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Fundamentals for remote structural health monitoring of wind turbine blades - a preproject. Annex C. Fibre transducer for damage detection in adhesive layers of wind turbine blades

Forskningscenter Risø, Roskilde

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Sendrup, P. (2002). Fundamentals for remote structural health monitoring of wind turbine blades - a preproject. Annex C. Fibre transducer for damage detection in adhesive layers of wind turbine blades. (Denmark. Forskningscenter Risoe. Risoe-R; No. 1342(EN)).

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Risø-R-1342(EN)

Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject

Annex C – Fibre Transducer for Damage Detection in Adhesive Layers of Wind Turbine Blades

Peter Sendrup

Risø National Laboratory, Roskilde, Denmark
May 2002

Risø-R-1342(EN)

Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject

Annex C - Fibre Transducer for Damage Detection in Adhesive Layers of Wind Turbine Blades

Peter Sendrup, DELTA Light & Optics

Risø National Laboratory, Roskilde
May 2002

Abstract This report (annex to the summary report "Grundlag for fjernovervågning af vindmøllevingers tilstand (Fase I: Forprojekt)", of a project partly supported by PSO-funding through Elkraft System, contract no. Bro-91.055, FU nr. 1102) describes the work carried out to design and test a fibre optic displacement transducer for detection of damage in adhesive layers of wind turbine blades. It was chosen to base the transducer on the fibre optic micro-bend principle. The report contains the result of measurements and optical simulations of light transmittance through optical fibres with micro-bends and a suggestion for a micro-bend transducer design specifically suitable for detection of damage in adhesive layers between larger composite structures, as the shells in a wind turbine blade. Such a damage will cause the joined parts to move slightly relative to each other, and the transducer is designed to change its optical transmittance in accordance to the displacement. Four transducers were manufactured on basis of a specific suggested design. The optical simulation showed that a sensitivity about 1.6 %/um could be expected. Preliminary experimental investigations showed, that the sensitivity of a fibre optic micro-bend transducer would be in the range between 0.5%/um to 1 %/um depending on the number of bends on the fibre. A measurement on the final transducer showed that the sensitivity was 1.2 %/um. A large 50 % change in transmittance, that is easy to measure, is then obtained for displacements of 40 um. The sensitivity is anticipated to be sufficient the application, because fully evolved cracks in the adhesive layer typically has a opening of 100 um – 200 um. The tests of the transducer ability to detect damage in adhesive layers both in the lab-test and in the ’full scale test’ were also fully satisfying, although the design of the transducer can be further improved.

ISBN 87-550-3058-0
ISBN 87-550-3059-9 (Internet)
ISSN 0106-2840

Print: Pitney Bowes Management Services Danmark A/S, 2002

Contents

Preface

This report is Annex C of the reports of the pre-project "Grundlag for fjernovervågning af vindmøllevingers tilstand (Fase I: Forprojekt)", supported by PSO-funding through Elkraft System, contract no. Bro-91.055, FU nr. 1102. The project was performed within 12 month 2001-2002 in collaboration between Risø National Laboratory (project leader), DELTA, Sensor Technology Center A/S, Force Technology, InnospeXion and LM Glasfiber. The project is reported in a summary-report and in some Annexes (A-F).

The title of the summary report is:

"Fundamentals for remote structural health monitoring of wind turbine blades - a pre-project", Bent F. Sørensen, Lars Lading, Peter Sendrup, Malcolm McGugan, Christian P. Debel, Ole J. D. Kristensen, Gunner Larsen, Anders M. Hansen, Jørgen Rheinländer, Jens Rusborg and Jørgen D. Vestergaard, Risø-R-1336(EN), May 2002.

The titles of the annexes are:

Annex A: "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex A - Cost benefit for embedded sensors in wind turbine blades", Lars Gottlieb Hansen and Lars Lading, Risø-R-1340(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex B: "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex B - Sensors and non-destructive testing methods for damage detection in wind turbine blades", Lars Lading, Malcolm McGugan, Peter Sendrup, Jørgen Rheinländer and Jens Rusborg, Risø-R-1341(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex C: "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex C - Fibre transducer for damage detection in adhesive layers of wind turbine blades", Peter Sendrup, Risø-R-1342(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex D: "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex D - Laboratory tests using condition monitoring sensors", Malcolm McGugan, Risø-I-1878(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex E: "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex E - Full-scale testing of wind turbine blade", Ole J. D. Kristensen, Malcolm McGugan, Peter Sendrup, Jørgen Rheinländer, Jens Rusborg, Bent F. Sørensen, Christian P. Debel and Anders M. Hansen, Risø-R1333(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex F: "Identification of damage to wind turbine blades by modal parameter estimation", Gunner Larsen, Anders M. Hansen and Ole J. D. Kristensen, Risø-R-1334(EN) Risø National Laboratory, Roskilde, Denmark, April 2002.

The conclusion of the STC report “Survey of embedded fibre based sensors for strain measurement in large composite structures” was that the microbend strain sensor and the fibre Bragg grating sensor were overall the most simple, the most well proven and potentially cheapest fibre based strain sensors. It was also suggested that the potential of these sensor types for detection of strain and damage in composites were further investigated experimentally in this project.

