NMO residual reduction on medium anisotropy in field “X” using Fomel and Stovas method

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Abstract. It has been done the study of reducing NMO residual on medium anisotropy in Field “X” by using Fomel and Stovas method. The anisotropic medium affected the seismic pre-stack of near, mid, and far offset when the NMO correction was being conducted. The correction principally used the isotropic medium approach where the seismic event often encountered problems in its far offset. The problem was the seismic trace appearance in form of hockey stick and NMO-stretching. The purpose of this study is to understand the best residual value of travel time by Fomel and Stovas, Alkhalifah, and conventional hyperbolic methods. The semblance analysis was used alongside all three methods to obtain the value of \( v_{NMO} \) and anisotropy (\( \eta \)). The values were then compared. The result shows that the non-hyperbolic Fomel and Stovas method is better in reducing residual NMO as indicated by the smaller residual value compared to Alkhalifa and conventional hyperbolic methods of travel time. The small residual contributed to eliminate the effect which was caused by anisotropy medium like hockey stick effect.

1. Introduction

Anisotropic seismic is expressed as the dependence of the seismic wave velocity on the direction of wave propagation in rocks [1]. Seismic wave velocity is actually depending on elastic modulus and density, such as bulk and shear modulus. Therefore, anisotropic seismic is, in fact, the form of elastic modulus which varies with its angle [2]. Knowledge of the effects of anisotropes is important in the processing and interpretation of seismic data.

Basically, the NMO (normal moveout) process needs the event’s shape derived from a reflector layer to be as flat as possible [3]. Performed with the assumption that the earth model used is isotropic, however in actual circumstances most of the rocks are anisotropic. Earth’s tectonic movement causes many variations of stress that cause rock anisotropic properties.

Sheriff and Geldart[4] state that prestack seismic data consisting of near offset, mid offset, and far offset often has problems with the far offset itself. But in an anisotropic medium, seismic data faces two problems, shallow layer medium and far offset. The problem in shallow positions is the seismic trace experiences frequency distortion, while infar offset there is stretching [3]. The existence of lithological heterogeneity of rocks in anisotropic medium also generate other problem, namely the existence of a hockey stick effect. The hockey stick effect is a seismic event that curves like a hockey stick shape.
Both problems are caused by the layer medium in shallow depth, the medium is anisotropic and also heterogeneous. The medium become more homogenous due to the stress and strain of the rock when the layer become deeper. Anisotropic medium which is expressed as a change in physical property such as velocity measured in a particular measurement direction, makes physical property (velocity) has different values in near offset and in far offset. Yilmaz [3] stated that the incoming ray velocity received by the receiver at a far offset has experienced frequency attenuation which makes the stretching effect. In the other hand, incident angle can be received with the assumption that the angle of arrival does not exceed 30° at the time of data acquisition [2]. If the incident angle exceeds 30°, then the assumption below the surface using hyperbolic travel time is not optimal to use.

The hyperbolic travel time method for NMO correction has not been maximized, so it takes non-hyperbolic travel time to eliminate these problems. If we use the travel time equation with the hyperbolic conventional method, the far offset that experiences the hockey stick effect will perform data muting which results in the loss of important information related to lithology, fluid, etc.[3].

In this study we try to reduce NMO residuals by using the equation of travel time with unconventional methods which are non-hyperbolic like the Alkhalifah and Fomel and Stovas methods. Alkhalifah [5] had succeeded in finding the travel time equation with a non-hyperbolic method which can overcome the problem in anisotropic medium, the hockey stick effect. Whereas Fomel and Stovas [6] generalized the function of non-hyperbolic travel time equations which can be applied to various seismic media.

This study will also compare the three NMO corrections. The best travel time method will be determined among hyperbolic conventional method, non-hyperbolic method (Alkhalifah method), and Fomel and Stovas method in determining the best travel time in reducing residuals. To see the three best travel time methods, we see the value of the residual reduction. The smallest the residual value indicate most precisely \( t_{NMO} \) at a certain offset against \( t_{NMO} \) (zero offset). The best travel time method will have implications for increasing the image quality in the seismic section.

