Iterative filtering for Time-Frequency Localised Pulse Optimisation in STFT-BOTDR

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ABSTRACT: Dynamic strain measurement in distributed fibre optic sensing (DFOS) is essential for structural health monitoring (SHM) of the strain changes induced by construction failure and other activities in infrastructure's life cycle. Among different DFOS systems, the Short Time Fourier Transform-Brillouin Optical Time Domain Reflectometry (STFT-BOTDR) takes the advantages of STFT obtaining full frequency spectrum to improve the performance of conventional BOTDR, providing an opportunity for dynamic sensing. The key parameters of distributed fibre optic sensors, spatial and frequency resolution, are strongly linked with the pulse's time-frequency localisation. In this paper, a set of Kaiser-Bessel functions is used to simulate different pulse shapes and compare their parameters in terms of Time-Frequency Localisation (TFL) and their Brillouin scattering spectrum. A method using iterative filtering algorithm to achieve the optimised pulse in terms of TFL is introduced to converge the Effective-pulse Width (TEW) in time-domain and Effective-pulse Linewidth (FEL) in the frequency domain, respectively, to the fundamental limitation. The optimised pulse can be fitted with 7^{th} order Gaussian (super-Gaussian) shape and offer the best experimental performance compared to Rectangular pulse.

1 INTRODUCTION

Distributed fibre optic sensing, especially Brillouin Optical Time Domain Reflectometry (BOTDR), allows measurement of strain and temperature at any location along a single mode optical fibre up to a hundred kilometres (Bao and Chen 2011). Comparing with conventional sensing systems, this provides new opportunity for distributed and dynamic Structure Health Monitoring (SHM). However, the Time-Frequency Localisation (TFL) in the signal pulse affects the signal-to-noise ratio (SNR) and limits the resolutions, sensing distance and measurement speed, which increasing the difficulty for dynamic sensing (Luo et al. 2016).

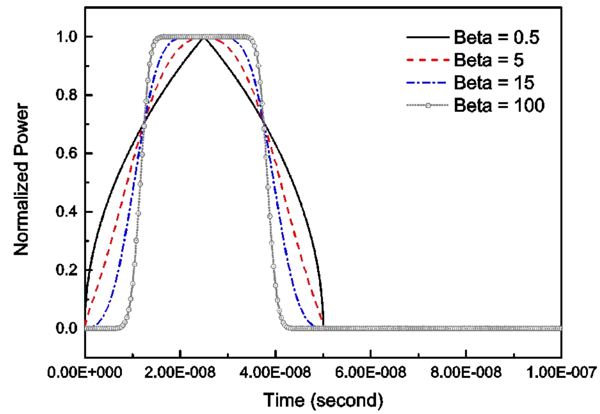
Shape of the pulse is considered as having significant contribution on reforming the Brillouin scattering spectrum, hence the shape needs to be optimised to provide a good SNR of the spectrum to enhance the frequency resolution and remain good spatial resolution simultaneously. Different pulse shapes resulted in different spectrum bandwidth and different frequency error (Naruse and Tateda 2000). Lorentzian shape was considered to be better than Triangular shape in terms of Brillouin spectrum's peak power (Hao et al. 2013). However, previous research analysed the frequency domain information independently but omitted its iteration with time domain information which would contribute to the spatial resolution. Because of the TFL limitation of time-frequency analysis, improving in frequency resolution will sacrifice the spatial resolution. Therefore, a balanced and optimised pulse need to be introduced to improve the spatial resolution and frequency resolution, simultaneously.

In this paper, Kaiser-Bessel functions with different parameters of attenuation slope are used to simulate Gaussian, Hamming, Rectangular pulses as the input of the BOTDR system. The pulses are compared in a mathematical model to reveal their relation with the frequency resolution. An iterative filtering algorithm is introduced to optimise the pulse shape to enhance the system TFL. The simulation result shows that the Brillouin spectrum bandwidth can be improved by more iterations. The experimental result demonstrates that the ratio of peak frequency power and total power can be enhanced by using the optimised pulse generated by the iterative filtering algorithm comparing with a rectangular pulse in the STFT-BOTDR system.

