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A New Algorithm to Estimate Attenuation Using Frequency Shift Methods

(Algoritma Baru Penganggaran Atenuasi Menggunakan Kaedah Anjakan Frekuensi)

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ABSTRACT

This paper presents the improvement of quality factor (Q) estimation using shift frequency method. A new method was developed based on two previous methods; peak frequency shift (PFS) method and centroid frequency shift (CFS) method. The proposed algorithm has been tested to gauge its performance using three different scenarios; Q variation, travel time variation, and signal to noise ratio (SNR) variation. The test was performed using the Ricker wavelet with random noise included. Based on the results obtained, it can be concluded that the new proposed method was able to improve Q estimation using shift frequency method. This method can also be implemented in the low and high Q condition, shallow and deep wavelet targets and in the low and high SNR conditions of seismic data. The limitations in the PFS and CFS methods can be reduced by this method.

Keywords: Attenuation; centroid frequency; peak frequency; variance; wavelet

ABSTRAK

Kertas ini membentangkan peningkatan penganggaran faktor kualiti (Q), menerusi kaedah anjakan frekuensi. Satu kaedah baru telah dibangunkan menggunakan 2 kaedah lazim yang sedia ada iaitu; kaedah anjakan puncak frekuensi (PFS) dan kaedah anjakan frekuensi centroid (CFS). Algoritma yang dicadangkan telah diuji untuk mengukur prestasi kaedah baru ini menggunakan tiga senario: perubahan Q, perubahan masa kembara dan perubahan nisbah isyarat ke hingar (SNR). Ujian ini dijalankan dengan menggunakan gelombang Ricker dengan disertakan hingar rawak. Berdasarkan kepada hasil keputusan yang diperoleh, boleh disimpulkan bahawa kaedah baru ini berupaya untuk meningkatkan penganggaran Q menggunakan kaedah anjakan frekuensi. Kaedah ini juga boleh diaplikasikan pada keadaan Q tinggi dan rendah, sasaran gelombang cetek dan dalam dan pada data seismik SNR tinggi dan rendah. Had-had sekatan bagi PFS dan CFS juga boleh dikurangkan dengan menggunakan kaedah ini.

Kata kunci: Atenuasi; frekuensi puncak; frekuensi tengah; varians; wavelet

INTRODUCTION

Along its propagation, the seismic wave energy will decrease due to several factors such as spherical divergent, scattering, reflection and attenuation process. In attenuation process, the high frequency content will be shifted into lower frequency. This phenomenon will affect the quality of seismic data. Consequently, information about attenuation is very important to be known, not only in the processing but also in the interpretation of seismic data. In seismic processing, Q estimation can be used as true amplitude recovery, as preserved amplitude recovery, and also as the inversed Q factor or Q deconvolution process. Meanwhile, in the interpretation process, it is used to improve the resolution of seismic images, to get better interpretation of the AVO effect, and inversion for material properties (Zhang & Ulrych 2002).

Attenuation is usually addressed as quality factor (Q) term which is always associated with its intrinsic properties of medium: pore fluid content and lithology variation. Medium with high attenuation such as gas bearing strata has low quality factor. In this condition, energy of seismic wave will be absorbed strongly by the medium. Attenuation is more sensitive than velocity due to fluid content changes. This fact can potentially be used as hydrocarbon indicator (Hedlin et al. 2002).

Seismic wave attenuation can be estimated from seismic data using several methods such as spectral ratio, rise time, and shift frequency method; Pinson (2008); Li et al. (2006); Tai et al. (2006) used continuous wavelet transform to estimate attenuation; they were successful to identify two events and estimated Q by comparing the spectral amplitudes. Meanwhile, Zhang and Ulrych (2002) estimated Q factor from common midpoint (CMP) records by using spectral ratio.

