Research on Route Planning Model Based on Multi-beam Sounding Technology

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Abstract. With the advancement of multi-beam sounding technology, designing an effective aerial survey route has become a crucial research area. This research aims to address the line layout problem for multi-beam sounding in various oceanic regions through the proposed route planning model. Firstly, analyze the functional relationship between the depth of seawater, the coverage width of the measurement line and the overlap rate between adjacent strips under the condition of different distance from the center point of the measurement line. Secondly, describe the coverage width of multi-beam sounding at different positions using trigonometric functions based on a stereoscopic model of the ship's cross-section at any course. Finally, under the condition of fixed gradient of seabed slope, the design and solution of aerial survey routes in the sea area is carried out by using the ox-ploughing reciprocal method, and the route planning model is established with the goal of achieving the maximum coverage area and the minimum distance of aerial survey and the aerial survey plan of the sea area is given.

Key words: Multi-beam Sounding, Route planning, Boustrophedon, 3D plane projection.

1. Introduction

Multi-beam sounding system is developed on the basis of single beam sounding. The system can send out a beam when sailing in the plane perpendicular to the track, and then receive the acoustic wave back from the bottom by the receiving transducer. The multi-beam sounding system overcomes the disadvantage of single beam sounding, and can accurately measure the full coverage depth strip with the survey ship line as the axis and a certain width in the flat sea area of the seabed. However, due to the large fluctuation of the real seabed topography, if the average depth of the sea is used to design the measurement line interval, although the average overlap rate between the strips can meet the requirements, it will affect the final measurement quality because of the leakage in the shallow water depth. On the contrary, if the water depth at the shallowest part of the sea is used to design the measurement line interval, although the overlap rate at the shallowest part can meet the requirements, there may be too much overlap in the deeper part of the water depth, resulting in large redundancy of the final data and affecting the measurement efficiency. In this regard, how to design a reasonable measurement line becomes an important research topic in multi-beam sounding technology.

Multi-beam sounding system is one of the most widely used means in national ocean exploration, which has good sounding effect. The significance of the multi-beam sounding system has been extensively explored in numerous literature sources. For example, Yu Dong[1]studied the working principle and operation flow of the multi-beam sounding system, and analyzed the advantages and characteristics of the sounding system.Chuanyu Fu[2] studied the advantages of autonomous navigation and autonomous measurement of seabed topography in designated river channels, sea lanes or offshore areas by unmanned craft equipped with multi-beam sounding system. Jie Xiao[3] studied the way of laying measurement line and the analysis and processing of data. ZhengMei Ma[4] proposed a multi-beam system based underwater terrain mapping in the Jingjiangmen Reach and proposed a terrain data acquisition and modeling method based on the multi-beam sounding system. However, most studies on multibeam sounding systems only revolve around data error and the processing of data, such as Xin Wang[5] studied the deformation of the multi-beam support due to the water flow speed and ship speed, which causes the attitude deviation of the transducer and the inertial navigation system, and affects the accuracy of the results. Xiangyun Zhou[6] investigated the causes of sound velocity errors and presented methods for correcting them, including adaptive layered sound line tracking and equal gradient sound line tracking. The correction effectiveness of these two methods was analyzed through experiments conducted at the same location but during different time periods. Xianghong Zhao[7] proposed a multi-beam bathymetric data gross error elimination method based on back propagation (BP) neural network. Haidong Yang[8] proposed a method for attitude fitting and combining correction based on the characteristics of multi-beam bottom survey data.

Existing research on how to design a reasonable line problem rarely mentioned, to this paper, the model of the line distance at different distance when water depth, covering width and the mathematical relationship between the adjacent strip overlap, measuring ship line direction for any Angle of different position multiple beam sounding cover width, finally gives a sea area aerial measurement line specific planning scheme. (This paper data source in http://www.mcm.edu.cn/html_cn/node/c74d72127066f510a5723a94b5323a26.html).

