Condition monitoring techniques for fibre mooring ropes

G. Rebel

Previously : Reading Rope Research, University of Reading, Reading, RG6 6AY, United Kingdom, tel.: +44 (0) 118 931 8564, email: g.rebel@reading.ac.uk

As of July 2000 : 6 Calcot Court, Reading, RG31 7RW, United Kingdom, tel.: 0118-942-3238, email: gerhard@bgisl.com

C.R. Chaplin

Reading Rope Research, University of Reading, Reading, RG6 6AY, United Kingdom, tel.: +44 (0) 118 931 8580, email: c.r.chaplin@reading.ac.uk

C. Groves-Kirkby

Previously : Marconi Materials Technology, Caswell, Towcester, Northants, NN12 8EQ, United Kingdom, tel.: +44 (0) 1327 350581, email: chris.groves-kirkby@gecm.com

As of Feb 2002 : 19 West End, Bugbrooke, Northampton, NN7 3PF, United Kingdom, tel.: 01604-832402, email: chris.gk@dunelm.org.uk

I.M.L. Ridge

Reading Rope Research, University of Reading, Reading, RG6 6AY, United Kingdom, tel.: +44 (0) 118 931 8445, email: i.m.l.ridge@reading.ac.uk

Paper Published as :

REBEL, G., CHAPLIN, C.R., GROVES-KIRKBY, C., RIDGE, I.M.L. (2000), Condition monitoring techniques for fibre mooring ropes, Insight - Journal of the British Institute of Non-Destructive Testing, Vol. 42, No. 6, June 2000.

Summary

Station keeping for floating oil production platforms for deepwater has been widely investigated to date. As the weight of long wire rope catenaries becomes a controlling factor in the efficiency of the mooring, an increasingly favoured solution (extensively implemented by Petrobrás) is to use taut leg mooring systems employing near neutrally buoyant polyester fibre ropes. The novelty of this solution raises concerns regarding the long term integrity of these ropes as none of the traditionally employed methods for the non-destructive testing (NDT) used on wire ropes are relevant to fibre ropes. This paper describes in general terms the possible approaches which have been considered elsewhere for condition monitoring of fibre ropes. The most promising technique is the use of distributed fibre optic sensors, especially those which use multiple intra-core Bragg reflection gratings. One of the main obstacles to the use of fibre optic strain monitoring for fibre ropes is the large mis-match between failure strains (1% compared with 10% to 15%). Consideration is therefore given to the effect which the necessary helical path of the fibre optic within the rope will have on strain attenuation and on the required fibre length. In conclusion a discussion is presented of the issues which are regarded as most important in the development of this technology for fibre ropes to the point where it could be applied to operational mooring systems.

Keywords: Fibre mooring ropes, Bragg gratings, Fibre optic, condition monitoring, NDT

1 Introduction and background

1.1 Fibre ropes for mooring

Efficient station keeping for floating oil production platforms for deepwater (2000 – 4000 m) has been widely investigated to date. A favoured solution (already implemented successfully by the Brazilian State Oil company, Petrobrás) involves the use of taut leg mooring systems using polyester fibre ropes. Figure 1 shows the typical construction of an externally-braided, parallel twisted-strand rope. Polyester provides a structurally efficient and cost effective alternative to steel wire rope, as discussed by Chaplin and Del Vecchio (1) and Komura (2). Fibre ropes offer many advantages, mostly deriving from the nearly neutral buoyancy of the fibre rope and corrosion resistance of the polyester. The novelty of the solution, pointed out by Francois et al. (3), does however, raise concerns regarding the long term integrity of these ropes where there is no previous track record as exists for the wire rope alternative. The magnetic NDT options, which are commonly used for wire ropes, are also not suitable as they are based upon the magnetic properties of the steel wire.

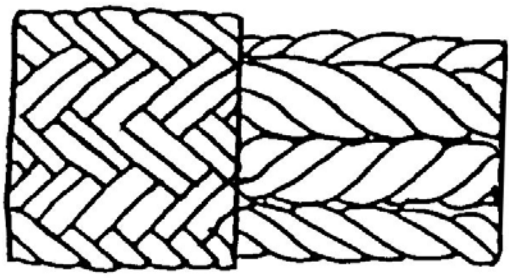


Figure 1: Parallel twisted-strand rope with a braided external jacket and an equal number of left and right hand lay sub ropes to give torque balance under tensile load.

The focus of current research on fibre mooring lines is primarily to determine the modes of degradation under various operating conditions with the view to specifying suitable discard criteria. A current Reading University industry funded program includes bending and bending-tension fatigue tests on representative model polyester mooring line. Destructive tests to quantify the effect of bending diameter ratio are also being conducted. All the tests are being carried out on profiled pulleys and cylindrical rollers also for assessment of the effect which radial support has on the rope's performance.

Other examples of investigations into the in-service performance of fibre ropes include the report of Seo et al. (4) who examined wear and fatigue in synthetic fibre lines in terms of mechanisms including:

- cumulative creep to rupture;
- hysteretic heating due to cyclic loading of filaments or to relative displacement of structural rope elements;
- internal wear caused by relative movement between yarns or strands;
- external abrasion against deck hardware or other rough surfaces within or around the mooring system during installation procedures.

It was noted that studies undertaken to evaluate fibre, yarn and rope responses to each of these mechanisms, singly or in combination, vary significantly with the test conditions including: cyclic load level (both axial and transverse); cyclic strain level; and, environmental conditions, such as temperature and moisture content (whether dry or wet in fresh or salt water). In service, cyclic load limits depend on the interactions between the vessel response and wave heights, wind velocity and mooring line dimensions and properties. These properties can vary largely and therefore complicate assessment of the loading history which the line has been subjected to.

Sember et al. (5) describe the recently issued American Bureau of Shipping (ABS) guide on the Application of Synthetic Ropes for Offshore Mooring. This guide has been developed to assist the industry with standardised criteria covering all aspects of fibre rope use in this application. Emphasis is given to identifying the primary differences between conventional steel components and their synthetic counterparts with regard to the influence of rope properties on the mooring system performance. Items covered by the Guide include mooring design and analysis; rope design; testing and manufacturing; rope handling and installation; and, rope inspection and maintenance.

