (2018)
140 combined experiments and theory to examine water depth's influence on wave amplitude,
141 demonstrating shallower depths lowered characteristic velocity while increasing wave
142 height at low speeds. Zemlyak *et al.* (2022) analyzed surface displacement induced by
143 near-surface/ice-proximity submerged bodies, quantifying ice layer effects on motion
144 parameters. Pogorelova *et al.* (2019) modeled snow-covered ice using viscous oil layers atop
145 elastic plates, showing that viscous damping significantly suppressed FGWs and reduced
146 ice-breaking. Most recently, Zemlyak *et al.* (2023) experimentally and theoretically studied
147 shallow submerged body forces and ice-breaking capacity in finite-depth water. A broader
148 methodological context is provided by Squire (2011), who cataloged modeling approaches
149 for elastic plate responses under complex ice parameters. Ni *et al.* (2024a) reviewed
150 theoretical/numerical studies on submerged moving object ice-breaking. Such research
151 typically simplifies either the object (ice as elastic plates, bodies as source-sink systems)
152 or flow conditions (inviscid potential flow) to enable analysis convergence ((Bukatov &
153 Zharkov 1995; Kozin & Pogorelova 2008; Das & Mandal 2010; Lu & Dai 2008; Pogorelova
154 & Kozin 2010; Pogorelova 2011; Sturova 2012, 2013; Pogorelova & Kozin 2014; Li *et al.*
155 2017; Ni *et al.* 2020, 2024b; Xiong *et al.* 2025). Current numerical studies predominantly
156 suffer from oversimplified wave-ice interactions, attempting to model attenuation and
157 diffusion effects within linear wave theory while entirely neglecting nonlinear vortex
158 structures.

159 Unlike conventional ice-breaking methods, orca pods form a distinctively wide distur-
160 bance array, generating relatively independent waves that constitute a previously unrecog-
161 nized ice-breaking mechanism different from wind, waves, or collisions (Montiel & Squire
162 2017). The waves produced by orcas exhibit significantly higher wave-height-to-wavelength
163 ratios compared to those generated by atmospheric, oceanic, or submarine forces. Seal-
164 inhabited ice floes typically feature characteristic dimensions much smaller than the
165 wavelengths excited by either ocean waves or elongated submarine models. Consequently,
166 their elastic responses may differ substantially from those of infinite/semi-infinite ice
167 sheets, with flexural wave effects potentially less pronounced. Inspired by natural hunting
168 strategies, the orca's behavior can be categorized into three phases: 1. Reconnaissance:
169 steady subsurface swimming for environmental assessment. 2. Fragmentation: high-energy
170 swimming to fracture large floes into smaller pieces. 3. Prey dislodgement: targeted wave
171 generation to wash seals off fragmented ice. Crucially, swimming posture may determine
172 ice-breaking efficiency. In this study, we experimentally investigated the mechanism of
173 wake depression waves generated by an orca model under different postures, and reproduced
174 and validated the ice-breaking strategies of orcas using artificially fabricated floating ice
175 models. The paper is structured as follows. Section 2 comprehensively introduces the

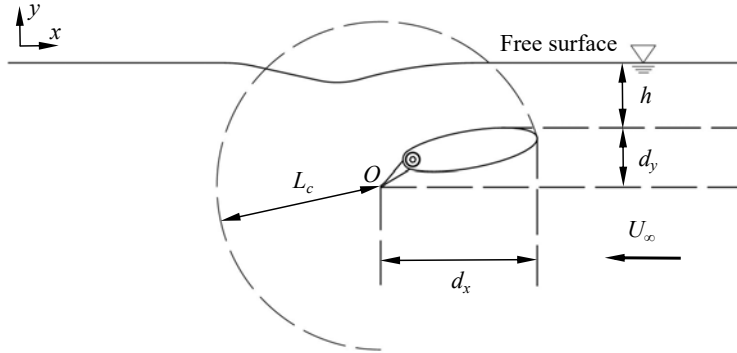


Figure 3. Overview of experimental arrangement and definition of flow and geometrical parameters.

176 experimental setup and measurement tools. Section 3 details the findings, explaining the
 177 wake regimes observed over the entire tested velocity range; in particular, Sections 3.1 and
 178 3.2 focus on the classification of wake regimes and the characteristics of the time-averaged
 179 flow field, instantaneous flow field, time-averaged vorticity, swirling strength vector field,
 180 and velocity profiles at specified locations. Sections 3.3 and 3.4 describe the capsizing
 181 effects of depression waves on large and small ice floes, as well as the force conditions of
 182 ice floe units in complex environments. Finally, Section 4 summarizes the main findings
 183 and implications of this study.

184 2. Experimental set-up

185

2.1. Orca model

186 According to the study of Kozin & Onishchuk (1994), the length of orca L_o scales linearly
 187 with the model length L_m :

$$L_o/L_m = \lambda_l. \quad (2.1)$$

188 The wavelength and amplitude of the waves also follow this scaling relationship:

$$\lambda_o/\lambda_m = A_o/A_m = \lambda_l, \quad (2.2)$$

189 where λ_o and λ_m represent the wavelengths of waves generated by real and model orcas,
 190 respectively, while A_o and A_m denote the corresponding wave amplitudes. The orca model
 191 was designed based on a scaled-down simplification of the real orca, featuring an elliptical
 192 cross-section with a major-to-minor axis ratio of approximately 15:4. The tail was modeled
 193 as a rotatable thin triangular plate, with a 0.5 mm thick rectangular cross-section edge
 194 reinforcement at its tip for enhanced structural integrity. The tail-to-body length ratio
 195 was set at 1:5. The tail and body were connected via an articulated hinge positioned at the
 196 posterior of the elliptical section, where hinge tightness could be adjusted to modify the tail
 197 angle. The orca's tail fluke can achieve an oscillation amplitude of up to 60° . Accordingly,
 198 the hinge allows tail to be adjusted within a $\pm 30^\circ$ range, relative to the central plane of the
 199 body. Remaining flippers and dorsal fin were geometrically simplified (figure 2(a)).

	Prototype	Model
Length (m)	5.6	0.05
Velocity (m s ⁻¹)	3.67 ~ 7.33	0.30 ~ 0.70
Froude Number	0.50 ~ 0.99	0.43 ~ 1.00
Weber Number	$1.06 \times 10^6 \sim 4.25 \times 10^6$	62 ~ 336

Table 1. Comparison of physical parameters between the real orca and the model.

200 Since the orca swims near the water surface, both Froude number and Weber number
201 were considered, calculated as:

$$\text{Fr} = \frac{U_\infty}{\sqrt{gL}}, \quad (2.3)$$

$$\text{We} = \frac{\rho U_\infty^2 L}{\sigma}, \quad (2.4)$$

202 where U_∞ represents the towing speed, and L denotes the characteristic length (taken as
203 the total length of the research object). The gravitational acceleration g is 9.81 m s^{-2} ,
204 seawater density ρ is $1.03 \times 10^3 \text{ kg m}^{-3}$, and surface tension coefficient σ is 0.073 N m^{-1} .
205 The swimming speed range ($3.67 \text{ m s}^{-1} < U_\infty < 7.33 \text{ m s}^{-1}$) and average length of the
206 orcas ($L_o = 5.6 \text{ m}$) were adopted from the study of You *et al.* (2019), who determined L_o
207 based on the average length of predominant female orca and derived the speed range from
208 video analysis (Visser *et al.* 2008).

209 Model dimensions and velocities were scaled using Froude number similarity (table
210 1). The orca model had a body length of 41.7 mm, tail length of 8.3 mm (total length
211 $L_m = 50.0 \text{ mm}$) and height H_m of 11.1 mm. The spanwise width ($W_m = 55.5 \text{ mm}$, 5 times
212 of model height) simulated the collective width of a 4 to 5 orca group. At flow speeds of
213 0.3 to 0.7 m s^{-1} , the Weber number ranged 62 to 336 $\gg 1$; thus, surface tension effects on
214 wave generation were neglected (You *et al.* 2019).

215 The orca model was fabricated using 3D-printed black photopolymer resin. Longitudinal
216 through-holes (0.5 mm diameter) were incorporated along the model's spanwise direction.
217 A 0.3 mm stainless steel wire was threaded through these internal holes and secured to
218 3.0 mm metal anchor rods mounted near the towing tank sidewalls, which connected to the
219 overhead towing carriage. During model installation, pliers were used to tension the steel
220 wire, and after achieving sufficient tautness, the free end was secured with an aluminum
221 wire sleeve clamp. The pre-tension force in the wire effectively minimized model vibration.
222 The above arrangement eliminated flow field disturbances from support structures as much
223 as possible. Body pitch angle was adjusted by varying the anchor points' relative heights on
224 the rods, with positive angles defined by leading-edge upward tilt. Tail inclination (positive
225 when uptilted) indicated the primary fluke orientation during water propulsion. Refer to
226 table 2, multiple representative orca postures, from Cases 1 to 9, were systematically
227 combined. Regardless of the installation configuration, the vertical distance h between the
228 dorsal high point of the orca body and the water surface was maintained approximately
229 $2H_{im}$ between the starting position (P_s) and the termination point (P_t). The ratio of h/d_y
230 in table 2 is equally important, as it reflects the model's relative submergence depth. This
231 relative position is annotated in figure 3. The orca model features a non-axisymmetric cross-
232 section with significant differences in the x - and y -directions. Therefore, two orthogonal
233 projection distances, d_x and d_y , are considered to define corresponding Froude numbers,

Case	Body angle (°)	Tail angle (°)	L_c (mm)	h/d_y	Re_c ($\times 10^4$)	Diagram
1	10	0	50.00	1.53	1.74 ~ 4.05	
2	10	30	49.05	1.53	1.70 ~ 3.97	
3	10	-30	49.05	1.13	1.70 ~ 3.97	
4	0	0	50.00	1.80	1.74 ~ 4.05	
5	0	30	49.05	1.67	1.70 ~ 3.97	
6	0	-30	49.05	1.60	1.70 ~ 3.97	
7	-10	0	50.00	1.53	1.74 ~ 4.05	
8	-10	30	49.05	0.88	1.70 ~ 3.97	
9	-10	-30	49.05	1.53	1.70 ~ 3.97	

Table 2. Statistics of orca model postures under varying body angles and tail angles.

234 Fr_x and Fr_y . The former one is expected to influence the coupling between the wake vortex
 235 structure and the free surface, while the latter primarily governs the free surface wave
 236 pattern deformation and is directly related to the volume of fluid displaced by the body and
 237 the pressure disturbances, which propagate as gravity waves on the free surface.

$$Re_c = \frac{\rho U_\infty L_c}{\mu}. \quad (2.5)$$

238 Furthermore, the Reynolds number for the orca model in flow also needs to be considered.
 239 As given in equation 2.5 and using the chord length L_c as the characteristic length, the
 240 Reynolds number was calculated. In the equation, the dynamic viscosity μ is 8.9×10^{-4} Pa s,
 241 and L_c is defined as the distance between the endpoints of the tail and the head, as illustrated
 242 in figure 3. Both L_c and Re_c are listed in table 2. The values confirm that the model's
 243 motion occurs within a turbulent wake flow regime. The instantaneous streamwise (x -axis),
 244 normal (y -axis), and spanwise (z -axis) velocity components at any point in the flow field
 245 are denoted as u , v , and w , respectively. These are composed of the superposition of the
 246 local mean velocities \bar{u} , \bar{v} , \bar{w} , and their corresponding fluctuating components u' , v' and
 247 w' . The resultant velocity at a point in the flow field should be understood as the vector
 248 sum of its component velocities, i.e., $U = \sqrt{u^2 + v^2 + w^2}$. This study mainly analyzes the
 249 velocity field on the central plane of the model. Considering symmetry, the contribution of
 250 the spanwise velocity component on the centerplane of the model is neglected; therefore,
 251 the spanwise velocity component w is scarcely discussed in this paper. Further explicit
 252 reference to the meaning of symbols will be omitted in subsequent sections.

2.2. Ice floe model

253
 254 Visser *et al.* (2008) reported ice-breaking widths of 4.5 to 18.0 m for orca groups, with
 255 maximum floe diameters reaching approximately 25 m and ice thickness ranging from
 256 below 0.5 m to over 1.5 m. Smith *et al.* (1981) observed floe diameters between 5 and
 257 15 m. The dimensions and mechanical characteristics of model ice must still satisfy the
 258 scaling relationship. Based on actual proportions, 1/5 of the orca model length L_m was
 259 selected as the model ice thickness $H_{im} \approx 10$ mm. The corresponding natural ice thickness
 260 can be estimated by the following equation:

$$H_{in} = H_{im} \lambda_l^{4/3} ([\sigma_u]_n / [\sigma_u]_m)^{-1/3}, \quad (2.6)$$

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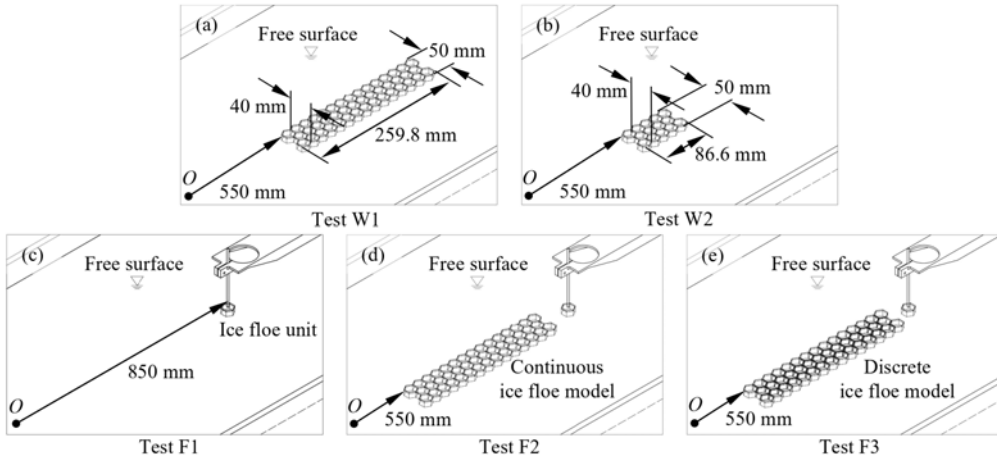


Figure 4. (a) and (b) illustrate the parameter configurations for experiments on wave-induced overturning of large and small continuous ice floe models. (c), (d) and (e) present the parameter configurations for experiments measuring the three-dimensional micro-force response of an ice floe unit under wave action. In (c), only the force on the isolated ice floe unit is measured. In (d) and (e), continuous and discrete ice floe models are placed upstream of the target unit. In all experiments, the ice floe unit, ice floe models, and orca model must be aligned on the same central plane. During preparation, the water surface must remain calm, and the positions of the ice floes must be carefully adjusted.

261 where H_{in} and H_{im} represent the thicknesses of natural ice and model ice, and $[\sigma_u]_n$
 262 and $[\sigma_u]_m$ denote the flexural strengths of natural ice and model ice, respectively. Using
 263 the upper limit of sea ice flexural strength reported by Timco & O'Brien (1994) as the
 264 reference value ($[\sigma_u]_n \approx 1.50$ MPa), the flexural strength of the model ice was designed
 265 as $[\sigma_u]_m \approx 9.53$ kPa to simulate natural ice thickness $H_{in} \approx 1/5L_o$.

266 As shown in figure 2(b), the ice floe substrate was fabricated using polystyrene foam
 267 boards cut into 10 mm regular hexagonal units (density of 0.42 g cm $^{-3}$) to simulate
 268 columnar ice cross-sections. Waterproof silicone adhesive was applied to bond hexagonal
 269 aluminum plates (density of 2.80 g cm $^{-3}$) of identical dimensions atop the foam units.
 270 When the aluminum plate thickness was $1/5H_{im}$ and the foam thickness $4/5H_{im}$, the
 271 model ice density reached 0.90 g cm $^{-3}$, which approximating real ice conditions (Dumont
 272 *et al.* 2011), with approximately 1/10 of its height exposed above water (Squire 2011). The
 273 large continuous ice floe model was assembled from small hexagonal ice units bonded with
 274 α -cyanoacrylate adhesive. The adhesive was applied to the side surface of the aluminum
 275 plate using 1 mm diameter metal rod, with transfer conditions deemed satisfied when
 276 the adhesive sufficiently wetted the rod's end surface. The adhesive-coated surfaces were
 277 then brought into contact with the aluminum plate sides of adjacent ice units and rapidly
 278 clamped for curing. As shown in figure 2(c), the large continuous ice floe model consisted
 279 of 44 units arranged in three columns: the first and third columns each consisted of 15 units,
 280 while the middle column contained 14 units. We also fabricated a discrete model, where
 281 individual ice units maintained gaps of approximately 1 mm and were interconnected with
 282 cotton threads. This discrete configuration was designed to simulate small ice floe groups
 283 consisting of fragmented but closely spaced floating ice pieces. It should be noted that the
 284 slender layout ignores the three-dimensional effects to some extent, focusing on the effect
 285 of the trailing waves generated by the orca model near its central plane on the floe.

286 Figure 2(d) illustrates that the equivalent flexural strength between bonded units was
 287 estimated via three-point bending tests (Timco & O'Brien 1994), with loading applied
 288 parallel to adhesive seams at a constant rate. The flexural strength is expressed as:

$$\sigma_f = \frac{3Pl}{2bH_{im}^2}, \quad (2.7)$$

289 where P is the applied load, $l = 40$ mm denotes the support span of the ice floe model
 290 beam, and $b = H_{im} = 10$ mm represents the width and height of the hexagonal ice
 291 model, respectively. As shown in figure 2(e), six independent measurements of the flexural
 292 strength of the ice floe beam were conducted. The mean results demonstrated that the
 293 beam exhibited linear deformation under loading until fracture occurred at displacements
 294 exceeding 0.06 mm, with a maximum recorded load of approximately 0.33 N. While
 295 initial deformation stages exhibited excellent reproducibility, displacement-dependent
 296 divergence emerged, likely due to variations in α -cyanoacrylate wetting and curing. The
 297 derived flexural strength at peak load was $\sigma_f \approx 19.80$ kPa $> [\sigma_u]_m$. Notably, flexural
 298 strength parameters display inherent variability influenced by hydrographic conditions,
 299 brine volume, ice temperature, and loading rate (Han *et al.* 2016). Elevated temperature
 300 or brine content reduces strength, with young ice exhibiting higher strength than aged
 301 ice (Fransson 2002). Reported sea ice flexural strengths range 0.1 to 1.5 MPa (Timco
 302 & O'Brien 1994). The artificial ice floe models in this study may simulate thicker ice
 303 than intended (i.e., ice floe with a thickness of 1.27 m), though all values remain within
 304 physically plausible ranges.

305 In all experiments presented in this study, the leading edge of the ice floe model was
 306 positioned 550 mm downstream in the towing tank. Figure 4(a) and (b) illustrate the
 307 experimental setups for investigating wave-induced tilting effects on large continuous ice
 308 floes (arranged in a $15 \times 14 \times 15$ array) and small continuous ice floes (arranged in a $5 \times 4 \times 5$
 309 array). High-speed cameras were employed to capture snapshots of the ice floe overturning
 310 process. Figure 4(c) depicts the force measurement setup for waves acting on an isolated
 311 ice floe unit (positioned 850 mm downstream in the towing tank). In configurations (d) and
 312 (e), modifications were made by placing continuous and discrete large ice floes upstream of
 313 the target unit to evaluate the dissipation effect of large intact ice floes or dense and discrete
 314 ice arrays on subsequent wave forces. A custom-designed force balance was used for force
 315 measurements. Further details regarding the high-speed camera and the force balance are
 316 provided in subsequent sections.

