USE OF VIBRATOR HARMONICS AS A SWEEP SIGNAL

ORHAN GÜRELI

ARAR Petrol ve Gaz AUP AŞ, Dumluca Sok No:19 Beysukent-Ankara,Turkey,

orhangureli2@yahoo.com.tr

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ABSTRACT

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In the conventional vibroseis method, the signal processing algorithms, including cross-correlation and deconvolution, are applied to convert the raw shot data into a seismic section. Vibrators are the best of the seismic sources and are widely used in exploration worldwide.

The vibroseis seismic data quality is directly related to sweep signal harmonics. In other words, if the harmonic noise level increases, seismic quality decreases.

In conventional vibrators, harmonic distortion is generated as a result of nonlinear coupling of vibrators and considered as coherent noises and consequently effects of these harmonic contaminations are subject to the elimination from the field records. Over the years different formalisms, using sweep parameters and phases, are proposed for the attenuation of these effects.

In this study a new algorithm is developed using harmonic components of the signal sweep as an auxiliary source, instead of striving to eliminate them, in order to broaden the frequency bandwidth of the seismic imaging.

Our approach is tested on synthetic and real data and results are discussed.

KEY WORDS: sweep, harmonic, harmonic distortion elimination, sweep signal, high frequency sweep.

INTRODUCTION

Harmonic distortions of seismic data acquired using a vibrator are a well-known event. These harmonics in the raw recorded data result in trains of correlated noise, known as harmonic ghosts, in the correlated data (Wei, 2010).

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The harmonics occur due to nonlinear effects of the vibrator mechanisms (Walker, 1995; Wei, 2007, 2010, 2011) and especially in the near surface (Lebedev, 2004). Many techniques have been developed which attempt to eliminate these harmonics during acquisition (Silverman, 1979; Rozemond, 1996; Moerig, 2004; Bagaini, 2006; Benabentos, 2006; Bagaini, 2010; Abd El-Aal, 2011) and the processing phase (Sorkin, 1972; Eisner, 1974; Rietsch, 1981; Schrodt, 1987; Martin, 1989, 1993; Okaya, 1992; Li, 1995, 1997; Walker, 1995; Polom, 1997; Dal Moro, 2007).

Harrison et al. (2011) used the Gabor transform and least squares methodology to successfully decompose a sweep from the first (H_1: fundamental) to eighth (H_8) harmonics. The decomposition is accomplished through the use of the Gabor transform to produce broadband estimates of the fundamental and harmonics of the vibroseis sweep. They tested their method on both field data and a synthetic sweep with time varying amplitude and phase. Babaia et al. (2012) provided a new method for the reduction of harmonic noise in slip sweep data. The method consists of estimating each harmonic component of a seismic trace, by applying a prediction operator of the considered harmonic.

Jianjun et al. (2012) provided a method which is based on singular value decomposition (SVD) in a time frequency (TF) domain. The process is implemented in the base-plate signal and the uncorrelated data, and harmonic interference can be suppressed after correlation.

Several techniques were essentially developed to attenuate the harmonics in raw data, which improves the data quality. (Sorkin, 1972; Eisner, 1974; Rietsch, 1981; Schrodt, 1987; Martin, 1989, 1993; Okaya, 1992; Anderson, 1995; Li, 1995, 1997; Walker, 1995; Polom, 1997; Scholtz, 2002, 2003, 2004; Meunier, 2003; Dal Moro, 2007; Larsen, 2007; Juan, 2014; Gang, 2014).

A phase-shift filter is widely used in harmonic distortion elimination. Each sweep is generated with a phase shift equal to 360/n where n is the number of sweeps per vibrator point (Sorkin, 1972; Eisner, 1974; Rietsch, 1981; Schrodt, 1987; Espey, 1988; Martin, 1989; Okaya, 1992; Martin, 1993; Anderson, 1995; Li, 1995, 1997; Walker, 1995; Polom, 1997; Sercel, 1999; Dal Moro, 2007; Abd El-Aal, 2010; Wuxiang, 2010; Yongsheng, 2011).

Li et al. (1995) and Wuxiang (2010) proposed the use of a pure phase-shift filter to eliminate the distorted part of the base plate signal and uncorrelated data based on the definition of the linear sweep signal, followed by correlation using the base plate signal. This method has suppressed the high-order harmonic interference but does not address the problem of low-order harmonics.

Sharma et al. (2009) recommended the use of an optimized filter to eliminate the harmonics. This generates a similar signal for a vibroseis source using the optimized filter. Then this filter could be used to generate harmonics, which can be subtracted from the main cross-correlated trace to get the better, undistorted image of the subsurface.

Iranpour (2010) presented a method to attenuate harmonics using multiple sweep rates. This technique includes generating sweep sequences. Each of the sweep sequences has an associated sweep rate. The technique includes varying the sweep rates to reduce harmonic distortion present in a composite seismic measurement produced in response to the sweep sequences.

Martin and Munoz (2010) recommend the use of a notch filter for elimination. This method removes harmonics without ground force signal and can be applied to correlated data (Meunier, 2002; Sicking, 2009; Baobin, 2012).

As seen above, different authors have been considering harmonics as a noise in their studies and have developed various methods to eliminate them. According to these authors, harmonics is considered as unwanted noises and should be removed from the records.

Harrison's (2011, 2012, 2013) new approach implying the decomposition of the vibroseis sweep into their respective fundamental and harmonic components, using Gabor transform, constitutes a pioneering work on the inclusion of the harmonics as an additional signal energy. They propose that harmonics and their associated higher frequency content can be harnessed for seismic imaging of shallow and thin reflectors. It should be noticed that in their implementation the fundamental sweep is not removed from the harmonic components.

At this point, we may assume that harmonics are considered not only as an undesirable noise but also, as an ultimate purpose, a signal that can be used to extend data bandwidth for a better seismic imaging.

In this paper we propose to exploit this double faced property that possess the harmonics. We will see that utilization of this property will give as the possibility of manipulating harmonics to neglect or strengthen some of them and to obtain the desired harmonic component(s) or the only fundamental as final signal.

ANALYSIS OF HARMONICS

Our theoretical harmonics analysis is based on the work of Seriff and Kim (1970). We extend their theory by investigating the effect of correlation on slip sweep data, in the presence of harmonic distortion. We considered linear up-sweeps and their k-th harmonic to determine the signal relationships after correlation.

The typical sweep used with the correlation technique is a frequency modulated sinusoid in which the “instantaneous frequency” varies linearly with time increasing from f_1 to f_2, $f_1 < f_2$.

Seriff and Kim (1970) examined the typical linear sweep-frequency sine wave $S_1(t,\theta)$ as defined by

$$S_1(t,\theta) = \alpha_1 Sin[2\pi(f_1 + \mathrm{Q}t)t + \theta] \quad , \tag{1}$$

where α_1 and Q are constants. The constant Q is as follows

$$\mathrm{Q} = (f_2 - f_1) / T \quad .$$

The k-th harmonic distortion of $S_1(t)$ will have

$$S(t,k\theta) = \alpha_k Sin[2\pi k(f_1 + \mathrm{Q}t)t + k\theta] \quad , \tag{2}$$

where α_k is the signal amplitude, f_1 is the sweep signal start frequency, f_2 is the ending frequency, T is the sweep length, k is the times of the harmonic, θ is the initial phase shift, $k\theta$ phase shift on the order-k harmonic in the Ground Force (GF) and t is time.

These harmonics will have the effect of adding to $S_1(t,\theta)$ a signal $S_k(t,k\theta)$. Seriff and Kim (1970) assume that the outgoing signal $S(t,\theta)$ from a harmonically distorted sweep consists of the sum of $S_1(t,\theta)$ and all of $S_k(t,k\theta)$.

$$GF(\theta) = \mathrm{S}(t,\theta)$$

$$= S_1(t,\theta) + S_2(t,2\theta) + S_3(t,3\theta) + S_4(t,4\theta) + \cdots + S_\mathrm{k}(t,k\theta), \tag{3}$$

where $GF(\theta)$ is a Ground Force signal. This is imparted into the earth by vibrators.

Our starting point, to introduce the harmonics as seismic signal, will be eq. (2). From this equation, at the first step we generate 2 sweeps A and B shown in developed from in eqs. (4) and (5) with H_4 being the highest order harmonic components and H_1 being fundamental component of these two sweeps are also reproduced in detail in Table 1 in relation with the initial phase shifts. At second step addition of these two A and B sweeps and subtracting B from A we create two new sweeps that we define as

$Sweep_{A+B}$ and $Sweep_{A-B}$

as seen in eqs. (7) and (8), respectively.

Table 1. Initial phase shift analysis of fundamental sweep and harmonics.

