Mooring buoys with natural rubber

H.P. Joosten, Datawell B.V., Zomerluststraat 4, 2012 LM Haarlem, The Netherlands
S. Hoekstra, Directie Noordzee, Koopmanstraat 1, 2288 BC Rijswijk, The Netherlands

The use of natural rubber as a flexible mooring for wave measuring buoys is common practice. Allowing the buoy to follow the wave motion under all tidal and current conditions is crucial for the correct operation of the wave-measuring buoy. Recent improvements of navigation buoys have made wear of the mooring chain one of the weakest point of the complete system. The use of an elastic mooring for navigation buoys constitutes a substantial improvement in life expectation. In the case of shallow water, the severe requirement on the maximum elongation of the elastic mooring is met by the combination of natural rubber cords and special terminals.

Introduction

The design of a buoy mooring includes a variety of aspects: size and purpose of the buoy, sea conditions like water depth, tidal range, water velocity, typical sea state, and maximum sea state, sea bottom material, sometimes even sea bottom slope and of course period of deployment, number and kind of passing vessels, etc. A proper buoy mooring keeps the buoy on the spot as well as provides flexibility to follow the waves. Both goals are attained by including a rubber cord in the mooring line. For a wave-measuring buoy, following the wave motion independently of the (tidal) current forces is crucial for the correct operating. For a navigation buoy, a rubber cord mooring secures a more accurate positioning. In addition it, reduces the wear of the mooring, resulting in larger inspection intervals. Thus, a rubber cord mooring is an adequate and cost-effective solution for both types of buoys.

Wave buoys

Waveheight

Waves at sea are the result of orbital motions of the water particles, characterised by their frequency ($f$), amplitude ($A$) and direction. The water forces at the hull of the buoy cause a mass equal to the displaced water volume to follow the orbital motion. Since the mass of the buoy (M) equals the mass of the displaced water volume, the buoy will follow the orbital motion as well. Measuring the vertical motion of the buoy (like the Waverider does (figure 1)) yields the wave motion.

The high frequency response of the wave buoy is limited by the dimensions of the buoy. The buoy does not follow the wave motion if the wavelength is much smaller than the buoy’s circumference. The low frequency response is determined by the buoy as well as the mooring. The mooring forces hinder the following of the waves. The extra mooring force on the buoy in an orbit of amplitude $A$ is $CA$, where $C$ is the
spring constant of the rubber cord (dimension Newton per meter).

Introducing the mass spring resonance frequency \( f_0 := \frac{\sqrt{C}}{M} \) and the wave forces being \( M (2 \pi f)^2 A \), we find the ratio of the forces to be:

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

For wave frequencies higher than \( f_0 \), the buoy rides the waves perfectly, whereas for wave frequencies lower than \( f_0 \) it is hindered by the mooring forces. The buoy will not follow the horizontal motion of the wave and the orbital energy will be spread over different frequencies [1]. Obviously, the more elastic the mooring is, the larger the frequency range the wave buoy can follow. As a matter of fact, the quantity M should be increased by the so called “added mass”, resulting in an improvement of the low frequency response.

The well-know Waverider is a spherical buoy with a diameter of 0.7 m or 0.9 m (see figure 1 and 2). Mooring forces are limited to 300 Kg in usual applications. In the case of breaking waves of the plunging type, the buoy is pulled through a wall of moving water, and mooring forces increase up to 1000 Kg.

**Wave direction**

Slope following directional wave buoys (like the Wavec) measure the wave direction from the correlation between the buoy’s tilt angles (pitch and roll) and heave motion. This type of buoy has a disk shape that follows the slope of the wave at any water velocity. By proper design the mooring force acts on the pivotal point of the buoy. In this way the mooring forces do not affect the tilt of the buoy. Due to its large diameter (\( 2.5 \) m), the mooring forces on a Wavec are far larger than in the case of a Waverider. Typically, maximum mooring forces are circa 5,000 Kg.

Measuring the direction of the waves by means of an orbital following buoy is an even greater challenge. Mooring forces cause the dynamic response tangent at the mooring line to differ from the dynamic response normal to the mooring line. As a result, the direction of motion of the buoy will deviate from the direction of motion of the water particles. To minimize the deviation, the mooring should be as elastic as possible.
Rubber cord for wave buoys

Providing the required elasticity for small wave buoys is a challenge. Since these buoys have a very limited buoyancy they are easily submerged by a chain mooring. On the other hand, in the presence of static current a rope mooring does not provide (sufficient) elasticity. The elasticity of the mooring required for wave following purposes is an elasticity around a working point. The working point is determined by the static (tidal) current. Thus a low differential elasticity in a large range of working points is required. Here, rubber having a fairly constant stress-strain ratio up to 300% elongation can serve well. For this reason, an elastic cord is incorporated in the mooring line of these buoys. Standard lengths of the rubber cord are 15 and 30 m of rubber with a hardness of either 45 or 60 Shore A, depending on size of the buoy and required specification of the wave buoy. Standard diameter is 35 mm.

