QUANTIFYING THE IMPACT THAT COXSWAIN BEHAVIOUR HAS ON WHOLE BODY VIBRATION - SIMULATOR TRIAL

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SUMMARY

A common risk to personnel is from Whole Body Vibration (WBV) and shock when transiting at speed in heavy seas, and much research has been done by maritime organisations to reduce this risk and the associated health impacts. It is well known that coxswain 'driving style' can radically affect exposure levels for a given sea state and sustained transit speed. A data-driven approach to define what makes a good coxswain from a WBV perspective is currently being developed by the Naval Design Partnering team (NDP). In phase 1, a systematic coxswain behaviour tracking methodology has been developed and demonstrated using a motion platform-based fast craft simulator at MARIN. The performance of several experienced volunteer coxswains from MOD, RNLI and KNRM has been evaluated based on a set pattern of tests. The advantages of using the simulator, over a sea trial, have been demonstrated: it is more repeatable, more controllable, accurate and more accessible. The potential disadvantages of the approach are also discussed with reference to feedback gathered from coxswains. Analysis has shown effective throttle control is much more important than steering to reduce WBV. Several interesting trends in WBV reduction potential have been shown which it is thought, with further validation, could aid mission planning, mission execution and provide data for training autonomous feedback/control algorithms. Further work is required before the findings of this study can be fully exploited. These subsequent phases, which include sea trials, aim to provide validation and further evidence to support the initial findings.

NOMENCLATURE

[Symbol]	[Definition] [(unit)]
$A(t)$	Acceleration time history (ms^{-2})
$A(t)_w$	Weighted acceleration time history (ms^{-2})
R	Pearson correlation coefficient
T	Exposure duration (hrs)
W_k	Vertical acceleration weighting
CFD	Computational Fluid Dynamics
CoG	Centre of Gravity
DIN	Defence Instruction Notice
dof	Degree of freedom
FRISC	Fast Raiding Interception Special Forces Craft
FSSS	Fast Small Ship Simulator
HMI	Human-Machine Interface
JONSWAP	Joint North Sea Wave Project
KNRM	Royal Netherlands Sea Rescue Institution
kts	Knots
MARIN	Maritime Research Institute Netherlands
MOD	Ministry of Defence, UK
NDP	Naval Design Partnering team
RHIB	Rigid-Hulled Inflatable Boat
RNLI	Royal National Lifeboat Institute
SAR	Search and Rescue
SS	Seastate
SWH	Significant Wave Height (m)
TT(E)LV	Time to Limit (Exposure) Limit Value (hrs)
VDV	Vibration Dose Value ($ms^{-1.75}$)
WBV	Whole-Body Vibration

1. INTRODUCTION

This document comprises the results of the first phase of a Naval Design Partnering team (NDP) study with the aim of improving understanding of how sustained transit speed affects shock exposure for Rigid-Hulled Inflatable Boats (RHIBs).

From a Ministry of Defence (MOD) procurement perspective, boat requirements are driven by defence Operational Analysis, which provides a mission profile that a boat needs to deliver. On paper, it is straightforward to set a requirement to achieve a particular transit in a given time. In reality there are two variables that are very hard to quantify: the sea state, and the coxswain's performance whilst navigating rough seas. Sea state is managed in the requirements by specifying a required speed in a chosen sea state, but it is difficult to predict how a boat will perform when these two variables strongly interact, and what impact that will have on shock exposure.

A large body of research has been undertaken by maritime organisations to characterise WBV/shock and associated health impacts (Gollwitzer et al., 1995; Bass et al., 2007; Garme et al., 2011; Schmidt et al., 2012). Much of the research concerns interventions e.g. suspension seats (Peterson et al., 2004; Coe et al., 2009; Marshall et al., 2018). Minimal research has been published on tracking coxswain behaviour to quantify reduction potential. This may due to the technical challenges with human-in-the-loop trials:

• at sea – require a significant number of variables to be recorded, including the boat control signals and dynamic sea conditions, which is difficult to do accurately/repeatably, or;

• on a simulator – very few simulators exist which accurately re-create the boat physics and coxswain stimuli associated with operating in rough seas.

In terms of sea trials, Nieuwenhuis took an experimental approach to model operator behaviour on board fast RHIBs, with the aim of aiding Dutch navy procurement (Nieuwenhuis, 2005). Three different RHIBs and operators from the Royal Netherlands Sea Rescue Institution and Royal Netherlands Navy were assessed. Using the data captured, they developed a model for throttle application and throttle duration related to the cues (e.g. wave height), to which the operator was responding. They noted the present sensor state of the art was insufficient to measure the wave height or pattern in front of the boat during the run. Instead, they inferred the wave height from boat heave and justified this using an existing boat dynamics model. They concluded from their model that the main cue for the operator to use throttle control (the most important control) is the incoming wave slope. Throttle control was applied in the wave trough and only in circumstances where the wave slope was within a certain range.

Using a simple desktop PC boat simulator, Godwin et al. studied the influence of expertise on maritime driving behaviour (Godwin et al., 2013). Eye-tracking sensors were used to measure the range of sea fixation points (i.e. field points where the eyes are looking) of expert and novice participants. They concluded that expert participants drove at higher speeds than novices, and decreased their fixation durations / increased fixation spread as wave severity increased. By connecting their findings to previous eye movement research in road driving, they suggested that novice drivers show inflexibility in adaptation to changing driving conditions. A significant limitation of this study was that the simulator consisted of a single screen with no motion platform, and therefore did not reproduce many of the coxswain stimuli that are important to study behaviour in rough seas. They also did not attempt to measure how coxswains respond in terms of the boat controls.

Neither of the above study approaches could provide an evidence base to satisfy the objectives of this study, and were therefore only taken as useful points of reference.

In order to study the ways in which a coxswain can minimise shock whilst maximising transit speed, a data-driven approach is proposed in which the above three interactions are measured or quantified simultaneously.

2. OBJECTIVES

The objectives of the overall study are:

1. Develop and demonstrate a systematic coxswain behavioural tracking methodology, with capabilities to:
   a. monitor coxswain subjects control responses to a rough sea state under trial conditions;
   b. monitor sea state and incoming waves which act as cues to the coxswain.
2. Undertake coxswain trials to quantify the impact sustained transit speed has on shock, with capability to:
   a. analyse transit times for experienced and inexperienced coxswains in repeatable conditions for different scenarios;
   b. expose coxswain to a range of realistic sea states in a controlled, controllable and recordable way;
   c. determine relative importance of throttle and steering;
   d. assess WBV exposure metrics and optimal behaviours;
   e. relate the cues for the coxswain to trends in how the subject responds, as a function of the conditions.

The approach and trial methodology to deliver these overall objectives are outlined in Section 3 and 4, respectively. The selection of coxswains participating in the trial is outlined in Section 4.3. Section 5 reports the results and discussion. The key conclusions drawn from these results are outlined in Section 6.

3. APPROACH

In order to provide a controlled, controllable, and recordable environment where the incoming wave conditions can be selected and repeated, the application of a highly immersive simulator is considered most suitable. A treatise on the advantages and disadvantages of using simulators for maritime research is given in (Lützhöft et al, 2017) which highlights the importance of simulator fidelity and covers important aspects such as study variability, the concept of 'true simulation', and other practical considerations. Various high-speed craft simulators exist and the most suitable of these has been found to be the Fast Small Ship Simulator (FSSS) developed by Maritime Research Institute Netherlands (MARIN) for the Royal Netherlands Navy.