Banfield and Casey (6) examined the use of laboratory tests on short sections of rope removed from lines in service, "insert strops", for evaluating the retained properties of the rope. It was concluded that this approach is currently the only available method for measuring changes in the properties of operating ropes, although the testing of a single strop only gives one data point for the entire rope length. Therefore, with the continually increasing interest in fibre mooring lines there is consensus within the industry for an urgent need to develop suitable distributed in-situ condition monitoring systems. Such systems will allow operators as well as the classification authorities to monitor the degradation of the lines from the platform deck at periodic intervals thereby ensuring the integrity of the mooring installation.

1.2 Overview of various approaches to condition monitoring

Besides the evaluation of the residual properties of an insert section of rope removed from the line there are a number of techniques that have been proposed by which the non-destructive testing of fibre ropes could be achieved. The main categories are reviewed below.

Vibrational techniques

Vibrational techniques have been used to try to identify parameters which indicate either damage to the rope or the nature of cyclic loading history that the rope has been subject to.

Williams et al. (7) introduced an impulse voltage into an excitation transducer and evaluated the resulting wave speed in the rope from the response measured by a separate monitoring transducer. The tests showed that ultrasonic wave speeds in double-braided nylon ropes were significantly affected by tension, strain and loading history. It was suggested that these effects should be taken into account when conducting non-destructive evaluation using ultrasonics and acoustic emission. Williams, Hainsworth and Lee (8) also examined the number of threshold crossings of a vibrational wave received by a transducer at a distance from a transmitting transducer (which could be linked to the relative efficiency of energy transmission through the rope), however, no simple correlation of this parameter between new, used and damaged ropes was found.

Williams and Lee (9) found that Acoustic Emission (AE) is generated randomly throughout a sample for up to 60 % to 70 % of the break load, after which most of the AE is concentrated in a more localised area which would be the eventual failure location. The tests were conducted on a new double-braided 6.3 mm diameter nylon rope in the dry condition at room temperature. A parameter called the "AE load delay" was defined as the tensile load required to produce a specified low baseline level of AE activity. It was also observed that the AE load delay can be correlated with the ultimate breaking load of a rope with cut core yarns and with a variety of stress-concentrating knots.

The feasibility of the non-destructive evaluation of wire and synthetic ropes using a transverse-impulse vibrational wave was investigated experimentally by Kwun and Burkhardt (10). The experiment was conducted using a 2.38 mm diameter stainless-steel wire rope and a 6.35 mm diameter double-braided nylon rope. Each sample was approximately 14 m long. Broken strands produced readily detectable partial reflection of the wave. The test results indicated that the transverse-impulse vibrational wave method can provide a fast and simple means of detecting flaws and determining both the load level and the average mass per unit length of a rope.

In an effort to evolve a quantitative measure of the state of degradation of synthetic fibre rope Winter and Green (11) excited taught rope by means of a very short burst of excitation (chirp) from a transducer. They then analysed the frequency response spectrum of the sample to identify resonance. Significant and repeatable differences between new and used ropes were found, but the frequency response curves were found to change with time under constant load (resonant frequency became higher).

Magnetic resonance

Bryden and Poehler (12), (13) discussed the use of magnetic resonance for the evaluation of damage in nylon ropes. The magnetic properties of stressed and unstressed nylon rope fibres were studied. Irradiation (ultraviolet and x-ray) and mechanical fracture (stressing to failure, cutting, and machining) were used to generate free radicals associated with broken bonds in the polymer chains. These paramagnetic defects were then examined using electron paramagnetic resonance (EPR) spectroscopy at various temperatures and in different atmospheres. Some long-lasting radicals were identified that correlate with the stress history of the rope. The origin of the radicals, their decay times and the mechanism that caused stabilisation were discussed as was the feasibility of a portable EPR spectrometer for use in the field.

Conductive internal elements

Insertion of conductive elements (such as copper wires with tuned strain sensitivities or conductive thermoplastics (14)) in a rope which would fail when their individual strain limits were reached is another possibility for fibre rope condition monitoring. Time domain reflectrometry techniques, applied from both ends of a line, could be used to determine the position of failure along the rope length. Using multiple conductive elements with a range of strain sensitivities (say from 7 % to 15 %) it is likely that adequate length-wise resolution could be achieved.

Wang and Chung (15) and Irving and Thiagarajan (16) both discuss the use of monitoring fatigue damage in carbon fibre composites by measuring the changes in electrical resistance. This technique might be extended to include a tape of carbon fibre as a condition monitoring sensor.

Obviously the electronic interrogation system needs to be carefully interfaced with the conductive elements to produce accurate and reliable strain history readings. In the case where fibre ropes are operating in conductive sea water careful consideration has to be given to the effect of the water on the break in conductivity for which the interrogation system would be monitoring. This problem could be addressed by coating the conductive elements with material of much higher strain tolerance which would maintain electrical insulation when the element fails.

Fibre optics

Ludden et al. (17) and Robertson and Ludden (18) considered the specific problem of monitoring Kevlar® Parafil® fibre mooring ropes in service. It was proposed that a sensor system for this application should satisfy the following requirements :

- yarn breakage monitoring by detection of acoustic emissions;
- distributed strain measurement along the rope length;
- access limited to one end of the rope for interrogation;
- robust and relatively simple detection opto-electronics;
- rope temperature measurement and compensation (0 to 50 °C);
- strain range of 0 to 2.5 % (which would not be sufficient for polyester lines);
- operational length up to 5 km.

For the acoustic detection of yarn breakage, inter-modal coupling in an optical fibre with event location by Optical Time Domain Reflectrometry (OTDR) using an array of mode selective partial reflectors was suggested as the most suitable solution. The strain and temperature was to be measured by monitoring the changes in reflection wavelength from an array of fibre Bragg grating pairs spaced along the optical fibre. The location of strains and temperatures would be quantified using wavelength tuneable OTDR methods. Figure 2 shows the method of inclusion of the optical fibre within the Parafil rope. The physical sensing principles were demonstrated to be effective by Robertson and Ludden (18).

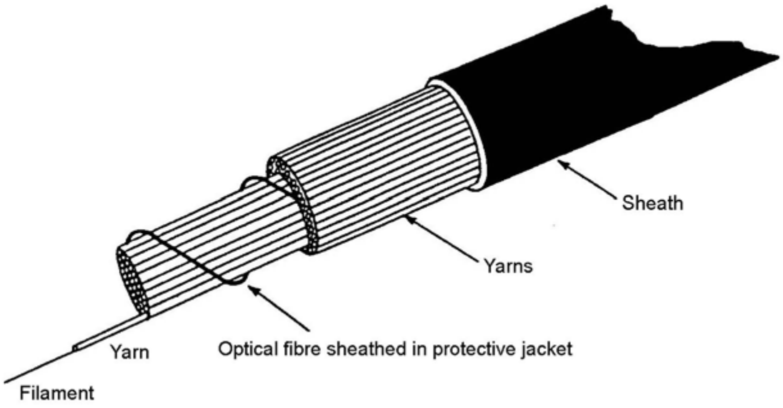


Figure 2: Structure of a parallel lay fibre rope with an embedded optical fibre sensor, from Robertson and Ludden (18).

