Wave-passing by ships in a single file formation

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HIGHLIGHTS

- Discover the wave-passing phenomenon by ships in a single file configuration
- Distinct wave interference phenomenon was found between individual ships

1 INTRODUCTION

It has been commonly observed on open waters that ducklings/goslings follow their mothers in a single file configuration. A recent research by Yuan et al. (2021) reveals the reason of such formation locomotion observed in nature: wave interference. Their findings are different from the existing literatures on formation movement by flying birds or swimming fishes, in which the vortices in wakes were considered as the main reason for energy savings by group locomotion (Liao 2007). When a body is moving on the free water surface, its resistance components are fundamentally different from those moving in a single media. A distinct Kelvin wave pattern will be observed on the interface between the air and water in the wake of the moving body, accompanied by a wave making resistance to the body, which is one of the major components of the total resistance. Therefore, it is essential to investigate the wave interactions among bodies travelling in highly organized groups. It was found by Yuan et al. (2021) that when a duckling swims at the "sweet spot" behind its mother, a destructive wave interference phenomenon occurs and the wave resistance of the duckling turns positive, pushing the duckling forward. More interestingly, this *wave-riding* benefit could be sustained by the rest of the ducklings in a single-file line formation. Starting from the 3rd one in a queue, the wave resistance of individuals gradually tended towards zero, and a delicate dynamic equilibrium is achieved. Each individual under that equilibrium acted as a wave passer, passing the waves energy to its trailing one without any energy losses. It inspires the present study to investigate the ships in a single file configuration and to see if we can learn this *wave-riding* and *wave-passing* skills from the waterfowl to improve our design of waterborne traffic and to eventually design a water train of minimized wave-making resistance.

As commented by Ellingsen (2021) that the benefits of *wave-riding* and *wave-passing* are not exclusive to waterfowl, but could equally apply to boats and vessels at a larger scale. A recent project, Sea Train, initiated by the US Defense Advanced Research Projects Agency (DARPA 2020), is envisioned to consist of four or more unmanned surface vehicles travelling in a row formation with the objective to minimize the collective wave-making resistance by creating 'the equivalent of a long parallel mid-body', as shown in *Figure 1.* Compared to a ship with a long parallel mid-body, multiple short ships in a single file configuration could achieve many benefits, e.g. better mobility, manoeuvrability, flexibility, etc. By intuition, one may think the multiple short ships might generate more waves than the single long ship, hence pocessing a larger wave-making resistance. The objective of this study is to quantify how much wave-resistance is increased or reduced by ships in single file formation, comparing to that of a single ship.

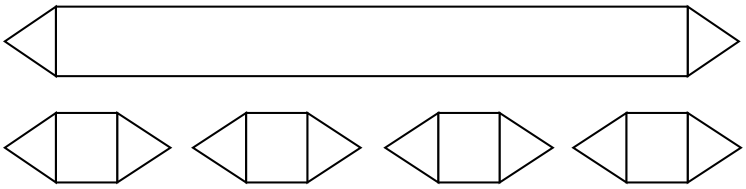

Figure 1. Upper half: a ship with very long parallel mid-body; lower half: four ships in a single file formation.

2 METHDOLOGY AND ASSUMPTIONS

The present study focuses on the wave-making problem, and no attempts are made to address the force or interaction caused by the viscosity of the fluid. The fluid domain can be described by using a velocity potential that satisfies Laplace equation. The three-dimensional boundary element method used in (Yuan, He et al. 2015) can then be applied to solve the Laplace equation and calculate the wave-making resistance with an implementation of linearized free-surface boundary condition.