317 2.3. Towing tank and flow field visualization system

318 The experiments were conducted in W. Zhou's wind tunnel laboratory at the School of
 319 Mechanical Engineering, Northwestern Polytechnical University. As illustrated in figure
 320 2(f), all towing experiments were conducted in a custom-built transparent acrylic water
 321 tank with internal dimensions of $L_t = 24.0L_m$ (length), $W_t = 9.1W_m$ (width), and $H_t =$
 322 $32.4H_m$ (water depth). Under these parameters, sidewall effects on wave generation were
 323 negligible, and deep-water conditions were satisfied. The laboratory is equipped with an air
 324 conditioning system to maintain a constant temperature of $25 \pm 1^\circ\text{C}$. Given the significant
 325 difference in viscosity between air and water at room temperature, the influence of air on
 326 the water flow is neglected to approximate the conditions of a free surface. Two 1200-mm-
 327 long linear metal rails were installed along the tank sides. A towing carriage, constructed
 328 from 2020 aluminum profiles with redundant structural reinforcement, was mounted on
 329 the rail sliders. The carriage featured dual rod holders, each securing two 3-mm-diameter,
 330 550-mm-long stainless steel rods positioned approximately 30 mm from the sidewalls,

331 perpendicular to the water surface. The carriage was towed via 1-mm steel cables driven
332 by a stepper motor at the tank end. Towing speed was calibrated using high-speed imagery
333 and scale markers. Calibrated anchor points on the rods enabled model pitch adjustment.
334 An LED panel (modified to display 10 mm black/white zebra stripes) was mounted atop
335 the carriage. A smartphone (Huawei P60 Art), fixed via a customized holder (orange
336 one in the upper-right subplot), recorded reflected patterns at 4K/60 fps to quantify free-
337 surface deformation and corresponding wake scars and striations (3840 × 2160 pixels). The
338 smartphone position was adjusted to maximize pattern coverage. A high-speed camera
339 (Cyclone-2-2000 M, Optronics; lens: AF-S Nikkor 24-120 mm f/4 ED VR, Nikon) was
340 mounted laterally on a platform to capture horizontal free-surface snapshots (1920 × 1080
341 pixels) at the model centerplane and the total field of view is approximately 220 mm × 70 mm
342 ($x \times y$). The camera sampling rate is set to 250 Hz. For particle image velocimetry (PIV),
343 the LED panel was replaced with a 7.5 W maximum power continuous laser (532 nm,
344 5W-EC31811, Changchun New Industries Optoelectronics Tech. Co., Ltd.) generating a
345 0.5-mm-thick light sheet (30° divergence angle) aligned with the orca model's centerplane
346 (see bottom-left subplot of figure 2(f)). A black velvet cloth was attached to the outer surface
347 of the acrylic water tank wall opposite the high-speed camera to improve image quality and
348 reduce unwanted laser reflections. Due to the mechanical structure of the support frame,
349 the laser sheet was incident on the water surface from the top. The refraction from the
350 deformed free surface introduced minor perturbations to the instantaneous velocity field
351 at the wake interface, where vortex structures frequently impinged. However, the averaged
352 results demonstrated a convergent trend, but it is still recommended that future studies
353 employ a bottom-incident laser sheet. The rod holder of the towing carriage caused minor
354 obstruction in the PIV sampling area, potentially introducing errors in cross-correlation
355 calculations near the obscured edges. Nevertheless, these regions were readily identifiable
356 and did not affect the conclusions of this study. The water was seeded with 50 μm polyamide
357 resin particles (PSP; refractive index: 1.56; density: 1.03 g cm⁻³), and the camera was
358 repositioned horizontally relative to the model, with the sampling rate set to 2000 Hz.
359 PIV data were processed using the PIVLab software package (version 3.06). A final
360 interrogation window of 8 × 8 pixels with 50% overlap was used to satisfy the Nyquist
361 criterion. Instantaneous and ensemble averaging of the flow velocity vectors was performed
362 using a cross-correlation algorithm. The time-averaged quantities were obtained from 500
363 frames of the instantaneous velocity field. All imaging stations were positioned within the
364 fully developed flow region, approximately 700 mm downstream of the towing tank. A
365 three-dimensional micro-force balance was positioned externally downstream of the towing
366 tank. To isolate the measurement system from vibrations induced by towing dynamics, the
367 force balance was mounted on an independent vibration-damping support. The balance's
368 sensing probe was fitted with an ice floe unit through a carbon fiber rod, positioned 850
369 mm downstream of the towing tank edge. The limit switch installed beside the rail ensured
370 consistent travel (between $P_s = 150$ mm and $P_t = 950$ mm from the upstream edge), with the
371 orca model having fully cleared the ice structures before motor deceleration was triggered.
372 Additional tank details are provided in figure 2(h).

2.4. *Decoupling-free balance for three-dimensional micro-force measurement*

374 As shown in figure 2(g), a custom-designed decoupling-free three-dimensional micro-force
375 balance was used to measure the micro-mechanical responses of an isolated ice floe unit
376 under wave action. The ice floe unit was fixed to the end of a 3-mm-diameter carbon fiber
377 rod, which was clamped to the front end of the balance's measuring probe (configured
378 as a cantilever-beam lever). When hydrodynamic forces act on the ice floe unit, the force
379 signals are transmitted through the cantilever beam to the balance for measurement.

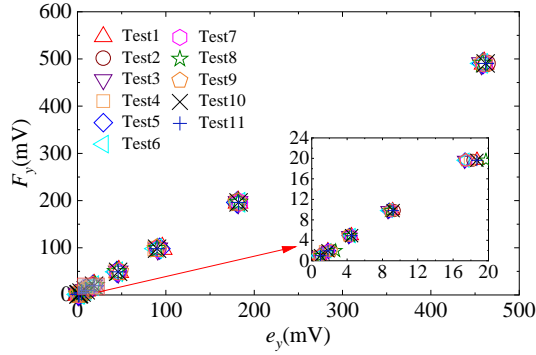


Figure 5. Calibration results along y axis. F_y denotes the reference force applied along the y -axis, generated by Class F1 standard weights, while e_y represents the voltage transducer output reading.

380 The balance operates on an air-floating principle, with its core component being
 381 an independently designed two-degree-of-freedom (2-DOF) air-bearing platform. The
 382 mechanical structure was inspired by the one-dimensional air bearing proposed by Zhou
 383 *et al.* (2025). When high-pressure gas is supplied, the air bearing achieves gas lubrication,
 384 reducing the frictional resistance of moving parts to negligible levels. The 2-DOF air
 385 bearing provides pre-decoupled force measurement in the horizontal x - and z -axes. The
 386 forces are calculated by measuring the micro displacements of the air-bearing slider in
 387 orthogonal directions within the horizontal plane, combined with the stiffness coefficients
 388 of elastic elements. The y -axis force is measured using a stress-strain sensor, with the
 389 lever structure enhancing force measurement resolution. The moving components of the
 390 balance are free from interference by external cables or mechanical structures, enabling
 391 pure three-dimensional micro-force measurements. The stiffness coefficients of the balance
 392 in the x - and z -axes are 23.451 N m^{-1} and 25.458 N m^{-1} , respectively. Given the use of
 393 an infrared laser sensor with $0.5 \text{ }\mu\text{m}$ resolution to measure micro-displacements, the force
 394 resolutions in these directions are approximately $1.17 \times 10^{-5} \text{ N}$ and $1.27 \times 10^{-5} \text{ N}$, with
 395 measurement ranges of $\pm 0.31 \text{ N}$ and $\pm 0.19 \text{ N}$, respectively. The combined uncertainties
 396 in each direction arise from the laser sensor and elastic elements, resulting in relatively
 397 expanded uncertainties of 0.68% and 0.33% for the x - and z -axes, respectively.

398 For the y -axis, the cantilever beam was modified with an extended length, and the
 399 position of the stress-strain sensor was altered, necessitating recalibration. Nine different
 400 Class F1 standard weights were sequentially and steadily placed at the probe's end, with
 401 the central axis of the weights aligned with the centerline of the carbon fiber rod mounting
 402 hole (indicated by a thick cyan arrow in figure 2(g)). The raw calibration data are presented
 403 in figure 5, and the results of 11 independent calibration tests are summarized in table 3.
 404 The stiffness coefficient was determined as the mean slope of the 11 calibration lines:

$$\bar{k}_y = \frac{\sum_i^n k_{yi}}{n}, n = 11, \quad (2.8)$$

405 thus, $\bar{k}_y = 1.0671 \text{ N V}^{-1}$, with a resolution of approximately $1.07 \times 10^{-4} \text{ N}$ and a
 406 measurement range of $\pm 0.6 \text{ N}$. The uncertainty of each independent calibration can be
 407 expressed by the residual standard deviation r_y :

$$u(k_y) = \frac{r_y}{\sqrt{\sum_{i=1}^n (e_{yi} - \bar{e}_y)^2}}, n = 9, \quad (2.9)$$

n	k_y (N V ⁻¹)	R^2	r_y (N)	$u(k_y)$ (N V ⁻¹)
1	1.0671	0.9999	1.8172	0.0043
2	1.0607	0.9999	1.9873	0.0046
3	1.0726	1.0000	0.5836	0.0014
4	1.0669	0.9999	1.6900	0.0040
5	1.0696	0.9999	1.2716	0.0030
6	1.0709	1.0000	1.0620	0.0025
7	1.0650	1.0000	0.7054	0.0017
8	1.0716	1.0000	1.0939	0.0026
9	1.0693	0.9999	1.5679	0.0037
10	1.0630	1.0000	1.1858	0.0028
11	1.0659	0.9999	1.3569	0.0032

Table 3. The results of the fitted stiffness coefficient k_y , goodness-of-fit R^2 , residual standard deviation r_y , and uncertainty $u(k_y)$.

408 where r_y can be calculated as follows:

$$r_y = \sqrt{\frac{\sum_{i=1}^n ((F_y)_i - (F_y)_{0i})^2}{n-2}}, n = 9. \quad (2.10)$$

409 In equations 2.9 and 2.10, n represents the number of different standard weights applied
 410 during an independent calibration, e_{yi} denotes the voltage reading difference before and
 411 after applying the i -th weight force $(F_y)_i$, \bar{e}_y is the mean value of e_{yi} , and $(F_y)_{0i}$ represents
 412 the calculated value corresponding to e_{yi} on the fitted line. The uncertainty of \bar{k}_y is
 413 expressed as:

$$u(\bar{k}_y) = \sqrt{\frac{\sum_{i=1}^n u(k_y)_i^2}{n(n-1)}}, n = 11, \quad (2.11)$$

414 here, n represents the number of independent calibrations, and the relative uncertainty of
 415 \bar{k}_y can be expressed as:

$$u_r(\bar{k}_y) = \frac{u(\bar{k}_y)}{\bar{k}_y}. \quad (2.12)$$

416 The calculated uncertainty of \bar{k}_y is approximately 0.001 N V⁻¹, corresponding to a
 417 relative uncertainty of 0.1%. The balance operates at a sampling rate of 10 Hz, with triaxial
 418 force signals transmitted to a microprocessor via LoRa wireless protocol before being
 419 collectively relayed to a computer. Testing confirmed that the system's clock drift remains
 420 below 10 ms over 20-minute operation periods. The influence of sampling circuitry on
 421 measurement results was negligible. For additional technical details regarding the balance,
 422 refer to the work by Zhou *et al.* (2026).

423 3. Results

424 3.1. Free-surface depression wave

425 Figure 6 presents the wave patterns on the central plane of the model for Cases 1 to 9
 426 under towing speeds of 0.3 to 0.7 m s⁻¹. The contour points were obtained from the

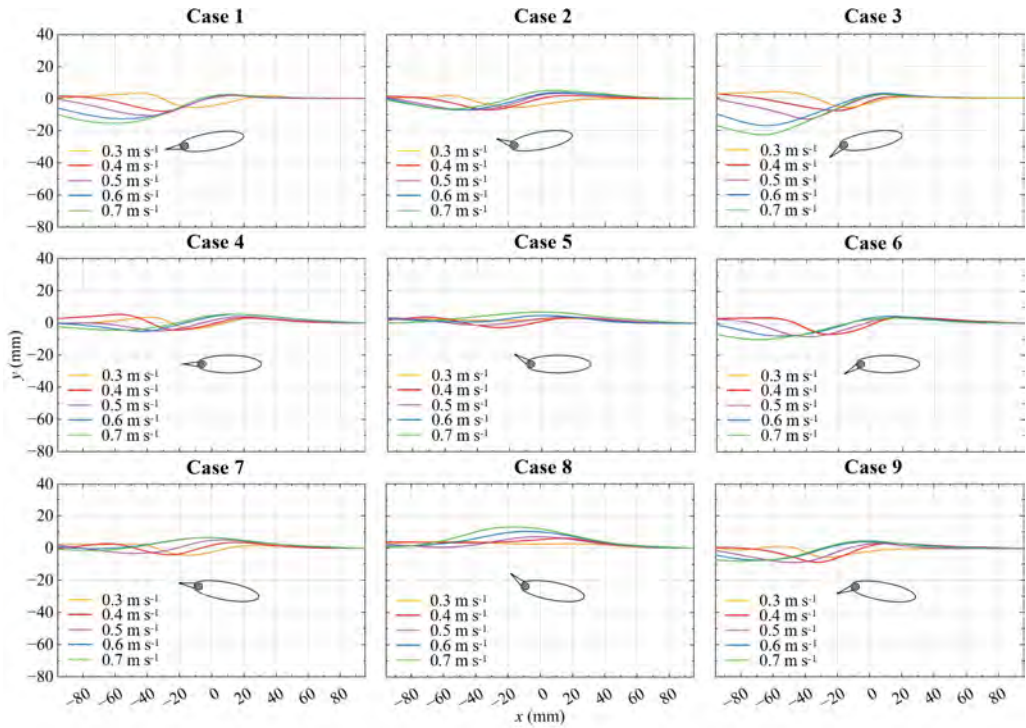


Figure 6. The free surface deformations under different cases and towing speeds are investigated. The background grid is solely used for evaluating surface deformation and is not associated with a specific reference position.

427 averaged statistical results of multiple stacked image frames. Spline curves defined by
 428 control vertices were used to connect the contour points, which were then transferred to a
 429 grid plot. This process temporarily neglected small-scale fluctuations of the liquid surface,
 430 thereby illustrating the macroscopic deformation of the free surface. Distinct differences
 431 in wave patterns are observed among the cases, with both the body and tail parts of the
 432 orca model influencing wave development.

433 Cases 1 to 3 all produced readily identifiable free-surface depression waves. The
 434 depression wave in this article specifically refers to the first trough appearing behind
 435 the model. The depression wave in Case 3 was the most pronounced, reaching a depth of
 436 22.8 mm at 0.7 m s^{-1} , followed by Case 1, which generated a depression wave of 15.9 mm
 437 at the same speed—the former being approximately 1.4 times deeper than the latter. The
 438 streamwise positions of the wave troughs (with the leading edge of the orca model's head
 439 as the origin) were 86.6 mm downstream for Case 3 and 81.3 mm downstream for Case
 440 1. However, when the model's tail was uptilted (Case 2, 5, 8), the depression wave was
 441 significantly suppressed, affecting both the trough depth and its streamwise position. In
 442 Case 2, the maximum trough depth was only 7.2 mm, located at 74.1 mm downstream,
 443 under a towing speed of 0.7 m s^{-1} .

444 In Cases 4 to 6 and 7 to 9, downward flipping of the tail resulted in more pronounced
 445 tail depression waves. Conversely, uptilting the tail suppressed the depression wave. Inter-
 446 group comparisons indicate that the wave depth and streamwise position in these cases
 447 are all smaller than those in Cases 1 to 3. Additionally, localized elevations of the liquid
 448 surface above the undisturbed free surface were observed in Cases 5 and 8, to the extent

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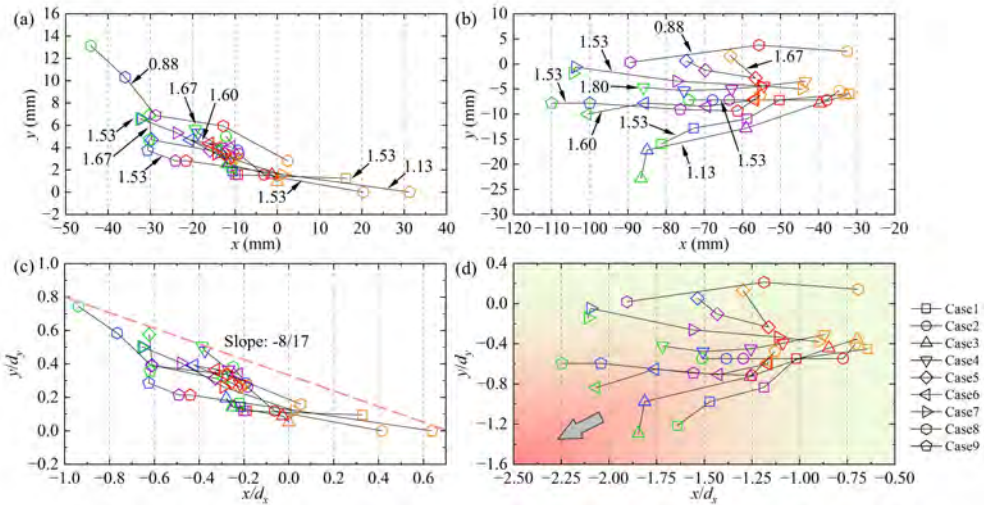


Figure 7. (a) and (b) show the positional data of the head wave crest and stern wave trough under different cases and towing speeds, respectively. (c) and (d) present the corresponding data normalized using d_y and d_x for the peak and trough points, respectively. ‘-’ indicates being below the calm water surface or downstream of the leading-edge reference point of the model. The color of the symbols in the figure represents different towing speeds, consistent with figure 6.

449 that in Case 8, the depression wave even rose above the free surface. This is often attributed
 450 to a locally increased Froude number above the model, where exceeding a critical value
 451 can induce a hydraulic jump. This Froude number is determined by the local velocity U
 452 and local liquid height h_l , i.e., $Fr_l = U/\sqrt{gh_l}$, which will be further explained later. More
 453 broadly, the depression wave depths in Cases 5, 7, and 8 were all relatively small, with
 454 troughs close to the free surface, and uptilted tails were a common feature among these
 455 three cases.

456 The bulge wave generated at the model’s head also attracts attention, primarily influenced
 457 by the blockage effect at the model’s frontal stagnation point. The height of the bulge wave is
 458 related to both h/d_y and the towing posture. Most bulge wave peaks are located 10 to 20 mm
 459 downstream of the model’s leading edge. Case 8, with the smallest $h/d_y = 0.88$, produced
 460 the most prominent bulge wave, reaching a peak height of 13.1 mm at 0.7 m s^{-1} , situated
 461 44.1 mm downstream of the head. In contrast, the wave heights in other cases were relatively
 462 moderate. Cases 1 and 3 exhibited the least sensitivity to bulge wave generation, with
 463 minimal variation in wave height with towing speed and limited streamwise displacement.
 464 As towing speed increased, the downstream shifting of the bulge wave slowed. An upward
 465 tilt of the head mitigated the blockage effect, thereby suppressing the growth of the bulge
 466 wave. Cases 5, 7, 8, and 9 showed relatively larger streamwise displacement ranges of the
 467 bulge wave. Among these, Case 5 featured an uptilted tail, while Cases 7 to 9 involved a
 468 downward pitching of the body. Their common feature is the deflection of the dorsal flow
 469 toward the water surface, which contrasts sharply with Cases 1 and 3. Figure 7(a) and (b)
 470 present the parameter distributions of the trough behind the model and the bulge wave peak,
 471 respectively, with the relative submergence depth annotated in (a) for reference.

472 Figures 7(c) and (d) present the normalized wave trough and peak positions in the
 473 normal direction and the streamwise position. In figure 7(c), the peak points exhibit a more
 474 uniform distribution pattern. All data points lie below a straight line with a slope of $-8/17$,
 475 showing a compact distribution. The slope reflects the trend of the peak position variation

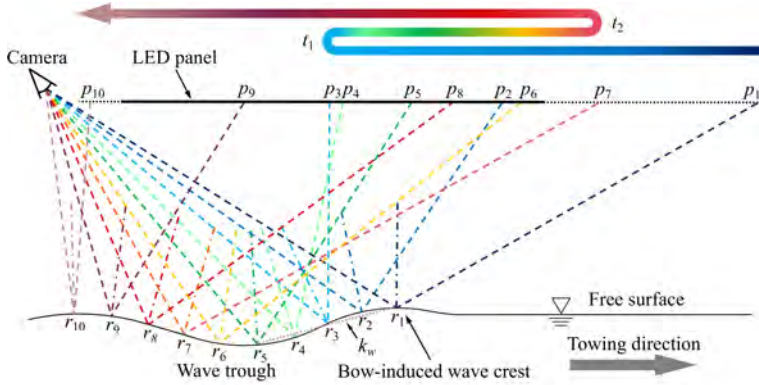


Figure 8. Optical path diagram of zebra stripes on the LED panel reflected by the wave surface. In this optical path diagram, the selected reflection points r_i ($i = 1 \sim 10$) maintain similar spacing, while the positions of projection points p_i undergo nonlinear changes due to the curvature of the free surface. The colored arrow above reflects the movement trend of the projection points in the camera, and the camera's shooting vector reverses direction twice (marked as t_1 and t_2). The slope k_w of the line connecting the wave crests and wave troughs in the figure is used to evaluate the depression degree of the waves. The figure is not drawn to scale strictly.

476 with towing speed. The physical significance of this line lies in the constraint imposed by
 477 the orca's attitude on the bulge wave peak, indicating that a higher bulge wave peak cannot
 478 form further upstream. This relationship satisfies:

$$\frac{y}{d_y} < -\frac{8}{17} \frac{x}{d_x} + \frac{28}{85}. \quad (3.1)$$

479 Conversely, Cases 1, 3, and 9 lie at the lower-left outermost side of the line, indicating
 480 that these three cases exhibit stronger suppression of the bulge wave compared to most
 481 other conditions. Similarly, in figure 7(d), only the curves of Cases 1, 3, and 6 continue to
 482 show a proactive downward trend in the lower-left corner. As the towing speed increases,
 483 the stern depression wave further deepens. A common feature of these three cases is their
 484 downward-tail configuration.