Distributed fibre optic sensor arrays have also been used for monitoring the condition of two Carbon Fibre Reinforced Polymer (CFRP) strands of a cable stayed bridge in Winterthur, Switzerland, as discussed by Brönnimann et al. (19). Owing to the novel design of the 35 m long strands (with 241, 5 mm diameter, CFRP elements) it was necessary to monitor their performance during the bridge construction, under traffic loading conditions and through seasonal changes. Meaningful monitoring results were obtained from this integrated system which had been operational for six months at the time of completion of their paper.

There are also two projects on the development of an Optical SCanning Apparatus for Ropes (OSCAR) which form part of a Fourth Framework Research and Technological Development programme in the field of industrial and materials technologies entitled "Basic Research in Industrial Technologies for Europe / European Research on Advanced Materials". The first six month project has been completed and the second two year programme is scheduled to end in February 2001 (20).

The aims of the OSCAR projects are to develop rope systems which can be remotely interrogated to determine local changes in tensile properties over long lengths, such as deepwater moorings for Floating Production Systems. The first OSCAR project showed that a distributed fibre optic strain measuring technique can detect the location and approximate magnitude of modulus changes in a small fibre rope.

The main additional innovation required as part of the second project is to develop an Optical Fibre Strain Transducer (OFST) particularly suited to full scale ropes. The fibre optics then need to be integrated into the ropes so that they are insulated from pressure, avoid breakage or damage and pick up only a controlled proportion of the rope strain. The proposers state that if successful in longer and larger ropes, the technology would become the first proven method of monitoring the local tensile properties of long (km) fibre ropes.

The total installed costs of the OSCAR system were estimated to be considerably less than 10 % of the mooring system cost. The system would have an obvious and major impact upon the safe operation of floating production platforms by reducing the risk of mooring failure and consequent safety and pollution hazards. Though the projects are principally concentrated on man made fibre rope, the new technology could have benefit in the wire rope industry too, for example in bridge support ropes as shown earlier in the work of Brönnimann et al. (19).

Comment on various monitoring techniques

Of the methods of non-destructively monitoring fibre ropes (discussed above) the use of fibre optic systems appear to be the most feasible and there are already specific examples of ongoing development of this technology for fibre ropes and steel strands. The proposed fibre optic techniques rely primarily on the application of distributed strain sensor systems which are already being used successfully in other “smart” materials and structures. In the case of ropes, and particularly fibre ropes, relatively high operating strains prevent simple insertion of the monitoring fibres into the structure and so strain attenuation schemes need careful consideration. At this stage it is useful to give a description of the operating principals of the fibre optic sensors.

2 Fibre optic strain sensor technology

2.1 Sensor categories

Under the title of fibre optic sensors there are various sensing principles that can be used, coupled with different interrogation techniques. The categories most commonly referred to in recent literature include:

- Mach-Zehnder interferometers;
- Sagnac / Michelson interferometers;
- Fabry-Perot interferometers;
- intensity based sensors;
- speckle pattern sensors;
- Brillouin scattering;
- intra-core Bragg reflection grating sensors.

A wide range of physical parameters can be measured using fibre optic technology such as strain, temperature, acceleration, state of corrosion, pH, acoustic emission and chemical composition of liquids and gasses. Rogers (21) gives a broad discussion on the science of distributed fibre optic sensors as well as highlighting their capabilities and future research and development trends.

The engineering application of fibre sensor technology has been widely reported with entire journal issues being devoted to the topic (22). In a similar but more recent publication, Measures (23) points out that although a number of different types of fibre optic sensor are discussed, of the 13 papers constituting the issue, nine involve fibre Bragg gratings. This ratio is consistent with the growing interest in this type of sensor due to its versatility, spectral encoding, ease of multiplexing, small profile, potential for automated production with the attendant low-cost, and consistent performance. Measures also comments on the significance of the number of papers that describe the use of fibre optic structural sensors in real structures, like bridges, and suggests that the development of this sensing technology in ongoing and at the beginning of its broad implementation phase.

Describing the operating principles of all of the above mentioned fibre sensors is beyond the scope of this paper. However, since the Bragg grating sensors are proving to be the most attractive for distributed strain and temperature sensing in Engineering structures they warrant a more detailed discussion.

2.2 Intra-core Bragg reflection grating sensors

Groves-Kirkby (24) describes the present status of Bragg grating fabrication technology in communications-grade optical fibre, including recent studies in both the fabrication and interrogation of extended arrays (multiple sensors in one fibre). Reports are also given on recent experiments in the application of these intrinsically simple and robust components to health monitoring in representative engineering structures such as portable aluminium military bridge section and 24-ply composite skins bonded to aluminium honeycomb.

The efficient application of the technology to strain monitoring in extended mechanical structures, however, necessitates the development of techniques for implementation of multi-element arrays, possibly incorporating many tens of discrete sensing sites. In addition to imposing additional constraints on grating fabrication technology, this requires the development of suitable instrumentation schemes for data acquisition and processing.

The intra-core fibre Bragg grating, shown schematically in Figure 3, comprises a segment of germanosilicate optical fibre (other doped glasses are also used) in which a periodic variation of the core index has been permanently formed, usually by exposure to an interference pattern of intense ultraviolet light (245 nm). This periodic variation of index creates a wavelength selective reflector, or rejection filter. The optical back-reflected spectrum of such a Bragg grating, which is also shown in Figure 3, comprises a very narrow spike occurring at a wavelength known as the

Bragg wavelength. This is related to the effective core index of refraction and the spatial period of the index modulation.

