On the interference of vorticity and pressure fields of a minimal fish school

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Abstract — In collective swimming, vorticity and pressure fields near a fish may be modified through hydrodynamic interactions between fish, and eventually influence swimming performance. We developed a three-dimensional (3D) computational approach and implemented a parametric study to: 1) make comparisons of the vorticity and pressure fields topology between a single fish and a pair of fish; 2) investigate the change of vorticity and pressure fields topology by varying the relative position and phase shift between the two fish in a pair; 3) investigate the perceivable pressure signals on the lateral line of fish due to the interference between the two fish.

Index Terms — collective swimming, vorticity field, pressure field, computational fluid dynamics, lateral line sensing

I. INTRODUCTION

Fish are usually observed to gather together. Such schooling behavior may offer them benefit in many aspects, including enhancement in predation and defense against predation, better chance in reproduction, and improvement in swimming performance.

Animals living and moving in fluids are always subjected to the interaction with the surrounding flow. Accordingly, swimmers need to adopt different kinematic strategies, in order to stabilize themselves in a changing environment, and do so with the least energy cost (e.g. [1-2]). The randomness level of the incoming turbulence matters much [3]. Fish tend to evade from high intensity of turbulence (e.g. [4]), but in turbulence with high regularity, fish can alter their body kinematics to synchronize with the oncoming vortices and get a beneficial effect (the so-called Kármán gait as a most famous example [5]). Despite that the wake created by a

swimming fish contains much stronger backward momentum [6] than that created by an in-flow obstacle, the wake of a neighboring fish may still serve the improvement of performance in fish swimming.

In our understanding, two mechanisms have been considered to serve swimming performance enhancement in schooling: 1) reducing the relative flow speed encountered by the fish. To reduce the relative flow, fish may adopt a diamond-shaped formation, where the wakes of two leading fish assemble a Kármán vortex street between them, thus reducing the relative velocity of the oncoming flow experienced by the downstream fish and decreasing their energy consumption [6]. Also, as many swimming fish approach, each fish may draft surrounding flow, then as the combined effect of the drafted flow of each fish, the relative flow speed may be reduced, and collective swimming may become more efficient. 2) the other thought is to consider the vortices in the wake of fish as a source of energy that could be exploited by its neighbors. Fish have been shown to exploit energy from Kármán's vortex street behind a cylinder [5]. Several recent numerical studies demonstrate that in leading–trailing fish interaction, by adopting optimized kinematics, the trailing fish may utilize the wake of the leading fish to substantially reduce transport cost [7-8].

However, recent experimental researches have observed interesting phenomenon taking place during schooling swimming in tetra fish: two fish swimming together tend to adopt a specific relative positioning, which is not a leading–trailing configuration, but a side-by-side configuration with one of the fishes positioned slightly advanced with respect to its neighbor. Also, neighboring fishes tend to swim in a synchronized gait at higher speed [9-10]. Swimming modes are dominated by ‘anti-phase (half tail beat cycle phase difference)’ and ‘in-phase (no phase difference)’ configurations.

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In order to unveil the fluid dynamical mechanisms behind collective swimming, understanding the interference of vorticity and pressure fields is necessary. We thereby utilized a numerical approach to demonstrate the interference of vorticity and pressure fields caused by relative positioning and phase difference for a pair of fish. Furthermore, when a neighbor fish is present and the interference of pressure fields occurs, the fish would need to detect the change of the flow field to plan their adjustment in swimming behaviors. We investigated what form of signal could be detected by a fish due to the presence of a neighbor, which is the basic problem linking fish behaviors with hydrodynamic interactions between a pair of fish.

II. MATERIAL AND METHODS

An in-house three-dimensional numerical approach based on finite-volume method was used [11-12], which has been validated and applied in fluid bio-mechanics studies on swimming and flying animals (e.g. [12-13]).

A. Fish model and kinematics

A three-dimensional surface model of a Red nose tetra fish (same as those used in [9], Fig. 1A) was made. We traced the body in a lateral and a dorsal view to construct a surface mesh by assuming elliptical cross sections for the body.

The deformation of the fish model was driven by a sinusoidal function to define a propagating wave from the snout to the tail:

$$z(x_{axis}, t) = a(x_{axis}) \times \sin\left[\left(\frac{x_{axis}}{\lambda}\right) - 2\pi t\right] \quad (1)$$

where t is the time, x_{axis} is the longitudinal coordinate along fish axis ($x_{axis} = 0$ at head and $x_{axis} = 1$ at tail tip), $a(x_{axis})$ is the an quadratic amplitude envelope at x_{axis} approximating experimental observations (Fig. 1C), λ is the wavelength set to 1.2 times the body length, and $z(x_{axis}, t)$ denotes the resultant lateral excursion at time t . The variation of body length caused by Eq. 1 was corrected to keep the body length constant. Note that the amplitude input here will slightly reduce in the simulation due to the angular recoil effect in fluid-body interactions.

