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Accuracy of measuring small heeling angles of a ship using an inclinometer

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Abstract

This article describes studies that evaluate the accuracy of measuring a ship's heeling angle with an inclinometer. It does so by comparing inclinometer readings with benchmark measurements made with the optical method. The first part of the article describes the measurement station used for gathering measurement data. This station included an inclinometer and a CCD camera, and was used to process digital images incorporating a horizon line to indicate the ship's heeling angle. The second part of the article describes the data gathering process carried out on a ship at sea. The final part describes a statistical analysis which compares the angular measurements based on an inclinometer with simultaneous optical benchmark measurements.

Introduction

A significant limitation on the accuracy of bathymetric measurements is the uncertainty of the angle between the positioning system's antenna and the acoustic wave reflected from the seafloor, especially when the ship's motion is disturbed. This problem can be resolved by using appropriate methods to compensate for the heeling angle of the ship. These methods should account for minor impacts on the estimated direction of the acoustic beam attributable to wave motion (Naus, Wąż & Nowak, 2012; Wąż & Naus, 2012a; 2012b; Nowak & Naus, 2014).

The direction of the acoustic beam is determined relative to a vertical line. Although the angle between the beam and the vertical can be measured with an inclinometer, doing so is a non-typical application of the apparatus. This is so because the true vertical changes with a frequency and amplitude determined by hydro-meteorological conditions on the body of water on which the measurements are being made. For that reason, studies have been made of the accuracy of estimating heeling angles with an inclinometer under actual marine conditions.

Research method

The study was based on a collection of measurements of heeling angles estimated with a clinometer and with video images. The measurements were carried out on the ORP "Wodnik" ship, using a measurement station specially prepared for the purpose. In order to maintain a "clean" horizon line, the ship was allowed to drift in a position outside the visibility of land when measurements were being made.

Measurement station

The measurement station incorporated an AGS005-2-CA1-H0-2RW type inclinometer manufactured by POSITAL, and a HDR-CX130 camera from Sony (Posital, 2015; Sony, 2015). Both devices were mounted on top of one another in the ship's porthole 6 m above the water surface (Figure 1).

The camera's optical axis and the OX measurement axis of the inclinometer were set perpendicular to the ship's centerline surface such that the horizon line as observed by the camera was in the center of the image (when not affected by the swaying of the ship).

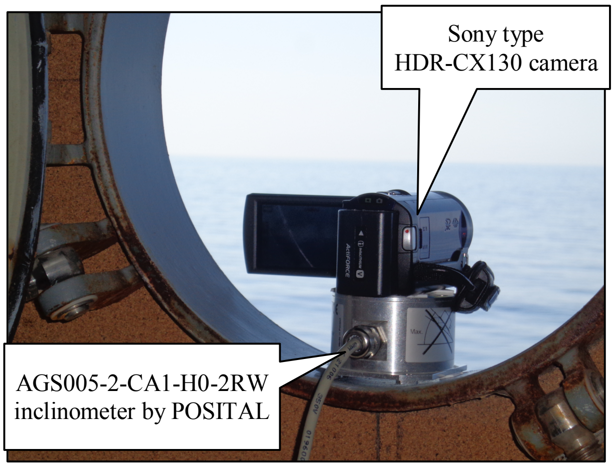

Figure 1. Measurement station

Method of determining the heeling angle from the camera image

The method employed to estimate heeling angle with a camera is based on the correlation between the heeling angle of the ship's hull and the angle created between the horizontal edge of the camera image and the horizon line. Making practicable use of this relationship required the development of software capable of running a special algorithm for processing and analyzing a single video frame – specifically, a 24-bit, bmp formatted digital image. Such an image is presented in the form of a block chart in Figure 2.

As summarized in Figure 2, this algorithm subjects an image to the following successive operations: noise removal, edge detection, designation of the horizon line, and designation of the heeling angle, α. Noise removal is carried out by using a modified version of the Gauss filter, which consists of the mathematical relationship shown in Eq. (1).

$$\mathrm{G}(k,l)=\frac{1}{2\pi\sigma_k\sigma_l}\exp\left(-\frac{(k\cos\alpha_o+l\sin\alpha_o)^2}{2\sigma_k^2}+ -\frac{(l\cos\alpha_o-k\sin\alpha_o)^2}{2\sigma_l^2}\right) \tag{1}$$

Equation (1) is to be used with the values of 4 for σ_k, and 0.1 for σ_l. Note that the values for these coefficients were chosen empirically (Naus, 2005).

Figure 3 is a graph of the Gauss function modified to be consistent with Equation (1).

