J. Marine Sci. Appl. (2015)14: 406-412
DOI: 10.1007/s11804-015-1331-9

The Application of a Smartphone in Ship Stability Experiment

Mohamed Abdelkader Djebli*, **Benameur Hamoudi, Omar Imine and Lahouari Adjlout**

Department of Maritime Engineering, Faculty of Mechanical Engineering,
University of Sciences and Technology of Oran Mohamed Boudiaf, BP 1505 El'Mnaouer, Algeria

Abstract: The inclining experiment is the only regulatory tool to assess ship stability. This experiment is a time consuming process for both real-life tests and ship model experiments. The difficulty is mainly due to a bias in the measurement of heel angle. Nowadays, digital inclinometers are available, but they are expensive. In this study, the use of a smartphone application is presented for ship inclination and rolling-period tests. The idea consists of using accelerometer and gyroscope sensors built into the current smartphones for the measurements. Therefore, some experiments are carried out on an example trawler model to exhibit the uses and advantages of this method. The obtained results are in good agreement with those provided from the pendulum method and natural roll-period test. This application is new, easy, and more accurately assesses metacentric height during the inclining and rolling-period tests.
Keywords: ship stability; GM-Meter; inclining experiment; rolling-period test; smartphone; accelerometer; gyroscopic sensor

Article ID: 1671-9433(2015)04-0406-07

1 Introduction

Smartphones can be accessed almost anywhere and anytime. The number of smartphone users worldwide is over 1.06 billion representing approximately 60% of cellular phone users at present and growing rapidly (Daponte *et al*., 2013). In 2015, the number of smartphone users, in the US only, is expected to be around 148.6 millions. Due to the growth of the smartphone market, there are an enormous number of applications in use. Today's smartphones are equipped with a gyro-sensor system that enables various applications related to engineering measurements. In this study, a smartphone is used with a clinometer application and a motion recorder. It can be used for stand-alone measurements, as mentioned by Kuhn and Vogt (2013). Such new technologies bring improvements in safety, security, and efficiency in navigation, to naval engineering and boating in general. Furthermore, the use of such devices for navigation will greatly reduce dedicated equipment costs.

In the present work, measurement of the centre of gravity 6 degrees of freedom (DOF) is carried out with a smartphone attached to the ship. This experiment uses an application implemented on Google™ Android™.

2 Experimental methods in ship stability

The instantaneous ship motion consists of 6 DOF, as shown in Fig. 1, and these movements need to be measured and recorded in the phone. The linear acceleration, surge, sway, and heave of a ship can be measured by using an acceleration sensor, while the instantaneous angular velocity, roll, pitch, and yaw of a ship can be measured by a gyroscopic sensor. Also, post-processing tools, such as recording, filtering, and integration of the signals, is necessary. Fortunately, all these features are available in smartphones. Fig. 2 shows the coordinate system related to a smartphone, allowing the direct readout of the 6 accelerations of the ship in real-time. In order to accurately transfer the ship movement to the smartphone's sensors, the device has to be properly attached to the ship.

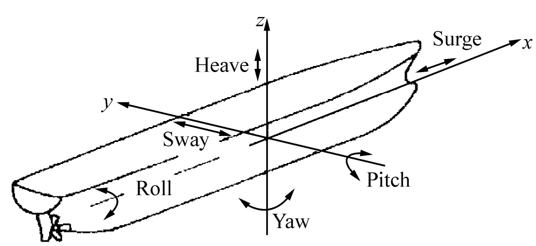


Fig. 1 Ship motions with the 6 DOF

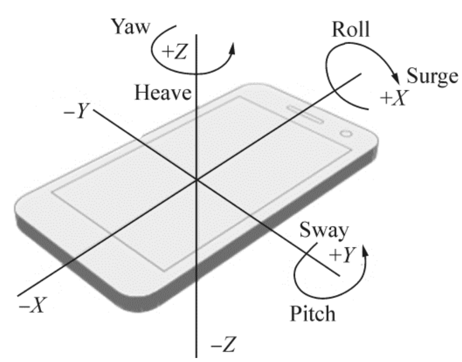
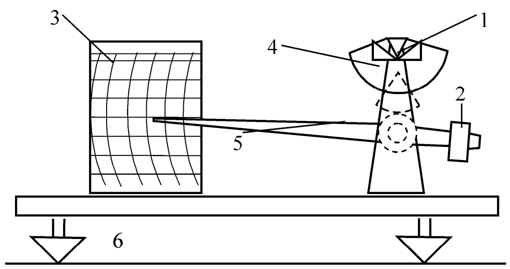


