A high accuracy position and attitude measure sonar for submarine docking

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***Abstract* — With the underwater vehicles used increasingly in marine development, the submersible's underwater docking has become an important technical issue to be solved urgently for the submersible's underwater material conveying and information exchange. Moreover, it is based on high-precision underwater acoustic positioning technology. This paper presents a high-precision position and attitude measurement sonar for submarine docking called DJUSBL, which is developed independently by Science and Technology on Underwater Acoustic Laboratory in China. The sonar can measure the locations of the submersible relative to the multiple transponders, solve the attitudes of the submersible with respect to the docking platform, and fulfill the submersible's leading and docking. The paper focuses on the structure of the sonar, the method of measuring the position and attitude, and the test results about the leading and docking trial. The trial results indicate that DJUSBL sonar can satisfy the need for submersible's underwater docking owing to its measured position and attitude precision less than 5cm and 5deg respectively.**

Keywords — underwater docking; position and attitude measurement sonar; USBL

I. INTRODUCTION

With the deepening of marine exploration and the rapid development of submarine technology, submarines performing more and more tasks in marine survey, which asks for higher and higher requirements for the AUV operation time and contents, and endurance capability. Subjected to carried energy of its own and after completing the missions, the submarine usually needs to go back to the supporting platform to supplement energy, replacement load, upload data and download new missions. Therefore, underwater docking is precondition to ensure submarine's underwater endurance and complex tasks.

The submersible's underwater docking can be divided into two stages involving underwater leading and short-range docking, with different positioning precision requirement in each stage. When the submersible approaches to the docking platform led by positioning sonar from a long range, the positioning precision needs not be very high of meters of order more or less. As the submersible gets close to the docking platform to a certain distance, the submersible needs to adjust its posture to fulfill the docking according to the position and attitude information measured by the positioning sonar, in which the measured position and attitude precision need be less than 5cm and 5deg respectively.

This paper presents a high-precision position and attitude measurement sonar for submarine docking called DJUSBL, which is developed independently by Science and Technology on Underwater Acoustic Laboratory, Harbin Engineering University in China. The sonar can measure the locations of the submersible relative to the multiple transponders, solve the attitudes of the submersible with respect to the docking platform, and fulfill the submersible's leading and docking. The paper focuses on the structure of the sonar, the method of measuring the position and attitude, and the test results about the leading and docking trial.

II. DJ-USBL SYSTEMS

DJ-USBL is a set of position and attitude measurement system based on the ultra-short baseline (USBL) positioning technology, which has its measured position and attitude precision less than 5cm and 5deg respectively in 10m range. So the submersible is equipped with the USBL positioning system, while the entrance to the docking platform is designed with the multiple transponders. It can determine the position and attitude information of the submersible relative to the docking platform, through solving the 3D position and attitude of the docking entrance via accurate ranging and positioning by multiple transponders. Therefore, the position and attitude solution method and solution accuracy are directly determined by the transponder formation.

The system consists of one USBL array mounted on submarine, one signal processor, one synchronizer and four acoustic beacons installed on docking platform, which is depicted in Fig. 1. Specifically speaking, the USBL array is used to transmit and receive the signal of interest; the signal processor fulfills acquisitioning and processing for the signal of interest, solving the 3D position and attitude, and outputting the final 3D data to submarine via RS232. In addition, the system works in a synchronous mode, of which the signal processor is powered by submarine and a synchronizer is equipped on the submarine to avoid the time confusion in condition of submarine's power-off. Moreover, the synchronizer is powered independently and not controlled by submarine. In order to simplify the process of solving the position and attitude, the acoustic beacons in docking platform are installed as a rectangular formation, the plane of which is

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parallel to docking plane in submarine. And their projection centers coincide to ensure the same position and attitude information between the beacons rectangular array and docking platform. So the USBL can solve such information via measuring positions of the four rectangular points relative to its own position. The corresponding schematic is shown in Fig. 2.

