Prediction of crabbing in the early design stage

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Crabbing is the ability of ships to move sideways without having a forward speed. Crabbing can be induced by the use of a combination of main propellers, rudders and lateral thrusters. The crabbing ability is a useful operating mode and a ship owner can have considerable profit from this ability because of a reduction of the time and costs in the harbour. Consequently, the crabbing ability is a design criterion, and needs to be assessed in early design stage. Ship yards need to know the power and amount of lateral thrusters that are to be installed in the ship. Some used criteria for crabbing are given. When the crabbing operating mode is chosen, a complex amount of circulation and fluid flows occur around the ship, which is effected considerably by the environment (quay and water depth). Using an example ship, it is shown that simple calculations are not sufficiently adequate to estimate the crabbing capability, so that advanced calculations or model tests are needed.

1 INTRODUCTION

Twin screw ships have due to their ability to use both main propellers in a different mode of operation, a special feature on board. By reversing one propeller and giving normal thrust with the second propeller, a circulating flow around the aft ship is produced. By steering with the rudder in the slipstream and by using eventual lateral thruster units, this can give the ship the ability to move sideways without having a forward speed. This ability has been called crabbing, traversing or the “push-pull” mode.

This ability is a very powerful one. It means that in the aft ship, a very powerful transverse force can be generated, able to manoeuvre the ship in complete lateral motion or to withstand currents, waves and wind.

This application is therefore the most interesting with ships who benefit from these large forces such as ferries and cruise ships. It saves the use of harbour tugs up to certain environmental conditions. Other types of ships which may benefit are the workboats.

Supply vessels, cable laying vessels are for example vessels where this system can be used in the DP system, in addition to stern thrusters and bow thrusters.

Hydrodynamically seen, this push-pull mode operation of the propellers gives a complex flow around the aft ship. A relative simple calculation technique is not sufficient to tackle the above problem. A large propeller-rudder-hull interaction is to be expected, yielding large transverse forces, which may be directed opposite of the desired forces. This system is again influenced by the working of stern thrusters and even by bow thrusters. The circulation of water around the aft ship is also influenced a lot by the presence of the quay if a berthing or unberthing procedure is carried out. The presence of the sea bottom is also a very important factor.

In this paper, crabbing as criterion in early design is emphasised. Some possible criteria are given, a calculation technique is introduced and shortcomings are sketched. It is shown that a simple calculation technique will not always work.

2 CRABBING CRITERIA

Already in the design process, the crabbing ability should be investigated. Several examples are inventoried here.

In [1], the example is given that a transverse speed of 0.25 m/s should be maintained against 22 knots of wind (Beaufort 6). For this transverse speed, all applicable means can be applied. The distance to the quay and the shallowness of the water for which the crabbing ability should be investigated are not specified.
Another criterion can be: the ability to withstand a transverse current of 3 knots.
For cruise ships, the design criterion is often the ability to berth and unberth in a wind speed corresponding to Beaufort 7 of any direction without help from tugs. This means that the vessel has to move sideways parallel to or from the quay against a 35 knots beam, wind, assuming this to be the worst direction, without any forward speed.
This illustrates that in these cases, the importance of the influence of the quay and the shallow water are indicated.
The US Coast Guard has some specific requirements in which they indicate that the ability to safely manoeuvre has to be proven once the lateral area above the waterline is larger then 3 times the lateral area below the waterline (LxT) [2]. This is the case with most modern cruise ships and ferries.
A fourth criterion which is emphasised more and more recently is the impact of the crabbing procedures on the environment. During berthing and unberthing procedures, the circulation in the harbour basins can be so large that damages can occur to the quay or other ships in the harbour. Therefore, optimisation can be required with respect to a minimum of environmental impact [3].
The speed which can be used during harbour manoeuvring is very important. If the ship has a good crabbing ability, very fast berthing procedures can be conducted. In [4], the example is given of a ferry whose berthing procedure has been speeded up so that the service speed could be lowered, resulting in a lower fuel consumption.
It is shown in [5] and [6] that if the berthing/unberthing procedure is optimised by a set of crabbing model tests and computer simulations where the crew is trained on this system, a considerable profit can be obtained.

