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Atomic Library Optimization for Pulse Ultrasonic Sparse Signal Decomposition and Reconstruction

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Abstract. Compressive sampling of pulse ultrasonic NDE signals could bring significant savings in the data acquisition process. Sparse representation of these signals using an atomic library is key to their interpretation and reconstruction from compressive samples. However, the obstacles to practical applicability of such representations are: large size of the atomic library and computational complexity of the sparse decomposition and reconstruction. To help solve these problems, we develop a method for optimizing the ranges of parameters of traditional Gabor-atom library to match a real pulse ultrasonic signal in terms of correlation. As a result of atomic-library optimization, the number of the atoms is greatly reduced. Numerical simulations compare the proposed approach with the traditional method. Simulation results show that both the time efficiency and signal reconstruction energy error are superior to the traditional one even with small-scale atomic library. The performance of the proposed method is also explored under different noise levels. Finally, we apply the proposed method to real pipeline ultrasonic testing data, and the results indicate that our reduced atomic library outperforms the traditional library.

INTRODUCTION

Pulse ultrasonic NDE signals have played a crucial role in diagnosing the structure integrity for over a half-century. However, the large scale of collected data has become the key problem for analyzing and processing of ultrasonic signals. Compressive sampling theory [1, 2] can bring significant savings in the data acquisition process. Applying this theory to the field of ultrasound NDE will reduce the amount of collected data, simplify the structure of hardware system, and improve the testing resolution and real-time processing ability. The precondition for interpretation and reconstruction original signals from compressive sampling is the sparse representation of these signals using an atomic library. Unfortunately, the obstacles to practical applicability of such sparse representations are: large size of the atomic library and computational complexity of the sparse decomposition and reconstruction.

To help solve these problems in ultrasonic NDE applications, some researchers mainly focus on improving the efficiency of the sparse decomposition algorithms based on over-complete atomic library, and others concentrate on constructing a more suitable library by using various atoms [3]. Matching Pursuit (MP) [4] has been widely used to decompose a wide range of ultrasonic NDE signals into a linear combination of functions that are selected from a redundant dictionary. The purpose of using the redundant atomic library is to maximize the waveform matching between the atom and the ultrasonic NDE signals. Various atoms, such as complex-Gabor, modulated real Gaussian, redundant Morlet wavelet, and chirplet, have been used to construct the library for this objective.

Optimization of the atomic library for ultrasonic NDE signal representation has also been studied in the literature. Yu et al. propose a MP method based on training an over-complete dictionary [5]. Lu and Michaels [6] propose a numerical implementation of the MP method designed for ultrasonic signal decomposition. These methods can reduce the number of atoms and computational complexity.

In this paper, we propose an atomic-library optimization method for the sparse decomposition and reconstruction of ultrasonic NDE signals, with goal to represent these signals accurately and efficiently using a library of small size. The pulse ultrasonic NDE signals measured from reflectors and scatters of tested structure have an approximate energy-concentration property both in time and frequency domains, which can be modeled well using modulated Gaussian functions with the parameters estimated from the echoes [7], [8]. Gabor functions are qualitatively and quantitatively similar to pulse-ultrasonic NDE signals and exhibit excellent energy

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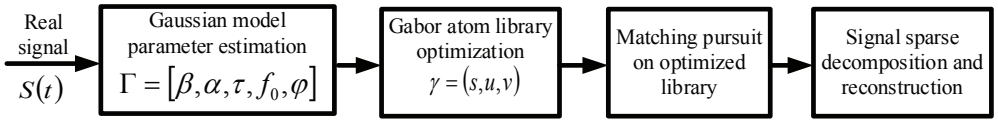

FIGURE 1. Global overview

concentration both in the time and frequency domains [6, 9]. By applying the MP method with atoms in the atomic library composed of Gabor functions, we can obtain high correlation between the Gaussian models of the pulse ultrasonic NDE signals and the atoms of Gabor functions.

To obtain the sparsest representation of ultrasonic NDE signals, the atomic library needs to be over-complete, with the parameters of the atoms in the library covering a range as large as possible. However, most atoms in the library are unnecessary, with negligible contribution. We propose to first estimate the modulated Gaussian model parameters from a transducer emission wave and then use them to optimize the atom library by selecting the range of Gabor atoms in the library so that their correlation with the modulated Gaussian model is maximized. The global overview of the approach is shown in Fig. 1.