2. Construction of aerial route planning model

2.1. Research on the correlation of seawater depth, coverage width and overlap rate

In this paper, the mathematical models of seawater depth, covering width and overlap rate between adjacent strips are established at different distances from the center point. According to the geometric relationship between the survey ship and the submarine slope, the depth and coverage width of the sea water at different distances from the center point can be calculated by sine theorem and cosine theorem, and then the overlap rate between adjacent strips can be obtained. The test data provided the following known conditions: the depth of the center point of the sea is 70m, the opening Angle of the multi-beam transducer is 120°, and the slope to be tested is 1.5°. The precise process of derivation is outlined below.

First of all, since the direction of the measurement of the survey ship is fixed, establish a plane model of the cross-section of the sailing direction of the survey ship, as shown in Fig 1, and according to the plane geometry relationship in the CEF can be deduced out the formula of α (indicating the angle between the plane perpendicular to the direction of the measurement line and the intersection line of the submarine slope and the horizontal plane) and the depth D (indicating the depth of water of the survey ship at the point) , as shown in equation (1) (2):

$$\tan\alpha = \frac{D}{-X + \frac{D}{\tan\alpha}} \tag{1}$$

$$D = -X\tan\alpha + 70 \tag{2}$$

In triangle ①, the relationship between L (denoting the length between AB) and D can be deduced, as shown in equation (3) :

$$L = \frac{D\,sin(90° - \alpha)}{sin(30° + \alpha)} \tag{3}$$

The relationship between L and W (denoting the coverage width of the multibeam sounding strip) can be derived in ΔABC, as shown in equation (4):

$$\frac{L}{\sin(30° - \alpha)} = \frac{W}{\sin 120°} \tag{4}$$

Through correlating equation (1) (2) (3), the relationship between W and D can be derived, as shown in equation (5):

$$W = \frac{\sqrt{3}}{2} D \frac{sin(90° - \alpha)}{sin(30° + \alpha)\,sin(30° - \alpha)} \tag{5}$$

Since D contains only the unknown X (X is the distance of the measuring ship from the center sea area), the relationship between W and X (which represents the distance of the measuring ship to the center point of the sea area) can be deduced, as shown in equation (6):

$$W = \frac{\sqrt{3}}{2}(-X\,tan\,\alpha + 70)\frac{sin(90° - \alpha)}{sin(30° + \alpha)\,sin(30° - \alpha)} \tag{6}$$

According to the definition of the overlap ratio between adjacent bands in the ocean multibeam water depth measurement system, the overlap ratio calculation formula is shown in equation (7):

$$\eta = 1 - \frac{d}{W} \tag{7}$$

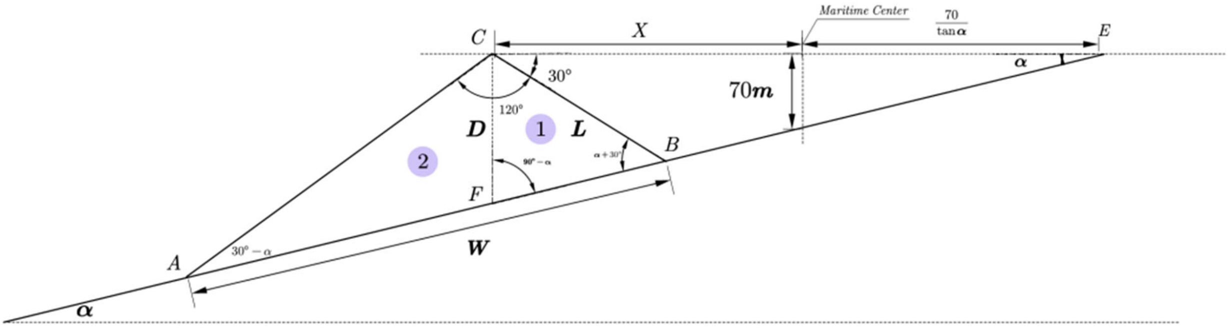

Fig. 1 Planar model of a cross-section of a survey ship in the direction of navigation

The seawater depth at different distance points, the measured strip coverage width and the overlap rate between adjacent strips were calculated using MATLAB software. The calculation results are shown in Table.1:

