Study on the submarine tracking method of anti-submarine patrol aircraft using passive omni-directional sonobuoys

Wang Xinwei, Wang Jianguo, Men Jinzhu
Dalian Navy Academy, Dalian 116018, China
E-mail: wangjianguo1981@163.com

Abstract: According to submarine tracking problem of the anti-submarine patrol aircraft (ASPA) using passive omnidirectional sonobuoy, the paper discusses on the layout of sonobuoy for tracking submarine, studies on the method of sonobuoy for tracking submarine, and analysis of the whole process of tracking submarine for anti-submarine patrol aircraft using sonobuoys. The papers also take the simulation analysis for 5 kinds of tracking index, and gives out the result as the chart or table, and provides the reference for the research of following submarine for anti-submarine patrol aircraft.

1. Introduction
Submarine tracking, is a combat operations between the anti-submarine patrol aircraft and submarines to keep contact and (or) in the lost contact recovery, it is an important stage of aviation antisubmarine action. It is as the continue to the submarine search and the base premise to the attacking.

Passive omnidirectional sonobuoy is an important submarine detection load of the anti-submarine patrol aircraft. It has the characteristics of good concealment, the maximum load, and should be considered using for tracking submarine.

According to the characteristics of target, the sea environment, performance and number of sonobuoy, the anti-submarine patrol aircraft could take two ways of tracking the enemy submarine, the continuous tracking and periodic tracking.

The anti-submarine patrol aircraft using passive omnidirectional sonobuoy system research of submarine tracking problem, provides a reference basis for the commander's decision.

2. Sonobuoy layout
When the anti-submarine patrol aircraft using passive omnidirectional sonobuoy to track submarine, it is mainly used for rough tracking, because the tracking accuracy is low. Although this method can’t accurately locate the target, but it can provide initial information and it could be combined with the battlefield situation, to strengthen the judgement.

Usually, the two methods, such as covering array and (or) intercepting array, are used, when the target through the covering array. The course and speed could be approximate by the buoy’s location and time, which detected the target. As shown in Fig1.

When the target through the blocking array, its rough sailing fan and speed could be estimated, according to the time between buoy lost contact and recovery to the target, and the distance between the buoy when detecting the target. As shown in Fig2.
3. Submarine tracking method

When the anti-submarine patrol aircraft using passive omnidirectional sonobuoy for submarine tracking, both the latent continuous tracking and the potential periodic tracking could be used.

In actual combat, the influence factors of determine are the target motion elements, anti-submarine patrol aircraft maneuvering performance, sonobuoy detecting distance and so on.

3.1. Continuity Submarine Tracking

The latent continuous tracking refers to the anti-submarine patrol aircraft, to maintain continuous contact to the submarine.

Continuous tracking, continuous contact high reliability, can continue to listen the target noise. It can attack the submarine at any time, and the restore the contact time is short, but it is difficult to the high speed target, and it need the anti-submarine patrol aircraft frequent maneuver, so the crew’s work intensity is large.

When using the sonarbuoy for continuous submarine tracking, the sonarbuoy layout should be perpendicular to the target route.

Buoy interval should be guarantee that the submarine buoy array can continuously find the target, and the time which the anti-submarine patrol aircraft from the monitor the sonarbuy array contact with the target to laying a buoy array end time, is less than the time the submarine throng the adjacent sonarbuoy array.

The distance of adjacent buoy array is not more than two times of the detected distance of the buoy, and the spacing of the buoys in the array can be placed according to the check search, general \(1.5 \sim 2 r_{fb}\), (the \(r_{fb}\) is the detected range of sonobuoy), as shown in Fig3[1].
3.2. Periodic Submarine Tracking

The tracking of potential cycle refers to the anti-submarine patrol aircraft at a certain time interval to maintain contact on the submarine.

The latent periodic tracking, can regularly keep the target contact, and anti-submarine patrol aircraft maneuvering and crew work intensity is low, but can’t attack the target at any time, and the resume contact time after lost contact is long.

The method can be used when the target speed is high or the carrying sonobuoy number is limited, and it is difficult to maintain continuous contact.

It should be noted that the decrease of the tracking probability is due to the decrease of the number of contacts and the number of buoys in the array. The increase of the lost contact will lead to the increase of the contact time and the increase of the buoy consumption[3].

Therefore, the latent periodic tracking, should guarantee sonarbuoy amount to meet the premise of laying buoys established tracking probability, as far as the possible to avoid the loss of contact with the target[4].

\[
\begin{align*}
\text{Among, when the anti-submarine patrol aircraft is used for submarine periodic tracking, the maximum interrupt time } & t_{u\text{ max}} : \\
& t_{u\text{ max}} = \frac{D_d - 2r_{fb}}{v_{qf\text{ min}}} \quad \ldots \ldots \ldots \ldots (1)
\end{align*}
\]

Where: \(D_d\) is the distance between the adjacent buoy array, \(r_{fb}\) is the detected range of the sonobuy, and \(v_{qf\text{ min}}\) is the minimum speed of the submarine.

