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Metering Method and Measurement Uncertainty Evaluation of Underwater Positioning System in Six Degrees of Freedom Space

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ABSTRACT Meterage is an important action to ensure the performance of underwater acoustic positioning system, but the commonly used measurement methods are mostly based on the low degrees of freedom (DOF) measurement and control platforms which could not realize the all-round and high efficiency evaluation of this equipment. In this paper, we develop a new metering method base on the conventional standard 4-DOF measurement and control platform to realize the whole exploration space high efficiency and high accuracy measurement of underwater acoustic positioning systems in 6-DOF space. First, a 4-DOF space to 6-DOF space quantity value propagation model is proposed, and a rigorous mathematical expression is established. Next, a measurement procedure is formed based on the building of a standard base-line field, so the channel of transforming measurable position coordinate of the measured field point in 4-DOF space to the 6-DOF space is established. Finally, the evaluation of the measurement uncertainty is done using both the Guide to the expression of uncertainty in measurement method (GUM method) and Adaptive Monte Carlo method (AMCM method), and the evaluation results of GUM method are verified by AMCM method correspondingly, the effectiveness of this metering theory and the corresponding uncertainty evaluation methods are also illustrated by analyzing the length of coverage interval and numerical tolerances of measurement uncertainty. The research results show that the relative combined uncertainty of the metering system is not higher than 0.18% with the parameters given in this paper.

INDEX TERMS Metering method, measurement uncertainty evaluation, quantity value propagation model, 6-DOF space, underwater acoustic positioning system.

I. INTRODUCTION

A. BACKGROUND AND RELATED WORKS

Underwater acoustic positioning system that calculates a three-dimensional subsea position of a transponder relative to a vessel-mounted transducer is a very important kind of sonar system to obtain the range and angle information of the target to be located [1]–[3]. In order to apply this system effectively, it is valuable to evaluate its performance accurately. Scientific programs generally require accurate standards and techniques of measurement to insure quantitative correlation and interpretation of phenomena under investigation. Only when an understanding of phenomena in quantitative terms has been achieved can accumulated data be effectively and efficiently applied to the design of a sonar system, to the improvement of present designs, and to prediction of results obtainable with such equipment. As early as the 1940s, this issue had been highly valued [4]. The same to other underwater acoustic equipment, the final criterion of underwater acoustic positioning system is also the effectiveness under operational conditions. However, operational tests of the underwater acoustic positioning system are not only expensive and time-consuming, but also difficult to control the measurement conditions in the field conditions [5], such as

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uncertainty caused by climate impact factors, water medium inhomogeneity, measurement platform sloshing, multi-factor coupling and so on [6]–[8]. At the same time, maintenance of the outdoor calibration and measuring system is also one of the problems [9]. Therefore, measurement under the indoor pool conditions with far-field facilities is still the main means used in the field of underwater acoustic equipment testing, especially for the high-precision underwater acoustic positioning system.

Nowadays, there are many effective methods have been proposed to measure and calibrate the underwater acoustic equipment, such as standard target method, electrical calibration, comparison calibration method, solid state method [10]–[13], while all these methods should be implemented on a measurement and control platform which is closely related to the schemes of these methods, especially for the underwater acoustic positioning system. This is because the located targets are usually doing real-time motions, and the positioning systems are generally applied on ships or some platforms that propelling at sea experiences three translational and three rotational motions each of which are surge, heave, sway and pitch, roll, yaw respectively [14]. So in the coordinate system of underwater acoustic positioning system, the targets should be moved in three dimensions, covering virtually the entire space of the detection zones [10], so the sonar metering system should allow the positioning system to be positioned and oriented at virtually any position and direction within the pool whose distance values are standard. In order to realize this measurement, a 6-DOF measurement and control platform that can describe all the motion states of underwater acoustic positioning system in a standard there dimension space is a good choice [15]. However, most of the present 6-DOF measurement and control technology researches are mainly focus on robot, aerospace, manipulator, marine vehicles design and measurement [16]–[19], and they are rarely applied in the field of underwater positioning equipment measurement and calibration, although there is a 5-DOF controlled system installed in water tank facilities was reported, there are few more higher DOF measuring systems have been used in this field [20].

The reasons leading to the present situations of this technology mainly include the following aspects. First, technology complexity of the 6-DOF measurement and control platform is higher than that of the lower degree of freedom system. Second, it is difficult to realize a corresponding low-cost and high effective measurement. Third, the scales of linear motion range and rotation angle around axis of the traditional 6-DOF system is limited. Fourth, the computation and control process of this system is complex. Finally, at present, most of the underwater acoustic experimental tanks in the worldwide have built standard 4-DOF measurement and control platforms, and most of the standards and measurement techniques are based on this kind of platforms, so further researches should be done on the measurement techniques corresponding to 6-DOF platforms.

Uncertainties of the outfield hydrological measurement conditions, the difficulties to guarantee the maintenance of system, high-cost, technology restrictions of high degree of freedom measuring system and relevant measurement methods are all the factors that restrict the development of the measurement and calibration technology of underwater acoustic positioning system. For this reason, a new quantity value propagation model base on the traditional standard 4-DOF measurement and control platform to realize the high efficiency whole exploration space measurement in 6-DOF space is proposed, and the measurement uncertainty of the measuring system for underwater positioning system is evaluated to illustrate the technical performance of this measuring method and scheme proposed in this article.

B. MOTIVATIONS AND OUR SCHEMES

Distance and azimuth are the most important values that obtained by underwater acoustic positioning system. In order to measure or calibrate the positioning system effectively, a standard and accurate underwater distance base-line field should be built primarily, in which the distance from underwater acoustic positioning system to the target is standard and the underwater positioning system can be measured or calibrated in this standard field. Get the root of the problem, standard three-dimensional coordinate position is the key values in the measurement and calibration.

In this paper, we propose a low-cost, easy-to-use, and high accuracy 6-DOF underwater acoustic positioning system measurement method based on conventional standard 4-DOF measurement and control platform, and realize the metering of underwater acoustic positioning system in the whole underwater three dimension space. First, a quantity value propagation mathematic model is proposed to transform the measurable quantity values (linear distances and rotation angles) in the 4-DOF space to the 6-DOF space. All these distance and angle values can be accurately measured in a standard base-line field corresponding to 4-DOF space. The underwater acoustic positioning system is mounted on the 4-DOF measurement and control platform by an expanded installation device and can be moved with it, an acoustic transponder as a field point to be measured is placed on a fixed position at the bottom of the pool. Then the measurable values are transformed to the coordinate system of underwater acoustic positioning system, which is equivalent to the measured field point is doing 6-DOF motions in this coordinate system. Moreover, in order to realize the measurement scheme standardly, we will establish a standard baseline field in an anechoic pool equipped with standard 4-DOF measurement and control devices, and propose a practicable measurement flow. Finally, measurement uncertainty evaluation is made, and the combined standard uncertainty of this metering system will be evaluated respectively. The GUM uncertainty framework and AMCM method are applied in the uncertainty evaluation. The measurement capability and performance of this metering system will be scientifically evaluated by the optimal selection of evaluation schemes and comparative analysis of the evaluated results.

The remainder of this paper is organized as follows. In section II, the 4-DOF space to 6 DOF space quantity value propagation model is described, and the corresponding rigorous mathematical expression is established. In section III, a standard base-line field build scheme and measurement flow are elaborated. In section IV, the numerical calculation of quantity value propagation model is made to illustrate this measurement method. In section V, GUM and AMCM measurement uncertainty evaluation methods are described, and the evaluation results are analyzed respectively. Finally, the conclusions are presented in section VI.

II. QUANTITY VALUE PROPAGATION MODEL

Nowadays, the widely used standard underwater acoustic measurement and control system can provide linear motion in three perpendicular directions and a rotation around a vertical axis in a three dimensional Cartesian coordinate system. The quantity value propagation model discussed in this paper that can transform values from 4-DOF space to 6-DOF space is descripted in Fig.1.

