OAR FORCES FROM UNOBTRUSIVE OPTICAL FIBRE SENSORS

M. DAVIS[1], R. LUESCHER[2]

[1]*Australian Institute of Sport. Biomechanics Department. Leverrier Crescent Bruce ACT Australia 2617.* mark.davis@ausport.gov.au
[2]*Australian Institute of Sport. Physiology Department. Leverrier Crescent Bruce ACT Australia 2617.* Raoul.luescher@ausport.gov.au

This project investigated the viability of mounting optical fibres (approximately three times the thickness of a human hair) on sculling oars to measure strain during rowing. The authors conducted successful pilot studies to measure oar force in the laboratory using optical fibres, however the results were obtained using traditional instruments mounted in large laboratory racks. Based upon our encouraging preliminary laboratory trials, the aim of this project was to miniaturise the electronics of a fibre sensor to fit within the shaft of an oar. The same technology could be applied to measure the flexure of any tube, such as in kayaking (paddle), sailing (mast and spars), pole vault and gymnastics applications. The principle of optical fibres as strain sensors is well established (e.g. Lo, 1998). Light passes down the core of a fibre via total internal reflection until it reaches a series of small etchings (called a Bragg grating); the periodicity through the grating changes as the fibre is stretched or compressed. This project customised the design of the Bragg sensor detector and laser electronics for the inside diameter of a carbon sculling oar. Custom signal processing circuitry and software was developed to allow two oars to be monitored simultaneously.

1 Introduction

The aim of this project was to miniaturise the electronics of an optical fibre sensor to fit within the shaft of an oar. The subsidiary aims were to calibrate the sensor with known masses and subsequently collect data on-water from two oars connected to data loggers. A data logger was required with a sampling frequency off at least 300KHz and with working analog inputs. It became clear early on that the development of a high speed miniature data logger with internal signal processing and telemetry was beyond the scope of this research project.

2 Methods and Results

Within this project there were two parallel sub projects which were developed over the last eighteen months.

1. The embedding of an optical fibre sensor array within the sculling oar. The end result would need to be sturdy, durable and impervious to water and invisible to the athlete.
2. The development of a miniature Laser Controller and Scanning Detector Electronics. This unit would need to be very small, light, able to dissipate heat from the laser driver, fit inside the oar and be centred around the oarlock. The electronics' development was a considerably larger portion of the total project.

Mounting Fibre Bragg Sensors on the Carbon Composite Rowing Oar

During the course of this research project, optical fibres with Bragg Grating sensors were placed on a sculling oar.
Three Bragg Grating sensors were embedded on the oar, with the sensors spaced at 500mm intervals. Two sensors were placed on the tension face on the 0 deg axis to measure the bending strain of the shaft, with the third being placed at a 45 deg axis near the blade to measure torsional strain of the shaft. The surface of the oar was sanded and prepared for bonding and a small hole was drilled under the sleeve on the oar to bring the fibre from the external surface to the inside of the shaft. The fibre was protected with microbore tubing along its entire length inside the shaft and strain relief was provided for the connector by securing Aramid cord to the shaft. The sensors were positioned and tacked in place using Loctite 401Cyanoacrilate instant adhesive, ready for the glass epoxy protective layer to be applied. The protective glass layer consisted of a strip of woven Glass fibre fabric (100g sqm plain weave) 15mm wide cut to match the length of the external fibre. Release film and breather fabric was also cut at this time to be used during the vacuum bag curing process. Epoxy laminating resin (SP Systems Ampreg 22) was mixed as per manufacturer's instructions and the area was "wet out" around the fibre. The glass strip was applied and the entire assembly vacuum bagged as per the resin cure schedule. This process fully sandwiched a fibre between the carbon oar shaft and the protective glass layer. The shaft was then sprayed with clear polyurethane lacquer which made the fibre almost impossible to see on the shaft.

2.2 *First laboratory trials*

In the laboratory, initial trials of the sensors were performed using an Optical Spectrum Analyzer. The laser light source was connected to the fibre using a splitter to check that the three sensors were working. The oar was loaded incrementally with a series of masses, and measurements were taken of the wavelength shift of the sensor. The oar was secured in a jig that held the sleeve and the handle, with a sling tied around the blade to which the masses were attached in increments of 1.14kg. The sensors were all reading well until after approximately 17kg when there was a sudden decrease in signal amplitude. All connections were checked and appeared sound, it was determined that the likely cause was a micro-fracture in the fibre, resulting in attenuation of the signal. The testing had otherwise gone well with the resultant curve linear up to the point of failure.