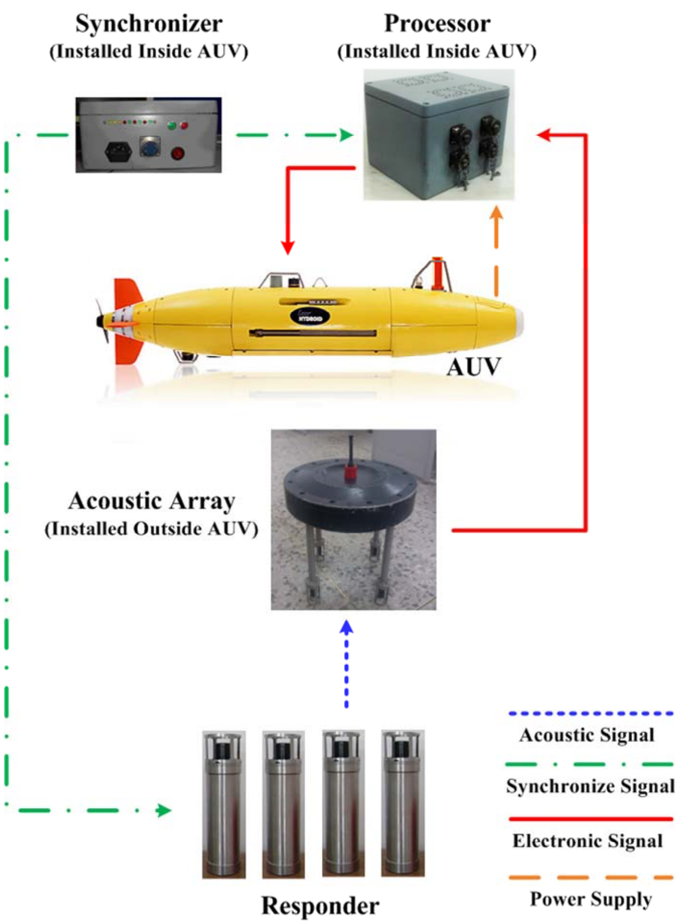

Fig. 1. Deployment configuration A

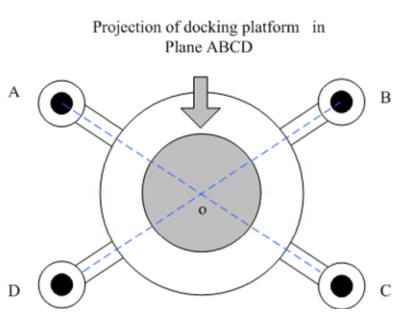

Fig. 2. Schematic of the responder array deployment

III. POSITION ANDATTITUDE SOLUTION

A. Coordinate system and attitude angle

P is a point in a Cartesian coordinate system {M}, which can be represented by a column vector ${}^{M}P = (P_x \quad P_y \quad P_z)^T$, where P_x, P_y and P_z are the three components of the point P in Cartesian coordinate system {M} respectively.

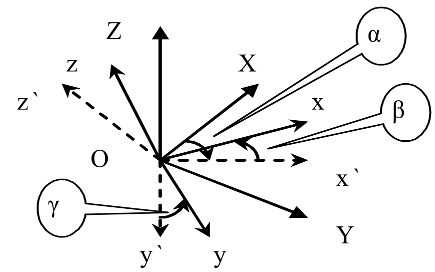

Fig. 3. Definition of relative attitude

As depicted in Fig. 3, firstly let's define the relative attitude angles from an arbitrary Cartesian coordinate system $\{M\}$ (O-xyz) to another arbitrary Cartesian coordinate system $\{N\}$ (O-XYZ).

Relative azimuth α: it's the angle between x-axis and OX direction in XOY plane, and it is positive if the orientation is east.

Relative pitch β: it's the angle between x-axis and the plane XOY, and it's positive if x-axis is above XOY plane.

Relative roll γ: it's the angle between y-axis and the plane XOY, and it's positive if y-axis is above XOY plane.