Table 1. Seawater depth, coverage width, and overlap rate calculation results

The distance of the line from the central point / m	**-800**	**-600**	**-400**	**-200**	**0**	**200**	**400**	**600**	**800**
Water depth / m	90.949	85.712	80.474	75.237	70.000	64.763	59.526	54.288	49.051
Cover width / m	315.813	297.628	279.442	261.256	243.070	224.884	206.699	188.513	170.327
Overlap with previous measurement line /%	——	33.6	29.6	25.0	19.8	13.8	6.8	-1.4 (Missed test)	-11.1 (Missed test)

2.2. Research on the beam cover width of any line direction

When the direction of the line is constantly changing, the projection angle between the line and the normal slope of the seabed is constantly changing[9]. According to the angle β between the direction of the survey line and the projection of the normal vector of the seabed slope on the horizontal plane, the angle γ formed by the projection of the survey line of the survey ship on the slope and the horizontal plane, vertical segment made by the survey ship towards the seabed, the mathematical relationship between angle γ , angle α , and angle β can be derived from the three-dimensional geometry relationships. Further a mathematical relationship can be obtained for the coverage width, the variables being the angle β and the distance X from the center of the sea area.The process is as follows:

According to the stereogeometric relationship in the cross section of the navigation direction, as shown in Fig 2, the relationship expression of γ , α and β can be derived and is shown in equation (8):

$$tan\,\gamma = tan\,\alpha \cdot sin\,\beta \tag{8}$$

Since γ is the angle made by the projection of an arbitrary heading on the slope and the seafloor, using the previous expressions for the depth of seawater and the width of cover, as shown in equation (5), the angle γ is equivalent to the angle α. An expression for W and D can be obtained, as shown in equation (9):

$$W = \frac{\sqrt{3}}{2} D \frac{sin(90° - \gamma)}{sin(30° + \gamma)\, sin(30° - \gamma)} \tag{9}$$

The final coverage width and water depth D , slope α, measurement line angle β and distance X are as follows:

$$W = \frac{\sqrt{3}\, sin(tan^{-1}(tan\,\alpha\, sin(\beta - 90°)))\, (D - X\, tan\,\alpha\, sin\,\beta - 90°)}{2\, sin(tan^{-1}(tan\,\alpha\, sin(\beta - 90°)) - 30°)\, sin(tan^{-1}(tan\,\alpha\, sin(\beta - 90°)) + 30°)} \# \tag{10}$$