Fig. 2 Smartphone motions with the 6 DOF

Although all 6 DOF have direct impact on ship behaviour, the rolling motion is probably the most important parameter for assessing ship stability. Usually ship inclining tests use a special tool called a stabilograph or stabilometer to measure the roll and heel (Lewis, 1988). Basically it consists of a

Received date: 2015-04-23.
Accepted date: 2015-09-11.
***Corresponding author Email:** djebli_k@yahoo.fr

heavy metal pendulum balanced on a knife edge and connected to a pointer to record the heel angle readings, as shown in Fig. 3. This measurement can also be carried out by the pendulum technique as shown in Fig. 4. It is well known, among professionals, that this method of measurement has a lot of hassles, such as readout, precision, and bulk. Furthermore, the experiment must be conducted with careful attention as required by regulations from the International Maritime Organization (IMO, 2009), and FAO Food and Agriculture Organization (Gudmundsson, 2009) and national authority.



1. Knife edge; 2. Weight; 3. Rotating drum; 4. Pendulum; 5. Pen arm; 6. Adjustable table

Fig. 3 Stabilograph

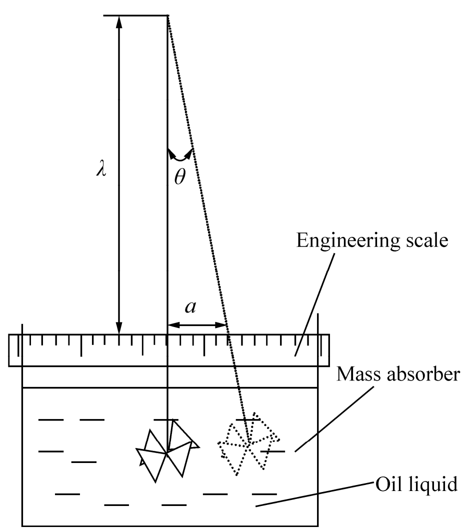


Fig. 4 Traditional tilt measurement based on a pendulum

Nowadays, the set-up shown above is replaced by a GM-meter (Cota, 1985) which is a dedicated electronic instrument that measures seaworthiness parameters (roll period, gyroscopic platforms). Such devices are based on accelerometer sensors. Sensor outputs can be fed directly to an on-board computer for stability evaluations (IMO MSC.1/Circ.1228). However, they are very expensive and must be used in accordance with the rules, so they are not common, especially in small ships. Several works have been devoted to this subject. Griffin *et al.* (1985) developed, and patented in 1987, an instrument based on spectral analysis of vessel roll movement in order to determine metacentric height. These instruments are not compulsory by international regulators such as IMO, except for passenger vessels which follow IMO resolution A749 and MSC.267 (85), as adopted 4th December 2008.

3 The assessment of metacentric height

3.1 The inclining experiment

The inclining experiment, also known as inclining test, is performed on a marine vessel to determine her stability atitude, empty ship weight, and the coordinates of her centre of gravity. The test is applied to newly constructed ships, to ships altered in ways that could affect stability, and for any changes in stability during a voyage. Inclining experiments and the rolling period test procedures are specified for all ships by the IMO and other international associations. For fishing vessels specifically, the FAO gives comprehensive and easy to understand instructions for fisherpeople.

The inclining test is usually done inshore in calm weather, in still water and free of mooring restraints, to achieve accuracy. Basically, the test determines the metacentric height *GM* by moving weights transversely as illustrated in Fig. 5. The displacement of a vessel Δ can be readily determined by reading the draft and comparing with known hydrostatic curves. The *GM* magnitude, which dominates stability, can be estimated from the design, but the inclining test gives a more reliable value of this parameter.

