HUMAN FACTORS IN THE OPERATIONAL PERFORMANCE OF FERRIES

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SUMMARY

The present paper focuses on the impact of human factors on ferry operations. Making use of new insights in the nature of motion sickness and a new technique for the assessment of the operational performance, the impact of passenger discomfort and risk avoiding measures of the master on the performance and reliability on ferry operations is quantified.

1 INTRODUCTION

The problem of quantifying the impact of human factors like seasickness and prudent seamanship on ferry performance requires a complete description of all normal operational conditions and the factors that lead to passenger discomfort. The present work illustrates results that are obtained when the operability analysis is extended to scenario simulations and the traditional sickness severity estimate, on basis of vertical accelerations only, is extended with the transverse motions and roll.

2 SHIP PERFORMANCE

In concept development and design verification (as well as in rule development or actually, the "risk behind the rule") not only the hydrodynamic aspects of seakeeping determine the result. The problem is complicated by it’s multi-disciplinary character. It requires a description of:

- all relevant physical aspects of the behaviour in all conceivable weather conditions (the domain of ship hydrodynamics);
- the frequency of occurrence and persistence of these weather conditions (climatology);
- the "mission profile", a what-if scenario describing the masters actions in particular circumstances with criteria for tolerable ship behaviour (seamanship).

The problem of describing a climatology and "prudent seamanship" is complicated further by "memory" effects. Memory in wave growth and decay implies that the waves at a given instant are not fully determined by the wind at that moment; the spectral shape and the presence of swell depend on the history as well. Memory in the performance implies that the performance (for instance the progress on a route) at a given moment does not only depend on the circumstances at that moment.

2.1 STATISTICAL APPROACHES

A common way to establish the performance is to indicate the operational limits in a scatter diagram reflecting all possible combinations of wave height and mean period in a given sea area. With assumptions on the wind speed related each of these combinations this statistical approach yields the mean fraction of time that the adopted criteria (for instance for sustained speed) are exceeded. This "operability" is a function of:

- ship speed;
- wave direction relative to the course of the ship;
- season.

Figure 1 shows a schematised sample result. For each wave period two limiting wave heights are shown, one for the seasickness and one for the available power to overcome waves. From the two lines it can be seen that for short wave periods the available power limits the ships operability, for higher periods the seasickness is the limiting criterion.

Combining the wind/wave statistics from various directions along various points of a route it is possible to account for the fetch limited characteristics of the wave climate in the coastal zone or changing climatology along longer routes.

A basic problem with a statistical approach is how to account for the reaction of the master on circumstances and to account for memory effects. The results of a statistical approach do not tell the effect of persistence of storms on the number of affected trips and the impact operational measures (like a temporary reduction of speed) on the reliability in terms of arrival statistics.
2.2 SCENARIO SIMULATIONS

A practical way around the problems and limitations of a statistical approach is based on a deterministic step-wise simulation of a given "mission". The use of hindcast data (from wind-wave models) as input for wind and waves solves the problem of accounting for the right coherence between wind and waves and the varying spectral characteristics of the waves.

For this paper we used our GULLIVER scenario simulation program (see Figure 2). A strong point of this code is the option to use a very detailed representation of the frequency- and directional characteristics of the underlying waves. As demonstrated in the work by Grin [1] it accepts the output of the DUT (Delft University of Technology) wind-wave model SWAN (see Figure 3). This makes it very suitable for applications in fetch-limited areas and the near coastal zone.

Other recent applications of the code were based on actual wave rider information (assuming that this information is valid over a certain area).

Extended versions were used in several projects. Noteworthy are investigations into the reliability of a trans-Atlantic service; the safety of sea-river ships in the coastal zone and a special transport risk analysis. In the HSF ARCOS project on behalf of IMTECH and GNK [2] we used the code (including a SWAN hindcast study to quantify the local wave climate) to quantify the merits of a ride control system on the operational performance of a high-speed ferry.