B. Computational grid system

The body surface model was expanded into a body-fitted mesh ($121 \times 97 \times 20$) that was clustered to the body surface. The grid is tightest at the body surface with the minimum grid spacing defined by $\sigma_{min} \leq 0.1L/\sqrt{Re}$, where Re is the Reynolds number used for the computation. As the fish body is driven to deform, the

entire body-fitted grid will follow the deformation.

To simulate a pair of fish, two body-fitted grids were deployed, of which the relative positions were variant. A global grid surrounded the body-fitted grids and covered a sufficiently large domain to enclose the swimming fish and their wake. The ensemble of body-fitted grids and global grid was set up as a multi-blocked, overset-grid system based on a chimera grid scheme [11].

During the simulation, the body-fitted and global grids share values on their interface through inter-grid communications based on an interpolation scheme.

Fig.1 Red nose tetra fish (*Hemigrammus bleheri*), three-dimensional surface model, and body deformation wave used in simulations.

C. Computational fluid dynamic (CFD) model

Three-dimensional, incompressible and unsteady Navier-Stokes (NS) equations in a strong conservative form for mass and momentum was solved [11-12].

Because the two fish body-fitted grids are immersed in the global grid, interpolations between them defined the boundary conditions on their interface surface. On the fish body, non-slip condition was applied to set the flow velocity at the body surface equal to the local surface velocity. For the global grid, the boundary conditions for velocity and pressure were: 1) upstream $(u, v, w) = (\text{balance speed}, 0, 0)$ while pressure p was set to zero; 2) downstream and at the external boundaries of the global grid a zero-gradient condition was enforced for both velocity and pressure.

Fig.2 Grid system. Two body-fitted grids were deployed, which deform as the fish models deform. Body fitted grids are covered by the global grid.

D. Dynamics and incoming flow

Our numerical approach can allow the fish model to swim freely in the horizontal plane. We used free-swimming simulation to confirm the balance speed. When exploring the hydrodynamic influence correlated to the relative position, we locked the position of center of mass for the model fish, while the rotational degree of freedom was still active to model the rotational recoil effect during swimming. In those fixed-CoM simulations, oncoming speed was set as balance speed computed in the free-swimming simulation.

We implemented simulations by varying the relative longitudinal and lateral positions, as well as the relative phase shift between two fish.

III. RESULTS AND DISCUSSIONS

A. Balance speed and Reynolds number

We implemented a free-swimming simulation with a single fish at 8 Hz and obtained a balance speed for free-swimming of 9.25 cm/s and a Reynolds number of approximately 4000. This balance speed accurately corresponds with experimental observations [9]. Also, the speed is in a medium level among observations, neither extremely fast nor slow.

The balance speed was then applied in all other two-fish simulations, in which the CoMs of fish were fixed.

Fig. 3 When two fish are close, the nearby high and low areas along fish bodies may interfere with each other. (A) single fish; (B) two fish with $0.4L$ lateral distance and zero relative phase shift (in-phase); (C) two fish with $0.4L$ lateral distance and half-period relative phase shift (anti-phase); (D) two fish with $0.4L$ lateral distance and one-quarter-period relative phase shift, this panel consists of two snap shots with one-quarter period time interval.

B. Pressure field interference between two close fish

As shown in Fig. 3A, when a fish swims alone, it generates three pressure areas on each side of the body in a staggered positive/negative pattern. Our results suggest that when two fish are close, the nearby high-

and low-pressure areas along the fish bodies may interfere with each other, strengthening or weakening the resulting pressure field as relative position and phase-shift change.

With zero relative phase shift (Fig. 3B), the high- and low-pressure areas on one fish body (shown by arrows) are adjacent to the opposite pressure areas on the other fish. The size and central magnitude of those high- and low-pressure areas appear to be reduced (smaller and weaker than the corresponding pressure areas in Fig. 3A), indicating the resulting pressure fields are weakened.

With half-period relative phase shift (Fig. 3C), when a high-/low- pressure area is generated on the side of the fish adjacent to the neighbor, it may interact with its correspondent high-/low- pressure area on the adjacent fish. Compared with the pressure field of a fish swimming alone (Fig. 3A), the high/low pressure areas (shown by arrows) appear to be strengthened in both magnitude and size. These adjacent high/low pressure areas even appear to merge.

With one quarter relative phase shift (Fig. 3D), the interference effect between the two fish becomes unstable: at some moments (upper in Fig. 3D), pressure areas are weakened because adjacent pressure areas are of opposite sign; while at other moments (lower in Fig. 3D), pressure areas are strengthened because adjacent pressure areas are of same sign.