485 Figures 9 to 11 provide further information on the free surface deformation through the
 486 zebra-stripe patterns. For an overview of the reflective pattern method used to measure
 487 free surface deformation, refer to the review by Gomit *et al.* (2022). In this study, the LED
 488 panel and smartphone lens were fixed relative to the towing carriage to capture the images
 489 of the surface deformation during the towing process. Before focusing on results, it is
 490 necessary to clarify the influence of wave peak and trough on the reflective stripes. Figure
 491 8 illustrates a simplified two-dimensional relationship among the camera, LED panel,
 492 waves, and optical path. Although the elements are not drawn strictly to scale, the diagram
 493 is sufficient for explanatory purposes. Ten equally spaced reflection points r_i ($i = 1 \sim 10$)
 494 were selected on the deformed surface. The reflected light paths from these points to the
 495 camera were constructed, and their intersections with the plane of the LED panel are
 496 denoted as corresponding projection points p_i ($i = 1 \sim 10$). The coloured arrows above
 497 the figure, matching the light paths, indicate the positional variations of these projection
 498 points. The stretch ratio of the zebra stripes is defined as:

$$\eta_i = \frac{\overline{p_i \rightarrow p_{i+1}}}{\overline{r_i \rightarrow r_{i+1}}}, \quad i = 1 \sim 9, \quad (3.2)$$

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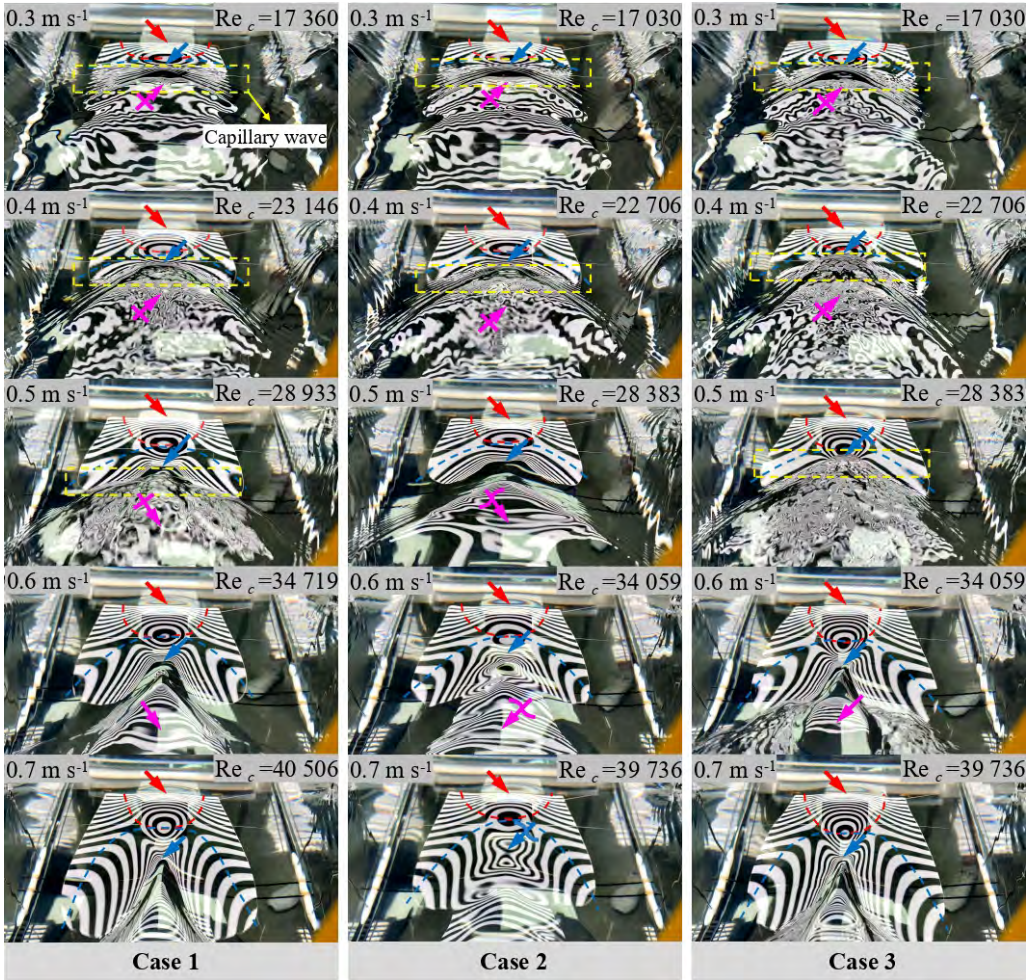


Figure 9. Zebra stripe patterns for Cases 1 to 3.

499 where η_i reflects the average stretch ratio between points p_i and p_{i+1} . Evidently, $\lim_{p_i \rightarrow p_{i+1}} \eta_i$
500 can represent the local stretch ratio. Considering that p_i may exhibit turning points at t_1
501 and t_2 , ‘ \rightarrow ’ is used here to distinguish the displacement between these two points from
502 the conventional arc length. When η_i is greater than 1, the pattern on the free surface is
503 compressed, resulting in denser stripes; conversely, it is stretched when η_i is less than 1.
504 The degree of compression or stretching is proportional to the magnitude of η_i .

505 For the reflection points in figure 8, η_1 at p_1 (bulge wave) reaches its maximum, η_1 at p_1
506 and decreases during the transition from $p_1 \rightarrow p_3$. The stripes are most densely concentrated
507 over the head wave peak. Near p_3 , a topological change in the stripes begins (i.e., the
508 inverse process at $t_1 \rightarrow t_2$), accompanied by a thickening of the stripes. When a gradient
509 in curvature exists along the spanwise direction (typically with curvature decreasing away
510 from the deformation core on both sides), the LED panel stripes reflected from the central
511 plane of the model generally appear further downstream. Thus, the topological pattern
512 manifests as concentric rings. In figure 8, the projection points $p_3 \rightarrow p_7$, corresponding
513 to reflection points $r_3 \rightarrow r_7$, reverse direction and point upstream until the end of t_2 in
514 the arrow diagram. Thereafter, projection points beyond r_7 ($p_7 \rightarrow p_{10}$) consistently move

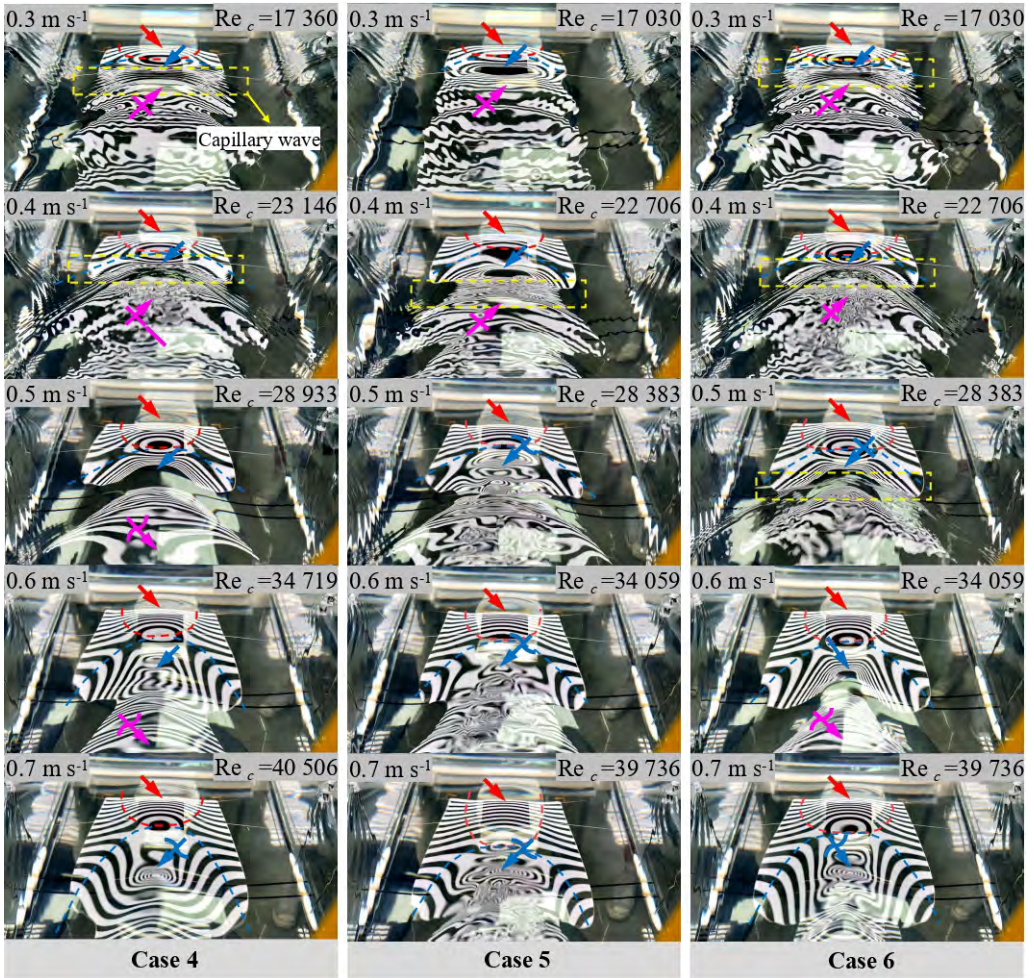


Figure 10. Zebra stripe patterns for Cases 4 to 6.

515 downstream, indicating that only regions downstream of r_7 in the camera view will exhibit
 516 reflective stripes with conventional distribution.

517 Observing p_3 to p_7 , one can find $\eta_5 = \text{Max}\{\eta_3, \eta_4, \eta_5, \eta_6\}$. The compressive effect can
 518 be used to identify the location of the trough at r_5 , where the stripes are locally most dense
 519 and close to the downstream position of the first topological concentric ring. Similarly,
 520 the decrease in stretch ratio as the projection points move toward p_{10} implies gradually
 521 widening stripes near the wake wave peak. It should be noted that the turning point t_2 in
 522 figure 8 lies outside the LED panel, indicating possible discontinuities between upstream
 523 and downstream stripes. This phenomenon is related to the curvature of the wave trough.
 524 If the depression at r_5 is shallow and the range of $\overline{p_3 \rightarrow p_7}$ is small enough such that t_2
 525 falls within the LED panel, the stripe pattern remains continuous despite the topological
 526 transition. Based on the principles described above, the approximate extent and peak
 527 location of the bugle wave are indicated by red dashed lines and arrows. The approximate
 528 starting boundary and trough of the depression wave are marked with blue dashed lines
 529 and arrows. The approximate peak location of the wake bulge wave is indicated by magenta

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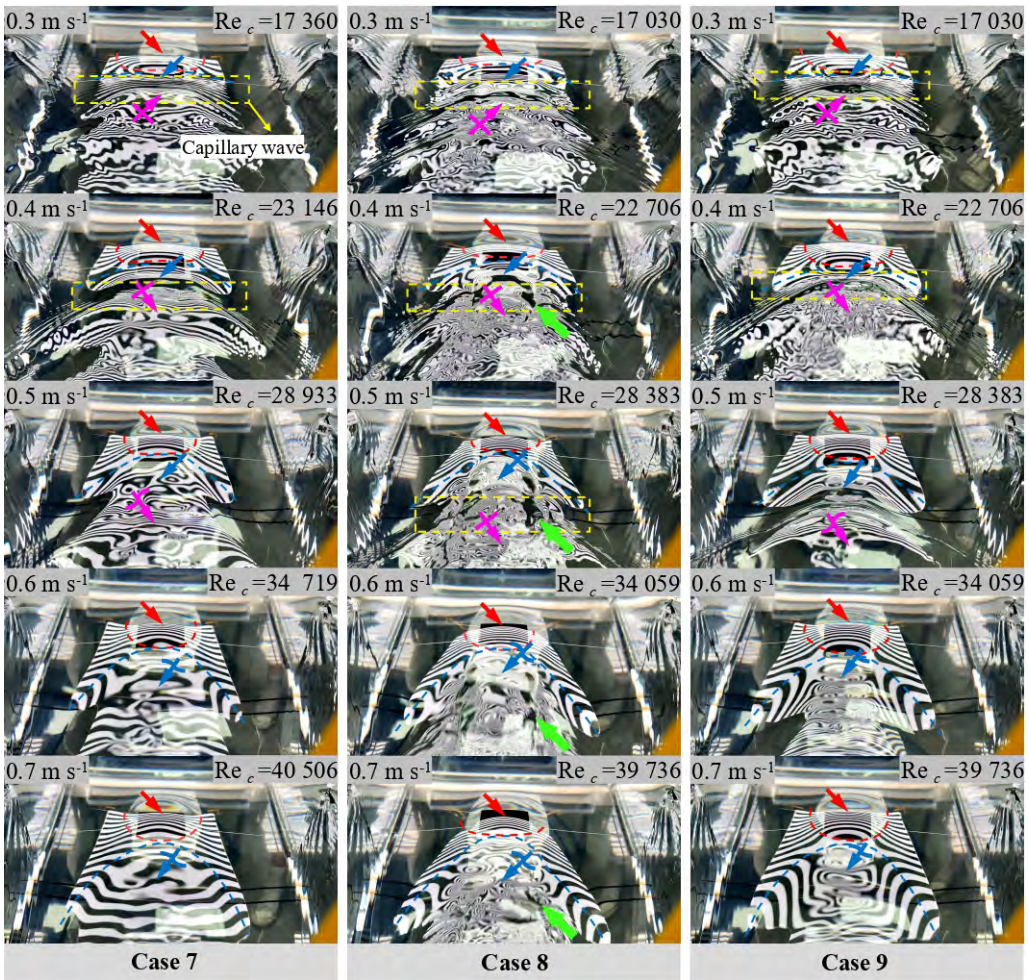


Figure 11. Zebra stripe patterns for Cases 7 to 9. The dark fringes indicated by the green arrows are traces of the model tip vortices striking the water surface (Zhang *et al.* 2020).

530 arrows. The absence of any annotation implies that no valid physical information can be
 531 identified.

532 The waves depicted in figures 9 to 11 exhibit three-dimensional characteristics. A small
 533 convex bulge typically forms above the model, while a concave bow wave develops at the
 534 model's stern, representing a specific derivative of Kelvin wave patterns under the given
 535 operational conditions(Xue *et al.* 2020). At low towing speeds (< 0.4 to 0.5 m s^{-1}), capillary
 536 waves are observed on the upward slope plane downstream of the trough (within the yellow
 537 dashed box). The liquid surface exhibits low steepness, and capillary waves display only
 538 localized instabilities. The wavelength of capillary waves decreases toward the center of
 539 the wave trough, where they are densely packed, while the wavelength gradually increases
 540 toward the outer flanks. The waves fan outward, and this spanwise variation arises from
 541 differences in the crest velocity and trough velocity of the capillary waves in the spanwise
 542 direction (Duncan *et al.* 1999). Outside the capillary wave region, the surface generally
 543 remains calm, except for faint vortex impingement traces immediately downstream of
 544 the depression wave—specifically in the region of maximum surface curvature—where a

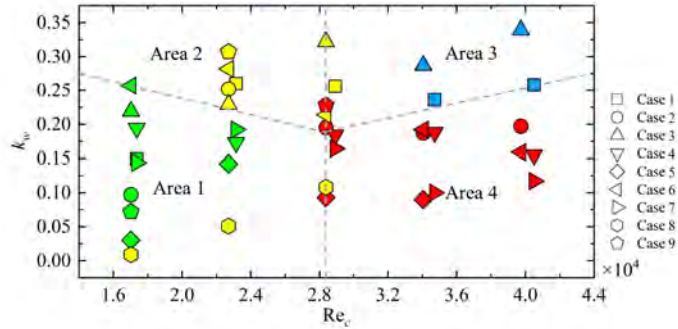


Figure 12. Distribution of wake types under different k_w (slopes of the line connecting wave crests and troughs) and towing speeds, where Type 1 to 4 wakes are represented by green, yellow, blue, and red respectively.

545 locally sharpened fine annular topological pattern emerges. As the towing speed increases
 546 continuously, this local vorticity rapidly diffuses and destabilizes, evolving into large-
 547 scale breaking waves that cover the entire area enclosed by the Kelvin wave pattern.
 548 A key transition occurs when the towing speed increases beyond a certain threshold
 549 (approximately 0.5 to 0.6 m s^{-1}): the capillary waves disappear. At this point, the vorticity
 550 near the interface downstream of the trough undergoes a complete transformation, leading
 551 to a flow state dominated either by large-scale vortices or a smooth, steady interface.
 552 According to the study of Longuet-Higgins (1992), the initial stage of short gravity wave
 553 breaking involves the appearance of parasitic capillaries. As the Reynolds number increases
 554 further, gravity induces a natural downward sliding of the interface along the sloped water
 555 surface behind the trough (Duncan *et al.* 1994). This sliding fluid impacts the leeward
 556 face of the wave; the intervening fluid is continuously entrained, forming a shear layer.
 557 Separation from the underlying fluid triggers a turbulent state, leading to the formation of
 558 a capillary roller (Longuet-Higgins 1992). Dimas & Triantafyllou (1994) indicated that
 559 intense horizontal shear is the primary trigger for small, sharp surface waves near the free
 560 surface at low Froude numbers. Interestingly, he capillary waves were absent in Case 5
 561 at the lowest Reynolds number. Observation of figure 6 reveals that the trough depth for
 562 Case 5 is shallow. A flatter wave surface is less prone to interface breaking. Deike *et al.*
 563 (2015) previously noted that waves with low initial steepness remain stable, propagating
 564 smoothly without breaking. When the trough steepness is small, capillary waves induce
 565 only localized interfacial vorticity near the trough.

566 Typically, vortices shed from the orca stern impinge on the water surface downstream of
 567 the wave trough (downstream of the blue arrow). However, in Case 8, vortex impingement
 568 is observed upstream of the capillary wave. Figure 11 presents snapshots of the interfacial
 569 vortex structures for Case 8 at different Reynolds numbers. At the lowest Reynolds number,
 570 evidence of large-scale vortex impingement is observed at the upstream trough location
 571 relative to the capillary waves, while the area downstream of the capillary waves shows
 572 dense, small striations formed by the impingement of small-scale, high-frequency waves.
 573 When the Reynolds number increases to 28 383, the impingement of large-scale structures
 574 even makes the wave trough difficult to discern. As the Reynolds number increases further,
 575 the wake becomes dominated by large-scale structures and the capillary waves disappear
 576 gradually. The upward flow-guiding tendency of Case 8 is highly evident, as it convects
 577 the tip vortices from both sides of the model to the vicinity of the interface, where their
 578 impingement on the free surface leaves visible ‘traces’, as indicated by the green arrows

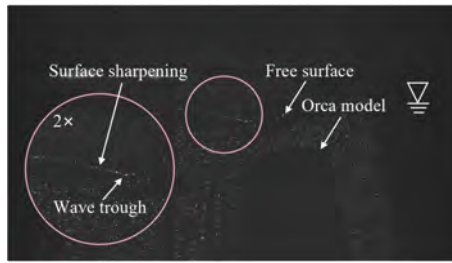


Figure 13. A snapshot of the deformed water surface for Case 3 at a towing speed of 0.3 m s^{-1} .

579 in the figure. The development path of vortices downstream of an irregular cross-section
580 body is closely related to its attitude (Subburaj *et al.* 2018), a point that will be discussed in
581 Section 3.2 regarding the underwater flow structures. The subsequent part of this section
582 continues to focus on the characteristics of vortex impingement on the interface.

583 Based on the morphological differences of the impinging vortices, the model wake is
584 categorized into four types. Type 1 features small-scale shedding vortex structures that
585 cause small-range vortex impingement on the surface. The diameter of a single vortex
586 is much less than W_m . These vortices shed from the wave trough and collide with the
587 deformed surface, with an emergence width of one to several times the diameter of the
588 impact vortex, which subsequently diminishes or vanishes as they follow the wake. Type
589 2 involves wide-range small-scale vortex structures. When the Reynolds number further
590 increases on the basis of the Type 1 wake, shortly after the formation of the depression,
591 the wake instantly transitions into a large-area ‘orange peel’ pattern covering the entire
592 downstream region of the depressed wave that induces large-area intensive fluctuations
593 in the wake region. The initial width is significantly larger than W_m , and its extent is
594 confined within the band-like depression region (the region downstream delineated by
595 capillary waves). The vortex impingement frequency is higher than in Type 1. Individual
596 vortex sizes are at the level of Type 1 and are distributed very densely. Type 3 forms a
597 steady wake region where the surface is smooth, the streak spacing is highly regular, and
598 the curvature variation is small. No action between the shedding vortices and the liquid
599 surface is observed. This scenario typically occurs in cases with deeper tail depression
600 waves. Type 4 involves large-scale shedding vortex structures, where the size of a single
601 vortex is often comparable to W_m . These structures gradually enlarge while developing
602 downstream. Adjacent vortex structures usually appear sequentially without clustering,
603 which may be related to the spanwise asymmetry of the vortex structures. Study showed
604 that this characteristic is one cause of the aperiodic nature of vortex shedding and is a
605 feature of wakes behind finite-aspect-ratio models, with asymmetric flows more prone to
606 occur at higher Reynolds numbers (Taira & Colonius 2009). In figures 9 to 11, a slash
607 bar ‘\’ added to an arrow indicates small-scale vortex structures, a wavy line ‘~’ denotes
608 large-scale vortex structures, and the absence of a symbol represents steady flow. If an
609 arrow lacks an annotation, it implies that the flow feature at that location is difficult to
610 identify, for instance, if it is outside the field of view.