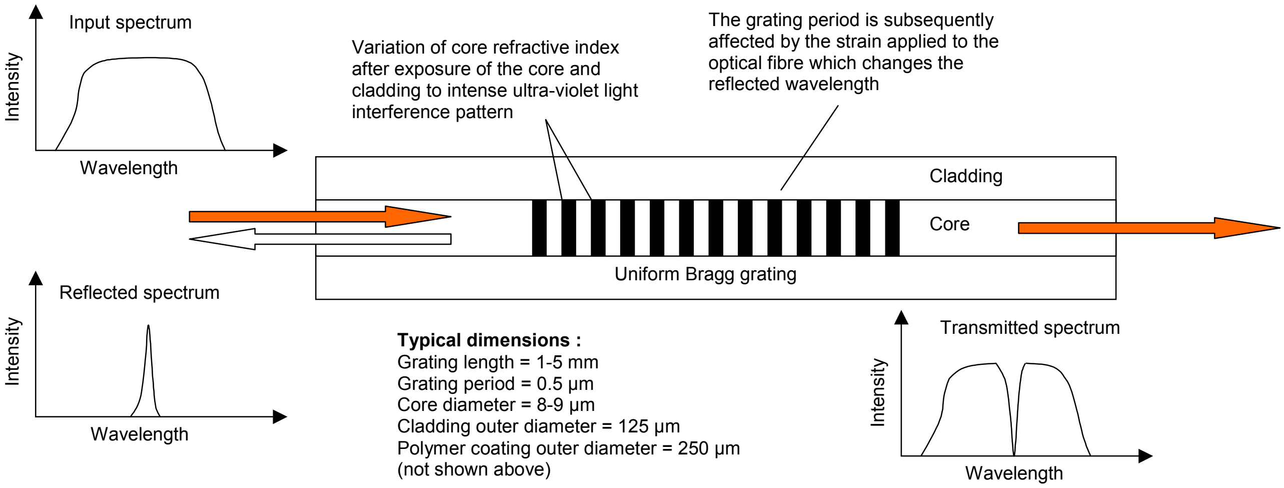


Figure 3: Structure and response of an intra-core fibre Bragg grating. Adapted from Du et al. (25)

Although significant advances in grating fabrication technology have been achieved, all techniques for fabrication of gratings in pre-manufactured fibre suffer from the drawback that a section of fibre must be stripped of its UV absorbing polymer coating in order for the grating to be written. The resultant surface contamination weakens the fibre at the site of the grating, even if the fibre is subsequently re-coated. In addition, it is difficult to mass-produce fibre gratings in the same piece of fibre on a commercially viable scale by this method. However, recent developments have shown that it is possible to overcome both of these problems by writing the gratings in the fibre during the drawing process, immediately prior to coating (26), (27). The availability of a technology for integrating multiple wavelength-selective elements within a single fibre has led to renewed interest in optical sensing applications based on the strain and thermal modification of the grating period, and hence its spectral response. Figure 4 shows the typical configuration and response of two systems incorporating multi-element Bragg fibre optic sensors.

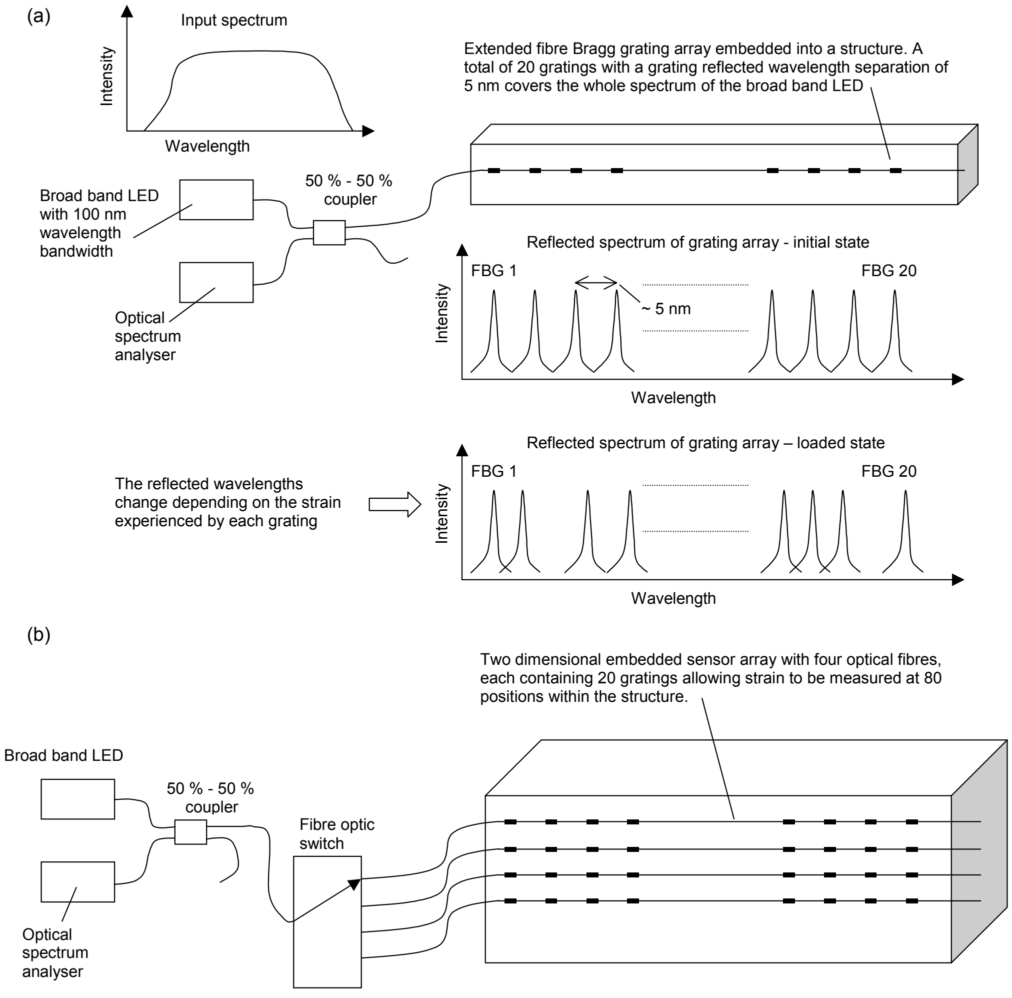


Figure 4: Basic configuration of distributed fibre optic sensing systems using Bragg reflection sensors. Adapted from Du et al. (25).

Sensor action of the Bragg grating is based on the physical behaviour of the core refractive index and the grating period, both of which alter under the influence of mechanical strain and/or temperature changes. Monitoring the wavelength of the narrow-band reflection thus permits determination of the strain or temperature environment to which the fibre is locally subjected. The Bragg grating strain sensor possesses several advantages that make it very attractive for structural condition monitoring applications:

- The centre reflected wavelength is a linear function of the measurand.

