

Spatiotemporal Characteristics of Submarine Magnetic Anomaly under Typical Motion Scenarios

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Abstract

Accurate modeling of submarine magnetic anomaly characteristics is a fundamental component in evaluating magnetic stealth capabilities. Previous studies have primarily focused on analyzing the spatial magnetic anomaly induced by stationary submarines, with insufficient attention given to the comprehensive impact mechanisms of varying speed, course, and depth in moving submarines. This paper provides a detailed analysis of the spatiotemporal characteristics of submarine magnetic anomaly under typical motion scenarios. Initially, a foundational research submarine model was established using the finite element method (FEM), followed by an examination of the spatiotemporal characteristics of magnetic anomaly during both routine cruise and evasive maneuver scenarios. The simulation results reveal several key findings: 1) During routine cruising, the magnetic anomaly induced by the submarine is not significantly affected by its speed, to reduce the risk of detection by aircraft with magnetic anomaly detection (MAD) sensors, submarines should maintain a relatively high speed to quickly exit hazardous waters. 2) During evasive maneuvering, the magnetic anomaly is slightly stronger when turning left than turning right at a fixed depth, and it is lower at larger elevator angles during emergency diving. Therefore, to reduce the risk of detection by aircraft, submarines should opt for a right rudder angle or a larger elevator angle. 3) When the angle remains the same during evasive maneuvering, submarine exhibits superior magnetic stealth capabilities in emergency diving compared to depth-fixed turning. 4) Combining a specific rightward rudder angle with an elevator angle is the most effective evasive maneuver for submarines. This approach ensures stability and safety by preventing excessive bow tilt and potential instability. The research methodology proposed in this paper has potential value to enhance the development of submarine magnetic stealth technologies.

Keywords Finite element method (FEM); Magnetic anomaly detection (MAD); Motion parameter; Spatiotemporal characteristic; Routine cruise scenario; Evasive maneuver scenario

1 Introduction

Modern submarine hulls are typically fabricated from ferromagnetic steel with low permeability and high strength

Article Highlights

- A novel submarine model is developed to analyze the spatial and temporal characteristics of magnetic anomaly.
- Three typical motion scenarios are compared to study the impact of varying speed, course, and depth on the magnetic anomaly of moving submarine.
- The practical guidance for submarine navigation strategies to reduce the risk of detection by aircraft are offered.

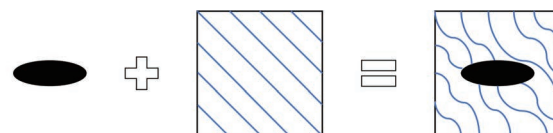
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(Levin et al., 2019). Consequently, the ferromagnetic hull, when magnetized by the geomagnetic field, generates an induced magnetic field (Li et al., 2015). This induced field superimposes on the surrounding geomagnetic field, thereby forming the detected magnetic field illustrated in Figure 1. This phenomenon, characterized by local disturbances in the geomagnetic field, is referred to as a magnetic anomaly (Zhao et al., 2021).



Induced magnetic field + Geomagnetic field = Detected magnetic field

Figure 1 Schematic diagram of the generation mechanism of magnetic anomaly

In recent decades, significant advancements in magnetic anomaly detection (MAD) technology, driven by insights into the magnetic anomaly, have enhanced its utility across various maritime operations (Wang et al., 2021a). As a non-

acoustic detection technology, MAD has become increasingly important in underwater target detection (Li et al., 2023). To mitigate the risk of detection by aircraft equipped with MAD sensors, submarines must carefully navigate at specific speeds, courses, and depths (Shariati and Mousavizadegan, 2017). However, traditional submarine magnetic stealth technologies still require further refinement (Modi and Kazi, 2020). In certain emergency situations, when aircraft threats are detected along their intended route, submarines promptly adjust their speed, course, or depth to evade potential dangers (Neira et al., 2021). Consequently, it is imperative to investigate the impact of motion parameters on the spatiotemporal characteristics of the magnetic anomaly.

Existing studies on the spatial distribution of submarine magnetic anomaly have primarily been conducted using simulation software that employs the finite element method (FEM). Notable programs include Ansys Maxwell (Cheng et al., 2023), Altair Flux (Brunotte et al., 1993), and COMSOL Multiphysics (Sheinker et al., 2009). The spatial characteristics of the magnetic anomaly are influenced by the submarine itself, particularly by the relative positions of the submarine and aircraft within the geomagnetic field (Woloszyn and Tarnawski, 2023). As illustrated in Figure 2, the factors influencing the magnetic anomaly are classified into four main groups, with plus and minus signs indicating direct and inverse proportions, respectively. The geometry of the submarine remains constant prior to undocking, and its magnetic signature is mitigated through regular degaussing operations (Choi et al., 2012).

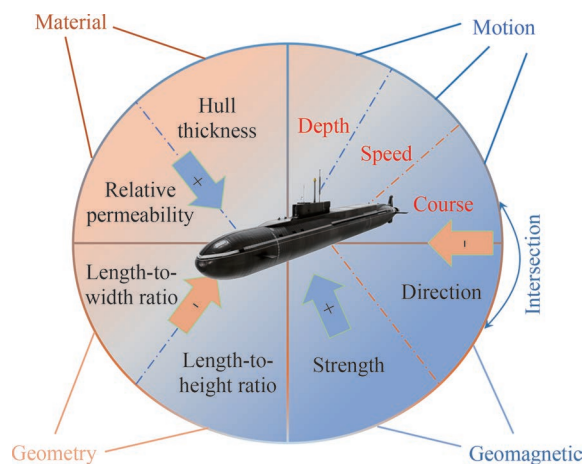


Figure 2 Factors influencing submarine magnetic anomaly

The temporal characteristics of the magnetic anomaly can be simulated using the speed identification method (Chen et al., 2022), which considers the location of the closest proximity approach (CPA) of the magnetic sensor to the submarine (Shen et al., 2019). Additionally, the temporal wave width of the magnetic anomaly is inversely proportional to the submarine's speed (Zhao et al., 2020). However, existing studies on the correlation between speed

and magnetic anomaly primarily depend on velocity recognition methods based on sensor data. This approach overlooks a detailed analysis of the underlying principles governing the magnetic anomaly induced by submarines, resulting in less comprehensive explanations for the observed trends in vector magnetic anomaly.

The course and depth of submarines significantly affect their positional relationship with aircraft (Lee et al., 2021), which in turn affects the magnetic anomaly detected by the aircraft. Specifically, the course of submarines has a considerable impact on the induced magnetic moment (Birsan, 2021). This moment reaches its peak when the course is aligned with the geomagnetic field direction (Koo et al., 2009), as explained by magnetization principles (Modi and Kazi, 2019). Furthermore, the magnetic anomaly is inversely proportional to the depth of submarines (Sheinker et al., 2008). Despite existing studies that have modeled the spatial magnetic anomaly of moving submarines in response to changes in course or depth, accurately characterizing the temporal variations of the magnetic anomaly remains a significant challenge.

