

Position Accuracy Analysis on Disc Storing Mechanism for Benthic Drill

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Abstract: The positional accuracy of disc storing mechanism for benthic drill is the guarantee of long hole coring in deep sea. Aiming the lack of positional accuracy analysis on disc storing mechanism, the mathematic model of the positional accuracy for disc storing mechanism is presented by using complex vector and matrix analyzing method. The analytical formula of crank rotation positional accuracy is acquired through rotation positional analysis of crank in disc storing mechanism driven by hydraulic cylinder. Adopting numerical nonlinear iteration solution method of Newton-Simpson, the variation rule of rotation positional error for disc storing mechanism to cylinder length is acquired, which supports an important theory, leading to tolerance design for dimensional parameters of disc storing mechanism.

Keywords: Benthic drill, complex vector, disc storing mechanism, Newton-Simpson, positional error.

1. INTRODUCTION

Benthic drill coring technology is currently the most potential marine resources exploration technology. With the increase of marine resources exploration depth, benthic coring drill rig has become the basic equipment in scientific investigation of deep sea, which supplies a strong basis for marine resources exploration [1-5]. The disc storing mechanism is the key part to guarantee the deep sea coring fulfillment in single sampling depth. The positional accuracy of the mechanism directly affects the coring pipe collection and exploration task completion. Therefore, in order to ensure the working reliability of disc storing mechanism, the positional accuracy analysis of the disc storing mechanism is absolutely necessary, which supply a great value to efficient completion of multiple core sampling, and a guarantee to deeper sea exploration. The disc storing mechanism is composed by swing cylinder, disc handle device, coring pipe, connecting base, transmission cylinder, and positional cylinder. Studies of similar mechanisms are mainly focused on kinematics simulation and motion control. Zhang [6] adopted virtue prototype technology to simulate the drill pipe transforms. Using a computer to simulate the actual motion of the drill pipe conveying system, Sha [7] analyzed the motion relation of each component. The displacement, velocity and acceleration of each component are also acquired providing a basis for the optimization of the mechanism. Molino [8] designed the monitoring system of drill rods delivery. Liu [9] studied the kinematics of each working state of rod storing mechanism, and introduced the automation control system of the mechanism. However, the

positional accuracy analysis of disc storing mechanism driven by hydraulic cylinder has not been studied yet.

The present study is organized as follows. First, the structure and working principle of disc storing mechanism is described. Then, the mathematic model of the positional accuracy for disc storing mechanism is presented by using complex vector and matrix analyzing method. Finally, in order to get the variation rule of rotation positional error for disc storing mechanism to cylinder length, the simulation using the model is done. These supply a lead to tolerance design for dimensional parameters of disc storing mechanism.

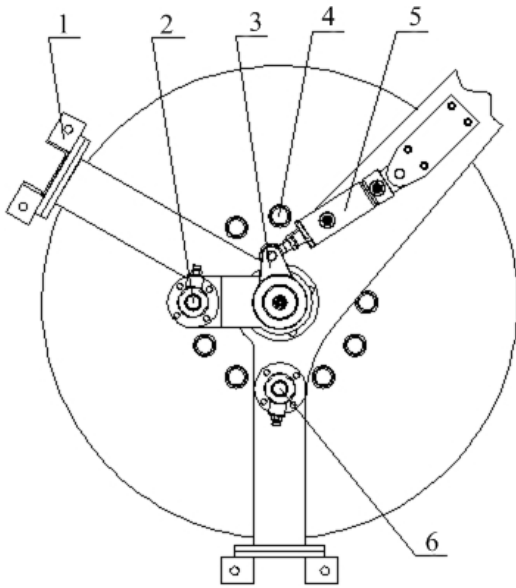
2. STRUCTURE AND WORKING PRINCIPLE FOR DISC STORING MECHANISM

The disc storing mechanism is shown in Fig. (1). It is composed of swing cylinder, disc handle device, coring pipe, connecting base, transmission cylinder, and positional cylinder. Many coring pipes are stored in disc storing mechanism to implement single deep hole sampling. Swing cylinder and positional cylinder are interlocked with each other. When the mechanism works in the status of transposition, transmission cylinder extends and the positional cylinder retracts. The chamber of swing cylinder without piston rod connects with high pressure. The piston rod of swing cylinder drives disc handle device turning, and transmission cylinder rotates a fixed axis. The transposition completes with the piston rod of swing cylinder as fully extended.

When the mechanism works in the status of return, transmission cylinder retracts and the positional cylinder extends. The chamber of swing cylinder with piston rod connects at high pressure. The piston rod of swing cylinder drives disc handle device turning, and transmission cylinder

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rotates a fixed axis. The return completes with the piston rod of swing cylinder as fully retracted.



1. connecting base 2. transmission cylinder 3. disc handle device
4. coring pipe 5. swing cylinder 6. positional cylinder

Fig. (1). Structure of disc storing mechanism.

The disc storing mechanism is driven by swing cylinder. Neglecting the effect of piston rod length, the piston rod is treated as a lumped mass. Consequently, the piston rod can be equivalent to a slider, and the engaging lugs at the ends of rod can be equivalent to revolve pair. The sketch of movement for disc storing mechanism is shown in Fig. (2). In the mechanism, slider is the driver, and rod AO is the follower. The mechanism makes the linear motion of the swing cylinder to turn the rotation of rod AO, which will realize the coring pipe transposition. L_{AB0} is the initial length of rod AB, and is equal to the length of swing cylinder barrel.