There are two well-known methods based on frequency shift method to estimate attenuation: centroid frequency shift (CFS) method (Quan & Harris 1997) and Peak frequency shift method (PFS) (Zhang & Ulrych 2002). Unfortunately, both methods have limitations for certain condition: PFS method satisfied low Q condition and far target wavelet but dissatisfied high Q condition and near target wavelet. Meanwhile, the CFS method gives high accuracy in high Q condition but will not concur for deep/far target. Therefore, to overcome these limitations, a new method is proposed. In this new method, two characteristics from previous methods (PFS and CFS methods) were combined by including correction factor into the CFS method. The improvement into shift frequency method was also previously done by Tu and Lu (2009) using fitting curve methods. However, the proposed method can be performed without using fitting curve to avoid iterative method.

BACKGROUND THEORY

The seismic traces are modeled as convolution between wavelet and earth reflectivity filter. The wavelet of seismic wave is usually unknown, but in some cases it can be measured or assumed as minimum phase wavelet. In this study we assumed the wavelet was approached by Ricker wavelet. The spectrum of Ricker wavelet can be expressed by:

$$B(f) = \frac{2}{\sqrt{\pi}} \frac{f^2}{f_m^2} e^{\left(-\frac{f^2}{f_m^2}\right)}, \tag{1}$$

where f_m is a dominant frequency, f is frequency content. When wavelet propagated in the medium, some parts of energy will be absorbed due to attenuation. After traveling t time, the Ricker wavelet will evolve to:

$$B(f,t) = B(f).H(f,t). \tag{2}$$

The value of $H(f,t)$ is the absorption filter in which the frequency spectral is given by:

$$H(f) = exp\left(-\int_{ray} a(f,l)\,dl\right), \tag{3}$$

where the integral is evaluated along ray path l. In several cases, attenuation is proportional to the frequency so it can be expressed as:

$$H(f) = exp\left(-f\int_{ray} \alpha_0\,dl\right), \tag{4}$$

the α_o describes the attenuation of medium along its ray path dl.

Quan and Harris (1997) have developed the correlation between complex velocities and attenuation factor that vary with frequency of signal:

$$v(\omega) = v(\omega_0)\left[1 + \frac{1}{\pi Q} log\left(\frac{w}{w_0}\right) - \frac{i}{2Q}\right], \tag{5}$$

where Q is quality factor of P or S wave and v is the velocity of P or S wave. Intrinsic attenuation coefficient also can be stated in quality factor (Q):

$$\alpha = \frac{\pi}{vQ}, \tag{6}$$

here, neither α_o or Q depend on depth or position in the medium.

CENTROID-FREQUENCY SHIFT METHOD (CFS)

Quan and Harris (1997) proposed the centroid frequency shift method to estimate attenuation. They defined the centroid frequency and variance of source and receiver respectively as:

$$f_s = \frac{\int_o f.S(f)\,df}{\int .S(f)\,df}, \tag{7}$$

$$f_R = \frac{\int_o f.R(f)\,df}{\int_o .R(f)\,df}, \tag{8}$$

$$\sigma_s^2 = \frac{\int_o (f - fs)^2 .S(f)\,df}{\int_o S(f)\,df}, \tag{9}$$

Q factor is calculated using equation:

$$Q = \frac{\pi t \sigma_s^2}{(f_s - f_r)}. \tag{10}$$

PEAK FREQUENCY SHIFT (PFS) METHOD

Zhang and Ulrych (2002) proposed peak frequency shift (FPS) method to estimate quality factor. Seismic wave spectrum is represented by the Ricker wavelet. The maximum of amplitude for the spectrum is defined as peak frequency or dominant frequency. They fitted the spectrum with the Ricker spectrum before calculating Q factor. Along its propagation, frequency of wavelet underwent attenuation and the peak frequency will be shifted into lower frequency dominant $f_p f_p$. The Q factor is calculated by:

$$Q = \frac{\pi t f_p f_m^2}{2\left(f_m^2 - f_p^2\right)}, \tag{11}$$

here the t (time) is travel time of wavelet.

A NEW PROPOSED METHOD

In the new proposed method, we calculated correction factor which was derived from CFS and PFS methods. Schematic of this algorithm is shown in Figure 1.

