DOI: 10.3901/CJME.2011.03.***, aviable online at www.cjmenet.com; www. cjmnenet.com.cn

Ultrasonic Nondestructive Signals Processing Based on Matching Pursuit with Gabor Dictionary

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Received Apri 28, 2010; revised March 17, 2011; accepted March 21, 2011; published electronically March 23, 2011

Abstract: The success of ultrasonic nondestructive testing technology depends not only on the generation and measurement of the desired waveform, but also on the signal processing of the measured waves. The traditional time-domain methods have been partly successful in identifying small cracks, but not so successful in estimating crack size, especially in strong backscattering noise. Sparse signal representation can provide sparse information that represents the signal time-frequency signature, which can also be used in processing ultrasonic nondestructive signals. A novel ultrasonic nondestructive signal processing algorithm based on signal sparse representation is proposed. In order to suppress noise, matching pursuit algorithm with Gabor dictionary is selected as the signal decomposition method. Precise echoes information, such as crack location and size, can be estimated by quantitative analysis with Gabor atom. To verify the performance, the proposed algorithm is applied to computer simulation signal and experimental ultrasonic signals which represent multiple backscattered echoes from a thin metal plate with artificial holes. The results show that this algorithm not only has an excellent performance even when dealing with signals in the presence of strong noise, but also is successful in estimating crack location and size. Moreover, the algorithm can be applied to data compression of ultrasonic nondestructive signal.

Key words: ultrasonic signal processing, sparse representation, matching pursuit, Gabor dictionary

1 Introduction

The ultrasonic technique is one of the widely used techniques for nondestructive (NDE) testing of materials. The technique requires efficient methods on the generation and measured waves in waveguides. It also requires the appropriate signal processing of measured signal for the estimation of crack location and size.

While dealing with highly scattering materials, the noise from grain boundaries would significantly affect the signal processing of the ultrasonic signal. Sometimes, the backscattering noise may be so great that the identification of the echo from some small cracks would become very difficult. In order to detect and locate small cracks, one needs a sophisticated signal processing technique. Different signal processing techniques have already been widely utilized, such as the time domain approaches[1] based on cross-correlations and Hilbert transform and the frequency domain approaches[2] based on spectral analysis. However, the backscattered ultrasonic signal is usually a broadband pulse modulated at a center frequency and the transient signal is usually time limited and frequency limited. The backscattering noise usually can not be cancelled by classical time averaging or matched band-pass filtering techniques[3].

Techniques for analyzing nonstationary signals have attracted considerable attention, such as methods based on time-frequency representation[4], wavelet transform[3] and empirical mode decomposition (EMD)[5]. The nonstationary characterization of the useful component of ultrasonic signals can be extracted by these methods while noise is suppressed. Sparse decomposition provides an interpretation of the inherent signal structures, which also can be used to processing ultrasonic NDE signals. Sparse decomposition of a signal can be obtained by iteratively projecting a signal onto a given overcomplete dictionary and chooses the dictionary atom that best matches the signal at each iteration. If the dictionary is so selected to represent well the characteristics of a given signal, only a few atoms will be required for the signal representation. Matching pursuit is a greedy algorithm to realize such decompositions, and has been widely used in many signal processing areas[6].

In this paper, based on matching pursuit algorithm, we decompose the ultrasonic signal in the Gabor dictionary

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This project is supported by National Natural Science Foundation of China (Grant No. 60672108, Grant No. 60372020)

to suppress noise and enhance flaw signals and use the sparse information to estimate the crack location and size. The algorithm is applied to both simulated and experimental ultrasonic signals for flaw detection and the results show it has an excellent performance even deal with signals in the presence of strong noise. Moreover, the proposed method meets the requirements of quantitative nondestructive evaluation[7] to a certain extent, due to it can evaluate the cracks size. In section 2, the matching pursuit algorithm and is briefly reviewed. Section 3 discusses the similarity between Gabor atom and the ultrasonic echo model. The architecture and strategy of the matching pursuit algorithm with Gabor dictionary is described in details. Simulation and experiment results are given in section 4, and our conclusions are drawn in section 5.

2 Matching Pursuit Algorithm

Matching pursuit (MP) is a practical algorithm that decomposes signal into a linear expansion of waveforms selected from an overcomplete dictionary. As opposed to other global optimization techniques, the MP is a greedy algorithm that finds suboptimal in local and its fundamental principle can be described as follows[6].

