CHARACTERIZING WAKE PATTERNS IN SCATTERED TWO-FOIL SCHOOLS

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SYNOPSIS

Wake patterns behind two-fish school configuration are numerically examined at $Re = 4000$. The horizontal and vertical positions are varied between $1c - 3c$, and $0.5c - 2c$, where c is the foil chord length, and St varies from 0.15 to 0.4. The results suggest that two wake patterns exist based on the formation and interactions of vortices: merged and separated. A threshold horizontal and vertical separation distance is identified between foils that facilitate certain wake topologies. The aim of this study is to identify and categorize wake topologies in staggered two-foil schools.

INTRODUCTION

The design of Autonomous Underwater Vehicles (AUVs) has been improved with the study of fish school mechanisms and their physical working principles (Kelly *et al.*, 2023). Fish school has been investigated in different configurations in literature, such as in-line (Boschitsch *et al.*, 2014; Heydari and Kanso, 2021; Yuan *et al.*, 2021), side-by-side (Dewey *et al.*, 2014; Gungor *et al.*, 2022) and staggered (Huera-Huarte, 2018; Lin *et al.*, 2022). These numerical and experimental studies involved different kinematics and aimed at characterizing wake patterns behind oscillating foils, and identifying correspondence with propulsive performance.

Boschitsch *et al.* (2014) performed experiments on two in-line pitching foils over a range of phase differences and vertical separation distances at $St = 0.25$. Two wake patterns were identified, namely coherent and branched. Coherent wake corresponded to local maximum in propulsive performance, and branched wake coincided with a local minimum. Dewey *et al.* (2014) experimentally studied side-by-side foils with in-phase and out-of-phase pitching motion under several vertical spacings at $Re = 4700$. They reported hydrodynamic benefits in thrust, power and efficiency for side-by-side configuration compared to isolated pitching foils. Wake patterns corresponded to merging wake and diverging wake for in-phase and out-of-phase pitching, respectively. Dai *et al.* (2018) conducted numerical simulations of two in-line undulatory filaments at different streamwise spacings, which showed the formation of 2S wakes that are unstable compared to other configurations, for compact (closely packed) and loose (distantly packed) in-line setup. Similarly, Han *et al.* (2022) simulated two and three in-line pitching foils at $Re = 500 - 1000$ and $St = 0.25$ at different pitching phase differences from $0°$ to $360°$. The two- and three-foil system show 2S, 2S reverse Von Karman and 2P wakes, mainly

Later, Huera-Huarte (2018) carried out experiments on in-phase and out-of-phase pitching foils in side-by-side and staggered configurations at $Re = 4000 - 11000$. They identified merging wakes and diverging wakes for in-phase and out-of-phase pitching foils in side-by-side configuration. Staggered configurations presented asymmetric merging and diverging wake patterns. Lin *et al.* (2022) simulated two tandem swimmers at different vertical and horizontal separation distances with free longitudinal movement at $Re = 200$. They identified three wake formations, referred to as semi-tandem, staggered and transitional. In semi-tandem formation, the follower foil intercepts the vortex shed by the leader foil and the wake of the follower is deflected. The staggered configuration involved a follower foil that swims outside of the vortex street of the leader foil. Both wakes are deflected and the direction of deflection is determined by the position of the follower. Finally, position of the follower periodically changes from one side to the other behind the leader in the staggered formation. Therefore, the wake of the follower alternately deflects to either side.

Dewey *et al.* (2014) experimentally studied the wake of side-by-side foils with in-phase and out-of-phase pitching motion under several vertical spacings at $Re = 4700$. Wake patterns corresponded to merging wake and diverging wake for in-phase and out-of-phase pitching, respectively. Gungor *et al.* (2021) studied 4 modes of burst-and-coast swimming of two parallel pitching foils for a range of $St = 0.25 - 0.5$ and $Re = 1000 - 4000$. Mode 1 and mode 2 had no suspended oscillations period, unlike mode 3 and 4. These 4 modes presented merging and separated wakes with the growth of secondary vortex streets at $St = 0.20$ and 0.5, respectively. Later, Gungor *et al.* (2022) numerically investigated side-by-side foils with different vertical distances during in-phase and out-of-phase pitching over a broad parameter space. Merging and diverging wakes were found at $St = 0.15 - 0.5$ at $Re = 4000$. From $St = 0.4$, there existed a secondary vortex street that separates from the primary street. This secondary street forms the merging wake pattern by adding to the circulation of the primary wake.