In the case study, the ship model is represented by a simple Wigley hull with B/L=1/4 and T/L=1/10, where B, L and T are ship breadth, length and draft respectively. Let's define R_s as the wave resistance of a single ship travelling solely in calm water. In a single file formation, all the individual ships are exactly the same, and the wave resistance for the n-th body in the formation is denoted by R_n, where n=0 represents the leading ship, and n=1 indicates the first coach in the train (the first trailing ship after the leading one). The wave drag reduction coefficient C_{DR} can be defined as

$$\boldsymbol{C_{DR}} = \left(\mathbf{1} - \frac{\boldsymbol{R_n}}{\boldsymbol{R_S}}\right) \times \mathbf{100\%} \tag{1}$$

The coefficient C_{DR} can be used to quantify the intensity of hydrodynamic interaction. $C_{DR} > 0$ indicates the wave resistance is reduced in a formation due to the hydrodynamic interaction; whilst $C_{DR} < 0$ represents an increase of wave resistance. No interaction is found at $C_{DR} = 0$, and the wave resistance is the same as that of independent moving. Obviously, it is desired by the trailing ships to get a C_{DR} as large as possible.

3 RESULTS AND DISCUSSIONS

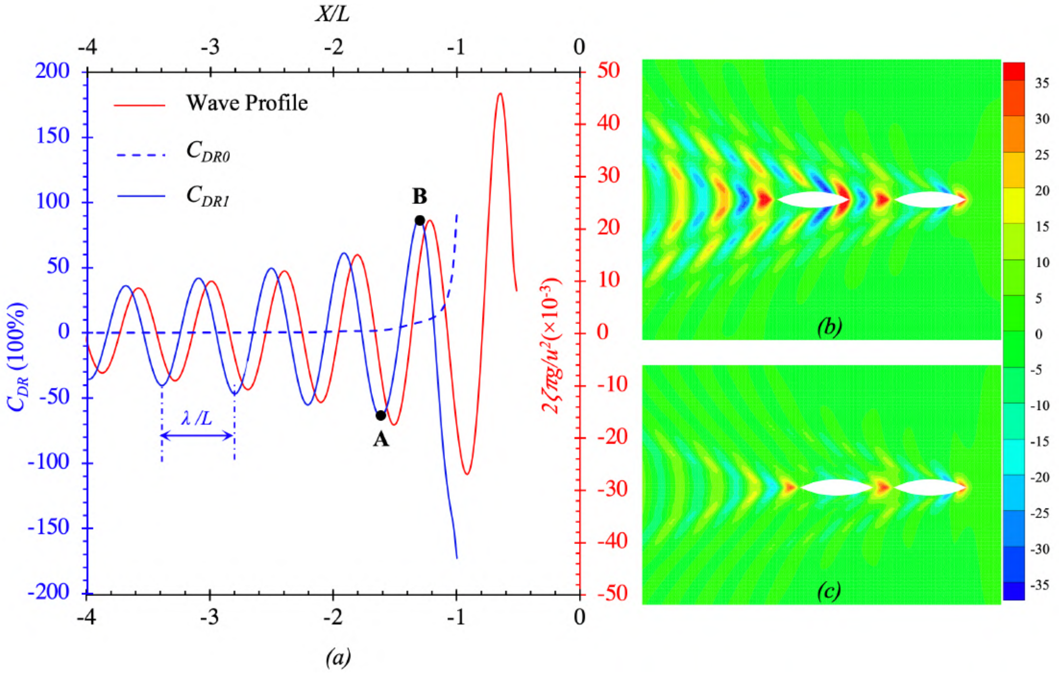

Figure 2. (a) C_{DR} of the trailing ship (n=1, blue solid curve) and the leading ship (blue dash curve) at Fr=0.3. Point A and B on the blue solid curve corresponds to two typical wave drag reduction positions. The red solid curve is the wave profile on the centre line behind the leading ship. λ is the wavelength. (b) Wave pattern when the trailing ship is swimming at position A. (c) Wave pattern when the trailing ship is swimming at position B.

Let's firstly put the trailing ship on the centre line behind the leading ship and let it gradually approach the leading ship from -4L to -1L. The wave drag reduction of both the trailing ship and leading ship, and the wave patterns, are shown *Figure 2*. There are three main findings from the results in *Figure 2*.