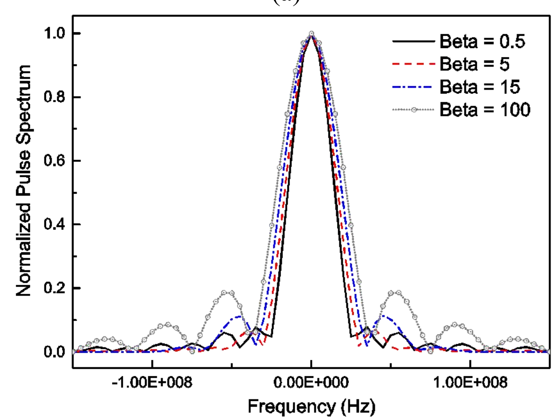
2 PULSE EFFECT ON BRILLOUIN SPECTRUM

To evaluate the effect of the pulses on the BOTDR, the pulses are simulated by Kaiser-Bessel functions (Rabiner and Gold 1975) (Lewitt 1990). The different pulses are represented as below:

Where N is the length of sequence. is the zeroth order modified Bessel function of the first kind, which is the solution of at zeroth order Bessel's differential equations. is a non-negative parameter that decides the shape of the window, which represents the trade-off between the main-lobe width and the side lobe level.



(a)



(b)

Figure 1- The representation of the Kaiser-Bessel shape pulses with different parameterisation beta (a)The time domain pulse shape and (b) frequency domain spectrum

Tuning can generate different pulse shapes such as Gaussian, Hamming, Rectangular, etc. These pulse shapes have attenuating spectrum distribution, shown in Figure 1, where the is chosen to be 0.5, 5, 15 and 100 with the same pulse width, and represent for shapes from Triangular to Rectangular, respectively. Assuming the noise effect can be omitted in the Brillouin scattering process, the pulses' effect on Brillouin scattering can be represented by a simplified mathematical model in Equation (3) (Naruse and Tateda 1999). After convoluting the pulses' spectrum and Brillouin scattering gain, the spectrum of Brillouin backscattered signals generated by different pulses are compared in Figure 2.

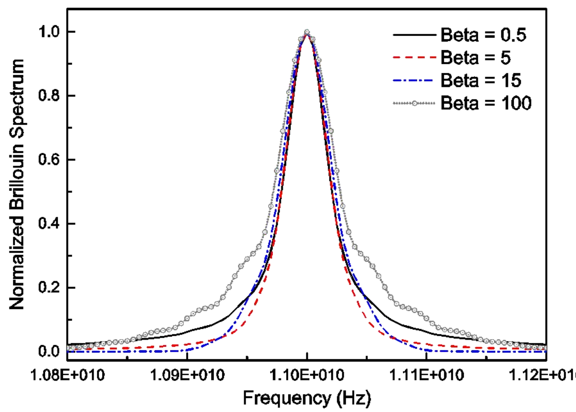


Figure 2 - The Brillouin spectrum of different pulses with different parameterisation β of Kaiser-Bessel shape.

where is the power spectrum of the launched pulse. H(v) is the Lorentzian shape spectrum of the Brillouin backscattering light with peak frequency of and the full width at half maximum (FWHM) of . The term expresses the frequency variation due to local acoustic waves, where the variation comes from the changes in the properties of the fibre, or the changes in strain or temperature.

Figure 2 shows that the ratio of the peak frequency power and the whole spectrum power increases while decreases, indicating that the Brillouin spectrum expands when the pulse has larger linewidth. The Figure 3 shows the standard deviation of the peak frequency for different pulse shapes on a uniform optical fibre without strain and temperature variance but with varied averaging numbers. When is equal to 5, the standard deviation is the smallest, which shows the best frequency resolution and the least measurement time among the four shapes using different values. As a comparison, it needs 32 times of averaging for equal to 5 to achieve a similar frequency resolution comparing with 256 times of averaging when is equal to 15.

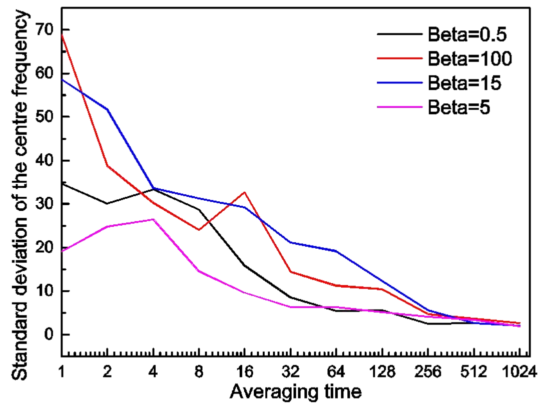


Figure 3 - The standard deviation of the centre frequency on the uniform strain section when different pulses with different average numbers are applied to the BOTDR system

