ASEG-PESA 2015
Geophysics and Geology together for Discovery
24th International Geophysical Conference and Exhibition
15–18 February 2015 Perth, Western Australia

Instantaneous frequency-slowness analysis applied to borehole acoustic data

Marek Kozak, PhD
SuperSonic Geophysical LLC
Donegal Ct, Newark, CA, USA
marek@acousticpulse.com

Jefferson Williams
SuperSonic Geophysical LLC
Donegal Ct, Newark, CA, USA
jeff.williams@acousticpulse.com

SUMMARY

The methods most frequently used to process borehole acoustic data are based on semblance analysis. Two most commonly utilized semblance implementations are: slowness-time coherence and slowness-frequency coherence. Both of them are relatively robust under noisy well conditions. They deliver slowness value across the receiver array, and, as the quality control measures, coherence peak value and frequency dispersion curve.

Semblance processing might be substituted by instantaneous frequency-slowness method based on complex wave form analysis. Instantaneous frequency - slowness delivers rich set of quality control measures. Among them are the velocities, the goodness and standard deviation across the receiver array, and instantaneous frequency and slowness wave forms computed between adjacent receiver pairs. Furthermore, since computations are performed across adjacent receivers, the vertical resolution is limited to the offset between receivers. Thus the effect of multiple semblance peaks observed while the receiver array is passing through the high acoustic impedance contrast is eliminated. Also, the method is capable to detect underperforming receivers. Finally it can help to control mixed acoustic mode conditions.

Instantaneous frequency-slowness method delivers robust results under good to moderately noisy well data. The set of quality measures it delivers is much broader than the one generated by the semblance method.

Key words: complex wave form analysis, phase processing, semblance method, instantaneous frequency, instantaneous slowness, borehole acoustic data analysis.

INTRODUCTION

Instantaneous frequency-slowness method (IFS) is based on complex wave form analysis. It delivers the same measures as complex wave form method e.g. slowness and standard deviation, goodness of the data and receiver responses across the neighbouring pairs. Additionally, IFS method computes instantaneous frequency and slowness wave forms as seen between adjacent receivers.

Classic semblance method delivers quite limited set of data quality measures. Among them are semblance peak value, semblance projection wave form, and frequency dispersion curves. Semblance method is executed across the entire or the subset of the receiver array. Thus the vertical resolution is limited to the offset between near and far receivers. The implications are that when the receiver array is crossing high acoustic impedance contrast then multiple semblance peaks will smear semblance projection wave form and therefore might make slowness readings erroneous. Furthermore, should it happen that one or more of the receivers are malfunctioning (in amplitude or in phase domain) then semblance method will not be able to flag such a condition. Small drop in semblance peak value might still be present. This effect is typically overlooked by the processing team. Finally, under mixed acoustic modes conditions, as when Stoneley wave contaminates flexural arrival present in the wave train data, semblance method will not able to indicate it.

In contrast IFS analysis delivers wider set of data quality measures. Among them are:

- Slowness across adjacent receiver pairs
- Slowness distribution, its standard deviation and goodness values
- Instantaneous frequency computed between neighbouring receivers
- Instantaneous slowness across adjacent receiver levels

The core of IFS method is based on complex wave form analysis, also known as phase velocity processing. Complex wave form method was explained in the past in numerous papers, among others: in 1997 Gill and his team was warranted patent for applying phase velocity method to process borehole acoustic data, at the 2001 SPWLA convention Kozak presented complex wave form analysis method applied to process LWD full wave form acoustic data. There are numerous other references to phase velocity algorithm utilized in a context of borehole acoustic data. The recent two different papers were presented by Ellington and by Kozak at the 2014 SWPLA convention.

The main difference between classic phase velocity analysis and its IFS version are new unique features introduced by the last one, as follows:

- Stacked slowness distributions (in a sense of common receiver depth) are calculated across adjacent receivers. Should the responses obtained at different sensor levels be similar then slowness distribution shall resemble the shape of a delta function, i.e. its standard deviation should be close to zero and its peak value ought to be reaching one (similar behaviour to the semblance projection wave form)

- Instantaneous frequency is computed across adjacent receiver pairs within the applied processing window in the time domain. Propagating compressional wave is not dispersed (not counting the P-leaky mode), therefore its instantaneous frequency response should be flat in the time domain. Should the monopole source excite signal of broad bandwidth then instantaneous frequency response shall follow it. On the other hand, the flexural data excited by a dipole source should clearly show dispersion effect e.g. earlier arrivals within the wave train should travel faster than the later arrivals. Additionally, mixed acoustic mode conditions present within processing window position and its width should be clearly indicated and affected by variable character of instantaneous frequency response.
- Finally, instantaneous slowness is also computed between adjacent receiver pairs, and it should deliver responses consistent to those described above in the instantaneous frequency paragraph.

