Evaluation of Flow Fields for their Impact on Manoeuvring

by

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ABSTRACT

When working on the design of a new port layout or other coastal infrastructure, PIANC’s publication “Approach Channels – A Guide for Design” (PIANC-IAP H (1997)) is a valuable tool for dimensioning a navigation channel. However, these guidelines do not apply for situations with a flow gradient. In coastal situations, with a tidal flow running along the coast and across the access channel to a port, a flow gradient near the port entrance is quite common. For this critical part of the channel, the guidelines do not provide an answer. For this reason, the determination of the required width requires manoeuvring simulations, using computed flow fields for the layout and possible alternatives under study. Very often, such flow fields will be available as these are also required for the study of coastal and environmental impacts.

In hydraulic advisory, the navigability is only one of the parameters playing a role in the design. Especially, when developing and evaluating layout alternatives or when considering construction phases, the project needs a quick expert opinion on the flow gradient as produced by the flow model. In these situations, setting up and performing manoeuvring simulations (even fast-time manoeuvring simulations) is often conceived as too elaborate and time consuming. However, in order to make his judgement, the expert has to relate the flow pattern to the characteristics of the ships. For such situations it was felt that an evaluation tool was needed to support the requested expert opinion, making use of the flow model results.

A situation of a ship trying to maintain a straight track while sailing through a flow gradient is in essence governed by the balance between the rotation in the flow field and the turning ability of the ship. The evaluation tool as developed matches these two elements. The rotation of the flow along the sailing line (the channel centre line) is extracted from the flow model in post-processing. The turning ability of the ship is, in a linearized form, described by the first order yaw equation of Nomoto (1956). In this equation the ship’s turning abilities are described by two basic manoeuvring coefficients, $K$ and $T$. Combining the two elements (flow and ship characteristics), the tool calculates the rudder angle as required in order for the ship to stay on the sailing line. This rudder angle is the indicator for the difficulty of the manoeuvre.

The predictions from the tool were compared with the results of fast-time simulations for the situation of a large ship approaching the Port of Rotterdam at the peak of the flood flow (see: Figure 1 to Figure 3). This comparison showed that the agreement was quite good, which confirmed that the tool is indeed capable of assessing whether a flow gradient could pose a problem for the manoeuvre.

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As was the intention, the computational effort involved is very limited. The tool runs as post-processing on the computed flow fields, making it possible to quickly analyse the difficulties for navigation in different layouts and also the navigability over the complete tidal cycle.

1. INTRODUCTION

In the preliminary design of ports or other coastal infrastructure often an optimisation of the layout is required to reach a layout that balances different requirements and limitations, such as sheltering to waves, navigation, coastal impact, sedimentation, and construction costs. Generally, flow conditions in the port and its approaches are often at first evaluated by applying PIANC’s publication “Approach Channels – A Guide for Design” (PIANC-IAPH (1997)). These guidelines include a contribution for a cross flow, but they do not provide an answer for situations with a gradient in the flow. In coastal situations, with a tidal flow running along the coast and across the access channel to a port, a flow gradient near the port entrance is very common. See for instance a picture of the entrance to the Port of Rotterdam in Figure 4. The picture shows the flood tide running to the north (left-side of the picture) with the salt sea water clearly separated from the fresh water discharge from the river.

![Figure 4: Flow gradient near the entrance to the Port of Rotterdam (Foto Service Nederland)](image)

For this critical part of the channel where a flow gradient occurs, the above-mentioned guidelines do not provide an answer. Therefore, the determination of the required channel width requires manoeuvring simulations, which in turn use computed flow fields for the possible layout alternatives. Very often, such flow fields will be available as these are also required for the study of coastal and environmental impacts.

In the practice of hydraulic advice work, the navigability is only one of the parameters playing a role in the design of a new port layout or other coastal infrastructure. Especially when developing and evaluating layout alternatives or when considering construction phases, the project needs a quick expert opinion on the flow gradient as produced by the flow model. For such a situation, setting up and performing manoeuvring simulations (even fast-time manoeuvring simulations) is often conceived as too elaborate and time consuming. However, in order to make his judgement, the expert has to relate the flow pattern to the characteristics of the ships. In these situations, it was felt that an evaluation tool was needed to support the requested expert opinion, making use of the flow model results.

