DISCUSSION

CFD-BASED HYDRODYNAMIC ANALYSIS FOR A SHIP SAILING ALONG A BANK IN RESTRICTED WATERS

M G Zhou, **S J Ma** and **Z J Zou**, Shanghai Jiao Tong University, China.
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COMMENT

Professor Katrien Eloot, Flanders Hydraulics Research and Ghent University, Belgium.

The paper is interesting, good structured and deals with an important problem concerning ship behaviour in restricted water. The use of a CFD method as FLUENT (code also used at Ghent University) shows the possibilities of numerical methods for the calculation of ship-bank interaction. The content could still be improved as some topics in the paper miss some depth.

Ship-bank interaction causes due to the forward speed of the vessel rather an important course change effect (ship motion towards the centre or the opposite side of the fairway) instead of a ship-bank collision. An example of a ship-bank interaction and the resultant motion is shown in Figure 21. This course change leads often to a ship-ship interaction or collision if a meeting or overtaking manoeuvre is influenced by ship-bank interaction for one ship.

Figure 21 – Ship-bank interaction for an inbound sailing ship on the Western Scheldt

The ship-bank interaction is referred to as a lateral force directing to the bank and a yawing moment pushing the stern towards the bank. Taking into account the forward motion of the vessels for most manoeuvres influenced by ship-bank interaction, the induced yawing moment is also referred to a bow-away moment as the bow is turning away from the bank (Figure 21).

In the introduction a reference is made to experimental methods and empirical formulas for the ship-bank effect prediction so that, although a benchmark ship model as the KCS container ship is used, the lack of Verification and Validation (V&V) of the executed numerical calculations with experimental results is an important shortcoming. In addition, most ships are operating nearby banks with the propeller working so that the future development of the propeller influence on the total hull-propeller-rudder contribution nearby a bank is of utmost importance. Especially in very shallow water with depth to draft ratios below 1.2 the propeller influences the ship-bank interaction considerably in comparison with a purely hull-rudder combination nearby a bank.

The calculations are only made for medium deep water (according to the PIANC convention) with depth to draft ratios of 2.0 and 1.5 and show an obvious change of the pressure fields and resultant lateral forces and yawing moments for increasing water depth (Statement: "the deeper the water depth, the weaker the bank effect"). It should be interesting to repeat the calculations (with V&V) for shallow (h/T = 1.2) and very shallow water (h/T = 1.1).

According to for example Figure 8 the influence of the rudder angle is important so that a V&V should be advised to validate the rudder lifting effect on the total hull-rudder system. The inflow into the rudder is only caused by the forward ship's speed and thus the wake without propeller action.

The conclusion: "Bank effect for a ship sailing along a bank can be predicted numerically" can be qualitatively correct but there is no V&V or thus comparison with experimental results that prove this conclusion quantatively.

Corrections in the text:

- Pg. 3 first and second paragraph: use of; instead of. This correction must also be made on other places (page 4);
- Pg. 7 last paragraph first column: It can be seen from these figures that the bank effect can also …;
- Pg. 7 last paragraph first column: One conclusion that can be drawn for the current case is that …;
- Pg. 7 last paragraph second column: Comparing Figure 15 … it can be seen that the pressure distribution on the hull is more symmetrical than that … These findings indicate that …;
- Pg. 8 first column: It can be seen that a more symmetrical … The explanation for these phenomena is similar to that when the rudder angle is …;
- Pg. 8 second column, second paragraph: … that the sway force and yaw moment at deeper water are smaller …;
- Pg. 9 last sentence: The numerical study is carried out …;
- Pg. 10 first column, third paragraph: … the hydrodynamic force and moment become larger with the increase …; and
- Pg. 10 first column, last paragraph: … Future study will focus on the influence …

Dr. Andreas Gronarz, DST, Germany

It is a good study with a lot of variations of the three variables bank distance, water depth and rudder angle. Such variations are possible since the CFD-codes run faster with higher computational power available.

The bank effect is affected by two more variables: the ship speed (the bank effect is increasing with something like the square of the speed) and the drift angle. The variation of these influences has not been taken into account.

Only two water depths have been investigated. This is not enough to draw conclusions about an influence of the water depth to the behaviour of the ship. Better would be 5 cases: deep water and 4 values for shallow water (down to h/T 1.2 or less).