IFS method was applied to the sets of borehole acoustic data of various qualities, from the moderate to good. It was tested against classic semblance analysis results. It delivers higher vertical resolution, limited only by the interspacing between adjacent receivers. Also, it detects malfunctioning receiver conditions and/or mixed acoustic mode that otherwise would pass through the processing flow undetected. Finally, IFS method is less sensitive to the receiver miss-calibration issues.

METHOD AND RESULTS

Following are procedural steps needed to derive instantaneous frequency and slowness wave forms.

In initial step receiver wave form signals in time domain are converted to the complex format via a Hilbert transformation $H_n(t)$. Subscripted symbol of n denotes the n-th receiver level within array. Hilbert transformed data is used to compute phase arrival vectors. This operation is performed in time domain and at each receiver level separately. Above calculations can be expressed by the following formula:

$$\phi_n(t) = arctan(im(H_n(t)) / re(H_n(t))) \qquad (1)$$

Where: $\phi_n(t)$ denotes signal phase as the function of time computed at the n-th receiver level. Functions $im(H_n(t))$ and $re(H_n(t))$ represent respectively the imaginary and real parts of Hilbert transformed data.

In the next step instantaneous frequency wave forms are computed as follows:

$$F_{ij}(t) = (d(\phi_i(t))/dt + d(\phi_j(t))/dt) / 2 \qquad (2)$$

Where: $F_{ij}(t)$ represents instantaneous frequency as recorded across the receivers i and j, i.e. the first derivatives of the phase over the time are averaged. In the most cases subscripts i and j correspond to the adjacent receivers. It ought to be highlighted that for the receiver array consisting of N levels the number of instantaneous frequency wave forms will be equal to N-1.

Instantaneous slowness calculations are based on the following formulas:

$$S_{ij}(t) = \frac{1}{Z}\left[P_j(t) - P_i(t)\right]$$

$$dT_{ij} = \tfrac{1}{N}\int_{t\min}^{t\max} S_{ij}(t)dt \qquad (3)$$

Where: $S_{ij}(t)$ represents instantaneous slowness computed at the time of t between the receivers i and j that are separated by the offset of Z. Slowness dT_{ij} across the receiver pair i and j is derived from the integral (3) where N equals to the number of samples within the integration range of t_{min}, t_{max}.

Examples of flexural wave forms and instantaneous frequency responses obtained with cross dipole tool are presented on the **Figure 1, Figure 2, Figure 3**, **Figure 4 and Figure 5**. For the image clarity only odd receiver levels are presented in this paper. Instantaneous frequency wave forms (both dipole Y and X excitations) show modest frequency increase from approximately 2.1 kHz (at the beginning of the processing window) up to maximum of 2.6 kHz. Due to dispersed nature of propagating flexural waves this is normal and expected phenomenon. Later parts of the wave train show gradual drop off frequency values. This effect indicates that processing window width was setup too wide (in time domain sense). Contamination results from later arriving Stoneley waves. Instantaneous frequency response is capable to detect mixed acoustic mode condition resulting from either difficult borehole environment or processing errors. **Figure 5** shows instantaneous frequency analysis results obtained while logging anisotropic formation with cross dipole tool. Tracks #3 and #5 display VDL's of instantaneous frequencies calculated using XX and YY wave forms respectively. Lower frequencies are mapped into the lighter grey colours. There are two distinct frequency peaks located in the middle and toward the end of processing window. This pattern indicates presence of azimuthal shear wave anisotropy. **Figure 6**, **Figure 7** and **Figure 8** show IFS results obtained while processing formation logged with the monopole tool. Within the vicinity of depth #2 the well was washed out. Instantaneous frequency dropped down below 2 kHz (see the signature presented on **Figure 7**). This effect is unwanted and might indicate the presence of a dispersed P-leaky mode. Under such a condition narrower processing window should be utilized. **Figure 8** presents IFS results computed at the depth #3 (**see Figure 6**). Frequency wave form curves indicate modest dispersion.

Figure 9 and **Figure 10** present instantaneous slowness wave forms derived from the dipole XX and YY data at the depth location #1. **Figure 11** and **Figure 12** show compressional wave instantaneous slowness computed at depths #2 and #3 respectively. As it was expected, dipole generated flexural wave displays frequency related slowness dispersion. Also, since the formation is anisotropic, two weak slowness humps are observed, especially in XX results. Instantaneous slowness obtained with the monopole source at the depth #2 is affected by very strong distortions, results of washed out zone. This phenomenon confirms observations made earlier while discussing the frequency response. Slowness compressional wave forms computed at depth #3 are flat, as anticipated.

