The calibration of wave buoys

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1. What is calibration?

It is giving a set of realistic and accurately known standard stimuli to an instrument and recording and evaluating the results. So we have to take a set of standard watery waves to the laboratory, put our wave buoy in it and record the results. Unfortunately we can not do that so the calibration of wave buoys is impossible! What we are calibrating in the laboratory is a set of sensors that is sometimes packed in a container that looks like a buoy but ceased to be a buoy on the moment that it left the water. When we calibrate dry we must always realise that we are missing the hydrodynamic response of the instrument. This response must be estimated from theory and model tests. For example, the hump at the high frequency end of the transfer function of the Waverider (fig. 1) is hydrodynamic, and as such never calibrated. It is calculated and at best corroborated by careful analysis of real data.

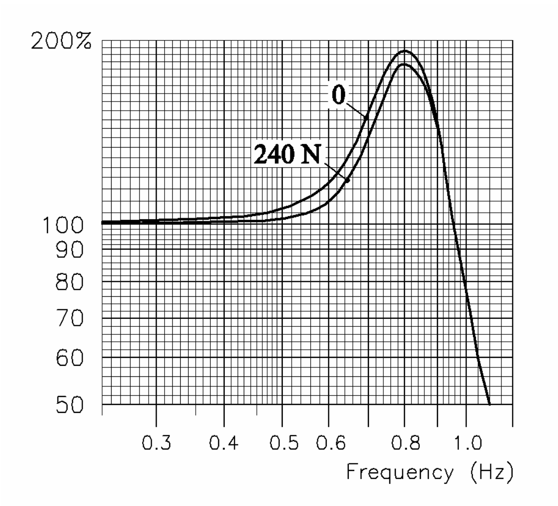

fig. 1 Waverider transfer function

2. Laboratory calibration

The next best is to move the buoy like we think it moves in the waves. A machine to do that in three dimensions on a realistic scale is still a formidable apparatus, well beyond the available space and budget. Fortunately, the acceleration in sea waves is always less than that of gravity, and usually less than half of that. The movement in a single wave would approximately be a circular orbit at constant speed and that is simple to implement. So, it is possible to excite a set of sensors with a movement that does approximate what we expect it to do at sea, but on a limited scale and at one single wave at the time only. To acquire reasonable confidence that the test results are applicable to reality additional tests will be necessary. These tests should be specifically aimed to the weak points of the system. To design such tests a good understanding of the physical basis of the device that is calibrated is necessary. What follows is an outline of methods that are applicable to Datawell products with a passive stabilisation system that can be regarded as a long pendulum. This system keeps one accelerometer physically vertical and is also used to measure the attitude of the buoy in directional wave buoys. The attitude (pitch-roll) data are input to a mathematical process that converts data from unstabilised additional sensors to a fixed North-East-vertical reference frame. Other systems may behave different and required other methods to test what the calibration may be missing.

3. A calibration fixture

About 5 m/s^2 is attainable in a modest machine, like the one in fig. 2. The size is usually limited by the room, our machines make a “wave” of 1.8 m height at continuously variable period times from minutes to 3 seconds. The motor is a 240 Watts D.C servo, with a maximum torque of 100 Nm.

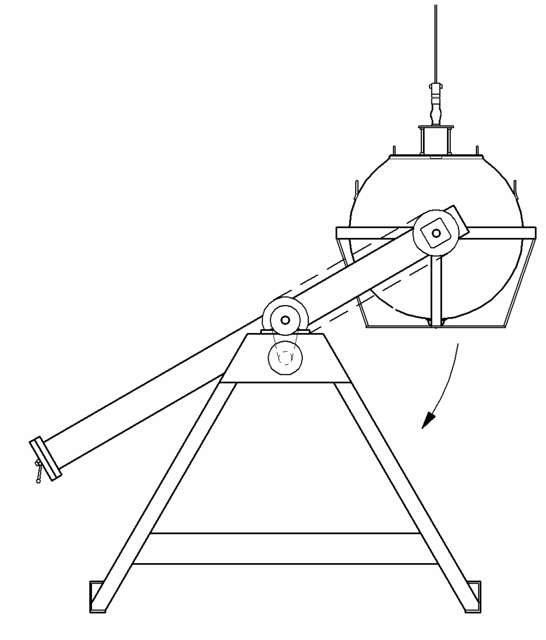

fig. 2 Calibration fixture

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The investment is in the order of one Waverider buoy. Although it is a rotating machine it is possible to run wires in and out without using sliprings as shown in fig. 3. The wires are flexed, not torqued and in our most busy machine they last more than a year.