The present study extends on previous investigations by changing vertical and horizontal positions of the follower foil in two-foil-staggered configuration at $St = 0.15 - 0.4$ and $Re = 4000$. The aim is to identify and categorize wake topologies associated with a broader parameter space in staggered schools.

COMPUTATIONAL METHODOLOGY

Simulations were carried out in OpenFOAM to directly solve three-dimensional incompressible Continuity and Navier-Stokes equations at $Re = 4000$. The computational domain is extended by 30c in the streamwise (x) and 16c in the cross-flow (y) direction, and it closely follows the setup pro-

Table 1. Parametric space of simulations

X^+	Y^+	St	Re	θ_0
1-3	0.5-2	0.15-0.4	4000	8°

vided by Gungor *et al.* (2022). Leading edge of the leader foil was located at a distance of 8c from the inlet, where c is the foil chord length. The vertical and horizontal positions of the follower foil ranges from 0.5c to 2c, and 1c to 3c from the leader foil trailing edge, respectively. This parametric space covers systematic variations previously used in other studies such as Ashraf *et al.* (2016) and Ashraf *et al.* (2017) for separation distances between red nose tetra fish and side-by-side configuration in fish tank experiments, respectively.

A non-homogeneous grid with 7.87×10^5 hexahedral elements was used with 600 nodes around each foil. The mesh is morphed at each time step to simulate the pitching motion. The inlet was assigned the Dirichlet boundary condition and the outlet boundary condition was Neumman outflow. Top and bottom boundaries were set as slip walls, and foil surfaces were prescribed with no-slip wall. The Courant number remained below 0.8 and the convergence threshold was set to 10^{-5}. The verification and validation of the numerical setup are described in Gungor *et al.* (2022).

Two teardrop foils in staggered configuration, shown in Figure 1, oscillate with pure in-phase pitching motion where the sinusoidal motion profile of pitch is represented by

$$\theta(t)_1 = \theta_0 \times sin(2ft\pi) \tag{1}$$

$$\theta(t)_2 = \theta_0 \times sin(2ft\pi) \tag{2}$$

where θ_0 is the pitching amplitude (fixed at 8°). The Strouhal number ranged from 0.15 to 0.4 in order to cover average values for fish schools (Ashraf *et al.*, 2016).

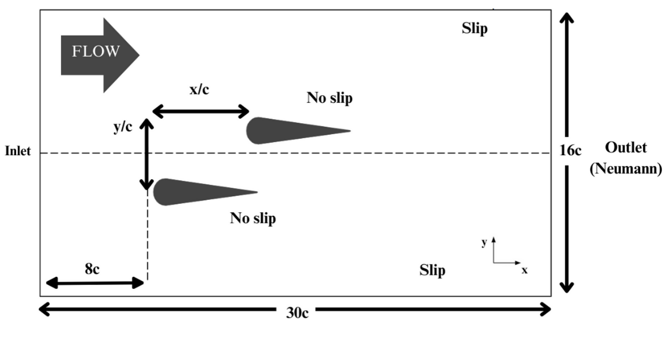

Figure 1. 2-D computational domain of two-fish school in staggered configuration with boundary conditions (not to scale)

RESULTS AND DISCUSSION

Two wake topologies are identified and categorized in two mechanisms: vortex-vortex interactions and vortex-body interference. The formation of wake patterns is explained across different kinematics for the two-foil system. This includes a range of Strouhal number $(0.15-0.4)$, defined as $St = \frac{fA}{U}$ where U is streamwise velocity, f is pitching frequency and A is pitching amplitude. Also, vertical and horizontal separation distances were implemented at the range of $y = 0.5c - 2c$ and $x = 1c - 3c$.

