Abstract - Buoy based seafloor observatories require lightweight synthetic strength member electro-optical anchor cables to be feasible. Typically these cables have maximum elongations of around 0.6% before damage occurs to the copper and optical elements and therefore provide minimal compliance to absorb wave and current forces acting on the surface buoy and cable. A stretchy mechanical system known as a snubber has been developed at WHOI for absorbing wave energy and protecting the buoy electro-optical cable from excessive strain. Results are presented from field trials of three different ocean mooring designs that all use snubber hoses as a key design element.

II. WHY ARE SNUBBERS NECESSARY?

A. Axial load modulation

All mooring systems must provide some compliance to absorb wave motions. Traditional moorings provide the needed stretch through a combination of mooring material compliance and geometric compliance achieved by including a catenary shape in the mooring design. For deep-water moorings, the inclusion of electrical and optical conductors in the mooring cable reduces the stretch of the mooring cable significantly and the inverse catenary shape does not provide sufficient compliance. This lack of compliance results in a significant increase in the peak loads experienced in the mooring system, potentially damaging the EOM cable and buoy system itself. The inclusion of very low stiffness snubber elements below the buoy provides the missing compliance and returns the mooring loading to a level that can be tolerated by the EOM cable. Traditional shallow-water moorings utilize a heavy, chain catenary arrangement where chain lays on the seafloor and compliance in the system is provided by the chain lifting off the seafloor as needed. This design does not rely on material compliance at all, so the inclusion of electrical and optical conductors does not pose an issue. However, a seafloor laid cable, positioned between a bottom observatory sensor and the buoy’s anchor, will most likely be damaged by the dragging of the chain catenary on the seafloor. Also the inclusion of survivable electrical and optical conductors in a chain mooring is a challenging undertaking. A mooring that consists of snubber elements from the buoy all the way to the seafloor provides an alternative mooring design for making a seafloor electrical connection in shallow water.

The WHOI Cable modeling software provides realistic predictions of mooring dynamics and loading in prescribed environmental conditions [1]. Application of this modeling technique to the two types of moorings described above illustrates the effectiveness of the snubber elements in each
Comparison of results for the MOOS test mooring that was deployed in 2004 with a similar design that does not include the snubber elements allows an estimate of the effectiveness of the snubber. The snubber elements themselves possess a nonlinear stress-strain curve, which is included without approximation in the nonlinear cable dynamics model. Fig. 1 shows the tensions below the surface buoy in storm conditions outside of Monterey Bay, California. For this analysis, a significant wave height of 9.2 meters is used, with the peak of the associated Pierson-Moskowitz spectrum occurring at a period of 16 seconds, these conditions approximate a storm with a 25 year return period. As shown, the presence of the 24 meter snubber reduces the expected peak load by 50% from 37 kN (8300 lbs) to 18 kN (4100 lbs), and reduces the load range between minimum and maximum tensions from about 36 kN (8,000 lbs) to 9 kN (2,000 lbs). The expected peak loads are calculated from the relatively short simulation record as four times the standard deviation above the mean. In addition to reducing the destructive snap loading evident in the simulations, the presence of the snubber is critical to reduce the peak loads and load range, the electrical and optical conductors in the MOOS EOM cable begin to fail when loaded beyond 27 kN (6000 lbs).

For the shallow water case, the snubber is also a critical element, a taught line mooring made of an EOM cable or even a relatively stretchy nylon rope does not have enough compliance to accommodate even moderate wave and current loading. For a 100 meter water depth, snubbers of the same construction as the MOOS snubbers are sufficient to accommodate the required motions if they are used for the whole depth of mooring. In this configuration, the un-stretched length of the mooring is 10% shorter than the water depth, so the snubbers operate in a pre-loaded manner, never going completely slack. Fig. 2 shows that predicted loads in conditions with 8.5 meter significant wave heights at a 16 second period. The preload in the mooring is sufficient to keep the mooring from going slack at any time. As described below, the snubber elements can be made to have more stretch than those used in the MOOS system, for water depths below 100 meters, this is required and was done for the 40 meter “Gumby” mooring and the fish pen buoy described below.

