RELATIONSHIP BETWEEN THE NUMBER OF SWEEPS AND HARMONICS ELIMINATION

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ABSTRACT

In vibroseis, the sweep is a signal sent into the ground by the vibrator. The fundamental sweep is generated by software on the recorder. The ground force signal is a sweep that includes both the fundamental and its harmonics. The harmonics are generated by the vibrator along with the fundamental sweep. Harmonics are considered noise and should be eliminated from field recordings. As the harmonic noise level increases, the seismic quality decreases.

Over the years, various methods using sweep parameters and phases have been proposed to mitigate these effects. The pure phase shift filter (PPSF) is one of these methods.

In this study, the pure phase shift filter is used to extract the relationship between eliminated and non-eliminated harmonics and the sweep number. Our approach is tested on synthetic and real data and the results are discussed.

KEY WORDS: Sweep, Harmonic, Harmonic Distortion Elimination, Sweep Number.

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INTRODUCTION

A vibrating machine is utilized to deliver a sweep signal into the ground (Fig-1). This machine sends a sine wave with pre-established frequencies into the ground.

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

These harmonic distortions are generated by non-linearities due to the coupling between the near surface and vibrator (Walker 1995; Wei 2007; Wei 2011; Lebedev 2004).

Figure-1: A view of the vibrator machine.

Harrison et al. (2011) used the Gabor transform and least squares methodology to successfully decompose a sweep from the first (H1: fundamental) to eight (H8) harmonics. The decomposition is succeeded by the use of the Gabor transform to produce broadband estimates of the fundamentals and harmonics of the vibroseis sweep. Their method was tested on both raw data and a synthetic sweep with time-varying amplitude and phase. Babaia et al. (2012) provided a new method for the removal of harmonic noise in slip sweep data. The method consists of estimating each harmonic component of a seismic trace, by applying an estimation operator of the considered harmonic.

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

The pure phase-shift filter are 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; Walker 1995; Li 1997; Polom 1997; Sercel 1999; Dal Moro 2007; Abd El-Aal 2010; Wuxiang 2010; Yongsheng 2011).

Li et al. (1995) and Wuxiang (2010) suggested the use of a 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 ground force signal. This method has depressed the high-order harmonic interference but does not address the problem of low-order harmonics.

Sharma et al. (2009) suggested 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 a 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.

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

Anderson (1995), Moerig (2004), and Benabentos (2006) applied the pure phase shift filter technique, similar to the combi-sweep technique.

Harrison’s (2011, 2012, and 2013) new approach implies the decomposition of the vibroseis sweep into their respective fundamental and harmonic components, using the Gabor transform constitutes an original approach to the inclusion of the harmonics. It should be noticed that in their implementation the fundamental sweep is not removed from the harmonic components.

Gureli (2021) preferred to use sweep harmonics as a signal instead of eliminating them. Two separate sweeps were recorded in the field using two different (0 and 180 degrees) sweep input phases. After recording, these two sweeps were first summed and then subtracted from each other in the time domain. After this process, cross-correlation was performed. Thus, two separate recordings were obtained. One of these recordings is a normal recording with some harmonics eliminated, and the other is a new recording with doubled frequency with the fundamental sweep and some harmonics eliminated. In other words, the sweep harmonics were not eliminated but used as a signal.

In this study, the relationship between the number of sweeps and the number of preserved and eliminated harmonics are investigated and a compact form for n sweeps case is formulated.

HARMONIC DISTORTION ANALYSIS

The theoretical harmonic analysis is based on the work of Seriff and Kim (1970) in this study. We have extended their theory by investigating the effect of the initial phase shift on the sweep data. We considered linear up-sweeps and their kth harmonic to determine the signal relationships before correlation.

Figure-2: Schematic presentation of the vibratory surface source technique (revised from Seriff and Kim, 1970)

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) and Gureli (2021) examined the typical linear sweep-frequency sine wave $H1 = S_1(t,\theta)$ as defined by

$$H1 = S_1(t,\theta) = \alpha_1 Sin[2\pi(f_1 + \mathrm{Q}t)t + \theta], \tag{1}$$

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

$$\mathrm{Q} = \frac{f_2 - f_1}{T}.$$

The k^{th} harmonic distortion of $S_1(t)$ will have

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

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 $H1 = S_1(t,\theta)$ a signal $Hk = S_k(t,k\theta)$. 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 $S_k(t,k\theta)$.

$$GF(t,\theta) = S(t,\theta) = S_1(t,\theta) + S_2(t,2\theta) + S_3(t,3\theta) + S_4(t,4\theta) + \cdots + S_k(t,k\theta),$$

$$GF(t,\theta) = \sum_{k=1} S_k(t,k\theta). \qquad 3$$

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

METHOD

The pure phase-shift filter is currently the most commonly used technique for eliminating harmonics from the ground force signal (GF). The equation below shows the relationship between the initial phase angle and the number of sweeps.

$$\theta = 360/n \qquad 4$$

The initial phase of the kth harmonic is kθ, while the initial phase of the sweep is θ. Therefore, the phases of harmonics are not equal to each other. Each harmonic has a different phase angle. Only when θ = 0 are the phases of all harmonics equal and zero.

The cross-correlation operation subtracts the sweep's initial phase from the fundamental sweep and all harmonics, as much as the initial phase of the fundamental sweep. Thus, the phase of all Fundamental sweeps becomes 0 degrees. The phases of the harmonics are shifted backward by the initial phase. If the sweep initial phase is calculated and applied using Eq.4 according to the number of sweeps (n), some or most of the harmonics are eliminated depending on the number of sweeps when summing after correlation.

If the number of sweeps is n=2, the initial phase angle (θ) becomes 180 degrees. In this case, the initial phase of the first sweep will be 0 degrees, and the initial phase of the second sweep will be 180 degrees. During the first sweep, the initial phase of all harmonics will always be 0 degrees. During the second sweep, the initial phase of the fundamental sweep will be θ=180 degrees and the angle of the harmonics will be kθ, i.e. 360, 540, and 720 degrees respectively. The second harmonic will have a phase of 0 degrees, the third harmonic will have a phase of 180 degrees, and the fourth harmonic will have a phase of 0 degrees.

Fig. 3a shows a fundamental sweep and the second harmonic. The initial phase angle of both is 0 degrees. Fig. 3b shows a fundamental sweep shifted by 180 degrees and a second harmonic shifted by 2x180=360=0 degrees. While the fundamental sweeps are in opposite directions, the harmonic angles of both are the same and 360=0 degrees.

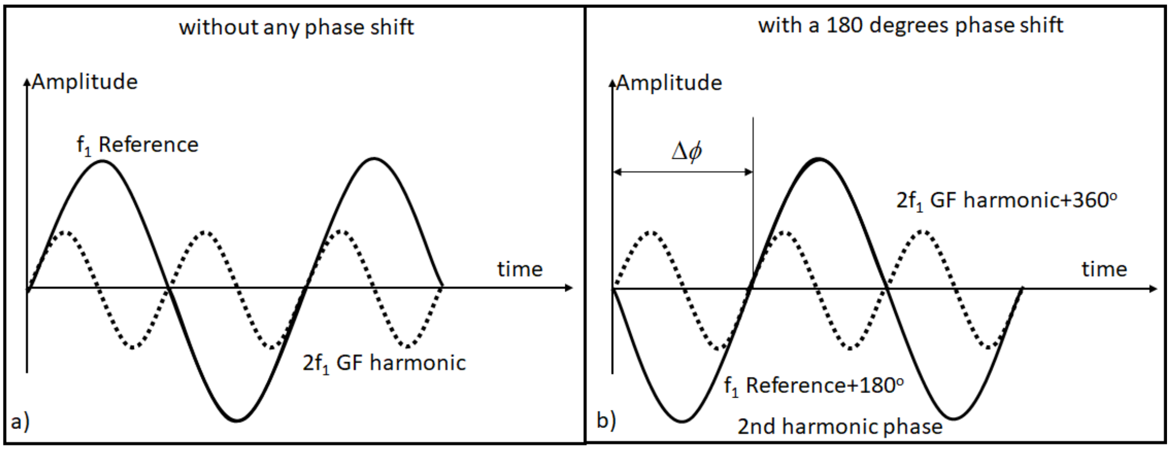

Figure-3: a) Reference signal and second harmonic without any phase shift, b) Reference signal and second harmonic with a 180 degrees phase shift (revised from Sercel, 1999)

If the first and second sweeps are correlated with their fundamental sweeps, the results will be the same. When the input phases are subtracted by the correlation process their phase will be the same phases. With the the cross-correlation process, since the input phase of the first sweep is 0 degrees, it does not change. Since the input phase of the second sweep is 180 degrees, 180 degrees are subtracted from both fundamental sweep and its harmonics. Thus, the phases of the Fundamental sweeps become 0 degrees (Fig. 4). On the other hand, the phase of the harmonics changes. In the first and second sweep, the harmonic phases were 0 degrees before correlation. When the input phases are subtracted by cross-correlation, the harmonic phase of the second sweep becomes -180 degrees. Thus, it has the opposite sign compared to the harmonic of the first sweep. After cross-correlation, the wavelets will be reversed (Fig. 5).

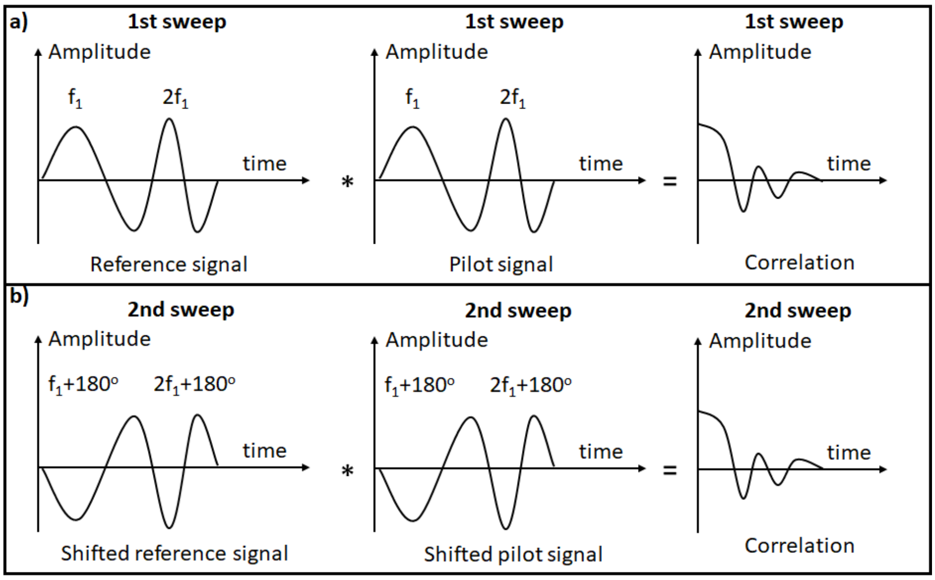

Figure-4: a) Referance signal, a pilot signal of the first sweep without any phase shift, and their correlation, b) Shifted reference signal, shifted pilot signal of the second sweep with a 180 degrees phase shift, and their correlation (revised from Sercel, 1999).

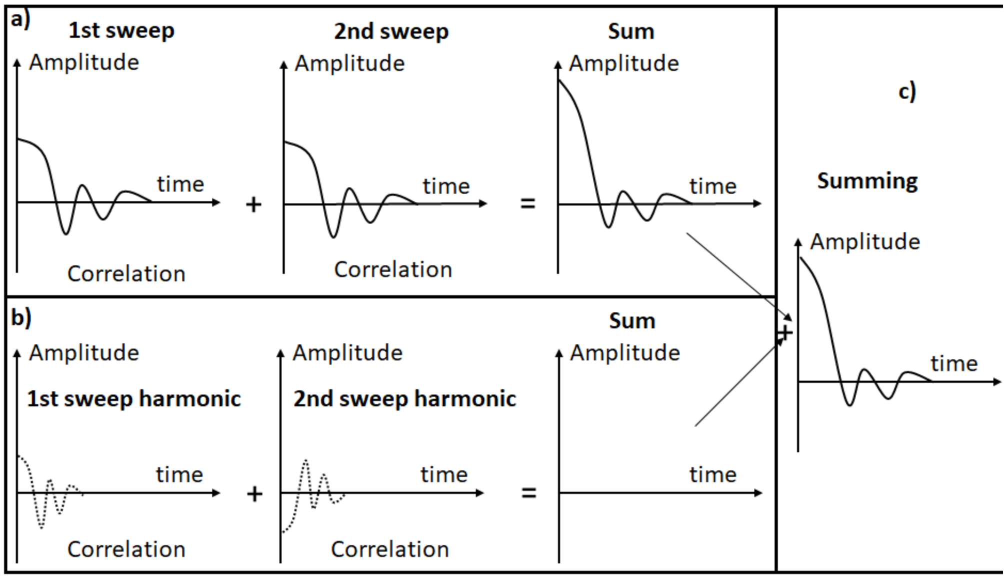

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Fig.-5: a) Reference signal and harmonic of the first sweep without any phase shift, and their correlation, b) Shifted reference signal, shifted harmonic of the second sweep with a 180 degrees phase shift, and their correlation (revised from Sercel, 1999).

When the correlations of the fundamental sweeps given in Fig. 4 and the cross-correlation of the harmonics given in Fig. 5 are stacked, the correlation wavelet of the fundamental sweeps becomes stronger, while the correlation of the harmonics removes each other. Thus, harmonic elimination is achieved by using the input initial phases (Fig. 6).

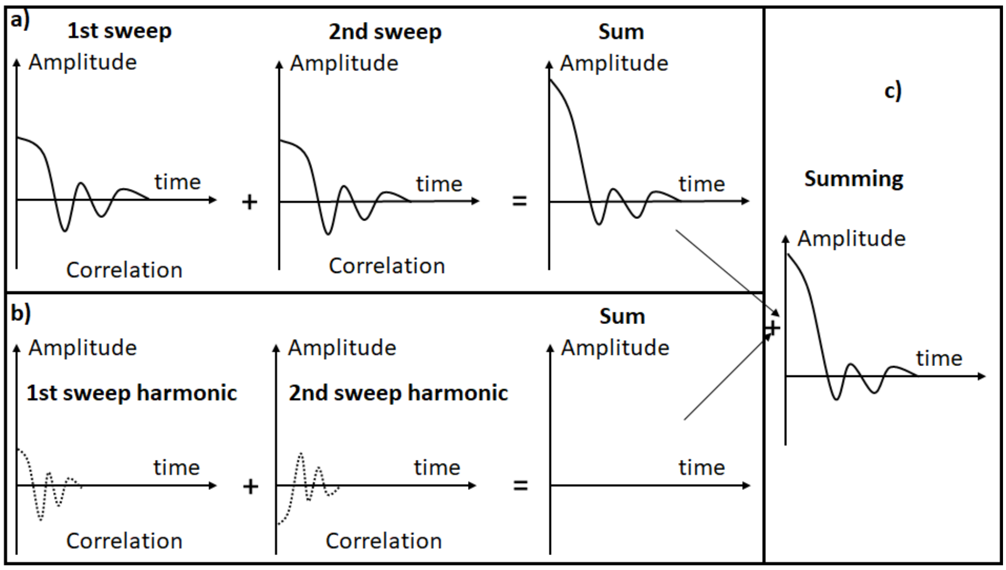


Figure-6: a) Summing of first and second correlation results, b) Summing of first and second harmonic correlation results, c) Summing of Fig. 6a and Fig.6b (revised by Sercel, 1999).

Figure-7: a) A synthetic fundamental sweep and its eight harmonics, b) A cross-correlation of fundamental sweep and its eight harmonics with fundamental sweep and their summing.

Fig. 7a shows the fundamental sweep and its harmonics. The frequency of the harmonics is a multiple of the fundamental sweep frequency (f1-f2). As the harmonic frequencies increase, their amplitudes decrease. As the harmonic order increases, the start and end frequencies increase at the same rate, while the amplitudes decrease. Fig. 7b shows the correlations of the fundamental sweep and the harmonics with the fundamental sweep separately. The sum of the cross-correlations of the harmonics and the autocorrelation of the fundamental sweep is equal to the cross-correlation of the GF (Ground force) and the fundamental sweep.