Figs. 5 and 6 show a common set-up for the inclining test. A plumb line is hung with a bob immersed in a water tank, that serves like an oscillation damper, as shown in Fig. 4. The mass w is displaced transversely with the distance d. The resulting heel angle, assumed small is given by (Biran, 2003):

$$\tan(\theta) = \frac{wd}{\Delta GM} \tag{1}$$

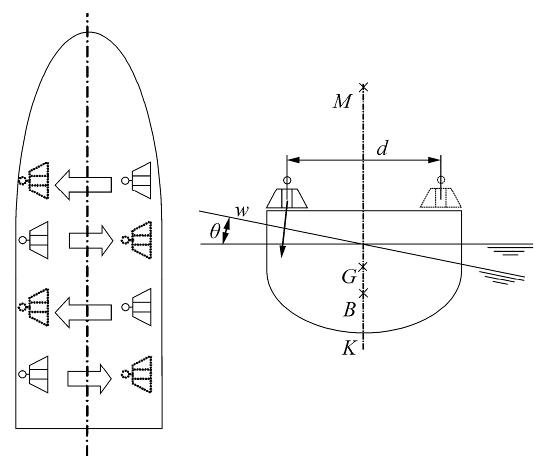


Fig. 5 Schematic diagram of the inclining experiment

A suitable way of checking the results is to verify the linear relationship between the heeling moments per unit displacement wd/Δ and the heel angle tangents $\tan(\theta)$.

It's worth noting that this theory is applied only for a small heel angle $\theta<5°$. Thus, it is assumed that $\tan(\theta)\approx\sin(\theta)\approx\theta$ where θ is in radians and wd/Δ can be assumed to be the uprighting lever *GZ*.

$$\frac{wd}{\Delta}=\overline{GM}\tan(\theta) \tag{2}$$

Eg. (2) shows that the ideal plot should be a straight line; with the slope *GM*. In the past, naval architects fitted a straight line by eye through the plotted points. Nowadays computers and many hand calculators easily do least-squares fit.

3.2 The rolling-period test

Even though the rolling-period test is just recommended, not compulsory, by the regulations, it can be a quick estimation of the $\overline{GM}$. This test is applicable only for a round bilge hulls without a bilge keel. Basically, in this test the ship is inclined to a small heel angle up to $\theta \approx 5°$ or even to $\theta \approx 10°$ and then released. The ship should oscillate with its natural roll period and the result is a damped oscillation around the static heel of equilibrium. Hence, the natural roll period and the damping increment can be determined. Usually a stopwatch is used to time at least four complete rolling periods in order to measure this period.

In linear theory, ship roll is assumed to be a one degree of freedom system. Hence her natural period is a function of restoring moment and a mass moment of inertia. Therefore, the period is determined by Eq. (s), per Weiss:

$$T_r = \frac{2C_r B}{\sqrt{\overline{GM}}} \tag{3}$$

where *B* is ship breadth in meters, *GM* in meters and C_r, the inertia coefficient for rolling motion, is in the range of $0.75<C_r<0.80$ for rounded hulls. Except for trawlers where C_r can reach unity.

There are different ways to obtain the value of C_r. It can be taken from shipyard documentation, or calculated according to the IMO Guidelines as:

$$C_r = 0.373 + 0.023\left(B/d\right) - 0.043\left(\mathrm{LPP}/100\right) \tag{4}$$

For a large vessel (length overall greater than 24 m). However, for a conventional fishing boat (length overall less than 24 m) the stability is found satisfactory when the rolling period T_r value in seconds is less than the value of the Breadth *B* (m). Regardless of the units, this is practical for fisherpeople to use, as stated by Gudmundsson (2009). It has to be noted that a rolling period test should be conducted when the vessel is loaded according to the operating conditions.

4 The experiment setup

In order to assess the capabilities of smartphones to perform a stability experiment, the tests are carried out in a ship stability laboratory. Fig. 6 shows the experiment apparatus.

