Research article

Research on aeromagnetic data error analysis and processing of multi-rotor UAV based on variational mode decomposition algorithm

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ABSTRACT

Aeromagnetic survey of multi-rotor UAV is widely used in small and medium-sized mineral resources survey, engineering investigation, non-explosive detection and other fields due to its advantages of high safety, low cost and convenient operation. The original data of UAV aeromagnetic survey includes interference from external environment, interference from UAV platform and interference from airborne electromagnetic equipment. The interference is mainly shown as striping anomaly along the direction of the survey line in the aeromagnetic anomaly map, which affects the accuracy of aeromagnetic compensation and information detection of geological anomaly body, thus affecting the accuracy of interpretation of geological anomaly body. In this paper, the algorithm of Variational Modal Decomposition (VMD) is introduced to filter and preprocess the aeromagnetic data to obtain high quality aeromagnetic data. At the same time, the source and characteristics of the errors are predicted according to the interference size and spectrum characteristics of the Modal function errors, which provides a reference for the optimization of aeromagnetic system.

1. Introduction

Mineral resources are an important material basis for the development of national economy and the guarantee of people's livelihood. With the rapid development of China's economy, the demand for mineral resources increases year by year (Wang and Gao, 2020). It is difficult to meet the demand only by relying on the mineral resources provided by the surface mining area, so resources must be obtained from the deep earth and some blank exploration areas with complex surface conditions. Aeromagnetic exploration has played an important role in the exploration of iron ore, copper ore, copper sulfide ore and chromite (Xiong, 2009; Yu et al., 2020; Jossing et al., 2013; Martelet et al., 2021; Cunningham et al., 2018; Qiao et al., 2021a,b). Among them, the aeromagnetic system of multi-rotor UAV is suitable for small and medium-sized area exploration tasks with its advantages of safety, flexibility and low cost, and can be a powerful supplement to human-machine aeromagnetic and ground magnetic survey. For safety reasons, the aeromagnetic system sensor of multi-rotor UAV is close to the fuselage, resulting in large noises such as interference from airborne electromagnetic equipment. In addition, the measurement data also contains interference from external environment, which requires data de-noising pretreatment (Qiao et al., 2020; Li et al., 2018a,b; Wood et al., 2016; Tuck et al., 2019, 2021).

In 1998, Huang et al. proposed empirical mode decomposition (EMD) denoising method, which is a nonlinear non-stationary signal analysis method based on Hilbert-Huang transform. The intrinsic mode function (IMF) can be used to decompose signals adaptively into a series of intrinsic mode functions (IMF) with practical physical significance (Huang et al., 1998). IMF has been widely used in nonlinear and non-stationary signal denoising, but EMD has endpoint effect and modal mixing. Especially in the case of low signal-to-noise ratio, the noise effect is worse. Therefore, researchers have proposed set empirical Mode decomposition (EEMD), improved Complete set Empirical Mode decomposition (ICEEMD) and partial set empirical Mode decomposition (ICEEMD) and partial set empirical Mode decomposition...
(PEEMD) to improve the modal mixing phenomenon to a certain extent, but they are based on empiricism and lack of mathematical basis (Kopcsinis and Mclaughlin, 2009; Wu and Huang, 2011; Rezaee and Osguei, 2016; Jia et al., 2021). In 2014, Dragomiretski and Zosso proposed Variational Mode Decomposition (VMD), which is based on three-dimensional variational constraint theory and uses non-recursive properties to simultaneously estimate multiple modes (Dragomiretski and Zosso, 2014; Yang et al., 2020; Li et al., 2018a,b; Wang et al., 2021). The computational efficiency is improved on the premise of ensuring feature integrity. This method has good performance of anti-noise and reducing mode mixing, and is suitable for denoising multi-rotor aeromagnetic data with high noise.

This article is based on a set of four rotor electric UAV aeromagnetic system study, detailed introduces the system composition, airborne equipment electromagnetic interference noise sources, such as innovative introduction of VMD algorithm of aeromagnetic data preprocessing, according to the mode of the decomposed component analysis error classification and size of error sources are analyzed based on the modular function spectrum. Finally, VMD algorithm is used to preprocess the aeromagnetic data of the measured work area to obtain high signal-to-noise ratio aeromagnetic data.