The development of the evaluation tool was the topic of the MSc. thesis work of the first author for her graduation from Delft University of Technology (Kaarsemaker (2008)). This paper will present the essence of the tool and the comparison of its results with the results from fast-time simulations.
2. BASIC APPROACH

2.1 The behaviour of a ship in a flow field

Before starting the development of the above-mentioned evaluation tool, we introduce two basic concepts relevant to the description of a ship moving through a flow field.

**Principle of relative motion**

The first concept is the principle of relative motion. The forces on a ship moving through the water are generally described for a situation of still water, not affected by flow due to a tide or a river discharge. When a ship is sailing through a flow field, the effect of this flow is not described by introducing additional forces in the equations of motion, but by applying the principle of relative motion: for the hydrodynamic forces, the motion of the ship has to be described relative to the water. For instance: the hydrodynamic forces on a captive ship (not moving relative to the ground) in a longitudinal current, a cross current and a flow gradient are identical to those in still water with the ship having an equivalent (though opposite) longitudinal velocity, a transverse velocity and a rotation (see Figure 5).

![Figure 5: The principle of relative motion](image)

captive ship in a longitudinal current, a cross current and a flow gradient

ship in still water, with a longitudinal motion, a transverse motion and a yaw motion

This principle of relative motion only applies to the hydrodynamic forces. For the inertial forces, the motions have to be described in absolute terms: relative to the ground, not relative to the water.

**A ship in a flow gradient**

The second concept, elaborating on the first, is the motion of a ship through a flow gradient. For the development of the tool we first assume the simple situation of a ship approaching a port on a straight track with a constant speed and with constant engine power. In the outer part of this approach track there is a cross current, related to the tide, which reduces as the ship approaches and enters the port.

- A ship sailing over a straight track in a constant cross flow will compensate the cross flow by taking a heading not parallel to the track, but somewhat into the current. The difference between the heading and the orientation of the track is referred to as the ‘set to current’. The combined motion, the motion of the ship through the water and the motion of the water relative to the ground, keeps the ship on the track. In a constant cross flow and with a constant speed, the rudder angle will be zero. This situation is shown in the left panel of Figure 6.

- When the same ship experiences a flow gradient (change in cross flow), the ship will have to turn in order to stay on the straight track: the rotation in the flow field forces the ship to make a counter-rotation relative to the track, a yaw velocity or rate of turn, changing its heading along the straight track. This is shown in the right panel of Figure 6. This rate of turn requires a certain rudder angle.

- The transition between these two situations is a variation in the cross flow gradient, or a variation of the rotation of the flow. This requires the ship to change its rate of turn, a yaw acceleration. This also requires a rudder angle.

![Figure 6: Ship in a constant cross flow (left) and a varying cross flow (right)](image)
The ability of the ship to maintain the straight track while sailing through a flow gradient will be determined by the rudder angles required: it is a balance between the rotation in the flow field and the turning ability of the ship.

2.2 Essence of the tool

Nomoto’s linear yaw equation

The turning behaviour of a ship is effectively described, in first order accuracy, by the linear yaw equation of Nomoto (1956):

\[ T\dot{r} + r = K\delta \]  

(1)

In which \( \delta \) is the rudder angle, \( r \) is the yaw velocity or rate of turn, \( \dot{r} \) is the yaw acceleration, and \( K \) and \( T \) are the basic manoeuvring coefficients as introduced by Nomoto.

The ship’s turning abilities are described by these two basic manoeuvring coefficients, \( K \) (a measure for the turning capacity) and \( T \) (a measure for the time). Both manoeuvring coefficients depend on certain characteristics of the ship, and can, for instance, be determined from the results of standard manoeuvring trials.