B. Plane position solution

Suppose the responders A, B, C and D have their coordinates ${}^{M}A(x_A, y_A, z_A)$, ${}^{M}B(x_B, y_B, z_B)$, ${}^{M}C(x_C, y_C, z_C)$ and ${}^{M}D(x_D, y_D, z_D)$ respectively in the Cartesian coordinate system{M}. So it's easy to achieve the center coordinate ${}^{M}O(x_O, y_O, z_O)$ of the plane ABCD as follows:

$$ {}^{M}O = \frac{1}{4}\left(\sum_{i=A}^{D} {}^{M}i\right) \tag{1} $$

C. Relative attitude angle solution

According to the definition of relative attitude angle, suppose the attitude angles α, β and γ of the plane ABCD(A-xyz) in arbitrary coordinate system {N}(O-XYZ).

As depicted in Fig. 4, the coordinates of the responders A, B, C and D in coordinate system O-XYZ have been determined beforehand. Making coordinate A-X'Y'Z' parallel to o-xyz with the origin of A, making the vertical line from B to the plane X'AY' with the pedal H_1 and making the vertical line from D to the plane X'AY' with the pedal H_2. So the relative azimuth α, pitch β and roll γ are $\angle X'AH_1$, $\angle BAH_1$ and $\angle DAH_2$ respectively. Then it can solve the relative azimuth α, pitch β and roll γ of the plane ABCD in any coordinate system O-XYZ:

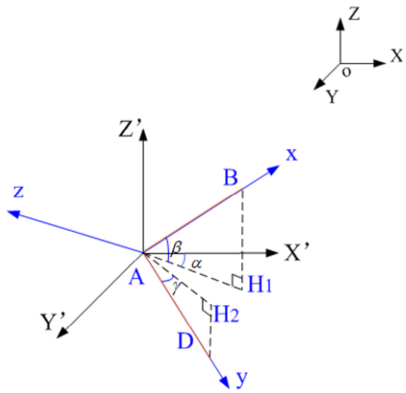

Fig. 4. Schematic of the resolving the relative attitude

$$\alpha = arctg\frac{y_B - y_A}{x_B - x_A} \tag{2}$$

$$\beta = \arcsin\frac{z_B - z_A}{\|AB\|} \tag{3}$$

$$\gamma = \arcsin\frac{z_D - z_A}{\|AD\|} \tag{4}$$

D. Error analysis

According to the previous section, the position and attitude precision both depend on the positioning precision of USBL no matter to solve the position information or the attitude information.

From (1), let all the transponder positions estimation error be σ_M, the error for the center coordinates of the target plane in the known coordinate system is:

$$\sigma_O = \frac{1}{\sqrt{2}}\sigma_M \tag{5}$$

DJ-USBL has the positioning precision of 1.5cm in short range with the corresponding estimation error of the center O of 1.06cm, which has satisfied the requirement of 5cm in docking.

Differentiating the (5) and simplifying:

$$\Delta\alpha = \frac{\cos^2\alpha}{x_B - x_A}\Delta y_B - \frac{\cos^2\alpha}{x_B - x_A}\Delta y_A - \frac{\sin\alpha\cos\alpha}{x_B - x_A}\Delta x_B + \frac{\sin\alpha\cos\alpha}{x_B - x_A}\Delta x_A \tag{6}$$

Considering each error in (6) is independent, so the root mean square error can be:

$$\sqrt{\overline{\Delta\alpha^2}} = [\frac{\cos^4\alpha}{(x_B - x_A)^2}\overline{\Delta y_B{}^2} + \frac{\cos^4\alpha}{(x_B - x_A)^2}\overline{\Delta y_A{}^2} + \frac{\sin^2\alpha\cos^2\alpha}{(x_B - x_A)^2}\overline{\Delta x_B{}^2} + \frac{\sin^2\alpha\cos^2\alpha}{(x_B - x_A)^2}\overline{\Delta x_A{}^2}]^{\frac{1}{2}} \tag{7}$$