2. Theory

Previous researchers have proposed algorithms or methods in estimating travel time from seismic data where the reflection seismic travel time can be approximated by Taylor series expansion [7]. Among them is the hyperbolic conventional moveout method that generally used for isotropic medium. It can be said conventional because the method assumes that the physical properties of the subsurface such as velocity, permeability and others are isotropic and homogeneous, so the equation of travel time is sufficient until the second part of the Taylor series. Hyperbolic conventional travel time \( t \) can be written as,

\[
 t^2 = t_0^2 + \frac{x^2}{v_{NMO}^2}
\]

where \( x \) is offset, \( t_0 \) is the travel time at zero offset, and \( v_{NMO} \) is the NMO velocity.

In anisotropic medium, the conventional method above causes problems in long offset and triggers other problems such as hockey stick effect. Therefore, a better method is needed and add a part of the travel time from the Taylor series.

Alkhalifah and Tsvankin used the third part of the Taylor series to deal with problems caused by anisotropic media [8]. They derive the quadratic part equation from Tsvankin and Thomsen to equation (2)[9],

\[
 t^2 = t_0^2 + \frac{x^2}{v_{NMO}^2} - \frac{2\eta x^4}{v^4(t_0^2 + (1 + 2\eta)\frac{x^2}{v^2})}
\]
where \( \eta \) is

\[
\eta = \frac{\varepsilon - \delta}{(1 + 2\delta)}
\]  

(3)

Fomel and Stovas [6] proposed a general form for approximation of non-hyperbolic functions that can be applied in various seismic media. The proposal involves five coefficients as a comparison for two coefficients in the approximation of classical hyperbolic functions (zero-offset time and moveout velocity). The five coefficients are:

\[
A = -4\eta, \quad B = \frac{1 + 8\eta + 8\eta^2}{1 + 2\eta}, \quad C = \frac{1}{(1 + 2\eta)^2}
\]  

(4)

So that the equation of Fomel and Stovas becomes [6]:

\[
t^2 = t_0^2 + \frac{X^2}{v^2} + \frac{A x^4}{v^4(t_0^2 + B \frac{X^2}{v^2} + \sqrt{t_0^4 + 2Bt_0^2 \frac{X^2}{v^2} + C \frac{X^4}{v^4}})}
\]  

(5)

The difference between the hyperbolic travel time method and the Alkhalifah method for the Fomel and Stovas method lies in the components of the Fomel and Stovas method of the equation (4). If the component value \( A = 0 \), the equation (5) will be reduced back to the conventional hyperbolic equation (1), in the other hand if the value \( A = -4\eta , B = 1 + 2\eta , C = (1 + 2\eta)^2 \) then equation (5) will be reduced to the equation proposed by Alkhalifah and Tsvankin [8] in equation (2).

The three travel time methods still produce residual after NMO corrections. Therefore, a comparison is made to show which travel time has smallest NMO residual reduction. Residuals are remnants of seismic events which should be perpendicular (flat) to zero offset after NMO correction but the seismic event is still deviated at a certain offset. Residuals generally occur at far offsets. The residual is shown in figure 1.

![Figure 1](image-url)

**Figure 1.** Residual reduction of move out (NMO) getting bigger at far offset [3].

Residual reduction is used to see the comparison of residual values using different travel time methods. In addition, residual reduction has implications for reducing the consequences of muting at far offsets. Muting at far offsets will have an impact on the lack of information obtained on seismic data such as lithology, fluid and others [3]. The smallest residual reduction indicates the smaller the residual value of an NMO correction or the more precise the \( t_{NMO} \) at a certain offset of \( t_{NMO} \) (zero offset). This relationship shown as the smallest percentage of the following equation,
Where the residual is,
\[ \text{residual} = \frac{\sum_{i=1}^{n} T_x - T_0}{T_0} \]  