For a better understanding of \( K \) and \( T \) and for the quantification of them, we consider another well known description of the manoeuvring behaviour, which is the model by Abkowitz (1964). In linearized form, Abkowitz’s yaw equation reads:

\[ vN_v + r \cdot (N_r - mx_Gu_0) + \dot{v} \cdot (N_v - mx_G) + \dot{r} \cdot (N_r - I_{zz}) = -\delta N_\delta \]  

(2)

In which:

\( u_0 \) = velocity of the ship in the x-direction;
\( v \) = velocity of the ship in the y-direction;
\( r \) = yaw velocity;
\( \dot{v} \) = acceleration of the ship in the y-direction;
\( \dot{r} \) = yaw acceleration;
\( x_G \) = location of the centre of gravity on the x-axis;
\( m \) = mass of the ship;
\( I_{zz} \) = moment of inertia of the ship;
\( N_v, N_r, \text{etc.} \) = manoeuvring coefficients, describing the turning moment (\( N \)) as proportional to \( v \) or \( r \) etc.

For a ship with its centre of gravity at half length (\( x_G = 0 \)) and with no transverse speed or acceleration through the water (\( v = \dot{v} = 0 \)), this equation can be reduced to:

\[ \dot{r}(I_{zz} - N_r) - rN_r = \delta N_\delta \]

This equation states that (right-hand side) the turning moment due to a rudder angle, is balanced by the combined effect of a turning moment related to the yaw acceleration and a turning moment related to the yaw velocity. It is now simple to rewrite this equation in the form of Nomoto’s linear yaw equation, yielding the following expressions for \( K \) and \( T \):

\[ K = -\frac{N_\delta}{N_r} \]  

(3)

\[ T = -\frac{I_{zz} - N_r}{N_r} \]  

(4)

These expressions were used to determine \( K \) and \( T \) for a ship for which the manoeuvring coefficients of the Abkowitz model were available.
Nomoto’s linear yaw equation and the flow gradient

In (1) the values for \( r \) and \( \dot{r} \) are the yaw motions made by the ship. These motions are the ship’s response to the spatial varying gradient in the flow across the track, such that the ship stays on this track. These parameters are determined from the flow fields in post-processing, in two steps.

First, the rotation in the flow is determined as a function of the distance along the track (\( x \)). While doing so, the flow parameters are averaged over the ship’s length (\( L_s \)), see also De Vries (1981). This is done to reflect the fact that the ship is not sensitive to very local effects, but will experience an ‘average’ over its entire length.

\[
\int_{-L_s}^{L_s} v_s(x) dx = \int_{-L_s}^{L_s} \frac{12}{L_s^2} \int_{-L_s}^{L_s} v_s(x) dx dx
\]

In this expression, \( v_s(x) \) is the flow velocity transverse to the track, and \( r_s \) is the representative rotation in the flow or flow gradient.

Note that in this evaluation the representative flow rotation is determined along the track, and not along the axis of the ship. It is expected that for practical cases, with a limited difference between heading and track, any difference in the flow rotation will be small.

In a second step, taking into account the speed of the ship, these flow parameters along the track are converted to a yaw velocity and a yaw acceleration of the ship along the track.

With this information of the ship and the required yaw motions, the rudder angle as required to stay on the straight track follows from Nomoto’s linear yaw equation. This rudder angle is the indicator of the difficulty as experienced by the ship, and is a measure of the feasibility or nautical safety of the manoeuvre.

The application of the linear yaw equation of Nomoto in this way assumes that the ship is steered perfectly and that the ship, through its rudder, is able to perform the required changes of heading and, as a result of this, will keep to its track. It is also assumed that the ship has straight line stability, which implies that the required rudder angles along the track will be determined only by the changes in the flow conditions around the ship, and will not be affected by rudder angles required to keep a straight course in a uniform environment. Any influences on the manoeuvre other than flow, such as the effects of wind and waves and effects of varying speed are not considered in the approach.

