

Assessing motion induced loss of operability on small and medium-sized fishing vessels through motion measurements

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ABSTRACT

Vessel motions directly affect the crew's ability to perform onboard tasks, influencing both operational efficiency and safety. This study investigates motion induced operability loss in real fishing conditions using onboard measurements collected from a commercial coastal trawler operating in the NW Mediterranean Sea. A dataset of 19 fishing trips was acquired using a low-cost inertial measurement unit (IMU) and Global Navigation Satellite System (GNSS) receiver installed in the wheelhouse, enabling the continuous recording of vessel accelerations and trajectory during normal fishing operations. The analysis focuses on two established motion-related indices: the Nordförs standard, based on root mean square (RMS) vertical accelerations, and the Motion Induced Interruption (MII) index, based on horizontal accelerations and task interruption probability. Results show a strong dependence of vessel accelerations on local wave conditions and operational regime. Lower vessel speeds are systematically associated with higher motion levels and increased exceedance of operability thresholds. Overall, the study demonstrates the applicability of existing indices to real operational data, while highlighting the need to adapt operability metrics to the specific conditions of small-scale fishing vessels.

1. Introduction.

Vessel motions directly influence the crew's ability to perform onboard tasks. This issue is particularly relevant for fishing vessels, where the main part of operational tasks is carried out at sea instead of when they are berthed in port. The unique operational characteristics of fishing activities have long been acknowledged by the International Maritime Organization (IMO), which established specific safety requirements through the 1977 Torremolinos International Convention for the Safety of Fishing Vessels.

These provisions were subsequently revised by the 1993 Torremolinos Protocol and further updated through the Cape Town Agreement of 2012, adopted as an annex to the Protocol (International Maritime Organization, 2012).

Despite ongoing regulatory efforts, the fishing sector continues to exhibit a disproportionately high accident rate. According to the European Maritime Safety Agency (EMSA), fishing vessels accounted for the 16% of all reported accidents involving European vessels in 2024. However, they were involved in 29% of all serious and very serious accidents. Notably, fishing was the only vessel category for which more than 50% of reported accidents were classified as serious or very serious, highlighting the elevated risk associated with fishing operations (European Maritime Safety Agency, 2025). The situation is even more pronounced in Spain, where fishing vessels were involved in 78% of all reported maritime accidents during the year 2024, according to the Spanish Maritime Accident and Incident Investigation Commission (CIAIM) (Comisión Permanente de Accidentes e Incidentes Marítimos, 2024). These fig-

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ures underscore the persistent safety challenges faced by the fishing industry and emphasize the need for improved risk assessment and mitigation strategies.

A defining characteristic of fishing activities is that cargo handling takes place at sea rather than in port, while both the quantity and distribution of the catch remain uncertain throughout the operation. This directly affects vessel stability, as hauling activities may generate heeling moments of unknown magnitude during gear recovery (Mantari et al., 2011). Consequently, the stability and dynamic behaviour of fishing vessels are critical factors for ensuring safe and efficient fishing operations. Moreover, the metacentric height (GM), may vary considerably throughout a fishing trip as catch is accumulated onboard and fuel and consumables are depleted. In this regard, Míguez González et al. (2016) and Santiago Caamaño et al. (2019, 2022) developed a methodology for estimating the evolution of GM during fishing operations, highlighting the importance of continuously assessing vessel stability under changing loading conditions. These issues are particularly relevant for small-scale fishing vessels, where the catch may represent a substantial fraction of the vessel displacement, resulting in significant changes in both displacement and the position of the centre of gravity. Despite their vulnerability, small fishing vessels remain subject to relatively limited regulatory requirements concerning stability and operational safety. To date, one of the most comprehensive efforts to establish common safety criteria for small fishing vessels has been undertaken by the Wolfson Unit (Deakin, 2006). Based on an extensive series of towing tank experiments involving vessels under different loading conditions, the proposed criteria establish minimum freeboard requirements for fishing vessels shorter than 15 m. Unlike many commercial vessels, coastal fishing vessels retain the possibility to decide on a daily basis whether to leave port. Such decisions are strongly influenced by weather forecasts and anticipated sea conditions, with adverse weather often leading fishers to postpone or cancel fishing trips (Pfeiffer, 2020). However, operational decisions are often evaluated primarily from a safety perspective, whereas less attention is paid to the gradual degradation of operability that may occur before safety limits are reached.

The study of vessel motions extends beyond traditional assessments of intact stability and specific dynamic phenomena. Motions directly affect crew welfare and performance, progressively reducing comfort, operability, and safety. The effects of vessel motion on human performance have been extensively investigated, particularly in relation to motion sickness. Early studies focused on understanding the physiological mechanisms responsible for seasickness among untrained individuals, such as ferry and cruise ship passengers, leading to the development of indices such as the Motion Sickness Incidence (MSI) (Lawther & Griffin, 1986b; O'Hanlon & McCauley, 1974). In addition, Lawther and Griffin (1986a) introduced the concept of the Vomiting Incidence (VI), a metric used to quantify the likelihood of motion-induced sickness, and discussed the influence of individual factors such as age, sex, and previous exposure to motion environments on susceptibility to seasickness. More recently, Arnardottir et al. (2022) investigated the prevalence

of motion sickness among Icelandic fishers through a large-scale survey involving more than 250 participants. The study highlighted the persistence of motion-related symptoms even among professional seafarers and explored potential associations between years of maritime experience and long-term occupational health effects, including hearing loss. However, the consequences of vessel motion are not limited to seasickness. Long before motion sickness develops, individuals may experience discomfort, fatigue, reduced concentration, and increased physical effort when performing routine tasks. These effects can occur even among experienced seafarers who are accustomed to working in a dynamic environment. As motion levels increase, the resulting degradation of human performance may progressively affect the execution of onboard operations, reducing productivity and increasing the likelihood of errors and accidents. In this context, vessel motions can be viewed as a continuum affecting comfort, operability, and safety, with each stage representing a progressively greater impact on crew performance and vessel operations (Baitis et al., 1984; Graham, 1990).