2. Aeromagnetic system of multi-rotor UAV

This study is based on the aeromagnetic system of quadrotor UAV independently developed by Zhejiang Danian Technology Co., Ltd. (Model: MAG-DN20G), the system is mainly composed of an electric quadrotor UAV flight platform, a three-axis fluxgate measuring instrument and a millimeter-wave radar altimeter as shown in Figure 1 and Table 1. It can realize functions such as one-click startup, autonomous flight along the track, and earth-like flight operation in complex terrain environment, so as to obtain high-precision geomagnetic anomaly data. In addition, the system is also equipped with a centimeter high precision positioning system, which can more accurately delineate the location of geological anomalies and meet the requirements of geological prospecting and engineering survey accuracy (Qiao et al., 2021).

3. Noise source and influence of aeromagnetic system

In order to reduce the interference of UAV platform for aeromagnetic sensors, UAV body structure choose high strength carbon fiber and aluminum fittings non-magnetic or weak magnetic materials, such as aerial magnetic sensor installation position as far as possible away from UAV body, but considering flight safety and the test data will be aeromagnetic equipment using hard-wired fixed at the bottom of the UAV frame, as shown in Figure 1. Airborne electronic equipment of the system mainly includes: battery, motor, electric modulation, GPS, data transmission, flight control. These electronic equipment emit and receive electromagnetic signals at work, which will interfere with the sensor. In addition, external environment such as ground industrial electricity will also produce noise interference.

In order to analyze the interference of electromechanical equipment of UAV aeromagnetic system on sensors and its characteristics, the static and dynamic tests of aeromagnetic system are carried out in the test site with flat terrain, stable magnetic field and small interference in Hangzhou Bay tidal flat area of Zhejiang province, as shown in Figure 2. It includes sensor static test (the sensor is placed separately on the test bench for data acquisition), system power off (the aeromagnetic system was placed on the test bench for data acquisition, and the UAV was in the state of power off), system power on, system 200 m in the air hovering test and spectrum analysis of the test data to study electromechanical interference characteristics and influence size, as shown in Figure 3(a, b, c, d) and Table 2.

It can be seen from the field test that the aeromagnetic sensor is interfered by UAV carrier and airborne electromagnetic equipment, in which the peak-to-peak value of interference by UAV carrier is 0.8 nT, the peak-to-peak value of interference by energized noise is 25 nT, and the peak-to-peak value of noise interference reaches 155 nT when hovering. The noise interference of electromagnetic equipment seriously affects the effective magnetic field signal.

In order to solve the electromagnetic interference of airborne equipment, we can adopt the following treatment methods:

(1) Increase the distance between sensors and electromechanical equipment, but it will reduce the wind resistance ability of UAV, and bring hidden dangers to system safety;
(2) Electromagnetic shielding of mechanical and electrical equipment will increase production cost, increase UAV body weight, reduce flight time and reduce operating efficiency;
(3) Analyze the spectrum characteristics of the data and design a reasonable filter for filtering processing. In this paper, VMD algorithm is introduced to preprocess the aeromagnetic data, and the spectral analysis of the decomposed modal function is carried out to study the size and characteristics of the noise, analyze the source of noise and the optimization scheme.

4. VMD algorithm

VMD (Variational Mode Decomposition), proposed by Konstantin Dragomiretskiy in 2014, is an adaptive completely non-recursive method of modal variation and signal processing. This technique has the advantage of determining the number of modal decompositions, and its adaptability is reflected in determining the number of modal decompositions of the given sequence according to the actual situation. The optimal center frequency and limited bandwidth of each mode can be
adaptively matched in the subsequent search and solution process. In addition, the effective separation of the intrinsic modal function (IMF) and the frequency domain division of the signal can be realized, and then the effective decomposition components of the given signal can be obtained, and finally the optimal solution of the variational problem can be obtained. VMD algorithm overcomes the problem of endpoint effect and mode component aliasing existing in EMD method, and has a more solid mathematical theoretical basis. It can not only reduce the non-stationary of high complexity and nonlinear strong time series, but also decompose to obtain relatively stable subsequences, which is suitable for non-stationary series. The core idea of VMD is to construct and solve variational problems.