3.1 FSSS TECHNICAL ASSESSMENT

The Royal Netherlands Navy operates 48 Fast Raiding Interception Special Forces Craft (FRISC). The FSSS was commissioned to provide a capability to exercise the boat in a simulator. This had to include the ability to accurately model hydrodynamic interactions such as broaching, surfing, planing, and capsizing. The fast craft time-domain model ('XMF/Dolphin' in Figure 1) uses a strip theory approach tuned and validated against model scale tests, sea trials and Computational Fluid Dynamic (CFD) simulations. The FSSS was built by MARIN, Cruden and Tree-C from 2015 - 2018. The simulator is located at MARIN's facility in Wageningen, Netherlands where the model scale tests were also performed (van Donselaar, 2017; Bovens, 2019).

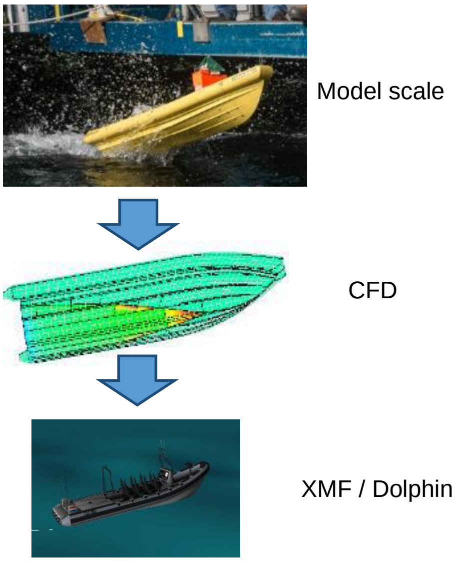

Figure: 1: Fast craft model implementation - reproduced from (Bovens, 2019)

3.2 FSS INTERFACE DESCRIPTION

The FSSS is a highly immersive simulator which aims to reproduce the audio-visual, motion, and human-machine interface (HMI) environments of a genuine high speed craft. An overview of the FSSS, which principally comprises a 6 degree-of-freedom (6 dof) motion base, console controls and dome is shown in Figure 2.

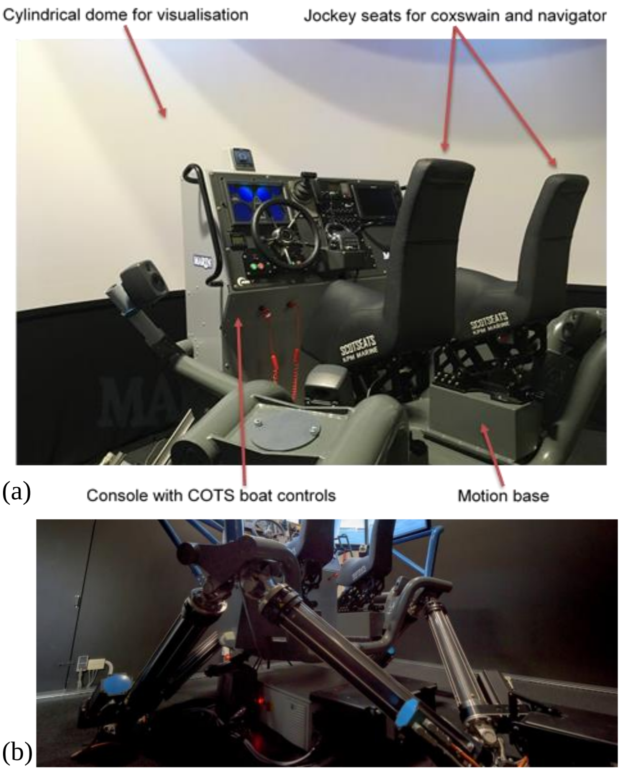

Figure 2: FSSS HMI showing (a) console controls, dome and (b) hexapod 6 dof motion base with actuators in an unextended position.

The steering, throttle, engine trim and navigation console on the motion platform are genuine boat hardware, as shown in Figure 3.

Figure 3: Console with steering wheel, throttle, engine trim and navigation screens situated on the motion base

3.3 ADAPTATIONS TO ACCOUNT FOR FSSS LIMITATIONS

A potential limitation identified in the simulator is the shortfall in peak acceleration between real impacts (of the order of 8g) and the safety limitations of the motion base (approximately 2g).

At the development stage of FSSS, feedback was gathered from experienced coxswains on whether the cues for wave slams are realistic. Visually, the cues were adjusted to provide a realistic experience to the coxswain based on their experience and feedback. In terms of peak acceleration and body forces for a heavy landing, feedback was that perhaps ‘knee pain would be higher in reality’. In many respects, this is a good sign that the visual cues were correct even if the forces/pain experienced were not.

Further, the aim of this study is to monitor how a good coxswain reduces high magnitude impacts. Therefore, in theory, there shouldn’t be too many impacts at the 8g level. The boat performance is still modelled at higher acceleration levels so the negative impact on transit speed and visual cues should still be realistic even if the motion base response is not.

The potential shortfall is further addressed through study design:

- Prior to the trial: briefing the coxswain to moderate their speed when reacting to rough seas compared to the way they would under real world conditions.
- During the trial: monitoring the acceleration levels being generated by the Fast Craft Model.
- Post-trial: a questionnaire to gather feedback on the coxswain’s experience that includes simulator fidelity and immersion to highlight any possible caveats to the outcomes of the study.

4. TRIAL SET-UP

The trial set-up is outlined in the sub-sections below.

4.1 RHIB CHOICE

To minimise time and cost, and maximise the validity of the study, the existing simulator model of the FRISC was re-used. This model had the advantage that it is has undergone detailed verification and validation prior to delivery to the Dutch Navy – see the validation report (de Jong, 2018).

The MST FRISC has a maximum speed in excess of 45 knots, and is broadly similar to the Pacific 28 employed by UK MOD. A new simulator model could have been built to represent the performance of the Pacific 28 however the additional effort required to do this was not deemed necessary as the main aim is to study coxswain behaviour, not craft performance.

4.2 GEOGRAPHICAL SETTING

The simulator was set to re-create an area of open sea with defined sea states and test pattern. The test pattern is defined in Section 4.7 and consists of 7 way-point markers inserted at a distance of 1.5 km apart.

4.3 TEST SUBJECT SELECTION

Five coxswains were recruited for the purposes of this trial. Four experienced candidates (i.e. candidates with a significant amount of time working professionally as a RIB coxswain) were recruited from within the UK MOD Marines user groups, the Royal National Lifeboat Institute (RNLI), and the Royal Netherlands Sea Rescue Institution (KNRM). In addition, an inexperienced coxswain (someone with no experience working as coxswain, or operating a boat as a hobby) was recruited from the NDP.

In order to preserve anonymity, the following terms will be used to refer to subjects, based on their organisation of origin. The experience of each coxswain, in years, is listed below for each Ministry of Defence (MOD) or Search and Rescue (SAR) coxswain:

- MOD 1 – 12 years military experience;
- MOD 2 – 20+ years military experience;
- SAR 1 – 15 years SAR/commercial experience;
- SAR 2 – 15 years SAR/commercial experience;
- No experience – no coxswain experience.

