Field measurements of angular motions of a vessel at berth: Inertial device application

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Abstract: The study of the oscillations of a moored vessel has a major importance in port operational efficiency, not only in the design of mooring and anchoring systems, but also in preventing the movement of the cargo, minimizing damages in the ship and dock and optimizing the operations which take place while the ship is moored. Also, this information provides useful data to develop new port regulations and recommendations.
The dynamic behavior of a moored vessel has been mathematically described and interactions between ships and environmental loads such as waves, wind, currents and ice are commonly tested for different docks and mooring systems in scale models. However, field studies of the behavior moored ships and its influence over critical situations, accidental events, and mooring breakage have not been properly addressed so far.
This paper proposes a novel application of Inertial Measurement Units to estimate the angular movements (roll, pitch and yaw) of a moored vessel which can contribute to improve operational conditions and establish new safety criteria for port regulators. The proposed technique has been validated in laboratory conditions and the behavior of the ship Urania Mella in the Outer Port of Punta Langosteira (A Coruña, Spain), has been analyzed, obtaining very promising results.

Keywords: Port operational, Inertial Measurement Unit, Ship orientation, Mooring.

1. INTRODUCTION

Operational efficiency is a major concern for port authorities, with new challenges to face for the civil engineering community. The construction of larger vessels leads to the necessity to develop new harbors, normally in outer locations with more severe climate conditions. To this purpose the analysis of the dynamic mooring conditions of the vessels, characterizing the movements and mooring is essential to increase the capacity of these new ports.

One of the key aspects for institutions and companies is the necessity to determine the limiting operational conditions and define in an optimal way which terminal should be better to use for each operation, reducing the probability for downtimes. Several international organizations have developed acceptable motions criteria for moored vessels during the cargo operation (PIANC 1995, 2012; Puertos del Estado, 2011). The values of these recommendations depend on the type of vessel and cargo handling equipment, being generally applicable in port facilities all over the world.

Keeping the ship moored with acceptable values of motion is important for the operational efficiency, since many ports suffer downtimes problems in some berths. An example can be found in the oil terminal of the port of Leixoes (Portugal) which has a berth zone with some problems, not assuring the operational conditions during about 20% of the time, with its associated economic losses (Jorge Rosa-Santos and Taveira-Pinto, 2013).

In addition to operational problems, excessive movements of vessels can cause the breaking of mooring lines, damage to the port fenders or to the ship, or even lead to serious accidents with significant costs, as happened with Discoverer Enterprise drillship in Ferrol (Spain). The vessel broke its moorings during a storm, coming adrift and hitting the As Pias Bridge which joins Ferrol to A Coruña. The impact destroyed four piers and their pertinent decks, which fell into the sea and caused major damage to the rest of the bridge structure (Quintero et al., 2000). The accident generated important socio-economic problems in the region. The city of Ferrol lost its main road transport network during three months and nearby urban areas such as Fene or Mugardos lost their water supply. A more recent accident occurred in Durban Harbour located in South Africa during autumn 2017. Due to a heavy storm, the container ship MSC Ines broke its moorings, drifted abeam and blocked the harbour entrance, forcing to suspend the port activity. Also, the vessel suffered serious damages on its rudder.

The scientific community has made many efforts to describe the vessels behavior at port, including civil, naval and industrial engineers. An early mathematical approach can be found in (Finkelstein, 1957), and these equations were later used to describe impulsive forces in a floating body (Wehausen, 1967). Other perspective was presented by (Cummins, 1962), introducing the analysis of six degrees of freedom, and the separation of the problem in instantaneous and memory effects in the vessel.

Mooring has been specifically analyzed in more recent studies (Kat and Pauling, 2001; Rosa-Santos et al., 2014), usually focused on the capacity to maintain the vessel as fixed as possible to the berth. Several companies have also invested resources in developing innovative mooring systems to minimize vessel motions and their associated problems. Some examples are MoorMaster™ automated vacuum pads mooring system (Automated Mooring | Cavotec SA) or the ShoreTension® constant tension system in mooring lines (Dynamic Mooring Systems - ShoreTension).

A particular hazardous situation is the breaking of mooring lines, which can result in damages to port structures and serious injuries to workers. These incidents are often related to extreme moored ship motions caused by waves, winds or passing vessels. In this field can also find different international publications which include recommendations for safe mooring of ships based on data recorded by mooring service providers or harbour pilots (BSRA, 1971; OCIMF, 1978).

The wave climate is another complex factor that affects the operational conditions. As the locations of the new ports are normally outside the main cities, these conditions tend to be more severe, especially waves, currents and winds. Other less studied mechanisms are harbour resonance and oscillations (Van Oortmerssen, 1976). Their effects, observed, among other locations, in Galician and Northern Spain coast, are usually formed by long period waves that are difficult to dissipate and influence dramatically the port operations (Rabinovich, 2009; Sammartino et al., 2014; Uzaki et al., 2010). These oscillations cause that small vertical motions may result in very large horizontal motion amplitudes when waves frequency is close to the natural frequency of the moored ship. This phenomenon increases the risk of damaging ships or harbour structures and affects harbour procedures. The excessive motions of moored ships as a consequence of long-period wave effect occur in many harbors, not only in exposed locations but also in sheltered areas. An example can be found in the Geraldton Harbour, located on the west coast of Australia. Some of its berthing zones have frequent issues like broken mooring lines and excessive motions resulting in a decrease of operability (van der Molen et al., 2015).

