

# Steady wave interference between human swimmers

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## HIGHLIGHTS

- The interaction between human swimmers is determined by the wave interference on the free water surface.
- A destructive wave interference phenomenon can be observed when drafter takes wave-riding positions.

## INTRODUCTION

This study focuses on the hydrodynamic interaction between two or three human swimmers in competitive swimming. Although the swimming performance of a single swimmer has been widely examined, the studies on the interaction between multiple competitive swimmers are very rare [1]. Experiments showed evidence that the drag of a swimmer could be modified by the existence of the other adjacent competitors [2]. The questions arise: 1) what mechanism determines the interaction; 2) which position experiences drag reduction or drag increase; 3) how much can drag be reduced or increased in a formation. According to the authors' knowledge, such questions have not been addressed by any published literature.

To demonstrate this wave-cancellation effect, we calculated the waves generated by a single translating source point (Figure 1a), and the waves generated by three source points in an optimal V-shape configuration (Figure 1b). The transverse waves generated by the two drafters are partly cancelled by travelling in the leader's wake. As a result, the wave energy propagated to the fluid domain is conserved. When this wave-cancellation effect occurs among multiple swimmers, the reduced wave energy is equivalent to the energy saved by the drafter. Although the waves generated by a swimmer's three dimensional body are much more complicated, as shown in Figure 1c, the wave interference phenomenon can be interpreted by the same principle.

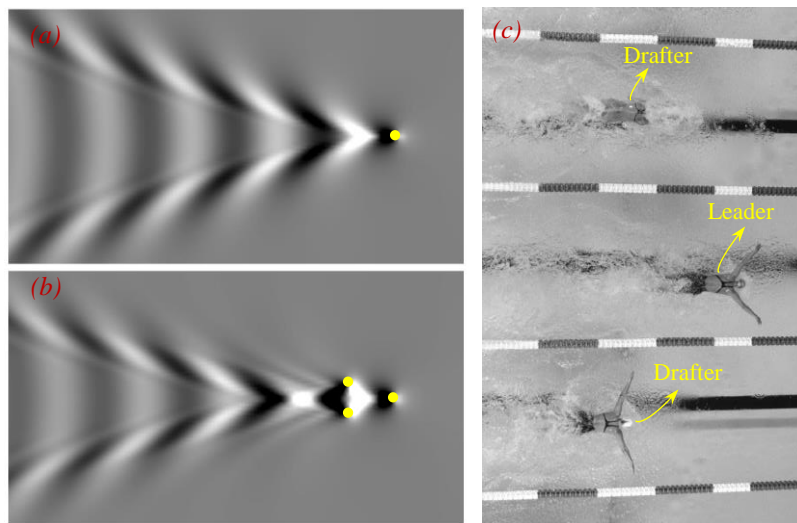


Figure 1. (a) The wave pattern generated by a single source point submerged at  $H = 0.3U^2/g$ ; (b) destructive wave pattern generated by three source points submerged at  $H = 0.3U^2/g$  in a V-shape configuration; (c) the formation of three swimmers in competitive swimming (<https://accidentalokie.files.wordpress.com/2012/07/11239827-essay.jpg>).

For a single competitive swimmer, the drag (resistance) is considered to be one of the most important factors which determines his/her swimming performance. In most of competitive swimming styles (apart from butterfly stroke), the total drag  $R_T$  of a swimmer is mainly made up of three components: wave drag  $R_w$  due to wave-making, and skin-friction drag  $R_f$  due to fluid viscosity, and pressure drag  $R_p$  arising as a result of distortion of flow outside of the boundary layer [3]. Of course, the spray could also induce a drag. In this study, we are only interested in the wave drag component. No attempt is made here to analyse the other drag components due to the viscosity of the fluid. The main purpose of this paper is to quantify the wave drag reduction in formation swimming and find the mechanism of the hydrodynamic interaction between human swimmers. To make the goals achievable, we make the following assumptions:

