Design, Manufacture, and Deployment of Buoyant Cables in Underwater Applications

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***ABSTRACT* - Strong, but thin, optical cables are a key component for many underwater applications such as ROVs, sensing systems and many DoD weapons systems. Strength members used in cable constructions are materials such as extruded Liquid Crystal Polymers (LCP) and aramid yarn.**

The cable may need to have controlled specific gravity (SG) so that it can float, sink or be suspended in the water column. Therefore, cable design must allow for easy manufacturing and customization to meet the SG needs of the application in long lengths.

Deployment from a moving platform may require the cable to be provided in a precision wound pack of several km length appropriate for the application. Precision winding of fiber optic cables allows for rapid deployment without a spinning spool of cable requiring a fiber optic rotary joint. This configuration of cable also prevents any spool momentum that would be generated by a large spinning spool of cable. In the case of a precision wound spool, the fiber can be deployed at variable speed without running the risk of extra cable being deployed and potentially hockling the fiber optic cable.

In many applications the cable is used as a communication link between discrete nodes deployed in the open ocean environment where the span can stretch from meters to miles. The cable may need to survive the constant pull and push of changing currents for days or even months. In this situation it is important to understand the dynamic strength but also the static strength of the cables.

Linden has developed a family of optical cables that are thin but strong, therefore, appropriate for the above applications (STFOC). The designs allow easy customization and control of SG and manufacture of 50 km continuous lengths. We have also developed methods to generate precision wound packs that are many km in length.

In this presentation we will discuss some of the considerations that go into the design and manufacture of precision wound cable packs for use in underwater applications.

1. INTRODUCTION

Many underwater applications such as ROV communication, and tethers for various applications including DoD weapons systems require and optical link. Optics are a preferred method of communicating underwater due to their low weight, small size and ability to transmit long distances. Almost universally the fiber optic will need to be strengthened to survive the subsea environment. Extruded Liquid Crystal Polymers (LCP) and aramid yarn are two examples of strength members used in cable construction.

In many of the applications the cable is used as a communication link between discrete nodes deployed in the open ocean environment where the span can stretch from meters to several kilometers. Deployment parameters – speed, depth, hardware through which cable deploys depends on the specific application. The most demanding applications are where the cable serves as communication conduit for high-speed deployment. The moving platforms need to carry on board precision wound packs of cable that deploy without the pack rotating. Therefore, the cable packs must have an extremely high degree of precision where the cable is stacked in perfect layers so that the cable deploys without entanglement even at high speeds. Potential imperfections are overlapping wraps, imperfect transition from one layer to the next. These can lead to more than one wrap coming loose during deployment which then produces a knot with loss of optics or a break in the cable. Since any cable has an OD tolerance, it is practically impossible to make a theoretically perfect pack. This paper will discuss the key parameters that must be monitored in pack fabrication to ensure successful deployment at speed.

2. PACKING EFFICIENCY

Pack efficiency is the obvious first parameter to assess pack quality.

2.1. Derivation of Formula for Capacity of a precision wound pack

Fig. 1 shows defines dimensions of a pack.

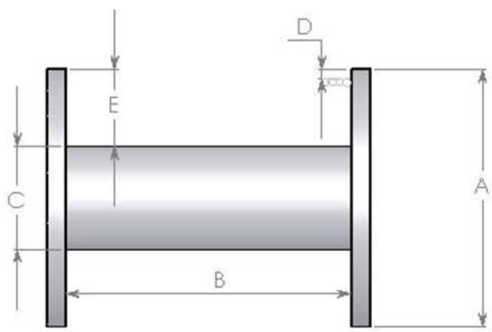

Figure 1. Dimensions of precision wound pack

A = Flange diameter
C = Barrel diameter
B = Traverse
D = cable diameter

We first calculate pack capacity using square stacking as shown in Figure 2

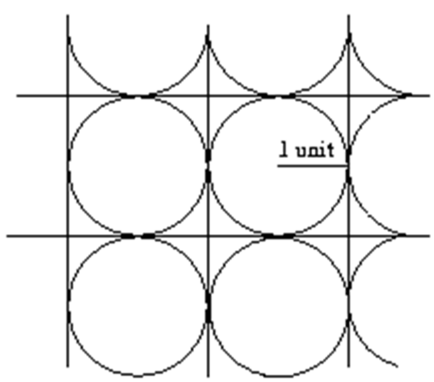

Figure 2. Square Packing

Pack capacity = RS = no. of turns per layer x no. of layers x average length of cable per turn

