Vibration-insensitive temperature sensing system based on fluorescence decay and using a digital processing approach

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Abstract. A fluorescence-based temperature sensor system using a digital signal processing approach has been developed and evaluated in operation on a working automotive engine. The signal processing approach, using the least squares method, makes the system relatively insensitive to intensity variations in the probe and thus provides more precise measurements when compared to a previous system designed using analogue phase-locked detection. Experiments carried out to determine the emission temperatures of a running car engine have demonstrated the effectiveness of the sensor system in monitoring exhaust temperatures up to 250°C, and potentially higher.

1. Introduction

The measurement of temperatures is particularly important in industry and to do so a wide range of technologies is available [1]. Among the many sensor applications seen today in the automotive field, it is important to be able to measure the temperatures of the exhaust gases as part of an overall monitoring scheme for pollutant gases [2], recognising as well that the optical absorption of the gaseous various species is temperature dependent [3]. Vehicle emissions can be hostile with hot with corrosive gases being present, in addition to which electromagnetic radiation is generated, and these factors may affect the sensor performance for the range of measurements that is required in a working engine. It is important to note that optical fiber sensor systems offer an important solution to the
effective monitoring of gas species and temperatures, as they can be miniaturized, and made robust and thus immune to the above deleterious effects.

A number of fluorescence-based optical fibre temperature sensors, such as the fluorescence intensity-ratio-based system [4], and the fluorescence decay lifetime-based system [5,6], have been developed over several years and have been widely used in a range of industrial applications. Their relative performance features have been discussed in some detail by Collins et al [7]. When they are designed for vehicle emission monitoring, they are exposed not only to high temperatures and a chemically corrosive environment but to vibration from the engine. This is an important issue which needs to be taken into account, as a working car engine creates a range of vibration conditions, whenever it starts, runs or stops. If the design and construction of the probe is not carefully carried out, the work herein has shown that the vibration of an engine will introduce an intensity fluctuation of the sensor signal received, and this may affect the precision of the sensor system installed in the engine or exhaust compartment. As a result, the monitoring system used is required to be vibration resistant for practical automotive applications. The fluorescence-based temperature sensor reported by some of the authors, using analogue phase-locked detection (PLD) technology and developed previously, has been tested and evaluated for temperature monitoring of engine emissions [5]. The results obtained have shown that the measurement precision of this analogue approach for a ‘spot’ measurement was dramatically decreased compared to that seen under vibration-free conditions. The main reason for this performance degradation is that the analogue signal system was affected by the small changes in the signal intensity arising from the system design and caused by the high-frequency vibration experienced by the probe mounted on the engine pipeline.

It is essential to develop a new method to improve the precision and utility of the fluorescence-based temperature measurement system for this important role in engine emission temperature monitoring to allow it to function effectively under the vibration conditions experienced in a working automotive engine. To do so the probe has been carefully redesigned and a new digital scheme, based on data processing approach, has been developed, evaluated, and cross-compared in this work with the results obtained using an analogue PLD method under both vibration and non-vibration conditions.

2. Signal processing schemes for fluorescence-based temperature measurement

2.1 The analogue PLD approach
The phase-locked detection (PLD) scheme has been used for the measurement of the fluorescence decay lifetime by some of the authors and this has been described in detail elsewhere [6]. In summary, the temperature is obtained through monitoring the fluorescence lifetime of a rare earth doped material, which is temperature dependent. A typical system setup is shown in Fig.1, where the fluorescent medium, Tm-doped YAG in this case, is excited by light from a laser diode light source operating at 785 nm, coupled to the active material through a silica Y-shaped fibre bundle. This material has been chosen as it covers the temperature range required and is robust in the presence of corrosive gases. The fluorescence emission fed back is detected with an InGaAs photodiode, and the lifetime is extracted using the PLD scheme. This system shows a high stability with a stable intensity
of the fluorescence signal; however, in tests an unacceptable level of fluctuation due to temperature changes was observed when the probe is mounted on an operating car engine, even when the emission temperature is constant. This is due to the vibration of engine which affects the fluorescence signal actually received and monitored with signal detection scheme and thus the precision of the temperature measurement obtained during these tests.