VMD algorithm determines the center frequency and bandwidth of each natural modal component by iteratively searching the optimal solution of the variational model, and then realizes the effective separation of signals from low frequency to high frequency. The process is the solution process of the variational problem. VMD decomposition mainly involves Wiener filtering, Hilbert transform and frequency mixing. By using Wiener filtering and Hilbert transform, the decomposition problem of the original signal is transformed into a variational problem for k modes. To minimize the sum of the estimated bandwidths of each mode, a constrained variational model is established, as shown in Eq. (1):

$$\min \left\{ \sum_k \left\| \sum_k \left[ \left( \delta(t) + \frac{j}{\omega_k} \right) \omega_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\}$$

$$\text{s.t.} \sum_k \omega_k = f(t)$$

where: \( \{ u_k \} := \{ u_1, \ldots, u_k \} \) are the set of IMF components; \( \{ \omega_k \} := \{ \omega_1, \ldots, \omega_k \} \) are the central frequency of all components; \( \left( \delta(t) + \frac{j}{\omega_k} \right) \omega_k(t) \) represents \( u_k(t) \) after get the Hilbert transform spectrum analytical signal.
of unilateralism; Lots of partial \( \| a \|_{L^2} \), \( \| a \|_{L^2} \) represents through calculating the square of the modulation signal gradient norm \( L^2 \) estimate of the bandwidth of each IMF, \( f(t) \) represents the input signal.

In solving the constructed constrained variational problem, the quadratic penalty function factor \( \alpha \) and the Lagrange multiplier \( \lambda \) are introduced to transform the constrained problem of Eq. (1) into an unconstrained variational problem. The extended Lagrange expression is shown in Eq. (2):

\[
\mathcal{L}(\{u_k\}, \{a_k\}, \lambda) = a \sum_k \left\| a \right\|^2 + \left\| f(t) - \sum_k u_k(t) \right\|^2 + \sum_k \left\| a_k \right\|^2 + \langle \lambda, f(t) - \sum_k u_k(t) \rangle
\]

(2)

where \( \hat{\delta}(t) \) represents the Dirac distribution, \( * \) represents the convolution operation, and \( (\cdot) \) represents the inner product operation.

By alternating direction of multiplier algorithm ADMM update each modal \( a_k^{n+1} \), \( \theta_k^{n+1} \), \( \lambda_k^{n+1} \). The minimization problem in formula (1) is transformed into the "saddle point" of formula (2) after the iterative sub-optimization sequence is expanded. The expressions required for alternating optimization of \( u_k \), \( a_k \) and \( \lambda_k \) are shown in Eqs. (3), (4) and (5).

\[
\hat{u}_k^{n+1}(\omega) = \hat{f}(\omega) - \sum_k \hat{u}_k(\omega) + \frac{\lambda_k^{n+1}}{2}(\omega - a_k^{n+1})^2
\]

(3)

\[
\hat{a}_k^{n+1} = \frac{\int \hat{u}_k(\omega)\hat{u}_k^*(\omega)d\omega}{\int \hat{u}_k^*(\omega)d\omega}
\]

(4)

\[
\lambda_k^{n+1}(\omega) = \lambda_k^{n}(\omega) + \tau [\hat{f}(\omega) - \sum_k \hat{u}_k^{n+1}(\omega)]
\]

(5)

where \( \hat{u}_k^{n+1}(\omega), \hat{f}(\omega), \lambda_k(\omega) \) respectively \( u_k^{n+1}(t), f(t), \lambda(t) \) corresponding to the Fourier transform. In the iterative calculation process, the center frequency of each component \( u_k \) is estimated by using the center of gravity of power spectrum.

On the whole, VMD algorithm constantly updates each mode in the frequency domain and converts it to the time domain by Fourier transform. The specific steps of updating the modal components are as follows:

1. Input raw signal, limit, delay, modal number, initial center frequency, noise tolerance.
2. Assume \( \hat{u}_k^{(n)}(\omega), \hat{a}_k^{(n)}, \lambda_k^{(n)}(\omega), n = 0 \).
3. Assume \( \hat{u}_k^{n+1}(\omega) \) can be updated using Formula (3) iteration.
4. Assume that Eq. (4) is iterated to update \( \hat{a}_k^{n+1} \).
5. type iterative update \( \lambda_k^{n+1}(\omega) \), until meet the condition \( \sum_k \| \hat{u}_k^{n+1} - \hat{u}_k^{n} \|^2 < \varepsilon \) stop cycle, when the output \( \hat{u}_k(\omega), \lambda_k \), Fourier transform is used to obtain each \( u_k \), where \( \varepsilon \) is the threshold.

5. Field test

5.1. Static test

As can be seen from Figure 3(c). Aeromagnetic system under the current situation, airborne electromagnetic devices work to produce a large number of electromagnetic interferences, noise peak-to-peak value as high as 25 nT, seriously affect the earth’s magnetic field signal recognition, effective data processing is required. In order to analyze the influence size and spectrum characteristics, this article uses the VMD algorithm of aeromagnetic data processing analysis system electricity condition test, modal decomposition number \( k = 5 \), modal component and its spectrum is shown in Figure 4 and Table 3.

