Surface Noise Cancellation for Acoustic Downhole Communication Systems

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***Abstract*—This article investigates the usefulness of using two sensors and a blind-separation algorithm in reducing the effect of surface noise in downhole communication systems. The acoustic channel provides a challenging environment for the acoustic waves that propagate from the downhole to the surface of an oil or gas well. As a result, acoustic waves experience a noticeable attenuation before reaching the surface of the well. Consequently, surface noise, which is generated by the surface tools, dominates the performance of acoustic downhole communication systems that have the receiver unit close to the well surface. The application of a two-receiver noise cancellation algorithm is investigated. The article also describes a testbed that was designed to study the effectiveness of the proposed algorithm in reducing the impact of the surface noise. The communication system was built using two speakers, five connected segments of 7 inch production pipes, and two microphones. One of the speakers was used to transmit a noise-like signal in order to simulate the surface noise. The noise cancellation algorithm was applied to the outputs of the two microphones, and the quality of the acoustic signals is investigated after applying the noise cancellation solution. Results of this work emphasize the usefulness of the proposed solution in enhancing the performance of the acoustic downhole communication systems.**

I. Introduction

The gas and oil industry has seen a growing need for wireless communication technologies to improve well performance and address challenges in exploration, drilling, and production stages. Well downhole data like flow rate, pressure, and temperature can be helpful for well operators in monitoring and enhancing the performance of the wells. Using acoustic waves to carry vital readings from the wellbore to the surface and vice versa through the production tubing inside the well is a technology currently being investigated to conduct wireless downhole communications. In this environment, acoustic waves can propagate from the downhole to the surface by vibrating the body of the production tubing; moreover, acoustic waves can use the space inside the interior of the tubing as a propagation medium as well.

In a typical acoustic downhole communication system, the acoustic downhole tool transmits the data from the bottom of the well to the surface. The receiver unit, assuming no repeaters are used, is usually located very close to the well surface. The acoustic wave propagates from the well bottom to the surface through the well's production tubing. A simplification of the downhole system is illustrated in Fig. 1. The findings of [1]–[4] indicated that acoustic waves undergo a challenging communication channel while propagating inside the well, and the tubing pipe string was found to severely attenuate and disperse the acoustic waves. In addition, the results of [5] revealed that acoustic waves experience an additional frequency-dependent attenuation if parts of the pipe string's exterior are encased in concrete.

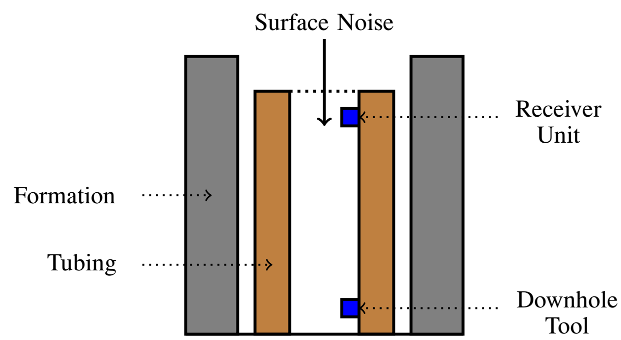

Figure 1. Downhole communications

While propagating inside the well to the surface, and in addition to the severe attenuation it suffers, the acoustic wave is corrupted with various noise signals originating from the downhole and surface tools. Because the downhole noise will experience the same challenging channel, this noise will be severely attenuated as well. On the other hand, because the receiver unit is very close to the well surface, the surface noise will not suffer such attenuation. Accordingly, the surface noise will have a dominant effect on the performance of the downhole communication system.

Surface noise cancellation was considered in [6], [7] in order to enhance the performance of the acoustic downhole systems. However, the work of [6] assumed a perfect knowledge of the details of the acoustic channel. Moreover, in order to cancel the noise signal, a model of single-wave reflection inside the well was assumed in [7]. Especially with the complicated nature of the acoustic channel and the multiple wave reflections inside the well due to the pipe joints, both mentioned approaches provide over-simplified solutions that might not work in an actual well setting.

