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Sea state monitoring based on ship motion measurements onboard an icebreaker in the Antarctic waters

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Abstract **– A new wave spectrum resembling procedure is applied to detect the sea state parameters, namely the wave peak period and the significant wave height based on the analysis of heave and pitch motion time series, obtained by on board measurements. The outlined procedure is applied to Laura Bassi oceanographic ship, assumed as reference vessel. Heave and pitch motion time histories are evaluated from the survey of the amplitudes of the vessel motions, starting from different sensors measures collected by a smartphone located on board the vessel. The obtained results were compared with the weather forecast data provided by the global-WAM (GWAM) model.**

I. INTRODUCTION

The real-time knowledge of the sea state conditions, encountered by the ship in the course of its route, is of fundamental importance for different aspects ranging from the safety of navigation to the comfort on board. In particular, the assessment of the weather conditions is useful to minimize the risks of navigation and reduce the costs, as it provides a decision support system to avoid potential dangerous phenomena in following and quartering seas, and, in order to detect the optimal route, the evaluation of the environmental conditions is also required when the ship voyage is planned by weather routing methods. Additional advantages coming from the knowledge of sea state parameters, are connected to the safety of crew and the assessment of the on-board comfort level. Finally, the continuous monitoring of sea state conditions is helpful to improve the statistics of long-term wave data, providing additional information where the weather buoys are very scattered.

The ship system can be considered as a mobile laboratory capable of carrying out in situ measurements for the estimation of ship motions and, subsequently, to derive the characteristics of the incident wave. The determination of the sea spectrum starting from the survey and analysis of vessel motions can lead to the onset of problems mainly related to the Doppler shift between the absolute and encounter wave frequencies. Heave and pitch motions are evaluated from the survey of the amplitudes of the ship vertical motions and pitch acceleration, the response spectra are evaluated and knowing the ship complex transfer functions, the sea spectrum generating the motions is determined. Finally, from the spectral distribution of the sea in the absolute frequency domain, the characteristic parameters are obtained.

II. LITERATURE REVIEW

Since the mid-70s a variety of research activities were carried out to explore the possible analogy between ships and wave buoys. In 1973 Takekuma and Takahashi [1] presented the first pioneering work on wave spectrum resembling, based on ship motion measurements, without forward speed. In the following years, Isobe et al. [2] and Kobune et al. [3] have carried out several attempts to include the Doppler shift for ships advancing in head and bow seas and, subsequently, in quartering and following seas by Iseki and Ohtsu [4]. Following these works, in the last two decades a variety of research activities was performed with the aim to apply a reverse analysis technique to obtain the wave spectra with sufficient accuracy, especially for ships advancing in following seas, considering that in this case the encounter frequency has a non-bijective relation with the absolute wave one (Iseki and Terada [5]; Nielsen [6]; Nielsen et al. [7], Montazeri et al. [8]). Brodtkorb et al. [9] developed a signal-based algorithm, to detect the wave spectrum by iteratively solving a set of linear equations, based on heave, pitch and roll motion measurements. Nielsen and Diez [10] analysed the motion measurements of a containership, focusing on the incidence of the advance speed and performed a comparative analysis between sea state estimates obtained by motion measurements and a hindcast study. Nielsen [11] provides an account of the available techniques for shipboard sea state estimation in both frequency and time-domain. As concerns the application of time-domain techniques, only few works, mainly based on Kalman filtering, applied to convert the ship motion measurements into the wave elevation time history, are available in literature (Pascoal and Soares, [12]; Pascoal et al. [13]), due to the high numerical effort required to resemble the unknown sea state parameters.

Piscopo et al. [14] presented a new wave spectrum resembling procedure, consisting of two subsequent steps and based on the analysis of heave and pitch motions. The significant wave height, the wave peak period and the wave spectrum shape parameter are obtained from the analysis of heave and pitch time-domain simulations but which can be obtained by onboard measurements. The incidence of time duration on resembled sea state parameters has been investigated, the statistics of errors on wave peak periods and significant wave heights have been analysed to select the proper time duration of onboard measurements that allows balancing the reliability of resembled data with the need of an almost real-time sea state monitoring.

