Dynamic assessment of safety in manoeuvring through constricted navigational channels using an online operational system

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Abstract
Highly constricted time windows for allowing safe and efficient manoeuvring of large ships in confined navigational channels are one of the largest growing sources of congestion in ports worldwide. With increasingly larger container vessels introduced to many shipping routes, this challenge is predicted to grow for years to come.

For decades, several ports worldwide have started to utilize the benefits from online systems that predicts safe dynamic under keel clearance (UKC) transit windows hence providing increase flexibility and capacity over old fashioned static port rules.

In this paper we will present a significant recent improvement to an operational decision support system for the effective dynamic management of safe transit windows through constricted waterways. In addition to incorporating the effect of dynamic UKC, the physics-based operational system calculates dynamic safe transit windows incorporating the constraints of safety in manoeuvring with the same level of accuracy as a top tier 3D full bridge simulator.

The paper will provide examples of the operational use of the live system in major Australian and overseas ports and present the underlying technical framework for how the system uses detailed vessel manoeuvring response predictions for deriving practical dynamic thresholds for safe transit planning.

Keywords: Manoeuvring, Port, UKC, Navigation, Simulator

1. Introduction
In Australian container ports, ship manoeuvring has come into attention again with introduction of containerships capable of carrying above 14k TEUs. Accommodating such ships is a serious challenge for many ports all around the world, specifically as there are several handling issues related to extremely high windage areas, large displacement weight which increase the hydrodynamic resistance forces and significant decrease of rudder area to windage area when compared to previous generations. Although shipyards provide helpful metrics of basic handling properties in terms of standard manoeuvres [1], those metrics are normally restricted to deep water and light forcing condition. However, some of the most challenging manoeuvres will take place in congested waters and often during energetic weather conditions. Full bridge simulations can provide high level details on manoeuvring quality using human pilots, but they are very time and budget consuming, and it is difficult to provide a full envelope of safe manoeuvring scenarios that covers all aspects of day to day operations and vessel loading conditions. Hence, robust operational, real-time manoeuvring decision support tools are becoming increasingly attractive in order to optimize safe and efficient shipping through constricted waterways.

The NCOS1 ONLINE Safe Manoeuvring Module is closely related to an accurate fast time simulation tool used in desktop versions of full bridge simulation. The main difference is that the NCOS ONLINE module is powered by a more highly sophisticated numerical navigator and that spatially and temporally varying metocean forcing occurring during the voyage are accurately forecast in real-time. This means that the NCOS ONLINE Safe Manoeuvring Module can accurately evaluate aspects of multiple alternative options for assuring a safe vessel transit extremely fast. The best options for safe passage to suit vessel configuration and weather can then be provided to the pilot and master well ahead of each transit with tremendous benefits to assuring safe passage and avoiding potential delays to arrival.

2. Technical Approach
Historically, there has been two main approaches towards numerical approximation of ship manoeuvring capabilities in full-bridge simulators. The first is the Modular Manoeuvring Group (MMG) method which considers hull, steering devices, propulsion and other influencing factors as separate

1 Non-linear Channel Optimization Simulator
units [2]. This will enable one to easily replace various devices and handle the between interactions separately. The second well established method using a tabular form of representing vessel response coefficients based on Abkowitz manoeuvring model [3]. The second method relies on non-dimensionalised hydrodynamic response coefficients obtained from extensive physical model tests, which allows for a very accurate representation of real vessel manoeuvring response. Force Technology’s SIMFLEX4 full bridge simulator utilizes this second approach in its engines. The hydrodynamic properties of hull, propeller and steering system are all based on 50 years of towing tank/wind tunnel and cavitation tunnel model tests carried out in-house in close collaboration with shipping lines and fully validated against full scale field data [4].

When compared to the MMG method, the SIMFLEX4 mathematical representation of vessel response does not suffer from lack of accuracy often experienced due to polynomial representation of hull hydrodynamic forces. The vessel manoeuvring response in NCOS ONLINE uses the same vessel response engine applied in SIMFLEX4.