Despite the recognized influence of vessel motions on crew performance, the assessment of welfare and operability onboard fishing vessels remains insufficiently addressed by existing reference indices. Most of the commonly used metrics were not originally developed for fishing operations and therefore do not fully capture the specific challenges faced by fishing crews. Among the most widely cited indicators are the MSI and the VI, both of which were primarily developed for passenger vessels and focus on predicting discomfort and motion-induced sickness rather than operational performance or task execution. While these indices provide valuable information regarding human exposure to vessel motions, they offer limited insight into the ability of professional seafarers to safely and effectively perform their duties onboard. More recent approaches, such as the ISO 2631 standard, evaluate human exposure to whole-body vibrations and accelerations, considering their effects on comfort, health, and the performance of manual and cognitive tasks (International Organization for Standardization, 2008). However, the standard was primarily developed for occupational environments on land, where exposure is typically associated with vibrations transmitted through machinery, vehicles, or fixed workstations. In contrast, seafarers operate within an environment in which the entire workspace is continuously subjected to large-scale oscillatory motions induced by waves and vessel dynamics. Another widely used criteria is the Nordforsk (1987) standard, which characterizes the ability to perform different tasks as a function of the root mean square (RMS) vertical acceleration, providing a practical framework for evaluating operational limitations in offshore environments (Zu et al., 2024). With regard to operability degradation, the only widely used index that explicitly relates vessel motions to task interruption is the Motion Induced Interruption (MII) index, originally developed for naval applications (Baitis et al., 1984; Graham, 1990). Although MII provides a direct link between ship motions and the probability of operational disruption, its formulation may not be fully representative of the operating conditions typically encountered by small and medium-sized fishing vessels, where

working tasks, vessel size, and loading conditions differ substantially from those assumed in naval contexts. These indices have recently been reviewed by Park et al. (2024), who conducted a comparative theoretical assessment across 16 fishing vessels. In that study, vessel seakeeping behaviour was numerically evaluated to estimate the occurrence of both MSI and MII under a range of sea states, highlighting the sensitivity of these indices to vessel characteristics and environmental conditions. Alternative approaches have also been proposed from a safety and accident-risk perspective. Islam et al. (2018) developed a probabilistic framework based on Bayesian networks to estimate the likelihood of human-error-related accidents in maritime environments. Their model incorporates multiple contributing factors, including environmental conditions, perceived stress, vibration levels, and vessel motions, to quantify accident probability as a function of operational context. Complementary insights have been obtained from experimental laboratory and field studies on human balance and postural stability under ship-like motions. Stoffregen et al. (2013) investigated postural activity in individuals exposed to motion environments both in laboratory settings and onboard a vessel. Their study examined several indicators of postural adaptation, including mean stance width, highlighting the strategies adopted by individuals to maintain balance under dynamic conditions. Fosha et al. (2024) investigated whether crew members on small-scale coast guard vessels require handrail support to maintain balance under different motion conditions, using the results to propose design improvements for bridge layout and handrail placement. Similarly, Choi et al. (2022) analysed human walking performance on a moving platform subjected to varying roll amplitudes, with the aim of identifying motion thresholds associated with loss of balance and fall risk. Collectively, these studies illustrate the multifaceted nature of motion-related operability degradation, although a unified framework specifically tailored to the operational realities of fishing vessels remains lacking.

A common underlying element across indices related to crew well-being, operability, and safety is that they are fundamentally driven by onboard accelerations. Excessive accelerations at sea have been formally recognized under the IMO's Second Generation Intact Stability Criteria (SGISC), where they are identified as a potential contributing factor to accidents onboard (International Maritime Organization, 2020). In this context, Rosano et al. (2023) investigated the occurrence of excessive accelerations on a fishing vessel by combining numerical simulations with experimental tank tests, highlighting the relevance of accurately predicting acceleration levels in realistic operating conditions. From the perspective of task performance, more recent studies have shifted the focus from vessel motion itself to the motion experienced by the crew. In this regard, Yang et al. (2026) monitored the linear and angular accelerations of 17 individuals while performing different onboard tasks, enabling the classification of human motion exposure under operational conditions. This approach reflects a growing interest in characterizing the dynamic interaction between vessel motions and human movement, rather than considering ship dynamics in isolation.

Furthermore, the experimental basis of most existing wel-

fare and operability indices relies predominantly on controlled laboratory studies or theoretical analyses. In many cases, human subjects are exposed to prescribed motion patterns under land-based experimental conditions. As a result, the direct applicability of these indices to the assessment of operability loss and crew welfare on fishing vessels remains limited. These limitations highlight the need for approaches that explicitly account for vessel motions under real operational conditions and, where necessary, for the development of new indicators of operability loss specifically tailored to small and medium-sized fishing vessels. In this context, the present study provides preliminary results based on the analysis of a coastal fishing vessel motions derived from onboard measurements. Data from Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU) sensors are combined to characterise vessel dynamics during fishing operations. The primary objective is to identify the most relevant components of vessel motion, with particular emphasis on linear accelerations, and to investigate their influence on crew welfare and operational capability in realistic working conditions.