Due to the complexity of these factors, and in order to reduce difficulty and other practical considerations, the study of the behavior of a moored vessel is commonly tested using scale models (Malheiros et al., 2009, 2013).

A different approach to analyze the vessel behavior is combining numerical models for vessel motions, mooring line tensions and wave climate (van der Molen et al., 2003; Oortmerssen et al., 1986). However, this tool is more appropriate for the hydrodynamic characterization of the basins under study (Grifoll et al., 2009; López et al., 2012; Sammartino et al. 2014), and rarely includes the moored vessels behavior (Ven, 2012).

Recently, with the development of instrumentation techniques and computer programming, a new approach is appearing using field data. The use of inertial measurement units, cameras, and computer simulations provides to the civil engineering and scientific community new capacities, that could be used by port regulators to increase their facilities efficiency. An example of the application of new technologies can be found in Bremen Port (Germany) where a full-automatic measuring system for berthing velocities has been developed.

This paper focuses on the application of Inertial Measurement Unit (IMU) and computing techniques in the study of a moored vessel at port, offering a powerful tool to analyze and improve the port operations. IMU systems are the main part of inertial systems in navigation (Ayub et al., 2012), allowing to characterize the orientation and position of a moving object such as a vessel regarding to an initial point.

While IMUs are commonly studied by industrial engineers and informatics, this research focuses on their application to civil engineering in combination with computing techniques. The construction and application of low-cost IMU unit without external positioning sources are described next.

2. MEASURING ANGULAR MOVEMENTS

The approach presented in this study focuses on the analysis of the three angular motions of a vessel, which represents a key part of the ship behavior at the port. (Fig. 1). The pitch represents the rotation around the transverse axis of the ship, which is referred here as the Y axis. Pitching periods are typically short and they are not significantly altered by the mooring system. The roll refers to the transverse stability, in the front to back or longitudinal one. Roll axis is referred to as the X axis. Rolling shares the characteristics of pitching, but can lead to the ship capsizing, even in moored ships. Rolling can affect port operations and may lead to damages in the cargo, the dock or the vessel. Finally, the yaw represents the rotation within the horizontal plane or vertical axis, which is referred as Z axis in the frame of reference of the vessel. Yawing is characterized for long periods of oscillation, and very dependent on the mooring mechanism. Large yaw motions can produce the breakage of mooring lines.

To measure these motions, the built IMU unit integrates data from different sensors (Figuero et al., 2016). The angular velocity of the moving object is measured with three orthogonal gyroscopes. Three accelerometers measure the acceleration of the body, and three orthogonal magnetometers, are used to calibrate the intensity and direction of the magnetic field.

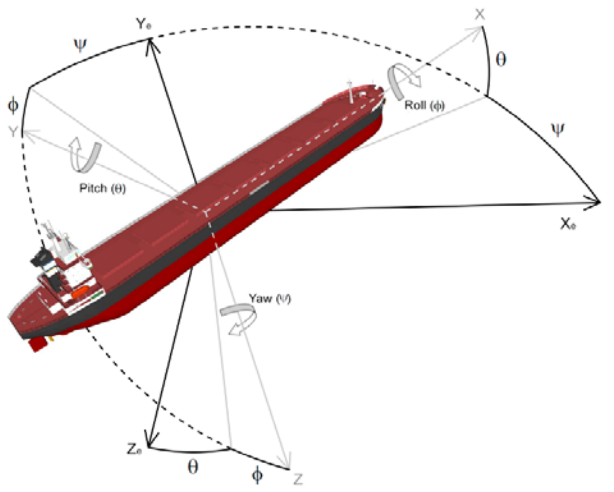

Fig. 1. Vessel gyros and orientation. Roll (ϕ), pitch (θ) and yaw (ψ).

The data provided by the sensors present two sources of error. First, the noise component or bias that is controlled subtracting the average signal registered in the long term analysis with no rotation (Groves, 2015; Woodman, 2007). The same procedure is applied to the three accelerometers to measure the acceleration of the body.

The second source of error is the tendency of the signal to drift out from the initial position. Drift is one of the biggest problems of gyroscopes in IMU units. This source of error is controlled using the information from accelerometers and magnetometers. Drift correction is discussed later in the results section.

From a numerical point of view, the orientation of a ship can be defined with rotation matrices that describe the orientation of one coordinate system (ship) with respect to another (Earth). A vector in one system can be transformed into the other system by multiplying it by the rotation matrix, which is orthogonal.

A moored vessel can suffer rotations in three axis X, Y, Z. That is, it may have three rotation angles ϕ, θ, ψ which rotations are called roll, pitch, and yaw respectively. Using the Earth frame reference, the vessel orientation is obtained, by applying consecutively the roll R_x, pitch R_y and yaw R_z transformations to the orientation of the vessel. These transformations can be described in Euler angles as follows:

$$R_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \quad R_Y = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad R_Z = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R(\mathrm{t}) = R_Z R_Y R_X = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \\ -\sin\phi & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \quad (1)$$

Therefore, the equation to rotate a vector measured in the frame of reference of the vessel to the frame of reference of the Earth is expressed as follows:

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = R \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \quad (1)$$

where u_x, u_y, u_z represent a vector in the frame reference of the Earth, and v_x, v_y, v_z represent a vector in the frame reference of the vessel. The R matrix is usually called Direction Cosine Matrix (DCM). The orthogonality of the R matrix, is expressed as follows:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = R^{-1} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = R^T \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} r_{xx} & r_{yx} & r_{zx} \\ r_{xy} & r_{yy} & r_{zy} \\ r_{xz} & r_{yz} & r_{zz} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \quad (2)$$

The vector $Row_X\,(r_{xx}, r_{xy}, r_{xz})$, representing the x row of the R matrix, is the projection of the x axis of the coordinate system of the Earth on the coordinate system of the vessel. Thus, the vector $Col_X^T\,(r_{xx}, r_{yx}, r_{zx})$ represents the x column of the R matrix and is the projection of the x axis of the coordinate system of the vessel on the coordinate system of the Earth.

