Sound source location for low-altitude aircraft based on sub-band extraction

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Abstract. The acoustic signal of low-altitude aircraft shows regular distribution in frequency and has obvious harmonic crest of both fundamental frequency and double frequency.Therefore, this paper presents a low complexity algorithm of acoustic location based on feature sub-band extraction for low-altitude aircraft. The algorithm firstly searches the eigenfrequency points which occupy the main energy in the sound signal. Then the cost function is constructed based on the MUSIC method by the sub-band corresponding to the eigenfrequency point. Finally, the amplitude is weighted by the maximum ratio combination principle to obtain the spectral function of array space, by which DOA estimation is realized for the spatial spectrum. Simulation results show that the algorithm is less complex than traditional wide-band DOA algorithm, and its main lobe is easier to recognize and has better spatial resolution.

1 Introduction

In recent years, with the continuous of unmanned aerial vehicle (UAV) technology, the safety problems caused by low-altitude aircraft, mainly composed of small UAVs become increasingly prominent[1].In the case of low altitude, the acoustic signal generated by the aircraft is accompanied with important information such as the position and the type of the aircraft, so the passive acoustic detection system has important research significance.

Acoustic signal location technology, mainly refers to the use of acoustic signals for passive detection and the use of microphone array to estimate the DOA of sound source, also known as spatial spectrum estimation. It has been highly valued in both military and civilian fields[2, 3].Therefore, in order to realize sound source location, researchers have proposed many effective sound source location algorithms. At present, the localization algorithm of this technology is mainly divided into three categories: acoustic source localization algorithm based on arrival delay[4], acoustic source localization algorithm based on high resolution spectrum estimation[5, 6] and acoustic source localization algorithm based

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on beamforming[7, 8].The DOA estimation's accuracy of MUSIC algorithm based on high-resolution spectral estimation is better than other algorithms, which consequently has been studied and improved by many scholars. Literature[9]proposed the Chicken swarm optimization based on MUSIC algorithm, which improves the accuracy of the algorithm. Literature[10, 11]improves the algorithm based on glowworm swarm optimization and reduced-Dimension, which improves the estimation accuracy and computation speed to a certain extent. In literature [12], ESPRIT algorithm is combined with that for continuous estimation, which improves the accuracy of estimation. In literature[13], improvements were made based on concept of the difference and sum coarray to improve the effectiveness of the algorithm. Compared with the traditional algorithms, these existing algorithms have some improvements, but their complexity and accuracy are still inadequate.

Based on the above problems, we proposes a location algorithm for low-altitude aircraft based on feature sub-band extraction. On the one hand, the Fourier transform and sliding filter are applied to the acoustic data of aircraft. The sub-band corresponding to characteristic frequency points can be quickly and accurately searched for and the key information carried by the signal can be used effectively according to the unique frequency domain characteristics of UAV sound signal. On the other hand, DOA estimation is carried out for some characteristic narrow-band signals, which greatly reduces the computation, and at the same time reduces the interference of partial invalid frequency components on DOA estimation in the case of low SNR, thus improving the accuracy and real-time performance of estimation.

2 Array signal model

In this paper, cross uniform linear array is selected as the topological structure of the array. The array is composed of M elements with array spacing d and K signal sources. The model is shown in Fig.1.

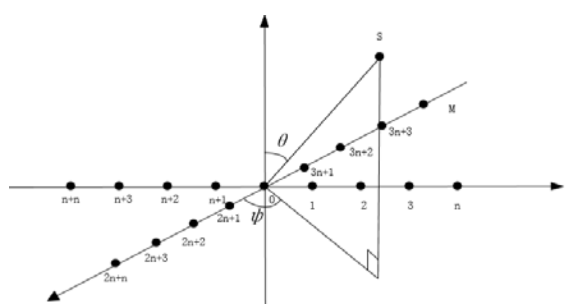


Fig. 1. DOA estimation model

During the flight of low-altitude aircraft, the relative position of the observation point is relatively large, so the acoustic signal can be processed into far-field broadband signal. Then the signal received by microphone element i can be expressed as:

$$x_i(t) = \sum_{k=1}^{K} a_{ik} s_k (t - \tau_{ik}) + n_i(t) \quad (1)$$

In the above equation, a_{ik} is element gain, which is usually is 1. $\tau_{\mathrm{ik}} = b_{ik} * h_{ik} / c$, h_{ik} is the direction vector from the origin to element ,$b_{ik} = -(\sin\theta_{ik}\cos\varphi_{ik}, \sin\theta_{ik}\sin\varphi_{ik}, \cos\theta_{ik})$.

