Optical Scanning Apparatus for Ropes
Non-Destructive Test Monitoring System

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Introduction

Non-destructive testing for synthetic fibre ropes is an important step to ensure their safe use as mooring lines for offshore floating platforms. At the present time, polyester parallel strand ropes have been adopted with special inserts. The inserts are short lengths of the same rope placed at the top of the mooring leg. Periodically these inserts are removed, examined and break strength tested. Clearly the mooring line has to be de-tensioned, disconnected, then reconnected and finally re-tensioned. Bearing in mind that these are large ropes with strengths of around 2000 tons, this is an expensive, time consuming and difficult operation.

OSCAR is a new, non destructive system that has been developed using an optical fibre transducer and a measurement technique known as Brillouin scattering. This is a distributed method and allows changes in the length to be detected along entire length of the optical fibre.

There is also a requirement to assess cut damage for which no proven method has yet been established how to measure in-situ damage. The splice integrity is also an issue because of the high number of terminations (circa 50) in these deepwater moorings systems.

API Recommended Practice RP 2 SM "Guide For Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Moorings" makes the following recommendation in Section 9.2.2 Internal Non-Destructive Inspection Techniques "*Presently, no reliable Non-Destructive Testing methods are available for fiber ropes ….When NDT techniques become available, full justification by trials, etc., should be performed to assess their accuracy and suitability for their intended usage*."

This paper describes the system and presents the results of the system testing.

System Overview

OSCAR is an acronym derived from **O**ptical **Sc**anning **A**pparatus for **R**opes. It consists of the Brillouin Optical Time Domain Refletometer (BOTDR) and the optical fibre transducer. The optical transducer is built into the rope in such a way that it elongates with the rope elongation. The transducer's fibres are connected to the BOTDR which detects the resultant elongation in the optical fibres. As the rope wears or is damaged there is both general and local loss of strain bearing synthetic fibre with a corresponding increase in elongation. When the elongation becomes excessive the rope is retired.

The increase in elongation as a rope reaches the end of its useful life is a general truth. Elongation measurements during tension-tension fatigue testing, cycling over sheaves and creep rupture all exhibit the same behaviour.

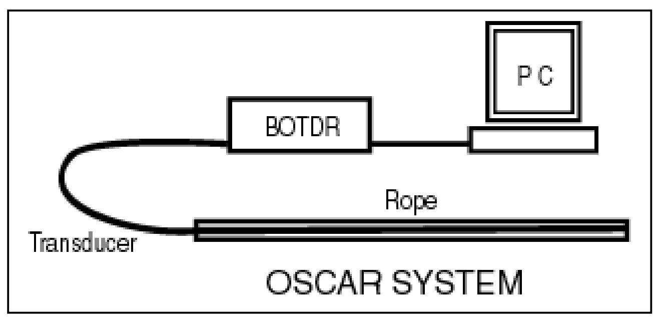

Fig 1 System Overview

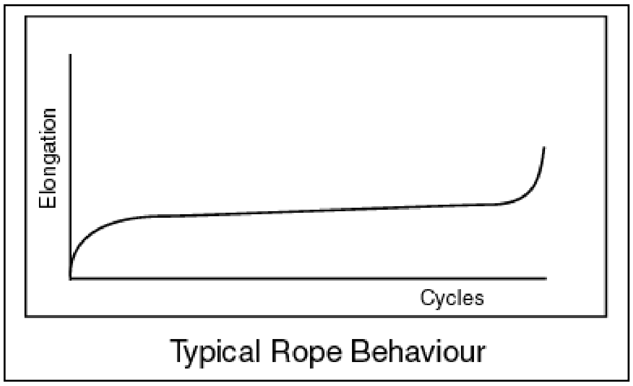

Fig 2 Rope Elongation over Life

Brillouin Scattering

Ando, the manufacturer of the BOTDR describe the system as follows: *"Brillouin scattered light occurs by an interaction between a high- coherence incident light and an acoustic wave generated by the incident light in an optical fiber. The scattered light frequency is shifted from incident light frequency by an amount determined by the material. This frequency is called Brillouin frequency shift and it is given by the following equation*

$V_B = 2\, nVA \sqrt{(\lambda)}$

n : Refractive index
VA : Acoustic wave velocity
λ : Wavelength of incident light

The equation above shows that the Brillouin frequency shift is directly proportional to the refractive index of the optical fibre. This, in turn, is proportional to strain.