The microbend strain transducer is for two principal reasons cheapest. First, the transducer is based on a multimode optical fibre system, whereas the FBG system is based on the more expensive single mode optical fibre. Not only is the single mode fibre itself more expensive, but also the light source is typically more expensive; the light source used in a multimode fibre system can be a simple LED. Second, the measured strain is in proportion to the wavelength of the light reflected from the grating in a FBG based system. The change of wavelength inevitable has to be converted to a change in power, which can be measured with a photo detector. Typically, this conversion will involve the use of relatively expensive, filters (chirped fibre gratings, Fabry Perot filters) and/or directional couplers for interferometric detection schemes. The relative change of wave length is small for an FBG based transducer, compared to the change in transmittance of a microbend transducer, which easily can be as large as 50%. Detection of small changes requires more sophisticated (expensive) measurement techniques than detection of large changes. The advantage of the FBG transducer is the potential of detecting small strain (10 ustrain) accurately and measured over small distances.

In this project, it was decided that the most severe damage mode for wind turbine blades is failure of the adhesive joints, especially in the trailing edge of the blade. Therefore, there is a need for a damage detection system, preferably for detection of damage in the adhesive joints in the trailing edge in the blade, but also in the adhesive joints between the webs and the shells. Inspection of blades with damage has shown that such damages typically are followed by a permanent crack with an opening of at least 0.1 mm. Because a damage is followed by relatively large displacements of the shells, it is not necessary to have a very sensitive sensor system as one based on FBG transducers. For these reasons, it was decided to primarily concentrate the development work on microbend transducers.

This report will describe the work carried out in the attempt to develop a transducer that is dedicated to detect cracks in the adhesive layers in wind turbine blades.

1 Computer simulations

1.1 Design considerations

The microbend strain transducers normally measure compression, rather than extension. Microbends are induced on a optical fibre when two surrounding pairs of periodic structures are forced together, with a decrease in transmittance as consequence. In the present case, it is necessary to measure the movement of two fibre composite parts that moves apart (away) from each other due to cracks in the in between adhesive layer. This could be done by a traditional microbend transducer if it was initially deformed. The transducer would then initially have a low transmittance and relative movement of the composite parts would then increase the optical transmittance. Use of such a microbend transducer would have three disadvantages:

1) It would not be possible to have many transducer on the same fibre without a larger decrease in the transmitted / detected power. For instance 10 transducers would, each with 50 % initial transmittance, in total have a transmittance of 10^-3.
2) It would be mechanically very difficult to insert a microbend transducer between the composite parts with an initial deformation of 50um - 100 um and keep this deformation during the curing of the adhesive. Deformation of a microbend transducer involves elastic deformation of the optical fibre, and the associated spring constant is not negligible.
3) If the detection system contained a number of transducers, the first transducer would work as intended, but the function of the following transducers would be less certain. The reason is, that a deformed transducer strips of high order modes (that is causing the decrease in transmittance). If these modes are not sufficiently re-exited in the propagation of the light to the next transducer, it will simply loose its sensitivity to deformation.

The idea was to transfer the movement of the traditional deforming surfaces to the opposite surface of the transducer. The transducer became in that way a 4 layered structure in which the two outer surfaces are connected to the deforming inner surfaces in opposite position. The two inner deforming surfaces will move together when the two outer surfaces are pulled apart.

The design of the transducer basically involves the choice of periodicity of bends, number of bends and a choice of optical fibre. The transducer can then be characterised by the transmittance as a function of the deformation. Following expression provides an estimate for the periodicity Λc of the fibre bends giving the transducer the maximum sensitivity for a step-index fibre with the radius a and refractive index η_0 of the core and a numerical aperture NA

$$\Lambda_c = \frac{2\pi a n_0}{NA} \qquad (1)$$

Largest periodicity is achieved for a fibre with a small NA and a large core radius. Such fibres will couple out light for small relative deformations.

A fibre of the type FVP-200 from Thorlabs was chosen because it has a combination of a relatively large core-radius and low numerical aperture. In addition, the thickness of the cladding and coating is small, so that the diameter of the fibre is only slightly larger than the diameter of the core. With this fibre the optimum periodicity is 2.7 mm.

There are no simple analytical expressions that provide the relation between the transmittance through a fibre with micro-bends and its deformation. This relation was instead attempted found by simulations using the optical simulation program Zemax (Focus Software Inc.).