C. Interference of vorticity field in fish school

The topology of the interacting vortex wakes are shown in Fig. 4 using a visualization of Q-surfaces [14].

As shown in Fig.4A, when the model fish swims alone, it forms a vortex street in its wake. The wake consists of two rows of vortices, respectively formed when the tail reaches its maximum left and right excursions. The vortex rings are deployed in a staggered configuration, while the trajectories of the two vortex rows are bilaterally symmetric. The distance between the left and right vortex rows keeps increasing after they are shed from the fish tail and gradually fade.

As shown in Fig. 4B, when the lateral distance between the two fish is as large as $0.8L$, the wake topology of each fish is similar to the wake behind a solely swimming fish.

When two fish are sufficiently close, their vortex streets may interfere with each other. When two fish swim side-by-side ($0.4L$ lateral distance) with zero phase shift (Fig. 4C), the vortex streets of each fish almost maintain the same wake structure as that of the single fish, but the vortex street (right vortex row of the left side fish and the left vortex row of the right side fish)

may insert into that formed by the neighbor fish and the vortices with same direction may merge (dash line zone).

When two fish swim in anti-phase (Fig. 4D), it appears that the vortex rows between them (right vortex row of the left side fish and the left vortex row of the right side fish) hinders the motion of each other as if there is an invisible boundary at the symmetrical plane between the two fish. Vortices near the symmetrical plane between the two fish appear to remarkably deform and become flattened near the symmetrical plane (dash line zone).

Fig.4E and F present cases when one fish swims behind the other fish and enters its vortex streets. In Fig. 4E, the trailing fish is directly behind the leading fish. The vortices of the leading fish wake is dramatically weakened (the number and size of the vortex rings represent vorticity strength), and merged with the trailing fish's anterior vortex. Meanwhile, the trailing fish's wake street is also influenced and becomes asymmetric (dashed line zone). Fig. 4F demonstrates an example when the trailing fish interferes with the right vortex row of the leading fish. Similarly, the right vortex row of the leading fish is dramatically weakened, and merged with the trailing fish's anterior vortex.

D. Lateral line may detect the neighbor fish

In nature, fish may use its lateral line to sense the flow, and the crucial roles of the lateral line in fish schooling has been recognized [15]. We used the simulations to test what form of signal could be detected by a fish due to the presence of a neighbor. During the simulations, the pressure history along a virtual lateral line of the model fish has been recorded. We compared the virtual lateral line pressure history between a single fish, and a fish with a neighbor swimming with various phase shifts.

As shown in Fig. 5, the comparisons show that pressure differences could be detected when fish swims nearby. On the side where a neighboring fish is placed, the pressure history received by the virtual lateral line is dramatically influenced by the neighboring fish. At the same time, on the opposite side where no neighboring fish exists, very minor changes in the pressure history occur. Therefore, fish may use lateral line to detect the existence of a neighbor fish and confirm on which side the neighbor fish stays.

Also, the comparisons demonstrate that the phase shift between two fish may cause detectable pressure signal for lateral line system. When the neighboring fish swims in in-phase, anti-phase or one-quarter period phase difference, the lateral line records different signals, as

Fig.4 Q-surfaces surrounding the swimming fish and in the wake. (A) Solely swimming fish; (B-D) two fish swimming in side-by-side configuration; (E-F) two fish swimming in leading-and-trailing configuration. The Q-surfaces are colored by the direction of vorticity, in top-view, blue color represents clockwise vorticity while red color represents anti-clockwise vorticity.

Fig.5 Pressure stress detected by virtual lateral lines in simulations.

shown in the right-side plots of Fig. 5.

These results indicate that the modified pressure field may be detected by lateral line system. Even in darkness, fish may detect the existence, position and phase shift between each other, and further adjust their schooling behavior.

IV. CONCLUSIONS

To explore the influence of schooling, we make a comparison of flow fields between a single fish and a pair of fish, in terms of pressure and vorticity fields. We vary the phase shift between the undulating kinematics of neighboring fish, as well as the relative position of one fish with respect to its neighbor by varying their lateral and longitudinal relative position. We have confirmed in our simulations that interferences of both pressure and vorticity fields occur between two closely swimming fish. Our results further indicate that the modified pressure field by a neighboring fish may be detected by the lateral line system. By using lateral line, fish may detect the existence, relative position and phase shift

between each other, and the sensed information may help fish to coordinate their schooling behavior. The present results can be taken as a reference of our future study on fish schooling hydrodynamics and energetics [16], as well as a reference for the design of artificial swimming devices and planning their collective operation strategy.

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