Application of long-period grating sensors to respiratory function monitoring

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ABSTRACT

A series of in-line curvature sensors on a garment are used to monitor the thoracic and abdominal movements of a human during respiration. These results are used to obtain volumetric tidal changes of the human torso showing reasonable agreement with a spirometer used simultaneously to record the volume at the mouth during breathing. The curvature sensors are based upon long period gratings written in a progressive three layered fibre that are insensitive to refractive index changes. The sensor platform consists of the long period grating laid upon a carbon fibre ribbon, which is encapsulated in a low temperature curing silicone rubber. An array of sensors is also used to reconstruct the shape changes of a resuscitation manikin during simulated respiration. The data for reconstruction is obtained by two methods of multiplexing and interrogation: firstly using the transmission spectral profile of the LPG's attenuation bands measured using an optical spectrum analyser; secondly using a derivative spectroscopy technique.

Keywords: Curvature Sensing, Long Period Gratings, Respiratory monitoring

1. INTRODUCTION

Non-invasive measurement of thoracoabdominal surface motion can provide a comprehensive appreciation of respiratory function and enhance our understanding of respiratory physiology. Knowledge of the total and regional deflection of the surface during breathing not only provides a key to the volumetric flow of gases but also provides an insight into the thoracic and abdominal contributions and the recruitment of muscles. Until now research in this field has been predominantly laboratory based, however the provision of a reliable quantitative clinical tool for making such measurements in ambulatory patients would advance routine respiratory function monitoring to a similar point as that which has been accomplished with 24 hour cardiovascular monitoring in recent years.

Konno and Mead [1] first demonstrated that respiratory gas flow could be measured at the surface of the chest and abdomen thus negating the need for measurement of flow at the mouth, which is the clinical standard at present. A number of measurement devices have been developed following Konno and Mead; techniques include: Respiratory Inductive Plethysmography (RIP) [2], Optical Reflectance Plethysmography (ORP) [3] and the use of magnetometers [4]. Each of these has certain limitations for use in ambulatory respiration monitoring; these pertain to the accuracy over wide variations in tidal volume and changes in posture after the calibration of RIP [5]. This can be addressed by using a sensor array [6], however the solution relies heavily on model based signal processing. The cost and realisation of a sufficiently dense array of magnetometers is prohibitive. Whilst the ORP methods lack such limitations they rely on an off body reference with which to track specified anatomical locations. Present instrumentation is bulky and generally has to be operated while the patient occupies a confined area. It follows that the technique is not suitable for routine ambulatory monitoring.

The fundamental requirement is to create a highly compliant sensor with which to track selected anatomical positions on the chest and abdomen surface. A possible solution to this problem is to use a fibre Long Period Grating (LPG) as the sensing element. Recent work [7-10] using fibre LPGs to monitor shape changes (bending) is promising but there is one major disadvantage: to interrogate the LPG an expensive broadband light source is required along with a bulky optical spectrum analyser (OSA), which is also expensive.

This paper presents a possible solution to mobile respiratory function monitoring, using a sensor that utilises an LPG sensing element. Several aspects of our investigations into these devices are presented. Firstly the curvature sensors are

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adhered to a garment which is used to detect the shape/curvature variations of the chest and abdomen regions of a human torso during respiration using the transmission spectrum of the LPG's attenuation bands. Secondly a sensor is used to reconstruct the shape variation of a resuscitation manikin during simulated respiration. Thirdly a sensor working in conjunction with a signal-processing scheme from derivative spectroscopy [11] is used in the same procedure with the resuscitation manikin. Fourthly, we provide demonstrations of the multiplexing capability of the interrogation scheme, which utilises fibre Bragg gratings (FBGs) to address an in-line series of LPGs to detect curvatures and hence reconstruct the shape of the resuscitation manikin.