- 1) The skin-frictional drag  $R_f$  and pressure drag  $R_p$  of a swimmer in formation swimming remain the same as those of the same swimmer swimming solely with the same speed.
- 2) The passive swimmer, either the drafter or the leader, is assumed to be a rigid and smooth body. The local movement of different parts of the body is not taken into account. The flexibility of active swimmer's body and the local movement of different body parts will definitely bring changes to the drag, as discussed by Vennell et al. [4]. However, this effect is consistent in single and formation swimming. Therefore, only a rigid swimmer model with the arms alongside the body is considered in the present study.
- 3) The gliding depth keeps constant. Neither sinkage nor trim will be considered in our calculations.
- 4) The swimmers are assumed to swim in open-water. No attempts are made here to calculate the wave absorbing effect of the lane ropes. Rizk [5] investigated and quantified the efficiency of the wave damping properties of the lane ropes. It was concluded that within the most efficient case of wave-damping, the swimming ropes attenuated about 70% wave height transmitted through it. However, it still has at least 30% of the wave energy transmitted to the adjacent lanes, which can be utilized by the drafter as a propelling aid.
- 5) Only the primary characteristics of swimmer's body shape are modelled in our calculations. The detailed geometry, e.g. fingers, hands, ears, is not considered in the 3D model.

## RESULTS AND DISCUSSIONS

The numerical calculations are conducted by using an in-house developed multi-body hydrodynamic interaction program "MHydro". The wave drag of a swimmer swimming alone in open calm water is denoted by  $R_{ws}$ . When the same swimmer swims at a certain position around another swimmer, the wave drag is denoted by  $R_w$ . The wave drag reduction coefficient can be expressed as

$$C_{DR} = \frac{R_{ws} - R_w}{R_{ws}} \times 100\% \quad (1)$$

The wave drag reduction coefficient  $C_{DR}$  can be used as an indicator to show the hydrodynamic interactive effect.  $C_{DR} > 0$  indicates a reduction of wave drag due to the hydrodynamic interaction;  $C_{DR} < 0$  represents an increase in the wave drag of a swimmer caused by the presence of the other swimmer(s). No interaction is expected when  $C_{DR} = 0$ . When  $C_{DR} > 100\%$ , the wave drag turns to be a thrust force, which is in the same direction of moving.

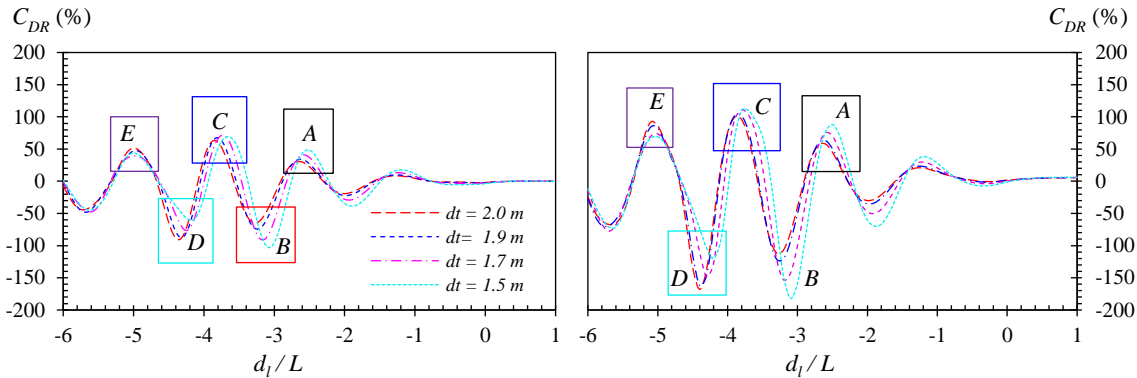


Figure 2. (a) Wave drag reduction coefficient of a drafter when he/she swims alongside a leader at different transverse distances at  $U = 2.0$  m/s. The x-axis is the non-dimensional longitudinal distance. (b) Wave drag reduction coefficient of a drafter swimming in the wake of two side-by-side leaders at both sides at  $U = 2.0$  m/s. Different curves correspond to various transverse distances. The x-axis is the non-dimensional longitudinal distance between the leaders and the drafter.

In competitive swimming, each swimmer must stay in his/her lane, swimming in parallel with a certain transverse distance  $d_t$ . As the position of the drafter changes from  $-7L$  to  $-1L$ , the drafter has to pass through the transverse waves, the divergent waves, and eventually reach a non-disturbed region. Figure 2 (a) shows the result of  $C_{DR}$  of a drafter in a two-swimmer configuration, where the lateral separation between the drafter and leader varies from 1.5 m to 2.0 m. By varying the longitudinal position, the  $C_{DR}$  curve exhibits fluctuations around  $C_{DR}=0$ . The most violent fluctuations can be observed at  $-5 < d_1/L < -3$ . This corresponds a region covered by the leader's divergent waves. The interactive force gradually vanishes after the drafter is completely out of the Kelvin wake. At  $d_1/L > -1$ , the hydrodynamic interaction can be negligible. When the drafter and leader are swimming side-by-side ( $d_1/L = 0$ ), no hydrodynamic interaction is observed. In a swimming competition, the most interesting position is in region C, where the drafter can experience the maximum wave drag reduction up to 70%. The wave drag increased

up to 102% if the drafter swims in region B due to undesired interaction. The discrepancy between the peak values at different  $d_t$  is not very obvious in region C, indicating that the wave drag reduction is not strongly sensitive to the lateral separation.