III. SEA STATE MONITORING ALGORITHM

A. Ship motion measurements

Heave and pitch motions are evaluated from the survey of the amplitudes of the vessel motions, starting from different sensors measures collected by a smartphone located on board the vessel. The best position to place the sensor on board is on the centreline plane in correspondence of the centre of mass, so as to obtain the heave motion amplitude from the vertical translational motion survey without the pitch contribution. Most smartphone devices have built-in sensors able to collect measures of motion, orientation, and various environmental conditions. These sensors provide raw data with high sample-rate, and are useful to monitor three-dimensional device motion or positioning. The sensors embedded into the smartphone belong to three major groups:

- Motion sensors, including accelerometers, gravity sensors, gyroscopes, and rotational vector sensors to measure device motion.
- Environmental sensors, such as ambient air temperature and pressure, illumination, and humidity using barometers, photometers (light sensors), and thermometers used to collect measurements of various environmental conditions,
- Position sensors, including magnetometers (geomagnetic field sensors) and proximity sensors, to provide information about the physical position of the device.

The acceleration, angular velocity, magnetic field, and orientation sensors log data referred to the smartphone coordinate system shown in Fig. 1. The coordinate origin is at the centre of the touch screen, x-axis points to the right direction, y-axis the front and z-axis the top. When the smartphone moves, the accelerometer and gyros provide three-axis accelerations and angular velocities components. The orientation sensor can output azimuth angle, defined as the angle between the projection of the y-axis on horizontal plane and the north direction.

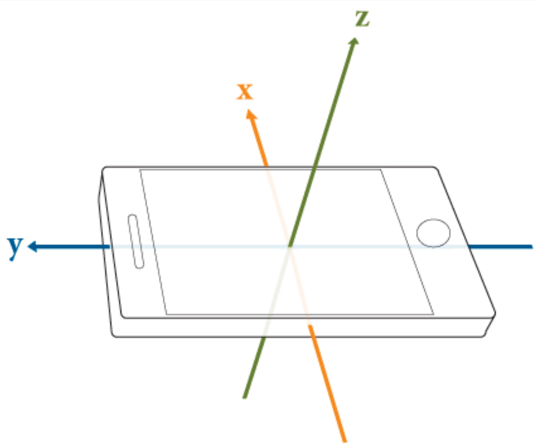

Fig. 1. System coordinates of the device (https://se.mathworks.com/help/supportpkg/mobilesensor/ug/phoneorv2.gif)

Smartphones are also equipped with a GNSS receiver which can computes the position and velocity in a global framework. The adopted Android smartphone is Xiaomi Mi 8 located approximately in the centre of mass of the vessel and MATLAB® Mobile™ is used to collect the desired measures. MATLAB support Android devices to obtain data of the built-in sensors, acquiring sensor data locally on an Android™ device, with or without a network connection. This is especially useful if the users want to collect sensor data while the device does not have a network connection. For the aim of the work, orientation and position sensors are used to collect, respectively, the temporal variations of the device pitch angle (defined as the angle between a plane parallel to the device's screen and a plane parallel to the ground) and of altitude (U). Specifically, the ship vertical motions between consecutive epochs (k) is computed as:

$$\Delta U_k = U_k - U_{k-1} \quad (1)$$

So, heave and pitch variations obtained from the smartphone are used as input parameters for the sea spectrum determination. In addition, the velocity and the course of the device are collected from position sensors using MATLAB Mobile, in order to evaluate the encounter frequencies.