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Motivated by the damping effect the channel has on the acoustic waves and the severity of the surface noise, this article investigates the application of a blind-noise cancellation algorithm in order to enhance the performance of the acoustic downhole systems. A two-receiver signal separation scheme is proposed as the core of this algorithm. Inspired by the work of [8], an algorithm that blindly separates two independent sources based on information maximization is utilized to cancel the surface noise. Because of the blind nature of this algorithm, there is no need to know the details of the acoustic channel. Consequently, the proposed solution has a practical advantage over the published literature.

Moreover, a testbed was designed to verify the usefulness of the noise cancellation algorithm. The communication system was built using two speakers that work as independent acoustic transmitters, five connected segments of 7 inch production pipes to resemble a pipe string, and two microphones that work as acoustic receivers. One of the speakers was used to transmit a noise-like signal in order to simulate the surface noise. The noise cancellation algorithm was applied to the outputs of the two microphones. In addition, the results of this algorithm are compared to those of a maximal-ratio combining (MRC) scheme.

The rest of this article is organized as follows. An overview of the designed testbed and experiment is given in Section II. The noise cancellation algorithm is detailed in Section III. Numerical results are shown in Section IV. Finally, Section V contains discussions and conclusions.

II. Testbed Design

This section describes the testbed that was designed to investigate the usefulness of the blind noise cancellation algorithm. Acoustic waves were generated using two speakers and received using two microphones. The microphones measured the two independent acoustic waves simultaneously. An illustration of the testbed setup is shown in Fig. 2.

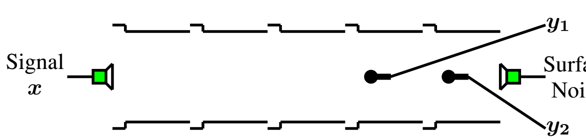


Figure 2. Testbed block diagram

Five segments of 7 inch production pipes were assembled to form a pipe string in order to imitate the production tubing inside an actual oil/gas well. Each pipe segment is around 40 feet long; accordingly, the overall length of the pipe string is approximately 200 feet. In addition, to minimize the interface between the pipes and earth, the pipe segments were positioned over wooden blocks.

The bottom segment of the production tubing is encased in concrete in many wells to prevent hydrocarbon gases from leaking to the surface. In order to mimic the effect of concrete on acoustic wave propagation, two concrete segments were wrapped around the third pipe segment. The first half of the third pipe segment (approximately 20 feet) was encased in concrete of 3/4 inch thickness, and the later part of the third pipe was also encased in concrete (approximately 20 feet of length and 3/4 inch of thickness).

Two independent speakers were used to generate downhole data and surface noise signals. The speaker of the data source was positioned at the beginning of the pipe string to resemble a downhole communication tool, while the speaker of the noise source was positioned at the end of the pipe string so that it functions like a surface noise source. Both signals (i.e., noise and data) were generated at the same time.

A computer program was used to generate the signals that will be fed to the speakers. The data signal was generated as a pulsed sinusoidal signal with a pulse width of 250 ms. Signals with input frequencies of 500, 750, 1000, 1250, and 1500 Hz were tested in this testbed. On the other hand, in order to imitate the surface noise, a pure noise signal was fed to the noise speaker.

On the receiver side, the acoustic waves were detected using two microphones. The microphones were inserted in the space inside the interior of the pipe string. The first microphone was positioned 25 feet away from the end of the pipe string (i.e., closer to the data transmitter), and the second microphone was placed 10 feet away from the end of the pipe string (i.e., closer to the noise transmitter). Consequently, the two microphones were separated by 15 feet. The measurements were made available to a computer through its sound card. The sound card simultaneously sampled the measurements of the microphones at a rate of 23.5 kHz. Moreover, the two microphones had different reception characteristics in order to simulate a more realistic case. Specifically, the first microphone (i.e., the one closer to the data source) was more directive in the direction of the data signal. Finally, a software application was developed to capture, display, and analyze the sound measurements.

III. Noise Cancellation Algorithm

The proposed noise cancellation algorithm comprises three building blocks:

- Filtration, decimation, and demodulation stage
- Entropy maximization algorithm
- Equalization stage

To describe the algorithm, the transmitted data signal is denoted as $\boldsymbol{x}$, the measurement of the first sensor is called $\boldsymbol{y_1}$ and that of the second sensor is termed $\boldsymbol{y_2}$, and the outputs of the first stage of the algorithm are denoted as $\tilde{\boldsymbol{y_1}}$ and $\tilde{\boldsymbol{y_2}}$. Moreover, the signal-like output of the second stage is termed as $\boldsymbol{u_1}$, while the noise-like output is denoted as $\boldsymbol{u_2}$. Finally, the output of the third stage is denoted as $\hat{\boldsymbol{x}}$. The block diagram of the proposed algorithm is shown in Fig. 3.