The elegance of the Datawell rubber cord design is its simplicity. It consists of a bare and solid cord, and two stainless steel terminals which are easily mounted or removed from the rubber cord (see figure 3 and 4). The rubber itself does not encounter fouling since it cannot stick to the regularly deforming surface of the cord. This is particularly important for small buoys which can not handle much extra drag.

Natural rubber has been chosen for its excellent creep and tear strength properties. The combination of hardness and tear strength requires some extra attention. Natural rubber obtains its excellent tear strength properties by crystallisation at the tear tip. At low temperature and under tension, the crystallisation tendency increases with decreasing hardness. Hardness, tear strength and crystallisation have been chosen carefully to make the rubber cords suitable for all seas.

Figure 3
35 mm diameter rubber cord on bollard based terminal.

Figure 4
35 mm rubber cord on bollard based terminal in operation.

“Newsletter of the Rubber Foundation Information Center for Natural Rubber”/No. 32, 4th quarter 2003
**Navigation buoys**

With increasing life time of navigation buoys, it is the wear of the mooring chain that mainly determines the service interval for these systems. Grinding by sand contributes substantially to this chain wear. The sand grains get between the chain links when the mooring line is slack, and do their damage when it is tightened again. The ongoing wave movement causes the mooring line to be alternately under tension and without tension. Although tides and currents distribute this wear somewhat over the chain, it is better to prevent this wear altogether. A way to reduce the grinding is by keeping the mooring line continuously tight, thus keeping the grains out of the link spacing. This is achieved by mounting an elastic cord in the mooring line (see figure 5). The requirements of this flexible part in the mooring line are that at high tide the largest waves can be handled, without losing pre-stress at low tide. In the typical location for navigation buoys these requirements can only be met by rubber cords.

**Shallow water**

Designing an elastic cord mooring is a challenge especially in shallow water with a relatively large tidal amplitude. In these circumstances, the ratio of the maximum cord length - needed to keep the buoy visible at high tide - and the minimum cord length - needed to keep the line under tension at low tide - is very large. This large ratio constitutes a requirement on the maximum elongation of the elastic cord (see figure 6). In order to discuss this problem in quantitative terms, we introduce the symbol $\lambda$, denoting the ratio of the actual cord length at any moment and the initial cord length when being unstressed. An elongation of 100% is thus indicated by $\lambda = 2$, a 200% elongation by $\lambda = 3$, etc. The maximum elongation of an elastic cord is denoted by $\lambda_{\text{max}}$. When we indicate the length ratio required by the circumstances as $\lambda_{\text{req}}$, the problem is...
reformulated as finding a cord mooring for which $\lambda_{\text{max}} > \lambda_{\text{req}}$.

Let us consider a typical shallow water situation having a low tide depth of 2.5 m, a tidal cycle of 3.5 m and a maximum current of 1 m/s. In addition, a maximum wave height in the range of a few metres is assumed. In these circumstances, $\lambda_{\text{req}}$ is about 4. Traditional overbraided rubber cords cannot meet this requirement, since their $\lambda_{\text{max}}$ is only 2 [2]. A rubber cord with loosely woven overbraid, sometimes used in open sea [3], do have a $\lambda_{\text{max}}$ of 4, however, in this case the wear problems are not solved but transferred to the rubber/braid strangles.

The proper choice in this situation is a bare cord of natural rubber, terminated by special bollard terminals, (see figure 3 and 4), the standard for Datawell rubber cords. The maximum elongation of the rubber itself is circa 4. However, since the bollard of the terminal holds a certain length of cord - that, when stressed, slips from the bollard and adds up to the cord length -, the effective $\lambda_{\text{max}}$ of the combination of cord and terminals is larger than this 4, and can in fact be as large as 5. The shorter the rubber cord is, the stronger is this positive bollard effect.

**Measurements and Results**

The rubber cord mooring has proved itself for the Wave-buoy over the past decades. In order to check the suitability for navigation buoys, the Dutch Lighthouse Authorities have performed extensive experiments over the past years. Four years ago tests started with unlighted buoys 1.1 m in diameter in 8 m deep water. These buoys have been unattended for all these years. Terminals are made of stainless steel 8 mm in diameter.