In conventional seismic data acquisition, the sweep initial phase is always 0 degrees. This ensures that all harmonics are present in the recordings. After cross-correlation, the ratio of the amplitudes of the GF and fundamental sweep should be below -40 dB. If the ratio is above -40 dB, the harmonics become too dominant and the recording is considered too noisy. To reduce the amplitude level below -40 dB, it is necessary to eliminate the harmonics.

A PURE PHASE SHIFT FILTER (PPSF) FOR HARMONICS ELIMINATION

Li et al. (1995) suggested a pure phase shift filter (PPSF) to eliminate harmonics in vibroseis data. It is possible to eliminate harmonics in the Ground force signal with this method. This method has been successfully applied to synthetic and real data.

The harmonics can be removed by adding two signals with opposite phases, but also by adding n sweeps shifted by 360 / n.

The initial phase angle is related to the number of sweeps. This relationship is given in Eq 4. According to this equation;

1 sweeps shifted by θ = 360/1 = 0-degree,

2 sweeps shifted by θ =360/2 = 180-degree,

3 sweeps shifted by θ =360/3 = 120-degree,

4 sweeps shifted by θ =360/4= 90-degree,

5 sweeps shifted by θ =360/5= 72-degree,

6 sweeps shifted by θ =360/6= 60-degree.

RELATIONSHIPS BETWEEN SWEEP NUMBER AND HARMONICS ELIMINATION

The Pure Phase Shift Filter (PPSF) method is dependent on the number of sweeps. The input phase angle of the sweep changes by the number of sweeps. The number of eliminated harmonics is also related to the number of sweeps. As the number of sweeps increases, so does the number of eliminated harmonics. If the number of sweeps is low, then the number of eliminated harmonics will also be low. If a low sweep number is used, it cannot be expected that too many harmonics will be eliminated. To eliminate more harmonics, the number of sweeps must be increased. The relationship of the harmonics eliminated according to the number of sweeps is given below.

The case of data acquisition with one sweep

If the sweep number is 1, the initial phase angle will be θ = 0 degrees, as calculated by Equation 4. In this case, the initial phase of both fundamental sweep and harmonics will be 0 (zero) degrees. As there is no summation process, no harmonics will be eliminated. Substituting this information into equation 5 yields the values in Table 1, which indicate that no harmonics are eliminated. According to Table 1, no harmonics are eliminated. If the number of sweeps is 1 or if the sweep initial phase is 0 degrees even if more than one sweep is used, no harmonics are eliminated.

Table-1 shows that the phases of both the fundamental sweep and the harmonics before and after correlation are 0 degrees. This is because the initial phase of the sweep is also 0 degrees. If the phase angle is consistently 0 degrees or the same in all sweeps, no harmonics will be eliminated, even if multiple sweeps are performed. Therefore, all harmonics are preserved.

Table 1: Status of fundamental sweep and harmonics for one sweep.

n	k	Harmonic No	Phase of harmonic before correlation	Phase of harmonic after correlation	GF(t, θ) = Vector Sum	Comment
			Swp#1	Swp#1		
1	1	Fundamental H1	0	0	H1	preserved
1	2	H2	0	0	H2	preserved
1	3	H3	0	0	H3	preserved
1	4	H4	0	0	H4	preserved
1	5	H5	0	0	H5	preserved
1	6	H6	0	0	H6	preserved
1	7	H7	0	0	H7	preserved
1	8	H8	0	0	H8	preserved
1	9	H9	0	0	H9	preserved
1	10	H10	0	0	H10	preserved
1	11	H11	0	0	H11	preserved
1	12	H12	0	0	H12	preserved

According to Table 1, the GF is as follows;

$$GF(t,\theta) = H1 + H2 + H3 + \cdots + Hk. \quad (5)$$

Eq.5 gives the harmonics that are not eliminated according to 1 sweep and form the GF. For 1 sweep, no harmonics are eliminated.

Fig.8a shows that as the frequency of the harmonics increases, their amplitudes decrease. The second harmonic (H2) has twice the frequency of the fundamental sweep (H1), the third harmonic (H3) has three times the frequency, and the kth harmonic (Hk) has k times the frequency of H1.

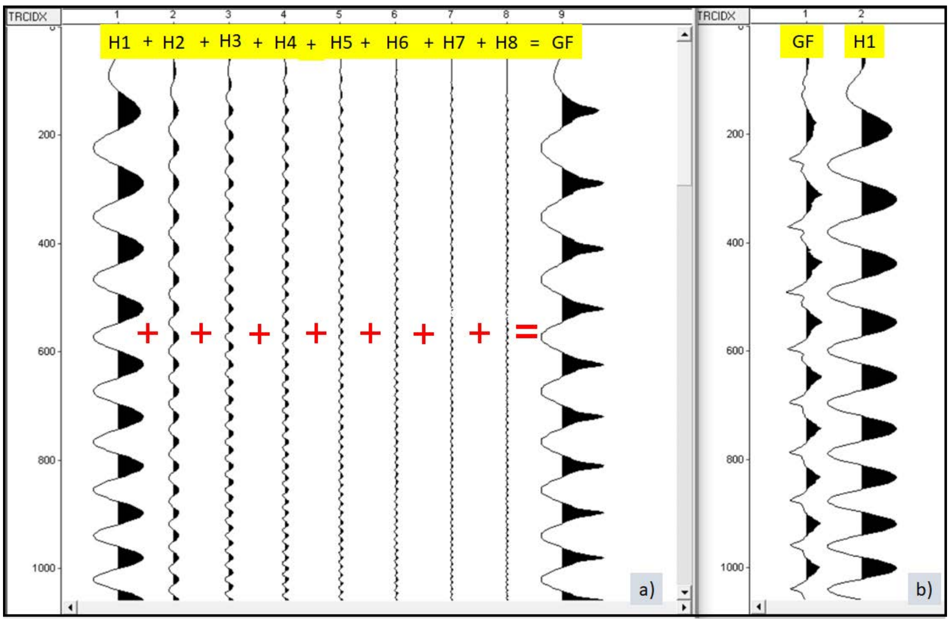


Figure-8: a) The part of synthetic fundamental sweep (H1), its harmonics (H2 to H8), and GF signal, b) the part of real fundamental sweep (H1) and GF signal.

Fig.8a displays the synthetic fundamental sweep, along with its eight harmonics and their sum (GF). The synthetic sweep ranges from 6 to 32 Hz and has a length of 4 seconds. The same parameters were used when applying the synthetic sweep to real data in the field, as shown in Fig.8b. Fig.8b illustrates the actual GF and Fundamental sweep (H1). Both Fig. 8a and Fig. 8b depict 1.1 seconds of the 4 seconds sweep. For the analyses in Fig.9, all 4 seconds of data were used.

GF is equal to the sum of the Fundamental sweep (H1) and the harmonics (H2, H3,...Hk). In this synthetic study, harmonics up to H8 are taken for analysis (Fig.8a).

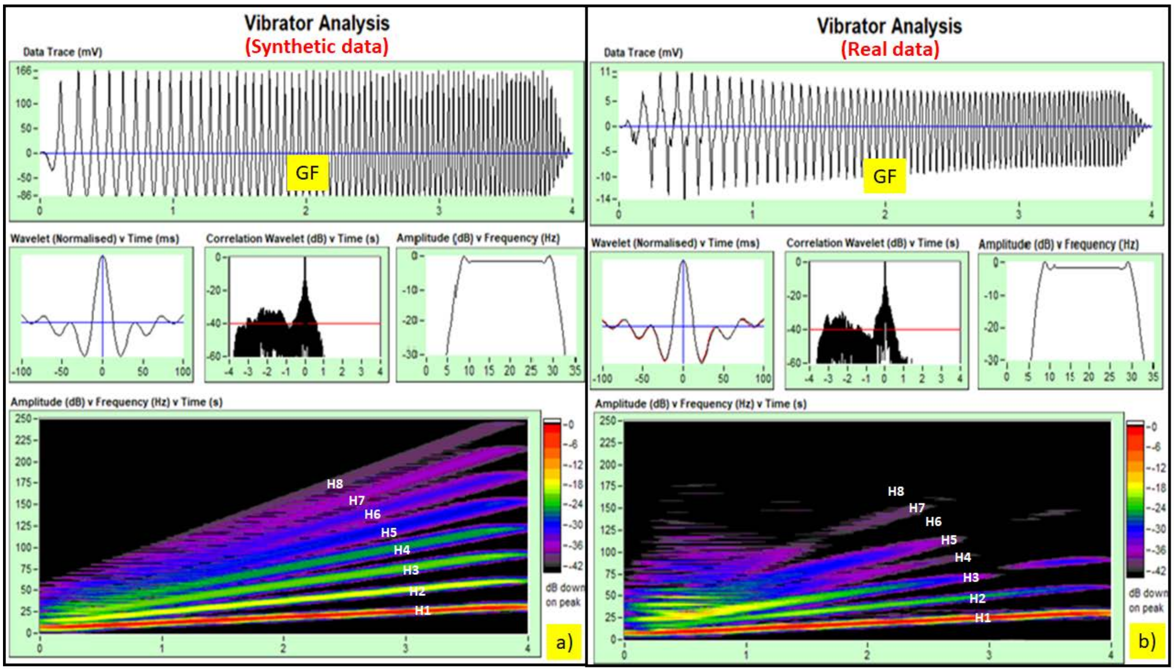


Figure-9: a) Analysis of synthetic GF signal in Fig. 8a, b) Analysis of real GF signal in Fig. 8b.

Fig.9 presents an analysis of the synthetic and real GF signals displayed in Fig.8a and Fig.8b. In Fig.9a, the synthetic GF signal is shown at the top, followed by the normalized correlation wavelet (in time), normalized correlation wavelet (in dB), the power spectrum in the middle, and the Gabor transform at the bottom. Fig.9b displays the real GF signal at the top, followed by the normalized correlation wavelet (in time), normalized correlation wavelet (in dB), the power spectrum, and the Gabor transform at the bottom. When analyzing both synthetic and real data using the Gabor transform, all harmonics remain unchanged. None of the harmonics could be eliminated and all of them are present in the recordings. The high level of harmonics is visible in the normalized correlation wavelet (dB), with a level above -40 dB. This indicates that the harmonics are strong and have not been eliminated.

n	k	Harmonic No	Phase of harmonic before correlation		Phase of harmonic after correlation		GF(t, θ) = Vector Sum	Comment
			Swp#1	Swp#2	Swp#1	Swp#2		
2	1	Fundamental H1	0	180	0	0	2*H1	preserved
2	2	H2	0	0	0	-180	0	removed
2	3	H3	0	180	0	0	2*H3	preserved
2	4	H4	0	0	0	-180	0	removed
2	5	H5	0	180	0	0	2*H5	preserved
2	6	H6	0	0	0	-180	0	removed
2	7	H7	0	180	0	0	2*H7	preserved
2	8	H8	0	0	0	-180	0	removed
2	9	H9	0	180	0	0	2*H9	preserved

Figure-10: a) View of a 1-sweep shot with an initial phase angle of 0 degrees, b) The power spectrum of this shot.

Fig.10 shows a real shot recording obtained in the field. The recording parameters are 6-32 Hz, 1 sweep, 8 s, linear sweep. As can be seen in the shot recording, the harmonics remain as they are in the recording.

The case of data acquisition with two sweeps

If the number of sweeps is 2, the initial phase angle will be θ = 360/2 = 180 degrees, as calculated by Eq.4. This will result in the elimination of some harmonics while others will remain. Substituting this information into Eq.5 will yield the values presented in Table 2, which displays the eliminated and non-eliminated harmonics. If the number of sweeps is 2 and the sweep initial phase angle is 180 degrees, the harmonics that are preserved include H1 (Fundamental), H3, H5, H7, H9, are eliminated include H2, H4, H6, H8, H10.

In the case of seismic data acquisition with 2 sweeps, the initial phase angle of the first sweep will be 0 degrees and the initial phase angle of the second sweep will be 180 degrees. In the first sweep, the initial phase angle of the harmonics will not change, while in the second sweep, the initial phase angle of the harmonics will be in multiples of 180 degrees. If the initial input phase angles of these 2 sweeps are subtracted from their fundamental sweeps and harmonics and then these 2 sweeps are vertically stacked with each other, some harmonics will cancel each other and the sum of the remaining ones will give the following GF signal.

GF is equal to the sum of the Fundamental sweep (H1) and the harmonics (H3, H5,...H11). In this synthetic case study, harmonics up to H8 are taken for analysis (Fig. 11a).

As seen in Eq.7, certain harmonics are eliminated while the non-eliminated harmonics form the GF. The GF signal is twice the sum of the non-eliminated fundamental and harmonics. The data in Eq.7 and Table 2 are obtained from Eq.5 according to 2 sweeps.

Table 2: Status of fundamental sweep and harmonics for two sweeps.

n	k	Harmonic No	Phase of harmonic before correlation		Phase of harmonic after correlation		GF(t, θ) = Vector Sum	Comment
			Swp#1	Swp#2	Swp#1	Swp#2		
2	1	Fundamental H1	0	180	0	0	2*H1	preserved
2	2	H2	0	0	0	-180	0	removed
2	3	H3	0	180	0	0	2*H3	preserved
2	4	H4	0	0	0	-180	0	removed
2	5	H5	0	180	0	0	2*H5	preserved
2	6	H6	0	0	0	-180	0	removed
2	7	H7	0	180	0	0	2*H7	preserved
2	8	H8	0	0	0	-180	0	removed
2	9	H9	0	180	0	0	2*H9	preserved
2	10	H10	0	0	0	-180	0	removed
2	11	H11	0	180	0	0	2*H11	preserved
2	12	H12	0	0	0	-180	0	removed

According to Table 2, the GF is as follows;

$$GF(t,\theta) = 2\,(H1 + H3 + H5 + H7 + H9 + H11 + \cdots). \quad 6$$

Eq.6 gives the harmonics that are not eliminated according to 2 sweeps and form the GF. For 2 sweeps, the even-numbered harmonics are eliminated and odd-numbered harmonics are not eliminated.

As seen in Table 2, since the initial phase angle of the first sweep is 0 degrees, the phases of the fundamental sweep and its harmonics after correlation are equal to 0 degrees. Since the initial phase of the 2nd sweep is 180 degrees, 180 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. After correlation, harmonics with opposite signs are eliminated, while harmonics with the same sign or same phase are summed on top of each other. Thus, some harmonics are eliminated (colored white) and some harmonics are not eliminated (colored yellow). The amplitudes of the non-eliminated harmonics and the fundamental sweep are doubled after summing (vector sum).

Fig.11a shows the elimination of certain harmonics while doubling the amplitudes of the remaining harmonics and the fundamental sweep. The non-eliminated harmonics have higher frequencies but lower amplitudes compared to the previous harmonic. The H3 harmonic has a frequency three times that of the H1 fundamental sweep, H5 has a frequency five times that of the H1, and H7 has a frequency seven times that of the H1.