Harmonic order	θ (degrees)	$k\theta$ (degrees)	$k(f_1 \text{ to } f_2)$	$S_k(t, k\theta)$	$Sweep_A$ (θ=0°)	$Sweep_B$ (θ=180°)	$Sweep_C$ (θ=0°)	$Sweep_{A+B} = Sweep_A + Sweep_B$	$Sweep_{A-B} = Sweep_A - Sweep_B$
k=1	0	0	f_1 to f_2	$H_1 = S_1(t, 0)$	H_1			0	$2H_1$
k=1	180	180	f_1 to f_2	$-H_1 = S_1(t, 180)$	+	$-H_1$			
k=2	0	0	$2f_1$ to $2f_2$	$H_2 = S_2(t, 0)$	H_2	+	H_2	$2H_2$	0
k=2	180	360=0	$2f_1$ to $2f_2$	$H_2 = S_2(t, 2x180)$	+	H_2	+		
k=3	0	0	$3f_1$ to $3f_2$	$H_3 = S_3(t, 0)$	H_3	+		0	$2H_3$
k=3	180	540=180	$3f_1$ to $3f_2$	$-H_3 = S_3(t, 3x180)$	+	$-H_3$			
k=4	0	0	$4f_1$ to $4f_2$	$H_4 = S_4(t, 0)$	H_4	+	H_4	$2H_4$	0
k=4	180	720=0	$4f_1$ to $4f_2$	$H_4 = S_4(t, 4x180)$		H_4			

$Sweep_A = S_A(t, 0^o) = S_1(t, 0^o) + S_2(t, 0^o) + S_3(t, 0^o) + S_4(t, 0^o) + \cdots + S_k(t, 0^o)$,

$$Sweep_A = H_1 + H_2 + H_3 + H_4 + \cdots + H_k, \quad (4)$$

$Sweep_B = S_B(t, 180^o) =$
$S_1(t, 180^o) + S_2(t, 360^o) + S_3(t, 540^o) + S_4(t, 720^o) + \cdots + S_k(t, k180^o)$, $Sweep_B = -H_1 + H_2 - H_3 + H_4 - \cdots \pm H_k$, (5)

$Sweep_C = S_C(t, 0^o) = +S_2(t, 0^o) + S_4(t, 0^o) + \cdots + S_k(t, 0^o)$,

$$Sweep_C = H_2 + H_4 + \cdots + H_k. \quad (6)$$

If $Sweep_A$ and $Sweep_B$ are vertically stacked in Eq.4 and Eq.5, the stacked uncorrelated sweep contains even order harmonics.

$$Sweep_{A+B} = Sweep_A + Sweep_B = 2H_2 + 2H_4 + \cdots + \textit{even order harmonics}, \quad (7)$$

If $Sweep_B$ are subtracted from $Sweep_A$ in Eq.4 and Eq.5, the difference of uncorrelated sweeps contains odd order harmonics.

$$Sweep_{A-B} = Sweep_A - Sweep_B = 2H_1 + 2H_3 + \cdots + \textit{odd order harmonics}, \quad (8)$$
where $Sweep_{A+B}$ and $Sweep_{A-B}$ are uncorrelated data.

$$Record_A = H_1 \otimes Sweep_A, \quad (9)$$
where H_1 is the fundamental sweep of $Sweep_A$,

$$Record_B = H_1 \otimes Sweep_B, \quad (10)$$
where H_1 is the fundamental sweep of $Sweep_B$,

$$Record_C = H_2 \otimes Sweep_C, \quad (11)$$
where H_2 is the fundamental sweep of $Sweep_C$.

$$Record_{A-B} = H_1 \otimes Sweep_{A-B}, \quad (12)$$

$$Record_{A+B} = H_2 \otimes Sweep_{A+B}, \quad (13)$$

where H_1 is the fundamental sweep of $Sweep_A$, $Sweep_B$ and $Record_{A-B}$. H_2 plays the role of the fundamental sweep for $Sweep_C$ and the input signal for $Record_{A+B}$ as seen in eqs. (6) and (13) respectively and $\otimes$ indicates correlation operator. $Record_{A+B}$ and $Record_{A-B}$ are correleted raw shots.

The H_2 harmonic of $Sweep_{A+B}$ and the H_2-fundamental of $Sweep_C$ are the same in frequency content. Only their amplitudes are different, and equal when they are normalized.

The fundamental sweep and the first three harmonics are used and higher order harmonics are neglected for synthetic analysis in Figs. 1 and 2.

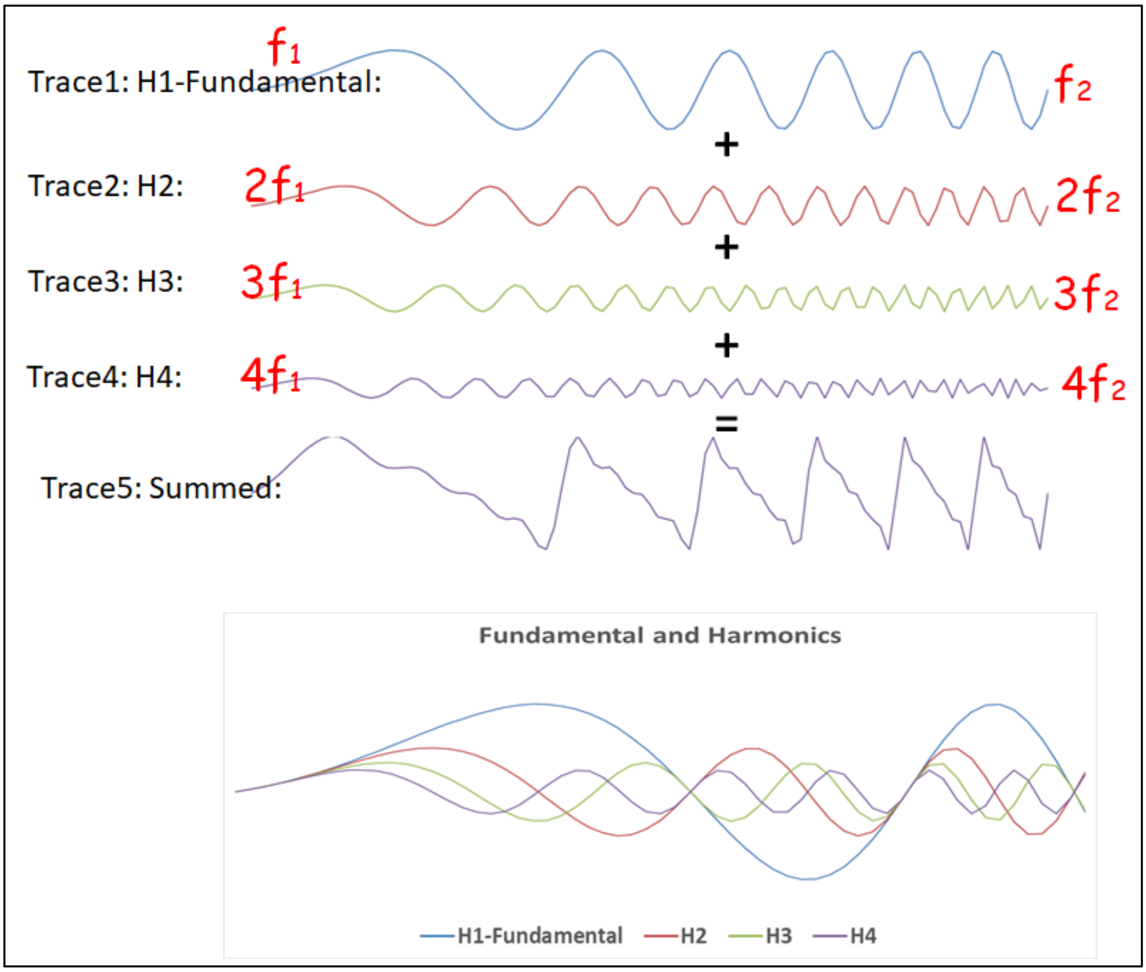

Fig. 1. Trace-1: The fundamental sweep-H_1 with α_1 = 100, Trace-2: first harmonic distortion- H_2 with α_2 = 50. Trace-3: second harmonic distortion- $H_3$with α_3 = 33. Trace-4: third harmonic distortion- $H_4$with α_4 = 25. Trace-5: Superposition of the harmonically distorted sweep $S(t, 0^o)$. Representation of sweep and harmonics together is at the bottom.

Fig. 1 shows a synthetic fundamental sweep and its harmonics. The H_1-Fundamental and harmonics in time domain (top), their stacked representation (middle) and common display them (bottom).

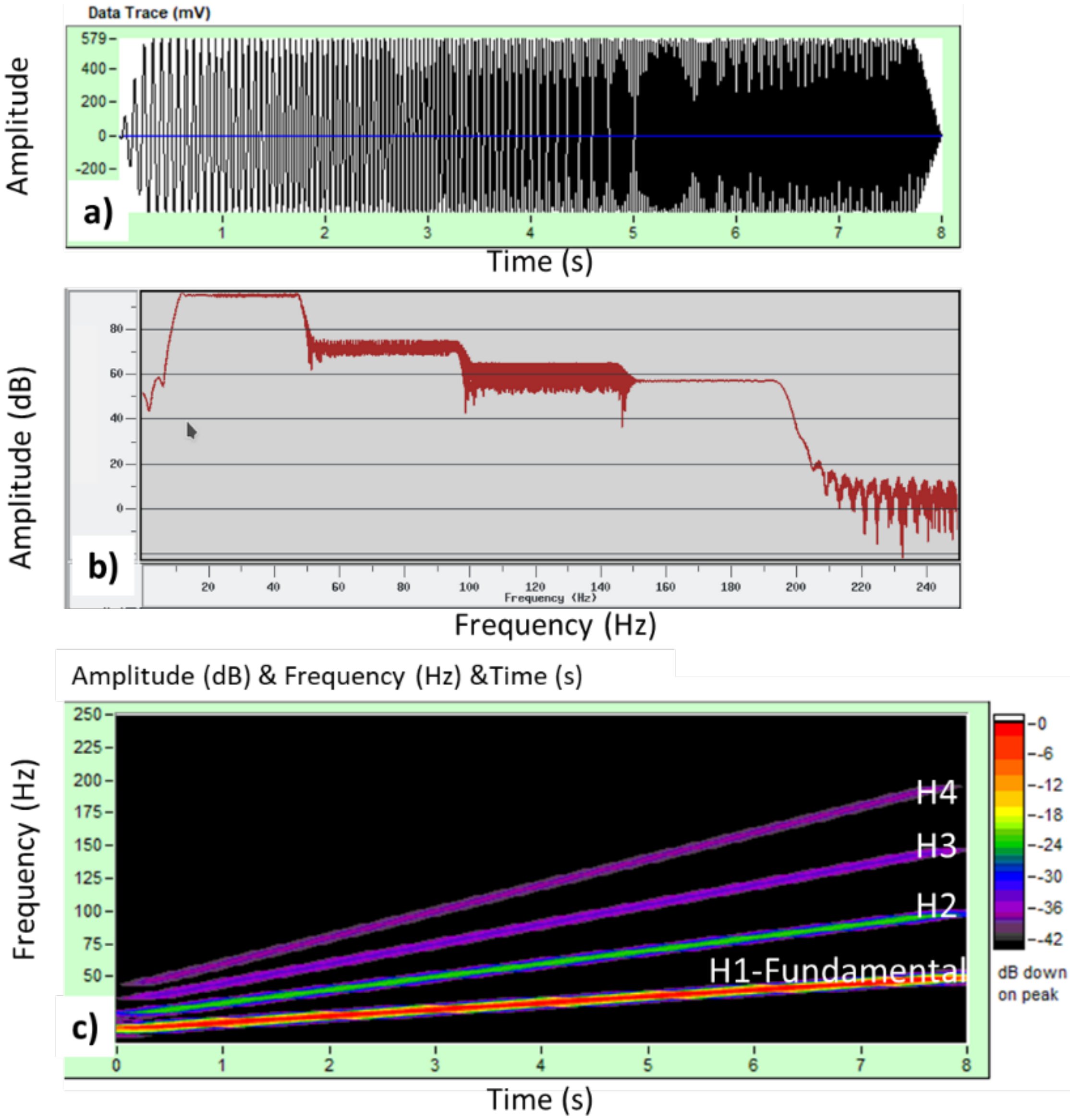

Fig. 2. Harmonically distorted synthetic sweep $S(t, 0^o)$, a) in time domain, b) in frequency domain, c) in Time-Frequency domain.