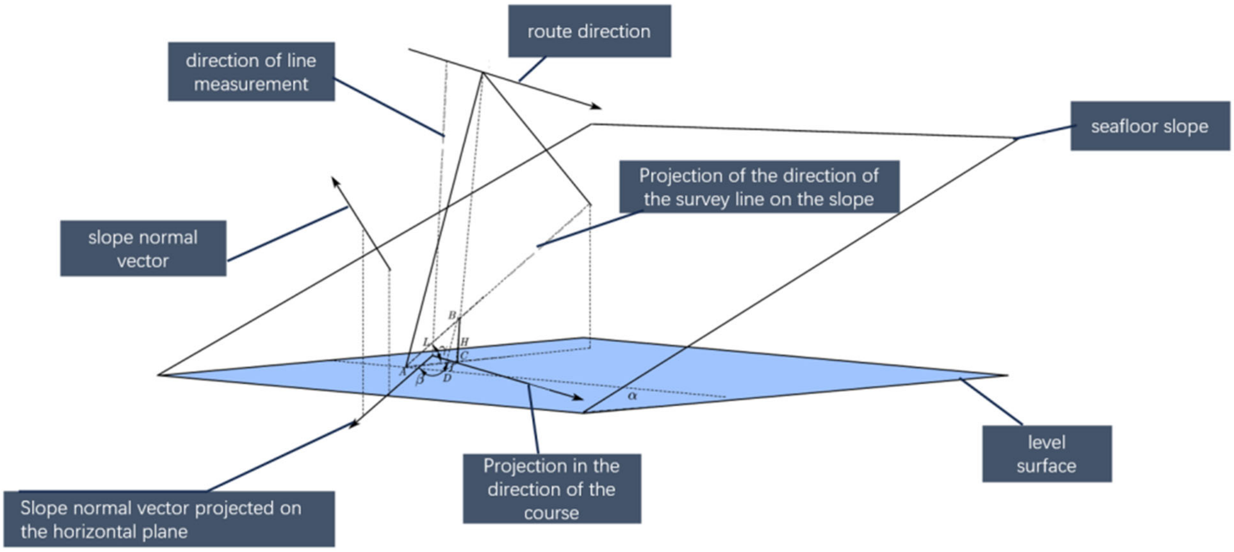

Fig. 2 A three-dimensional model of the cross section of a ship in any navigation direction

According to the data in the contest, the coverage width of any Angle and multiple beam depth at different positions are calculated by MATLAB software. The calculation results are shown in Table 2:

Table 2. Cover width of the beam depth at any angle

Cover width / m		**Measure the distance of the survey ship from the center point of the sea area (nautical mile)**							
		0	**0.3**	**0.6**	**0.9**	**1.2**	**1.5**	**1.8**	**2.1**
Measurement line direction angle / °	**0**	416.6919	467.2119	517.732	568.2521	618.7721	669.2922	719.8122	770.3323
	45	416.1915	451.8717	487.5519	523.2321	558.9123	594.5924	630.2726	665.9528
	90	415.6922	415.6922	415.6922	415.6922	415.6922	415.6922	415.6922	415.6922
	135	416.1915	380.5113	344.8312	309.151	273.4708	237.7906	202.1104	166.4302
	180	416.6919	366.1718	315.6517	265.1317	214.6116	164.0916	113.5715	63.0514
	225	416.1915	380.5113	344.8312	309.151	273.4708	237.7906	202.1104	166.4302
	270	415.6922	415.6922	415.6922	415.6922	415.6922	415.6922	415.6922	415.6922
	315	416.1915	451.8717	487.5519	523.2321	558.9123	594.5924	630.2726	665.9528

2.3. Route planning for aerial surveys in an ocean area

Multi-beam measurement can be regarded as a case of measurement operation under a certain coverage width W. Combined with the study of the beam coverage width in any direction of the measurement line, the coverage width of any heading at any position can be analyzed. Therefore, the area to be operated can be divided into different sub-operating areas, and the width of the operating area is related to the course direction, water depth and slope. In order to facilitate the calculation, the seabed of the operation area is three-dimensionally coordinated, and the results of the beam coverage width study in the direction of any measurement line are programmed by computer to find out a set of coordinate values that make the measurement route the shortest under the condition of satisfying the coverage.

Given a rectangular sea area of 4 nautical miles in length and 2 nautical miles in width, the problem of the contest is to plan and design a shortest aerial survey route so that the surveyed area by the survey ship covers the whole area and the overlap rate satisfies between 10% and 20%. It is assumed that the steering of the navigational vessel at the edge of the sea area is accomplished directly, without considering the time of steering and the swept area. Combined with the calculation results in Table 2, it is concluded that the coverage width of the survey ship from the west side to the east side of the survey ship is from 770m at the maximum to 63m at the minimum, which is too large a span, and the coverage width of the west is too large and the east is too small, so that if the east-west transverse measurements or oblique measurements of any angle are made, they will all produce irregular quadrangles, which will lead to different degrees of omission of the measurements or the overlap rate is too high, and result in an increase in the number of measurements. Therefore, the optimal aerial survey route is possible when the heading is determined as north-south navigation. And in the case of the slope is known, the measurement range is clear, according to the "multi-beam bathymetric system measurement technical requirements"[10] standard, the main survey line should be laid according to the needs of the measurement of the terrain of the operation to choose parallel to the isobath towards the direction of the channel axis or the longest side of the measurement area, etc. one of the direction of the laying, so that the survey ship measurement of the way there are mainly Boustrophedon method and the internal and Spiral algorithm[11], as shown in Fig 3. The main factors affecting the measurement route are the undulation of seabed topography, overlap rate, leakage rate, and so on.