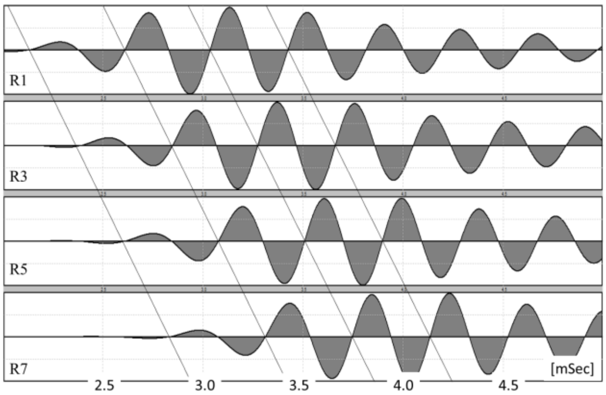

Figure 1. Example of dipole Y in line wave forms.

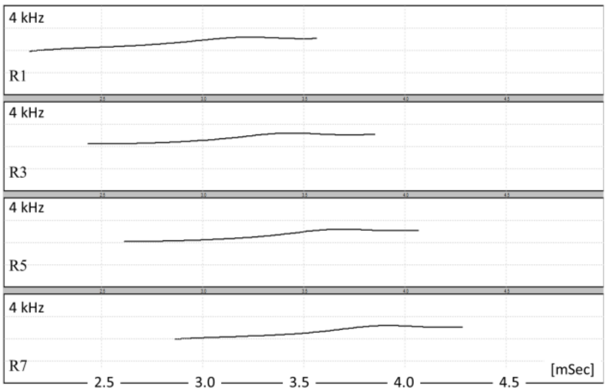

Figure 2. Instantaneous frequencies of dipole Y wave train. Picture shows in line YY component.

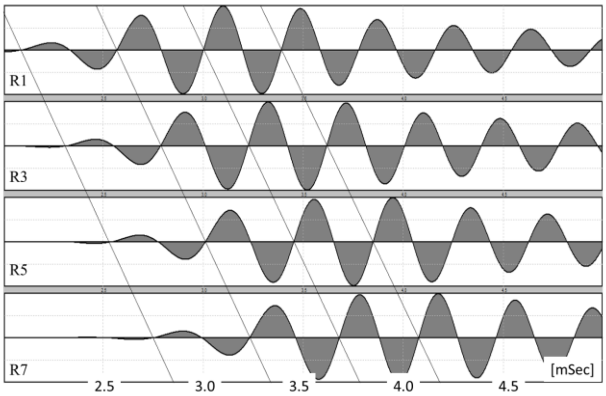

Figure 3. Example of dipole X in line wave forms.

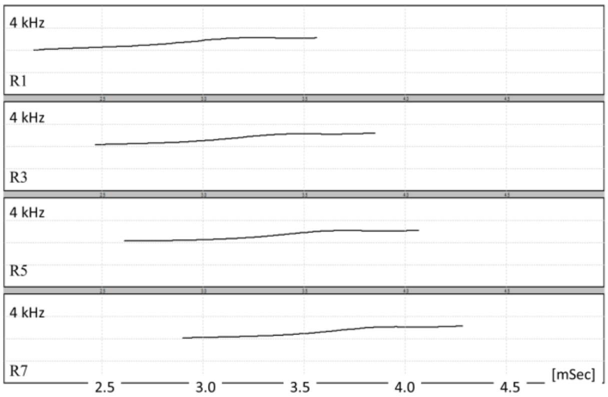

Figure 4. Instantaneous frequencies of dipole X wave train. Picture shows in line XX component.

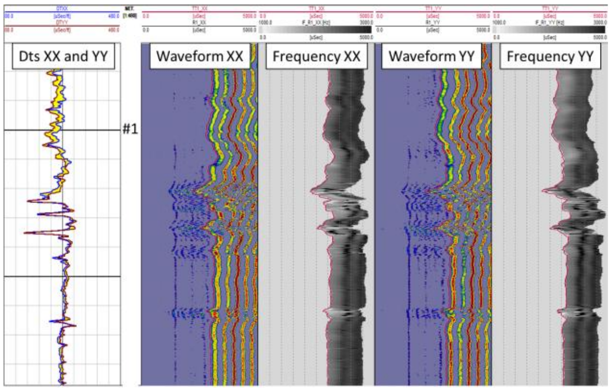

Figure 5. Cross dipole data recorded under anisotropic formation conditions. Track #1 shows flexural wave velocities (DTS XX – blue and DTS YY – brown) obtained with IFS method. Tracks #2 and #3 display raw flexural DXX wave and its instantaneous frequency respectively. Tracks #4 and #5 present dipole YY responses.