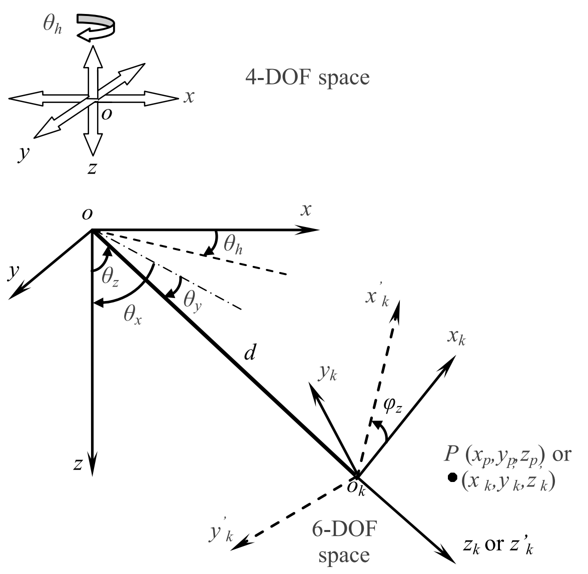

FIGURE 1. Quantity value propagation model. "-----" denotes the projection of oo_k to *xoy*, "-·-·-·-·" denotes the projection of oo_k to *xoz*.

This model is constituted with three coordinate systems: the 4-DOF measurement and control platform coordinate system *oxyz*, the underwater acoustic positioning equipment coordinate system $o'_k x'_k y'_k z'_k$ and the positioning system installation reference coordinate system $o_k x_k y_k z_k$. The rotation angles $\theta_h, \theta_z, \theta_x, \theta_y$, and φ_z are shown in Fig.1, and the arrows that representing angles in the figure point to the directions these angles increase. When $\theta_h = \theta_z = 0$, $o_k x_k y_k z_k$ is the parallel motion of *oxyz* along axis z in the positive direction, and the displacement distance is d, it is equal to the length of oo_k. Coordinate origins and the axis z of $o_k x_k y_k z_k$ and $o'_k x'_k y'_k z'_k$ are the same, or $o'_k x'_k y'_k z'_k$ is the φ_z degrees rotation of $o_k x_k y_k z_k$ around axis z_k.

The three dimensional position coordinates of the same field point in these three coordinate systems are (x, y, z), $(x_{p\_k}, y_{p\_k}, z_{p\_k})$, and (x'_k, y'_k, z'_k) respectively, it can be expressed as

$$P\left(x_p, y_p, z_p\right) \leftrightarrow P\left(x_{p\_k}, y_{p\_k}, z_{p\_k}\right) \leftrightarrow P\left(x'_k, y'_k, z'_k\right) \quad (1)$$

Building a quantity value propagation matrix $\mathrm{M}_1(\theta_h, \theta_z, d)$, and propagating the coordinate (x, y, z) of field point P from *oxyz* in the 4-DOF space to $o_k x_k y_k z_k$, we can achieve the position $(x_{p\_k}, y_{p\_k}, z_{p\_k})$ of P in $o_k x_k y_k z_k$, the process can be expressed as

$$\mathrm{C_{MS}}\left(x_{p\_k}, y_{p\_k}, z_{p\_k}\right) = \mathrm{M}_1\left(\theta_h, \theta_z, d\right) \mathrm{C_{4D}}\left(x_p, y_p, z_p\right) \quad (2)$$

where $\mathrm{C_{MS}}(x_{p\_k}, y_{p\_k}, z_{p\_k}) = [x_{p\_k}\ y_{p\_k}\ z_{p\_k}\ 1]^T$ is the three dimensional space expression of field point P in $o_k x_k y_k z_k$, $\mathrm{C_{4D}}(x_p, y_p, z_p) = [x_p\ y_p\ z_p\ 1]^T$ is the three dimensional space expression of field point P in *oxyz*, the value propagation matrix M_1 is

$$\mathrm{M}_1\left(\theta_h, \theta_z, d\right) = \begin{bmatrix} \cos\theta_x & 0 & -\sin\theta_x & 0 \\ \sin\theta_x \sin\theta_y & \cos\theta_y & \cos\theta_x \sin\theta_y & 0 \\ \sin\theta_x \cos\theta_y & -\sin\theta_y & \cos\theta_x \cos\theta_y & -d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The quantity value propagation matrix $\mathrm{M}_2(\varphi_z)$ is used to propagate positon coordinate $(x_{p\_k}, y_{p\_k}, z_{p\_k})$ of field point P in $o_k x_k y_k z_k$ to the 6-DOF space, this process is expressed as

$$\mathrm{C_{6D}}\left(x'_k, y'_k, z'_k\right) = \mathrm{M}_2\left(\varphi_z\right) \mathrm{C'_{MS}}\left(x_{p\_k}, y_{p\_k}, z_{p\_k}\right) \quad (4)$$

where $\mathrm{C_{6D}}(x'_p, y'_p, z'_p) = [x'_k y'_k z'_k]^T$ is the three dimensional coordinate of field point P in $o'_k x'_k y'_k z'_k$, $\mathrm{C'_{MS}}(x_{p\_k}, y_{p\_k}, z_{p\_k}) = [x_{p\_k} y_{p\_k} z_{p\_k}]^T$, the quantity value propagation matrix M_2 is

$$\mathrm{M}_2\left(\varphi_z\right) = \begin{bmatrix} \cos\varphi_z & \sin\varphi_z & 0 \\ -\sin\varphi_z & \cos\varphi_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

In order to implement this scheme easily, θ_h and θ_z should be used in the quantity value propagation procedure. This is because θ_x and θ_y could not be measured directly in the 4-DOF space. There are some relationships between these angles (Proof: see Appendix A).

$$\sin\theta_x = \sin\theta_z \cos\theta_h / \cos\theta_y \quad (6)$$

$$\cos\theta_x = \cos\theta_z / \cos\theta_y \quad (7)$$

$$\sin\theta_y = \sin\theta_z \sin\theta_h \quad (8)$$

By introducing θ_h and θ_z, we can get the coordinate series of the field point P in the underwater acoustic positioning equipment coordinate system $o'_k x'_k y'_k z'_k$, thus we have realized the whole space expression of the field point coordinates in the 6-DOF space.

III. STANDARD UNDERWATER BASE-LINE FIELD AND MEASUREMENT SCHEME

In this section, we will establish a standard underwater base-line field, and introduce the relationship between this base-line field and the quantity value propagation model. Furthermore, because the scale of indoor pool is limited, it is usually could not measure the big scale location distance values directly, in order to solve this problem, a target's acoustic simulation measurement method is proposed to realize the big distance quantity measurement of underwater acoustic positioning system in a small scale pool. Finally, measurement flow and scheme is presented.

A. STANDARD UNDERWATER BASE-LINE FIELD

Standard underwater base-line field is built in an anechoic pool equipped with a 4-DOF measurement and control platform. This platform can move linearly along axis x, y and z in both the directions of positive and negative half-axis, and can rotate around axis z. The underwater acoustic positioning system is installed on the 4-DOF measurement and control platform with a distance d from its acoustic center to the origin of coordinate system $oxyz$. We have designed an extended installation device to realize this installation and related rotation control. The scheme of standard underwater base-line field is descripted in Fig.2. The midpoint in the rotation axis of the rotating arm is the origin of the 4-DOF measurement and control platform coordinate system $oxyz$.