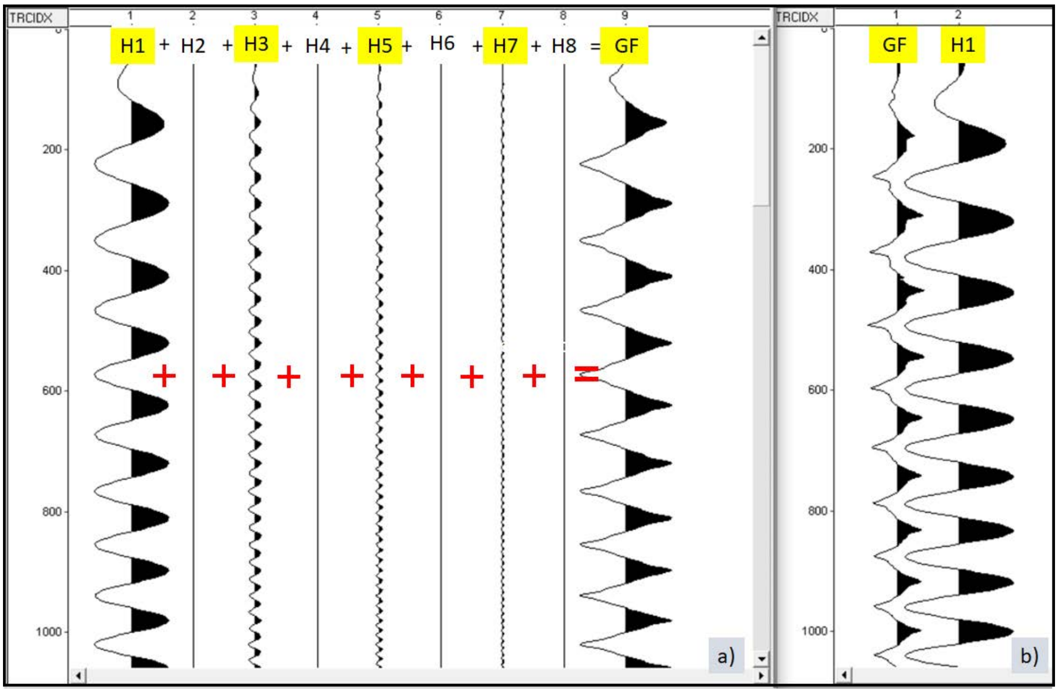


Figure-11: a) the part of synthetic fundamental sweep (H1), its harmonics (H3, H5, H7), and GF signal, b) the part of real fundamental sweep (H1) and GF signal.

Fig.11a shows the synthetic fundamental sweep, its three harmonics, and their sum (GF). The synthetic sweep is 6-32 Hz with a sweep length of 4 s. It was also applied to real data in the field with the same parameters (Fig. 11b). Fig. 11b shows the actual GF and Fundamental sweep (H1). These data were used for the analyses in Fig. 12. Fig. 11a and Fig. 11b show 1.1 s of the 4 s sweep. For the analyses in Fig. 12, all of this 4 s data was used.

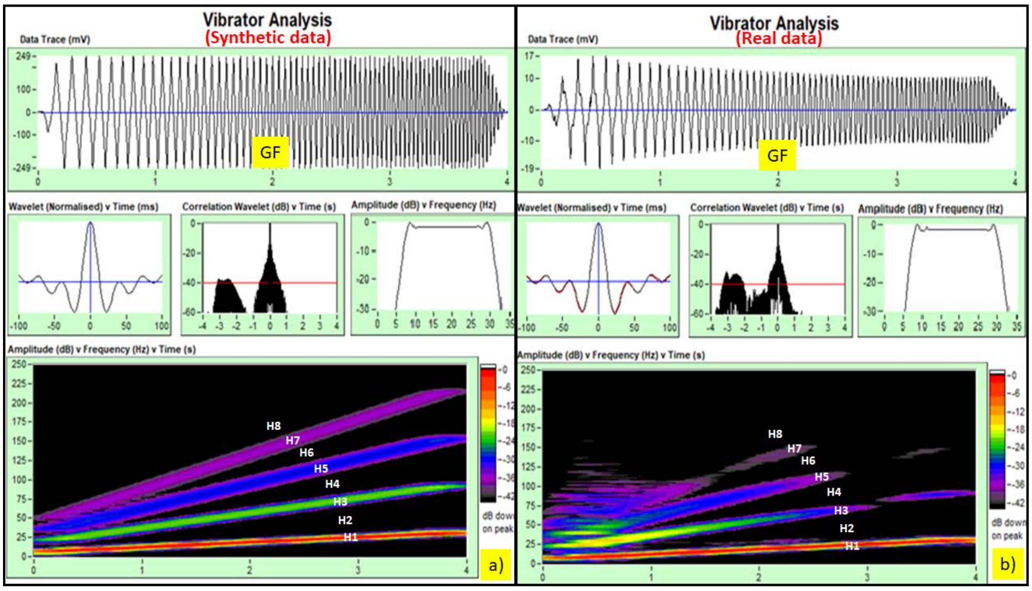


Figure-12: a) Analysis of synthetic fundamental sweep signal in Fig.11a, b) Analysis of real fundamental sweep signal in Fig.11b.

Fig.12 shows the analysis of the synthetic and real GF signals given in Fig.11a and Fig.11b. Fig.12a shows the synthetic GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. Fig.12b shows the real GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. When both synthetic and real data are analyzed in the Gabor transform, it is seen that some harmonics are eliminated. As in Table 2, it is also seen here that harmonics such as H2, H4, H6, and H8 are eliminated. It is also seen in both the synthetic and real data analyses in Fig. 12. The reduction in the harmonic level is seen in the normalized correlation wavelet (dB). Above the -40 dB level, the harmonic level decreases by a certain amount. This shows that some of the harmonics are eliminated.

Fig.13 and Fig.14 show a real shot obtained in the field. In Fig.13, the recording parameters are 6-32 Hz, 2 sweeps, 8 s, and linear sweep. The initial phase angle of both sweeps is 0 degrees. In Fig.14, the input phase angle of the first sweep is 0 degrees and the second sweep is 180 degrees. After each sweep was recorded in the field, they were cross-correlated with their fundamental sweep and then stacked vertically in the time domain. As can be seen in the shot in Fig.13, all harmonics remain. In Fig.14, some harmonics are eliminated and some harmonics are not eliminated in accordance with Table 2. Fig.15 shows that this difference can be seen both in the shots and in the difference spectra.

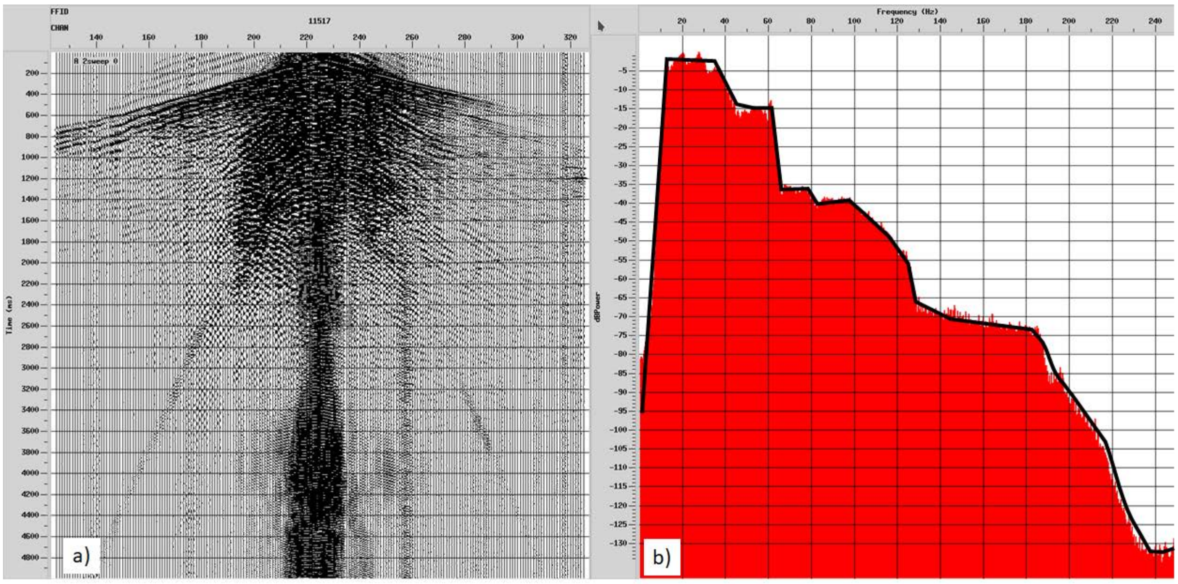


Figure-13: a) View of a 2-sweep shot with an initial phase angle of 0 degree, b) The power spectrum of this shot.

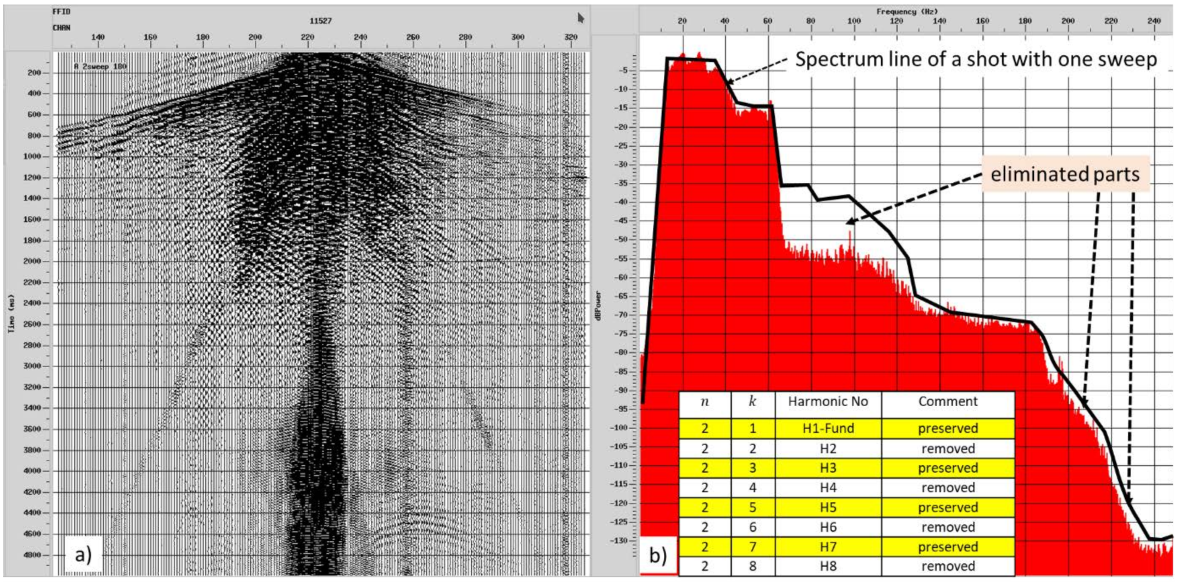


Figure-14: a) View of a 2-sweep shot with the initial phase angles of 0 and 180 degrees, b) The power spectrum of this shot.

Fig. 15 shows the difference between these two shots and the spectrum of the difference. Analysis of the shot difference shows that harmonic elimination is greater at receivers closer to the source. Harmonic elimination is higher at low frequencies and lower at high frequencies. Because this is the amplitude of the eliminated harmonic (H2) is larger than the others. Therefore, it is more dominant in the frequency domain.

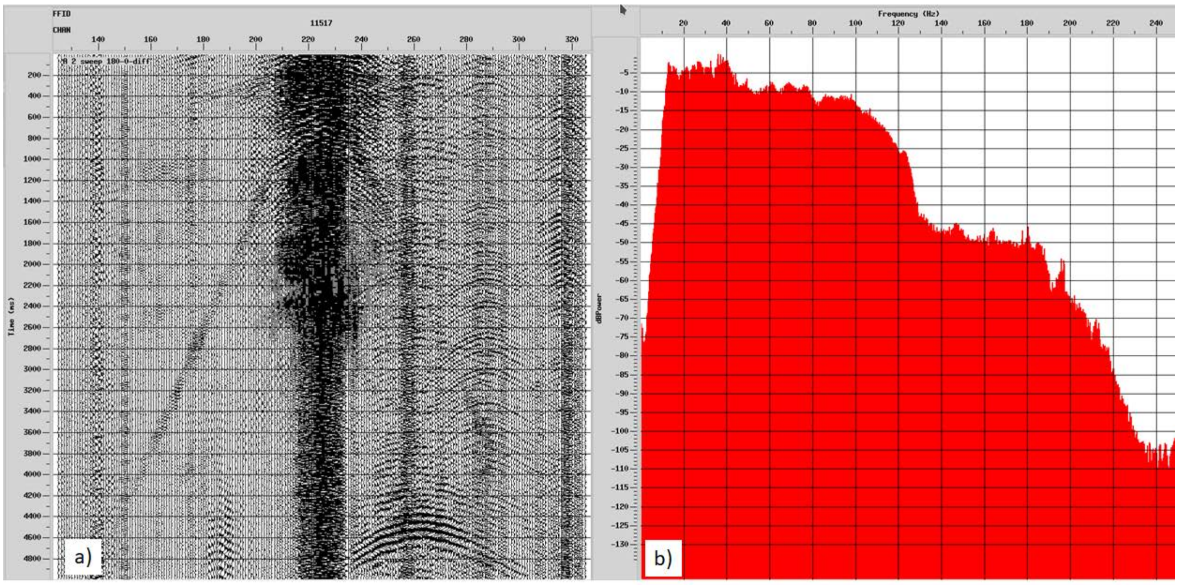


Figure-15: a) Difference between Fig. 13 and Fig. 14, b) The power spectrum of difference.

The case of data acquisition with three sweeps

If the number of sweeps is 3, the initial phase angle will be θ= 360/3=120 degrees as calculated by Eq.4. This will result in the elimination of some harmonics while others will be preserved. Substituting this information into

Eq.5 will yield the values presented in Table 3, which displays the eliminated and non-eliminated harmonics. As a result of the number of sweeps being 3 and the sweep initial phase angle being 120 degrees, H1 (fundamental), H4, H7, H10, ... harmonics are preserved, while H2, H3, H5, H6, H8, H9 harmonics are eliminated.

In the case of seismic data acquisition with 3 sweeps, the initial phase angle of the first sweep will be 0 degrees, the initial phase angle of the second sweep will be 120 degrees and the initial phase angle of the third sweep will be 240 degrees. In the first sweep, the initial phase angle of the harmonics will not change, while in the second sweep, the initial phase angle of the harmonics will be in multiples of 120 degrees, and in the third sweep, the initial phase angle of the harmonics will be in multiples of 240 degrees. If the initial phase angles of these 3 sweeps are subtracted from their fundamental sweeps and harmonics and then these 3 sweeps are vertically stacked with each other, some harmonics will remove each other and the sum of the remaining ones will give the following GF signal.

GF is equal to the sum of the Fundamental sweep (H1) and the harmonics (H4, H7,…H10). In this synthetic case study, harmonics up to H8 are taken for analysis (Fig.16a).

As seen in Eq.8, certain harmonics are eliminated while the non-eliminated harmonics form the GF. The GF signal is three times the sum of the non-eliminated fundamental and harmonics. The data in Eq.8 and Table 3 are obtained from Eq.5 according to 3 sweeps.

Table 3: Status of fundamental sweep and harmonics for three sweeps.

$$GF(t,\theta) = 3\,(H1 + H4 + H7 + H10 + \cdots).$$

According to Table 3, the GF is as follows;

$$GF(t,\theta) = 3\ (H1 + H4 + H7 + H10 + \cdots). \tag{7}$$

Eq.7 gives the harmonics that are not eliminated according to 3 sweeps and form the GF. Although the fundamental sweep and harmonics such as H4, H7, H10, etc. are not eliminated, other harmonics are removed during three sweeps. The amplitude of the remaining fundametal sweeps and harmonics increased as the number of sweeps.

As seen in Table 3, since the initial phase angle of the first sweep is 0 degrees, the phases of the fundamental sweep and its harmonics after correlation are equal to 0 degrees. Since the initial phase of the 2nd sweep is 120 degrees, 120 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 3nd sweep is 240 degrees, 240 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. After correlation, harmonics with opposite signs are eliminated, while harmonics with the same sign or same phase are summed on top of each other. Thus, some harmonics are eliminated (colored white) and some harmonics are not eliminated (colored yellow). The amplitudes of the non-eliminated harmonics and the fundamental sweep become three times (vector sum).

Fig.16a shows that certain harmonics are eliminated, while the remaining harmonics and fundamental sweep amplitudes are tripled. The non-eliminated harmonics have higher frequencies but lower amplitudes compared to the previous harmonic. The H4 harmonic has a frequency four times that of the H1 fundamental sweep, H7 has a frequency seven times that of the H1, and H10 has a frequency ten times that of the H1.

