

Effects of source mismatch on multipole Logging

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Abstract

The effects of mismatched multipole sources were investigated. Multipole sources considered here are those that they are constructed of monopoles with appropriate sign combination. To simulate mismatched dipole and quadrupole sources, we made the amplitude of one of monopoles smaller than those of the other monopoles. The dipole and quadrupole component were obtained with four monopole receiver array system by subtracting or adding appropriate responses. Mismatched dipole source excites nondipole modes in addition to the flexural mode. The strongest of these is the Stoneley mode, whose amplitude increases with increasing mismatch. Similarly, mismatched quadrupole sources produce nonquadrupole modes such as the Stoneley mode in addition to the screw mode. The amplitude of the Stoneley mode increases with mismatch. However, we can obtain the flexural mode by A-C and the screw mode by A-B+C-D processing, respectively. The Stoneley mode, which has the same amplitude at the same radial position from the borehole axis, is cancelled out by A-C and A-B+C-D processing as long as the tool is placed at the center of the borehole.

1 Introduction

In full waveform logging, multipole sources were proposed and developed to overcome monopole source's failing to measure the shear velocity of the slow formation. In addition, we can obtain the anisotropy properties of the formation with cross dipole source system, where two dipole sources are implemented at right angles.

A dipole source is usually realized by using a bender element or a movable cylinder in a wireline tool. However, the dipole source of Logging-While-Drilling (LWD) tool is constructed of two monopoles of opposite polarity for allowing the conduit of the mud at the center of the tool. Similarly, the quadrupole source of LWD is implemented using four monopoles of alternate sign positioned at right angles to each other. To make an ideal multipole source, the amplitudes and phases of monopoles, which construct a multipole source, should be the same. In reality, these monopoles' amplitudes and phases are only approximately equal. This mismatch in the amplitudes and the phases of the monopoles in the multipole source can lead to additional complex wavefields in the recorded logs. It is thus important to characterize the response of mismatched multipole sources.

In this paper, we investigate the acoustic fields produced and recorded by mismatched dipole and quadrupole sources. We examine the cases of mismatched amplitudes and the mismatched phases separately. We computed the response of multipole source by discrete wavenumber method (Cheng and Toksöz, 1981; Tubman et al., 1984; Schmitt and Bouchon, 1985). To simulate mismatched dipole and quadrupole sources, we used multipole sources which are constructed of monopoles with appropriate signs. In addition, we used four monopole receiver array system and synthesized dipole or quadrupole component by addition or subtraction of their responses (Byun and Toksöz, 2003).

2 Theory and Approach

In this study, the dipole source is constructed of two point sources of opposite sign (Figure 1a) and quadrupole source is constructed of four point sources of alternate sign at right angles to each other (Figure 1b). Four monopole receiver array system was used. If we designate responses at receiver arrays as A, B, C, and D depending on their locations associated with point sources as shown in Figure 1, the dipole component was obtained by A-C and the quadrupole component by A-B+C-D, respectively.

The response at each receiver array due to a dipole or a quadrupole source was calculated based on the response due to an off-centered point source. For example, in the case of a dipole source, the response of one receiver array was calculated by combining the response due to the positive point source of the dipole source and the response due to the negative point source of the dipole source. During calculation, the

different amplitudes were used for the positive point source and the negative one to simulate the mismatched dipole source.

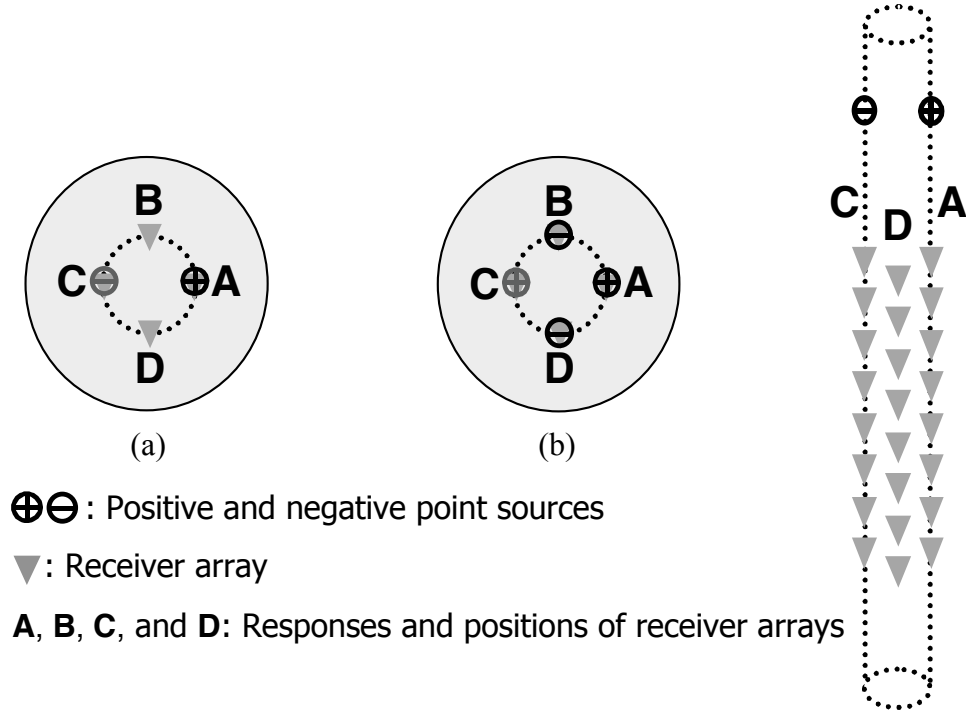


Figure 1: The configuration of the source-receiver assembly used in the numerical modeling.