B. Bending strain relief at the buoy

In addition to the need for axial load modulation, a mooring connected to a riser cable requires a bending strain relief or cable bend limiter at the base of the buoy bridle to protect the cable from repetitive bending as the buoy pitches and rolls in a seaway. Several alternative designs have been developed for addressing this problem, for example the Bailey bracket cable clamp as used on the PMEL TAO array for temperature string cable and the WHOI mechanical universal joint and electro-mechanical chains used on the NOOTKA mooring [2]. The use of a snubber hose bolted directly to the buoy bridle with integrated internal wiring solves this problem very effectively. The snubber hose is relatively stiff and has excellent fatigue properties. This allows continuous flexing at the buoy base with minimal wear. The design is simple and robust with no moving or rubbing parts.

III. SNUBBER DESIGN REQUIREMENTS AND DESIGN DETAILS FOR THREE UNIQUE MOORING TYPES

A. The Monterey Ocean Observing System (MOOS) mooring

The MOOS mooring is designed to provide 100 Watts of power and optical communications to scientific experiments deployed on the seafloor in depths to 4000 meters [3]. The snubber assembly is required to provide for eight copper conductors and four single-mode optical fibers. The mooring performance was modeled using the WHOI Cable Modeling program with the environmental forcing parameters extracted from a 10 year record of a NDBC data buoy 16km SW of the MOOS deployment site. The modeling results showed that the longer the snubber the lower the peak loads on the mooring cable. A total snubber
length of 24 meters was specified which is a tradeoff between the best modeled performance and the operational challenges of deploying and recovering a very long snubber at sea. The working load for the snubber hose assembly determined from modeling is 18 kN (4000 lbs.) and the design worst-case short term maximum load is 26.7 kN (6000 lbs.)[4]. The 10 cm (4 inch) internal diameter of the snubber was dictated by the “coilcord” size needed to maintain a minimum bend radius of optical fibers in the coilcord’s core, needed to avoid excessive optical attenuation, see Fig. 3.

The “coilcord” cable is spiraled in the interior of the snubber hose providing electrical and optical conductivity through the snubber. This arrangement of an internal coilcord is the first generation snubber design and is similar to previous coilcords used on moorings [5], with the additional complexity of incorporating optical fiber. The cable that is used to fabricate the coilcord is carefully designed to maximize the number of conductors, have adequate tensile strength and to have a small enough core to leave space to extrude a thick enough neoprene rubber jacket to provide a rubber to core area ratio of around 70:30 to have enough “shape memory” to provide good firm coil retraction. Firm retraction is necessary because the coilcord must support it’s own weight vertically in the snubber hose (in water). One of the coilcord design limitations was a maximum rubber diameter of 20mm, the maximum diameter extrusion die available. The optical fiber is selected for good performance at the small bend radii needed. The first bend occurs as the core cable is twisted during construction and the minimum radius is decreased further on the inside elements when the cable assembly is then coiled and its rubber jacket vulcanized to “freeze in” the coilcord shape. The snubber hoses are filled with water and sealed in order to provide the correct elongation stiffness profile and to help support and lubricate the interior coilcord. The completed coilcord assembly must be able to able to stretch at least 30% for millions of cycles without causing attenuation in the optical elements or damaging the copper power conductors.