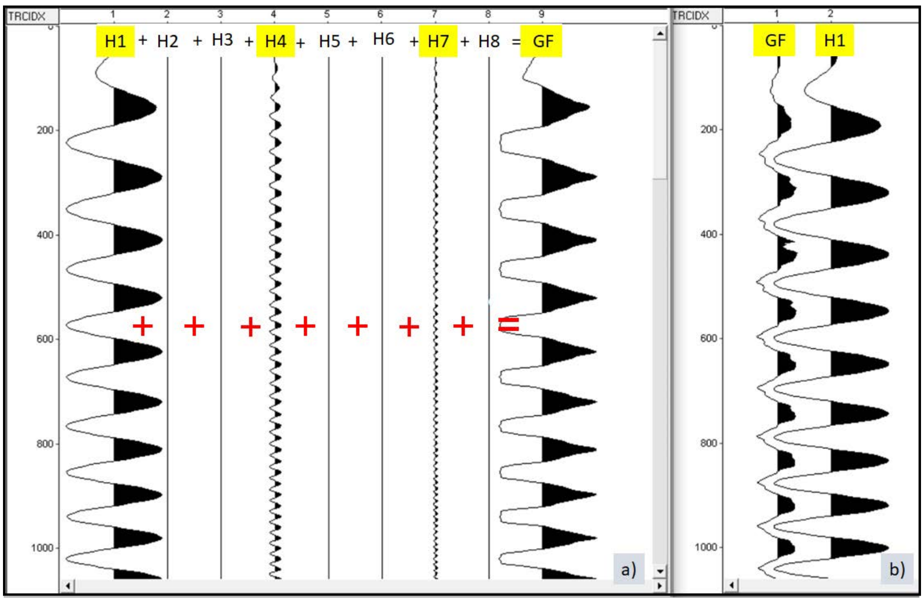


Figure-16: a) the part of synthetic fundamental sweep (H1), its harmonics (H4, H7), and GF signal, b) the part of real fundamental sweep (H1) and GF signal

Fig.16a shows the synthetic fundamental sweep, its two harmonics, and their sum (GF). The synthetic sweep is 6-32 Hz with a sweep length of 4 s. It was also applied to real data in the field with the same parameters (Fig.16b). Fig.16b shows the actual GF and Fundamental sweep (H1). These data were used for the analyses in Fig.17. Fig.16a and Fig. 16b show 1.1 s of the 4 s sweep. For the analyses in Fig.17, all of this 4 s data was used.

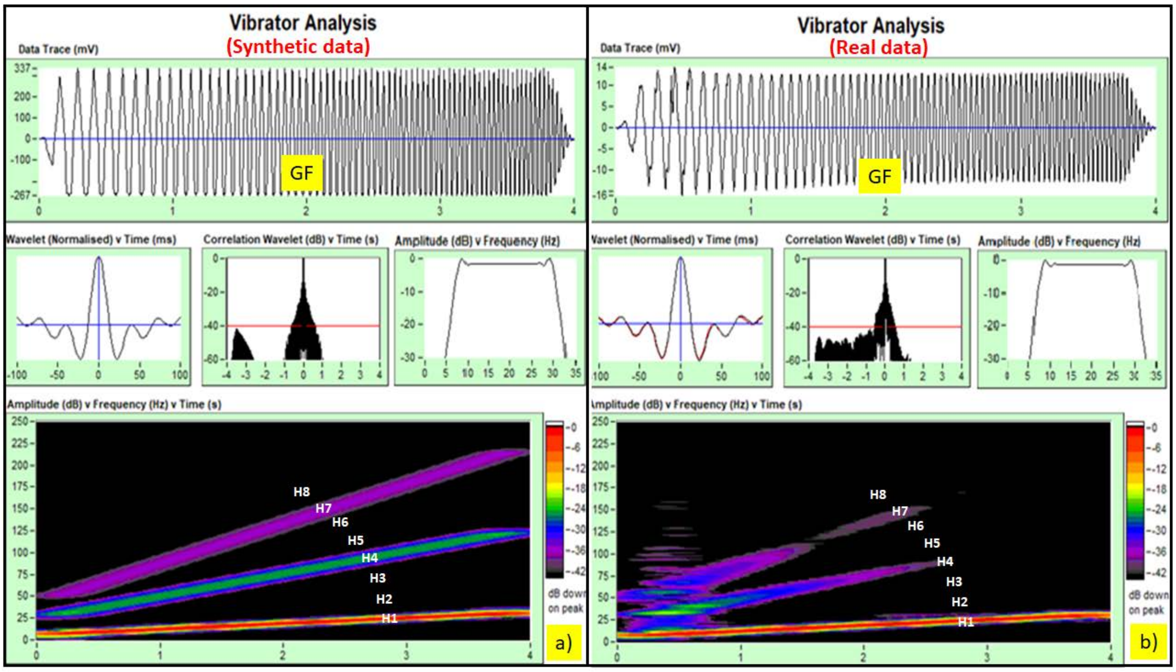


Figure-17: a) Analysis of synthetic fundamental sweep signal in Fig. 16a, b) Analysis of real fundamental sweep signal in Fig. 16b.

Fig.17 shows the analysis of the synthetic and real GF signals given in Fig.16a and Fig.16b. Fig.17a shows the synthetic GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. Fig.17b shows the real GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. When both synthetic and real data are analyzed in the Gabor transform, it is seen that some harmonics are eliminated. As in Table 3, it is also seen here that harmonics such as H2, H3, H5, H6 and H8 are eliminated. It is also seen in both synthetic and real data analyses in Fig.17. The reduction in the harmonic level is seen in the normalized correlation wavelet (dB). Above the -40 dB level, the harmonic level decreases by a certain amount. This shows that some of the harmonics are eliminated.

Figs.18 and 19 show a real shots obtained in the field. In Fig.18, the recording parameters are 6-32 Hz, 3 sweeps, 8 s, and linear sweep. The initial phase angle of three sweeps are 0 degrees. In Fig.19, the initial phase angle of the first sweep is 0 degrees, the second sweep is 120 degrees and the third sweep is 240 degrees. After each sweep was recorded in the field, they were cross-correlated with their fundamental sweep and then stacked vertically in the time domain.

As can be seen in the shot in Fig.18, all harmonics remain. In Fig.19, some harmonics are eliminated and some harmonics are not eliminated in accordance with Table 3. Fig. 20 shows that this difference can be seen both in the shots and in the difference spectra.

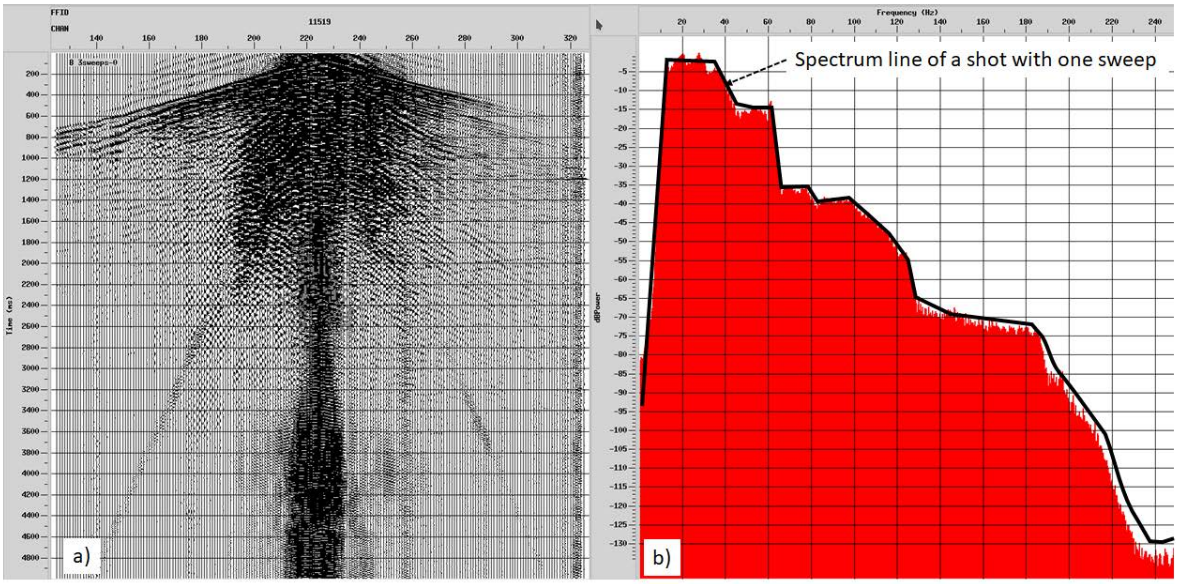


Figure-18: a) View of a 3-sweep shot with an initial phase angle of 0 degree, b) The power spectrum of this shot.

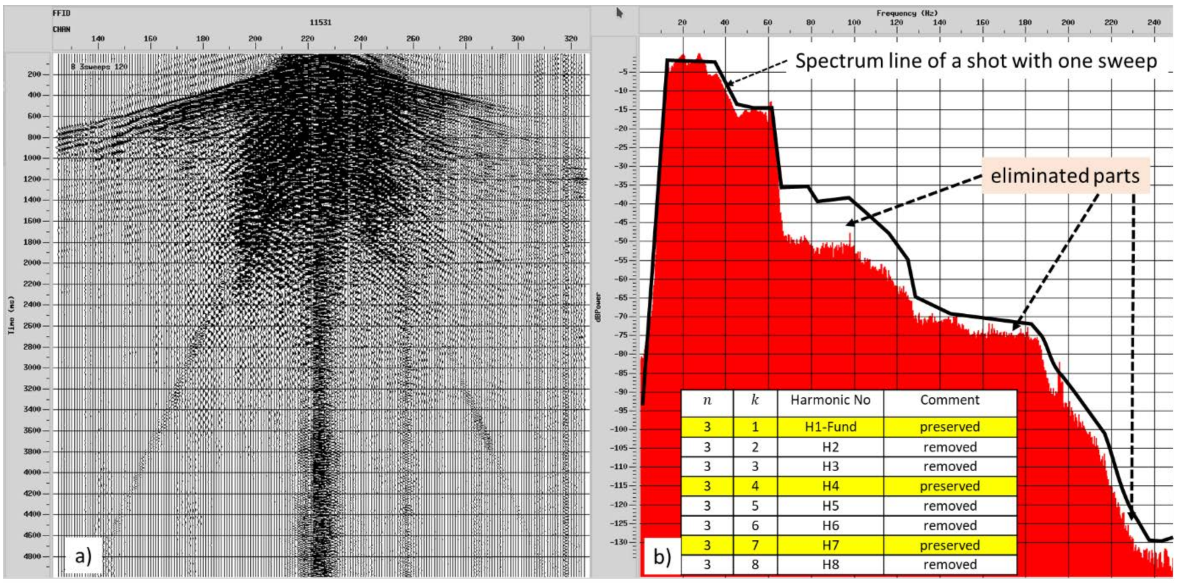


Figure-19: a) View of a 3-sweep shot with the initial phase angles of 0, 120 and 240 degrees, b) The power spectrum of this shot.

Fig.20 shows the difference between these two shots and the spectrum of the difference. Analysis of the shot difference shows that harmonic elimination is greater at receivers closer to the source. Harmonic elimination is higher at low frequencies and lower at high frequencies. Because this is the amplitude of the eliminated harmonic (H2) is larger than the others. Therefore, it is more dominant in the frequency domain.

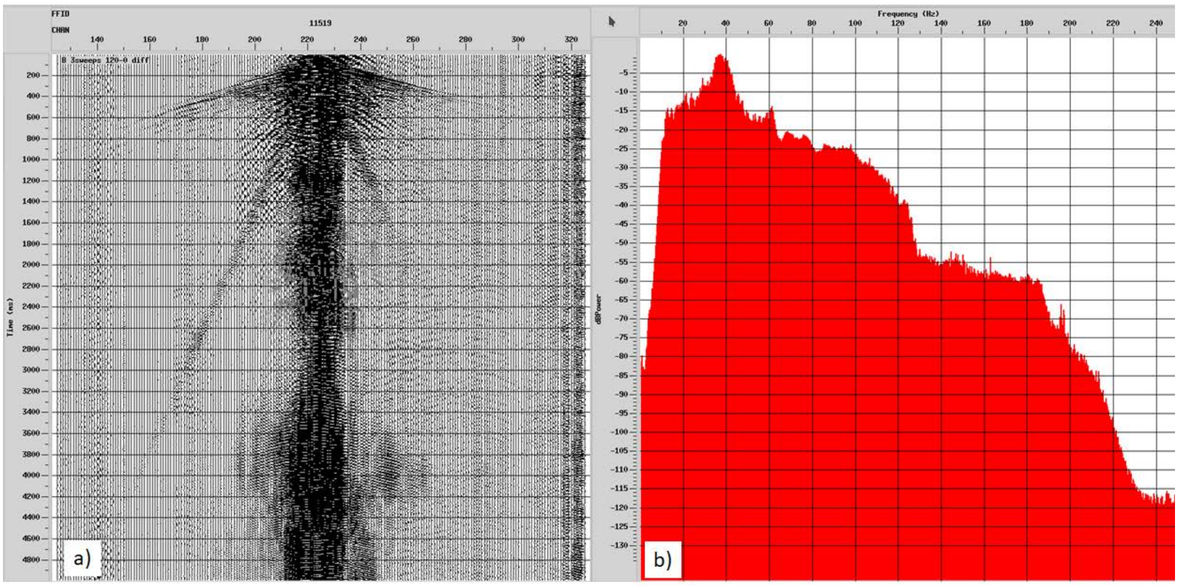


Figure-20: a) Difference between Fig.18 and Fig.19, b) The power spectrum of difference.

The case of data acquisition with four sweeps

If the number of sweeps is 4, the initial phase angle will be θ= 360/4=90 degrees as calculated by Eq.4. This will result in the elimination of some harmonics while others will be preserved. Substituting this information into Eq.5 will yield the values presented in Table 4, which displays the eliminated and non-eliminated harmonics. As a result of the number of sweeps being 4 and the sweep initial phase angle being 90 degrees, H1 (fundamental), H5, H9, ... harmonics are preserved, while H2, H3, H4, H6, H7, H8 harmonics are eliminated.

In the case of seismic data acquisition with 4 sweeps, the initial phase angle of the first sweep will be 0 degrees, the initial phase angle of the second sweep will be 90 degrees, the initial phase angle of the third sweep will be 180 degrees and the initial phase angle of the fourth sweep will be 270 degrees. In the first sweep, the initial phase angle of the harmonics will not change, while in the second sweep, the initial phase angle of the harmonics will be in multiples of 90 degrees, in the third sweep, the initial phase angle of the harmonics will be in multiples of 180 degrees and in the fourth sweep, the initial phase angle of the harmonics will be in multiples of 270 degrees. If the initial phase angles of these 4 sweeps are subtracted from their fundamental sweeps and harmonics and then these 4 sweeps are vertically stacked with each other, some harmonics will remove each other and the sum of the remaining ones will give the following GF signal.

GF is equal to the sum of the Fundamental sweep (H1) and the harmonics (H5, H9…). In this synthetic case study, harmonics up to H8 are taken for analysis (Fig.21a).

As seen in Eq.9, certain harmonics are eliminated while the non-eliminated harmonics form the GF. The GF signal is four times the sum of the non-eliminated fundamental and harmonics. The data in Eq.9 and Table 4 are obtained from Eq.5 according to 4 sweeps.

Table 4: Status of fundamental sweep and harmonics for four sweeps.

$GF(t,\theta) = 4\,(H1 + H5 + H9 + \cdots).$

According to Table 4, the GF is as follows;

$$GF(t,\theta) = 4\,(H1 + H5 + H9 + \cdots). \qquad 8$$

Eq.8 gives the harmonics that are not eliminated according to 4 sweeps and form the GF. Although the fundamental sweep (H1) and harmonics such as H5, H9, etc. are not eliminated, other harmonics are removed with four sweeps. The amplitude of the remaining fundamental sweeps and harmonics increased as the number of sweeps.