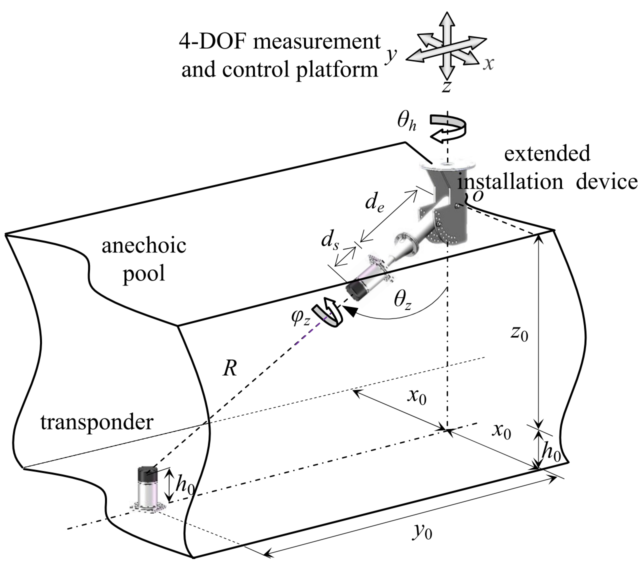

FIGURE 2. Structure of the standard underwater base-line field.

The length of d in the quantity value propagation model is

$$d = d_e + d_s \tag{9}$$

where d_e is the length of rotation arm of the extended installation device, and d_s is the distance from reference acoustic center of the transducers of underwater acoustic positioning system to the end of rotation arm.

A transponder is fixed on the bottom of the anechoic pool as the target to be detected, and its reference acoustic center is corresponding to the field point P in the quantity value propagation model, h_0 is the height of the reference acoustic center of the transponder to the bottom of anechoic pool. Coordinate position of the transponder's acoustic center in the 4-DOF measurement and control platform coordinate system is (x_0, y_0, z_0). The angle between axis z and the rotation arm of the extended installation device is θ_z, the rotation arm can also rotate angle φ_z around its central axis. All the length quantities (x_0, y_0, z_0, and d) and angle quantities (θ_z and φ_z) can be measured directly using standard measurement equipment in the measurement and control platform coordinate system. Then we can propagate these quantities from the 4-DOF space to the underwater acoustic positioning equipment coordinate system corresponding to the 6-DOF space accurately. Thus, a standard underwater base-line field is built, and it can be used directly to measure the underwater acoustic positioning systems precisely.

B. TARGET ACOUSTIC SIMULATION MEASUREMENT METHOD

Sound pressure level is one of the basic acoustical quantity values in acoustic metrology. For the underwater acoustic positioning system, sound pressures near the transducers of positioning system are different with the changes of distance to the transponder that mounted on the located targets, such as underwater vehicle, dives, wrecked ships to be got out of water, and so on. The sound pressure level near the transducer of positioning system can be expressed as [21]

$$SPL = SL - (\alpha R + 20 \log R) \tag{10}$$

where SL is the source level of transponder, α is the acoustic attenuation coefficient in water, R is the distance between reference acoustic centers of transponder and transducer, the unit is m. Presuming the characteristics of water medium unchanged, we can get two variables (SL and R) that could cause the changes of SPL.

In the standard underwater base-line field, fixing the transponder on the bottom of pool, and keeping R unchanged, we can get different sound pressure levels by configuring transponder to radiate acoustics with different source levels. Then we can use smaller transponder SL to express or simulate large scale distance between the reference acoustic centers of transponder and transducer of underwater acoustic positioning system. The relationship between the transponder's source level and the large positioning distance D that exceed the scale of pool is

$$SL_{R|D} = SL_R - \left[\alpha\,(D - R) + 20 \log \frac{D}{R}\right] \tag{11}$$

where $D \geq R$. This scheme can only be used when the distance is bigger than the scale of pool or standard base-line field, and at this time, the transponder used in the measuring system can be called target acoustic simulation transponder.

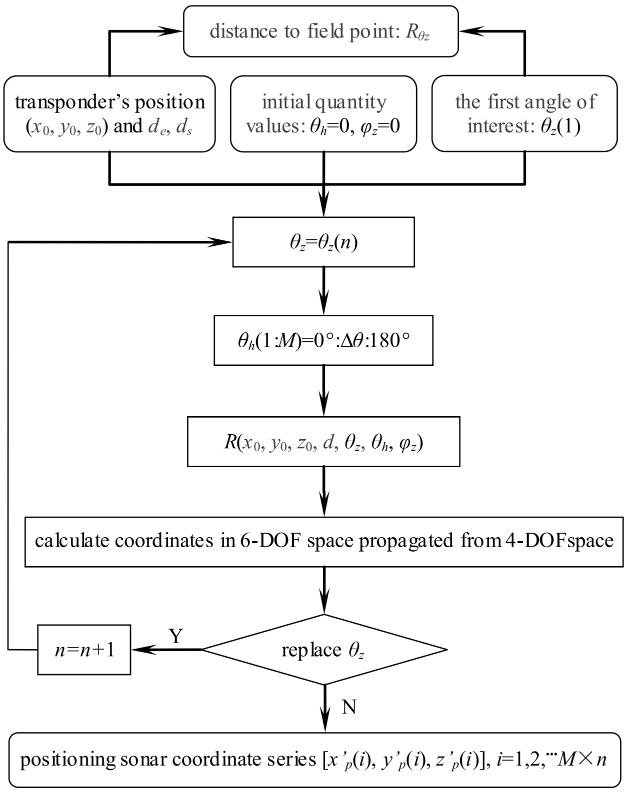

FIGURE 3. Measurement flow and scheme of measuring underwater acoustic positioning system.

C. MEASUREMENT FLOW AND SCHEME

The underwater acoustic positioning system measurement flow and scheme is shown in Fig.3. There are some preparatory works should be done before the metering of underwater acoustic positioning system. First, install the measuring system according to the structure diagram of standard underwater base-line field and ensure $\theta_h = 0°$, $\varphi_z = 0°$. Second, all the distance and angle quantity values that include x_0, y_0, z_0, d_e, d_s and θ_z corresponding to distance R should be decided and measured by standard measurement equipment. Moreover, the source level of transponder also should be configured if the measured distance D is larger than the scale of standard underwater base-line field, that is the source level of transponder should be configured to $SL_{R|D}$ refers to (11). Thus, we have got a standard underwater base-line field ready to measure an underwater acoustic positioning system.

When angle θ_z is a certain value and x_0, y_0, z_0, d_e, d_s, φ_z are unchanged, controlling the 4-DOF measurement and control platform to rotate 180° with an appropriate step $\Delta\theta$ around axis z, we can efficiently get a series of three-dimensional space coordinates on a curve in the 6-DOF space. Change θ_z to another interesting value, and repeat the above process, we can get another group of three-dimensional space coordinates. Repeat these process, we can achieve $M \times N$ space coordinates in the underwater acoustic positioning equipment coordinate system, where M is the number of θ_h, or the number of space coordinates samples when the 4-DOF measurement and control platform rotates 180° around axis z, N is the number of the angle quantity θ_z.

As mentioned above, by controlling 4-DOF measurement and control platform and changing the angle of rotation arm of the extended installation device, we can realize the propagation of standard quantity values from 4-DOF space to 6-DOF space to get a series of three-dimensional space coordinates in 6-DOF space, then we have achieved the standard distance quantities corresponding to the position coordinates of field point P in the underwater acoustic positioning equipment coordinate system.

IV. NUMERICAL CALCULATION OF QUANTITY VALUE PROPAGATION MODEL

In this section, the mathematic model introduced in Section II is used, and we will take a group of specific actual quantity values for example to illustrate this numerical calculation, all the parameters are summarized in Table 1.

TABLE 1. Quantities used in the calculation of measurement model.

Symbol	Quantity	Value	Unit
x_0	length of x-dimension in 4-DOF space	10.0	m
y_0	length of y-dimension in 4-DOF space	0.0	m
z_0	length of z-dimension in 4-DOF space	2.0	m
d	distance of sonar acoustic center to the origin point of 4-DOF platform	1.1	m
θ_h	clockwise rotation angle of the 4-DOF platform when looking down	-89:2:89	°
θ_z	angle of rotating arm to the vertical direction	0:5: 90	°
φ_z	angle of rotating arm rotate around its central axis	0 or 180	°

For a single measurement of the underwater acoustic positioning system, with other quantities unchanged, we should only rotate the rotating arm and make $\varphi_z = 0°$ or 180°, this is because each aforementioned value of φ_z corresponds to one half part of the whole three dimension underwater space. This specific effect will be explained in details in the following analysis of the numerical calculation results.