Taking into account the kinematics implications of rigid body rotation (Premerlani and Bizard, 2009), the time evolution of the orientation can be expressed in terms of the vector rotation rate, which can be measured by the gyroscopes. The measurements obtained by the IMU unit are performed in the vessel coordinate system, so the solution is to track the Earth axes as seen in the reference frame. The resulting equation is expressed as follows:

$$r_e(t) = r_e(0) + \int_0^t r_e(\tau) \times d\varpi(\tau) = r_e(0) + \int_0^t r_e(\tau) \times w(\tau)\, d\tau \quad (4)$$

where $r_e(t)$ represents the rotating vector in the Earth frame reference, viewed from the plane of the moving ship with a rotation angle ϖ; and $r(0)$ is the starting value of the vector. The integral represents the change in the vector and $w(t)$ represents the rotation rate of the vector.

The vectors in the previous equation represent the rows of R matrix in Eq. (1). Taking this into account, previous equation can be expressed using a matrix approach:

$$r_e(t + dt) = r_e(t) + r_e(t) \times w(t)\, dt \quad (3)$$

Considering the previous equation for each of the Earth axes, the result is expressed as follows:

$$R(t + dt) = R(t) \begin{bmatrix} 1 & -w_z(t)\,dt & w_y(t)\,dt \\ w_z(t)\,dt & 1 & -w_x(t)\,dt \\ -w_y(t)\,dt & w_x(t)\,dt & 1 \end{bmatrix} \quad (4)$$

Using Eq. (6), the DCM matrix can be updated from gyro signals. However, since it is expected that numerical errors in the integration gradually violate the orthogonality of R expressed in Eq. (3), an adjustment step to enforce the orthogonality constraints is necessary. This step is described in detail in (Ayub et al., 2012).

In this point, rotation angles can be obtained from the R matrix, using the following equations:

$$\begin{aligned} Yaw &\rightarrow \psi = \arctan\left(r_{yx}, r_{xx}\right) \\ Pitch &\rightarrow \theta = \arctan\left(\frac{\mathrm{r}_{zx}}{\sqrt{r_{zy}^2 + r_{zz}^2}}\right) = -\arcsin(\mathrm{r}_{zx}) \\ Roll &\rightarrow \phi = \arctan\left(r_{zy}, r_{zz}\right) \end{aligned} \quad (5)$$

However, as stated before, gyroscopes are not reliable enough to measure positions in long periods of time due to its drift. Taking that into account, gyroscopes measurement need to be corrected in the long term. This is expressed as follows:

$$w(t) = w_{gyro}(t) + w_{correction}(t) \tag{6}$$

Corrections in IMU systems are usually done with different sensors (Gebre-Egziabher et al., 2004). Normally, the main orientation source are the gyros, complemented with other data to minimize errors (Ayub et al., 2012; Premerlani and Bizard, 2009). In other works, such as (Setoodeh et al., 2004; Yun and Bachmann, 2006) general data fusion algorithms based on Kalman filtering are discussed for this application. In this work, yaw and roll-pitch correction vectors are calculated using the magnetometers and accelerometers, respectively.

To increase the measurement predictions, in particular, the heading of the ship, both magnetometers and accelerometers correct the rotation and orientation of the Z axis, respectively. To compute the correction vector for each operation, the cross product of a measured reference vector with a corresponding vector computed from the *R* matrix is used.

In the first step, yaw (rotations in the *Z* axis, with angle ψ) correction vector is obtained. Yaw can be considered as the deviation in course parallel to Earth surface. Magnetometers obtain a reliable measurement of yaw using Earth magnetic field as a reference. Magnetic compasses have been widely used for navigation for hundreds of years, though they have an important drawback as they are affected by ferromagnetic metal, typical in a ship's hull. Therefore, the IMU unit has to be placed carefully. In large vessels, magnetometers may be replaced by a GPS based compass or gyrocompasses.

In the proposed work, three orthogonal anisotropic magnetoresistive (AMR) sensors have been used. The output of these sensors is a cosine function of the heading angle, providing the *X, Y, Z* magnetic components (north, east and vertical components of the magnetic field). In this scenario, an error source is introduced by tilt angles (Xisheng et al., 2009) and magnetic field components must be corrected according to the roll and pitch angles ϕ and θ, respectively. This can be expressed as follows (Xisheng et al., 2009):

$$\begin{aligned} x_c &= x_{mag}\cos(\theta) - z_{mag}\sin(\theta) \\ y_c &= y_{mag}\cos(\phi) + z_{mag}\sin(\phi) \end{aligned} \tag{7}$$

where x_{mag}, y_{mag}, z_{mag} represent the output of the magnetometers, x_c, y_c, z_c are the corrected values and ϕ, θ are obtained from the DCM matrix according to Eq. (7). Once the magnetic components are corrected to the horizontal plane, and considering the resulting normalized heading 2D vector in $Z=0$, with components $(x_c,\ y_c)$, the following relations can be stablished with the yaw measured by the magnetometers:

$$\begin{aligned} Yaw_{mag} \rightarrow \psi_{mag} &= \arctan(y_c, \mathrm{x}_c) \\ x_c &= \cos(\psi_{mag}) \\ y_c &= \sin(\psi_{mag}) \end{aligned} \tag{8}$$

