Designing a GPS-based mini wave buoy

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Based on available GPS technology, a small, easy to handle and easy to deploy wave buoy has been developed. This 'mini buoy' is an ideal tool for the monitoring of sea state during short-term marine operations. It also opens up additional wave measuring opportunities, a fascinating example of which is the swift deployment of a mini buoy from a helicopter just before the arrival of a hurricane [4]. In the design of such a small GPS-based buoy, issues such as seawater washing over the buoy, mooring forces and wind drag on the antenna all pose their particular challenge to the development and operation of the buoy. This paper focuses on the hydrodynamic response and its consequences for the design of the buoy. One hydrodynamic aspect is the undesired heave resonance of the hull, another being the pitch-roll resonance. It is shown how these challenges were met, resulting in a well-balanced design.

Figure 1. The small GPS-based directional wave buoy (DWR-G4) can be deployed by hand

Currently available GPS technology has proved to be sufficiently accurate for the measurement of wave height and wave direction, as demonstrated by the DWR-G7 (70-centimetre diameter) and DWR-G9 (90-centimetre diameter) Datawell buoys [1]. A by-product of this technology is the considerably reduced sensor module size which enables a much smaller end product – a mini buoy. This device, called DWR-G4 (40-centimetre diameter), mainly comprises a GPS receiver, some batteries and processing/communication electronics, all housed in a 40-centimetre diameter hull. The compact size means that transportation, handling and deployment (see Figure 1) costs are all relatively low compared to larger versions. This results in considerable operational cost savings.

The advantages of a mini buoy are not only practical and financial. A bonus is that a smaller buoy can cope with higher wave frequencies, thereby extending the measuring range. On the other hand – disadvantages have to be reported as well – a small buoy offers limited buoyancy, thereby creating a mooring design challenge. This is even more critical for a GPS-based wave buoy than for an accelerometer based wave buoy, since water, washing-over of the GPS antenna, interrupts the GPS satellite signals and thus corrupts the wave measurement process.

Also, a smaller buoy is more vulnerable to tilting due to wind forces on, for example, the HF antenna. Using a shorter antenna reduces the drag but restricts the transmission range. The one-metre long antenna on the DWR-G4 mini buoy limits its transmissions to line-of-sight (typically 10 kilometres). In comparison, the two-metre long HF antenna on the conventional (70-centimetre and 90-centimetre diameter) Waveriders enables a transmission range of at least 50 kilometres. The smaller volume available within the hull also limits the battery capacity.

Such factors contribute to the mini buoy establishing its own, unique field of applications, notably short-term operations near a vessel where the limited energy supply, absence of a mooring and the restricted radio transmission range are all acceptable criteria. The mini buoy can also be very suitable for use in lakes and closed seas, or as a free-floating drifter with onboard logger.

Heave response of a sphere

For the correct measurement of ocean waves, a buoy has to follow, as closely as possible, the orbital motion of the water particles induced by the waves. Resonances in the hydrodynamic response of the buoy, whether heave or pitch-roll, hinder the proper operation of the wave buoy.

The first design issue requiring attention is the buoy's shape. A long, slender shape like that of a spar buoy is notorious for its heave resonance and must be ruled out. A flat, disk-like shape is, likewise, not suitable since its slope following principle implies a lot of pitch and roll motion. These motions, experienced by a GPS antenna outside the buoy's centre of rotation, are not acceptable as they introduce pseudo wave motion. Placing the GPS antenna in the centre of rotation would remove this objection, but would make the system more vulnerable to submersion and washing-over by seawater. When "long" and "flat" are ruled out, "spherical" remains as the leading contender.

Theory shows that the heave response of a sphere, submerged up to its equator, has a resonance just below the cut-off frequency [2]. The response at this resonance frequency equals approximately two. An experiment at sea during the design programme, where all three GPS buoys – 90-centimetre, 70-centimetre and 40-centimetre – were deployed, the latter both with and without a fender, confirmed this to be the case.