Fig. 2 illustrates the synthetic sweep in time (top), frequency (middle) and Time-Frequency domain (bottom). Examination of the amplitude spectrum displayed in this figure shows significant decreasing behavior of amplitudes with respect to the increasing orders of harmonics.

HARMONIC DISTORTION ANALYSIS OF SYNTHETIC DATA

A synthetic sweep is created using parameters given in Table 2 with only the first four harmonics and the fundamental (Fundamental-H_1, H_2, H_3 and H_4) and we neglected the higher order components taking into consideration their weak contribution as mentioned above.

Table 2. Sweep parameters for synthetic data analysis.

	Phase shift	Sweep frequencies	Sweep Length
$Sweep_A$	0 degree	12-64 Hz.	8 sec.
$Sweep_B$	180 degrees	12-64 Hz.	8 sec.
$Sweep_C$	0 degree	24-128 Hz.	8 sec.

Synthetic sweep parameters were used for harmonic analysis in Table 2.

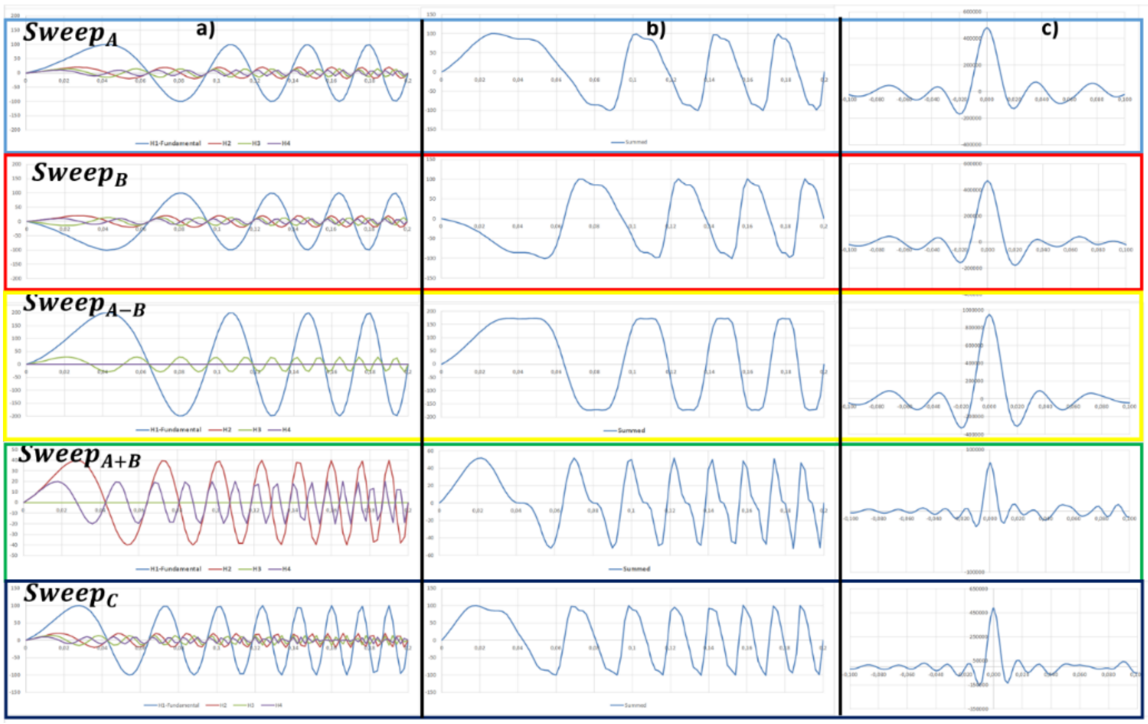

Fig. 3. Analysis of $Sweep_A$, $Sweep_B$, $Sweep_{A+B}$, $Sweep_{A-B}$ and $Sweep_C$, a) Display of fundamental sweep and harmonics together, for each sweep, b) Summed representation of fundamental sweep and harmonics for each sweep, c) Correlations of summed sweep and their fundamental sweep for $Sweep_A$, $Sweep_B$, $Sweep_C$, $Sweep_{A-B}$ and correlation of summed sweep and second harmonic sweep for $Sweep_{A+B}$.

Fig. 3 shows the analysis of $Sweep_A$, $Sweep_B$, $Sweep_C$, $Sweep_{A+B}$ and $Sweep_{A-B}$. $Sweep_A$ and their harmonics have 0 degrees of initial phase shift. But $Sweep_B$, and only odd-order harmonics have 180 degrees of initial phase shift, while even-order harmonics have 0 degrees of the initial phase shift. $Sweep_C$ and its harmonics have zero degrees of the initial phase shift. Its start and end frequencies have twice of $Sweep_A$ and $Sweep_B$.

Table 3 gives the description of sweep codes and the type of data for synthetic data. Synthetic sweeps of $Sweep_A$ and $Sweep_B$ and their harmonics are generated in the processing stage. After there were synthetic generated sweeps with harmonics of $Sweep_A$ and $Sweep_B$. Both $Sweep_{A+B}$ and $Sweep_{A-B}$ are obtained according to eqs. (7) and (8) respectively. $Sweep_{A+B}$ is compared with $Sweep_C$.

Table 3. The description of sweep codes and the type of data.

Channel No	Sweep code	Type of data
1	$Sweep_A$	H_1=Fundamental
2	$Sweep_A$	H_2
3	$Sweep_A$	H_3
4	$Sweep_A$	H_4
5	$Sweep_A$	H_1(Fundamental)+H_2+H_3+H_4
6	$Sweep_B$	H_1=Fundamental
7	$Sweep_B$	H_2
8	$Sweep_B$	H_3
9	$Sweep_B$	H_4
10	$Sweep_B$	H_1(Fundamental)+H_2+H_3+H_4
21	$Sweep_{A-B}$	Ch1-Ch6
22	$Sweep_{A-B}$	Ch2-Ch7
23	$Sweep_{A-B}$	Ch3-Ch8
24	$Sweep_{A-B}$	Ch4-Ch9
25	$Sweep_{A-B}$	Ch5-Ch10
31	$Sweep_{A+B}$	Ch1+Ch6
32	$Sweep_{A+B}$	Ch2+Ch7
33	$Sweep_{A+B}$	Ch3+Ch8
34	$Sweep_{A+B}$	Ch4+Ch9
35	$Sweep_{A+B}$	Ch5+Ch10

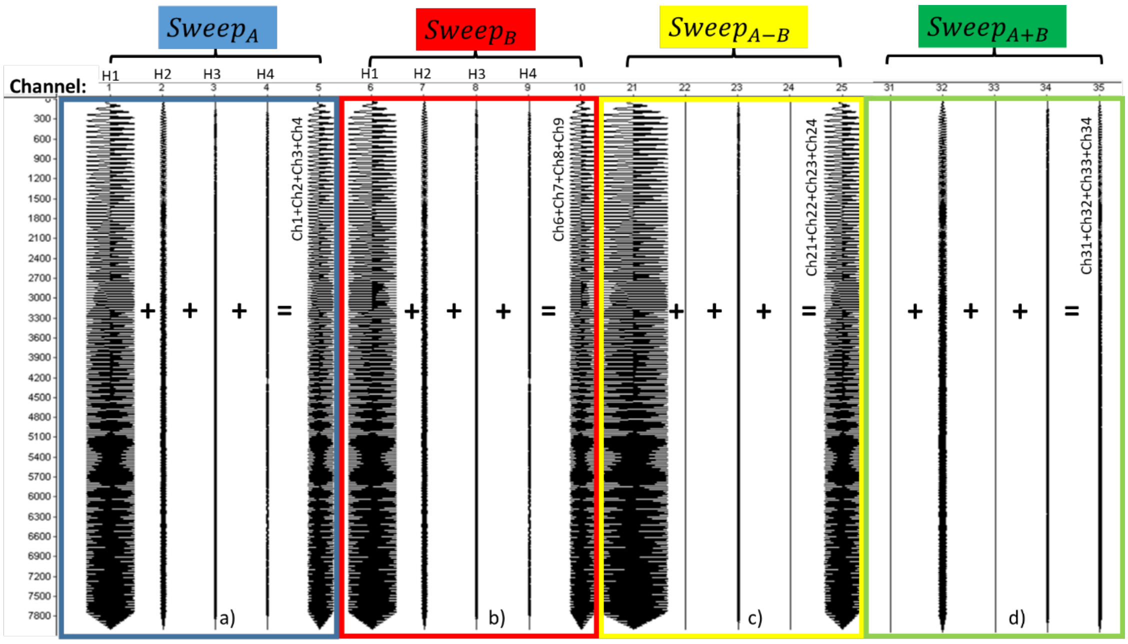

Fig. 4a. a) $Sweep_A$ (fundamental, harmonics and their summing), b) $Sweep_B$(fundamental, harmonics and their summing), c) Subtracting $Sweep_B$ from $Sweep_A$, d) Adding $Sweep_A$ to $Sweep_B$.