Taking the previous results into account, and since measurements of magnetometers are performed in the coordinate system of the Earth, the yaw correction vector is estimated. This is obtained as the cross product of the heading vector measured by the magnetometers and the projection of the *X* axis of the vessel in the plane $Z = 0$ of the Earth (which represents the sea plane). Then, the obtained result is translated to the vessel coordinate system with the *R* matrix. This is computed as follows:

$$\begin{aligned} Correction_{Yaw,Earth} &= \begin{bmatrix} r_{xx} \\ y_{yx} \\ 0 \end{bmatrix} \times \begin{bmatrix} x_c \\ y_c \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ r_{xx}y_c - r_{yx}x_c \end{bmatrix} \\ Correction_{Yaw} = R^T Correction_{Yaw,Earth} &= \begin{bmatrix} r_{zx}\left(r_{xx}y_c - r_{yx}x_c\right) \\ r_{zy}\left(r_{xx}y_c - r_{yx}x_c\right) \\ r_{zy}\left(r_{xx}y_c - r_{yx}x_c\right) \end{bmatrix} \end{aligned} \tag{9}$$

In the next step, roll and pitch drift correction vectors (rotations in the *X* and *Y* axis, with angles ϕ, θ) are estimated from accelerometers.

Accelerometers output indicates the gravity minus the acceleration in the axis *X, Y, Z* with a long term reliability. Therefore, roll and pitch can be corrected just by estimating the position of the gravity vector. However, the measurements of gravity obtained by the accelerometers are only reliable when the vessel is not accelerating, since acceleration due to non-gravity forces interfere with the gravity estimation.

In general, the main non-gravitational acceleration components are the forward acceleration directly induced by the propulsion system and the centrifugal acceleration caused by the inertia of a rotating vessel.

A moored vessel, by definition, remains stationary, and these main acceleration components may be disregarded. However, it suffers from accelerations and decelerations forward, backward and side to side due to waves, wind, currents and the mooring system itself. In this work, the assumption that these accelerations are canceled on mid-long term is carried out, so that, on average, accelerations of the vessel can be disregarded. Therefore, used acceleration values are averaged values with a lower frequency than gyroscopes, and outliers are explicitly filtered out if the magnitude of acceleration vector is lower than 0.5g or higher than 1.5g, where 1g represents the magnitude of gravity force on Earth (9.80665 m/s^2).

Taking this into account, the accelerometers give us a reference measurement for the gravity vector in the body frame of reference, and pitch and roll are directly calculated from the accelerometers measurements as follows:

$$\begin{aligned} Pitch_{acc} \rightarrow \theta_{acc} &= \arctan\left(\frac{x_{acc}}{\sqrt{y_{acc}^2 + z_{acc}^2}}\right) = -\arcsin(x_{acc}) \\ Roll_{acc} \rightarrow \phi_{acc} &= \arctan(y_{acc}, \mathrm{z}_{acc}) \end{aligned} \tag{10}$$

where x_{acc}, y_{acc}, z_{acc} represent the output of the accelerometers.

At this point, the correction vector for pitch and roll, is provided simple by the cross product of the accelerometers measurement vector and the projected Earth gravity vector (the *Z* axis) to the vessel coordinate system. This is expressed as follows:

$$Correction_{Pitch-Roll} = \begin{bmatrix} r_{zx} \\ r_{zy} \\ r_{zz} \end{bmatrix} \times \begin{bmatrix} x_{acc} \\ y_{acc} \\ z_{acc} \end{bmatrix} \quad (11)$$

where r_{zx}, r_{zy}, r_{zz} is the *Z* row of the direct cosine matrix.

Finally, the yaw and pitch-roll correction vectors are weighted and fed to a proportional plus integral (PI) feedback controller.

$$Out_{PI}(t) = K_P e(t) + K_I \int_0^t e(\tau)\, d\tau \quad (12)$$

where $Out_{PI}(t)$ is the output of the PI controller, K_P and K_I are constant tuning parameters called proportional and integral gain respectively, and *e(t)* represents the estimation error in moment *t*.

The output of the PI controller is the additive correction term to the gyroscopes output as expressed in Eq. (8). It is used to update the *R* matrix as expressed in Eq. (6). In practice, this correction value is calculated as follows:

$$w_{correction}(\mathrm{t}) = w_P(t) + w_I(t) + K_I e(t)\, dt$$
$$w_P(t) = K_P e(t)$$
$$w_I(t) = K_I e(t)$$
$$e(t) = W_{Yaw} Correction_{Yaw}(t) + W_{Pitch-Roll} Correction_{Pitch-Roll}(t) \quad (13)$$

where W_{Yaw} and $W_{Pitch\text{-}Roll}$ are weight parameters which are adjusted empirically to provide a rapid response (large weighting) to yaw relative to pitch and roll as justified in (Premerlani and Bizard, 2009), K_P and K_I are tuned using the Ziegler–Nichols method (Ziegler and Nichols, 1942).

3. EXPERIMENTAL RESULTS

The validation of the system was done in physical modelling tests, and further applied to a real case.

