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Ultrasonic tomography based temperature distribution measurement method

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ABSTRACT

The temperature distribution information plays an important role in industrial applications. Owing to the advantages such as non-intrusive sensing and low cost, the ultrasonic tomography (UT) is considered to be a promising method for temperature field visualization. The ultrasonic time-of-flight (TOF) measurement and the reconstruction algorithm are crucial for practical applications of the UT measurement. In this paper, a dual-threshold measurement method is proposed to ensure a high-quality TOF measurement. In view of the inaccurate nature of the reconstruction model and TOF data, a new reconstruction method that integrates the advantages of the Tikhonov regularization method and the least squares support vector machine (LSSVM) is proposed to improve the reconstruction quality. The experimental results were compared against thermocouple measurements and the results show that the temperature distribution can be reconstructed with the error of 1.3%, which validates the feasibility and effectiveness of the proposed Tikhonov-LSSVM reconstruction algorithm.

1. Introduction

Obtaining the high-quality measurement of temperature distribution plays a significant role in a wide range of industries [1–3], such as boiler furnace, and stored grain. As a temperature field visualization method, the ultrasonic tomography (UT) measurement has been widely used owing to advantages such as non-intrusive sensing and low cost [4,5]. Therefore, the UT measurement is employed to implement the temperature distribution measurement in this paper.

The UT measurement principle shows that the temperature can be obtained by the TOF data. Therefore, it is vital to measure the TOF data accurately using an appropriate method. Common TOF measurement methods [6–9] include the phase difference method, the cross-correlation method and the threshold method. Many factors, such as response delay and additional path of transducers, lead to the change of the phase difference. They are the main reasons that the phase difference method requires the high precision hardware. The cross-correlation method calculates the maximum correlation coefficient of the received signal and the reference signal. However, in practice the received signal attenuates and leads to the distortion of the waveform. The threshold method [10] records the instant when the received signal voltage exceeds a prescribed threshold, and the ultrasonic TOF is determined from the time difference between the transmit and receive instants. Owing to advantages like easy implementation, low complexity, the threshold method has found wide applications in various measurement fields [11]. Additionally, in this paper, ultrasonic wave is used to reduce the influence of environmental noise and amplifier circuits are employed to receive the ultrasonic signals, which alleviates the effect of dispersion.

Another key issue in the UT measurement is to improve the reconstruction quality. Existing methods include the truncated singular value decomposition (TSVD) method [12], the Landweber iteration algorithm [13], the Tikhonov regularization method [14–18], the algebraic reconstruction technique (ART) [19,20], the simultaneous iterative reconstruction technique (SIRT) [21,22], and the simultaneous algebraic reconstruction technique (SART) [23,24]. The TSVD method can achieve a stable numerical solution via truncating the small singular values that approximate zero. However, determining the truncated singular values is difficult, especially when the singular values of the coefficient matrix are continuously descending. In essence, the Landweber iteration algorithm belongs to the steep descend method from the viewpoint of the numerical optimization, and the convergence speed is relatively low. In addition, the disadvantages, such as semi-convergence characteristic and excessive smoothness effect, restrict its applications. The Tikhonov regularization method is a popular approach to solving the inverse problem, which has found

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wide applications in various fields [14–18]. The ART and the SIRT methods are considered as an iterative solver of the system of linear equations. For relatively complex reconstruction problems, however, the results reconstructed by both algorithms are far from satisfactory. The SART method is proposed as a major improvement of the ART, which has received increasingly more attention. Generally, the acquisition of the high-quality reconstruction results is important in the field of the UT measurement.

In this paper, an ultrasonic TOF measurement method based on dual-threshold and a reconstruction algorithm that incorporates Tikhonov and LSSVM methods are proposed to address the above challenges. The main contributions are summarized as follows:

(1) The dual-threshold method alleviates the problem that the negative half-cycle of the received ultrasonic signals may be firstly received, which leads to improved accuracy of the TOF data.
(2) In contrast with existing reconstruction methods, with the simultaneous consideration of the inaccurate properties of the reconstruction model and the TOF data, the Tikhonov-LSSVM algorithm is proposed to improve the reconstruction quality.
(3) Numerical simulations and experimental studies are carried out to validate the feasibility and effectiveness of the proposed methods.

The rest of this paper is organized as follows. We present the dual-threshold based ultrasonic TOF measurement method in Section 2. The Tikhonov-LSSVM reconstruction algorithm is presented in Section 3. In Section 4, experimental studies are conducted to evaluate of the feasibility and effectiveness of the proposed methods. Finally, the main conclusions are drawn in Section 5.