Meanwhile, considering the following formula:

$$\overline{\Delta y_B{}^2} = \overline{\Delta y_A{}^2} = \overline{\Delta x_B{}^2} = \overline{\Delta x_A{}^2} = \overline{\Delta x^2}$$

$$x_B - x_A = \cos\beta\sin\alpha$$

Then we can get:

$$\sqrt{\overline{\Delta\alpha^2}} = \frac{\sqrt{2}}{m}\sec\beta|\cot\alpha|\sqrt{\overline{\Delta x^2}} \tag{8}$$

It can be seen from (8) that the relative azimuth estimation error in some Cartesian coordinate system is related to array spacing m of AB for the responder array, relative azimuth and pitch, and the positioning error of the responders. In detail, if the length of AB is larger, the relative pitch is smaller and the positioning precision is higher, the relative azimuth estimation error is smaller. In addition, if the relative azimuth is close to π /2, the relative azimuth measurement error can become smaller.

In the same way, the root mean square errors for relative pitch and roll can get as follows:

$$\sqrt{\overline{\Delta\beta^2}} = \left[\frac{4}{m^2}\sec^2\beta\overline{\Delta x^2} + \frac{1}{m^2}\tan^2\beta\overline{\Delta m^2}\right]^{\frac{1}{2}} \tag{9}$$

$$\sqrt{\overline{\Delta\gamma^2}} = \left[\frac{4}{n^2}\sec^2\gamma\overline{\Delta x^2} + \frac{1}{n^2}tg^2\gamma\overline{\Delta n^2}\right]^{\frac{1}{2}} \tag{10}$$

Obviously, the relative pitch and roll estimation errors have inverse relation with the array spacing m and n. In common sense, spacing m and n usually have less than mm precision, which can be omitted in comparison with $\sqrt{\overline{\Delta x^2}}$. So (9) and (10) can be simplified as:

$$\sqrt{\overline{\Delta\beta^2}} \approx \frac{2}{m}|\sec\beta|\sqrt{\overline{\Delta x^2}} \tag{11}$$

$$\sqrt{\overline{\Delta\gamma^2}} \approx \frac{2}{n}|\sec\gamma|\sqrt{\overline{\Delta x^2}} \tag{12}$$

It can be seen from (11) that the relative pitch estimation error in some Cartesian coordinate system is related to array spacing m of AB for the responder array, relative pitch, and the positioning error of the responders. In detail, if the length of AB is larger, the relative pitch is smaller and the positioning precision is higher, the relative pitch estimation error is smaller.

Likewise, the relative roll estimation error in some Cartesian coordinate system is related to array spacing n of AD for the responder array, relative roll, and the positioning error of the responders. In detail, if the length of AD is larger, the relative roll is smaller and the positioning precision is higher, the relative pitch estimation error is smaller.

IV. WATER TANK TRIAL

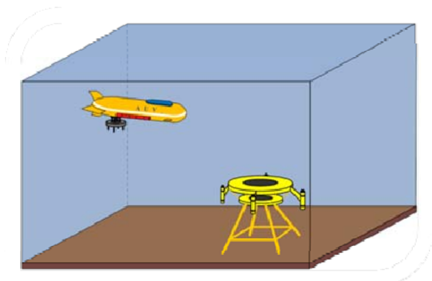

Fig. 5. Schematic of the AUV docking trial in the water tank

Fig. 6. Schematic of the responder array deployment inthe AUV docking trial

The water tank trial of underwater leading and docking was conducted in Harbin Engineering University, of which the tank size is 50m×30m×10m. The schematic of water tank trial is indicated in Fig.5. USBL array of the position and attitude measurement sonar is installed on the head direction of AUV with the range of about 1m to docking entrance. The signal processor and synchronizer are mounted inside the AUV. The beacon array is installed on the simulated device of docking platform with square formation of 1m spacing. In trial, the simulated device is deployed in the center and near the water tank bottom via the crane, which is depicted in Fig. 6. And the top of the beacon responders has a distance of 1.5m to the bottom.