611 Deike *et al.* (2015) indicated that the Bond number and the initial wave steepness can be
612 used to classify wave regimes, as surface tension significantly influences interfacial wave
613 development. We propose that the wake type is associated with both the Reynolds number
614 and the steepness of the wave concavity. We have plotted the wake type, Reynolds number,
615 and the downslope steepness k_w (defined in figure 8) in a single diagram. When the wave
616 depression is limited and the towing speed is low, Type 1 wake dominates and is distributed
617 in Area 1. Capillary waves downstream of the wave trough are typically observed in this

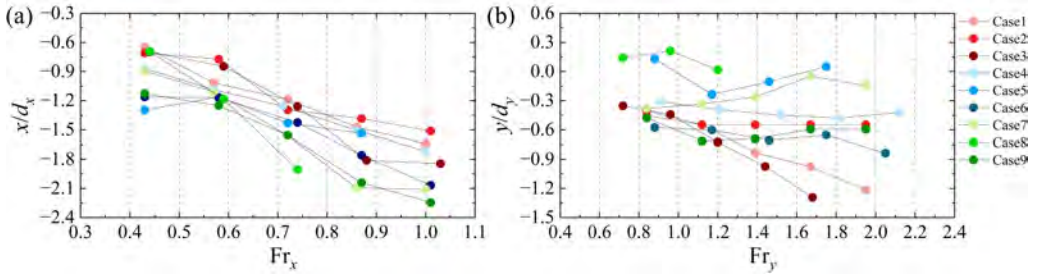


Figure 14. (a)

618 regime. Case 8 unexpectedly appears in this region because its attitude forcibly guides
 619 the trailing vortices toward the surface. As k_w increases, the wake transitions from Type
 620 1 to Type 2. The spatial extent of Type 2 wake is considerably larger than that of Type
 621 1, and their underlying formation mechanisms differ. The steeper slope promotes the
 622 formation of a jet beneath the trough and a large-scale mixing layer near the free surface,
 623 generating numerous surface vortices, Lin & Rockwell (1995) investigated wave breaking
 624 phenomena downstream of a hydrofoil and observed that with increasing Froude number,
 625 capillary waves are replaced by large-scale free-surface distortions, which are induced by
 626 flow separation near the free surface at the wave trough where the radius of curvature is
 627 large. Figure 13 displays a wave profile for Case 3 at the lowest towing speed, in which
 628 the trough and the subsequent upslope exhibit sharpening. As the flow velocity increases,
 629 the sharpened trough becomes more prone to intense flow separation. When both the
 630 depression depth and the velocity are relatively high, the wake transitions from Type 2 to
 631 Type 3. In this case, the capillary waves behind the trough disappear, and severe curvature
 632 variations on the interface are significantly reduced. The free surface in Type 3 is smooth,
 633 indicating a steady flow state, and no vortex impingement is observed within the camera's
 634 field of view. It is worth noting that Type 3 may require a specific deeper wave trough. In
 635 most cases where a sufficiently deep concave wave cannot be formed, the wake exhibits
 636 patterns left by the impingement of large-scale vortices, that is, the Type 4 wake. We tend
 637 to believe that Type 3 and Type 4 are essentially the same underwater flow pattern, i.e.,
 638 strouhal vortex shedding state, with the distinction lying in whether the large-scale wake
 639 vortices are convected to shallower surface-sensitive regions.

640 It is evident that the initial state of the liquid surface corresponds to Type 1. As the
 641 wave trough deepens and its curvature increases, flow shear instability beneath the trough
 642 triggers a transition to Type 2. With a further rise in the Reynolds number, capillary waves
 643 disappear, and stable flow at the trough replaces flow separation. If the wake intensity is
 644 high or its position is close to the water surface, the large-scale vortex structures will reach
 645 the interface, leading to a transition to Type 4. Conversely, if the wake intensity is weak
 646 or is guided by the model to deeper layers, it becomes insufficient to affect the interface,
 647 resulting in a transition to Type 3. The presence of capillary waves serves as a critical
 648 indicator of the transition from Type 1/2 to Type 3/4, corresponding to a Reynolds number
 649 range of 28 000 to 29 000.

650 At low Froude numbers, the free surface can stabilize the flow field, while high Froude
 651 numbers typically induce large-amplitude waves. The Froude number is closely related to
 652 the stability of the downstream wake (Triantafyllou & Dimas 1989). Some studies indicated
 653 that at low Froude numbers, the interaction between vortices and the free surface resembles
 654 that with a rigid surface, whereas at high Froude numbers, significant deformations occur
 655 (Yu & Tryggvason 1990; Tryggvason *et al.* 1991). Although free-surface deformations

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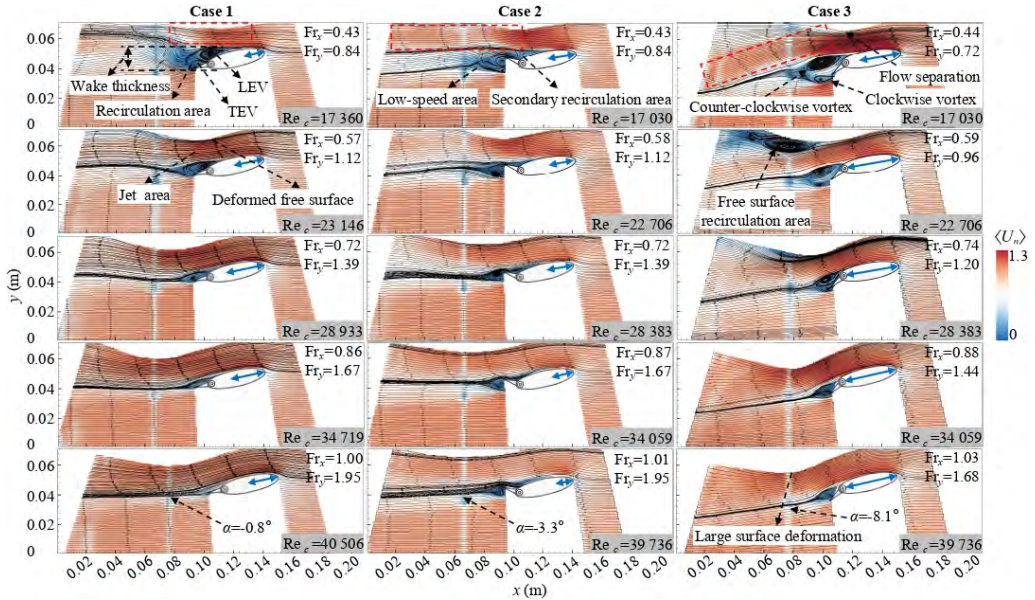


Figure 15. Time-averaged velocity for Cases 1 to 3 at different Reynolds numbers.

656 induced by near-surface cylinders have been extensively studied (Sheridan *et al.* 1995,
 657 1997; Reichl *et al.* 2005; Sun *et al.* 2025), the Froude number for a cylinder is determined
 658 solely by its diameter. In contrast, the present model involves two distinct Froude numbers:
 659 the streamwise Froude number Fr_x and the normal Froude number Fr_y . The dimensionless
 660 depth and streamwise position of the trough of the depression wave are plotted against
 661 the corresponding directional Froude numbers in figure 14. For all cases, as Fr_x and Fr_y
 662 increase, the wave trough moves farther away from the orca model. However, the depth
 663 of the trough is influenced by the model's attitude. Several differences are noteworthy.
 664 Regarding the streamwise position x/d_x , the trough in Cases 1 to 3 remains closer to the
 665 model, with a moderate rate of change as Fr_x increases. In contrast, cases 7 to 9 exhibit
 666 a more pronounced downstream shift with increasing Fr_x . Although data for Case 8 is
 667 incomplete, its trend suggests a substantial displacement, and based on the results in figure
 668 6, it can be anticipated that the trough will appear further downstream. In comparison,
 669 Cases 4 to 6 show lower sensitivity to Fr_x , with x/d_x being the least responsive to changes
 670 in Fr_x .

671 Regarding the dimensionless trough depth y/d_y , Cases 1 and 3 show a rapid deepening
 672 of the trough with increasing Fr_y , resulting in significant depression waves at high Froude
 673 numbers. Case 6 exhibits a similar trend but at a reduced rate. The remaining cases show
 674 minimal change in y/d_y with increasing Fr_y . For complex models, the trend of free surface
 675 variation cannot be evaluated solely by the Froude number, as the contribution of the
 676 geometry of the flow-disturbing cross-section may be comparable to that of the Froude
 677 number. The study by Daichin & Lee (2004) indicated that even for elliptical cylinders
 678 with aspect ratios of 3 to 4, the influence of surface curvature on free surface deformation
 679 and wake flow structure exceeds that of the Froude number. Given the greater complexity
 680 of the model in this study, the influence of the Froude number is likely to be less significant
 681 than in traditional bluff bodies. The interaction mechanism between the vortex structures
 682 behind the orca model and the free surface is complex and requires further analysis of the
 683 flow field below the water surface.

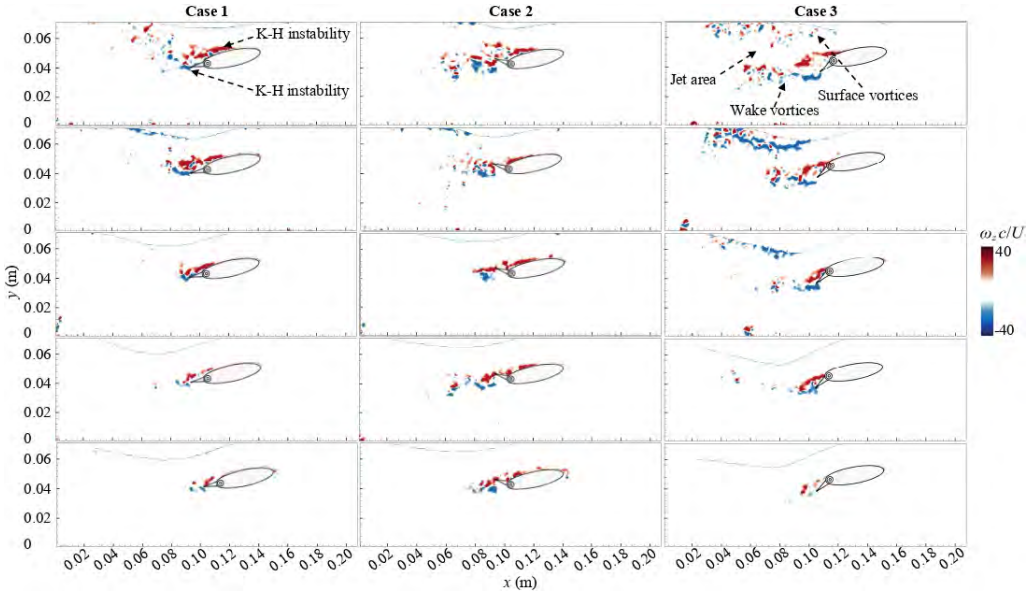


Figure 16. Instantaneous vorticity for Cases 1 to 3 at different towing speeds.

684

3.2. Flow field below the water surface

685 The geometric shape features an elliptical cross-section with major and minor axes in
 686 approximately a 4:1 ratio. The model has two free ends and will be installed at a pitching
 687 angle of attack in some cases. Additionally, a rudder is attached to the downstream trailing
 688 edge, which can flip upward or downward along the spanwise axis. When towed beneath
 689 the free surface, the model satisfies both asymmetric boundary conditions and asymmetric
 690 geometric conditions (Inoue & Sakuragi 2008; Subburaj *et al.* 2018; Samsam-Khayani &
 691 Seyed-Aghazadeh 2025). The asymmetric boundary conditions arise from the combined
 692 effects of the geometry and the free surface. Unlike the periodic wake patterns typically
 693 observed under symmetric boundary conditions, the wake flow structure of the orca model
 694 is expected to undergo significant alterations due to additional constraints (Taneda 1965;
 695 Alzabari *et al.* 2023). The asymmetric wake induced by the angle of attack was initially
 696 investigated by Fage & Johansen (1927). Primary focus is often placed on boundary layer
 697 development, subsequent shear layer instability, and the separation of leading- and trailing-
 698 edge vortices, phenomena that have been extensively analyzed in studies of flow around flat
 699 plates (Perry & Steiner 1987; Nakamura *et al.* 1991; Samsam-Khayani & Seyed-Aghazadeh
 700 2025). This section examines the flow dynamics around the orca model in different attitudes
 701 using time-averaged velocity fields, time-averaged vorticity fields, time-averaged swirling
 702 strength vector fields, instantaneous vorticity, and streamlines.

703 The dimensionless vorticity $\omega_{z,n}$ is obtained by normalizing the vorticity $\omega_z = \partial v / \partial x -$
 704 $\partial u / \partial y$ using the chord length c and the towing speed U_∞ :

$$\omega_{z,n} = \frac{\omega_z c}{U_\infty}, \quad (3.3)$$

705 The time-averaged dimensionless vorticity $\langle \omega_{z,n} \rangle$ characterizes the average distribution
 706 of vorticity over time in the wake of the model. The coherent-structure identification
 707 criterion based on λ_{ci} is employed to detect and characterize vortex structures in complex
 708 flow fields. This method is grounded in the concept of swirling strength and involves

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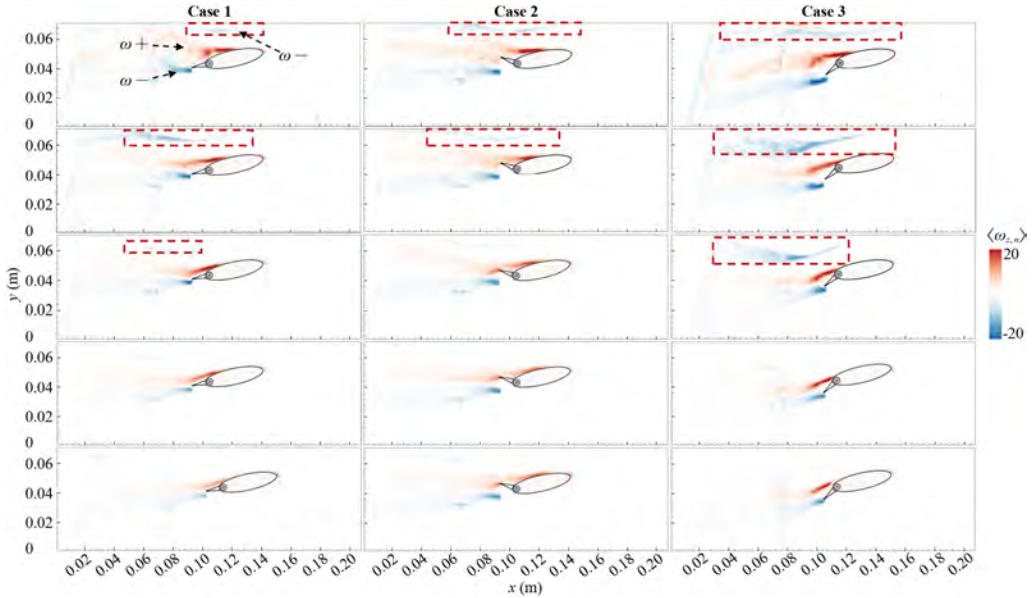


Figure 17. Time-averaged vorticity for Cases 1 to 3 at different towing speeds. The red dashed box marks the negative vorticity diffusing into the water from the wave trough.

709 analyzing the eigenvalues of the velocity gradient tensor $\mathbf{eig}(\nabla \mathbf{u})$. Regions with enhanced
 710 vortex activity are identified by the presence of a complex eigenvalue pair, with higher
 711 λ_{ci} values indicating stronger swirling motion and highlighting the presence of coherent
 712 vortices (Zhou *et al.* 1999; Haller 2005). Samsam-Khayani & Seyed-Aghazadeh (2025)
 713 applied this approach to analyze vortex shedding from an inclined plate near a free
 714 surface. A vortex is identified by a complex eigenvalue pair of the velocity gradient tensor,
 715 representing rotational motion within a defined plane. The swirling strength is defined as
 716 follows:

$$\lambda_{ci} = \text{Im}(\mathbf{eig}(\nabla \mathbf{u})) = \text{Im} \left(\mathbf{eig} \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix} \right), \quad (3.4)$$

717 swirling strength is non-dimensionalized using the chord length c and the towing speed
 718 U_∞ :

$$\lambda_{ci,n} = \frac{\lambda_{ci} c}{U_\infty}. \quad (3.5)$$

719 Its time-averaged value $\langle \lambda_{ci,n} \rangle$ can simultaneously characterize both the time-averaged
 720 distribution of vortex strength in the flow field and the development trajectory of coherent
 721 structures.

722 Figures 15 to 18 present the time-averaged velocity (with streamlines), instantaneous
 723 vorticity, time-averaged vorticity, and time-averaged swirling strength for Cases 1 to 3
 724 at different Reynolds numbers. When the model is at an angle of attack, shear layers of
 725 varying strength and size form at the leading and trailing edges, causing an imbalance in the
 726 wake (Nakamura *et al.* 1991). For Case 1, at the lowest Reynolds number ($\text{Re}_c = 17\,360$),
 727 an accelerated jet forms at the model's leading edge, undergoes laminar separation a short

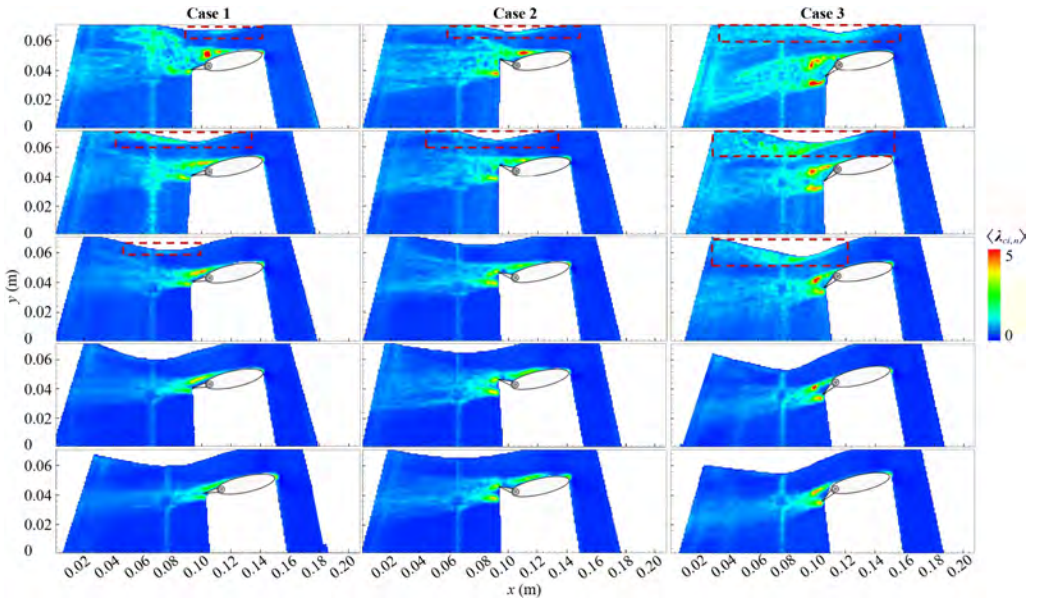


Figure 18. Time-averaged swirling strength for Cases 1 to 3 at different towing speeds. The red dashed box marks the active vortex activity caused by surface wave breaking.

728 distance downstream, and generates a counterclockwise leading-edge vortex (LEV) on the
 729 model's suction side. A clockwise trailing-edge vortex (TEV) forms above the tail fin,
 730 and the positions of these two vortices show significant asymmetry, together constituting
 731 a large-scale, low-velocity recirculation area. In case 1, the low-velocity recirculation area
 732 remains attached to the model's dorsal surface. As the Reynolds number increases, the
 733 recirculation area compresses towards downstream, the wake thickness decreases, and
 734 the asymmetric dual vortex ring structure degenerates into a single vortex ring before
 735 eventually disappearing.