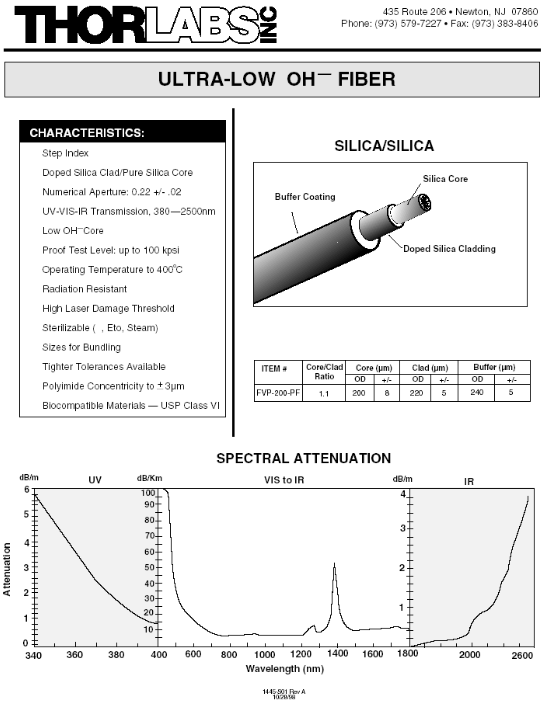

Figure 1. Data sheet for employed optic fibre.

1.2 Zemax model

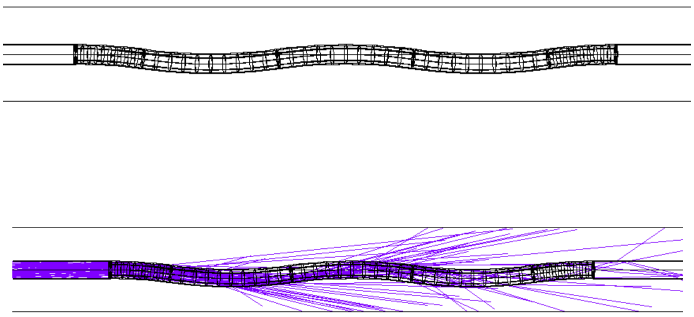

Figure 2. Optical fibre with micro-bends as simulated in Zemax.

A bended fibre is defined in Zemax as a number of closelying torus sections. The model shown here consisted of 5 pieces of torus and 2 pieces of cylinder to make up the core. The same number of torus and cylinder is used to define the cladding. Finally, the outer coating is simulated with a single cylinder, containing core and cladding. It is necessary to include the coating in the simulation because the coating has the important function to strip of the cladding modes, which otherwise could carry a large fraction of the power with little loss, even when the fibre is bended.

A circular light emitting disc, with the same diameter as the core was used as light source. The light emitting disc was assigned a so-called cosine light distribution, in which the intensity is in proportion to the directional cosine, here raised to the power 28. This power will make the half-value angle of the light-distribution correspond to the numerical aperture of the fibre. The cylindrical sections are 100 mm long (not illustrated in complete extension in figure 2) in order to strip of non-guided modes, before the bended section.

1.3 Results

Simulations were carried out for a deformation of 1 um, 10 um, 50 um and 100 um. Although the number of data points are low, the simulation indicates that there is a linear relation between the transmittance and the deformation, until the transmittance has fallen to about 20 %. The transmittance will hereafter presumably converge asymptotically to zero. The simulations shows that the transmittance must be expected to decrease from the first deformation and the change in transmittance per um deformation is -1.6 %/um; a microbend strain transducer can potentially be very sensitive. It was originally the intention to use simulation to determine the relation between transmittance, deformation and the number of bends by use of simulations. But because the simulations turned out to be relative time consuming and because the results of simulations are always inflicted with an uncertainty, which can be very difficult to predict, it was decided to get this relationship experimentally.

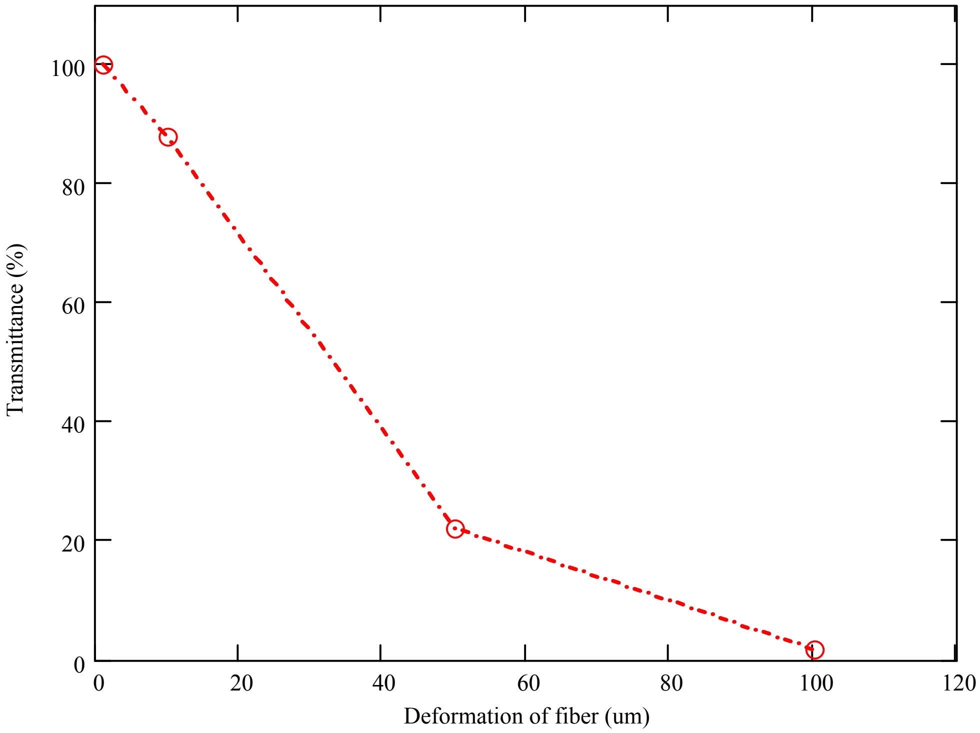

Figure 3. Transmittance as function of fibre deformation for the model shown in figure 1

