Effect of Frequency and Migration Aperture on Seismic Diffraction Imaging

Y. Bashir\textsuperscript{1}, D. P. Ghosh\textsuperscript{1}, S.Y. Moussavi Alashloo\textsuperscript{1} and C. W. Sum\textsuperscript{1}

\textsuperscript{1}Centre for Seismic Imaging (CSI), Department of Petroleum Geoscience, Universiti Teknologi PETRONAS, Tronoh, Perak, Malaysia

E-mail: Yasir.bashir@live.com

Abstract. Conventional processing and migration frequently give successful results in using specular reflections to estimate the subsurface geometry and strength of continuous reflector geology. However, the correct interpretation of the true geological gaps, such as fault, fracture, karsts and pinch-outs, is one of the main objectives in seismic data processing and interpretation. In regular processing/migration sequence the diffraction response is suppressed because of the lack of choosing the right migration aperture. Kirchhoff migration is a tool to represent the seismic data as a summation of diffraction hyperbolas governed by the velocities at their apex. In this paper, we have investigated two different velocity models to show the effects of different frequencies and aperture size. We used the diffraction-based and data oriented approach that is dependent on the migration aperture from a low to high aperture to properly image the section. We have done the error analysis between the un-imaged and imaged section after processing and observed that the low aperture can give the undesired result for sharp edges. For the same model, we have applied different frequencies to show the effect of frequencies on seismic Imaging and migration.

1. Introduction

Seismic data Acquisition and imaging are inverse processes in exploration geophysics. Acquisition belongs to the propagation of the wave to get the true geology but unfortunately that wave is affected by many factors in the subsurface and also depends on the property of the wave. One of the factors here is that the initial frequency of our seismic wave is affected by many factors during the wave propagation. This is because high frequency wave give us high resolution but less depth of penetration and a low frequency one have high depth of penetration but less resolution\textsuperscript{1}. A relation between the frequency, penetration, resolution, wavelength, and diffraction hyperbola can be defined as.

- High Frequency \(\rightarrow\) Less depth of Penetration \(\rightarrow\) High Resolution
- Low Frequency \(\rightarrow\) Deep depth of Penetration \(\rightarrow\) Low Resolution

Frequency is inversely proportional to the wavelength.

High Frequency \(\rightarrow\) Small Wavelength

\textsuperscript{1} Yasir Bashir (Yasir.bashir@live.com)
Low Frequency $\rightarrow$ Large Wavelength

$$f \propto \frac{1}{\lambda}$$

High Frequency $\rightarrow$ Less diffraction
Low Frequency $\rightarrow$ high diffraction

Where $f$ is the frequency and $\lambda$ is the wave-length. Resolution will be $\lambda/4$, which means that if we are using a high frequency that will illuminate a small object; but, increasing the frequency will also have an effect on the depth of penetration. So, we can define the frequency according to our objective. Seismic methods use low frequencies. Thus, they have low resolution but high depth of penetration. This suits us for imaging the earth. The thinnest layers are in the order of several metres and may be a few kilometres deep. The seismic waves can propagate down to such depths and resolve these layers[1].

There are different phenomena in wave propagation, e.g., Refraction, reflection, diffraction and transmission. Diffraction hyperbolic patterns occur frequently in a seismic section, and their existence is usually taken as evidence of abrupt discontinuities in subsurface reflector geometry[2]. The curvature of the diffraction hyperbola is dependent on the different depths and velocities of the layer. As a high frequency will produce less diffraction then a low frequency and with the depth increase, the diffraction hyperbola will spread out more and the apex will be gentle[3]. Kirchhoff migration sums the amplitude along the diffraction hyperbola and brings all the energy at the apex. The aperture size is used for the summation of the hyperbola amplitude and this is very important parameter in migration.

Seismic data processing and imaging is a tool to image the wave propagation travel time and illuminate the actual geology. This paper deals with increasing the understanding of Kirchhoff migration, precisely on the different frequencies and aperture sizes on seismic imaging.

2. Methodology

2.1. Theory and Method

Diffraction theory states that a diffraction hyperbola extends to the infinite time and distance. In practice, we have to deal with truncated hyperbolic summation paths[4]. Spatially, the extent of the actual summation path span or aperture width is measured in terms of the number of traces the hyperbolic path spans[5]. In general theory, diffraction hyperbola will be increase with time and distance and in exercise we have to sum the travel time which is calculated on different position. Aperture width can be measure in term of the traces numbers per hyperbola[5]. The equation describing the hyperbola is given as

$$t^2(x) = t^2(0) + \frac{4x^2}{V^2}$$

Where $x$ is the distance in (m) from the output trace to that of the input trace location and $t(x)$ is the input time computed and $V$ is the velocity in (m/sec).

Kirchhoff migration is the best method to describe the kinematics. The source and receiver compute the energy from the reflection point in time at each point diffractor, which is a point from the reflector to the receiver and is recorded in time[6]. Technically, the constant velocity Kirchhoff migration programme needs each input un-image data to visit each output data traces with in a migration aperture exactly once. This parameter allows one simulate, accurately the number of additions that will be performed in the migration algorithm[6].
2.2. *Velocity Model*
In this study, we have considered two geological Models called hole in reflection. Model-1 had a hole width of 100 m (Figure 1) and Model-2 had a Hole width of 300 m (Figure 2). For convenience, we chose the constant velocity and variable density model. Having a velocity of 2500 m/sec, density of the 1st layer was 2.2 Kg/m$^3$ and 2.7 Kg/m$^3$, respectively, and the total depth of the model was 2000 m.