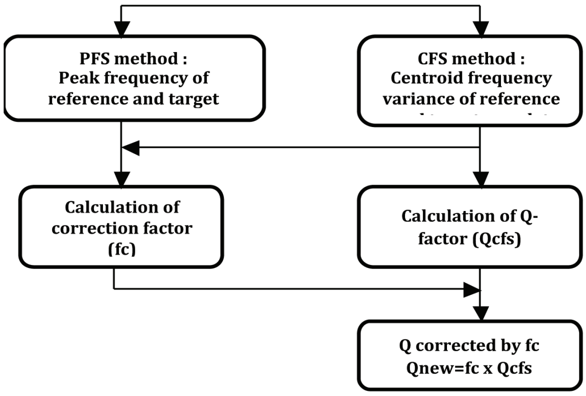


FIGURE 1. Algorithm of new method for attenuation estimation

To calculate correction factor (*fc*) we defined variance of target wavelet as:

$$\sigma_r^2 = \frac{\int_0^\infty \left(f - fr\right)^2 R\left(f\right) df}{\int_0^\infty R\left(f\right) df}, \tag{12}$$

where *fr* is centroid frequency and *R(f)* is spectral of target wavelet. We tolerate that variance of wavelet has evolved; however, we need to calculate correction factor *fc*. Finally, Q was calculated by equation:

$$Q = fc.Q_{cfs}, \tag{13}$$

where $Q_c f_s$ is Q which is calculated using the CFS method.

PERFORMANCE TEST DESIGN

A test was conducted in order to evaluate the performance of the new proposed method. The design of this test is as follows. Firstly, a synthetic wavelet is generated in the time domain with noise random included - here wavelet is regarded as reference wavelet. Then, the reference wavelet was transformed into frequency domain using Fourier Transform and lastly the transformed wavelet will simulate the attenuation effect in a given condition. This simulated wavelet is called the target wavelet. After the target wavelet is obtained, the next step is to calculate parameters and Q from the target wavelet for all methods. The Q resulted from calculation is compared with real Q which is used in the synthetic generation. The errors were calculated in percentages. We used a hundred of Ricker wavelet at every test; thus the root mean square errors (RMSE) were calculated.

In some cases, if attenuation is too small, the PFS method failed to re-calculate Q from the target wavelet, so we generated another new wavelet with noise random was renewed. Consequently, all of the synthetic wavelet that was used in this test can be calculated by all the before mentioned methods. The illustration of the noise and its spectral which were used in this test are depicted in Figure 2.

In this test we focussed on three different conditions which are: Q-factor, travel time of wavelet, and SNR variation.

