Elastic mooring of wave and navigation buoys
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Preface

Having noticed a general interest of the maritime and oceanographic community in elastic mooring, Daniel Johnson, editor of International Ocean Systems (IOS), asked Datawell to write a series on this topic. With the assistance of Roger Scrivens (RSAqua) four contributions to the journal have been written. These preprints were adapted to the journal’s format and were published in the course of 2006. Each contribution deals with a specific topic and can be read as an independent paper. The author hopes that this collection of the four preprints may serve as a first introduction to the interesting subject of elastic mooring of buoys.

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1 Wave buoys and their elastic mooring

1.1 Introduction

Ever since it’s introduction in 1968, the Datawell Waverider has been recognized as a standard wave data acquisition tool. In 1988, the Directional Waverider was launched and soon overhauled the non-directional buoy in popularity. Both types of wave buoys have contributed in no small measure to the standardization of wave height and wave direction measurement, and have found appreciation by the world-wide oceanographic community. Hence, measuring the sea-waves with a moored wave buoy has been common practice for over four decades. The technique and the interpretation of the results are now well established. Initially, however, there was considerable scientific discussion on this approach to measuring waves. Although such debate is now settled, occasional questions arise concerning the quality of moored wave buoy measurements. Good, comprehensible text books exist on this topic [1]. This paper focuses on aspects relating to an elastically moored wave buoy, without going into scientific details. Addressed topics are the nature of sea waves, the differences between measurements by a Waverider and by a wave-staff, types of wave buoys and the relevance of an adequate mooring for the quality of the measurement data.

“Directional wave buoys and their elastic mooring”, “Elastic mooring of navigation buoys” and “Rubber as a mooring material” will be the subject of subsequent papers.

1.2 Waverider/Wave staff

For small disturbances of the sea surface, the hydrodynamic equations can be linearized and solved to give a freely propagating long-crested sinusoidal wave train. In a sinusoidal wave train on deep water (depth $d > \lambda/4$) the water particles travel in circular orbits with the particles moving forward in the crest and backward in the troughs. This is visualized in Fig. 1.1. Water particles at a rest position below the surface have an orbital motion with the same phase as the particles at the surface, but with a smaller amplitude.
The plotted contour through the endpoints of the upper circles shows the sea water surface. With increasing amplitude of the circular orbits the crests of the waves become sharper and the troughs become longer, as can be seen in Fig. 1.2. This is remarkable since the water particles move in perfect circles, of one frequency and one amplitude. Figure 1.2 is like a snapshot of the sea: at a single moment in time the water height is measured at different locations. Considering it the other way around: measuring the water height at a single location at different moments, is how waves are measured by wave staffs (fixed instruments, like the resistance-wire and capacitance–wire gauges).

Figure 1.2

Water-air surface for increasing amplitude of the orbital motion of the water particles

When the circle motion in Fig. 1.1 progresses with time, it is easily imagined that the shape of the contour is preserved and only changes position: the wave travels to the right. Thus, the wave staff measures the same peaked curve. A (Waverider) buoy, on the other hand, following the water particle in its orbit, measures a perfectly circular motion at a single frequency. This is a fundamentally different way of measuring waves. In scientific literature these different methods are sometimes referred to as Lagrangian (buoy) and Eulerian (wave staff). In agreement with [2] we use “Waverider” and “wave staff”.

Obviously the wave spectrum (relating energy to wave frequency), based on wave staff measurements differs from that computed from Waverider data. In the presented example, the Waverider measures the single frequency of the orbital motion of the wave particle. All wave energy is attributed to this orbital frequency. The wave staff on the other hand will distribute the wave energy over all harmonics of the orbital frequency. Here, a fundamental problem of the wave staff measurement shows up: it cannot tell which part of the energy that it attributes to a particular frequency $f$ is due to orbital motion at that frequency $f$, and which part results from an orbital motion at a lower frequency, of which $f$ is a harmonic.

Sometimes the question is asked whether the (Directional-) Waverider measures the sharp peaked waves that are observed at sea when it has a narrow spectrum. Obviously, based on the above discussion, the answer is “yes”.

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1.3 Wave buoy

In principle, a wave buoy, like the Waverider, follows a water particle which is set in motion by the waves. Thus, by measuring the buoy motion, the wave motion is measured. From a fundamental point of view this may sound simple, however, there are some pitfalls:

- The shortest wavelength that a buoy can follow is determined by the size of the buoy. Large buoys require long waves to be set into motion.
- Any buoy shape has a heave resonance. Spar buoys are notorious for it. The design of the buoy should be such that the resonance is reasonably damped, and outside the frequency range of interest.
- Since the wave forces are applied by pressure variation on the outside of the buoy, one should avoid these forces to result in pitch roll motion of the buoy. Any pitch roll motion of the buoy results in artificial heave of the sensor unit, when this sensor is not in the pivoting point of the pitch roll motion.
- Since waves decay with depth, the forces on deeper parts of the buoy are not equal to the wave motion at the surface.

Figure 1.3

Waverider as has been commercially available from Datawell since the 1960s

Datawell has opted for a spherical shape for the Waverider, with a fender around its equator. The buoys are half submerged which results in the upper frequency wave following limits for the various diameters of the Waveriders as presented in table 1.1.