BACKGROUND AND REVIEW

For any given real pulse-ultrasonic NDE signal $s(t) \in H$, the linear combination of M atoms can be found in a given set of atoms, which is called atom library D.

$$s(t) = \sum_{m=0}^{M-1} c_{k_m} g_{k_m} \tag{1}$$

where H is Hilbert space; D is a set of K atoms, $D = \{g_k, k = 1, 2, 3, \dots, K\}$, and c_{k_m} can be obtained by applying the MP method with atoms in library D as follows $k_m = \text{argmax}_k |\langle R^m s(t), g_k \rangle|$, $c_{k_m} = |\langle R^m s(t), g_{k_m} \rangle|$, $R^m s(t) = R^{m-1} s(t) - \langle s(t), g_{k_{m-1}} \rangle g_{k_{m-1}}$, $R^0 s(t) = s(t)$, $m = 0,1, \dots, M-1$. Suppose a redundant atom library is composed with a set of Gabor functions, which is often chosen because the ultrasonic signal is usually a broadband pulse modulated at the center frequency of the transducer [3]. Each atom is defined by the parameters $\gamma = (s,\ u,\ v)$ as

$$g_\gamma = \frac{1}{\sqrt{s}} g\left(\frac{t-u}{s}\right) \mathrm{e}^{\mathrm{j}2\pi v(t-u)} \tag{2}$$

where $g(t) = \mathrm{e}^{-\pi t^2}$ and s, u and v are the scale factor, time shift, and modulation frequency, respectively. By discretizing γ over its parameter space, we obtain K atoms $\{g_k\}_{k=1}^K$, i.e., the atom library D.

Real pulse-ultrasonic NDE signals can be approximately expressed as modulated Gaussian pulses [7, 8]

$$s(t) = \beta \mathrm{e}^{-\alpha(t-\tau)^2} \cos(2\pi f_0 (t-\tau) + \varphi) \tag{3}$$

where $\beta > 0,\ \alpha > 0,\ \tau,\ f_0$ and φ are the amplitude, bandwidth factor, arrival time, center frequency, and phase, expressed as $\Gamma = [\beta,\ \alpha,\ \tau,\ f_0,\ \varphi]$. These parameters represent the wave structure of the signals, which contains useful information about the tested object.

In theory, the parameter space of the Gabor functions is infinite [4] and the atom library D defined by the parameters γ is over-complete, which could lead to high computational complexity of the sparse decomposition and reconstruction when employing the MP method. Here, we propose to optimize the Gabor atom dictionary using the estimated Γ from the Gaussian model (3).

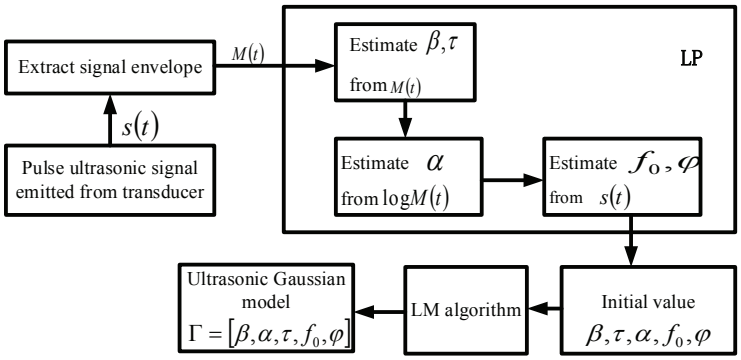

FIGURE 2. Gaussian model parameter estimation.

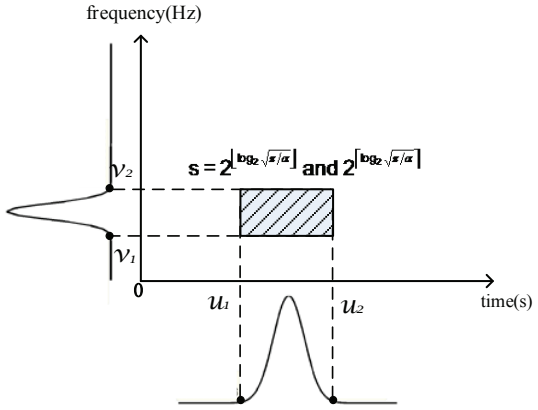

FIGURE 3. Effective range of optimized Gabor-atom library in time-frequency domain.