3 BASICS OF CRABBING

As put forward in [1], the following actuators can be used during the crabbing process for ordinary twin screw ships:
- Main propellers
- Rudders
- Stern thrusters
- Bow thrusters
When the main propellers work in different loadings, a strong propeller rudder hull interaction is induced, yielding a pressure field around the aft ship. In addition to this, the neighbourhood of the quay is of importance. It is also observed that the water depth is of large influence on the flow of the water.
In the attached figure, it is illustrated which water flows occur around the ship.

The major transverse force in the aft ship will come from the lift of the rudder in the jet stream of the balancing propeller. Also, it is clear that it is possible that a strong flow due to the backing propeller can exist between the quay and the ship, resulting in a negative pressure, which causes a suction force towards the quay.

4 STANDARD MODEL EXPERIMENTS TO INVESTIGATE CRABBING

Crabbing performance is investigated at MARIN by means of captive model tests: the ship is attached to a towing carriage by means of force transducers. This enables the measurement of forces developed by the
ship propulsive gear on the ship. For instance, all combinations of main propellers, stern thrusters and bow thrusters can be combined with any particular rudder angle. The quay and the water depth are of major importance towards the crabbing behaviour. If the neighbourhood of the quay is desired, this is simulated by the solid side wall of the basin. The water depth is adjusted to the desired scaled value. It is of importance that the basin is wide and long enough. During the crabbing, a strong interference is present with any "quay" in the neighbourhood. This can be observed in harbour basins and locks in real life.

5 CALCULATION PROCEDURE WHILE NEGLECTING INTERACTIONS

Using a simple calculation procedure, it may be possible to calculate the forces working on the ship in the zero speed case. The following calculation scheme is focussed on assessing the forces due to working propellers, rudders and thrusters. This simple calculation procedure can be created in a spreadsheet. It contains a summation of the forces of the lateral thrusters, the main propellers and the lift effect of the rudder due to the propeller slipstream.

5.1 Thruster forces
The forces generated by the lateral thruster can be calculated as a function of the available power. According to Brix [7], a specific lateral force of the lateral thrusters of 100 N/kW may be assumed.

5.2 Propeller forces
The thrusts of the propellers can be calculated based on the 4 quadrant - curves of propellers [8], given the propeller design data. The propeller thrust is given by:

\[ T_p = C_T \left( \beta_{PR} \right) \frac{1}{2} \rho \frac{\pi}{4} D_p^2 \left( u_p^2 + (0.7 \pi n D_p)^2 \right) \]  

in which:
- \( T_p \) is the propeller thrust
- \( D_p \) is the propeller diameter

The required power is given by:

\[ P_p = C_Q \left( \beta_{PR} \right) \rho \frac{\pi^2}{4} D_p^3 \left( u_p^2 + (0.7 \pi n D_p)^2 \right) n \]  

in which \( n \) is the number of propeller revolutions per second and \( D_p \) is the propeller diameter. The angle \( \beta_{PR} \) in the above equation is the indicative angle of incidence of the flow to the propeller blade:

\[ \beta_{PR} = \arctan \left( \frac{u_p}{0.7 \pi n D_p} \right) \]  

in which \( u_p \) is the longitudinal component of the undisturbed flow velocity through the propeller. In the crabbing case, this speed is zero, therefore \( \beta_{PR} \) is zero for the balancing propeller and \( \pi \) for the backing propeller. Values of \( C_T \) and \( C_Q \) can be obtained for forward and astern bollard pull conditions. Using these coefficients together with the maximum available backing power \( P_p \), the maximum astern RPM can be calculated.

Having established the RPM, a thrust is found. This thrust will be compensated with a forward thrust of the balancing propeller and the longitudinal force of the rudder. \( T_{P,balancing} \) will be calculated as:

\[ T_{P,balancing} = F_{x,rad} - T_{P,backing} \]  

Given the required forward thrust, the RPM and required power of the forward propeller can be calculated. The forward thrust will be used to calculate the rudder forces.

5.3 Rudder forces
Because the rudder behind the backing propeller is not located in the propeller slipstream and therefore the inflow velocity will be small, the forces on this rudder are supposed to be negligible.