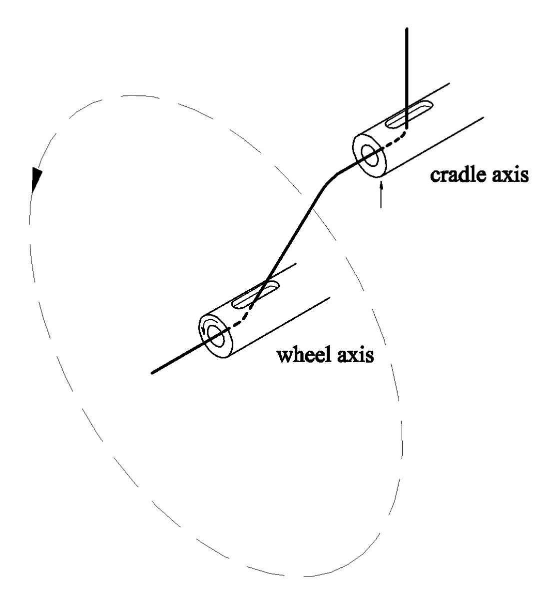

fig. 3 Cable configuration

It is not necessary to keep the instrument under test horizontal, to the contrary: Since the horizontal acceleration is as in the wave, the roll movement of a cradle that is free to swing is realistic. When certain precautions are taken, even so realistic that it makes the machine usable for the dynamic calibration of pitch-roll directional buoys like the WAVEC. Also for a "vertical only" device such as the Waverider this is good, as internal gimbals and the stabilised platform are excited realistically. A good safety device is a coupling that decouples when a set torque is exceeded. It should be set so that the motor can deliver enough torque to trip it. This prevents burning out motors or servo amplifiers when the servo is accidentally activated while the machine is blocked. It also offers some prevention against excessive roll since that causes a large moment on the main shaft.

4. Accuracy

The accuracy that can be achieved with a machine like this depends on what sensors are calibrated, and how. It has a fixed vertical displacement, that is easily calibrated by measuring the distance between the main- and cradle shaft. When the device under test delivers vertical displacement and its transfer function does not vary too much with the period time then we need only approximate knowledge of the revolution speed. An ordinary stopwatch is good enough in this case, but when we look at acceleration then we deal with the square of the period time. That means that we must measure the period time with at least twice the accuracy required for the acceleration, e.g. if 1% is required then we have to know the time of revolution within 0.5%, that is 20 milliseconds at 4 seconds period time. A stopwatch will not do.

5. Directional buoys

Directional wave buoys have some special problems: First they have a compass. That requires that the testrig is made of material that is not ferromagnetic, say stainless steel 316 or aluminium. That can be done, a more difficult problem is the building that we are in. This is usually an existing one and not easy to modify. If it has steel beams or columns in the construction then we have a problem. Analyzing the problem of a distorted local magnetic field we find that it need not to be so bad, provided that the offsets of the sensors are properly calculated and compensated for. But this takes at least several hours. The practical way is to switch the buoy on (in the rig) at the end of the day and calibrate the next morning. Our production facility is a steel building, but taking this precaution we have a reproducibility of the direction of about one degree and measure directional spreadings of less than 4°. If the testrig itself is made of steel then the magnetic problem is too bad. One can "fix" the compass by replacing the compass outputs by fixed values while calibrating in the rig and calibrate the compass separately in some place outside the building.

6. Pitch-roll buoys

The directional calibration of pitch-roll devices like the WAVEC Buoy leads to another special requirement: The main shaft and the shaft of the cradle should be very well aligned. The reason is that we are dealing with very small angles. For instance: when running at 20 seconds period time in a rig with 1 metre radius we run at .314 radians per second and have a horizontal acceleration of $0.1\ m/s^2$, that is 0.01 g. Thus the maximum roll angle is only about 0.6 degrees. Now, if we have a misalignment of 0.1 degree between the shafts then the direction to which the measured tilt points varies sinusoidally over each revolution with an amplitude of 10 degrees. If the shafts are in the same plane then that gives a 10° error in the direction. If the cradle shaft is tilted from the plane through the main shaft it results in a directional spreading of 10 degrees.

7. Processing the results

Recording and processing with the same equipment and procedures as in the field is safe and requires the least thinking. But it is very time consuming. Half an hour or so would be needed for every single frequency run. For routine testing three minute runs are adequate, provided that the data set is well tapered and Fourier transformed. With our modern number crunchers this is easy, but it is still good to look at the plot of the data since the human brain is equipped with the “Fuzzy Logic” that is capable to detect the unusual.