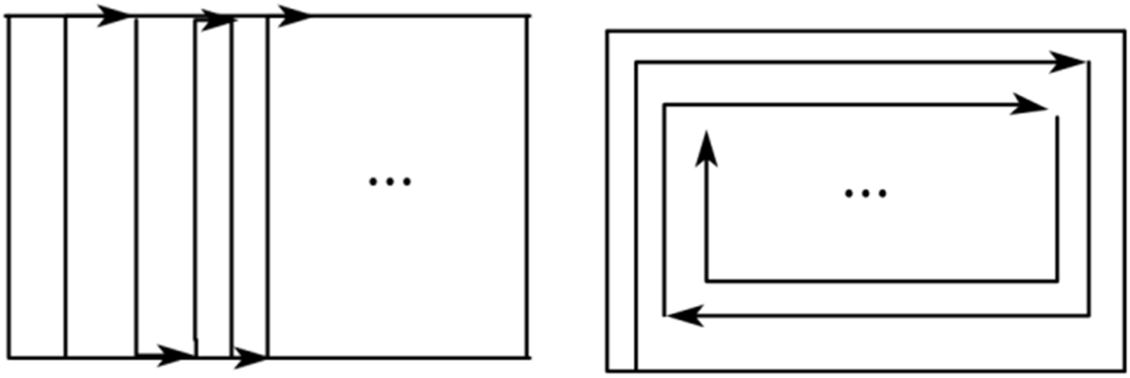

Fig. 3 Boustrophedon method and Spiral algorithm

The two measurement methods were analyzed, and when the Spiral algorithm was used, when the course was in the east-west direction, the overlap rate would be too large or leakage would occur. If the Boustrophedon method is used, the projection of the survey line in the horizontal plane for north-south navigation will only appear as a regular rectangle, and only the magnitude of the overlap rate η will need to be considered, not whether or not missed measurements will occur. Therefore, determining the preferred Boustrophedon method of coverage may result in the optimal situation required by the question.

Since the measurement operation of a survey ship is a reciprocating covering movement, each operation route independently corresponds to a beam covering area with a width W as the sub-operation area, so the operation route of the survey ship is obtained by dividing the sub-operation area. The horizontal plane projection width is shown in equation (11):

$$W_{projector} = W \cdot cos\alpha \tag{11}$$

From the research of the correlation between seawater depth, coverage width and overlap rate, it can be seen that the beam measurement coverage on the left side and right side of the ship is different, and the widths of the two neighboring sub-operating areas are also different. Let a total of N sub-operating areas are needed, and X_i is the course transverse coordinate of the ith sub-operating area. Therefore the spacing d between the two measuring lines has the following relationship,as shown in equation (12):