It is worth mentioning that a wave buoy, by its very nature as a floating object, has solved a difficult question: Where exactly is the sea surface, when, in heavy sea condition, the transition from sea to air is filled with foam, spray and air bubbles? Remote sensing techniques such as Radars and ADCPs suffer from such transition layer definition difficulties. But for the Waverider it holds that, by definition, the water level is where the buoy floats!
### Table 1.1.

<table>
<thead>
<tr>
<th>Buoy diameter (m)</th>
<th>-3dB point frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1.04</td>
</tr>
<tr>
<td>0.7</td>
<td>0.93</td>
</tr>
<tr>
<td>0.9</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Cutoff frequency of a half submerged free floating sphere as a function of diameter

#### 1.4 Static mooring consideration

In this section we concentrate on the static situation, and then introduce the wave aspects in the next section. On the one hand, small wave buoys have a high frequency limit and are easy to transport, handle and deploy. On the other hand, since they have only very little buoyancy, mooring a small buoy is quite a challenge. The buoyancy of a buoy is proportional to the third power of the diameter, while the drag forces on a half submerged buoy are proportional to the square of the diameter. Thus, halving the diameter of a buoy reduces the drag forces to a quarter, but reduces the buoyancy to one-eighth, effectively doubling the mooring challenge.

![Figure 1.4](image)

Conversion of drag force into submerging force via the mooring line

The horizontal drag force on the buoy is, via the mooring, turned into a downward submerging force, as can be seen in figure 1.4. The static (tidal) current results in a drag force ($F_{drag}$) on the buoy. Depending on the mooring line angle $\alpha$, this results in a mooring force ($F_{moor}$). The horizontal component of the mooring force, $F_{moor} \cos(\alpha)$, compensates the drag force. Its vertical component, $F_{moor} \sin(\alpha)$, is a submerging force ($F_{submerging}$). Hence, the submerging force is proportional to the drag force, as:

$$F_{submerging} = F_{drag} \tan(\alpha).$$

Obviously the submerging force reduces by lessening the mooring line angle. This can be accomplished by increasing the mooring line length.

Until now, we have ignored the current drag on the mooring line itself. This drag contribution will increase the submerging force on the buoy. With small buoys, the drag contribution of the mooring line can be substantial.
The underwater weight of the mooring adds to the submerging forces on the buoy as well. This is a drawback of chain mooring. By using synthetic rope (polypropylene, Dyneema, nylon etc.) which has a specific weight close to that of sea water, this contribution to the submerging force can be minimized.

1.5 Following the waves

Since the mooring line is approximately neutrally buoyant, even the smallest wind or current force will straighten the line from the anchor weight to the buoy. Such a straight mooring offers no geometric freedom and buoy motion would only be possible perpendicular to the mooring line. Thus the buoy would not be able to follow the orbital motion of the water particle. It follows then that an elastic component in the mooring line is indispensable in order to enable the wave buoy to follow the orbital motion. As described below, the spring constant of this elastic part determines the lowest frequency that a particular buoy can properly follow.

Waves at sea are the result of orbital motions of the water particles, characterised by their frequency \(f\), amplitude \(A\) and direction. A free floating buoy perfectly follows these orbital motions, as can be demonstrated in the following virtual experiment. Consider an imaginary hemisphere of water just below the surface of the sea: the pressure forces on the surface of this hemisphere cause the enclosed water to follow the wave motion exactly. Now replace the hemisphere of water with a Waverider buoy that will have, according to Archimedes’ principle, the same mass as the water volume it displaces. Hence the pressure forces on the hull of the buoy will also cause the buoy to follow the orbital motion. Measuring the vertical motion of the buoy, as the Waverider does, yields the wave motion.

Although essential in keeping the buoy from drifting, the mooring always hinders the buoy to some extent from following the path of the water particles. If the mooring is too rigid, the buoy will have a variable draught, which is of course disastrous to its accuracy as a wave buoy. Applying a rubber cord is therefore vital to the quality of measurement. It provides the required flexibility and keeps the buoy steadily half-submerged.

In the horizontal plane, the rubber cord allows the buoy to follow the sideways motion of the water: to move forward in the crests and backward in the troughs. The ratio of the horizontal mooring force to the horizontal wave force is easily obtained. The centripetal force required to keep a buoy of mass \(M\) in an orbit of amplitude \(A\) is \(M(2\pi f)^2 A\), where \(1/f\) is the period of orbit. If the mooring is modelled as a spring having a horizontal spring constant \(C\), then the mooring force on the buoy is \(CA\). The ratio of these horizontal forces is given by:

\[
\frac{\text{disturbing horizontal mooring forces}}{\text{wave following water forces}} = \frac{CA}{M(2\pi f)^2 A} = \left(\frac{f_0}{f}\right)^2
\]

where \(f_0 = \frac{1}{2\pi} \sqrt{\frac{C}{M}}\) is the mass-spring resonance frequency. Thus, for wave frequencies higher than \(f_0\), the horizontal buoy motion is hardly hindered by the mooring, whereas for frequencies lower than \(f_0\), the effect of the mooring becomes significant. Here, the buoy does not perfectly follow the wave motion and the heave energy is spread over a wide range of frequencies [2]. Obviously, the more elastic the mooring, the wider the frequency range the buoy can follow.
Actually, the mass in the above equation should include the added mass of the buoy. Taking the added mass into account will reduce $f_0$. With a Datawell standard mooring, horizontal motion is adequately followed up to a frequency of 0.05 Hz, or a period of 20 sec.