2. The Curvature Sensor

The curvature sensor utilises an LPG as the sensing element. LPGs are photoinduced fibre devices that couple light from the core of a single-mode optical fibre into the cladding at discrete wavelengths and thereby generate attenuation bands in the transmission spectrum of the optical fibre core. LPGs are sensitive to strain (ε), temperature (T), and the surrounding refractive index (n_s) [10,12]; the LPG's sensitivity to these parameters can manifest itself in two ways: firstly the central wavelength of the attenuation band can shift in the spectral domain and secondly a change in the spectral transmission profile of the attenuation band may occur. Also, LPGs have been used as a shape/bend sensor [13,14], since the LPG's attenuation bands are spectrally sensitive to bending, which induces both a wavelength shift and a change in the spectral profile of the attenuation band. The spectral shift of the attenuation band arises from the phase match condition of the LPG, given by

$$\lambda_i = \delta n_{eff}\Lambda \equiv \left[n_{co}\left(\lambda_i, n_1, n_2, T, \mu\varepsilon, R\right) - n_{cl}{}^{1\nu}\left(\lambda_i, n_1, n_2, T, \mu\varepsilon, n_s, R\right)\right]\Lambda \tag{1}$$

where n_{co} is the effective index of the core mode and $n_{cl}^{1\nu}$ is the effective index of the 1νth radial cladding mode, both indices being dependent on the core refractive index n_1, the inner cladding refractive index n_2 and the wavelength λ. Also, $n_{cl}{}^{1\nu}$ is a function of the refractive indices of the surrounding medium, n_s. Λ is the period of the LPG, T the temperature, ε the strain and R the curvature experienced by the fibre. Whilst equation 1 gives the spectral position of the attenuation band, the magnitude of the spectral shift induced by the measurands (ε, T, n_s) is dependent upon two factors: the difference between the effective refractive indices and also the difference between the group effective refractive indices of the two modes [14]. The spectral sensitivity of LPGs to bending arises from two major components, the strain sensitivity (ε) and the effective change in the refractive index profile of the fibre induced by the bend itself; the sensitivity can be calculated using a conformal mapping technique [15]. The bending of the optical fibre induces changes to the propagation constants of the cladding modes thus changing the group refractive indices as well as the effective refractive indices.

The curvature sensor consists of a LPG (length 7cm) that is written in a progressive three layered fibre using a point-by-point method [16]. The result of using such a fibre is that the LPG produces attenuation bands that are insensitive to changes in the surrounding medium's refractive index. The LPG is laid upon a carbon fibre ribbon, which is then encapsulated in a low temperature (90°C) curing silicone rubber. This type of silicone rubber is used to reduce any changes of the LPG's attenuation bands that may arise due to thermal annealing. The sensor construct was designed to prevent the fibre from experiencing significant axial strain and to provide a flexible stage for bending as well as a thermally insulating layer for the respiratory function monitoring application (reducing the effects of rapid ambient temperature fluctuations). The thermal spectral sensitivity results are illustrated in figure 1 along with the normal temperature variation of the skin [17]. The sensor is intended to be worn close to the skin and be insulated from the surrounding air, and so this is the temperature range that the sensor must normally accommodate