2 Experimental determination of basic transducer parameters

2.1 Device for controlled deformation of fibre

A fibre bending device as shown in figure 4 was manufactured. The device consists of two jaws, whose mutual distance can be adjusted by the micrometer screw. The micrometer screw moves one jaw indirectly though a variable mechanical exchange. Moving the knife edge between its outer positions, changes the exchange ratio between 3 and 10. The resolution of the micrometer screw is 10 um, and the maximum resolution of the device is therefore 1-2 um. Standard tooth bars of various tooth distances and various numbers of teeth can be inserted into the jaws and fixated. In the present application, one tooth bar had a fixed number of teeth, and inserting various tooth bars with a smaller number of teeth in the second jaw, varied the number of bends on the fibre.

The distance between the tooth bars was measured on the basis of following calibration method. A gauge blade with a thickness of 0.3 mm was inserted between the jaws. The micrometer screw was turned until the blade was just able to move. The distance between the jaws was here defined to be 0.3 mm and the micrometer screw was read. This fix-point was encumbered with an uncertainty of about 0.05 mm = 50 um. The exchange ratio was determined from the distance between the ball and micrometer screw and the distance between the knife blade and the micrometer screw. The exchange ratio, the 0.3 mm distance and the corresponding micrometer-screw reading established the linear relationship between micrometerscrew reading and the distance between teeth. Although the uncertainty on the absolute distance between the teeth (and hence the absolute deformation of the fibre) is relatively large (50 um),the uncertainty on differences are much less.

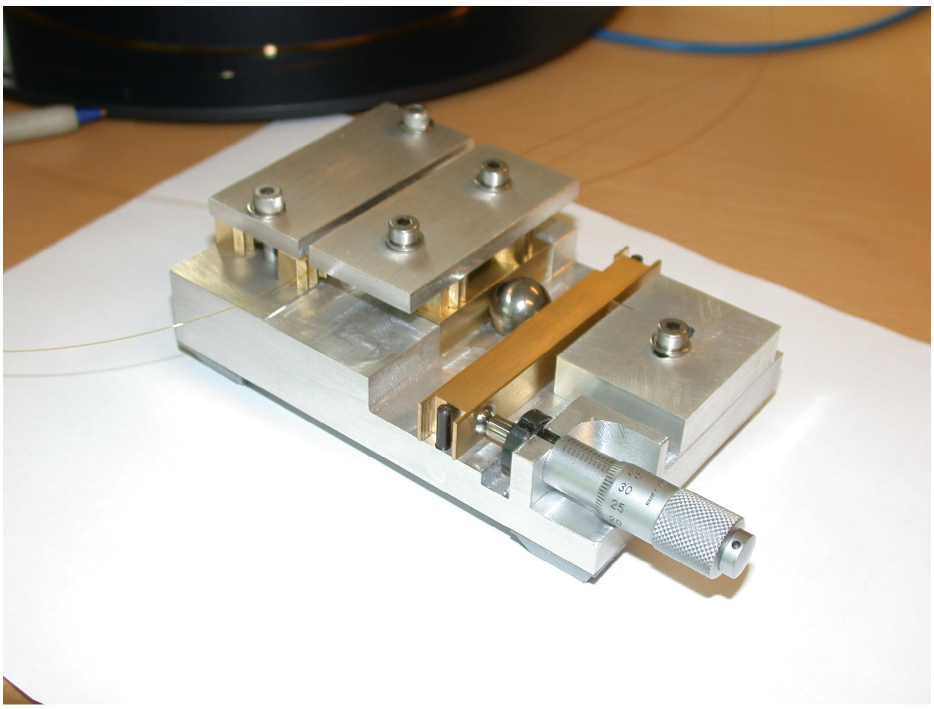

Figure 4. Device for controlled deformation of fibre.

2.2 Transmission measurement

First a Laser Precision Corp. (AP420) was used as light source for the transmission measurements. It turned out that there was no decrease in transmittance for small deformations. The reason was assumed to be that high order modes were not excited. In the ray-picture, this corresponds to a situation where there are no rays, propagating in the core, with a reflective angle close to the critical angle. These latter rays are those, which are most likely to transmit out though the core-cladding interface when the fibre is slightly bended. A simple light source was made by a EGIPAP 870 nm LED, and two lenses. (figure 5). By use of the lenses an (1:1) image of the light-emitting chip in the LED was made on the fibre end. The numerical aperture of the optical system was made larger than the numerical aperture of the optical fibre, so that light enters the fibre under the largest possible angle. A Laser Precision Corp. AM420 was used for detection.