Preceding discussions have highlighted the scarcity of studies examining the relationship between submarine motion parameters and the spatiotemporal characteristics of the magnetic anomaly. The primary motivation of this paper is to conduct a detailed investigation into the spatiotemporal characteristics of submarine magnetic anomaly under typical motion scenarios, thereby laying the theoretical groundwork for the practical application of submarine magnetic stealth technologies. The contributions outlined in this paper are as follows: First, a foundational research model for the submarine was developed using the FEM. Second, a detailed analysis was conducted on the spatiotemporal characteristics of submarine magnetic anomaly under two typical motion scenarios: routine cruising and evasive maneuvering. Third, the influences of motion parameters—such as speed, course, and depth—on the magnetic stealth performance of the submarine were discussed in detail.

The remainder of this paper is organized as follows. Section 2 introduces a mathematical model for studying submarine magnetic anomaly. Section 3 examines the spatiotemporal characteristics of magnetic anomaly under typical motion scenarios. Section 4 discusses the simulation results. Finally, Section 5 presents the conclusions drawn from this study.

2 Basic theory and numerical method for modeling magnetic anomaly

The presence of the geomagnetic field is an essential prerequisite for aircraft to conduct MAD. The ferromagnetic hull of a submarine becomes magnetized under the

influence of the geomagnetic field, thereby causing disturbances in the otherwise uniformly distributed geomagnetic field. Establishing an accurate finite element model and further analyzing the spatiotemporal characteristics of the magnetic anomaly, can lay the foundation for enhancing the submarine's magnetic stealth capabilities.

2.1 Theoretical derivation of magnetic anomaly

The geomagnetic field can be conceptualized as a uniform field in a local area, where its strength and direction remain constant (Liu et al., 2024). The direction of the geomagnetic field is illustrated in Figure 3(a). Assuming that the positive direction of the x-axis corresponds to geographic north, the positive direction of the y-axis to geographic west, and the positive direction of the z-axis is oriented vertically upward (Dai et al., 2019). The vector $\mathbf{B}_E$ represents the geomagnetic flux density, while $\mathbf{B}_{Exy}$ denotes its projection onto the xy plane. The angle between $\mathbf{B}_{Exy}$ and $\mathbf{B}_E$ is termed the magnetic inclination angle I , with downward deviation considered positive. The angle between $\mathbf{B}_{Exy}$ and the geographic north is termed the magnetic declination D , with eastward deviation considered positive.

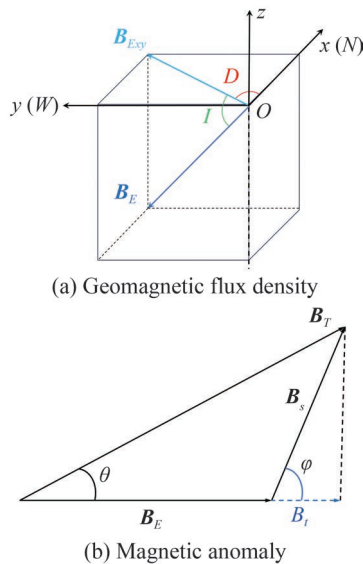


Figure 3 Schematic diagrams

The geomagnetic flux density $\mathbf{B}_E$ projected on the x-, y-, and z-axes is:

$$|\mathbf{B}_{Ex}| = |\mathbf{B}_E| \cos I \cos D \quad (1)$$

$$|\mathbf{B}_{Ey}| = -|\mathbf{B}_E| \cos I \sin D \quad (2)$$

$$|\mathbf{B}_{Ez}| = |\mathbf{B}_E| \sin I \quad (3)$$

where the total geomagnetic flux density $|\mathbf{B}_E|$ is measured at 44 031 nT, with a magnetic inclination I of $26^\circ 9' 39''$ and

a declination D of $-1^\circ 52' 48''$. These values are derived from latitude and longitude data according to the International Geomagnetic Reference Field (IGRF). The information of the vector geomagnetic flux density is presented in Table 1. Compared to the x- and z-components, the y-component of the geomagnetic flux density is relatively smaller.

Table 1 Information of the vector geomagnetic flux density

Parameter	Value (nT)	Direction
$\mathbf{B}_{Ex}$	39 499	positive x-axis
$\mathbf{B}_{Ey}$	1 297	positive y-axis
$\mathbf{B}_{Ez}$	19 413	negative z-axis

Under the influence of the external geomagnetic flux density $\mathbf{B}_E$, the ferromagnetic submarine induces a magnetic flux density $\mathbf{B}_T$ both internally and on its surface. This phenomenon is commonly referred to as magnetization.

From Figure 4(a), it is evident that the magnetization behavior of a submarine in the geomagnetic field resembles that of a cylinder. Specifically, internal magnetic dipoles are oriented along the direction of the geomagnetic field, leading to the cancellation of positive and negative poles of adjacent magnetic dipoles. Consequently, magnetic charges manifest exclusively on the end faces of the cylinder. The magnetic field generated by magnetic charges are directed from the geomagnetic north pole to the south pole, as illustrated in Figure 4(b).

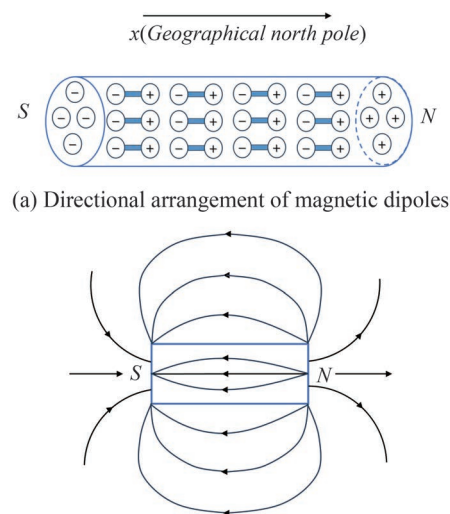


Figure 4 Schematic diagrams

Furthermore, the demagnetization $\mathbf{H}_d$ produced by the internal magnetic charge is oriented in the opposite direction to the magnetization $\mathbf{M}$. The relationship between them is given by:

$$|\mathbf{H}_d| = N |\mathbf{M}| \quad (4)$$

where N denotes the demagnetization factor, which is related to the geometric and motion parameters of the submarine and ranges from 0 to 1.