**Figure 1.** Schematic of the analogue fluorescence-based temperature system discussed in this work

### 2.2 The digital signal processing approach

In order to reduce the fluctuation of the temperature measurement seen from the use of the analogue scheme, a novel approach based on digital data processing was proposed and implemented. The digital fluorescence sensor system is illustrated in Fig. 2. A TTL pulsed signal is used to modulate the laser diode and trigger the Data Acquisition (DAQ) card. The fluorescence decay signal is acquired and passed to a computer by the DAQ card. A Labview-based data processing program was developed to obtain and display the fluorescence lifetime and calculate the corresponding temperature, using an appropriate data processing method discussed below.

The least squares method is used in this work for the data processing, as it offers advantages over the others in terms of accuracy and response time. The optimum sampling rate was chosen, based on the theoretical analysis and the experimental results obtained.

**Figure 2.** Schematic of the digital fluorescence-based temperature system developed for this work
2.2.1. The least squares method used for fluorescence decay time analysis.

After the termination of the excitation light, the temperature-dependent fluorescence decay signal may be described as a single-exponential by:

\[ I(t) = I_0 \exp(-t / \tau) \]  

(1)

where \( I_0 \) is the initial fluorescence intensity, \( I(t) \) is the signal intensity at time \( t \), and \( \tau \) is the corresponding fluorescence lifetime, which is temperature dependent and acts as the basis of the measurement. The digital approach proposed in this work is used to calculate the lifetime, \( \tau \), from the signal, \( I(t) \), using the least squares method, and the temperature is obtained by calibration against the lifetime \( \tau \) using an oven, as discussed in section 2.2.2.

For a single-exponential regression, the Levenberg-Marquardt Method\[8\] can offer a high accuracy in the calculation, but at a cost of a longer computing time-longer than is suitable for the real time measurement application of this work. The least squares method, however, provides a solution with faster speed and acceptable accuracy, and this is discussed as follows.

Assuming that \( \{I_{im}, t_{im}\}, (where \ i = 1,2,3) \), is a set of measured data, which may satisfy Eq.(2):

\[ I_{im}(t_{im}) = I_0 \exp(-t_{im} / \tau) + \delta \]  

(2)

in which \( x_{im} = t_{im} \), then Eq.(2) can be re-written as

\[ y_{ic} = a \cdot x_{im} + b \]  

(3)

where, \( b = \ln I_0 \), \( a = -1 / \tau \), \( y_{ic} \) is an estimated value, and \( \delta \) is the excitation leakage or baseline of the signal. The sum, \( Q \), of the square residual between the measured and the estimated \( y \)-value is given by

\[ Q = \sum_{i=1}^{n} (y_{ic} - y_{im})^2 \]  

(4)

where \( y_{im} = \ln(I_{im} - \delta) \) and \( n \) is the number of data points. The preferred values of \( a \) and \( b \) are obtained by minimizing the parameter \( Q \) which is shown in Eq.(4) [9].

\[ a = \frac{\sum_{i=1}^{n} (y_{im} - \frac{1}{n} \cdot \sum_{i=1}^{n} y_{im}) \cdot x_{im}}{\sum_{i=1}^{n} (x_{im} - \frac{1}{n} \cdot \sum_{i=1}^{n} x_{im}) \cdot x_{im}} \]  

\[ b = \frac{1}{n} \cdot \sum_{i=1}^{n} y_{im} - a \cdot \frac{1}{n} \cdot \sum_{i=1}^{n} x_{im} \]  

(5)
Thus the fluorescence lifetime, which may be calibrated as a function of temperature, $T$, can be given by Eq. (6).

$$\tau = \frac{1}{a}$$  \hspace{1cm} (6)

2.2.2 The sampling rate.

The single-exponential fluorescence decay signal in the time domain can be transformed to one in the frequency domain by using a Laplace transform as shown:

$$I(s) = \frac{I_0}{s + 1/\tau} \quad (s = j \cdot \omega)$$  \hspace{1cm} (7)

where $\omega$ is the frequency of the exponential decay signal in frequency domain. For a non-periodic continuous exponential signal, the bandwidth of $\omega$ is infinite. In practical applications, the bandwidth is set at a cut off frequency $\omega_{\text{max}}$, which satisfies Eq. (8):

$$|I(j \omega_{\text{max}})| = \beta \cdot I(0)$$  \hspace{1cm} (8)

where $|I(j \omega_{\text{max}})|$ is the modulus, given by $I(0)$ at $\omega = 0$. To ensure effective sampling, the value $\beta$ was empirically set to 0.05, and the maximum value was calculated to be $\omega_{\text{max}} = 2\text{kHz}$ for a lifetime value of 0.01s. The sampling rate to reconstruct the original signal is required to be faster than twice the value of $\omega_{\text{max}}$ according to the Shannon Sampling theorem[10], and a higher sampling rate may result in noise and thus a large variation in both $\tau$ and thus the temperature.

