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Magnetic anomaly detection based on stochastic resonance

Chengbiao Wan*, Mengchun Pan, Qi Zhang, Fenghe Wu, Long Pan, Xiaoyong Sun

College of Artificial Intelligence, National University of Defense Technology, Changsha, 410073, China

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ABSTRACT

Orthonormal basis function (OBF) decomposition method and minimum entropy (ME) detector are two typical methods of magnetic anomaly detection. The OBF detector works effectively only when the assumptions of the target signal and noise are appropriate, and the ME detector is limited by low signal-to-noise ratio (SNR). In order to improve magnetic anomaly detection performance in the case of low SNR and no prior information of the target signal, we proposed a novel detector by using stochastic resonance (SR) method and named it SR detector in the paper. The SR detector consists of a bistable SR system and a corresponding receiver. Firstly, the noise is used to enhance the magnetic anomaly signal with the help of SR system, instead of being suppressed in a traditional method; then the anomaly signal can be detected more effectively by the receiver. Experimental results show that the SR detector did work well, its detection probability approximated to 70% even if the input SNR was −3 dB, and was about 100% if the input SNR was 0dB, when the false alarm rate (FAR) was 1.5%. Furthermore, the SR detector provided higher detection probability than the ME detector under the same basis. In a word, due to the good detection performance and simple implementation, the SR detector would be more attractive in practice.

1. Introduction

Magnetic anomaly detection has been widely used for detecting magnetic object underwater or underground [1–5], it is always accomplished by a magnetic field measurement system and an anomaly signal detection algorithm. In general, the pivotal equipment of measurement system is a scalar magnetometer [6,7], which can monitor the earth's magnetic field and detect changes created by magnetic anomalies. As a matter of fact, the magnetic anomaly signal is usually buried deeply in the geomagnetic noise [8,9]. Thus, the effective detection algorithm is always needed to maximize the detection probability. At present, many approaches of magnetic anomaly detection based on noise suppression have been introduced. Such as the matched filtering using three orthonormal basis functions (OBF), which is optimal for revealing the magnetic anomaly signal buried in white Gaussian noise [10]. But the real geomagnetic noise is usually colored and confirms to non-Gaussian distribution for the presence of geomagnetic pulsations. Generally, real noise has a power spectral density of $1/f^{\alpha}$, f is the frequency, and α represents noise exponent. Hence, a whitening filter was designed based on the fact that the noise can be considered as an autoregressive process, but it will not work effectively until the filter order is high enough [11]. The narrowband filtering before the OBF detector was also introduced for changing the non-Gaussian noise to Gaussian variable [12]. Performance of the OBF detector was also improved by the modified orthonormal basis functions, where the autocorrelation function of geomagnetic noise was used, too [13]. With the in-depth research, the traditional magnetic anomaly detection model was broadened to more general case that the magnetometer and target move simultaneously at any speed and relative track angle [14]. In addition, the magnetic anomaly detection approach has been generalized to the detection of magnetic multi-poles [15], the principal component analysis was also used to construct an effective detector for detecting a non-dipole source [16], and the vertical component of the magnetic anomaly was used to detect oil field underground pipelines [17]. On the other side, the nonparametric detection method has also been studied for magnetic anomaly detection, such as minimum entropy (ME) detector [18] and high-order crossing method [19]. The ME detector is constructed by the probability density function of magnetic noise samples. The high-order crossing method is an alternative method for spectral analysis and signal discrimination by using zero-crossing count. These two methods benefit from the fact that they do not need a assumption of the target, both are easy to implement, but their detection performances may be limited by low SNR.

Taking into account the insufficiency of existing approaches, we tried to find a more effective method for magnetic anomaly detection. Stochastic resonance (SR) is a kind of nonlinear phenomenon that the signal is enhanced by noise, because that partial noise energy is converted into the signal energy. Since SR was first introduced by R. Benzi et al. [20] to explain the periodicity of

* Corresponding author.
E-mail address: chengbiaowan@foxmail.com (C. Wan).

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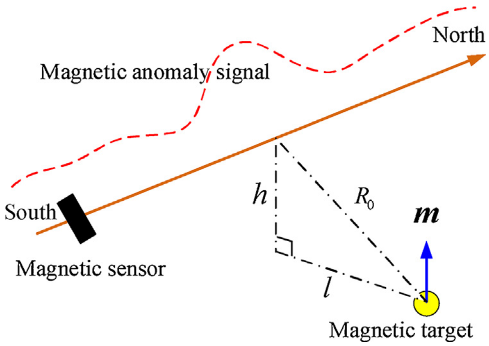

Fig. 1. Traditional magnetic anomaly detection model.

ancient earth's ice ages, its application scope has been expanded by some noteworthy contributions [21–23], such as frequency-shifted and rescaling transform [24], normalized scale transform, modulation and demodulation [25]. Now, the SR principle has been used to explain much phenomenon of nature, physics and biology [26–31], and the most widely used one is classical bistable SR method. It has been determined that the bistable SR method has a lot of advantages in the domain of dynamic system, chemic system and nerve net [32–35], especially for weak characteristic signal detection [36–44]. In summary, SR method is desirable for magnetic anomaly detection, because of two potential advantages: 1) In magnetic anomaly detection, the linear methods always attempt to suppress the additive noise, whereas the SR method utilized the noise to enhance the anomaly signal and improve the output SNR; 2) SR method needs not the deterministic parameters of signal and is applicable to colored noise.