Estimating the Parameters of the Gaussian Model

We apply our method in [9] to estimate the parameters Γ of the Gaussian model directly from real ultrasonic signal emitted from ultrasonic transducer. In particular, we estimate Γ by minimizing the least-square (LS) error between the sampled measurements and the modulated Gaussian pulse model in (3). Here, we use a hybrid method that employs linear prediction (LP) and Levenberg-Marquardt (LM) algorithms, see Fig. 2. The approach in [9] first uses LP to initialize and then the LM algorithm to minimize the LS objective function.

OPTIMIZING THE GABOR ATOM LIBRARY

Gabor atoms are determined by the parameters $\gamma = (s,\ u,\ v)$, see (2). To obtain the sparsest signal representation, we need redundant atoms and to expand the parameter space to infinity. According to the MP algorithm, the more similar the wave structure of the signals is, the bigger the corresponding decomposition coefficient. Hence, choosing the parameter space of the Gabor functions by matching the signal Gaussian model of the pulse ultrasonic NDE signals will narrow the search space of the parameters γ. We illustrate the proposed narrowed search space in Fig. 3.

Scale-factor Optimization

Both the signal Gaussian model and the Gabor atom in (2) and (3) have Gaussian envelopes. The scale-factor s is related to the bandwidth factor α in terms of waveform similarity. We extract the Gaussian envelopes of both the Gaussian signal model and the Gabor atom, and do not consider the amplitude attenuation and phase delay in the envelope extraction process. The absolute value of the correlation function p between the two envelopes at point τ can be obtained by using the property that the area of a Gaussian density function is one:

$$|p| = \left| \int \beta \mathrm{e}^{-\alpha(t-\tau)^2} \times \frac{1}{\sqrt{s}} \mathrm{e}^{-\pi\left(\frac{t-\tau}{s}\right)^2} dt \right| = |\beta| \sqrt{\pi} (\alpha s + \pi/s)^{-0.5}. \tag{4}$$

The correlation magnitude in (4) is maximized at $\alpha = \pi/s^2$, meaning that the signal Gaussian model and the Gabor atom are most similar in waveform of the envelope at $s = \sqrt{\pi/\alpha}$. Due to the discrete nature of the Gabor atom library, we cannot simply select the scale-factor value $s = \sqrt{\pi/\alpha}$. Considering that the main lobe of the correlation function is concave, we use two values of s near the maximum value instead of one maximum. Hence, we select the optimized scale-factor values as $2^{\lfloor s_p \rfloor}$ and $2^{\lceil s_p \rceil}$, where $s_p = \sqrt{\pi/\alpha}$, $\lfloor s_p \rfloor$ is the largest integer smaller than or equal to s_p; $\lceil s_p \rceil$ is the smallest integer greater than or equal to s_p.

Time-shift Optimization

Pulse-ultrasonic NDE signals have compact support in the time domain. The Gaussian model for these signals in (3) and Gabor atoms in the atom library have the same time-domain behavior, with limited time durations, which can be determined from the Gaussian function envelopes. Due to the properties of correlation function between two signals, only when the time shift falls into the signal time-duration range, the correlation coefficient will be nonzero. So, the time-shift range can be determined by matching the Gaussian envelopes of the Gaussian model and the atoms in the library. By treating the envelope of Gaussian model as a Gaussian probability density function, we obtain a confidence interval of the time-shift range using the 3-standard-deviation rule. The optimized time-shift range is

$$u \in [u_1, u_2] \tag{5}$$

where $u_1 = \tau - \frac{3}{\sqrt{2}} \alpha^{-0.5}$ and $u_2 = \tau + \frac{3}{\sqrt{2}} \alpha^{-0.5}$.

Modulation-frequency Optimization

Modulation frequency v is a Gabor-atom parameter with theoretically infinite range. Because the spectra of both the ultrasonic signal Gaussian model and the Gabor atom are Gaussian-like functions band-limited in frequency domain, the correlation coefficients of these two kinds of functions are related to the center frequency f_0 of the transducer and the bandwidth factor α. The correlation coefficients can be obtained by convolving them in the frequency domain. According to the properties of convolution, only when the frequency range of the Gabor atom falls into the frequency range of the ultrasonic signal, the correlation coefficient will be nonzero. Hence, by using the same approach as for time-shift optimization, we obtain the optimized frequency range:

$$v \in [v_1, v_2] \tag{6}$$

where $v_1 = f_0 - \frac{3}{\sqrt{2}} \alpha^{-0.5}$ and $v_2 = f_0 + \frac{3}{\sqrt{2}} \alpha^{-0.5}$.