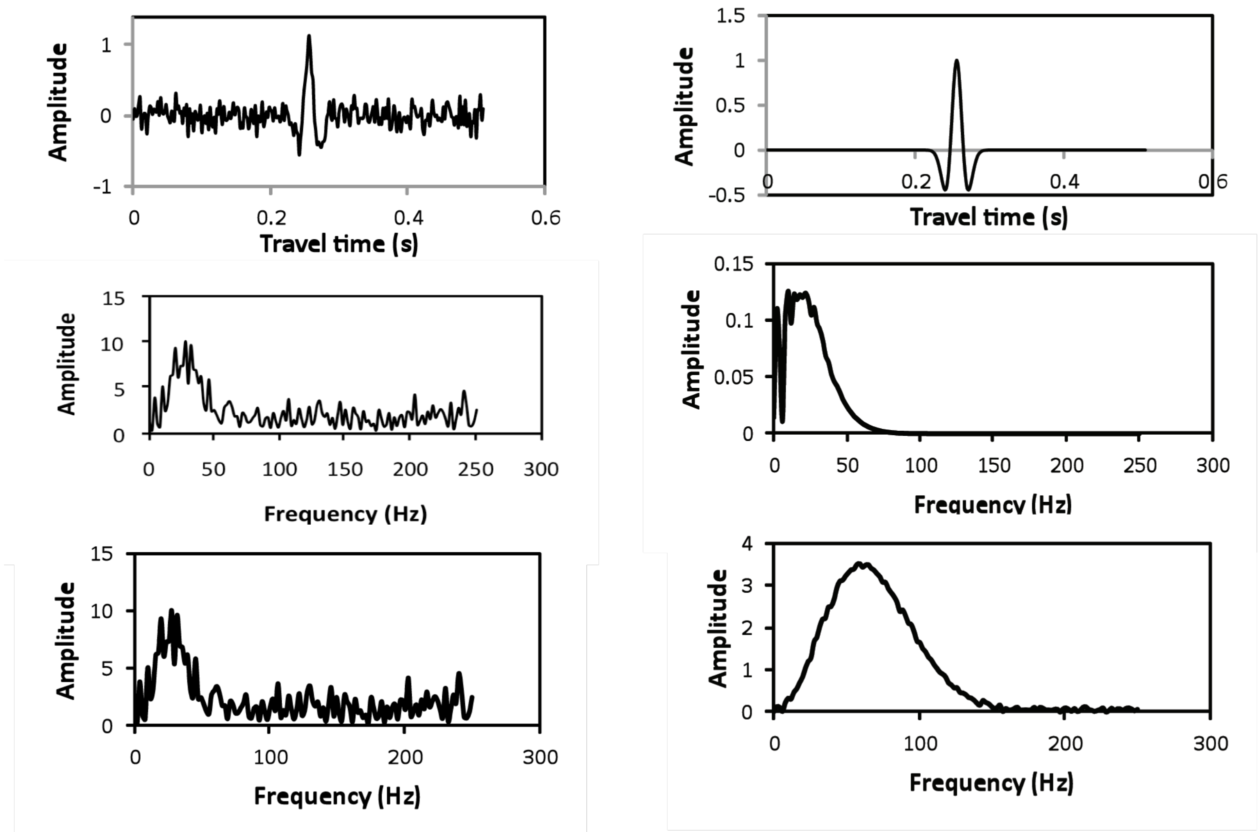


FIGURE 2. (a) Ricker wavelet 25 Hz, SNR 10dB and (b) 60 Hz, 40dB. Ricker wavelet in the time domain (top), spectrum of reference wavelet (middle) and target wavelet (bottom)

Results and Discussion

The Q-factor variation test was conducted to measure sensitivity method due to the Q variation. The Q value that was selected in this test was based on Bradley and Newman (1966) investigation that is the Q for sedimentary rock are varied from 20 – 200. For every value of Q, we used hundreds of Ricker wavelets; 60 Hz with noise level varies for 10 dB, 15 dB, 25 dB, and 40 dB. Meanwhile the travel time is maintained uniform at 0.3 s. The results are shown in the Figure 3.

From the graphs obtained, it is clear that the two previous methods have different characteristics. The CFS method produces fewer errors in high Q condition, but the PFS method produced more errors in this condition especially at SNR 40db. The CFS method seemed not to be greatly affected by SNR variation. Meanwhile, the PFS method did not robust with SNR variation. Fortunately, a new proposed method produced less error than both previous methods. In very low SNR, the errors resulted from this method were more than CFS method. However, in parallel with increasing SNR, the performance of this method increased more than both previous methods.

Travel Time Variation Test

The following test was conducted by varying the travel time of wavelet propagation in the medium. The test is to find out the effect of travel time wavelet to the error determination of Q. In this test, travel time is varied from 0.05-0.5 s. Hundreds of Ricker wavelets at 60 Hz were used with SNR varies for 10 dB, 15 dB, 25 dB and 40 dB and the Q was maintained constant at 80. The results are depicted in Figure 3.

The errors in CFS method increased as travel time was increased. This method has systemic error due to travel time propagation. The PFS method did not robust by the increment in travel time. Meanwhile, the performance of the new method is not affected by increasing travel time. In general, the performance of the new method is more powerful; except at noise level 10 dB, the errors that were produced by this method are larger than the CFS method but still less than the PFS method.