$$X_{i+1} - X_i = d \tag{12}$$

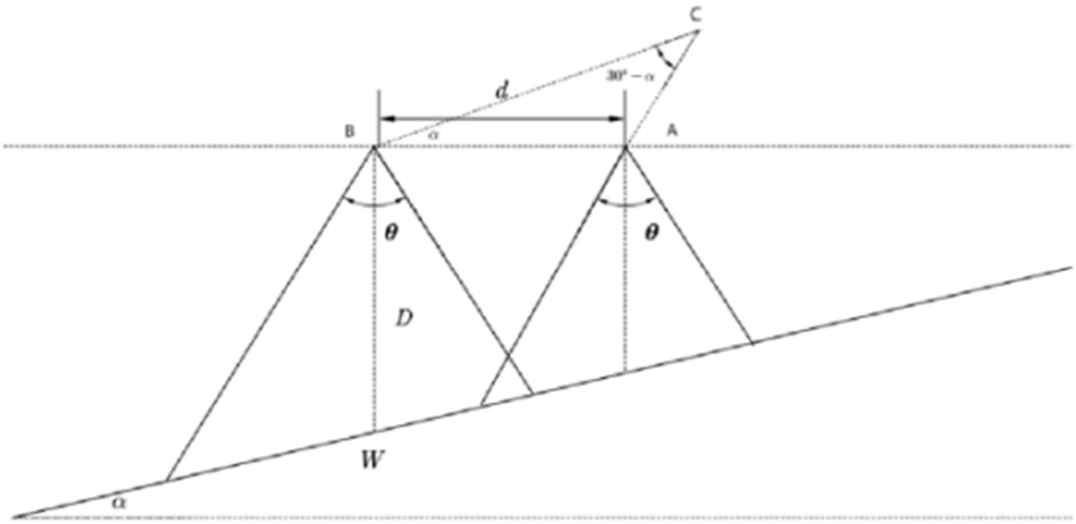

Fig. 4 Schematic cross-section of adjacent sub-operating areas

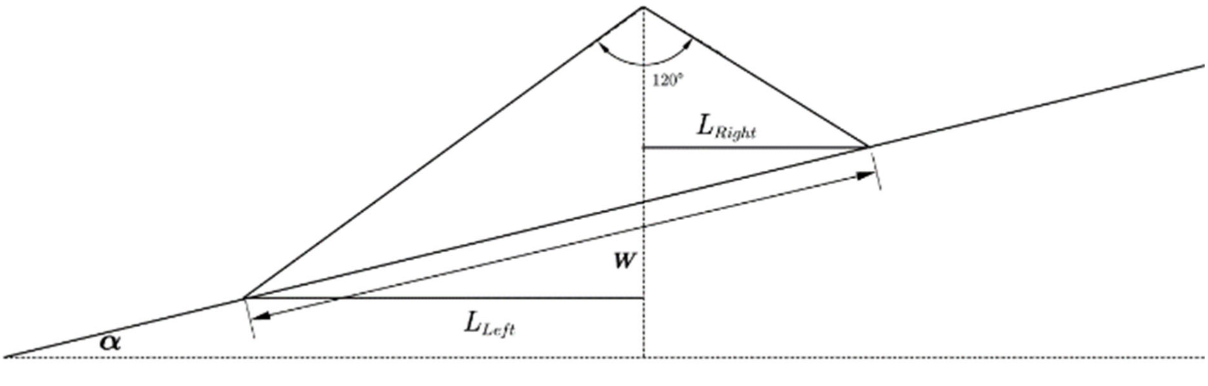

Fig. 5 Coverage projection

Equation (13) can be derived according to the geometric relation in Fig 4:

$$X_{i+1} = X_i + 2 \cdot sin(30° - \alpha) \cdot (1 - \eta) \cdot W_{projector} \tag{13}$$

Secondly, for the coverage of any point, from the geometric relationship in Fig 5, equation (14) (15) can be derived.

$$L_{Left} = \frac{\sqrt{3}}{2} D \frac{\cos\alpha}{\sin(30° + \alpha)} \left(\frac{\sin(90° - \alpha)}{\sin(30° - \alpha)} - 1 \right) \tag{14}$$

$$L_{Right} = \frac{\sqrt{3}}{2} D \frac{1}{sin(30° + \alpha)} \tag{15}$$

Substituting the previous equation (5) yields a coverage width of 718m at the origin of the coordinates, and in order to ensure the shortest route, the left measurement edge should be as close to the boundary as possible. From equation (10), it can be seen that when $\mathrm{X} = 370\mathrm{m}$, the measurement beam can completely cover the boundary. Therefore, the distance of the departure point of the north and south sides from the west side of the border is selected as 370m as the departure point of the first measurement line.

Calculations using MATLAB software can be made to obtain the total length of measurement lines, coverage area, and number of scans when changing the overlap rate η value. The total length of the measurement lines, the coverage area, and the number of scans are shown in Table 3.

Table 3. Relationship between coverage area and total measurement line length within fixed areas

η /%	coverage area /m^2	Total line length / m	Number of north-south longitudinal scans
10	23617612	16*1852*2=59264	16
11	23747221.12	16*1852*2=59264	16
…	…	…	…
19	25611892.34	17*1852*2=62968	17
20	26510005.64	18*1852*2=66672	18

According to Table 3, it can be seen that under the condition of satisfying the complete coverage, the number of north-south longitudinal scans will become less as the coverage becomes smaller. Therefore in the case of coverage η between 10% and 20%, in order to design the shortest route for sailing, choose a value of 10% for η.