In the context of MAD, the detected magnetic flux density $\mathbf{B}$ represents the vector superposition of the geomagnetic flux density $\mathbf{B}_E$ and the submarine's magnetic flux density $\mathbf{B}_S$ (Zhou et al., 2017), as illustrated in Figure 3(b). The relationship is given by:

$$\mathbf{B} = \mathbf{B}_E + \mathbf{B}_S \quad (5)$$

Furthermore, based on the cosine theorem, the relationship among the detected magnetic flux density, the geomagnetic flux density, and the submarine's magnetic flux density can be derived as follows:

$$|\mathbf{B}| = |\mathbf{B}_E| \times \sqrt{1 + \frac{|\mathbf{B}_S|^2 + 2|\mathbf{B}_E| \times |\mathbf{B}_S| \cos \theta}{|\mathbf{B}_E|^2}} \quad (6)$$

Note that the submarine's magnetic flux density is significantly smaller than that of the geomagnetic flux density, which can be expressed as $|\mathbf{B}_S| \ll |\mathbf{B}_E|$. Therefore, (6) can be approximated as:

$$|\mathbf{B}| = |\mathbf{B}_E| \times \left(1 + \frac{|\mathbf{B}_S|^2 + 2|\mathbf{B}_E| \times |\mathbf{B}_S| \cos \theta}{2|\mathbf{B}_E|^2} \right) \quad (7)$$

As illustrated in Figure 3(b), the magnetic anomaly $\mathbf{B}_t$ is given by:

$$|\mathbf{B}_t| = |\mathbf{B}| - |\mathbf{B}_E| \quad (8)$$

Based on equation (5), (7), and (8), the magnetic anomaly can be derived as follows:

$$|\mathbf{B}_t| \approx \frac{|\mathbf{B}_S \cdot \mathbf{B}_E|}{|\mathbf{B}_E|} = |\mathbf{B}_S| \cos \theta \quad (9)$$

where the magnetic anomaly $\mathbf{B}_t$ induced by the submarine is equivalent to the projection of its magnetic flux density $\mathbf{B}_S$ in the direction of the geomagnetic flux density $\mathbf{B}_E$. Given the significantly lower strength of $\mathbf{B}_t$ compared to $\mathbf{B}_E$, it is essential to subtract $\mathbf{B}_t$ from $\mathbf{B}_E$ to facilitate a comparative analysis (Wang et al., 2021).

2.2 Finite element modeling of a submarine

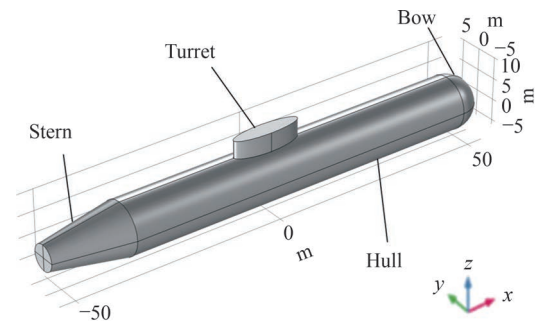
This paper examines the Seawolf-class nuclear submarine model. The main geometric parameters of the model are presented in Table 2, where the turret is extruded from an ellipse located at the midpoint of the submarine.

To conduct a comprehensive analysis of the submarine model, COMSOL Multiphysics software is employed as

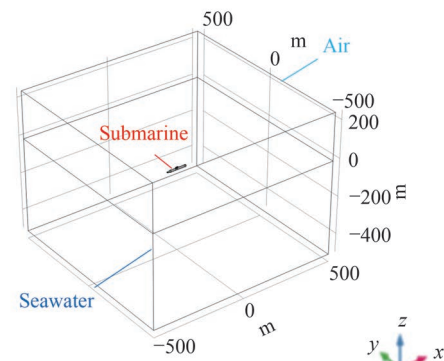
Table 2 Main geometric parameters of the submarine model

Parameter	Value (m)
Total length	107.6
Bow diameter	12.2
Stern diameter	6
Stern length	18
Turret height	4
Turret long semi-axis	8
Turret short semi-axis	2

the primary computational platform. The model constructed using the FEM is illustrated in Figure 5(a). Surrounding the submarine model is a seawater domain measuring $1000 \text{ m} \times 1000 \text{ m} \times 500 \text{ m}$, complemented by an air domain measuring $1000 \text{ m} \times 1000 \text{ m} \times 250 \text{ m}$ above sea level, as illustrated in Figure 5(b).



(a) Simulation model of submarine



(b) Computational domain

Figure 5 Simulation object

In terms of meshing, the software enables precise control over mesh size to enhance computational accuracy. For this study, the meshing parameters are configured with a maximum element size of 10 m and a minimum element size of 2 m. This setting balances mesh refinement with computational efficiency, ensuring accurate representation of the submarine's complex geometrical characteristics. Given effective degaussing of the submarine, the material's relative permeability is set to 200, ensuring that the simulation results are both reliable and reflective of real-world conditions.

3 Spatiotemporal characteristics of magnetic anomaly under typical motion scenarios

During actual underwater navigation, if a submarine experiences a minor change in any of its motion parameters, the magnetic stealth performance can be studied by analyzing the spatial distribution of magnetic anomaly on the aircraft detection plane or the temporal variations at a detection point. In this section, the typical motion scenarios of submarine are primarily categorized into two types: routine cruising and evasive maneuvering.

3.1 Characteristics of magnetic anomaly under routine cruise scenario

Nuclear submarines possess an extremely strong endurance capability, enabling them to conduct long-duration underwater routine cruising in specific maritime areas. To achieve high magnetic stealth and low noise levels, submarines typically select appropriate depths and speeds based on mission requirements to mitigate the risk of detection by aircraft. This section focuses on the spatiotemporal characteristics of submarine magnetic anomaly under routine cruise scenario.

3.1.1 Spatial characteristics of magnetic anomaly

During routine cruising, submarines operate at speeds ranging from 3–5 kn. This speed range optimizes battery consumption by avoiding excessively low speeds, which can lead to inefficient energy use, and excessively high speeds, which can generate increased noise levels. To mitigate the risk of detection by aircraft equipped with MAD sensors and to avoid potential collisions with surface vessels with drafts of 20–30 m, submarines typically select a safe working depth of approximately 100–300 m.

Typical Scenario 1: Suppose that at a specific moment ($t = 0$ s), the initial position of the submarine, as illustrated in Figure 6, indicates that it is cruising in a straight line from south to north along the x -axis at a speed of 3 kn and at a depth of 100 m. The aircraft is positioned 50 m above sea level, with the detection plane illustrated as the red dashed surface and the detection point denoted by the red circle. The path projection of aircraft and submarine on the xy plane is represented as OO' , with its midpoint designated as point A .

Under the influence of a locally geomagnetic field, Figure 7 illustrates the magnetic anomaly both inside and on the surface of the submarine. The black arrows denote the geomagnetic field at the model's location, indicating a uniform distribution of magnetic flux density. Meanwhile, colored arrows depict magnetic anomaly caused by the submarine's disturbances in the geomagnetic field: the redder the arrow, the stronger the strength. The arrows at the bow surface are the reddest because the projection of the geomagnetic field is along the positive x -axis, and the sub-

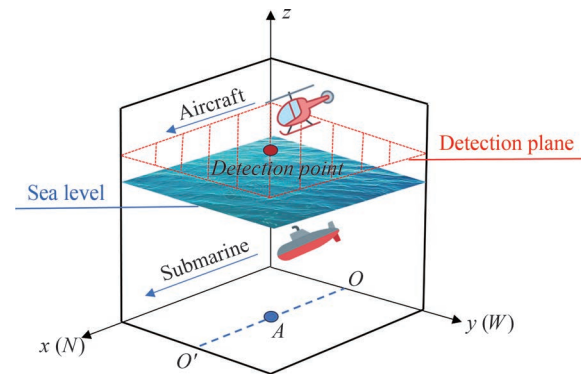


Figure 6 Submarine routine cruise scenario in a 3-D view

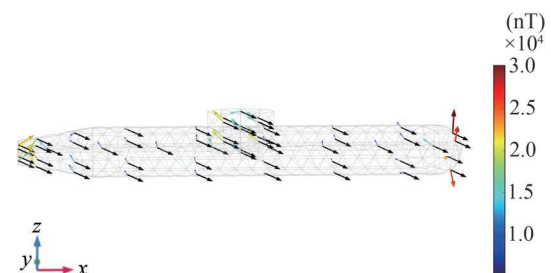


Figure 7 Magnetic anomaly caused by a submarine in the geomagnetic field

marine gradually magnetizes along the stern towards the bow. It is evident that the submarine's induced magnetic field significantly disrupts the geomagnetic field.