As seen in Table 4, since the initial phase angle of the first sweep is 0 degrees, the phases of the fundamental sweep and its harmonics after correlation are equal to 0 degrees. Since the initial phase of the 2nd sweep is 90 degrees, 90 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 3th sweep is 180 degrees, 180 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 4th sweep is 270 degrees, 270 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. After correlation, harmonics with opposite signs are eliminated, while harmonics with the same sign or same phase are vertically stacked on top of each other. Thus, some harmonics are eliminated (colored white) and some harmonics are not eliminated (colored yellow). The amplitudes of the non-eliminated harmonics and the fundamental sweep become four times (vector sum).

Fig.21a shows that certain harmonics are eliminated, while the remaining harmonics and fundamental sweep amplitudes are quadrupled. The non-eliminated harmonics have higher frequencies but lower amplitudes compared to the previous harmonic. The H5 harmonic has a frequency five times that of the H1 fundamental sweep and H9 has a frequency nine times that of the H1.

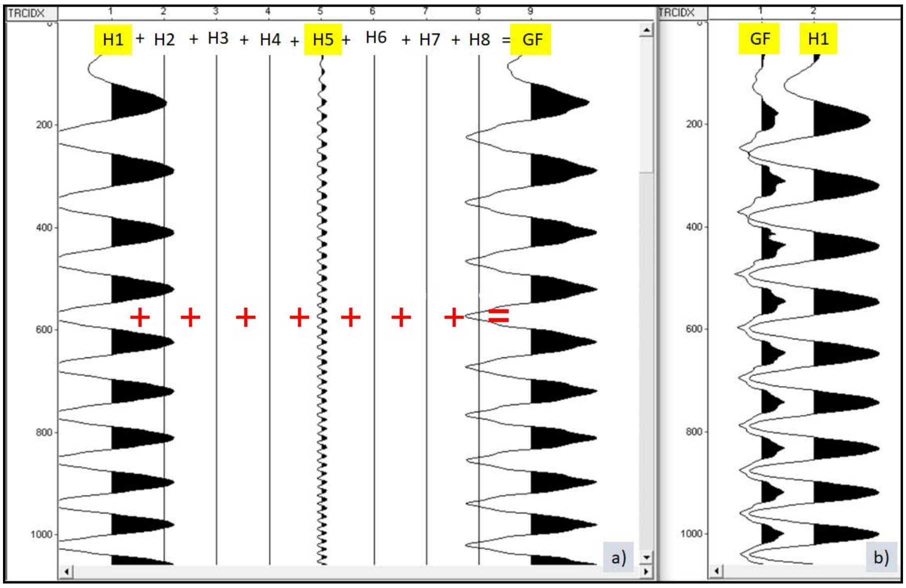


Figure-21: a) the part of synthetic fundamental sweep (H1), its harmonics (H5), and GF signal, b) the part of real fundamental sweep (H1) and GF signal.

Fig.21a shows the synthetic fundamental sweep, its one harmonic, and their sum (GF). The synthetic sweep is 6-32 Hz with a sweep length of 4 s. It was also applied to real data in the field with the same parameters (Fig.21b). Fig.21b shows the actual GF and Fundamental sweep (H1). These data were used for the analyses in Fig.22. Fig.21a and Fig.21b show 1.1 s of the 4 s sweep. For the analyses in Fig.22, all of this 4 s data was used.

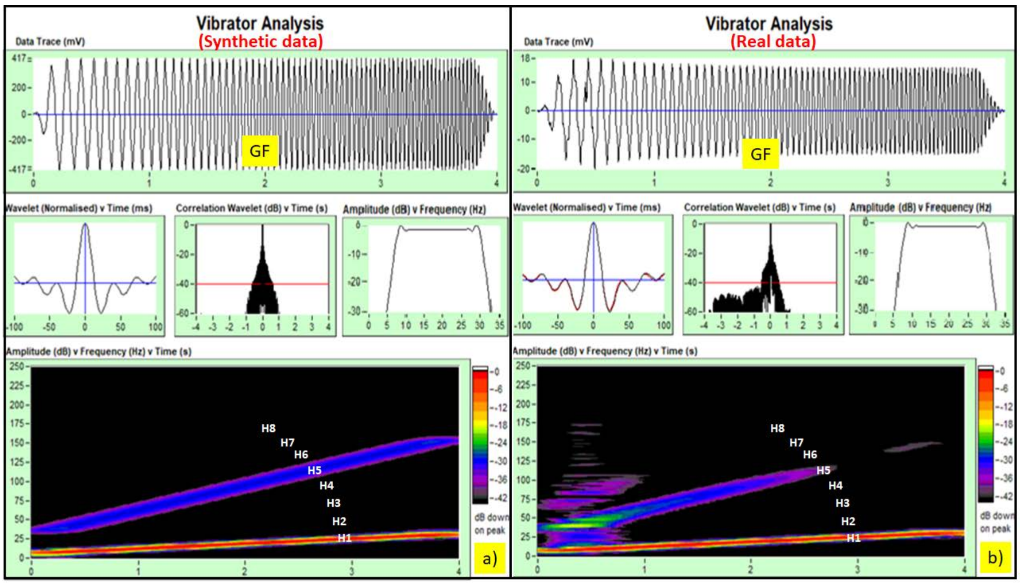


Figure-22: a) Analysis of synthetic fundamental sweep signal in Fig. 21a, b) Analysis of real fundamental sweep signal in Fig. 21b.

Fig.22 shows the analysis of the synthetic and real GF signals given in Fig.21a and Fig.21b. Fig.22a shows the synthetic GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. Fig.22b shows the real GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. When both synthetic and real data are analyzed in the Gabor transform, it is seen that some harmonics are eliminated. As in Table 4, it is also seen here that harmonics such as H2, H3, H4, H6, H7 and H8 are eliminated. It is also seen in both synthetic and real data analyses in Fig.22. The reduction in the harmonic level is seen in the normalized correlation wavelet (dB). Above the -40 dB level, the harmonic level decreases by a certain amount. This shows that some of the harmonics are eliminated.

Figs.23 and 24 show a real shots obtained in the field. In Fig.23, the recording parameters are 6-32 Hz, 4 sweeps, 8 s, and linear sweep. The initial phase angle of four sweeps are 0 degrees. In Fig.24, the initial phase angle of the first sweep is 0 degrees, the second sweep is 90 degrees, the third sweep is 180 degrees and the fourth sweep is 270 degrees. After each sweep was recorded in the field, they were cross-correlated with their fundamental sweep and then stacked vertically in the time domain. As can be seen in the shot in Fig.23, all harmonics remain. In Fig.24, some harmonics are eliminated and some harmonics are not eliminated in accordance with Table 4. Fig.25 shows that this difference can be seen both in the shots and in the difference spectra.

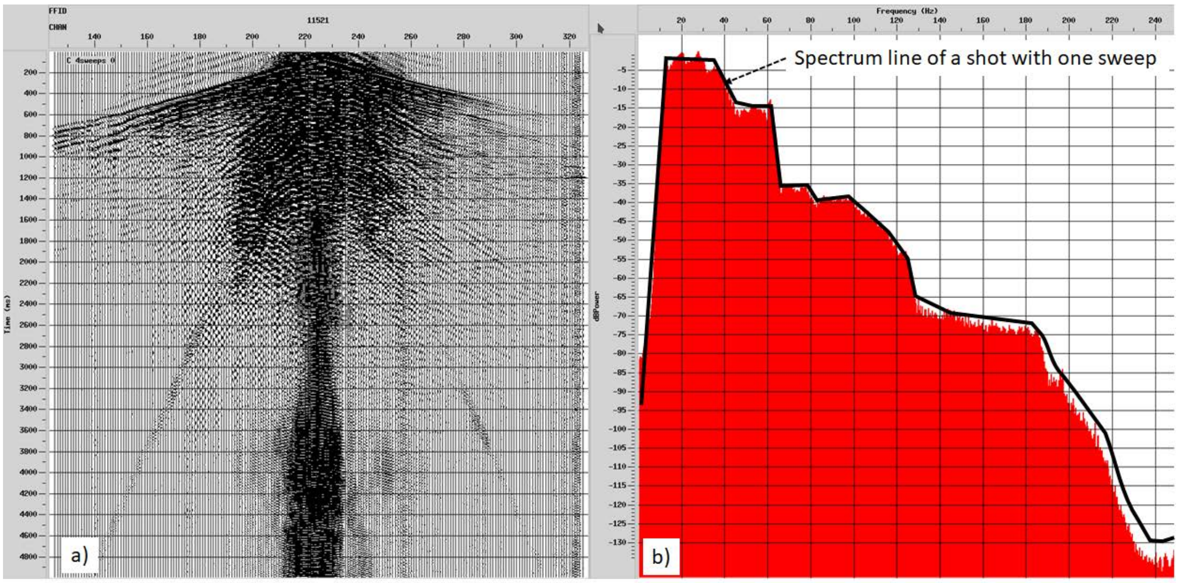
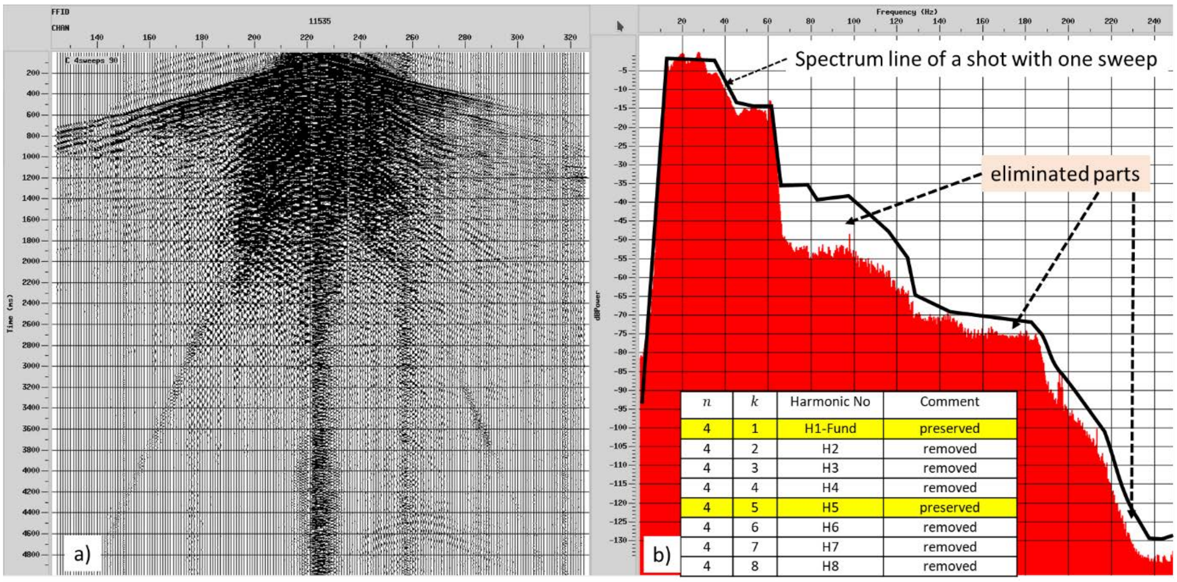


Figure-23: a) View of a 4-sweep shot with an initial phase angle of 0 degree, b) The power spectrum of this shot.



n	k	Harmonic No	Comment
4	1	H1-Fund	preserved
4	2	H2	removed
4	3	H3	removed
4	4	H4	removed
4	5	H5	preserved
4	6	H6	removed
4	7	H7	removed
4	8	H8	removed

Figure-24: a) View of a 4-sweep shot with the initial phase angles of 0, 90, 180 and 270 degrees, b) The power spectrum of this shot.

Fig.25 shows the difference between these two shots and the spectrum of the difference. Analysis of the shot difference shows that harmonic elimination is greater at receivers closer to the source. Harmonic elimination is higher at low frequencies and lower at high frequencies. Because this is the amplitude of the eliminated harmonic (H2) is larger than the others. Therefore, it is more dominant in the frequency domain.

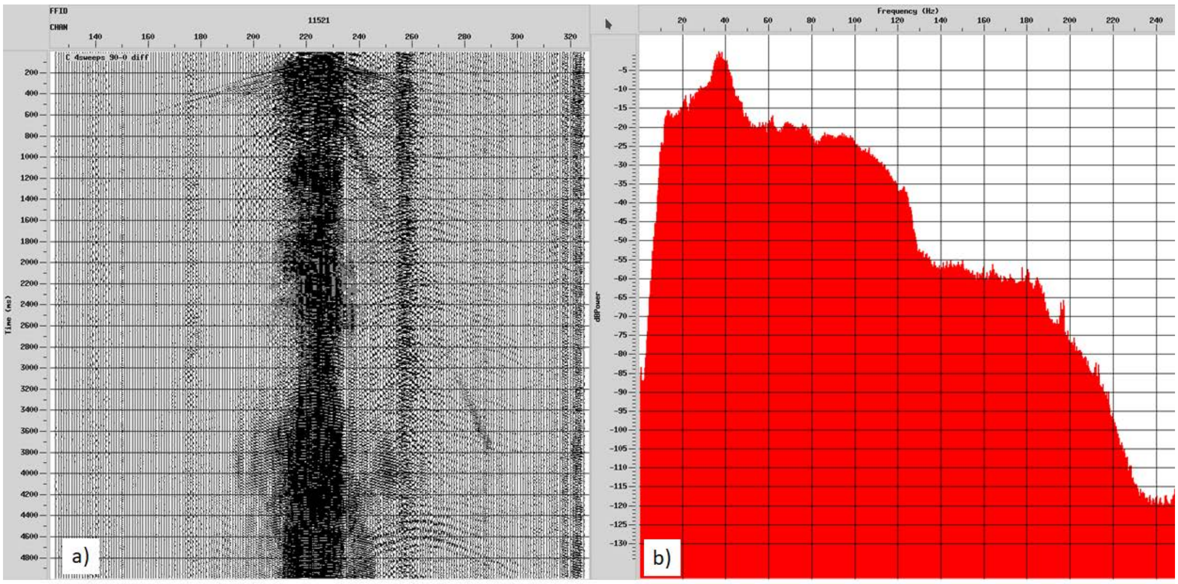


Figure-25: a) Difference between Fig. 23 and Fig. 24, b) The power spectrum of difference.

The case of data acquisition with five sweeps

If the number of sweeps is 5, the initial phase angle will be θ= 360/5=72 degrees as calculated by Eq.4. This will result in the elimination of some harmonics while others will be preserved. Substituting this information into

Eq.5 will yield the values presented in Table 5, which displays the eliminated and non-eliminated harmonics. As a result of the number of sweeps being 5 and the sweep initial phase angle being 72 degrees, H1 (fundamental), H6, H11, ... harmonics are preserved, while H2, H3, H4,H5, H7, H8, H9 and H10 harmonics are eliminated.

In the case of seismic data acquisition with 5 sweeps, the initial phase angle of the first sweep will be 0 degrees, the initial phase angle of the second sweep will be 72 degrees, the initial phase angle of the third sweep will be 144 degrees, the initial phase angle of the fourth sweep will be 216 degrees and the initial phase angle of the fifth sweep will be 288 degrees. In the first sweep, the initial phase angle of the harmonics will not change, while in the second sweep, the initial phase angle of the harmonics will be in multiples of 72 degrees, in the third sweep, the initial phase angle of the harmonics will be in multiples of 144 degrees, in the fourth sweep, the initial phase angle of the harmonics will be in multiples of 216 degrees and in the fifth sweep, the initial phase angle of the harmonics will be in multiples of 288 degrees. If the initial phase angles of these 5 sweeps are subtracted from their fundamental sweeps and harmonics and then these 5 sweeps are vertically stacked with each other, some harmonics will remove each other and the sum of the remaining ones will give the following GF signal.

GF is equal to the sum of the Fundamental sweep (H1) and the harmonics (H6, H11…). In this synthetic case study, harmonics up to H8 are taken for analysis (Fig.26a).

As seen in Eq.10, certain harmonics are eliminated while the non-eliminated harmonics form the GF. The GF signal is five times the sum of the non-eliminated fundamental and harmonics. The data in Eq.10 and Table 5 are obtained from Eq.5 according to 5 sweeps.