3 PASSENGER DISCOMFORT

Passenger discomfort is often regarded as an important issue in the design of ferries. Up to recently the work by McCauley [3] (see also the work of Colwell [4]) limited the focus primarily on vertical accelerations. A quantification of discomfort related to roll and transverse accelerations remained out of reach, apart from the impact on human mobility [5]. The frustrating fact that we were unable to quantify the impact of rolling and yawing (and motion control) on passenger comfort made us keen on recent progress at TNO Human Factors in the Netherlands. In theory their model of the human vestibular system would facilitate a more complete comfort assessment.

To explore this possibility MARIN ordered a set of simulations with a systematic variation of horizontal (surge as well as sway) and vertical accelerations, roll and pitch. In addition to the isolated components, interactions were covered to some extent. The work is described in some detail in the contribution of TNO to this symposium [6].

An observation in the TNO results is the fact that the character of human sensitivity regarding seasickness to lateral accelerations and angular motions resembles that regarding vertical accelerations. Here, we will further quantify the sickness severity by the motion sickness incidence (MSI), i.e. the percentage of a certain population that has reached the limit of vomiting due to motion of a certain duration. The TNO results share relatively high MSI levels for oscillation frequencies around 0.15 Hz and a very similar trend in MSI with increasing oscillation amplitude.

Figure 4 illustrates a typical result of the TNO simulations. It shows the effect of oscillation amplitude (0.15 Hz) on the MSI after 2 hours; note that the roll motion is characterised in terms of the quasi-static lateral component of gravity.
3.2 FUTURE DEVELOPMENTS

Issues that are neglected in the present first reconnaissance are the (slight) frequency dependency of the "equivalence" factors, cross terms to cover possible interactions (although the TNO work suggests that these are limited) and non linear effects that might not justify the linear superposition of the frequency components in an irregular wave.

The problems of quantifying the effects of passenger habituation in a varying motion environment (in stationary condition MSI peaks after about 6 hours) and passenger activity and posture were recognised but not addressed.

Because only linear motion components are considered, the effect of hull girder whipping (due to keel and bow-flare slamming) on the passengers perception is neglected altogether.

4 SAMPLE APPLICATION

4.1 CLIMATE DESCRIPTION

In the present work a Biscay ferry route was evaluated to demonstrate typical results.

The discussed 440 mile route from Santander to Plymouth is shown below in Fig. 6.

The adopted operational scenarios are:

- A "just-in-time" ("JIT") scenario in which on the first part of the (fixed, north-bound) route the master tries to create a safety margin by sailing at a relatively high power. The targeted trip duration is 26 hours.
- A "comfort" scenario in which the master reduces speed in head and bow-quartering seas if the MSI in the forward half of the ship exceeds 10 %.

The simulations cover 6 years (January 1994 up to December 1999) in which the vessel leaves every second day at 21:00 hrs. The simulation time step was 1 hour.
**Encountered conditions**

ECMWF hindcasts were used as input for the evaluation of the ship behaviour and added resistance. Wind, waves and swell were available for the points in the above figure. A departure every second day yields around $6 \times 365/2 = 1095$ trips with $1095 \times 26 = 28470$ evaluations of sustained speed, ship behaviour and passenger comfort.

The available weather information comprises, among others, the wind speed, the height and mean period of the wind-sea and the swell and their directions. Figure 7 indicates time histories and the "scatter" diagrams of the coherence of the height and period of the total wave system and the coherence of the wave height and the wind speed.

The winter periods can be recognised from the periods with higher wave conditions. Very interesting is the fact that the summer seasons are not without relatively high wave conditions.

The substantial scatter in the relation between wave height and mean period and between wind speed and wave height illustrates the danger of using the "mean" or "typical" relations that are often used in naval architecture. (Shown in Figure 7 as continuous curves.)

**4.2 SHIP MOTION CHARACTERISTICS**

The considered ship is a ferry equipped with fin stabilisers. A high and a low level of roll stabilisation are evaluated.