According to the characteristics of underwater acoustic test, the transducers of positioning system are usually installed on the measurement and control platform and just entering the shallow water. The transponder is fixed in the lower half space of the horizontal plane on which the transducer of positioning system is located.

Without loss of generality, we set the angle of rotating arm θ_z to the vertical direction from 0° to 90° in the step of 5°, and set the clockwise rotate angle of the 4-DOF platform θ_h when looking down from −89° to 89° in step of 2°, then we can get the transponder's three dimension position distribution in the 6-DOF space. Take $\theta_z = 45°$, $\varphi_z = 0°$ and $\theta_h = [-89°:2°:89°]$ for example, we can propagate the standard length quantities $x_0 = 10.0$m, $y_0 = 0.0$m, $z_0 = 2.0$m and angle quantity θ_h in the 4-DOF space to the

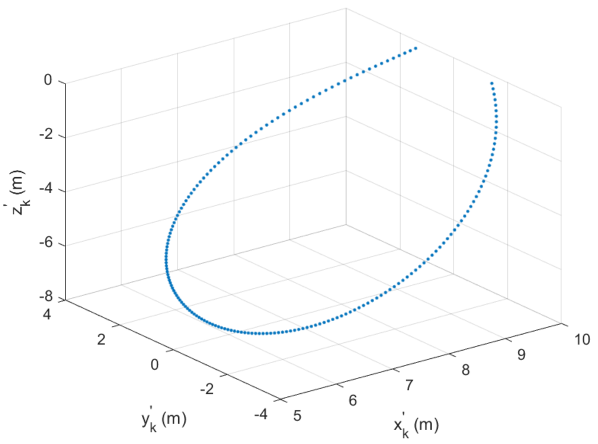

FIGURE 4. Space position coordinates of field point in the underwater acoustic positioning equipment coordinate system when $\theta_z = 45°$.

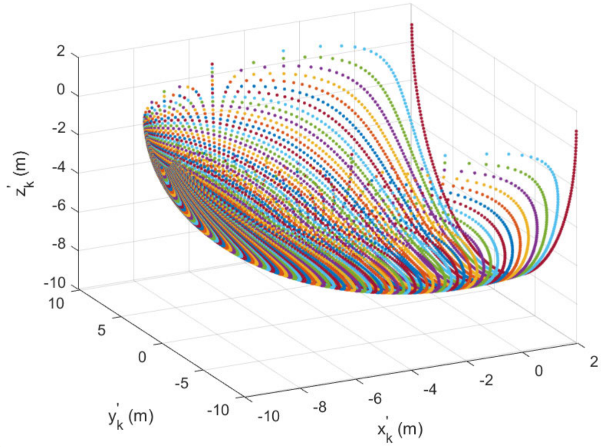

FIGURE 6. Case (b): Field point distribution in the coordinate system of underwater acoustic positioning system when $\varphi_z = 180°$.

6-DOF space and get 90 space position coordinates on a curve in the underwater acoustic positioning equipment coordinate system $o_k'x_k'y_k'z_k'$, see Fig.4. The position coordinates are regularly distributed on the curve in the 6-DOF space. Similarly, we can obtain the spatial coordinates of the field point in the whole 6-DOF space with the correspondence of multiple quantity values of θ_z.

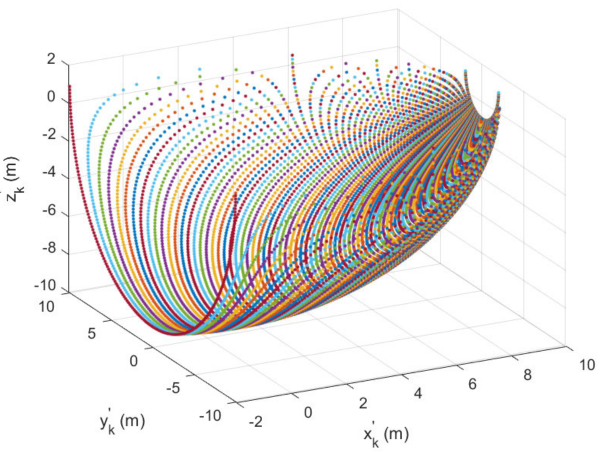

FIGURE 5. Case (a): Field point distribution in the coordinate system of underwater acoustic positioning system when $\varphi_z = 0°$.

In order to illustrate the quantity value propagation function of the model proposed in this paper, the output forms have to be considered and categorized into two cases. With all the quantity values referred above unchanged, the different values of φ_z correspond two typical cases, see the case (a) and case (b) illustrated in Fig. 5 and Fig.6 respectively. When $\varphi_z = 0°$, the quantity values of the propagation model outputs are corresponding to the coordinates of the lower half space in the direction of the positive half axis of axis x_k'.

When $\varphi_z = 180°$, the outputs of the model are corresponding to the coordinates of the lower half space in the direction of the negative half axis of axis x_k'. This characteristic of the standard underwater base-line field and quantity value propagation model can realize the whole 6-DOF space field point position coordinates expression only by choosing and changing the value of φ_z equal to 0° and 180°. So the quantity value propagation model has the capability to realize the whole space expression of the field point in the 6-DOF space.

Although the relative position between the origin of 4-DOF measurement and control platform coordinate system and the field point remains unchanged in the process of measurement, the 6-DOF space measurement capability could also be realized in the standard underwater base-line field by using the quantity value propagation model proposed in this paper, the 6-DOF space dynamic ranges in each linear distance dimension and the rotation of angles are all large enough to express the relatively motions of the field point in the coordinate system of underwater acoustic positioning equipment, all these have indicated that this technique has a good adaptability, especially can work very well based on traditional standard 4-DOF measuring systems.

V. MEASUREMENT UNCERTAINTY EVALUATION

Measurement uncertainty is a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information [22]. In this paper, the evaluated measurement uncertainty is mainly consisted of two components, they are the Type A instrumental measurement uncertainty and Type B uncertainty about acoustic interference and noise occurring in the underwater environment.

We will evaluate the measurement uncertainty of the measuring system using the GUM method firstly, and then AMCM method will be applied to test the effectiveness of the schemes of the GUM method, this is because the specific methods used in calculating the sensitivity coefficients and stochastic independence of the input quantities may be inadequate in many situations, which could lead to more or less incorrect results, thus, validation of GUM method by other methods is highly recommended generally [23]. Finally, we will scientifically and accurately give the evaluation results of the relative combined measurement uncertainty, and analysis the optimal methods can be used to evaluate the measurement uncertainty of the metering system researched in this paper.