A. Filtration, decimation, and demodulation

In this stage, the received signals (i.e., $\boldsymbol{y_1}$ and $\boldsymbol{y_2}$) are first bandpass filtered. The bandpass filter is centered around the input frequency of the transmitted signal ($\boldsymbol{x}$). The goal of this step is to reduce the noise content in the measurements.

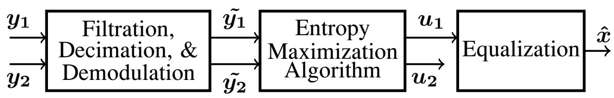


Figure 3. Algorithm block diagram

The signals have lower operating frequency after filtration; consequently, the filtered signals are decimated in order to reduce the processing time. Next, the decimated signals are demodulated using sine and cosine signals with the same input frequency. The sine and cosine-demodulated signals are then combined together in one signal. The goal of this step is to move the frequency content into the low-frequency band.

B. Entropy maximization

This stage implements a blind source-separation algorithm inspired by the work of [8]. Blind separation of two independent sources (i.e., the data signal and the surface noise) from their convolved mixture in the measurements is accomplished through minimizing the mutual information between the algorithm outputs. The operation of this algorithm requires no knowledge of the way the data signal and the surface noise were mixed in the channel; accordingly, adaptive filters can be used to achieve signal separation.

The inputs to this stage are $\tilde{\boldsymbol{y_1}}$ and $\tilde{\boldsymbol{y_2}}$, and the outputs are $\boldsymbol{u_1}$ and $\boldsymbol{u_2}$. The goal of this stage is to increase the entropy (i.e., uncertainty) between $\boldsymbol{u_1}$ and $\boldsymbol{u_2}$, and this will result in $\boldsymbol{u_1}$ being an $\boldsymbol{x}$-like signal while $\boldsymbol{u_2}$ being a noise-like signal. Consequently, $\boldsymbol{u_1}$ is fed to the next stage while $\boldsymbol{u_2}$ is discarded. More details about this algorithm can be found in [8].

The signal-like output of this stage imitates that of the data signal that was transmitted over the acoustic channel. In other words, $\boldsymbol{u_1}$ is effectively the result of the convolution between $\boldsymbol{x}$ and the acoustic channel. This finding motivates applying an equalizer on $\boldsymbol{u_1}$ to undo the dispersive effects of the channel.

C. Equalization

The equalizer's job is to find $\hat{\boldsymbol{x}}$ such that $|\boldsymbol{x} - \hat{\boldsymbol{x}}|^2$ is minimized. Let the equalizer be represented as a finite impulse response filter, termed as $\boldsymbol{h}$, of length L with filter coefficients $\{h_0, h_1, \ldots, h_{L-1}\}$, then $\hat{\boldsymbol{x}}$ is the result of the convolution between $\boldsymbol{u_1}$ and $\boldsymbol{h}$. Moreover, $\hat{\boldsymbol{x}}$ can also be represented as a summation of L shifted and weighted copies of $\boldsymbol{u_1}$ as

$$\hat{\boldsymbol{x}} = \sum_{j=0}^{L-1} \tilde{\boldsymbol{u_1}}_j h_j \ ,$$

where $\tilde{\boldsymbol{u_1}}_j$ is a shifted copy of $\boldsymbol{u_1}$ with the first j elements are zeros. Consequently, $\hat{\boldsymbol{x}}$ can be rewritten as

$$\hat{\boldsymbol{x}} = \tilde{\boldsymbol{U}}\boldsymbol{h} \ , \tag{1}$$

where $\tilde{\boldsymbol{U}}$ is $[\tilde{\boldsymbol{u_1}}_0, \tilde{\boldsymbol{u_1}}_1, \ldots, \tilde{\boldsymbol{u_1}}_{L-2}, \tilde{\boldsymbol{u_1}}_{L-1}]$.