The hydrodynamic interaction does not only occur between two swimmers. Apart from the swimmers at the first and last lanes, a swimmer usually interacts with the other two adjacent swimmers. The hydrodynamic interaction between three swimmers is very interesting. There are various possible configurations of three swimmers in a formation, among which the V-shape configuration is of particular interest. As shown in Figure 1 (c), when a drafter is located in the wake of two leaders at both sides, he/she may achieve more wave drag reduction by utilising the waves produced by two leaders. The results of  $C_{DR}$  in a V-shape configuration are shown in Figure 2 (b). Similar fluctuations of  $C_{DR}$  curves are observed in V-shape formation swimming. Compared with two-swimmer case (see Figure 2 (a)), the amplitudes of the  $C_{DR}$  curves shown in Figure 2 (b) are much higher. For example, at  $d_t = 2.0$  m, the maximum and minimum wave drag reduction are 110% and -182% respectively in three-swimmer case, while in two-swimmer case, the maximum and minimum values are 69% and -102%. The corresponding longitudinal separations in the three-swimmer and two-swimmer cases are consistent. The most interesting position is also found in region C, where the drafter can experience a maximum wave drag reduction of up to 110%. As indicated in Eq.(1), when the wave drag reduction is larger than 100%, the wave drag turns to be a thrust force, which pushes the drafter forward. The results in Figure 2 (b) indicate the drafter could potentially save more energy by following two side-by-side leaders.

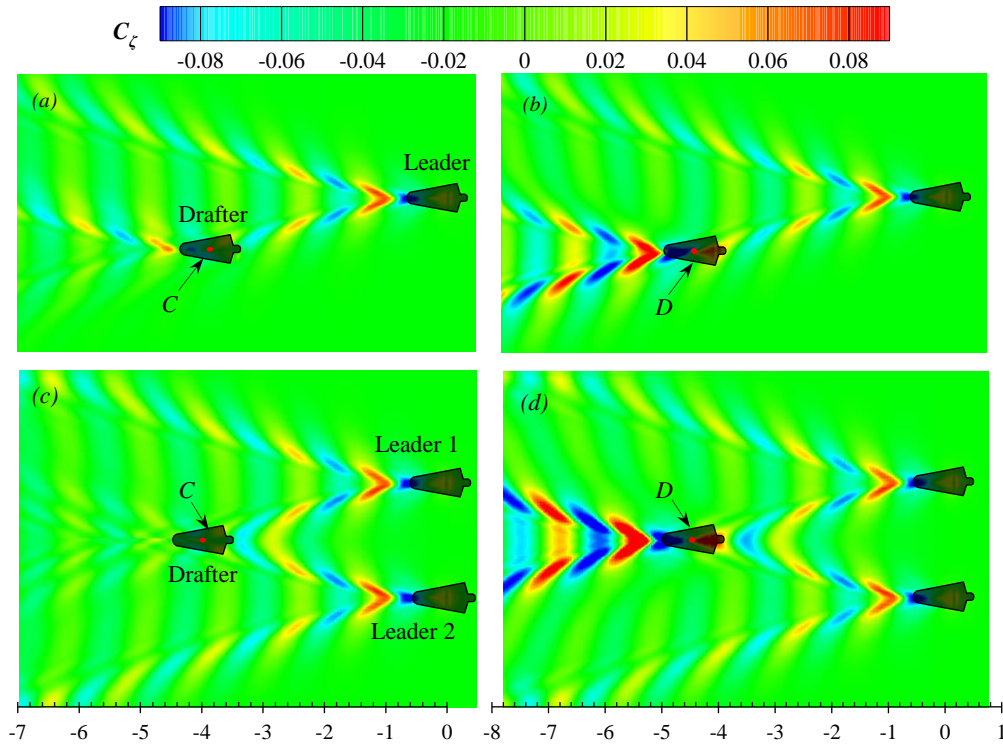


Figure 3. Wave patterns generated by two swimmers at  $d_t = 2.0$  m and  $U = 2.0$  m/s. The  $x$ -axis is the non-dimensional longitudinal distance  $d/L$ . Two typical positions are selected, namely C and D, which represent the peak values in corresponding boxed regions in Figure 2. (a) and (b) correspond to two-swimmer case when the drafter is swimming in regions C and D in Figure 2 (a); (c) and (d) correspond to three-swimmer case when the drafter is swimming in regions C and D in Figure 2 (b).