4.4 COXSWAIN TASKING

During all runs, the coxswains were tasked to undertake transits in accordance with the test pattern defined by Figure 5 at maximum possible safe speed, given the simulated sea conditions. To attain this maximum speed and to find the optimal path through the incoming waves, the coxswains were instructed to actively control the steering and/or throttle, depending on the run type.

To exclude the influence of any initial ‘learning curve’ - which is required even for a highly experienced coxswain – coxswains executed a familiarisation run in advance of later runs. During the simulator familiarisation, feedback was given to coxswains on the peak acceleration of the impacts, particularly if it exceeded a reasonable limit.

4.5 COXSWAIN BRIEFINGS

The pre-trial briefing to coxswains included the following mission briefing on how to regulate their speed during the runs:

“We will not mandate a specific speed in which to complete each run, and you are expected to use your own judgement. The aim is for you to balance speed and risk according to the prevailing conditions. A good guide for this is the return to shore following a successful search and rescue operation: You should aim to get back to shore quickly to ensure the survivor can receive vital medical attention, but not so fast that you put them at additional risk.”

Following the main set of runs, the coxswains were asked to complete a short de-brief interview to gauge their impression of the quality of the simulator and the shock mitigation techniques employed. Coxswains were then given the opportunity to experiment with the simulator - Figure 4.

Figure 4: Post-trial experimentation with one of the experienced coxswains

4.6 CONTROL CONDITIONS

Given the aim is to investigate the influence of both control types in isolation by excluding one control type at a time, three control permutations were tested:

- Free/free – both control types (throttle & steering) are allowed.
- Throttle only - The coxswain is tasked to use the steering wheel as little as possible. Only yaw

corrections are allowed to change course once each marker has been reached.

- Steering only - At the start of the run, the cox-swain is tasked to set the throttle in the right position so that the RHIB travels with maximum acceptable speed. During the run they are only allowed to change this throttle position while transitioning from one heading to another. Steering control is allowed.

4.8 SEA STATES

An undisturbed, spectral-based deep-water wave model was used with separate wave systems for 'sea' (wind waves generated locally) and 'swell' (longer wavelength waves generated far away). The wave spectra used to generate each sea state was a Joint North Sea Wave Project (JONSWAP) spectrum set according to definitions given in Table 1.

Table 1: Sea state (prevailing sea) definitions

Sea state	Significant wave height (m)	Wave period (s)	Wind speed (kts)
2	0.3	4.5	8
3	1.0	6.0	12
4	2.0	8.0	15

Superimposed on the sea spectrum, there was constant swell of 0.5 m significant wave height and 12s period at a 10-degree offset from the prevailing sea direction.

4.7 TEST PATTERN

The test pattern ensured coxswains travelled in every cardinal approach to the prevailing wave direction, i.e., following seas, quartering seas, etc. and is shown in Figure 5. Markers were placed in a pattern at a set distance of 1.5 km apart such that each 'leg' (i.e. moving from one marker to the next) is the same distance. Coxswains were required to go around the outside of the markers as indicated.

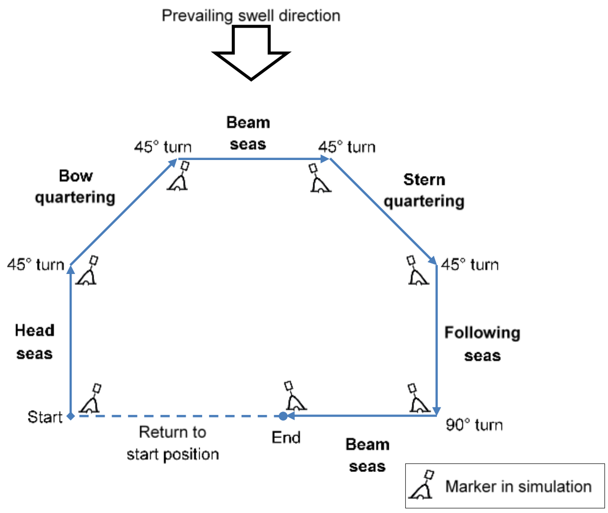

Figure 5: Test pattern

Since the distance between the markers was fixed, the number of wave encounters clearly varied depending on the chosen boat speed for a given sea state. Even if the boat movements had been identical between two different runs in the same sea state, the wave height as a function of position would not be the same due to statistical variation of the JONSWAP spectrum. However since the sea states were statistically stationary, the long-term average quantities (like SWH) remained constant and therefore one coxswain's performance was directly comparable to another, provided that comparison was made over a reasonable (i.e. statistically significant) number of wave encounters; as was the case for each 1.5 km leg or indeed the full 9 km test pattern. Putting it another way, the coxswains are essentially presented with the same mean conditions (and transit distance) and any differences in overall performance are attributable to the abilities of the coxswain to control the craft effectively.

4.9 RECORDED DATA

A range of quantities in the simulated environment and on the motion base were recorded. These are listed in Table 2. During the trial, raw time series logs of these quantities were written to a file.

Table 2: Data recorded during the trials.

Quantity	Location(s)	Data
Incoming wave height	Moving points located 1 m, 2 m and 3 m ahead of the craft bow.	Sea surface elevation
Incoming wave direction	Same as above	Sea surface wave direction of travel relative to the craft
Acceleration	Coxswain position	Accelerations in x, y, z-directions
Craft speed	Craft CoG (Centre of Gravity)	Velocity in x, y, z-directions
Craft heading	Craft CoG	Heading
GPS position	Craft CoG	Geographical position trace of craft
Throttle position	Throttle	Percentage application of the throttle.
Steering position	Steering wheel	Angle of the steering.
Boat force contributions	Body force contributions	Forces in x, y, z-directions as output by the boat model
Acceleration (real-world)	Coxswain position on the motion base	Accelerations in x, y, z-directions
Video recording (real-world)	Coxswain position	'Fly-on-wall' video

4.10 TRIAL SCHEDULE

NDP obtained a period of 2.5 simulator days. This excluded time to initialise the simulator and install real-world sensors, but included time for briefings, before and after the runs with trial participants. Each participant was given a half-day slot. The trial took place between 3rd – 5th March 2020.

Each coxswain undertook nine standard runs corresponding to three sea states and three control conditions. Several additional runs were also executed although these are not reported here for brevity.

4.11 POST-PROCESSING

Each run was output to a separate run logging file. This Section provides a high-level description of processing of raw time histories of the quantities described in Table 2. All processing was automated using MATLAB routines.

4.11 (a) Spatial windowing

One of the first steps in producing the results was to remove the following unwanted parts of the time histories:

- Corners: where the heading changes significantly from e.g. head seas to bow quartering seas,
- Initial acceleration and 'false starts': the boat getting up to speed at the run start and occasional short delays in starting a run where the boat could drift,
- Overshoots: at the end of the run, some coxswains stopped the boat while others carried on.

As illustrated in Figure 6, these unwanted time history Sections were identified based on spatial windows shown in red. This resulted in six separate legs for the different headings of approximately equal distance covered.