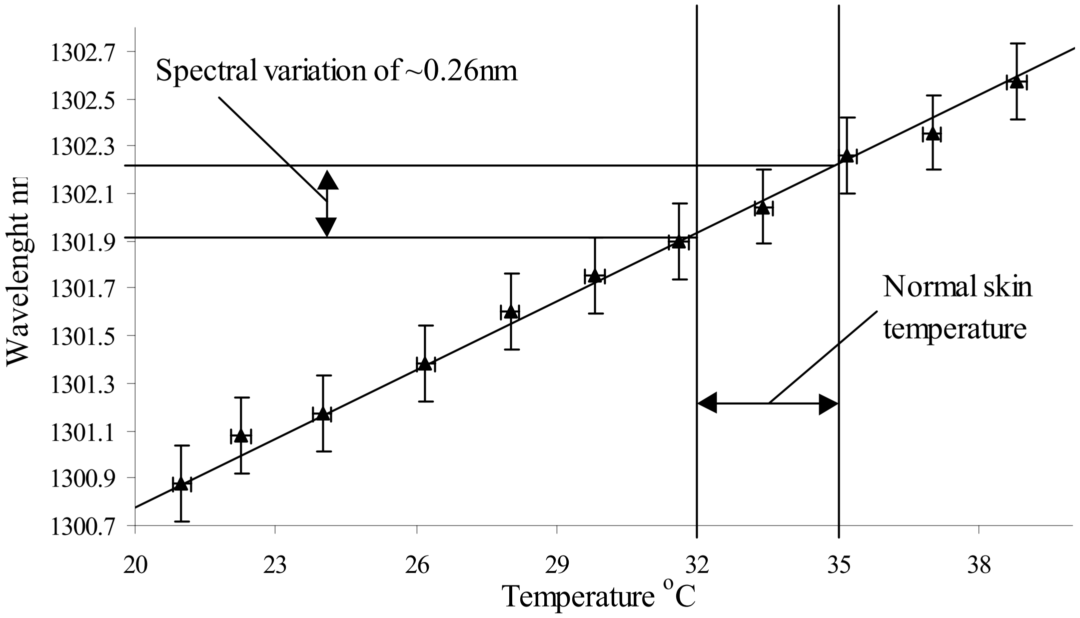


Figure 1. The spectral sensitivity of a curvature sensor using a LPG with period 350×10^{-6}m. The error bars indicate the accuracy of the OSA (±0.04nm).

3. Interrogation Schemes

Derivative spectroscopy was originally developed for wavelength modulation absorption spectrometry and involves applying a small sinusoidal wavelength modulation to the optical source wavelength [18]. This technique is mostly used for environmental monitoring and remote sensing as well as spectrochemical applications, e.g. NO_2 and CCl_4 detection.

This approach is used to detect the changes in the spectral transmission profile of the LPG's stop band induced by the bending of the LPG. Modulating the wavelength of a narrow line-width source, such as distributed feedback (DFB) laser, at a given frequency will generate a series of harmonics of the modulating frequency [19] in the output signal reflected from the LPG. It has been shown that the in-phase component of the nth harmonic output is proportional to the nth derivative of the spectral profile under investigation [18]. The amplitudes of the first and second harmonics are therefore proportional to the first and second derivatives of the spectral transmission function of the sensor, and the utility of our approach relies on the ratio of those derivatives being a unique function of the position in the spectral profile as well as being independent of any attenuation in the system. This interrogation technique has been demonstrated with a single LPG using a pigtailed DFB laser as the light source [19].

Interrogating several in-line LPGs would require a matching number of DFB lasers, which could prove to be expensive. To reduce the cost of the interrogation scheme a single light source was used to illuminate the in-line LPGs: a Superluminescent Light Emitting Diode (SLED) with an output power of 5mW. The SLED illuminates a series of in-line fibre Bragg gratings via a circulator, each of them attached to a Piezoelectric Transducer (PZT) extender to mimic a series of in-line DFB lasers. Whilst the cost of a SLED is similar to a single DFB laser, the combination of a single SLED and FBGs can, in principle, interrogate several LPGs in-series over a large range of wavelengths, therefore simplifying the overall sensor array architecture and reducing the total number of sources and detectors required to service the LPG sensors, thereby reducing cost.

The FBG's reflected spectra, have typical bandwidths in the range of 0.2nm to 0.4nm; they are spectrally matched to the sensing LPGs, which have bandwidths around 12 nm (with the FBGs initially at slightly longer wavelengths than the central wavelength of the LPG's attenuation bands). A sinusoidal voltage is applied to the PZT extenders to induce a sinusoidal wavelength modulation in the reflected spectra of the FBGs, which are then used to interrogate the LPGs, mimicking the modulated DFB laser in [11] (see figure 2 for a schematic of the interrogation/multiplexing scheme).