At the midpoint A of submarine's route, the four spatial distribution maps of magnetic anomaly presented in Figure 8 illustrate that on the detection plane, the x -component constitutes the largest proportion, followed by the z - and y -components. Specifically, the x -component shown in Figure 8(a) exhibits a “medium low, circumference high” pattern. The y -component shown in Figure 8(b) displays a 45° “high to low” clover-like pattern. The z -component shown in Figure 8(c) is symmetric about the line $y = 0$, with positive and negative peaks observed in front of and behind the submarine, respectively. Finally, the total magnetic anomaly illustrated in Figure 8(d) shows a “medium high, circumference low” pattern, with the maximum value concentrated at the submarine's boundary.

3.1.2 Temporal characteristics of magnetic anomaly

Assuming that other motion parameters remain constant, the submarine's speed increases to 5 kn. The midpoint of the detection plane is designated as the detection point, as illustrated in Figure 6. The temporal characteristics of the vector magnetic anomaly, both before and after the speed change, are illustrated in Figure 9. When the submarine navigates the same nautical miles, the time expended is inversely proportional to the speed. This relationship does not affect the amplitude of the temporal characteristics of the vector magnetic anomaly. The waveform of the magnetic anomaly remains consistent across the same component.

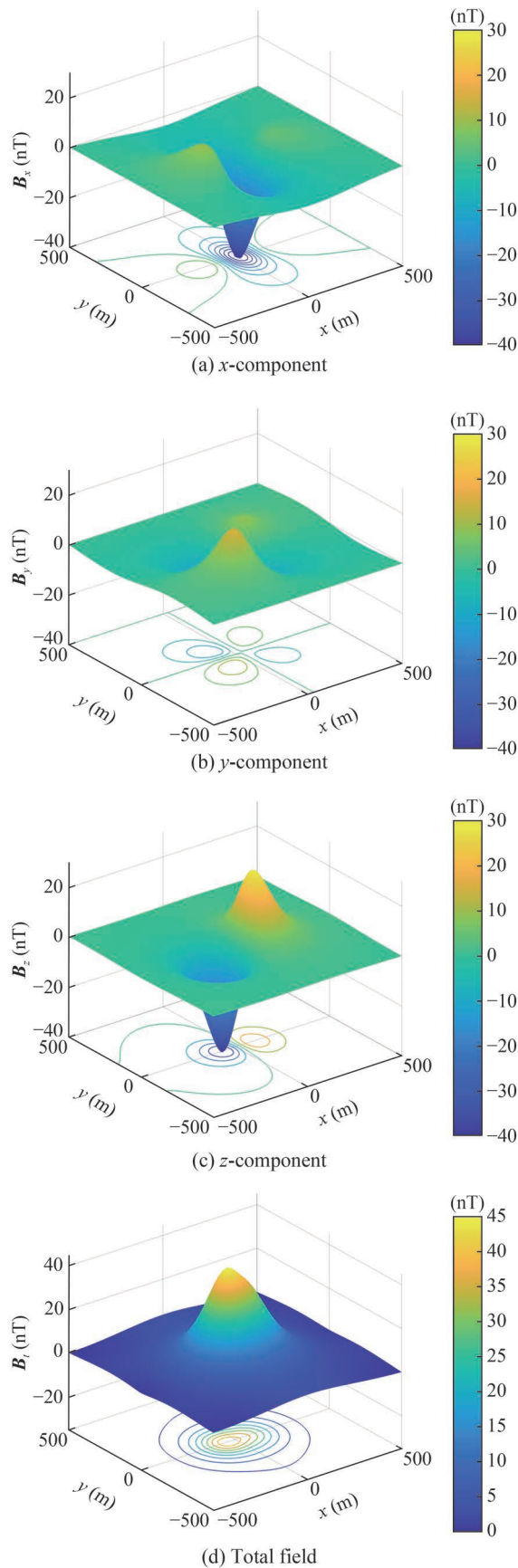


Figure 8 Spatial distribution of magnetic anomaly

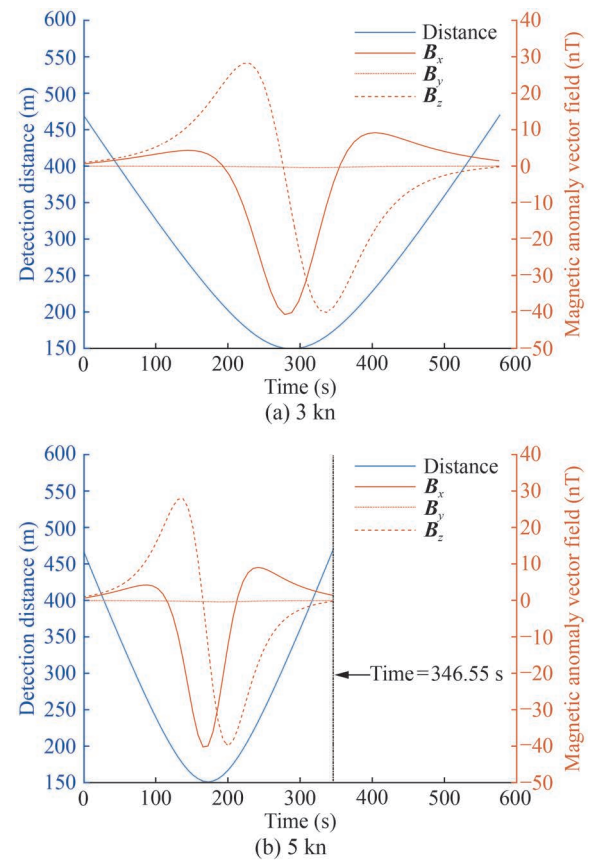


Figure 9 Temporal variations of vector magnetic anomaly at different speeds

The relationship between the total magnetic anomaly B_t and each vector components (B_x , B_y and B_z) is given by:

$$|B_t| = \sqrt{|B_x|^2 + |B_y|^2 + |B_z|^2} \quad (10)$$

Consequently, the speed does not exert a significant influence on the amplitude of the total magnetic anomaly. As the detection distance decreases, the strength of the x-component exhibits a gradual increase, while variations in the y-component remain negligible. Table 1 demonstrates that the geomagnetic flux density is predominantly concentrated along the x-axis of the xy plane, with the submarine being magnetized from bow to stern. The strength of the z-component first increases and then decreases, peaking when the detection point is closest to the cross-sections of the submarine's bow and stern. This phenomenon is attributed to the distribution of positive and negative charges on slices, as illustrated in Figure 4(a).