When a point source is placed from the axis of borehole, the incident potential can be written in terms of waves at the origin in the cylindrical coordinates (Tadeu, 1992):

$$\varphi_{inc}(\varphi, r, \varphi, k_z) = \frac{iA}{2} \sum_{n=0}^{\infty} (\varphi 1)^n \varphi_n H_n^{(2)}(k_{\varphi} r_0) J_n(k_{\varphi} r) \cos(n\varphi) \quad (1)$$

when $r < r_0$

$$\varphi_{inc}(\varphi, r, \varphi, k_z) = \frac{iA}{2} \sum_{n=0}^{\infty} (\varphi 1)^n \varphi_n H_n^{(2)}(k_{\varphi} r) J_n(k_{\varphi} r_0) \cos(n\varphi) \quad (2)$$

when $r > r_0$

where the $J_n(\varphi)$ are Bessel functions of order n , φ is the azimuth, and

$$\varphi_n = \begin{cases} 1 & \text{if } n = 0 \\ 2 & \text{if } n \neq 0 \end{cases}$$

$r = \sqrt{x^2 + y^2}$ is the radial distance to the receiver,

r_0 is the radial distance from the cylindrical axis to the source, and

$\cos \varphi = x/r$, $\sin \varphi = y/r$.

In the (φ, k_z) domain, the scattered field in the fluid can be expressed as

$$\varphi_{sca}^f(\varphi, r, \vartheta, k_z) = \sum_{n=0} D_n J_n(k_{\vartheta_f} r) \cos(n\varphi) \quad (3)$$

where index f indicates the fluid, and

$$k_{\vartheta_f} = \sqrt{\frac{\vartheta^2}{\vartheta_f^2} - k_z^2}.$$

D_n is also determined from boundary conditions. The total field inside the borehole fluid is the sum of the incident field and the scattered field in the fluid:

$$\varphi_{tot} = \varphi_{inc} + \varphi_{sca}^f \quad (4)$$

3 Numerical modeling results

The effects of the mismatch in a multipole source were examined for both slow and fast formations. Table 1 shows the material properties used in the numerical simulations.

Table 1. Model parameters used in the simulations of mismatched multipole sources.

	Soft formation	Hard formation
$V_{p,fluid} \text{ (m/s)}$	1500	1500
$\rho_{fluid} \text{ (g/cm}^3\text{)}$	1.0	1.0
$V_{p,formation} \text{ (m/s)}$	2000	4210
$V_{s,formation} \text{ (m/s)}$	1000	2655
$\rho_{formation} \text{ (g/cm}^3\text{)}$	2.0	2.14

For the source, we used Ricker wavelets with center frequencies of 1.5, 8 kHz for dipole sources and 4, 8 kHz for quadrupole sources. Each receiver array had eight receivers spaced in 0.1524 m. The distance between source and the first receiver was 2.44 m. The diameter of the borehole was 0.2 m.

3.1 Mismatch in a dipole source

Figure 2 shows the change in the response at receiver array A as the mismatch amount varies 0.5, 1, 2, 5, 10, 20, and 50% in a dipole source. The formation was a slow formation. The mismatch amount 0% means an ideal dipole source. In the case of an ideal dipole source, only flexural ($n=1$) mode is present. Refracted P waves also exist, but they do not show clearly in the figure because of their small amplitudes. If the amplitudes of the monopoles in the dipole source are different, modes other than flexural mode are also excited.

The contaminations by the nondipole ($n \neq 1$) modes are shown more clearly in the frequency spectrum of the response A (Figure 3). Frequency spectrums of eight receivers in the array are depicted together in each figure panel. As shown in Figure 3, the Stoneley ($n=0$) mode energy already appears at low frequency region for 1 % mismatch. The Stoneley mode becomes more dominant with increasing the mismatch amount. Finally the Stoneley mode is more dominant than the flexural mode in 20% mismatch. The responses of the receiver array C have the similar patterns.

In practice, when a tool has four receiver array system, we acquire the dipole mode by subtracting the response C from A (A-C). The frequency spectrums of A-C are displayed in Figure 4. As shown in the figure, the flexural mode is dominant even in the 50% mismatch. For given source frequency and geometry, the mismatched dipole source yields the nondipole modes, and the Stoneley mode is the strongest among

the other modes. However, the amplitude of the Stoneley mode is the same at the same radial distance from the borehole axis. Thus, it is cancelled out by A-C processing.

