Ultrasonic signal denoising technology based on SMP algorithm

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Abstract: Flip chip technology has been rapidly developed and widely used in the field of microelectronic packaging, and defect detection has received increasing attention. The ultrasonic detection method is used to detect the defect information of the packaged chip. However, the ultrasonic signal obtained during the detection process is disturbed by noise, which seriously affects the true information of the defect signal. For this problem, the matching matching pursuit (SMP) algorithm is used in combination with Gabor. The atomic library realizes adaptive matching of noisy ultrasonic signals. The linear combination of selected atoms is used to represent the denoised signals to achieve the denoising effect of noisy ultrasonic signals. The denoising effect of the SMP algorithm in the experiment is compared with the MP algorithm, and the results show that the denoising effect of the SMP algorithm is better.

1. Introduction

Flip-chip packaging technology, as a fast-growing and widely used microelectronic packaging technology, has many advantages such as high alignment accuracy, short interconnect lines, and high input-output density [1-2]. Ultrasonic echo estimation carries the defect information of the interface through each ultrasonic reflection echo [3]. When performing ultrasonic non-destructive testing, noise is often accompanied by noise interference, which will change the true information returned by the ultrasonic echo, which will cause great difficulties in subsequent analysis of defect information. Therefore, how to effectively remove the noise doped in the ultrasonic signal and obtain the true characteristics of the signal is of great significance for the subsequent development of packaging technology.

The main methods of signal denoising at this stage include wavelet transform and empirical mode decomposition. Although some results have been achieved, there are still some shortcomings. The calculation of wavelet transform is large, and there are some problems in the choice of wavelet base and threshold setting. Empirical mode decomposition leads to the problem of mode aliasing. In 1993, Mallat and Zhang proposed a matching pursuit (MP) algorithm based on overcomplete libraries [4], which represented signals as linear combinations of several atoms in an overcomplete library. It is widely used in image processing, signal processing, compression and feature extraction. In 2010, Etai Mor, Amnon Azoulay introduced support based on the MP algorithm, and proposed a support matching pursuit (SMP) algorithm [5]. When selecting atoms in an overcomplete database, each atom can more accurately extract signal features. In this paper, the Gabor atomic library is used as an over-complete library combined with the SMP algorithm to denoise the ultrasonic signals, and compared with the denoising results of the MP algorithm.
2. Matching Pursuit (MP) algorithm

MP algorithm is a kind of sparse decomposition algorithm. The basic idea is to select an atom that most closely matches the signal \( y \) from the overcomplete atomic library to sparse approximation, find the signal residual, and then continue to choose in a overcomplete atom library with the atoms best matches the residual signal, repeated iterations. The signal \( y \) can be represented by the linear sum of these selected atoms. In each iteration of MP algorithm, the atom with the largest inner product of atom and signal in the overcomplete library is selected to approximate the signal \([6]\). The larger the inner product, the greater the correlation between the signal and the atom in the dictionary library, and this atom can be used to approximate the signal characteristics. The specific steps to MP algorithm are as follows:

1. Input signal \( y \) to be processed, calculate the inner product of signal \( y \) and all atom in the overcomplete library, and select the atom with the largest inner product absolute value from them, which must satisfy the condition:
   \[
   \| < y, x_r > \| = \max_{r \in \{1,...,k\}} | < y, x_r > |
   \]  
   \( r_0 \) represents a column index of atoms in an overcomplete library.

2. The signal \( y \) is decomposed into the component of the best matching atom and the residual signal. The decomposition process is as follows:
   \[
   y = < y, x_{r_0} > x_{r_0} + R_0 f
   \]  
   \( R_0 f = y \), \( R_0 f \) represents the residual signal after the first iteration of the algorithm.

3. The decomposition of the residual signal is repeated repeatedly in the manner of step (2), and after \( k \) decompositions, it is obtained:
   \[
   R_k f = < R_k f, x_{r_k} > x_{r_k} + R_{k+1} f
   \]  

4. After \( K \)-step decomposition, the signal \( y \) is finally expressed as:
   \[
   y = \sum_{n=0}^{k} < R_n f, x_n > R_n f + R_{k+1} f
   \]

3. Ultrasonic signal denoising based on support matching pursuit (SMP) algorithm

3.1. Support matching pursuit algorithm

The SMP algorithm is an improved MP algorithm. Based on the matching pursuit algorithm, the concept of support is introduced. When selecting a signal atom, an atom with a correlation coefficient higher than a specific threshold is selected to obtain the residual with the lowest robust support Difference, the residuals at each iteration can be accurately approximated by a single atom in the super-complete library. The support formula is as follows:

\[
\| r \|_\xi = \sum_{i=1}^{N} | r(t_i) | ^\xi, 0 \leq \xi \leq 1
\]

for \( \xi = 0 \), \( \| r \|_0 \) is non-zero points in \( r(t_i) \). It satisfies the theory of support mentioned above, and selects the signal atom that best matches the residual while reducing the residual energy at each iteration.

