Ship Hydrodynamics of Several Typical Scenes During Inland Waterway Transport

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Abstract. Environmental effects on ship hydrodynamics during inland waterway transport are investigated using both CFD (Computational Fluid Dynamics) and towing tank experiments. Three important scenes, the confinement effect of the waterway, head-on encounter and ship-bridge pier interactions are studied. The testing conditions cover a wide range, including various channel dimensions, water depths, ship draughts and speeds. The ship resistance, wave pattern, Kelvin angle and wave elevations are investigated as functions of these parameters.

1. Introduction
Inland vessels are always maneuvered in the confined waterway, whose width and depth are limited. This space restriction will modify the hydrodynamics of the vessel. Normally, the ship resistance will increase and the velocity will decrease. The propulsion efficiency also drops compared with open water. In this kind of area, the turning radius will increase, and the so-called “squat” phenomenon occurs, which decreases the distance between the keel and channel bottom. The vessel may collide with bank/bottom, cause damage and fuel consumption to the vessel.

**Figure 1.** Ship resistance curves in open, shallow and confined waters [1].

**Figure 2.** Confinement effect distribution in the cross section [2].
As shown in Figure 1, the flow regimes can change with the difference of the restriction level. Subcritical, critical \((Fr_s = 1)\) and supercritical regimes can occur based on the depth Froude number \((Fr_h)\). In the subcritical region, the accelerated flow between the wall and the vessel results in an attraction force towards the wall. The ship waves can transfer upstream and overtake the downstream flow. In the supercritical region, the vessel will catch up with the waves and cause a very different flow pattern around the vessel.

**1. Resistance**

Figure 1 clearly shows the typical curves of resistance in open, shallow and confined areas. In shallow water, only the channel bottom restricts the ship motion. The undulotary effect happens. Under this condition, the parameter \(h_w / T_d\) is dominant. A critical speed \((Fr_h = 1)\) exist, where the resistance change dramatically. In the restricted area, an additional hydraulic effect appears. The parameter \(A_s / A_t\) dominates the resistance change.[1]:

\[
\text{Subcritical} \quad Fr_h^{sub} = \left(2\sin\left(\frac{\text{Arcsin}(1 - m_b)}{3}\right)\right)^{1.5}
\]

\[
\text{Supercritical} \quad Fr_h^{sup} = \left(2\sin\left(\frac{\pi - \text{Arcsin}(1 - m_b)}{3}\right)\right)^{1.5}
\]

where \(m_b = A_s / A_t\) is the blockage ratio. The weight distribution of the confinement effect can be represented by a decreasing exponential function [2]:

\[
\omega_w = e^{-\left(\frac{\xi_w}{\gamma_{inf}}\right) - \left(\frac{\xi_w}{T_d}\right)}
\]

where \(\xi_w\) and \(\gamma_{inf}\) are determined from experiments. \(\gamma_{inf} = B_s(5Fr_h + 5)\) is the influence area in the horizontal direction caused by the bank effect [3]. \(T_d\) and \(B_s\) are the ship draught and beam. As shown in figure 2, the weight becomes higher close to the ship hull, which mean a high restriction effect there. Ships can experience a decrease of the speed by 30% in shallow water and 60% in restricted waters [4].

**2. Ship waves**

The movement of the vessel can generate the traditional Kelvin wave pattern on the water surface. In the shallow water, the wave pattern changes with the water depth. The wave angle follows the following equation:

\[
\sin \alpha_w = \frac{1 + 2k_w h_w \sinh^{-1}(2k_w h_w)}{3 - 2k_w h_w \sinh^{-1}(2k_w h_w)}
\]

The wave angle increases with the vessel speed. When the speed reaches the critical speed, the wave angle becomes nearly 90°. In the supercritical condition, the vessel will leave the transverse waves behind and only divergent waves exist [4]. The wave angle follows the equation as a function of the Froude number:

\[
\alpha_w = \text{arcsin}(1 / Fr_h)
\]

In the restricted waterway, the bank wall will reflect the ship waves and create a more complex wave pattern.

The interactions between the ship and other structures, such as channel bank, bottom or another ship are summarized in this part. They can alter the maneuverability and controllability and introduce additional hydrodynamic effects for ships.

**1. Ship-bank interaction**

During the maneuvering, when the vessel approaches the wall, the flow there will be accelerated and the pressure drops in the gap. Normally, an attraction force will be generated and the vessel is dragged...
towards the wall, known as bank suction. Because of the special geometry of the vessel, a bow-away moment is also generated, known as the bank cushion. When approaching the wall, the fluid will be squeezed and a repulsion force will be generated at last. The vessel will be pushed away from the bank. During this process, the stern is prone to collide with the bank, which can be counteracted by the rudder action [5].