Fig. 4a and Fig. 4b show all sweeps and their harmonics mentioned in Table3.

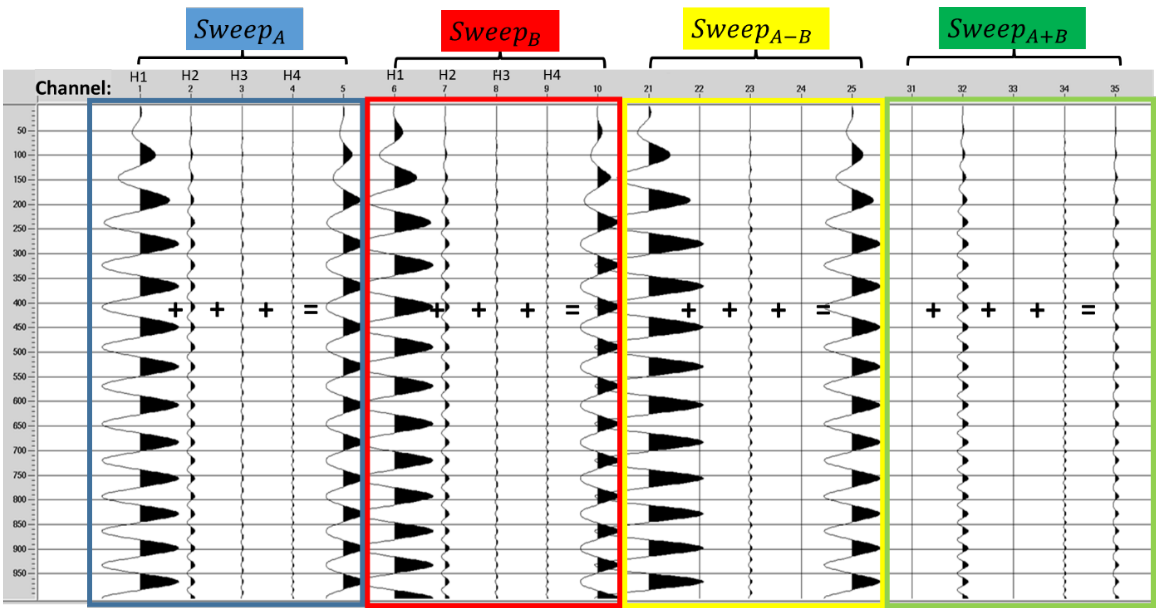

Fig. 4b. Low frequency part of sweep signal from Fig. 4a.

Fundamental and harmonics are seen separately in Figs. 4a and 4b. When $Sweep_A$ and $Sweep_B$'s fundamentals and H_3 harmonics are examined, it is seen that their polarity is reversed. This is because the initial phase of $Sweep_B$ is 180 degrees. When $Sweep_A$ and $Sweep_B$'s H_2 and H_4 harmonics are examined, it is seen that their polarities are the same. When $Sweep_B$ is removed from $Sweep_A$, H_1 -Fundamental and H_3 harmonic become stronger, while H_2 and H_4 harmonics disappear due to their polarity reversal. In this sense, it is similar to usual harmonic elimination works. H_1-Fundamental and H_3 harmonic disappear if $Sweep_A$ and $Sweep_B$ are vertically stacked. Only H_2 and H_4 harmonics remain. Both high frequency components remain and some harmonics disappear.

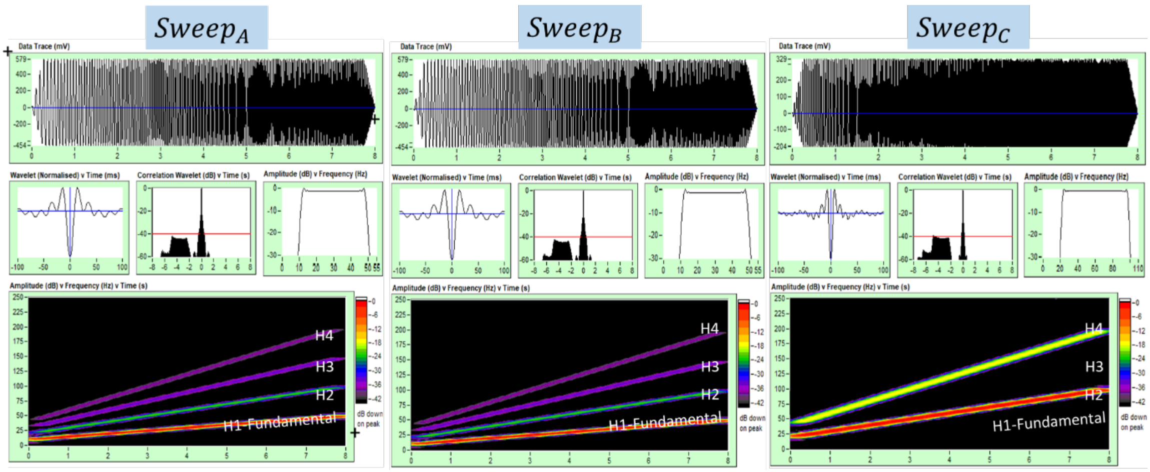

Fig. 4c. Analysis of synthetic sweeps given in Table 2 and Fig. 4b.

Fig. 4c shows analysis of synthetic sweeps in Table 2, Fig. 4a, and Fig. 4b. As seen in Fig. 4c, when $Sweep_A$, $Sweep_B$ and $Sweep_C$ are generated separately, the harmonics do not disappear, so they remain in the records. When $Sweep_A$ and $Sweep_B$ are compared, there is no effect of phase difference, and the results are same in the analysis. Therefore, whatever processing is desired to be made, it should be done before the correlation. After correlation, the result does not change. The analysis was done for the same processing flow in $Sweep_C$.

Fig. 4d shows the analysis of $Sweep_{A-B}$, $Sweep_{A+B}$ and $Sweep_C$. Examining the result of the $Sweep_{A-B}$ analysis, it is seen that the H_2 and H_4 harmonics have been eliminated and the H_1-fundamental and H_3 harmonic remains, but their amplitudes are also low. When $Sweep_{A+B}$ is examined, it is seen that the harmonics H_1-fundamental and H_3 are harmonic disappear. The H_2 and H_4 harmonics remain. It appears from the analysis that the frequency contents of $Sweep_{A+B}$ and $Sweep_C$ are the same as seen in eqs. (14) and (15). Although the amplitudes of the H_2 and H_4 harmonics of $Sweep_{A+B}$ and $Sweep_C$ are different, their frequency content is the same.

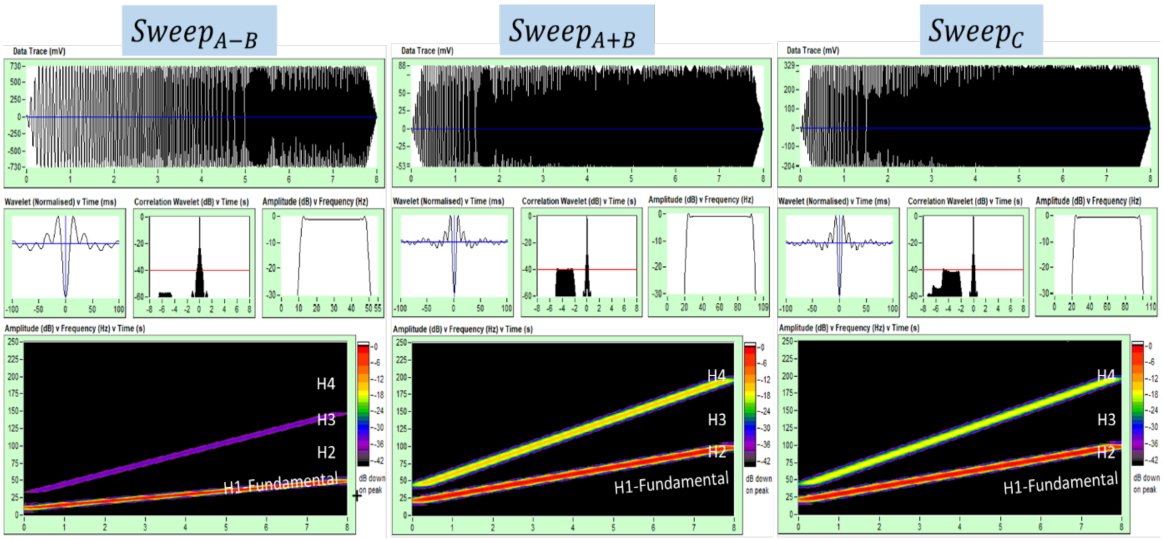

Fig. 4d. Analysis of synthetic sweeps given in Table 2 and Fig. 4b.

$$Sweep_{A+B} = 2H_2 + 2H_4 + \cdots \tag{14}$$

$$Sweep_C = H_2 + H_4 + \ldots \tag{15}$$

The H_2 harmonic of $Sweep_{A+B}$ and the H_2-fundamental of $Sweep_C$ are the same in frequency content. Only their amplitudes are different, and equal when they are normalized.

HARMONIC DISTORTION ANALYSIS OF FIELD DATA

Table 4. Sweep signal parameters for real data analysis.

	Phase shift	Sweep frequencies	Number of Sweep	Sweep Length
$Sweep_A$	0 degree	12-64 Hz.	2	12 sec.
$Sweep_B$	180 degrees	12-64 Hz.	2	12 sec.
$Sweep_C$	0 degree	24-128 Hz.	2	12 sec.

The sweep parameters in Table 4 were used for harmonic analysis of sweep signal. The field application is carried out with the parameters given in Table 4. $Sweep_A$, $Sweep_B$ and $Sweep_C$ are on the same line and at the same shot point. They are produced separately and recorded as uncorrelated. The purpose of the production of $Sweep_C$ is to check and compare with Sweep $Sweep_{A+B}$.