NUMERICAL EXAMPLES

In order to generate the Gabor atom library, we discretized the parameters γ as [10]

$$\gamma = (2^j,\ 2^{j-1}\alpha,\ 2^{-j})$$

where $0 < j \leq \log 2N$, $0 \leq a \leq \log N 2^{j+1}$, N is signal length.

Our performance metric is the relative square error (RSE), defined as

$$e = \frac{\|x - \hat{x}\|_2}{\|x\|_2} \tag{7}$$

where the vectors x and $\hat{x}$ represent the true and reconstructed sampled signals, respectively.

Simulation Examples

We select a simulated pulse ultrasonic signal with the following Gaussian-model parameters:

$$\Gamma = [\beta,\ \alpha,\ \tau,\ f_0,\ \varphi] = [1,\ 10^{12},\ 5 \times 10^6,\ 2 \times 10^6,\ \pi/4]$$

The sampling frequency of this simulation signal is $f_s = 3 \times 10^7$Hz, the range of time is $t \in [1, 1 \times 10^7]$, and the signal length is $N = 300$. The simulation signal is shown in Fig. 4(a), and the spectrum is shown in Fig. 4(c).

Then, optimizing the parameter space of the Gabor atoms in atom library according to the proposed method, the values of scale-factor is 32 and 64, and the phase's effective range is $[0,\ \pi)$. The time-shift and modulation-frequency range are $[87, 215]$ and $[7.452 \times 10^{-3},\ 9.031 \times 10^{-3}]$ respectively.

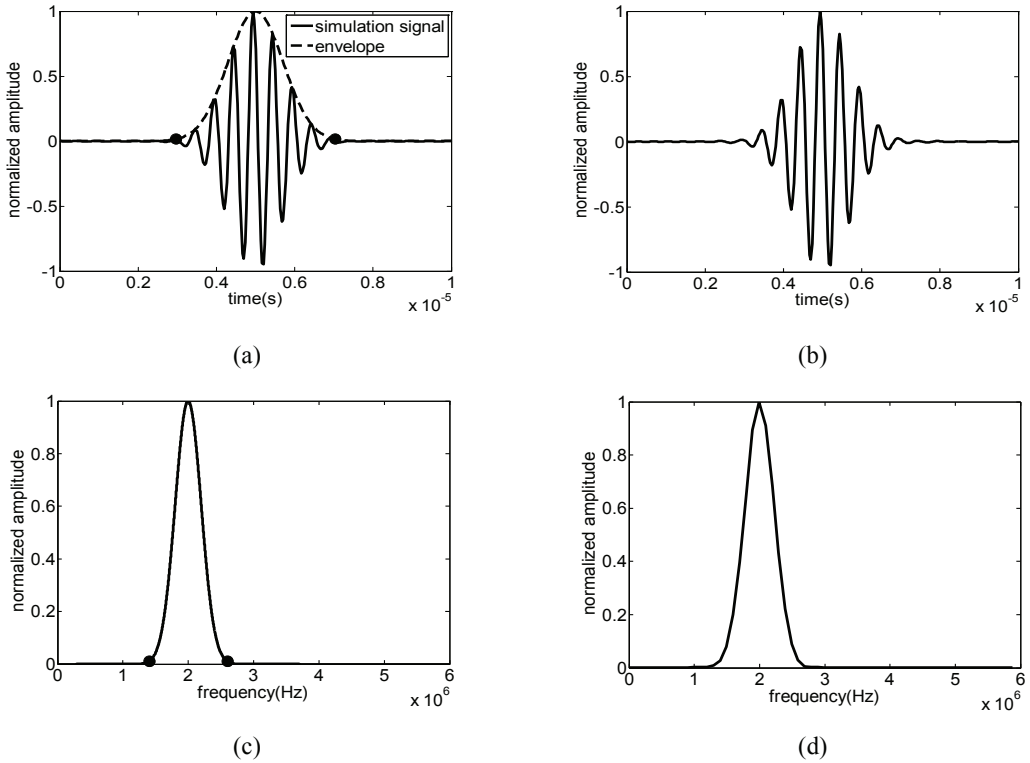

FIGURE 4. (a) Simulated pulse-ultrasonic signal and its envelope; (b) reconstructed signal; and (c)-(d) magnitude spectra of the simulated and reconstructed signals.