Therefore, we proposed a novel magnetic anomaly detector that uses a SR system to improve detection performance. In the advanced detector, magnetic anomaly signal is enhanced via a SR system before binary hypothesis testing, and the standard deviation of window signal sequence is regarded as the test statistic quantity, here the output of SR system constitutes the signal sequence [45]. Due to the high SNR gain brought by the SR system, the proposed SR detector would have better detection performance for detecting magnetic objects. In the paper, the principle of the SR detector is introduced, its validity is demonstrated by testing with the measured noise, finally the detection performances of the SR and ME detectors are compared.

2. Detection theory

2.1. Magnetic anomaly signal

In the traditional magnetic anomaly detection model (Fig. 1), the target is assumed to be placed at the origin of a Cartesian coordinate system, and the sensor is assumed to move along the straight-line for searching target. In theory, the total magnetic field consists of geomagnetic field and anomaly field generated by ferromagnetic object, namely

$$\mathbf{B}_t = \mathbf{B}_e + \mathbf{B}_r \tag{1}$$

where $\mathbf{B}_t$ is the total field vector, $\mathbf{B}_e$ represents geomagnetic field vector and $\mathbf{B}_r$ is the magnetic anomaly field vector. However, the measured magnetic field obtained by a scalar magnetometer is a scalar that equals $\left|\mathbf{B}_t\right|$, where $|*|$ means the magnitude of vector $*$. Thus, the anomaly signal $\Delta T = \left|\mathbf{B}_t\right| - \left|\mathbf{B}_e\right|$ is generally obtained by subtracting the geomagnetic field magnitude $\left|\mathbf{B}_e\right|$ from the measured scalar $\left|\mathbf{B}_t\right|$.

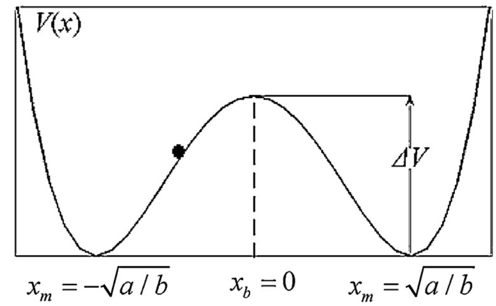

Fig. 2. Potential function of stochastic resonance system.

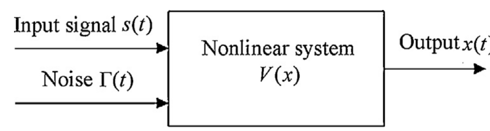

Fig. 3. The diagram of stochastic resonance system.

2.2. Stochastic resonance principle

The classical bistable SR model can be described by the nonlinear Langevin equation as below [36].

$$\dot{x} = ax - bx^3 + S + \Gamma \tag{2}$$

Where x represents the displacement of Brownian particle in the adiabatic approximation theory. In our study, x is the output of SR system, S is the deterministic signal, Γ denotes the sum of external noise and inherent noise, a and b are the system parameters characterizing the system. The symmetric double-well potential is given by $V(x) = -ax^2/2 + bx^4/4$, its curve is displayed in Fig. 2, which shows that the minima locate at $x_m = \pm\sqrt{a/b}$. A potential barrier separates the two minima with the height given by $\Delta V = a^2/4b$, the barrier top locates at $x_b = 0$. When the bistable system is driven by simultaneous action of the signal and additive noise (Fig. 3), it will be asymmetric. And if the input deterministic signal, additive noise and the nonlinear system cooperate well, the potential barrier may be reduced. At this time the particle that stays in one potential well, may surmount the energy barrier and enter another potential well, this phenomenon is called SR. When the SR phenomenon happens, the intensity of the useful signal is augmented, accordingly the output of SR system has a higher SNR in comparison with the input [46].

In general, noise is considered to be detrimental for detecting a useful signal. However, with the help of SR system, weak signal can be reconstructed and amplified effectively with the assistance of noise. Therefore, it is believed that the SR method may detect the weak magnetic anomaly signal embedded in the noisy background more effectively, compared with the traditional techniques [47].

2.3. Magnetic anomaly detection using a stochastic resonance system

According to Sections 2.1 and 2.2, the magnetic anomaly signal embedded in noise can be enhanced with the help of a SR system, and the output SNR can be improved obviously. Accordingly, the detection probability will be increased to some extent if the receiver is appropriate. However, the anomaly signal shape will be changed by the SR system, hence matched filter is hardly designed. Luckily, the output status of SR system will switch when an anomaly signal appears, and the standard deviation (STD) of this part will increase obviously. Based on this, a receiver was designed, in which the STD is treated as the binary hypothesis testing statistic quantity. Fig. 4