A. Static test

Static positioning is an important part to analyze the position and attitude measurement precision, and it can also reflect the positioning precision performance of the overall system. The USBL array is hanged via the lane and is at stationary state in the test. The measured most standard error in x, y and z coordinate are 0.018m, 0.014m and 0.005m respectively. And the estimated center position of the docking platform is shown in Fig. 7-Fig. 9. Fig. 7 gives the horizontal positions of the four responders relative to the center of the docking platform measured by the DJ-USBL sonar. And Fig. 8 is its local enlarged view, from which it can be seen that the most coordinate change in x and y direction are less than 0.02m and 0.01m respectively. Fig. 9 illustrates the estimated depth of the docking platform, of which the right graph is its enlarged view with change less than 0.01m.

The measured relative attitude angles are given from Fig. 10 to Fig. 12, from which it can be seen that the attitude variations are 1deg or less. Table I summarizes the measured attitude angles and their standard error.

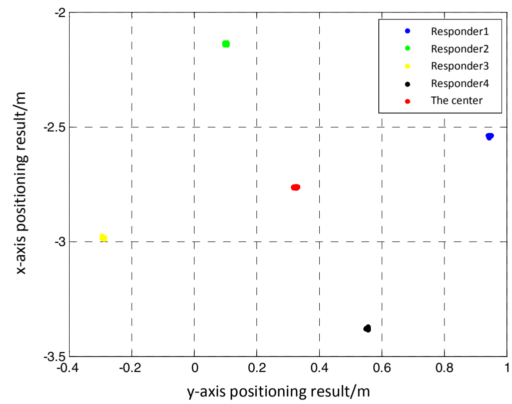

Fig. 7. Horizontal position of the four responders relative to the center of the docking platform