B. Ship motion analysis and wave spectrum resembling

The modulus of heave and pitch motion transfer functions have been derived after solving the heave/pitch motion equations in the encounter wave frequency-domain [14], both for swell and wind waves, the zero-speed added mass and radiation damping values are determined by the open source code NEMOH and subsequently corrected to account for the forward speed using the corrective factors provided by Salvesen et al. [15]. The heading angle between the vessel route and the prevailing wave direction is assumed to be known, the weather forecast data from GRIB file are used. Based on relevant time histories, recorded by the onboard equipment, the encounter spectra of heave and pitch motions, are assessed. The wave spectrum resembling procedure consists of two subsequent steps, the procedure belongs to the class of parametric methods. At the first step the wave peak period and the spectrum shape parameter are iteratively varied and determined by a best-fit parametric procedure. The best-fit iterative procedure leads to the assessment of the two unknown variables or to the detection of the only wave peak period, if the shape parameter is preliminarily known, as it occurs for fully developed seas (γ=1). The number of tentative peak periods and shape parameters, to be embodied in the iterative procedure, needs to be selected in order to obtain an accurate assessment of the two variables, paying attention to not excessively increase the time effort amount required to perform the calculations. At the end of Step I the wave peak period and the shape parameter of the JONSWAP spectrum are obtained. Subsequently, the significant wave height is assessed, based on single or combined heave/pitch motion analysis, at the end of Step II the significant wave height is assessed, so resembling all sea state parameters. All the procedure is in detailed reported in Piscopo et al. [14].

IV. MAIN DATA OF REFERENCE SHIP

The Laura Bassi oceanographic ship, used for scientific activity and logistical support for Italian Antarctic explorations, is assumed as reference vessel in the case study performed in the following. The main dimensions are listed in Table 1, while in Fig. 2 and Fig. 3 are reported the pitch and heave RAOs, i.e. the response amplitude operator, separating the transfer function due to wind waves and swell.

Table 1. Main particulars of Laura Bassi

Length overall	80.00	m
Length between perpendiculars	72.40	m
Beam on WL	17.00	m
Design draught	6.15	m
Displacement	4736	t
Waterplane area	1074	m^2
Block coefficient	0.599	

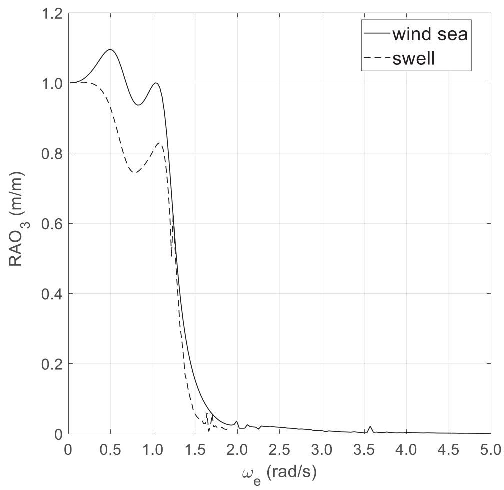

Fig. 2. Heave RAO

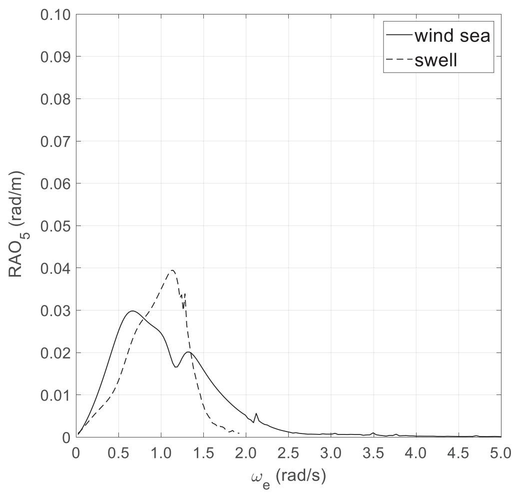

Fig. 3. Pitch RAO

V. ONBOARD SHIP MOTION MEASUREMENTS

A. Data collections

To assess the capabilities of smartphones to provide measurements to be used for the wave spectrum resembling, the tests are carried out using real data collected by the smartphone Xiaomi Mi 8 located on board the Laura Bassi oceanographic ship. In detail, a data collection of one hour is chosen on 14th of February

2020 starting from 13:21 (local time) and with a sample rate of 1 Hz. The selected route falls in Antarctic Ocean and has (60.15°S, 167.08°E) departure and (59.96°S, 167.19°E) arrival coordinates.

B. Reference weather data

The performance of the results obtained by the proposed wave spectrum resembling procedure are compared to the sea state conditions based on weather forecast data provided by Global Wave Model (GWAM) and collected in GRIB (GRIdded Binary) file.