We are often asked whether fouling hinders the proper working of the Waverider. “On the contrary”, is our invariable reply. The fouling will increase the added mass of the buoy and, as can be seen from the above equation, thereby increase the frequency range in which the buoy correctly follows the horizontal motion of the water particle. Assuming that the fouling consists of soft bio-material, the cut-off frequency at the high-frequency end of the heave response is hardly changed. The effect of fouling is therefore a mere increase of drag, resulting in a lowering of the maximum current speed limit for operating the buoy.

1.6 Rubber cord

A Waverider mooring will be prestressed due to the static (tidal) current. About this so-called working point, a differential elasticity is required for following the orbital motion of the water. This differential elasticity must be large (i.e. small Young’s modulus) and fairly constant over the whole range of working points. These requirements are met by natural rubber. When the mooring line incorporates a rubber cord of the correct dimensions, the buoy can measure the waves accurately, independent of the static current. The rubber cord recommended by Datawell for a non-directional Waverider is 15 m long with a hardness of 45 to 50 Shore A. In combination with the dimensions of the buoy this rubber cord provides the required wave response, independent of the current velocity or the water depth.

1.7 Conclusion

A wave buoy has to be moored with sufficient flexibility, allowing it to follow the orbital motion of the water. With a small buoy this can only be accomplished by incorporating a rubber cord in the mooring line.

References


2 Directional wave buoys and their elastic mooring

This paper is the second in a series dealing with the elastic mooring of wave and navigation buoys. This edition concentrates on directional measurements by wave buoys. The paper “Wave buoys and their elastic mooring” presented in the previous IOS issue focused on the heave measurement. “Elastic mooring of navigation buoys” and “Rubber as a mooring material” will be the subject of the two subsequent papers. The papers in this series address the subject without going into scientific detail, this aspect being left to comprehensible textbooks such as “Waves in Ocean Engineering” by M.J. Tucker[1].

2.1 Introduction

In this paper, the relevance of elastic mooring for the measurement of wave direction is discussed. Since there exist several methods of directional measurement, each making different demands on the mooring system, we will inevitably digress on the types of directional wave buoys and their methods of operation. The two methods on which we will focus our attention are slope following and orbital following being represented by the Wavec and the Directional Waverider buoys, respectively.

In 1983 Datawell introduced the Wavec, the first commercially available directional wave buoy. The Wavec is a discus buoy that follows the slope of the sea surface. Wave direction is measured by correlating the heave motion with the pitch and roll motion of the buoy.

Five years later, the Directional Waverider was launched. This is a spherical buoy that follows the orbital motion of the water particles. Wave direction is measured by correlating the heave motion with the horizontal buoy motion. The Directional Waverider, being smaller, easier to handle and, last but not least, cheaper, soon overhauled the Wavec in popularity.

Figure 2.1
The Wavec, a discus buoy.
Diameter: 2.5 m
Weight: 750 Kg
2.2 Slope following direction wave buoy

A slope following directional wave buoy such as Datawell’s Wavec, see Fig 2.1, measures the wave direction by correlating the pitch and roll motion of the buoy with the heave motion. The magnitude of the wave slopes gives an idea of the required accuracy of the slope following quality of the buoy. Typically the wave slope does not exceed 15°, whereas a 20 second wave of 5 m wave height has a maximum slope of only 1.5° [2].

![Figure 2.2](image)

**Figure 2.2**

*Design of the Wavec, top float, disk, instrument canister and mooring cross. The rubber cord plus safety line is connected to a short chain.*

A disk shape is the most natural hull shape for a slope following buoy. However, wind and current drag forces, along with mooring forces, cause a floating disk to tilt. When towing a disk with a diameter D and a velocity V, the pitch angle $\phi$ in radians (nose down) is found to obey the empirical relation $\phi = \frac{2F^3}{gD}$, where $F = V/\sqrt{gD}$, and $g$ is the gravitation constant [2]. Hence, a 1 m disk in a 1 m/s flow incurs a ‘DC’ tilt of 4°. For a disk with a diameter equal to the diameter of the Wavec (2.5 m) this is still approximately 1°. Note that the tilt is contra-intuitive: ‘nose-down’.

Obviously this current induced tilt, interfering with the slope following behaviour of the buoy, and synchronised to the waves, heavily hinders a reliable directional measurement. The following measures try to minimize such tilting caused by the water velocity:

- Sloping the circumference of the disk causes the bow-wave to push the disk up again.
- Making the instrument housing (canister) protrude below the disk. The pressure increase in front of the canister assists in pushing the disk up.
- Applying a cruciform ridged frame causes the line of action of the mooring force to pass through the centre of drag.
- Applying a rubber cord in the mooring line enables the buoy to follow, more or less, the orbital motion of the water particles. This reduces the relative velocity between the buoy and the water, thereby reducing the tilt error.