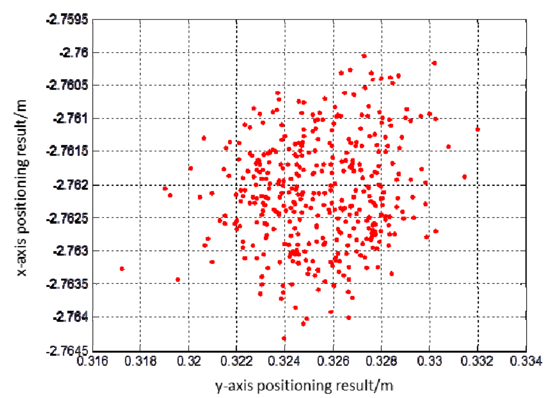

Fig. 8. Enlarged view of the center of docking platform

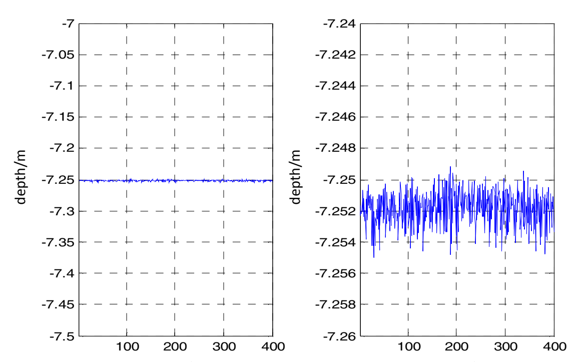

Fig. 9. Depth of the center of docking platform

TABLE I THE MEASURED ATTITUDE ANGLES AND THEIR STANDARD ERRORS IN STATIC TEST

	azimuth	pitch	roll
mean(deg)	192.02	2.11	3.68
std(deg)	0.20	0.11	0.08

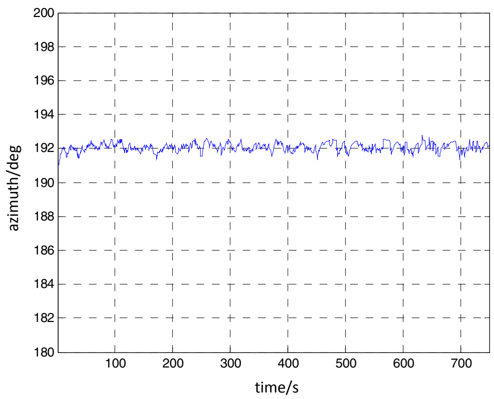

Fig. 10. Relative azimuth

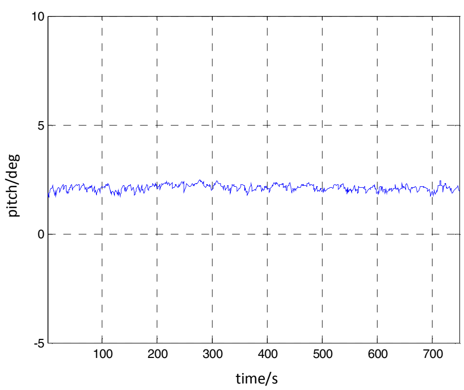

Fig. 11. Relative pitch

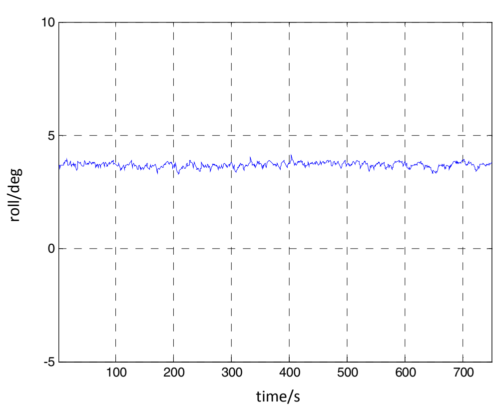

Fig. 12. Relative roll

B. Dynamic test

In dynamic test, AUV is deployed into water tank via the crane and lead to the simulated docking platform via the DJ-USBL sonar, in which it's in the high-precision position and attitude area. The DJ-USBL sonar supplies the measured position and attitude information in real time of 1Hz speed, according to which the control unit of AUV adjusts itself until docking successfully. AUV starts dynamic positioning in the depth of 4m, and the corresponding positioning results are given in Fig. 13-Fig. 15.