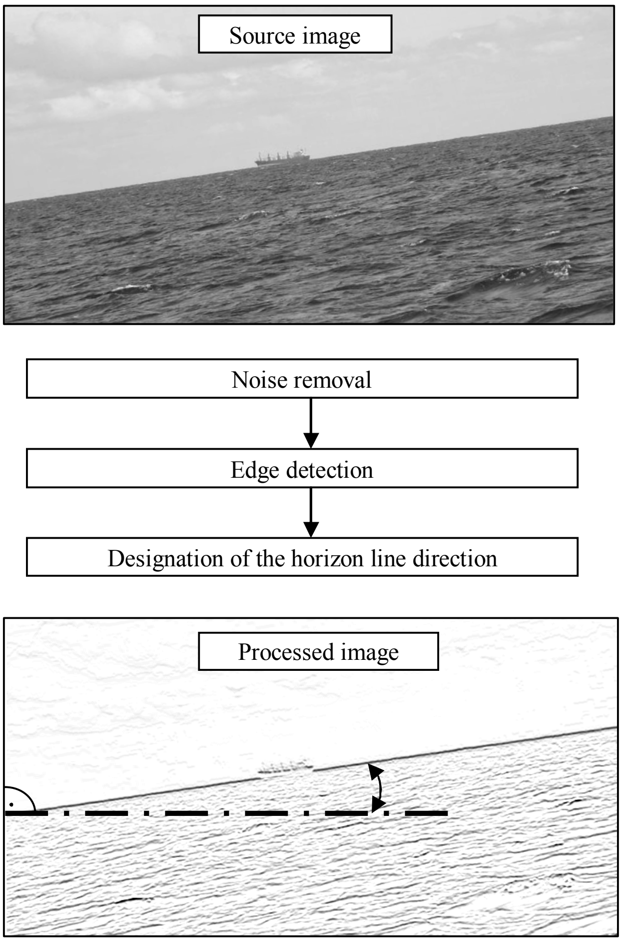

Figure 2. Algorithm for designating the heeling angle

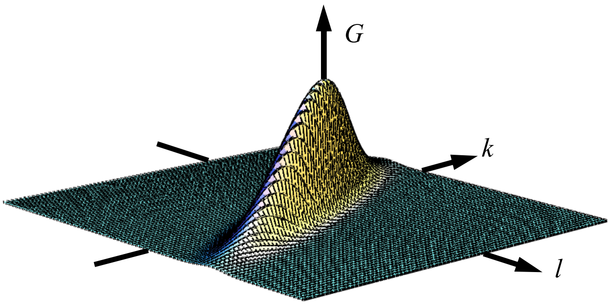

Figure 3. Graph of a modified, two dimensional Gauss function

A filter modified by Eq. 1 smoothes the image heavily along the horizon line (described by the angle α_o in the previous step), but only very slightly in the direction perpendicular to the horizon line.

Edge detection was carried out using the differential or gradient method, based solely on the vertical element of the image gradient (partial derivative value). Determination of the gradient's value in this direction only eliminates vertical edges, and emphasizes horizontal or nearly horizontal edges, which includes the edge comprising the horizon. Values for the image gradient's vertical elements expressed as the point (x, y) were determined by using the following formula:

$$\nabla_y(x, y) = \left|\frac{\partial f(x, y)}{\partial y}\right| \text{ mask} \begin{bmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad (2)$$

Finally, the direction of the horizon line was determined by finding a set of pixels in the processed image that formed a straight line, and that had values higher than the neighboring pixel on the vertical side. The angle α is estimated as the angle between the line of pixels representing the horizon line and the horizontal edge of the image.

Analysis of results

Using the measurement station depicted in Figure 1, a 12 minute measuring session was conducted. During that time a compilation of digital video images (frames) was recorded using the camera at a frequency of 25 Hz. The digital images collected in this way were subsequently processed according to the algorithm of Figure 2 to generate angular values corresponding to the ship's longitudinal heeling. These values were subsequently compared to the angular values of the ship's longitudinal heeling measured at the same time with the inclinometer. Figure 4 plots simultaneous estimates of the longitudinal heeling angle over the entire measurement session as measured by both the video process and the inclinometer. Video-based heeling angle estimates represent the means of the angular values computed over each of the 25 sequential frames recorded during a specified second, while the corresponding inclinometer-based values were simply the measurements read from the inclinometer during that same second.

To highlight discrepancies between methods, Figure 5 plots the absolute value of the deviation of video- and inclinometer-based angles as a function of the image frame number.

Statistical figures and a bar chart were used to facilitate the interpretation of absolute differences summarized in Figure 5. Table 1 presents the statistics on the variability of the absolute differences in heeling angle estimates.

Table 1. Statistics quantifying the variability of the absolute difference of heeling angle values between methods

Average absolute value of heeling angle differences	0.028615°
Maximum absolute value of heeling angle differences	0.152558°
Minimum absolute value of heeling angle differences	0.000058°
Standard deviation of the absolute value of heeling angle differences	0.02304°

Figure 6 is a bar chart that makes it possible to evaluate the incidence of absolute values of all observed differences between heeling angle estimates.

