Measuring Vessel Motions using a Rapid-Deployment Device on Ships of Opportunity

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Abstract
Vessel motion data have many uses including seakeeping, vessel response model validation, under-keel clearance and cargo studies. However accurate measurements using survey-grade DGPS equipment on ships of opportunity can be hazardous for both the instruments and the personnel attending them in extreme weather conditions. These are frequently the very conditions for which the measurements are most desirable. For waterway-specific investigations where particular conditions are targeted, a portable, robust and easy to set-up/dismount solution is required to opportunistically measure vessel motions when conditions of interest occur.

This paper describes OMC International's development and implementation of such a device for full scale vessel motion data collection, the “iHeave” vessel motion recorder. The OMC iHeave is a carry-on, set-and forget device for the accurate recording of short-duration vessel motions. Originally designed for use by marine pilots for an under-keel clearance study at the "Graveyard of the Pacific" Columbia River Bar, the iHeave is simple to use and self-contained. It can be rapidly mounted inside the bridge of almost any vessel while underway and requires no additional cabling or connections. At the time of writing some 32 winter transits over the Columbia River Bar have been measured by the Bar Pilots using an OMC iHeave device. Based on IMU technology (solid state accelerometers and gyroscopes), the iHeave measures and records all 6 degrees of motion (roll, pitch, yaw, surge, sway and heave) experienced by a vessel with accuracy comparable to the more traditional DGPS based approach.

Keywords: vessel motion, seakeeping, underkeel clearance.

1. Introduction

At the request of the Columbia River Bar Pilots, OMC International was commissioned to perform an under-keel clearance (UKC) study for the mouth of the Columbia River. As a part of this study, OMC was required to analyse the accuracy of the vessel wave response modelling used in the study by performing Full Scale Vessel Motion Analysis (FSVMA) for vessels transiting the Columbia River Bar under pilotage.

The treacherous entrance to North America’s Columbia River, which flows into the Pacific Ocean, is known as the ‘Graveyard of the Pacific’ because it has claimed about 2,000 ships and 700 lives since 1792 [1]. The established FSVMA measurement technique [2] that requires three survey-grade GPS sensors to be positioned externally on the target vessel’s hull represents a hazardous operation for equipment and personnel during the extreme weather conditions that have made the Columbia River Bar infamously treacherous to shipping. In particular, the large winter swell waves which average 3 meters and regularly exceed 6 meters in height can induce hazardous wave response motions in the Post Panamax, Handymax and other large vessel that traverse this American trade route.

Two separate measurement campaigns were therefore planned; a summer validation data set using the Global Positioning Satellite (GPS) based technique in the relatively calm conditions of summer, and a winter set.

The summer campaign was designed to accurately measure vessel squat and heel using one Differential GPS (DGPS) receiver on each of the bridge wings and one on the ship’s bow. These can only be installed on ships during fair weather due to the hazards of setting up and retrieving the instruments and the transfer of personnel and equipment on and off vessels in such conditions (Figure 1).

Figure 1 - Hazardous conditions at the Columbia River Bar make external placement of sensors problematic (image courtesy of the Columbia River Bar Pilots)

The purpose of the winter vessel motion measurements campaign was to validate numerical modelling of the high amplitude vessel motions caused by the infamous seasonal swells. Thus the need to develop a bridge mounted instrument was identified to safely measure these motions. As no self-contained, portable devices of sufficient accuracy to conduct these measurements were available, OMC took it upon itself to develop the "iHeave" FSVMA technique to meet this need.

The iHeave measurement device was designed as a self-contained unit for measuring vessel wave response motions (with periods of 5 to 25 seconds) from a vessel's bridge. Considerable effort went toward ensuring that it was suitable and convenient for installation and operation by marine pilots whilst performing their duties with the ship underway. Based on an inertial measurement unit (IMU) with solid state accelerometers and gyroscopes, it measures 6 degrees of motion (heave, pitch, roll, surge, sway and yaw, Figure 2) experienced by a vessel from a single position on the vessel's bridge with the high precision required to resolve vessel wave response at the extremities of the vessel with decimetre accuracy. Given the design fleet included vessels with length over all up to 300 meters, the (relative) pitch angle accuracy of 0.02° became a key constraint for sensor selection.