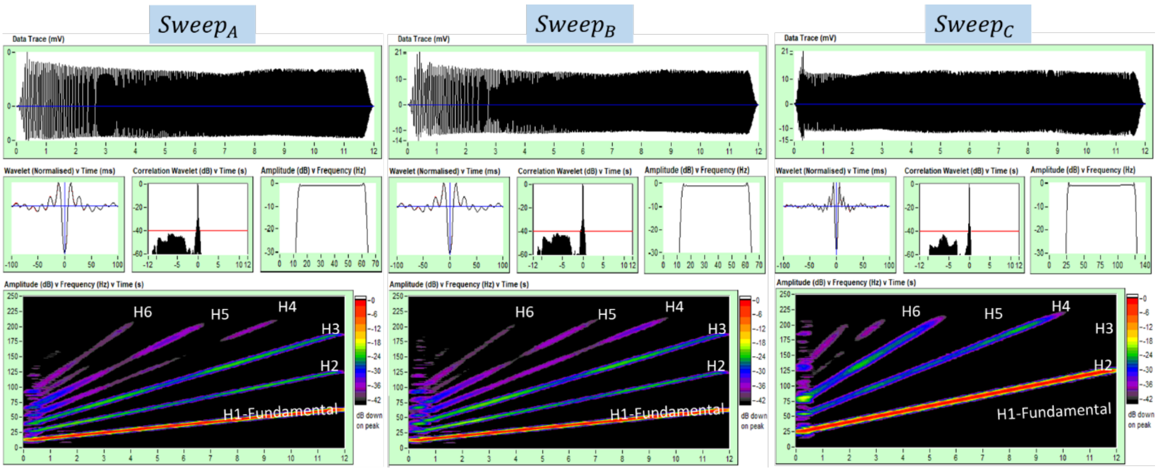

Fig. 5a. Analysis of real sweep signals with given parameters in Table-4.

Fig. 5a shows the analysis of real sweep signals in Table 4. Fig. 5b shows analysis of $Sweep_{A-B}$, $Sweep_{A+B}$ and $Sweep_C$ in Table 4.

Fundamentals and harmonics remain intact when real data of $Sweep_A$ and $Sweep_B$ are separate, as seen in synthetic work. In Fig. 5a, it is seen up to the 6th harmonic. In $Sweep_C$, on the other hand, there are no harmonics in the frequency of odd-numbered harmonics such as H_1, H_3, H_5, depending on the starting and ending frequency. The fundamentals of $Sweep_C$ is the same as the H_2 of the others. In other words, H_2 harmonic is a fundamental sweep in $Sweep_C$. Compared to H_2 of $Sweep_A$ and $Sweep_B$, it is the same as the fundamental of $Sweep_C$. Only their amplitude is different, but their frequency is the same, their amplitudes are normalized and balanced.

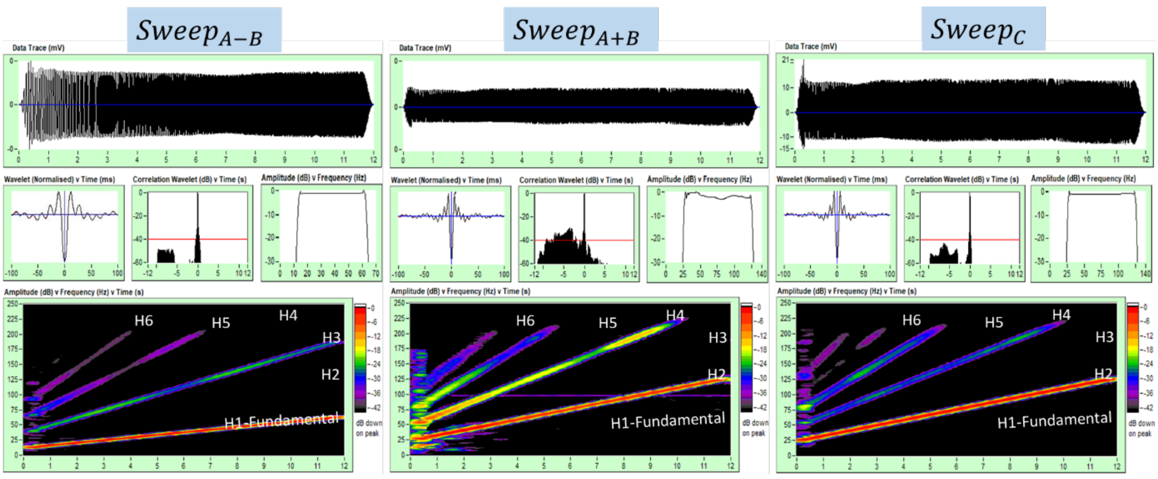

Fig. 5b. Analysis of real sweep signals in Table 4.

Examining $Sweep_{A-B}$, we see that the result obtained is the same as the well-known harmonic elimination process through phase-shift method.

The process of $Sweep_{A+B}$ is the main topic of this study. When $Sweep_{A+B}$ is examined, odd-numbered harmonics such as H_1-Fundamental sweep, H_3 and H_5 are eliminated. H_2 is used for the correlation as a fundamental sweep in this record. When $Sweep_C$ is examined, the parameter of the fundamental sweep and H_2 are the same. It should be noticed that fundamentals and harmonics of $Sweep_C$ are perfectly matched with H_2, H_4, H_6, and harmonics of $Sweep_{A+B}$. $Sweep_C$ has been produced for comparison with $Sweep_{A+B}$. The frequencies of fundamentals and harmonics are the same and amplitudes appear to be different.

Table 5. Survey and sweep parameters.

Survey Parameters of real data			
	$Sweep_A$	$Sweep_B$	$Sweep_C$
Initial phase shift	0 degree	180 degrees	0 degree
Number of sweep	2	2	2
Sweep Length	12 sec	12 sec	12 sec
Sweep description	12-64 Hz	12-64 Hz	24-128 Hz
Sweep type	Linear	Linear	Linear
Sweep taper-sinus	400ms (start)-400 ms (end)	400ms (start)-400 ms (end)	400ms (start)-400 ms (end)
Sample rate	2 msec	2 msec	2 msec
Source parameters			
Source	Vibrator	Vibrator	Vibrator
Vibrator type	AHV-IV	AHV-IV	AHV-IV
Number of Vibes	4	4	4
Peak force	61.000 pounds	61.000 pounds	61.000 pounds
Derive level	80 %	80 %	80 %
Survey parameters			
Receiver group interval	20 m	20 m	20m
Shot interval	20 m	20 m	20 m
Number of acttive channel	400	400	400
Geophone type	SM24	SM24	SM24
Number of geophone per group	24	24	24
Natural frequency	10 Hz	10 Hz.	10 Hz.

FIELD DATA APPLICATION

Acquisition flow

In 2020, Arar Petrol ve Gaz AUP AS designed a survey with the specified goal of capturing a finely sampled wave field as a basis for harmonic analysis. The survey comprised a total of 28 shot sweep points using 500 receiver groups which spaced every 20 meters. A linear 12 second long sweep signal 12-64 Hz was shot every 20 meters, in Northern Osmaniye, City of Turkey.

Table 4 contains the details of the sweep and acquisition parameters of the test study. At each shot point, there are 3 shots with 2 sweeps, namely $Sweep_A$, $Sweep_B$ and $Sweep_C$.

As can be seen in Table 5, with the exception of $Sweep_A$, $Sweep_B$ and the start and end frequencies of $Sweep_C$, same acquisition parameters are used. Different parameters are indicates in red color in this table.

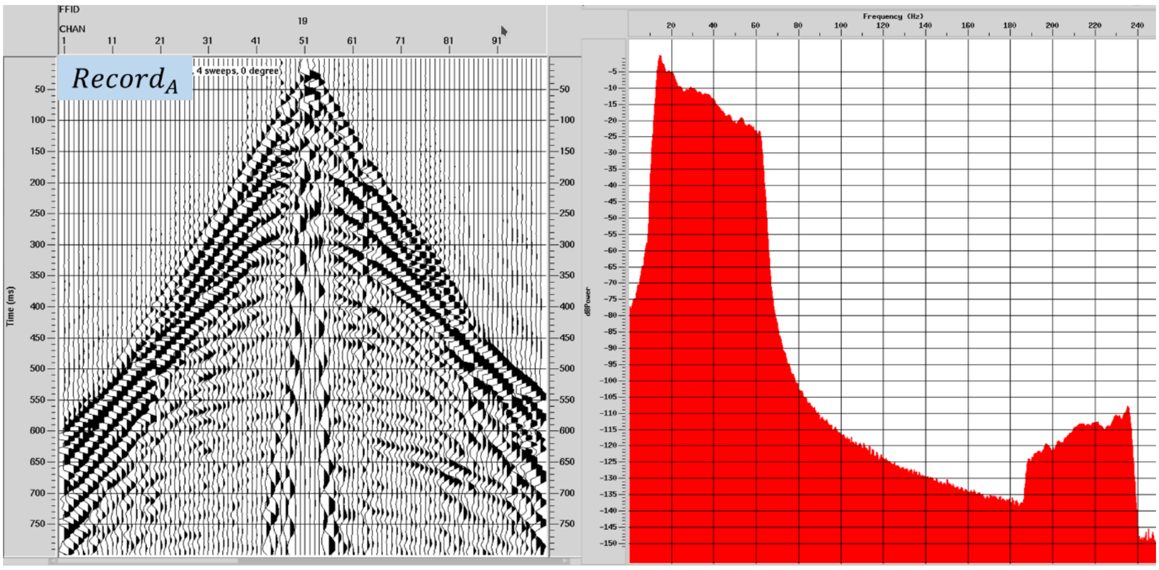

Fig. 6a. Shot gather of $Record_A$ and its amplitude-frequency.