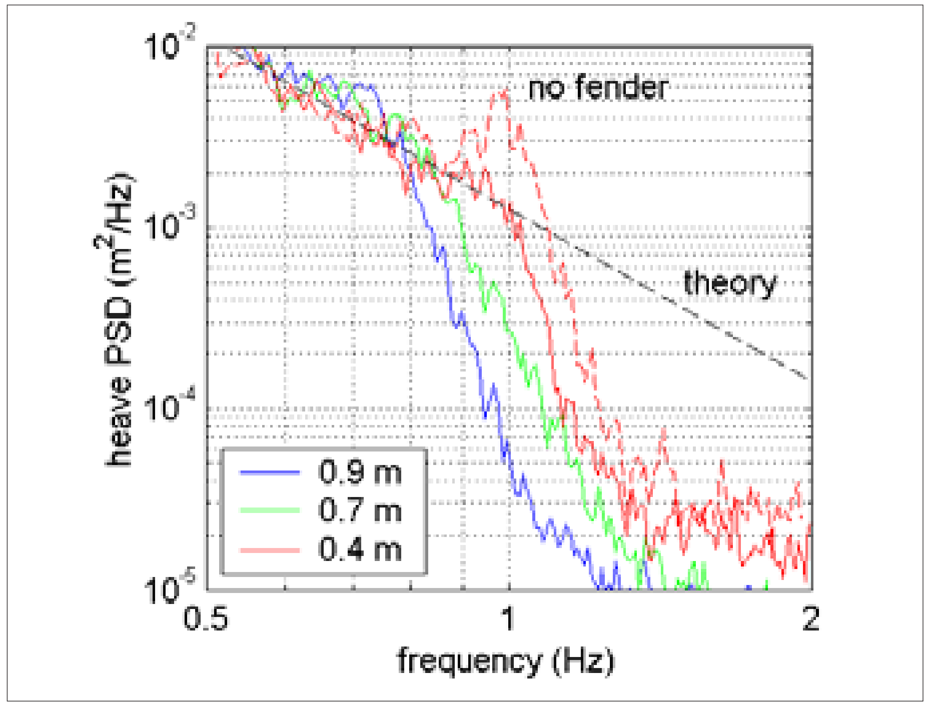

Figure 2. Detail of the free-floating measured heave spectrum (Power Spectral Density) of a 70-centimetre and 90-centimetre Waverider, and a 40-centimetre diameter sphere with and without fender. The theory curve is a simple power law based on the low frequency measurements

The heave spectrum (Power Spectral Density) measured by the buoys is shown in Figure 2. The curve marked as "no fender" (dashed red) was measured by the 40-centimetre 'bare' sphere and clearly shows the expected heave resonance just below the cut-off frequency. With an appropriate fender applied round the equator, the resonance disappears (solid red curve). The bigger buoys, equipped with a fender as standard, show no resonance (blue and green curves). They do illustrate the increasing cut-off frequency versus decreasing buoy diameter as mentioned previously.

Pitch-roll resonance

In order to keep the buoy upright, the centre of mass must be below the centre of the sphere, but this naturally creates a