3.2 Characteristics of magnetic anomaly under evasive maneuver scenario

To effectively evade aircraft searches, submarines must execute side-to-side maneuvers within a horizontal plane

or up-and-down maneuvers within a vertical plane. The stern rudder, a crucial structure for controlling both horizontal and vertical maneuvers, consists of the rudder and the elevator (Ye et al., 2023). The rudder controls the submarine's course, while the elevator controls its depth. This section examines the spatiotemporal characteristics of submarine magnetic anomaly under depth-fixed turn and emergency dive scenarios.

3.2.1 Spatiotemporal characteristics of magnetic anomaly under depth-fixed turn scenario

When an aircraft equipped with MAD sensors conducts a search mission, the detection of magnetic anomaly signals suggests the potential presence of a submarine in the hazardous area. In such circumstances, the submarine should adopt an appropriate course and execute a rapid turn, positioning the rudder at a specific angle. This maneuver enables the submarine to navigate through the oblique water flow, facilitating evasive action and enhancing its concealment effectiveness.

Typical Scenario 2: Suppose that at a specific moment ($t = 0$ s), a submarine is situated in an unfavorable position at point O , located 100 m below sea level, while an aircraft is traversing a flight path directly above the submarine's route. To evade detection, the submarine will increase its speed to 5 kn and execute a maneuver at a rudder angle α , either turning left along route OO' or right along route OO'' . The left rudder angle is considered positive. The midpoints of these two routes are designated as B and C , respectively, as illustrated in Figure 10.

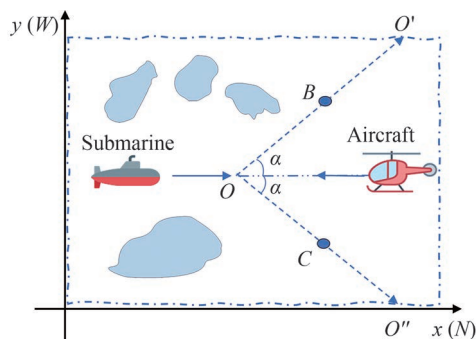


Figure 10 Submarine depth-fixed turn scenario in a 2-D horizontal view

To avoid detection by aircraft, the submarine can adjust its rudder to the left or right by an angle α of 10° . Upon reaching the midpoint of its route (B or C in Figure 10), the total magnetic anomaly along the detection path is illustrated in Figure 11. As shown in Figure 11(b), when the x -coordinate is approximately -35.8 m (half of the total length 53.8 m, minus the stern length 18 m), the total magnetic anomaly reaches its maximum strength. This strength is reduced by about 12 nT during left- or right-turning maneuvers, compared to straight cruising. Meanwhile, for

the same magnitude of rudder angle, the maximum strength is slightly greater when the submarine turns left compared to when it turns right, with a difference of 1 nT. As illustrated in Figure 3(a), compared to right-turning or straight cruising, the angle between the submarine's course and the total geomagnetic field direction is smaller when it turns left, which produces a greater magnetic anomaly.

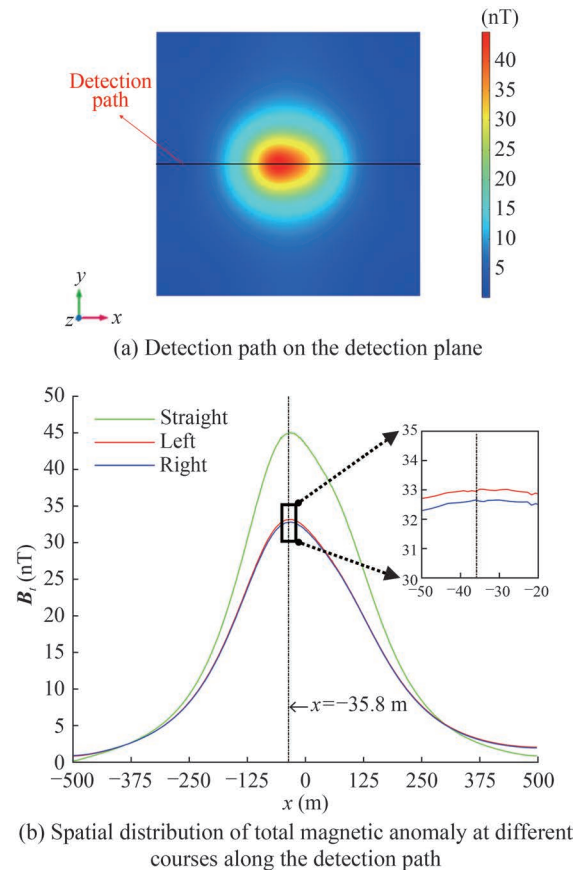


Figure 11 Magnetic anomaly under depth-fixed turn scenario

The temporal variations of vector magnetic anomaly under two distinct turning scenarios are illustrated in Figure 12. When the projected length of the submarine's route along the x -axis is the same, the required navigation time for both scenarios is equivalent. The y -component magnetic anomaly induced by the submarine's left and right turns exhibits opposite directional characteristics at any given moment, while the strength during a left turn is marginally greater than that observed during a right turn. Given the positive projection direction of the geomagnetic field along the y -axis, the angle between the submarine and the geomagnetic field decreases when the submarine turns left, resulting in increased magnetization. Meanwhile, the x - and z -components remain nearly constant, as shown in Figure 12(a) and Figure 12(b), leading to a total magnetic anomaly during a left turn that is slightly greater than that during a right turn.

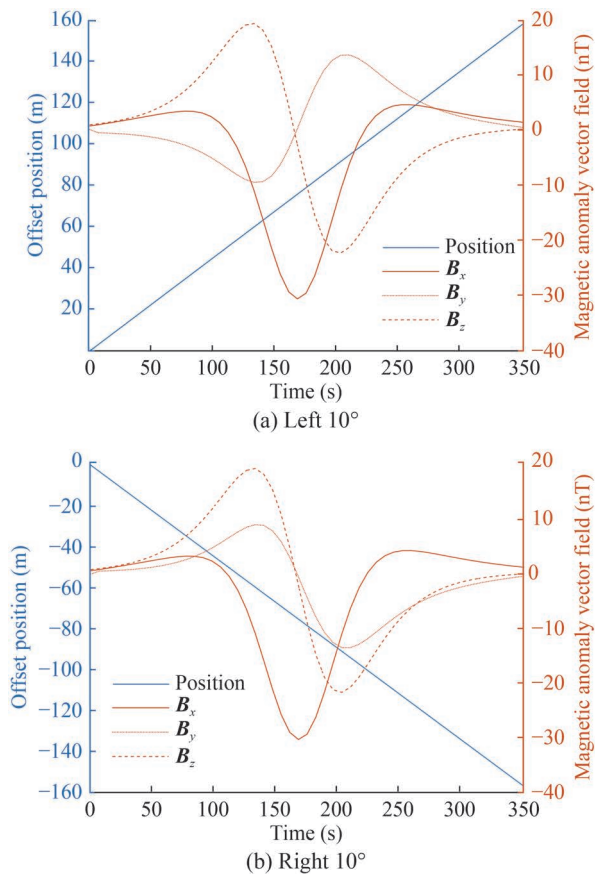


Figure 12 Temporal variations of vector magnetic anomaly at different rudder angles

Assuming constant submarine speed and depth, depth-fixed turning maneuvers are executed at rudder angles of 6° , 8° , 10° , 12° , and 14° to the left or right. Table 3 presents the peak-to-peak values of the vector magnetic anomaly during the submarine's navigation from the starting point O to the ending points O' or O'' . The data indicate that as the rudder angle increases, the peak-to-peak values of the x - and z -components gradually decrease, while those of the y -component gradually increase. Furthermore, for rudder angles of equivalent magnitude, the vector magnetic anomaly is higher for left turns than for right turns. Consequently, to reduce the risk of detection by aircraft equipped with magnetic anomaly detection (MAD) sensors, submarines are advised to execute right turns. This strategy not only enhances stealth capabilities but also provides tactical flexibility in evasive scenarios, ensuring operational effectiveness and safety.