Wake Patterns Identification

Two different wake patterns were identified based on $St = 0.15 - 0.4$. These topologies were (1) separated wake and (2) merged wake. The separated wake showed v-shaped and parallel types, as identified in Gungor *et al.* (2022). The v-shaped separated wake is formed by the shedding of counter-rotating vortex pairs. The interaction of these pairs leads to the formation of a secondary vortex street that prevents wakes from merging, as depicted in Figure 2a and determined by Gungor *et al.* (2022). Conversely, parallel separated pattern is formed by independent wakes, where no interference is observed between vortex streets, as depicted in Figure 2c. Merging wakes are formed by foils shedding pairs of counter-rotating vortices at trailing edges during their pitching motion, as depicted in Figure 2b. While pairs of vortices are moving downstream, the two streets amalgamate to each other and merge. Both of these patterns occur at $y < 1c$.

Merging wakes are shown in Figure 3, when the two vortex pairs shed by the leader and follower foils amalgamate and experience filamentation process to merge, as explained by Cerreteli & Williamson (2003) for two co-rotating vortices. This pattern is formed by two shed TEVs from the pitching foils at sufficient proximity labelled as A2 and B2, which eventually move towards each other as A and B. Once, they are close enough, they start merging with their legs growing, as counter-clockwise co-rotating TEVs repeat the same process. Figure 3b shows the merging of A+B. Figure 3c depicts A2 and B2 moving towards each other and co-rotating vortices (A3 and B3) shed at the same horizontal positions, which merge later. When merged, they diffuse and start moving dowsntream (Figure 3d). Instantaneous vorticity contours of the merging topology suggest that vortex pairs advect with induced velocities towards the centerplane between the foils. This is shown in Figure 6a with time-averaged streamwise velocity fields where two angled momentum jets are formed and converge into a single jet downstream of the follower foil.

Parallel and v-shaped near-wakes differ from each other due to their mechanism. Parallel separated wakes do not present vortex-vortex interactions whereas v-shaped pattern is formed when trailing edge vortex pairs diverge, as depicted in Figure 4. This topology is produced when two pairs of counter-rotating vortices are shed by the leader, labelled as A, and follower foil, labelled as B (see Figure 4a). Figure 4b shows the two pairs, A and B, are located in front of one another. These pairs are aligned where clockwise-rotating poles are facing counterclockwise-rotating poles. Therefore, both wakes are kept separated, in Figure 4c.

At the next upstroke, two new pairs are shed, labelled P1. Pairs A and B move downstream, following their respective wakes, while P1 interacts and forms counterclockwise and clockwise-rotating poles. These poles are aligned and diverge later, as depicted in Figure 4c and Figure 4d. Instantaneous vorticity contours of the separated topology suggest that the vortex pairs advect with induced velocities in opposite directions, so that wakes are prevented from moving towards each other. Figure 6 depicts time-averaged streamwise