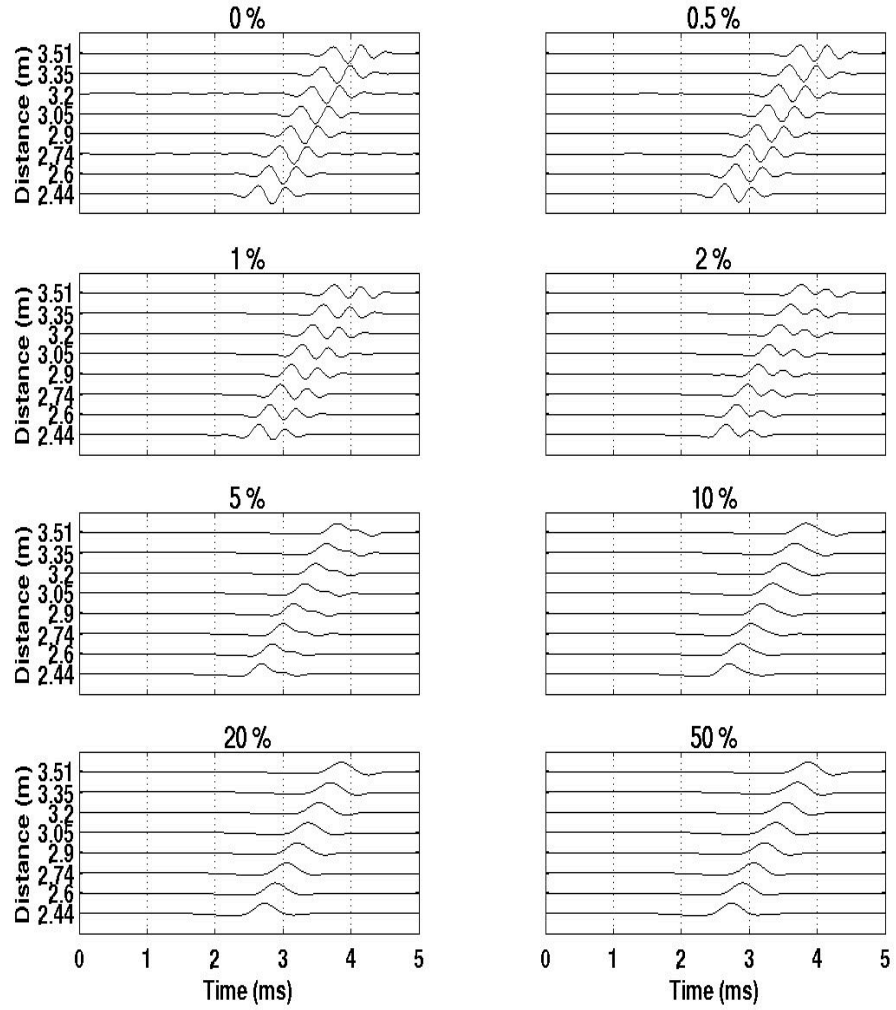


Figure 2: The change in the waveforms of the responses at the receiver array A with increasing the amount of the mismatch for a dipole source.

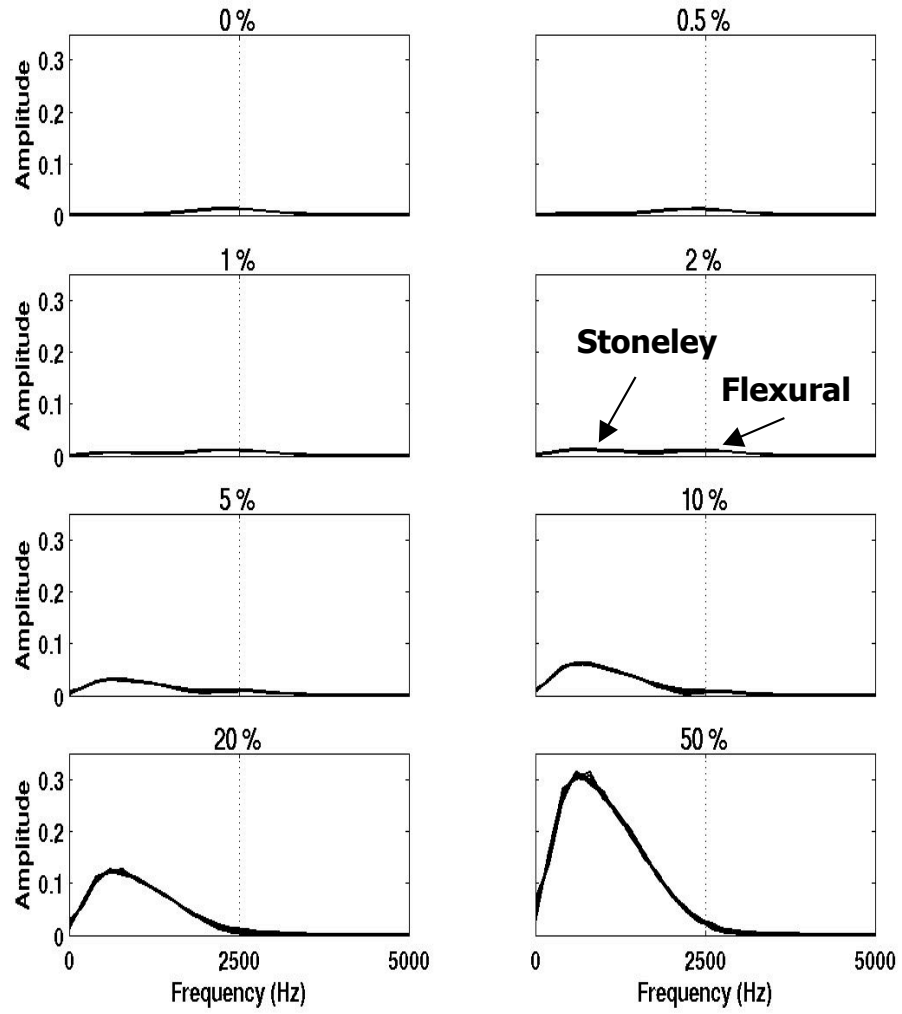


Figure 3: The change in the frequency spectrums of the responses at the receiver array A with increasing the amount of the mismatch for a dipole source