Despite all the above actions, residual disturbing tilting moments will still be present. To keep the difference between buoy and water slope within the required limits the disk has to have a certain minimum diameter.

To clarify: The tilt angle due to a certain moment e.g. from the wind on the antenna, decreases with the fourth power of the diameter of the discus. Thus a minor decrease of the diameter of the buoy will result in a significant reduction of the data quality.

2.3 Safety line parallel to the rubber cord

The spherical Waverider, measuring the wave height, is moored with a 15 m, 45 Shore A rubber cord in the mooring line [3]. This rubber cord provides the flexibility that the buoy needs to follow the orbital motion of the water particles induced by the waves. Even in extreme conditions (a combination of large static water velocity and the occurrence of breaking waves) the mooring loads do not increase dramatically. On the one hand the drag force increases “only” quadratic with the current velocity, whilst on the other hand the buoy can be pulled through an occasional breaking wave. In this way the mooring forces (e.g. 300 Kg at 4 m/s) stay well below the maximum load which a rubber cord can accommodate (1000 Kg for a 35 mm diameter rubber cord).

As with the Waverider, the Wavec requires a flexible mooring under normal operational conditions. The flexibility is again provided by a rubber cord (30 m length, 35 mm diameter, 60 Shore A) but now a single cord does not suffice when mooring under extreme conditions. Drag forces on a discus buoy sharply rise above a certain current velocity (3.4 m/s for the Wavec) [2]. By squaring up to the mooring, the disk attitude is perpendicular to the current, and its projected surface increases substantially, as does the drag force (4000 Kg at 4 m/s). These forces cannot be handled by the rubber cord and it has, hence, to be protected by a parallel safety line that limits the elongation of the cord. In addition, the safety line should have some elasticity within itself to provide a ‘braking distance’ so that the rubber elongation comes to a gradual halt.
A suitable safety line is a nylon cord activating at three times the initial length of the rubber cord. The nylon cord is capable of elongating by circa 30 %, creating a braking distance of 30 m and elongating the rubber cord to a maximum of 4 times its initial length. The elasticity of an 8 ton nylon cord enables the Wavec to pass the breaking wave top without sharp peaks in the mooring load.

2.4 Particle following directional wave buoy

A particle following directional wave buoy such as the Directional Waverider (DWR), see Fig 2.3, measures the wave direction by correlating the buoy’s horizontal and vertical motion. In contrast to a surface following buoy, no specific buoy shape is required.

Figure 2.3

*Directional Waverider*

*Diameter: 70 cm*

*Weight: 100 Kg*

Free-floatingly, the buoy follows the motion of the water particle, both vertically and horizontally, allowing for a perfect directional wave measurement. In moored status, there will inevitably be a difference between the horizontal direction parallel to the mooring and that perpendicular to the mooring. An accurate directional measurement requires the measuring system to provide an equal response to a passing wave in both directions. However, the mooring force is felt only in the former direction, whereas in the latter direction the buoy is quasi free-floating.

This is visualized in the helicopter view of the mooring situation in Fig. 2.4. The arrow labelled “Wave direction” represents the orientation of the water particle’s orbital motion. This vector is decomposed parallel and perpendicular to the horizontal projection of the mooring line. Obviously, the perpendicular response is 100 %, since here the buoy is quasi free-floating. If the buoy were to be moored inadequately, such that a parallel response of only 50 % would be achieved, then the measured wave direction would clearly be wrong, deviating away from the current direction.
To minimize the directional error, the resilience of the mooring must be as small as possible. For a 90 cm Directional Waverider, a directional accuracy of 1.5° requires 30 metres of 35 mm diameter, 45 Shore A rubber cord [4]. The demands on the mooring made by the directional measurement are hence twice as high as those by the heave measurement. A sketch of a DWR with standard mooring in a sea with 6 sec waves, is presented in Fig 2.5.

In the above discussion, the horizontal response is simplified to a mere amplitude whereas, in reality, it has a phase as well. The response of the rubber cord/buoy system can be described in terms of a mass-spring system that has a resonance. The magnitude of this resonance depends on the available damping. At high water velocity, the drag creates sufficient damping to avoid substantial resonance build-up. For low water velocity, the resonance does not build up either, since here the mass-spring model no longer holds good. For lengths smaller than the initial length of the rubber cord, the mooring does not push the buoy back to its center position thus breaking down the spring equivalent.
2.5 Conclusion

By comparing the slope following and the particle following directional wave buoys, it may seem that, from a fundamental point of view, the slope following principle is preferable. With the proper engineering it gives a perfect buoy whereas, inevitably, a moored particle following directional wave buoy will always be hindered by its mooring.

From a practical point of view, however, the particle following directional wave buoy is evidently the winner: no shape restrictions, no bi-stability problems and a directional quality which can be tuned by the elasticity/mass ratio of the mooring/buoy.

Both types of directional buoys require an elastic mooring for the correct heave measurement. Furthermore, the Wavec requires an elastic mooring to avoid secondary effects that interfere with the directional measurement. The Directional Waverider requires an elastic mooring to be able to measure directional waves in the first place.