A. MODEL OF MEASUREMENT

In order to measure underwater acoustic positioning systems based on the method proposed in this paper, we should measure the linear distance quantities and rotation angles in the underwater base-line field standardly, they are x_0, y_0, z_0, d, θ_h, θ_z and φ_z. At the same time, they are not only the inputs of the measurement model, but also the main sources of the instrumental measurement uncertainty. For the metering system of underwater acoustic positioning system, the direct measurement outputs are the coordinate values of field point $P(x'_k, y'_k, z'_k)$. Based on the quantity value propagation model, the measurement model can be expressed as

$$x'_k = x_p\left(\sin\theta_x\sin\theta_y\sin\varphi_z + \cos\theta_x\cos\varphi_z\right) + y_p\cos\theta_y\sin\varphi_z + z_p\left(\cos\theta_x\sin\theta_y\sin\varphi_z - \sin\theta_x\cos\varphi_z\right) \tag{12}$$

$$y'_k = x_p\left(\sin\theta_x\sin\theta_y\cos\varphi_z - \cos\theta_x\sin\varphi_z\right) + y_p\cos\theta_y\cos\varphi_z \times z_p\left(\cos\theta_x\sin\theta_y\cos\varphi_z + \sin\theta_x\sin\varphi_z\right) \tag{13}$$

$$z'_k = x_p\sin\theta_z\cos\theta_h - y_p\sin\theta_z\sin\theta_h + z_p\cos\theta_z - d \tag{14}$$

When evaluating instrumental measurement uncertainty, distance R between reference sound centers of underwater positioning system and the field point (responder) in standard base-line field has to be analyzed. Especially, quantity R is the primary parameter of underwater acoustic positioning system. The coordinate values x'_k, y'_k and z'_k should be expressed using input quantity values according to the relationships in (6), (7), and (8), then we can get the ultimate expression of measurement model as

$$\begin{aligned} x'_k &= f\left(x_p, y_p, z_p, \theta_h, \theta_z, \varphi_z\right) \\ &= \frac{1}{\sqrt{1\text{-}\sin^2\theta_z\sin^2\theta_h}} \\ &\quad\times\Big[x_p\left(\sin^2\theta_z\sin\theta_h\cos\theta_h\sin\varphi_z + \cos\theta_z\cos\varphi_z\right) \\ &\quad+ y_p\left(1-\sin^2\theta_z\sin^2\theta_h\right)\sin\varphi_z \\ &\quad+ z_p\left(\sin\theta_z\cos\theta_z\sin\theta_h\sin\varphi_z\right. \\ &\quad\left.-\sin\theta_z\cos\theta_h\cos\varphi_z\right)\Big] \end{aligned} \tag{15}$$

$$\begin{aligned} y'_k &= g\left(x_p, y_p, z_p, \theta_h, \theta_z, \varphi_z\right) \\ &= \frac{1}{\sqrt{1\text{-}\sin^2\theta_z\sin^2\theta_h}} \\ &\quad\times\Big[x_p\left(\sin^2\theta_z\sin\theta_h\cos\theta_h\cos\varphi_z\right. \\ &\quad\left.-\cos\theta_z\sin\varphi_z\right) + y_p\left(1-\sin^2\theta_z\sin^2\theta_h\right)\cos\varphi_z \\ &\quad+ z_p(\sin\theta_z\cos\theta_z\sin\theta_h\cos\varphi_z + \sin\theta_z\cos\theta_h\sin\varphi_z)\Big] \end{aligned} \tag{16}$$

$$\begin{aligned} z'_k &= h\left(x_p, y_p, z_p, \theta_h, \theta_z, d\right) \\ &= x_p\sin\theta_z\cos\theta_h - y_p\sin\theta_z\sin\theta_h + z_p\cos\theta_z - d \end{aligned} \tag{17}$$

Then the output quantity R can be derived as

$$R = \sqrt{x'^2_k + y'^2_k + z'^2_k} \tag{18}$$

B. UNCERTAINTY EVALUATION OF INPUT QUANTITIES

The uncertainties of the measurement model input quantities are analyzed based on the equipment acceptance report of the 4-DOF measurement and control platform and actual measurements. The distance quantities are measured by laser range finder whose expanded measurement uncertainty is 15μm+6μm/m when coverage factor $k = 2$. The angles are measured by angle measuring instrument whose expanded measurement uncertainty is 8.3" when coverage factor $k = 2$. Because these uncertainties of the measurement equipment are too small, they are neglected in the measurement uncertainty evaluation of the positioning system.

The measurement uncertainties of input quantity values are evaluated by Range Method (also known as grey relational approach) [24]. We do N times independent measurement of each distance quantity X that obeys normal distribution, so we can get the difference ΔX between the measured maximum value and the minimum value. The experimental standard deviation of x_k can be evaluated as

$$u\left(x_k\right) = s\left(x_k\right) = \frac{\Delta X}{C} \tag{19}$$

where C is range coefficient. There are some relationships between C and N, it is shown in Table 2.

TABLE 2. Relationships between range coefficient and measurement times.

N	2	3	4	5	6
C	1.13	1.69	2.06	2.33	2.53
N	7	8	9	10	15
C	2.70	2.85	2.97	3.08	3.47

Previous researches indicate that the Range Method can be used when N is small, especially when the measurement quantity value obeys normal distribution and $N \leq 9$, it has been proved that this method is better than Bessel Method under this condition, and it is better to select the number of N between 4 and 9.

TABLE 3. Uncertainty evaluation results of input quantity values.

Input quantity value x_i	Unit	ΔX	N	$u(x_i)$
x_p	mm	1.10	5	0.021
y_p	mm	0.34	5	0.065
z_p	mm	0.32	5	0.061
d	mm	0.24	5	0.046
θ_h	°	0.10	2	0.063
θ_z	°	0.15	2	0.094
φ_z	°	0.15	2	0.094

All the measurement model input values corresponding to the metering system are quantity values that are measured directly using standard metering instruments, and these quantity values are measured on measurement repeatability conditions, the related parameters used in Rang method and the measurement uncertainty evaluation results of these input quantity values are given in Table 3. These standard deviations of input quantity values will be used in the measurement uncertainty evaluation of the underwater acoustic positioning system in the following sections.

The uncertainties introduced by acoustic interference and noise occurring in the underwater environment are related to the measurement instruments that used in measuring the background noise of the anechoic tank. These instruments include standard hydrophone, measuring amplifier and digital voltmeter, the uncertainties of these instruments u_h, u_a and u_v are Type B uncertainties in the form of relative standard measurement uncertainties, and they are shown in Table 4.

TABLE 4. Relative standard measurement uncertainties of the instrument used in measuring background noise.

Instrument	maximum error module	$u_r(x)$
Standard hydrophone	0.20%	0.12%
measuring amplifier	0.20%	0.12%
digital voltmeter	0.10%	0.058%

C. GUM MEASUREMENT UNCERTAINTY EVALUATION

In the process of GUM measurement uncertainty evaluation, the most important segment is the calculation of uncertainty components corresponding to each input quantity value of the measurement model.

If the standard measurement uncertainty of input x_i is $u(x_i)$, the uncertainty component of x_i can be expressed as [25]

$$u_y(x_i) = c_i u(x_i) = \left|\frac{\partial f}{\partial x_i}\right| u(x_i) \tag{20}$$

where f is the measurement model, c_i is the sensitivity coefficient that is obtained from the partial derivative of the measurement model for x_i. At this time, we could call the uncertainty evaluation method as partial derivative GUM method.

There is another method can be used to calculate the sensitivity coefficient. When the measurement model is a nonlinear model, the measurement model is usually complex, and it is inconvenient to calculate the partial derivative of input quantity values, then we can use numerical GUM method to calculate the sensitivity coefficient that equals to the change of the measurement model output corresponding to the unit quantity value change of each input quantity. The numerical method to calculate sensitivity coefficient can be expressed as

$$c_i = \left|\frac{f(x_{i2}) - f(x_{i1})}{x_{i2} - x_{i1}}\right| \tag{21}$$

where $x_{i2} = x_{i0} + u(x_{i0})$, $x_{i1} = x_{i0} - u(x_{i0})$. x_{i0} is the estimated value of x_i, $u(x_{i0})$ is the standard measurement uncertainty of x_{i0}.