The simulations do not include the propeller. No ship will sail along a wall without running propeller in reality. Due to the fact that the propeller slipstream acts on the rudder, the effect of the wall distance to the rudder forces will be much smaller than the steering force of the ruder behind a rotating propeller. Additionally the propeller suction will increase the yaw moment when moving close to the wall. This will result in a dangerous attraction of the stern with the risk of a collision.

The numerical investigation has been carried out without free surface. The channel effect results in an additional sinkage of the ship which can lead to grounding at a much smaller speed than on unrestricted water.

Taking the drift angle into account a more realistic simulation may be performed. In most cases an equilibrium condition can be found by the attraction of the wall (sway force) being compensated by the drift angle and the yaw momentum being compensated by the rudder angle. By finding the equilibriums for different speeds, water depths and wall distances the limit of safe navigation can be detected using a maximum allowable rudder angle of about 20°.

Dr. Da-Qing Li, SSPA, Sweden AB

The authors are to be congratulated for another interesting paper on the application of a CFD tool to study the interaction between hull, rudder and banks.

The particular CFD tool solves a set of Reynolds-Averaged Navier-Stokes (RANS) equations together with a standard k-ε turbulence model to determine the viscous flow around the hull, rudder and banks. The paper presents computational results of the integrated forces and moments. More importantly, it presents the flow field data like velocity and pressure distributions that are very useful information for understanding the inherent hydrodynamic interaction effects.

One of the interesting plots is the iso-curves of Y=0 and N=0 presented in Figure 12, where these curves indicate the critical state that the bank effect is counteracted by the rudder effect. The authors divide the plot area in three different zones (A, B and C) and discuss the direction of interaction force and moment in respective zones. It would be desirable that the authors give some more discussions or comments on what a proper manoeuvring action a ship operator should take under these situations, as this aspect is of most concern from a practical point of view.

In most of the cases, a rudder is located behind the propeller, meaning that the rudder is working in the propeller slipstream. Could the authors give some explanation why the propeller effect is not included in the present study and what will be the likely consequence if ignoring the propeller effect?

In the text on page 3 about boundary condition for the bank and bottom, it reads "no-slip moving wall condition is imposed on them". However, the sketch in Figure 2 shows that the boundary condition for Bottom is "symmetry". I suppose this was written by mistaken, isn't it?

Professor D.C. Lo, National Kaohsiung Marine University, Taiwan

A well presented by the title, there are two main aspects in this paper which are described:

- The use of the Reynolds-averaged Navier-Stokes (RANS) equations
- The use of the rudder as a control force and moment for a ship sailing along a bank in restricted waters.

First a few comments on the hydrodynamic analysis: From a physical point of view, I think that the suitability for operating the rudder of a ship when navigating along a bank to ensure the safe passage in restricted waterway. While operating a rudder angle is large enough, the sway force may point away from the bank and yaw moment may push the stern off the bank. At the condition, a suction effect is decreased toward the stern of the ship, while a cushioning effect is decreased at the bow. The authors present a series of simulations using CFD software and a KCS container ship model to examine the effects of the hull-rudder system sailing with different rudder angles at different ship-bank distances. For a constant value of the ship-bank distance, the sensitivity of the sway force and moment increase with an increasing rudder angle turning away from the bank. In general, an decreasing value of the sway force and moment or even change to the opposite direction with the increase of rudder angle turning to the bank, whilst an increasing value of counteract force through the rudder effect to reduce the bank effect. At a certain ship-bank distance, the sway force and moment increase with a reducing distance to bank. The results obtained are agreement with Lo et al. (2007) [11]. Irrespective of the distance of a ship from the bank, the bank effect increase significantly in shallow water, while the rudder effect is stronger in deep water.

It would have been better if the authors had given clear way to describe the analysis of stern vortex flow. The evolution of the flow field at the stern of the ship at various conditions may be analysis in the study. The authors can describe the vortex structure on the port side of the stern, which drives the stern toward or away from the bank, resulting in a yaw motion of the bow for various cases.

Professor Bjørnar Pettersen, NTNU, Trondheim, Norway

First I must congratulate the authors with a nice piece of work. Very systematic investigation and a very clear presentation of the results.