The fact that it is now possible to weigh the motion components in terms of their contribution to the MSI offers a first-time insight in the relative magnitude of the underlying factors. Figure 10 indicates (top to bottom) contourplots of the transfer functions of the quasi-static transverse accelerations due to roll, the transverse accelerations (which include the foregoing component), the vertical accelerations and the total "equivalent" acceleration (used, after convolution with the wave spectrum, to evaluate the MSI). The transfer functions are given as a function of wave frequency (0 to 1.5 rad/s, horizontal scale) and heading (following to head, vertical scale). Points at one-quarter and three-quarter ship length (ship centre line) were considered, for the first point a high and a low degree of roll stabilisation were
considered. The contour levels in the graphs refer to the same acceleration level (per m wave).

The highest equivalent accelerations are found for the ship with the relatively high roll response. Because they are related to rolling, the most unfavourable wave direction is aft of beam seas. Reducing the roll response by means of stabilisers has a clear effect; for the same point at one-quarter-ship length the highest levels are reduced by 50%. The area that remains is located around beam seas where they are caused by an inevitable combination of sway and heave motions (note that roll is almost absent in this area).

Comparing the points at one- and three-quarter ship length demonstrates the effect of the higher vertical accelerations in the forward half of a ship. The area with high levels extends now all the way to head seas.

### 4.3 RESULTS OF THE SCENARIO SIMULATIONS

**Motion Sickness Incidence**

The MSI levels are evaluated for each of individual time steps in the simulation. Figure 8 indicates the timetrace of the MSI due to combined motions over the full simulation period. Although the summer and winter periods can be clearly recognised, a notable number of events with high MSI levels remains in the summer.

![Figure 8: Combined MSI during all crossings](image)

**MSI statistics and ship performance**

Ikeda [7] discusses the impact of passenger comfort on ferry economy. In our evaluation we will assume that (at least from a ship economic point of view, where return-passengers are important), a single “seasickness event” spoils a trip.

<table>
<thead>
<tr>
<th>MSI Levels over 6 Years</th>
<th>Uncorrelated samples</th>
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<tbody>
<tr>
<td>Correlated samples</td>
<td>Actual trip maxima</td>
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<tr>
<td>Actual (simulations)</td>
<td>Estimate from 1 hr samples</td>
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</table>

Figure 9: Cumulative distributions of combined MSI

An operability based on a statistical approach yields a result that is comparable with the distribution of the MSI from the 1-hr samples.

To obtain an estimate of the number of “bad trips” from this result one might assume that the weather and related conditions on board are more or less constant over a trip. In this case the fraction $F$ of unacceptable trips is simply the same as the fraction $F$ of unacceptable 1-hour time steps.

In case one assumes that the conditions during subsequent time steps are totally independent, the frequency of trip $F_{TR}$ that exceeds the comfort criterion in $N = 22$ steps would follow from:

$$F_{TR}(N) := 1 - (1 - F)^N$$

Noteworthy is the fact that the last result heavily overestimates the number of unacceptable trips. The scenario simulations, which account for the actual persistence of wind and weather, indicate a result that is about half way both results. See Figure 9.

Relevant for extreme value statistics (like in the engineering of transports) is that the trip maxima and the results that are based on total independence of conditions during subsequent time steps converge (see Ochi [8]).
Roll Stabilisation:

<table>
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<th>Location</th>
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Transverse Acceleration

Vertical Acceleration

Total

Figure 10: Contourplots of combined MSI contributions in regular waves (wave frequency on horizontal axis, wave direction relative to ship on vertical axis)

Seasonal influences
The absolute MSI levels obtained in the foregoing seem relatively high. A level of 10% is exceeded once or more on around 40% of the trips.

Since the majority of winter cargo may consist of trucks, it might be assumed that the MSI does not play a significant role as a decision parameter for voluntary speed loss during this season. Figure 11 explores the effect of season; it shows the fraction of trips in which particular MSI levels are exceeded once or more for all seasons and just the summer season. The fraction of trips in which a 10% level is exceeded reduces from 30% (all seasons) to 17.5% (summer). For the higher levels the reduction is larger: the 40% MSI level reduces from 3% of the trips (all seasons) to 0.5% of the trips (summer).