8. Additional tests and field methods

When using the compass in the testrig is not possible then we have to calibrate that in the garden. Fig. 4 shows the principal sensor configuration of a directional buoy that has a (heave)-pitch-roll meter and three fixed magnetometers as a compass.

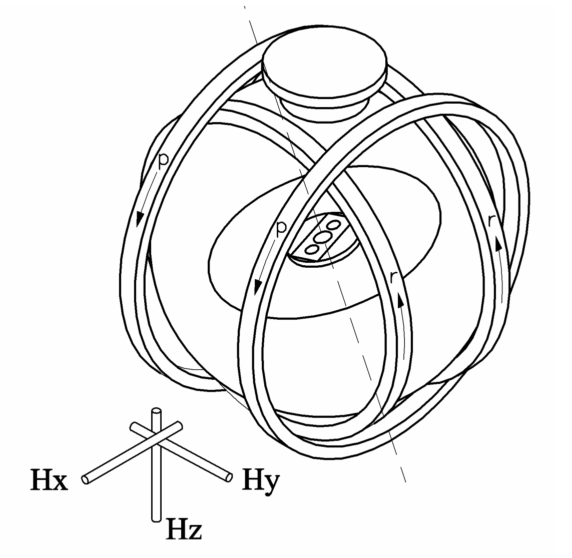

fig. 4 Buoy sensors

The formula to calculate the magnetic inclination as used for the WAVEC and Directional Waverider looks formidable but has a certain beauty:

$$I = \arcsin \left[\{p.Hx - r.Hy + Hz\sqrt{(1-p^2-r^2)}\} / \sqrt{(Hx^2+Hy^2+Hz^2)} \right]$$

p = sine of pitch angle
r = sine of roll angle
Hx, Hy, Hz are the components of the magnetic field along the buoys reference frame.

The beauty is that we need a good pitch-roll meter and a good compass to find the right value, and that this value is local constant (which can be found from Admiralty chart number 5383). This is the reason that the magnetic inclination is among the standard data that are transmitted by the Directional Waverider. If one calculates this constant for a series of headings and fairly large (30 to 60 degrees) pitch and roll angles then the maximum error in any of the input values is in the order of the variation in the resulting inclination angle. The cluster of pitch-roll and magnetic sensors can be effectively calibrated in any garden, without special equipment. For the Directional Waverider this test is even stronger since it uses for the horizontal movement unstabilised accelerometers that move with the buoy. It then calculates North and East displacement from the readings of two fixed “horizontal” accelerometers, three fixed magnetometers and a pitch-roll meter. If there is an error in any sensor in this whole cluster then a change in attitude results in a step in North or East acceleration. This is then integrated twice to a (temporary) displacement that reaches 10 times the acceleration error. Changing the tilt from 0° to +30° changes the acceleration in the equatorial (“X-Y”) plane of the buoy from zero to 5 m/s^2. Without the pitch-roll-magnetometers cluster this would result in a displacement of 50 metres. The same when the buoy is rotated 90 degrees around the antenna (“Z”) axis while tilted 30 degrees. If we get a 0.5 metre horizontal excursion from this tilting then the error in the pitch-roll-magnetometers-fixed accelerometers cluster is in the order of 1%. A typical result is shown in fig. 5. This means that we have a simple “bush test” for everything except the vertical acceleration.

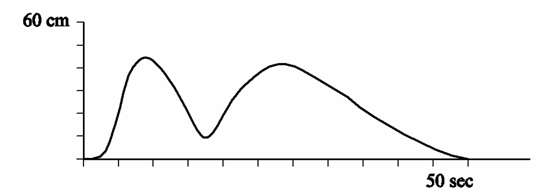

fig. 5 Result of tilt test

9. Vertical accelerometer tests

A rig of 1 metre radius produces when running at 2 radian per second (3.14 seconds revolution period) an acceleration of 4 m/s^2. That is not overdone. Vertical accelerations close to 10 m/s^2 can be achieved using springs. Strong springs are needed to suspend a complete wave buoy weighing 100 (Waverider) to 200 (Directional Waverider) Kg or even 280 Kg (WAVEC instrument container). For a field test the rubber cords used in the mooring are well usable, in a laboratory a set of steel spring make a more tidy installation. If a spring is stretched a length L by suspending a mass from it then the natural period of that system is $P = 2\pi\sqrt{(L/g)}$, so if the springs are stretched half a metre by loading them with the buoy then the natural period will be 1.4 seconds. This is short, but perfectly suitable to check accelerometer linearity. In the rest position the acceleration of gravity acts on the buoy, so 0.5 metre excursion equals 10 m/s^2. The maximum that can be applied linearly is to make such an amplitude that the spring is just not unloaded when the buoy is in the highest position. It is not necessary to take a lot of readings of the acceleration over one period 1.4 seconds to look at the linearity. A non-linearity will cause a non zero integral over a full period. This means that it will cause a shift in the average acceleration from while hanging still to while oscillating. And after integration to displacement this will show as a "bump" in vertical position. For the Waverider the maximum of this bump is 25 times the error, for a Directional Waverider 10 times. A typical outcome of such an experiment with a Waverider is shown in fig. 6. One small division is 5 cm. We see a downward excursion at the start of the oscillation and an upward one after it. The applied acceleration amplitude is 6 m/s^2, the excursion is 5 cm. That means a 5/25 = 0.2 cm/s^2 shift in average acceleration caused by 600 cm/s^2 or a non-linearity of about 1/3000.