3.1 Laboratory tests

Several tests were done in the wave-current flume in the Center of Technological Innovations in Construction and Civil Engineering (CITEEC) of the University of A Coruña (Spain), with dimensions 25x0.8x0.6 m. Two scaled ship models were analyzed to determine the system precision with a battery of different pairs of wave heights and periods.

First, a seven hours experiment was performed to correct the drift term. Stationary conditions at the beginning and end of the test were used, and a constant frequency and amplitude of waves (frequency: 0.8 Hz, amplitude: 8 cm). An example of the obtained results is shown in Fig. 2.

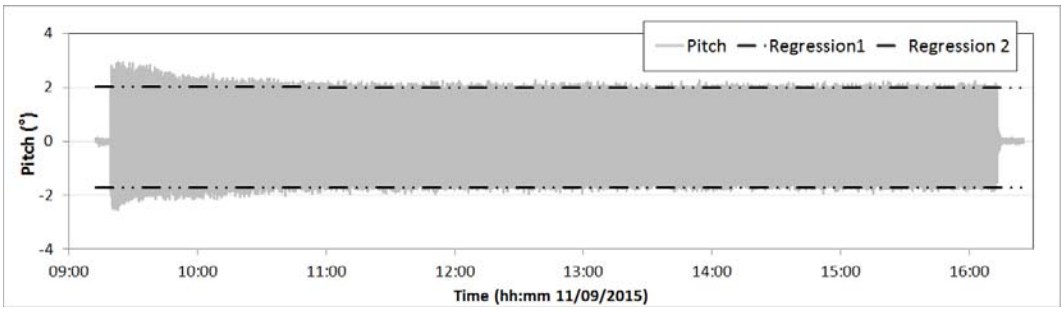

Fig. 2. Pitch measurements in the long term experiment conducted to validate the pitch correction.

The residual values were averaged in the entire test showing a deviation of 0.0015º, so no drift in the long term was found, solving one of the main concerns about the application of these devices. Also, a peak analysis was done, firstly to set initial values to be avoided in the analysis and that could be affected by the external force to move the object, and secondly to apply a regression technique between peaks, once again checking that no drift was found in those peaks.

The second battery of tests was done to validate the IMU comparing its results with a computer vision system, previously used in a similar case (Malheiros et al., 2009). The computer vision system used a video camera installed on a side of the wave-current flume to record the experiment, and track a set of visual targets in the model, with a block matching algorithm (Rodriguez et al., 2012).

An image of the experimental set-up and some results are presented in Figures 3 and 4. More details about the correlation analysis and results are explained in previous publications (Figuero et al., 2016).

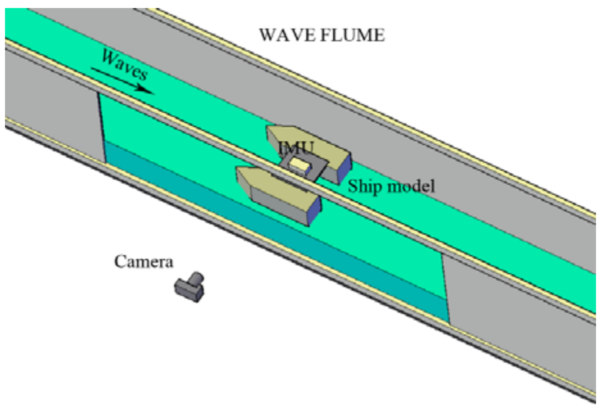

Fig. 3. Testing model in the R&D CITEEC wave-current flume.

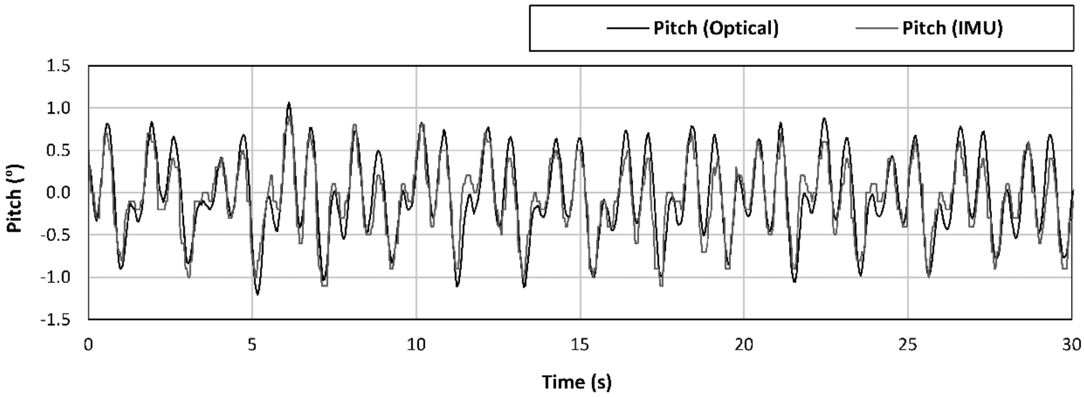

Fig. 4. Pitch measurements with the Computer Vision system and the proposed technique for a wave frequency of 0.5 Hz.

3.2 Field Campaign

The proposed technique was validated in a real scenario for the Port Authority of A Coruña (Spain), in the facilities of the Outer Port of Punta Langosteira. This port has a main breakwater of 3.3 km length that provides protection for a basin of actually 178 hectares. The field campaign was developed in the antipollution vessel Urania Mella moored at port during 3 months in winter, with dimensions of 72 m length and 15 m beam, gross and deadweight tonnage of 1,676 tons and 3,180 tons, respectively (Fig. 5).