The results in the next sections have been based on summer trips only, for we here focus on passenger transport, which peaks in summer time.

Figure 11: Seasonal influence on MSI
Effect of roll and transverse accelerations on MSI

Figure 12 compares the fraction of summer trips that exceed 5% and 20% MSI that is obtained according to the traditional MSI estimate (vertical accelerations only) and the new method (using combined motions). The result is presented as a function of the longitudinal position on the ship. It suggests that the traditional result dramatically underestimates the incidence of seasickness.

Figure 12: Effect of location on MSI and combined MSI (summer)

Effect of On-Board Location and Transverse Motions

The underlying motion characteristics suggested a substantial influence of the longitudinal position on the vertical accelerations in head and bow-quartering seas. Figure 13 shows that this observation also materialises in the traditional MSI estimate from the vertical accelerations. When accounting for transverse accelerations and roll the number of unacceptable trips becomes much higher and the effect of longitudinal position becomes less pronounced.

Effect of reducing Speed

In the foregoing results it is assumed that the master gives the time schedule of the ship the highest priority, this was simulated with a “Just-in-Time” scenario, in which the ship creates a margin in early stages and slows down in the second half (as far as the Estimated Time of Arrival permits). The effect of reducing speed on comfort was established by introducing a “Comfort” scenario in which the master reduces speed in reaction to vertical accelerations at e.g. three-quarter ship-length (an MSI limit of 10% was adopted, the minimum speed was 10 knots). This comfort scenario is denoted in Figure 13 as “Comfort 3/4Lpp”, where Lpp stands for the ship’s length between perpendiculars.

Figure 14 shows the cumulative distribution of the trip maxima of total MSI. The effect of the above operational measure is that the fraction of trips that exceeds 10% MSI is reduced from 2 to 0.6%.

Figure 14: Influence of scenario on trip duration (summer)

Effect of roll stabilisers

Figure 15 shows the cumulative distribution function of the trip-maximum rms roll angles experienced during all crossings for two configurations (low and high roll stabilisation, resulting in high or low roll angles). On average, the roll angles are reduced by roughly 40% when using a high roll stabilisation.

Figure 16 (north-bound trips, reference point at ¼ ship length) shows that the effect on the maximum MSI levels is considerably smaller. This somewhat surprising result may be related to the contributions of sway and yaw to the local transverse accelerations and the non-linear way the various motion components are added (see section 3).
5 CONCLUSIONS, FUTURE APPLICATIONS AND DEVELOPMENTS

The present work presents new insights in the mechanisms underlying seasickness. Using scenario simulations the impact on the performance of a ferry is quantified.

Considering the sample case it seems justified to conclude that:
- roll and transverse motions contribute significantly to the over-all MSI; the traditional estimate on basis of the vertical accelerations under estimates the number of unacceptable trips significantly;
- stabilisers help to reduce the number of unacceptable trips;
- despite the above, the MSI levels in the forward half of the ship still dominate passenger discomfort. Concentrating critical passenger areas around mid-ship improves ship performance.

- reducing speed in reaction to passenger discomfort can have a significant influence on the number of unacceptable trips.

Important uncertainties that need further work are:
- the non-linear interactions between motion components in MSI,
- the effects of passenger behaviour, activities and posture;
- passenger habituation and it's modelling in varying circumstances (storm persistence, changes in course along a given route) and:
- the effects of hull girder and superstructure vibrations due to slamming.

A careful validation, with emphasis on economic issues like on-board revenues and return passengers, for different vessels and different routes seems important. With the present simulation technique this validation is not limited to a statistical approach; individual trips can be reproduced and evaluated to obtain a detailed insight.

6 ACKNOWLEDGEMENTS

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7 REFERENCES