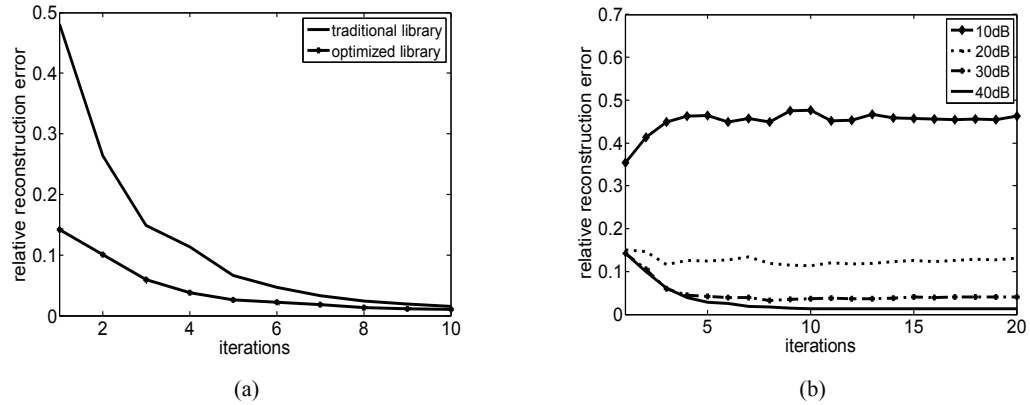

FIGURE 5. RSEs as functions of MP iteration index for (a) traditional and optimized Gabor-atom libraries without noise and for (b) optimized library with additive white Gaussian noise at different SNRs.

In this simulation experiment, the number of atoms in optimized Gabor-atom library is only 17.6% of the traditional one, reduced to 23220 from 132080.

The reconstructed signal waveform with iteration index $M = 10$ using optimized Gabor-atom library is shown in Fig. 4(b), and with its spectrum in Fig. 4(d). There is no significant difference between reconstructed waveform and simulated waveform.

The RSEs of the MP method for the traditional and optimized Gabor-atom libraries are respectively displayed in Fig. 5 (a); clearly the optimized Gabor-atom library outperforms the traditional one.

To evaluate the performances of the proposed method at different noise levels, we add white Gaussian noise to the simulated signal with the signal-to-noise ratio (SNR) varying between 10dB and 40dB. When the SNR exceeds 30dB, the RSE is strongly convergent. The results averaged by 100 samples are shown in Fig. 5 (b).

Finally, 10 groups of simulation signals have been employed with different parameters to evaluate the performances of the proposed method. The experimental results are shown in Table 1, which shows that the RSE based on optimized library is lower than that based on the traditional library, even though the optimized library

TABLE 1. MP reconstruction performances using traditional and optimized atomic libraries.

No.	RSE		Operation Time/s	
	Traditional Library	Optimized Library	Traditional Library	Optimized Library
1	0.015	0.010	75.27	13.19
2	0.046	0.006	75.86	13.50
3	0.028	0.013	240.65	35.71
4	0.018	0.004	240.75	40.20
5	0.030	0.006	242.66	38.05
6	0.009	0.006	73.59	13.39
7	0.009	0.007	73.95	13.33
8	0.017	0.005	73.74	13.92
9	0.033	0.008	73.60	13.16
10	0.035	0.006	74.06	14.00

FIGURE 6. Schematic diagram of testing system.

uses fewer atoms than the traditional library. Due to fewer atoms, the computational (time) efficiency is improved significantly as well.

Experiments on Pipeline Ultrasonic Testing and Discussion

Experiments have been performed on pipeline ultrasonic testing. The sample pipeline consists of seamless steel pipes with the diameter and thickness 219mm and 14mm, respectively. The pulse ultrasonic probe is employed with central frequency 5MHz and wafer diameter 10mm. Water is used as couplant. The sampling frequency is 25MHz. The setup of the testing system is shown in Fig. 6.

Figure 7(a) shows the real tested ultrasonic signal and its spectrum Fig. 7(c). Then the parameters of the real tested signal are estimated by using the hybrid method, and the parameter spaces of the Gabor atoms are determined according the estimated signal Gaussian model. The estimated signal parameters are as follow:$\alpha = 3.356 \times 10^{12}$, $\tau = 1.7 \times 10^{6}\mathrm{s}$, $f_0 = 3.75 \times 10^{6}\mathrm{Hz}$, $\varphi = 1$ and $\beta = 1$. The length of the analyzed signal is $N = 120$. The reconstructed signal and its spectrum are shown in Fig. 7(b) and (d).

We plot relative reconstruction error of the real tested signal versus iteration index M. Fig. 8 shows the results. It can be seen that the relative construction error of optimized Gabor-atom library is convergent and superior to the traditional Gabor-atom library. Meanwhile, the relative reconstruction errors are bigger than the numerical simulation results with same iteration time because of the existence of noise in real tested signal.