MATLAB software was used to carry out the calculation of the distance of the north-south departure point from the western boundary, and the results are shown in Table 4.

Table 4. Distance of point of departure from the western boundary at the time of operation

The n th starting point	The distance of the north and south starting point from the western boundary
The first starting point	370m
The second starting point	957m
…	…
The 34th starting point	7366m
The 35th starting point	7405m

From Table 4, it can be seen that the survey ship went back and forth to carry out the survey work 35 times, and finally arrived at the total length of the survey line:

$$L_{Total} = 35 * 1852 * 2 = 129640m = 70 \text{ nautical miles}$$

The specific route planning diagram is shown in Fig 6:

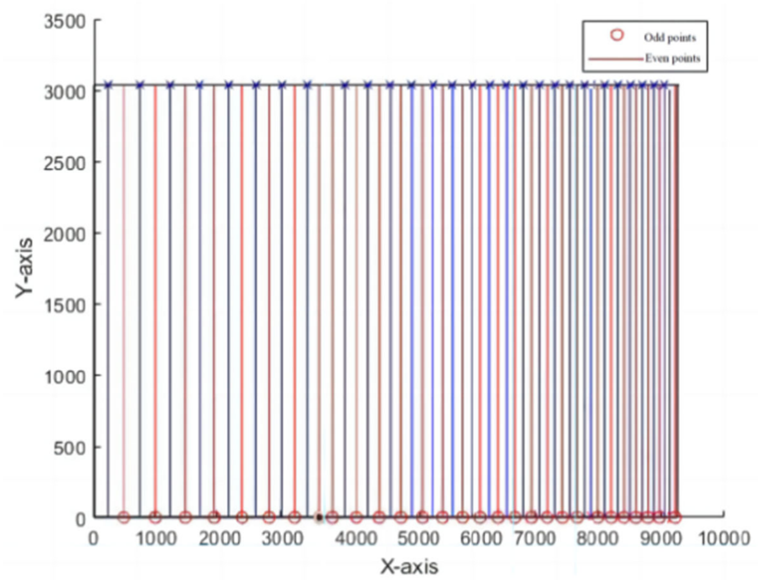

Fig. 6 Route planning diagram

3. Model analysis and evaluation

The model uses the ideas of partition planning and dimension reduction, captures the important factors affecting the overlap rate range problem, transforms the complex three-dimensional three-dimensional problem into a simple planar two-dimensional problem, and sets the parameters reasonably, and the output of the model meets the practical requirements and can solve the practical problems. In addition, the model output of the survey ship route planning is characterized by high efficiency and stable output, which can effectively improve the efficiency and quality of the survey route planning under the existing conditions. The model simplifies the conditions when the survey ship is carrying out operations, for example, assuming that the survey ship is always sailing on a horizontal plane, and the final model obtained is close to the actual situation and has high application value.

4. Conclusion

Multibeam bathymetric system is widely used in the fields of ocean mapping, ocean survey, ocean engineering construction, etc., which can provide high-precision and high-resolution seabed topography with good application effect. At the same time, reasonable route planning can improve the measurement efficiency of the survey ship, save the fuel of the survey ship, and achieve better measurement results, etc. Therefore, reasonable aerial survey route is of great significance to the further application and development of multibeam bathymetric system. In this paper, we firstly analyze the functional relationship between seawater depth, survey line coverage width and overlap rate between adjacent strips under the conditions of different distances of the survey line from the centre point, and secondly, we use trigonometric function to portray the coverage width of multibeam bathymetry at different positions, and come to the following conclusions: the direction perpendicular to the projection of the normal direction of the underwater slope to the horizontal is the optimal scheme, i.e., the direction perpendicular to the descending direction of the ramp. Therefore, it is the optimal solution to measure the sea area by using the ox plough reciprocating method. Finally, combined with the specific seabed slope, a specific planning route for route planning is given. This model can be extended to measure the topography of any unknown sea area, just divide the sea area into different slopes, and then the model can be used to calculate the optimal ship survey line.

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