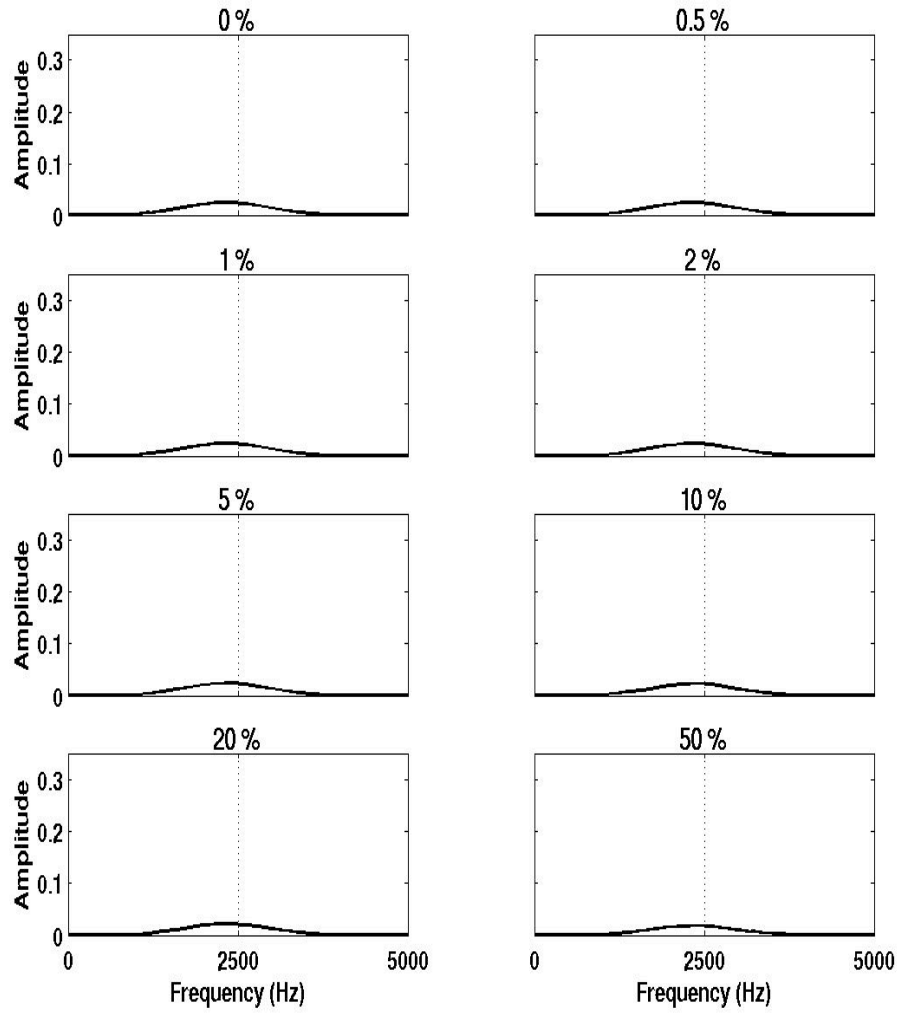


Figure 4: The change in the frequency spectrums of the responses A-C with increasing the amount of the mismatch for a dipole source.

3.2 Mismatch in a quadrupole source

The case of a mismatched quadrupole source shows similar patterns to those with a mismatched dipole source. Because a quadrupole source is constructed of four monopoles, there are many possible cases of amplitude mismatch. In this study, we consider that the monopole right above the receiver array C has smaller amplitude than the other monopoles. Figure 5 shows the frequency spectrums of the responses at receiver arrays A, B, C, D, and the result of A-B+C-D processing with which we obtain a quadrupole component in practice. The center frequency of the quadrupole source is 4 kHz and 5, 10, 20% amplitude mismatch cases are considered. As shown in Figure 5, only screw ($n=2$) mode is present in the case of an ideal quadrupole source. However, with mismatched sources, nonquadrupole ($n \neq 2$) modes are also excited. The Stoneley mode is prominent among nonquadrupole modes and it becomes stronger with increasing amplitude mismatch. However, similar to the case of the mismatched dipole source, the Stoneley mode is cancelled out by A-B+C-D processing because the amplitude of the Stoneley mode is the same at the same radial position from the axis of the borehole.