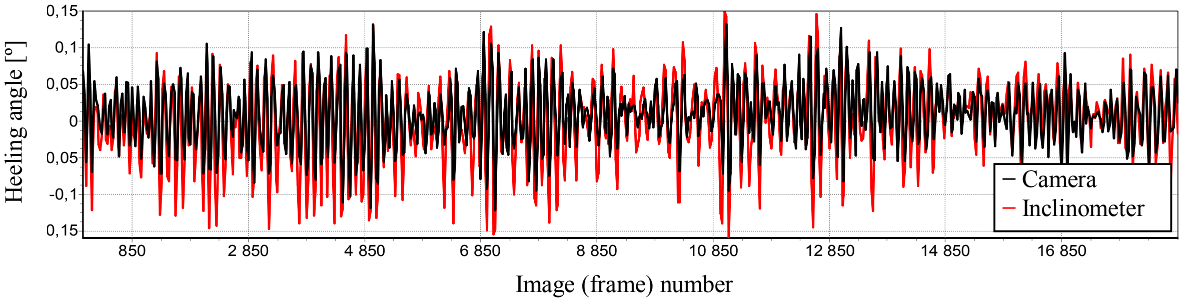

Figure 4. Graph of the ship's longitudinal heeling angle derived from the video image and inclinometer (one reading each second)

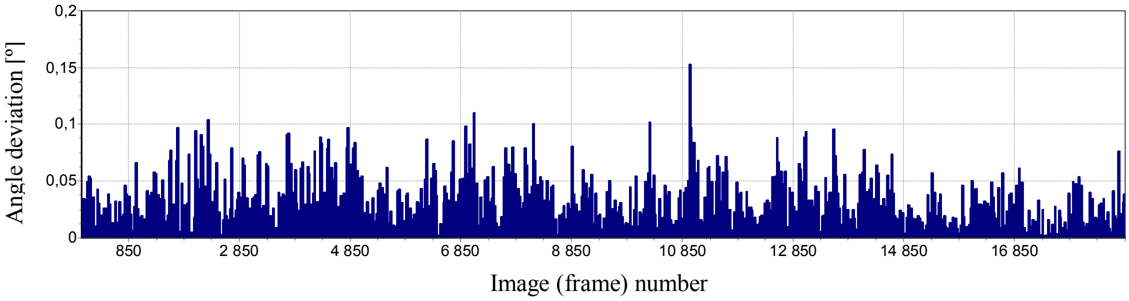

Figure 5. Graph of the absolute difference between the angles derived from the video image and as measured by inclinometer (1 image estimate per second)

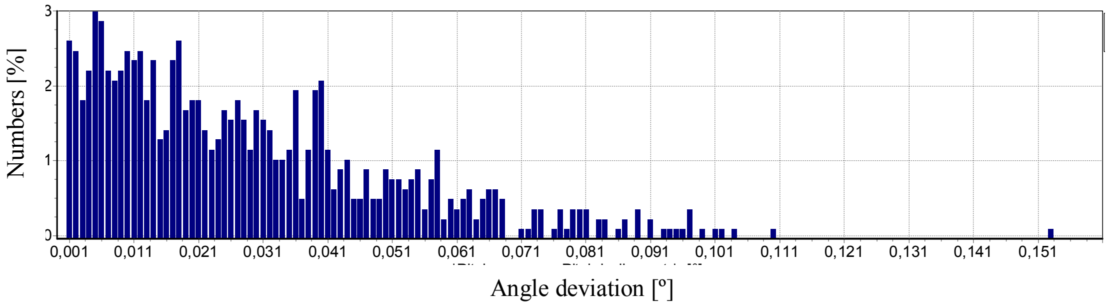

Figure 6. Bar chart of the relative frequency of absolute values of differences between heeling angles as measure by video images and an inclinometer

Conclusions

From an analysis of Figures 4–6, and the statistics summarized in Table 1, it is possible to make three general conclusions:

1. The accuracy of inclinometer measurements is on the level of one-hundredth of a degree (see Table 1), which is consistent with the manufacturer's declaration (Posital, 2015);
2. Although some measurements represented errors exceeding one-tenth of a degree, such relatively large errors were very infrequent (see Figure 6);
3. An increase in the frequency and amplitude of the ship's sway influences the accuracy of inclinometer measurements, a fact that is quite evident in Figures 4 and 5.

The following detailed conclusions may also be drawn:

1. Inclinometer measurements of a ship's heeling angle may be carried out with high accuracy (up to one-hundredth parts of a degree in the case of a AGS005-2-CA1-H0-2RW type inclinometer by POSITAL);
2. The inclinometer may be used to determine the direction of the acoustic beam during bathymetric measurements conducted under conditions of minor wave action;
3. Inclinometer measurements conducted when waves were frequent and of large magnitude should be corrected. An appropriate correction method is applying the Kalman filter.

It should be noted that the preceding conclusions relate exclusively to liquid capacitive inclinometers with electrolytic fluids in which the electrolytic fluid level in the cell indicates the heeling angle.

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