In the condition that the measurement model input x_k, y_k, z_k, d, θ_h, θ_z and φ_z are independent, we use numerical GUM method to calculate the uncertainty components, and the instrumental relative combined standard uncertainty of measurement model output can be wrote as

$$u_{cr}(R) = \frac{\sqrt{u^2_{c\_x'_k} + u^2_{c\_y'_k} + u^2_{c\_z'_k}}}{R} \tag{22}$$

where

$$\begin{aligned}
u_{c_x'_k} &= \sqrt{\begin{aligned}&u^2_{x'_k}(x_p) + u^2_{x'_k}(y_p) + u^2_{x'_k}(z_p) + u^2_{x'_k}(\theta_h)\\ &+ u^2_{x'_k}(\theta_z) + u^2_{x'_k}(\varphi_z)\end{aligned}},\\
u_{c_y'_k} &= \sqrt{\begin{aligned}&u^2_{y'_k}(x_p) + u^2_{y'_k}(y_p) + u^2_{y'_k}(z_p) + u^2_{y'_k}(\theta_h)\\ &+ u^2_{y'_k}(\theta_z) + u^2_{y'_k}(\varphi_z)\end{aligned}},\\
u_{c_z'_k} &= \sqrt{\begin{aligned}&u^2_{z'_k}(x_p) + u^2_{z'_k}(y_p) + u^2_{z'_k}(z_p) + u^2_{z'_k}(\theta_h)\\ &+ u^2_{z'_k}(\theta_z) + u^2_{z'_k}(d)\end{aligned}}.
\end{aligned}$$

And the relative combined standard measurement uncertainty of the metering system is

$$u_{cr} = \sqrt{u^2_{cr}(R) + u^2_{rh} + u^2_{ra} + u^2_{rv}} \tag{23}$$

where u_{rh}, u_{ra} and u_{rv} are the relative standard measurement uncertainties of hydrophone, measuring amplifier and digital voltmeter respectively.

Using the parameters as presented in Table 3 and Table 4, the spatial distribution of the relative combined standard measurement uncertainties evaluated by numerical GUM method is shown in Fig.7, we can see from the figure clearly that the relative combined standard measurement uncertainty magnitude is not bigger than 0.1797%.

The measurement model proposed in this paper is a nonlinear model, so the measurement uncertainties evaluated by partial derivative GUM method are usually bigger than that calculated by numerical GUM method. This is because the input quantity values are overrepresented in the uncertainty components for the partial derivative method, and

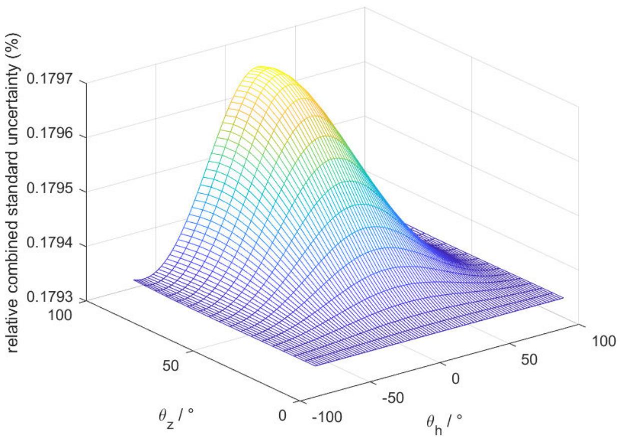

FIGURE 7. Spatial distribution of relative combined standard uncertainties that evaluated by numerical GUM method.

this directly leads to repeat computations of the combined standard measurement uncertainties. We will firstly focus on using the numerical method to calculate the sensitivity coefficient corresponding to each input quantity of the measurement model. This is also because the numerical method is a more universal approach. In the next section, we will also give a concrete comparative analysis of the evaluation results of these two GUM measurement uncertainty evaluation methods.

D. AMCM MEASUREMENT UNCERTAINTY EVALUATION AND GUM METHOD VERIFICATION

Although the GUM method is applicable in many cases, it is not always easy to determine whether all of its application conditions are suitable, especially when the model of measurement is a non-linear model, it is difficult to calculate the sensitivity coefficients or the uncertainty components corresponding to the input quantity values are not similar in size. The Monte Carlo measurement uncertainty evaluation Method (MCM) is a general purpose method to evaluate models with single input quantity or multiple input quantities, and it is also a method to be used to test the effectiveness of GUM uncertainty evaluation method admittedly, and the basic principle of AMCM uncertainty evaluation method is that as the number of experiments increase, the required results are statistically stable [26]. Determination of the number of experiment, design of uncertainty evaluation process, and judgment of the stability conditions are all the key technologies of AMCM method.

Let p as the coverage probability of measurement output quantity, the number of AMCM experiment M can be expressed as

$$M = \max\left(J, 10^4\right) \tag{24}$$

where J is a integer greater than or equal to $100/(1-p)$. For the first time of AMCM experiment, according to the probability density functions of the N inputs X_i $(i = 1, 2, \cdots, N)$ of the measurement model, extract M sample values $X_{ik}(k = 1, 2, \cdots, M)$ respectively, and calculate $Y_k = f(X_{1k}, X_{2k}, \cdots, X_{Nk})$. Then the standard measurement uncertainty is calculated as follows

$$u\left(Y_h\right) = \sqrt{\frac{\sum_{k=1}^{M}\left(Y_k - Y_h\right)^2}{M-1}} \tag{25}$$

where Y_h is estimated arithmetic mean value of the output quantity Y_k of measurement model in the hth Monte Carlo experiment. Meanwhile, we calculate the coverage interval of output quantity $[Y_{h\text{-}low}, Y_{h\text{-}high}]$. If pM is integer, the sample number of the coverage interval is $q = PM$, otherwise q is integer part of $pM + 1/2$. For each value of $r = 1, 2, \ldots, M$, $Y_{h\text{-}low} = Y'_h(k)$, $Y_{h\text{-}high} = Y'_h(k+q)$, where Y'_h is no decrease sort of Y_h.

Repeat the above process, we can get the hth output quantity arithmetic mean value Y_h, standard measurement uncertainty $u(Y_h)$, the maximum values of coverage interval $Y_{h\text{-}low}$ and $Y_{h\text{-}high}$. Calculating the experimental standard deviation of the mean values of these quantities using the following equation

$$s_y = \sqrt{\frac{\sum_{n=1}^{h}\left(y_n - \bar{y}\right)^2}{h\left(h-1\right)}} \tag{26}$$

Using the same formula, s_{Yh}, $s_{u(Yh)}$, s_{Yh_low}, and s_{yh_high} can be calculated respectively. In addition, calculating standard measurement uncertainty of all the $M \times h$ output quantities as in (24), we can get $u(Y)$. Finally, the numerical tolerance of $u(Y)$ is computed as follows

$$\delta = 0.5 \times 10^L \tag{27}$$

where L is an integer. When $u(Y)$ is expressed as $c \times 10^L$, c is a n_{dig} digits decimal integer, and $L = \text{round}(10\log u(Y) - n_{dig} + 1)$. The numerical tolerance is the difference between the estimated value and the actual value, and it is a quantity that can be used in evaluating the accuracy of calculation results. If any quantity of $2s_{Yh}$, $2s_{u(Yh)}$, $2s_{Yh\_low}$, and $2s_{yh\_high}$ is bigger than δ, another Monte Carlo experiment should be done, otherwise all the calculations are stable, and output all the calculation results. The evaluation process of AMCM method is described in Fig.8, the final output results are all corresponding to the $M \times h$ model output quantities. When we analysis relative uncertainty, $u(Y)$ is expressed as $u_r(Y)$.