3 ITERATIVE FILTERING ALGORITHM

Due to the TFL, the improvement in frequency resolution sacrifices spatial resolution (Luo et al. 2016). Hence, an optimised pulse is needed to offer an optimised resolution in both time and frequency domain. As stated in earlier section, the sideband in frequency domain can increase the standard deviation of the peak frequency in BOTDR, i.e. reduce the frequency resolution. Similarly, in time domain, the increasingly length of the signal tail of the pulse shape will reduce the spatial resolution. Therefore, optimisation should focus on the reduction of the signal tails in time domain and the signal sidebands in frequency domain.

In this paper, an iterative filtering method to optimise the pulse shape and enhance the TFL is introduced by applying iterations to cut off the tails in time domain and sideband in frequency domain in consequence cycles to converge to the optimised pulse shape. The principle is:

1. Start with a rectangular pulse shape with a predefined frequency spectrum and time length.
2. Transfer the pulse into frequency domain and find its first positive frequency point that crosses zero at frequency. Then cut off the power of the rest harmonics in the sideband by making them to zero.

3. Transfer the modified frequency domain signal back to time domain. Find its first positive point which crosses zero along the signal at point and cut off the power of the rest power after the first zero point by making them to zero.

4. Repeat step 2 and 3 until the pulse is converged, which offers the optimised localisation in both time and frequency domain

In general terms, assume is the signal after N iterations, the signal after N+1 times iteration will be

Assume the is the fourier transform of signal , then in frequency domain,

whereis the inverse Fourier transform of and is the Fourier transform for . is the ideal low pass filter with cut-off frequency at expressed as

while is the ideal rectangular window with close time at expressed as

The iteration method can also enhance the SNR of Brillouin scattering spectrum as shown in Table 1. The SNR enhancement is different for different pulse shapes with same iteration number.

Table 1 - The original SNR for pulses given different and the SNR after the Modification

Pulse	Original SNR	Modified SNR
	23.308	25.495
	26.797	28.244
	20.257	29.086

The SNR increases when the iteration number is augmenting (Figure 4). For one iteration, the frequency sideband reduction is an imperfect cut-off using a low pass filter and only the main lobe remains. The tail of the pulse still exists in time domain. For more iterations, the tail in time domain approaches to its limit and the sideband power in frequency domain is gradually compressed to a tiny level which can be omitted comparing with the mainlobe power. In Figure 5, the SNR enhancement will converge after many iterations, which offers the optimised time-frequency localised pulse using this iterative filtering algorithm.

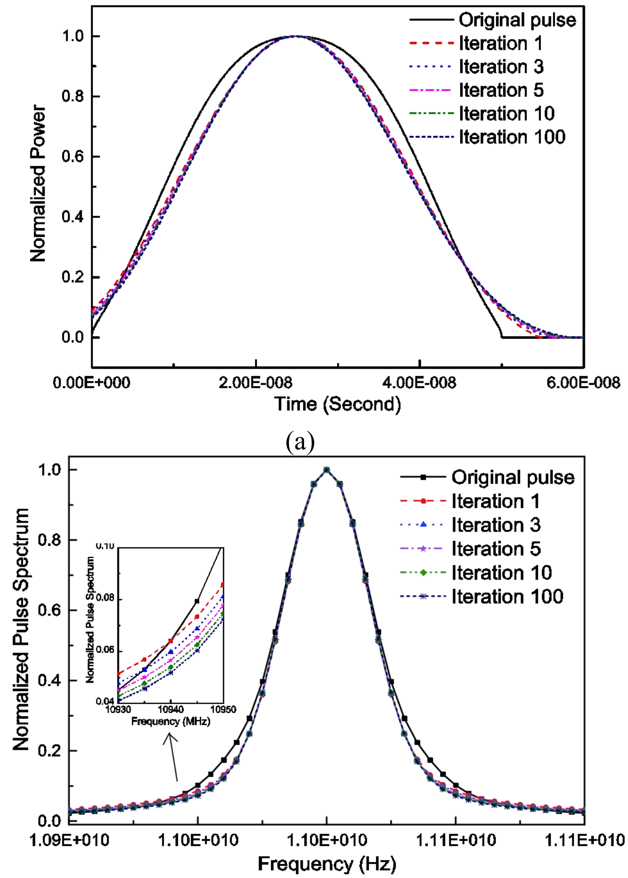


Figure 4 – (a) The simulation result of pulse shape in time domain when pulse is original shape with =5 and pulses are the modified shapes with different iteration numbers. (b) The simulated Brillouin scattering spectrum when these pulses are sent into BOTDR system.

