Reliable realization of target source detection technology under laboratory conditions

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Abstract. Target source detection technology has been widely applied in the fields of military, aviation, and navigation, etc. In order to enable students to master target source detection technology, it is necessary to be applied to the practical education of students. In the paper, one method of planar target source detection based on the time delay estimation and the sensor placed in a line is analyzed. To verify the reliability of the implementation of planar target source detection technology under laboratory conditions, with the aid of INV acceleration sensor, INV signal acquisition instrument and DASP analysis software, the detecting experiment of vibration target source on the plane was carried out by using the target source detection method that has been analyzed. The results of experiment showed that the relative errors of the distance and direction angle between the detected target and each sensor are less than 9%.

Key words. Target source detection, target location algorithm, time delay estimation method, error analysis

1. Introduction

Target source detection technology is a technology that uses a certain target location algorithm to detect the target source location, which has important applications in military, aviation, navigation, and other fields. At present, the target source detection technology has been paid more and more attention [1], and various target source detection methods are also emerging. In many methods of target source detection, different detection methods are put forward mainly according to the different array arrangement of sensors. In literatures [2-6], target source detection method based on four element arrays, five element array, six element arrays, seven element array and multi element arrays were put forward respectively. These detection methods are often able to achieve more accurate target source location in plane or space, which are mainly applied in the fields of aviation, navigation, military and other large-scale occasions. However, the application of target source detection technology for students in practical teaching is less. In order to enable students to master the target detection technology, it is necessary to make the technology applied in practical teaching. Based on the analysis of existing target source detection methods, a target source detection method that is convenient for practical teaching is chosen in the paper. Under the laboratory condition, the target source detection experiment is completed, the error between the detected parameter value and its actual value is analyzed, and the accuracy evaluation is given to ensure the reliability of its implementation. Furthermore, it lays the foundation for students to master the target source detection technology and carry out the practical teaching of target detection.
2. Principle of target source detection

2.1. Target location method
Among many target location algorithms, a method of plane target location based on time delay estimation and the sensor placed in a line is selected to make the target source detection realized reliably in the laboratory. The model of target source detection experiment [7] is shown in Figure 1. Three sensors marked $b_1$, $b_2$ and $b_3$ are placed on a straight line, and the fixed distance between two of them is $a$. The distance between the position of the target source marked $O$ and each sensor are represented by $x_1$, $x_2$ and $x_3$ ($x_1 < x_2 < x_3$), and the direction angles between the position of the target source marked $O$ and each sensor are represented by $\alpha_1$, $\alpha_2$ and $\alpha_3$ respectively.

![Figure 1. Schematic diagram of target source detection model.](image)

If $b_1$ is used as the reference sensor shown in figure 1, compared with the time from the target signal sent by the target source $O$ to $b_1$, the time from the target signal sent by the target source $O$ to $b_2$ and $b_3$ will produce delay (time delay), which are respectively recorded as $\tau_{21}$ and $\tau_{31}$. The propagation velocity of the target signal received by the sensor is set as $v$. Target source detection parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ can be obtained by cosine theorem and sine theorem, as shown in formulas (1) and (2), which can describe the specific location of the target source $O$.

\[
x_1 = \frac{2a^2 - v^2 \tau_{31}^2 + 2v^2 \tau_{21}^2}{2v \tau_{31} - 4v \tau_{21}}
\]

\[
x_2 = v \tau_{21} + x_1
\]

\[
x_3 = v \tau_{31} + x_1
\]

\[
\alpha_1 = \arccos \frac{x_2^2 - x_1^2 - a^2}{2x_1a}
\]

\[
\alpha_2 = \frac{x_1(\pi - \alpha_1)}{x_2}
\]

\[
\alpha_3 = \frac{x_1(\pi - \alpha_1)}{x_3}
\]

2.2. Time delay estimation method
In the process of the target source detection, time delay $\tau_{21}$ and $\tau_{31}$ are important parameters and need to be estimated. In a wide range of time delay estimation methods, the cross-correlation method is a simple and feasible method of time delay estimation, which can be mastered by students easily. Therefore, the cross-correlation method is used to calculate the time delay $\tau_{21}$ and $\tau_{31}$ in the experiment of target detection.