C. Design of the Coilcord and Coilcord Cable

The coilcord core cable was manufactured at Cortland Cable Company by starting with a braided Vectran center strength member. Optical fibers and electrical conductors are spiraled around the center strength member with a pitch length calculated to maintain a minimum optical fiber radius of curvature of 37mm (1.47 inches). This radius was specified after laboratory tests were conducted on test mandrels and one-off cable test sections that were built up with several different single mode fiber and fiber buffer types. Although mandrel wrap tests and calculations showed that standard SMF-28 type fiber should work well, when the completed coilcord test pieces were optically checked, the fibers had extremely high attenuation and the cable was unusable. It was discovered that the material and construction techniques used to make the core cable were tending to bunch up the optical and copper wire bundle during subsequent manufacturing steps, creating numerous tight radius bends. Two approaches were taken to solve this problem: First a special binder wrap tape was used that provided continuous support for the cable core elements during the subsequent rubber jacket extrusion step. Secondly,
a specialty high numerical aperture fiber optimized for bend insensitivity [6] was selected. A second test cable core and coilcord was manufactured and performed well. This fiber has a disadvantage in that the small core diameter results in coupling losses of 1-2 dB when connector mated to SMF-28 fiber. This loss was considered acceptable and well within the system optical design budget. The final coilcord design was tested for optical attenuation at 3447 kPa (500 PSI) hydrostatic pressure and stretched 30% for 560,000 cycles without exhibiting any significant increase in attenuation.

The core cable with center strength braid and its surrounding electrical and optical conductors is over-extruded with a heavy jacket of unvulcanized neoprene rubber at a second manufacturer, the Whitney Blake Company, creating a final outside diameter of 18 mm, see Fig. 4. Due to the soft, easy deformable plastic condition of the uncured neoprene the cable can be bent with little resistance. Wrapping one end of the cable around a 2.5 cm diameter mandrel into a tight spiral forms a coilcord. The cable is placed in an oven, where the coiled section is permanently shaped and vulcanized. The Vectran braid supports the weight and acceleration generated tensions of the coilcord, and transfers the tensions through an eye-splice termination to a clevis in the upper bulkhead of the snubber hose. The coiled section can be extended up to three times its tightly spiraled length under a few pounds tension, upon removal of the tension the coil snaps back instantly to its original length. The conductor assembly does not stretch during the coilcord extension because of theVectran strength member support. Due to the neoprene rubber’s elasticity the coilcord extends and retracts without plastic deformation, and without electrical and optical degradation.

D. MOOS Snubber Hose Design Details

The snubber hose is hand-built over a steel supporting mandrel in 8 meter long segments, starting with an inner liner from neoprene rubber, over which counter-helical layers of nylon tire cord are wound. Two non load-carrying layers of Kevlar tire cord are positioned over the nylon cord layers to provide resistance against shark bite, and the hose is completed with an outer rubber jacket. Near each termination extra nylon tire cord layers are applied and generate a transition zone, which builds up the hose diameter, strength, and stiffness towards the hose coupling. A stretch and bend limiting section is generated this way, in which the high stretch in the free hose length is gradually reduced to near zero [7]. The modular 8 meter segment length was chosen to keep the self-weight loads on the vertically suspended coilcord from sagging the coils and allowing them to chafe on the hose interior. The eight meter length also simplifies assembly and shipping. At each junction a splice tube and instrument cage provide an electrical and optical breakout and mounting bracket for upper water column instrumentation. When the depth of the mounting point on the mooring bridle is taken in to account this results in permanent instrument mounting locations at depths of 2 meters, 10 meters, and 18 meters deep in the water column.

The hose coupling consists of a standard ANSI 316 stainless steel 4 inch weld-neck flange with an attached section of steel tubing with several steel rings welded around the tubing’s outside. The inner liner and the nylon tire cord layers are wrapped over the tubing, and are pressed into the “valleys” between the steel rings with tight wraps of thin steel wire. When hose loads tension the tire cords, they try to pull off the coupling. The tight wire wraps arrest the cord layers’ positions in the valleys between the steel rings preventing the cord layers from pulling off the coupling under tension. With this technique the cord tension is effectively transferred to the hose coupling. This is a proven method developed by hose manufacturers to terminate hand-built pressure and suction hoses, which we modified to support high axial tensions.

The hose termination area greatly benefits from the fact that the extra-reinforced hose end section can be built up gradually, near zero hose stretch in the coupling area is achieved this way, in break tests the hose fails in the free length away from its termination zones. The additional cord and rubber layers also provide load sharing for the hose tension, adding ruggedness and supporting the reinforcement where it is most vulnerable due to the “crowbar” effect at the interface, which tries to pull more compliant and flexible tubing off an inflexible coupling section under the constant flexing of the hose by the buoy motions in waves. The additional reinforcing layers support much of the extra flex tensions in the termination area and increase the survivability of the hose in service.