736 Generally, the edges of the vortex ring produce strong shear, and the separated shear
 737 layer undergoes Kelvin-Helmholtz (K-H) instability, forming numerous irregular small-
 738 scale vortical structures, see figure 16. As the flow interacts and merges with the large-scale
 739 recirculation vortex ring. According to experimental results from Lin *et al.* (1995), K-H
 740 small-scale vortices are the core feature of the instantaneous flow in the present Reynolds
 741 number range. These small-scale structures are embedded within the large-scale structure,
 742 forming a complex wake topology. In Case 1, the LEV attached to the model's back impedes
 743 the attachment of the jet to the surface at the lowest Reynolds number ($Re_C = 17\,360$). As
 744 the boundary layer separates, the jet detaches from the model surface and deflects upward
 745 along the edge of the recirculation area. The deformed free surface then exerts an 'elastic'-
 746 like constraint on the jet (Barker & Crow 1977), causing it to deflect again downstream
 747 beneath the free surface, with its strength significantly weakened. The high-speed flow
 748 beneath the model wraps around the edge of the low-velocity recirculation area, entraining
 749 fluid to compensate for the wake. The asymmetric instability of the vortex ring causes the
 750 low-velocity fluid to deflect and diffuse toward the free surface. Studies on the wake of
 751 upward-inclined hydrofoils by Taira & Colonius (2009) indicate that after the leading-edge
 752 vortex separates, its position elevates away from the model surface, consistent with the
 753 observations in this study. The separated wake structure displaces to approximately $0.5d_x$

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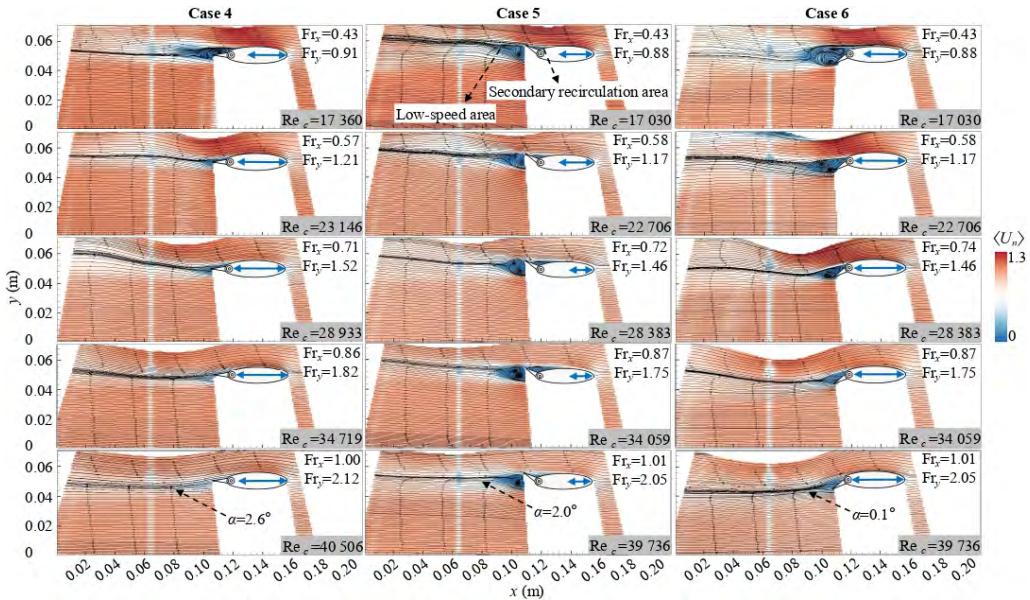


Figure 19. Time-averaged velocity fields for Cases 4 to 6 at different Reynolds numbers.

754 downstream of the model below the water surface and interacts with it. Figure 18 illustrates
 755 the diffusion path of the vortex structure within the recirculation area.

756 As the Reynolds number increases, the recirculation area compresses, reducing its
 757 obstruction to the jet. The reattachment length L_a of the jet (refer to the blue double-headed
 758 arrow) initially increases and then decreases, reaching its maximum ($L_a = 26.59$ mm,
 759 $L_a/c = 0.53$) at $Re_c = 28\,933$. Below this Reynolds number, the increase in reattachment
 760 length ($L_a = 14.6\text{mm} \rightarrow 26.59\text{mm}$) is dominated by the increased dynamic pressure in
 761 the flow field above the stagnation point at the model's leading edge. Above this Reynolds
 762 number, the subsequent decrease in reattachment length ($L_a = 26.59$ mm \rightarrow 21.06 mm)
 763 is caused by the increased cross-flow kinetic energy between the leading edge and the
 764 free surface, leading to flow detachment from the surface and suppressing the Coandă
 765 effect (Samsam-Khayani & Seyed-Aghazadeh 2025). The jet attached to the model's
 766 back can guide the wake to deflect downward, increasing the degree of free surface
 767 deformation. When the $Re_c > 28\,933$, the jet streamlines and the deformed free surface
 768 exhibit synchronized curvature, as if the jet is adhering to the deformed surface. At lower
 769 Reynolds numbers, localized negative vorticity (ω^-) diffusing from the surface into the
 770 fluid interior can be observed at the wave trough locations, as circled by the red dashed box
 771 in figure 17. When $Re_c > 28\,933$, this localized negative vorticity at the trough disappears.
 772 Correspondingly, figure 9 shows that the capillary waves also vanish, and the downstream
 773 wake interface becomes smooth. The instantaneous vorticity and swirling strength results
 774 indicate that, at this stage, the jet hinders the contact between the model's trailing vortices
 775 and the interface, and the jet area is almost devoid of vortical structures.

776 In Case 2, influenced by the raised tail fin, the separated vortex ring is located downstream
 777 of the fin, exhibiting better symmetry compared to Case 1. A small-scale, low-velocity
 778 secondary recirculation area forms in the region enclosed by the model's back and the
 779 raised tail fin. This low-velocity region persists across all tested towing speeds in Case 2
 780 and connects with the low-velocity region in the wake. As the Reynolds number increases,
 781 the secondary recirculation area extends upstream, while the reattachment length of the jet

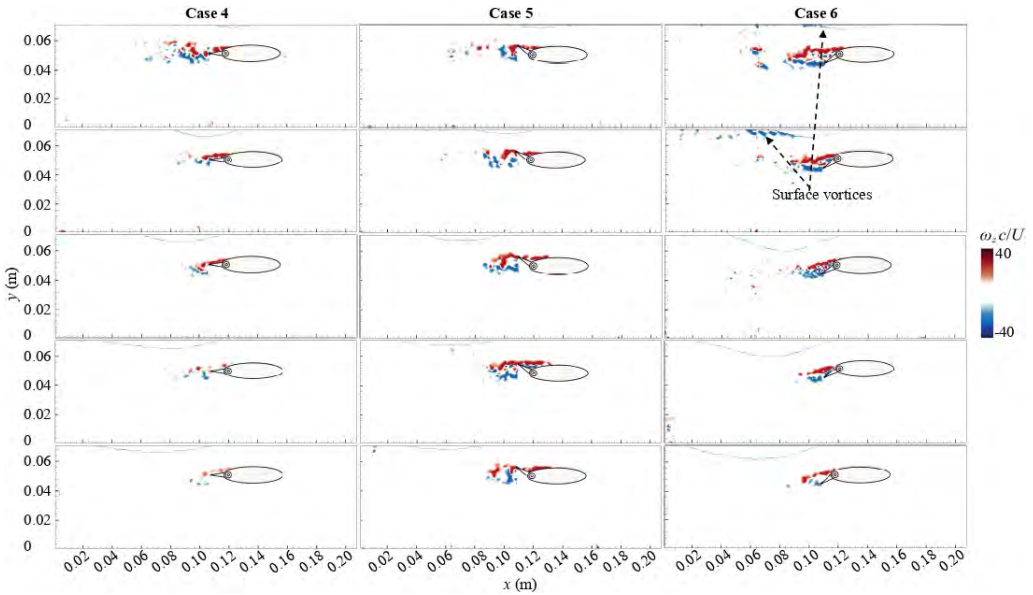


Figure 20. Instantaneous vorticity for Cases 4 to 6 at different towing speeds.

782 continues to shorten ($L_a = 19.81 \text{ mm} \rightarrow 12.98 \text{ mm}$), leading to earlier flow separation.
 783 Both the secondary recirculation area and the vorticity near the tail fin exhibit positive
 784 vorticity ($\omega+$), and they dominate the shedding of trailing vortices. Since the primary
 785 recirculation area is confined below the tail fin, the jet passes over the fin tip without a
 786 block. Compared to Case 1, the more symmetric trailing vortex ring balances the wake,
 787 resulting in smoother streamlines. However, the low-velocity wake region in Case 2 is
 788 thicker than in Case 1, and the squeezing effect of the jet on the wake is weak. It is
 789 hypothesized that the extended low-velocity region along the model's back weakens the
 790 kinetic energy of the jet. This hypothesis is supported by the subsequent results; the time-
 791 averaged velocity profiles behind the model show that the minimum velocity in the wake
 792 recirculation area and the maximum velocity in the jet area of Case 2 is both lower than in
 793 Case 1, especially at higher Reynolds numbers ($Re_c \geq 28\,383$). Another effect of the raised
 794 fin is that it elevates the trailing vortices, which is associated with substantial shedding
 795 of positive vorticity at the higher fin tip. The continuous region of positive vorticity ($\omega+$)
 796 intensifies this effect. When $Re_c > 34\,059$, large-scale vortex impingement occurs on
 797 the free surface, classified as a Type 4 wake, induced by the large-scale Strouhal vortices
 798 shedding from the tail. When these large-scale structures convect near the interface, they
 799 cause pressure fluctuations, forming localized surface elevations. In Case 2, due to the
 800 effect of attitude, the shed vortices do not propagate into deeper water regions, and their
 801 trajectories exhibit a roughly horizontal motion pattern (refer to the streamline angle α in
 802 figure 15). The jet does not completely isolate the large-scale vortices from the surface,
 803 which may be attributed to its own weakened state and the greater thickness of the wake in
 804 Case 2 (see figure 18).

805 In contrast, the downward-folded tail fin in Case 3 leads to markedly different outcomes.
 806 The trailing vortex ring in Case 3 is almost entirely located downstream of the model. The
 807 absence of a secondary recirculation area on the model's back eliminates any obstruction to
 808 jet attachment, allowing the jet's reattachment length to increase continuously with rising
 809 Reynolds number ($L_a = 28.18 \text{ mm} \rightarrow 36.11 \text{ mm}$). When $Re_c > 22\,706$, the jet nearly

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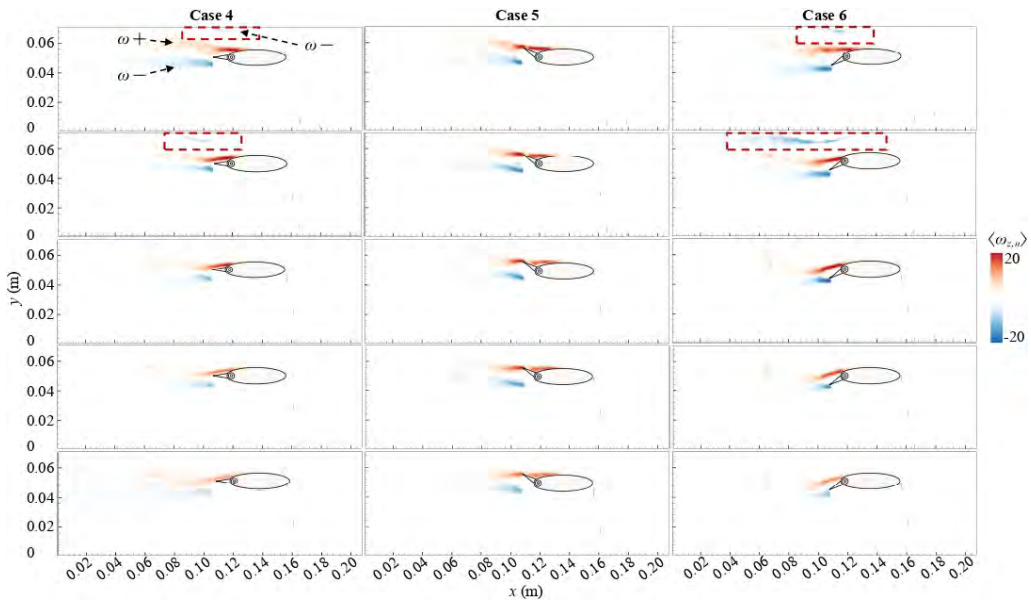


Figure 21. Time-averaged vorticity for Cases 4 to 6 at different towing speeds. The red dashed box marks the negative vorticity diffusing into the water from the wave trough.

810 completely covers the model's upper surface. At higher Reynolds numbers, inertial forces
 811 dominate over viscous forces, promoting flow attachment to the wall (Samsam-Khayani &
 812 Seyed-Aghazadeh 2025). The thickness of the low-velocity wake region decreases as the
 813 Reynolds number increases, and the symmetric vortex ring is progressively compressed
 814 into a single, small vortex core.

815 At the lowest Reynolds number ($Re_c = 17\,030$), the downstream part of the low-velocity
 816 recirculation area closes rapidly. After closure, the streamlines form an angle ($\alpha \approx -8.1^\circ$)
 817 with the incoming flow, intensifying the jet's pulling effect on the free surface. This angled
 818 wake streamline pattern is a common feature in Case 3. Time-sequence animations of the
 819 instantaneous vorticity field (not shown in the paper) reveal that large-scale vortex structures
 820 are carried deeper into the flow by the jet. The jet's deflection triggers interfacial instability
 821 on the downstream slope of the wave trough. The severe separation between the jet and the
 822 overlying low-velocity fluid at the trough location leads to a more pronounced transition
 823 to wave breaking further downstream, generating a more extensive breaking region than
 824 in Cases 1 and 2. The vorticity being convected originates from the amplification of
 825 disturbances within the mixing layer formed by prior flow separation. The initiation point
 826 of the shear layer rests at the trough of the deformed surface, i.e., the location of maximum
 827 curvature, consistent with the analysis in Section 3.1.

828 For $Re_c = 22\,706$ and $28\,383$, a counterclockwise recirculation area appears downstream
 829 of the wave trough. Multiple vortex lines are observed terminating at the deformed surface,
 830 indicating intense energy exchange. The termination of streamlines at the free surface is
 831 a key indicator of the vortex region's visibility (Samsam-Khayani & Seyed-Aghazadeh
 832 2025). 16 and 17 show that free-surface breaking at this stage generates a large area of
 833 negative vorticity, which diffuses downstream from the wave trough (red dashed box in
 834 figure 17). In contrast, the swirling strength figure indicates that vorticity levels near the
 835 free surface remain relatively low. Research by Lin & Rockwell (1995) suggests that the
 836 maximum circulation values for Type 1 and Type 2 small-scale breaking waves are of the

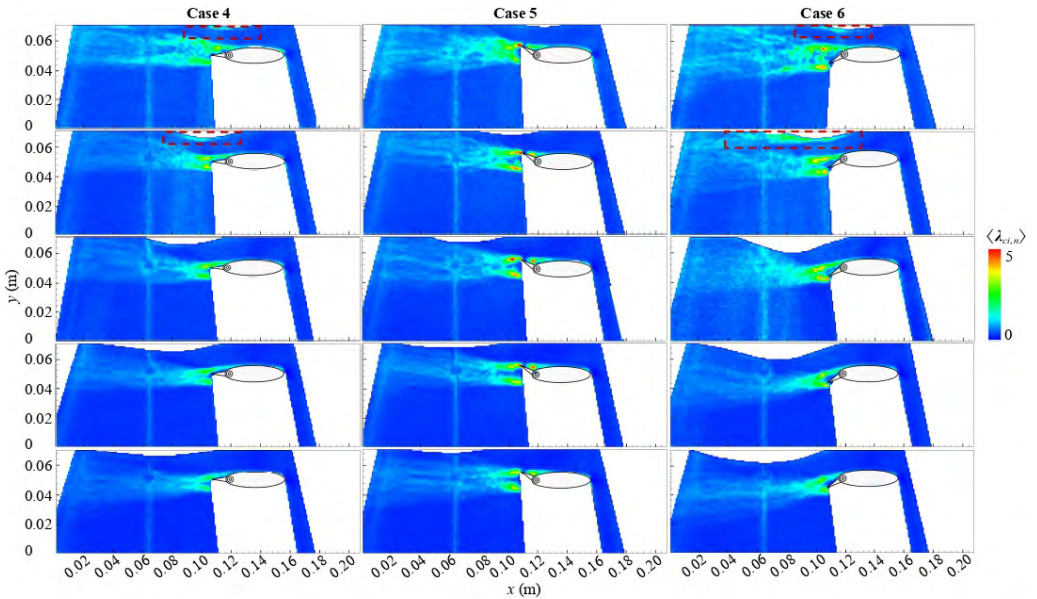


Figure 22. Time-averaged swirling strength for Cases 4 to 6 at different towing speeds. The red dashed box marks the active vortex activity caused by surface wave breaking.

837 same order of magnitude. The jet above the model acts as a barrier, separating the negative
 838 vorticity from the free surface and the positive vorticity from the model's upper surface.
 839 Within the viewing range, these two regions do not interact, thus preventing crossover and
 840 mutual annihilation.

841 The study of Shen *et al.* (1999) shows that surface vorticity is generated by the zero
 842 tangential stress condition at the free surface. The development and trajectory of vortices,
 843 as well as their evolution with other vortices, are influenced by the interface morphology
 844 and surface tension (Ohring & Lugt 1991). The conclusions of Terrington *et al.* (2022)
 845 indicate that both the normal velocity and curvature of the free surface increase with
 846 the Froude number, leading to the generation of more significant secondary vorticity
 847 at the free surface, which is consistent with the observed results. Reichl *et al.* (2005)
 848 studied the flow disturbance near a surface-piercing cylinder, where the downstream jet
 849 caused significant curvature changes in the depression wave, resulting in the generation of
 850 counter-signed shedding vortices on the upper surface. Different from the present study,
 851 the jet in their work could not sufficiently isolate these vortices from interacting with the
 852 shedding structures in the wake; therefore, they rapidly diffused away from the free surface
 853 and underwent crossover and annihilation with the large-scale wake vortices downstream.
 854 Numerous studies on bluff body disturbances near the air-water interface have documented
 855 vortex breaking and vorticity aggregation phenomena induced by depression waves (Lin
 856 & Rockwell 1995; Duncan & Dimas 1996; Iafrati & Campana 2005; Longo *et al.* 2014;
 857 Brøns *et al.* 2014; Bouscasse *et al.* 2017; Subburaj *et al.* 2018; Karmakar & Saha 2020;
 858 Jin *et al.* 2021; Zhao *et al.* 2022; Guo *et al.* 2023; Alzabari *et al.* 2023; Alzabari 2025; Sun
 859 *et al.* 2025). The numerical study by Patel *et al.* (2025) also observed the entrainment of
 860 micro-bubbles into the wake, noting that the absence of interface deformation or rupture
 861 can suppress the generation of interfacial vorticity. Recently, Samsam-Khayani & Seyed-
 862 Aghazadeh (2025) documented capillary waves generated downstream of a deformed free
 863 surface behind an inclined plate, accompanied by the generation of secondary vortices

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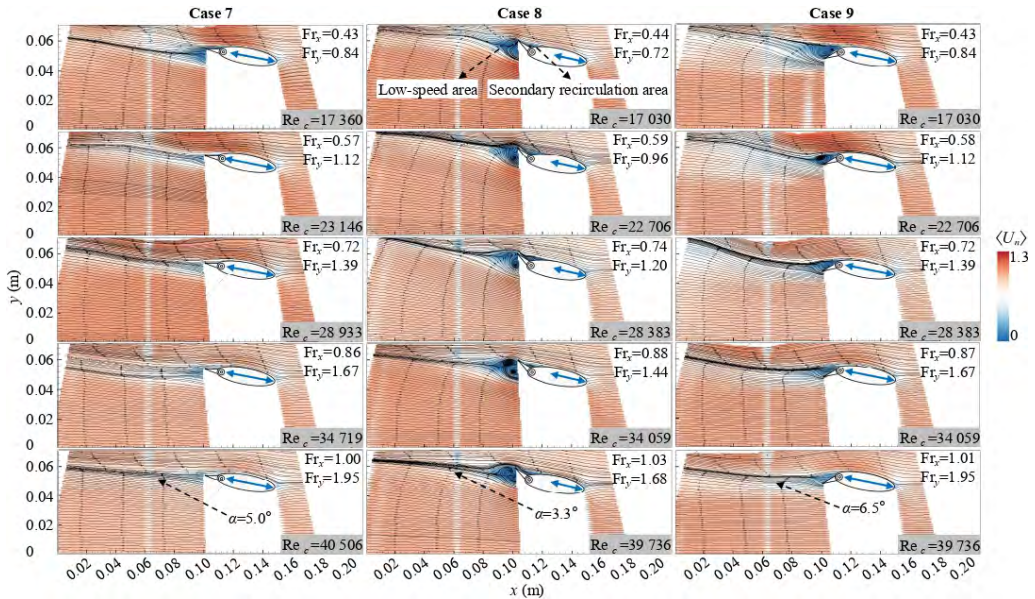


Figure 23. Time-averaged velocity fields for Cases 7 to 9 at different Reynolds numbers.

864 beneath the free surface and wavy shear mixing layers, which resemble the observations
 865 in this study. At the high Reynolds numbers, the free surface undergoes more extensive
 866 deformation. Influenced by the Coandă effect, the jet can undergo secondary attachment,
 867 adhering to the deformed free surface. At this stage, the free surface recirculation area
 868 disappears, and the negative vorticity associated with wave breaking is no longer visible.
 869 Figure 18 clearly record the sudden disappearance of active coherent vortex structures near
 870 the water surface.