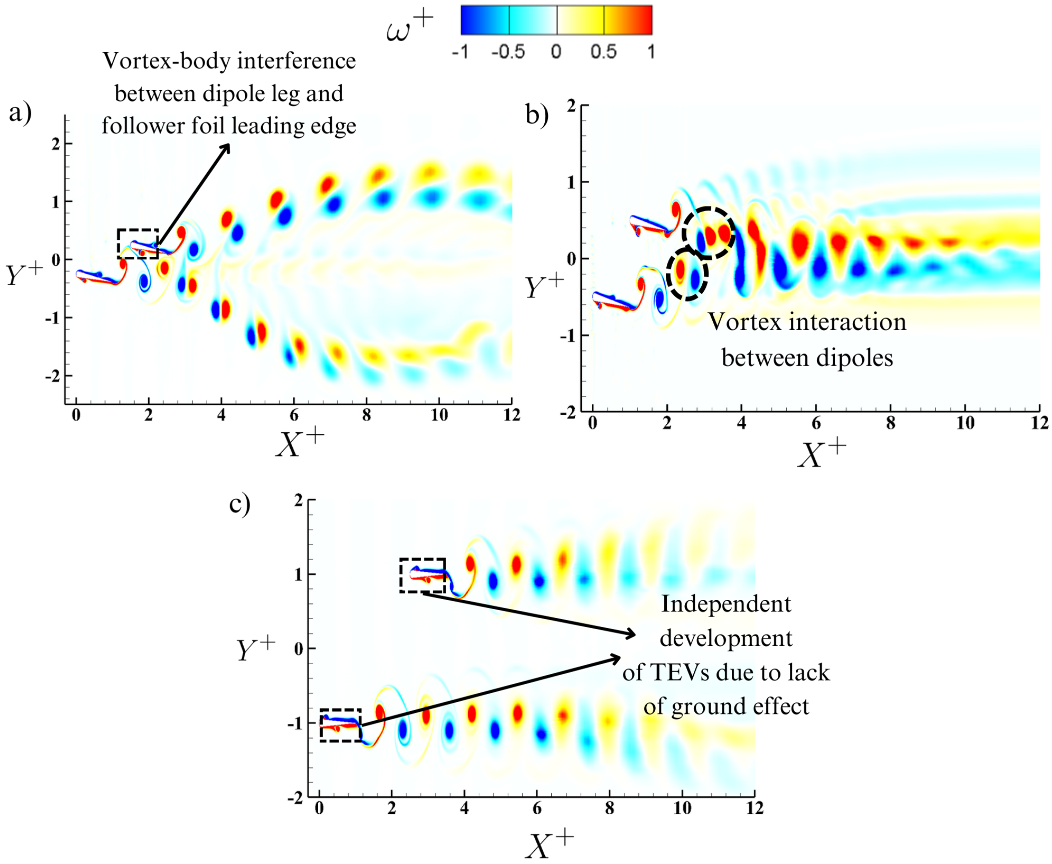

Figure 2. Contours of spanwise vorticity of staggered foils for (a) St = 0.3, v=0.5c, h=1.5c (v-shaped separated wake), (b) St = 0.4. v=1c, h=1c (parallel separated wake) and (c) St = 0.4, v=2c, h=0.5c

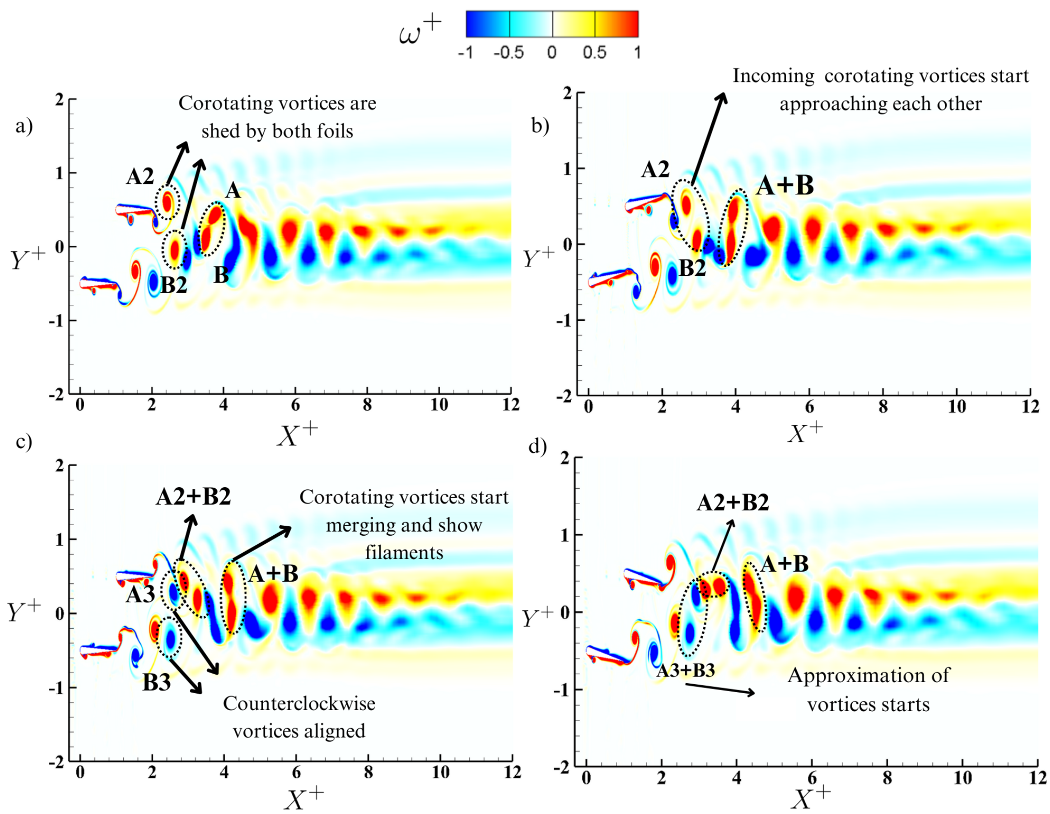

Figure 3. Temporal snapshots of vorticity contours depicting formation of merging near-wake pattern at $Re = 4000$ for separation distances of $x = 1c$ and $y = 1c$ at $St = 0.40$ at (a) 60th, (b) 60.2th, (c) 60.5 (d)60.7 pitching cycle