The snubber hose is built from suitable rubber compounds with tire cord reinforcement, components with greatly different properties. Rubber stretches up to 600 percent with little resistance, we use rubber compounds with an elastic modulus in the 200 to 250 psi range. Nylon tire cords stretch about 20 percent at break, their elastic modulus is 3 to 4 * 10^5 psi, over 1,000 times higher than rubber. Under axial compression the fine fiber structure of the cords buckles and has near zero resistance. The cords are tightly substance. The shrink cloth wrap tightens up under steam, thereby pressing the hose wall’s rubber tire cord matrix against the center steel mandrel and bonding all elements tightly together, the hoses have a tire-like tough feel.
Spaced and arranged parallel – in one direction only – to form a loose “woven cord” fabric, also called tire cord fabric, with widely spaced and weak thin cotton filling yarns holding the fabric together. The cords in the fabric are covered and surrounded by soft rubber, and the fabric is processed into thin reinforced rubber sheets. We use Nylon tire cord fabric, embedded in 0.8 mm thick rubber sheets with a breaking strength of 1,750 N/cm (1,000 lbs/inch). Ribbons of the coated fabric are cut and counter-helically butt-wrapped around the steel mandrel and inner rubber liner to form the torque-free strength member. By changing the wrap angle, the compliance of the reinforcing nylon tire cord layers can be very effectively modified. For a given diameter the hose strength can be increased by adding layers of nylon tire cord, and to a lesser degree by increasing the rubber cross section in the hose wall.

The design calculation process for the tire-cord rubber composite structure is based on textile mechanics, and is adapted to compute the stretch hose behavior [8]. The larger the wrap angle, the shorter is a spiraled layer’s pitch length, and the more constructional stretch is provided by the spiraled reinforcement – the “slinky” effect (or the spiraling of the tire cord layers has the effect of a multiplier of the tire cords’ stretch). The higher constructional stretch is coupled with a reduction in the effective breaking strength. Through adjustment of the tire cord wrap angle, snubber hoses with a specified elastic modulus can be designed. The tire cord reinforcement is sharing the mooring loads together with the low modulus rubber portions of the hose wall, in particular at higher loads the reinforcement supports the major portion of the hose tension.

The snubber design software calculates stepwise the hose load elongation behavior. It uses the hose elongation, the tire cord wrap angle, and the tire cord’s non-linear load elongation curve as input, together with certain hose dimensions and information about the number of cords in the hose wall. At a selected hose elongation the stretch of the tire cord material is calculated, (as function of the elongated cord geometry in the hose wall), and the resulting tire cord tension obtained from the cord’s non-linear load elongation curve. Summing the tire cord tension determines the reinforcement loading and its axial and radial components relative to the hose axis. To the axial component loading the rubber loading at the same hose elongation is added to obtain the hose load at the selected hose elongation.

The program also calculates the fill-fluid pressure, which is generated by the spiraled and tensioned tire cords, which cannot contract the inner hose diameter beyond what the incompressible constant volume of the fill fluid inside the sealed hose cavity permits. The fill fluid pressure also generates a force against the hose bulkheads, which is loading the tire cord reinforcement. This pressure-generated force has to be subtracted from the reinforcement loading, to obtain the net tension that effectively can support external hose loading.

The final output is a hose load elongation curve, and a curve showing how fill pressure versus hose elongation for a specific design. The theoretical hose breaking strength is determined as the hose load at the hose elongation, where the tire cords are stretched to their breaking loads and fail. The rated breaking strength of a hose is set at 80% of the theoretical value. The predicted hose behavior agrees well with experimental results [9], see also Fig. 6.