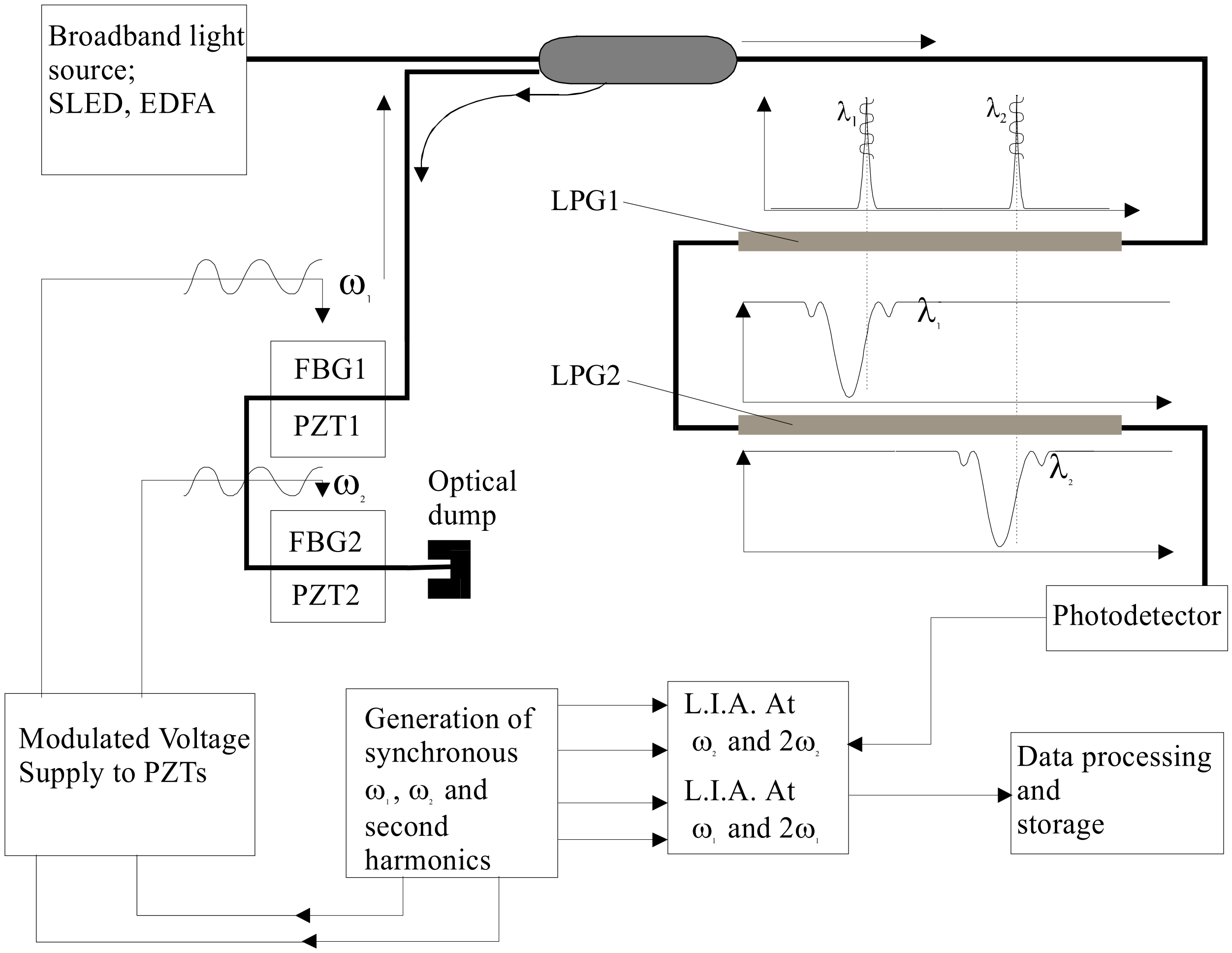


Figure 2. A schematic of interrogation/multiplexing scheme.