$n_i(t)$ refers to the additive noise in the propagation process. The received signals of the entire array can be expressed as:

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ \cdots \\ x_M(t) \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{K} s_k(t-\tau_{1k}) + n_1(t) \\ \sum_{k=1}^{K} s_k(t-\tau_{2k}) + n_2(t) \\ \cdots \\ \sum_{k=M}^{K} s_k(t-\tau_{Mk}) + n_M(t) \end{bmatrix} \tag{2}$$

Fourier transformation of the received signal expression (2) can be obtained as follows:

$$\boldsymbol{X}(f) = \left[X_1(f), X_2(f), \ldots, X_M(f)\right]^T = \boldsymbol{A}(f,\theta)\boldsymbol{S}(f) + \boldsymbol{N}(f) \tag{3}$$

$A(f,\theta)$ is the array direction matrix function related to f .

3 The SE-MUSIC acoustic location algorithm based on sub-band extraction

3.1 Sub-band extraction

Based on the analysis of a large number of experimental data and literature[14-18], it can be concluded that:

1.The flight acoustic signals of low-altitude aircraft are concentrated in the frequency domain of 100Hz-2000Hz.

2.The statistical characteristics of acoustic signals of low-altitude aircraft conform to the characteristics of generalized stationary random signals and can be approximated as generalized stationary random signals in processing.

The cross microphone array discussed in Section 1 is used for the low-altitude aircraft acoustic signal acquisition. The sound data collected by a single element is processed by Fourier transform FFT(Fast Fourier Transform) and the part of 100Hz-2000Hz is intercepted to obtain in Fig.2.

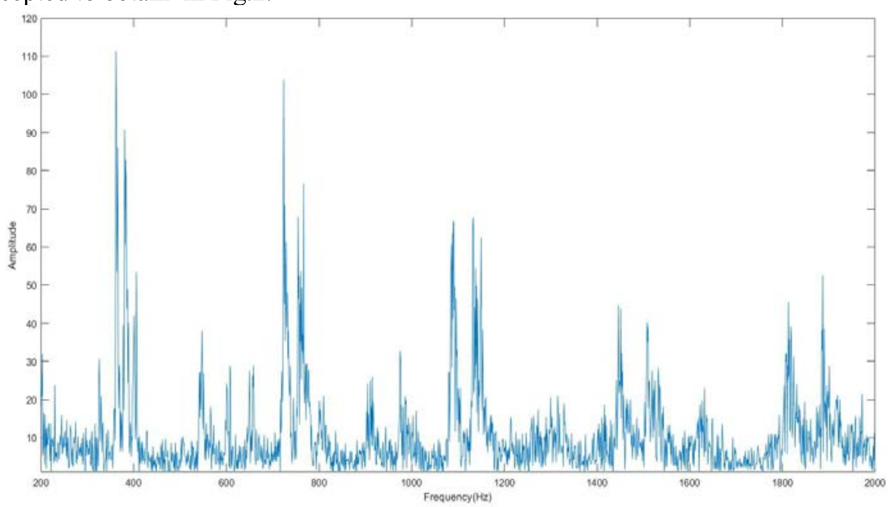


Fig. 2. Frequency domain diagram of sound signal of low-altitude aircraft.

It can be seen from Fig.2 that the flight acoustic signal presents a regular distribution in frequency, showing obvious characteristics of harmonic crest of fundamental frequency and double frequency. This kind of wave peak mainly appears near the frequency band with frequency points of 375Hz, 750Hz, 1175Hz, 1500Hz and 1900Hz as the center frequency points.

Set the threshold and use the peak search algorithm to search for the spectral peak and the results are shown in Fig.3:

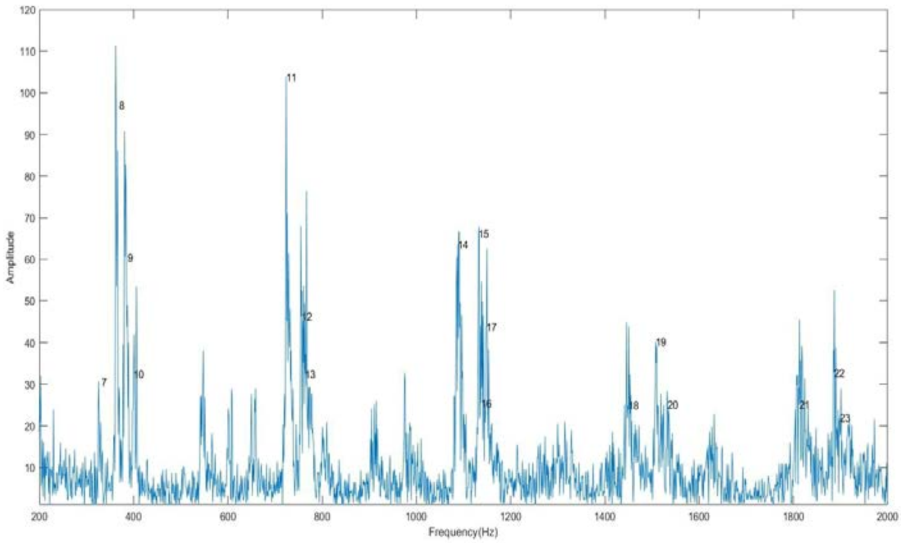


Fig.3. Spectral peak search diagram.