3.2.2 Spatiotemporal characteristics of magnetic anomaly under emergency dive scenario

Emergency diving is a tactical maneuver employed by submarines. In certain circumstances, submarines must increase their depth of submergence to minimize the probability of detection. Given that vulnerable appendages are located at the stern, it is generally recommended to exe-

Table 3 Comparison of vector magnetic anomaly under depth-fixed turning scenario

Turn	Rudder angle ($^\circ$)	B_x (nT)	B_y (nT)	B_z (nT)
Left	6	39.38	16.38	47.29
	8	35.77	19.06	40.67
	10	31.85	20.37	34.36
	12	27.87	20.47	28.50
	14	24.65	19.70	23.42
Right	-6	38.44	16.06	46.72
	-8	34.69	18.75	40.19
	-10	30.71	20.02	33.86
	-12	26.84	20.06	28.43
	-14	23.77	19.29	22.97

cute a dive with a bow inclination to protect the structural integrity of the stern.

Typical Scenario 3: Suppose that at a specific moment ($t = 0$ s), a submarine is situated in an unfavorable position at point O , located 100 m below sea level, while an aircraft is traversing a flight path directly above the submarine's route. To evade detection, the submarine's bow will tilt downward at an elevator angle β , its speed will increase to 5 kn and remain constant during descent from point O to point O' . The midpoint of OO' is designated as point D , as illustrated in Figure 13.

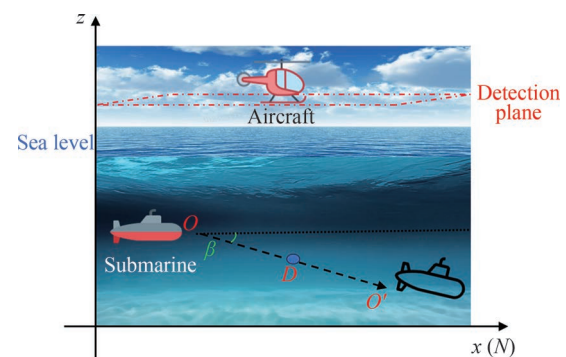


Figure 13 Submarine emergency dive scenario in a 2-D vertical view

The results in Figure 14 were obtained at an elevator angle β of 8° . As the depth increases by about 40 m, the maximum strength of the magnetic anomaly on the detection plane decreases to roughly 1/10 of its initial value. When the depth increases by about 80 m, the maximum strength decreases to roughly 1/20 of its initial value. The attenuation rate of the magnetic anomaly strength decreases as the submarine descends from the starting point O to the ending point O' . At any given moment during the descent, the strength is greatest directly above the submarine, as evidenced by significant changes in the contours.

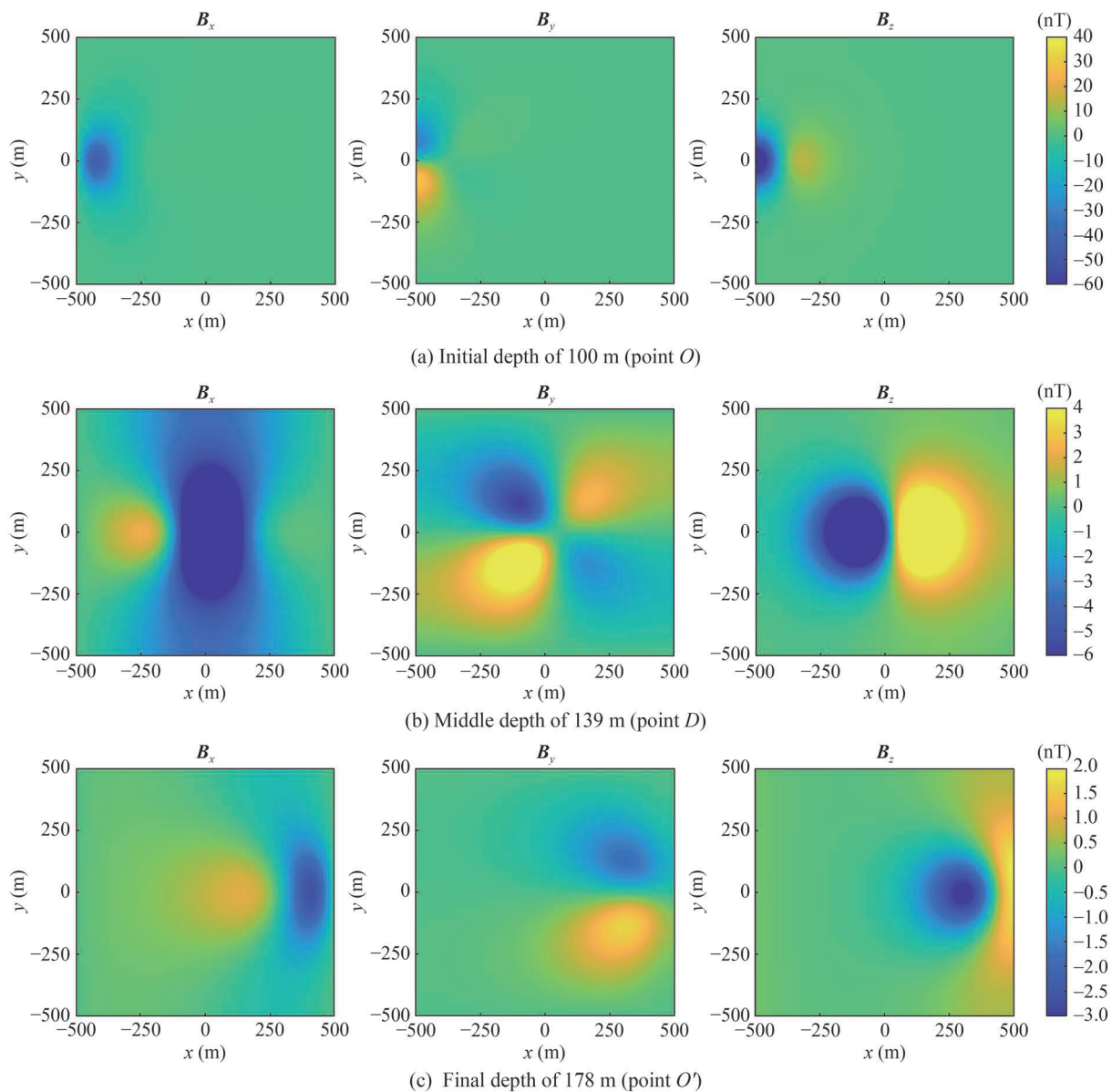


Figure 14 Spatial distribution of vector magnetic anomaly at different depths

Under practical motion scenarios, the elevator angle of the submarine typically ranges up to 10° . Consequently, the simulated model executes diving at elevator angles of 8° and 10° , and temporal variations of the vector magnetic anomaly under both conditions are illustrated in Figure 15. When the projection of OO' is aligned along the x -axis, it is evident that a larger elevator angle requires a slightly longer duration for the maneuver. Meanwhile, a larger elevator angle correlates with a deeper dive of the submarine at any given time, accompanied by a reduction in the magnetic anomaly.