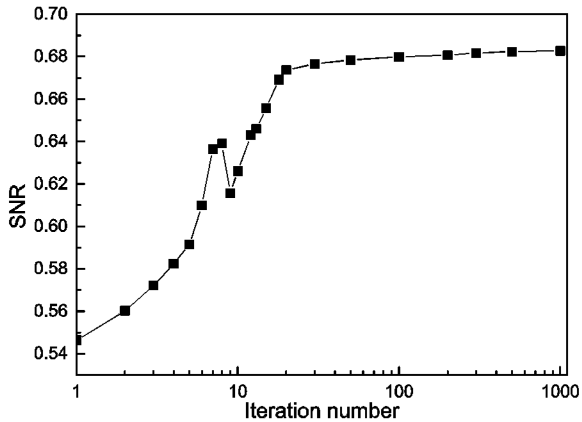


Figure 5 The SNR trend when iteration number increases

4 SUPERGAUSSIAN FITTING AND EXPERIMENTAL RESULTS

The initial pulse is a rectangular pulse with the pulse width of 50 ns and the period of 1 us. The iterative filtering method is then applied on the initial pulse to reduce its tail and sideband in time-frequency domain in iteration cycles. The optimised pulse shape is found out to a super-Gaussian curve, which can be fitted by 7^{th} order Gaussian equations, whose coefficients are shown in Table 2.

Table 2 – The fitted 7^{th} order super-Gaussian equation and the coefficients

Equation	f(x) = a1*exp(-((x-b1)/c1)^2) + a2*exp(-((x-b2)/c2)^2) + a3*exp(-((x-b3)/c3)^2) + a4*exp(-((x-b4)/c4)^2) + a5*exp(-((x-b5)/c5)^2) + a6*exp(-((x-b6)/c6)^2) + a7*exp(-((x-b7)/c7)^2)				
Coefficients:					
a1	0.33280	b1	0.04529	c1	0.05135
a2	0.00019	b2	-0.00397	c2	0.00696
a3	0.00000	b3	0.01891	c3	0.00000
a4	0.88100	b4	-0.01279	c4	0.06381
a5	-0.02095	b5	-0.02148	c5	0.03517
a6	0.12900	b6	-0.08062	c6	0.05222
a7	0.10550	b7	0.09070	c7	0.04861

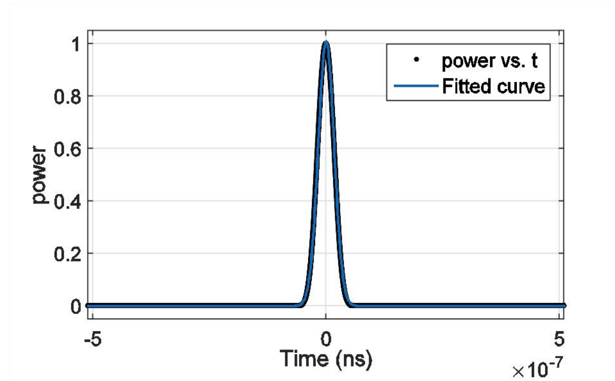


Figure 6 – Modified pulse and its 7^{th} order Super-Gaussian fitted curve

The Super-Gaussian pulse, shown in Figure 6, is experimentally tested in a STFT-BOTDR setup shown in Figure 7. An ultra-narrow-line-width laser with 1554.12nm wavelength was used as the light source. In branch A, after passing a coupler, a part of the continuous-wave (CW) light was modulated by an electro-optic modulator (EOM) with the 50 ns pulse generated by an Arbitrary Wave Generator (AWG, Agilent 33600). The pulsed light was then amplified by an Erbium-doped fibre amplifier (EDFA) and circulated into the sensing fibre to generate the Brillouin backscattered signal. This signal was heterodyned with the reference CW light in branch B and then down-converted to the radio frequency (RF) range using a wideband photo-detector. The signal was further down-converted to the intermediate frequency (IF) range, which was digitised in time domain and processed using the STFT signal processing algorithm to obtain the frequency peaks along the fibre under test.