E. New Hampshire Fish Pen Mooring

The second mooring example is found in the Open Ocean Aquaculture (OOA) demonstration project of the University of New Hampshire. The OOA design needed a high stretch hose for mooring an automated feed buoy to a submerged fish cage. The design required that this hose had to simultaneously serve as a conduit to deliver a fish feed/water mixture from the feed buoy to the cage, had to provide an electrical link to illuminate the net cage and its fish content, and to transmit environmental and video data up from the cage to the feed buoy. Since the hose cavity had to be free of obstacles to allow the fish feed transport, the conductors had to be integrated into the hose wall of the snubber hose (An alternative, spiraling conductors around the hose outside is not a survivable solution). Integrating the conductors into the snubber hose wall is the second generation of the overall snubber design.

The 52 meter deep project site, located 10 km off the New Hampshire coast, is fully exposed to Gulf of Maine’s severe Nor’easter storms with 9 meter waves. The net cage is moored to a rope grid mid water with its top 9 meters below mean low water. An 8 meter long hose flanges into the bottom of the feed buoy and the to top of the net cage. A mooring scheme for the feed buoy was developed using a combination of rubber tethers [10], ropes, and a highly stretching feed hose with electrical conductors. More detailed information about the complex mooring system is found in [11].

F. Feed Hose Design and Construction Details

To satisfy the requirements, a stretch hose with about 140% elongation at maximum working load had to be built. The design takes advantage of a shift in the load-sharing pattern of the helically wrapped tire cord layers that occurs in a fluid filled rubber hose when the wrap angle is increased above the “optimum” angle of 54°. A stretched hose reduces its diameter at the same time due to the suction effect of the fill fluid’s constant volume. The length of the spiraled path of a tire cord at wrap angles larger than the optimum angle shortens due to the hose diameter reduction. Under this condition the cord buckles because the cord load is zero, or the hose wall’s rubber material solely supports the hose load. When the hose is stretched beyond a wrap angle dependent elongation, the tire cord’s helical path starts to extend and tensions the previously buckled tire cords. At even higher elongations the cord tension rapidly increases and carries the major portion of the hose load. This effect allows building highly stretching hoses, where the rubber material solely supports the hose load, until the hose stretch reaches a known value and the tire cords engage and quickly support

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3 In all cases the hose responds to tension with axial stretch, and simultaneously reduces its diameter. The diameter reduction is caused by the smaller diameter of the fill fluid volume in the stretched hose, following the constant volume law.
further increases in mooring load.

In order to provide the power and signal link along the hose, twelve special compliant #18 AWG copper conductors were spiraled to form part of the hose wall at a steeper angle than the nylon cords to maintain about zero stretch up to the maximum hose load. The maximum working load of this hose is 13.7 kN (3,100 lbs), its calculated breaking strength is 30 kN (6,800 lbs) at 170% elongation of its compliant center section.

G. WHOI Gumby Mooring

The WHOI “Gumby” mooring consists entirely of snubber hose. The mooring was deployed in 40 meters water depth and will be used to telemeter data from an ocean floor seismic sensor to a shore station. A single 30 meter long high stretch snubber hose with embedded electrical conductors provides a power and data link and mooring anchor connection to the sea floor. The sea-state and tides require that the hose must stretch about 140 percent at maximum working load, which is achieved with a counter-helical tire cord wrap angle that picks up tension at about 100 percent hose elongation (see information about the feed hose above for details).

H. High Stretch Snubber Design Details

The hose was designed to stretch 100 percent at about 4.4 kN (1,000 lbs) tension, at which point the nylon tire cords start to share the hose load. At its maximum service load of about 13.3 kN (3,000 lbs) the hose stretches about 140 percent, and its reinforcement would fail above 31 kN (7,000 lbs) and 170 percent hose stretch. Five compliant quads of #22 AWG copper conductors form the conductor link. An optical fiber assembly was also applied as a test, but the high vulcanization temperatures damaged the optics, and incorporation of optics will require the development of a more heat resistant optical fiber package. More information is found in [10].