2.3 Development of the tool and interpretation of results

In order to check the performance of the tool, a comparison is made of the rudder angles as follow from the tool with rudder angles as follow from the fast-time manoeuvring simulation program SHIPMA (WL|Delft Hydraulics & MARIN (2002)). In SHIPMA the ship is steered by an automatic pilot, steering the ship along a user-defined track, using user-defined engine settings or adjusting the engine to obtain a user-defined speed. The automatic pilot calculates the required rudder angle based on deviations in position and orientation between the ship and the track. Using an automatic pilot the rudder angles are an output of the simulation, not an input by the user. This makes SHIPMA a good benchmark for the tool.

It is important that the rudder angles following from the tool are realistic values, and are close to those resulting from manoeuvring simulations, as this allows the interpretation of these rudder angles in much the same way. This leads to the following criteria:

- In general, for ships sailing at a power not larger than ‘half ahead’, the maximum allowable rudder angle used is set at 20°.
- For shorter stretches, a ship can use a larger amount of engine power, thereby increasing the effectiveness of the rudder. This cannot be described by our tool. As the tool assumes a constant speed, constant engine power, and is based on a linear equation, the tool can produce rudder angles, much larger than realistic, in places with large cross flow gradients. Rudder angles between 20° and 60° are interpreted as a situation where a ship would use a power burst to maintain heading.
Beyond this, it is assumed that the ship will not be able to stay on the straight track and the manoeuvre is considered to be unfeasible.

In reality and also in SHIPMA, rudder angles are generally limited to 35°. In order to be able to compare the results of the evaluation tool with those from SHIPMA, this maximum rudder angle as implemented in SHIPMA is deactivated, so that also SHIPMA would deliver larger rudder angles when the flow condition asks for such larger rudder angles.

3. FIRST APPLICATION OF THE TOOL: ANALYTICAL FLOW FIELDS

A first comparison between the results of the evaluation tool and the output of a fast-time simulation model is made by applying the tool to analytical flow fields. The definition of these flow fields is presented in Figure 7 below.

The flow field is described by an initial (sea ward) cross flow with a velocity of 1 m/s and a gradient towards a cross flow of 0 m/s over a certain length ($L_g$).

The ship under consideration is a Panamax sized bulk carrier with main dimensions length x beam x draught = 225 x 32.2 x 12.0 m. The ship sails along the track with a speed of 6 m/s, approximately 12 knots. Figure 8 shows the results of the calculations for two values for the length of the flow gradient: $L_g = 1.5 \cdot L_s$ (top panels) and $L_g = 1.0 \cdot L_s$ (bottom panels).

![Figure 7: Schematic presentation of analytical flow field](image)

![Figure 8: Comparison results fast-time simulation model versus evaluation tool](image)
From this comparison, it is clear that the evaluation tool basically works well. It can provide values of the required rudder angles along the track that are similar to those calculated with a fast-time simulation model. Furthermore, the shape of the curve for the longer flow gradient shows three typical phases of the manoeuvre: in the (short) central phase a constant rudder angle is required for the constant rate of turn of the ship as the cross flow reduces, and the heading of the ship becomes more parallel to the track. At the beginning of the gradient a larger rudder angle is needed to initiate this turn, and at the end an opposite rudder angle is needed to reduce the rate of turn to zero.

The calculation was repeated for different lengths of the flow gradient. It appeared that the differences between the peak values of the rudder angles become larger when the flow gradient has a smaller length, and the rudder angles are larger. This is illustrated in Figure 9.

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There are two possible reasons for this deviation. One is that the tool uses Nomoto’s linear yaw equation, which will only be applicable when the variations in the values of relevant parameters are limited. For short gradients (with the same initial cross flow velocity) this no longer applies. A second reason is that the tool computes required rudder angles directly from the flow and ship characteristics, whereas the fast-time simulation model uses an anticipating auto-pilot and solves the rudder angle in a full simulation. This anticipation distance, generally set at a value of 1.25\cdot L_s, tends to reduce the peak values of the rudder angle, by giving rudder earlier in the manoeuvre, anticipating on changes to the flow condition (or in the case of a curved track, to changes in the required course over the ground). By giving rudder earlier, the rudder works over a longer period of time, thereby generating the same cumulative effect with a lower maximum rudder angle.