Table 5: Status of fundamental sweep and harmonics for five sweeps.

$GF(t,\theta) = 5\,(H1 + H6 + H11 + \cdots).$

According to Table 5, the GF is as follows;

$$GF(t,\theta) = 5\,(H1 + H6 + H11 + \cdots). \tag{9}$$

Eq.9 gives the harmonics that are not eliminated according to 5 sweeps and form the GF. Although the fundamental sweep (H1) and harmonics such as H6, H11, etc. are not eliminated, other harmonics are removed with five sweeps. The amplitude of the remaining fundamental sweeps and harmonics increased as the number of sweeps.

As seen in Table 5, since the initial phase angle of the first sweep is 0 degrees, the phases of the fundamental sweep and its harmonics after correlation are equal to 0 degrees. Since the initial phase of the 2nd sweep is 72 degrees, 72 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 3th sweep is 144 degrees, 144 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 4th sweep is 216 degrees, 216 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 5th sweep is 288 degrees, 288 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. After correlation, harmonics with opposite signs are eliminated, while harmonics with the same sign or same phase are vertically stacked on top of each other. Thus, some harmonics are eliminated (colored white) and some harmonics are not eliminated (colored yellow). The amplitudes of the non-eliminated harmonics and the fundamental sweep become five times (vector sum).

Fig.26a shows that certain harmonics are eliminated, while the remaining harmonics and fundamental sweep amplitudes are fivefold. The non-eliminated harmonics have higher frequencies but lower amplitudes compared to the previous harmonic. The H6 harmonic has a frequency six times that of the H1 fundamental sweep and H11 has a frequency eleven times that of the H1.

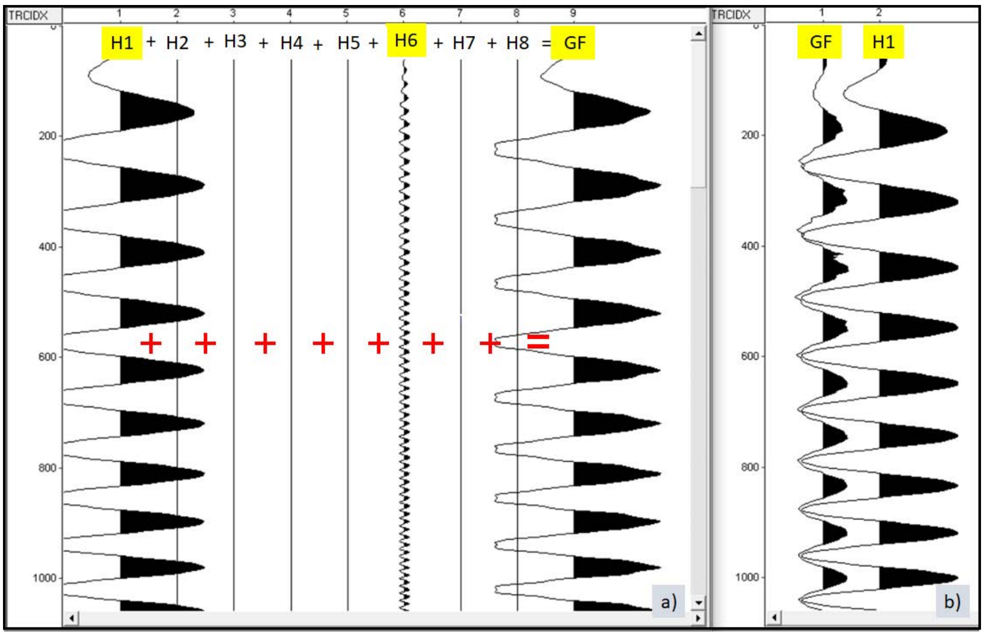


Figure-26: a) the part of synthetic fundamental sweep (H1), its harmonics (H6), and GF signal, b) the part of real fundamental sweep (H1) and GF signal.

Fig.26a shows the synthetic fundamental sweep, its one harmonic, and their sum (GF). The synthetic sweep is 6-32 Hz with a sweep length of 4 s. It was also applied to real data in the field with the same parameters (Fig.26b). Fig.26b shows the actual GF and Fundamental sweep (H1). These data were used for the analyses in Fig.27. Fig.26a and Fig.26b show 1.1 s of the 4 s sweep. For the analyses in Fig.27, all of this 4 s data was used.

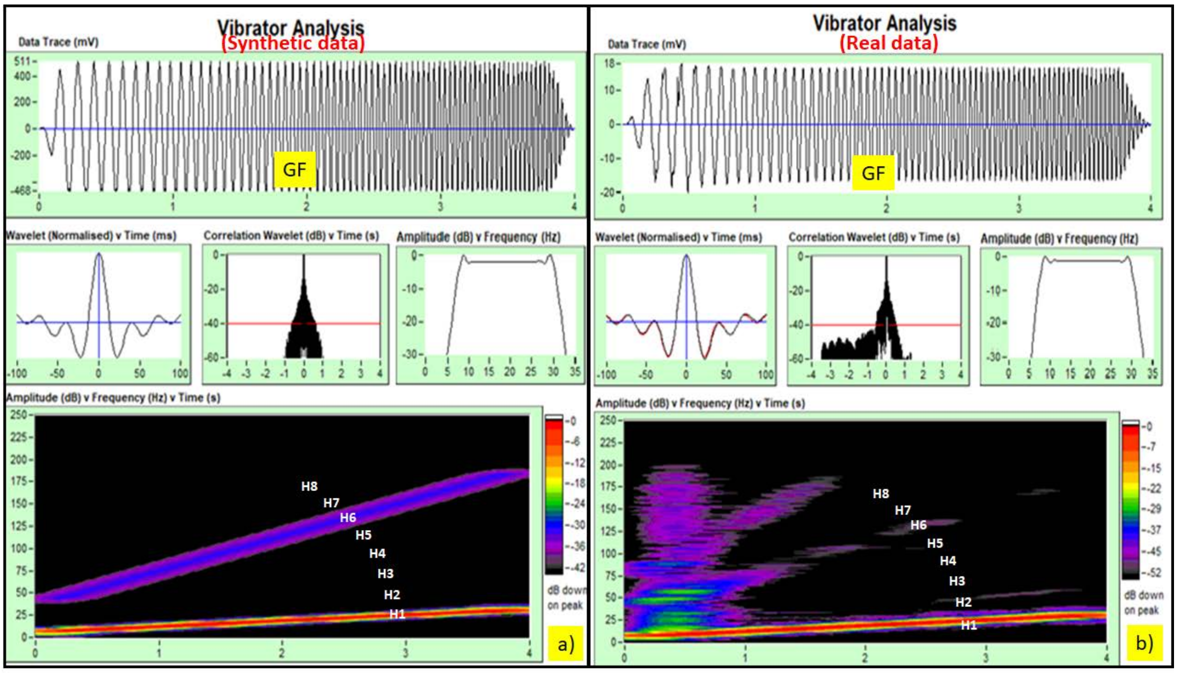


Figure-27: a) Analysis of synthetic fundamental sweep signal in Fig. 26a, b) Analysis of real fundamental sweep signal in Fig. 26b.

Fig.27 shows the analysis of the synthetic and real GF signals given in Fig.26a and Fig.26b. Fig.27a shows the synthetic GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. Fig.27b shows the real GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. When both synthetic and real data are analyzed in the Gabor transform, it is seen that some harmonics are eliminated. As in Table 5, it is also seen here that harmonics such as H2, H3, H4, H5, H7 and H8 are eliminated. It is also seen in both synthetic and real data analyses in Fig.27. The reduction in the harmonic level is seen in the normalized correlation wavelet (dB). Above the -40 dB level, the harmonic level decreases by a certain amount. This shows that some of the harmonics are eliminated.

Figs.28 and 29 show a real shots obtained in the field. In Fig.28, the recording parameters are 6-32 Hz, 5 sweeps, 8 s, and linear sweep. The initial phase angle of five sweeps are 0 degrees. In Fig.29, the initial phase angle of the first sweep is 0 degrees, the second sweep is 72 degrees, the third sweep is 144 degrees, the fourth sweep is 216 degrees and the fifth sweep is 288 degrees. After each sweep was recorded in the field, they were cross-correlated with their fundamental sweep and then stacked vertically in the time domain. As can be seen in the shot in Fig.28, all harmonics remain. In Fig.29, some harmonics are eliminated and some harmonics are not eliminated in accordance with Table 5. Fig.29 shows that this difference can be seen both in the shots and in the difference spectra.

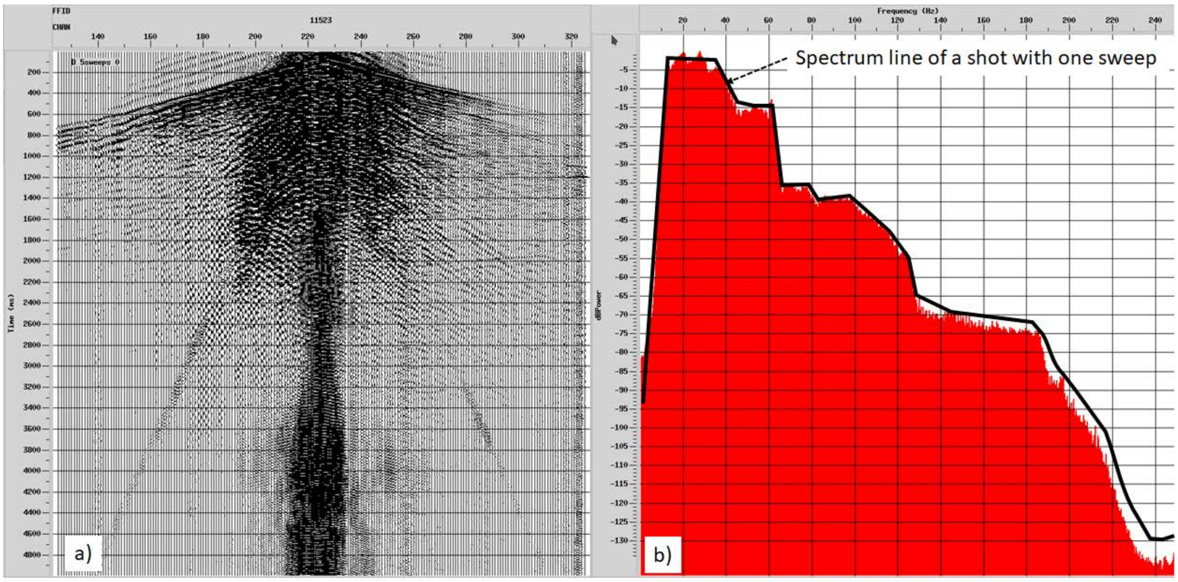
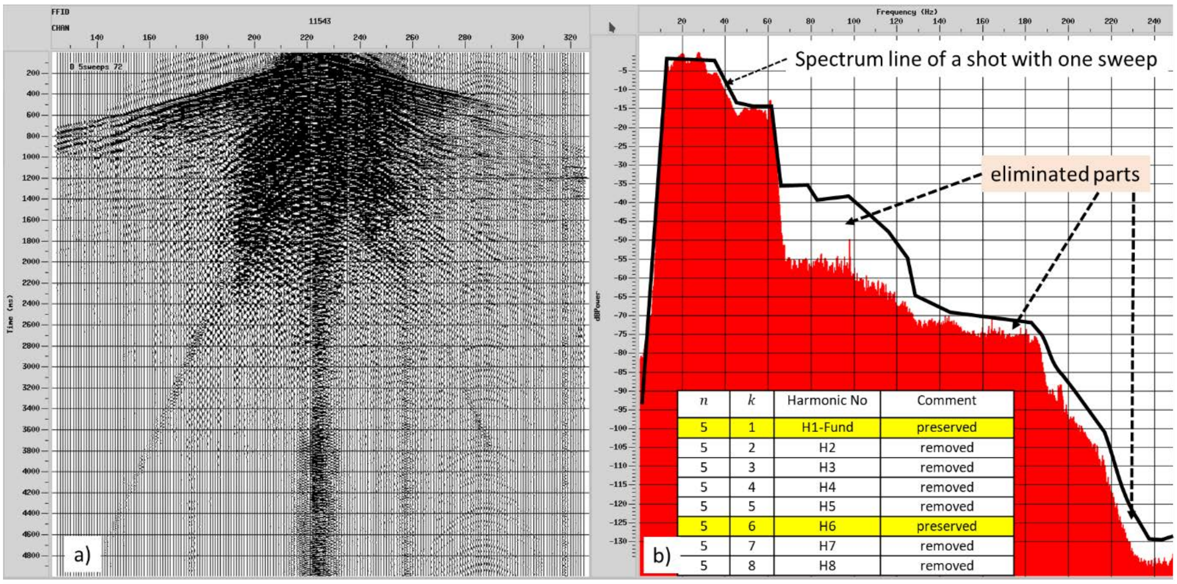


Figure-28: a) View of a 5-sweep shot with an initial phase angle of 0 degree, b) The power spectrum of this shot.



n	k	Harmonic No	Comment
5	1	H1-Fund	preserved
5	2	H2	removed
5	3	H3	removed
5	4	H4	removed
5	5	H5	removed
5	6	H6	preserved
5	7	H7	removed
5	8	H8	removed

Figure-29: a) View of a 5-sweep shot with the initial phase angles of 0, 72, 144, 216 and 288 degrees, b) The power spectrum of this shot.

Fig.30 shows the difference between these two shots and the spectrum of the difference. Analysis of the shot difference shows that harmonic elimination is greater at receivers closer to the source. Harmonic elimination is higher at low frequencies and lower at high frequencies. Because this is the amplitude of the eliminated harmonic (H2) is larger than the others. Therefore, it is more dominant in the frequency domain.

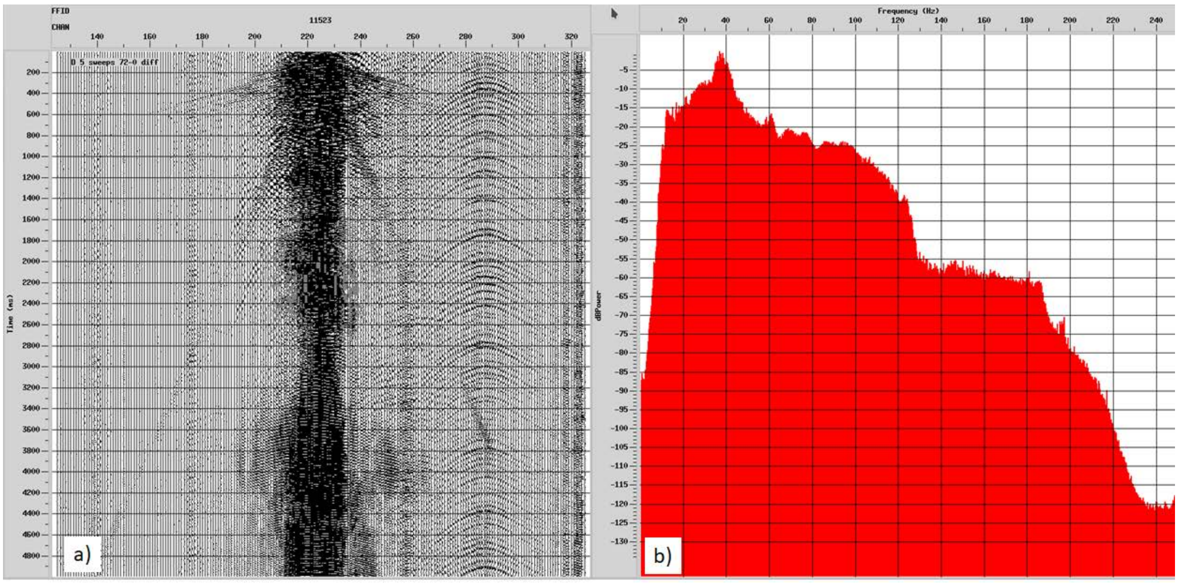


Figure-30: a) Difference between Fig. 28 and Fig. 29, b) The power spectrum of difference.