2.2.3 Temperature calibration.

The probes constructed were calibrated against the output of a K-type thermocouple held in intimate contact with the fibre optical-based probe using a CARBOLITE tube oven installed in the laboratory.

The temperature variation from a typical probe used in such a calibration was recorded under different sampling frequencies when the initial intensity was varied within a value corresponding to 2 volts on the detector output of the initial value. At a temperature of 200°C, the results obtained are illustrated in Fig. 3, which shows that the minimum recorded temperature variation can be achieved when the sampling rate was 6 kHz. The optimum sampling rate was found to vary accordingly with the measured temperature changes. In this work, a 5kHz sampling rate was chosen for the specific engine emission monitoring as this enabled the range of temperature experienced to be measured successfully.
3. Experiments and results

3.1 Experimental setup

The fluorescence-based temperature sensor systems discussed above, using both the analogue and digital approaches, were subjected to various vibration conditions created in a test on a working automotive engine at the University of Liverpool. The optical probes, used with a K-type thermocouple for comparison, were fixed inside the exhaust pipe of the engine, as shown in Fig.4.

3.2 Temperature monitoring of the emission of a running car engine

A series of tests on the fibre optic probes and signal processing scheme discussed was carried out under different vibration conditions, these being achieved by careful control of the engine conditions: i.e. running at a constant speed, at a regularly changing speed and a randomly changing speed respectively. Fig.5 shows the results obtained from the two fluorescence-based sensors, with the temperature readings from the thermocouple shown for comparison. In the experiments carried out, the vibration and temperature inside the engine were changed as a result of the changing engine speed. The temperature conditions in the engine rise with the increase in the engine speed. Each step shown in Fig.5 represents a result taken at a different value of engine speed. Compared with the graph (a) in Fig.5, the graph (b) was obtained when the engine was run for a longer time to test the performance at the lowest practical engine speed. That result showed that temperature fluctuation experienced at the room temperature by using the digital system was smaller than that seen for the analogue system. The different temperature readings across the two signal processing systems is due to the probes being located at slightly different positions as shown in Fig.4(b) and experiencing different temperatures but it can be seen that the trends are very similar. The results showed that the digital scheme system achieved a better performance than the analogue system in terms of its relative insensitivity to engine vibration. The maximum temperature fluctuation measured over the range from room temperature to 250 °C under different vibration conditions is ~±3°C for the digital scheme and ~±8°C for the analogue scheme, while the values obtained are ±2°C and ±3°C for the digital and analogue schemes when there is no vibration present, i.e. the engine is stopped. A faster response time was observed in the digital system, which is less than 2 seconds.

Figure 3. Temperature variation as a function of the digital sampling rate at 200°C
4. Summary
An improved fluorescence-based fibre optic temperature sensor system has been developed to overcome the performance degradation observed in the previously used analogue signal processing scheme and sensor system under high vibration conditions. The least squares method was introduced to process the signals from the probe under high vibration conditions. The experimental results showed that the digital scheme offered a better performance in terms of precision and response time. This demonstrated that the digital-based fluorescence temperature sensor is more suitable for the temperature monitoring of the emission of a vehicle engine.

Figure 4. The experiment setup showing (a) the probes mounted on the exhaust pipe and (b) the positions of the probes in the pipe

The work was carried out as part of a broader project on optically-based engine monitoring of vehicle emission and the probe used will provide temperature data for the correction of optically-based gas monitoring systems. The precision obtained in the measurement (±3°C) is satisfactory for this application.

Figure 5. Temperature monitoring of a vehicle engine exhaust under vibration conditions (a) temperature monitoring with temperature being changed regularly with the analogue signal showing the greatest level of ‘noise’ (b) temperature monitoring under the long lowest temperature
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