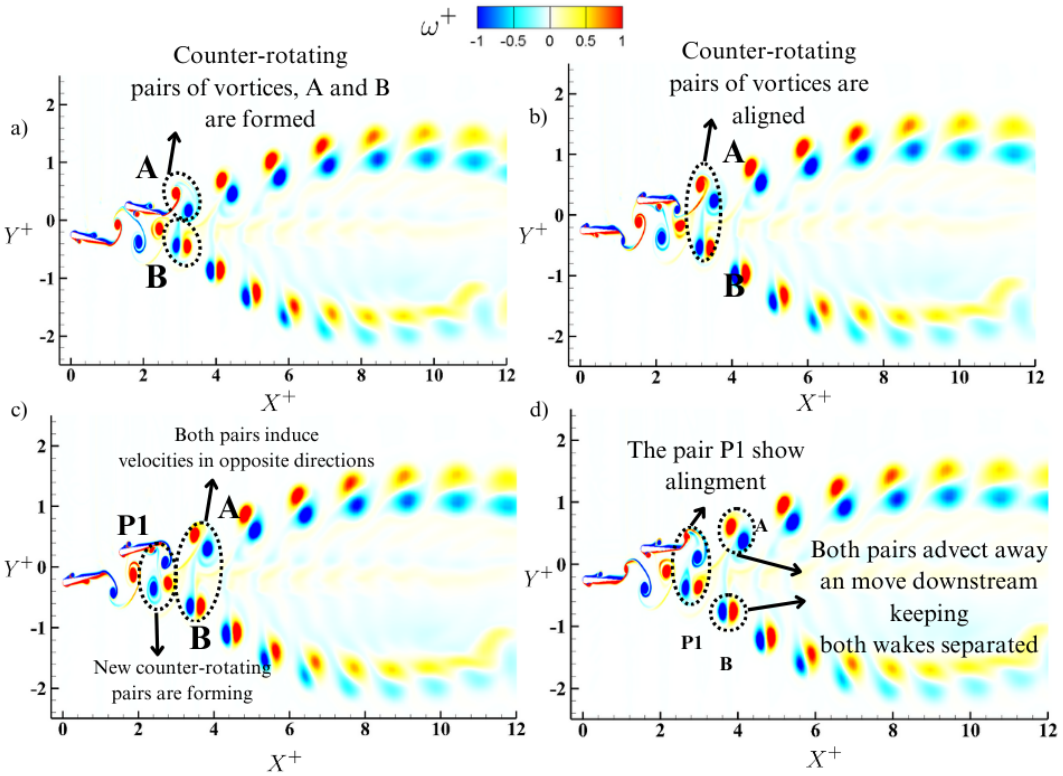

Figure 4. Temporal snapshots of vorticity contours depicting formation of separated near-wake pattern at $Re = 4000$ for separation distances of $x = 1.5c$ and $y = 0.5c$ at $St = 0.3$ at (a)14.65th, (b)14.98th, (c) 15.19th and (d) 15.42th pitching cycles