The case of data acquisition with six sweeps

If the number of sweeps is 6, the initial phase angle will be θ= 360/6=60 degrees as calculated by Eq.4. This will result in the elimination of some harmonics while others will be preserved. Substituting this information into Equation 5 will yield the values presented in Table 6, which displays the eliminated and non-eliminated harmonics. As a result of the number of sweeps being 6 and the sweep initial phase angle being 60 degrees, H1 (fundamental), H7, H13, ... harmonics are preserved, while H2, H3, H4,H5, H6, H8, H9, H10, H11 and H12 harmonics are eliminated.

In the case of seismic data acquisition with 6 sweeps, the initial phase angle of the first sweep will be 0 degrees, the initial phase angle of the second sweep will be 60 degrees, the initial phase angle of the third sweep will be 120 degrees, the initial phase angle of the fourth sweep will be 180 degrees, the initial phase angle of the fifth sweep will be 240 degrees and the initial phase angle of the sixth sweep will be 300 degrees. In the first sweep, the initial phase angle of the harmonics will not change, while in the second sweep, the initial phase angle of the harmonics will be in multiples of 60 degrees, in the third sweep, the initial phase angle of the harmonics will be in multiples of 120 degrees, in the fourth sweep, the initial phase angle of the harmonics will be in multiples of 180 degrees, in the fifth sweep, the initial phase angle of the harmonics will be in multiples of 240 degrees and in the sixth sweep, the initial phase angle of the harmonics will be in multiples of 300 degrees. If the initial phase angles of these 6 sweeps are subtracted from their fundamental sweeps and harmonics and then these 6 sweeps are vertically stacked with each other, some harmonics will remove each other and the sum of the remaining ones will give the following GF signal.

GF is equal to the sum of the Fundamental sweep (H1) and the harmonics (H7, H13…). In this synthetic case study, harmonics up to H8 are taken for analysis (Fig.31a).

As seen in Eq.11, certain harmonics are eliminated while the non-eliminated harmonics form the GF. The GF signal is six times the sum of the non-eliminated fundamental and harmonics. The data in Eq.11 and Table 6 are obtained from Eq.5 according to 6 sweeps.

Table 6: Status of fundamental sweep and harmonics for six sweeps.

$GF(t,\theta) = 6\,(H1 + H7 + \cdots).$

According to Table 6, the GF is as follows;

$$GF(t,\theta) = 6\,(H1 + H7 + \cdots). \qquad (10)$$

Eq.10 gives the harmonics that are not eliminated according to 6 sweeps and form the GF. Although the fundamental sweep (H1) and harmonics such as H7, etc. are not eliminated, other harmonics are removed with six sweeps. The amplitude of the remaining fundamental sweeps and harmonics increased as the number of sweeps.

As seen in Table 6, since the initial phase angle of the first sweep is 0 degrees, the phases of the fundamental sweep and its harmonics after correlation are equal to 0 degrees. Since the initial phase of the 2nd sweep is 60 degrees, 60 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 3th sweep is 120 degrees, 120 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 4th sweep is 180 degrees, 180 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 5th sweep is 240 degrees, 240 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation. Since the initial phase of the 6th sweep is 300 degrees, 300 degrees are subtracted from the fundamental sweep and harmonics by the cross-correlation . After correlation, harmonics with opposite signs are eliminated, while harmonics with the same sign or same phase are vertically stacked on top of each other. Thus, some harmonics are eliminated (colored white) and some harmonics are not eliminated (colored yellow). The amplitudes of the non-eliminated harmonics and the fundamental sweep become six times (vector sum).

Fig.31a shows that certain harmonics are eliminated, while the remaining harmonics and fundamental sweep amplitudes are by a factor of six. The non-eliminated harmonics have higher frequencies but lower amplitudes compared to the previous harmonic. The H7 harmonic has a frequency seven times that of the H1 fundamental sweep.

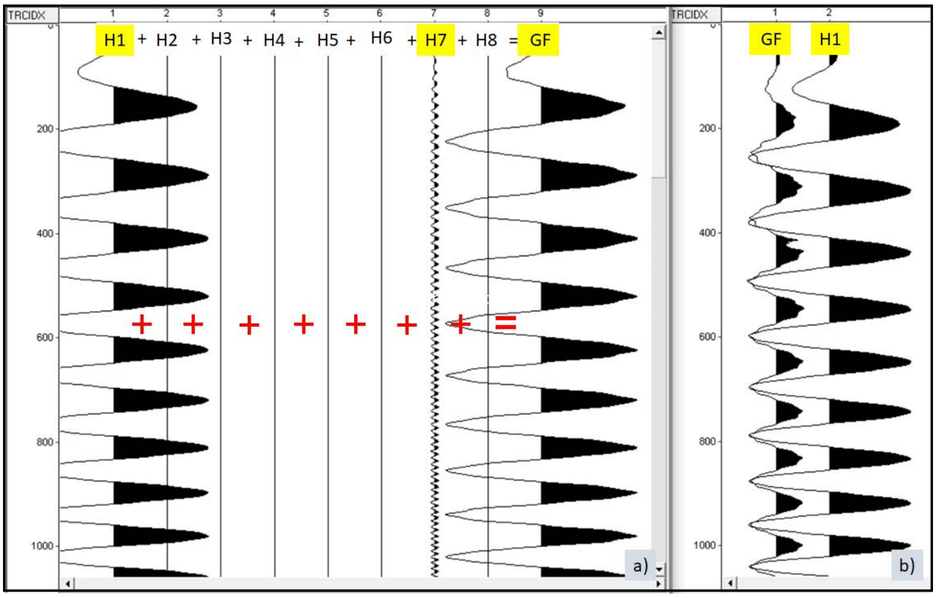


Figure-31: a) the part of synthetic fundamental sweep (H1), its harmonics (H7), and GF signal, b) the part of real fundamental sweep (H1) and GF signal.

Fig.31a shows the synthetic fundamental sweep, its harmonic, and their sum (GF). The synthetic sweep is 6-32 Hz with a sweep length of 4 s. It was also applied to real data in the field with the same parameters (Fig.31b). Fig.31b shows the actual GF and Fundamental sweep (H1). These data were used for the analyses in Fig.32. Fig.31a and Fig.31b show 1.1 s of the 4 s sweep. For the analyses in Fig.32, all of this 4 s data was used.

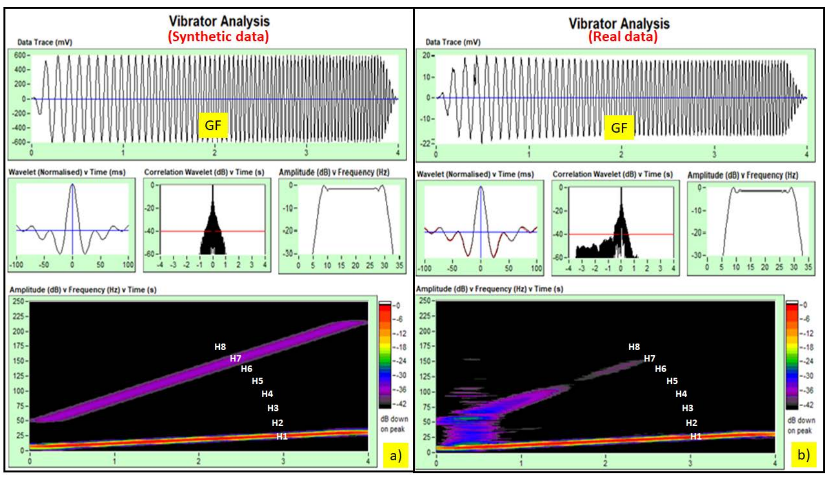


Figure-32: a) Analysis of synthetic fundamental sweep signal in Fig. 31a, b) Analysis of real fundamental sweep signal in Fig. 31b.

Fig.32 shows the analysis of the synthetic and real GF signals given in Fig.31a and Fig.31b. Fig.32a shows the synthetic GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. Fig.32b shows the real GF signal at the top, the normalized correlation wavelet (in time), the normalized correlation wavelet (in dB), the power spectrum and the Gabor transform at the bottom. When both synthetic and real data are analyzed in the Gabor transform, it is seen that some harmonics are eliminated. As in Table 6, it is also seen here that harmonics such as H2, H3, H4, H5 and H8 are eliminated. It is also seen in both synthetic and real data analyses in Fig.32. The reduction in the harmonic level is seen in the normalized correlation wavelet (dB). Above the -40 dB level, the harmonic level decreases by a certain amount. This shows that some of the harmonics are eliminated.

Figs.33 and 34 show a real shots obtained in the field. In Fig.33, the recording parameters are 6-32 Hz, 6 sweeps, 8 s, and linear sweep. The initial phase angle of six sweeps are 0 degrees. In Fig.34, the initial phase angle of the first sweep is 0 degrees, the second sweep is 60 degrees, the third sweep is 120 degrees, the fourth sweep is 180 degrees, the fifth sweep is 240 degrees and the sixth sweep is 300 degrees. After each sweep was recorded in the field, they were cross-correlated with their fundamental sweep and then stacked vertically in the time domain. As can be seen in the shot in Fig.33, all harmonics remain. In Fig.34, some harmonics are eliminated and some harmonics are not eliminated in accordance with Table 6. Fig.34 shows that this difference can be seen both in the shots and in the difference spectra.

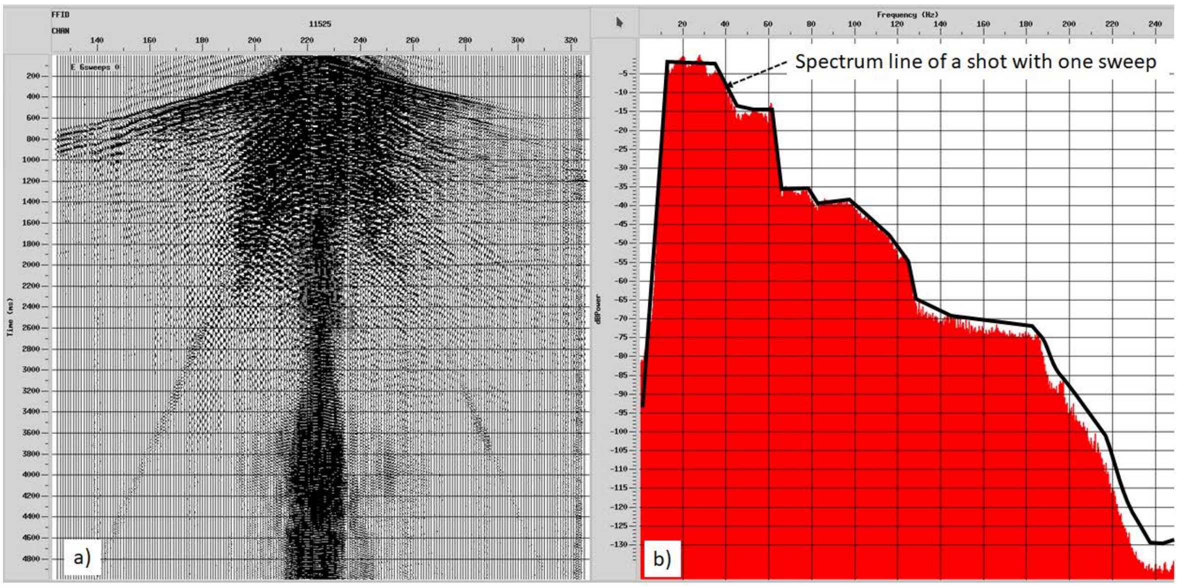


Figure-33: a) View of a 6-sweep shot with an initial phase angle of 0 degree, b) The power spectrum of this shot.

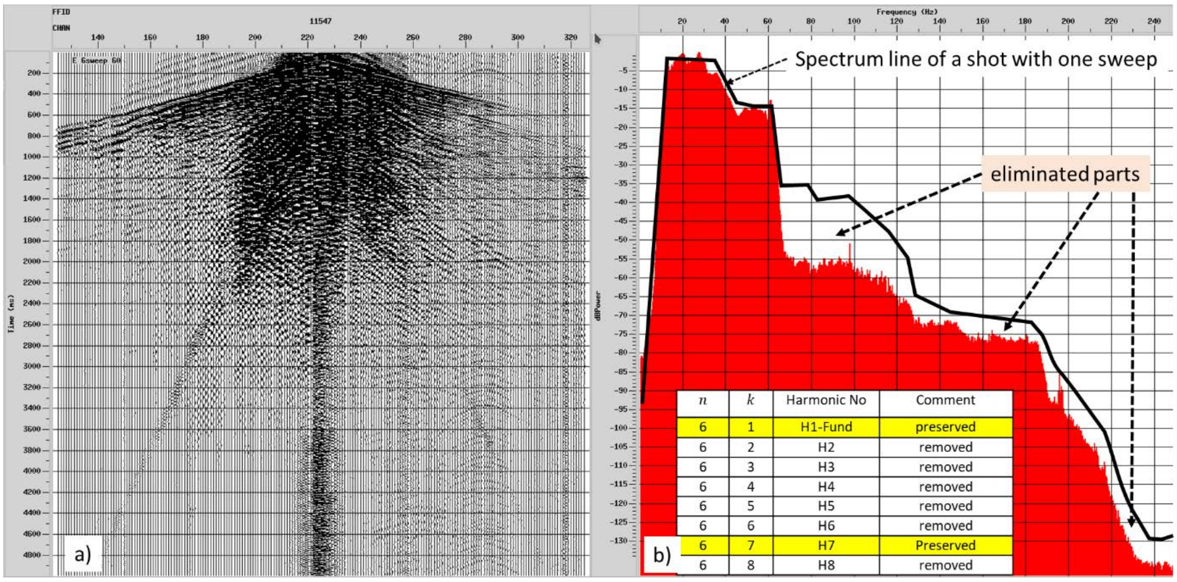


Figure-34: a) View of a 6-sweep shot with the initial phase angles of 0, 60, 120, 180, 240 and 300 degrees, b) The power spectrum of this shot.

Fig.35 shows the difference between these two shots and the spectrum of the difference. Analysis of the shot difference shows that harmonic elimination is greater at receivers closer to the source. Harmonic elimination is higher at low frequencies and lower at high frequencies. Because this is the amplitude of the eliminated harmonic (H2) is larger than the others. Therefore, it is more dominant in the frequency domain.

$GF(t,\theta) = 2\ (H1 + H3 + H5 + H7 + H9 + H11 + \cdots)$

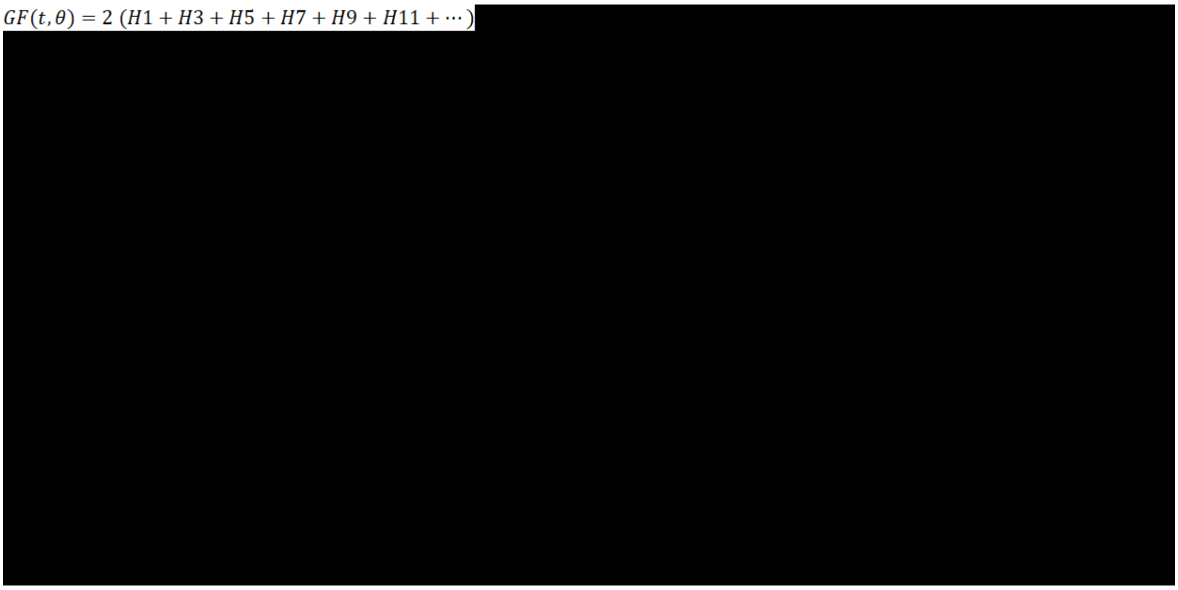


Figure-35: a) Difference between Fig. 33 and Fig. 34, b) The power spectrum of difference.