In order to understand more about the physics, I am sure the authors have available details about the flow (velocities) in the vicinity of the hull, bank and sea bottom. This may open for further studies and understanding how hull geometries, i.e. different ship types or loading conditions, may be influenced by the restrictions, and how rudder forces may play a role as a controlling device.

What are the most severe factor of influence, shallower water (h/T<1.5), or closer distance to the bank (yt/B<1.0)?

The constant speed forward is 8 knots in full scale. Are there any justification of not taking surface wave generation into account, especially in the gap between ship and bank? Are there any indications that the chosen free surface boundary condition may play a role?

The big question is also how the propeller stream influences the results? And dependent on the forward speed, can the propeller help increasing the rudder force to avoid critical situations? The propeller action may influence the overall flow and pressure distribution around the hull itself and the vertical bank, and may also depend on under keel clearance and sideway gap.

I look forward to further results from this study.

Professor Hironori Yasukawa, Hiroshima University, Japan

The authors showed CFD results of hydrodynamic forces acting on a ship with constant rudder angle moving along a bank in shallow water. On the other hand, discusser's group carried out captive model tests to capture the hydrodynamic force characteristics of a container ship moving in a channel with changing various parameters such as water depth, rudder angle, off-center lateral distance, hull drift angle, ship speed etc. (Sano et al., 2012 [20]). Here, the measured results of lateral force Y and yaw moment N acting on the ship with constant rudder angle straightly moving in a channel are shown in Figure 22. Y and N are non-dimensionalized by (1/2) ρLdU^2 and (1/2) ρL^2dU^2 respectively where ρ denotes the water density, L the ship length, d the draft, and U the ship speed. The tests were carried out in propelled condition of F_n=0.084 where F_n is

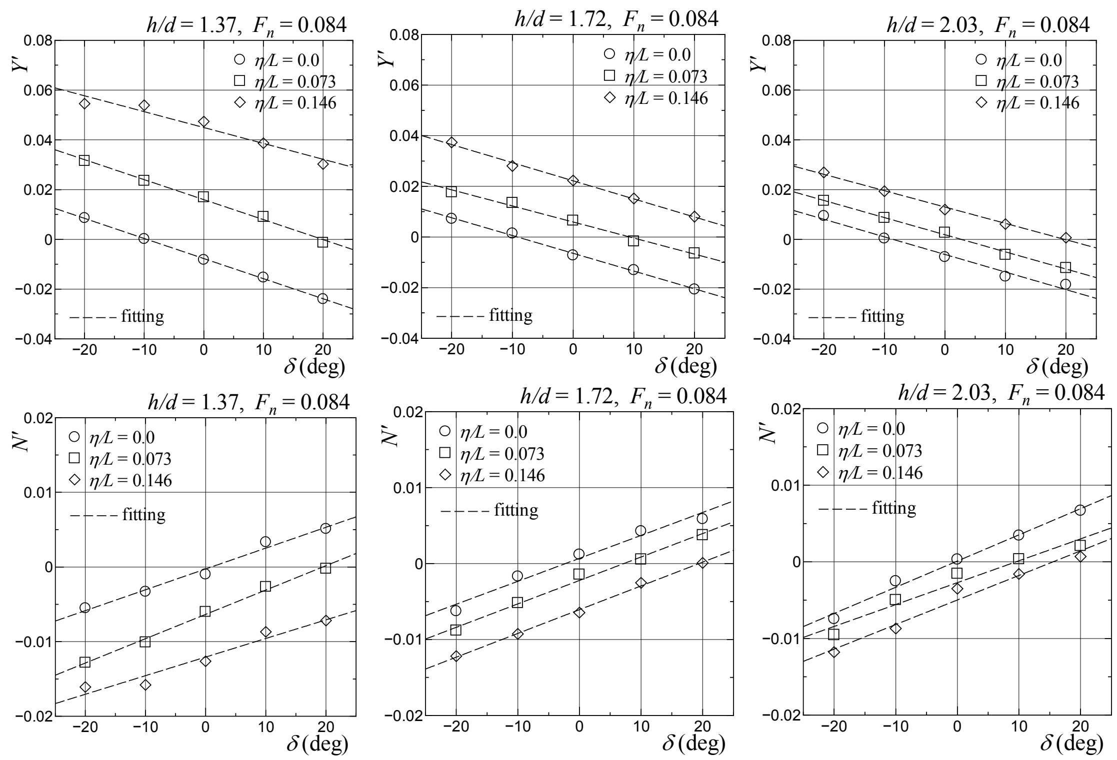


Figure 22: Measured results of lateral force (Y) and yaw moment (N) acting on the ship model with constant rudder angle (δ) straightly moving in a channel. The h/d means water depth to ship draft ratio. The η /L denotes the off-center lateral distance ratio to ship length, η/L=0 means that the ship moves just on the centerline of the symmetrical channel.