In order to improve the match between the results of the tool and those from fast-time simulations, the tool should deliver lower rudder angles for shorter (steeper) flow gradients. One way to achieve this is to reduce the peak-values of such steep gradients by increasing the length over which the flow gradient is averaged. As indicated in Section 2.2, the flow gradients are determined by an average over the ship's length, but this distance could be made longer or shorter. The factor by which this length is increased or decreased, relative to the ship’s length, is called the integration factor (\(q\)).

A large series of computations was done to investigate the effect of different values of \(q\) for different values of the cross flow velocity (relative to the ship's speed) and cross flow gradients, but this did not yet lead to a clear conclusion. In the second series of application of the tool to realistic flow fields, the results for different values of \(q\) were considered.

4. APPLICATION OF THE TOOL TO REALISTIC FLOW FIELDS

After the promising results for the analytical flow fields, the evaluation tool is applied to realistic flow fields as they occur at the entrance to the Port of Rotterdam, see Figure 10 (see also Bijlsma e.a. 2004). The situation examined represents the situation before the start of the construction of the new expansion called Maasvlakte 2. For this situation detailed 3D flow computations were made available by the Port of Rotterdam from the Maasvlakte 2 project, focussing on the ‘design’ spring tide of 23 August 2001. From these computations flow fields were available each 15 minutes.
Two phases of the tide were examined: High Water (05:30), at which time the maximum cross flow occurs, and 01:15 hours after High Water (06:45), when a small eddy is developing inside the entrance to the port. The 2D flow patterns are shown in Figure 11 below.

**Preparation of 2D flow fields from 3D results**

As stated above, the flow computations were made in 3D in order to be able to describe the density effects and flow stratification as a result of the fresh water discharges from the rivers Meuse and Rhine on the flow conditions at the port entrance. Both the evaluation tool and SHIPMA require the determination of an equivalent 2D flow field, valid for the draught of the specific ship. As the hydrodynamic forces on the hull are proportional to the square of the velocity, this processing from 3D to 2D is done through the computation of a root mean square value of the two orthogonal components of the velocity, resulting in an equivalent velocity with the correct direction.

**Impact of flow velocity component parallel to the track**

The flow patterns show that, especially at High Water, there is a significant component of the flow velocity in the direction of the track. This makes it necessary to take into account the difference between the velocity of the ship along the track, as defined for the manoeuvre, and the speed through the water. As we want to limit ourselves to Nomoto’s equation and we do not want to introduce an equation for a varying speed, we have to assume a constant speed over the ground and assume that any change in flow velocity parallel to the track leads to a different speed through the water. For equilibrium this requires a change of the propeller speed. Both changes, the speed through the water and the propeller speed, have an effect on the manoeuvring characteristics. This means that the manoeuvring characteristics have to be computed during the computation, based on the speed through the water and the corresponding propeller speed. This has been implemented in the evaluation tool.
Evaluation and choice of ‘q’

The approach manoeuvre is examined for a large tanker, which has been one of the design ships for the Maasvlakte 2 development. Its main dimensions are length x beam x draught = 378.0 x 62.0 x 22.0 m. For this evaluation a constant speed of approach of 5 m/s, approximately 10 knots, was selected.

Having prepared the 2D flow fields, the velocity of the cross flow and the rotational flow along the track were determined. Then the rudder angles were calculated with the fast-time simulation model (based on the 2D flow fields) and with the evaluation tool. Computations with the tool were made for four different values of ‘q’, the integration factor. The flow parameters and the rudder angles are presented in Figure 12 below.

Figure 12 shows how closely the computed rudder angles (bottom panels), both for SHIPMA and the evaluation tool, follow the general trend of the rotational velocities along the track (blue line in the top panels).

Furthermore the results show that using an integration factor of $q = 1.25$ leads to the best match between the results of the evaluation tool and the rudder angles as computed by the fast-time simulation model.