2. Dual-threshold based ultrasonic TOF measurement method

The UT measurement has received wide popularity in various fields [1–3]. However, in real-world ultrasonic TOF measurements, it is known that measurement errors may arise in the following situations:

(1) Due to the ultrasonic attenuation, amplifier circuits are used to condition the ultrasonic signals [25], which leads to the deviation of received wave signals, and the phenomenon of zero drift will appear.
(2) In the receiving process, the possibilities of trapped wave and short wave in received signals will increase, which results in the situation that the negative half-cycle of the signals may be firstly received. If the influence is ignored, the starting point of received signals will be postponed for a half cycle, thereby leading to measurement error.
(3) With the variation of external environment, the amplitude of noise signals will change, which is difficult to distinguish the starting point of the received signals. Consequently, the constant threshold may misidentify the real received wave signals.

In this paper, we propose a dual-threshold based ultrasonic TOF measurement technique to improve the measurement accuracy of the ultrasonic TOF data. The specific flowchart is shown in Fig. 1.
Specifically, the method can be divided into the following steps:

Step 1. Data acquisition card receives the ultrasonic signals.
Step 2. The received signals remove the trend item.
Step 3. The *Daubechies* wavelet is employed to de-noise the signal [26–28] owing to its good numerical performances. The de-noising algorithm is described by

$$d_t = D(q_t) = D(u_t - \hat{u}_t) = D[u_t - (\alpha_0 + \alpha_1 t + \alpha_2 t^2 + \alpha_3 t^3)] \\ = D\left[u_t - \sum_{j=0}^{3} \alpha_j t^j\right] \quad (t = 1, 2, \cdots, n) \tag{1}$$

where q_t represents the received wave signals without the trend item; u_t is the real measurement signal sequence; $\hat{u}_t$ stands for the third-order polynomial to fit the trend item; α_i ($i = 0, 1, 2, 3$) represents the polynomial coefficient; $D(\cdot)$ defines the program of the *Daubechies* wavelet de-noising, and d_t is the data after de-noising process.
Step 4. The threshold voltage of the processed signals is determined in both positive and negative half-cycle directions, in which the adjacent time points t_i that are shown in Fig. 2 are obtained according to the intersection of the threshold voltage line and received signals.
If the adjacent time difference is satisfied with Eq. (2), the threshold line stops delineate, and the threshold voltage is obtained

$$t_3 - t_1 \approx t_4 - t_2 \approx \cdots \approx t_{i+2} - t_i \approx \Delta t \approx \frac{1}{f} \quad (i = 1, 2, \cdots) \tag{2}$$

where Δt represents the adjacent time difference; f stands for the transmitting frequency of the ultrasonic transducer.
Step 5. The voltage with the larger absolute values in the positive and negative half-cycle is considered as the final threshold voltage. The final threshold voltage contains the signs of positive and negative.

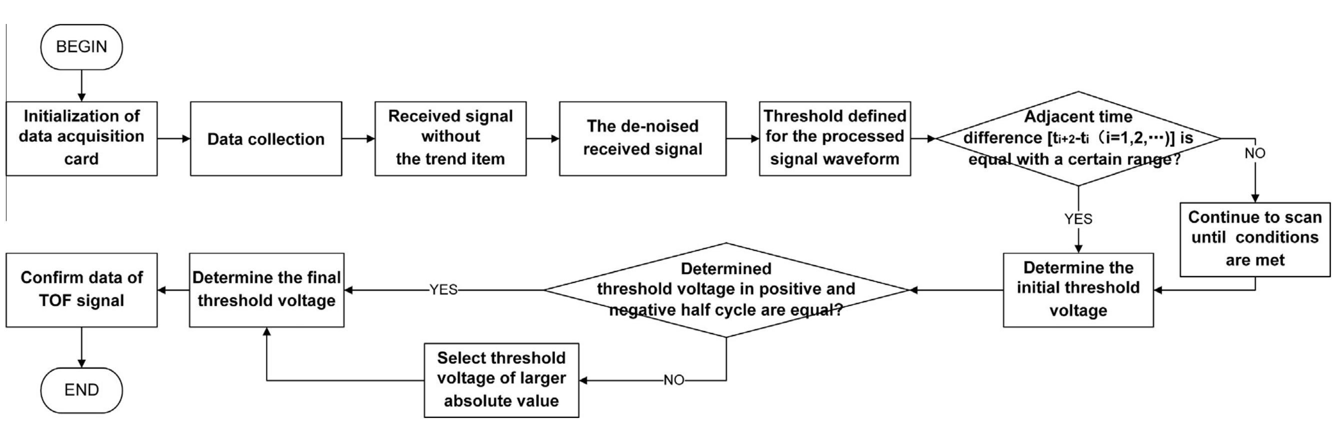

Fig. 1. Flowchart of the dual-threshold based ultrasonic TOF measurement. This figure illustrates the specific flowchart of the dual-threshold ultrasonic TOF measurement technique.