IV. FIELD DEPLOYMENTS AND RESULTS

A. MOOS Mooring Results

The MOOS mooring system was field tested during a one year deployment (2004-5) off of the California coast 23nm west of Moss Landing in 1400 meters of water. The buoy system was equipped with a 44.5 kN (0-10,000lbs.) load cell at the bridle and anchor attachment points to measure tension in the snubber and riser cable. A Triaxys directional wave sensor, ASIMET wind speed/direction and downward looking acoustic Doppler current profiler measured environmental conditions. Optical loop attenuation was measured at 1550nm in the snubber and riser cable and was looped back in the anchor termination.

During the field trial optical attenuation and mooring loads were monitored at 4 Hz and the data recorded. Ten minute binned statistics of the data were returned to shore via Globalstar satellite every hour. Over the course of the year long test optical attenuation gradually increased 1.2 dB. Each segment of the riser system was tested on recovery to try and determine the location of the optical impairment. No significant increases in attenuation were found in the coilcord or interconnect optical connectors. The two junction boxes that connect snubber segments were found to be flooded and are the probable cause of the slight attenuation increase. The internal electro-optical coilcord was examined for wear effects after the field trial. There were concerns that the coilcord may chafe against the inside of the snubber hose and eventually wear through the jacket. The only evidence of the coilcord contacting the interior of the hose was a slight burnishing of the rubber, see Fig. 5.

At the conclusion of the field test the top most snubber hose section that extended from the mooring bridle to the
first splice tube was pulled to destruction at Tension Member Technology Laboratories. The results were compared with the pull results from an identical new snubber hose. The stress-extension behavior of the two tested snubber sections are similar, see Fig. 4. In the working load region of below 20 kN there is very little change in the stress-extension performance after the one year deployment. The ultimate breaking strength in the deployed snubber is also little changed, it was actually equal to the calculated full breaking strength of the new hose, suggesting that minimal fatigue damage had occurred. Interestingly the deployed snubber that had been exercised in the field trial failed at the lower snubber end, not at the upper end below the buoy where there was the most wave-induced bending. Based on the test results the conclusion is that the snubber sections can be expected to have a lifetime of three years of field service. If accurate records are kept of snubber use and hose sections are rotated in position or swapped end-for-end, it’s reasonable to expect that snubber hose sections can be used for multiple extended mooring deployments.

B. New Hampshire Fish Cage Mooring Results

The feed hose with its mooring system was deployed in late 2002. Several electrical conductors failed in the winter of 2005 when bolts securing the hose flange to the submerged fish cage broke due to cyclic loading fatigue. Impulse connectors spliced with a pigtail cable to the conductors in the hose were pulled apart with a great deal of force. Troubleshooting at sea revealed that the failure points were located where the pigtail wires were spliced into the hose wall conductors, disconnecting the video stream, the wires transporting environmental data were not destroyed. The feed hose was retrieved in the spring of 2005 after two years of use, several severe storms, and failure of one of the two additional mooring members of the buoy in one of the storms. After all wire ends were “excavated” from the hose it was found that all conductors in the hose wall were still intact. New Impulse connectors with their pigtail cables were installed, and the hose section where the wires exit the hose body was potted, see Fig. 5. The hose will be deployed again in August 2005.

C. WHOI Gumby Mooring Results

The Gumby mooring was deployed in February 2005 at the WHOI “Buoy Farm”, an offshore test site, fully exposed from Southeast to Southwest, located 25 nm from Woods Hole. It was subsequently recovered three months later after a very stormy weather period, since the transmission of data from the buoy to shore had stopped. A problem was found in the buoy’s computer, tests showed that the hose and its conductors were in excellent shape. The system will be redeployed later this year for further testing.

V. CONCLUSIONS

Snubber hoses have been proposed as a promising technology for modulating wave and current induced axial strain on mooring anchor lines while simultaneously solving the problem of transitioning electrical and optical cables from buoy anchor cables to mooring bases. Snubbers can be commercially manufactured, are cost effective, and relatively straightforward in design and execution. Now that snubber hoses have been deployed for multi-year field trials the results have proven the prediction: well designed snubber hoses effectively modulate strain, are extremely robust, and are able to withstand the rigors of millions of strain cycles over multiple year at-sea deployments.

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