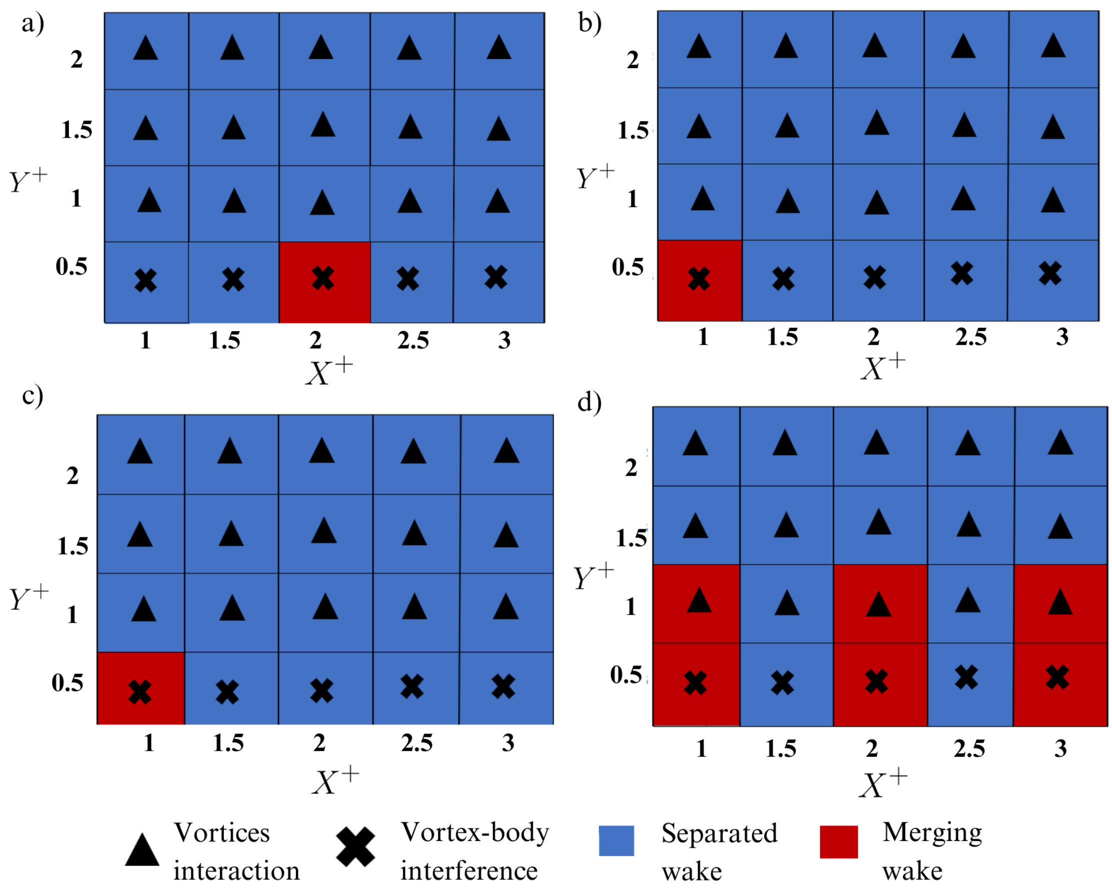

Figure 5. Classification of wake patterns of foils in staggered configuration for Re=4000 and a range of vertical and horizontal separation distances at St (a) 0.15, (b) 0.25, (c) 0.3 and (d) 0.4

velocity fields where two single jets moving away from each for separated v-shaped patterns in Figure 6b.

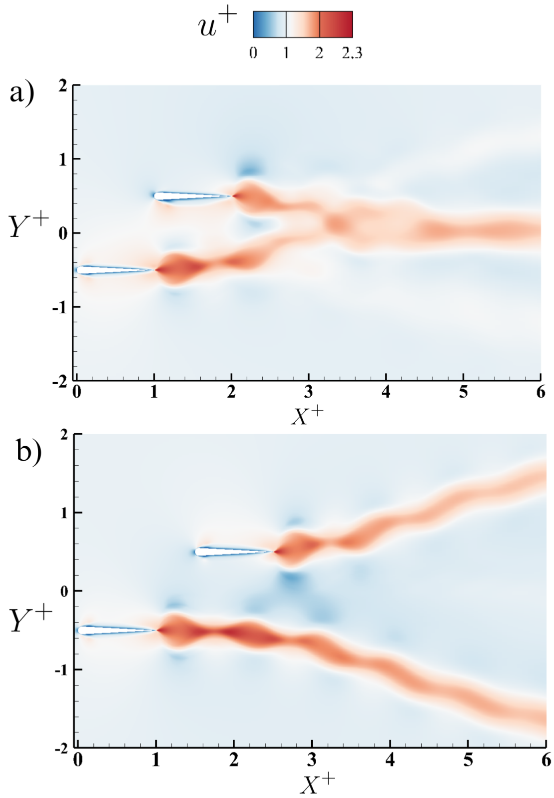

Figure 6. Time-averaged streamwise velocity fields for (a) merged pattern and (b) separated pattern