Despite the Wavec being a fundamentally superior device, the practical and cost benefits of the Directional Waverider enable it to “win” in the real world.

References

3 Elastic mooring of navigation buoys

This paper, the third in a series on the mooring of ocean buoys, focuses on the use of elastic moorings for navigation buoys. The first two papers in this series, published in the previous IOS issues, dealt with the elastic mooring of wave buoys. “Rubber as a mooring material” will be the subject of the final edition. This paper addresses the subject without going into scientific detail, this aspect being comprehensively covered by textbooks such as “Coastal and Oceanic Buoy Engineering”, by Henri O. Berteaux [1].

3.1 Introduction

Traditionally, navigation buoys have been moored with chain. This type of mooring offers good service in most cases and considerable experience has been gained with respect to material specification, equipment handling and operational procedures. However, with recent developments in navigation aiding, such as solar panels, LED-lights and PE-hulls (figure 3.1), the wear of the mooring chain is now highlighted as the prime factor in the determination of servicing intervals. Replacing the chain with a rubber cord obviously eliminates such chain wear and, as we shall see later, the replacement hardware suffers only negligible long term wear.

The results of a 5 year test program are presented in the section “wear”.

Figure 3.1

A 2.6 m diameter navigation buoy moored with rubber cords ready for deployment in 9 m deep water
3.2 Summary benefits

Replacing a rugged and heavy mooring chain with a light and (seemingly) vulnerable rubber cord is not an obviously wise decision at first glance. The section “maximum mooring forces” delves into this matter and explains why rubber not only matches chain as a mooring material but, in some shallow water situations, becomes the preferential option.

Significant advantages of the rubber cord based approach to mooring navigation buoys are:

- Retention of elasticity at any water depth - In shallow water a chain mooring loses geometric flexibility, resulting in peak forces on the chain, which in turn can drag the anchor weight from position during a storm. The intrinsic elasticity of a rubber based mooring remains operative in both deep and shallow waters.
- An elastic mooring is lightweight – An impressive, typical weight reduction factor of 10, versus chain, is achievable. This greatly eases handling on deck which impacts positively on Health and Safety issues.
- Low weight and drag compared to chain mooring - This is particularly important when mooring a small spar buoy in relatively deep water with large tidal water velocities
- An elastic mooring will generally be shorter – Allowing the buoy to be more accurately positioned.

3.3 Wear

Chain wear is caused by the grinding of sand particles between the links. The ongoing wave movement causes the mooring line to be alternately under tension and then without tension. The part of the chain that is alternately lying on the seabed and then raised into the water column is the most affected. The sand grains get between the chain links when the mooring line is slack and do their damage when the line tightens again.

Figure 3.2

*Life of this, initially 26 mm, chain has reached the end of its lifetime due to wear.*
Figures 3.2 and 3.3 show some typical examples of chain wear. The wear illustrated in figure 3 is indicative of permanent torsion of the chain. This chain was affixed to a single point moored rotationally symmetric buoy. Tidal rotation causes the chain links to twist up thereby reducing the length of the mooring line. A shorter line will in turn encounter stronger mooring forces and be even more liable to failure.

Although tides and currents tend to distribute the wear somewhat over the length of the chain, the best option is to remove the source of the wear altogether. That is achieved by employing a mooring consisting of synthetic rope plus a rubber cord. In the presence of waves, the rubber cord smoothes the load on the mooring line thereby avoiding the continual tension/no tension cycle. In this way the potential wear is reduced to a small fraction of that encountered by the traditional chain mooring.

In cooperation with the Vaarwegmarkeerdienst of Rijkswaterstaat (Dutch government water authority), a 5 year test program was established to quantify the wear reduction accomplished by a rubber cord. Arrays of lighted and unlighted buoys were moored alternatively with chain and rubber cord. Based on regular inspections during this period it has been concluded that, in contrast with the chain-based mooring which showed wear rates of a couple of millimetres per year, the wear on the connections of the rubber cord mooring lines were in the order of 0.1 mm per year [2]. Hence the rubber cord mooring has proved to be a very successful and important factor in wear reduction.

3.4 Maximum mooring force

Initially, the idea of mooring a navigation buoy with rubber was greeted with great scepticism. Common sense prompts us to replace a failing chain mooring with a stronger (or longer) chain and we know that, historically, it works. In the light of this experience, it seems illogical that a rubber cord, having only a fraction of the maximum load of chain, could handle the mooring forces equally well or, sometimes, even better. Now, after many years of experience with rubber cords on navigation buoys [2], this initial scepticism has been replaced by confidence and willingness to accept and embrace rubber cords as suitable mooring materials.
Peak forces will arise when a moving buoy, set in motion by a wave, decelerates. The elasticity of the rubber mooring allows the buoy movement to slow down gradually, thus reducing the maximum mooring forces. This feature results from the stress-strain characteristics of the rubber. For the elastic mooring line, the stress-strain relationship is determined by the dimensions of the rubber cord and the material specifications of the rubber. To enable a comparison between a chain mooring and an elastic mooring, we define what could be termed an ‘effective’ (or ‘virtual’) stress-strain relationship for the chain mooring in the following manner. Using a one-dimensional model, we calculate the horizontal displacement (ΔX) of a buoy, from its zero-velocity position, caused by the horizontal force of the chain on the buoy (see figure 3.4). In equilibrium this force equals the drag force on the buoy. In a dynamic situation this force also accelerates and decelerates the buoy. This chain-force/displacement relationship depends on the length and the specific weight (weight per metre) of the chain and the water depth.