The essence of cross-correlation method is to obtain correlation function of two signals with delay through correlation analysis, and find out the peak position $\tau_m$ of correlation function which is the time delay value desired. It is assumed that the signal model collected by sensors $b_1$, $b_2$ and $b_3$ is shown in formula (3), according to which, how to use cross-correlation method to calculate the delay value is analyzed as follows.

$$x_1(t) = s(t) + n_1(t)$$
$$x_2(t) = s(t - \tau_{21}) + n_2(t)$$
$$x_3(t) = s(t - \tau_{31}) + n_3(t)$$

In the formula (3), $s(t)$ is the signal emitted by the target source $O$, $n_1(t)$, $n_2(t)$ and $n_3(t)$ are noise signals, and $s(t)$, $n_1(t)$ and $n_2(t)$ are incoherent to each other. In order to obtain the time delay $\tau_{21}$ and $\tau_{31}$, the correlation functions $R_{12}(\tau)$ of $x_1(t)$ and $x_2(t)$ and $R_{13}(\tau)$ of $x_1(t)$ and $x_3(t)$ need to be calculated respectively, as shown in formula (4).

$$R_{12}(\tau) = \int_{-\infty}^{\infty} x_1(t) x_2(t - \tau) dt$$
$$R_{13}(\tau) = \int_{-\infty}^{\infty} x_1(t) x_3(t - \tau) dt$$

In the correlation functions above, when the time delay $\tau = \tau_{21}$ and $\tau = \tau_{31}$, $R_{12}(\tau)$ and $R_{13}(\tau)$ will achieve the peak value. Here, $\tau_{21}$ and $\tau_{31}$ are the time delay value of the target signals sent by the target source $O$ arriving at sensor $b_2$ and $b_3$, compared with arriving at sensor $b_1$ [8-9].

3. Experimental process of target source detection

In Laboratory, INV signal acquisition instrument (as shown in figure 2), INV 9821 acceleration sensor (as shown in figure 3), computer and DASP software are mainly included in the experiment of target source detection. Acceleration sensor is mainly used to test the vibration signal. INV signal acquisition instrument can realize the acquisition of multiple vibration signals. DASP software is loaded on the computer through which correlation analysis for the acquired vibration signal is carried out to obtain the delay $\tau_{21}$ and $\tau_{31}$.

![Figure 2. INV signal acquisition instrument.](image1)

![Figure 3. INV 9821 acceleration sensor.](image2)

The target source in the experiment is selected on the floor of laboratory. Due to the complexity of the floor material, the propagation velocity of vibration signal on the floor cannot be directly obtained. Therefore, it is necessary to calibrate the propagation velocity of target signal received by
the sensor. Referring to figure 4, White paper is laid on the ground, and the Small square grid with a side length of 5cm is drawn on the white paper to express the distance. Vibration target source is selected between two acceleration sensors, and the vibration signal is generated by knocking at the position of vibration target source. The propagation velocity is calculated according to the distance difference between the vibration signal and the two sensors and the time difference of vibration signal transmitted to two sensors obtained from the correlation analysis, as shown in formula (5).

\[ v = \frac{\Delta d}{\Delta t} \]  

(5)

In the formula (5), \( v \) is the propagation velocity of vibration signal, \( \Delta d \) is the distance difference between the vibration signal and the two sensors, and \( \Delta t \) is the time difference of vibration signal transmitted to two sensors.

In the experiment of velocity calibration, the propagation velocity of vibration signal is measured when the distance difference between the vibration signal and the two sensors is 55cm, 60cm, 70cm and 80cm respectively. After repeated measurements, the propagation velocity of the vibration signal generated by knocking on the laboratory floor is calibrated as 167.22 m/s.

After the propagation velocity calibration of vibration signal, referring to figure 5, a piece of white paper with a length of 120cm and a width of 90cm is laid on the floor of laboratory, on which the small square grid with a side length of 5cm was drawn in advance. On a flat surface laid with white paper, three sensors marked \( b_1 \), \( b_2 \) and \( b_3 \) are placed in a straight line and firmly pasted with adhesive tape. The distance between adjacent sensors is equal to 50 cm. The distance from the actual position of the target source to the three sensors \( x_1 \), \( x_2 \) and \( x_3 \) are 65cm, 85cm and 123cm respectively, and the direction angle \( \alpha_1 \), \( \alpha_2 \) and \( \alpha_3 \) of the target source to the three sensors are 85°, 50° and 31° respectively. The INV signal acquisition instrument, acceleration sensor and computer are well connected. Small steel hammer is used to knock at the target source position to generate vibration signal. Target source detection experiment is carried out according to the target source detection principle put forward above, and the parameters \( x_1 \), \( x_2 \), \( x_3 \), \( \alpha_1 \), \( \alpha_2 \) and \( \alpha_3 \) are calculated respectively by Programming with MATLAB. In order to analyze the detection accuracy of the target source, the difference between the detected value and the actual value is compared.