- The reflected Bragg wavelength determines the measurand in terms of some known reference state.

- Measurements are not dependent on the intensity of the reflected spectrum.

- The gratings are optically etched into the fibre core and do not affect the mechanical strength of the fibre, except where post-drawing grating preparation requires the physical/chemical removal of the primary jacket.

- The narrow band reflection characteristic allows for the inclusion of multiple gratings within a single fibre which can each be monitored independently from one end.

- The strain and temperature response of the gratings are not affected by electromagnetic interference.

3 Strain ratios and monitoring fibre length

In the design of a fibre optic monitoring system for rope, there are two important parameters which need initial consideration which are more specific to the rope problem than the grating sensor design characteristics discussed thus far:

(i) Strain attenuation is required for the optical fibre so that it operates within acceptable strain limits compared to the relatively large strains which the rope would experience. The optical fibres are unlikely to tolerate strains in excess of 1 %, whereas a fibre mooring rope may have a total failure strain of around 15 %, comprising about 8 % elongation at time of installation, and a further 7 % up to failure (28).

(ii) The monitoring system needs to be suitable for rope lengths up to 3 km. If the strain attenuation techniques, such as helical wrapping proposed by Robertson and Ludden (18), require large fibre to rope length ratios (say greater than 5) then the monitoring system's performance could be affected by optical signal attenuation. A typical value for signal attenuation in fibre optic cable is 0.3 dB/km (29), so assuming a fibre optic to rope ratio of 5:1 in a 3 km rope, this would give a loss of 4.5 dB. This level of signal attenuation is acceptable.

(iii) A third consideration of the incorporation of the fibre optic in the rope, is the curvature of the helix which the fibre optic is wound in. This issue can be better addressed once the strain and length ratios for the fibre optic/rope have been discussed.

Since ropes are mostly produced with rotating machinery the inclusion of monitoring fibres within the rope which are helically wrapped around some of the internal structural or filler components should not be problematic. Assuming this technique as the attenuation method, the strain and length ratios between the fibre and the rope can be determined from simple geometrical relationships.

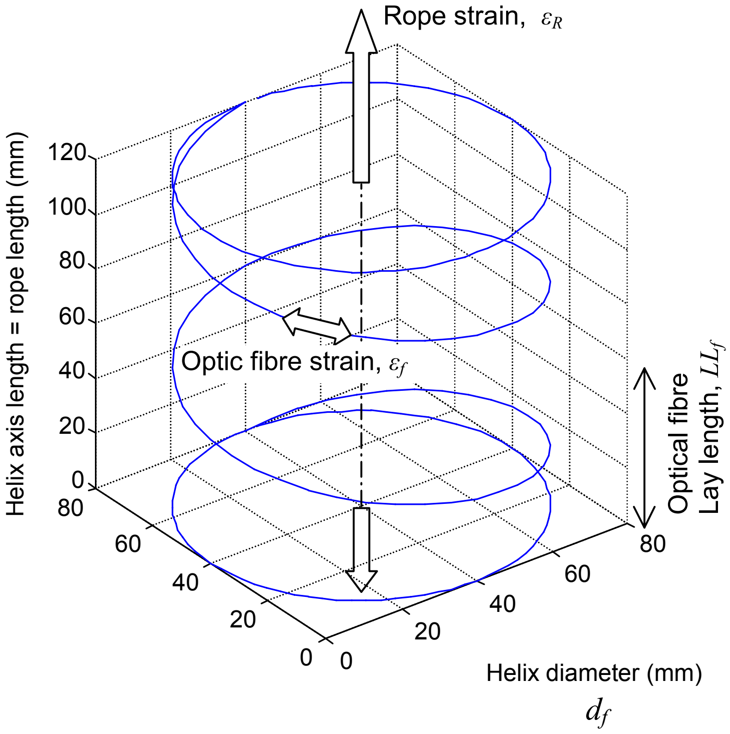


Figure 5: Helical path of an optical monitoring fibre within a rope.

Considering the helical path shown in Figure 5 the length ratio between the rope and the optical monitoring fibre can be determined by the product of the number of fibre lay lengths per metre of rope length and the helical length of the fibre:

$$l_f / l_R = 1 / LL_f \cdot \sqrt{((\pi \cdot d_f)^2 + LL_f^2)} \qquad [1]$$

Originally Hruska (30) and more recently Raoof (31) used the following approximate formula for calculating the strain ratio of a helical element within a rope to the overall strain of the rope assuming negligible changes in helix diameter under load:

$$\varepsilon_f / \varepsilon_R = \cos^2 (\arctan \alpha) \qquad [2]$$

where:

l_f = length of optical fibre

l_R = length of rope

LL_f = lay length of optical fibre

d_f = helix diameter of optical fibre

ε_f = axial strain in optical fibre

ε_R = axial strain in rope

α = helix pitch angle ($\pi \cdot d_f / LL_f$)

Raoof [31] demonstrated through laboratory based experiments and more detailed numerical analysis that Equation [2] produces realistic results for helical wire strains in full scale spiral strands.

With both equations [1] and [2] being functions of the fibre helix diameter and lay length it is possible to produce a set of curves showing the dependence of the strain ratio and length ratio on the helix geometry. Figures 6 and 7 show these two ratios for diameters from 50 mm to 100 mm and lay lengths from 30 to 90 mm.

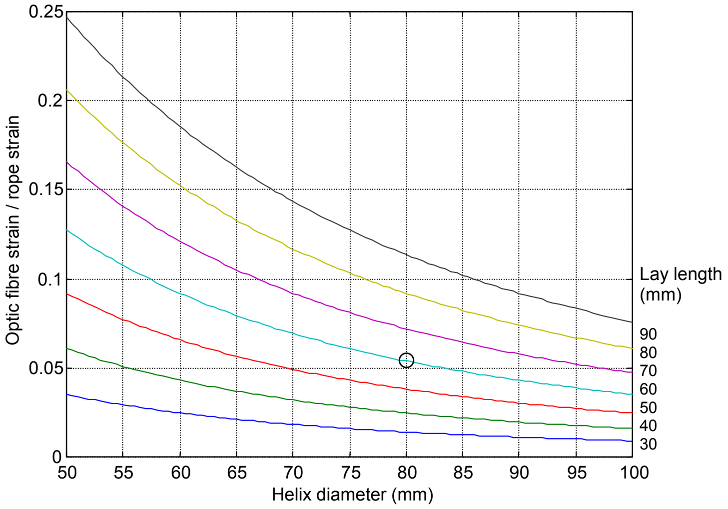


Figure 6: Example of achievable strain ratios for varying optical fibre helix diameter and lay length.