The next key task was to determine where, how and why the failure occurred. A visible laser was used to check for discontinuities in the fibre, a power meter was also attached so we could test the fibre attenuation pre and post attachment. This evaluation led us to the belief that the flaw existed prior to mounting. Problems were also found in the way the fibre was protected in the oar cavity and the associated strain relief and termination of the connector.

2.3 Mounting of the FBG sensor on the second oar

It was decided to change to a tougher Polyimide fibre coating to provide more durability for future trials. The way the fibre was housed inside the shaft was also changed. A short piece of composite tube was cut to fit into the tapered oar shaft. A bulkhead connector was then attached to this tube and a commercial fibre optic patch cord was used to provide strain relief. In this way there is less chance of damage to the bare fibre.

The visible laser was connected to the fibre to check for damage or stress on the new fibre, and the laser was left attached for the entire mounting process to highlight any problems. The layout of the sensors was planned and the shaft prepared as previously described. The fibre was placed on the surface in position and excess fibre was wound and secured within the bulkhead tube for protection. This time all three sensors were placed on the tension face on the 0 deg axis at 500mm centre spacing between the sensors. The fibre was tacked in place with “Magic tape” to position the fibre until the epoxy was ready and removed during the epoxy adhesive application. The fibre was then sandwiched with epoxy and glass fibre cloth and vacuumed down as before. All this was performed with the visible laser attached and no problems were encountered.

2.4 *Second laboratory trial*

In the lab the fibre was connected to the Optical Spectrum Analyser and there was a clear strong signal. The oar was first flexed manually to observe the wavelength shift and then the same testing protocol as before was adopted, adding masses in 1.14 kg increments up to approximately 20 kg at the blade. This was done multiple times without any failure of the fibre, and the testing of the sensor response to load was a success. No hysteresis was observed when the test was repeated. Refer to Figure.1 for these results.

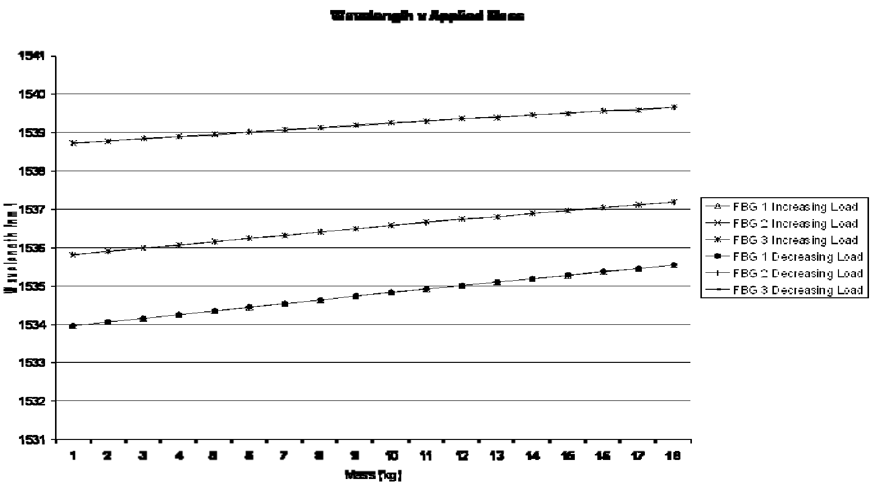

Figure.1 Force Vs Wavelength Calibration chart for Polyimide Bragg sensors.
Note: Minimal hysteresis from several test cycles.

2.5 *Development of miniature electronics circuitry for sensor interrogation*

After assessing a number of different system setups, the development of an electronics system which has three major components was agreed upon:

1. Laser Controller – This circuitry provides current control to the laser diode, it has closed loop control of the Peltier Cooling Pump via a thermistor inside the laser casing, and control is effected by PID circuitry. The laser controller also has a number of failsafe mechanisms. Current and optical power feedback, over and under voltage inhibits and Peltier Cooler failure inhibit. These inhibits will immediately shutdown the laser if any problems are encountered.

2. Scanning Detector circuitry – The scanning detector (Mosquito TOD050) is an optical detector with a very narrow wavelength bandwidth. By applying a logarithmic drive current to this device a narrow bandpass region can be ramped through certain optical wavelengths. In our case between 1540nm and 1565nm.

3. Data Logger – Due to limited resources a miniature data logger was not built. For proof of concept we used a laptop computer and a National Instruments PCMCIA data acquisition card (DAQCard-6024E). Vbragg Pty Ltd developed a program using LABVIEW software for the signal processing. Using this software the power spectrum wass subjected to a peak fitting algorithm to determine the Bragg wavelength of each reflected peak. The Bragg wavelength was then tracked and monitored during scans.