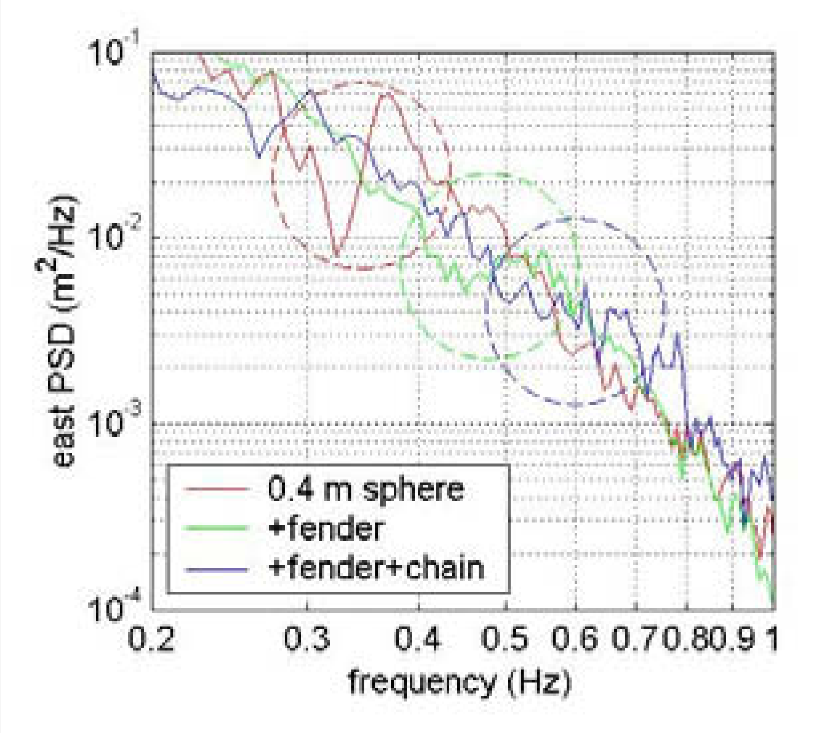

Figure 3. Detail of the wave spectral horizontal (east) energy (Power Spectral Density). Pitch-roll resonances are encircled

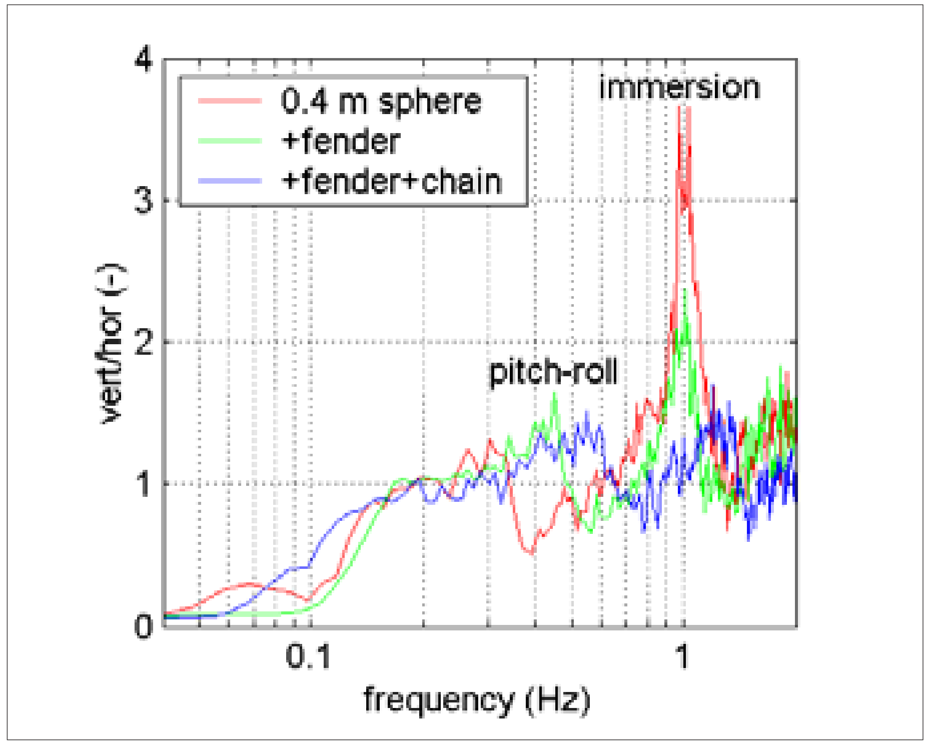

Figure 4. Check ratio (of vertical and horizontal energy) for various configurations

pendulum system with a certain pitch-roll-resonance. This resonance is undesirable for various reasons. First of all, since the GPS antenna is located on top of the buoy, pitch and roll motion causes the GPS antenna to move (mainly horizontally and, to a lesser degree for an upright buoy, in the vertical direction), which is wrongly interpreted as orbital motion. Secondly, the GPS antenna works best when levelled. Since it is more sensitive to satellite signals from above and less to those from below, pitch and roll motion unfavourably affect the antenna's outlook and performance.

Pitch-roll amplitudes can be reduced by damping the pitch-roll resonance. The fender, suppressing the heave resonance, also attenuates the pitch-roll resonance somewhat. A further attenuation is achieved by attaching a small ballast chain beneath the buoy. The chain damps the pitch-roll oscillation via its drag. Furthermore, the motion of the chain turns out to be generally out of phase with the buoy's motion, which restricts the build-up of a serious resonance.