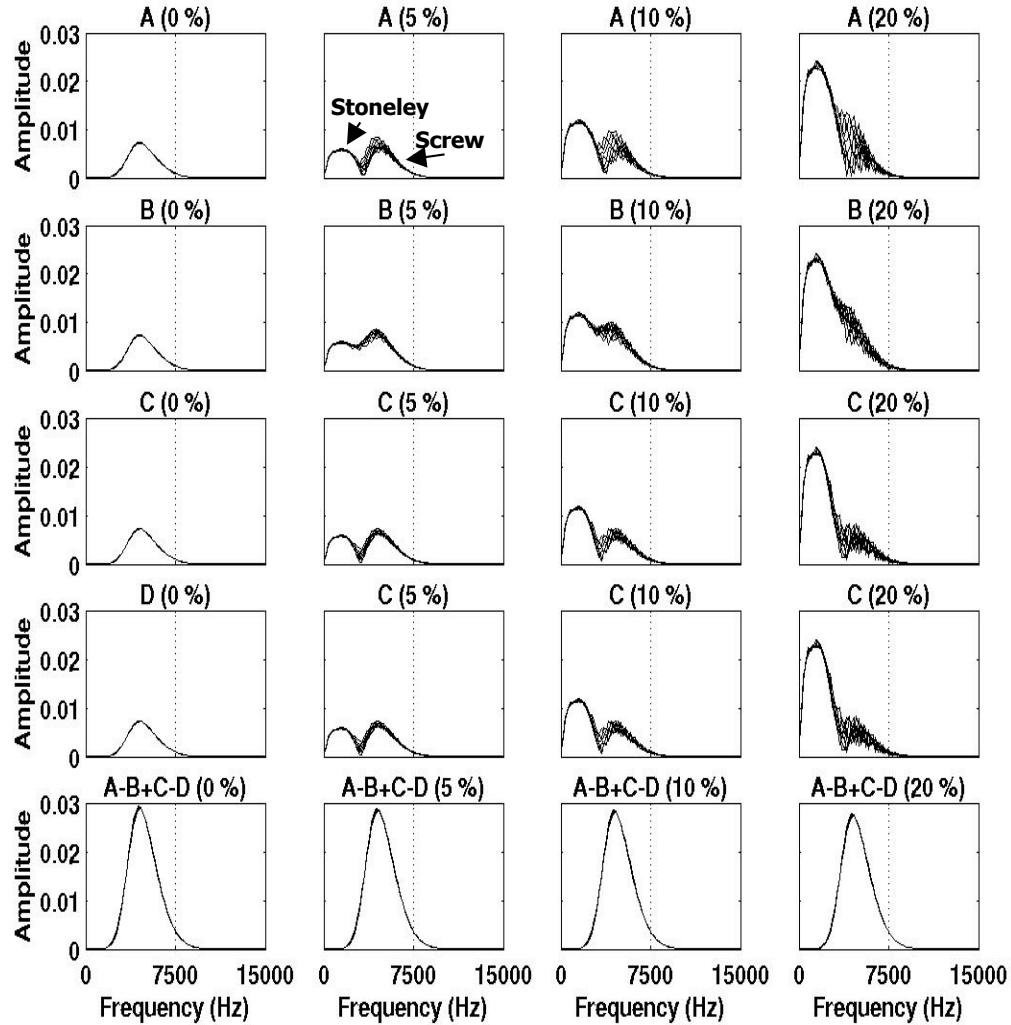


Figure 5: The change in the frequency spectrums of the responses at receiver arrays A, B, C, D and the result of A-B+C-D processing with increasing the amount of amplitude mismatch for a quadrupole source.

3.3 Source mismatch combined with other factors

The effects on the response were investigated when the source mismatch was combined with the other factors: random noise, mismatch in the receivers, and off-centered tool. A dipole source of 1.5 kHz center frequency with the 5% amplitude mismatch was used. To investigate the effects of mismatch source with random noise, we added random noises to the responses in receiver array A and C. Different random noises were designed for each receiver in A and C, and they were filtered with shaping filters which have the similar characteristic to the frequency spectrum spectrums of the responses in receiver arrays A and C. The amplitude of the random noise was about 20% of the amplitude of the signal. Figure 6 shows the responses of the receiver array A and C in 5% source mismatch case, the spectrums of the filtered random noise, and the responses after being combined with the random noises.

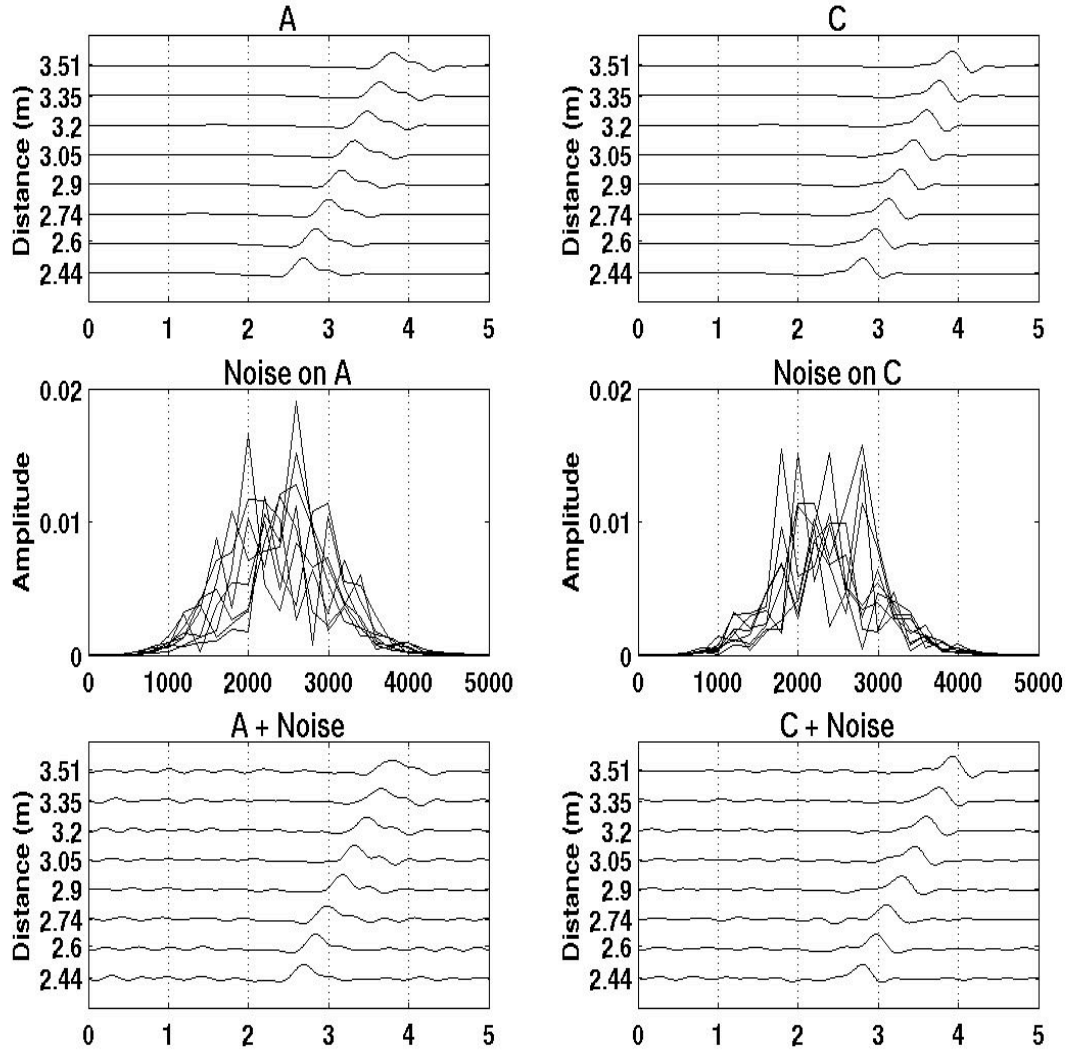


Figure 6: The responses of the receiver array A and C in 5% mismatch case, the spectrums of the filtered random noise, and the responses after being combined with the random noises.