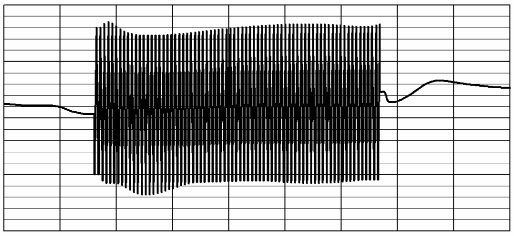

fig. 6 Linearity test

10. Vertical reference test

Another test that requires apparatus not more impressive than a piece of rope allows to measure the offset of the vertical reference. When a buoy is suspended from a rope and swung gently like a pendulum then it will move the same distance upwards at both ends of the swing. That is, respective to the true horizontal plane but not necessarily so respective to the buoy's "horizontal" reference plane, as shown in fig. 7. The offset angle in the direction of swinging follows directly from the geometry: in radians it is the difference in height at the ends of the swing divided by the horizontal distance.

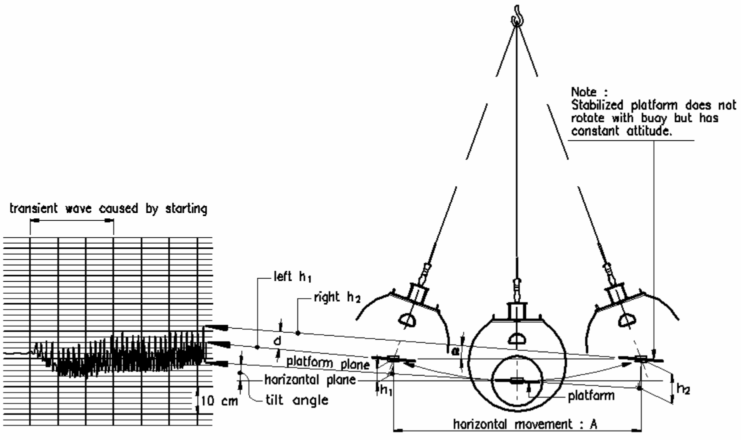

fig. 7 Vertical reference test

The "bump" in zero position at the beginning of the swinging (and after the end of it) contains also significant information, but that needs a little more explanation: The vertical reference behaves like a long pendulum. We move its suspension point in a tempo that is much faster than its natural period. With a real pendulum the mass stays in the same place in these circumstances. As shown in fig. 8 the suspension line moves an angle h/Lp (radians).