Fig. 5. The vessel Urania Mella moored in the Inner Port of A Coruña.

Fig. 6 shows the mooring system of Urania Mella, which is one of the most commonly used nowadays. It consists in tying the ship to the harbour with different lines (chains, wire rope or a combination of the two), tied from the bow and stern of the ship to the dock called long forward and long aft lines, respectively. Additionally, ropes called spring lines are disposed running from the front of the ship to a tie point at the rear or vice versa, to prevent the ship from advancing or moving back. Finally, fenders are used between the boat and the dock or pier.

During the wave generation and propagation through the ocean, the nonlinear interaction among swell generates long waves, called infragravity waves. When the swell moves into shallow water and breaks, the associated infragravity waves are released as free waves which may reflect back towards the shore and keep propagating or radiate into deep ocean basins. Their periods may coincide with the eigen periods of the port basin producing oscillation amplifications and induced currents, or with the natural motion periods of the moored ship amplifying its movements.

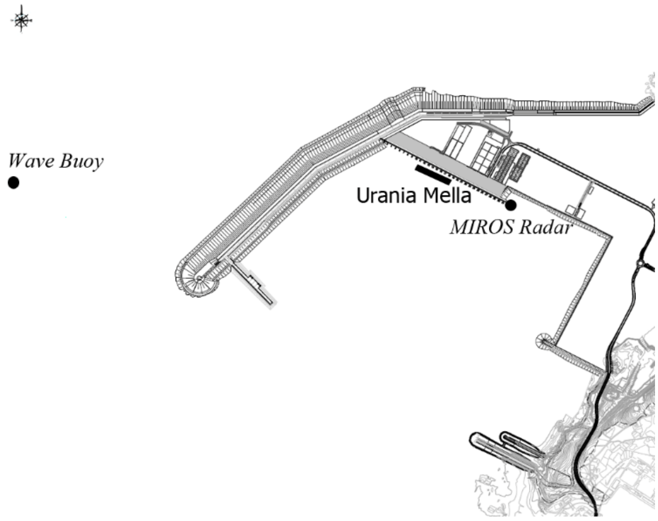

Fig. 6. Facilities at the Outer Port of Punta Langosteira (A Coruña, Spain) and location of the Urania Mella vessel (black shape, not scaled).

The obtained results for the monitored movements are shown in Figs. 7 and 8, where maximum and significant values of pitch and yaw angular motions are represented.

A strong linear relation between the three angular motions is observed. Since yaw is the easiest oscillation to measure onboard (most ships are equipped with a compass), relations of roll and pitch with yaw are discussed in this section, although the obtained results are generalizable to any other relation. Therefore, studying the correlation of these oscillations, Pearson values of roll and pitch with yaw of 0.87 and 0.97 respectively, with a p-value < 0.05, were obtained.

Taking this into account, an experiment was carried out to measure the predictability of roll and pitch motions when knowing yaw. Thus, a linear model was adjusted with the first half of the obtained measurements and used it to predict the response in the second half.

Obtained results are shown in Figs. 9 and 10. Analyzing the previous results, it can be seen that two oscillations of a moored ship can be estimated from the third one in some conditions for a fixed mooring orientation and mooring system. Obtaining and average prediction error of 0.14º in pitch and 0.16º in roll with a standard deviation in error of 0.06º and 0.14º, respectively. This result, although performed with a non-exhaustive cross validation method and without considering different ship sizes, mooring systems or mooring orientations is important since it may help in the understanding of moored vessel behavior and provides useful information to prevent operational downtimes and critical situations with damages to the dock and vessel.

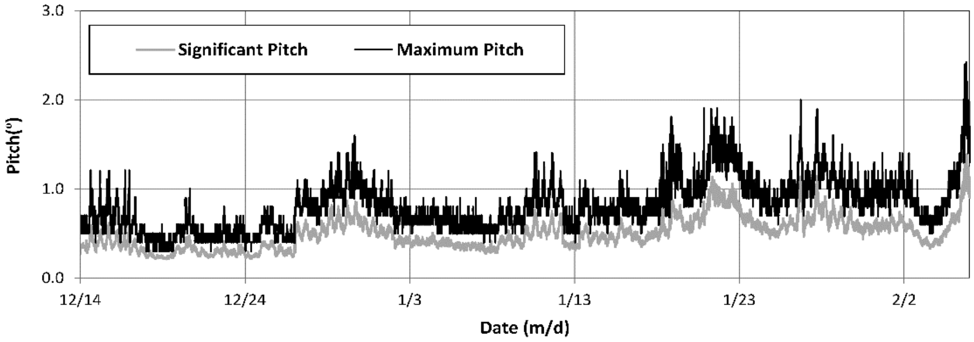

Fig. 7. Significant and maximum pitch measured with the proposed technique.