NCOS ONLINEs Manoeuvring Module is using a high precision numerical navigator scheme (NNS) to automatically steer each vessel through navigational channels. It combines a robust Proportional/Derivative/Integral (PID) controller optimised based on ship manoeuvrability measures with a so-called Look Ahead Distance Algorithm, which converts the track offset into rudder commands to correct the ship heading [5]. Planned navigation route, target speed profile and environmental forcing (wind, current and wave as time and spatially varying variable) are inputs into NCOS Manoeuvring Solver Engine that in turn calculates the vessel 6 DOF response at each time instance and compared to desired target speed and route. Based on the differentials to meet target course and speed, the numerical navigator corrects rudder and engine accordingly, which will affect vessel response in the subsequent time step as illustrated in Figure 1. When approaching a channel bend, a real pilot will use his experience to decide the value of rudder angle and how far from the bend to execute the rudder command. In comparison the NCOS ONLINE Manoeuvring Module is using an algorithm, which decides on the values of look ahead distance based on several navigation factors including:

- Rate of turn
- Bend sharpness
- Under keel clearance as low UKC’s will make the ship sluggish on the bend
- General manoeuvrability of the vessel in terms of the metrics of standard manoeuvres test

3. Validation

Ship handling simulation is a complicated problem as the nature of unsteady hydrodynamic forces and interactions of different degrees of freedom during ship motion is still subject to ongoing research often using very sophisticated numerical methods. As result it is as always important to validate a numerical approach against realistic events.

At each time step, the vessel’s centre of gravity is assumed to be in the centre of a circle with radius equal to the calculated look ahead distance for each bend. The intersection point of this circle with the target route is found and the required rudder angle to correct the relative course is determined. This approach creates a numerical approximation to real navigation where the NNS will try its best to complete the transit according to the target transit plan based on what the vessel is capable of in relation to the weather and tide on the day. If the transit plan is challenging or potentially unsafe, it will automatically be identified through excessive use of rudder, excessively high vessel drift angles and too close vessel proximity to the channel toe line. This is almost to how safety in manoeuvring is assessed in full bridge simulations using human navigators. By quickly evaluating multiple transit plans with different course and speed profile, it is then possible to identify safest option to suit both vessel and weather condition on the time of transit. In some instances, it may not be possible to find a suitable mitigation option for challenging weather and a vessel transit is flagged as challenging and potentially unsafe. Note that this does not always mean that an experienced human pilot cannot complete the transit.
The main intention in this validation has been validating the performance of the numerical navigator against human pilot in terms of:
- Overall performance of PID controller
- Look ahead algorithm
- Speed matching during the transit

The results of the full bridge simulation comparisons to NCOS ONLINE provided advantages for comparison as:
- transit scenarios and environmental forcing would be identical and enable the full comparison of vessel response in challenging scenarios in a safe controlled environment.
- The hydrodynamic models of ship hull, steering and propulsion devices and environmental forces on the ships are identical which allows for isolated test of the significance of the human element in safe navigation.

The Smartship Australia facilities in Brisbane were used for full bridge simulation which applies the bridge and manoeuvring solver of Force Technology SIMFLEX, which is the same as NCOS ONLINE Manoeuvring Module solver. The ship vessel response mathematical model and manoeuvring solver itself are the same as all the NCOS ONLINE inputs.

A 14,000 TEU containership at 14.0m draught was used for this study. The vessel was configured with a single propeller, single rudder and with full container tiers on deck (Table 1). The manoeuvring simulation test matrix contained wind speeds from 20 to 40 knots from all dominant directions and realistic flood tide currents and water levels in the channel. The scenario presented in this paper involved a 20 knot winds from the Northwest, high tide and low tidal currents. The purpose of this test was to assess the isolated effect of wind on manoeuvring as isolated as possible.

Table 1 Particulars of the 14,000 TEU Containership

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Lpp (m)</td>
<td>350.06</td>
</tr>
<tr>
<td>B (m)</td>
<td>48.11</td>
</tr>
<tr>
<td>T (m)</td>
<td>14.00</td>
</tr>
<tr>
<td>CB</td>
<td>0.669</td>
</tr>
<tr>
<td>Speed (knots)</td>
<td>26.0 Service Condition</td>
</tr>
<tr>
<td>Propeller</td>
<td>8.800m FPP 6 Blades</td>
</tr>
<tr>
<td>Rudder Area / Lpp x T</td>
<td>1.62 %</td>
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In the full bridge simulator the human navigator undertook a relatively high-speed approach on the deep part of the channel followed by a gradual reduction RPMs aimed to reduce the speed due to UKC limitations of inner channel and being able to reach a full stop once approaching the port basin.

The human pilot used a kick ahead (increase the propeller rate output) in the channel bend to increase the propeller slip stream onto the rudder for better turning performance.