SNR variation test verified the performance of Q determination for all methods due to noise level condition. The test was conducted using Ricker wavelets 25 Hz, 40 Hz, 60 Hz and 80 Hz. Value of Q and travel time was set

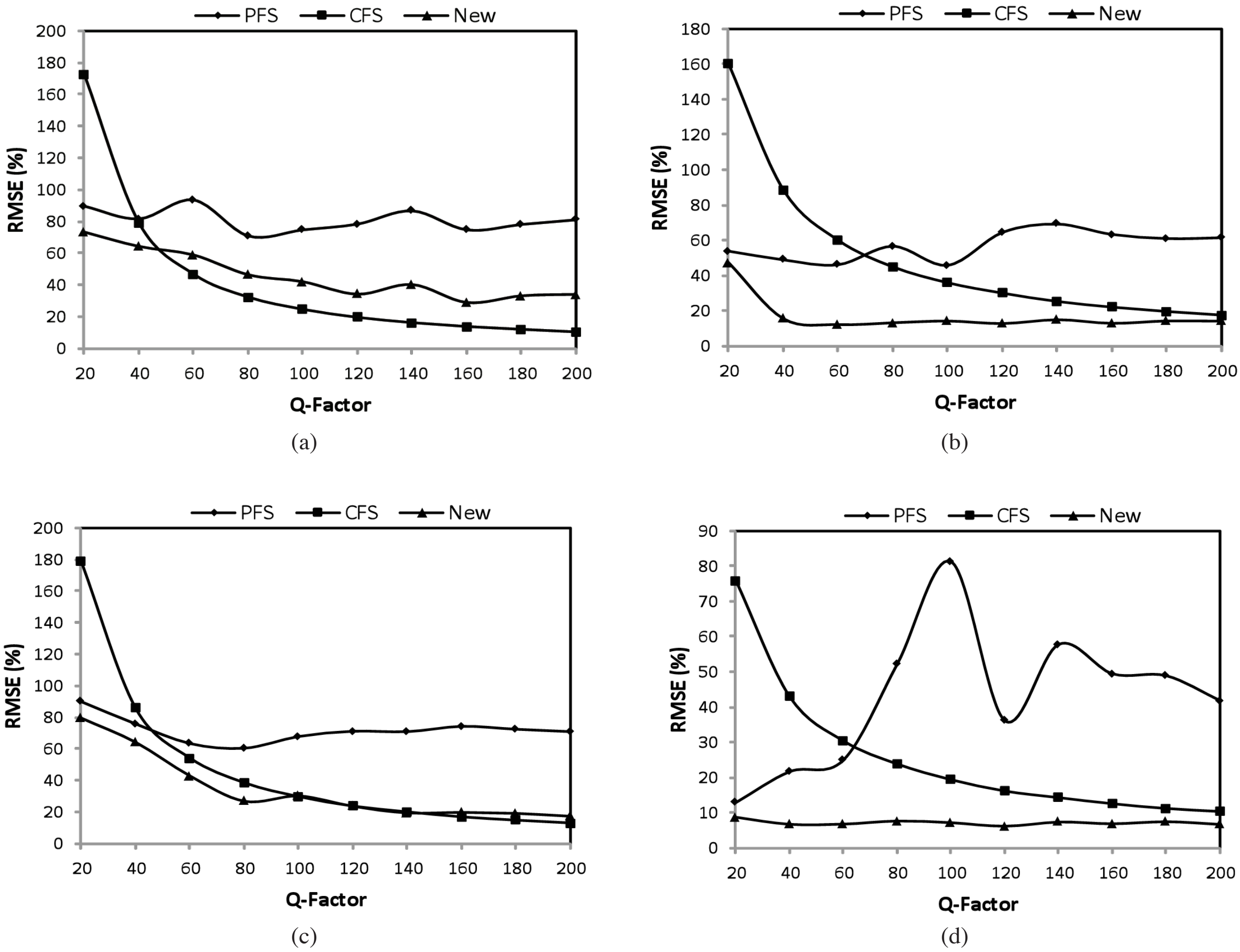


FIGURE 3. Plot of RMSE versus Q for travel time 0.3s, frequency dominant 60 Hz and SNR: (a)10 dB, (b)15 dB, (c)25 dB and (d)40 dB