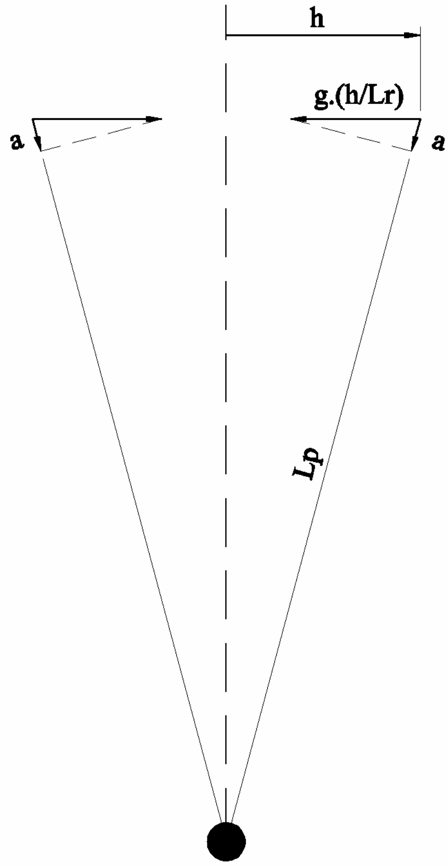

fig. 8 Accelerations

The horizontal acceleration is towards the centre at both ends of the swing and thus has a component in the same direction along the suspension line. And this is the buoy's "vertical". Again we have a shift in average acceleration. The buoy is hanging on a rope of length Lr (from suspension point to the position of the accelerometer) and is driven inward by the acceleration of gravity g. The component of g that accelerates the buoy horizontally is g.h/Lr. The component of this acceleration in the buoys "vertical" direction becomes $a = g.(h/Lr).(h/Lp) = g.h^2 / (Lr.Lp)$. The horizontal excursion h is a sine function of time and its square averages ½ h^2. So the shift in average vertical acceleration becomes: $A = \frac{1}{2} .g.h^2 / (Lr.Lp)$. From this follows for the apparent length Lp of the stabilisation system: $Lp = \frac{1}{2} .g.h^2 / (Lr.A)$. In fig. 7 the swing in zero position is 20 cm, that means a shift in average acceleration of $0.2/25 = 0.008$ m/s^2. The horizontal amplitude h was 1 m and the rope length Lr was 1.7 m. So the apparent pendulum length of the suspension system was: $5 \times (1^2) / (0.008 \times 1.7) = 368$ metres. A 368 metre pendulum has a natural period of $2\pi\sqrt{(Lp/g)} = 38.1$ seconds. This checks pretty well for a Waverider that has a stabilising system with a nominal natural period of 40 seconds. All the Datawell sensors contain a fluid solution that starts to separate at –5°C. The effect of this is a substantial shortening of the natural period of the stabilising system, say from 40 to 10 seconds. There is little risk of this happening while the buoy is in fluid water, but it may happen during transport in very cold weather. If a buoy has been subjected to that during more than a few hours then it is wise to check the natural period time.

11. Field calibration of vertical response

To achieve a resonant period of more than a few seconds with a buoy suspended from rubber cord springs the elongation of the cords by loading with the buoy is substantial. For instance for 6 seconds resonant period an elongation of 10 metres is required. So the main problem in doing this is to find a suitable and sufficiently high suspension point. A 70-cm Waverider weighing 105 Kg has a resonance at about 4.5 seconds when suspended from a rubber cord like drawn in fig. 9 and for a ground clearance of 1.5 to 2 metres the suspension point must be about 15 m high.

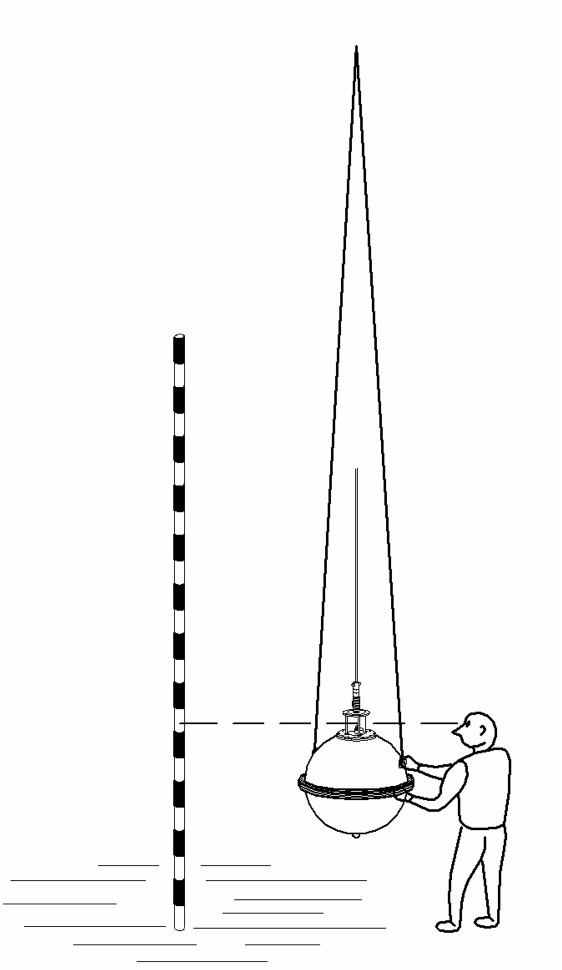

fig. 9 Field calibration

Given that opportunity (a harbour crane usually will do) then the procedure is as follows: Pull the buoy down to some mark let go. Try to estimate the minimum height above the mark after one period. The loss over the half period from down to top can be taken as half that. Now keep the buoy oscillating by making good for the loss by pulling it gently down. In this way a sinusoidal vertical motion with a well known height can be maintained. This height is twice the stationary height minus half the loss observed over the first full period. When the matter is taken seriously an accuracy of a few centimetres on a down to top "wave height" of 3 to 4 metres can well be achieved.

12. Conclusion

The conclusion is that proper calibrations require more investment in brainwork than in money.