This experiment selects 6.5 min of data, a total of 78000 points. Due to fixed-point measurement and short time, it can be considered that the geomagnetic field is unchanged. The changes in the original aeromagnetic data mainly come from the interference of airborne equipment and the surrounding environment, see Figure 4(a). Since the geomagnetic field is far greater than the interference, the frequency spectrum of the original aeromagnetic data mainly shows the low-frequency characteristics of the geomagnetic field, see Figure 4(g).

After VMD processing, the original data is decomposed into five modal components: The IMF1 component is the filtered effective aeromagnetic data, where the geomagnetic field data is 48556.9–48557.7 nT, the variation range of geomagnetic field is only 0.8 nT, and the frequency spectrum is low frequency, see Figure 4(b) and (h). The residual amplitude of filtered aeromagnetic data and ground daily transformer station magnetic data (GSM-19T proton magnetometer) is only 0.87 nT, which verifies the effectiveness of filtering effect.

The IMF2, IMF3, IMF4, and IMF5 components are noise terms, with variation amplitude of 0.8 nT, 20 nT, 4 nT, and 3 nT respectively (as shown in Figure 4c, d, e, f), and corresponding frequencies are 1-10Hz and 25 Hz, 40 Hz, 50 Hz, and 75 Hz (as shown in Figure 4i, j, k, l), among them, 25 Hz interference has the greatest impact on aeromagnetic data, as shown in Table 3. The data processed by VMD can effectively remove noise interference and return the real information of in-situ magnetic field. Meanwhile, the noise amplitude and spectrum characteristics can be quantitatively analyzed to analyze the source of noise.

5.2. Dynamic test

In order to verify the effect of VMD algorithm on noise analysis and processing of aeromagnetic measured data, the aeromagnetic measurements were carried out in Wuhu city, Anhui province, China in this paper as shown in Figure 5. The aeromagnetic system of the UAV flies at an altitude of 100 m, the speed was 8 m/s, and the aeromagnetic sampling frequency was 200 Hz. In this paper, VMD processing was performed on the original aeromagnetic data of L4 and L5 survey lines, as shown in red survey line in Figure 5. According to the preliminary analysis and comparison of multiple treatments, the number of modal decompositions in this paper \( k = 5 \), and the processing results and spectrum analysis of the modal components can be obtained as shown in Figure 6. The peak-to-peak value, center frequency, signal energy amplitude of modal component data was counted and the signal source was predicted as shown in Table 4.

In this paper, two continuous aeromagnetic lines L4 and L5 are selected for experiments, with a total of 162000 measured data, the VMD processing results are shown in Figures 6 and 7: Original aeromagnetic data exist obvious noise, as shown in Figure 6(a), the average value of the peak to peak value of the noise is about 50nT, which is far less than the 200 m hover interference amplitude in Figure 3(d). Because the UAV needs to adjust its attitude in real time to maintain a fixed height and position during hovering, and electromechanical devices such as motors produce greater interference, which is also the most power consuming state of the system. But, local interference up to 300 nT, as shown near the 40000 point in Figure 6(a), According to the magnitude and location of the impact in Figure 6(e) and the 50 Hz center frequency in Figure 6(k), it is inferred that the source of the interference at this location is industrial high-voltage line. According to the records during field operation, it is confirmed that there is high-voltage line at this location.

VMD filtering can effectively remove the noise interference in aeromagnetic data, which improve the signal-to-noise ratio, make the geomagnetic field signal clearer and have obvious low-frequency characteristics, as shown in Figure 6(b) and (b). The data modal components and spectrum characteristics in Figures 6 and 4 are consistent, indicating the same source of interference. As shown in Figure 6(c) and (f), the central frequency of IMF2 and IMF5 are 25 Hz and 75 Hz, as shown in
Figure 6(i) and (l), which are speculated that these two interference sources are airborne electromagnetic equipment. As shown in Figure 6(d) and (j), the amplitude of IMF3 interference is uneven, and the data bandwidth with the center frequency of 40 Hz is large. It is analyzed that the interference is caused by the UAV motor. During the operation of the

Table 3. VMD modal components and their spectrum statistics.

| Item | Peak-Peak (nT) | Frequency (Hz) | The signal source            |
|------|----------------|----------------|------------------------------|
| Raw data (Figure 4a) | 25 | low | Total magnetic field        |
| IMF1 (Figure 4b) | 0.8 | low | Geomagnetic field           |
| IMF2 (Figure 4c) | 20 | 1-10, 25 | Noise                       |
| IMF3 (Figure 4d) | 0.8 | 40 | Noise                       |
| IMF4 (Figure 4e) | 4 | 50 | Noise                       |
| IMF5 (Figure 4f) | 3 | 75 | Noise                       |

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system, due to the influence of the external environment, the flying state of the UAV is not the same, the motor speed will also change, and the interference size and spectrum will also change to some extent.