Figure 7 shows the waveforms, the frequency spectrums, the semblance plot in time domain, and the semblance plot in frequency domain of the response after A-C processing. By comparing plots in Figure 7 to plots from the noise free case (Figure 8), we see that the semblance peaks in frequency domain are deviated from the theoretical dispersion curve of the flexural mode due to the random noise even though the Stoneley wave is cancelled out with A-C processing. In addition, we cannot find the arrival of the refracted P wave in time domain semblance plot because it has weak amplitude and is covered by random noise.

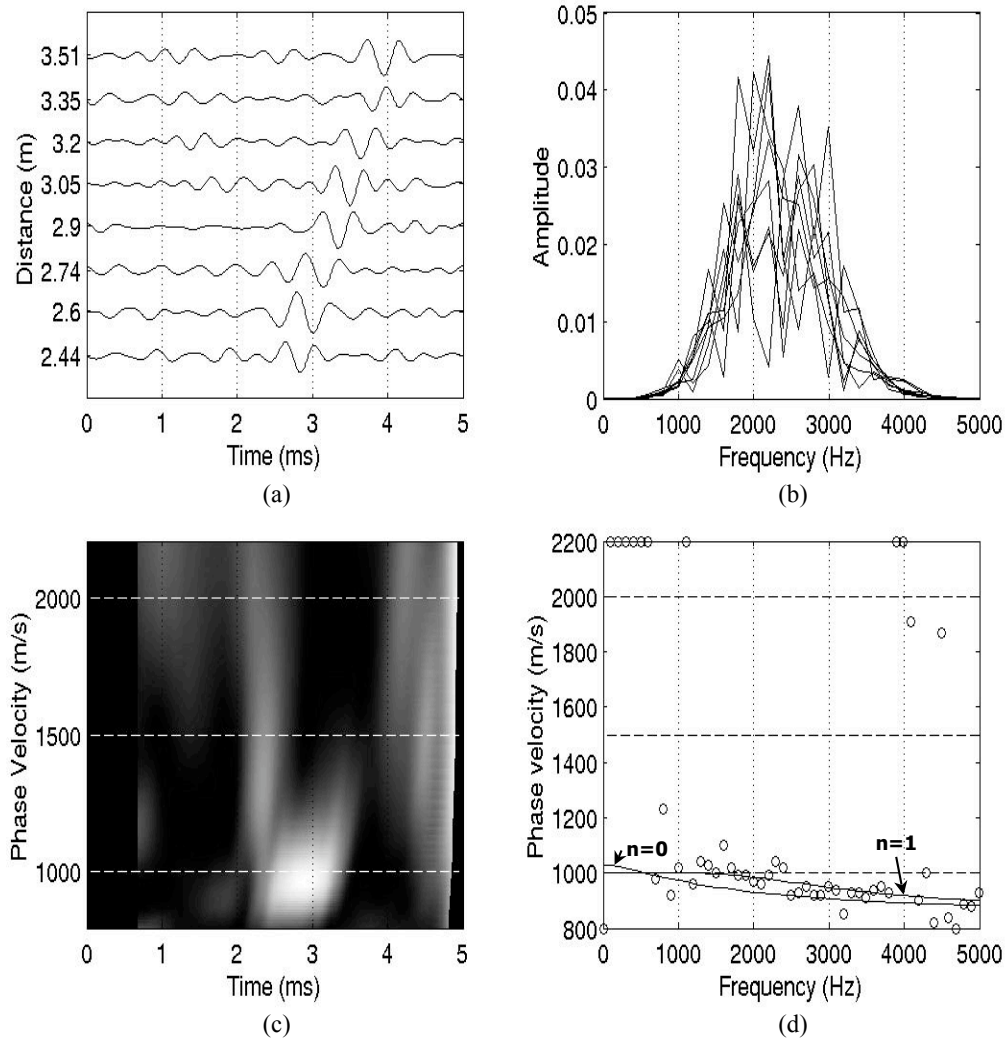


Figure 7: The responses after subtracting C from A shown in Figure 6. (a) Waveforms (b) frequency spectrums (c) the semblance plot in time domain (d) the semblance plot in frequency domain.