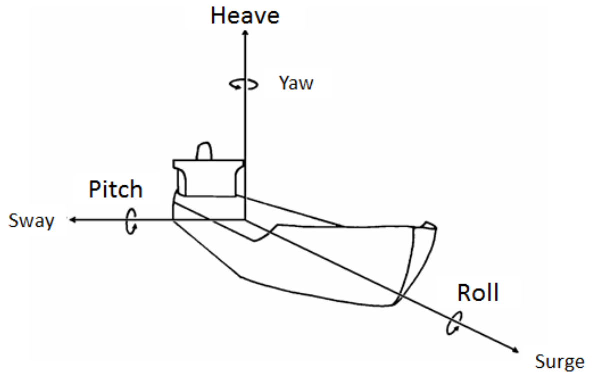


Figure 2 - Vessel motions in 6 degrees of freedom

Time and vessel track referencing are provided by an integrated consumer-grade GPS unit.

2. Development of the "iHeave" FSVMA technique

The unpredictability of shipping schedules has long been a major constraint on GPS-based vessel motion analysis (and many other operations beside). The work of organising items such as the technicians, pilot transfer operators, customs paperwork and personnel indemnity forms (to name but a few) to conduct such measurements have often come to nothing due to unforeseen variations in vessel timing. This can be wasteful, frustrating and expensive for all concerned and is exacerbated by the unpredictability of the ocean swells which cause the vessel motions of interest. Further, extreme weather conditions can mean that deploying the instrumentation may be hazardous in terms of equipment damage, loss and risk to personnel safety due to the necessarily exposed positions of the GPS antennae and the additional transfers of personnel and equipment at sea. As a consequence, very little full-scale vessel motion data has been collected in large swells.

In contrast, deployment of the iHeave was designed to require no extra personnel and a minimum of extra effort for a marine pilot. The pilots are trained to quickly and efficiently mount and activate the iHeave at commencement of measurements and similarly to shut-down, remove and repack the unit just prior to departure.

Figure 3 - iHeave packed into transport case prior to deployment

Once the iHeave in its transport case (Figure 3) has been brought to the wheelhouse (usually by a crewman), the pilot unpacks it and places it on the forward windscreen, attaching it using the two suction-pad mounting arms (as shown in Figure 4). The sensor is aligned to the ship's centreline by sighting the foremast through the attached scope, adjustable using the mount handles. It is then a simple matter of switching the device on, requesting a copy of the vessel and loading particulars for later vessel motion modelling and analysis. The iHeave device is never directly exposed to the weather but instead records from the safety of the bridge.

Figure 4 - iHeave recording vessel motions while mounted on wheelhouse windscreen (image courtesy of the Columbia River Bar Pilots)

In this way, a pilotage group can choose which vessels to target and under which meteorological conditions to do so with a minimum of extra logistics, encumbrance and effort to deploy the iHeave when the conditions are of interest.

During the development of the iHeave, careful attention was devoted to understanding the needs of the pilots who would normally be operating the device. Issues such as mounting and start-up complexity, portability and ease of use were early recognised as vital constraints to the project, so several marine pilots and industry experts were consulted in developing the iHeave requirements. Weight and size limits were imposed based on pilot boat transfers via haulage lines at sea. The complexity of mounting and operating the device were streamlined such that a trained operator could complete all necessary actions within 2 minutes, in order that the essential task of piloting the ship was not impeded through the presence or operation of the instrument.

These use-case constraints combined with the requirements for the FSVMA outputs translated into a series of design criteria, including: simplicity, portability, mounting flexibility, runtime endurance, reliability, weight, size and measurement accuracy.