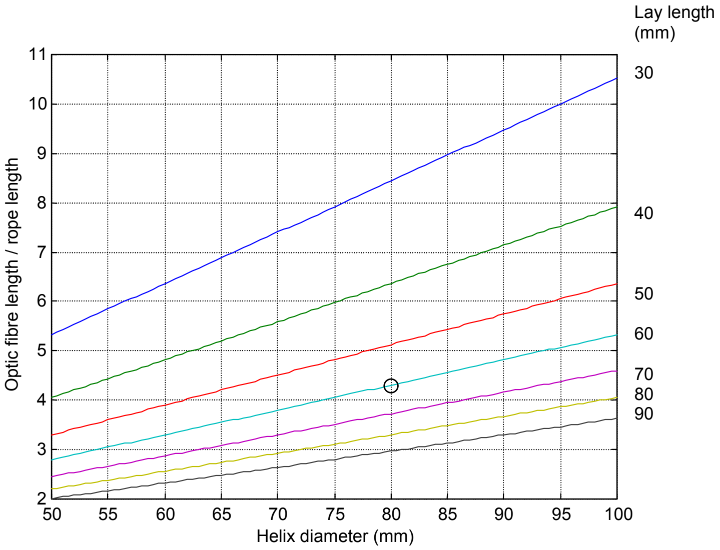


Figure 7: Example of effect of optical fibre lay length and helix diameter on the length ratio between the fibre and the rope.

From the data in Figures 6 and 7, if for example, the optical fibre helix diameter is 80 mm and its lay length 60 mm (as highlighted in the figures) then the strain in the fibre will be 5.39 % of the rope strain. This configuration will require that the fibre is 4.31 times the rope length. As mentioned before, consideration needs to be given to the maximum curvature which the optical fibre (with Bragg gratings) can tolerate when selecting the helix geometry. The radius of curvature of a helix, ρ, is given by, (for example), Hruska (32):

$$\rho = (d_f/2) / \sin^2\alpha \qquad [3]$$

For the example above, with a helix diameter of 80 mm and lay length of 60 mm, the radius of curvature will be 42.3 mm. Corning (29) specifies an induced attenuation of ≤0.05 dB/100 turns for a radius of curvature of 37.5 mm. Assuming this level of attenuation is also applicable to the 42.3 mm curvature, for a 3000 m rope, the total attenuation is 25 dB. This level of attenuation would be unacceptable and so the radius of curvature requires very careful consideration. It is reasonable to assume that there is a critical level of curvature at which the signal attenuation will decrease dramatically so that it approaches the 0.3 dB/km loss in a straight fibre. A further possible source of attenuation, the physical distortion of the Bragg grating itself, is expected to have a negligible effect on its response.

4 Development requirements

Assuming that a distributed fibre optic sensor system using Bragg gratings is the most appropriate technology for monitoring of fibre ropes in-service, there are several major development issues which need to be addressed to bring the technology to the point where it could be implemented in an operational mooring system.

A clear definition of the rope failure criteria with which the measured strain differences would be compared, needs to be established. It is expected that any monitoring system will be most suited to identifying sections of the rope which show larger strains than the mean. These areas would most likely be linked with more rapid deterioration and may also be subjected to visual examinations using remote observation vehicles (ROV's). The magnitude of strain difference between adjacent sections of rope which indicates immanent failure is currently not known.

The Bragg grating system is only capable of measuring strain at discrete points along the fibre optic (i.e. points where the gratings are positioned). Rogers (21) stated that the current limit for interrogation systems is around 30 gratings in a single fibre. Over 3000 m of rope length this would not provide sufficient resolution so multiple fibres would be required to form a two dimensional sensor array, as shown earlier in Figure 4b. Using 20 fibres, each with 30 gratings this would bring the strain measurement resolution down to 5 m over a 3000 m length. Careful assessment needs to be made of the way in which ropes fail to determine whether this resolution would be fine enough. If deterioration occurs in a very localised area (say 0.25 m) it may be that two sensors spaced 5 m apart would not detect any strain disturbance. There are various arrangements which can be used to position sensors equally along the rope length using multiple fibres. Figure 8 shows two such possibilities. In designing the monitoring system, the merits of the distribution approach need to be judged in terms of cost, reliability and accuracy of relating a specific sensing site to the physical position along the length of the rope.

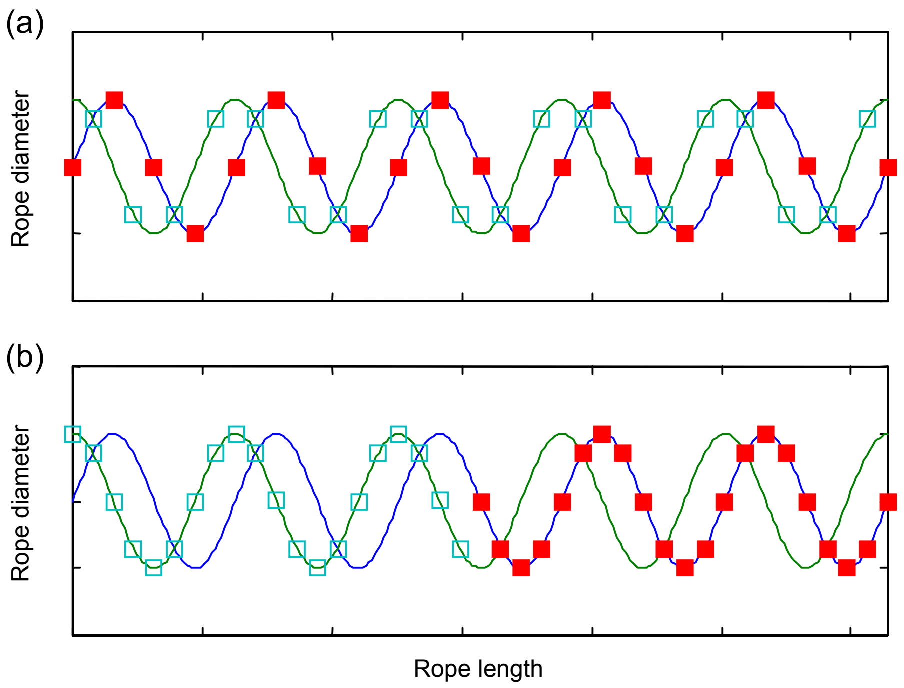
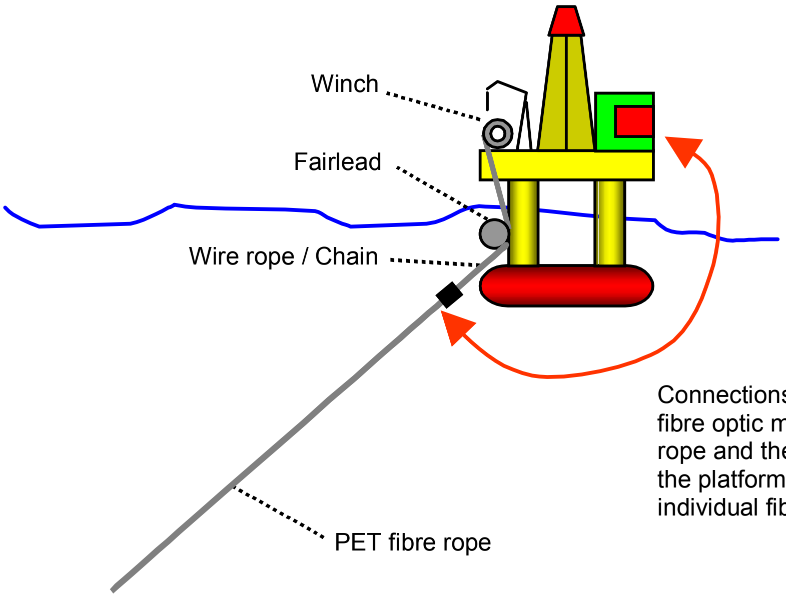