The derivative spectroscopy interrogation technique has been demonstrated by our research group using LPGs in conjunction with FBGs; for more details see [11]. This technique also has multiplexing capability, which has been demonstrated using two pairs of spectrally matched uniform gratings with central wavelengths of 1522.5nm (FBG1) and 1535.4nm (FBG2), giving a 13nm spectral separation. The PZTs holding the two FBGs were modulated at various voltages to obtain a range of amplitudes of wavelength modulation ($\Delta\lambda$) at the fundamental frequencies of 4.65 kHz and 5.25 kHz; this will affect the amplitudes of the harmonics generated from the LPGs. The transmitted signal from the pair of sensing LPGs was fed to a single photodetector and the resulting electrical signal passed to two sets of lock-in-amplifiers for synchronous detection at the fundamental frequencies and their second harmonics at 9.3 kHz and 10.5 kHz. The lock-in amplifiers are combinations of electronic components which include a quadrature oscillator that generates the fundamental frequencies used to drive the PZTs as well as 90° phase shifted outputs used in the demodulation of the signals. The references for the second harmonics are generated using two electronic multipliers by squaring and subtracting the quadrature waveforms to obtain $\cos(2\varphi)$ and multiplying the waveforms to get $\sin(2\varphi)$. Signal demodulation is achieved by using synchronous rectifiers; these are used to discriminate against other frequencies, phase generated noise and thermal drift.

The output spectrum of the photodetector was monitored on a spectrum analyser (Tektronix, 340A) with a resolution of 50Hz and a typical frequency spectrum is shown in figure 3, which illustrates the simultaneous multiplexing capability of this sensing scheme.

Inspecting the frequency spectrum of the signal from the photodetector over a range of modulation voltages applied to the PZT extenders showed that the maximum signals were typically between 30dB to 40dB above the noise-floor for the fundamental modulation frequencies and 20dB to 30dB for the second harmonics. The signal to noise ratio varied with the curvature experienced by the LPG sensors. The stabilities of the harmonics were monitored over a ten minute period and it was found that the standard deviations from the means of the first harmonic amplitudes generated an error of ±0.4% and the second harmonics ±0.8% of the curvature range, a little higher than for the single channel. We feel this slight increase is not significant, probably being due to slightly increased ambient temperature