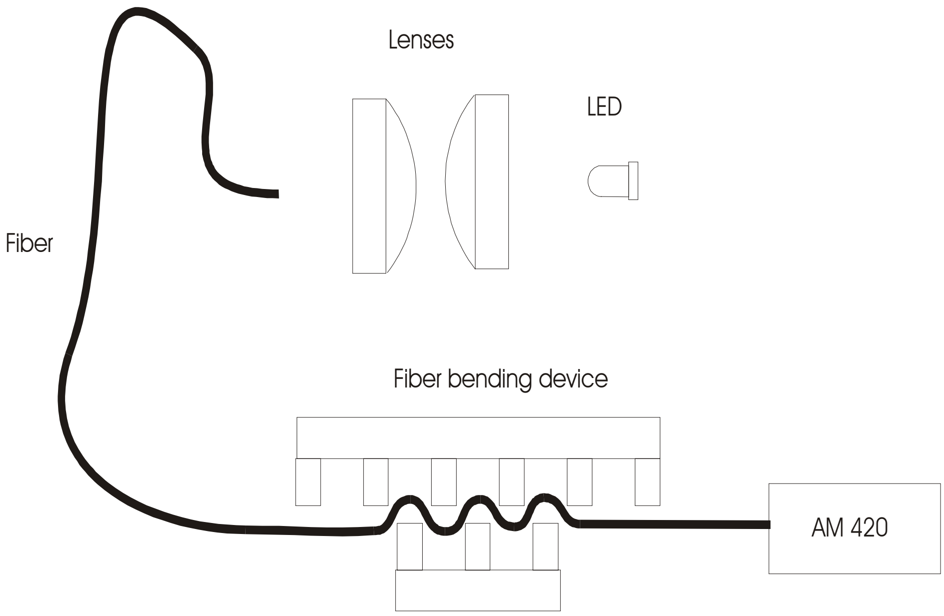

Figure 5. Set-up for measurement of transmittance. This set-up has also been used in the lab-test and in the full-scale test.

2.3 Results

Figure 6, 7 and 8 show the transmittance as a function of the distance between the teeth bars. Figure 6 shows the transmittance as a function of the distance between the teeth bars when the teeth bars creates 2 bends on the fibre. The graph shows that the transmittance decreases for a distance less than 225 um. Although the diameter of the fibre is 240 um, the measurement does not indicate that the fibre does not change transmittance for small deformations, because it must be remembered that there is a measurement uncertainty of about 50 um on the origo of the distance axis. The measurement shows linearity between deformation and transmittance within a large range, just as shown in the computer simulation. The sensitivity is estimated by a linear fit to be .52 %/um.s Figure 7 and 8 show the variations of transmittance for respectively 5 and 10 bends on the fibre. These graphs have the same qualitative features, with the only difference that the sensitivity increases with the number of bends. The sensitivity is in all three cases smaller than the simulation indicates.

First of all the measurements show that the sensitivity will not change by orders of magnitude, depending on the number of bends. With a reasonable sized transducer the sensitivity will lie in the region between 0.5 %/um and 1 %/um and in that case the change of transmittance will be about 50 % for 100 um=0.1 mm deformations. Such a change in transmittance is easily measurable and the combination of optical fibre and fibre bend periodicity seems suitable for the present application.

The sensitivity is apparently not proportional to the number of teeth and the benefit of increasing the number of bends becomes smaller the larger the number of bends are. This agrees well with the ray-tracing simulations; they show that the major part of the optical power is coupled out at the first few bends. (See figure 2) The periodicity of the deformation is 2.7 mm and 10 bends corresponds to the length 2.7 cm, corresponding closely to a maximum size of a transducer allowable for practical and mechanical reasons.

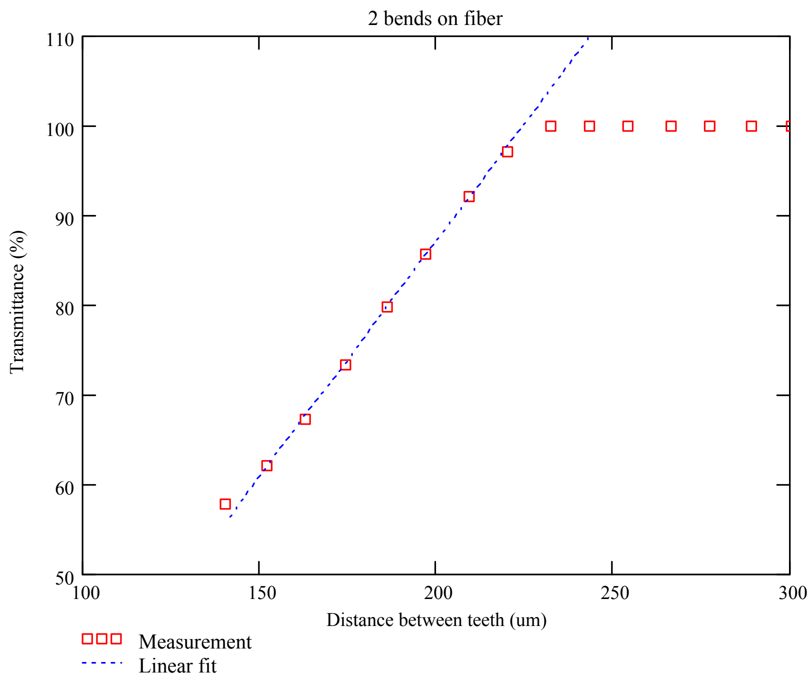

Figure 6. Transmittance as function of distance (between teeth-bars) for a 2 teeth-bar corresponding to 2 bends. The sensitivity is 0.53 %/um.