Due to the complexity of the frequency domain waveform, it presents the characteristics of multi-pole points and burrs. In Fig.3 , at least one peak extremum point is searched on each crest. If sub-band extraction is carried out with each search peak and extremal point as characteristic frequency point, overlapping sub-bands will be obtained. Therefore, the spacing threshold is set as 50. When the frequency point spacing of adjacent peak poles is less than 50Hz, the sub-band with a width of 100Hz is taken as the center; when the frequency point corresponding to the adjacent poles is more than 50Hz, the sub-band with a width of 100Hz is taken as the center. Thus, the characteristic sub-bands containing the main acoustic information of the low-altitude aircraft are extracted out.

3.2 SE-MUSIC sound location algorithm based on sub-band extraction

By combining feature sub-band extraction with MUSIC algorithm, the covariance and feature decomposition of the signal in the frequency domain corresponding to the feature frequency points obtained by spectral peak search are made to divide them into two subspaces: signal subspace and noise subspace. Then the spatial spectral function in the sub-band frequency domain is constructed as the objective function, and the spatial spectral functions of each characteristic peak and frequency point component are super posed and averaged to obtain the signal spatial spectral function, as shown in Equation (4):

$$\boldsymbol{P}=\frac{1}{\sum_{j=1}^{N}\varphi_j\boldsymbol{a}\left(f_j,\theta\right)\boldsymbol{U}_N\left(f_j\right)\boldsymbol{U}_N^{\boldsymbol{H}}\left(f_j\right)\boldsymbol{a}^{\boldsymbol{H}}\left(f_j,\theta\right)} \quad i=1,2,\ldots,N \qquad (4)$$

Where, φ_j is the amplitude weighting parameter, and the maximum ratio combination idea in diversity combination technique is used to give a large proportion to the large value sub-band, that is $\varphi_j = \frac{W_j}{W_1 + W_2 + ... + W_N}$. Increasing the amplitude weighting function can enhance the influence of high amplitude frequency point on the final DOA result to optimize the direction estimation result. Then, by changing the value of θ, the peak value of the above equation is searched to obtain the incidence angle of the sound source signal.

4 Experimental analysis

The aim of the algorithm in this paper is to reduce the algorithm complexity and reduce the operation time while maintaining and improving the location accuracy of the sound source of small low-altitude aircraft. Two low altitude targets were set in the experiment, and the array form was the cross uniform linear array discussed in the first section. The array element number was 12, the spacing between elements was half wavelength, and the search range was [-90,90].

4.1 Comparison of operation time under different snapshot numbers

The azimuth angle of the low altitude target was set as -30° and 30°, the SNR was fixed as 8dB, and the number of snapshot was 2048,4096,8192 and 10240 respectively. For different rappels, 100 independent repeated experiments were conducted for each group. The operation time of traditional MUSIC algorithm and SE-MUSIC algorithm was recorded and then mean value was calculated, and the relationship curve between the operation time and rappels were depicted. The results are shown in Fig.4.

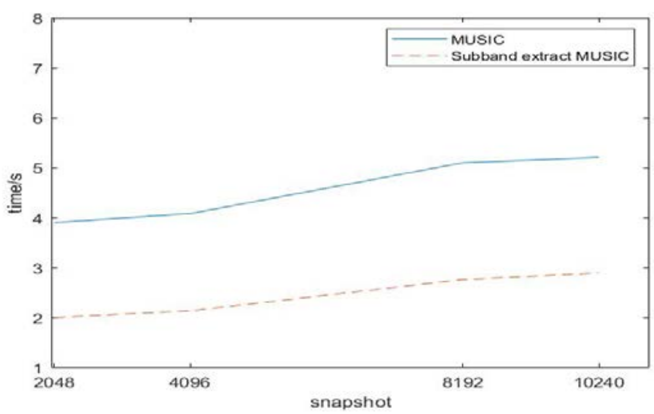
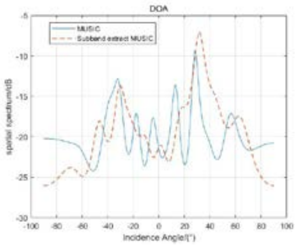


Fig.4. Comparison of operation time of different snapshot.