3.3. The whole process of submarine tracking

Based on the above analysis, in the whole process of tracking of submarine, submarine speed is an
important prerequisite, which influences the tracking method of the anti-submarine patrol aircraft using the sonar buoy.

According to the different speed of submarine, the whole process of the anti-submarine patrol aircraft to submarine tracking, should include four parts, the suspicious signal, the suspicious signal recognition and classification, to maintain the continuity of contact and (or) maintain periodic contact, and contact recovery with the submarine when lost, as shown in Fig 5.

4. Submarine tracking tactical calculation
Based on the tracking method of anti-submarine patrol aircraft deployed sonar buoy array for submarine tracking, a series of tactics calculation is needed, which includes 5 important indexes: to determine the sonobuoy array radius, tracking efficiency, unit time consumption, and probability of submarine tracking, and the number of anti submarine patrol aircraft dispatched aircraft[5].

4.1. Determination the sonobuoy array’s radius
The radius of sonobuoy array is mainly related with the target speed, and the greater target speed, the larger radius of the buoy array[6].

The increase of the radius is related to the increase of the target speed. If the submarine speed obeys the uniformly accelerated motion, then the sonobuoy array radius $R_{fb}$ can be expressed as:

$$R_{fb} = \frac{[v_{fq} + (v_{fq} + \Delta v_{fq})] \cdot t_{jc} + \Delta q_t}{2p_{fx}}$$  \hspace{1cm} (2)

Where: $v_{fq}$ is the submarine’s speed(kn), $\Delta v_{fq}$ is the submarine speed increase(kn), $t_{jc} \Delta q_t$ is contact interval time of the adjacent buoy array(min), $\Delta q_t$ is the submarine position error(m); $p_{fx}$ is the buoy array detection probability, and it should not be less than 0.8.

If the $p_{fx} = 0.8$, then the radius of the sonobuoy array is given out as table 1.

| $v_{fq}$ | $\Delta v_{fq}$ | $\Delta q_t$ | 5  | 10  | 15  | 20  |
|----------|-----------------|-------------|----|-----|-----|-----|
| 4        | 2               | 300         | 1.1| 2.2 | 3.2 | 4.2 |
| 6        | 2               | 300         | 1.7| 3.0 | 4.4 | 5.7 |
| 10       | 4               | 400         | 2.7| 5.0 | 7.3 | 9.7 |
| 15       | 0               | 500         | 3.4| 6.3 | 9.2 | 12.1|
| 20       | 0               | 500         | 4.4| 8.2 | 12.1| 15.9|

4.2. Tracking efficiency
Tracking efficiency of anti-submarine patrol aircraft, could be described by the average tracking time or within a given time tracking probability. The average tracking time can be determined by the average
tracking period $\overline{t}_{gc}$ and average tracking period $\overline{n}$, That is

$$\overline{t}_{gc} = \overline{t}_{gc} \cdot \overline{n} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

Where: $\overline{t}_{gc}$ is the tracking period mean, and contains two parts, one is $t_{bj}$ (Maintain contact time), the other is $t_{hj}$ (Restore contact time), That is:

$$\overline{t}_{gc} = t_{bj} + t_{hj}$$

$$t_{bj} = D_d \cdot P_{bj} / \left[ v_{qt} \cdot (1 - P_{hj}) \right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

$$t_{hj} = R_{fb} / v_{qt}$$

Where: $P_{bj}$ is target discovery probability; $P_{hj}$ is the recovery contact probability, $R_{fb}$ is the radius of the enclosed buoy array, $D_d$ is the spacing of adjacent buoy array, $v_{qt}$ is the submarine speed.

In order to restore contact with the target, the average number of tracking cycles $\overline{n}$ can be expressed as follow:

$$\overline{n} = \frac{P_{hj}}{1 - P_{hj}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5)$$

From formula (3), (4), (5), average tracking time $\overline{t}_{gc}$ can be expressed as following:

$$\overline{t}_{gc} = \left[ D_d \cdot P_{bj} + R_{fb} \cdot (1 - P_{hj}) \right] \cdot P_{hj}$$

$$t_{bj} = D_d \cdot P_{bj} / \left[ v_{qt} \cdot (1 - P_{hj}) \cdot (1 - P_{hj}) \right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6)$$

Where $D_d$ should meet the condition:

$$2R_{fb} \leq D_d \leq v_{qt} \cdot t_{jc} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (7)$$

If the $P_{bj}=0.8$, $P_{hj}=0.85$, $v_{qt}=6$, $t_{jc}=20$, $\Delta v_{qt}=400$, the relation between $\overline{t}_{gc}$ and $D_d$ as shown in Fig 6:

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4.3. Unit time consumption of sonobuoy
Sonobuoy consumption in unit time, is also an important index of anti-submarine patrol aircraft, submarine tracking, and can reflect the capability of submarine single or multi frame to frame anti-submarine patrol aircraft tracking. This value can be determined when the delivery number of submarine tracking buoy (the number of buoys deployed) and anti-submarine patrol aircraft sorties and rotation, and anti-submarine patrol aircraft tracking duration can be planned.
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Set on the survival rate of the sonar buoy as $P_{ch}$, and target contact probability as $P_{jc}$, the mechanical
unit time consumption for sonobuoy is $n_{th}$:

$$n_{th} = \frac{\theta}{2\arcsin\left(\frac{d_{pl}}{2v_{qf}}\right)} \cdot \frac{2r_{fb}}{P_{ch} \cdot P_{jc} \cdot d_{pl}} \ldots \ldots (8)$$

In order to find out the relation between the consumption of sonobuoy in unit time and speed of submarine linear, the chord length calculation can be transferred into the arc length calculation, the consumption sonobuoy in unit time can be expressed as:

$$n_{th} = \frac{\theta \cdot \pi \cdot v_{qf}}{180 \cdot d_{pl} \cdot P_{ch} \cdot P_{jc}} \cdot \frac{2r_{fb}}{d_{pl}} \ldots \ldots (9)$$

If $P_{ch}=0.8, P_{jc}=0.8, r_{fb}=2km, v_{qf}=6kn(\text{or } 8kn), \theta=90^\circ, 120^\circ, 180^\circ$, then the corresponding relationship between the unit time consumption of sonobuoy and spacing of the adjacent buoys is shown in Fig 7, Fig 8 and table 2.

![Fig 7 Unit time consumption of sonobuoy when submarine speed 6kn](image)

![Fig 8 Unit time consumption of sonobuoy when submarine speed 8kn](image)

**Table 2 Unit time consumption of the sonobuoy**

| $v_{sf}$ | $\theta$ | spacing of the adjacent buoy |
|---------|--------|-------------------------------|
|         | $0.75r_{so}$ | $1.0r_{so}$ | $1.25r_{so}$ | $1.5r_{so}$ | $1.75r_{so}$ |
| 6       | 90     | 15.5          | 11.6          | 9.3          | 7.8          | 6.6          |
|         | 120    | 21.6          | 16.2          | 12.9         | 11.4         | 9.2          |
|         | 180    | 33.7          | 25.3          | 20.2         | 16.8         | 14.4         |
| 8       | 90     | 21.6          | 16.2          | 12.9         | 10.8         | 9.2          |
|         | 120    | 29.6          | 22.2          | 17.8         | 14.8         | 12.7         |
|         | 180    | 45.8          | 34.3          | 27.5         | 23.4         | 19.6         |
The above analysis shows that: when the speed of submarine is certain, it is independence between unit time consumption of sonar buoy and the radius of the sonar buoy array for maintain and (or) contact recovery, but it is proportional to the speed of submarine, and inversely proportional to the spacing of adjacent buoy.

Therefore, the consumption of the sonar buoy and the required number of antisubmarine patrol aircraft could be obtained according to the speed of submarine.

4.4. Probability of submarine tracking

The probability of submarine tracking can be expressed as [7]:

\[
\begin{align*}
    P_{\text{gc}} &= e^{-\frac{v_{\text{gd}}}{T_{\text{gd}}}}, \\
    T_{\text{gc}} &= \frac{[D_{\text{a}} \cdot P_{\text{b}} + R_{\text{b}} \cdot (1-P_{\text{b}})] \cdot P_{\text{b}}}{v_{\text{gd}} \cdot (1-P_{\text{b}}) \cdot (1-P_{\text{h}})}
\end{align*}
\]

Where: \( T_{\text{gd}} \) is specified submarine tracking time; \( T_{\text{gc}} \) is the average time of submarine tracking.

4.5. The dispatched number of the anti-submarine patrol aircraft

When using the anti-submarine patrol aircraft for submarine tracking, the required number \( n_a \) can be expressed as:

\[
    n_a = \frac{T_{\text{gd}} \cdot n_b}{T_{\text{a}} \cdot K}
\]

Where: \( n_b \) is the number of the anti-submarine patrol aircraft in one batch; \( T_{\text{a}} \) is the actual work time of the anti-submarine patrol aircraft; \( K \) is the dispatched strength coefficient.

Tactical calculations show that: when the radius of the buoy array is determined, (according to the submarine speed), the bigger the submarine speed, the larger the average tracking time and the tracking probability of the anti-submarine patrol aircraft.

Therefore, when tracking the submarine, the same radius of the buoy array could be used, it also reduces the difficulty of anti submarine patrol aircraft maneuvering.

5. Conclusion

Aimed at the problem of the anti submarine patrol aircraft using passive omnidirectional sonobuoy submarine sonar buoy tracking, the paper analyzes the submarine tracking arrangement and the method of tracking of submarine sonar buoy. It also discusses the whole process of submarine tracking, and the corresponding tactics calculation, simulation analysis of 5 tracking kinds of index. The conclusion has reference basis to study potential tracking for anti-submarine patrol.

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