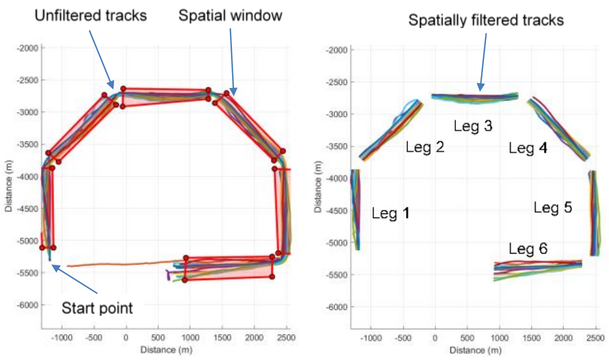

Figure 6: Splitting of unfiltered tracks using spatial windows to remove corners & initial acceleration at run start

4.11 (b) Vibration Dose Value (VDV)

The most common ways to describe the vibration experienced by a human occupant are the root-mean-square (rms) acceleration, the 8-hr normalised level (A(8)), and the Vibration Dose Value (VDV). For many vibration applications, the use of the A(8) value is preferred, as it provides a reference value which can be used to easily demonstrate the way exposure increases as a function of time relative to action and limit values.

The A(8) value, however, is not well suited to evaluating the exposure to combined shock and vibration, as it is insensitive to one-off, high-magnitude events typically associated with high speed craft operation. Acceleration time histories containing shock events are better represented by the Vibration Dose Value, which is an effective dose-response relationship between the human body and the input acceleration.

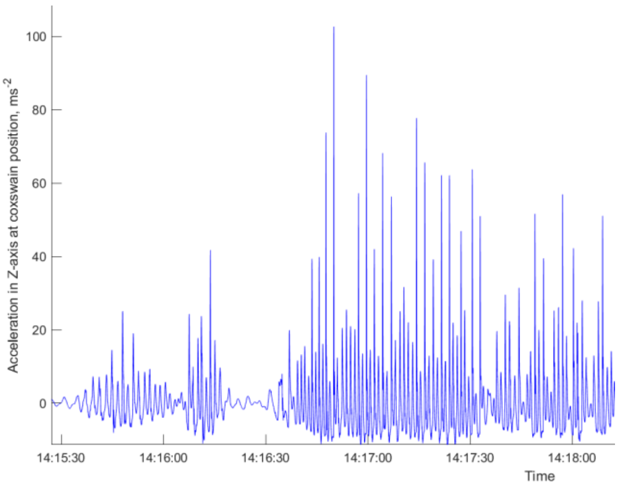

Figure 7: Acceleration time history at coxswain position

An example of the vertical acceleration trace from the simulator is shown in Figure 7.

The VDV of the acceleration time history is calculated as the integral of the fourth-root of the weighted acceleration time history raised to the fourth power. This is shown in equation format below:

$$VDV = \left(\int A(t)_w^4 \; dt \right)^{\frac{1}{4}}$$

where $A(t)_w$ is the weighted acceleration time history, with the exact weighting depending on; direction of stimulus, point of input to the human body, and purpose of the vibration assessment, and; the integration is made with respect to time. For the purposed of this study, as we are considering vertical vibration up into the human body only, the W_k weighting factor is applied, as defined in ISO 2631-1.

4.11 (c) Time to Limit Value (TTLV)

The Time To Exposure Limit Value, TTELV or TTLV, is back-calculated from the overall VDV for the given period to generate the amount of time the activity can be carried out for before an occupant is above the exposure limit value. For the purposes of this study, the following equation is used based on a daily limit value of $VDV_{threshold}$ = 21 ms$^{-1.75}$:

$$T_{VDV} = T\left(\frac{VDV_{threshold}}{VDV}\right)^{\frac{1}{4}}$$

where T_{VDV} is the time taken to reach the $VDV_{threshold}$ and T is the duration over which the VDV has been calculated.

4.11 (d) Impact-by-impact analysis

An algorithm was developed to identify and extract the conditions at each impact. Impacts are identified by being acceleration maxima over 2 m/s^2. Sections of the incoming sea surface elevation time history are cross-correlated against the acceleration time history to establish causality between acceleration peaks and a specific wave period as shown in Figure 8. The wave height is defined as trough-crest upward-crossing distance. The wave slope is the instantaneous steepness of the sea surface elevation.

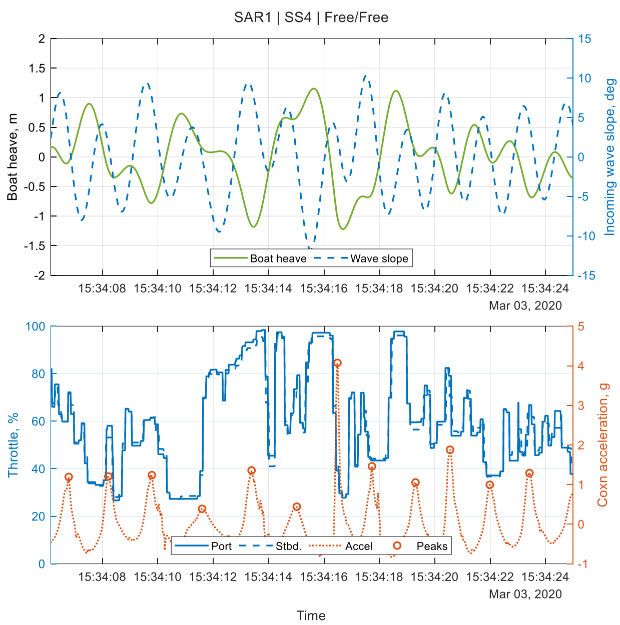

Figure 8: Impact-by-impact time series analysis

5. RESULTS & DISCUSSION

5.1 OVERALL PERFORMANCE

The overall VDV, transit time and distance travelled for each coxswain was calculated along with the sustained transit speed and Time to Limit Value (TTLV). Figure 9 shows that generally a higher sea state leads to higher VDV as expected. This is due to larger amplitude and/or more frequent shock events. The wave height increase means the boat drops from a greater height when leaving the crest of one wave, and hits the next wave resulting in a greater force on the boat and therefore acceleration at the coxswain position.

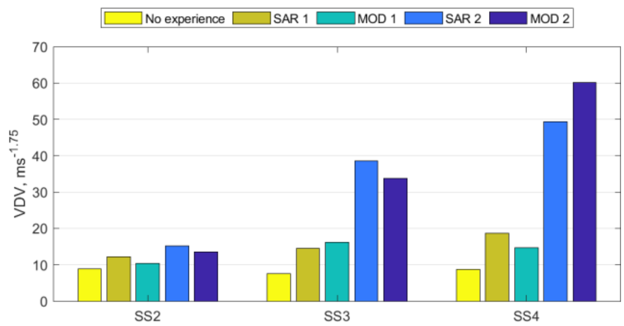

Figure 9: VDV across full test pattern for each coxswain as a function of sea state (Free/free control)

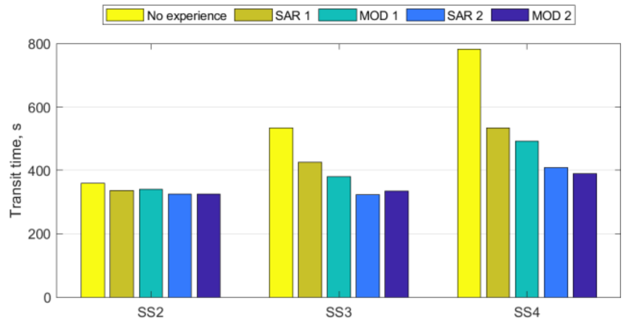

Figure 10: Transit time across full test pattern for each coxswain as a function of sea state (Free/free control)