In order to meet the fully self-contained requirement for the iHeave, it was necessary to integrate several electronic and mechanical components:

- Inertial Measurement Unit (IMU)
- GPS
- Control & data logging computer
- Power supply (battery/external)
- Alignment scope
- Adjustable mounting arms
- Controls and indicators

The SMC IMU-108 selected for the iHeave is designed and calibrated for ship motion measurements. It features an in-built Kalman filter to provide the sensor fusion for the inertial gyroscopes and accelerometers, which accounts for dynamical motions and reduces the effects of drift, vibration and other noise sources.

The on-board Gumstix Overo computer has an ARM processor and runs a Linux operating system to provide data logging, status indication and power control. Sealed lead-acid batteries were selected to enable self-contained operation for up to 14 hours while avoiding the hazards and logistical complications of using lithium-based batteries. Careful component selection ensures low power consumption and minimum enclosure size. The internal operating algorithms were developed to ensure robust operation and that status indication is concise and meaningful so as to minimise distractions for the pilot and bridge crew.

The mounting system was designed to be quick to mount and dismount, secure, flexible, and adjustable to allow the IMU to be aligned with the vessel's centreline (to achieve the required angular accuracy). The first design iteration included the alignment sight rigidly attached to a rotating platform with the IMU suspended beneath it, resulting in a complex and bulky prototype design as shown in Figure 5. The alignment sight was retained for the second (final) design, in which the suction-cup mounting arms feature adjustable lengths to provide the alignment (Figure 4). This approach greatly reduced bulk and construction complexity and was validated for usability and robustness during the validation experiment (section 3). A simpler mounting approach was developed for long-term deployments (days to months), replacing the suction mounts and arms with hook-and-loop adhesive strips on the base of the unit.

Figure 5 - prototype iHeave testing through Port of Melbourne waterways

Once the data recorded by the iHeave have been transferred electronically (usually via secure FTP services) along with the vessel particulars and load state parameters, detailed vessel motion reports can be generated within minutes. These reports typically include maximum and significant heave, pitch, roll and overall vertical wave response, a map of vessel tracks and vessel speed profiles. Extra information such as surge and sway, wave conditions, statistical and spectral analysis and calculated UKC at waypoints can be added.

The iHeave data processing performs four essential tasks:

- GPS and IMU data synchronisation
- separation of long and short period motions
- removing noise and detecting anomalies
- calculation of vessel centre of mass (COM) displacements from the local dynamic

motions observed by the IMU on the vessel bridge

The calculation of COM displacement is achieved using a vessel geometry model with the assumption that the vessel hull is a rigid body, i.e. that vessel flexure is negligible. The translated motions (surge, sway and heave) are calculated taking into account vessel particulars and stability data produced by the vessel loading computer.

The processed six degree of freedom vessel motion data can be provided at up to 50-Hz resolution (10-Hz typical). Engineering analysis and consulting services utilising these data can then be performed, particularly for UKC, mooring and cargo studies.

3. Validation Experiments

Having developed the iHeave vessel motion measurement device and analysis technique, it was necessary to validate the usability of the equipment and to verify that the resulting analysis data met client and internal requirements.

DGPS-based FSVMA is the established means of measuring vessel motion for the purpose of DUKC® model validation, including wave response models. It was therefore selected as the comparison standard for the validation of the iHeave FSVMA approach.
With the assistance of TOLL/ANL Bass Strait Shipping, verification and validation tests were carried out during a voyage of the Victorian Reliance RO/RO (Figure 6) across Bass Strait, where the iHeave was set to record data concurrently with three DGPS devices for the established FSVMA technique.