This paper is organised as follows. Section 2 presents the case study, including the characteristics of the vessel under investigation, the operating area and the instrumentation used for data acquisition. Section 3 describes the proposed methodology, including the procedures adopted to compute the motion-induced operability loss indices. Section 4 presents the results obtained from the application of the two indices used across the different fishing trips and discusses the findings as they are introduced. Finally, Section 5 summarises the main conclusions of the study and outlines directions for future work.

2. Case study.

The present study provides a dataset of real operational measurements collected onboard a commercial fishing vessel, which is used to evaluate the applicability of two existing welfare and operability indices, the Nordforsk standard, based on vertical accelerations, and the MII index, based on horizontal accelerations, under real fishing conditions. The case study focuses on the Catalan bottom trawling fleet operating in the north-western Mediterranean Sea. Bottom trawling constitutes the 36% of the Catalan fishing fleet in terms of vessel numbers and accounts for 34% of total landings, while generating nearly 60% of the economic revenue of the sector (ICATMAR, 2024). The average vessel within this fleet is 20 m in length and has a gross tonnage (GT) of 53 t (European Commission, 2025). Vessel motions were monitored onboard a commercial trawler measuring 21 m in length and 44 GT, which can therefore be considered representative of the Catalan bottom trawling fleet. The dataset comprises 19 independent fishing trips, each corresponding to a complete fishing day lasting between 9 and 12 hours. Data were collected during field campaigns conducted between June 2024 and March 2026. Table 1 summarises the sampling campaigns and the prevailing sea-state conditions during each survey, including the mean significant wave height and wave period within the fishing area. The resulting dataset provides a unique opportunity to assess vessel motions and associated

welfare and operability indicators under real operational conditions, complementing previous studies based primarily on theoretical analyses or controlled laboratory experiments.

Vessel motions were monitored using a low-cost, open-source instrument integrating an IMU and a GNSS receiver (Figure 1). The system is based on a SparkFun OpenLog Artemis board equipped with an ICM-20948 IMU, which incorporates a three-axis accelerometer and a three-axis gyroscope, together with a SparkFun ZOE-M8Q GNSS receiver for monitoring vessel position, speed, and trajectory (SparkFun, 2024). The accelerometer supports full-scale measurement ranges of up to ± 16 g, while the gyroscope can measure angular velocities up to $\pm 2,000$ $^{\circ}/s$. For the present study, the accelerometer was configured to a range of ± 2 g in order to maximise measurement resolution, as the expected vessel accelerations were well within this interval.

Following each fishing trip, the vessel motion dataset was complemented with environmental data describing the wave conditions encountered during the operation. Wave information was obtained from the Copernicus Marine Service (2026), which provides hourly estimates of wave height, period and direction with a spatial resolution of $1/24^{\circ}$. To obtain wave conditions representative of the vessel's actual operating environment, the Copernicus data were interpolated both spatially and temporally along the recorded vessel trajectory. This procedure enabled the assignment of local sea-state parameters to each position and time instant within the motion dataset, thereby allowing the relationship between vessel motions and environmental forcing to be analysed under real operational conditions.

Table 1: Summary of the field campaigns.

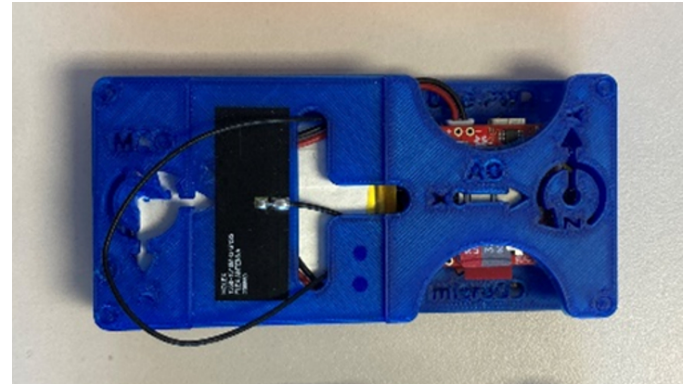
Campaign	Mean significant wave height (m)	Mean wave peak period (s)
01	1.1	5.7
02	0.5	4.2
03	0.5	5.7
04	0.5	5.4
05	0.6	5.2
06	0.8	5.7
07	1.7	7.2
08	1.8	7.2
09	1.6	7.4
10	1.0	6.7
11	0.4	5.6
12	1.1	8.7
13	0.4	6.6
14	0.5	4.9
15	0.9	7.4
16	0.7	4.3
17	0.5	6.0
18	0.4	3.9
19	1.3	9.4

Source: Authors.

The instrument was partially validated in previous studies by Carrasco-Serra et al. (2024) and Mujal-Colilles et al. (2022), where monitoring campaigns were conducted onboard three different vessels. These validation exercises included independent reference measurements to assess the accuracy of the orientation estimates derived from the IMU data. Data were acquired

at a sampling frequency of 10 Hz, providing sufficient temporal resolution to capture vessel motions while simultaneously recording GNSS information. Raw sensor measurements were subsequently post-processed to estimate vessel orientation using the MATLAB *imufilter* algorithm (MATLAB, 2026), which combines accelerometer and gyroscope data through sensor fusion techniques to obtain continuous estimates of roll and pitch.