No. of turns per layer $= \frac{B}{D}$

No. of layers $= \frac{(A-C)}{2D}$

Average length of a turn = (length of turn on barrel + length of turn at flange OD)/2

$$= \frac{\pi(A+C)}{2}$$

Therefore, RS $= \frac{B}{D} \text{x} \frac{(A-C)}{2D} \frac{\pi(A+C)}{2}$

$$= \frac{\pi(A^2-C^2)B}{4D^2}$$

$$= \frac{\pi(Flange\ Diameter^2 - Barrel\ Diameter^2)B}{4(Wire\ OD)^2} \qquad (1)$$

Figure 2 is considered a "square packing profile" and the maximum area coverage in this configuration is 78.5%.

In the case of a perfect precision wind, the cable stacking is hexagonal as shown in Figure 3. The maximum coverage in this area is 90.7%, an improvement over square packing.

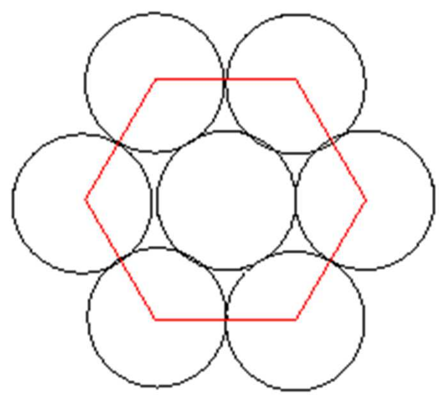

Figure 3. Hexagonal Packing

In hexagonal packing, the number of layers that can be accommodated is larger since the layers are separated by less than twice the cable diameter, D, because the cable sits in the well created by adjacent cables in the previous layer. It is easy to show that the layer separation in this configuration is 0.866D, therefore, the total number of layers increases by a factor of 1.155

(inverse of 0.866) Therefore, the pack capacity, RH, is given by

$$RH = 1.155 \times \frac{\pi(Flange\ Diameter^2 - Barrel\ Diameter^2)B}{4(Wire\ OD)^2} \qquad (2)$$

This assumes the following: a) that the fiber optic cable is a perfect circle; b) that each cross section of cable in any given plane would have the same OD; c) that the set-up points at the layer cross overs would occur at the exact same location throughout the pack. All of these assumptions are true in theory, but in practice the cable will have some ovality, will have some variation in OD along the length, as a result cross over locations will vary. We have found in practice that while winding, a cable will naturally stack hexagonally, but this is more prevalent for the inner layers. As the pack OD increases and tolerances "stack-up" the level of "perfection" in the wind decreases as does packing efficiency.

3. PRECISION PACK METRICS

3.1. Packing Efficiency (PE)

Once fabrication of a pack is complete, one can input the pack dimensions in eqn. 2 to calculate the pack capacity. The actual length is measured with an OTDR and the ratio of actual length to theoretical length from eqn. 2 is defined as the pack efficiency (PE). A randomly wound spool of cable (on standard respooling equipment) has PE of about 80%. This seems to be the case independently of the pitch used in respooling. A precision pack that needs to deploy at speed over several kilometers should have a PE > 90%.

3.2. Layer Uniformity

High packing efficiency is not sufficient to ensure successful deployment since it measures overall PE but not local PE. Overall PE may be high merely because stacking of inner layers is perfect whereas stacking of outer layers has PE < 90%. Such a pack will not deploy successfully for the full length. It is critical that the number of wraps in each layer must be tracked during fabrication. Ideally each layer must have the same number of wraps. However, cable defects such as ovality, OD tolerance and discrete lumps, result if the wraps per layer varying from layer to layer.