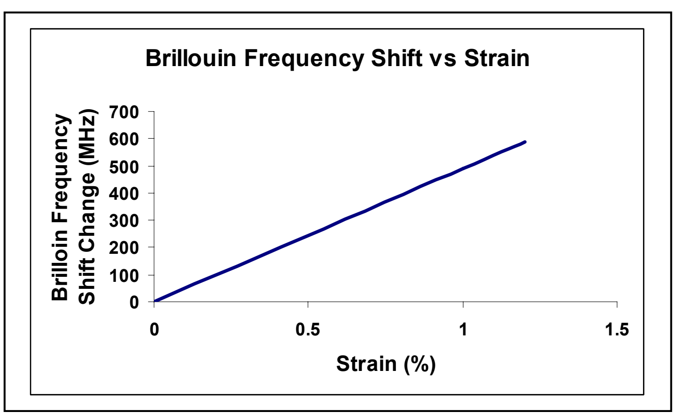

Fig 3 Brillouin Response to Strain (1.55 µm Band)

Brillouin scattering is also sensitive to temperature but this is a small effect compared to strain.

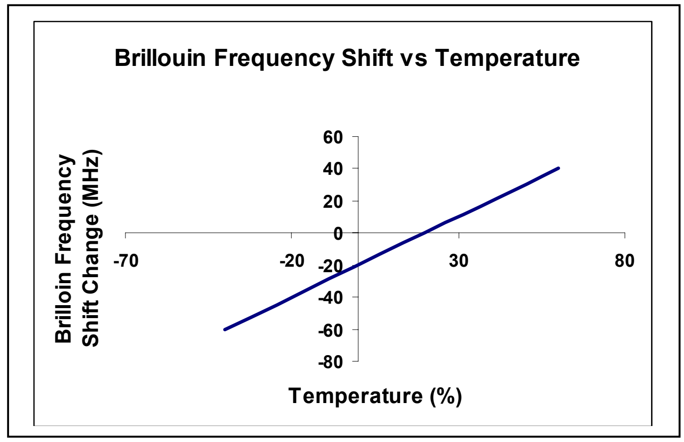

Fig 4 Brillouin Response to Temperature (1.55 µm Band)

The Transducer

Brillouin Scattering is clearly an excellent method to determine the elongation in an optical fibre. The problem concerning ropes is that the working elongation of a glass optical fibre is little more than 1% compared to the working elongation of polyester ropes of typically 5%.

Plastic optical fibres exist which can elongate several percent but the loss in these fibres is so great that measurements can only be made over relatively short lengths. There is a relatively new plastic optical fibre based on perfluorocarbon. This is reported to have low loss and appears to be a good candidate for this application. However it remains experimental and is only available in short laboratory produced lengths.

At the present time the OSCAR system is based on single mode glass optical fibre, since this is the only currently viable solution technically and commercially. The fibre is built into a transducer so that a large elongation of the transducer produces a much smaller elongation in the optical fibre. This is known as the gearing.

The transducer makes use of a combination of loose tube technology and a relatively high helix angle. The loose tube and helix angle combine to provide a threshold elongation of the transducer up to which there is no elongation of the optical fibre. The helix angle also determines the gearing or ratio of transducer elongation to optical fibre elongation.

Loose tubed optical fibres are cabled over the core of the transducer. Initial elongation of the transducer causes the fibres to shift in their gel filled tubes towards the centre of the transducer, thereby adopting a shorter path. No optical fibre elongation has taken place. When the fibre reaches the inner wall of the tube further transducer elongation imparts elongation to the optical fibre.

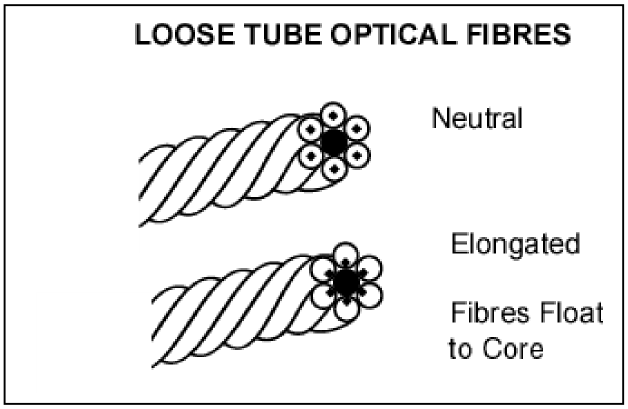

Fig 5 Loose Tube Optical Fibres

This principle is built into a transducer of the following design.