Fig. 6 Experimental setup

4.1 Vessel model

The vessel model, referenced NA8-14 according to the manufacturer, is chosen both for its well documented hydrostatic data and its high finish grade. This model is the parent form of the British Ship Research Association (BSRA) trawler series (Pattulo and Thomson, 1965). Furthermore, this trawler series is a subject of extensive research and publication. Its principal characteristics are depicted in Table 1. Fig. 7(a) shows the body plan, whilst the 3D view of the experimental hull is shown in Fig. 7(b).

The model is fitted with internal bulkheads, and supplied with the necessary ballast and trimming weights. It is constructed and moulded in glass reinforced plastic (GRP). The hull is fitted with a number of transverse watertight bulkheads in their correct positions. Flooding valves are also fitted. In this study, only one partly loaded draft is tested. The model is loaded at its design load line draft DWL.

To carry out the experiment some conditions are carefully set to be as close as possible to full scale conditions, such as draft, loadcase, and centre of gravity. The chosen loadcase of the model gives a draft of $d = 160$ mm to reflect the real ship.

The experiment parameters are summarized in Table 2. It has to be noted that the smartphone weight 144.58 g is included in the model displacement. The smartphone is mounted along the model's centerline, in order to avoid vertical acceleration due to the roll motion. This is achieved using high strength double-sided tape.

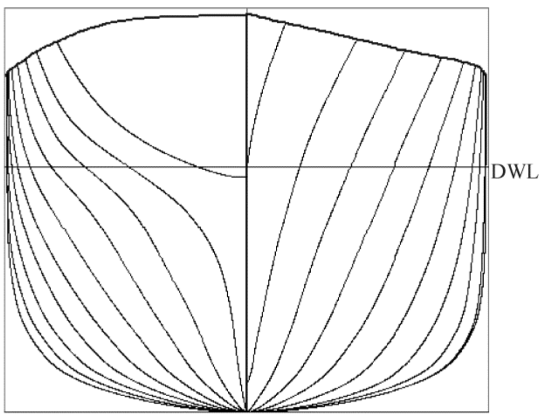
Several tests were carried out with different *GM* while keeping the displacement constant. This experiment was performed with a known sliding weight positioned at different heights as shown in Fig. 6.

Table 1 Principal particulars of BSRA trawler hull

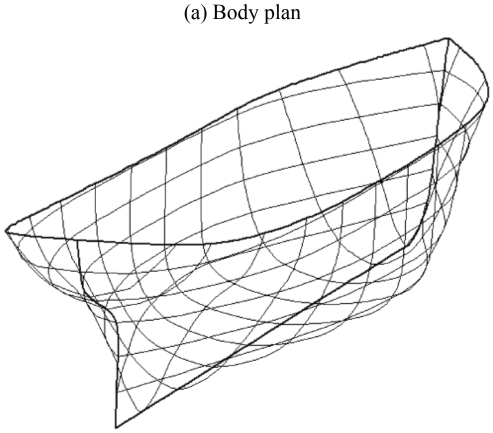
Parameters	Ship	Model
Scale	1:1	1:25
Length between perpendiculars LPP/m	45.72	1.82
Breadth *B*/m	8.03	0.32
Depth *D*/m	6.40	0.256
Draft at DWL *T*/m	4.06	0.16
Displacement volume at DWL/m^3	839.5	0.05
Block coefficient C_b	0.564	

Table 2 Experimental setup data

Parameters	Values
Number of weight	6
Weight moved *w*/kg	0.200
Distance moved by the weight *d*/mm	278
Length of pendulum *λ*/mm	795
Displacement *Δ*/kg	51.787
Draft *T*/mm	160
LCB (from amidships)/mm	17.3
LCF (from amidships)/mm	−25.6
Sliding weight/kg	3.026
$\rho/(\text{kg}\cdot\text{m}^{-3})$	1.004



(a) Body plan



(b) Body sections and 3D view

Fig. 7 The fishing vessel

4.2 Sensors in smartphones

The 3-axis accelerometer and 3 axis gyroscopic sensor built nto the smartphone used in the experiment, is the MPU-6050 sensor, manufactured by InvenSense™ (2013). The sensor contains a MEMS (micro-electro-mechanical systems) accelerometer and a MEMS gyro in a single chip. It is very accurate, as it contains a 16 bit analog to digital converter. For precision tracking of both fast and slow motions, it features user-programmable full-scale gyro and accelerometer ranges. Some interesting features, drawn from the manufacturer datasheet (MPU-6000/MPU-6050 Datasheet 2013), are shown in Table 3.