Let H be a Hilbert space and $D=\{g_\gamma(t)\}_{\gamma\in\Gamma}$ be the overcomplete dictionary in H. The atom $g_\gamma(t)$ is defined by the index γ which is an element of the index set Γ. The atoms are also normalized, hence $\|g_\gamma(t)\|=1$. Let f be the signal and $f\in\mathrm{H}$. Then, f can be decomposed into

$$f=\sum_{n=0}^{m-1}\left\langle R^n f, g_{\gamma_n}\right\rangle g_{\gamma_n}+R^m f, \qquad (1)$$

and

$$\|f\|^2=\sum_{n=0}^{m-1}\left|\left\langle R^n f, g_{\gamma_n}\right\rangle\right|^2+\left\|R^m f\right\|^2, \qquad (2)$$

where $R^m f$ is the residual after the mth iteration (such that $R^0 f=f$), and g_{γ_n} is the atom that best matches the residue $R^n f$. The inner product of $R^n f$ and g_{γ_n} is denoted by $\left\langle R^n f, g_{\gamma_n}\right\rangle$. We assume that g_{γ_n} satisfies

$$\left|\left\langle R^n f, g_{\gamma_n}\right\rangle\right|\geq\alpha\sup_{\gamma\in\Gamma}\left|\left\langle R^n f, g_\gamma\right\rangle\right|,\ 0<\alpha\leq 1. \qquad (3)$$

MP algorithm searches the atom that best matches the last residual, and such process is iterated until the residual energy is below some threshold or until some halting criterion is met. While g_{γ_n} satisfying Eq. (3), MALLAT and ZHANG have proved that the residual energy $\left\|R^m f\right\|^2$ decays exponentially in finite dimensional spaces.

3 Ultrasonic Echo Model and Gabor Dictionary

In this paper, we use a previously developed ultrasonic echo model[7, 8]. The backscattered echo from a flat surface reflector is given by

$$s(t)=\beta\exp\left(-\alpha(t-\tau)^2\cos(2\pi f_0(t-\tau)+\varphi)\right). \qquad (4)$$

The parameters of the echo model are independent and closely related to the physical behavior of the ultrasonic signal inside the material. Time of arrival τ determines the distance between the transducer and the reflector. The attenuation of the original signal and the size of the reflector relative to the beam field are defined by β. Parameter f_0 is the center frequency and α is bandwidth factor modified by the propagation path. The difference in phase φ of the signal is sensitive to the orientation of the reflector.

A Gabor dictionary is defined as an extremely redundant collection of Gabor atoms. Due to the optimal time-frequency resolution of Gabor atoms, the Gabor dictionary is attracted by many researchers and is widely used in problems on sparse signal decomposition[9, 10]. The Gabor atom is a modulated Gaussian function, which having a prescribed center frequency and time spread property, and can be expressed as

$$g_\gamma=\frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)\exp\left(\mathrm{i}\xi t+\varphi\right), \qquad (5)$$

where $g(t)=\exp\left(-\pi t^2\right)$ is the Gaussian window. Therefore, the Gabor atom can be characterized by a index $\gamma=(s,u,\xi)$ of three parameters (s is spread in the time axis or time scale, u is time delay, ξ is center frequency, φ is phase).

The similarity between Gabor atom and the echo model brings many advantages in the decomposition of the ultrasonic signal. The developed ultrasonic echo model is actually the Gabor function. Hence, with the help of matching pursuit algorithm, the reflected pulse may be well approximated by several Gabor atoms. Once the parameter sets are determined by the matching pursuit algorithm, the estimation of the crack in a waveguide is rather straightforward. The parameters estimated from measured echo waves can be then directly used to assess not only the location but also the size of a crack. In this paper, we select the discrete Gabor dictionary proposed in Refs. [6] as the overcomplete dictionary.