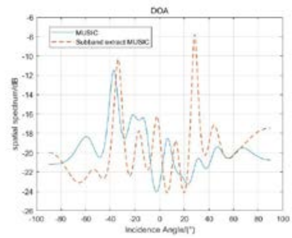
It can be seen from Fig.3 that under the data conditions of different rapids, the operation time of SE-MUSIC algorithm is nearly half that of traditional MUSIC algorithm. This also reflects that the complexity of SE-MUSIC algorithm is lower than that of traditional MUSIC algorithm, which has obvious advantages.

4.2 DOA estimation performance comparison under different SNR

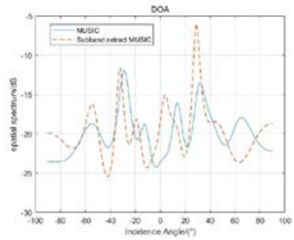
The azimuth of the low altitude target was set to -30°and 30°, and the number of fast beats was set to 4096. Signal to noise ratio(SNR) was set to -20dB, -10dB, 0dB, 10dB and 20dB.The experimental results of different SNR were shown in Figure a-e.



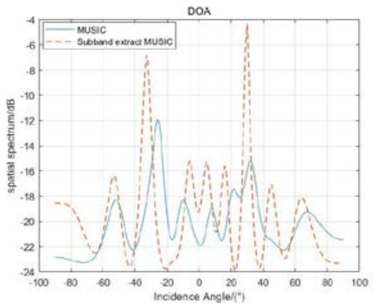
(a)-20dB



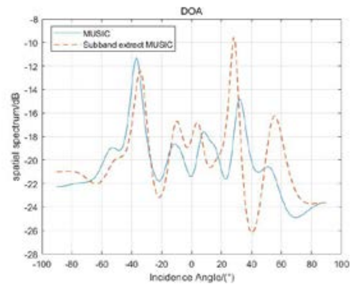
(b)-10dB



(c) 0dB



(d) 10dB



(e)20dB

100 independent repeated experiments were conducted for each group with different SNR, and the DOA estimation error mean of traditional MUSIC algorithm and SE-MUSIC algorithm was recorded, and the relationship curve between DOA estimation error mean and SNR was depicted. The results are shown in Fig.5.

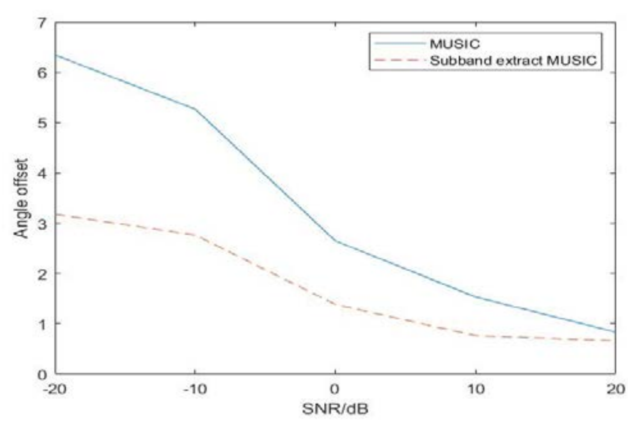


Fig.5. Comparison of DOA errors of different SNR.

It can be seen from the above that, in the case of low SNR, the spatial spectrum of the traditional MUSIC algorithm is not easy to distinguish the main lobe in the two sound source directions, while the spatial spectrum of the SE-MUSIC algorithm can distinguish the main lobe in the two sound source directions, and the DOA estimation error of the SE-MUSIC algorithm is smaller than that of the traditional MUSIC algorithm. In the case of high SNR, the spatial resolution performance and DOA estimation error of the two algorithms are close, while the main lobe width of the SE-MUSIC algorithm is narrower, the peak side lobe ratio is larger, and the spatial resolution is better.

5 Conclusion

A SE-MUSIC algorithm based on feature sub-band extraction is proposed. This algorithm quickly and accurately searches for the sub-bands corresponding to characteristic frequency points, and then uses the corresponding sub-bands to do DOA estimation. According to the amplitude weighted parameters and the principle of maximum ratio combination, the array spatial spectrum results are calculated. Experiments show that the algorithm has a lower computational complexity, and the operation time is reduced by nearly half. Compared with MUSIC algorithm, the main lobe is easier to resolve and the spatial resolution is better in the case of low SNR. Under the case of high SNR, SE-MUSIC algorithm has slightly better resolution performance than MUSIC algorithm.

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