871 The K-H instability near the wave trough perfectly corresponds to the small-scale
 872 turbulent patterns recorded in figure 9. The presence of this instability correlates with
 873 observable wave breaking at the water surface, indicating that the small-scale turbulent
 874 structures on the surface are induced by interfacial K-H instability. Small-area wave
 875 breaking is only observed at low Reynolds numbers associated with small-amplitude
 876 depression waves, suggesting that the minor deformation (both in extent and depth) at
 877 the center of the depression wave cannot induce wave breaking far from its center. The
 878 vorticity is concentrated within a thin layer near the interface. Research by Deike *et al.*
 879 (2015) indicates that vorticity is generated at both the troughs and crests of capillary
 880 waves. This result demonstrates universality, as vorticity typically emerges from regions
 881 of high interfacial curvature (Lugt 1987; Lugt & Ohring 1992). These observations are
 882 not unique to Case 3. A cross-comparison of the vorticity fields for Cases 1 and 2 reveals
 883 that localized negative vorticity is generated at the trough of the depression wave in Case
 884 1 at $Re_c = 17\,360$, $23\,146$, and $28\,933$; and in Case 2 at $Re_c = 17\,030$ and $22\,706$.
 885 Swirling strength plots provide corroborating evidence. Cross-referencing with figure 9
 886 shows that capillary waves appear on the water surface, accompanied by downstream
 887 small-scale wave breaking. Furthermore, observation of the vorticity fields reveals that
 888 when the jet reattachment length is short, the vorticity intensity associated with the shear
 889 layer in the model wake decays rapidly. Conversely, in Case 3, the jet boundary is not
 890 weakened by a low-velocity recirculation area, resulting in a more pronounced Coandă
 891 effect. Consequently, the wake shear layer maintains a high shear intensity. Figure 16

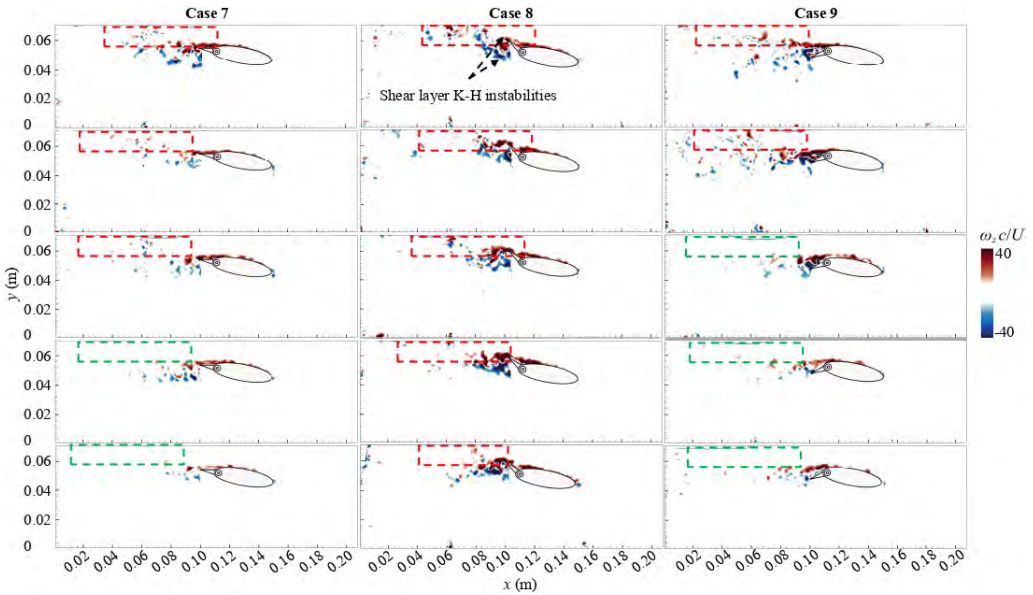


Figure 24. Instantaneous vorticity for Cases 7 to 9 at different towing speeds. The red dashed box marks the diffusion of dense small-scale vortex structures toward the interface, while the green dashed box shows no significant diffusion of small-scale vortices.

892 further indicates that the jet exerts a compressing and constraining effect on the diffusion
 893 of the trailing vortices, but it has little effect on altering the positions of the active vortex
 894 cores within the wake under convective action (highlighted regions). These positions reflect
 895 the active trajectories of periodic coherent structures.

896 When a jet approaches an inclined or curved surface, the Coandă effect can cause the
 897 fluid to adhere to and develop along the solid wall. Viscous forces promote jet attachment
 898 to the wall, while inertial forces drive the jet along its original path. Their combined
 899 action can cause the jet to deviate from its expected trajectory. Wall morphology can guide
 900 and constrain fluid flow. This effect, induced by fluid viscosity, is governed by multiple
 901 factors, including flow velocity, curvature, position, and boundary conditions (Ahmed
 902 2019). Given that this effect can alter the flow field around an object, when a disturbance-
 903 generating object approaches a free surface, the deformed free surface constitutes a second,
 904 different attachable surface distinct from the solid wall. The curved deformed surface, shed
 905 vortices, and the flow around the body can form a more complex interaction mechanism.
 906 Sheridan *et al.* (1997) documented the critical state of trailing vortices induced by the brief
 907 attachment of a jet to a free surface. Hoyt & Sellin (2000) reproduced the experiments
 908 of Sheridan *et al.* (1997), observing various jet attachment phenomena in experiments
 909 with different submergence depths. Carberry (2002) recorded three wake modes for a
 910 cylinder approaching a free surface, one of which involved flow attachment to the free
 911 surface. The presence of a deformable free surface introduces an asymmetric boundary
 912 condition, thereby influencing wake shedding. Non-ideal jet attachment can lead to free
 913 surface deformation, thereby causing the formation of surface vorticity (Sheridan *et al.*
 914 1995; Reichl *et al.* 2005; Sareen *et al.* 2018; Cleaver *et al.* 2013). Shallow submergence
 915 depth is likely a key factor enabling jet attachment. Research by Chen & Chwang (2002)
 916 suggests that the jet on the upper surface of a hydrofoil with a higher submergence ratio
 917 is not as pronounced as observed in studies like Sheridan *et al.* (1997). Samsam-Khayani
 918 & Seyed-Aghazadeh (2025) argue that the free surface further constrains and guides the

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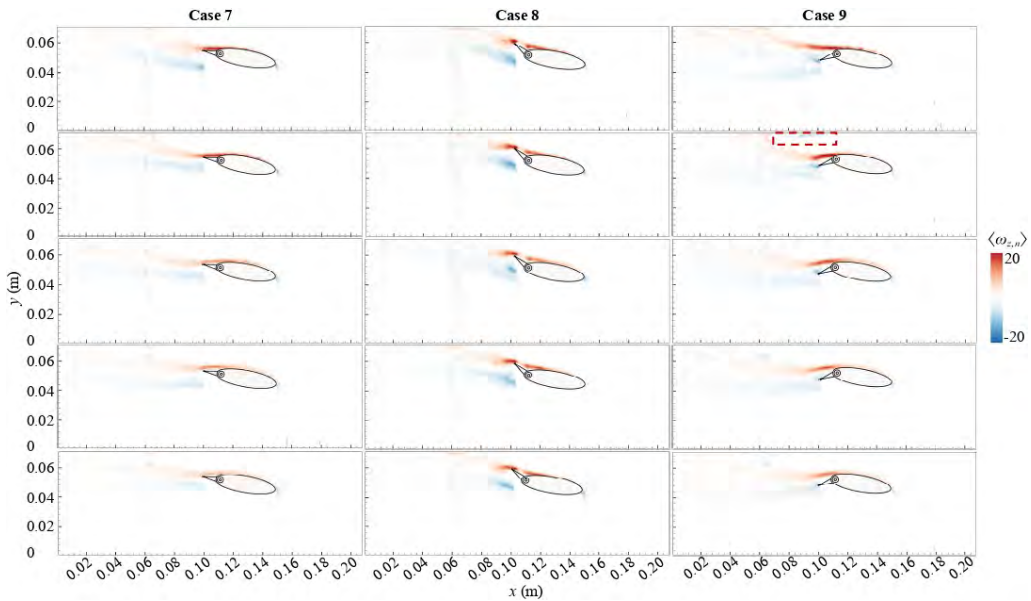


Figure 25. Time-averaged vorticity for Cases 7 to 9 at different towing speeds. The red dashed box marks the negative vorticity diffusing into the water from the wave trough.

919 flow over a plate via the Coandă effect. The second Coandă regime (CII) mentioned in
 920 their work involves the jet being compressed by larger free-surface deformation, thereby
 921 increasing the attachment length covering the plate's leading edge.

922 Observing figures 16 and 17, it is evident that at high Reynolds numbers, the jets in
 923 Case 3 transport large-scale vortex structures into deeper water flow, reducing the impact
 924 of trailing vortices on the interface. This is the reason for the smooth interface of the Type
 925 3 wake. In the present study, the large trailing depression wave in Case 3, together with
 926 the curved back surface of the model, forms an ideal jet channel. The stable and robust
 927 jet enhances the stability of the depression wave. This large-scale depression wave and
 928 associated jet attachment have never been observed in cylinder-induced disturbances. The
 929 upward-tilted head and downward-swept tail behavior in Case 3 is the posture we observed
 930 and consider optimal for the killer whale's ice-breaking during hunting. The large, smooth
 931 depression wake generated by Case 3, devoid of interfacial wave breaking, implies that
 932 interfacial energy is not dissipated, leaving significant surface potential energy within
 933 the system (Deike *et al.* 2015). Zhao *et al.* (2021) suggests that fluctuations in both the
 934 jet velocity component and hydrodynamic forces are suppressed. This sets the stage for
 935 efficiently utilizing the depression wave to manipulate and subsequently break ice.

936 Figures 19 to 22 present the time-averaged flow fields, instantaneous vorticity, time-
 937 averaged vorticity fields, and time-averaged swirling strength fields for Cases 4 to 6 at
 938 different Reynolds numbers. When the model body angle is 0° , the model's blocking effect
 939 on the flow field is weakest. For Case 4, a recirculation area attached to the upper surface
 940 of the tail fin is only observed at the lowest Reynolds number. As the Reynolds number
 941 increases, this recirculation area is compressed and degenerates, with the low-velocity
 942 region located directly behind the model. The reattachment length of the upper-surface
 943 jet is very weak, showing an initial increase followed by a decrease. The depth of the
 944 depression wave also exhibits a trend of first increasing and then decreasing. For Cases 5
 945 and 6, the downstream recirculation vortex ring consistently appears on the side opposite

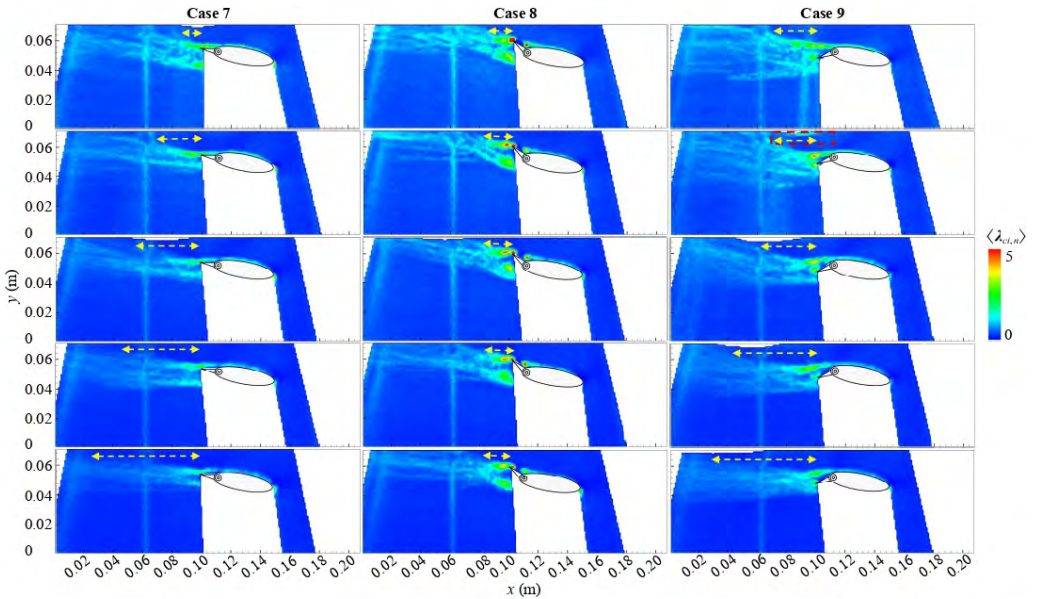


Figure 26. Time-averaged swirling strength for Cases 7 to 9 at different towing speeds. The yellow arrows in the figure mark the extension length of the jets.

946 to the direction of the fin's flip, near its back. The sharp fin tip induces strong flow
 947 separation, leading to the aggregation of high vorticity (see figures 20 and 21) and the
 948 formation of a larger downstream recirculation area. In Case 5, the secondary recirculation
 949 area and the wake recirculation area remain connected, forming a longer low-velocity
 950 boundary. The displacement effect of the secondary recirculation area also leads to a
 951 shorter jet wall-attachment effect. In contrast, Case 6 experiences less flow interference on
 952 its back. The jet separation point is located further downstream, and when $Re_c > 22\,706$,
 953 the jet can completely attach to the surface of the model's back. Consequently, Case 6
 954 can generate a stronger back-jet with a larger outflow angle, thereby inducing greater
 955 free-surface deformation. A cross-comparison of the relationship between depression
 956 wave depth and reattachment length for Cases 4 to 6 reveals a positive correlation; the
 957 reattachment capability of the back jet likely determines the degree of wake depression.
 958 This is corroborated by the lateral comparison of Cases 1-3 before. Due to the suppression
 959 of the depression wave, although capillary wave breaking occurs in Case 5 (at towing speeds
 960 of 0.4 m s^{-1}), the trough depression is insufficient to generate concentrated vorticity, which
 961 is not effectively identified in figures 21 and 22. The vorticity induced by capillary waves is
 962 related to the jet strength, free-surface curvature, and local capillary wave intensity under
 963 specific operating conditions.

964 When the model body is at a negative angle, the trailing depression wave is significantly
 965 suppressed, which is related to the flow above the model being forced towards the free
 966 surface. Figure 23 presents the wake streamlines for Cases 7 to 9, all showing an upward
 967 inclination. This angle is larger at moderate Reynolds numbers and smaller at low or
 968 high Reynolds numbers. Benefiting from the effect of a favorable pressure gradient in
 969 the incoming flow, the jet reattachment lengths in Cases 7 and 9 are close to the model
 970 body length. Nevertheless, the flow directed towards the water surface cannot stretch the
 971 free surface and cause large-scale deformation like a downward-impinging jet. It is also
 972 observed that jet development is impeded by both the low-velocity region near the tail and

973 the free surface, leading to a significant reduction in jet intensity. Interestingly, in figure 11,
974 Case 7 forms a Type 1 wake at low Reynolds numbers. When the $Re_c > 34\,719$, the pattern
975 transitions to large-scale periodic vortex shedding. Considering that concentrated negative
976 vorticity never appears at the depression wave location, the small-scale impinging vortices
977 are likely induced by K-H shear vortices at the edge of the recirculation zone. They diffuse
978 and impinge on the free surface due to entrainment by the jet. The instantaneous vorticity
979 field shows the diffusion of these small-scale vortex structures beneath the free surface.
980 The development length of the dorsal jet increases significantly (yellow arrow in figure
981 26). However, except for the velocity above the model's highest point still exceeding the
982 towing speed, a distinct and consistent jet is no longer apparent. At this stage, large-scale
983 vortex structures in the wake dominate, eventually disturbing the free surface to form a
984 Type 4 wake.

985 For Case 8, intense laminar separation occurs at the tip of the upward-flipped tail fin.
986 The shear action generates numerous small-scale K-H vortex structures. Given that Case 8
987 has the smallest relative submergence depth (h/d_y), these vortex structures shedding from
988 the fin tip are more prone to interact with the surface. The zebra-stripe results show that the
989 interaction between vortex structures and the free surface in Case 8 is very active. Ring-like
990 topological patterns from impingement even appear upstream of the wave trough, and large
991 areas of small-scale impinging vortices exist downstream at all Reynolds numbers, with a
992 width $> W_m$. Referring to figure 26, the short jet development length causes the entrained
993 vortex structures to impinge on the free surface before significant dissipation. According
994 to the instantaneous vorticity field, a multitude of K-H shear vortices are transported near
995 the free surface, a feature clearly captured in the figure (see the red dashed box). Although
996 the flow above the model is still referred to as a 'jet', in Case 8 it accelerates only above
997 the tail fin tip, with no acceleration over the main back surface of the model, making the
998 term 'jet' somewhat tenuous. It is important to note that when $Re_c \leq 28\,383$, capillary
999 waves can be observed behind the wave trough. These capillary waves disappear as the
1000 Reynolds number further increases. This suggests that for $Re_c \leq 28\,383$, the interface
1001 might originally have been a Type 1 or Type 2 wake, depending on the depression wave
1002 depth, but the fin's flow-guiding action forced a conversion to the current Type 2 wake.
1003 This also explains why the wake type for Case 8 in figure 12 appears in the Area 1 region.

1004 In contrast, when the tail fin is flipped downward (Case 9), the jet can be stretched,
1005 having a relatively larger extension space, forming the deepest depression wave among
1006 Cases 7 to 9. When $Re_c = 22\,706$, negative vorticity is generated beneath the free surface
1007 at the wave trough (red dashed boxes in figures 25 and 26), corresponding to the Type 2
1008 wake in figure 11. As the Reynolds number increases further, it transitions to a Type 4
1009 wake.

1010 Figure 27 presents the non-dimensional time-averaged velocity profiles along the
1011 vertical height, taken approximately $1/5d_x$ downstream of the model's trailing edge. The
1012 recirculation zone induced by the separation of the sharpened wave trough at the free
1013 surface causes the profile to exhibit an inverted 'S' shape. The jet immediately adjacent to
1014 the free surface leads to local curves in the upper right subplot exceeding the critical value
1015 of $U/U_\infty = 1$ (black dashed line). The dual-vortex ring structure within the low-velocity
1016 region behind the model results in an 'M'-shaped double-peak profile, whereas a single
1017 peak indicates a single vortex ring in the wake. Case 3 and Case 8 exhibit the deepest
1018 and shallowest low-velocity wake regions, respectively, which is related to the jet ejection
1019 angle. Case 3 forms the most distinct and thickest jet across all towing speeds. In contrast,
1020 the jet in Case 8 is almost degenerate, with its velocity even lower than the freestream
1021 velocity. In Case 3, the most pronounced jet occurs at 0.6 m s^{-1} , while the maximum wave
1022 trough depth appears at 0.7 m s^{-1} . The Case 3 configuration demonstrates the strongest

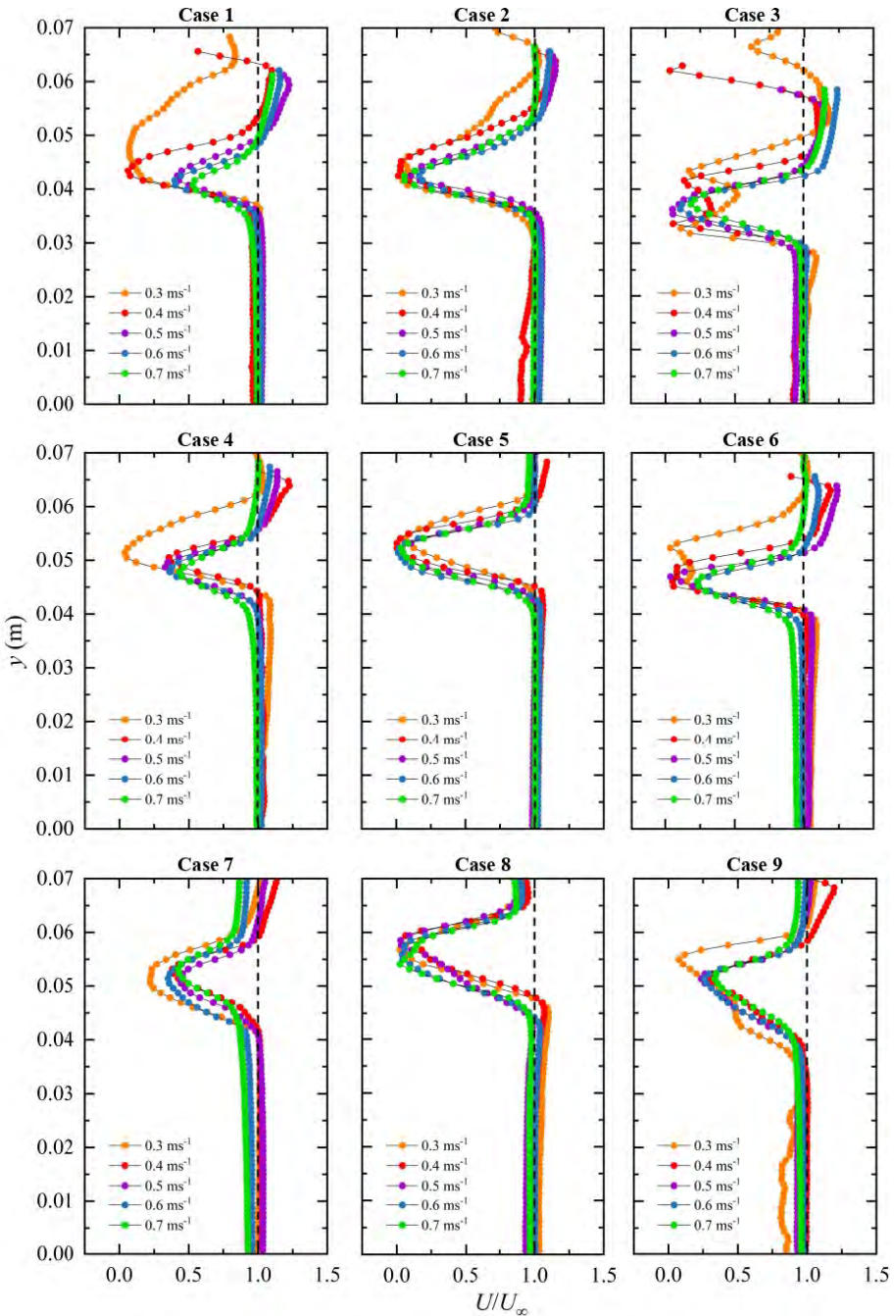


Figure 27. Mean velocity profiles in vertical direction.