1) The trailing ship has equal probability to experience an increased drag (C_{DR} <0) and reduced drag (C_{DR} >0) by following the leading ship's wake, depending on its relative position to the leading ship, as shown by the solid blue curve in *Figure 2* (a). The trailing ship's C_{DR} curve exhibits a periodical property, fluctuating around a neutral value. The oscillation amplitude decays as the trailing ship stays in positions further downstream. The decay rate matches very well with that of the waves propagating to the far-field downstream. The distance (d) between two consecutive crests on C_{DR} curve is approximately a wavelength (λ). Since the wavelength on the centre line behind a moving body is speed dependent ($\lambda=2\pi U^2/g$), we could always find the best energy saving position of the trailing ship by adjusting its distance to the leading one. The maximum wave drag reduction of 96% is found at the

first crest of C_{DR} curve, indicating the trailing ship's total wave drag is only 4% of a single ship moving solely at the same speed. The amplitude of the curve is subject to a decrease as the leading-to-trailing ship distance increases. At the 5th crest, where the trailing ship is 3.7L away from its leader, the trailing ship could still receive up to 36% of wave drag reduction. The other side of the coin is that some regions exist where the drag increases. In particular, a -172% drag reduction is observed at position X/L=-1, where the trailing ship's bow is contacting the leading ship's stern.

2) It is not a surprise that the trailing ship is subject to a strong hydrodynamic interaction when travelling at the leading ship's wake. However, would the leading ship receive a drag reduction due to the presence of the trailing ship, leading to mutual benefit in a formation movement? The calculations provide the evidence to support this hypothesis that the trailing ship moving close behind a leading ship will also assist the leader. It can be seen from the blue dashed curve in *Figure 2* (a) that the wave drag of the leading ship can be reduced by 90% when the trailing ship is moving directly behind her. The pressure distributed over the rear part of the leading ship is increased due to the trailing ship's frontal waves. As a result, the leading ship receives benefit by riding the trailing ship's bow wave. However, at this position, the trailing ship is the looser. Its wave drag reduction becomes -172%, which indicates the trailing ship has to spend more than twice its efforts to overcome the wave drag, compared to that when travelling independently. A win-win situation is observed when the trailing ship is swimming at position B, where the leading ship saves 8% and the trailing ship saves 96% of its wave drag. This kind of mutual benefit is essential to configurate the optimal formation of a water train, as it could save on the amount of energy as a whole. As the separation increases, this benefit of the leader's drag reduction diminishes rapidly. There is nearly no interactive effect on the leading ship as the separation becomes larger than a trailing ship's body length.
3) Why can the trailing ship save energy when it swims at position B, while it consumes more energy at position B? The wave patterns in *Figure 2* (b) and (c) help to reveal these reasons. When the trailing ship is riding the waves at position B, a destructive wave interference phenomenon is observed, as shown in *Figure 2* (b). The wave cancellation mainly occurs in the leading ship's aft wedge region. The phase of the waves generated by the trailing ship is different from that of leading ship's waves. By superposition, the downstream waves are partially cancelled. Taking the leading ship and trailing ship as a whole system ("0+1"), it requires less work done by the system to maintain the resultant wave energy. As the waves are confined downstream within a Kelvin wedge, the leading ship can only receive very limited benefit from wave cancellation. In contrast, when the trailing ship is swimming on the waves at position A, a constructive wave interference is observed. The extra energy carried by the amplified waves is mainly extracted from the trailing ship's energy expenditure due to the downstream propagation nature of the Kelvin waves. It coincides with the fact that drag increases at position A, as shown in *Figure 2*.