Figure 1: SparkFun OpenLog Artemis IMU installed in a custom-designed housing.



Source: Authors.

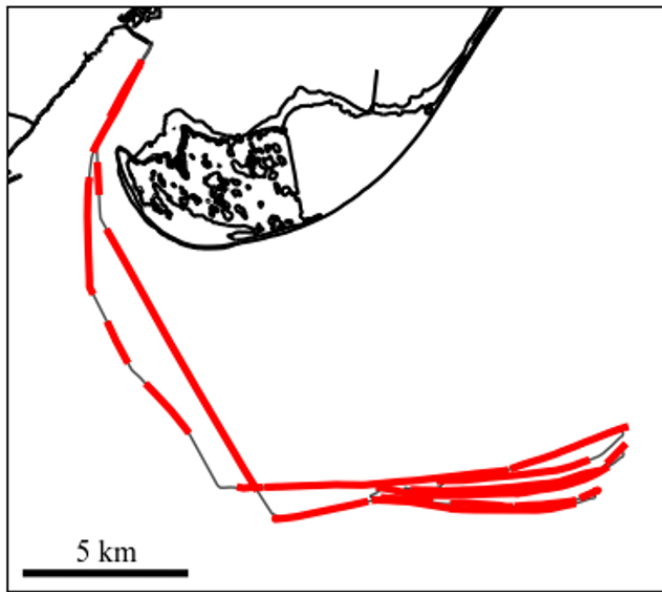
During the field campaigns, the instruments were installed inside the wheelhouse, slightly offset towards the starboard side to avoid interfering with the skipper's normal operations. Two identical devices were deployed simultaneously to provide measurement redundancy and minimise the risk of data loss in the event of sensor malfunction or recording failure.

3. Methodology.

The analysis was conducted on a set of steady-navigation segments identified from the 19 fishing trips included in the study. A segment was considered steady when the vessel maintained an approximately constant speed and course. To identify these periods, the Speed Over Ground (SOG) and Course Over Ground (COG) records were analysed using a 3-minute moving window, within which the standard deviation of each parameter was computed. A time interval was classified as part of a steady-navigation segment when the standard deviation remained below 1 knot for SOG and 2.5° for COG. A segment was considered to terminate when either of these thresholds was exceeded. Figure 2 illustrates the steady-navigation segments identified during one representative fishing trip.

For each segment, both the Nordforsk vertical acceleration criteria and the MII horizontal accelerations were evaluated. Prior to the analysis, the acceleration signals were low-pass filtered to retain only frequency components below 1 Hz. This cut-off frequency was selected based on established comfort and operability criteria, which indicate that the motion frequencies most strongly associated with motion sickness, discomfort, and reduced operational performance typically occur below 1 Hz (International Organization for Standardization, 2008;

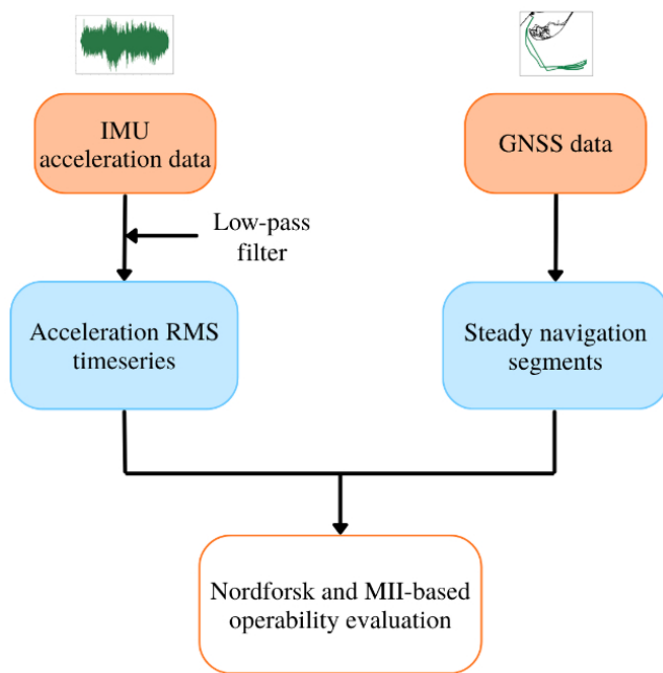
Figure 2: Steady-navigation segments for one representative day.



Source: Authors.

Lawther & Griffin, 1986b; O'Hanlon & McCauley, 1974). Figure 3 summarises the overall analysis workflow, from IMU data acquisition and filtering to segment identification, motion metric computation, and the evaluation of their relationship with wave conditions and vessel speed.

Figure 3: Schematic overview of the data-processing workflow.



Source: Authors.

