Distributed optical sensors: reliability and lifetime performance

Synaptec's optical sensor technology enables passive, distributed measurement of voltage, current, temperature, strain and vibration over 100 km of fibre optic.

This document evaluates the expected reliability and lifetime performance of these devices through review of studies to date and results of accelerated lifetime testing.

Introduction

Synaptec's distributed sensing platform consists of a compact interrogation device that passively and accurately measures values from up to 50 sensors measuring any combination of current, voltage, strain, vibration and temperature, using a single optical fibre over a distance of 100 km.

The core components forming each of these sensors are fibre Bragg gratings (FBGs) and multilayer piezoelectric stacks. Both of these are ubiquitous in fields such as instrumentation, medical devices, control systems, and precision engineering, and so have been studied extensively from the reliability standpoint.

In this document, the reliability of each component is considered in isolation, followed by preliminary accelerated lifetime testing performed by Synaptec for the core electrical sensing component.

Fibre Bragg Gratings

The core technology underpinning Synaptec's sensors is the fibre Bragg grating (FBG). FBGs are periodic perturbations in the refractive index along a fibre core, having peak optical reflection at a specific wavelength, known as the Bragg wavelength [1], and a typical physical length of 10 mm. In sensor applications, their wavelength-encoding nature, coupled with their simple reflected spectra, means that FBGs are relatively easy to interrogate and multiplex, and are effectively immune to the problems of intensity fluctuations, EM interference and attenuation [2]. For these reasons, the FBG is now ubiquitous in the field of optical instrumentation [3].

Peak optical reflection from an FBG occurs at a wavelength, λ, equal to twice the period of the grating; i.e. at $\lambda = 2n\Lambda$, where n is the fibre refractive index and Λ is the pitch of the grating. Straining or compressing the fibre longitudinally at the location of the grating will change the grating pitch, thus shifting up or down respectively the peak reflected wavelength. Similarly, changing the temperature of the fibre at the location of the grating will change the refractive index, again shifting up or down respectively the peak reflected wavelength. Illumination of the FBG by broadband light, and with suitable packaging to isolate the FBG from strain or temperature as required, may therefore be employed to utilise the FBG as a point sensor for strain or temperature.

Besides the optical fibre itself, FBGs are probably the most extensively-studied passive fibre sensor component with regard to reliability and lifetime performance [4]. Known fatigue modes include high and/or continuous applied strain, moisture or chemical ingress, and exposure to elevated temperatures.

Stress corrosion under high strain can lead to strength degradation and mechanical failure in FBGs [5]. One study of 45 typical FBGs indicates an average failure strain of 20,000 με, or 0.2%, noting that this value depends strongly on the mechanical assembly of the grating and is vastly superior to traditional electrical resistance strain gauges [6]. Studies by the Swiss Federal Laboratories for Materials Testing and Research (EMPA) conclude that FBG-based strain sensors experiencing strain levels of 0.2% demonstrate "flawless" performance over a period of several years, and notes "the potential of Bragg gratings for long term monitoring at strain levels even above 2%" [7]. Other studies have shown that lifetimes in excess of 5 years were achievable with as much as 0.5% continuous strain [4] [8]. Synaptec's electrical sensors are designed to experience a maximum strain of <0.05%, far below the strain fatigue limits suggested above.

Moisture or chemical ingress into the fibre coating or core can lead to undesirable humidity-dependent performance [9] [10]. For this reason, the active elements of Synaptec's sensors are sealed off from the environment; e.g. ceramic housings for temperature sensors and hermetically-sealed telecoms-style packages for electrical sensors, ensuring that that this particular failure mode is removed.

FBGs are commonly deployed for pressure and temperature sensing in oil wells, during which operating temperatures can regularly be in excess of 200 °C. Studies have shown that correctly housed and annealed FBGs remain stable to within a wavelength perturbation of 1 pm at 230 °C over a period of five years [5]. Synaptec's sensors are typically deployed to maximum temperatures of 80 °C (for strain, vibration and electrical sensing) and 120 °C (for temperature sensing), for which high-temperature degradation of the FBG is expected to be negligible.