Input quantity samples choosing is another important segments in the AMCM measurement uncertainty evaluation process. Because small probability events are usually considered to occur with probability less than 5% in the hypothesis test, and they are considered as unlikely events. For normal distribution, the proportion of area between normal curve and transverse axis interval $[\mu - \sigma, \mu + \sigma]$ is 68.27%, and that for transverse axis interval $[\mu - 3\sigma, \mu + 3\sigma]$ is 99.73%,

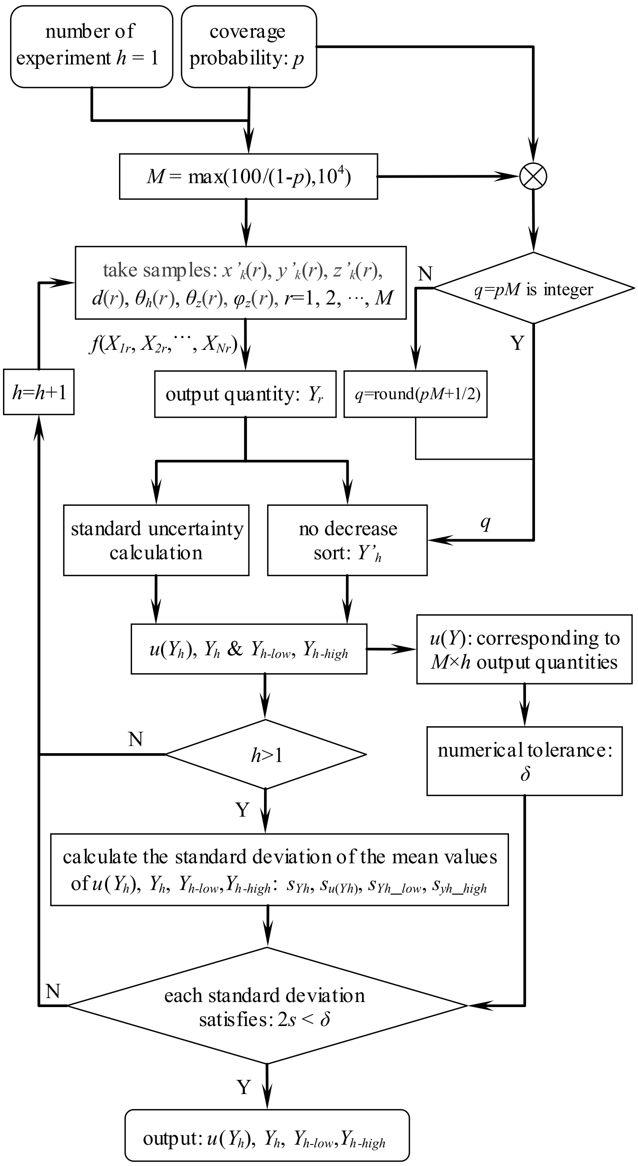

FIGURE 8. **Measurement uncertainty evaluation diagram of AMCM method.**

so the probability events out of this interval are not supposed to happen in the practical problems.

For normal distribution, if the number of samples is big enough and the standard deviation is $s(x)$, the probability that the absolute value of residual error exceeds three times the standard deviation of the test is very small, so it can be considered as impossible events, namely the maximum residual satisfies the following conditions:

$$|x - \bar{x}| > 3s\,(x) \tag{28}$$

where $\bar{x}$ is the average of multiple measurements of quantity x. Therefore, this criterion is used in producing the M random samples of each input quantities of the measurement model in AMCM measurement uncertainty evaluating process analyzed in this paper.

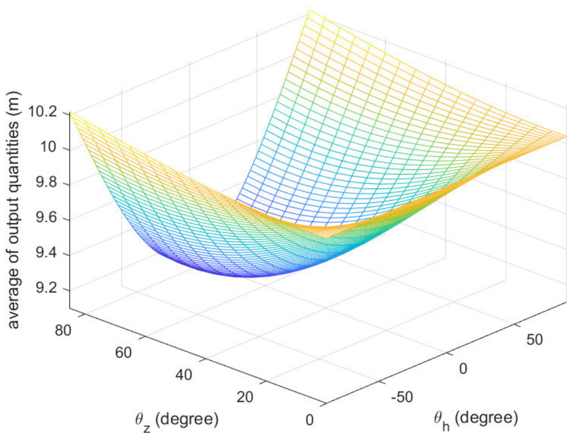

FIGURE 9. **Spatial distribution of the average of output quantity *R*.**

According to the quantity values in Table I, III and IV, when φ_z =0, we will calculate the measurement uncertainty using AMCM method. The coverage probability of output quantity is set to be 95%, decimal integer digits n_{dig} is 2, and the spatial distribution of the average value of output based on the quantity value propagation model proposed in this paper is given in Fig.9. The output quantity R is changing smoothly in the three dimensional space, and the trend of its spatial distribution is related to the field point distribution in the coordinate system of underwater acoustic positioning system as in Fig.5.

Residual error distribution of the average of output quantity is also given in Fig.10, which indicated the changing trend of measurement errors in 6-DOF space that produced by the input quantity values errors propagation from 4-DOF space. From another point of view, the spatial distribution of combined standard uncertainties calculated by GUM method is verified at the same time (see Fig.7), this is because the data corresponding to Fig.10 have the similar trend of magnitude change in Fig.7.

The three dimensional spatial distribution of relative combined standard measurement uncertainty evaluated by AMCM method is given in Fig.11. It is demonstrated that the measurement uncertainties evaluated by GUM method and AMCM method have the same order of magnitude, and the validity of GUM method applied in measurement uncertainty evaluation of underwater acoustic positioning measurement scheme proposed in this paper is preliminarily verified.

We also compared the numerical tolerances of the combined standard measurement uncertainties that calculated by GUM method and AMCM method, they are shown in Fig.12 (a) and (b) respectively. The high coincidence degree of these numerical tolerances in the main space further illustrates the effectiveness of the GUM method.

As mentioned in part C of section V, partial derivative method and numerical method are two basic methods when using GUM theory to evaluate the measurement uncertainty.

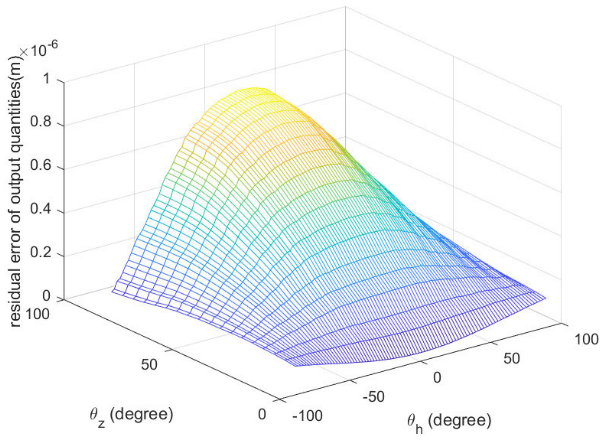

FIGURE 10. Residual error distribution of the average of output quantity ***R***.

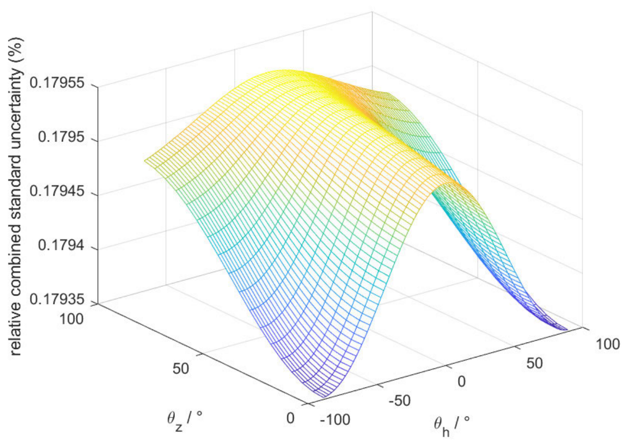

FIGURE 11. Spatial distribution of the relative combined standard uncertainty evaluated by AMCM method.

In order to analysis which method is more suitable for uncertainty evaluation of the measuring method proposed in this paper, we also calculated the numerical tolerance of the combined standard measurement uncertainty evaluated by partial derivative GUM method, the spatial distribution of its numerical tolerances is shown in Fig.13. It is easily to see that the values of numerical tolerances calculated by partial derivative GUM method are two orders of magnitude larger than both the numerical GUM method and AMCM method. So the evaluated results of AMCM method have verified that numerical GUM method can be used to evaluate the measurement uncertainty of underwater positioning system.