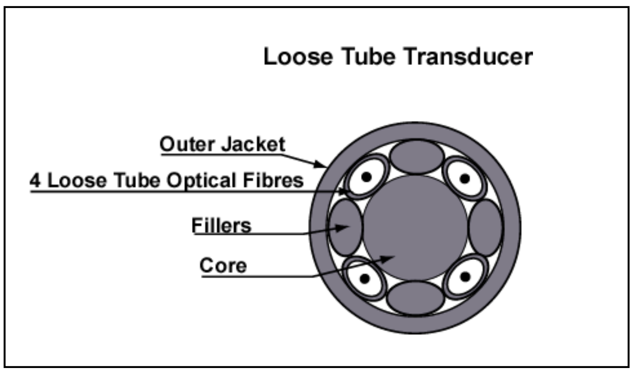

Fig 6 Transducer

The precise helix angle and the dimensions of the loose tubes determine the response of the transducer. Typically the tube inside diameter is 1mm and the helix angle around 35°. Larger tubes have a higher threshold of elongation. Higher helix angles increase the gearing between the transducer elongation and the optical fibre elongation. Fig. 7 shows the response for a number of different tubes all at a helix angle of 34°

Whilst higher helix angles give correspondingly greater gearing, the transducer becomes increasingly less accurate with small manufacturing variations. The maximum acceptable fibre elongation is about 2%, therefore this helix angle can interrogate over a range of 3% rope elongation. One potential strategy would be to specify the tube size so that the elongation threshold is equal to the strain at the rope's mean load and monitor strain excursions above the mean load. The transducer can be supplied with several loose tubes of different dimensions, thereby increasing the inspection range

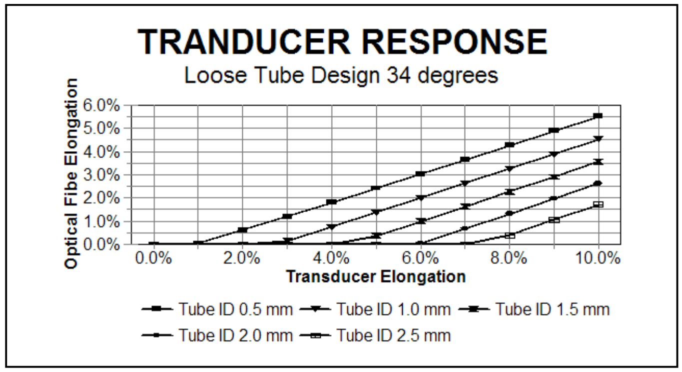

Fig 7 Transducer Response

OSCAR Testing

OSCAR is the result of several years of experiment and testing. Early tests demonstrated that Brillouin Scattering was a viable method and revealed the need for a transducer. When simply wound round the outside of a rope, there was unacceptable variability in the elongation of the optical fibre. Three prototypes of the transducer were produced before the current design was adopted. Full details of the development and testing of OSCAR are presented in "Optical Scanning Apparatus for Ropes - Technical Review of Work to Date"

Transducer Testing

An early version of the transducer was subjected to strain as shown in Fig 8

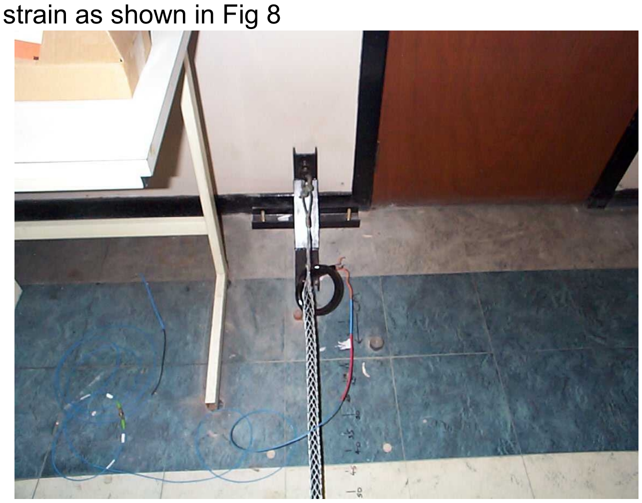

Fig 8 – Transducer Straining Arrangement

The transducer was strengthened and weakened to induce higher and lower elongations. The test sample had the following measured elongations at increasing overall transducer strain

Overall Strain	Strengthened 0 - 5m	Weakened 5 – 10m	Normal 10 – 15 m
1%	0.4%	2.5%	1%
2%	0.8%	2.5%	1.8%
3%	1.2%	4.5%	2.4%

