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Hydrodynamics of a tandem fish school with asynchronous undulation of individuals

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ABSTRACT

We perform numerical simulations using immersed boundary method for flow over a single and two fish in tandem performing traveling wave like motion for a range of Strouhal numbers. We investigate the hydrodynamic performance of single- and tandem-fish configurations using unsteady profiles of lateral side-force and drag coefficients, their time-averaged values, and wake behind these bodies. We present the spectra of hydrodynamic forces and find that the nature of these forces for a single fish resembles to those of stationary/oscillating bluff bodies and oscillating airfoils. For tandem cases, we vary the phase speed of undulatory motion of the rear fish while keeping the free-stream velocity constant. We show that hydrodynamic forces of the upstream and rear fish contain harmonics which are produced by nonlinear interaction of the oscillation frequencies of both fish. We find that the wake and time-averaged drag of the upstream fish remain almost independent of the undulating frequency of the rear fish at a certain Strouhal number. We also relate this observation with the absence of oscillation frequency of the rear fish in the Fourier spectra of hydrodynamic forces of the upstream fish. For the complete range of parameters, it is inferred that swimming in a tandem configuration seems more beneficial for the upstream fish. It happens due to wake-splitting effect of the rear fish that causes an enhancement of pressure in its wake. For the rear fish, it gains an advantage of drafting under certain conditions and its performance deteriorates at Strouhal numbers greater than 0.40.

1. Introduction

Nature always inspires researchers to investigate natural phenomena and take advantage of those mechanisms to design better and efficient machines. Since advent of micro-aerial and swimming robots and their future prospects in civil and military environments, various research efforts have been devoted to devise techniques for enhancing their performance. A great aspect of fish swimming is to make use of the surrounding environment for efficient propulsion. Due to this fact, many species in fishes tend to swim in the form of groups, known as schools. Various schooling patterns are observed in fish-swimming (Fish, 1999) that include line, diamond, triangular, and phalanx formations (Hemelrijk et al., 2015). Advantage of

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these congregations lies in the fact that each fish tends to gain energy from surrounding vortical flows generated by neighboring bodies. In this way, each individual tries to enhance its efficiency while reducing its muscle activity. To capture energy from the flow around it, fish performs a traveling wave-like motion known as undulatory motion.

Weihs (1973) studied hydrodynamic interaction among individuals in fish-schools and found the diamond pattern as a more suitable configuration for efficient swimming through a three-dimensional inviscid flow model. However, Partridge and Pitcher (1979) observed that many species did not follow the diamond-shaped configuration for schooling. Earlier mathematical models, proposed by Lighthill (1960), Wu (1961, 1971a, 1971b, 1971c) and Cheng et al. (1991) to investigate this hydrodynamic mechanism of fish-swimming, were based on inviscid flow theories and assumed flow patterns in their wakes. Liao et al. (2003) performed experiments to observe the reduced muscle activity by a fish while swimming in the wake of a D-shaped cylinder. The D-shaped cylinder produced a wake as two fish are assumed to produce by swimming in front of another fish. Beal et al. (2006) also performed similar experiments to get a dead fish propelled in the wake of a bluff body. They found that the flexible body of the dead fish undulated resonantly with oncoming vortices. Development of advanced numerical techniques and computational resources also allowed researchers to study this complex hydrodynamic phenomenon using unsteady Navier–Stokes equations. Eldredge and Pisani (2008) studied behavior of a body, modeling it as a combination of two-dimensional linked bodies, in the wake of a cylinder. Undulatory motion was not found to be essential for passive propulsion in these numerical simulations. Using the immersed boundary method (IBM) (Mittal and Iaccarino, 2005) based numerical scheme, Dong and Lu (2007) examined performance of two side-by-side undulating foils. They concluded that swimming power might be saved through their out-of-phase movement while in-phase undulation enhanced force production. Deng et al. (2007) investigated hydrodynamic interaction between two wavy foils placed in tandem arrangement. Contrary to the observation of Weihs and Webb (1983), they found that the downstream fish did not always experience greater drag if it swam exactly behind another fish. In this case, enhancement or reduction of thrust for the downstream fish was found to be a function of Strouhal number (Sr). For the upstream body, thrust was always observed to be greater than that for a single fish. Akhtar and Mittal (2005, 2007) found that hydrodynamic performance of the fish in tandem was dependent on the phase between the kinematics of the two fish. Zhang and Zheng (2009) performed numerical simulations through IBM to investigate the performance of a tandem configuration of two fish as a prey–predator model and measured pressure fluctuations in the vicinity of undulating bodies. They reported that the rear fish might use sensors in its head and tail to identify the speed of its predecessor. Chung (2011) examined the performance of a triangular-shaped pattern of a fish school. They found optimum vertical and longitudinal distances between the bodies to achieve maximum thrust efficiency. Marras et al. (2014) reported that an individual fish took benefit from the vortical flow around it irrespective of its position within a school.