In order to verify the processing effect of VMD filtering on multiple test lines (test lines in the whole test area) and single test lines, L4 test lines were processed separately in this paper, and the processing results of L4 and L5 two continuous test lines were compared, as shown in Figures 8 and 9: The modal components and spectrum of L4 test lines were completely consistent with the processing results of the first half of Figure 6. Compared with the filtered data, the standard deviation of the residuals between the two is only 0.00035, and there is only a slight difference at the end. The reason is that the VMD algorithm has boundary effect, which can be processed by adding boundary point data in practical application, as described above: the VMD algorithm can be applied to all the data at the same time and need to process the boundary effect.

In order to verify the reliability of the aeromagnetic system and the effectiveness of VMD filtering, this paper uses repeated survey lines for accuracy evaluation. The repeated survey lines are shown in blue survey lines in Figure 5. The aeromagnetic data of the round-trip repeated survey lines after compensation, filtering and correction are shown in

![VMD filtering on multiple test lines](image)

**Figure 6.** Aeromagnetic data, VMD modal components and their spectrum of L4 and L5 (a: Raw data; b: IMF1; c: IMF2; d: IMF3; e: IMF4; f: IMF5; g: Spectrum of raw data; h: Spectrum of IMF1; i: Spectrum of IMF2; j: Spectrum of IMF3; k: Spectrum of IMF4; l: Spectrum of IMF5).

| Item           | Peak-Peak (nT) | Center Frequency (Hz) | Signal source                          |
|----------------|----------------|-----------------------|----------------------------------------|
| Raw data (Figure 6a) | 50-300         | low                   | Total magnetic field                   |
| IMF1 (Figure 6b)    | <1             | low                   | Geomagnetic field                      |
| IMF2 (Figure 6c)    | 5              | 25                    | Airborne electromagnetic equipment     |
| IMF3 (Figure 6d)    | 10             | 40                    | UAV motor                              |
| IMF4 (Figure 6e)    | 40-300         | 50                    | High-voltage line                      |
| IMF5 (Figure 6f)    | 2              | 75                    | Airborne electromagnetic equipment     |

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Figure 7. Aeromagnetic data before and after VMD filtering of L4 and L5.

Figure 8. Aeromagnetic data, VMD modal components and their spectrum of L4 (a: Raw data; b: IMF1; c: IMF2; d: IMF3; e: IMF4; f: IMF5; g: Spectrum of raw data; h: Spectrum of IMF1; i: Spectrum of IMF2; j: Spectrum of IMF3; k: Spectrum of IMF4; l: Spectrum of IMF5).
Figure 10. According to the aeromagnetic standard, the precision of repeated survey lines is 2.3 nT, which meets the requirements of mineral resource exploration and investigation.

6. Conclusion

(1) There is electromagnetic interference caused by airborne electromagnetic equipment and external environment electromagnetic interference in the original aeromagnetic data of UAV, which is as high as hundreds of nT, affecting the aeromagnetic measurement accuracy and interpretation accuracy of geological anomalies.

(2) VMD algorithm is an adaptive and completely non-recursive mode variational and signal processing method, which can effectively remove the interference in the original aeromagnetic data. Meanwhile, it can analyze the impact amplitude and spectrum characteristics of various interference in detail, which is helpful to analyze the source and distribution of aeromagnetic interference and guide the optimization and upgrade of aeromagnetic system in the later stage.

(3) In the field practical work of UAV aeromagnetic system, the largest interference comes from 50Hz external high-voltage interference and 25 Hz, 40Hz, 75 Hz airborne electromagnetic equipment interference, and the local interference amplitude is up to 300 nT. VMD algorithm can effectively remove these interference and analyze the impact, and the algorithm can be applied to all the data at the same time. Finally, VMD processing is performed on the field measured aeromagnetic data to improve the signal-to-noise ratio and obtain higher precision aeromagnetic data.

Declarations

Author contribution statement

Zhongkun Qiao: Concepted and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Peng Yuan: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ruo Hu, Linfei Wang, Linling Li, Zongyu Zhang and Jiajun Zhang: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Bin Wu and Qiang Lin: Concepted and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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