For the aim of the work, the GRIB file is downloaded for the 14th of February 2020, with 3-hour forecast interval and 0.25° x 0.25° grid spacing and the weather forecast data are extrapolated for the considered route and temporal period. The model outputs, used as reference, are the significant wave height, the mean wave period and direction of both wind and swell components.

It would also be interesting, for future developments, to compare the obtained results with different reference data as a current profiler measurements based on Acoustic Surface Tracking.

C. Sea state resembling

The wave spectrum resembling procedure is tested against a sea state conditions characterized by a combination of swell and wind waves, both by separating the two contributions and considering them together by evaluating a total component of significant wave height and peak period. The peak periods of swell and wind wave spectra are generally quite different, so as it is possible to separate the spectral components due to swell and wind waves, located up to and beyond the so-called separation frequency respectively, the separation frequency can be efficiently detected based on the only heave motion encounter spectrum. In Fig. 4 and Fig. 5 are shown the heave and pitch motion amplitude encounter spectrum, in black the same applying the smooth, as it is possible to see from the figure the separation frequency is too high, theoretically it is approximately zero. The high value of the separation frequency is clearly attributable to the values of the wave period very similar for swell and wind waves, also the prevailing sea state directions do not belong to very different ranges and consequently the Doppler effect does not intervene for a clear separation between encounter frequencies. In Fig. 6 are reported the significant height, the peak period and the angle between the ship route and the prevailing direction of swell and wind wave provided by the global wave model Wavewatch III (WWIII). The high value of the separation frequency makes the clear separation of the components limited meaning, the sea spectrum is a single-mode spectrum and there is no effective separation between the two peaks. In Fig. 7 and in Table 2 it has been reported only the results relative the reconstruction of the sea spectrum considering the two contributions together. The results shown a difference for the combined spectrum on the significant height of about 2% and on the peak period of 3 seconds.

Table 2. Parameters of rebuilt spectrum for a combined sea spectrum

	H_S (m)	T_P (s)
Data from WWIII	4.441	9.001
Resembled combined sea spectrum	4.346	9.300