Figure 6 - TOLL/ANL Victorian Reliance RO/RO (source: Wikimedia Commons)

The instruments recorded several hours' worth of data across the straight in 2 to 3.5 meter swells (significant), resulting in vessel wave responses up to 1.9 degrees of pitch, 6.3 degrees of roll and 2.2 meters of heave (single amplitude). The results from the iHeave FSVMA compared favourably with the GPS-based analysis, as shown in Table 1. A sample of the time-series comparison can be seen in Figure 7.

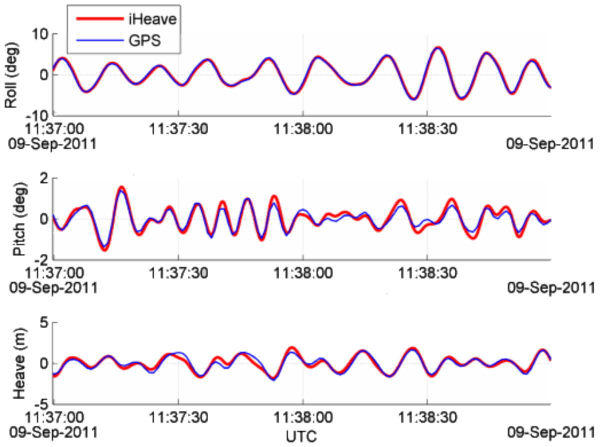


Figure 7 – sample from FSVMA comparison (Victorian Reliance, Bass Strait, South-bound)

Table 1 - FSVMA comparison results for iHeave vs. GPS based techniques (Victorian Reliance, Bass Strait, South-bound)

Motion	Maximum	R	RMSE	%NSR
Heave	2.2m	0.95	0.19m	9.5%
Pitch	1.9°	0.99	0.11°	5.8%
Roll	6.3°	0.99	0.19°	1.5%

Maximum - maximum observed dynamic motion (single amplitude)
R - Pearson's correlation
RMSE - Root Mean Square Error (noise RMS)
%NSR - percentage RMS Noise-to-Signal ratio

The comparison between GPS-based and iHeave FSVMA resolved vessel centre-of-mass heave (vertical) displacement indicates that the there is more discrepancy for this motion than for pitch and roll angles. Indeed, the signal-to-noise ratio for this estimated motion varied between 2.7% to 36.7% for subsequent Bass Strait transits. Notably, the North-bound (running with the swells) transits generally resulted in less accurately calculated vessel COM heave motions while roll and pitch motions remained consistently precise. Discussions with the IMU manufacturer suggest that alternative Kalman filter settings may improve this behaviour. This can only be confirmed by conducting further sea trials. Nonetheless the magnitude and phasing of vessel heave was found to be sufficiently accurate for wave response model validation and cargo studies.

4. Deployments

In the winter of 2011-2012, twenty-four vessel transits were recorded by the Columbia River Bar Pilots using the first iHeave device over the Columbia River Bar in swells of up to 4.5 meters (measured at Clatsop Spit). These vessels included Handymax, Panamax and Post Panamax size ships (185 to 230 meters length) carrying a variety of cargos such as containers, grain and logs. Amongst these transits, maximum roll of 5.6 degrees, pitch of 3.0 degrees and heave to 2.7 meters (single amplitude) and a maximum downward wave response of 5.2 meters at the bow were recorded/calculated. The resulting FSVMAs were used to generate a series of reports (a sample can be seen in Figure 8) and used as validation data for the UKC study wave response model. A follow-up campaign was conducted in the winter of 2012-2013 where a further nine transits were recorded. Analysis and reporting are in progress at the time of writing.

Subsequent to the successful winter deployment at the Columbia River Bar, the iHeave featured on the cover of the International Bulk Journal (IBJ) [3]. OMC was also awarded the 2012 IBJ Innovative Technology Award for development of the iHeave.