Froude number based on *L*. The present experimental results qualitatively agree well with the CFD results by the authors. This means that the CFD computation is basically valid. However, it looks like that the CFD results are too small in a quantitative point of view. This is probably due to not accounting the propeller effect in the CFD model. The propeller effect cannot be neglected in general when discussing the effective rudder forces of the ship moving in the proximity of the bank. How do you think about that?

AUTHOR'S RESPONSE

The authors would like to express their sincere thanks to the discussers for their constructive comments and questions concerning our paper.

We would like to give the following responses to **Professor Katrien Eloot**:

(1) Much information about CFD calculation is included in Section 2. The validation of the numerical method, including the rudder lifting effect, is implemented by comparison with experimental data and presented in another paper by the authors, "Numerical Study on Hydrodynamic Interaction among Hull, Rudder and Bank" which is submitted to the Journal of Hydrodynamics in 2012 and is accepted for publication with minor revision. Verification and validation (V&V) will be one of major efforts of our future research.

(2) The hydrodynamic interactions among hull, propeller and rudder in restricted waters can be rather complicated. The propeller out-stream will increase the longitudinal flow velocity around the rudder, which will result in a larger rudder force. In addition, the propeller suction may also influence the flow between the hull and the bank (or bottom), which will influence the hydrodynamics of the hull as well. The influence of propeller will be studied in our future research.

(3) It is true that, according to the PIANC convention, our calculations are only carried out for medium deep water with water depth to draft ratio of 2.0 and 1.5. However, from the point of view of ship manoeuvring, when the water depth to draft ratio is smaller than 3.0, the influence of the restricted water depth has to be taken into account. When $h/T<1.2$, it is very shallow water. In Li et al. [21], the following conclusion is drawn: For the tanker, results indicated that there is a critical water depth to draft ratio of approximately 1.10, where the sway force changes from a suction force to a repulsion force. Hence in very shallow water, the bank effect and rudder effect may be very different from those when h/T =1.5 or 2.0. More simulations in various water depths with V&V will be implemented in the future.

(4) We agree most of the correction suggestions except the first one.

Regarding the comments given by **Dr. Andreas Gronarz**, we would like to respond as follows:

(1) Ship speed, drift angle and water depth are indeed important factors influencing bank effect. The drift angle will induce a sway force which helps to compensate the attraction force between the ship and wall. The focus of our paper is put on the influences of ship-bank distance and rudder angle, and only two shallow water depths are selected as an example study. The influences of ship speed, drift angle and more water depth will be dealt with in the future study.

(2) As for the influence of propeller action, please see the response (2) to Professor Katrien Eloot.

(3) In the paper, only the low ship speed case of U=0.6135m/s is selected for the numerical simulation. In this case, the Froude depth number Frh is 0.3265 when h/T=1.5 and 0.2827 when h/T=2.0. The corresponding ship squat calculated from Huuska's formula (1976) [22] is 0.27m and 0.19m for full-scale ship, which is 2.5% and 1.8% of the ship draft, respectively. Hence, we assumed that the influence of ship sinkage can be neglected.

Regarding the comments given by **Dr. Da-Qing Li**, we would like to respond as follows:

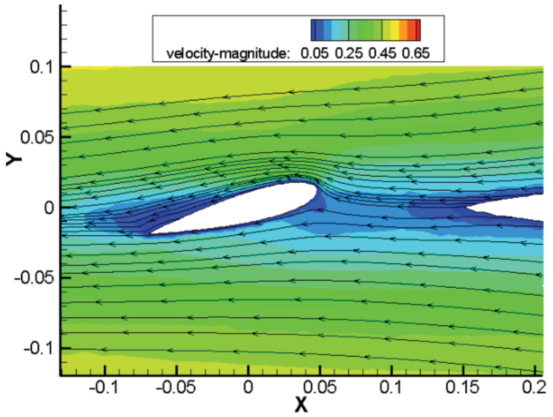
(1) The next step of our study is to carry out simulations for a ship sailing along a bank with drift angle being taken into consideration. Similar curves like Y=0 and N=0 which are presented in Figure 12 will be obtained. Then safety analysis will be performed and some more discussions or comments on what a proper manoeuvring action a ship operator should take under these situations will be given.