The coefficients of the equalizer filter that achieve the minimum estimation error are found as [9]

$$\boldsymbol{h} = (\tilde{\boldsymbol{U}}^T\tilde{\boldsymbol{U}})^{-1}\tilde{\boldsymbol{U}}^T\boldsymbol{x} \ \cdot \tag{2}$$

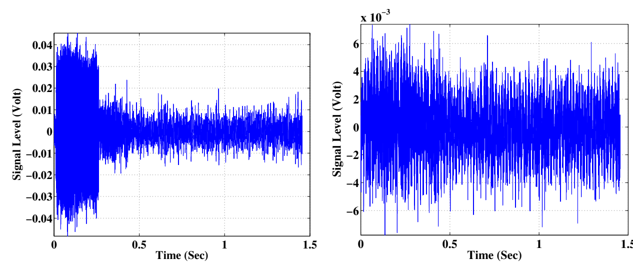
Accordingly, $\hat{\boldsymbol{x}}$ that minimizes $|\boldsymbol{x} - \hat{\boldsymbol{x}}|^2$ is expressed as

$$\hat{\boldsymbol{x}} = \tilde{\boldsymbol{U}}(\tilde{\boldsymbol{U}}^T\tilde{\boldsymbol{U}})^{-1}\tilde{\boldsymbol{U}}^T\boldsymbol{x} \ \cdot \tag{3}$$

IV. NUMERICAL RESULTS

This section displays numerical results about the performance of the noise cancellation algorithm. In addition, the results of applying this algorithm are compared with those of an MRC scheme. The following figures display the details of the measured 1500 Hz signal along the algorithm blocks.

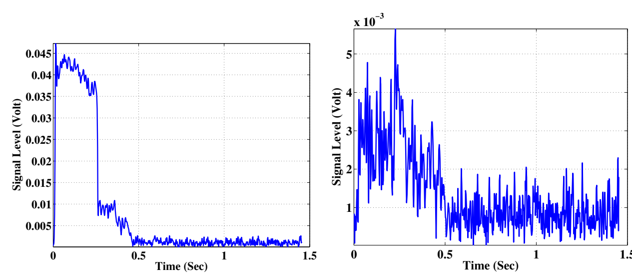
Fig. 4 shows the measured signals out of the two microphones. Because the first microphone was closer to the source and had better reception characteristics, its output (i.e., y_1) appears stronger than the output of the second microphone. On the other hand, as noted from the figure, y_2 is more overwhelmed by the surface noise. The values of y_1 and y_2 emulate a practical well situation in which the surface noise is dominating the measurements.



(a) $\boldsymbol{y_1}$ (b) $\boldsymbol{y_2}$

Figure 4. Measured signals

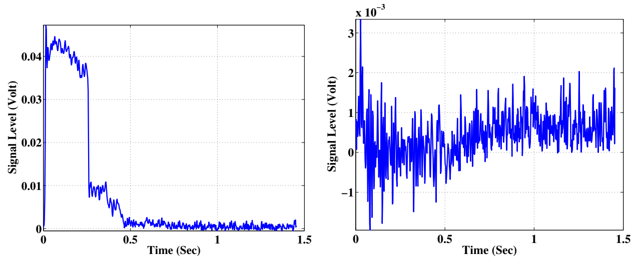
The outputs of the algorithm's first stage (i.e., $\tilde{\boldsymbol{y_1}}$ and $\tilde{\boldsymbol{y_2}}$) are shown in Fig. 5. In this stage, the signals are bandpass filtered, down sampled, and demodulated. Consequently, comparing Fig. 5 with Fig. 4, $\tilde{\boldsymbol{y_1}}$ and $\tilde{\boldsymbol{y_2}}$ appear less corrupted with noise and both have low-frequency components. However, $\tilde{\boldsymbol{y_2}}$ still suffers from a strong noise component.