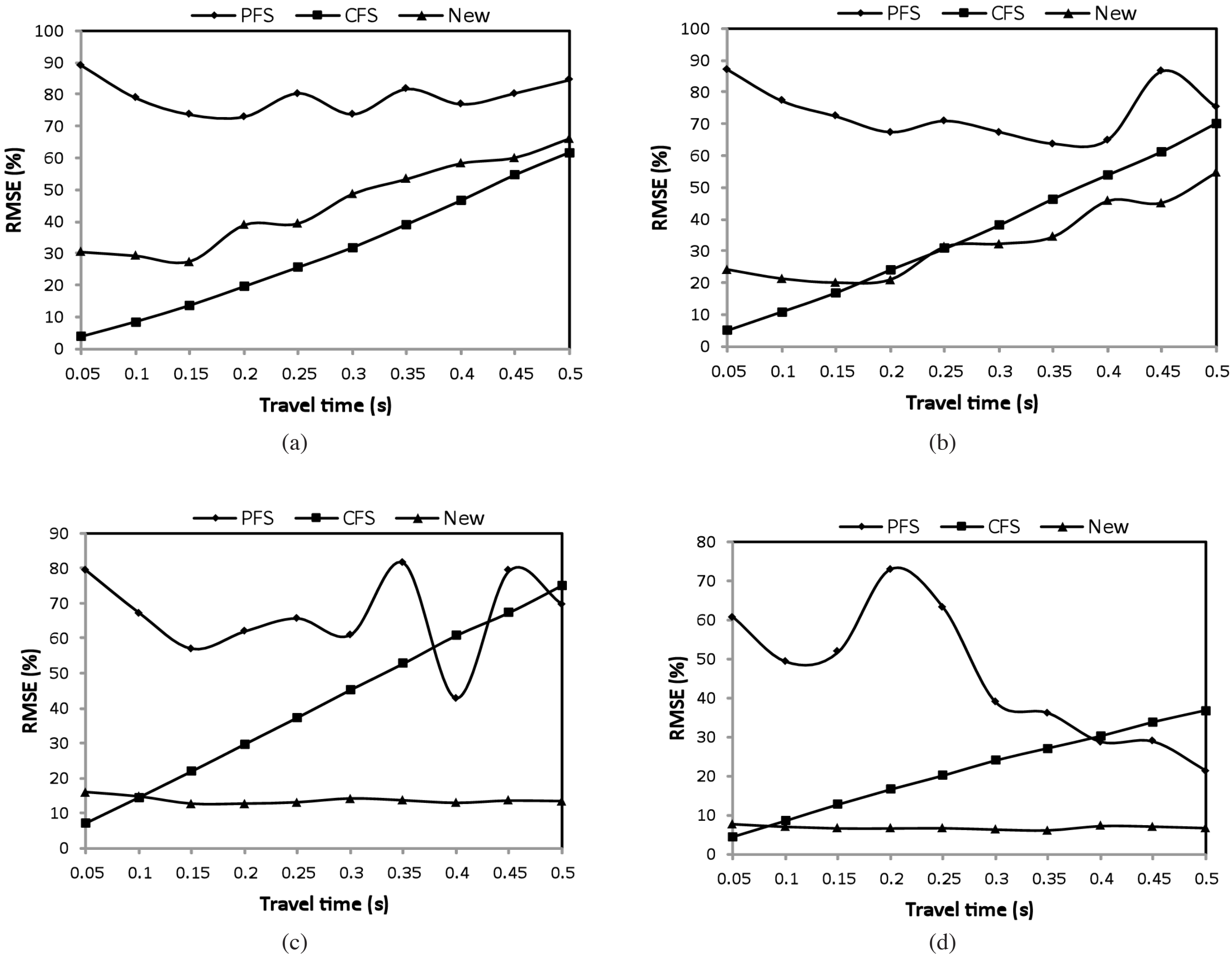


FIGURE 4. Plot of RMSE versus travel time for SNR (a) 10dB, (b) 15dB, (c) 25dB and (d) 40dB