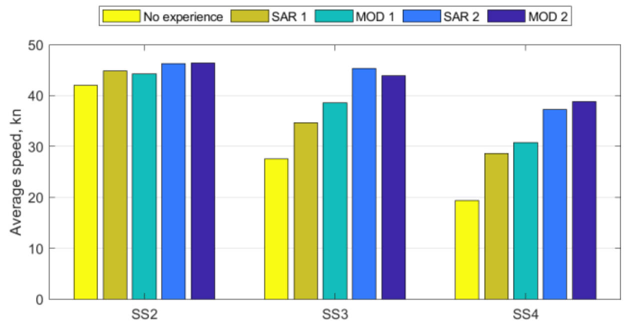

Figure 11: Sustained transit speed across full test pattern for each coxswain as a function of sea state (Free/free control)

It is important to note that, for all the results in this sub-section, the performance is taken over the test pattern as a whole. The test pattern takes 5-10 minutes to complete (excluding corners) and includes six different headings over an equal distance. As discussed further in Section 5.2, certain headings (e.g. head or bow quartering seas), have a dominant contribution to the VDV and will have been executed at a lower speed than other headings.

For a given sea state, there is a large variation in the VDV for different coxswains, even excluding the inexperienced coxswain. This is due to differences in the way each coxswain chose to control the craft. Some coxswains (SAR2 & MOD2 in particular) chose a significantly more aggressive speed (Figure 11), which led to lower transit time (Figure 10) at the expense of higher VDV (Figure 9). Clearly, although all coxswains were given the same brief, the interpretation of that brief by the experienced coxswains varied. It is postulated that, although all coxswains were all trying to balance risk in terms of achieving the mission quickly while exposing the 'casualty' to minimal unnecessary risk from shock, the experience and perception of risk was different for the SAR2/MOD2 coxswains compared to the SAR1/MOD1 coxswains. This led to a significant difference in sustained transit speed, and therefore VDV and transit time. The most risk averse and least confident was the inexperienced coxswain who had very long transit time and low VDV.

Plotting the range of transit speeds against the corresponding VDVs for each sea state, Figure 12 demonstrates that, in general, higher speed leads to a higher VDV. There are a few minor exceptions, such for SS4, where there is a slight decrease in VDV at a higher transit speed between the SAR1 and MOD1 coxswains. In this case, the MOD1 coxswain's control was clearly 'more optimal' than the SAR1 coxswain's. More effective control of the boat in terms of application of the throttle/steering is thought to be behind this, and this will be analysed later. Overall, speed is the biggest factor in determining the trend in VDV, and the selection of an 'optimal' speed will also require careful consideration of the risks of a mission as a whole (e.g. other factors that could lead to higher risk for the crew if the mission was accomplished more slowly). Further analysis to aid this decision process is given below.

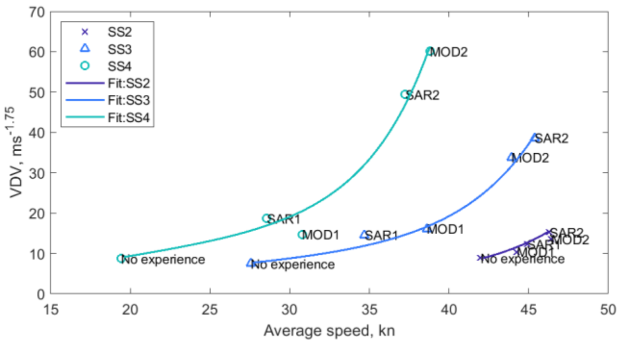

Figure 12: VDV as a function of sustained transit speed across test pattern for each sea state (Free/free control)

The data of Figure 12 can be normalised to highlight the benefit of reducing speed on minimising VDV and therefore shock exposure. Figure 13 plots the percentage reduction in VDV as a function of percentage reduction in speed. The percentage reductions are relative to the 'worst-case' coxswain with the highest VDV / speed for each sea state. There is a strong general trend (dashed line) in decreasing VDV with decreasing speed that applies independently of sea state. An equation of best fit is included. This shows the following:

- Initially a very steep curve: a small decrease in transit speed leads to a large decrease in VDV → a 10% speed reduction gives a 40% reduction in VDV.
- Diminishing returns: beyond a certain point, reducing the speed as the mission will take much longer but there is little to be gained in terms of VDV reduction.

Certain coxswains outperformed or underperformed by 5-10% compared with the general trend outlined above. This is attributable to the behaviour of individual coxswains in the way that they controlled the craft to minimise WBV whilst maximising transit speed, or otherwise.

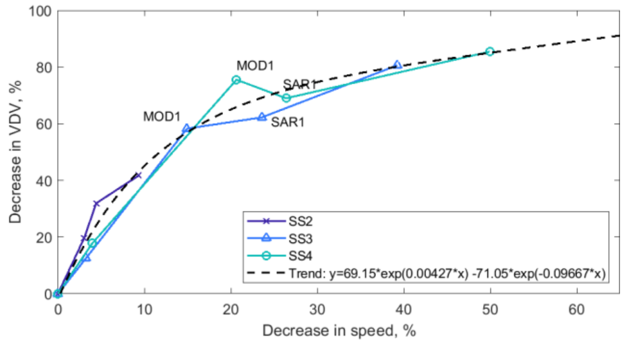

Figure 13: Benefit of decrease in transit speed on VDV relative to 'worst-case' coxswain (Free/free control)

The TLLV times vary greatly for each coxswain and sea state. In rough seas, the limit value is reached with only a few heavy (~8g) wave impacts and this is reflected in the results of the trial, particularly for the SAR2/MOD2 coxswains. Figure 14 shows the trends in TTLV as a function of speed for each sea state:

- Even in SS2, it shows the limit value is exceeded in less than an hour of continuous operation at a range of headings at the maximum speed.
- In SS3, to avoid exceeding the limit value in an 8 hour day, the speed would have to be reduced from the maximum ~45 kts to around 30 kts.
- In SS4, even at 30 kts instead of the maximum observed speed of ~40 kts, the limit value is exceeded in approximately 30 minutes.

The trends in seen in Figure 14 are approximate but compare favourably with those presented in the WBV DIN (Raeburn, 2016) for MOD high-speed craft. They could be further validated and extended by gathering more data using the simulator with different coxswains operating craft at different speeds and sea states. It should also be noted that the overall performance shown here represents a 'cumulative average' over the different headings. The TTLV could be even lower for continuous operation in, for example, head seas and this is discussed further in Section 5.2.

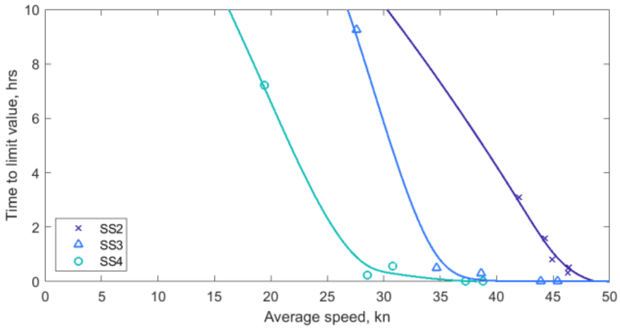

Figure 14: Time to limit value (TTLV) as a function of speed for each sea state

5.2 OVERALL VARIATION WITH HEADING

The approximately 8 km test pattern is made up of six headings, starting with head seas and finishing with beam seas. The results in this Section show how the same key metrics from Section 5.1 broken-down for each heading.