1.1 Figure 3.4:

The horizontal force on a buoy as a function of the displacement ΔX.

Having established the stress-strain relationships of the elastic and chain moorings, we are now equipped to compare the two types of moorings in a numerical study of the buoy response to the load of breaking waves [3]. Successive breaking waves impinging on the buoy result in maximum mooring forces. A breaking wave is modelled by a wall of water having a constant velocity. These walls of water are modelled as having equal length and height and adjacent waves are separated by a distance equal to three times the length of the wave. The horizontal force on a chain moored navigation buoy for various water depths is presented in figure 3.5. On decreasing water depth from 7 to 4m, the maximum force increases...
dramatically. At 3m the peak force increases to over 10 times the static force of the breaking wave. Consequently, a mooring that is adequate at high tide, may no longer be so at low tide. Figure 3.6 shows the same model being used to evaluate the mooring forces on a navigation buoy moored with rubber cords of various lengths. In the numerical simulation, the initial peak forces disappear as soon as the length of the rubber cord exceeds 30cm. By lengthening the rubber cord to 1m, the buoy can travel along with the wave until the latter has passed the buoy completely. The maximum force during the passage is less than the static drag force. Before jumping to the conclusion that a rubber cord of a couple of decimetres suffices to moor a navigation buoy, it must be kept in mind that the results presented in figure 3.6 are based on calculations using static water current and do not take into account the hysteresis in the stress-strain component of rubber. Comparison of the results explains why, in shallow water, rubber cords perform significantly better than chain moorings.

Figure 3.5:

The horizontal force on a buoy moored with chain while a breaking wave passes. Water depth: 3m, 4m, 5m, 6m, 7m.

Figure 3.6:

The mooring force on a buoy moored with a rubber cord while breaking waves pass. Rubber cord lengths: 2cm, 8cm, 32cm, 1.3m and 5.1m.
The numerical analysis shows that a chain moored buoy is very sensitive to variations in water depth. A moderate tidal range can induce a dramatic increase in mooring force. Furthermore, the quality of the chain mooring depends on the length and specific weight of the chain. If the chain is too light, or not long enough, peak forces increase dramatically. The quality of the elastic mooring, on the other hand, depends solely on the rubber cord. Peak forces can be avoided regardless of the water depth, which makes the rubber cord mooring superior in shallow water situations.

3.5 Weight of the mooring

Handling the appropriate mooring chain for navigation buoys is a back breaking job which is greatly alleviated by the use of rubber cords. The weight of a rubber cord mooring is approximately 10% of an equivalent chain mooring. At Vlissingen, The Netherlands (VR 6), close to open sea, a 3,800 Kg, 2.6 m diameter buoy (figure 3.1) is moored in 9.2m water depth with a tidal range of 4m and tidal currents of approximately 1.7m/s (3 knots). The used chain has a specific weight of 16Kg/m. The mooring consist of 40m chain and a bridle made of two 5m chains. Its total weight is circa 900 Kg. The equivalent elastic mooring comprises two parallel rubber cords of 50mm diameter running from two mooring eyes on the buoy to a common swivel (like a rubber bridle) and a synthetic rope from the swivel to the seabed ballast weight. The total weight is approx. 75 Kg. The conclusion is obvious - elastic moorings are far easier to handle.

3.6 Mooring polyethylene (PE) spar buoys

A PE spar buoy has a special feature over all other navigation buoys: it tips over when hit by ice pans and pops up again when the ice field has passed, see figure 3.7. Being able to survive floating ice fields, these buoys can be left at sea in the winter. A disadvantage of the spar buoy is its limited buoyancy. In areas affected by tidal currents and relatively large tidal ranges, the weight of the mooring line coupled with the fouling properties of the buoy and mooring are determinant features. In such scenarios a PE spar buoy with built-in radar reflector moored with a rubber cord makes a low-cost, low-maintenance navigation aid. In the Wadden Sea, notorious for its ice fields sliding backwards and forwards with the tidal currents, many PE spar buoys with rubber cord moorings are installed.

Figure 3.7:

PE-spar buoy tipping over when ice floes pass in the tidal current.
3.7 Conclusion

Natural rubber cords providing the required elasticity for (Directional) Waveriders have now been proven to be a reliable mooring for navigation buoys. Long term experiments with elastically moored navigation buoys demonstrate an impressive reduction of wear. Since an elastic mooring can be much shorter than a chain mooring, its positional accuracy is far superior. Considerably reduced total weight greatly eases operational and consequent Health & Safety issues. A projected financial advantage is the lengthened inspection interval, resulting in substantially reduced annual inspection costs.