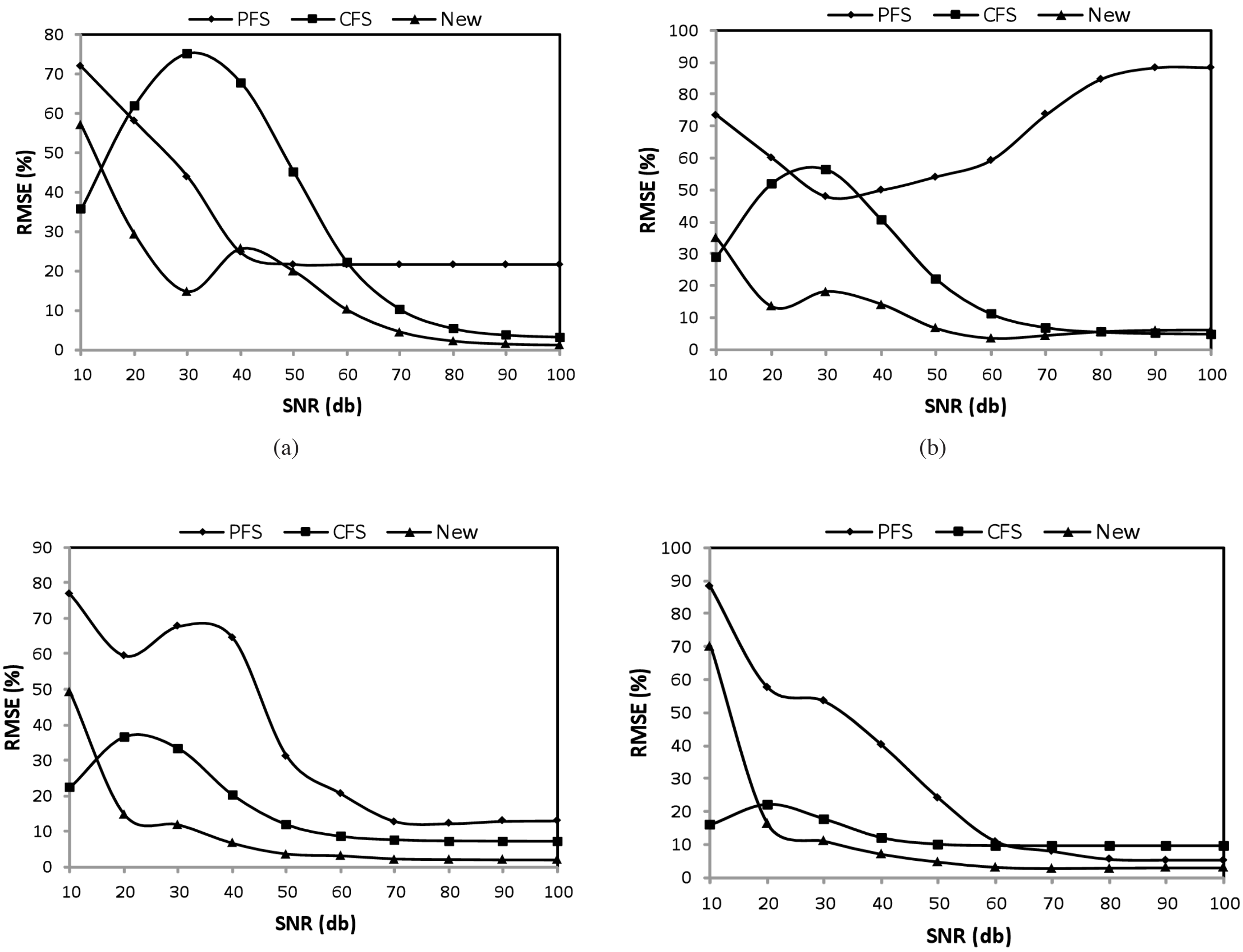
to 80 and 0.25 s, respectively. The noise random levels (SNR) were varied from 10 to 100 dB. To further illustrate the SNR effects that contributed to the error determination of Q, the graph in Figure 4 was plotted.