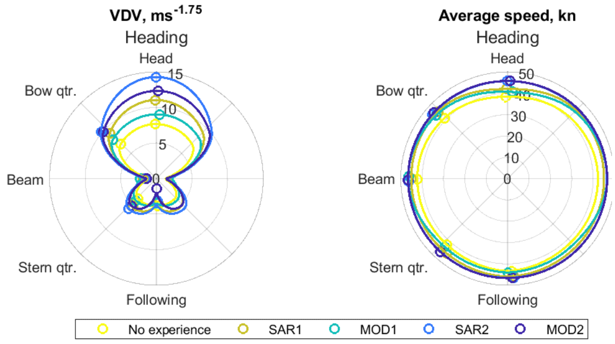

Figure 15: VDV / Transit speed variation with heading for each coxswain in Sea State 2 (Free/free control)

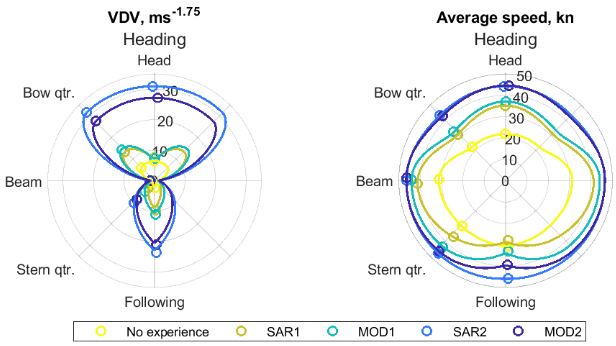

Figure 16: VDV / Transit Speed variation with heading for each coxswain in Sea State 3 (Free/free control)

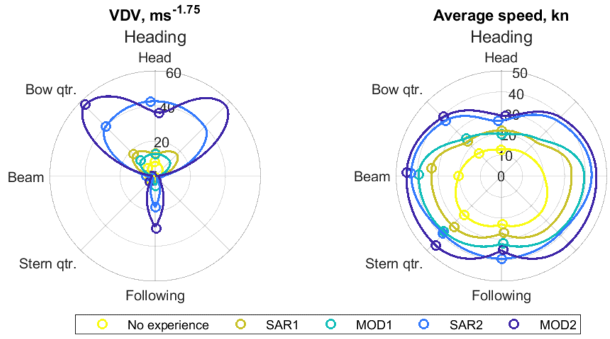

Figure 17: VDV / Transit Speed variation with heading for each coxswain in Sea State 4 (Free/free control)

Figure 15 shows that in SS2, while the transit times are similar for each heading, the overall VDV is dominated by the exposure during either the head or bow quartering seas. This is as expected because these headings involve travelling into and over the waves, and leads to wave impacts when the craft hits a wave or lands in a trough between waves. When travelling at most other headings, the coxswain is able to mitigate large impacts by navigating a path that does not involve such abrupt changes in heave.

Figure 16 shows that in SS3, the highest VDV is generally seen in bow quartering seas rather than head seas. The transit times are also noticeably longer for bow quartering seas, but also for following seas due to the coxswain's trying to avoid the waves overtaking the craft and subsequent yaw/broaching. The overall VDV is dominated by the exposure during either the head or bow quartering seas. The highest overall VDV values are seen where there is also a significant contribution to VDV during following seas.

Figure 17 for SS4 displays similar trends to SS3 except with a much higher VDV and transit time due to the waves being much larger. Again, the overall VDV is dominated by the exposure during either the head or bow quartering seas. The highest VDV values are seen where there is also a significant contribution to VDV during following seas.

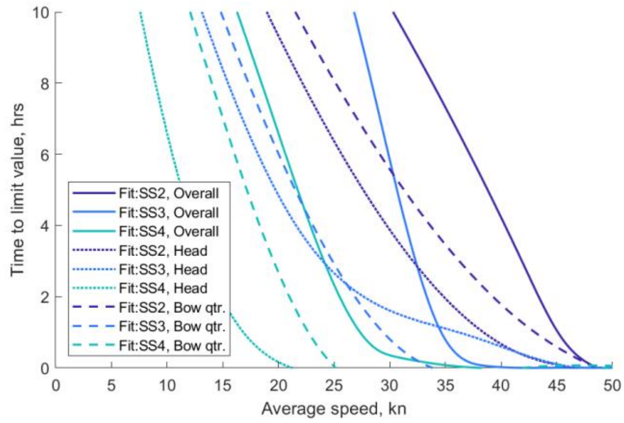

Figure 18: Comparison of TTLV as a function of speed for different headings and the overall TTLV (curve fits only, individual data points not shown)

The trends in TTLV with speed for the two worst headings in terms of VDV (Head / bow quartering seas) are shown in Figure 18. It is apparent that the overall TTLV (solid lines) are not a conservative estimate of the time it takes to reach the limit value if the majority of a mission is conducted in head or bow quartering seas (dash and dash-dot lines). This applies for all the sea states tested. Such performance curves taken in head seas or bow quartering seas could be used to estimate the worst-case TTLV in the event that the heading is not known, or if a mission will be carried out predominately in head or bow quartering seas.

5.3 OVERALL VARIATION WITH CONTROL CONDITION

The results in this Section show how the same key metrics from Section 5.1 compare for each of the control conditions:

A. Free/free – both control types (throttle & steering) are allowed. These are the values already presented in Section 5.1.
B. Throttle only
C. Steering only

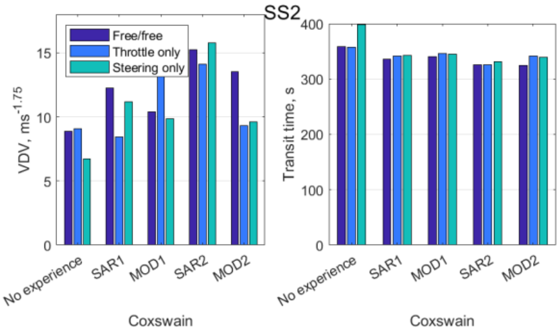

Figure 19: VDV / Transit time variation with control condition for each coxswain in Sea State 2

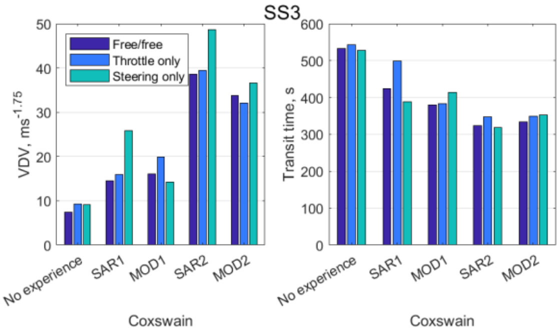

Figure 20: VDV / Transit time variation with control condition for each coxswain in Sea State 3

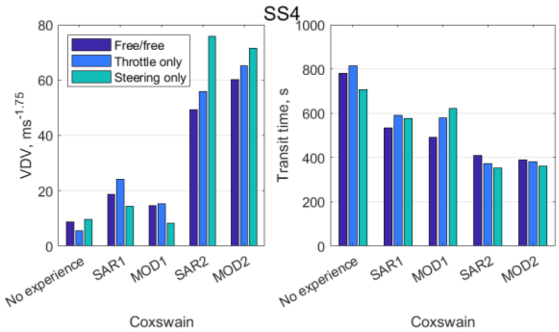

Figure 21: VDV / Transit time variation with control condition for each coxswain in Sea State 4