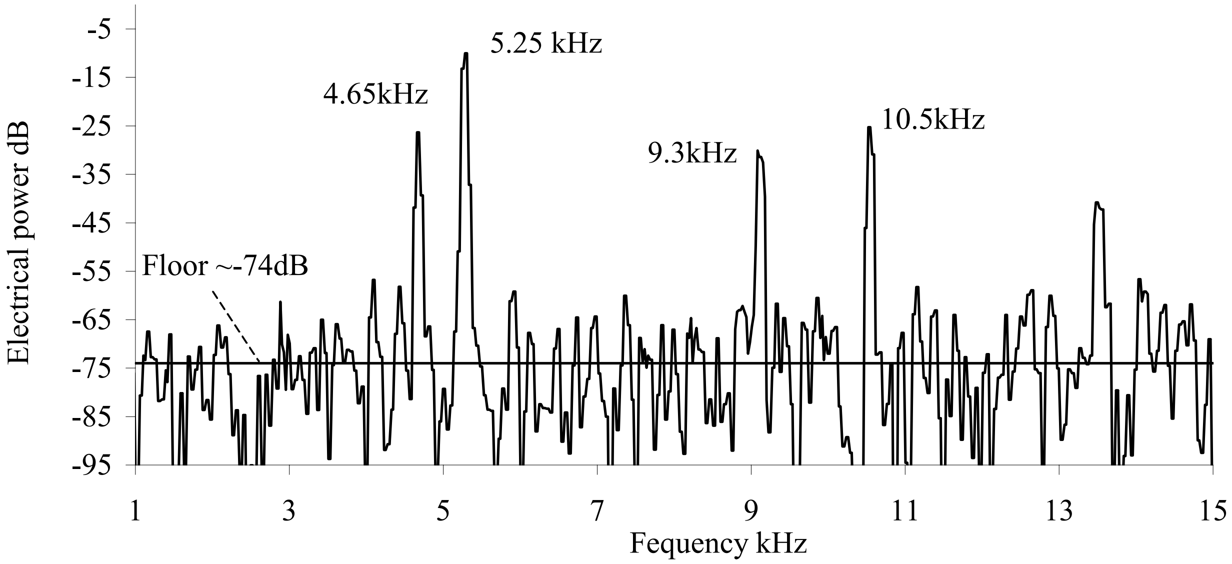
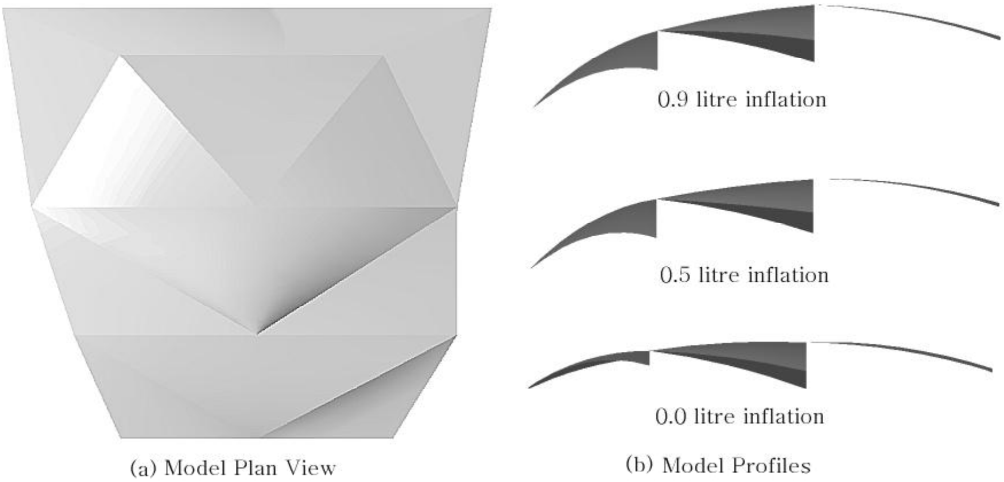


Figure 3. The output frequency spectrum of the interrogation/multiplexing technique. A photodetector is monitoring two in-line LPGs that are spectrally matched to FBGs with wavelength amplitude modulations of FBG1 ($\Delta\lambda$ =±0.063nm) and FBG2 ($\Delta\lambda$= ±0.05nm).

4. Detection and Monitoring of Respiration using a Curvature Sensor Array

Firstly, in order to validate the sensor design and the derivative spectroscopy interrogation technique for the intended application, a commercial manikin used as a resuscitation training aid was employed [20]. This comprises a rigid under-frame over which is stretched a polymer skin. An air bag placed between the frame and skin, when inflated or deflated, is then used to simulate expansion and contraction of the surface of the torso in similar volumetric proportions to that of breathing. This provides a test platform of similar dimensions and shape variation to those that are expected in use but capable of providing far greater repeatability.