3. Methodology

3.1 Modeling

The initial modeling was made using synthetic data as shown in table 1. The model has four vertical layers where each layer has a P wave velocity, density (\( \rho \)) and values of different anisotropic factors, namely delta (\( \delta \)) and epsilon (\( \varepsilon \)). This synthetic model is made in such a way to follow Thomsen's table for the values of \( v, \rho, \varepsilon, \) and \( \delta \) as follows [10]:

| Layer | Two way time | Velocity of P wave | \( \rho \) (g/cm\(^3\)) | \( \varepsilon \) | \( \delta \) |
|-------|--------------|------------------|-----------------|--------|--------|
| 1     | 500ms-1000ms | 2000m/s          | 2.00            | 0.00   | 0.00   |
| 2     | 1000ms-2000ms| 2300m/s          | 2.2             | 0.22   | 0.02   |
| 3     | 2000ms-3000ms| 2500m/s          | 2.3             | 0.34   | 0.03   |
| 4     | 3000ms-4000ms| 3000m/s          | 2.4             | 0.46   | 0.04   |

The values in the first layer of table 1 is made with the assumption that subsurface of the layer is an isotropic medium and in the second layer to the fourth is an anisotropic medium. Anisotropic medium is affected by one factor, namely etha (\( \eta \)). The value of etha (\( \eta \)) is seen in equation (3). Subsequently modeling is made in the seismic gather domain.

3.2 Seismic/CMP gather and velocity analysis with hyperbolic moveout

The modeling on seismic gather/common depth points (CDP) gather uses offsets from 0 to 4000 m. It was done to be able to see the phenomenon of anisotropic media, namely the hockey stick effect. This phenomenon can only be seen if it has a far offset. If the offset is close, the phenomenon will not appear. The model of the seismic/CMP gather then experienced velocity analysis to obtain the actual velocity at the subsurface layers that can be seen in the figure 2.
Figure 2. (a) Modeling in seismic gather and (b) Semblance analysis using conventional travel time modeling.

In figure 2 (a) there are 3 reflectors in the subsurface. In the first reflector to the last (third) reflector, a splitting phenomenon occurs. This is because the second and third layers have a faster velocity than the previous layer along with increasing depth. Figure 2 (b) is a velocity semblance. Choose the velocity on the second reflector where we choose the velocity semblance by looking at the coordinates of the x-axis and y-axis directions, where x coordinates indicate the velocity and y coordinates indicate depth in time (TWT). Velocity analysis is useful for getting real velocity, where the NMO correction process requires velocity.

3.3 NMO correction and re-semblance analysis with non-hyperbolic moveout

After the semblance analysis, a normal moveout (NMO) correction has been performed. In NMO correction, hyperbolic travel time is used, where the hockey stick effect phenomenon will be occurred. It happens because in synthetic modeling the anisotropy factor is eta ($\eta$) so that the velocity entered in the calculation of NMO correction is not appropriate. The magnitude of the hockey stick effect depends on the strength of the anisotropy factor eta ($\eta$) on the layer above it.

Figure 3. (a) After NMO correction using conventional methods and (b) picking of velocity and eta ($\eta$) using non-hyperbolic methods.
In figure 3 (a) it can be seen that in the second layer of TWT 2000 ms and the third layer of TWT 3000 ms, there is a hockey stick effect. However, in both the second and third layers, the hockey stick effect has not been seen at an offset near about 1000 m and the farther off the offset, the more visible the layer deviation is. This shows that the hockey stick will appear if the offset is a far offset. The existence of a factor from anisotropic media, namely etha ($\eta$), requires a step to do the velocity selection step by means of a velocity analysis method to eliminate the effect of the hockey stick. Previously it used hyperbolic conventional travel time but now it is done using unconventional travel times. To overcome the effect of hockey stick, an additional semblance analysis process is done, namely the etha semblance analysis ($\eta$). This is based on the relationship on the anisotropic medium which has been influenced by the etha value ($\eta$). The etha ($\eta$) and velocity ($v$) values obtained from the semblance analysis process are models that will be used in stacking using the Fomel and Stovas travel times as shown in figure 3 (b).