Figure 8: Side view of fibre rope showing possible configurations for distribution of Bragg grating sensors. (a) Sensors distributed evenly along each fibre but staggered between fibres. (b) Each fibre containing sensors covering only a specific portion of the rope.

Differences in local temperatures along a mooring line need to be compensated for (electronically) so as not to affect the strain readings. Rogers (21) explained that the Bragg system allows for simultaneous strain and temperature measurement by means of two gratings overlaid at the same position, but with different grating periods, and by decoupling one from the strain. The measured temperature can then be used to make adjustments to the strain values but this requires an increase in complexity of the interrogation system.

Demonstrated ruggedness and reliability in the offshore environment is one of the most important issues which needs to be dealt with. This may also require parallel systems to improve reliability and tolerance to damage. Figure 9 illustrates the complication of connection of the fibre optics from the end of the polyester line to the deck where the instrumentation systems will most likely be mounted. In a practical design there are different options as to how much of the system is deck mounted and how much is place at the top of the fibre rope. These decisions impose requirements on the nature of the connection to the surface (optical/electronic – bandwidth/power).



Connections are required between the fibre optic monitoring system in the rope and the deck for 8 to 12 lines on the platform – so potentially up to 240 individual fibre connections.

Figure 9: Operational complications in the implementation of fibre optic condition monitoring systems.

To ensure system ruggedness much detailed design of connections between the internal rope sensor arrays and the deck mounted electronics will be required (33).

This is also linked to the termination issues – in the case of resin socket it is possible for the fibre optics to be lead through the termination, but a splice would require a different approach. There are decisions relating to when, where and by whom the connections are made, and how this would affect the other aspects of mooring design and deployment methodology. Demonstrated environmental tolerance of the fibre optic sensors to sea water, hydrostatic pressure, sand ingress to the rope, fatigue, and abrasion is also necessary in the development stages. It will be equally important to show that the system is tolerant to handling during deployment, and that contact between the optical fibre and the polyester fibre does not cause one to damage the other.

Consensus needs to be reached regarding monitoring practice (whether continuous or occasional) with consideration given to implications for cost and interaction with other systems on the platform. If an occasional inspection scheme is adopted it would be feasible to use the same interrogation electronics for all eight or twelve lines on a single platform with obvious cost savings.

Rope manufacturing procedures must be developed to avoid damage to sensor arrays during helical insertion into the rope construction. Techniques for mechanical coupling between the monitoring fibres and rope also need consideration as compression induced friction may not be sufficient.

5 Conclusions

In order to allow the extensive use of polyester fibre ropes, which is desirable for deepwater mooring applications, a method of condition monitoring is required. Of the various options discussed, optical fibres with intra-core Bragg gratings seem most appropriate. The development of new techniques which allow the Bragg gratings to be formed non-invasively in the core of commercially available germanium-doped optical fibre, mean that Bragg gratings are a practical proposition.

Bragg grating wavelengths are sensitive to both temperature and strain but, by exploiting various physical processes, they may be made responsive to a variety of measurands. A significant advantage of the Bragg grating sensor is that it responds with a linear wavelength change rather than an intensity change, removing important ambiguities associated with amplitude-responding sensors, while the intrinsic wavelength-selectivity of Bragg gratings lends itself naturally to Wavelength-Division Multiplexing techniques. Practical, field-deployable WDM grating interrogation systems are becoming available commercially, reflecting the perceived importance of this technology, however, there is still a need for work to address the sensor/equipment interface, especially for the mooring application discussed.

Other concerns which need to be addressed are: the required resolution for the system; the ruggedness of the optical fibre within the fibre rope (this is especially a concern at time of installation); and, the fatigue behaviour of the combined optical/PET fibre rope.

6 References

1. Chaplin, C.R. and Del Vecchio, C.J.M. (1992), *Appraisal of Lightweight Moorings for Deep Water*, Proc. 24th Annual Offshore Technology Conference, Houston Texas 4th-7th May 1992, Paper No. OTC 6965, pp 189-198.

2. Komura, A.T. (1998), *Experiences in some installations of mooring lines with polyester, ongoing and short future developments in the Campos Basin Brazil*, Proc. Mooring and Anchoring, IBC Aberdeen, June 1998.

3. Francois, M., Pereira, M.A., Raposo, C. (1997), *Classification of fibre rope moorings for floating production units*, Offshore Engineering, 1997, Ch. 35, pp155-165.

4. Seo, M. Wu, H.C., Chen, J., Toomey, C.S. and Backer, S. (1997), *Wear and fatigue of nylon and polyester mooring lines*, Textile Research Journal, 1997, Vol.67, No.7, pp 467-480.