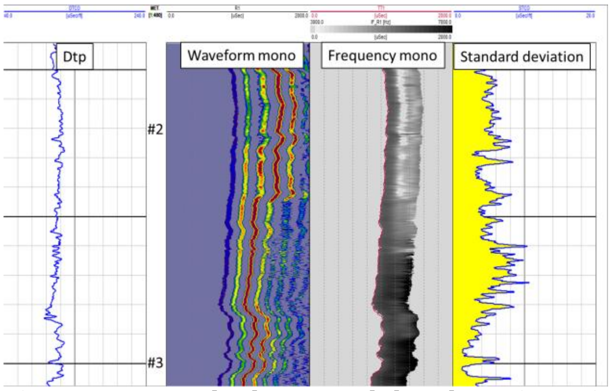

Figure 6. Monopole data recorded under anisotropic formation conditions. Track #1 show compressional wave slowness obtained with IFS method. Tracks #2 and #3 display raw compressional wave and its instantaneous frequency respectively. Track #4 presents standard deviation log computed from slowness distribution.

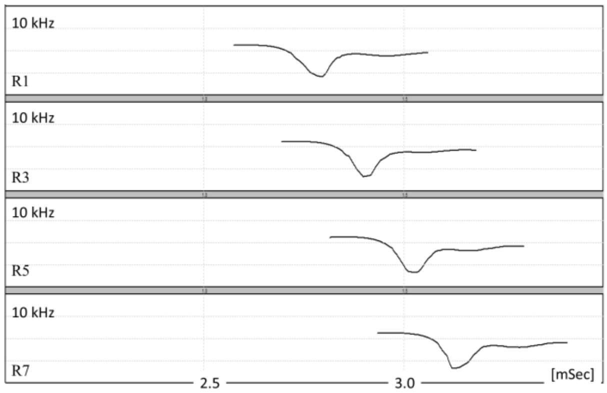

Figure. 7. Instantaneous frequencies of monopole wave train recorded at the depth #2 (see Figure 6).

Since instantaneous slowness wave forms are derived from large number of phase points (see the equation (3)) then it is possible to stack them in the sense of common receiver mode. This in turn allows construct its distribution vector (see **Figure 13**), corresponding standard deviation *Sdev* and goodness value *G* defined as:

$$G = (1 - Sdev/dT) \qquad (4)$$

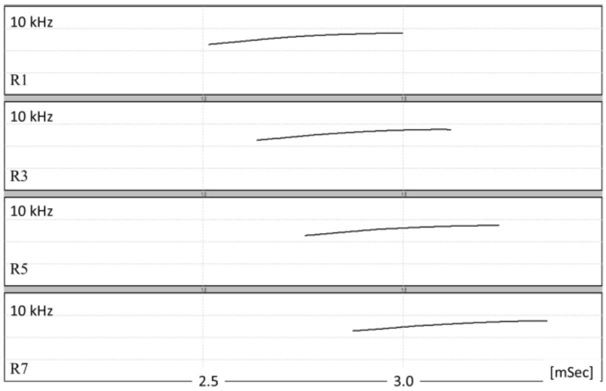

Figure 8. Instantaneous frequencies of monopole wave train recorded at the depth #3 (see Figure 6).

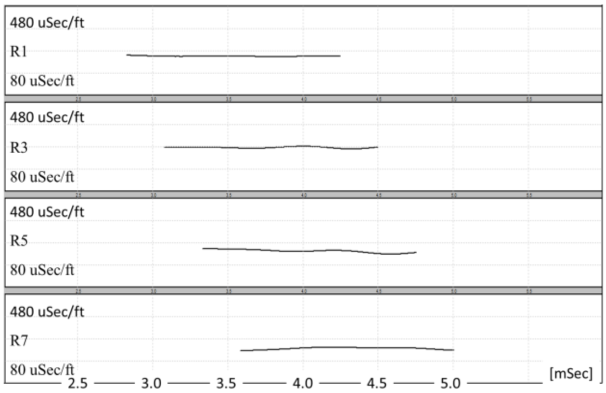

Figure 9. Instantaneous slowness data of dipole XX wave train recorded at the depth #1 (see Figure 5).