Table 3 Principal particulars of MPU6050 sensor

Gyro full scale range/$((°)\cdot\text{s}^{-1})$	Gyro Sensitivity/ $(\text{LSB}/((°)\cdot\text{s}^{-1}))$	Accel Full Scale Range/g	Accel Sensitivity/ $(\text{LSB}\cdot\text{g}^{-1})$
±250	131	±2	16384
±500	65.5	±4	8192
±1000	32.8	±8	4096
±2000	16.4	±16	2048

4.3 Smartphone data acquisition DAQ

The sampling rate can reach up to 100 Hz in the present test. The Shannon sampling theorem (Webster, 1999) states the conditions, "to be able to completely recover the continuous signal from sampled data, the signal may be sampled at least at the rate of 10 to 20 times the harmonic frequency of the sample", is respected in present experiment. It is well known that for ship motion (Lewis, 1989), this frequency is a natural roll frequency which cannot exceed the limit of 1 Hz for a ship.

In order to obtain high sampling frequency, it is advised to turn off unnecessary applications, such as WIFI, GPS, Compass, and Bluetooth.

Another important parameter in DAQ is the amplitude resolution in bits. Despite the high resolution capability of current smartphone processor, 16 bits, the processor has to be adjusted in order to match the activated sensor resolution see MPU-6000/MPU-6050 Product Specification Datasheet (InvenSense™, 2013).

4.4 Smartphones application

The graphical user-interface of the smartphone application visualizes and backs up the parameters of the ship motion as shown in Figs. 8 and 9. The measurements are directly given in international units. The application has a calibration feature which resets the readout to zero in order to match the upright position of the ship. In addition, the application includes a digital low pass filter in order to eliminate high frequency noise which may occur during the experiment. The application captures and plots accelerometer and gyroscope data on screen. Fig. 8 shows the captured data in a comma separated value (CSV) file for post-processing. Notice that the tilt angle i.e. static heel, list of the ship, can be determined with the measured linear accelerometer. According to the smartphone related coordinate *z* axis, the acceleration *γz* is proportional to the gravity *g*. When the smartphone tilts around its local *x*-axis, the tilt angle is determined in Ripka and Tipek (2007) and given by the formulas:

$$\theta = \arctan\left(\frac{\gamma_y}{\gamma_z}\right) \tag{5}$$

or

$$\theta = \operatorname{arcos}\left(\frac{\gamma_z}{g}\right) \tag{6}$$

where γ_y and γ_z are the measured acceleration in *y*-axis and *z*-axis, respectively. It is worth noting that the tilt above is valid only for static or slow movement. This method is very sensitive to accelerations and gravity variation with geographical location. The latter can be a drawback fo measuring the tilt angle with high accuracy (Webster, 1999). Fig. 9 shows the application (Clinometers Apps) based on Eq. (6) to measure a heel angle. Alternatively, the heel angle θ can also be deduced from the roll angle with the gyroscope sensor. In fact, the gyroscope actually measures the angular velocity around the three-axis ω_x, ω_y, ω_z. Consequently, the instantaneous angle can be easily obtained by numerical integration (Bennett *et al*., 2014). However, when the integration time interval is long, the accumulated error of angle measurement with the gyroscope sensor can be significant (Webster, 1999).