To find the relationship between  $C_{DR}$  and the waves, we calculate the wave patterns generated by two and three swimmers when the drafter is swimming in region C and D. These two regions correspond to the drag-reduced and drag-increased region respectively. The results in Figure 3 (a) show, in two-swimmer case, the maximum wave drag reduction is achieved when the drafter's fore part is in the wave trough while the aft part in wave crest. This is called wave-riding configuration. The work done by a swimmer to overcome the wave drag can be transferred into the energy of the Kelvin waves on the free water surface, which is proportional to  $\zeta^2$ . For a swimmer swimming alone in unrestricted water,  $\zeta$  is mainly determined by swimmer's body shape, posture, speed and submerged depth. The relative position becomes another factor which affects the free surface elevation if two or more swimmers are swimming in close proximity. The results in Figure 3 (a) clearly show how the wave patterns are affected by the drafter's position. In wave-riding position, a destructive wave interference

phenomenon can be observed, where the waves generated by the swimmers are  $180^\circ$  out of phase. The starboard divergent waves of the leader are partly cancelled by the drafter's starboard divergent waves. This effect can be referred as *partial divergent wave cancellation*. As a result, the free surface elevation in the starboard wake of the drafter is reduced, hence conserving energy. This wave cancellation effect has been proved to have a beneficial effect on multihull configuration in order to minimize the wave resistance of a multihull vessel [6, 7]. Conversely, if the drafter is located in positions *D*, as shown in Figure 3 (b), the starboard divergent waves generated by the swimmers are in phase. More energy is dissipated in terms of the amplified waves, which requires the drafter to do extra work in order to overcome the increased wave drag. Obviously, positions *D* are the most undesirable positions in formation swimming. To 'escape' from these drag-increased positions, the drafter has to generate an additional thrust to move towards positions *C* where the wave drag can be minimized. Similar phenomenon is found in three-swimmer case, as shown Figure 3 (c) and (d). Destructive wave phenomenon can be observed in Figure 3 (c) when the drafter takes the wave-riding position. With the head and shoulders located in the troughs of the divergent waves generated by the leaders, the drafter generates a divergent wave system which is  $180^\circ$  out of phase with Leader 1's starboard divergent waves and Leader 2's portside divergent waves. As a result of superposition, the divergent wave system behind the drafter can hardly be observed. This effect can be referred as *full divergent wave cancellation*. Compared with the *partial divergent wave cancellation* effect in two-swimmer formation swimming, it is obvious that the *full divergent wave cancellation* could achieve a higher wave drag reduction (almost twice), hence saving more of the drafter's energy. On the contrary, if the drafter is located in position *D*, as shown in Figure 3 (d), the divergent waves generated by the three swimmers are in phase. The amplified waves will dissipate more energy, which requires the drafter to do more work in order to overcome the increased wave drag. The results in Figure 3 confirm that the interaction between three swimmers could be more significant than that between two swimmers.

## CONCLUSIONS

The interaction between human swimmers is determined by the wave interference on the free water surface. The energy-saving position of the drafter is determined by the wave drag reduction. The maximum wave drag reduction is observed when the drafter's fore part is in the wave trough while the aft part is in the wave crest. By taking this wave-riding position, a destructive wave interference phenomenon can be observed, where the waves generated by the swimmers are  $180^\circ$  out of phase. As a result of the wave cancellation effect, the wave drag can be minimized. In a two-swimmer configuration with lateral separation of 2.0m, the maximum wave drag reduction of the drafter swimming at  $U = 2.0$  m/s is 64%, when the partial wave cancellation effect occurs. In a three-swimmer configuration, a full wave cancellation effect can be observed, where the maximum wave drag reduction achievable is 102%. In this case, the wave drag turns to be a thrust force, pushing the drafter forward. It should be noted that the above conclusions are based on wave drag computations for a simplified model. The effects of fluid viscosity, lane ropes and immersed depth were not taken into account.

The principle finding of this work is that the competitive swimmers could experience a strong hydrodynamic interaction when swimming in formation. By swimming in an optimum position behind one/two leading swimmers, the drafter could utilize the Kelvin waves as a propelling aid to preserve energy, hence improving the swimming performance.

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