4. Experimental results and analysis

According to the process of target source detection experiment above, 12 groups of target source detection experiment were carried out, and the obtained parameter values are shown in Table 1.
Table 1. Results of target source detection experiment.

| groups | $x_1$ (cm) | $x_2$ (cm) | $x_3$ (cm) | $\alpha_1$ (°) | $\alpha_2$ (°) | $\alpha_3$ (°) |
|-------|-----------|-----------|-----------|---------------|---------------|---------------|
| 1     | 57        | 77        | 131       | 90            | 56            | 37            |
| 2     | 59        | 74        | 137       | 73            | 51            | 30            |
| 3     | 59        | 74        | 130       | 79            | 53            | 38            |
| 4     | 61        | 81        | 129       | 74            | 55            | 29            |
| 5     | 55        | 80        | 122       | 75            | 52            | 33            |
| 6     | 59        | 82        | 132       | 91            | 52            | 32            |
| 7     | 62        | 79        | 130       | 90            | 52            | 33            |
| 8     | 58        | 78        | 128       | 79            | 57            | 34            |
| 9     | 56        | 75        | 129       | 78            | 51            | 36            |
| 10    | 64        | 81        | 135       | 77            | 51            | 32            |
| 11    | 61        | 80        | 136       | 78            | 52            | 34            |
| 12    | 62        | 77        | 127       | 81            | 52            | 35            |

According to the data measured in Table 1, the parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ do not equal the actual values preset in the experiment, and there are errors in measured parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$. In order to make the experimental results of target source detection more close to the actual values, the parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ obtained from 12 groups of experiment are averaged as the Experimental results of target source detection. Compared with the actual value, the relative errors of the parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ were calculated. Both the average values and the relative errors of the parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ are shown in Table 2.

Table 2. Results of target source detection experiment.

| type of result | $x_1$ (cm) | $x_2$ (cm) | $x_3$ (cm) | $\alpha_1$ (°) | $\alpha_2$ (°) | $\alpha_3$ (°) |
|---------------|-----------|-----------|-----------|---------------|---------------|---------------|
| experiment    | 59.4      | 78.2      | 130.5     | 80.4          | 52.8          | 33.6          |
| actual value  | 65        | 85        | 123       | 85            | 50            | 31            |
| relative error| 8.6%      | 8.0%      | 6.1%      | 5.4%          | 5.4%          | 8.4%          |

It can be seen from table 2 that the parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ obtained from the experiment have errors compared with the actual values, and the relative errors of $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ are 8.6%, 8.0%, 6.1%, 5.4%, 5.4%, 8.4% respectively. Because of the uneven material of the ground selected in the experimental plane, the interference noise of the vibration signal generated by the vibration source in the process of acquisition, the sensitivity error of the sensor, the random environmental interference, the human operation error and other factors, the calibrated velocity ($v$) and the time delay $\tau_1$ and $\tau_2$ calculated by the cross-correlation method all may be produced errors, which also can be transmitted to the parameters $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$, and make them produce errors finally. However, compared with the actual value, the relative errors of $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ are all less than 9%, which can meet the needs of some practical projects. Therefore, the target source detection technology proposed above under laboratory conditions can be reliably realized, and it can be applied to the practical teaching for students.

5. Conclusion
One method of planar target source detection based on the time delay estimation and the sensor placed in a line is analyzed, in which the time delay estimation is realized by cross-correlation method. Under laboratory conditions, with the aid of INV acceleration sensor, INV signal acquisition instrument and DASP analysis software, the propagation velocity of vibration signal was firstly calibrated, and then the detection experiment of vibration target source on plane was carried out by using the target source detection method that has been analyzed. Compared with the actual values, the relative errors of $x_1$, $x_2$, $x_3$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ obtained from experiment are all less than 9%. Therefore, the target source detection technology proposed in the paper under laboratory conditions can be reliably realized, and it can be applied to the practical teaching for students.

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