Fig. 6a shows a shot gather of $Record_A$ which acquisition parameters are given in Table 5. This shot is obtained using eq. (9). Namely, $Sweep_A$ is correlated with its H_1-fundamental sweep to get $Record_A$. Its spectrum is in accordance with the recording parameters.

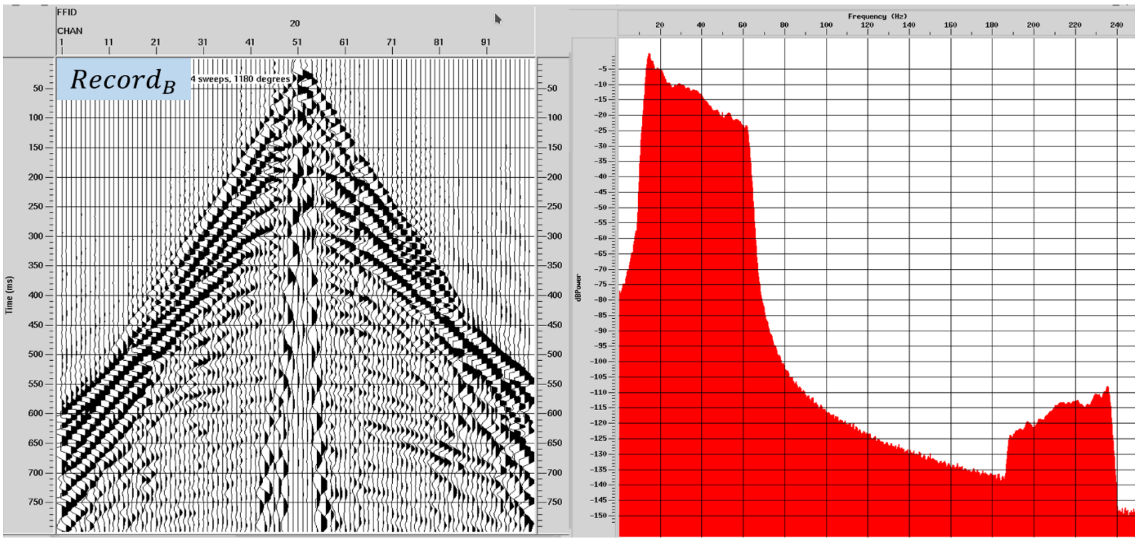

Fig. 6b. Shot gather of $Record_B$ and its amplitude-frequency spectrum.

Fig. 6b shows a shot gather of $Record_B$ which acquisition parameters are given in Table 5. This shot was obtained using eq. (10). Namely, $Sweep_B$ was correlated with its H_1-fundamental sweep for $Record_B$. Its spectrum is in accordance with the recording parameters.

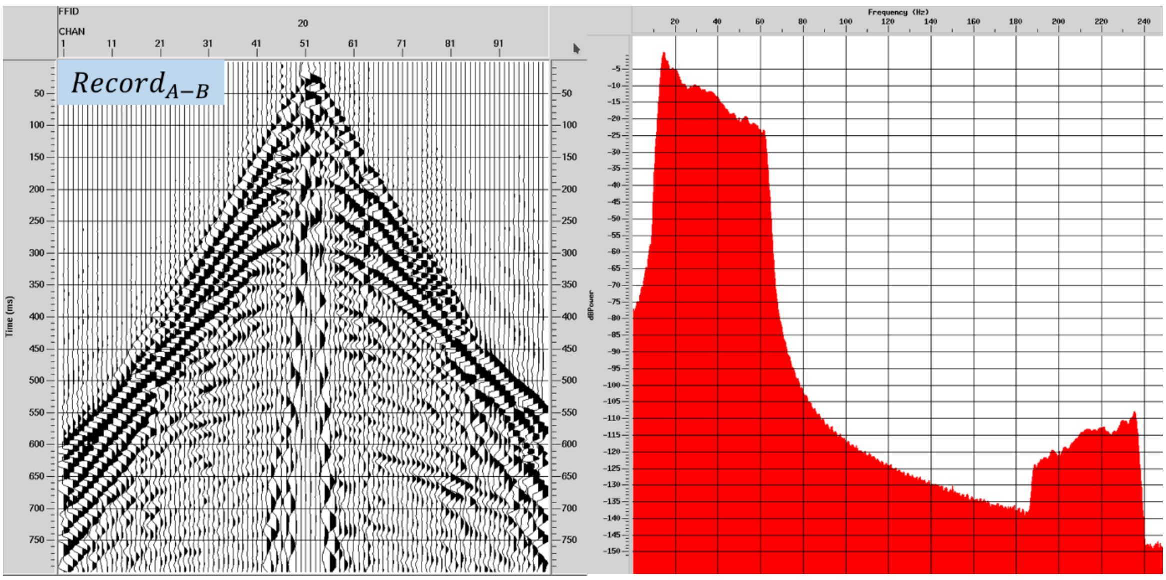

Fig. 6c. Shot gather of $Record_{A-B}$ and its amplitude-frequency spectrum.

Fig. 6c shows a shot gather of $Record_{A-B}$. This record was obtained by subtracting $Sweep_B$ from $Sweep_A$. First subtracted, then was correlated with H_1-fundamental of $Sweep_A$ so that even numbered harmonics such as H_2, H_4, etc. were destroyed. Although similar to Figs. 6c, 6a and 6b, even-numbered harmonics have been eliminated. This data will be used in the processing.

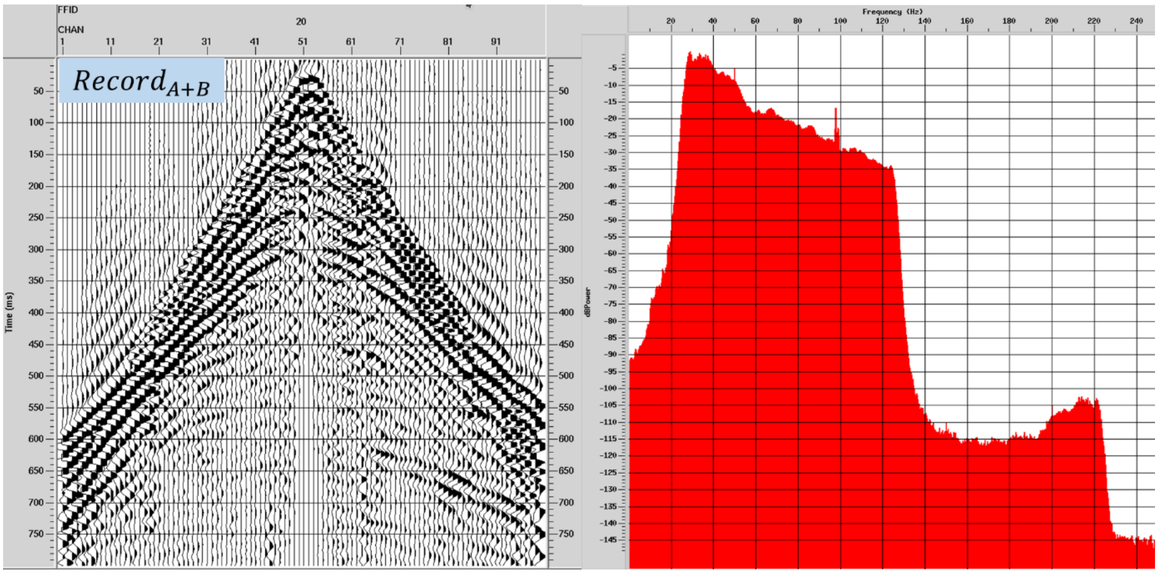

Fig. 6d. Shot gather of $Record_{A+B}$ and its amplitude-frequency spectrum.

Fig. 6d shows a shot gather of $Record_{A+B}$. This shot was obtained by the vertically stacked, $Sweep_A$ and $Sweep_B$. First, vertically stacked, then correlated with H_2-fundamental sweep of $Sweep_C$. Thus, even-numbered harmonics such as H_1-fundamental sweep , H_2, etc. were destroyed.

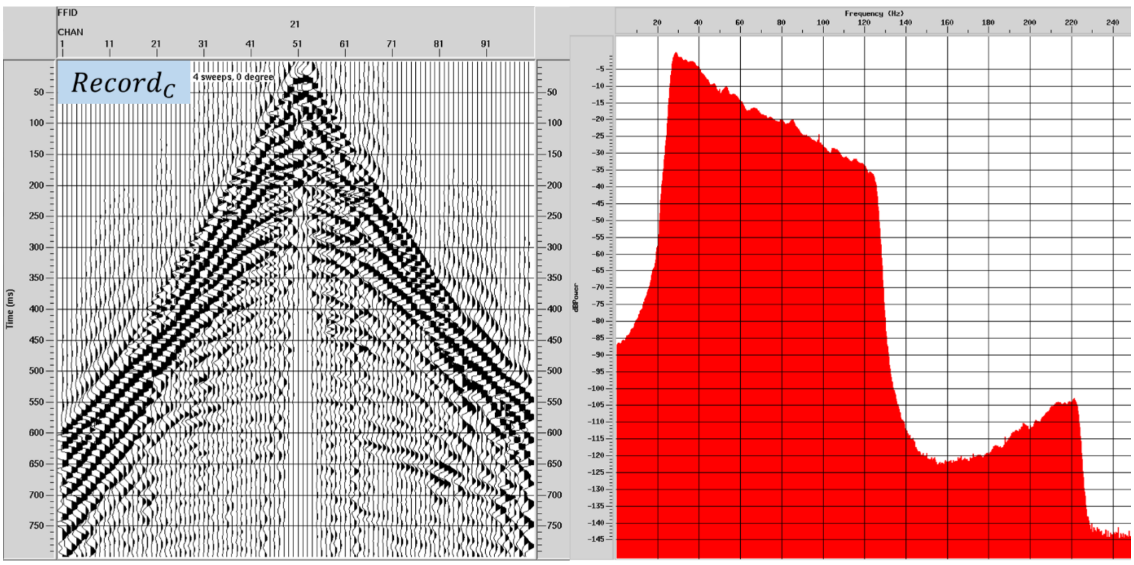

Fig. 6e. Shot gather of $Record_C$ and its amplitude-frequency spectrum.