Three years ago a variety of buoys, all made of polyethylene, have been moored with rubber cords. Buoys ranging from spar buoys with a diameter of 0.5 m to light buoys with a diameter of 1.8 m. By inserting a Mooring Force Monitor forces on the mooring line have been registered. Although the dynamics of the rubber-moored buoy differs substantially from that of an equivalent chain-moored buoy, the overall peak forces are comparable. Some typical autumn results are shown in figures 7 A and B. The weather in the shown time span was a mild autumn weather, with occasional severe storms.

![Rubber Cord, Maximum Mooring Force](image-url)

"Newsletter of the Rubber Foundation Information Center for Natural Rubber"/No. 32, 4th quarter 2003
A more detailed evaluation of these measurements is presented in an IALA “Guidelines on Synthetic Mooring Lines” [4]. It is concluded that, in contrast with the chain-based mooring that shows a wear rate of a couple of millimetres per year, the wear of the connections in the rubber cord mooring lines are in the order of 0.1 mm per year. Hence the rubber cord mooring is very successful in wear reduction. The distance between the buoy and the mooring stone for the rubber cord mooring is maximally 4 m. Chain length used in this location is 20 m, making the rubber cord mooring by far the more precise way of mooring navigation buoys. Handling of a rubber-moored buoy has proved to be more difficult. The mooring stone can not be lifted via the rubber cord. Ground chain and barbed hook construction have been used to lift the mooring stone.

**Polyethylene spar buoys**

Based on the initial success of the rubber cord mooring of navigation buoys, tests by the Dutch Lighthouse Authorities have been extended. On various locations in the Wadden Sea polyethylene spar buoys have been moored with rubber cords. Both PE and deforming rubber hardly suffer from fouling, which is important for long term deployments of navigations buoys with low buoyancy. Furthermore the Wadden Sea is notorious for its ice fields, sliding backwards and forwards with the tidal currents. A PE spar buoy is tipped over by the ice, popping up again when the ice field has passed. Such a buoy, equipped with built-in radar reflector and moored with a rubber cord, is a potential low cost low maintenance navigation aid.

---

“Newsletter of the Rubber Foundation Information Center for Natural Rubber”/No. 32, 4th quarter 2003
Mooring larger navigation buoys with rubber cords is of interest as well. Here another aspect of rubber cord moorings shows up. Handling the appropriate chain is a back breaking job which can be avoided by using rubber cords since their weight is approximately 10% of the equivalent chain. At Vlissingen (VR 6), close to open sea, a 3,800 Kg 2.6 m diameter buoy (figure 3.1) is moored in 9.2 m water depth with a tidal swing of 4 m and tidal currents of approximately 1.7 m/s (3 knots) (see figure 8). The mooring consisted of two rubber cords from the mooring eyes of the buoy to the anchor stone, like a rubber bridle.

**Measurements and results**

Mooring forces showed to be higher than expected from water velocity and size and shape of the buoy. Inspection of the mooring force dynamics, and the dynamics of the buoy itself, showed that sheering of the buoy added significant to the velocity relative to the water, which in turn added to the mooring force (see figure 9). Despite the higher than expected mooring forces, the mooring survived a severe winter storm.

![Image of buoy](image_url)
Fatigue

After having been in use for approximately half a year the rubber cord mooring failed. On inspection the rubber had deteriorated significantly. Fatigue had shown up. From literature [5] it is known that the maximum number of cycles (N) is given by: \( N = \frac{C}{E^2} \) where E is the elastically stored energy per unit volume (Joule/m³), and C equals 5.10^{16} (J/m³)^2-Assuming rubber to obey Hooke’s law, the maximum number of cycles decreases with the fourth power of the maximum force divided by the un-stretched cross-section of the rubber cord. Therefore, the cord diameter is increased from 35 mm to 50 mm. Since this cord is less elastic it will not endure 16 times more cycles, as a straightforward reasoning would suggest, but a lifetime increase by a factor of 7 is expected which is regarded as sufficient.

Conclusion

Natural rubber cords providing the required elasticity for (Directional) Waveriders have shown to be a reliable mooring for navigation buoys as well. Long term experiments with rubber moored navigation buoys show indeed a impressive wear reduction. Since the length of the rubber mooring is much shorter than the length of the chain mooring, its position accuracy is much better. An expected advantage is the increase of the inspection intervals, resulting in a substantial reduction of annual inspection costs.

References