References

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4 Rubber as a mooring material

*This paper is the fourth and final one in a series dealing with the elastic mooring of wave buoys and navigation buoys. In this issue we explain why natural rubber is an ideal mooring material, a claim founded on investigation of its material properties. The first two papers in this series addressed the elastic mooring of wave buoys and the third paper focussed on the elastic mooring of navigation buoys. The papers in this series address the subjects without going into scientific detail, this aspect being left to comprehensible textbooks such as “The Physics of Rubber Elasticity” by L.R.G. Treloar [1] and “The Chemistry and Physics of Rubber-like substances”; edited by L. Bateman, [2].*

4.1 Introduction

Previous articles in this series have, time and again, emphasised rubber as a pre-eminent mooring material. It is the rubber cord in the mooring that gives a wave buoy the flexibility to accurately follow the waves. It is the rubber cord in the mooring that minimizes the peak forces on a navigation buoy (see figure 4.1). The facts that a cord of natural rubber can elongate to several times the unstressed length, can demonstrate excellent tear-strength properties and has a smoothly sloping stress-strain curve, are all unique features that establish it as an outstanding mooring material. The basics behind these features will be addressed in this paper. Armed with this knowledge, the reader should gain a high level of confidence in buoy moorings based on rubber cords.

This paper focuses on the use of natural rubber (NR), produced from the latex of the Hevea brasiliensis tree. Although general purpose synthetic rubbers, such as SBR (Styrene-Butadiene Rubber) and NBR (Acrylonitrile-Butadiene Rubber), can also serve as mooring materials, Datawell has chosen natural rubber because of its superior tear strength, tear propagation and creep properties.

*Figure 4.1*

A 1.8 m diameter navigation buoy. The bridal of this buoy is assembled using two rubber cords of diameter 35 mm and length 1.2 m.
4.2 Stress-strain relationship

The outstanding performance of a rubber cord mooring results from the characteristic stress-strain relationship of rubber (or force-elongation of the rubber cord). Initially, the stress increases smoothly with applied strain. However, there then follows a sharp upturn in the curve, see figure 4.2. The symbol $\lambda$ (lambda) denotes the ratio of the actual cord length and the unstressed cord length and is a measure of the elongation.

![Figure 4.2](image)

The force-strain relation of 45 Shore A natural rubber for a 35 mm diameter rubber cord.

$\lambda$: the actual rubber length divided by the unstressed length

The shape of the stress-strain curve can be understood by looking at the molecular structure of rubber. The rubber strings in the latex are long chains of isoprene units ($\text{C}_5\text{H}_8$ see figure 4.3). Each individual isoprene unit can rotate, making the long-chain rubber molecule a randomly kinked chain. The (straight line) distance between any two points on the chain is typically only a very small percentage of the distance measured along the molecular string. Basically the rubber in the latex is a liquid. It can be thought of as a pan of spaghetti. By cross-linking the chains a three-dimensional network is made. This converts the rubber into a solid. The chemical reaction with sulphur introducing the cross-links is called vulcanization.

![Figure 4.3](image)

The basic building unit (isoprene) of a natural rubber string. Many units are joined together forming long strings. Via vulcanization some of the double bonds are opened and linked together. This fixes all strings and making the rubber a solid

Elongation of the rubber does not involve increasing the distance between individual atoms but, rather, changing the sequence of rotation in the chain. As long as the distance between two successive cross-links remains only a small fraction of the chain length, the stress required to bring about a particular strain is determined by statistics. In this regime the distance between two successive cross-links has a so called Gaussian distribution [1]. The force required to elongate the rubber opposes the thermal randomization that tends to keep the distance between two successive cross-links small. For a given strain $\lambda$, this force $f$ is: $f = NkT (\lambda^{-1}/\lambda^2)$, where $N$ is the number of segments connecting two cross-links per unit volume, $k$ the Boltzmann constant, and $T$ the absolute temperature.
Note that the resilience of rubber at a given temperature is determined by $N$, the number of segments connecting two cross-links per unit volume. An easy way to obtain a softer rubber is to add an inert filler like chalk. However, amongst other effects, this decreases the breaking strength and deteriorates the creep properties of the rubber. The best way to obtain a soft rubber is to minimise the number of cross-links without affecting parameters like break and tear strength. Here the quality of the original latex is an important factor: the longer the initial chains and the better they are entangled, the fewer cross-links are required to obtain a high quality soft rubber end product.

When elongated beyond the Gaussian region (i.e. when the straight line distance between two successive cross-links is no longer small compared to their distance along the chain), the chains are straightened out and the stress-strain curve shows a sharp rise. The combination of these two stress-strain regimes makes rubber an ideal mooring material for (wave) buoys. Under normal conditions, there is a nice linear stress-strain relation always yielding the same incremental force per unit of extra elongation. Under extreme conditions (when forces are due to other phenomena such as plunging waves or being overrun by a boat etc.), survival of the mooring is the essential target. A sharp rise in the stress strain relation to high values of the mooring force allows the bare rubber cord to survive the overload.