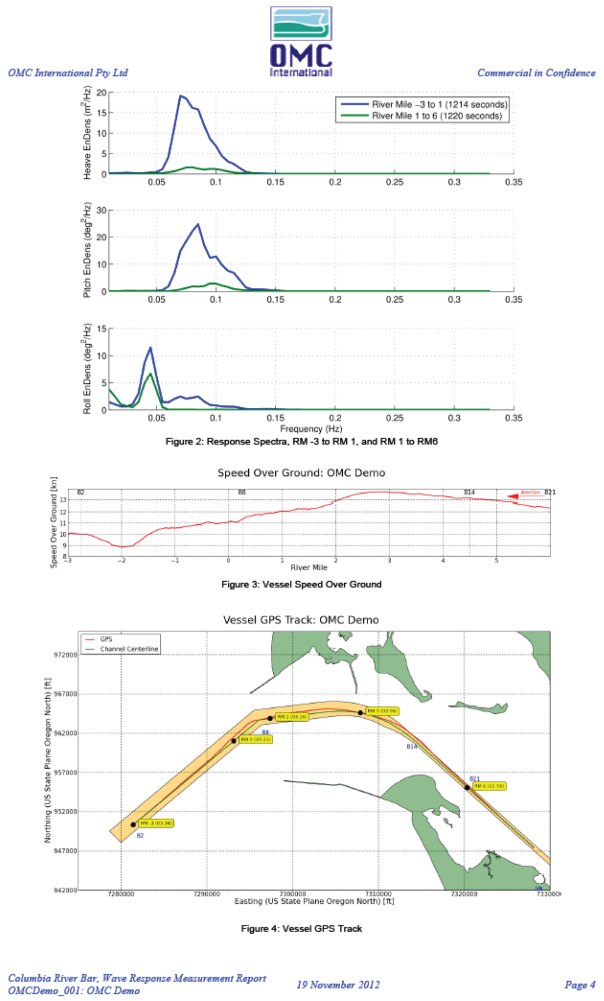


Figure 8 - sample diagrams from iHeave FSVMA report including spectral, speeds and GIS analyses

Since the development and initial deployment of the first iHeave device for the Columbia River Bar winter measurement campaign, further opportunities to use this FSVMA technique led to the creation of a further four devices to support an international cargo study. During this study, over 300 days of at-sea vessel motion data were recorded and analysed from five bulk carriers. In this study, which included voyages across the Pacific, North and South Atlantic and Indian Oceans, extreme vessel motions of 13.7 degrees of roll, 4.3 degrees of pitch and 9.2 meters of heave were measured (for different voyages). The vessel tracks and maximum calculated vertical hold accelerations (indicative motion severity) are shown in Figure 9.

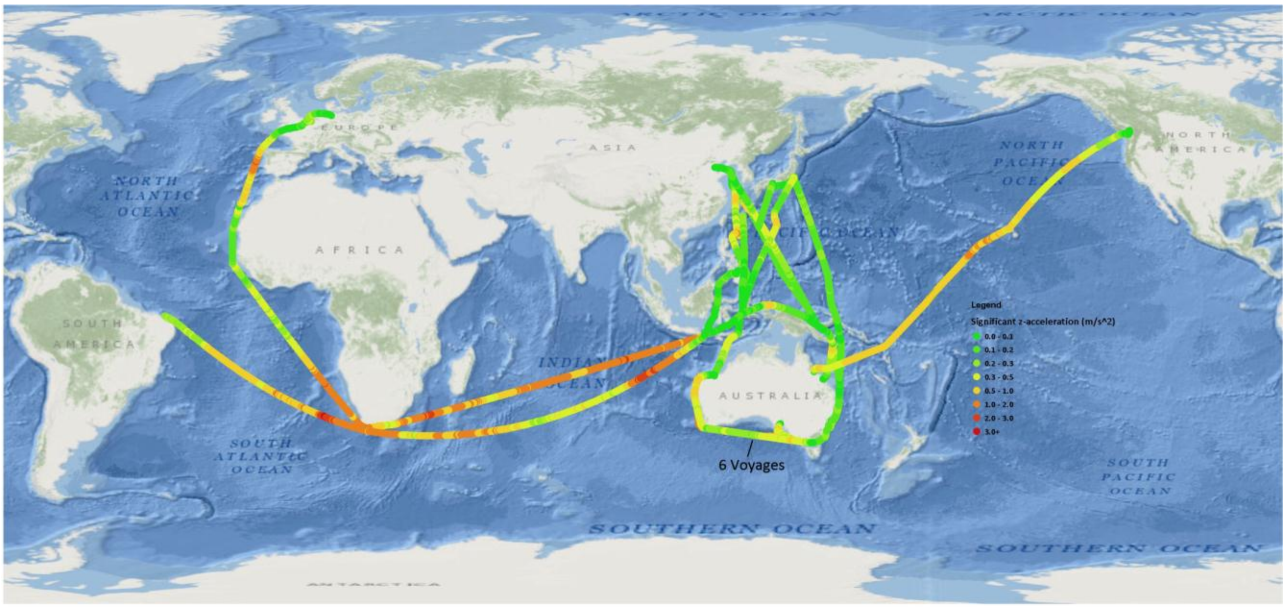
An iHeave unit has also been deployed for use by the Brisbane marine pilots who have completed 14 successful measurements at the time of writing.