Using the thrust of the balancing propeller, the inflow velocity at the location of the rudder behind the balancing propeller can be calculated. In case of a zero forward speed, the induced speed at the rudder \( u_R \) is found to be:

\[ u_R = c_{UR} \frac{8 T_{P, balancing}}{\pi D_p^2} \]  

A value of 0.7 \( D_p/H_R \) is suggested for \( c_{UR} \) according Inoue et al [9].

Using the above calculated inflow velocity at the rudder, a rudder lift force can be calculated using the lift formulas according [10]:

\[
In this formula, the following nomenclature is adopted:

- \( A_R \) is the rudder area
- \( \lambda_R \) the rudder aspect ratio
- \( \delta \) is the rudder angle
- \( C_{L\delta} \) is the lift coefficient which can be calculated for conventional rudders [9] as:

\[
C_{L\delta} = \frac{6.13\lambda_R}{2.29 + \lambda_R}
\]  

(7)

Together with the lift induced drag on the rudder, the longitudinal and transverse forces of the rudder on the hull can be calculated. The longitudinal force of the rudder on the hull is used again in equation (4), so that this last series of equations is an iterative process.

For an imaginary cruise ship [11], this can result in the calculation results as shown in Table 1. In this example, the ship is equipped with a stern thruster and three bow thrusters and the main propellers are used to balance the ship for zero forward speed. In the table, it is seen that for a sideways unberthing manœuvre, a transverse force \( F_y \) of 520 kN can be generated when the starboard rudder is set to 35°.

### 6 FORCES TO BE OPPOSED

The crabbing capability can be calculated using techniques sketched in the previous paragraph. The forces which are to be opposed, follow directly from the crabbing criteria as put forward in paragraph 2. In general, a wind resistance and a speed through the water are important.

The wind resistance can be estimated using the techniques put forward by Brix et al. [7]. A relatively simple calculation technique can give the force and moment generated by the wind. The wind force is calculated by:

\[
F_{\text{wind}} = \frac{1}{2} \rho v^2 A_{\text{wind}} C_{D,\text{wind}}
\]  

(8)

while for the wind moment a similar formula is used. The forces and moments generated by a speed through the water can be calculated using the cross flow drag theory [12].

For the example ship in paragraph 5, having a criterion of 22 knots and a pure sideways motion of 0.25 m/s, a side force \( F_y \) of 270 kN is required.

### 7 COMPARISON WITH MEASUREMENTS

In this paragraph, the calculation method presented in paragraph 5 is used to calculate the lateral force \( F_y \) and yawing moment \( M_z \) for a cruise vessel, using the main propellers and rudders, one bow thruster and without stern thruster. This is illustrated in Table 2 where the calculation results are compared with corresponding model tests.

<table>
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<tr>
<th>Rudder (port)</th>
<th>Stern thr</th>
<th>Bow thr</th>
<th>Reversing propeller (starboard)</th>
<th>Balancing propeller (starboard)</th>
<th>Rudder Total</th>
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<tbody>
<tr>
<td>Angle [deg]</td>
<td>( F_y ) [kN]</td>
<td>( F_y ) [kN]</td>
<td>Power [kW]</td>
<td>Thrust [kN]</td>
<td>Thrust [kW]</td>
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</tbody>
</table>

Table 1: Sample calculation of crabbing forces

\[
L = \frac{1}{2} \rho C_{L\delta} A_R \mu^2 \sin \delta
\]  

(6)

In this formula, the following nomenclature is adopted:

- \( A_R \) the rudder area
- \( \lambda_R \) the rudder aspect ratio
- \( \delta \) the rudder angle
- \( C_{L\delta} \) is the lift coefficient which can be calculated for conventional rudders [9] as:

\[
C_{L\delta} = \frac{6.13\lambda_R}{2.29 + \lambda_R}
\]  

(7)
It can be seen that although the trend and forces in the lateral force seem to conform, the moment is completely out of range. This has the following consequences. Based on the simple calculations, a lateral force of approximately 100 kN can be resisted when the yawing moment should be approximately zero. By installing additional bow thruster capacity, the moment Mz is increased and by doubling the bow thrust capacity, a pure transverse force of about 280 kN can be generated. However, the model tests show that already a force of some 320 kN is obtained in the original configuration.