2.6 *Development of Scanning Detector circuitry*

The original prototype of the Scanning Detector Interrogator was built quite large for ease of construction and to prove the concept. It was housed in a diecast box so that it could be cycled in a heat chamber and a temperature characterisation realised. The circuitry generates a 25Hz logarithmic pulse of 6 milliSeconds duration. The amplitude of this pulse is adjustable but ideally is set to 190 milliAmps. The scanning detector (Aegis Semiconductor TOD050) uses this current to heat the substrate and ramp through the intended wavelength range. There is also circuitry to provide feedback on detector substrate temperature, a photo detector transimpedance amplifier and V-Filter output.

The final version of the Scanning Detector Interrogator circuitry was merged with the Laser Controller circuitry on to a single printed circuit board. From lab tests it seems the scanning detector device develops some self heating problems if operated above 30Hz. The control pulse generated by this circuitry is not quite ideal but is the best that could be achieved with analog circuitry. Preferably an on board microcontroller would be used to generate these pulses. With the processor generating the curve as recommended by the manufacturer (refer to online datasheet), it is the authors belief that the pulse frequency could be increased, possibly up to 50Hz.

2.7 *Development of Laser Controller circuitry*

Development of the Laser Controller circuitry took place in two major stages. Initially a large prototype was built incorporating a Superlum Inc. SLD-761-LP-DIL-SM super luminous diode. This prototype was large, used conventional components and it was used to prove the concept.

The original larger Laser Controller worked well but there were concerns that there might be some limitations with optical output power (i.e. Max. Optical power for this laser is 170 micro watts). It was decided that we would accommodate a higher power (10 milliWatt) super luminous diode in the later miniature Laser Controller design. The higher power laser diode used is the Superlum Inc. SLD-761-HP1-DBUT-SM (refer to online datasheet).

The new design would also power the lower powered laser if retro fitting was required. The smaller board used surface mount technology integrated circuits which are much smaller than conventional components. The circuit board itself has four circuit layers. All of the components were mounted on the top and bottom layers, the internal layers route most of the power supply wiring and ground planes.

Two high density Lithium Ion Polymer battery packs were used to supply the +/-14.8 volt rails. On board power supplies brought this down to regulated +/-12 volts. There was also a 10 volt reference for the Peltier Cooler PID controller and a -2 volt reference for biasing of circuits. The circuitry had provision for system timeout, once the oar was turned on via a magnet and reed switch it could only run for a predetermined time (i.e. 2 hours) before it automatically shuts down.

3. Conclusions

The authors believe the first failure was caused by fibre damage prior to mounting and was independent of the embedding procedure. It is also possible to place the fibre on the compression face of the oar to reduce the likelihood of micro-fractures. At this point, the authors believe that the fibre will be mounted as a secondary step to oar manufacture due to the requirement of the fibre to exit into the internal cavity of the shaft. Other composite manufacturing methods may allow the fibre to be placed within the composite material during manufacture avoiding this secondary step.

Although this force sensing system will provide reliable hysteresis-free data, there are still a number of tasks to be completed before this is a reliable on-water training aid. Once the oar is characterized against temperature recalibration will not be necessary. The laser controller still needs some refining; there are some restrictions in the laser current control on the more powerful laser device. Machining of some special heat sinks to fit inside the oar will be necessary.

The authors have begun experimenting with heat pipes; a refrigerant pipe which can remove the heat down to the oar blade where the water can be used as a heat sink.

At present the authors are using an optical coupler to split the optical signal; an optical coupler reduces the optical power level by at least half. Optical circulators have a very low optical loss; if an optical circulator were to be used there will be no need to run the laser at a higher optical power level. If the optical power is reduced this will in turn reduce the current being drawn by the laser diode, and will also reduce the amount of current used to cool the laser device. With less current being drawn, it may be possible to reduce battery size and most importantly weight, and there will also be less heat dissipated from the heat sinks.

Acknowledgments

The authors would like to thank Vbragg Pty Ltd for their support during this project.

References

Aegis Semiconductor Pty. Mosquito TOD-050 Preliminary Datasheet (online). Available: http://www.oida.org/PTAP/prototypes/us_83_1.pdf (Accessed: 2006).

Lopez-Higuera J.M. (2002) Handbook of Optical Fibre Sensing Technology. *John Wiley & Sons,* West Sussex.

Lo Y.L. (1998) Using in-fiber Bragg grating sensors for measuring axial strain and temperature simultaneously on surfaces and structures. Opt. Eng. 37 (8).

Othonos A., Kalli k. (1999) Fibre Bragg gratings: Fundamentals and Applications in Telecommunications and Sensing. *Artech House*, Boston.

Superlum Diodes Pty. SLD-761-HP1-D134t-SM Preliminary Datasheet (online). Available: http://www.superlumdiodes.com/pdf/76hp.pdf (Accessed: 2006).