Generalization of the Harmonic Elimination Relationship with Sweep Numbers

When Eq.5, Eq.6, Eq.7, Eq.8, Eq.9 and Eq.10 are rewritten;

$$GF(t,\theta) = 1\ (H1 + H2 + H3 + \cdots + Hk)$$

$$GF(t,\theta) = 2\ (H1 + H3 + H5 + H7 + H9 + H11 + \cdots)$$

$$GF(t,\theta) = 3\ (H1 + H4 + H7 + H10 + \cdots)$$

$$GF(t,\theta) = 4\ (H1 + H5 + H9 + \cdots)$$

$$GF(t,\theta) = 5\ (H1 + H6 + H11 + \cdots)$$

$$GF(t,\theta) = 6\ (H1 + H7 + \cdots)$$

The generalized formulation of the above formulas in compact form is as follows.

$$\mathrm{GF}(\mathrm{t},\theta) = \quad n * \sum_{k=n*(m-1)+1}^{\infty} \sum_{i=1}^{n} S_k[t,(i-1)*k*\theta] \qquad 11$$

where,

n: number of sweep

m: 1, 2, 3, 4, …

k: the preserved harmonic number

θ= 360/n, the sweep initial phase angle.

Eq.11 is the most general equation that gives the relationship between the number of sweeps and the number of non-eliminated harmonics.

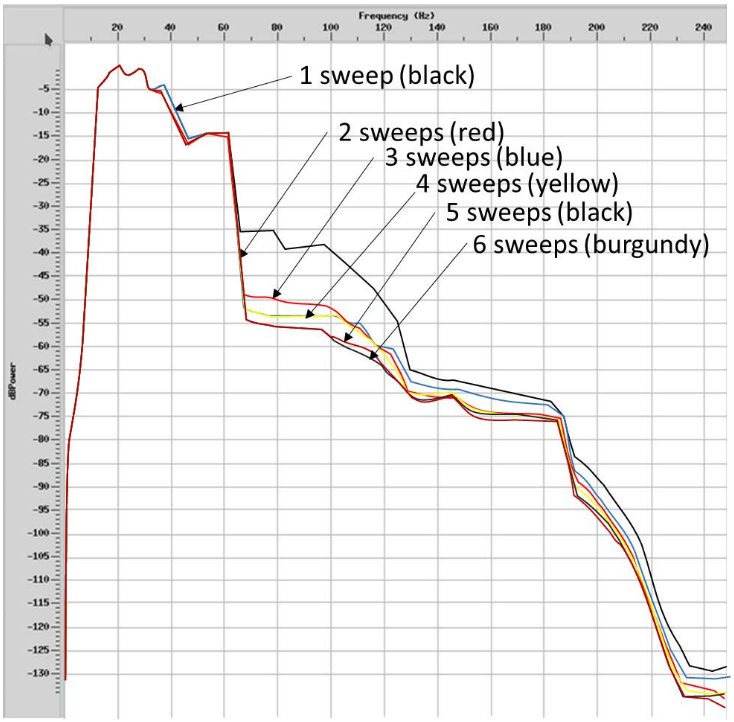


Figure-36: Graphic for harmonics elimination by sweep number.

Fig.36 shows harmonics elimination in relation to sweep number. The graph illustrates that elimination is more effective at lower frequencies, with a decrease in harmonic elimination as frequency increases. As the harmonic order increases, its frequency also increases. On the other hand, harmonic amplitudes decrease.

FIELD DATA APPLICATION

Acquisition flow:

In 2023, Arar Petrol AS/RR Sismik Mühendislik AŞ had seismic data acquired in the field for harmonic analysis. The survey consisted of 200 shot points and 500 receiver groups spaced every 20 meters. A linear 8-second long sweep signal of 8-48 Hz was recorded every 20 meters in the Eastern Adana region of Turkey.

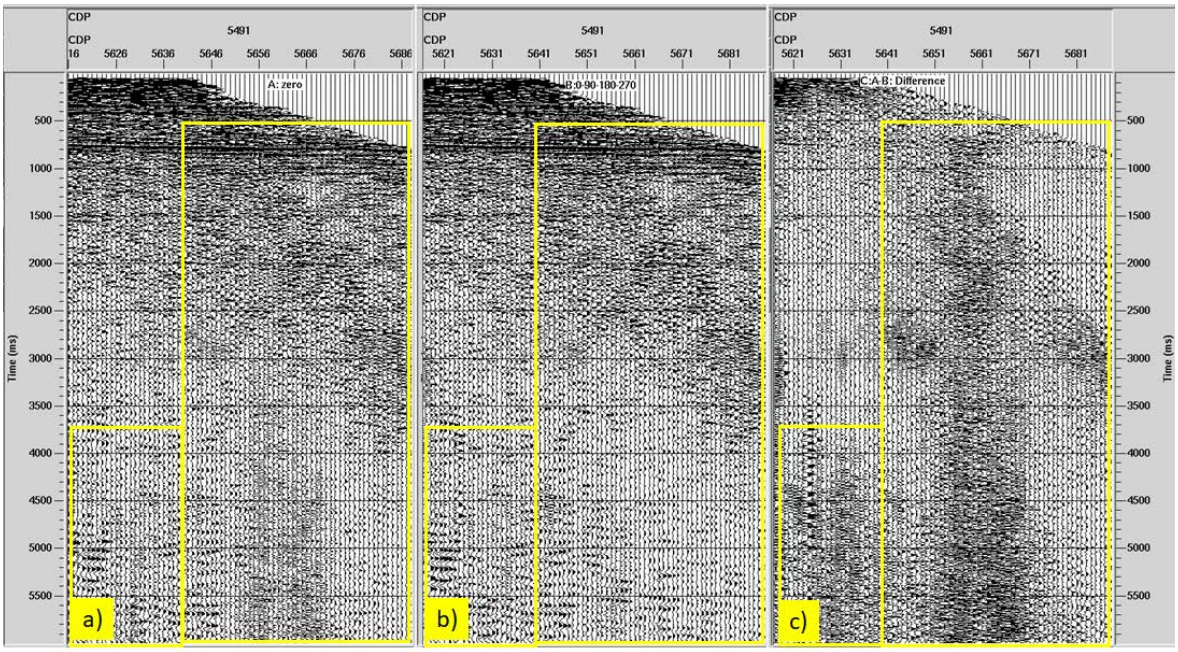


Figure-37: a) View of a 4-sweep stack with an initial phase angle of 0 degree, b) View of a 4 sweeps stack with the initial phase angles of 0, 90, 180 and 270 degrees, c) Difference between Fig.37a and Fig.37b.

Harmonic elimination was tested on the processed sections using data acquired with 4 sweeps. Fig.37a shows the results of the 4 sweeps with zero phases. Fig.37b also shows the results of 4 sweeps but with the initial phases of 0, 90, 180, and 270 degrees. Some harmonics (H2, H3, H4, H6, H7, H8, ...) were eliminated, while the fundamental and some harmonics (H1, H5, H9) were not removed. Fig.37c illustrates the difference between these two sections. As can be observed in the difference section, the harmonics have been significantly reduced (yellow box). After the elimination of harmonics, the seismic section is clearer in Fig.37b (yellow box).

CONCLUSIONS

Harmonics generated by the vibrator are conventionally considered as noise to be removed from the sweeps and data/field records during the seismic data acquisition and processing phases.

In this paper, we established the relationship between the number of sweeps and the non-eliminated harmonics as a function of the sweep numbers, in compact form for the general cases. When fewer sweeps are used, fewer harmonics are eliminated. To eliminate more harmonics, it is necessary to produce more sweeps at different angles.

A hardware similarity test is performed in the field initially. The number of sweeps is then selected to eliminate strong harmonics based on the test results.

As the number of sweeps increases, more harmonics are eliminated, resulting in a GF signal that approaches an ideal signal.

If the initial phase angles are consistently 0 degrees or the same angle, the signal-to-noise (S/N) ratio increases as the number of sweeps increases. However, all harmonics remain in the recordings (see Figs. 10, 13, 18, 23, 28, and 33).

When analyzing the amplitudes of non-eliminated harmonics, it is observed that there are greater amplitude losses in the high-frequency parts of these harmonics.

For high-resolution seismic, high frequencies are used, resulting in a low number of harmonics and a very high-frequency content. Therefore, a low sweep number is sufficient for harmonic elimination.

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REFERENCES

Abd El-Aal, A. E. K. (2010), Eliminating Upper Harmonic Noise in Vibroseis Data via Numerical Simulation, Geophys. J. Int. (2010) 181, 1499–1509. doi: 10.1111/j.1365-246X.2010.04594.x.

Andersen, K.D. (1995), Method for Cascading Sweeps for A Seismic Vibrator, U.S. patent, 4 410 517.

Babaia, F., Mender, M., and Benchabana, C. (2012), Vibroseis Harmonic Noise Cancelling by Time Varying Filtering with Reference, Kuala Lumpur 2012 World Gas Conference.

Baobin, W., Hequn, L., Bo, Z., Zhi, H., Mugang, Z., and Lulu, M. (2012), Cross-Harmonic

Noise Removal on Slip-Sweep Vibroseis Data. SEG Technical Program Expanded Abstracts, 48. 1-5. DOI: 10.1190/segam2012-0059.1.

Benabentos, M., Ortigosa, F., Moldoveanu, N., and Munoz, P. (2006), Cascaded Sweeps - A Method to Improve Vibroseis Acquisition Efficiency: A Field Test, The Leading Edge June (693-697).

Dal Moro, G., Scholtz, P. and Iranpour, K. (2007), Harmonic Noise Attenuation for Vibroseis Data, GNGTS – 26. C. Nazionale.

Eisner, E. (1974), Method for Determining Optimum Seismic Pulse, US Patent. 3,815,704.

Espey, H., R. (1988), Attenuation of Vibrator Harmonic Ghosts, ASEG/SEG Conference-ADELAIDE.

Gureli, O., 2021. Use of Vibrator Harmonics as A Sweep Signal, Journal Of Seismic Exploration 30, 505-528.

Harrison, C. B., Margrave, G., Lamoureux, M., Siewert, A., Barrett, A. (2011), Harmonic Decomposition of Vibroseis Sweeps Using Gabor Analysis, CREWES Research Report 2011.

Harrison, C.B., Margrave, G., Lamoureux, M., Siewert, A., Barrett, A., and Isaac, L. H. (2012), Towards Using Harmonic “Contamination” as Signal for Thin Reflectors, CREWES Research Report-Vol: 24.

Harrison, C.B., Margrave, G., Lamoureux, M., Siewert, A., and Barrett, A. (2013), Harmonic Decomposition of a Vibroseis Sweep Using Gabor Analysis, AAPG Datapages/Search and Discovery Article #90174, Calgary, AB, Canada.

Iranpour, K. (2010), Harmonic Attenuation Using Multiple Sweep Rates, U.S. patent, 0 085 837.

Jianjun,X., Jie, Y., Yong, G., and Xiling, C. (2012), Suppressing Harmonics Based on Singular Value Decomposition in Time Frequency Domain, SEG Technical Program Expanded Abstracts, 1052-3812, DOI http://dx.doi.org/10.1190/segam2012-0119.1.

Lebedev, A. V., and Beresnev, I. A. (2004), Nonlinear Distortions of Signals Radiated by Vibroseis Sources, Geophysics 69(4): 968-977.

Li, X. P. (1997), Decomposition of Vibroseis Data by the Multiple Filter Technique. Geophysics 62(3): 980-991.

Li, X. P., Sollner, W., and Hubral, P. (1995), Elimination of Harmonic Distortion in Vibroseis Data, Geophysics 60(2): 503-516.

Martin, F.D. and Munoz, P.A. (2010), Deharmonics, a Method for Harmonic Noise Removal on Vibroseis Data. Expanded Abstracts, 72nd EAGE Conference & Exhibition, 5 pages.

Martin, J. E. (1993), Simultaneous Vibroseis Recording, Geophysical Prospecting 41: 943-967.

Martin, J. E., White, R.E. (1989), Two Methods for Continuous Monitoring of Harmonic Distortion in Vibroseis Signals, Geophysical Prospecting 37: 851-872.

Meunier, J. & Bianchi T. (2002), Harmonic noise reduction opens the way for array size reduction in vibroseis operations, SEG Technical Program Expanded Abstracts 70–73.

Moerig, R., Barr, F.J., Nyland, D.L., and Sitton, G. (2004), Method of Using Cascaded Sweeps for Source Coding and Harmonic Cancellation, U. Patent. US. 6,687,619.

Okaya, A. D., Karageorgi, E., McEvilly, T. V., and Malin, P. E. (1992), Removing Vibrator Induced Correlation Artifacts by Filtering in Frequency-Uncorrelated Time Space.

Geophysics 57: 916-926.

Polom, U. (1997), Elimination of Source-Generated Noise from Correlated Vibroseis Data (the 'Ghost-Sweep' Problem), Geophysical Prospecting 45: 571-591.

Rietsch, E. (1981), Reduction of Harmonic Distortion in Vibratory Source Records, Geophysical Prospecting 29: 178-188.

Schrodt, J. K. (1987), Techniques for Improving Vibroseis Data, Geophysics 52: 469-482.

Sercel (1999), VE432 Training Course Manuel, Chapter: 8, 6-1,6-10.

Seriff, A.J. and Kim, W.H. (1970), The Effect of Harmonic Distortion in The Use of Vibratory Surface Sources, Geophysics 35(2), 234–246.

Sharma, S. P., Tildy, P., Iranpour, K., and Scholtz, P. (2009), Attenuation of Harmonic Noise in Vibroseis Data Using Simulated Annealing, Geophysical Research Abstracts, Vol. 11, EGU2009-8693.

Sicking, C., Fleure, T., Nelan, S., and McLain, B. (2009), Slip Sweep Harmonic Noise Rejection on Correlated Shot Data, SEG, 28. 36-40., DOI: 10.1190/1.3255636.

Sorkin, S. A. (1972), Sweep Signal Seismic Exploration, U.S. Patent. 3,786,409.

Walker, D. (1995), Harmonic Resonance Structure and Chaotic Dynamics in The Earth-Vibrator System, Geophysical Prospecting 43: 487-507.

Wei, Z., and Hall, M.A. (2011), Analyses of Vibrator and Geophone Behavior on Hard and Soft Ground, The Leading Edge Feb: 132-137.

Wei, Z., T. F. Phillips, and M. A.H. (2010), Fundamental Discussions on Seismic Vibrators, Geophysics, 75, no. 6, W13–W25. http://dx.doi.org/10.1190/1.3509162.

Wei, Z., Sallas, J.J., Crowell, J.M. and Teske, J.E. (2007), Harmonic Distortion Reduction on Vibrators – Suppressing the Supply Pressure Ripples, SEG conference, Expanded Abstract 26(1), 51–55.

Wuxiang, C. (2010), To Attenuate Harmonic Distortion by the Force Signal of Vibrator, SEG, Denver, Annual Meeting.

Yongsheng, S., Changhui, W., Mugang, Z., Xuefeng, Z., Zhenchun, L., Fenglei, L., and Lieqian, D. (2011), A Method for Harmonic Noise Elimination in Slip Sweep Data, SEG Technical Program Expanded Abstracts, 30. 10.1190/1.3627600.