4. Results and Discussion
4.1 Synthetic modeling and residual reduction
From synthetic modeling with the travel time of anisotropic medium Fomel and Stovas travel time and Alkhalifah travel time, we obtained velocity values ($v$) and etha ($\eta$) in the first layer up to the last layer. The value obtained from the synthetic modeling will then be corrected by NMO. The results of NMO's corrections are as follows:

![Figure 4](image)

**Figure 4.** (a) Comparison after NMO corrections Fomel and Stovas to Alkhalifah, (b) at layer 2, and (c) layer 3
The results obtained after the NMO correction is carried out still produce residuals from the effects caused by the offset between the seismic wave source and the geophone on a trace coming from one CDP. The residuals are calculated to see which travel time is the best. Calculation of the residuals reduction has been done at the time of Fomel and Stovas and on the travel time of the Alkhalifah using semblance analysis. Residual reduction results at different travel times are as shown in figure 6.

![Figure 5](image)

Figure 5. Residual comparison in synthetic modeling between the three methods.

It is found that the model in the first layer is formed as an isotropic medium. The physical property such as velocity is not affected by the direction of measurement, so the value in the first layer of the residual is 0.5 ms. The second and third layers behave as an anisotropic medium where the velocity changes depending on the direction of measurement. Better residual reduction is obtained from the accuracy of the travel time. In the third layer, the travel time of Fomel and Stovas and Alkhalifah has the same residual value of 0.5 ms and the hyperbolic travel time of -214.5 ms. In the second layer, the residual value for the hyperbolic travel time is -214.6 ms, the travel time of Fomel and Stovas is 4.5 ms while the Alkhalifah travel time is 14.65 ms. The residual value for conventional travel time affected by non-hyperbolic travel time at the time of data acquisition so that the hyperbolic travel time equation increases the residual value. The best residual reduction method is indicated by the smallest residual value.

Equation (6) is applied to the residual value of both the hyperbolic conventional method, the Fomel and Stovas method and the Alkhalifah method in the first layer. Reflectors in the first layer have residual reduction values of 0.05%. The hockey stick effects caused by an anisotropic medium do not appear. The residual value similarity and the absence of the hockey stick effect caused by the fact that the first layer of the model is an isotropic medium. It makes applying the three different travel time methods have no effect to the both travel time and hockey stick effect.

The residual reduction value for the reflector at the second layer from Fomel and Stovas method is 0.25%, the Alkhalifah residual method is 0.75% and the hyperbolic conventional residual method is 10.73%. The residual reduction results from the Fomel and Stovas method are smallest because the method has a better formula concentration level than the others. In addition, the hyperbolic method has the largest residual reduction value because the method still assumes that the layer is isotropic although the subsurface is actually anisotropic. The anisotropic medium during NMO correction needs to add a new parameter, namely etha ($\eta$), to overcome the residual from the isotropic assumption. This is what causes the conventional travel time method to have a large value compared to the other two methods.

The residual reduction values for reflectors at the third layer of the Fomel and Stovas method and the Alkhalifah method are the same of 0.02%, and the hyperbolic conventional method is 7.15%. In addition, the residual reduction value in the hyperbolic conventional method in the deep layer is
smaller than the previous layers. It is caused by the fact that the deeper layer of the reflector (TWT), the influence of the anisotropic medium has become less influential. The statement can be strengthened by the information about the angle of incidence ($\theta$) in the rock layer, where the deeper the layer, the angle coming from the incoming ray as it passes through the layer is smaller where $\theta_{\text{shallow}} > \theta_{\text{deep}}$. In modeling, it can be said that the travel time of Fomel and Stovas is "better" in reducing NMO residuals compared to both Alkhalifah travel time and hyperbolic conventional travel time method as indicated by the smaller residual value of an NMO correction or more accurate at a certain offset against (zero offset).