Assuming a constant submarine speed and an effective detection distance of 600 m for the MAD sensor, emergency diving maneuvers are executed at elevator angles ranging from 8° to 20° . The simulated detection distances

of the aircraft when the submarine reaches the midpoint and endpoint of its route is shown in Figure 16. The results indicate that at the same time points, the detection distance increases with the elevator angle. However, as time progresses, the overall detection distance of the aircraft decreases. Specifically, when the elevator angle reaches 16° , the detection distance at the endpoint exceeds the effective detection range of the MAD sensor. Therefore, selecting a relatively larger elevator angle during emergency diving enables the submarine to more securely exit hazardous waters, thereby reducing the risk of detection by aircraft. This approach not only enhances operational safety but also provides tactical flexibility in evasive maneuvers, ensuring optimal performance under threat conditions.

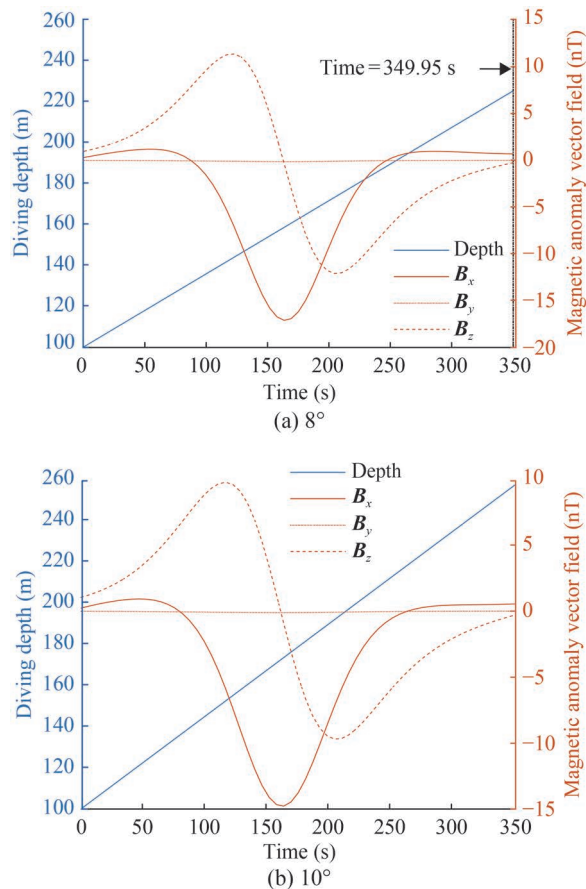


Figure 15 Temporal variations of vector magnetic anomaly at different elevator angles

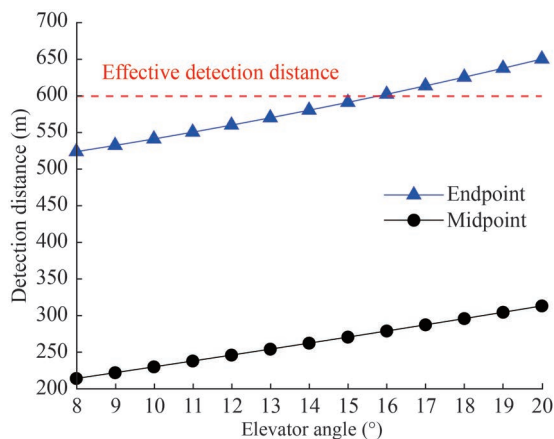


Figure 16 Detection distance change with elevator angle during emergency dive scenario

3.2.3 Spatiotemporal characteristics of magnetic anomaly under depth-increasing turn scenario

To evade detection by aircraft equipped with MAD sensors, submarines must execute complex maneuvers involving adjustments to both rudder and elevator angles. This combined adjustment allows the submarine to perform a depth-increasing turn, simultaneously altering its course and depth to avoid detection while maintaining stealth. As

previously discussed in subsections 3.2.1 and 3.2.2, turning right or diving deeper both reduce the risk of detection by the aircraft. Therefore, it is essential to integrate these two scenarios to compare and optimize the results.

Typical Scenario 4: Suppose that at a specific moment ($t = 0$ s), a submarine is situated in an unfavorable position, located 100 m below sea level. To evade detection by the aircraft, the submarine will increase its speed to 5 kn and execute a combined maneuver involving rudder and elevator adjustments. The rudder angle α is set to a negative value, causing a right turn, while the elevator angle β is set to control the depth change. The spatial distribution of the total magnetic anomaly at the midpoint of the submarine's course is illustrated in Figure 17.

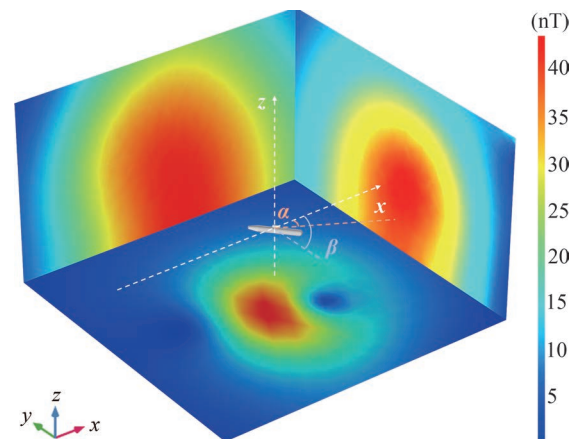


Figure 17 Submarine depth-increasing turn scenario in a 3-D view

Configure the submarine to perform evasive maneuvers with a rightward rudder angle of 10° and an elevator angle of 15° . The temporal variations of the vector magnetic anomaly under different evasive maneuver scenarios are illustrated in Figure 18. As time progresses, the detection distance between the aircraft and the submarine initially decreases and then increases for all three evasive maneuvers. Notably, depth-fixed turning maneuvers require less time overall. According to subsection 3.2.2, the effective detection range of the MAD sensor equipped on the aircraft is set to 600 m. When the submarine executes a depth-increasing turn, it exits the detection range at approximately 361 s.