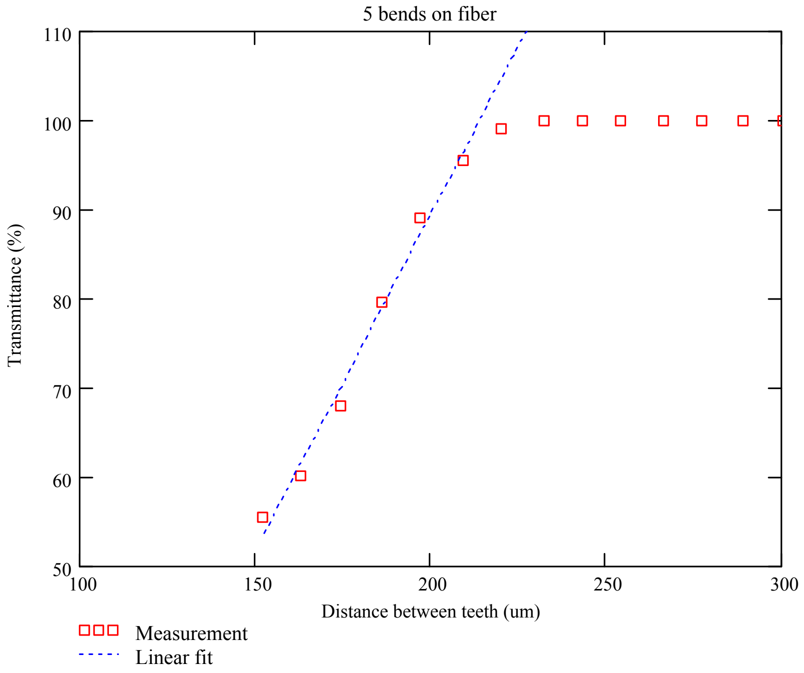

Figure 7. Transmittance as function of distance (between teeth-bars) for a 5 teeth-bar corresponding to 5 bends. The sensitivity is 0.76 %/um.

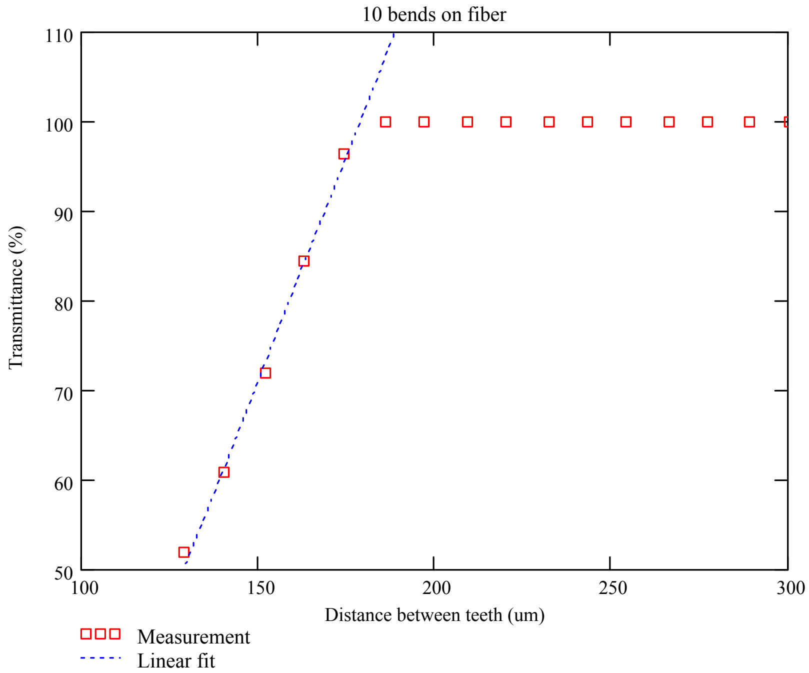

Figure 8. Transmittance as function of distance (between teeth-bars) for a 10 teeth-bar corresponding to 10 bends. The sensitivity is 1,0 %/um.

3 The final prototype version

3.1 Transducer design

At the time this report is written it has not been decided whether the design of the transducer is going to be patented. As a consequence, the institution behind the development of the transducer, DELTA, has decided not to inform on details about its design.

The 4 identical prototypes were made in stainless steel and as figure 9 shows the parts were assembled with screws. This choice material and method of assemblence is well suited for construction of prototypes, but not for a mass-produced commercial product. DELTA has ideas about a design that is based on a few plastic components that can be clicked together as 'LEGO' -bricks. The plastic components can for instance be injection moulded, and the price of the transducer could be very low (1$).