### 4.3 Tear strength

From everyday experience, it is known that plastics can have very low tear strength. Once a nick has been applied, the material offers hardly any resistance to tear propagation. Since cuts and bruises to the rubber are hard to avoid in buoy moorings, the rubber must have good tear strength. Fortunately, this is an intrinsic quality of natural rubber. When placing the rubber under sufficient stress, the individual strings become aligned to such a degree that crystalline structures are formed. This is what happens at the tip of a nick: the forces involved are such that protective crystalline structures are formed and tear propagation is blocked. This tendency to form crystalline structure decreases with temperature. At $-26^\circ$C the rubber crystallizes spontaneously; at higher temperatures, crystallization occurs only when force is applied. The size and shape of the resulting crystals depends on the temperature and stress applied, but the process is always reversible.

![Figure 4.4](image)

*The Datawell test unit. It tests a rubber ring (30 mm diameter, 3mm x 3mm cross section) by monitoring the force and elongation, with nicks applied, for the tear strength, without nicks, for tensile strength.*
4.4 Terminal for the rubber cord

The actual performance of a rubber cord depends both on the quality of the used material and the applied terminal. With any cord or rope, the terminal is always the weakest link. A terminal for rubber not only has to deal with large deformations of the rubber but also with fouling, both on the terminal and on the rubber cord itself. Razor-edged barnacles are notorious in this respect and the terminal must prohibit such fouling from damaging the rubber cord. Furthermore, seawater acts as a lubricant for rubber, changing the friction coefficient from >1 to nearly zero. Also, seawater corrosion and galvanic corrosion aspects should be taken into account. Finally, in situations where a compass is part of the buoy’s sensor system, the terminal should not disturb the local earth magnetic field. All in all, these requirements result in a complicated engineering design task.

Over the years, the knot based terminal supplied by Datawell (see figure 4.5) has proved itself to be very adequate. Provided the knot is applied with care, it can handle loads of at least 50% of the intrinsic rubber cord strength. For a 35 mm diameter, 45 Shore A rubber cord this amounts to 1500 kg, far above the forces that a wave buoy would ever experience.

![Figure 4.5](image)

A 0.5 m long 35 mm diameter rubber cord made of 45 Shore A natural rubber with knot based terminals applied.

4.5 The assembled rubber cord

The elegance of the Datawell rubber cord design is its simplicity and reliability. It consists of an arbitrary length of bare rubber and two terminals. In rare circumstances and conditions where the possibility exists that the rubber cord might not be strong enough, there is an option to apply a safety line parallel to the rubber cord in order to limit its elongation. Apart from the extra financial cost, the main disadvantage in using a safety line is the increase of drag forces, especially when it becomes fouled. The operational security of a safety line is limited. Having a typical breaking force of a couple of tons, it can hardly be expected to withstand vessel interference.
4.6 Fatigue and rubber cord life time

Nothing lasts forever and rubber is no exception to that. However, a reliable and durable rubber cord can be engineered by using high quality ingredients, like natural rubber and carbon black, and by adding protective supplements like wax to protect against ozone. The sheer size of the cord offers protection as well, since the penetration depth of UV-radiation and ozone is small, making any such degradation only superficial. Further degradation of underlying rubber is avoided by the protection offered by the affected material at the surface. Durability in operation is further increased since UV-radiation and ozone are hardly present in seawater.

In contrast to factors for concern such as chain wear, or the state of a battery, the condition of rubber can only be checked in a destructive way. Over the years, however, a lot of experience has been assembled. Based on many returned rubber cords for wave buoys, we at Datawell have observed that no degradation, other than to the surface, occurs during the first five years, regardless of whether the rubber cord has been in use or kept in stock (in a dark and cool place). For rubber older than 5 years the tear strength is affected. According to ISO standards the tear strength is the median of 5 measurements (see figure 4.4). This median value does not change much over the years, but the spread of the 5 values increases significantly. Thus, the reliability of the tear strength reduces somewhat and it is wise to consider replacement of the rubber cord.

Since navigation buoys are generally much larger than wave buoys, rubber fatigue can come into play. Fatigue refers to the maximum number of cycles \( N \) of stretching and releasing that a cord can be subjected to. It has been found [2] that \( N \approx \frac{C}{E^2} \), where \( C = 5.10^{16} \text{ J/m}^6 \) is a constant, and \( E \) is the elastically stored energy per unit volume (J/m\(^3\)). Since \( E \) is proportional to the square of the maximum stress (at least according to Hooke’s law which rubber obeys more or less), and the stress is in turn proportional to the square of the (tidal) current speed \( u \), we have that \( N \sim u^{-8} \), approximately. Likewise, the maximum number of cycles increases with the eight power of the cord diameter. By design the rubber cord smoothes out the effects of the waves and the typical maximum force on the rubber cord is determined by the tidal current. This makes the fatigue limit predictable. As an example, a 4 tons navigation buoy in a tidal current of 3 knots, moored with two 35 mm cords, has an estimated lifetime of 8 months and, during tests, failed after half a year. The same buoy, at the same location, moored with two 50 mm cords, has an expected lifetime of 13 years and presently shows no signs of fatigue.

4.7 Conclusion

Natural rubber, with its characteristic stress-strain curve of a linear Gaussian regime ending in a sharp upturn, has proved itself in numerous applications with both wave buoys and navigation buoys, to be the natural choice for buoy moorings.

References