As illustrated in Figure 2 to Figure 4, NCOSs numerical navigators scheme automatic control of rudder and propulsion was very similar to the human pilot. The NNS applies same rudder angles on the critical part of the transit starting from Entrance Channel Beacon waypoint to Inner Bar. While the rudder angles and propulsion kick-ahead are very close in the bend. It is observed that NCOS overall is giving conservative values when compared to the full bridge simulation. The width of the channel swept by the vessel is also in good agreement as presented in Figure 2.
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Figure 2  Vessel swept path (NCOS blue line, Full bridge simulation in red), 20 knot winds 315° NW

Figure 3  Responses of steering and propulsion devices

Figure 4  Vessel dynamic responses, drift angle and forward speed
4. An Example of Operational Use

One of the most challenging scenarios for pilots and ship masters is operational handling of vessels at high velocity following currents. While high winds can pose significant challenges to safe navigation, it is easier to assess both for planning purpose and during transit and avoid dangerous situations. In most ports, currents can vary significantly temporally and spatially, they are often difficult to forecast and live measurements in areas of interest are rarely available. In challenging manoeuvring situations, a common solution is to increase vessel speed. However in most navigational channels, there are restrictions on the under-keel clearance and bank effects, which will in turn restrict the maximum allowable forward speed. One of the most problematic scenarios consists of high-speed currents coming from the stern as the relative speed of water flow over the rudder is reduced, and as the ship rudder is considered a passive control element, it may not be able to steer the ship effectively.

The high current speeds in the river mouth and through bay entrances usually happen close to flood tides where port operators tend to take advantage of the rising water to accommodate deep draught ships. Although flood tides can unlock transit windows effectively from the UKC point of view, loss of controllability on manoeuvring can be a very serious issue during these time windows if not assessed accurately.

An example of this scenario is highly relevant occurs through Port Phillips Heads for large, deep drafted containerships looking to take advantage of flood tides to enter the bay. The current speed in some cases can exceed 5.0 knots which significantly limits safe transit windows for large containerships. In this example below we demonstrate how NCOS ONLINE Manoeuvring Module can be used to identify risks to safe navigation in up to 2.8 knot current and how increasing vessel speed from 8 to at least 10 knots in this instance can assure the safe control of the vessel whilst maintaining safe UKC. This scenario example is hypothetical and does not to our understanding reflect current operations through Port Phillip Heads.

The handling of the same 14,000 TEU containership (Table 1), on a flood tide scenario entering the Port Phillip bay is studied here at different transit speeds. Two factors influencing the handling quality are:

- Track offset ($TO$), which is the normal distance to track ($y_n$) at each time incident integrated over transit time and made non-dimensionl based on ship beam ($B$).

$$TO = \int_{t_0}^{t_1} y_n \, dt / B(t_1 - t_0) \quad (2)$$

- Rudder effort ($RE$) in equation 1, which is the rudder angles ($\delta$) integrated over transit times, made non dimensional by maximum allowable rudder angle ($a_r$) which is set to 35 degrees in this study, which shows how much rudder capacity is left on each transit to respond to unexpected circumstances.

$$RE = \int_{t_0}^{t_1} \delta \, dt / a_r(t_1 - t_0) \quad (1)$$

Figure 5 Comparing vessel swept and transit metrics at low 8kn and high 14kn speeds, 14k TEU containership arrival in high currents and in 10 knots NW wind.
According to Figure 6, increasing the speed above 10 knots will leave a good amount of reserved rudder capacity behind of more than 70% and reduce the vessel swept path width and track offsets. At the same time NCOS ONLINE is able to identify the drawbacks of forward speed increase like reduced UKC and high turn rates on the bend to optimise the speed profile for accommodating the transits.

Online Application

The combination of accuracy and fast computation times, makes the NCOS Manoeuvring Module is suitable to further improve the operational safety and efficiency of vessel transit planning through constricted waterways such as into ports. The module forms part of the physics-based decision support system NCOS ONLINE, which is used by port operators worldwide daily to assure safe transit planning of ships into port. When planning the safe transit of a vessel, the system automatically screens for the entire operational window of opportunity and provide a compliance check based on safety in manoeuvring and UKC. These checks are based on the detailed vessel configuration and spatially and temporally variations in forecasted weather and tide during the time of transit. Safe time windows for scheduling a transit are displaced in a secure web interface as illustrated in Figure 8.

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Summary

In this paper we have presented a recent improvement to an operational decision support system for the effective dynamic management of safe transit windows through constricted waterways. By operationalizing the core vessel response engine from an established full bridge simulator combined with a powerful numerical navigator scheme, we have created a new type of decision support tool for evaluating better safe and efficient navigation through constricted waterways which is subject to occasional strong winds or
currents. We also consider the tool an accurate and cost-effective alternative to assist in design of new navigational waterways that will allow for a more extensive options assessment before the final design options proceeds to full bridge validation with the assistance from a human navigator.

5. References