Based on the graph, it is clear that the performance of the new method increased as SNR was increased. Unfortunately, at low SNR, this method still performed below the CFS method. All methods satisfy high SNR especially at dominant frequencies 60 Hz and 80 Hz. These results consequently are helpful in achieving the objective of this investigation that performance of shift frequency method can be improved even though SNR of signal is low.

Discussion

It is shown that the quality factor is a function not only of the inelastic properties of medium crossed through but also of inhomogeneity of the wave considered. Through the test, the Q estimation from spectral signal using shift frequency method is very sensitive with dominant frequency content, propagation distance between references to target, the quality of signal that represented by SNR and the value of Q itself in the medium.

The results showed that in different value of Q variations, such as in the low Q condition, the CFS method gave errors for the most part of all methods. It can be explained that in this condition, high frequency content of signal will be absorbed rapidly. The shape of the spectra will tend to be asymmetric. The variance of this function has the tendency to increase, so the CFS method that is based on variance calculation tend to give more errors. Meanwhile, peak frequency in the low Q condition will shift significantly. Therefore, estimation based on peak frequency shift will tend to give less errors. Fortunately, our method gave smallest error in this condition due to the correction factor, which is included in the calculation. The changes in the spectral shape are compensated by this correction factor as well. *Vice versa*, in the high Q conditions, the attenuation tends to be insignificant. Spectral shape are likely to be symmetric, variance tend to decrease and the peak frequency shift insignificantly. This situation explains why the CFS errors produced are less than PFS errors. Unfortunately, if the quality of the signal is low, the new proposed method produces errors larger than CFS. The critical SNR to give best performance of this method lies on 15 dB. Above this value, the performance of the new proposed method is better than the others.



(a) (b) (c) (d)

FIGURE 5. Plot of RMSE versus SNR for dominant frequency
(a) 25Hz, (b) 40Hz, (c) 60 Hz and (d) 80 Hz

In the increasing travel time cases, the attenuation will increase significantly. Consequently, the peak frequency and symetricity of spectral shape tend to increase with time. These conditions are not favorable for the CFS method. Errors of this method increase consistently with time. The errors of PFS method is inconsistent with time, but generally tends to decrease by time. Because our correction factors are included in the calculation, the CFS and PFS characteristics were adopted. In the low SNR case the CFS characteristics are more dominant than the PFS method. Consequently errors which are produced by this method are likely to follow CFS trend. In the high SNR condition, the proportionality of correction factor is obtained; hence the errors tend to become stable in the low values.

Finally, in the last test, the effect of SNR variation into performance of this method was assessed. From the results as shown in Figure 5, performance of the new method increased significantly when SNR was increased. In the low SNR condition (below 15 dB), the performance of this method is less than CFS method but still above the PFS method.

CONCLUSION

The new proposed method for attenuation estimation based on the shift frequency method underwent various tests. Based on the result obtained, it can be concluded that this method can improve the shift frequency method to estimate Q factor. This method can be applied in the low and high Q conditions, shallow and deep wavelet targets, low and high SNR conditions and various dominant frequencies of wavelet. In the future, this method will be implemented into real seismic data to estimate Q from seismic data. Spectral decomposition can be used to get the distribution of frequency in the time series to substitute Fourier transform technique. This result will be used to characterize reservoir especially to identify hydrocarbon appearance and monitoring CO_2 injection into depleted oil reservoir.

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