Two in-line curvature sensors were used to record the variation of the curvature at various states of inflation from 0 litres to 0.9 litres in increments of 0.5 litre. Sensors at two locations were simultaneously monitored over the volume range then moved to different locations and inflated over the same volume range. The manikin was inflated using a calibrated 1 litre syringe [21]. The curvature was measured in two ways, firstly with the transmission spectrum obtained directly from an OSA and secondly using the derivative spectroscopy interrogation technique described above; both sensors having been calibrated for curvature. Using the OSA, the spectral sensitivities of the two sensors were $d\lambda/dR$=7.4±0.3nm m and $d\lambda/dR$=7.5±0.3nm m, which provided a curvature resolution for the sensors of $3.5\times10^{-2}m^{-1}$. The derivative spectroscopy technique yielded sensitivities of $d(\mathrm{Arctan}\{\mathrm{Ratio}\})/dR=1.563\pm7\times10^{-3}$nm m and d(Arctan{Ratio})/dR=1.617±9×10^{-3}nm m, which translate to an average curvature resolution of about 6.2×10^{-2}m^{-1} for each sensing element. Figure 4 depicts the static reconstruction of experimental data from the manikin using commercial Computer Aided Design software. In this model the location of each centre of curvature is confined to the vertical plane where it existed on the non-inflated manikin. The overall profile is determined by successively linking the arcs of curvature in those respective planes. Figure 4(a) shows the location of sensing sites on the experiment at the edges of the triangular patches, giving 13 sensors (two on the top edge). Smoothing of the profile is accomplished by setting peripheral relationships between curves and the application of lofting algorithms built into the software. The relatively small number of sensing locations employed in this experiment reduces the fidelity of the model. Figure 4 shows that the sensors are sensitive enough to distinguish between various inflation volumes as shown in the lateral profiles 4(b).



(a) Model Plan View (b) Model Profiles

Figure 4. A shape reconstruction of a resuscitation manikin using the derivative spectroscopy interrogation scheme with the curvature sensors at 13 locations; (a) shows the overall reconstruction of the manikin (b) shows the cross-sectional variation of the manikin at various volumetric inflation.

5. MONITORING HUMAN RESPIRATION USING CURVATURE SENSORS

Four curvature sensors (length of 15cm) were connected in-line. The sensor array was stitched to a Lyrca vest for a practical evaluation of the sensors. In addition to the two characterised sensors from the previous section two additional sensors were used with central wavelengths of 1299nm and 1548nm. These additional sensors were characterised for wavelength shift as a function of curvature, giving spectral sensitivities of $d\lambda/dR$ = -1.53±0.04nm m and $d\lambda/dR$ = 8.3±0.3nm m, respectively; these gave a similar curvature resolution ($3.5\times10^{-2}\text{m}^{-1}$) to those of the previous sensors. The Lyrca vest was placed on a human male at two different locations: the front and side of the torso. The sensors were illuminated with a broadband light source and the wavelength shifts of the attenuation bands were monitored with an OSA controlled by a computer. The sweep time of the OSA over the wavelength range was 20ms and the spectral resolution was 0.1nm. Whilst the sensors were being monitored during inspiration and expiration, the volume changes were simultaneously recorded at the mouth of the subject using a turbine transduction Spirometer system (Micro Medical, UK). Linear regression was applied to predict mouth volume from the sensor signals for the two spatial locations of the sensor array. It was found that an accurate assessment of tidal breathing can be made which is similar to the accuracy found with an external optical system using 80 sensor points on the thorax [22,23]. A direct comparison is shown in figure 5 of the volume measured from the mouth with the spirometer and the volume calculated from the curvature-sensing array