1023 capability to maintain both a low-velocity region and a developed jet. In the region below
 1024 the mixing layer, the velocity profiles tend to converge into a single curve; fluctuations in
 1025 individual curves at greater depths are caused by errors from laser sheet refraction at the
 1026 deformed surface.

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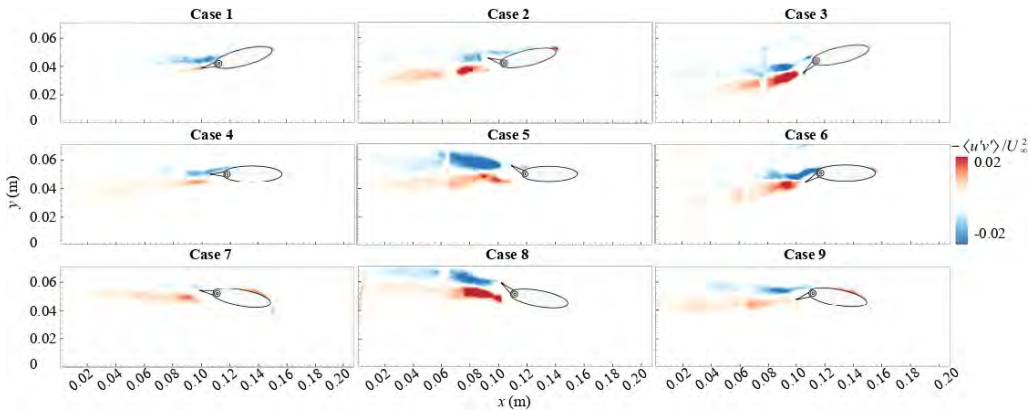


Figure 28. Distribution of time-averaged Reynolds stress for each case at the towing speed of 0.7 m s^{-1} .

1027 Figure 28 displays the Reynolds stress distribution beneath each configuration at the
1028 maximum towing speed, revealing locations of the most intense turbulent momentum
1029 exchange in the model's wake. It can be observed that when the tail fin angle is 0° (Cases
1030 1, 4, and 7), the interface resembles a hydrofoil with smooth surface curvature, leading
1031 to weaker turbulent activity and stable, well-ordered flow fields on both the upper and
1032 lower surfaces. When the raised tail fin interacts with the jet (Cases 5 and 8), localized
1033 acceleration and intense shear separation occur at the fin tip, generating high-intensity,
1034 extensive areas of negative Reynolds stress. This indicates more vigorous vortex structure
1035 oscillation and shedding. Corresponding positive Reynolds stress forms beneath the model,
1036 signifying unstable separated flow. The tip stress in Case 8 is weaker than in Case 5, which
1037 is associated with the weaker back-jet in Case 8. In Case 2, the low-velocity area extending
1038 continuously from the secondary recirculation region to the wake envelops the tail fin tip.
1039 Some vortex structures separated from the model's leading edge merge directly with the
1040 trailing vortices. The separation at the fin tip is mitigated by the low-velocity area, resulting
1041 in a corresponding decrease in Reynolds stress. In Cases 3, 6, and 9, the flow separation
1042 at the tail fin tip remains strong, but its intensity and extent are less than in Cases 5,
1043 and 8. When the tail fin is submerged within the turbulent wake without forming direct
1044 shear with the incoming flow, the region immediately behind the fin shows lower Reynolds
1045 stress, potentially leading to lower flow resistance and a reduced model blockage effect.
1046 Furthermore, the jet influences the transport of Reynolds stress. Readers are encouraged to
1047 compare the turbulence level in the zebra-stripe patterns in figure 9 to 11 at the maximum
1048 towing speed with the magnitude and spatial distribution of the Reynolds stress. It will
1049 be apparent that Reynolds stress directly affects the level of interfacial turbulence. As it is
1050 currently not feasible to quantitatively assess the turbulence intensity from the zebra-stripe
1051 images, a direct data comparison on this aspect is not performed in this study.

1052 3.3. Wave-induced ice breaking

1053 A moving free-surface depression wave can generate disturbances on floating objects. We
1054 first selected a large, continuous ice floe as the study object and conducted experiments for
1055 different cases at towing speeds ranging from 0.3 to 0.7 ms^{-1} , performing 15 independent
1056 tests at each speed. Before the experiments, the ice floe model was carefully positioned
1057 on the water surface, with the spanwise center plane of the floe aligned with the spanwise
1058 symmetry plane of the orca model. Since the ice floe remained unconstrained during the
1059 experiments, it could drift during towing. To ensure result accuracy, the 10 most ideal

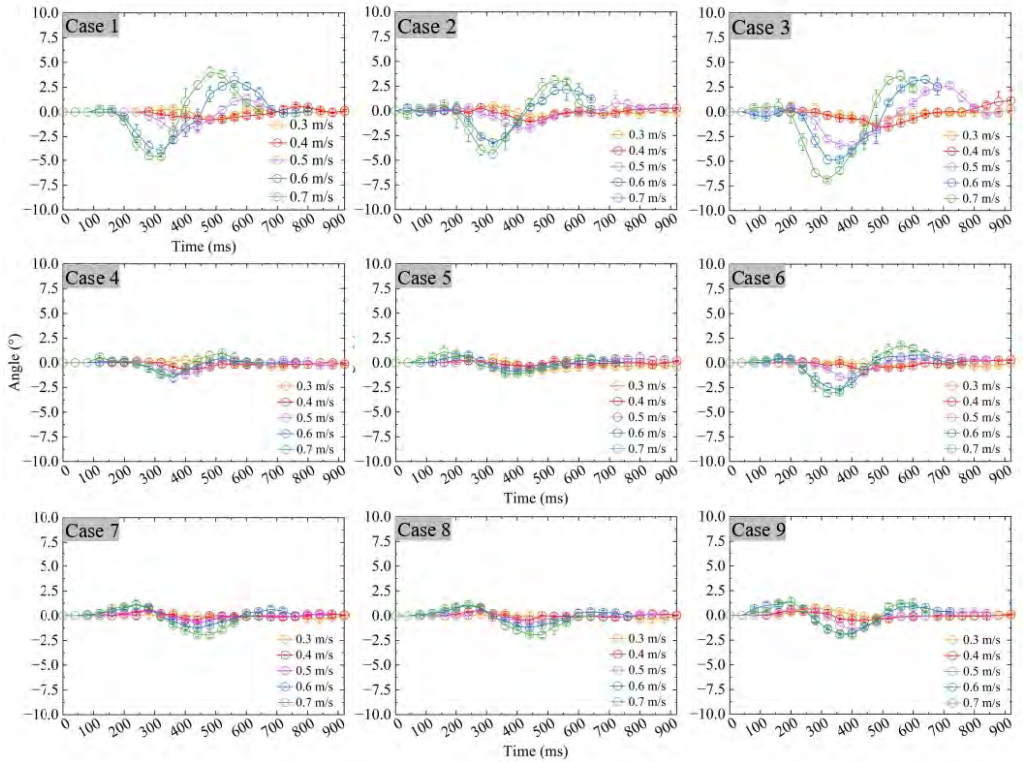


Figure 29. The variation of the tilt angle α_T of large ice floes over time. The results were obtained by averaging 10 independent measurements, with error bars representing the standard deviation of the statistical results. The tilt angle becomes negative as it tilts downward from the horizontal towards the wave trough.

1060 outcomes were ultimately selected. Additionally, in some cases, the depression waves
 1061 caused the ice floe model to fracture; such exceptional results were excluded. The time-
 1062 varying curves of the ice floe tilt angle are shown in figure 29. Across different postures,
 1063 higher swimming speeds tended to produce more pronounced ice floe tilting. Specifically,
 1064 Case 3 at 0.7 ms^{-1} generated the largest tilt angle, approximately -6.9° , whereas Case
 1065 5 exhibited the least significant tilting effect, with a tilt angle of only -1.1° at 0.7 ms^{-1} .
 1066 A comparison with figure 6 indicates that the downslope gradient k_w of the depression
 1067 wave influenced the tilting potential of the ice floe, and a deeper depression wave led to a
 1068 more significant tilt angle. It should be noted that the tilt angle of the large ice floe was
 1069 significantly smaller than the inclination angle of the depression wave's downslope surface.

1070 Following the conclusion in the previous section, the posture with the head oriented
 1071 downward and the tail raised tends to generate a hydraulic jump, forming a convex wave
 1072 above the model. The ice floe initially compresses the convex wave, causing an upward
 1073 tilt, and then flips downward into the trough of the depression wave after passing over the
 1074 convex wave. If the body posture remains unchanged, flipping the tail fin downward tends
 1075 to generate a more pronounced depression wave. In figure 30, we present snapshots of the
 1076 interaction between the ice floe and Cases 3, 6, and 9. The development time relative to the
 1077 first snapshot is labeled in the figure. In all three cases, the ice floe reaches its maximum
 1078 tilt angle at approximately $+160 \text{ ms}$ after the depression wave reaches the edge of the ice
 1079 floe. In Case 9, the impact between the ice floe and the convex wave near the head is

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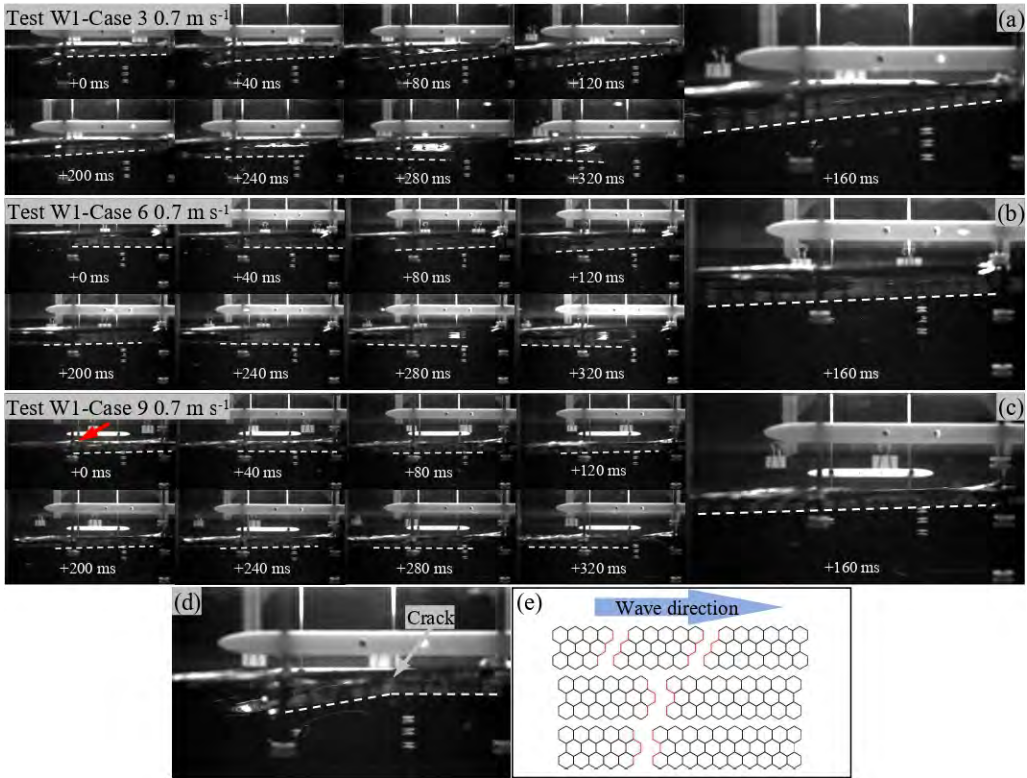


Figure 30. Tilting effect of depression waves on the large ice floe model at maximum towing speed. The figure presents a snapshot of one selected set of experimental results. Subfigure (a), (b), and (c) correspond to Cases 3, 6, and 9, respectively. The dashed lines in the images indicate the inclined state of the ice floe model in each frame. (d) shows the moment when the leading edge of a large ice floe enters the depression wave and subsequently fractures. (e) illustrates the distribution of fracture cracks in a large ice floe induced by the trailing depression wave in Case 3.

1080 observed (indicated by the red arrow). The ice floe first tilts slightly upward (1.4°)
 1081 and then flips downward into the wave trough (-2°), which is consistent with the statistical
 1082 results in figure 29. The impact of the convex wave appears to have no significant effect
 1083 on the subsequent behavior of the ice floe. Among all the results, fracture of the ice floe
 1084 only occurred at the highest towing speed in Case 3, when the leading edge of the large ice
 1085 floe moved above the trough of the depression wave. Figure 30(d) shows a snapshot of the
 1086 moment of fracture. Out of all 15 experiments, fracture occurred only three times, and the
 1087 locations of the three sets of cracks are shown in figure 30(e). If the ice floe is simplified
 1088 as a rectangular plate with finite thickness, neglecting the effects of viscous forces in water
 1089 and the inertial forces of the ice floe on ice breaking, the buoyancy of the overhanging
 1090 portion decreases sharply when it moves above the depression wave. The moment induced
 1091 by the gravity of the overhanging part will cause the ice floe to tilt. The bending stress
 1092 generated at the front end of the ice floe due to its own weight can be expressed as:

$$\sigma_b = \frac{M(x) \cdot 0.5H_{im} \cdot \cos(\alpha_T)}{I_z}, \quad (3.6)$$

1093 among them, $M(x)$ is the moment of the overhanging portion of the ice floe, $0.5H_{im}$ is
 1094 the half-thickness of the ice floe, and $\cos(\alpha_T)$ is the tilt angle coefficient, which is related

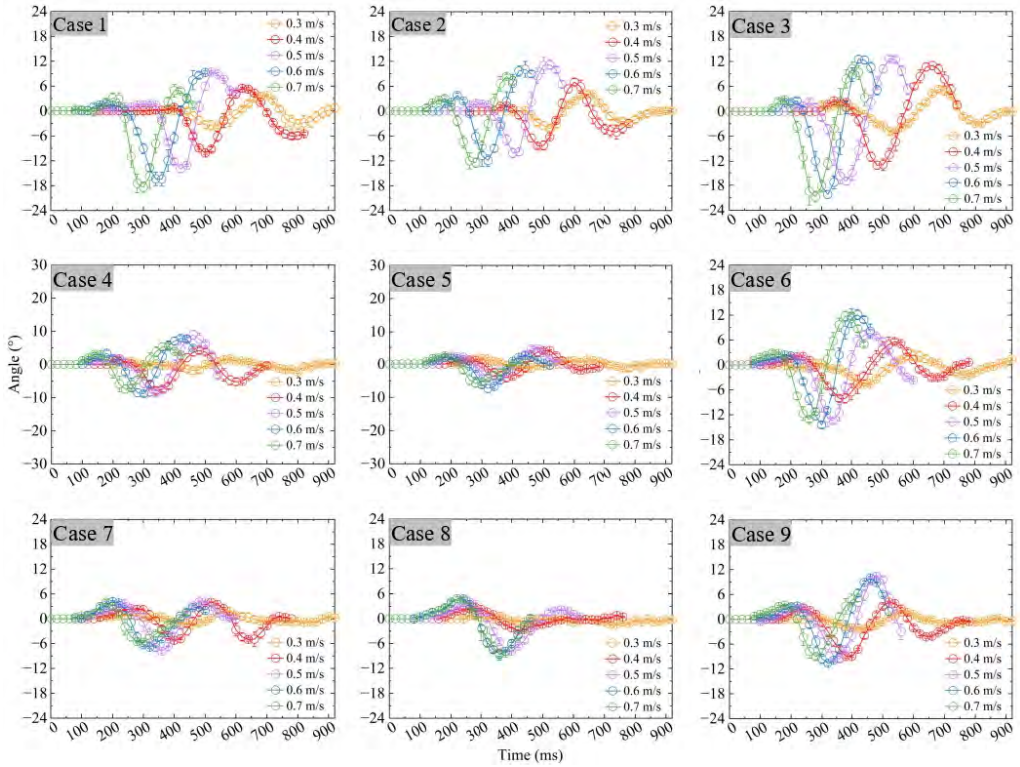


Figure 31. The variation of the tilt angle α_T of small ice floes over time. The results were obtained by averaging 10 independent measurements, with error bars representing the standard deviation of the statistical results. The tilt angle becomes negative as it tilts downward from the horizontal towards the wave trough.

1095 to the tilt angle α_T before the ice floe fractures. Using the tilt angle of Case 3 at +40 ms
 1096 in figure 30(a) as a reference, $\alpha_T \approx -2^\circ$. I_z is the moment of inertia of the cross-section
 1097 of the ice floe model, which is simplified as a rectangular section with a width of 40 mm
 1098 and a height of 10 mm (data referenced from figure 4(a)). The flexural strength of the ice
 1099 floe model is $\sigma_f = 19.80$ kPa. Setting $\sigma_b = \sigma_f$, the fracture length can be calculated as
 1100 $x \approx 86.6$ mm, which is approximately equal to the length of 5 ice floe units. This is close
 1101 to the number of sub-floes ahead of the crack observed in figure 30(e). The self-weight
 1102 of the overhanging portion of the ice floe model can generate sufficient bending moment
 1103 to cause fracture. Considering that manual errors may be introduced during the ice floe
 1104 preparation process, the fracture location may vary.

1105 Figure 31 shows the tilt angle curves of small ice floes. After the ice floe is broken into
 1106 smaller pieces, its moment of inertia decreases, making it easier to adhere to and overturn
 1107 along the deformed water surface. The resulting tilt is significantly greater than that of the
 1108 intact large ice floe, with the maximum tilt angle being essentially consistent with the slope
 1109 angle of the depression wave. Cases 3 and 5 still induced the maximum and minimum
 1110 floe tilting, respectively. For Case 3, the tilt angle reached -20.7° at a towing speed of
 1111 0.7 ms^{-1} (wave slope angle approximately -22.4°). For Case 5, the maximum tilt angle
 1112 occurred at 0.6 ms^{-1} , reaching -7.3° (wave slope angle approximately -7.8°). It was also
 1113 found that the convex wave more easily caused tilting of small ice floes. Compared to
 1114 the large ice floe, upward tilting induced by the convex wave occurred in most cases for
 1115 small floes, possibly due to their lower inertia. Cases 3, 6, and 9 still produced the most

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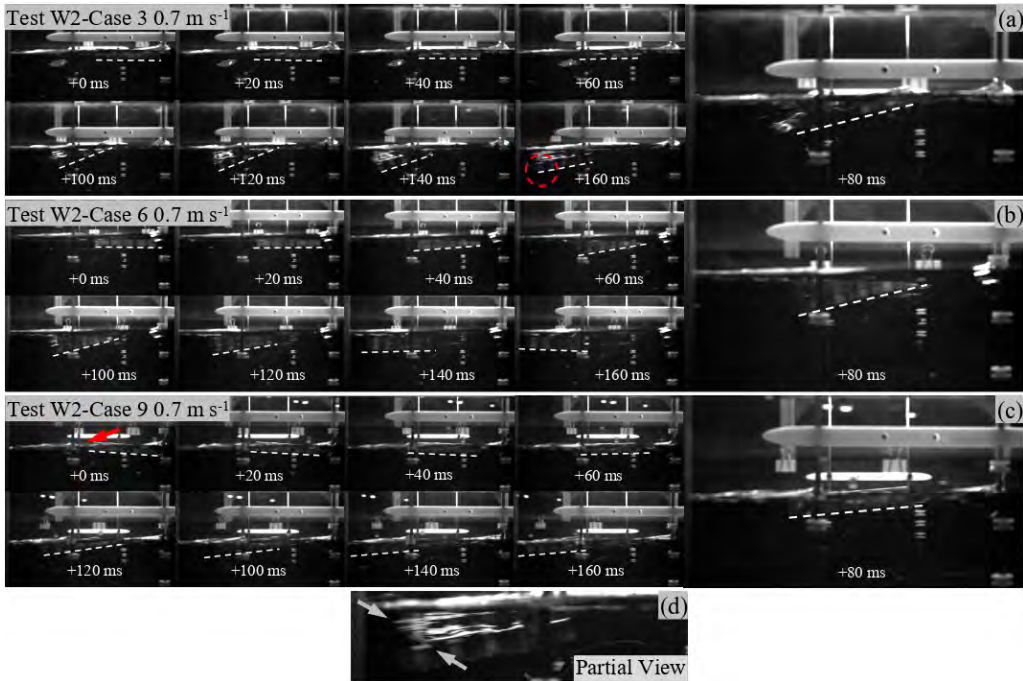


Figure 32. Tilting effect of depression waves on the small ice floe model at maximum towing speed. The figure presents a snapshot of one selected set of experimental results. Subfigure (a), (b), and (c) correspond to Cases 3, 6, and 9, respectively. The dashed lines in the images indicate the inclined state of the ice floe model in each frame. (d) A partial view of the area marked by the red-dashed circle in subfigure (a), with gray arrows indicating waves washing over the floating ice.