Hence, to be able to fulfil the criterion in paragraph 6, based on the simple calculation an additional bow thruster would be purchased, while based on the model tests this will not be necessary. The reason for the discrepancies is that certain interaction forces are omitted, which have influence, not only on the attained lateral force, but also on the moment and the longitudinal force. This has its effects on the thrust of the balancing propeller and hence the side forces. An erroneous prediction on certain aspects can therefore be more critical than expected.

8 INTERACTIONS

Although in literature reference is given to the different interaction processes, see [6] and [13], it is not quantified how large the impact of neglecting the interactions actually is. The interactions are described quantitative below.

8.1 Bow thruster forces

In addition to the thrust generated by the bow thruster, a bow thruster-hull interaction takes place. For cranking in harbours, two environmental aspects are considered to be important. The water depth causes an increase of the thruster effective force with decreasing water depth. The distance between the outlet of the thruster and the quay is a reason for retardation effects and increased thruster hull interaction.

The assumption of a specific lateral force value of for example 100 N/kW [7] is questionable. The value is dependent on the relative loading of the lateral thruster and on the interaction between any other lateral thrusters. When for example three bow thrusters are present, the generated lateral force will be less than three times the lateral force of only one bow thruster.

8.2 Rudder forces

When a strong circulation is initialised around the aft ship, a change of the flow around the rudder is found. It is observed that in most cases stall of the rudder does not occur. Due to the highly instationary flow, there is no dramatic decrease in lift force at higher rudder angle.

A second aspect is that due to the changed flow towards the rudder(s) the neutral rudder angle will change, depending on the circulation around the ship. The form of the circulation itself is dependent on the underwater shape of the aft ship, the size of the skeg and the water depth. Even the shape of the neighbouring quays is of influence.

As mentioned before, the rudder which is located behind the backing propeller has almost no influence on the generated forces.

8.3 Main propeller interaction forces

As put forward in [14] and [15], by reversing one propeller, and balancing the other, several physical phenomena are introduced. The "shoulder moment" is a direct moment generated by the different thrusts. The "lateral stream effect" is caused by the different pressure fields on port and starboard at the hull [7] due to the fact that the streamline of the reversed propeller "hits" the hull of the ship. When the ship is equipped with fixed pitch propellers, the "paddle wheel effect" is introduced, caused by reversing the rotation of the backing propeller.

All these main propeller effects are affected by: the choice of propeller; fixed pitch or controllable pitch; outward turning or inward turning propellers [13]. Furthermore, we see that even more interactions are taking place. The "blockage" of the flow has an impact on the propeller coefficients cQ and cT, so that
we can state that the rudder angle, the water depth and the distance to the quay have influence on the propeller characteristics.

8.4 Quay interactions
As already indicated in the previous paragraph, a strong quay interaction exists due to suction between ship hull and the quay. Due to the working of the backing propeller in the neighbourhood of the quay, a strong current is generated between the ship's hull and the quay. This results in a large suction force, causing the ship to be pulled towards the quay, instead of a correct unberthing procedure. This is then the reason for the fact that the unberthing condition is often the most severe condition for a crabbing ship. Based on model tests it was found that the most critical situation is the situation with the ship located at half its breadth from the quay.

9 CONCLUSIONS
A summation of some common practice crabbing criteria is given. Several criteria are related to the specific target operational area of the ship, some are general criteria.
A recapitulation is given of a calculation technique to assess the crabbing capability, using elementary thruster, propeller and rudder forces. Although in literature, reference is given to the different interaction processes, it is not quantified how large the impact of the interactions is. In this paper, the significance of the interactions is shown, based on an example ship for which calculations are compared with measurements. Apparently, neglecting the interactions leads to erroneous conclusions. Therefore, more detailed calculation procedures or model tests have to be carried out to predict the crabbing ability properly and reliably. As the influence of quay and water depth are important for the interactions and hence for the crabbing ability, the distance to the quay and the water depth should be mentioned in the crabbing criterion.

REFERENCES
1. Hooren, C.M. van and Huisman, J.M.; Crabbing performance of ferries. 6th Lips symposium, Drunen, 1985