Distributed temperature measurement for battery thermal runaway with frequency-resolved-multiplex OFDR

Zhen Guo[1], Gaoce Han[1,2], Jize Yan[2], David Greenwood[1], James Marco[1] and Yifei Yu[1*]
1. Warwick Manufacturing Group (WMG), University of Warwick, Coventry, CV4 7AL, United Kingdom
2. Electronics and Computer Science (ECS), University of Southampton, Southampton, SO17 1BJ, United Kingdom
Yifei.Yu.1@warwick.ac.uk

Abstract: Frequency-resolved multiplex is proposed for both high resolution and fast measurement in the optical frequency domain reflectometer. 100 Hz measurement with 2 cm sensing resolution is experimentally verified for thermal runaway monitoring in battery system. © 2022 The Author(s)

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1. Introduction

Thermal runaway is one of the most severe failure modes in batteries, which is caused by chains of unexpected exothermic reactions [1]. It will lead to a significant temperature increase inside the battery and even further venting, fire or explosion. To avoid such threats to properties and human beings and improve the safety of batteries, series of test specifications are advised by the International Organization for Standardization (ISO) and International Electro-technical Commission (IES) to evaluate the performance of battery [2], such as overcharge/over-discharge test, overheating test and mechanical impact test, et al. However, mounts of test specifications cannot guarantee the elimination of the thermal runaway in complicated practical environment. During thermal runaway, batteries may experience a voltage/current anomaly, temperature rise or gas venting. Thus, estimation of above signals is one of the most effective ways to monitor thermal runaway.

Optical fibre sensing is a promising method for the temperature/strain/gas measurement in batteries owe to the ability to realise an accurate, reliable and battery internal measurement with a compact size. Varieties of optical fibre sensors based on fibre Bragg grating, optical interferometer, evanescent waves and photo-luminescent, have been investigated for batteries [3]. Besides, with the increasing number of cells in one battery pack and large-scale energy storage system, optical fibre could also provide distributed sensing by light backscattering (Rayleigh, Brillouin, Raman et al.). Compared to other optical fibre distributed sensors, optical frequency domain reflectometer (OFDR) employs a tuneable laser source for the ultra-high spatial resolution, making it a preferred candidate in the battery system [4].

However, the practical thermal runaway usually experiences a sudden temperature change in milliseconds (after often a period of gradual rise). Due to the trade-off between the laser tuning (speed/range) and sensing resolution, it is difficult for a conventional OFDR to detect such high-speed thermal runaway and maintain ultra-high spatial resolution as well. In this paper, a frequency-resolved-multiplex OFDR is newly proposed for the fast distributed thermal runaway measurement in the battery. The cm-level sensing resolution is achieved by efficient suppression of nonlinear noise.

2. Principle

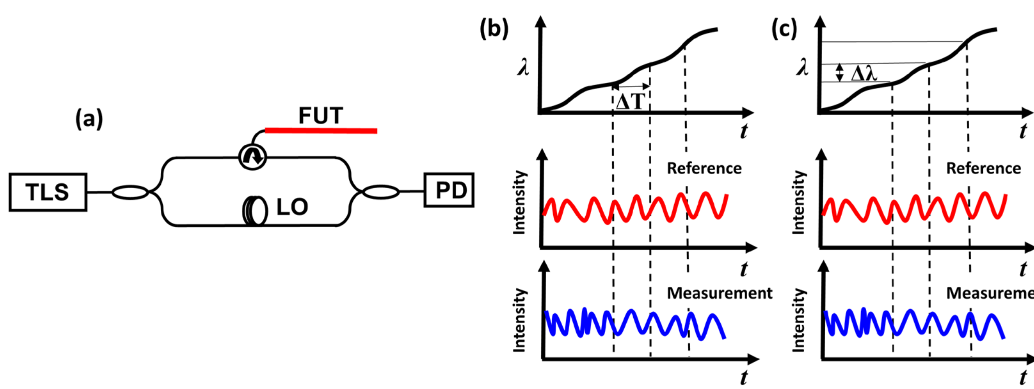

Fig.1. (a) Schematic diagram of OFDR (b) time resolved multiplex (c) frequency-resolved-multiplex

Coherent OFDR is composited of a tuneable laser source (TLS) and an interferometer (Fig. 1(a)). There is a local oscillator (LO) in the reference arm and fibre under test (FUT) in the sensing arm. The beating signal of reference and sensing arms are detected by a photodetector (PD). Two times measured signals, noted as reference and measurement, will be transferred to frequency domain by fast Fourier transform and compared for the frequency shift by a cross-correlation