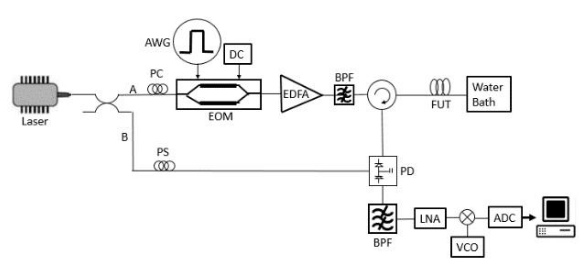


Figure 7 – The experiment set up of the STFT-BOTDR

As a comparison, the super-Gaussian pulses (optimised from the 50ns rectangular pulse) is used as the input and sent into the STFT-BOTDR. The Brillouin scattering spectrums from the two pulses are compared, which are both averaged by 1000 times and shown in Figure 8. The super-Gaussian pulse offers narrower bandwidth of the Brillouin scattering spectrum comparing with the original rectangular pulse. The super-Gaussian pulse offers a larger SNR in the Brillouin scattering signal while the width of the pulse has changed a little bit, that remains a similar spatial resolution.

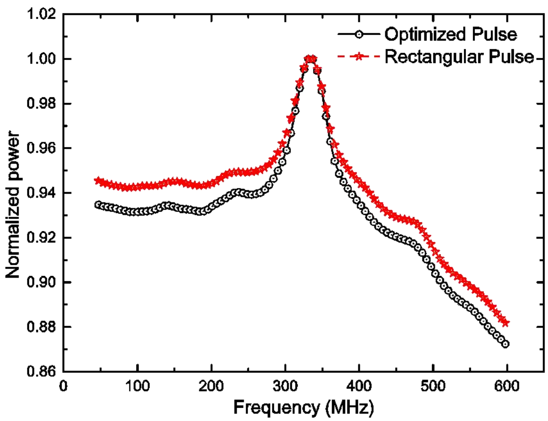


Figure 8-The normalised plot of experiment result of Brillouin spectrum generated by optimised pulse and rectangular pulse with same pulse width

5 CONCLUSION

In this paper, the Kaiser-Bessel functions with different attenuation slopes were used to simulate the Gaussian, Hamming, Rectangular, and other shapes. The pulse shapes were compared in terms of the Brillouin scattering spectrum, showing that the existence of the sideband in frequency domain would reduce the SNR of the Brillouin spectrum and limit the frequency resolution. To compress the sideband effects without sacrificing spatial resolution, an iterative filtering algorithm was developed using iterated cut-offs to reduce the tail and sideband in the time and frequency domain. The pulse shape was iteratively optimised in the time and frequency domain and therefore increases the ratio of the mainlobe power over the sideband power. The SNR was improved by optimised iterations. A rectangular pulse was modified as an illustration and the optimised pulse was fitted with a 7th order Super-Gaussian curve. In the experiment of STFT-BOTDR, the result demonstrated that the optimised pulse offered a narrower bandwidth of the Brillouin scattering spectrum comparing to the original rectangular pulse.

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7 REFERENCE

Bao, X., and L. Chen. 2011. "Recent progress in Brillouin scattering based fiber sensors." *Sensors* 11 (4): 4152-4187.

Hao, Y., Q. Ye, Z. Pan, H. Cai, and R. Qu. 2013. "Analysis of spontaneous Brillouin scattering spectrum for different modulated pulse shape." *Optik* 124: 2417– 2420.

Lewitt, R.M. 1990. "Multidimensional digital image representations using generalized Kaiser–Bessel window functions." *Journal of the Optical Society of America A*: 1834-1846.

Luo, L., B. Li, Y. Yu, X. Xu, K. Soga, and Y. Yan. 2016. "Time and Frequency Localized Pulse Shape fo Resolution Enhancement in STFT-BOTDR." *Journal of Sensors* 2016: 10.

Naruse, H., and M. Tateda. 2000. "Launched pulse-shape dependence of the power spectrum of the spontaneous Brillouin backscattered light in an optical fiber." *Applied Optics* 39 (34): 6376-6384.

Naruse, H., and M. Tateda. 1999. "Trade-off between the spatial and the frequency resolutions in measuring the power spectrum of the Brillouin backscattered light in an optical fiber." *Applied Optics* 38 (31): 6516-6521.

Rabiner, L.R., and B. Gold. 1975. *Theory and Application of Digital Signal Processing.* Englewood Cliffs, N.J.: Prentice-Hall.