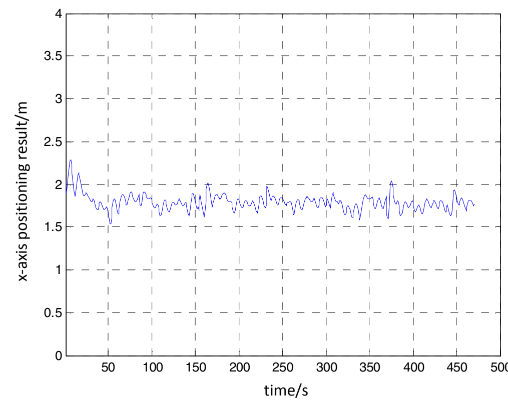

Fig. 13. x-axis positioning result when AUV's depth measurement

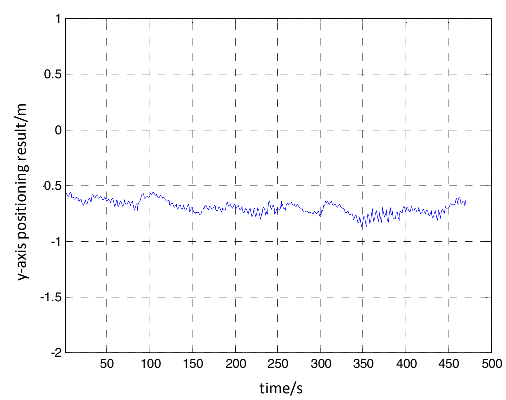

Fig. 14. y-axis positioning result when AUV's depth measurement

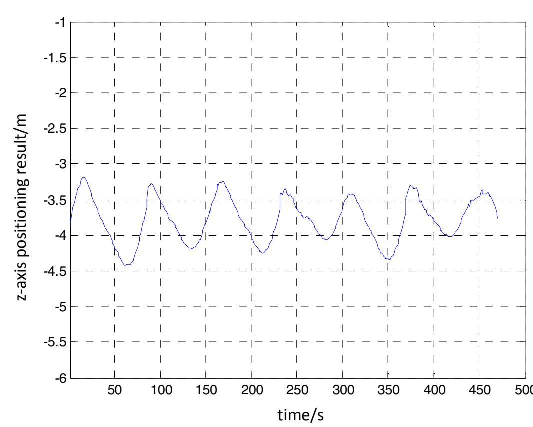

Fig. 15. z-axis positioning result when AUV's depth measurement

In the AUV's dynamic positioning, it will adjust itself in some position and the relative attitude of the docking platform also will change. As seen in Fig.16-Fig.18, they give the measured attitudes in dynamic positioning, and table 2 summarizes the corresponding attitude angles and their standard error. It can be seen obviously that the AUV adjusts its depth all the time, which causes the measured attitude to have relatively large fluctuations.

TABLE II THE MEASURED ATTITUDE ANGLES AND THEIR STANDARD ERRORS IN DYNAMIC TEST

	azimuth	pitch	roll
mean(deg)	251.72	1.23	-2.66
std(deg)	0.60	1.28	0.97

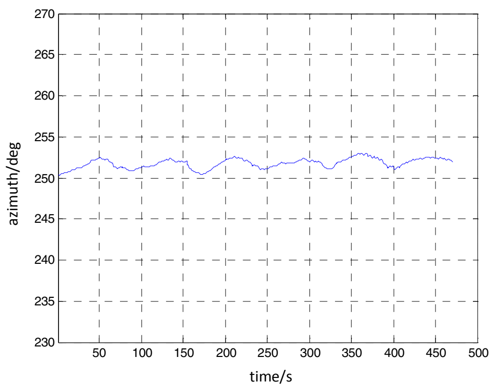

Fig. 16. Relative azimuth when AUV's depth measurement

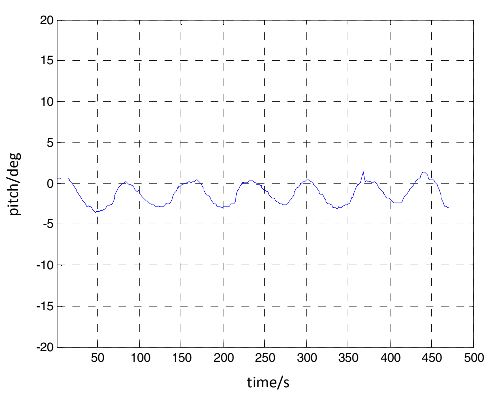

Fig. 17. Relative pitch when AUV's depth measurement

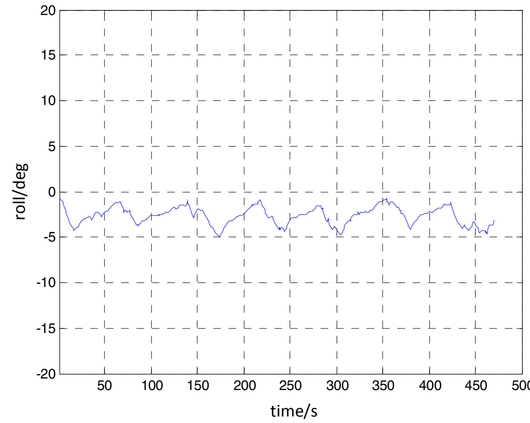

Fig. 18. Relative roll when AUV's depth measurement

V. CONCLUSION

For the AUV's underwater docking, the prominent difficulty is to obtain the relative position and attitude information of the two docking plane. A solution based on acoustic measurement is presented in this paper. Trial results indicate that the position and attitude measure sonar named DJ-USBL developed by Harbin Engineering University has the performance of single-axis positioning error less than 2cm and attitude variation less than 1deg, which can satisfy the need for submersible's underwater docking in the future.

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