Fig. 6e shows a shot gather of $Record_C$ which acquisiton parameters are given in Table 5. This shot is obtained using eq. (11). Namely, $Sweep_C$ was correlated with its H_2-fundamental for $Record_C$. Their spectrum are almost the same. H_2 of $Sweep_C$ was used for correlation of both $Sweep_C$

and $Sweep_{A+B}$. $Record_C$ was acquired in the field for comparison with $Record_{A+B}$. Their quasi-similarity can be easily observed. This result shows us that even if we do not produce $Sweep_C$, it is possible to obtain with $Sweep_{A+B}$.

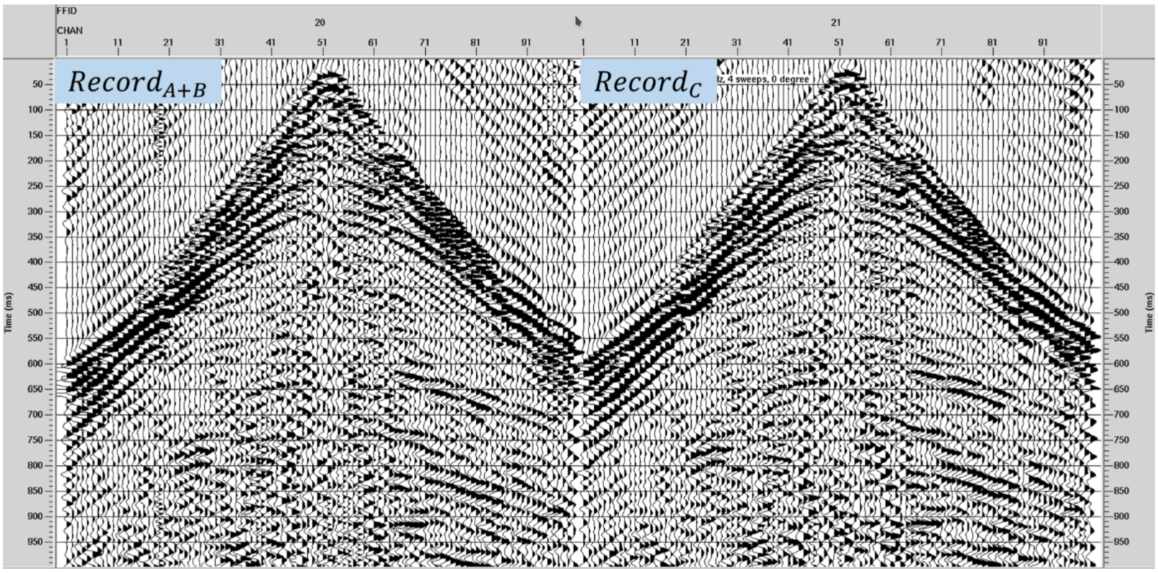

Fig. 6f. A comparison of $Record_{A+B}$ and $Record_C$.

Fig. 6f shows a comparison of $Record_{A+B}$ and $Record_C$. When compared, these two shots are almost the same. The first break and reflection times in these two records are the same time. There are not any shifts between two recorded events. Comparison of these two sections show that our methods work accurately.

Processing flow

The field data was processed in five separated flows using the industry standards. A basic processing flow in Table 6 (below) shows how each data set is handled. The correlation using the pilot sweep as described above for cross-correlation was the first flow. Geometry, deconvolution, statics, final velocity, final residual statics, bandpass filter, NMO and CMP-stack were applied to all data. The results of final process are given in Figs. 7a, 7b, 7c and 7d.

$Stack_A$, $Stack_B$, $Stack_C$, $Stack_{A-B}$ and $Stack_{A+B}$ were obtained by the processing of respective records in conformity with the basic processing flow given in Table 6.

Table 6. Basic processing flow.

Basic processing of field data					
	$Stack_A$:	$Stack_B$:	$Stack_C$:	$Stack_{A+B}$:	$Stack_{A-B}$:
Input data:	$Record_A$	$Record_B$	$Record_C$	$Record_{A+B}$	$Record_{A-B}$
Number of Shots	28	28	28	28	28
Data type	Uncorrelated data	Uncorrelated data	Uncorrelated data	Uncorrelated data	Uncorrelated data
Pilot sweep for cross-corelation	H_1 of $Sweep_A$ H1: 12-64 Hz	H_1 of $Sweep_B$ H1: 12-64 Hz	H_2 of $Sweep_C$ H2: 24-128 Hz	H_2 of $Sweep_C$ H2: 24-128 Hz	H_1 of $Sweep_A$ H1: 12-64 Hz
Geometry	yes	yes	yes	yes	yes
Deconvalution	yes	yes	yes	yes	yes
Elevation statics	yes	yes	yes	yes	yes
Velocity analysis-1	yes	yes	yes	yes	yes
Residual static-1	yes	yes	yes	yes	yes
Bandpass filter	yes	yes	yes	yes	yes
Normal Move Out (NMO)	yes	yes	yes	yes	yes
Common Mid Point (CMP) Stack	yes	yes	yes	yes	yes

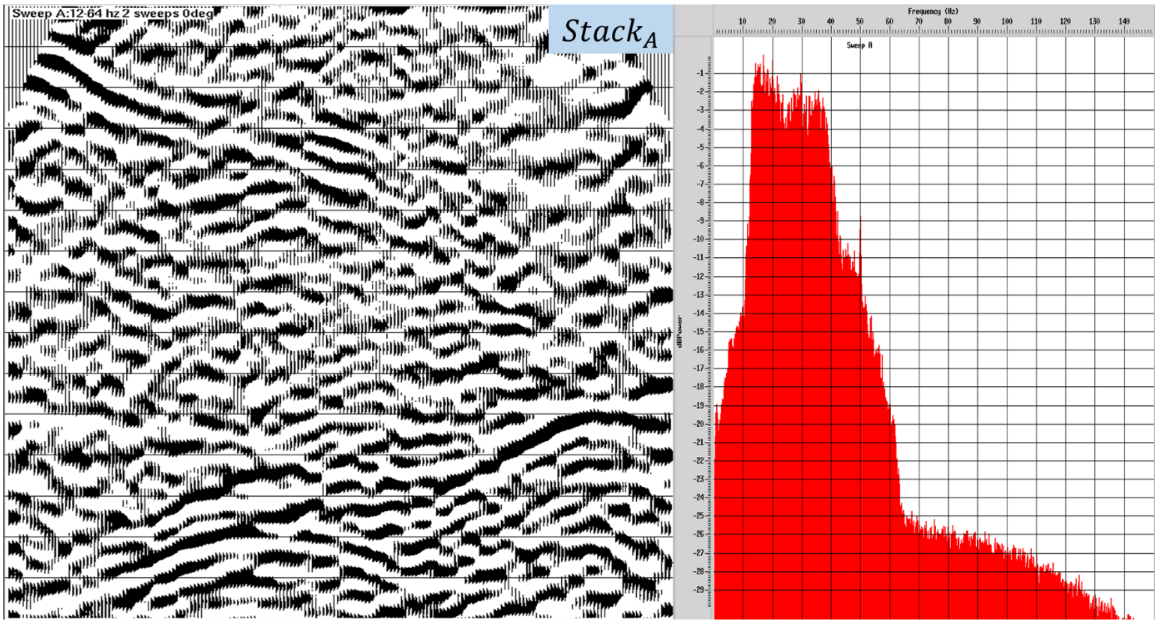

Fig. 7a. Final velocity stack of $Stack_A$ ($Record_A$) and its amplitude-frequency spectrum.

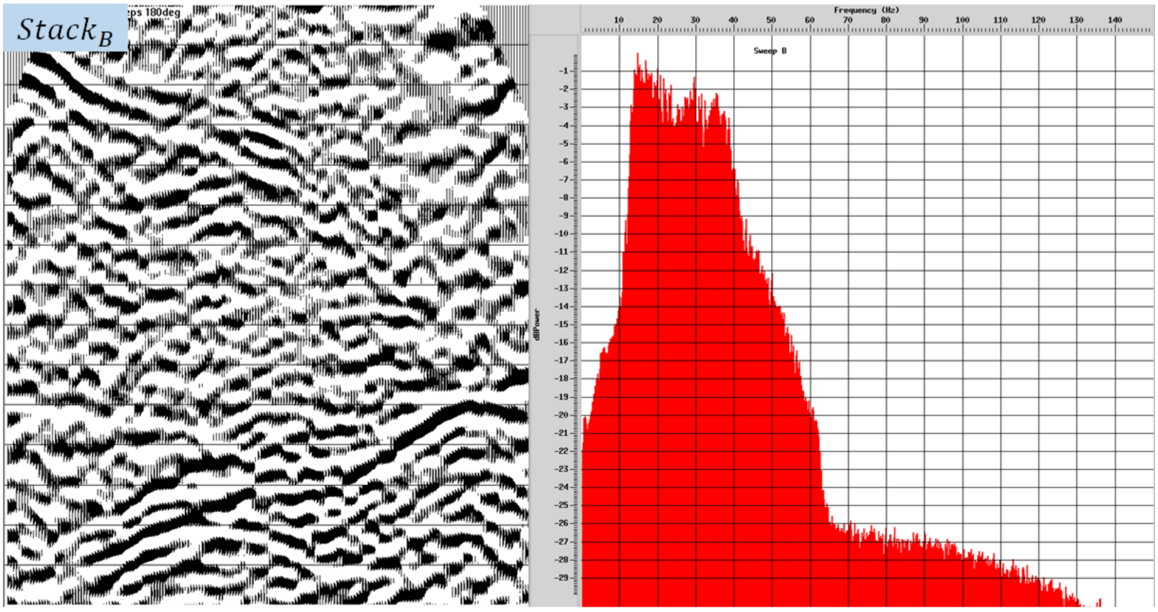

Fig. 7b. Final velocity stack of $Stack_B$ ($Record_B$) and its amplitude-frequency spectrum.