1116 pronounced floe tilting. Figure 32 records their sequential snapshots as they swim beneath
1117 the ice floe at the maximum towing speed; typically, the maximum tilt angle is reached
1118 between +80 ms and +100 ms in the figures. In Case 9, it can be seen that the convex
1119 wave lifts the floe, which then collides with the convex wave. Subsequently, the convex
1120 wave is suppressed until the floe slides into the wave trough, after which the convex wave
1121 recovers (see +140 ms to +160 ms). Due to the smaller size of the floe, its potential energy
1122 is converted into kinetic energy as it slides down the depression wave. The leading edge
1123 of the floe submerges into the upward slope on the downstream side of the wave trough,
1124 and the following wave crest then submerges the upper surface of the floe. This moment
1125 is captured in the +160 ms subplot of figure 32(a), with a detailed local view shown in
1126 figure 32(d). The area between the grey arrows indicates the upward slope downstream
1127 of the wave trough. This phenomenon is entirely consistent with documented footage of
1128 orcas using waves to wash seals off ice floes. Considering that the inertia of real ice floes
1129 is much greater than that of the models used in this experiment, the actual wave-washing
1130 effect in nature is likely more pronounced. The tail-generated depression waves produced
1131 by cooperating orca groups can first be used to break up large ice floes, and subsequently
1132 to wash seals off smaller ice floes.

1133 3.4. The effect of depression wave on the forces acting on an ice floe unit.

1134 Killer whales adjust their ice-breaking strategies based on the surrounding ice conditions
1135 when hunting seals. When numerous ice fragments are present, they collaborate to push
1136 the seal-bearing floe to open water using their heads before forming a line to generate

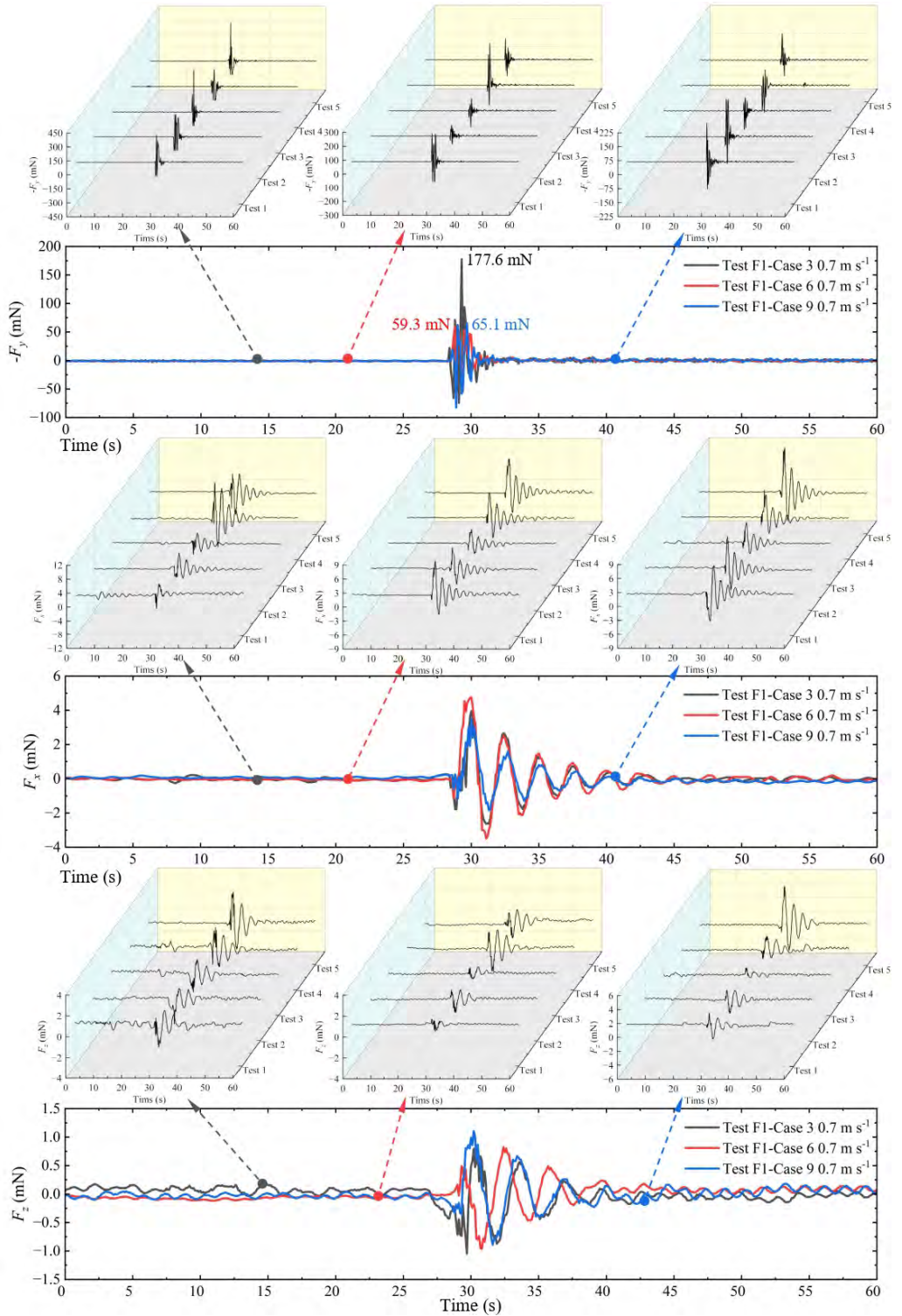


Figure 33. The effect of depression waves on the normal (y -axis), streamwise (x -axis), and spanwise (z -axis) force components acting on the single ice floe unit for Cases 3, 6, and 9 at a towing speed of 0.7 m s^{-1} .

1137 waves for hunting. To validate the rationale behind this behavior, we designed a set of
1138 micro-force measurement experiments to assess the influence of depression waves on ice
1139 floe units. In Test F1, the ice floe unit model was set up without any obstruction between it
1140 and the killer whale model. In Test F2, a large, continuous ice floe was placed upstream of
1141 the target ice floe unit to evaluate its effect on the force response of the downstream unit. In
1142 Test F3, discrete large ice floes were arranged upstream to assess the impact of fragmented
1143 ice fields on the force experienced by the downstream floe unit. The experimental setup is
1144 illustrated in figure 4.

1145 In Section 3.3, only Case 3 achieved ‘ice breaking’ at the maximum towing speed. To
1146 compare the effects of stern waves with different depression depths on the force responses
1147 of ice floe units, representative Cases 3, 6, and 9 were selected for investigation at the
1148 maximum towing speed. Each case was tested five times independently (see the 5 curves in
1149 the sub-figures), and the average of the results was taken. Figure 33 shows the time-varying
1150 three-dimensional forces measured by the force balance, with a time resolution of 0.1 ms.

1151 For the spanwise force, it is observed that $F_z \sim O(10^{-1})$ mN. Considering the symmetry
1152 of the floe’s environment, the effect of the depression wave in the spanwise direction is
1153 extremely limited. The streamwise force increases significantly, with $F_x \sim O(10^0)$ mN.
1154 The amplitude and phase of F_x are essentially consistent among the three cases, reaching
1155 a maximum of about 4.0 mN. Hence, the streamwise force on the ice floe unit is largely
1156 unaffected by the geometric dimensions of the depression wave.

1157 In contrast, the normal force differs substantially. For Case 3, the maximum normal force
1158 reaches 177.6 mN, with a peak duration < 0.2 ms whereas for Cases 6 and 9 the values
1159 are only 59.3 mN and 65.1 mN, respectively. The corresponding depression-wave depths
1160 for the three cases are 22.8 mm, 10.0 mm, and 7.8 mm. A deeper depression wave appears
1161 to induce a larger peak normal force. Notably, the gravity of the ice floe unit is only about
1162 22.9 mN, so the maximum downward force generated by the wave is 7.8 times the floe’s
1163 weight. This indicates that, in addition to gravity, other forces contribute significantly over
1164 a limited time during the floe’s capsizing into the depression wave. These forces may
1165 include the viscous force induced by the descending liquid surface along the floe wall
1166 and the pressure-difference force caused by the pressure difference between the upper and
1167 lower surfaces of the floe. However, their contributions to moment generation are likely
1168 limited, as both depend on the relative position and motion state of the solid-liquid two-
1169 phase system. Saddier *et al.* (2024) studied the fragmentation of particle rafts (composed
1170 of tens-of-micron particles) under wave action and pointed out that the breakup is mainly
1171 caused by viscous forces associated with surface waves. Although the fracture patterns
1172 resemble those of ice floe break-up, viscous forces are negligible for real-world sea-ice
1173 scenarios, where ice fracture is primarily driven by bending stresses.

1174 Figure 34 shows the effect of a large ice floe in front of the measurement point on the
1175 results. The spanwise force remains at a relatively low level, $F_z \sim O(10^{-1})$ mN, with no
1176 significant differences in amplitude or phase. In contrast, when a large, continuous ice floe
1177 is present upstream of the measurement point, the second peak of the streamwise force
1178 F_x increases sharply, rising by approximately 3.3 times. This is likely due to resonant
1179 interaction between the subsequent oscillations of the large ice floe and the measurement
1180 point (Li *et al.* 2024), where vibrations from the large floe are transmitted through the water
1181 surface to the ice floe unit (experimental observations showed that after the depression
1182 wave passed, the large floe drifted downstream, reducing the distance between them). The
1183 amplitude of the first peak of F_x (3.5 mN) is essentially consistent with the result obtained
1184 without a large continuous floe (4.0 mN), although a slight phase shift is observed, possibly
1185 related to the reduced speed of the depression wave as it interacts with the large ice floe.
1186 For the discrete large ice floe configuration, no significant change in the amplitude of

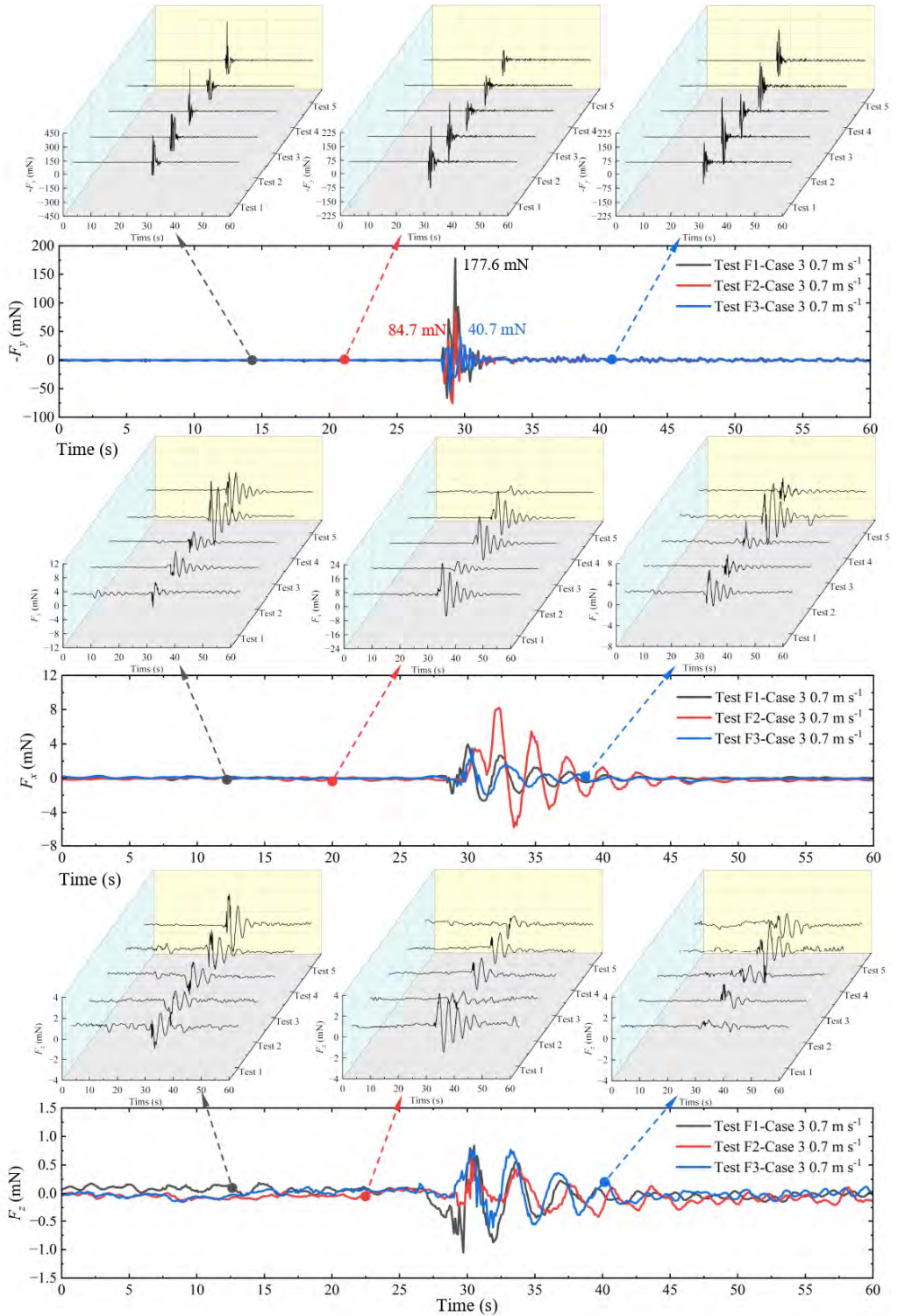


Figure 34. The effects of the depression wave on the normal (y -axis), streamwise (y -axis), and spanwise (y -axis) force components acting on a single ice floe unit; a single ice floe unit downstream of a large continuous ice floe; and a single ice floe unit downstream of a large discrete ice floe, for Case 3 at a towing speed of 0.7 ms^{-1} .

1187 the streamwise force is observed, only a minor phase delay. Before a brittle fracture, a
1188 continuous ice floe can be considered a rigid body with high inertia. When the wavelength
1189 of the depression wave is smaller than the floe length, it generally cannot induce large tilting
1190 or oscillations in the floe; however, the subsequent vibrations of the floe can still disturb
1191 the surrounding waves. In contrast, the sub-units of a discrete ice floe tend to distribute and
1192 conform to the curved water surface individually, rather than vibrating as a single entity.
1193 Collisions between surrounding small ice floes and viscous damping in the water dissipate
1194 energy more effectively (Guyenne & Părău 2017). As shown in the normal-force results in
1195 figure 34, the attenuation of the normal force is more pronounced behind the discrete large
1196 ice floe, where the measured peak normal force is only 40.7 mN. Behind the continuous
1197 large ice floe, the peak normal force is 84.7 mN. Both values are significantly lower than
1198 the peak normal force (117.6 mN) measured on an isolated ice floe unit in open water.
1199 Clearly, when the target is located in unobstructed open water, the depression wave can
1200 produce the most significant normal force, thereby generating sufficient bending moment
1201 for ice breaking. Finally, it should be noted that the experiments in this section also have
1202 limitations. First, the experiments cannot simulate the overturning process of large ice
1203 floes, nor can they capture the contribution of various force components to the bending
1204 stress during tilting. Monitoring the dynamic parameters of large-scale simulated or real
1205 ice floes presents a significant challenge. Second, the ice floe unit is rigidly connected to
1206 the force balance carbon rod during measurement, which differs from the actual floating
1207 state of ice on the water surface. This discrepancy may introduce errors in the results.

1208 **4. Conclusion**

1209 In this paper, we investigate a compelling topic: how orcas capture seals resting on ice
1210 floes. We observed that when a pod of orcas approaches an ice floe, they consistently
1211 raise their heads, tilt their bodies upward, and slap their caudal fins downward against
1212 the water, thereby generating a pronounced stern depression wave. They utilize this wave
1213 to break up ice or wash over the surface of the floe, ultimately driving the seals into
1214 the water to complete the hunt. Through towing tank experiments, this study examines
1215 the hydrodynamics of a complex biomimetic orca pod model near a free surface, aiming
1216 to explore how variations in body and caudal fin posture influence wake structures and
1217 free-surface depression waves. We systematically investigated the wake and interfacial
1218 regimes across a posture matrix defined by three body inclination angles ($10^\circ/0^\circ/-10^\circ$)
1219 and three caudal fin angles ($30^\circ/0^\circ/-30^\circ$) at towing speeds ranging from 0.3 to 0.7 m s⁻¹.
1220 The aforementioned findings were validated and analyzed in detail.

1221 In most of our experimental cases, a jet flow can be observed between the model and the
1222 free surface. Due to the Coandă effect, the jet attaches to the model surface, and adjusting
1223 the posture can modify the attachment length of the jet and the development direction of the
1224 wake. For Case 3 (body angle 10° , caudal fin angle -30°), at the maximum towing speed,
1225 the jet successively attaches to both the model surface and the deformed depression wave
1226 surface, forming a continuous channel. The downward-directed jet pulls the free surface,
1227 causing larger surface deformation. The energy of the jet sustains interfacial stability
1228 and directs trailing vortices away from the free surface. As a result, the depression wave
1229 maintains a low potential energy state, making it available for subsequent ice-breaking and
1230 wave-washing processes.

1231 Four distinct wake regimes downstream of the orca pod model have been identified. At
1232 low Reynolds numbers and shallow depression depths, capillary waves emerge downstream
1233 of the depression wave, inducing localized vorticity aggregation near the trough. The
1234 diffusing fine-scale vortex structures interact weakly with the free surface over a limited

1235 region, gradually attenuating or disappearing as they develop downstream. As the Reynolds
1236 number increases and the depression deepens, the interface and trough become sharpened,
1237 and intense flow separation occurs at the trough bottom. This results in a large area
1238 of densely broken vortex structures downstream, diffusing substantial surface vorticity
1239 downward into the water. With a further increase in Reynolds number, the jet above the
1240 model attaches to the free surface, leading to the disappearance of capillary waves. The
1241 interface downstream may then exhibit either large-scale vortex-induced disturbances or a
1242 smooth free surface, depending on the strength of the jet and the trajectory, intensity, and
1243 extent of the shed large-scale vortex structures. When the jet propagates toward deeper
1244 water, it carries trailing vortices away from the free surface, isolating energy exchange
1245 between them, thereby promoting the formation of a smooth interface. Conversely, if
1246 the thickness or intensity of the trailing vortices is significant and the jet is weakened
1247 such that effective isolation cannot be established, the interface is perturbed by large-scale
1248 structures, leading to periodic undulations. The degree of free-surface deformation induced
1249 by a complex bluff body cannot be simply assessed by the Froude number alone, as the
1250 influence of bluff-body disturbance on free-surface shape may be comparable to that of
1251 Froude-number effects.

1252 Experiments on the coupled interaction between ice floes and moving depression waves
1253 demonstrate that for large ice floes, the moving depression wave first induces tilting on
1254 the outer side of the floe. When the tilting speed of the floe lags behind the propagation
1255 speed of the depression wave, a cantilever state forms at the floe edge. Once the bending
1256 stress exceeds the internal strength of the ice, fracture occurs. Smaller ice floes, by contrast,
1257 adhere to the curved surface of the depression wave and undergo large-angle overturning.
1258 The upslope surface downstream of the trough then washes over the upper surface of
1259 the sliding floe, producing a wave-washing effect, which aligns with existing observational
1260 records of orca ice-breaking. Force-measurement experiments reveal that the instantaneous
1261 force exerted on the ice floe unit as the depression wave passes is significantly greater than
1262 the floe's own weight. It is inferred that viscous and pressure-difference forces induced by
1263 relative motion also contribute to the normal force. When the ice floe unit is surrounded
1264 by either a continuous large ice sheet or discrete ice fragments, the peak normal-force
1265 response decreases sharply, indicating that surrounding ice dissipates wave energy. This
1266 explains why orcas tend to perform wave-generation hunting in clean, ice-free waters.

1267 This paper proposes that flow-jet control can be achieved by modifying the shape and
1268 posture of underwater objects or submersibles, thereby enabling active intervention in wake
1269 development patterns, interface geometry, and interface flow regimes. This approach holds
1270 significant implications for extending research on bluff-body hydrodynamics beneath a
1271 free surface.

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1280 The authors have no conflicts to disclose.

1281 **Data availability statement**

1282 Data will be made available on request.

1283 **Declaration of generative AI in scientific writing**

1284 AI and AI-assisted technologies have only been used in the writing process to improve the readability and
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