The Nordforsk (1987) standard defines reference thresholds,

based on the RMS value of vertical acceleration, for assessing crew welfare and the ability to perform manual and cognitive tasks. These thresholds are used to identify vibration levels beyond which human comfort and task performance are progressively degraded. Table 2 summarises the maximum RMS vertical acceleration levels associated with different categories of onboard activities, indicating conditions under which the execution of specific tasks may become impractical or unsafe. In the present study, the RMS value of vertical acceleration is computed using a 3-minute moving window applied over the entire fishing trip, providing a quantitative description of the acceleration levels experienced in the vessel wheelhouse throughout the day. The selected 3-minute window length represents a compromise between capturing the overall dynamic behaviour of the vessel and filtering out short-duration transient phenomena, such as individual wave impacts, while still preserving sufficient temporal resolution to identify variations in operability within the analysed period (Santiago Caamaño et al., 2018). According to International Organization for Standardization (2008), human exposure should be evaluated in terms of the vertical accelerations transmitted to the body in a global reference frame. In this study, it is assumed that fishing vessel crews partially adapt their posture to vessel motions during normal operations, so that the effective vertical direction of the human body is more closely aligned with the global vertical axis than with the ship-fixed reference frame.

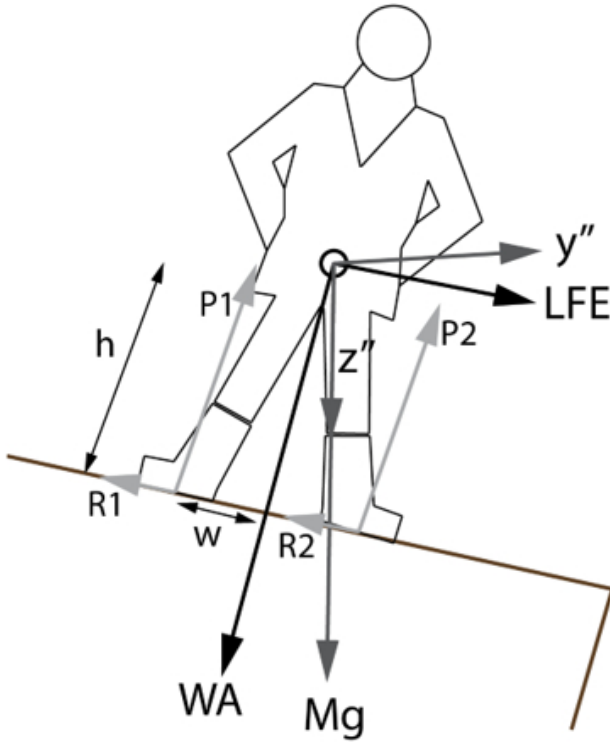
Table 2: Reference RMS vertical acceleration thresholds for task performance (Nordforsk, 1987).

Vertical acceleration (m/s ² RMS)	Associated activity
0.50	Passenger transit
1.00	Intellectual tasks
1.50	Heavy manual tasks
2.00	Light manual tasks
2.70	Basic activities

Source: Authors.

The MII, proposed by Baitis et al. (1984) and Graham (1990), relates the lateral accelerations experienced by individuals to the probability of task interruption resulting from the need to hold onto surrounding structures or adjust foot placement in order to maintain balance. This index is based on a simple force-balance approach: when the inertial force generated by lateral accelerations exceeds an individual's restoring capability, loss of balance occurs. To quantify the effective horizontal acceleration acting on a person, the Lateral Force Estimator (LFE) is used, as defined in Eq. (1). The force-balance model is illustrated in Figure 4. The restoring capability is influenced by several factors, including the position of the centre of gravity, stance width, and body orientation relative to the direction of acceleration.

Figure 4: Force-balance diagram used in the definition of the Lateral Force Estimator (LFE). Adapted from González Álvarez-Campana (2007).



Source: Authors.

$$LFE = m [(g - \ddot{z}) \sin \theta - \ddot{y} \cos \theta] \quad (1)$$

where:

m = mass of the person

g = acceleration due to gravity

z = vertical acceleration

y = the lateral acceleration

θ = inclination angle of the deck

To facilitate the practical estimation of MII events, González Álvarez-Campana (2007); Matsangas et al. (2014) adapted the reference thresholds originally proposed by Baitis et al. (1984), linking lateral acceleration levels to expected interruption rates and providing a simplified framework for assessing the likelihood of motion-induced interruptions. This approach enables a first-order assessment of the impact of lateral accelerations on onboard activities, independently of the specific characteristics or orientation of the exposed individual. Table 3 summarises the expected rate of motion-induced interruptions as a function of RMS horizontal acceleration. As with the analysis of vertical accelerations, the LFE is computed using a 3-minute moving window in order to characterise temporal variations in operability throughout the analysed period.

Table 3: Reference thresholds of RMS horizontal acceleration for the MII index (Baitis et al., 1984; Matsangas et al., 2014).

Lateral acceleration (m/s ² RMS)	Expected MII
0.79	Possible interruptions
0.98	Probable interruptions
1.18	Serious interruptions
1.37	Severe interruptions
1.57	Extreme interruptions

Source: Authors.