(a) $\tilde{\boldsymbol{y_1}}$ (b) $\tilde{\boldsymbol{y_2}}$

Figure 5. Outputs of the first stage

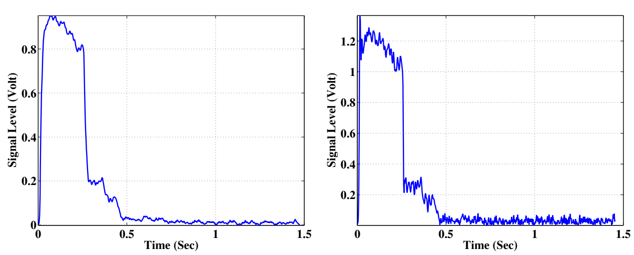
Fig. 6 displays the outputs of the entropy maximization algorithm. The signal-like output ($\boldsymbol{u_1}$) looks similar to a strong low-pass replica of $\boldsymbol{x}$. On the other hand, the noise-like output of the algorithm ($\boldsymbol{u_2}$) imitates that of a noise signal. It is obvious that the algorithm achieved its goal of blindly separating the surface noise from the actual signal.



(a) $\boldsymbol{u_1}$ (b) $\boldsymbol{u_2}$

Figure 6. Outputs of the second stage

The output of the final stage of the algorithm is shown in Fig. 7(a). As expected, $\hat{\boldsymbol{x}}$ appears as an equalized version of $\boldsymbol{u_1}$ and more similar to the transmitted signal ($\boldsymbol{x}$). For the sake of comparison, the MRC of $\tilde{\boldsymbol{y_1}}$ and $\tilde{\boldsymbol{y_2}}$ is shown as well in Fig. 7(b). Comparing the two results, $\hat{\boldsymbol{x}}$ appears a healthier estimate of $\boldsymbol{x}$.



(a) $\hat{\boldsymbol{x}}$ (b) MRC of $\tilde{\boldsymbol{y_1}}$ and $\tilde{\boldsymbol{y_2}}$

Figure 7. Output of the third stage vs. the MRC signal

Table I contains a detailed list of the signal-to-noise ratio (SNR) values for the measured signals, outputs of each stage of the algorithm, and the MRC signal. The average SNR value of the measurements is about 8.4 dB. However, the first stage of the algorithm yields an average SNR gain of around 16.4 dB, the gain of the second stage is approximately 25.4 dB, and the overall gain of the algorithm is about 27.6 dB. On the other hand, the average SNR gain of the MRC scheme is about 20.9 dB. The results of this table show that the proposed noise cancellation algorithm enhances the quality of the measurements and suppresses the surface noise efficiently. Moreover, the proposed solution outperforms the MRC scheme.

Frequency (Hz)	500	750	1000	1250	1500	Average
$\boldsymbol{y_1}$	18.6	12.7	9.3	9.6	10.0	12.0
$\boldsymbol{y_2}$	14.3	6.9	0.4	1.6	1.0	4.8
$\tilde{\boldsymbol{y_1}}$	28.1	33.2	30.5	27.8	29.2	29.8
$\tilde{\boldsymbol{y_2}}$	29.1	27.2	20.4	14.0	8.9	19.9
$\boldsymbol{u_1}$	30.6	37.4	37.8	31.3	32.2	33.9
$\hat{\boldsymbol{x}}$	**31.1**	**41.0**	**40.8**	**33.1**	**34.3**	**36.0**
MRC ($\tilde{\boldsymbol{y_1}}, \tilde{\boldsymbol{y_2}}$)	25.9	32.1	31.3	28.1	29.4	29.4

Table I
SNR COMPARISON

V. CONCLUSIONS

This article investigated the usefulness of using two sensors and a blind-separation algorithm in reducing the impact of surface noise in downhole communication systems. Because of the damping effect of the acoustic channel inside the wells, surface noise dominates the performance of the acoustic downhole systems. This article proposed applying a blind noise-cancellation algorithm on the outputs of two sensors as a practical solution to this problem. A testbed was designed to confirm the effectiveness of the proposed solution. The testbed comprised two speakers that worked as acoustic sources, five connected segments of 7 inch production pipes to simulate a pipe string, and two microphones that worked as acoustic receivers. One of the speakers was used to transmit a noise-like signal to mimic the surface noise. The noise cancellation algorithm was applied to the outputs of the two microphones.

Numerical results show that there is a great enhancement in signal quality after applying the proposed solution. In addition, the results of the proposed solution outperform those of a maximal ratio combining scheme. Moreover, the proposed solution has the advantage that it does not need to know the details of the acoustic channel in order to separate the surface noise from the data signal. Results of this work emphasize the usefulness of the proposed solution in reducing the effects of surface noise and enhancing the performance of the acoustic downhole communication systems.

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