In the time resolve multiplex OFDR (Fig. 1(b)), the received signal is evenly divided in time sequence with ΔT, which determines the measurement frequency of applied temperature/strain on the FUT. If there are N portions within one laser tuning period of T, the maximum measurement frequency should be $N/(2T)$ due to the Nyquist sampling theorem [5]. Nonlinear wavelength tuning is one of the most important noises in OFDR, especially for the high-resolution sensing. In the time resolve multiplex, evenly divided portions in time domain would inevitably induce the mismatch of tuning range due to the nonlinear wavelength tuning (top of Fig. 1(b)). In the following OFDR demodulation, the Fourier transforms of two times measurements are:

$$\begin{aligned} \widetilde{I}_{ref} &= \frac{1}{N_{ref}} \sum_{j=0}^{N_{ref}-1} I_{ref} \exp\left(-imj\frac{2\pi}{N_{ref}}\right) \quad at \text{ step } \Delta z_{ref} = \frac{c}{2\pi\upsilon_{ref}} \\ \widetilde{I}_{sen} &= \frac{1}{N_{sen}} \sum_{j=0}^{N_{sen}-1} I_{sen} \exp\left(-imj\frac{2\pi}{N_{sen}}\right) \quad at \text{ step } \Delta z_{sen} = \frac{c}{2\pi\upsilon_{sen}} \end{aligned} \tag{1}$$

The tuning range of v_{ref} and v_{sen} determine the actual spatial step in the frequency domain. Therefore, the mismatch of tuning range would deteriorate the calculation of frequency shift in the cross-correlation. 0.01 nm deviation of tuning range could cause 12 points offsets at 1 m fibre length [6].

A schematic diagram of the frequency-resolved multiplex is shown in Fig.1 (c). The fixed frequency range of Δλ is employed to divide one frequency tuning into several segments instead of time interval in time-domain-multiplex OFDR. This frequency tuning interval also determines the limitation of sensing resolution. Then, both the reference and measurement signals will be divided into corresponding segments with the same frequency interval. Fixed frequency interval is introduced to guarantee a high spatial resolution by dealing with frequency mismatch in the time domain multiplex OFDR.

3. Experiment and Results

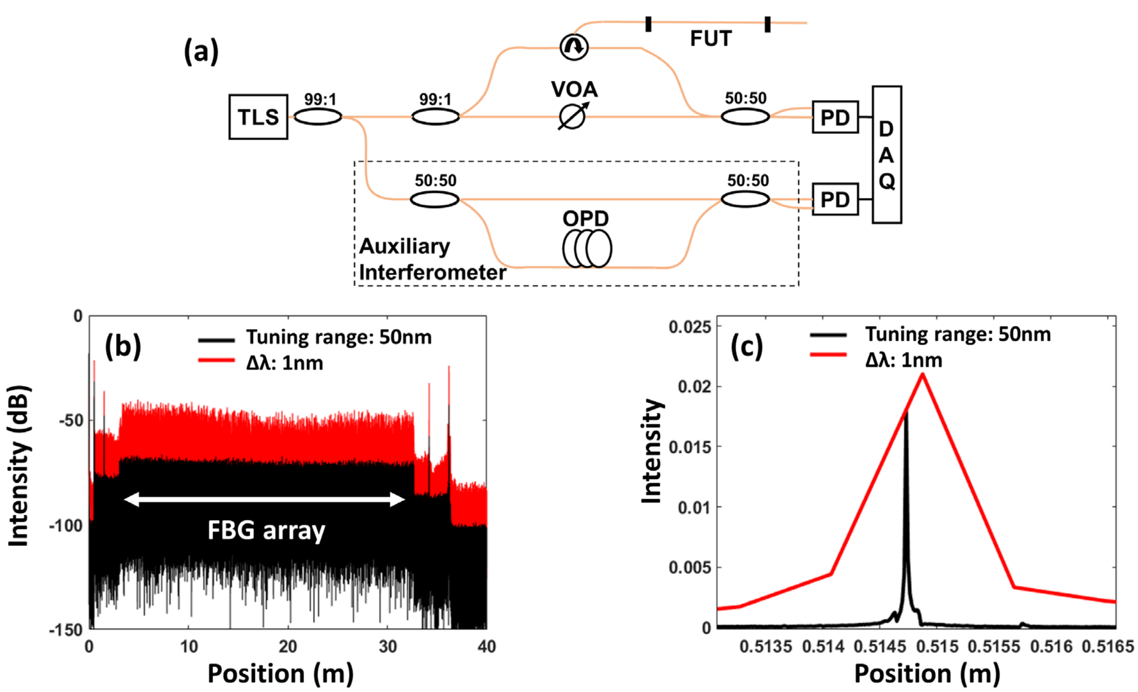

Fig.2. (a) Experimental setup of OFDR (b) comparison of spectrum distribution with the tuning range of 50 nm and Δλ of 1nm (c) spatial resolution