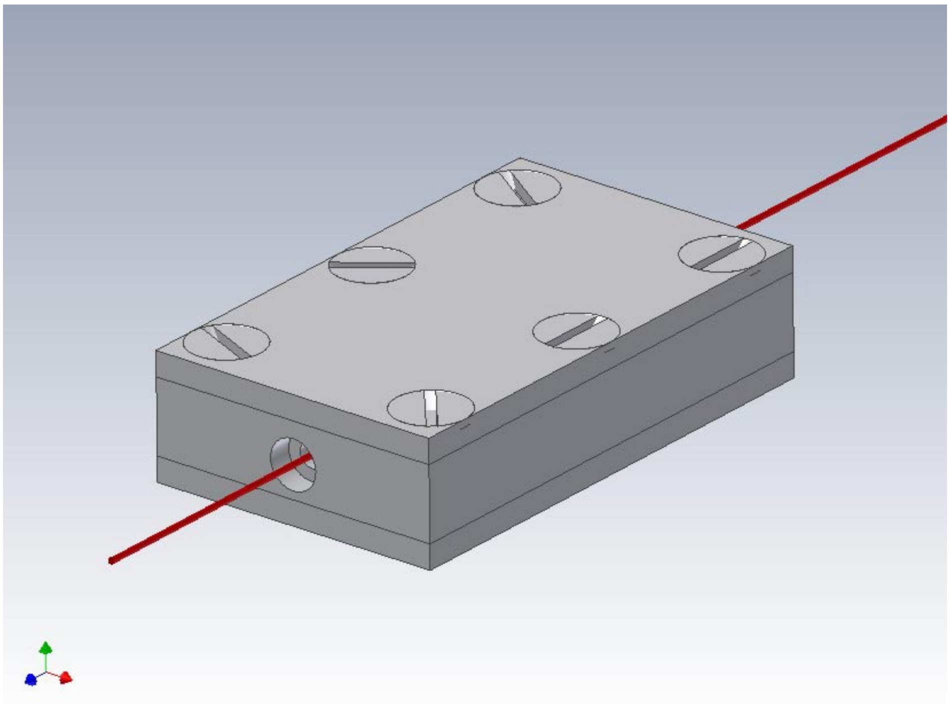

Figure 9. The transducer developed for detection of damage in the adhesive layers of wind turbine blades.

3.2 Sensitivity of the transducer

The sensitivity of the final prototype was determined using the extensometer calibrator shown in figure 10. The extensometer calibrator is popularly described a combination of a vice and a micrometer screw. Turning the wheel with the scale on the left in the picture makes the two rods move relative. The extensometer calibrator has a displacement resolution of 0.1 um.

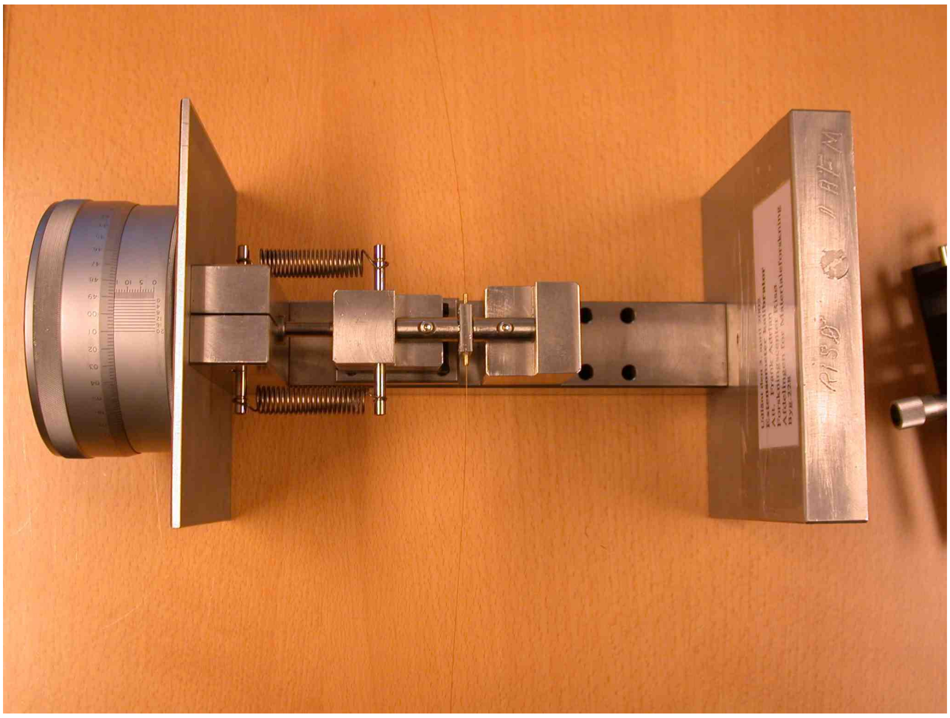

Figure 10. Fibre transducer mounted in extensometer calibrator for measurement of the sensitivity.

The transducer with fibre was glued to the rods by use of adhesive from Casco, named Araldit Super Quick.