(2) Ship overtaking
To characterize the overtaking process, a parameter denoting the relative position between two ships is normally defined:

$$\xi = \frac{x}{L}$$

where $x$ is the longitudinal distance between the two vessels. $L$ is the average of the ship lengths. The overall overtaking process can be divided into 5 phases [6-7]. In phase 1 ($\xi = -1$), the longitudinal force speeds up the faster ship and drags the slower ship. A repulsion force and a yaw moment are generated. An attraction force is formed by the restricted space between the two vessels. In phase 2, this attraction force becomes dominant. In phase 3 ($\xi = 0$), a repulsion force is formed near the bows and an attraction force is generated at the stern. In phase 4, the faster ship overtakes the slower one. A ‘bow-in’ and a ‘bow-out’ moment are generated for the slower and faster vessel respectively. In phase 5 ($\xi = 1$), the two vessels repel each other. The risk of collision is high for phases 2-4. Counter helm may be necessary for the safety of the vessels.

(3) Head-on encounter
For the head-on encounter between two ships, a parameter similar with Eq.6 can be defined to characterize the relative positions [8-10]. In Phase 1 ($\xi = -1$), additional resistances will be induced. Both ships are laterally repelled and “bow-out” in this stage. In Phase 2, the lateral forces and yaw moments turn to the opposite directions because of the Bernoulli effect. Longitudinal resistances and yaw moments disappear temporarily in Phase 3 ($\xi = 0$). In Phase 4, the longitudinal forces change directions and exert resistances again on both ships. Bow-out phenomenon appears since the sterns are attracted to each other. In the final Phase ($\xi = 1$), lateral forces change to repulsion and yaw moments have the bow-in effect. It can be observed that the longitudinal force always drags the ship motions.

In this work, the environmental effects on ships are simulated using the CFD method. The results will be compared with the experimental data. The following three effects are emphasized: The confinement effect induced by the channel bank and bottom; Head-on encounter between two inland vessels in the confined waterway; Interaction between the ship and bridge piers during the crossing. The resistance are ship waves are analyzed as functions of the ship speed, draughts, water depth, etc. to characterize the hydrodynamics of these process.

2. Framework of the numerical solver
Reynolds-Averaged Navier-Stokes (RANS) equations are solved for the problem in this work:

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p^* + \nabla \cdot (\mu \nabla \mathbf{u}) + \rho g + \mathbf{f}$$

The VOF (Volume-of-fluid) method is adopted for the free surface. An artificial compression term is added to compress the interface:

$$\frac{\partial \alpha_p}{\partial t} + \nabla \cdot [\alpha_p \mathbf{u}] = 0$$

where $\alpha_p$ is the phase fraction ($0 \leq \alpha_p \leq 1$). $\alpha_p = 0$ and $\alpha_p = 1$ represent air and water. $\mathbf{u}_p$ is the grid velocity $\mathbf{u}_p$ is taking into account for the mesh motion. $\mathbf{u} = \alpha_p \mathbf{u}_a + (1-\alpha_p) \mathbf{u}_a$ is the effective
velocity, \( \mathbf{u}_w = \mathbf{u}_s - \mathbf{u}_a \) represents the relative velocity between the two phases. ‘\( w \)’ and ‘\( a \)’ represent water and air respectively.

3. Results and discussions

3.1. Confinement effect

The computational domain is shown in figure 3. The domain is designed with two ship lengths upstream and three downstream. The outlet boundary is specialized to maintain the water level.

![Figure 3. (a) Computational domain and mesh. (b) and (c) show the refined meshes near the stern and the bow.](image)

![Figure 4. Comparison between experimental and numerical results of the resistance.](image)

![Figure 5. Ship-generated waves of the convoy 2.](image)

![Figure 6. Computational domain.](image)

The resistance results of the convoy are shown in figures 4. The numerical simulations agree with the experimental results. Narrower channel width, smaller water depth and larger ship draught result in higher advancing resistance because of the confinement of the waterway. Return currents appear around the hull and added mass effect induces higher resistance. The ship-generated waves are shown in figures 5. The Kelvin wave patterns can be observed. For the convoy 1, the bow waves of the pusher and the stern waves of the barge superimpose with each other at the connection part. The bow waves of the barge are reflected by the channel wall and superimpose with the downstream waves. With a larger channel width, this reflection happens further downstream. The ship waves of the convoy 2 are more complicated since another barge creates additional waves. Because the vessel is longer, the interfering region of the ship waves is also larger, creating more complex wave patterns.