At the same time, we calculated the coverage interval when the coverage probability is 95%, spatial distribution of the length of coverage interval in three dimensional space is shown in Fig.14, the evaluated results indicate that the length of coverage interval is not bigger than 0.0332% in the whole 6-DOF space, which demonstrated that the performance of the measuring system and measurement scheme proposed in this paper is stable.

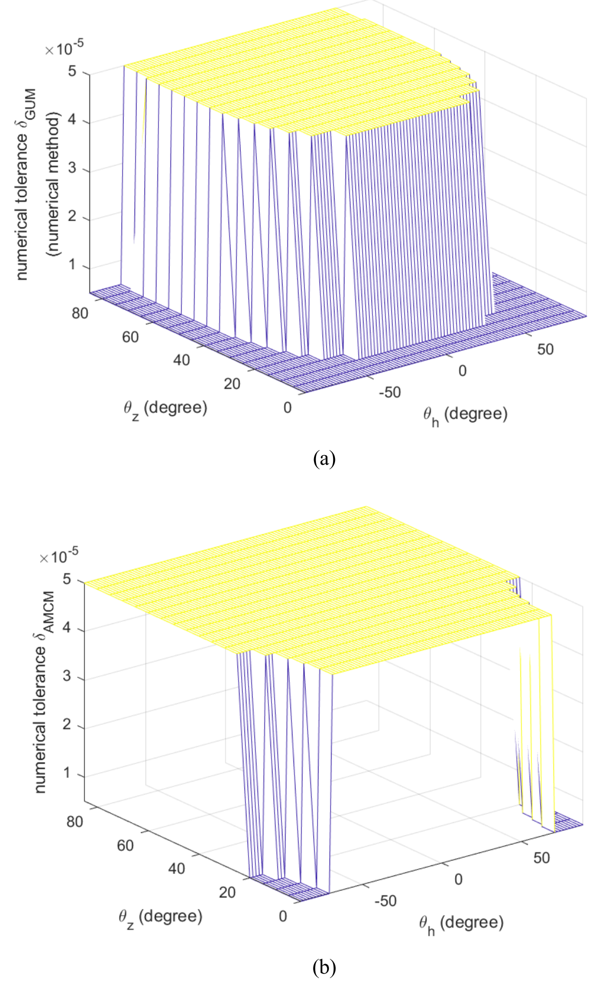

FIGURE 12. Spatial distribution of numerical tolerances of the combined standard measurement uncertainty. (a) Numerical tolerances corresponding to numerical GUM method; (b) Numerical tolerances corresponding to AMCM method.

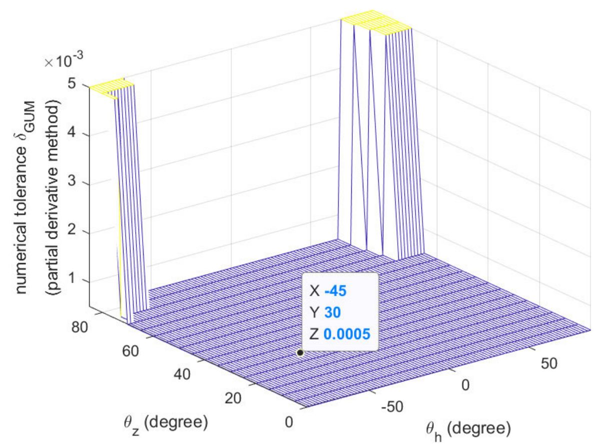

FIGURE 13. Spatial distribution of numerical tolerances of the combined standard measurement uncertainty evaluated by partial derivative GUM method.

If the measurement uncertainty evaluated by Monte Carlo method is basically the same as that evaluated by GUM method, it demonstrates that GUM method is

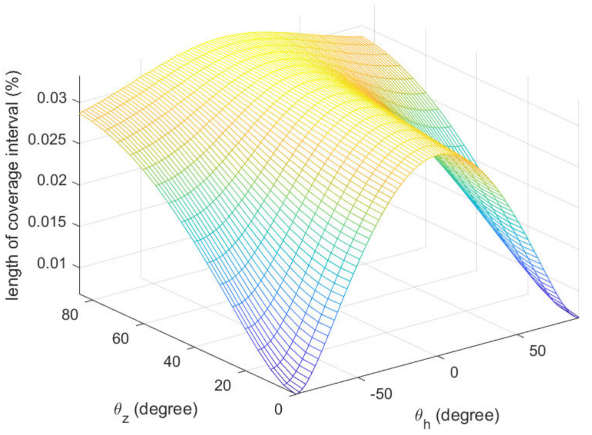

FIGURE 14. Spatial distribution of the length of coverage interval when the coverage probability is 95%.

obviously applicable. We can directly apply the GUM method to evaluate the measurement uncertainty of the actual metering systems.

VI. CONCLUSION

In this paper, we proposed a model of quantity value propagate from low DOF space to high DOF space, specifically realized the propagation of measurable quantity values from the 4-DOF space to the 6-DOF space that corresponding to the coordinate system of underwater acoustic positioning system to be measured. Based on this quantity value propagation theory and standard 4-DOF measurement and control platform, a standard underwater base-line field is designed and built to measure underwater acoustic positioning system efficiently in the whole three dimensional underwater space, and a target's acoustic simulation method was proposed to solve the problem of big scale positioning distance quantity value could not be measured in small scale indoor pool, it makes the metering scheme researched in this paper more practical. Two measurement uncertainty evaluation methods are researched, AMCM method verified that the numerical GUM method can be used to evaluate the measurement uncertainty of the metering method and metering system researched in this paper, and the relative combined uncertainty of the metering system is not higher than 0.18% include considering the underwater interference and noise factors. This measurement theory and metering method can be used in typical underwater positioning systems, such as ultra-short base line positioning system, short base line positioning system, and also suitable to measure the underwater optical positioning systems [27]. Although the underwater noise environment factor is the main factor that causes the measurement uncertainty, but the small instrumental measurement uncertainty ensured the small magnitude of the combined measurement uncertainty of the metering system. The following-up work is to research the technique to reduce the underwater environment noise in the standard base-line field of the metering system and reproduce this metering technology in Standard Metrology Department and to compile the normative documents for measurement and testing of underwater positioning system.

APPENDIX

A. PROOF OF (6), (7) AND (8)

The 4-DOF measurement and control platform coordinate system $oxyz$ and the angle quantities, such as θ_x, θ_y, θ_h, θ_z, φ_z, and related length quantities are all shown in Fig.15.

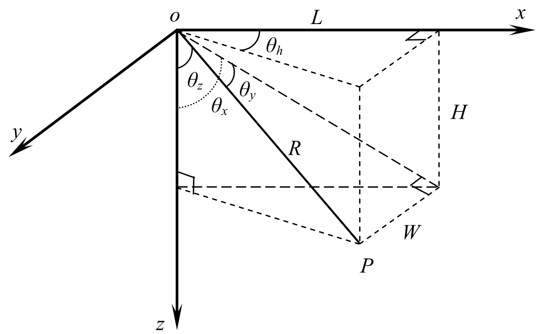

FIGURE 15. Coordinate system of the 4-DOF measurement and control system.

From the geometric relationship in the upper graph, the following relations can be obtained:

$$L = R\cos\theta_y \sin\theta_x = R\sin\theta_z \cos\theta_h \tag{A.1}$$

and

$$W = R\sin\theta_y = R\sin\theta_z \sin\theta_h \tag{A.2}$$
$$H = R\cos\theta_y \cos\theta_x = R\cos\theta_z \tag{A.3}$$

Therefore, the relationships of (6), (7), and (8) can be solved respectively as:

$$\sin\theta_x = \sin\theta_z \cos\theta_h \big/ \cos\theta_y \tag{A.4}$$
$$\cos\theta_x = \cos\theta_z \big/ \cos\theta_y \tag{A.5}$$
$$\sin\theta_y = \sin\theta_z \sin\theta_h \tag{A.6}$$

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