‘Mean time before failure’ (MTBF) statistics are often difficult to obtain from sensors deployed in the field. However, anecdotal evidence from companies that employ FBGs as strain gauges indicate that significant lifetimes are commonly achievable; Micron Optics, for example, note that of roughly 20,000 FBG-based mechanical sensors sold since 2012, a total of nine have shown signs of failure, or a failure rate of <0.05%. Again, the stresses applied to Synaptec’s sensors during operation are significantly smaller than those considered in that study.

Multilayer Piezoelectric Stack Actuators

In Synaptec’s electrical sensors, a multilayer piezoelectric stack actuator is employed to convert an applied voltage into a strain on an FBG. Multilayer piezoelectric stacks have a number of known failure modes, including thermal breakdown, excessive acceleration or loss of polarisation due to very high voltage impulses, and high humidity leading to degradation of the material performance. Each of these is addressed by the design of Synaptec’s electrical sensors: the active elements are housed in a telecoms-style package, baked out to remove moisture, filled with inert nitrogen gas, and hermetically sealed to limit environmental influence on device lifetime. The voltage applied to the stack is also limited to reduce the potential for self-heating and loss-of-polarisation.

With the actuator isolated from these effects, the remaining fatigue modes relate to ageing of the piezoelectric material. ‘Ageing’ refers to reduction in remnant polarisation, and hence reduced sensitivity to an applied voltage. The same multilayer piezoelectric stack used by Synaptec has been extensively tested in this regard by both the manufacturer, Physik Instrument GmbH [11] [12], and NASA [13] [14], indicating that these same multilayer actuators can be exposed to more than 100 billion cycles without failure, which in a power systems application is equivalent to a lifetime in excess of **68 years at 60 Hz** and **82 years at 50 Hz** with 100% duty cycle.

Results of the NASA tests for ten actuator samples are shown in Figure 1. For all stacks tested, after 100 billion cycles there were found to be no catastrophic failures. A predictable, logarithmic degradation in the stroke length of the piezos was measured to degrade at a predictable rate of 0.65% per decade time. Synaptec actively compensates for this known lifetime degradation in the sensitivity of the piezoelectric to an applied voltage to ensure that sensor accuracy is maintained over the lifetime. It was also noted that the actuators could be re-poled to their original stroke by application of 100 VDC. Note that throughout this test, the actuators were subjected to a 20 V ac signal and 10 V dc offset; this is a significantly larger nominal voltage than is applied during normal operation of Synaptec’s electrical sensors, and so degradation of performance can be expected to be even slower.

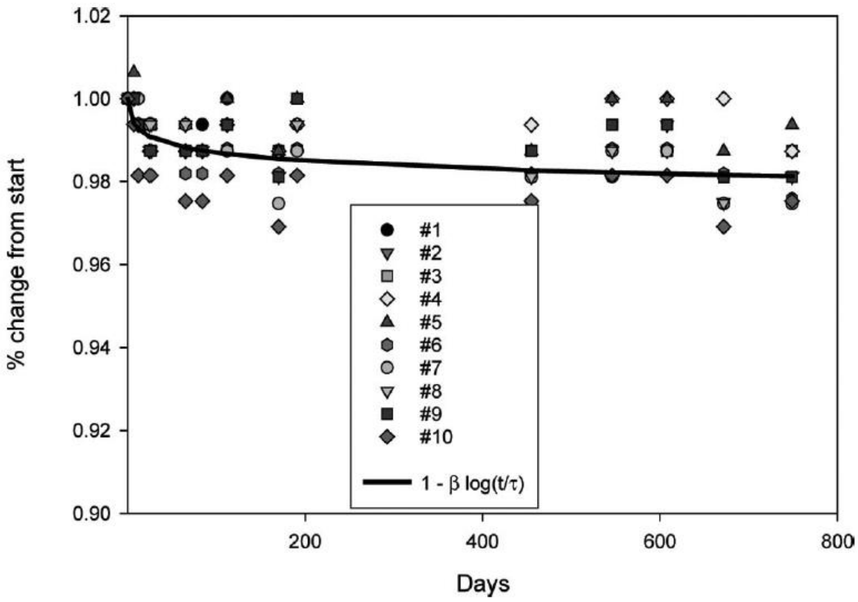

Figure 1: Stroke length of ten piezoelectric stacks of the type employed by Synaptec (from [14]). Each device was cycled at 2 kHz for a period of 749 days, corresponding to equivalent lifetimes of 68 years at 60 Hz and 82 years at 50 Hz.