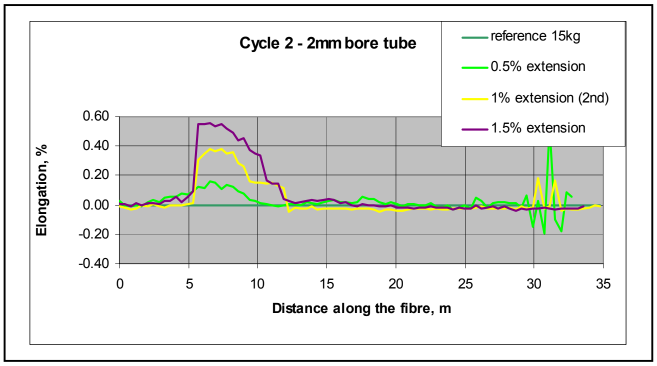

Fig 9: Brillouin Measured Response of Fibre in 1.5 mm Tube

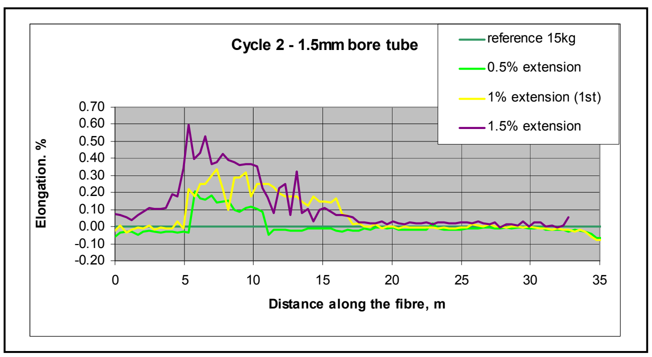

Fig 10: Brillouin Measured Response of Fibre in 2 mm Tube

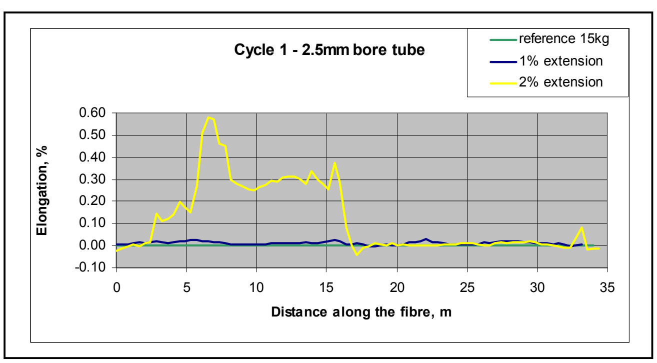

Fig 11 Brillouin Measured Response of Fibre in 2.5 mm Tube

From these results we can clearly pick out weakened normal and strengthened parts of the transducer. It can also be seen that the loose tubes do provide a threshold of transducer strain and that threshold does increase with increasing tube size. There were difficulties in manufacturing this transducer; the larger tubes became somewhat oval. The transducer core selected was too soft and this interfered with the proper control of the helix angle. Also, as a consequence of these difficulties, the attenuation was exceptionally high. Bearing these problems in mind, the results were considered surprisingly good and it was decided to conduct tests in a rope.

In Rope Testing

In rope testing was carried out on a parallel strand rope. The object of this test was to determine that variations in the rope would be detected by the transducer.

Transducer & Rope Construction

The transducer in these ropes had a 23mm outer diameter and a 34° fibre optic lay angle. Each transducer consisted of 5 loosely buffered optical fibres. All of these fibres were single mode, each contained in different protective tubings with bore diameters ranging from 0.5mm to 2.5mm. The ropes were polyester in a parallel strand construction, 6 strands in total with a breaking load was 60 tonnes. The ropes and transducer exiting in the crotch of eye are shown in figure 12.

Fig 12; Transducer Built into Rope

Procedure

The ropes were weakened locally by completely cutting the jacket and severing half the strands. There were two weakened zones in the rope.