The experimental setup of proposed method is shown in Fig.2 (a). The output power of the tuneable laser source is split by a 99/1 coupler. The 99% light launches into the main interferometer where the fibre under test lies. A drawing tower FBG array is employed as FUT to enhance the Rayleigh backscattering. The variable optical attenuator (VOA) is used to adjust for the interference visibility. Distributed Rayleigh backscattering from the FUT will interfere with the other arm and be digitised by a photodetector. The rest 1% light in the auxiliary interferometer is used to compensate the nonlinear tuning noise of the laser. The distribution of frequency tuning can be derived from the Hilbert transform:

$$\nu(t) = \arctan\left(\frac{H\{I(t)\}}{I(t)}\right) \Big/ (2\pi\tau) \tag{2}$$

where $I(t)$ is the signal from the auxiliary interferometer, $H\{\}$ is the Hilbert transform. The wavelength tuning range is 1555-1605 nm with a speed of 100 nm/s. A fixed frequency interval of Δλ is set to 1 nm for a 100 Hz measurement. The OFDR signal from the main interferometer will be resampled and divided into corresponding segments with the Δλ.

The spectrum distribution of frequency resolve multiplex with Δλ of 1 nm and 50 nm are shown in Fig.2. (b). Theoretical spatial resolution can be calculated by:

$$\Delta z = c/2n\nu_{range} \tag{3}$$

where c is light speed, n is fibre index and ν_{range} is the tuning range. The nonlinear tuning noise can be efficiently suppressed by equal frequency resample [7]. As shown in Fig. 2. (c), the measured spatial resolution with tuning range of 50 nm and Δλ of 1 nm are 32.1 μm and 1.6 mm, respectively. The experimental resolution both agree with the theoretical predication, proving the elimination of the nonlinear tuning noise.

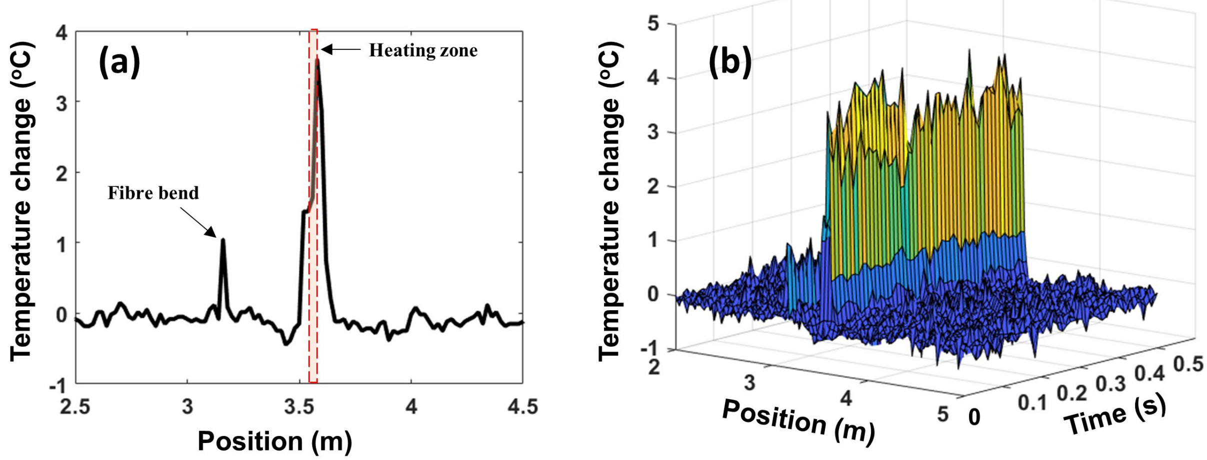

Fig.3. (a) Distributed temperature measurement (b) 100Hz distributed temperature measurement with a 2 cm sensing resolution

Experimental measurement of distributed temperature with a frequency interval of 1 nm and a sensing resolution of 2 cm is shown in Fig.3 (a). It's noted that, under a 1 nm frequency interval, there are only 24 points with slidewindow of 2 cm. The minimum detectable frequency shift is 5.21 GHz, which cannot meet the optical fibre thermal coefficient of 1.76 GHz/°C. Therefore, times of zeros are padding to each filtered spatial domain signals to improve the distributed measurement.

A heated metal cube with 2 cm width is placed on the fibre at the position around 3.58 metres. The measured temperature change is 3.7°C. Our previous study can confirm that the expansion area of the increased temperature (compared to the red zone in Fig.3 (a)) is caused by thermal transfer of the heated metal rather than resolution degradation [6]. The peak at 3.16 metres is the fibre bend for position calibration. 100 Hz measurement with a 2 cm resolution is shown in Fig.3 (b). There are 50 times distributed measurement within one tuning period of 0.5 seconds. The precision of such high frequency distributed measurement can be estimated by the data from the non-heating area, which is limited to ±0.2 °C.

4. Conclusion

Measurement speed and resolution are trade-off in the conventional OFDR. Compared to time resolve multiplex OFDR, frequency resolve multiplex is proposed in this paper to eliminate the mismatch of tuning range for the distributed temperature measurement with high resolution. Both high resolution of 2 cm and fast measurement of 100Hz are delivered to provide a straightforward and efficient way for the distributed thermal runaway monitor in batteries.

Acknowledgement

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