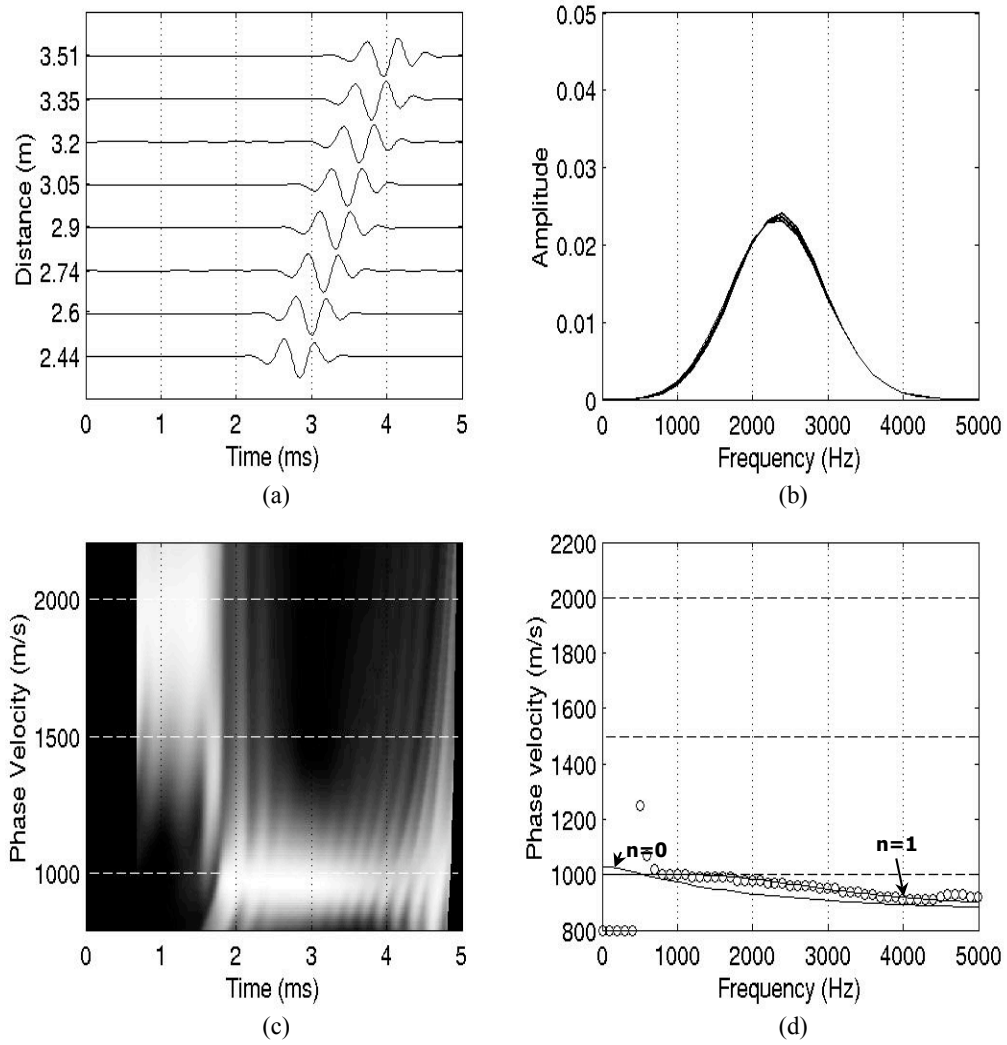


Figure 8: The responses after subtracting C from A, which are produced from a 5% mismatched dipole source (without random noise). (a) Waveforms (b) frequency spectrums (c) the semblance plot in time domain (d) the semblance plot in frequency domain.

As similarly to the mismatch in the source, mismatch between receiver arrays was simulated by making the amplitude of the response in the receiver array C smaller than the responses in the other receiver arrays. Figure 9 shows the results of A-C when 5% mismatch exists between receiver array A and C. Due to the discrepancy between the amplitudes of Stoneley modes in A and C, the Stoneley mode is still remained after A-C processing although the flexural wave is enhanced by A-C processing (Figure 9).

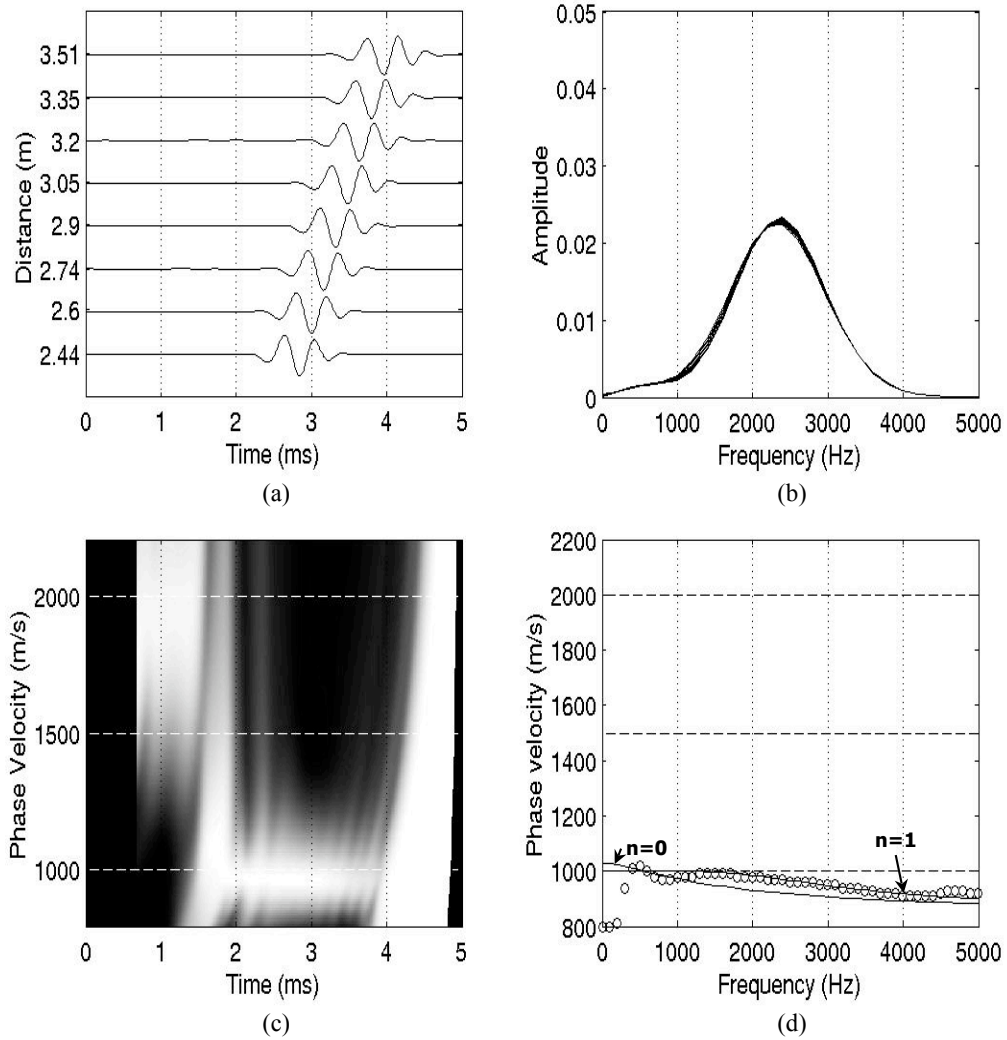


Figure 9: The responses after subtracting C from A in the case of mismatched receiver array (5%).
 (a) Waveforms (b) frequency spectrums (c) the semblance plot in time domain (d) the semblance plot in frequency domain.