Furthermore, the impact of different evasive maneuvers on the detection distance of submarines is shown in Table 4. These maneuvers involve varying the rudder angle, elevator angle, or both simultaneously. The simulation results are categorized into three groups (A, B, and C), each comprising three scenarios: a depth-fixed turn, an emergency dive, and a depth-increasing turn using the corresponding angle. The results indicate that when the rudder angle is fixed, executing an emergency dive is more effective at reducing detection risk than performing a depth-fixed turn alone. Conversely, when the elevator angle is fixed, incor-

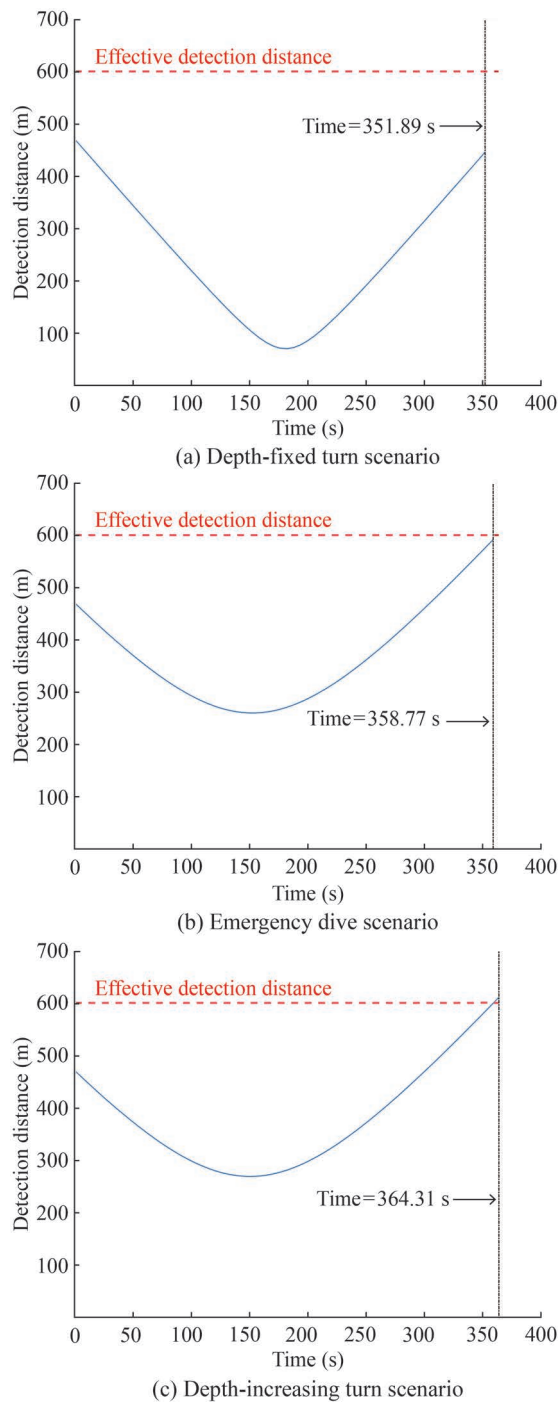


Figure 18 Variations of detection distance under different evasive maneuver scenarios

porating a right turn further reduces the detection risk compared to an emergency dive alone.

The simulation results in this subsection show that to optimize evasive maneuvers for enhanced stealth and safety, submarines should combine an increased rightward rudder angle with a specific elevator angle. This strategy not only reduces the detection risk to enhance stealth but also minimizes the risk of excessive bow tilt. Excessive eleva-

Table 4 Maximum detection distance under evasive maneuver scenario

Group	Rudder (°)	Elevator (°)	Maximum detection distance (m)
A	-10	0	445.76
	0	16	602.63
	-10	16	622.79
B	-10	0	445.76
	0	15	591.48
	-10	15	612.01
C	-12	0	447.44
	0	15	591.48
	-12	15	621.09

tor angles can compromise the submarine's control and safety, thereby risking instability or capsizing.

4 Discussions

In the process of simulating typical submarine motion scenarios, it is essential to adjust relevant motion parameters, including speed, course, and depth. As the submarine navigates from its initial point *O* to the midpoint of the route under different scenarios, a comparison of the maximum total magnetic anomaly, as measured by aircraft at the detection point, is presented in Table 5.

Table 5 Comparison of total magnetic anomaly under different motion scenarios

Motion scenario	Rudder (°)	Elevator (°)	Speed (kn)	Time (s)	Magnetic anomaly (nT)
Routine cruise	0	0	3	288.89	34.49
	0	0	5	173.27	34.49
Depth-Fixed turn	-12	0	5	177.15	24.95
	12	0	5	177.15	25.77
	-10	0	5	175.95	30.42
	10	0	5	175.95	30.95
Emergency dive	0	10	5	175.95	15.49
	0	8	5	174.98	18.35
Depth-Increasing turn	-10	16	5	183.04	8.66
	-12	15	5	183.39	8.77

As elucidated in this study, simulations of three typical motion scenarios for submarines were performed using the finite element method. A single-variable approach was employed to change each motion parameters for comparative analysis. Furthermore, based on the data in Table 5, the following discussions are presented:

1) During routine cruising, the amplitude of the magnetic anomaly induced by the submarine exhibits no signif-

icant correlation with its speed. Therefore, to mitigate the risk of detection by aircraft equipped with MAD sensors, submarines should maintain a relatively high speed to expeditiously exit hazardous waters.

2) During evasive maneuvering, the strength of the magnetic anomaly is marginally greater when turning left compared to turning right at a fixed depth. Additionally, during emergency diving, the magnetic anomaly is lower at larger elevator angles. Consequently, to mitigate the risk of detection by aircraft equipped with MAD sensors, submarines should opt for a right rudder angle or a larger elevator angle.

3) When the submarine evades at the same angle of 10° , the magnetic anomaly during emergency diving is reduced by about 50% compared to that during depth-fixed turning. Consequently, the implementation of diving evasive strategies can significantly enhance the submarine's magnetic stealth capabilities.

4) Combining an increased rightward rudder angle with a specific elevator angle is the most effective evasive maneuver for submarines to reduce detection risk by aircrafts. It is also crucial to balance the elevator angles to avoid excessive bow tilt, which can lead to instability or capsizing, thus compromising control and safety.

5 Conclusions

In this paper, a novel finite element model was developed to elucidate the spatiotemporal characteristics of submarine magnetic anomaly under typical motion scenarios. Initially, the modeling of the submarine and the boundary conditions of the geomagnetic field were described in detail. Following the subtraction of the geomagnetic field, the three components of the total spatial magnetic anomaly, simulated using the FEM, were utilized to elucidate the magnetization state of the submarine. Furthermore, the temporal characteristics of the magnetic anomaly were computed using a parameterized scanning method. The results indicated that increasing speed during routine cruising can facilitate a more rapid exit from hazardous waters. Additionally, the analysis showed that opting for a right rudder angle or a large elevator angle during evasive maneuvers can significantly mitigate the risk of detection by aircraft. Moreover, when the angles are the same, diving proves to be a more effective strategy for risk reduction compared to turning. More importantly, combining a specific rightward rudder angle with an elevator angle is the most effective and safe evasive maneuver for submarines. The studies presented in this paper offer valuable theoretical results for the advancement of submarine magnetic stealth technologies.

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