In the present work, the overall horizontal acceleration is computed as the magnitude of the horizontal acceleration vector (Eq. 2). The presented MII indices are primarily defined in terms of lateral accelerations transverse to the vessel. It is noted that most on board horizontal accelerations are indeed associated with transverse ship motions. However, any horizontal acceleration, regardless of whether it acts in the transverse or longitudinal direction, may potentially interrupt onboard tasks performed by individuals. For this reason, all horizontal acceleration components are considered in the present analysis. Since the IMU is fixed to the vessel and rotates with its motions, the measured local acceleration components inherently include the effects of deck inclination, which is explicitly accounted for in Eq. (1) through the inclusion of the tilt angle.

$$A_H = \sqrt{a_x^2 + a_y^2} \quad (2)$$

where:

a_x = longitudinal in the fore-aft axis

a_y = transversal in the port-str axis

Across all fishing trips, the temporal evolution of RMS acceleration over the full day is analysed, together with its statistical behaviour during steady-navigation periods. In addition, time-weighted mean RMS values are computed for these steady segments in order to investigate their dependence on vessel speed and wave incidence angle. This dual approach enables both a global characterization of acceleration variability over time and an assessment of operability under the quasi-stationary navigation conditions that characterize the steady segments. Two operational regimes are considered in the analysis: a low-speed condition, defined as vessel speeds below 4.5 knots, and a high-speed condition, defined as speeds above this threshold. This threshold is used to distinguish between fishing operations, which are typically conducted at low speeds, and transit phases, including navigation between port and fishing grounds, between fishing areas, or returning to port. This separation enables the evaluation of how speed influences motion exposure and associated operability indicators under varying environmental conditions.

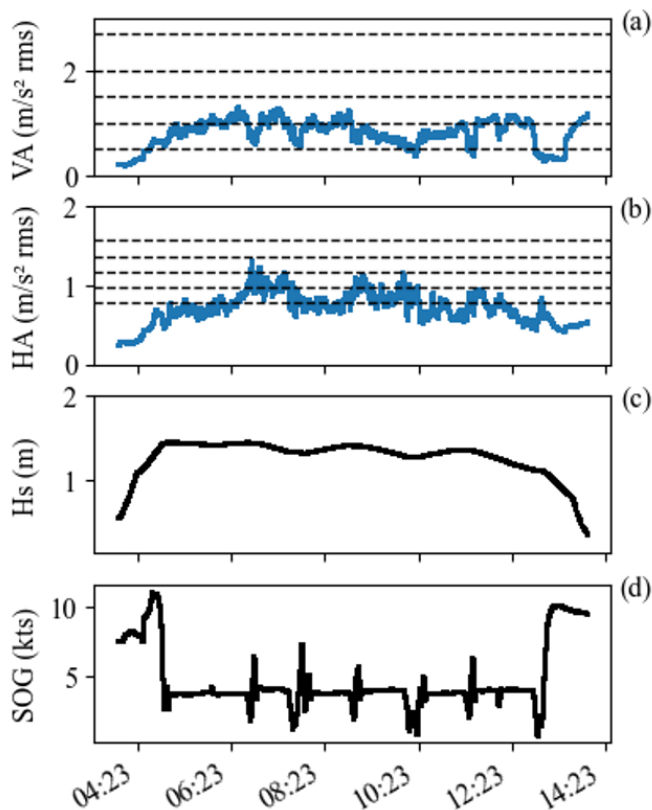
4. Results and discussion.

This section presents the results obtained by applying the RMS to both vertical and horizontal acceleration signals using a 3-minute moving window. In addition, the values obtained

within each steady-navigation segment are analysed across all days included in the study. The results are compared with the reference thresholds defined by Nordforsk and the MII criterion (Tables 2 and 3).

Figure 5 shows the time series of vertical and horizontal acceleration for one representative day, together with the corresponding significant wave height (Hs) and vessel's SOG throughout the same period. Both indices exhibit a strong dependence on the local environmental and operational conditions at the time and location of measurement. A clear relationship can be observed between the measured vessel accelerations and the wave conditions present during the navigation, with increasing wave height generally leading to higher acceleration levels and a corresponding reduction in operational capability onboard. In particular, low acceleration levels are observed at the beginning and end of the time series, which coincide with low wave conditions and correspond to the first and last steady-navigation segments identified in Figure 2.

Figure 5: Time series of (a) Vertical acceleration (VA) and Nordforsk thresholds; (b) Horizontal acceleration (HA) and MII thresholds; (c) Significant wave height (Hs); (d) Vessel speed over ground (SOG).