The schematic diagram shown by Fig. 1 is an explicit interpretation of the algorithm presented in Refs. [6]. The signal under analysis $R^0 f$ is composed of four Gabor atoms. The matching pursuit method proceeds as follows. After finishing the first iteration, the first atom g_{γ_0} was selected, which best matched the dominating component of $R^0 f$; Subtracting this weighted atom from $R^0 f$ gave the residual signal $R^1 f$. After finishing the second iteration, another atom g_{γ_1} was chosen that best matched the governing component of $R^1 f$. Taking this weighted atom away from $R^1 f$ yielded the residual signal $R^2 f$. After the third iteration, we got the third atom g_{γ_2} and the residual signal $R^3 f$. It is clear that, as the greedy iteration progresses, the energy of residual signal decreases.

$$
\begin{aligned}
f &= R^0 f \\
&= R^1 f + \left\langle R^0 f, g_{\gamma_0} \right\rangle g_{\gamma_0} \\
&= R^2 f + \sum_{n=0}^{1} \left\langle R^n f, g_{\gamma_n} \right\rangle g_{\gamma_n} \\
&\ \vdots \\
&= R^m f + \sum_{n=0}^{m-1} \left\langle R^n f, g_{\gamma_n} \right\rangle g_{\gamma_n} \\
&\ \vdots \\
&= \sum_{n=0}^{+\infty} \left\langle R^n f, g_{\gamma_n} \right\rangle g_{\gamma_n}
\end{aligned}
$$

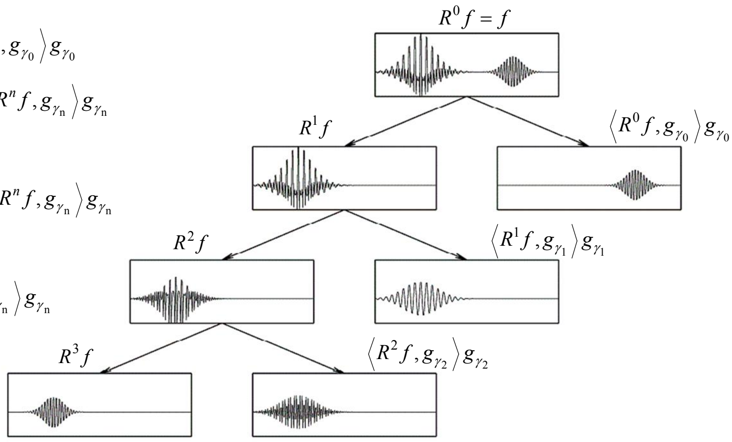

Fig. 1. Pyramidal structure of matching pursuit algorithm

Based on the traditional MP algorithm, several improved fast algorithms have recently been proposed in order to reduce the computational complexity[11–13]. In this paper, we select the improved matching pursuit algorithm[11] which was designed for Gabor dictionary. This algorithm decomposes signal in so called Gabor subdictionaries and is noticeable in reducing computational complexity and memory requirement simultaneously, meanwhile it has similar performance or resolution compared to MALLAT's traditional matching pursuit algorithm[6]. As the traditional MP, we use the residue-to-signal ratio as the halting criteria. The residue-to-signal ratio is defined as $10\log_{10}\left(\left\|R^m f\right\| / \left\|f\right\|\right)$, where $R^m f$ is the final residue after the m th iteration.

4 Performance Evaluations with Simulated and Experimental Ultrasonic Signals

In this section we analyze the performance of the parameter estimation method using simulated and experimental signals. Fig. 2 shows a simulated ultrasonic signal with 3 interfering echoes in the time domain. The signal generated with SNR (signal-to-noise ratio) equals 2.5 dB and we decompose the signal by matching pursuit method with Gabor dictionary. Each echo can be well approximated by a Gabor atom. After all echoes are estimated, they are added to form the reconstructed signal. Fig. 3 gives the constructed signal by adding 3 Gabor atoms obtained. The proposed method successfully extracted meaningful pulses from measured noisy signals. Three flaw echoes can be clearly detected. Very small echoes reflected from a crack, which would be difficult to defect by other methods, were captured by the approach.

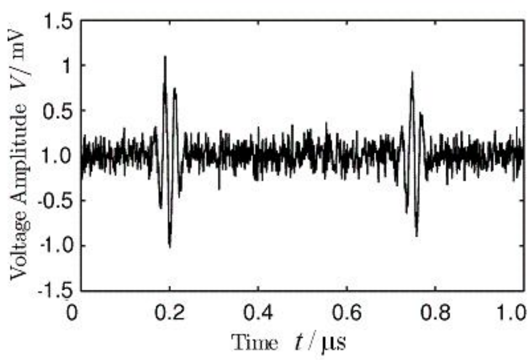

Fig. 2. Simulated signal with three flaw echo (SNR=2.5 dB)