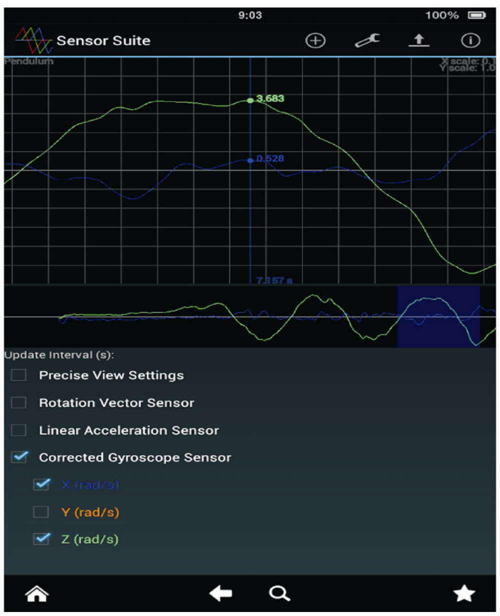


Fig. 8 Snapshot of the interface in the data logging apps of the smartphone's 6 DOF

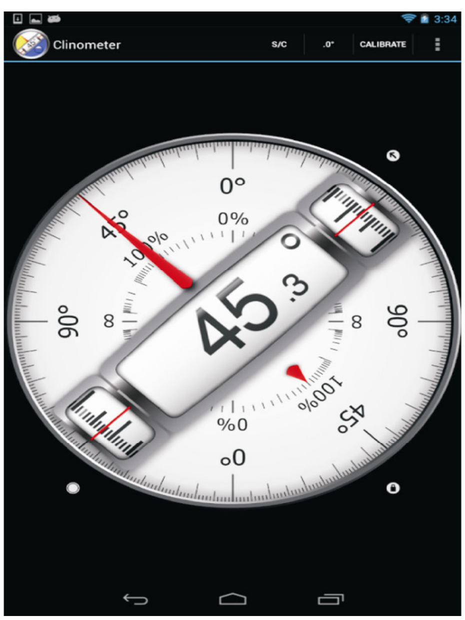


Fig. 9 Snapshot of the interface clinometer's apps based on accelerometer sensor

Fig. 10 illustrates an example using both methods. The data are recorded from an accelerometer sensor with a sampling rate of 20 Hz, over 40 s. The results are obtained by shifting weights causing the ship model to roll. Then this motion is damped over time to its desired equilibrium list angle.

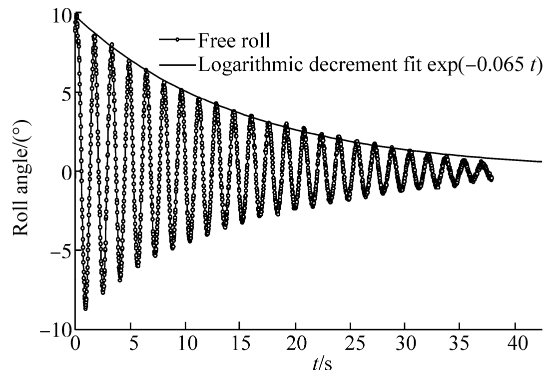


Fig. 10 Plot of the recorded CSV file of the free roll

5 Results and discussion

The experiments carried out in the model test are simultaneous smartphone and pendulum tests. The results are presented in Table 4 and plotted in Fig. 11. It has to be noted that when θ is in radians then the slope of the curve and the linear fitting is the magnitude of $\overline{GM}$. The curves are linear as expected. For the starboard side a good agreement is found. However, a slight difference is observed for the port side.

A linear regression analysis (least square method), represented in solid and dashed curves, is used to fit the measured points. Table 5 shows the comparison of the determined GM between the two methods. The standard deviation for smartphone measurement is 0.085 mm which is significantly lower than that obtained for the pendulum; 0.32 mm for a magnitude GM of 28.75 mm. Thus, the standard deviation deduced from the smartphone measurement seems to be more accurate. The relative error between the two values of GM is about 5%. As shown in Fig. 6, different GM values are obtained by adjusting the height of the sliding weight. As a result, different roll periods T_r are obtained from Fig. 12, which provides smartphone time history data. The signal is free of noise and thus no filter is required.