Accelerated Lifetime Tests

Synaptec has performed limited accelerated lifetime testing of electrical sensors (although it should be noted that these tests necessarily include accelerated fatigue of the core FBG element, and so the results are equally applicable to the mechanical sensors).

In these tests, a representative sample of Low-Voltage Transducers (LVT), the core embodiment of Synaptec's electrical sensing technology comprising an FBG and multilayer piezoelectric stack actuator, were subjected to a sinusoidal voltage signal of amplitude 1 V and frequency 5 kHz. Since these sensors are designed for power systems applications with an assumed nominal operating frequency of 50 Hz, driving at this frequency is assumed to age the transducer at a rate 100x faster than in its deployment environment. For these preliminary tests, sensors were monitored at regular intervals for approximately 18 months at room temperature, corresponding to an equivalent lifetime of almost **140 years**. The sensitivity of each sensor record over this time is shown in Figure 2. During this time, no failures were recorded, and the sensitivity of each device was not observed to degrade beyond the limits expected from the NASA study shown in Figure 1.

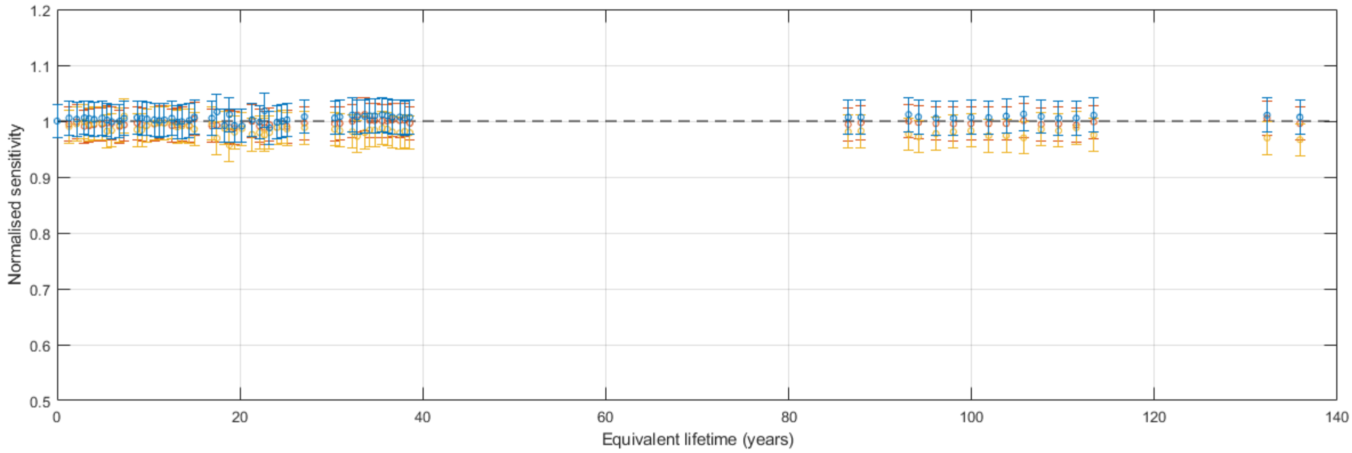

Figure 2: Preliminary accelerated lifetime testing of Synaptec sensors.

Synaptec intends to embark on additional accelerated lifetime testing (including temperature cycling and variable applied voltages) during 2020. However, the extensive studies performed on the core subcomponents and discussed above imply that the lifetime of these sensors is far in excess of that demanded by core instrumentation for the power sector.

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