5. Sember, W.J., Lee, M-Y., Flory, J. and Yam, R. (1999), *Development of a guide for synthetic ropes in offshore mooring applications*, IBC 4th Annual Conference - Continuous Advances in Moorings and Anchorings, 26 - 27 May 1999, Aberdeen.

6. Banfield, S. and Casey, N. (1998), *Evaluation of fibre rope properties for offshore mooring*, Ocean Engineering, 1998, Vol. 25, No.10, pp 861-879.

7. Williams, J.H., Connolly, M.J., Malek, K.M. and Lee, S.S. (1984), *Ultrasonic wave velocity in double braided nylon rope*, Fibre Science and Technology, 21(1984), pp 41-57.

8. Williams, J.H., Hainsworth, J. and Lee, S.S. (1984), *Acoustic-ultrasonic non-destructive evaluation of double-braided nylon ropes using the stress wave factor*, Fibre Science and Technology, 21(1984), pp 169-180.

9. Williams, J.H. and Lee, S.S. (1982), *Acoustic emission / rupture load characterisations of double braided nylon rope*, Marine Technology, 19(1982)3, pp 268-271.

10. Kwun, H. and Burkhardt, G.L. (1988), *Feasibility of non-destructive evaluation of synthetic or wire ropes using a transverse-impulse vibrational wave*, NDT International, 21(1988)5, pp 341-434.

11. Winter, J.M. and Green, R.E. (1985), *Non-destructive evaluation of synthetic nylon rope using mechanical spectroscopy*, Through the eyes of an eagle : 11th World Conference of Non-Destructive Testing, Las Vegas USA, 1985, pp 799-805.

12. Bryden, W.A. and Poehler, T.O. (1985), *Non-destructive testing of nylon ropes using magnetic resonance techniques*, Through the Eyes of an Eagle: 11th World Conference on Non-Destructive Testing, Columbus Ohio, USA, 1985 Vol. 3, pp 1746-1750.

13. Bryden, W.A. and Poehler, T.O. (1986), *NDT of nylon ropes using magnetic resonance techniques*, Review of Progress in Quantitative Non-destructive Evaluation, 1986, pp 1393-1396.

14. Javidinejad, A. and Joshi, S.P. (1999), *Design and structural testing of smart composite structures with embedded conductive thermoplastic film*, Smart Materials 8(1999) 585-590.

15. Wang, X. and Chung, D.D.L. (1997), *Real-time monitoring of fatigue damage and dynamic strain in carbon fibre polymer–matrix composite by electrical resistance measurement*, Smart Materials 6 (1997) 504-508.

16. Irving, P.E. and Thiagarajan, C. (1998), *Fatigue damage characterization in carbon fibre composite materials using and electrical potential technique*, Smart Materials 7(1998) 456-466.

17. Ludden, B.P., Carroll, J.E. and Burgoyne, C.J. (1995), *Distributed optical fibre sensor for offshore applications*, IEE Electronics division colloquium on Optical Techniques for Structural Monitoring, 1995 8/1-8/5.

18. Robertson, P.A. and Ludden, B.P. (1997), *A fibre optic distributed sensor system for condition monitoring of synthetic ropes,* IEE Colloquium (Digest) No. 033 1997. pp 12/1-12/6.

19. Brönnimann, R., Nellen, P.M. and Sennhauser, U. (1998), *Application and reliability of a fibre optical surveillance system for a stay cable bridge*, Smart Materials and Structures, Vol. 7, No. 2, April 1998, pp 229-236. Brönnimann, R., Nellen, P.M. and Sennhauser, U. (1998), *Application and reliability of a fibre*

optical surveillance system for a stay cable bridge, Smart Materials and Structures, Vol. 7, No. 2, April 1998, pp 229-236.

20. European Communities (1999), *Fourth Framework Programme BRITE / EURAM 3*, Optical scanning apparatus for ropes, Project References BRST970533 and BRST985527, Information extracted from European Community Research and Development Information Service, http://www.cordis.lu.

21. Rogers, A. (1999), *Review Article : Distributed optical-fibre sensing*, Measurement Science and Technology, Volume 10, Number 8, August 1999, pp R75-R99.

22. Uttamchandani, D. (1997), *Special Issue Editorial : Optical fibre sensors and their applications*, IEE Proceedings – Optoelectronics, Vol. 44, No. 3, June 1997.

23. Measures, R.M. (1998), *Special Issue Preface: Fibre Optic Structural Sensing*, Smart Materials and Structures, Vol. 7, No. 2, April 1998.

24. Groves-Kirkby, C.J. (1998), *Optical-fibre strain sensing for structural health and load monitoring*, GEC Journal of Technology, Vol.15, No.1 1998, pp 16-26.

25. Du, W., Tao, X.M., Tam, H.Y. and Choy, C.L. (1998), *Fundamentals and applications of optical fibre Bragg grating sensors to textile structural composites*, Composite Structures 42 (1998), pp 217-229.

26. Dong, L., Archembault, J.L., Reekie, L., Russell, P.St.J. and Payne, D.N. (1993) Single pulse Bragg gratings written during fibre drawing, Electron. Letts., 29(1993) 1577-1578.

27. Askins, C.G., Tsai, T.E., Williams, G.M., Putnam, M.A., Bashkansky, M. and Friebele, E.J. (1992), *Fibre Bragg gratings written by a single excimer pulse*, Opt. Letts. 17(1992) 833-835.

28. Del Vecchio, C.J.M. (1992), *Light weight materials for deep water moorings* Thesis submitted for the degree of Doctor of Philosophy Department of Engineering University of Reading, June 1992.

29. Corning (1999), *Corning SMF-28 CPC6 Single-Mode Optical Fiber* Corning Optical Fiber Product information PI1036 1999.

30. Hruska, F.H. (1951), *Calculation of stresses in wire ropes*, Wire and Wire Products, Vol. 26, pp 766-767 and 799-801.

31. Raoof, M. (1990), *Comparison between the performance of newly manufactured and well used spiral strands*, Proceedings of the Institute of Civil Engineers, Part 2, Vol. 89, March 1990, pp 103-120.

32. Hruska, F.H. (1952), *Radial Forces in Wire Ropes*, Wire and Wire Products Vol. 27, May 1952, 459-463.

33. Christiansen, M. (1998), *Fibre optic connections in the sea*, Proc. Ocean Community Conference ’98, The Marine Technology Society Annual Conference, Baltimore, USA, vol. 2, 16-19 ISBN 0-933957-21-1 919-923.

List of Figures