3.2. Head-on encounter between two ships

The computational domain is designed as the experiments (figure 6). Sliding mesh technique is used to move the ships. Two moving parts are created separately for the convoy 2 and the tanker. Only the average resistance values of the convoy 2 were calculated during the experiments. In figure 9, the simulation values agree well with experiments. The ship waves at the position \( \xi_s = 0 \) are specially shown in figures 8, which are clearly modified by the appearance of another ship. The superposition of these waves creates a very complicated wave pattern in the confined channel. The ship waves of the tanker are disturbed and nearly not observable any more since its velocity is small. The drawdown on the channel banks can also be observed. It is responsible for the erosion of the soil and the failure of the bank structure. Higher velocity, greater draught and smaller confinement area will induce greater
wave elevation changes of the free surface, and also larger drawdown on the banks. Since the velocity of the convoy 2 is higher, the drawdown on its side is greater than that of the tanker.

3.3. Ship passing bridge piers

During inland shipping, vessels will inevitably pass bridges, where the bridge piers exert stronger confinement apart from the channel banks. The ship dynamics and maneuverability change during this process. The increase of the squat may lead to grounding and the asymmetrical moment on the hull may result in collision. In this part, the convoy 2 passing the bridge piers in the confined waterway is tested and simulated. All the tests are done with a channel width 1.44 m. Two pier distances, two draughts and three water depths are tested within the subcritical conditions \( Fr < 1 \). The piers are composed of two concrete blocks of dimensions 40 cm x 16 cm whose edges are cut.

**Figure 7.** Comparison between experimental and numerical results of the resistance.

**Figure 8.** Ship-generated waves with different draughts and widths of the waterway.
Figure 9. Experimental and numerical resistances of the convoy 2.

![Figure 9](image1)

Figure 10. Ship-generated waves with different speeds.

![Figure 10](image2)

Symmetry BC is used to reduce the domain size. Sliding mesh technique is adopted here, whose positions are marked as red lines. The free surface, ship hull and bridge regions are refined to capture the water level and flow fields. Each simulation uses 52 processors and takes about 12 cpu hours to finish. The resistance during the passing process is averaged. Figure 9 shows the resistance comparison between experiments and simulations, which agrees well. With a smaller water depth, the vessel is more confined, leading to a higher resistance, which is also the case for the draught. The wave contours with the influences of the ship speed, water depth and bridge pier distance at two positions \( \xi_0 = 0/1 \) are extracted in figures 10. The wave fields are clearly modified by the presence of the bridge piers. The isolines are clearer with a higher ship speed, denoting that the change of the wave elevation is larger and the waves propagate to a further distance. The wave angles remain nearly the same since the largest Froude number \( (Fr) \) is 0.593 in the subcritical region. A larger speed makes the wave profile higher in front of the ship and lower in the middle. Wave crests can be clearly observed near the bow and stern of each pusher and barge. Near the bridge pier, the wave pattern becomes more complicated. This is caused by the wave reflection by the pier, which further superimpose with the original wave pattern.
4. Conclusions
In this work, the influences of the confinement, ship-ship interaction and ship-structure interaction were simulated and compared with experimental data. For the confinement effect, two convoy models in a fully-confined channel were investigated with three water depths, three channel widths, two draughts and several vessel speeds. A wide range of real conditions were covered by these combinations. The simulations were conducted without sinkage and trim. The advancing resistance agrees well with experiments. Since the convoys consist of the barge and pusher, these wave patterns superimpose with each other and create a very complex waves in the confined channel. The head-on encounter between the convoy 2 and the inland tanker was simulated using the sliding mesh technique under the conditions of two channel widths, two draughts and two vessel speeds. The ship wave analysis shows that larger vessel speed, draught and smaller channel width contribute more to the wave elevation and drawdown on the banks. The ship passing bridge piers was simulated to investigate the influence of the appearance of structures in the confined channel. The case design included one channel width, two bridge pier distances, two draughts, three water depths and several ship speeds. The ship waves near the bridge pier become complicated since the waves are reflected by the wall of the pier and superimpose with the original wave patterns. Overall, the advancing resistance, ship wave pattern, Kelvin angle were emphasized for these studies. The findings provide important clues for the ship motions in the confined waterway and ship interactions.

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