In each of the afore-mentioned studies for wavy foils to model fish schooling, all bodies were made to undulate with the equal frequency. In a school, it is observed that the rear fish performs an undulating motion with lower tail-beat frequencies as compared to their leaders (Herskin and Steffensen, 1998; Killen et al., 2012; Liao, 2007). Although highlighted by other researchers (Deng et al., 2007; Hemelrijk et al., 2015), no study has been devoted towards this factor to the authors' best knowledge. To gain deeper understanding and knowledge of fish-schooling mechanisms, it is very important to investigate what benefit the upstream and downstream fish find in these situations and what mechanisms do they follow. We devote our present study in this direction as it portraits a complex yet more physical scenario. Here, we perform numerical simulations to investigate this phenomenon for two fish swimming in a tandem configuration. To study the effect of presence of a body swimming asynchronously to another body in its vicinity, we initially analyze wake characteristics of a single fish. We quantify its hydrodynamic performance using drag coefficient (C_D), both pressure and viscous components, and lateral side-force coefficient (C_Y). We also highlight unsteady character of these force coefficients through respective time-histories and relevant Fourier spectra. The spectra reveal important information regarding the response typical to any nonlinear system (Marzouk et al., 2007; Khalid et al., 2015a, 2015b). We, then, perform simulations for the flow past fish in tandem. We compare their hydrodynamic performance in terms of unsteady and time-averaged force coefficients, and relate it with the flow patterns around the undulating bodies. It is true that the currently investigated phenomenon is three-dimensional (3D), yet it is also customary to assume a two-dimensional (2D) flow for analysis. This assumption is justified by considering a primary direction of the flow, for example; bluff bodies and wings are investigated simulating the flow past cross-sections and airfoils, respectively. Using the similar analogy, we consider top view of the fish at mid-plane for both single and tandem cases. In this manner, we analyze the primary flow features around fish bodies. It is quite pertinent to mention that since fish schooling involves complex interaction not only with the other bodies but also with flow itself in lateral/transversal directions, 2D investigations can serve as an appropriate choice to start hydrodynamic analysis and quantification of the flow characteristics (Liu et al., 2011, 2012; Dong and Lu, 2007; Deng et al., 2007). For comparison, it is also important to mention the conclusions drawn by Liu et al. (1996, 1997) through numerical simulations over a swimming tadpole. They showed that pressure and velocity contours remained almost the same for 2D and 3D cases. In addition, a little vertical cross-flow component was observed over fins and tail surfaces. Based on the 3D waving plate theory, Cheng et al. (1991) showed that 3D effects in the flow could be reduced through an undulatory motion.

The remainder of this paper is organized as follows. Section 2 provides details of the numerical methodology, kinematic modeling, and boundary conditions employed in this study. In Sections 3 and 4, we present results of the current research work. Its earlier part is devoted to hydrodynamics of a single fish, and later part describes the same for an upstream and a downstream fish swimming in a tandem like fish-school. We conclude this paper with a summary of this study and prospects to the future work.