In the case of the off-centered tool, the tool was moved from the center of the borehole by the radial displacement 0.03874 m (38% of the borehole radius). In this case, the receiver array A and C are located at different radial position from the borehole axis. Therefore, the Stoneley mode is not cancelled out even after subtracting C from A (Figure 10).

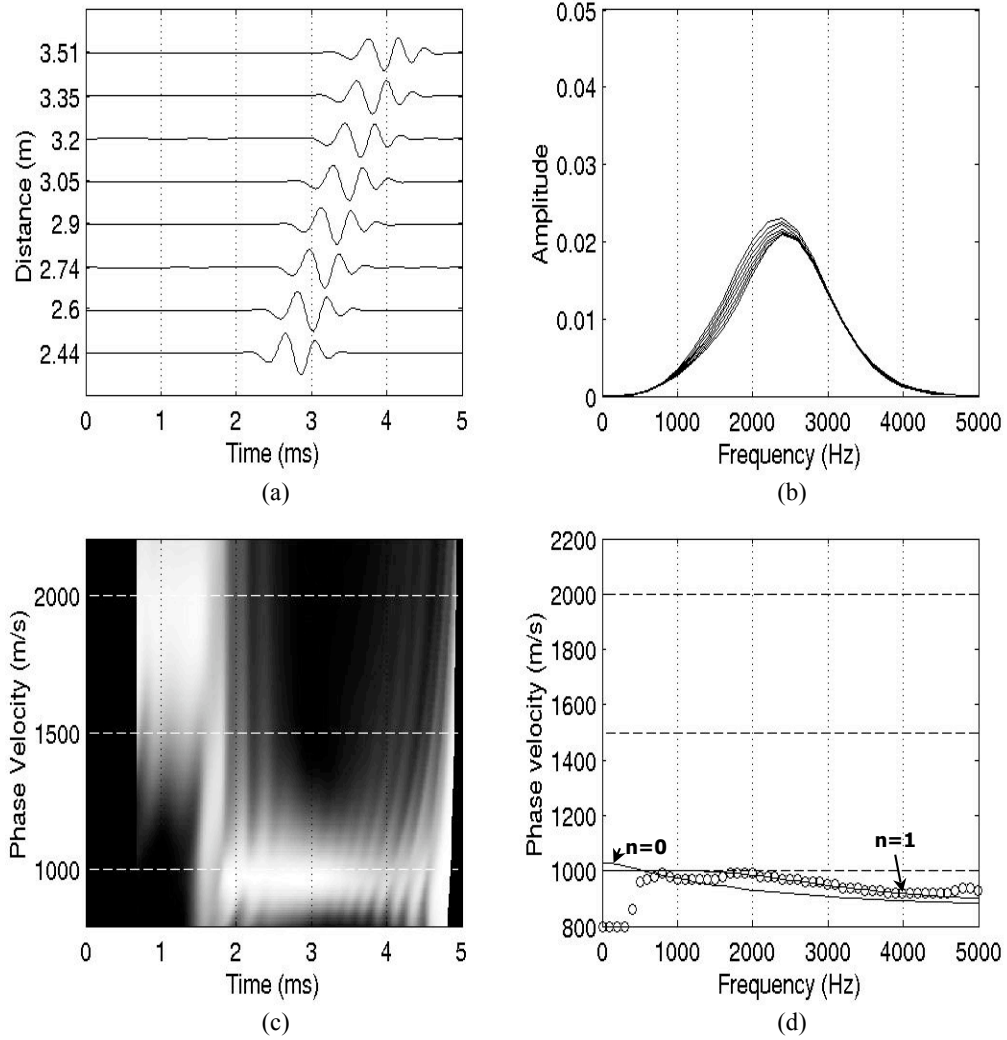


Figure 10: The responses after subtracting C from A from an off-centered tool with a 5% mismatched dipole source. (a) Waveforms (b) frequency spectrums (c) the semblance plot in time domain (d) the semblance plot in frequency domain.

4 Conclusions

The effects of dipole and quadrupole sources constructed from mismatched monopoles were investigated. When the amplitudes of monopoles constructing dipole source are not the same, nondipole modes as well as flexural mode are excited. The Stoneley mode is present in the response at each receiver array and its amplitude increases as the mismatch amount increases. However, this Stoneley mode is cancelled out by A-C processing leaving the flexural mode intact. Similar to the dipole source, amplitude-mismatched quadrupole source produces nonquadrupole modes in addition to screw mode. Among the nonquadrupole modes, the Stoneley mode is the strongest, and its amplitude increases with increasing the mismatch amount. We can separate the screw mode by A-B+C-D processing where the Stoneley mode is cancelled out. However, in addition to a mismatched dipole source, when the receivers are mismatched or if the tool is off-centered, the Stoneley mode remains even after A-C processing.

5 Acknowledgements

This work was supported by the MIT Earth Resources Laboratory's Founding Member Consortium, and the Borehole and Acoustic Logging Consortium.

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