The diversity of wake topology is also attributed to differences in the wake formation and interaction. Position of foils determines two classes of wake dynamics: Vortex-body interference and Vortex-vortex interactions. The wakes presented in Figure 2a and 2c visualize the two classes, respectively. Vortex-vortex interactions occur from a vertical separation distance of 1c. The ground effect of the follower foil over the leader foil plays a crucial role on these interactions and the formation of wake topologies. In this study, ground effect is referring to as the presence of a solid wall such as the upper and lower surfaces of the foils. Shedding of vortex dipoles from the leader foil interacts with the follower foil and their respective dipoles. It is hypothesized that there is a vertical separation distance threshold between the two staggered foils at each Strouhal number for the formation of separated wake, as shown in Figure 2b. Above this threshold, ground effect is small on the leading edge, enabling vortices to mantain their strength and circulation while moving downstream independently. Gungor *et al.* (2022) reported this behaviour for side-by-side foils at $y > 1c$. Similarly, there is a correspondence between the formation region of the Trailing Edge Vortex (TEV) of the follower foil and the horizontal spacing between foils. This horizontal separation distance will determine the alignment of co-rotating or counter-rotating vortices. It is expected that at certain horizontal spacing, only separated wakes are presented since there would not be close interaction of vortices that could vary their advection.

Vortex-body interference occurs when the follower foil is positioned at a vertical separation distance of at most $y = 0.5c$ from the leader foil. Vortex dipoles of the leader foil interfere with the follower foil leading edge. This impacts the strengthening of Leading Edge Vortices (LEVs) and triggers the separated wake with the growth of a TEV at certain horizontal positions. Conversely, when dipole legs do not interfere with LEVs, vortex streets advect and coalesce. The horizontal spacings also determines the development of certain wake topologies due to vortex-body interference.

Wake Topology Maps

The vortex patterns described were gathered in a wake diagram for each Strouhal number. Figure 5 shows the wake maps for each Strouhal number from 0.15 to 0.4, based on the near-wakes topologies. Here four distinct topologies associated with foils pitching frequency, (f), vertical (Y^+), and horizontal separation (X^+) distances. Pitching frequency varies the formation length of the trailing edge vortex. This length is indirectly proportional to the pitching frequency. Apart from this, the horizontal and vertical separation distances vary and these define the locations of shed vortices and their alignment to interact, which is linked with the formation of a merging or separated wake pattern.

These three kinematic parameters determine unique locations of vortices, whose interactions and dynamics depend on their positioning. These dynamics lead to the formation of merged or separated wakes. This positioning enables alignment of co-rotating vortices, which is observed in merging wakes. Merged and separated formation do not happen at the same vertical and horizontal separation distances at different Strouhal numbers. According to Quinn *et al.* (2014), formation length depends on equation 3, where U is streamwise velocity, f is pitching frequency and L_d is the shed vortex formation length at a quarter of cycle for a single pitching foil.

$$L_d = \frac{U}{4f} \tag{3}$$

Therefore , the streamwise convection of structures, and positioning of co-rotating vortices, define the wake dynamics. The presence of co-rotating vortices that align in the two vortex streets coincide with the formation of merged wakes. The mechanism of vortex-pairs breakdown due to ground effect forms the basis of our next study.

Evidently, for this parametric space, all wake maps show a clear vertical separation distance threshold (i.e. $y = 1c$) above which only separated wakes are observed. Below $y = 1c$, wake patterns show different topologies based on the changes in horizontal and vertical separation distances, and pitching frequency of the foils.

CONCLUSIONS

Two wake topologies were identified for two pitching foils in staggered configuration at $Re = 4000$. These were merging and separated. Results suggest that there exists a vertical threshold for the formation of separated wake. The dependance of that threshold on Strouhal number was evaluated at $St = 0.15 - 0.4$. This limit avoids the ground effect of the follower foil over the leader foil and allows the development of separated wake. Moreover, two wakes mechanisms were differentiated as vortex interactions and vortex-body interactions. The latter has a horizontal separation distance threshold of 0.5c, where dipole legs interfere with the leading or trailing edge of the follower foil. Also, it is proposed that there is a correspondence between the formation region of the leader foil TEVs and their interference with the follower foil that may develop certain topologies. Evaluation of performance parameters for each of the staggered cases will further elaborate on the mechanism of wake behaviour and its impact on the fish swimming efforts.

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