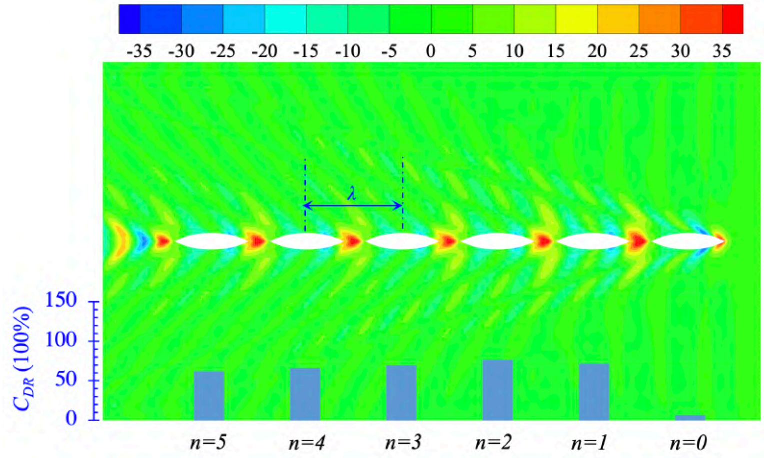

Figure 3. The optimum swimming formation by a leading ship (*n*=0) followed by trailing ship(s) in an array of 5. The contour is the wave pattern by "0+5" in an optimum formation. *n* represents the *n*-th trailing ship in the formation. The columns represent the wave drag reduction of the *n*-th individual *n*.

Assuming the first trailing ship ($n=1$) stays at a position with maximum wave drag reduction (position B), let’s put the second trailing ship ($n=2$) to follow “*0*+1”. Obviously, the wave energy generated by the leading ship has been partly extracted by the 1st trailer. The aft wedge region in *Figure 2* (c) may not provide enough energy for the 2nd trailer to achieve the same amount of drag reduction as the first one. This leads to other interesting questions, if there is more than one trailing ship~~s~~ following a leading ship: 1) what is the best configuration? 2) how much wave drag can be saved by each individual in a formation? To answer these questions on “*0+n*”, a large computation needs to be performed by repeating the above-mentioned process of “0+1”, and we can find the best position for each individual in sequence from the 1st to the nth body, and eventually an optimum formation can be obtained.

Figure 3 shows the optimum swimming formation of “*0+5*” system. The separation between adjacent trailing ships is nearly uniform, i.e. a wave length. The most exciting finding from the results in Figure 3 is a *wave-passing* phenomenon. The leading ship generates the waves in the wake, leaving energy potentially available for the trailing ships to extract. As the first trailer is moving directly behind the leading ship, it is supposed to receive the best benefit. However, its wave drag reduction is slightly less than the 2nd trailer, whose C_{DR}=102%, in which 100% is used to overcome its wave drag, and the remaining 2% turns to be a propulsive force. Although the wave drag reduction fluctuates around 90% (one possible reason of the fluctuation is the numerical error in the calculation, in which only limited positions are calculated), the remaining wave energy is still sufficient for the rest of the trailing ships to gain a large stable wave drag reduction, indicating the benefit of wave drag reduction is passed from the 1st trailer to the last one in a queen. This *wave-passing* phenomenon can also be observed in the wave patterns shown in Figure 3. The waves behind the leading ship are passed by its trailer, and then the same waves are maintained behind each ship. Repeating this process, the wave energy initiated from the leading ship will eventually reaches the n-th trailing ship, regardless of the separation.

It should be noted that not all the trailing ships receive a 100% of wave drag reduction. This is different from the observation by Yuan et al. (2021), in which the size of the leading one in a formation is much larger than the trailing individuals. As a results, the leading one could initiate sufficient waves for the trailers to ride and to pass. Therefore, when designing a water train, the size and hull form of the engine ship could be an important factor, which determines how much drag reduction can be achieved by the trailing coaches. The idea case is to design a configuration that all the trailing coaches received 100% of wave drag reduction, so that the train made by multiple short ships could be equivalent of a single long parallel mid-body.

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