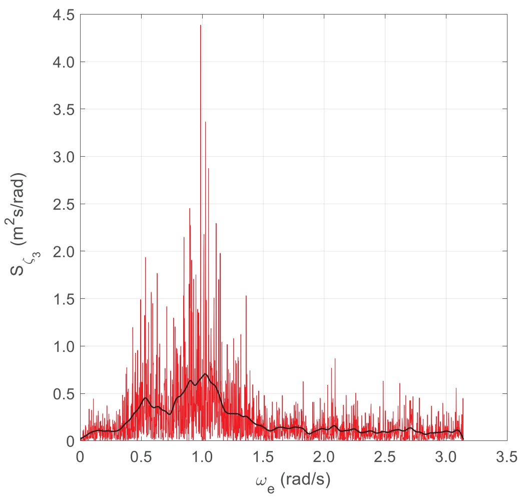

Fig. 4. Heave motion amplitude encounter spectrum

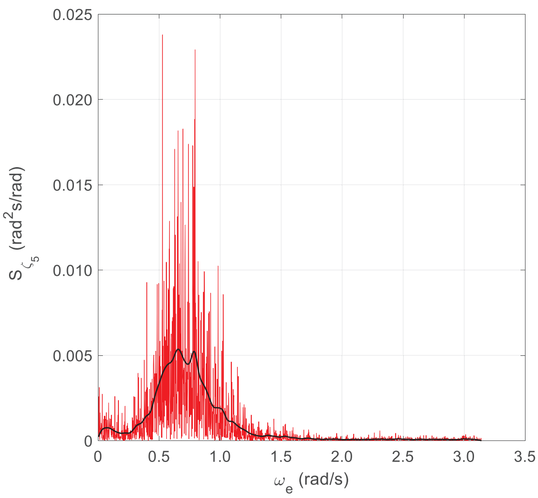

Fig. 5. Pitch motion amplitude encounter spectrum

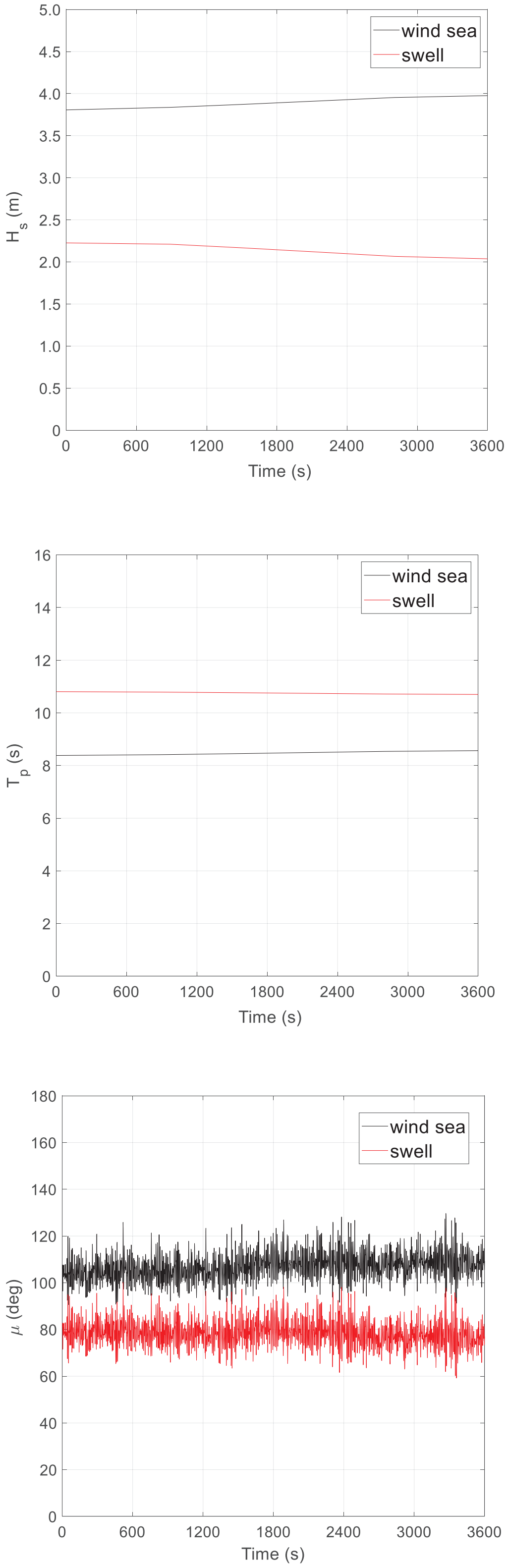

Fig. 6. Characteristics of swell and wind wave

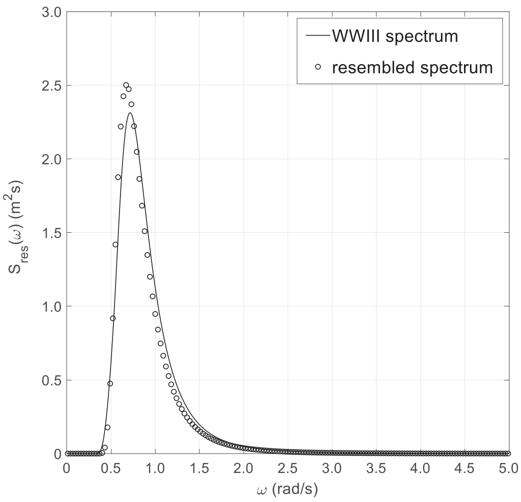

Fig. 7. Resembled combined sea spectrum

VI. CONCLUSIONS

A new wave spectrum resembling procedure based on the analysis of heave and pitch motion time series, presented in detail in [14], has been applied to assess the sea state parameters. The Laura Bassi oceanographic ship was the reference vessel and the procedure was tested using real onboard measurements for heave, pitch, velocity and ship course. The sea state parameters have been compared with weather forecast data showing a good agreement, furthermore, it stands to reason a further improvement in the results for sea states with a more distinct separation between swell and wind waves. Current outcomes seem to be promising for further developments, mainly devoted to investigate the possible employment of windowing functions in the Fourier analysis of ship motions and the incidence of time duration on resembled sea state parameters.

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