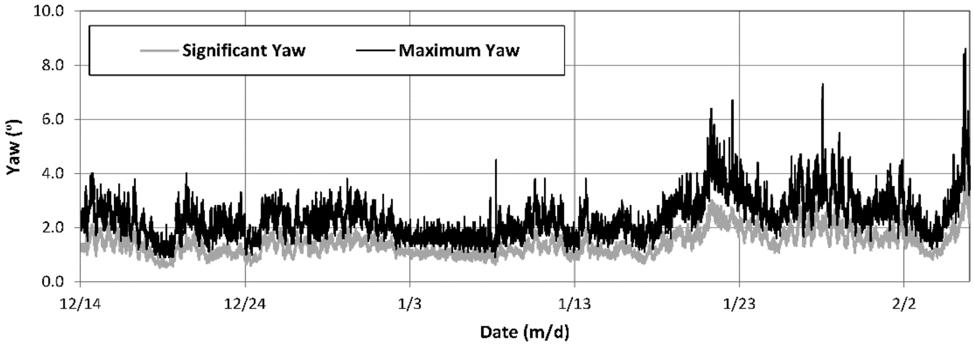

Fig. 8. Significant and maximum yaw measured with the proposed technique.

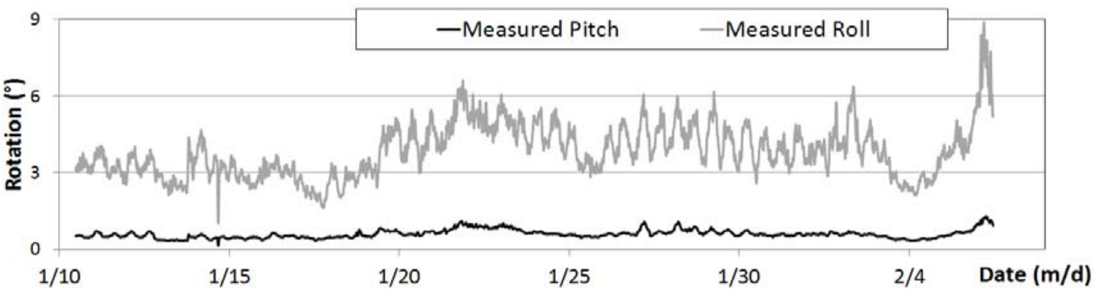

Fig. 9. Significant pitch and roll measured with the proposed technique.

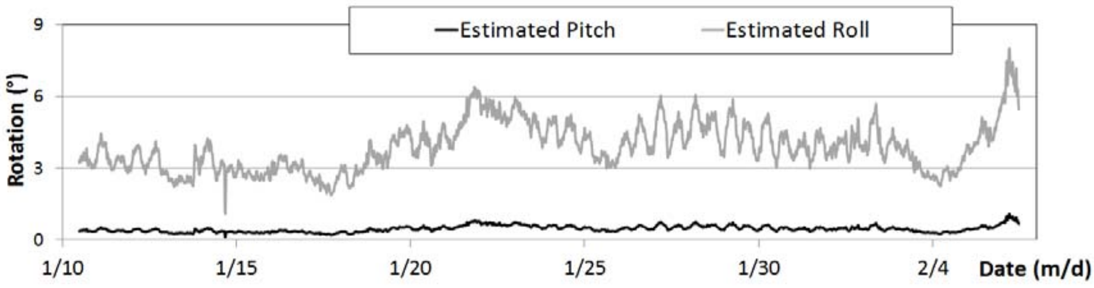

Fig. 10. Significant pitch and roll estimated from measured yaw.

During a part of the field campaign, different measurements were obtained regarding the mooring and sea conditions. On the one hand, gravity waves coming from the Atlantic Ocean were measured with a wave buoy located 1 km away from the main breakwater, and with a MIROS radar in the berthing line where the Urania Mella was moored (Fig. 6). On the other hand, maximum loads were measured on the forward and stern mooring lines with calibrated load cells.

Figs 11, 12, 13, and 14 show the comparison of loads in mooring lines and wave heights with roll oscillations.

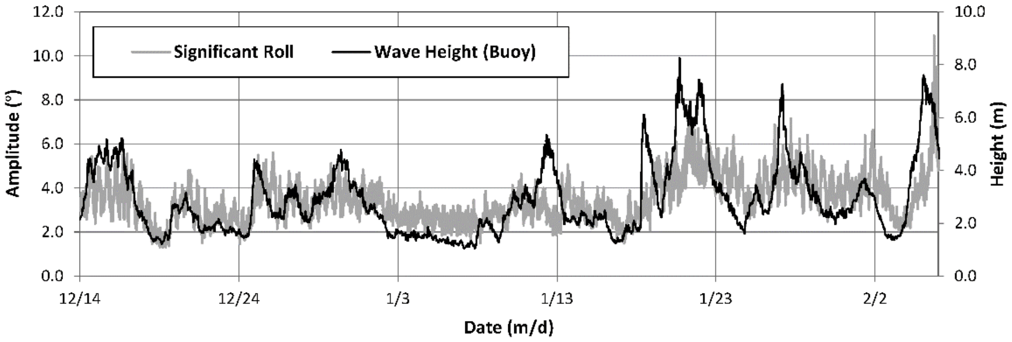

Fig. 11. Evolution of significant wave height measured with a nearby wave buoy compared with significant roll.