Nine spools of buoyant, optical cable were fabricated and wound into packs. The characteristics of these packs are summarized in Table 1 whereas deployment test results are summarized in Table 2

Table 1. Precision Pack Characterization

Cable ID	Pack Length (m)	OD (mil)	1550 loss (dB/km)	PE, %	Wraps/ layer (avg.)	wrap stdev
1911104K	23,000	36.2	0.203			
1911104C	20,183	36.2	0.200	87.9	242	12.7
1911104J	20,314	36.0	0.205	90.4	251	7.8
1911104G	20,326	36.0	0.196	92.6	257	3.6
1911104E	21,792	36.1	0.205	94.0	260	1.3
1911104D	20,084	36.1	0.197	96.2	262	1.0
1911104B	20,531	36.2	0.201	95.6	260	1.1
1911104H	20,357	36.0	0.197	95.9	262	1.3
1911104A	20,304	36.1	0.199	94.8	261	1.0

Table 2. Summary of Deployment Tests

Precision Pack ID	Pack Length, m	PE, %	wrap STDEV	Deployment results
1911104KPP	23,000			Results VERY POOR; since wind is semi-precise
1911104CPP	20,183	87.9	12.7	Not tested. STDEV too high
1911104JPP	20,314	90.4	7.8	Tested; results POOR
1911104GPP	20,326	92.6	3.6	Tested; results GOOD; deploys well at low and medium
1911104EPP	21,792	94.0	1.3	Results VERY GOOD; 20 km successful deployed
1911104DPP	20,084	96.2	1.0	Rresults EXCELLENT;20 km successful deployed
1911104BPP	20,531	95.6	1.1	Results EXCELLENT;20 km successful deployed
1911104HPP	20,357	95.9	1.3	Results EXCELLENT;20 km successful deployed
1911104APP	20,304	94.8	1.0	Results EXCELLENT;20 km successful deployed

In Table 1 we show the improvement in pack quality from the first to the last pack. The average number of wraps per layer in the last 6 packs is higher than 260, while the standard deviation in the wraps per layer has decreased from a high of 12.7 to around 1.

Underwater deployment tests were conducted for all eight of the nine packs. The results are shown in Table 2. It is clear that a PE > 90% coupled with standard deviation in wraps per layer around 1, results in a pack that will deploy successfully.

In addition to factors discussed above, the choice of binder is a critical parameter in pack fabrication. Binder must be specifically chosen to adhere well to the outer jacket of the cable. A binder that allows the use of very little binder is preferable since it does not impact cable density significantly. However, it is possible that for deployment at high depths it may be needed to fill the air voids in the pack, if not with binder, then with other fillers post fabrication.

Fig. 4 shows the layer uniformity in number of wraps per layer of a pack that did deploy successfully and one that did not.

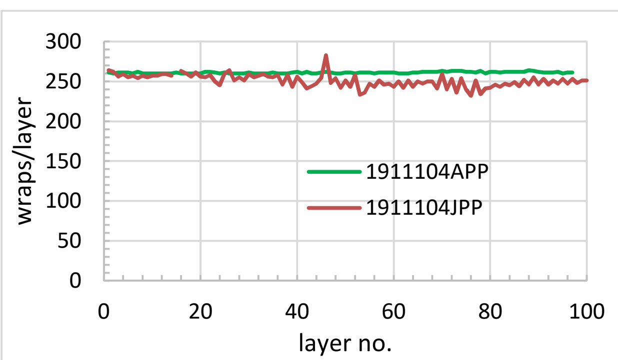

Fig. 4 Wraps/layer for two different packs shows the improvement in layer uniformity

4. Summary

We have only discussed some parameters that must be monitored to fabricate precision packs of cable.

However, there are several other issues that are not discussed. For example, the choice of binder is critical since it must be appropriate for adhesion to the material of the cable. Binder and cable jacket must be picked to have suitable surface tension to allow adhesion of one to the other.

Packs may be used on the ocean surface, in littoral waters, or at depth. Attack from aquatic creatures, biofouling in long term applications, effect of hydrostatic pressure at depth on optical loss – will all impact cable design and pack design.

In summary, the criteria for pack fabrication for it to deploy successful are:

a. Packing Efficiency, PE > 90%
b. Layer uniformity, wraps/layer STDEV < 1.5
c. No crossovers during pack fabrication.