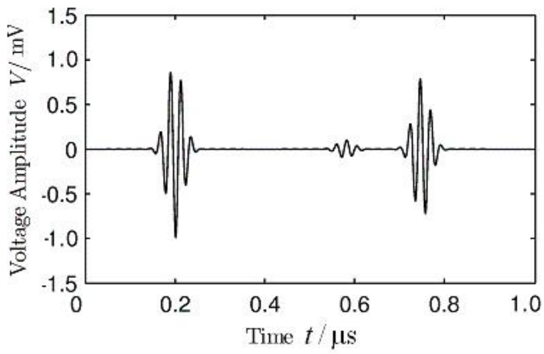

Fig. 3.　Constructed signal by adding 3 Gabor atoms obtained with matching pursuit algorithm

The algorithm was also additionally tested with an experimental ultrasonic signal. The data represents multiple backscattered echoes from a thin metal plate with artificial hole measured via a 2 MHz longitudinal transducer. The cylindrical blind hole is at the bottom side of the plate and underside of the transducer. Fig. 4 shows the experimental signal. Fig. 5 shows the estimated signal by adding 9 Gabor atoms obtained. For the examples in this paper, the criteria for the stopping the MP decomposition is the final residue-to-signal ratio equals –16.3 dB approximately. The incident pulse and the echoes reflected by crack and the end of the metal rod are clear revealed. It can be observed that background noise energy is reduced considerable with the proposed technique, while flaw energy is maintained.

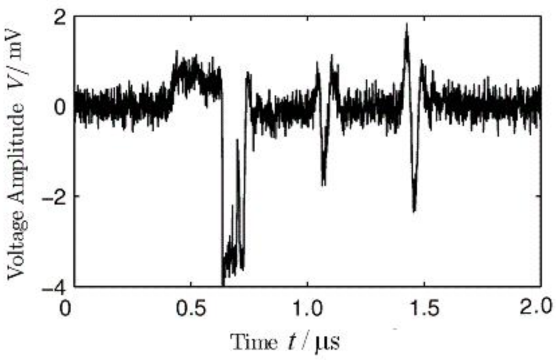

Fig. 4. Experimental ultrasonic signal

Traditionally, the size of the crack can be estimated by the amplitudes of the incident and reflected echoes. However, when the crack size is very small and the SNR is low, the arrival time and the amplitude of echo would be difficult to estimate by traditional methods. Compared with those traditional methods, the amplitudes of the incident and reflected echoes can be directly obtained by the proposed algorithm and used to estimate the crack location and size. First, the time localization of the Gabor atom is good because the energy is concentrated near the time center. This property helps to estimate the crack location. Second, the amplitude of the Gabor atom gives more accurate estimation of the amplitude of the crack echo due to avoid the influence of noise. In Table 1, the estimated locations and crack sizes are tabulated. The exact values are also presented for the comparison. The effectiveness of the proposed method in identifying the location of incident and reflected pulses from noisy signal is shown.

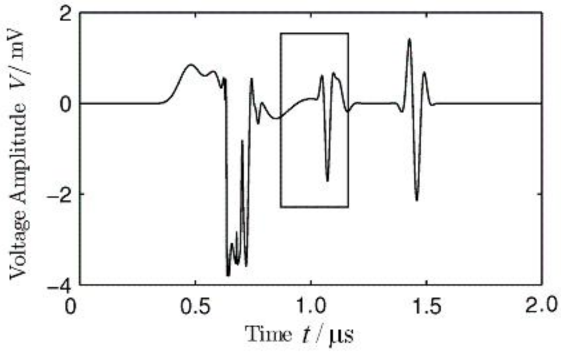

Fig. 5. Constructed signal by adding 9 Gabor atoms obtained with matching pursuit algorithm (The echo in the rectangle box is the echo reflected through crack.)

Table 1.　Exact and estimated crack locations and sizes

Estimation item	Exact value	Estimated value
Crack location *x*/mm	4	4.13
Crack diameter *d*/mm	6	5.67

Comparing with traditional ultrasonic signal processing technology, the proposed method does have special changes or requirements on the waveform generation and measurement steps. Hence, the proposed method can be used in general ultrasonic inspection signal processing and ultrasonic imaging, especially while dealing with heavy noise and materials that have a high scatter nature. The guided-wave inspection technology has been widely used for long-range damage detection and covers a wider range by propagating elastic pulses along waveguide and capturing the reflected pulses from the damage in waveguides. The traditional sine pulse is not concentrated in time and frequency domain. Pulse signal will become considerably dispersed as it propagates in highly scattering materials and the time localization would become bad. Correspondingly, the effect of dispersion is not severe with the Gabor function due to good time and frequency localization. Hence, the Gabor pulse is sometimes selected as the incident pulse to replace the common truncated sines especially by the guided-wave technology. A two-stage matching pursuit algorithm is developed as an effective guided-wave inspection signal processing method[14].