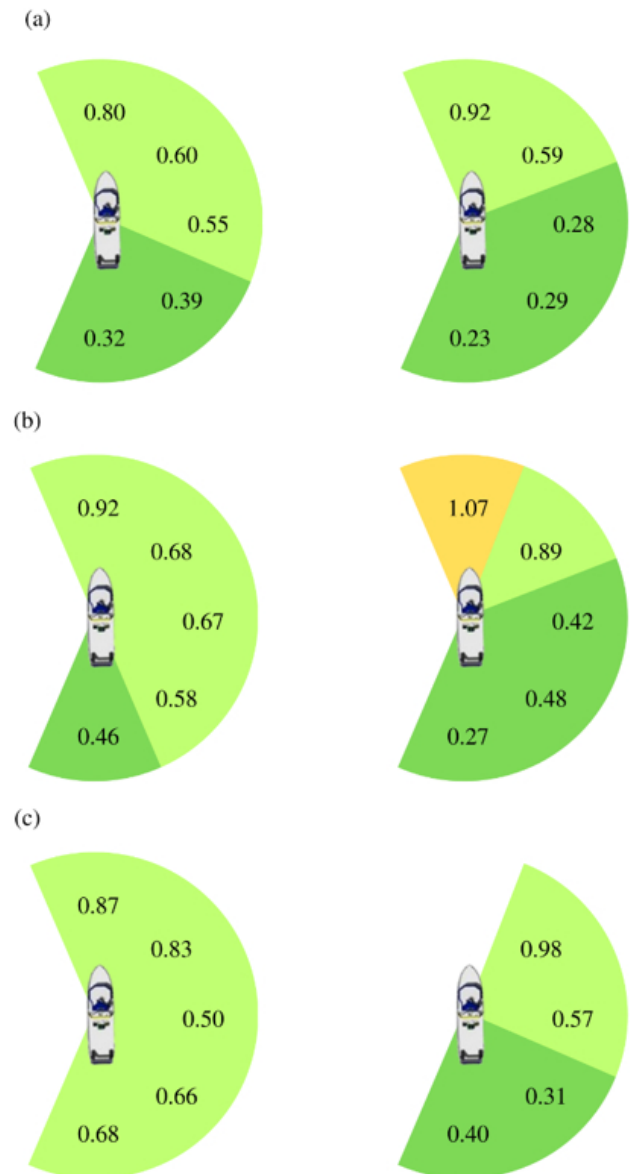


Source: Authors.

It is noted that, during the final navigation segment, an increase in vertical accelerations is observed, coinciding with a high-speed operating regime. This suggests that vessel speed may contribute to onboard acceleration levels, although it is not the only influencing factor, as high vessel speeds observed dur-

ing the early part of the day are not consistently associated with large accelerations. Additional environmental parameters, such as wave height and wave incidence angle, must therefore also be considered, as they strongly influence the vessel's dynamic response.

Figure 6: Mean RMS values of vertical acceleration computed over all steady segments. Left: low-speed segments; right: high-speed segments. (a) Wave height < 0.5 m; (b) wave height 0.5–1.0 m; (c) wave height > 1.0 m. The colour scale is segmented according to the thresholds presented in Table 2.



Source: Authors.

During the day, the vessel performs different operational modes, including free sailing, trawling operations, and periods of near-zero speed associated with gear deployment or retrieval. Consequently, onboard motion and its impact on operability are not solely governed by significant wave height, but are also

strongly dependent on the vessel's operational state. This highlights the combined influence of environmental conditions and operational mode on the observed motion response and associated operability indices.

Figures 6 and 7 present the mean RMS values of vertical and horizontal accelerations, respectively, computed across all steady-navigation segments identified in the 19 days of measurements. Figure 6 specifically shows the RMS values of vertical accelerations measured at the wheelhouse. In this location, vertical accelerations are primarily driven by vessel pitch motion; hence, an increase in pitch amplitude is expected to directly translate into higher vertical acceleration levels.

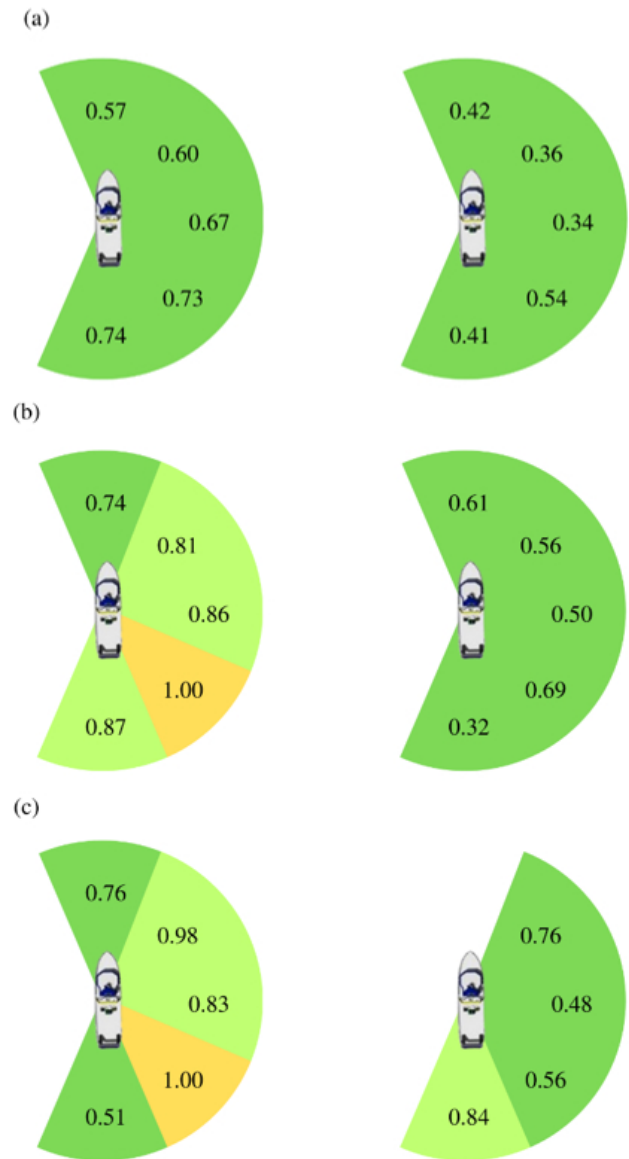
A clear influence of speed on vessel motions is observed, with lower sailing speeds consistently associated with higher acceleration levels for both indices. This behaviour can be explained by the increased exposure of the vessel to wave-induced motions at reduced speeds, which leads to stronger roll and pitch responses. Notably, low-speed conditions typically correspond to operational phases in which onboard work is being carried out, such as trawling operations, gear handling, or captures sorting. Therefore, the conditions under which operability loss is most relevant coincide with those exhibiting the highest levels of vessel motion, with higher vertical accelerations systematically occurring at lower vessel speeds.