Calculations with the evaluation tool using integration factors smaller than 1.0 produce larger, but unrealistic, peaks in the required rudder angles. This is illustrated in the left panel of Figure 13.

However, in areas with lower flow rotation and hence smaller rudder angles, using an integration factor of $q = 1.25$ may lead to under-prediction of the rudder angles. Considering that in an evaluation the smaller lower rudder angles are generally less important than the larger rudder angles, this is concluded to be acceptable.
5. APPLICATION OF THE TOOL TO THE FUTURE LAYOUT OF ROTTERDAM

Having established a basic confidence in the value of the evaluation tool and the best value for the integration factor \( q = 1.25 \), the tool is now applied to two future layouts of the Port of Rotterdam, including the new Maasvlakte 2 expansion (see Figure 14). Two layouts will be considered, which have been examined during the design process for the Maasvlakte: the final layout and one option for a construction phase which has been rejected. It will be demonstrated whether or not the tool would have come to a similar judgement of these layouts, thereby illustrating how the evaluation tool could contribute to a quick expert opinion on the suitability of the flow fields for manoeuvring.

For these layouts the results of 3D flow computations were made available by the Port of Rotterdam. From these data, 2D flow fields were prepared as described in Chapter 4.

From the point of view of nautical safety, as defined for the evaluation tool, the required rudder angles during the approach manoeuvre to the final layout of Maasvlakte 2 should not be larger than 20°. The construction phase of Maasvlakte 2 considered in this paragraph is a configuration which was rejected because of the impact on navigation. From the point of view of nautical safety this means that rudder angles larger than 20° or even larger than 60° should be expected.

Results are presented in Figure 15 for the flow conditions at half an hour before High Water. At this phase of the tide the largest rudder angles occurred for both layouts. (Note that this selection was done using the evaluation tool, illustrating the value of the tool in the process of selecting a critical tidal phase.) The ship is the same large tanker as used in Chapter 4, approaching at a speed of 5 m/s (10 knots).
In the final layout the flow pattern is generally smooth and the computed rudder angles are moderate: both the result of the evaluation tool and the fast-time simulation model give rudder angles much smaller than 20° along the track (these limits are indicated by the thick black lines in the graph), so the evaluation tool gives the same indication for the nautical safety as the fast-time simulation model.

In the rejected construction phase, a significant eddy develops over the approach channel. This leads to large flow gradients and very large rudder angles: both the evaluation tool and the fast-time simulation model give rudder angles larger than 60° at 11500 m, and larger than 20° along 2 km of the approach track.

The plot also shows that for both cases the evaluation tool over-estimates the rudder angles when compared to the fast-time simulation, leading to a conservative judgement of the nautical safety. Nevertheless, from the comparison it can be concluded that the evaluation tool gives the same indication for the nautical safety as the fast-time simulation model.

Based on this, it can be concluded that the evaluation tool gives a good indication whether or not the flow patterns could cause a problem for safe navigation.
6. CONCLUSIONS

An evaluation tool has been developed for the evaluation how gradients in the cross-flow over an entrance channel can pose a threat to safe navigation. The tool feeds parameters from the flow field and a few essential characteristics of the ship into the linear yaw equation of Nomoto, producing the rudder angles as required to follow a straight track at a constant speed and with constant engine power. It has been shown that the results as produced by the model are comparable to those computed by fast-time simulations, although on the conservative side.

Notwithstanding this good agreement, the evaluation is limited to a straight track, a constant speed of the ship, and constant engine power and covers only the effect of the flow. This means that fast-time simulations still have their value to cover such additional elements, and to come to more exact predictions for the required rudder angle, and of the required channel width.

The advantage of the tool is that it can be run in post-processing on flow computations, as are commonly made when considering design alternatives. The tool can rank the alternatives on their impact on manoeuvring and can indicate critical phases in the tidal cycle, thereby supporting the evaluation and development of the layout design and, as shown, in the evaluation of construction phases. In this way, the tool as developed assists in the evaluation of the flow conditions beyond the limit of the PIANC’s guidelines for the design of approach channels.

References