The specific steps to support matching pursuit algorithm are as follows:

1. Enter the signal to be processed \( y \), the super-complete atomic library \( D \), the threshold \( \xi \), and the initial residual \( r_0 = y \), and calculate the inner product of the current residual and all atoms in the super-complete atomic library according to the following formula:
   \[
   c_\xi = D^T r_\xi
   \]
(2) According to a preset threshold, select all the atoms with a residual inner product greater than the threshold from the overcomplete atomic library \( D \) to obtain a new candidate atom library \( P_z \);

(3) Calculate the residual at the next iteration of each atom in \( P_z \) according to the formula:

\[
r_{p,z+1} = r_z - c_z(p)d_p
\]

\( p \) is the position of the selected atom in \( D \), and \( d_p \) is the \( p \)-th column vector of \( D \).

(4) When \( P_z \) is not empty, the atom with the smallest \( r_{p,z+1} \) similar parameter is selected as the optimal atom; when \( P_z \) is the empty set, the atom with the largest inner product is the optimal atom.

(5) Update residual \( r_z \);

(6) When the residual is less than the residual threshold, which is \( \| r_z \|_2 < \varepsilon \), stop the algorithm iteration, otherwise return to step (2);

(7) When the termination condition is satisfied, the linear combination of the selected atoms is used to represent the denoised result;

3.2. Denoising principle
A noisy signal is a signal composed of a noiseless signal and a noise signal. The noiseless signal can be approximated by a matching pursuit algorithm combined with an overcomplete atomic library, and a noiseless signal is represented by a limited number of atoms. The noise is randomly distributed and cannot match the atomic approximation in the overcomplete library, that is, the noise cannot be represented by a finite number of atoms.

In order to obtain a more accurate signal representation, an appropriate overcomplete atomic library is selected. Reference [6] shows that Gabor atomic library has a good feature representation for ultrasonic signals, and sparse decomposition of noise-containing signals is carried out by combining SMP algorithm to finally achieve the goal of noise removal.

4. Experimental results and analysis
In the experiment, the collected ultrasonic signal without noise was used as the original signal, and the same original signal was used to add the same Gaussian white noise to synthesize the noisy signal. In order to verify the denoising effect of SMP algorithm, we used Gabor atomic library as the supercomplete atomic library, and combined SMP algorithm with overcomplete atomic library to denoise the denoising signal. At the same time, MP algorithm combined with the overcomplete atomic library is used to denoise the same noise signal, and compared the denoising effect of two sparse decomposition algorithms on the noisy signal.

In order to compare the denoising effects of the two algorithms, the signal-to-noise ratio (SNR) is used as the evaluation criterion. The formula for calculating the signal-to-noise ratio is as follows:

\[
SNR=10\log\left(\frac{P_s}{P_n}\right)
\]

Where \( P_s \) represents the effective power of the original signal and \( P_n \) represents the effective power of the noise.

Part of the experimental results are shown below. The experimental results after increasing the noise are shown as follows. Figure 1 (a) shows the original signal. Figure 1 (b) shows the noise signal synthesized after adding strong noise. Figure 1 (c) shows the results of SMP algorithm after denoising. Figure 1 (d) shows the denoising results of MP algorithm.
In order to compare the denoising effects of the SMP algorithm and the MP algorithm more intuitively, we add Gaussian white noise with a signal-to-noise ratio of 5dB, 10dB, 15dB, 20dB, and 25dB to the original signal, through the two algorithm combined with complete Gabor super atom library after denoising after denoising the reconstructed signal, to produce the output signal-to-noise ratio such as shown in the table1 below:

| Input SNR | SMP algorithm output SNR | MP algorithm output SNR |
|-----------|--------------------------|-------------------------|
| 5dB       | 4.8344                   | 4.2208                  |
| 10dB      | 9.3520                   | 8.7642                  |
| 15dB      | 12.7587                  | 11.9586                 |
| 20dB      | 15.0586                  | 14.2423                 |
| 25dB      | 16.1136                  | 15.5932                 |

The following shows a set of measured signals as the original signals, and the denoising results of the MP algorithm and the SMP algorithm after adding strong noise. Fig. 2 (a) is a measured ultrasonic signal; Fig. 2 (b) is a noisy signal after adding strong noise to the measured ultrasonic signal; Figure 2(c) shows the results of SMP algorithm after denoising. Figure 2(d) shows the denoising results of MP algorithm.
5. Conclusion
In this paper, we selected the Gabor atomic library that best matched the ultrasonic detection signal characteristics as the overcomplete atomic library, which was combined with SMP algorithm and MP algorithm respectively to conduct denoising processing on the defect signal in the inverted packaging chip. The simulated ultrasonic signal was denoised by two algorithms to obtain the signal-to-noise ratio after denoising. Through multiple sets of experiments, the SNR of the SMP algorithm is higher than the SNR of the Mp algorithm. Therefore, the SMP algorithm has a better denoising effect on noisy ultrasonic signals.

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