CONCLUSIONS

We proposed a method for optimizing the parameter space of traditional Gabor-atom library using estimated parameters of Gaussian signal model. This optimization helps solve the problems of large size of the atomic library and computational complexity in sparse decomposition and reconstruction of pulse ultrasound NDE signals, and also provides superior reconstruction performance compared with the traditional schemes. We optimized the range of Gabor atoms in the library so that their correlation with the modulated Gaussian model is maximized. Numerical simulations have been performed for evaluating the feasibility and efficiency even in the situation of additive white Gaussian noise. Real ultrasonic testing experiments have been performed on pipeline specimen. Experimental results show that the performance of optimized Gabor-atom library is superior to the traditional one, both in terms of computational complexity and signal reconstruction accuracy.

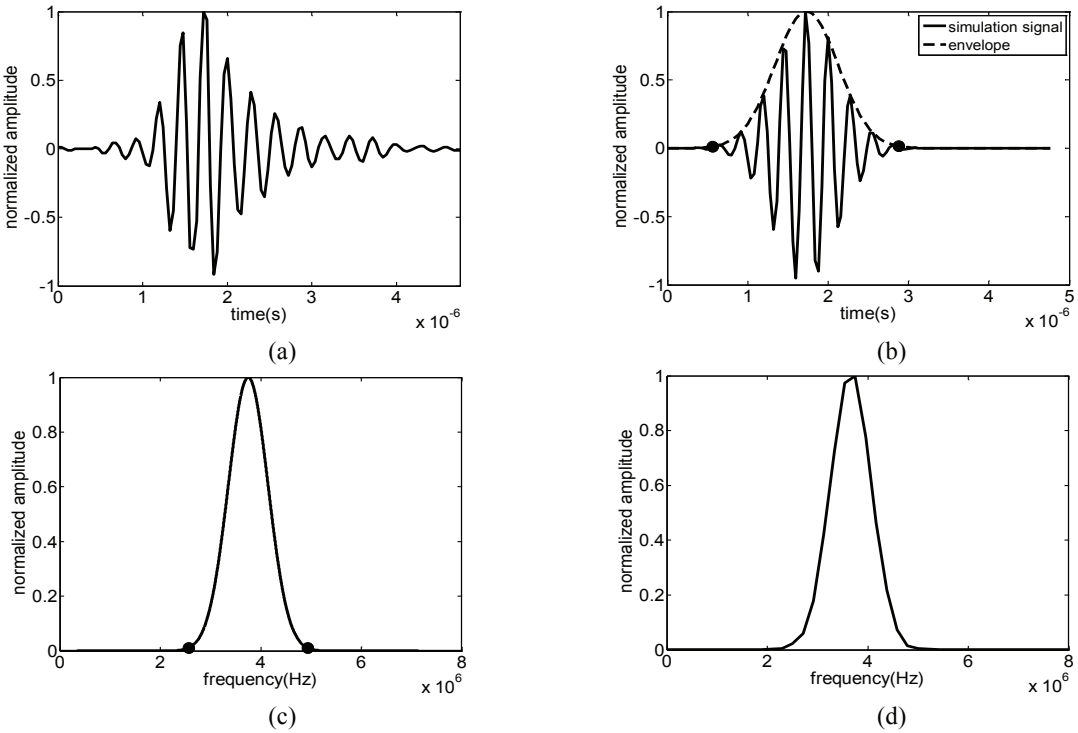

FIGURE 7. Waveform analysis of real signal in time-domain and frequency-domain (a) real signal; (b) estimated signal; (c) spectrum of real signal; (d) spectrum of estimated signal.

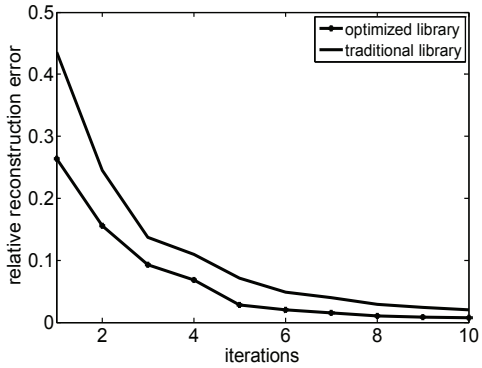

FIGURE 8. RSEs as functions of MP iteration for traditional and optimized Gabor-atom libraries.

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