Looking across all sea states in Figure 19 to 21, there is a general trend of a significant increase in VDV for the steering only case while the transit times remains similar or increases (i.e. transit speed goes down). The trend is clearest in SS3/4 for the SAR2 and MOD2 coxswains who attained the highest speeds. There is also a general increase in VDV for the throttle only case but this appears to be less significant than the increase from having steering only. Figure 22 compares free/free control (solid curve) to throttle/steering only cases for SS3-4. It shows that, for a given transit speed, the lowest WBV is generally obtained under free/free conditions but for a few exceptions at very high or very low transit speed. These results indicate that the throttle is the most important control coxswains use when driving to minimise WBV at higher speeds. This is to be expected as all the experienced coxswains stated in their trial de-briefs that they use the throttle much more than steering to respond to the fast-changing conditions associated with rough sea operation.

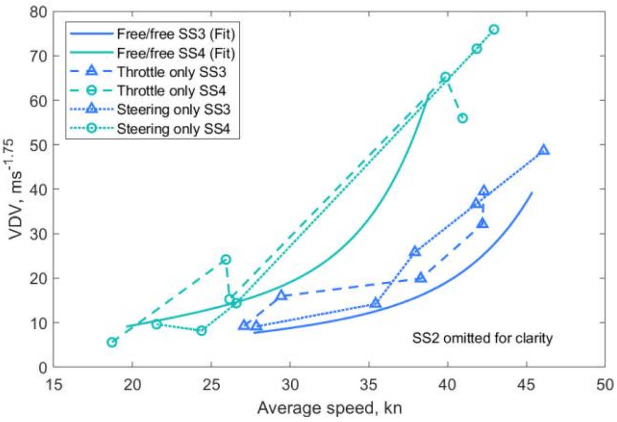

Figure 22: VDV as a function of sustained transit speed across the test pattern for SS3-4. Solid line shows free/free control and dash/dot line shows corresponding throttle or steering only results.

5.5 IMPACT-BY-IMPACT PERFORMANCE CHARACTERISATION

5.5 (a) Impact acceleration correlation parameters with boat speed and wave height or wave slope

For each individual impact, the wave height and wave slope are estimated as discussed in Section 4.11 (d).

Nieuwenhuis (Nieuwenhuis, 2005) found that both wave height and slope act as cues for coxswains to moderate craft speed in order to reduce the acceleration peak associated with impacting the sea surface while planing. However, it was to be determined for our simulator dataset which of these wave properties correlates most strongly with peak acceleration.

Figure 23 shows peak accelerations recorded in head seas for all coxswains plotted against craft speed multiplied by (a) wave height or (b) wave slope. The inclusion of craft speed in the correlation is important as the peak acceleration clearly depends on how fast the boat is travelling as well. This figure shows that for a broad range of boat speeds (0 – 45 knts) and wave slopes (0 – 12 deg), peak acceleration correlates most strongly with wave slope (R=0.81) compared to wave height (R=0.67). Intuitively this make sense that it is the steepest waves, not just those with the greatest height, that lead to the hardest impacts and therefore highest acceleration peak. Sea trial data also suggested a better correlation with wave slope over wave height (Nieuwenhuis, 2005).

It is apparent from Figure 23 that while there is a strong general trend (see dashed line) in impact acceleration, there is also significant scatter which increases in range with increasing boat speed/wave slope. This range is approximately +/- 2g either side of the general trend. In the remaining Sections, wave slope is used to characterise the severity of the encountered waves and the coxswain's ability to minimise impacts.

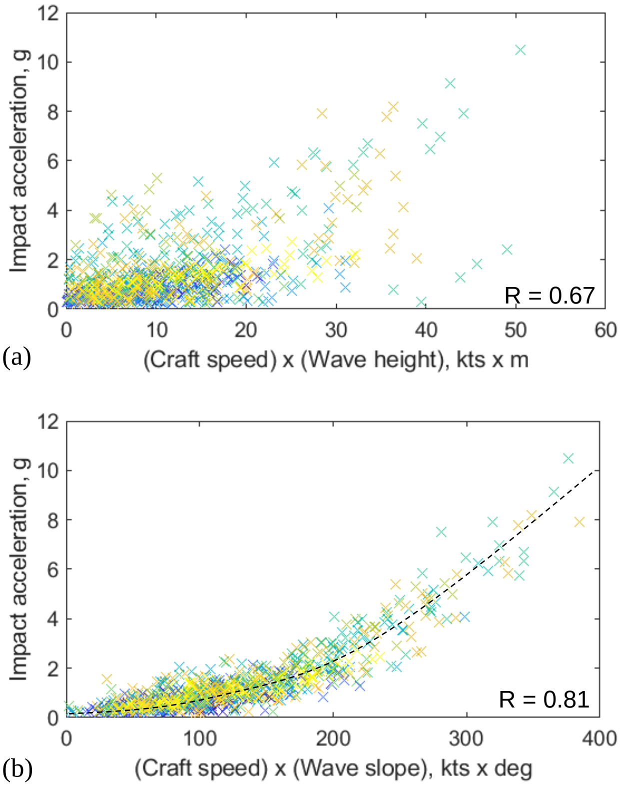

Figure 23: Correlations between impact peak acceleration and (a) Craft Speed x Wave height, compared to (b) Craft Speed x Wave slope. Different shades represent different runs.

5.5 (b) WBV operational maps

Using the same data presented in Figure 23, a performance map for each coxswain can be produced. This shows performance across all impacts in sea states 2-4 as a function of craft speed and wave slope. For the same craft speed and wave slope, there are data points with a range of peak accelerations. The performance map represents the mean peak acceleration across that range.

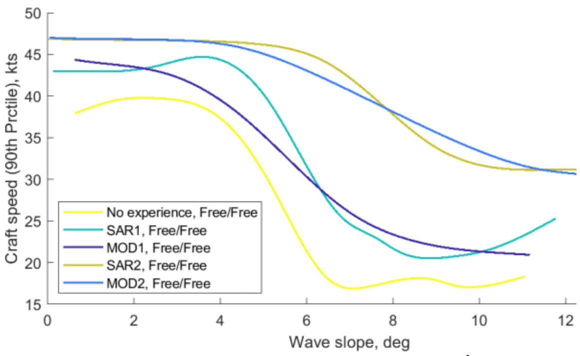

Figure 24: Top speeds for each coxswain (90th percentile) under all free/free control in head seas and sea states 2-4

Typical top speeds for each coxswain are shown in Figure 24. As further illustrated in Figure 25, two of the experienced coxswains (SAR2/MOD2) chose to operate at much higher speeds in steeper waves than the other two (SAR1/MOD1). Operating in top right of the operational map results in peak accelerations in the range 4-8g or more. The other two coxswains avoid operating in this range at all and hence their overall WBV levels are much lower. Additionally, for SAR2/MOD2 at around 35 knts, 8 deg, MOD2 is able to reduce peak accelerations to 4 – 6 g compared with 6 – 8 g or more for SAR2. In other words, for nominally the same incoming conditions, one coxswain reduces peak acceleration by ~10-20% relative to the other through effective use of throttle/steering. A similar advantage can be seen between SAR1/MOD1 at around 25 kts, 9 deg.