A consistent pattern is also observed with respect to wave direction. The highest acceleration levels occur under head seas and bow conditions, where pitch responses are typically more pronounced. As wave height increases, elevated acceleration levels extend to a broader range of wave incidence angles. In the most severe conditions, low speed combined with significant wave heights exceeding 1 m, elevated acceleration values are observed across nearly all wave directions. However, it is also observed that acceleration levels tend to stabilize once the initial threshold is exceeded, with limited further increase at higher wave heights. This behaviour may be attributed to the vessel's inertial characteristics and hull form, which constrain excessive motion responses. Unlike smaller and more lightweight fishing vessels, the studied vessel exhibits sufficient mass and hydrodynamic damping to avoid uncontrolled amplification of motions under increasing wave excitation.

Figure 7 presents the RMS values of horizontal accelerations obtained across all steady-navigation segments. The results indicate that reference thresholds begin to be exceeded when the significant wave height surpasses 0.5 m. Below this threshold, no meaningful loss of operability attributable to vessel motions is observed, independently of vessel speed or wave incidence angle. As wave height increases beyond this value, the frequency of conditions exceeding the assumed thresholds also increases. In particular, wave incidence angle plays a significant role, with quartering seas generally leading to the highest levels of horizontal acceleration, while beam and head seas also contribute to increased responses and a greater likelihood of operational interruption. Under low-speed conditions, beam and quartering seas are associated with the highest acceleration levels, reaching values consistent with probable task interruptions according to the thresholds defined in Table 3. When wave height exceeds 1 m, exceedances of the operability thresh-

olds occur in both low and high-speed regimes. In this range, low-speed conditions continue to follow the same general trend, while at higher speeds a transition towards conditions associated with possible interruptions is also observed, particularly under following sea conditions.

Figure 7: Mean RMS values of horizontal acceleration computed over all steady segments. Left: low-speed segments; right: high-speed segments. (a) Wave height < 0.5 m; (b) wave height 0.5–1 m; (c) wave height > 1 m. The colour scale is segmented according to the thresholds presented in Table 3.



Source: Authors.

As previously noted, the measured accelerations strongly dependent on vessel roll and pitch motions. In the case of horizontal accelerations, the response is primarily governed by roll motion. Consistently, the highest horizontal acceleration levels are observed under quartering and beam seas, which are known to induce larger roll amplitudes. In the combined condition of

wave heights above 1 m and high vessel speed, the measured horizontal accelerations may also be influenced by pitch-related dynamics when the vessel interacts with following waves. This situation may introduce additional dynamic effects that are not limited to comfort or operability considerations, but may also be associated with safety-critical phenomena such as broaching, as identified within SGISC framework (International Maritime Organization, 2020).

5. Conclusions.

In this work, two of the main onboard welfare and operability indices, Nordforsk and the MII index, have been applied to 19 real fishing trips, each characterised by different meteorological and wave conditions. Time series of vertical and horizontal accelerations were analysed for a representative day and compared against the corresponding threshold values of both indices. In addition, a statistical analysis was performed over the 19 trips to assess the distribution of experienced accelerations under different combinations of vessel speed, wave height, and wave incidence angle. The analysis is based on time series of accelerations measured onboard the vessel, representing a significant advancement with respect to the original formulation of these indices, which were primarily developed from controlled laboratory experiments and theoretical assumptions. The results show that both Nordforsk criteria and the MII index can provide useful first-order estimates of operability loss in fishing vessels when applied to real operational data. However, human welfare at sea is inherently subjective, and its assessment must be interpreted in relation to the specific tasks and working conditions onboard. Fishing vessels, in particular, operate under conditions that differ substantially from those of passenger, naval, or merchant ships, for which most existing indices were originally designed.

The vessel considered in this study operates in coastal fisheries and returns to port on a daily basis, with trips not exceeding 12 hours. Onboard, the skipper typically controls the vessel manually from the wheelhouse, with limited reliance on autopilot systems. In addition, all deck operations are performed manually, without heavy mechanical assistance. Under these conditions, the most relevant aspects of operability degradation are motion-induced fatigue and the increased likelihood of accidents associated with loss of balance or motion-induced task interruptions. Consequently, existing comfort and operability indices should be adapted to better reflect the operational characteristics of coastal fishing activities. The results obtained in terms of possible and probable operability loss due to vessel motions are generally consistent with the trends predicted by the existing indices. Nevertheless, these outcomes remain partly ambiguous, as they ultimately depend on the individual operator's experience, fatigue state, and perceived performance during the working day, which are not directly captured by the indices.

Future work should incorporate the subjective perception of crew members regarding the impact of vessel motions on their performance and comfort, while comparing these results with the thresholds established in different standards. This would

enable a direct comparison between perceived discomfort and objectively measured motion indicators. Such studies should also account for individual factors such as years of sea experience, physical condition, and specific role onboard. In addition, future measurement campaigns should include acceleration measurements on the working deck, rather than being limited to the wheelhouse. This would allow the evaluation of operability indices at multiple onboard locations, recognising that local accelerations vary significantly depending on spatial position within the vessel. In the studied vessel, the wheelhouse is located forward of midship and on an elevated deck relative to the working deck, which extends from midship towards the stern. Finally, it would be relevant to investigate whether the observed acceleration levels are amplified when encounter frequencies approach the natural frequencies of vessel roll or pitch, which may lead to resonance effects and potentially increase the risk of motion-induced operational limitations or safety-critical events.

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