4.2 Real data
Real data is obtained from sea data acquisition and applied in SEG.Y format with Gather CDP domain form. The real data with an offset ranging of 130 – 6030 m and has been pre-processed. The pre-processing itself started from reformating the data obtained from the field until the filtering process to eliminate noise and multiple. The real data has also been carried out by the pre-stack migration process to eliminate diffraction effects so that when the velocity selection process through semblance analysis, no more noise can disrupt the velocity during the picking process. Real data can be seen in figure 7 (a).

![Figure 6](image)

**Figure 6.** (a) before NMO correction and (b) after hyperbolic NMO correction.

Figure 6 (b) is the result of NMO's correction. In the red box of TWT 1800 ms - 2000 ms and TWT 3000 ms - 3300 ms it is seen an effect of the anisotropy medium. The hockey stick effect still causes seismic trace curved up or not straight (flat). That is natural because the NMO correction still uses hyperbolic travel time. In hyperbolic travel time there is no coefficient of anisotropic medium of eta ($\eta$) included in. To overcome the hockey stick effect, it is necessary to do the semblance analysis process which involves the coefficient of eta ($\eta$) uses the Alkhalifah, and Fomel and Stovas methods.
Figure 7. After NMO correction by (a) Alkhalifah and (b) Fomel and Stovas method.

Figure 7 (a) is the result of NMO (normal moveout) correction using the Alkhalifah method and (b) the Fomel and Stovas method. In these images, the process involves the selection of speed ($v$) and the anisotropic parameters etha ($\eta$) which use the travel times of Alkhalifah and Fomel and Stovas (equations (5 & 7)). In the area that we examined shown in the red box also shows that on TWT 1800 ms - 2000 ms and on TWT 3000 ms - 3300 ms seismic events have been straight (flat) after NMO correction with travel time Fomel and Stovas. Furthermore, the three results are compared to see the residuals in the hyperbolic travel time, the travel time of Fomel and Stovas and also the travel time of the Alkhalifah. The comparison can be seen in the best residual reduction from the three methods in figure 9 below,

Figure 8. Residual comparison of Alkhalifah, Fomel and Stovas, and hyperbolic method (left to right).

Figure 8 shows a comparison of residuals after the NMO correction process that has been taken from one of the reflector layers at TWT 2380 ms. The residual value for the Fomel and Stovas travel time method is -95.96 ms while the Alkhalifah method is -136.5 ms and the hyperbolic conventional method is -409.1 ms. The residual value of the Fomel and Stovas method is smaller than the two others
method. This is because the travel time of Fomel and Stovas has more accurate concentration level in anisotropic factors as described in advance. Comparation of the residual reduction value can be performed by applying it to the equation (5). From this equation, we get the residual reduction value of the Fomel and Stovas method is 4.03%, the Alkhalifah method is 5.73%, and the hyperbolic conventional residual is 17.18%. Residual reduction value with the smallest percentage indicates the smaller the residual value of an NMO correction or the more precise the offset (zero offset). It can be said that the travel time of Fomel and Stovas is better in reducing residuals of NMO correction than the Alkhalifah and hyperbolic conventional.

5. Conclusions
From the results of anisotropy study, here are some conclusions obtained from the results of processing synthetic and real data:
1. The Fomel and Stovas method is the best method compared to the hyperbolic conventional and non-hyperbolic Alkhalifah method for NMO correction in an anisotropic medium.
2. The value of residual reduction in real data NMO correction from Fomel and Stovas travel time has smallest value of 4.03% compare to Alkhalifah (5.73%) and hyperbolic conventional (17.18%).
3. Velocity values ($v$) and etha ($\eta$) have an effect on increasing the accuracy of non-hyperbolic NMO residuals. Speed ($v$) influences to correct NMO at near offset. While the anisotrope etha parameter ($\eta$) is more influential in correcting NMO at far offsets which has implications for better seismic cross-sectional image quality so that the information obtained is more precise.

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