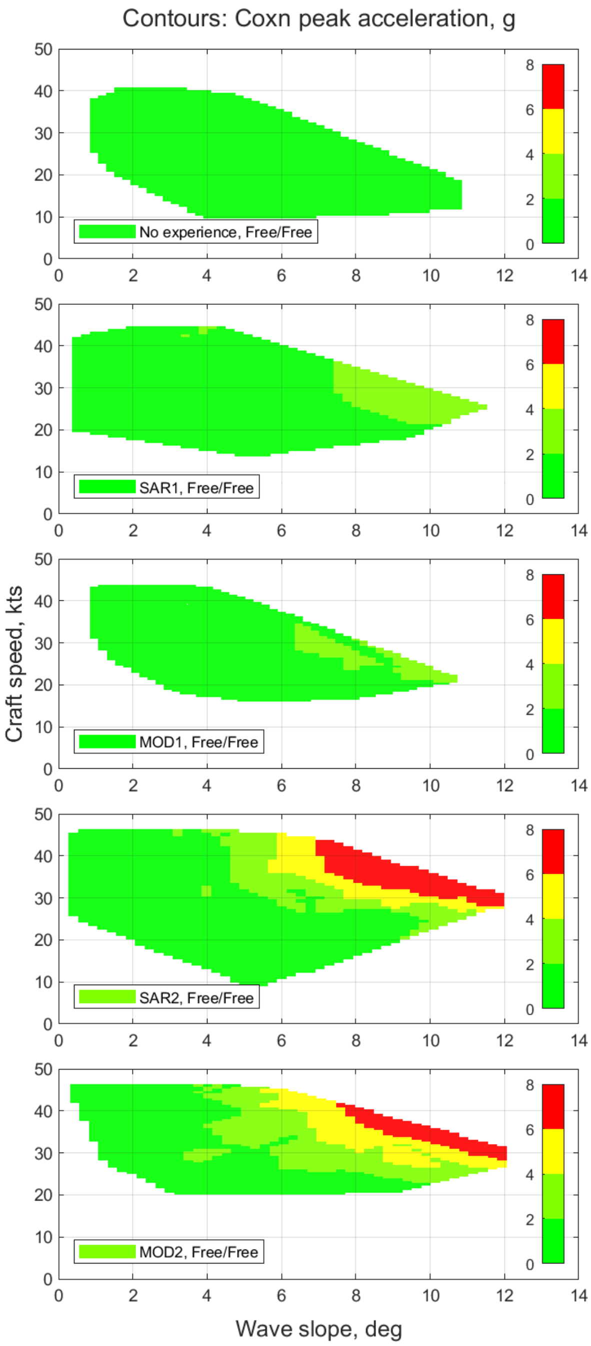

Figure 25: Operational map for each coxswain under free/free control in head seas and sea states 2-4

6. CONCLUSIONS

With reference to the two primary study objectives, the following conclusions are presented.

Objective 1: develop and demonstrate a systematic coxswain behaviour tracking methodology

This objective has been achieved by devising an innovative approach in which a high-fidelity fast craft simulator (developed by MARIN for the Dutch navy) is re-purposed to assess WBV. To the author's knowledge, a simulator approach has not been used before to study WBV and this has been enabled by new simulator technology. The demonstrated advantages of this approach, over the sea trial alternative, have been that it is:

• More repeatable: sea state can be easily fixed such that it presents the same conditions for each coxswain, eliminating the large variations in conditions which are always present in seas trials;
• More controllable: sea state conditions can be varied to give specific conditions within the range of interest.
• Accurate: the simulator been developed by a world-leading maritime research organisation for a similar purpose to our use case and as such is a highly accurate simulation. The trends recorded in WBV exposure compare favourable both in terms of magnitude and range with existing real-world data sources, such as (Raeburn, 2016).
• More accessible: it does not suffer from the many of the difficulties associated with getting good measurements of quantities such as boat accelerations, wave heights, boat control signals, etc. for multiple participants in a short timeframe.

The potential disadvantages of this approach for tracking coxswain behaviour are that:

• Coxswains may behave differently in studies to how they behave on a real boat as the perception of risk by coxswains will be different to in reality. There will always be coxswains who drive too aggressively because it is considered more of a game. This issue can be somewhat mitigated as long as there are multiple participants; it can actually make it easier to draw out trends in the data with a range of behaviours to compare. In the case of this study, confidence in these trends can be increased through further sea trial work, informed by the simulator trial data.
• Impacts 'hurt less' on a simulator. The peak accelerations are limited by the motion platform and are lower than output by the fast craft model. While this was not a significant issue for this study, if the simulator was used to train less experienced coxswains, it may provide an unrepresentative example to trainees of what happens if they drive too fast. Simulator motion platforms with higher peak accelerations are being developed.
• Some experienced coxswains moderate their speed based on the impacts/pain they feel and are more likely to 'drive too fast' without simulator study controls in place.

As a methodology for tracking coxswain behaviour, on balance, the approach is well suited to WBV studies of this type. Other applications of this approach could be to benchmark coxswains under controlled conditions (*viz* a driving test), to provide systematic feedback on training needs and identify coxswains best suited to execute a certain mission. Simulators are already being used extensively for lifeboat emergency training (Billard et al, 2020). They can also be used for other human factors research studies.

Objective 2: quantify the impact of sustained transit speed on shock

This objective has been achieved in a simulated setting and the following key conclusions drawn:

• The experienced coxswains demonstrate a range of behaviour and this is distinct from that of an inexperienced coxswain. Overall there is no single optimum transit speed to reduce WBV but several straightforward trends have been identified that could aid mission planning for WBV reduction.
• A general trend has been established around the benefit of reducing speed on WBV, independent of the sea state (SS2 – 4). On the assumption that VDV is a good indicator of risk associated with WBV, this trend indicates that mission planners could significantly reduce WBV risk to crew with modest (i.e. 5%) reduction in sustained transit speed (equivalent to increasing transit time). This general trend requires further validation using sea trial data. Certain coxswains out-performed or under-performed relative to the general trend by 5-10% which would be a significant reduction in VDV if achieved through increased training and experience alone.
• By breaking-down the contribution to VDV by heading (head seas, bow quartering seas, etc.), the importance of taking into account the prevailing sea conditions into mission planning on WBV has been demonstrated. Overall TTLV curves such as those in Figure 14 or the DIN (Nieuwenhuis, 2005) may be non-conservative. A more accurate approach would be to include curves as a function of the prevailing swell direction.
• By quantifying the relative performance of coxswains when they are not able to control the boat using either the throttle or the steering; effective throttle control has been shown to be much more important than steering to reduce WBV. While this is to be expected based on feedback, it highlights the importance of understanding what constitutes effective throttle control (i.e. what is one coxswain doing that another is not) to reduce WBV.

Further work is required before the findings of this study can be fully exploited. Later phases would aim to provide validation and further evidence to support (or potentially contradict) the conclusions outlined above. This work should include a sea trial where coxswain behaviour is tracked in a similar way but under real-world conditions. This verified dataset can also be used to train or test autonomous feedback/control algorithms which aim to minimise potentially damaging impacts.

7. ACKNOWLEDGEMENTS

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