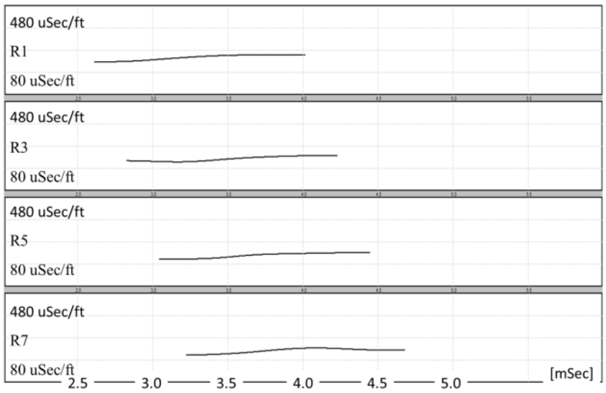

Figure 10. Instantaneous slowness data of dipole YY wave train recorded at the depth #1 (see Figure 5).

CONCLUSIONS

Complex wave form method was augmented by instantaneous frequency and slowness analysis. Both additions performed properly regardless of the type of the source excitation (e.g. monopole or dipole) and proved to be reliable quality measures. In particular, instantaneous frequency wave forms can be utilized to detect processing setup errors, mixed acoustic mode, frequency dispersion effects and shear wave anisotropy. Presence of the P-leaky mode might be signalled as well. Instantaneous slowness can be utilized similarly and additionally provide data needed to calculate slowness distribution.

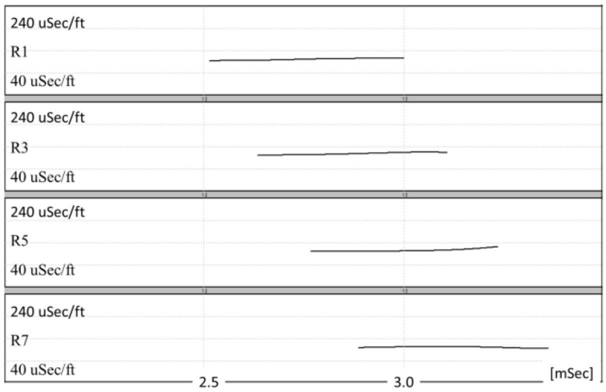

Figure 11. Instantaneous slowness data of monopole wave train recorded at the depth #3 (see Figure 6).

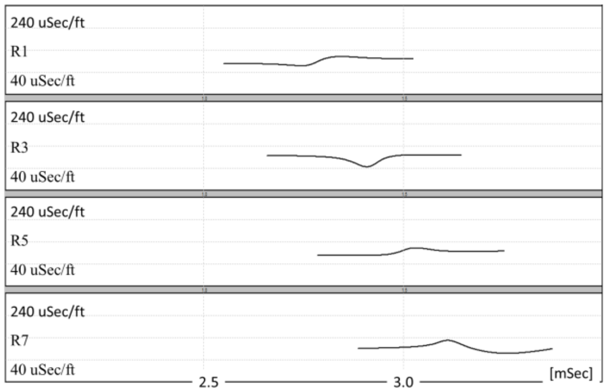

Figure 12. Instantaneous slowness data of monopole wave train recorded at the depth #2 (see Figure 6).

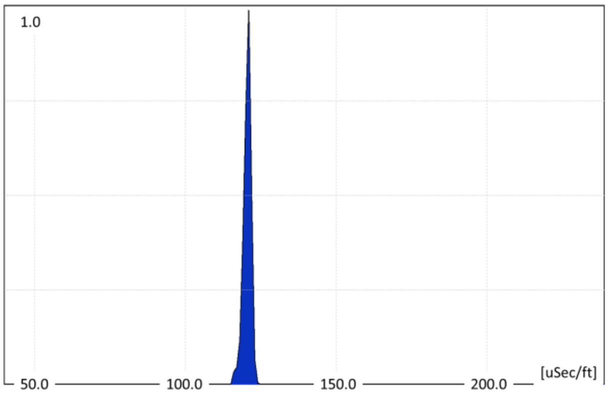

Figure 13. Example of compressional wave slowness distribution derived from high quality data.

REFERENCES

A.Cheng, X-M.Tang, 2004, Quantitative Borehole Acoustic Methods, Handbook Of Geophysical Exprolation

S.Gill, M.Kozak, T.Prowten, 1997 US Patent: Signal Processing Method For Improved Acoustic Formation Logging System.

P.Boonen, M.Kozak, D.Seifert, 1999 SPWLA conference, Phase Velocity Processing For Acoustic Logging-While-Drilling Full Waveform Data.

M.Kozak, J.Williams, 2014 SPWLA conference, Azimuthal Shear Wave Anisotropy Analysis, Guided In Time Domain.