Strains were measured using Brillouin Scattering in the set up shown in Fig 13. The optical fibres were looped through by connecting them together at both ends of the transducer. The total optical path was approximately 250m. {Total length is 60 + 30(*4) + 20(*3) + 10 = 250m}

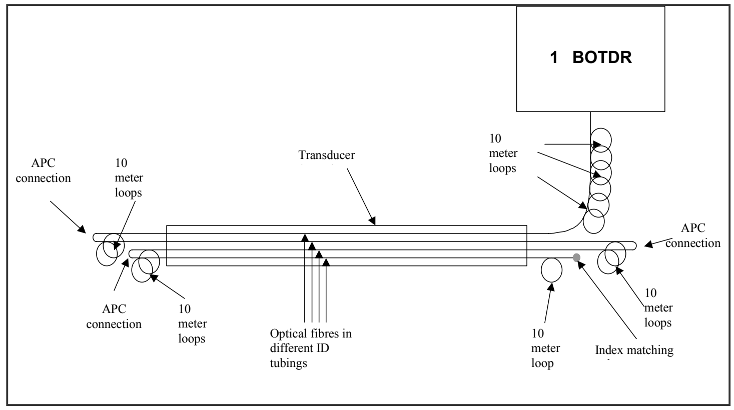

Fig 13: Arrangement for in Rope Test

The rope was loaded to 75kN (7.5 tonnes) and the following trace was obtained

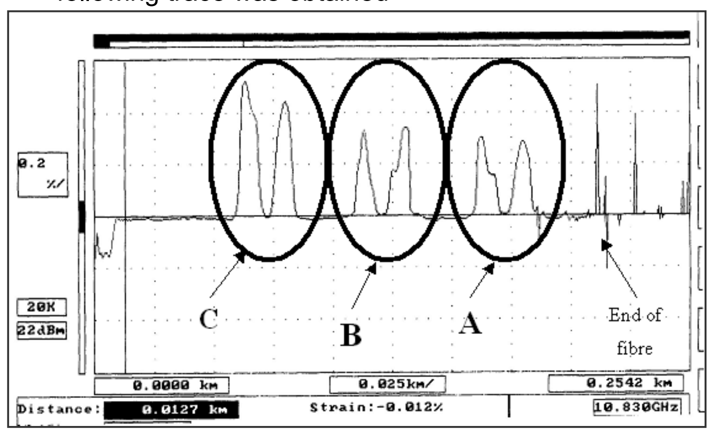

Fig 14: Brillouin Trace at 75kN

The marked areas correspond to the fibres in the transducer. Region A corresponds to the fibre in the 2.0 mm ID bore tube. Region B corresponds to the fibre in the 1.5mm ID bore tube. Region C corresponds to the fibre in the 0.5 mm ID bore tube. The scan shows that the fibres either side of the central section of the rope experienced significantly higher levels of strain. The spatial resolution of the BOTR was 5m. The amplitudes differ because of the different threshold strains designed into these three optical fibers. The above figure does not include approximately 50m of "dead-zone" at the beginning of the scan.

This test demonstrated that the transducer was capable of picking up differences in strain in a parallel strand polyester rope. Trace B is the mirror image of the other two traces since this was measured on the return path.

Pressure Testing

Pressure was applied to the transducer and attenuation was monitored. As can be seen from Fig 16, there was no increase in attenuation due to pressure up to 150 bar.

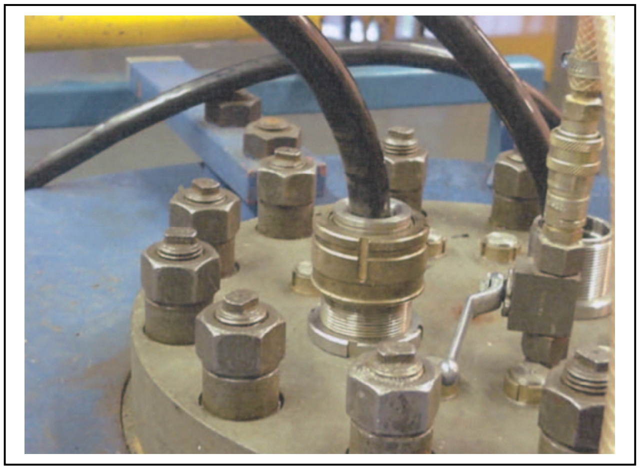

Fig 15 Detail of Pressure Vessel

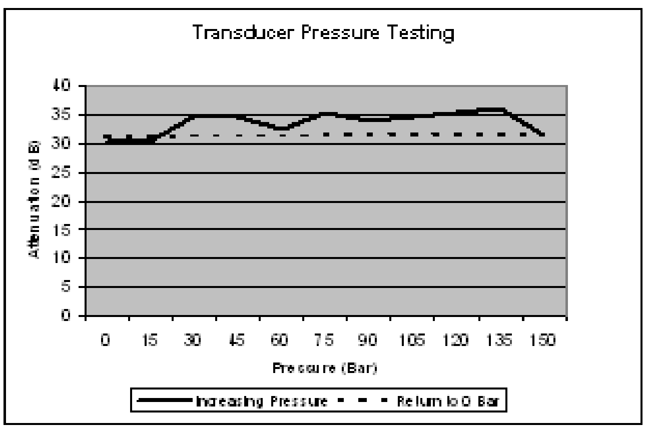

Fig 16: Attenuation vs Pressure

The test was then continued for 29 days and the transducer was then dissected. Four of the tubes were in "as new" condition but the largest tube with the 2.5 mm ID had become oval and partially collapsed. However, this tube size is not required for a polyester parallel strand rope; the preferred sizes being 1.0 and 1.5 mm ID.