Table 4 Heel angle from the pendulum and smartphone sensors

Test No.	Angle from pendulum $\tan\theta = a/\lambda$	Angle from smartphone apps
0	0.00	0.00
1	2.23	1.90
2	4.49	4.10
3	6.63	6.25
4	−6.77	−6.70
5	−4.52	−4.40
6	−2.27	−2.10
7	0.00	0.00

Table 5 Comparison of the determined *GM* between the two methods

Measurement	*GM*/mm	Standard deviation/mm	Correlation factor
Pendulum	28.75	0.328 61	0.999 61
Smartphone apps	27.46	0.085 35	0.999 97
Error/%	4.50	–	–

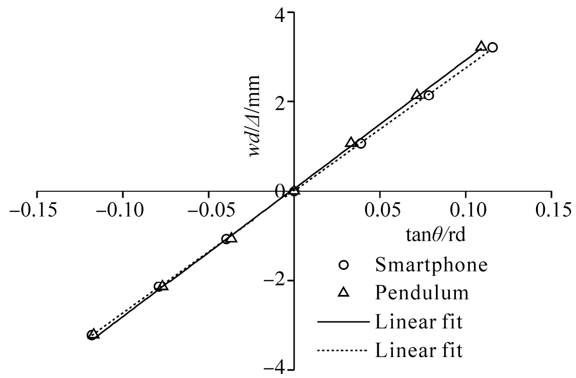
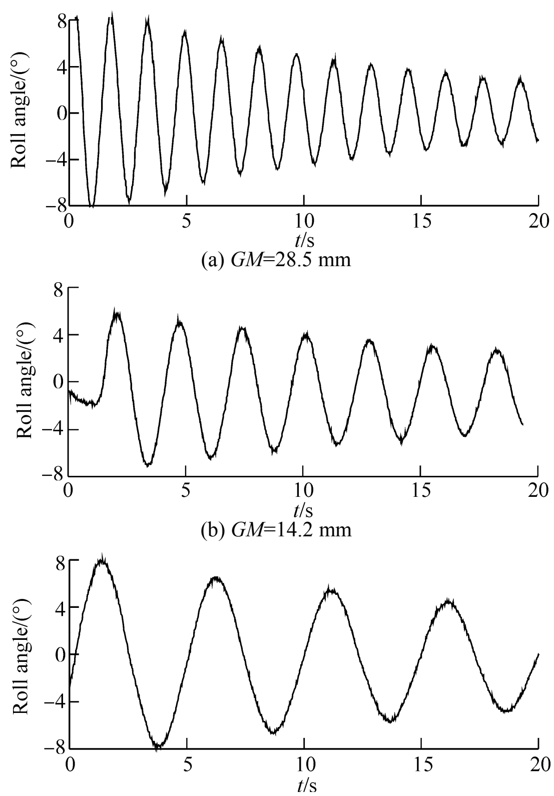


Fig. 11 *wd/Δ* vs. tan(*θ*) from the inclining test



(a) *GM*=28.5 mm

(b) *GM*=14.2 mm

(c) *GM*=6.2 mm

Fig. 12 Time histories data acquisition of natural rolling test for different *GM*

It is clear that it is easy to determine the period from the curves of Fig. 12 instead of the stopwatch. The data logging sampling rate reaches 10 Hz, during recorded roll motion, when the two sensors are activated simultaneously. The frequency rises to 20 Hz when only one of the sensors is activated. The T_r interval range of the test roll period varies from 1 s to 5 s, which corresponds from 0.2 Hz to 1 Hz.

Furthermore, the decay constant of the roll period can also be determined from recorded time history. It is clear from the recorded data that the decay is noticeable. For example, in Fig. 12 this parameter is 0.065 s^{-1}. Furthermore, in Fig. 13, where *GM* versus the natural roll period is plotted, shows a good agreement for both results.