5 Conclusions

(1) The Gabor atom has the optimal time-frequency concentration while the noise does not has any time-frequency characteristic, hence, matching pursuit algorithm with Gabor dictionary can not only realize signal sparse representation but also work as a denoising algorithm. With suitable stopping rule, the matching pursuit algorithm can remove the white noise effectively.

(2) The similarity between Gabor atom and the echo model brings many advantages in the decomposition of the ultrasonic signal. The proposed method can successfully extract meaningful pulses which are represented by Gabor atoms from measured noisy signals. Complex ultrasonic signal can be decomposed into the superposition of multiple single Gabor atoms. The accurate estimation of time center and amplitude of Gabor atoms can help to estimate the crack locations and sizes. Hence, the proposed method meets the requirements of quantitative nondestructive evaluation to a certain extent.

(3) By matching pursuit algorithm, the ultrasonic NDE signal is represented by a few of Gabor atoms. This kind of representation is sparse. Hence, this algorithm can be used as a kind of data compression techniques to facilitate the analysis and remote access of ultrasonic information.

References

[1] GRENNBERG A, SANDELL M. Estimation of subsample time delay differences in narrowband ultrasonic echoes using the Hilbert transform correlation[J]. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* 1994, 41(5): 588−595.

[2] LI Yen, KURKJIAN A. Arrival time determination using iterative signal reconstruction from the phase of the cross spectrum[J]. *IEEE Transactions on Acoustics Speech Signal Processing*, 1983, 31(2): 502−504.

[3] ABBATE A, KOAY J, FRANKEL J, et al. Signal detection and noise suppression using a wavelet transform signal processor: Application to ultrasonic flaw detection[J]. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 1997, 44(1): 14−26.

[4] NIETHAMMER M, JACOBS L J, QU Jianmin, et al. Time-frequency representations of Lamb waves[J]. *The Journal of the Acoustical Society of America*, 2001, 109(5): 1 841−1 847.

[5] MAO Yimei, QUE Peiwen. Ultrasonic flaw detection using EMD-based signal processing[J]. *High Technology Letters*, 2006, 12 (1): 14−17.

[6] MALLAT S G, Zhang Zhifeng. Matching pursuits with time-frequency dictionaries[J]. *IEEE Transactions on Signal Processing*, 1993, 41(22): 3397–3415.

[7] ACHENBACH J D. Quantitative nondestructive evaluation[J]. *International Journal of Solids and Structures*, 2000, 37(1): 13–27.

[8] CARDOSO G, SANIIE J. Data compression and noise suppression of ultrasonic NDE signals using wavelets[C]//*IEEE Symposium on Ultrasonics*, Lake Tahoe, CA, October 2003: 250–253.

[9] LOBO A P, LOIZOU P C. Voiced/unvoiced speech discrimination in noise using Gabor atomic decomposition[C]//*IEEE International Conference on Acoustics, Speech, and Signal Processing*, Dallas, Texas, April 2003: 820–823.

[10] STURM B L, Gibson J D. Matching pursuit decompositions of non-noisy speech signals using several dictionaries[C]//*IEEE International Conference on Acoustics, Speech, and Signal Processing*, Toulouse, May 2006, 3: 456–459.

[11] GUO Jinku, LIU Guangbin, YANG Xiaojun. A novel matching pursuit algorithm with adaptive subdictionary[C]//*ICSP 2008 9th international Conference on Signal Process*ing, Beijing, China, October 2008: 207–210.

[12] JOST P, VANDERGHEYNST P, FROSSARD P. Tree-based pursuit: algorithm and properties[J]. *IEEE Transactions on Signal Processing*, 2006, 54(12): 4685–4697.

[13] KRSTULOVIC S, GRIBONVAL R. MPTK: Matching pursuit made tractable[C]//*IEEE International Conference on Acoustics, Speech, and Signal Processing*, Toulouse, May 2006: 496–499.

[14] HONG Jin-Chul, SUN K H, KIM Y Y. Waveguide damage detection by the matching pursuit approach employing the dispersion-based chirp functions[J]. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* 2006, 53(3): 592−605.

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