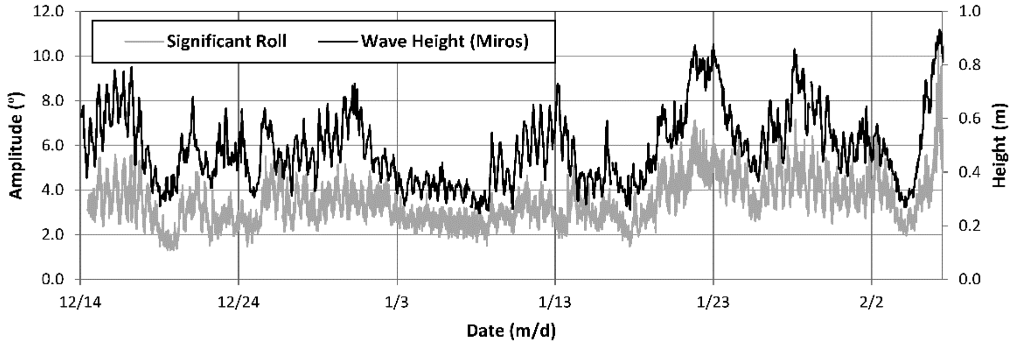

Fig. 12. Evolution of significant wave height measured with a nearby MIROS radar compared with significant roll.

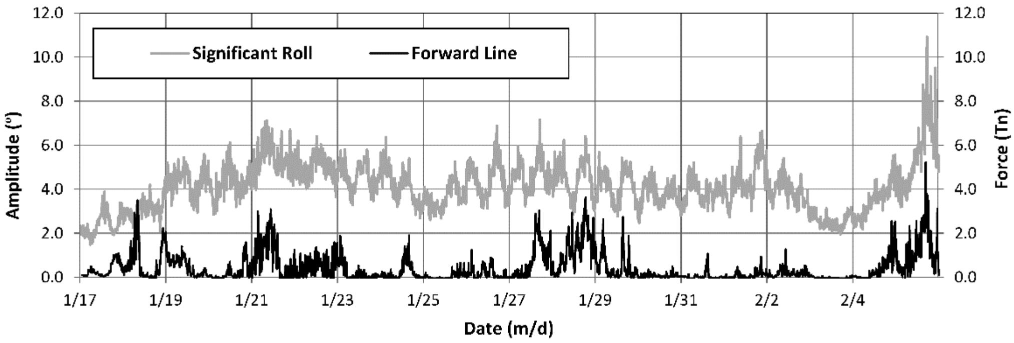

Fig. 13. Evolution of significant forces in a forward line, measured in tons-force units with a load cell, compared with significant roll.

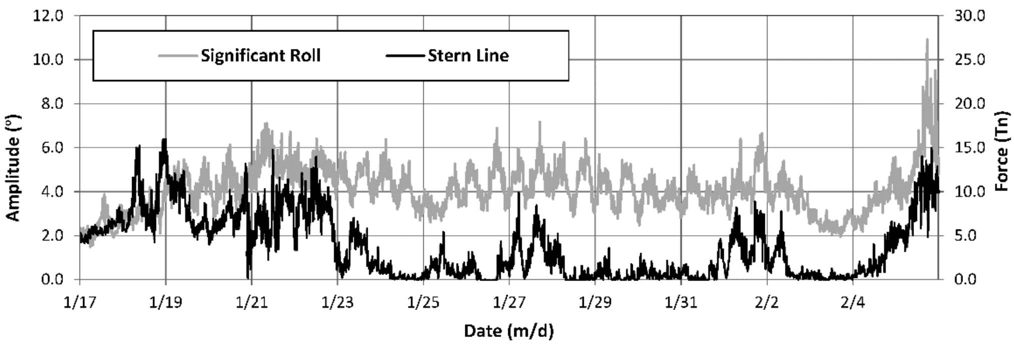

Fig. 14. Evolution of significant forces in a stern line, measured in tons-force units with a load cell, compared with significant roll.

A strong linear relation of the angular motions with wave height measured inside the port was detected. Additionally, a light linear relation with wave height in the open ocean and with loads in the mooring lines was observed using Pearson equation. The results are statistically significant (p-value < 0.05) and are shown in Table 1.

Table 1. Pearson correlation of angular motions with wave height and loads in the mooring lines.

	Wave Height Ocean	Wave Height Port	Forward Line Load	Stern Line Load
Roll	0.64	0.79	0.29	0.39
Pitch	0.62	0.72	0.51	0.53
Yaw	0.68	0.83	0.33	0.47

4. CONCLUSIONS

An inertial measurement system to study the orientation of a moored ship was designed in this work. This system is based on the use of gyroscopes, accelerometers and magnetometers to measure the angular movements of a moored ship.

This IMU device was validated in laboratory conditions, checking that it is not affected by significant drifts, and obtaining similar results to the ones from far more complex techniques, such as a computer vision based system. In addition, computing techniques were applied to increase the accuracy of the device in order to make it useful in this relevant civil engineering field of port operational efficiency.

The proposed technique was tested with a real ship, the Urania Mella, an antipollution vessel moored in the Outer Port of Punta Langosteira in A Coruña (Spain). During the field campaign, roll, pitch and yaw were measured and compared with wave heights and loads in the mooring lines, obtaining very promising results. In particular, the angular motions showed a significant correspondence with wave height measurements inside the port, obtaining correlation coefficients of 0.79, 0.72 and 0.83, respectively.

The IMU system may contribute to characterize the behavior of the moored ships inside the port, in order to establish limiting operation conditions, quantify the availability of the terminals, evaluate meteorological forecast tools developed for the operation of the port and finally establish a methodology to analyze the impact on operations of new port final layout and how to manage new traffics.

In addition, this technique, can lead to stablish a more effective way of evaluating berthing and mooring equipment of the terminals, analyzing new mooring systems to reduce downtimes of the terminals and to establish recommended mooring arrangements. Definitely, this system will provide useful information for port regulators to prevent critical situations that may generate important economic losses and personal safety risks.

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