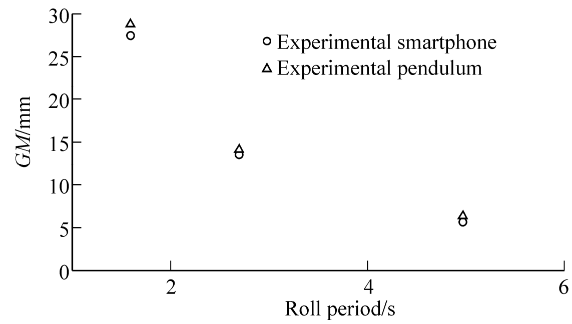


Fig. 13 Comparison of the experimental natural roll period

6 Conclusion and recommendations

A smartphone application visualizing the direct parameters of movement is presented, i.e. the angular inclinations and accelerations of a ship model in real-time. A classical inclining experiment with a smartphone as a heel angle instrument is investigated. In this standalone study, a new idea is suggested for measuring the heel angle during an inclining test with a smartphone application as inclinometer. With the new generation of water proof smartphones, this method can be suitable for masters, yachtspeople, fisherpeople, *etc*. Some recommendations are required such as the location of the smartphone on board. Particularly for the rolling-period test, some skill and basic mathematical user knowledge are needed in order to draw the information from the recorded data. In addition, the time history record for a rolling test can be archived in order to compare with other measurements.

As seen in the results, the accuracy of the obtained measurements using this new method is similar to the classical method based on pendulum measurements and is even better regarding simplicity, bulk, accuracy, readout, and robustness. The standard deviation for this method is much lower than for the classical one. Moreover, measurement with a smartphone, in both the full-scale inclining experiment and the rolling-period test, is simpler than that performed on the model. Because the roll period of a full-scale ship is larger than that of the model.

The satisfactory results from the present work could make this method of measurements widely used. Moreover, it can be recommended by the IMO, the FAO, and other regulating authorities for the inclining experiment and rolling period test. There is no doubt that the use of this technical method may popularize experimental work and data collection using such affordable ways of data logging.

Acknowledgement

The authors would like to thank the staff of the Ship Stability Laboratory at the Maritime Departement, University of Sciences and Technology of Oran Mohamed Boudiaf, Algeria.

References

Bennett SS, Brooks CJ, Winden B, Taunton DJ, Forrester AIJ, Turnock SR, Hudson DA (2014). Measurement of ship hydroelastic response using multiple wireless sensor nodes. *Ocean Engineering*, **79**, 67-80. DOI: 10.1016/j.oceaneng.2013.12.011

Biran A (2003). *Ship hydrostatics and stability*. Butterworth-Heinemann, Oxford, UK, 166-171.

Cota A (1985). *GM-Meter automatic instrument for continues measurement of ships stability*. ATMA, 97-113. (in French)

Daponte P, De Vito L, Picariello F, Riccio M (2013). State of the art and future developments of measurement applications on smartphones. *Measurement*, **46**(9), 3291-3307. DOI: 10.1016/j.measurement.2013.05.006

Griffin MJ, Lawther A, Lewis C (1985). Stability meter for floating objects. World Patent WO1987003855 A1.

Gudmundsson A (2009). *Safety practices related to small fishing vessel stability*. FAO Food and Agriculture Organisation, Rome, Italy, FAO Fisheries and Aquaculture Technical Paper No. 517.

IMO (2009). *SOLAS, consolidated edition, 2009*. 5th edition, International Maritime Organization, London, UK.

InvenSense™ (2013). MPU-6000/MPU-6050 Product Specification Datasheet, PS-MPU-6000A-00, InvenSense™, Sunnyvale, USA. (2013).

Kuhn J, Vogt P (2013). Applications and examples of experiments with mobile phones and smartphones in physics lessons. *Frontiers in Sensors (FS)*, **1**(4), 67-73.

Lewis EV (1988). *Principles of naval architecture, Volume I: Stability and strength*. SNAME, New York, USA.

Lewis EV (1989). *Principles of naval architecture, Volume III: Motion in waves and controllability*. SNAME, New York, USA.

Pattulo RNM, Thomson GR (1965). The B.S.R.A. trawler series. *Transactions of Royal Institution of Naval Architects*, **107**, 216-236.

Ripka P, Tipek A (2007). *Modern sensors handbook*. ISTE Ltd., London, UK, 200-242. DOI: 10.1002/9780470612231

Webster JG (1999). *Measurement, instrumentation, and sensors handbook*. CRC Press LLC, New York, USA.