Further opportunities to employ the iHeave FSVMA technique to support under-keel clearance and ship motion modelling studies are anticipated for major shipping ports around Australia and internationally in the near future.

5. Conclusions & Discussion

OMC International has developed, verified and deployed a simple, portable, yet sufficiently accurate inertial sensor based technique for measuring and recording vessel wave response motions. This technique takes into account the needs of port operations and marine pilotage groups by providing a rapid-deployment device with minimal logistical overheads suited to providing measurements on vessels of opportunity during conditions of interest.

The relatively low cost of the iHeave measurements compared with the established GPS-based technique in terms of hardware, logistics, extra personnel hire and the risks of deploying in hazardous conditions enables vessel motion studies that would otherwise be impossible to perform or prohibitively expensive. This has enabled greater sample sizes and larger-scale studies than were previously viable. The ability to collect such high quality datasets will, in time, enable a corresponding improvement in ship motion modelling and consequent improvements in shipping efficiency and safety.



Sources: GEBCO, NOAA, National Geographic, DeLorme, and Esri

Figure 9 - International bulk carrier voyages measured with iHeave (showing vertical acceleration magnitude for an extreme hold point)

6. Future Developments

One use of the iHeave FSVMA has been to address pilot concerns regarding observations of vessel heel (roll) indicators. These pendulous inclinometers can be affected by the dynamic movement of the vessel in all six degrees of freedom, resulting in poor accuracy as vessel excitation increases. To address this concern, work has begun on producing a real-time data display using a wireless link from the iHeave data stream. This display, the iHeave Visualiser, takes the form of an application for users to install and run on their smart phone or tablet device. A prototype visualiser is currently available.

The inertial sensor based approach of the iHeave device precludes its capacity to be used in applications where absolute levels with reference to the Earth's coordinates are necessary, due to long-period sensor drift. It is therefore not possible to use the measurements recorded by the iHeave alone to determine vessel squat (sinkage due to speed through water) and other long-period motions such as heel and trim.

However experiments where both DGPS receivers and an iHeave were deployed on board a vessel in parallel were revealing. The iHeave measurements predicted the vertical movements of the receivers relative to ship coordinates with good accuracy (%NSR around 5%). Hence the absolute position and attitude of the vessel could be determined by relating the GPS position to those predicted from the iHeave measurements, obviating the need for a GPS sensor placed at the vessel bow. Further experimentation is required to determine practical arrangements for accurate long-period motion aiding to complement the iHeave short-period measurements.

7. Acknowledgements

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The authors would also like to acknowledge and thank the Columbia River Bar Pilots for their assistance during the development of the iHeave and the use of their photos and measurement data.

8. References

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