(2) As for the influence of propeller action, please see the response (2) to Professor Katrien Eloot.

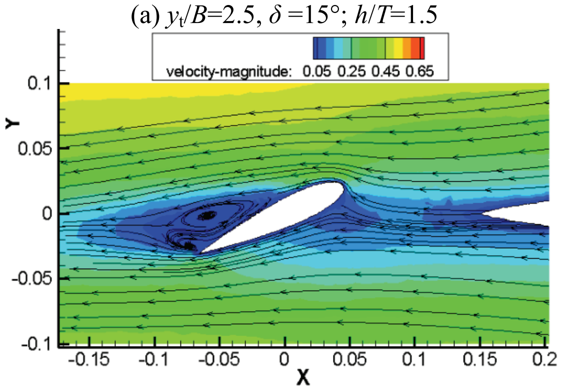
(3) Thanks for pointing out this mistake. For the water bottom, no-slip moving wall condition is imposed on it. So the boundary condition for water bottom should be "moving wall" rather than "symmetry". This correction has been made.

Regarding the comments made by **Professor D.C. Lo**, we would like to respond as follows:

It is a good suggestion to analyze the stern vortex flow at various conditions. Figure 23 shows two examples about the flow pattern behind the stern. In Figure 23(b), there is a vortex flow on the port side of the rudder, while no obvious flow separation can be observed near the rudder in Figure 23(a). The reason may be that when the rudder angle is smaller and ship-bank distance is larger, the vortex flow is not significant and higher grid resolution may be needed. The vortex flow in Figure 23(b) indicates a sway force to push the stern away from the bank and a yaw moment which may drive the bow towards the bank.



(a) y_t/B=2.5, δ =15°; h/T=1.5



(b) y_t/B=2.0, δ =25°; h/T=1.5

Figure 23 Stern flow pattern under two different conditions

Regarding the comments given by **Professor Bjørnar Pettersen**, we would like to respond as follows:

(1) Our CFD-based method has the advantage in providing detailed information of the flow field. The variables, such as pressure, velocity, vorticity, turbulent viscosity on different target surfaces, can be exported and displayed. It is true that the analyses about physics are not enough in the paper, and more effort is needed to reveal the physical mechanism behind the bank effect and rudder effect. This will be one part of our future study.

(2) In our study, only one ship speed and two water depths are selected. According to the previous study on bank effect (Li, et al. [21]), when the water depth is very shallow (h/T is approximately 1.10 for the tanker), the sway force is repulsive force. This case of very shallow water condition is not included in our study. Based on our simulation results, the distance to the bank is the most severe factor of influence compared with the water depth. This can be proved as follows: According to Figure 10 and Figure 11, the sway force or yaw moment increase sharply when the ship-bank distance is less than 1.5; From Figure 17 to Figure 19, it can be seen that the sway forces or yaw moments at different water depths are close to each other except when the ship-bank distance is very small.

(3) Under the assumption of low ship speed, we neglected the influence of surface wave generation in the study. But in fact, in restricted water, even if the ship speed is small, the free surface elevation may have significant influences on the ship hydrodynamic behaviors. Taking the effect of free surface elevation into account will be one of the focuses of our further study.

(4) As for the influence of propeller action, please see the response (2) to Professor Katrien Eloot.

Regarding the comments given by **Professor Hironori Yasukawa**, we would like to respond as follows:

Yes, we agree with the discusser's comment that not taking the propeller effect into account in the CFD calculation is one main reason that leads to the underestimation of the control effect of rudder. As explained in the response (2) to Professor Katrien Eloot, the propeller out-stream will increase the longitudinal flow velocity around the rudder, and this can result in a larger rudder force. On the other hand, it should be pointed out that both the ship and the waterway in our study are different from those in the study by the discusser's group; hence a quantitative comparison may be not applicable.

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