The transducer passed the 150 bar, 1 month pressure test

Terminations

Offshore mooring is a tough environment and it will be necessary to ensure that entire system including the links can withstand installation as well as last the duration of the mooring lines; typically 30 years.

It will be necessary to connect the transducer to an armoured lead in cable at the rope/chain interface. Furthermore, if the polyester mooring line is in more than 1 segment, connections between the segments will also be required.

Rugged, pressure resistant terminations will be required for this and a design has been prepared.

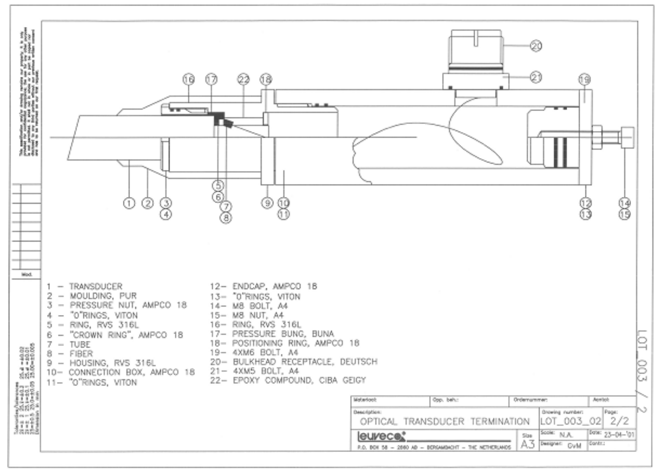

Fig 17: Rugged Pressure Resistant Termination Design

8 Further Work

The system has not been subjected to tension-tension fatigue and this is required to establish long term durability. The system integration software needs to be developed and a field trial is recommended.

The OSCAR Consortium

Oscar has been developed by the efforts of the consortium members firstly under a UK Government SMART award and subsequently with a European Union CRAFT grant.

The consortium consists of 5 companies, each expert in with their own field with a unique contribution to the system. The system was designed and patented by TTI and the University of Strathclyde.

BPP is a group of offshore consultants responsible for system integration, software and installation.

Leuveco is a Dutch manufacturer of terminations for offshore and defence applications, in particular the Dutch Navy.

Selantic is a Norwegian manufacturer of tethers, slings and straps for strapping, towing, lifting, anchoring and mooring. The company's other activities include anchor design and manufacturing

TTI is a group of consultants, specializing in the design and performance of synthetic fibre ropes and in particular the factors determining rope lifetime.

The University of Strathclyde Department of Opto-Electronics is responsible for the Brillouin Scattering Method.

Vermeire is a Belgian manufacturer of high strength synthetic fibre ropes.

Conclusions

OSCAR is a viable system capable of monitoring the distributed or local rope elongation in real time over the entire length of the mooring line. It has been demonstrated that Oscar is capable of detecting damage to the rope. Further work is required to establish the fatigue resistance of OSCAR and system integration software needs to be developed.

In summary, it provides a method to detect:

- magnitude and position of cut damage
- gradual deterioration in strength
- integrity of spliced terminations
- measurement of modulus

It also offers the opportunity to revisit the need for insert test strops with a view to eliminating the high cost over lifetime insert method.

References

1. T Kurashima, T Horiguchi, H Izumita, S Furukawa and Y Koyamada, "Brillouin optical fibre time domain reflectometry", IEICE Trans. On Comms., 1993, vol E76B, pp382-390

2. L Thevenaz, M Nikles, A Fellay, M Facchini, P Robert, "Applications of distributed Brillouin fibre sensing", International Conference on Applied Optical Metrology, 1998, SPIE vol.3407, pp.374-381

3. D Uttamchandani, B Culshaw. M.S. Overington, M Parsey, N.O'Hear L Thevenaz, M Facchini, "Distributed optical fibre sensing in synthetic fibre ropes and cables" Marinflex 1999