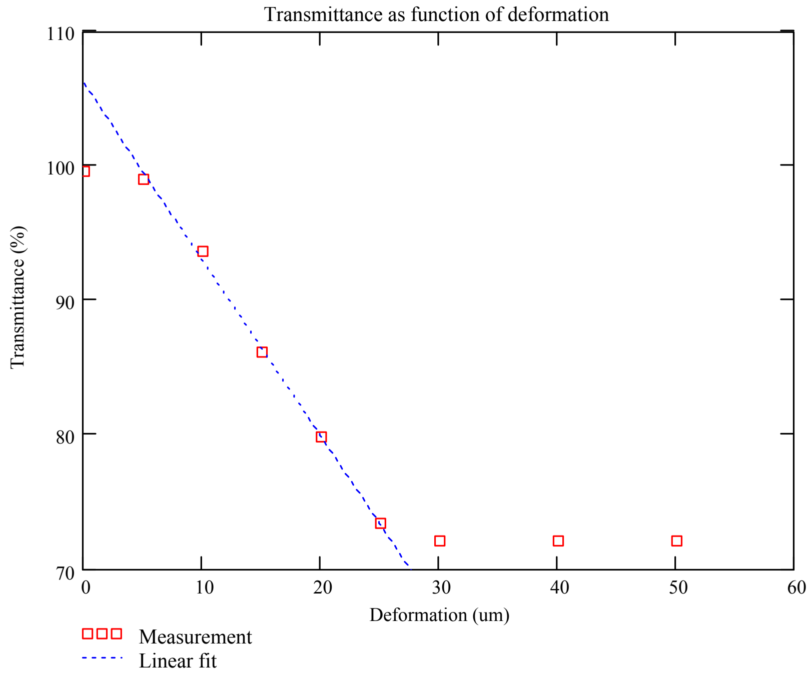

Figure 11. Transmittance of transducer as function of displacement.

The rest of the optical set-up is as shown in figure 5.

The two rods were pulled apart in steps of 5 um, and the transmitted power was measured for each position and normalised to a transmittance.

Figure 11 shows the result of the measurement. The transmittance is nearly unaltered for the first 5 um step. Even though the wheel initially was turned to a point where it reacts to further rotation, to compensate for the unavoidable mechanical clearance, it is not quite certain that first turn on the wheel causes movement of the rods. The point where the first counter-force is observed is encumbered with an uncertainty of about 5 um-10 um.

The transmittance decreases with 1.3 %/um in the range between 5 um and 25 um. Further displacements of the rods do not result in a change of light transmission through the transducer. The extensometer calibrator was slowly turned to the end of the scale, 4 mm displacement in total, but the transmittance remained constant as indicated in the right part of the graph in figure 10. The adhesive layer did not crack, but was visibly stretched. The explanation is simply that the adhesive layer cannot deliver sufficient force to create further deformation of the fibre in the transducer. Turning the wheel in the opposite direction, towards the starting point, did not lead to any increase in transmittance, except for the last 25 um, before the starting point. The deformation of the adhesive layer were apparently (and surprising), fully elastic.

4 Future improvement of design

As the full-scale test shows, it is advantageous, if the transducer can absorb larger relative displacements of the shells, without loosing contact to them or become damaged. The tested transducers can absorb 200 um displacement without damaging the optical fibre. This deformation is only associated with a relatively small spring constant. If the deformation is between 200 um and 240 um, the deformation is inelastic and it requires a large force, because the deformation causes the fibre to be crush. For deformations larger than 240 um the transducer will simply act as a small steel block. A more flexible transducer must be expected not to loosen its contact to the shells, as easy as a rigid transducer.

No matter the deformation, the optical fibre should not be crushed, especially if many transducers are going to be mounted on the same optical fibre. The maximum limit of deformation can for instance be defined by a requirement for a minimum transmittance, and the limit shall be built into the transducer as a 'mechanical stop'.

5 Conclusion

Four copies of a fibre-optic transducer have been manufactured on basis of a specific suggested design. The transducer has a sensitivity of 1.3 %/um. A large 50 % change in transmittance, that is easy to measure, is then obtained for displacements of 40 um. The sensitivity is anticipated to be sufficient and suitable for the application, because fully evolved cracks in the adhesive layers typically has a opening of 100 um – 200 um. The tests of the transducers ability to detect damage in adhesive layers both in the lab-test and in the 'full scale test' were also fully satisfying, although the design of the transducer can be further improved.

Bibliographic Data Sheet **Risø-R-1342(EN)**

Title and authors

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Peter Sendrup, DELTA, Light & Optics

ISBN	ISSN
87-550-3058-0 87-550-3059-9 (Internet)	0106-2840

Department or group	Date
Materials Research Department	May 2002

Groups own reg. number(s)	Project/contract No(s)
PSO Funding Through ELKRAFT System	Bro-91.055 FU nr. 1102

Sponsorship

Pages	Tables	Illustrations	References
17	0	11	0

Abstract (max. 2000 characters)

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Descriptors INIS/EDB

ADHESIVES; DAMAGE; FIBER OPTICS; JOINTS; LIGHT TRANSMISSION; REMOTE SENSING; TRANSDUCERS; TURBINE BLADES; WIND TURBINES

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ISBN 87-550-3058-0
ISBN 87-550-3059-9 (Internet)
ISSN 0106-2840

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