![Figure 1: Velocity model-1 with a hole width of 100 m and synthetic seismic gather.](image1)

![Figure 2: Velocity model-2 with a hole width of 300 m and synthetic seismic gather.](image2)

2.3. *Seismic Data*
Over the velocity model, 2D synthetic data were acquired using the finite-difference wave equation technique. The common shot section was acquired along a 2000 meter seismic line. In this model, we used the zero-offset survey design, and the distance between each shot was 10 meters and the sampling interval was 2 Milliseconds.
Seismic data was acquired in two different frequencies, 30 Hz and 80 Hz. As stated in the theory, the diffraction hyperbolic effect was more in the low frequency than the high frequency as shown in Figures 3-5.

2.4. *Seismic Migration*
Implementation of the Kirchhoff migration was accomplished with the use of asymptotic calculation that is effective for large values of frequency and time. In this paper, we have applied the Kirchhoff migration on low frequency and high frequency.
3. Results and Discussion

The example shown in the synthetic seismic gather illustrates a pitfall to avoid with the use of migration aperture. Figure 3 illustrates the different aperture sizes affecting the diffraction hyperbola to be imaged using the Kirchhoff summation algorithm. It can be observed by visual interpretation during processing how much aperture size was necessary to image the proper geological feature. For some of the case we did not need a large migration aperture because if the aperture size was large then the processing time would be high and computational power would also increase to bring all the energy from the flanks to the apex. Generally, if the depth increases then the velocity will also increase; so, according to the theory, if the velocity is high, then the curvature of the hyperbola will be less. During processing, Kirchhoff actually sums the energy from the flanks and combines it on the apex; but, in the case of high depth, we could not sum it correctly because of not knowing which energy belonged to the hyperbola and which reflection amplitude it was. So, for a high velocity area, we still had difficulties to image the diffraction hyperbola. In this situation, we need to refer to the wave-equation migration that is in two domains, One-way and two-way.

For Model-1 and 2, we generated a synthetic gather in two different frequencies to show the effect on the seismic imaging. Low frequency data was imaged on a larger aperture size than the high frequency data as shown in Figures 3-6.
Figure 4: Hole in reflection model with a dominant frequency of 30 Hz and Hole width of 300m. (a) Un-Image section, (b), (c) and (e) are migrated sections on different aperture sizes, 100, 300 and 500 m, respectively.

Figures 3 and 4 illustrate the low frequency data on Model-1 and Model-2, respectively, which had 100 m and 300 m hole widths. 3a and 4a show the un-Image zero-offset seismic gather, 3b and 4b are after the application of the Kirchhoff migration using the aperture size of 100 m; but, we can see an error because of choosing the small aperture. For sections 3b and 4b, the sharp edges are not illuminated until we increased the migration aperture until 400 m as shown in Figures 3d and 4d.

Here, if we imagine the real earth model, generally increasing the depth, the frequencies will also effected by earth materials wave and the high frequencies will be absorbed. So, in deep sections we have only low frequencies; these low frequencies will give us high diffraction responses as stated above. In actuality, we have to use a larger aperture for a deep diffraction response summation. For our model, we did not have that depth, so we used a small aperture that was enough to image the diffractions.

Figures 5 and 6 illustrate the high frequency synthetic seismic gather on Model-1 and Model-2, the hole width was 100 m and 300 m, respectively. 5a and 6a are zero-offset un-Image seismic gathers in which we cannot interpret the fault, which is described by the blue colour arrow. 5b and 5c are after application of the Kirchhoff migration using the aperture size of 100 m. 5c and 6c are also after the migration using aperture length of 300 m. We have observed that in a high frequency, the migration aperture of 300 m is enough to image the section rather than the low frequency as shown in Figures 3 and 4. High frequencies are good for the resolution purpose but for the deep events, we have to use a low frequency that can be imaged by increasing the migration aperture size.
**Figure 5:** Shows traces with a dominant frequency of 80 Hz and a Hole width of 100m. (a) Zero-offset Synthetic Seismic gathers on Model-1, (b), (c) and (d) are traces after application of the Kirchhoff Migration on different aperture sizes.

**Figure 6:** Hole in reflection synthetic gather with a dominant frequency 80 Hz and a Hole width of 300m. (a) Un-image section, (b) Migrated section with aperture of 100 m, (c) Aperture of 300 m and (d) Aperture of 500 m.
Conclusion

We have demonstrated that the traditional processing/migration regard the diffractive wave field as noise and ignore the structural events which are conveyed by the diffraction. During processing (NMO/DMO, multiple attenuation), events that are not originating from a flat and robust reflector are usually filtered out. These results make images only the highlight reflectors and obscure non-reflecting structures such as faults, edges, pinch-outs and small scattering objects. The main challenges of the diffraction analysis are that the diffractions are usually tangent to the reflection and phase change is 180 degrees with the exponential energy decay. Seismic imaging using the Kirchhoff migration algorithm has been applied to sum the diffraction response from the edges of the reflector and using the different aperture sizes to image the diffractions. We have Optimised that data which had high frequencies that needed the small aperture length, and for low frequencies a small migration aperture. Results include the error analysis because of wrong selection of migration aperture for different frequencies in seismic migration. A good quality migrated image requires a migration aperture with an optimal size. Disproportionately small apertures cause destruction of the steeply dipping events and edges of the reflector. More importantly, large apertures will degrade the migration quality in a poor signal-to-noise ratio and increase the cost and computational power without quality improvement.

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