In order to check the effect of the various damping mechanisms, an experiment was performed including a 'bare' buoy, a buoy with a fender, and a buoy having both a fender and a ballast chain. The energy (Power Spectral Density) of the horizontal (east-west) motion is plotted in Figure 3. The resonance of the bare sphere is pronounced. With the fender being applied it is still visible but, when adding the chain, it can hardly be seen.

Overall hydrodynamic performance

The previous sections concentrated on the heave and pitch-roll resonances and how to damp them by applying a fender and a chain. The overall hydrodynamic performance can be studied by measuring the square root of the ratio of the vertical energy and the horizontal energy – the so-called check ratio. In the case of circular orbits (as in waves in deepwater), this ratio is unity. In shallow-water, when the orbits are horizontal ellipses, the energy ratio is less than unity. The results of experiments at sea with free-floating buoys, with some wind waves present and hardly any swell, are presented in Figure 4.

The heave resonance around 1Hz is clearly seen, as is the pitch-roll resonance at lower frequencies. At very low frequencies, below 0.2Hz, the measured ratio drops to zero. This is due to the absence of wave energy at the test location, whilst there was some wind and current driven horizontal motion present. At the high frequency end, above 1Hz where the buoy's ability to follow the orbital motion comes to an end, the ratio is basically determined by noise originating from GPS and electronics and does not correspond to real motion. Since, for GPS, the vertical noise is larger than the horizontal noise, the ratio is greater than unity. This asymmetry between the two directions stems from the fact that, in the horizontal plane, the satellites are 'on all sides', whereas, in the vertical dimension, the satellites are only 'above'.

In the relevant frequency interval, up to 1Hz, the configuration with both the fender and the chain performs best, i.e. keeps closest to unity. This configuration is now the standard for the DWR-G4 mini buoy.

Mooring

Mooring a mini buoy of 40-centimetre diameter is a real challenge, if not an impossibility [3]. The slightest current will generate drag forces, both on the buoy and on the mooring line, that will easily exceed the available buoyancy and cause the buoy to submerge. Where the buoy is not submerged, the mooring cannot be expected to provide sufficient flexibility to accurately follow the orbital motion. The inevitable conclusion is that the DWR-G4 mini buoy cannot be moored and should be considered a free-floating device.

A possible alternative to a vertical mooring could be a horizontal mooring to a vessel or float. Such a configuration solves the problem of buoy submersion whilst preventing the buoy from getting adrift. However, any velocity difference between buoy and seawater would give rise to an upstream 'bow wave'. In sufficiently strong currents this bow wave would grow as high as the buoy itself, wash over and cover the GPS antenna and thus block the satellite signals, interrupting the measurement process. This phenomenon limits the application of a horizontal mooring to moderate current or vessel speeds.

For optimal wave measuring performance, the DWR-G4 is used free-floating. Retrieval requires knowledge of the buoy's location. As long as the buoy is within line of sight, the HF link can be used to transmit the GPS position. At longer distances, when the buoy has been free-floating for a couple of days, a satellite communication link, such as Argos is required.

Figure 5. Using a helicopter to deploy the DWR-G4 in the path of a tropical cyclone [4]. ***Picture courtesy of EPA***

Experience and future

Despite being a reasonably recent addition to the available product range, the DWR-G4 buoy has already found several applications within a variety of short-term wave monitoring projects. Ship's trials, naval operations and civil engineering projects all stand out as logical user applications. However, the most outstanding usage was the successful deployment of a mini buoy from a helicopter by the Environmental Protection Agency (EPA) of Queensland, Australia [4], just before the passage of a tropical cyclone (see Figure 5).

Conclusion

Currently available GPS technology, combined with hydrodynamic engineering expertise, has enabled the design of a small, easy to handle, easy to deploy, cost effective directional wave buoy. The resultant DWR-G4 mini buoy is already providing a valid contribution to the range of wave buoys available to the oceanographic community. ■

References

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