$Record_A$ and $Record_B$ were processed separately. These two stacks and spectrums are almost identical ($Stack_A$ and $Stack_B$).

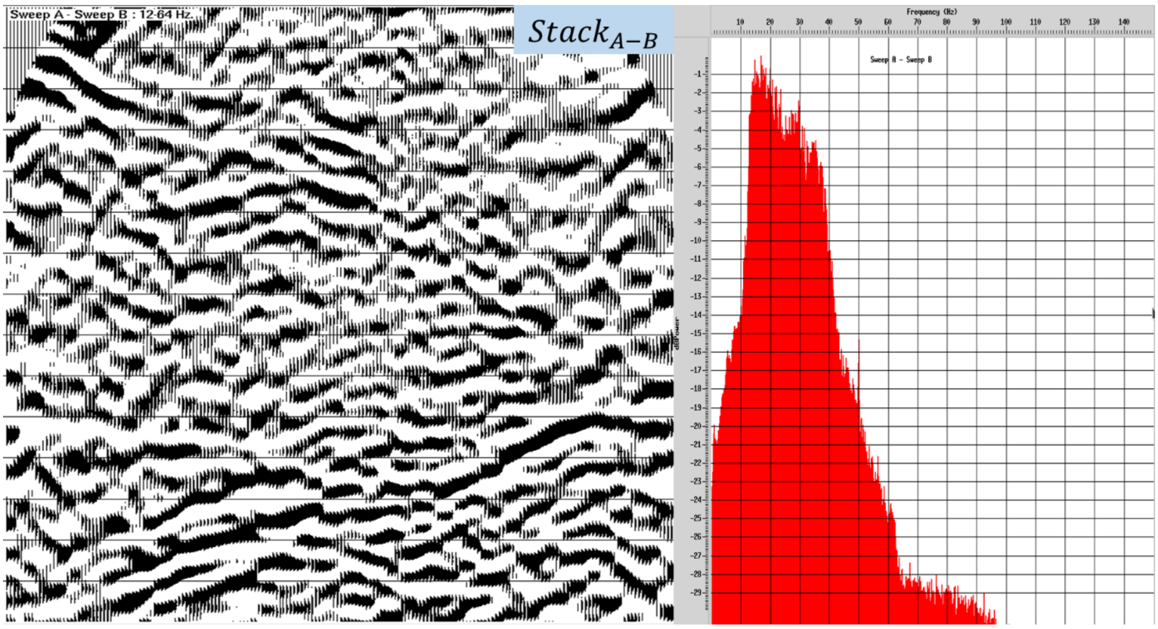

Fig. 7c. Final velocity stack of the $Stack_{A-B}$ ($Record_A - Record_B$) and its amplitude-frequency spectrum.

Fig. 7c shows the $Stack_{A-B}$ processed according to the processing flow in Table 6. In this stack, some of the harmonics have been removed. When compared Figs. 7a, 7b with 7c, the differences are very small, but comparison of their spectrums shows slightly more difference. The reason for the difference is that harmonics (H_2, H_4, H_6, etc) have been eliminated in the records.

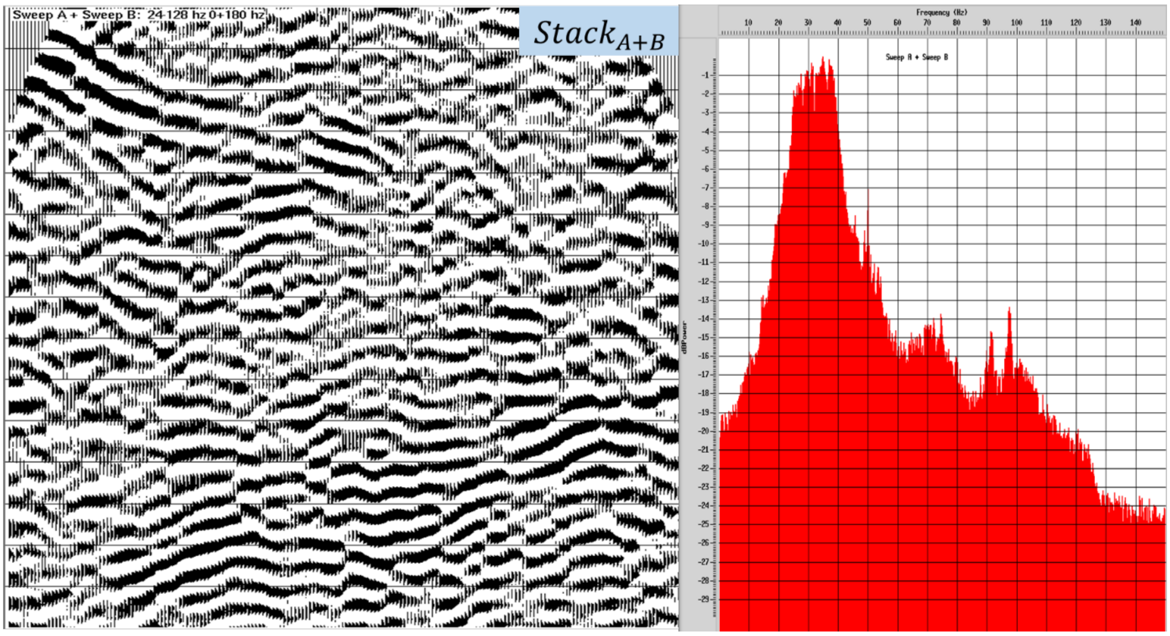

Fig. 7d. Final velocity stack of $Stack_{A+B}$ $(Record_A + Record_B)$ and its amplitude-frequency spectrum.

Fig. 7d shows the $Stack_{A+B}$ processed according to the processing flow in Table 6. In this stack, some of the harmonics and fundamental sweep have been removed. Compared to Figs. 7a and 7b, there more differences. The reason for these differences is that harmonics and Fundamental sweep (H_1, H_3, H_5, etc) have been eliminated from the records. When Fig. 7d is examined, it is seen that a higher frequency section is obtained with better discrimination of thin layers.

By the application of this new technique, it is possible to obtain two separated stacks. One of them is conventional stack section ($Stack_{A-B}$) and the other one is high-resolution stack section ($Stack_{A+B}$). Even if the high frequency sweep signal is not imparted into the earth in the field, it is possible to obtain a stack section as if high frequencies are generated with this new vibroseis data acquisition technique.

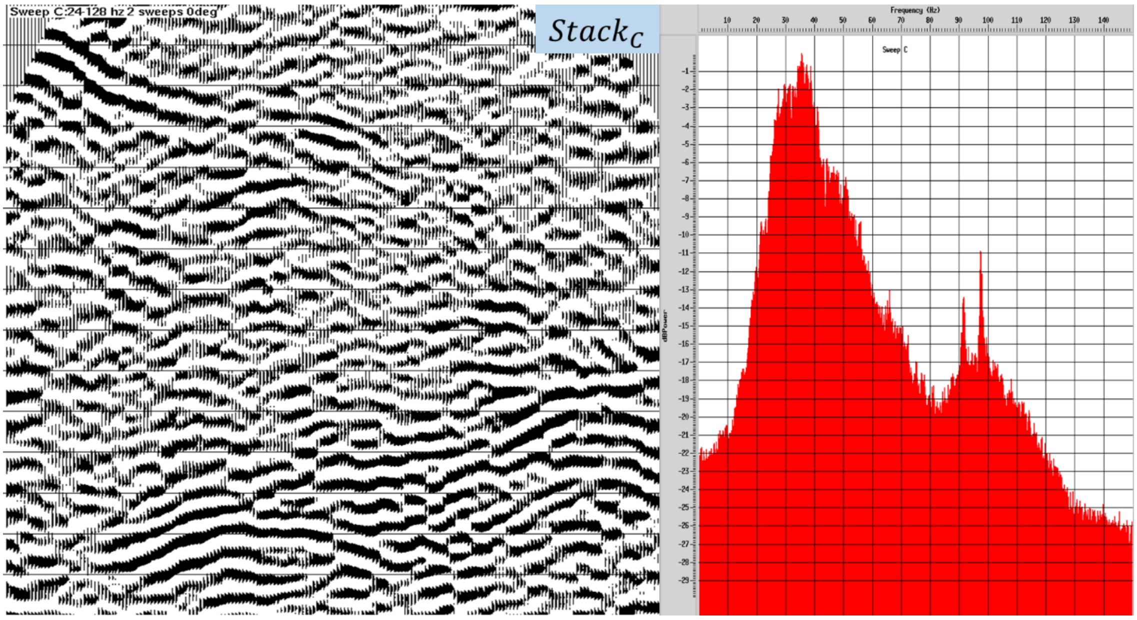

Fig. 7e. Final velocity stack section of $Stack_C$ ($Record_C$) and its amplitude-frequency spectrum.

Fig. 7e shows the $Stack_C$ section which processed according to the processing flow in Table 6. $Stack_C$ was processed for comparison with $Stack_{A+B}$. When the two sections are compared, it is clearly seen that they are identical. This result shows us that even if we do not produce $Stack_C$, it is possible to obtain it with $Stack_{A+B}$.

Comparison of their spectrums in Fig. 7d and Fig. 7e shows that the dominant frequencies are the same, but the higher frequencies are different, this is because some harmonics are eliminated in $Stack_{A+B}$. But all harmonics in $Stack_C$ are conserved.

CONCLUSIONS

Harmonics generated by the vibrator have traditionally been seen as noise to be attenuated out of the sweeps and traces during the acquisition and seismic data processing phases. It is shown in this experimental and research study that the higher harmonic frequencies, without fundamental sweep, can be harnessed for imaging shallow, thin reflector layers. Also, a new approach is presented to use the harmonic distortion in the vibroseis data. This technique gives us two different stacks. The stacks include a conventional velocity stack section and a velocity stack section with high frequencies.

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