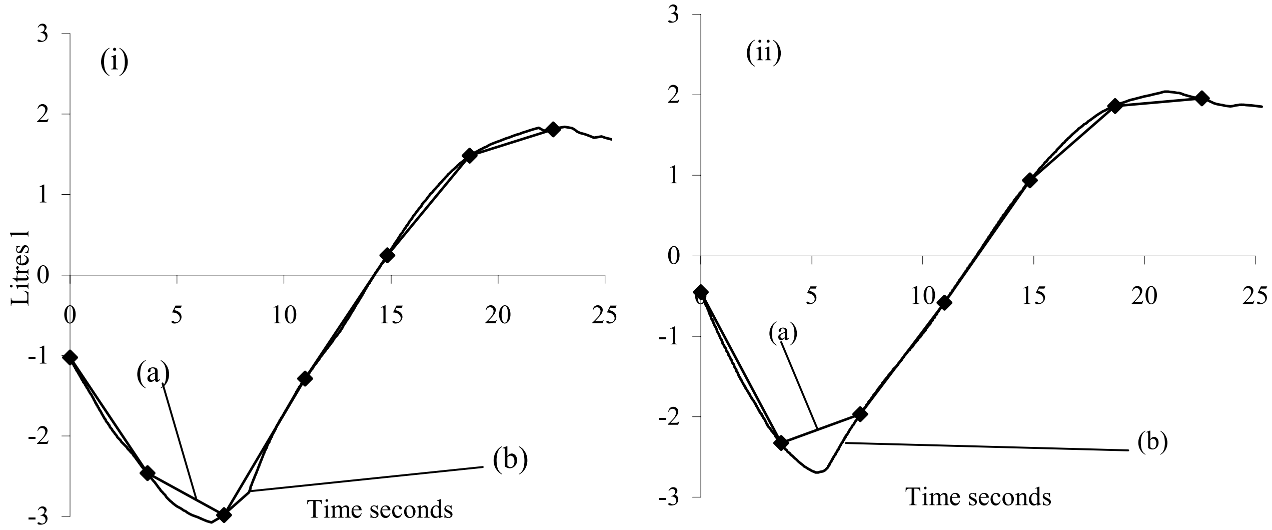


Figure 5. Two typical (i and ii) volumetric variations during a long tidal breath as measured using the Spirometer and the calculated volume from the curvature sensors as a function of time with array location on the front of the torso, (a) the measured tidal volume from the mouth, (b) the predicted volume obtained from the response of the curvature sensors.

Whilst the data show reasonable agreement there are only five points obtained from the sensing system; this was due to the limited capture rate of the Labview program on the computer, but the exercise demonstrates the sensors' capabilities for this application. The implementing of the derivative spectroscopy interrogation technique will significantly increase the sampling rate of the interrogation scheme. It is no surprise that for the current implementation a reasonable fit can be obtained, but the issue will be how stable are the regression (calibration) coefficients for each curvature sensor with respect to time, body position and movement when a many sensor-array vest is used. This is the subject of current work.

Using these fibre optic curvature sensors it is possible to measure movement of the chest wall without any inhibition of that movement. Also when these sensors are incorporated in a vest and working in conjunction with the derivative spectroscopy interrogation technique, they have the potential to be made small and portable for ambulatory respiratory monitoring. The fibre optic sensing array/garment will be developed with shorter length sensors with an increased number of sensors in accordance with reference [7] (20 sensors) to improve the accuracy and range of ventilatory manoeuvres that can be recorded.

6. CONCLUSION

A number of curvature sensors were fabricated. The sensors are based upon long period gratings that are written in a progressive three layered fibre, which is insensitive to refractive index changes. The sensor consists of the long period grating laid upon a carbon fibre ribbon, with this then encapsulated in a low temperature curing silicone rubber, the complete assembly exhibiting negligible response to axial stress. A curvature sensing interrogation and multiplexing scheme based upon a derivative spectroscopy technique was successfully implemented. An array of sensors were used to reconstruct the shape changes of a resuscitation manikin during simulated respiration.

A series of in-line curvature sensors on a garment have been used to monitor the thoracic and abdominal movements of a human during respiration. These results are used to obtain volumetric tidal changes of the human torso which showed reasonable agreement with a spirometer used simultaneously to record the inspired and expired volume at the mouth. It has been demonstrated that such sensors can be used to distinguish between the various geometric variations associated with different locations on the thorax and abdomen during respiratory movement. It was also observed that the general functionality of the curvatures for a given torso location as a function time are repeatable for each breath. This respiratory system has the potential to be made small, portable and cost effective for field operation and ambulatory respiratory monitoring.

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