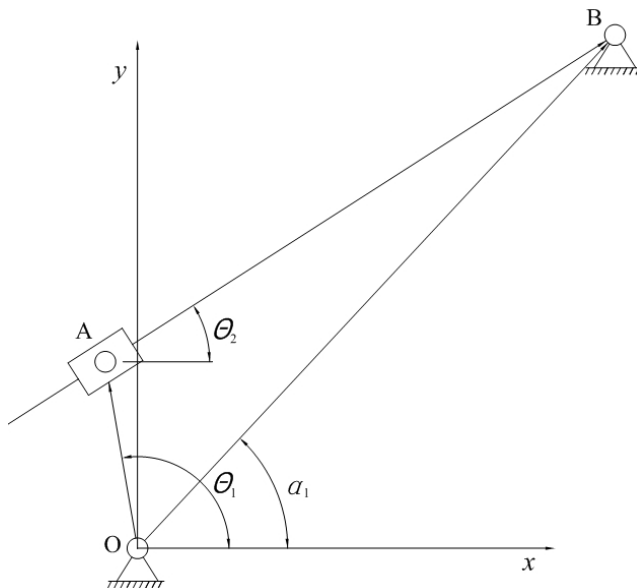


Fig. (2). Sketch of disc storing mechanism.

3. CALCULATION MODEL FOR POSITIONAL ACCURACY ANALYZING DISC STORING MECHANISM

3.1. Analytical Theory for Positional Accuracy Analyzing of Disc Storing Mechanism

In disc storing mechanism, rod AO is the follower. The position is changed when the length of the cylinder is changed. The position formulation for disc storing mechanism can be written as follows:

$$f(\mathbf{q}, \mathbf{l}, \mathbf{x}) = 0 \tag{1}$$

where, $\mathbf{f} = (f_1, f_2, \dots, f_n)^T$ is the positional function composed by functions with numerical value n . $\mathbf{l} = (l_1, l_2, \dots, l_m)^T$ is m dimensional vector for the relative position of dimensional parameters and kinetic pairs. $\mathbf{q} = (q_1, q_2, \dots, q_c)^T$ is c dimensional imputing vector of the mechanism with c freedom. $\mathbf{x} = (x_1, x_2, \dots, x_n)^T$ is n dimensional vector for position of the follower.

Using \cdot^0 to denote parameters of ideal mechanism, the m dimensional vector for the relative position of dimensional parameters and kinetic pairs in ideal mechanism is expressed as $\mathbf{l}^0, \mathbf{l}^0 = (l_1^0, l_2^0, \dots, l_m^0)^T$. The c dimensional imputing vector of the mechanism with c freedom in ideal mechanism is expressed as $\mathbf{q}^0, \mathbf{q}^0 = (q_1^0, q_2^0, \dots, q_c^0)^T$, and the n dimensional vector for position of the follower in ideal vector is expressed as $\mathbf{x}^0, \mathbf{x}^0 = (x_1^0, x_2^0, \dots, x_n^0)^T$. Accordingly, the dimensional error can be expressed as follows. Accordingly, the dimensional error of components can be expressed as follows:

$$\Delta \mathbf{l} = (\Delta l_1, \Delta l_2, \dots, \Delta l_m)^T = (l_1 - l_1^0, l_2 - l_2^0, \dots, l_m - l_m^0)^T \tag{2}$$

The positional error of driver to ideal mechanism can be expressed as follows:

$$\Delta \mathbf{q} = (\Delta q_1, \Delta q_2, \dots, \Delta q_c)^T = (q_1 - q_1^0, q_2 - q_2^0, \dots, q_c - q_c^0)^T \tag{3}$$

Therefore, the position error of the follower can be written as:

$$\Delta \mathbf{x} = (\Delta x_1, \Delta x_2, \dots, \Delta x_n)^T = (x_1 - x_1^0, x_2 - x_2^0, \dots, x_n - x_n^0)^T \tag{4}$$

The actual mechanism and ideal mechanism should meet the same position equations. Hence, we can get:

$$f(\mathbf{q}^0, \mathbf{l}^0, \mathbf{x}^0) = 0 \tag{5}$$

where, $\mathbf{f}^0 = (f_1^0, f_2^0, \dots, f_n^0)^T$ is the vector of positional function composed by functions with value n . According to Eq. (1) and Eq. (5), we can get:

$$\Delta f(\mathbf{q} - \mathbf{q}^0, \mathbf{l} - \mathbf{l}^0, \mathbf{x} - \mathbf{x}^0) = 0 \tag{6}$$

$$f(\mathbf{q}^0 + \Delta \mathbf{q}, \mathbf{l}^0 + \Delta \mathbf{l}, \mathbf{x}^0 + \Delta \mathbf{x}) - f(\mathbf{q}^0, \mathbf{l}^0, \mathbf{x}^0) = 0 \tag{7}$$

It also can be written as:

$$f(q_1^0 + \Delta q_1, \dots, q_c^0 + \Delta q_c, l_1^0 + \Delta l_1, \dots, l_m^0 + \Delta l_m, x_1^0 + \Delta x_1, \dots, x_n^0 + \Delta x_n) = 0 \quad (8)$$

The left part of Eq. (8) is nonlinear functions. The errors of $\Delta \mathbf{q}$, $\Delta \mathbf{l}$ and $\Delta \mathbf{x}$ are very small. Expanding Eq. (8) on \mathbf{q}^0 , \mathbf{l}^0 and \mathbf{x}^0 , the equation is changed to follow by neglecting high-order trace.

$$\sum_{k=1}^c \frac{\partial f_i^0}{\partial q_k^0} \Delta q_k + \sum_{s=1}^m \frac{\partial f_i^0}{\partial l_s^0} \Delta l_s + \sum_{j=1}^n \frac{\partial f_i^0}{\partial x_j^0} \Delta x_j = 0 \quad (i=1,2,\dots,n) \quad (9)$$

where, $\frac{\partial f^0}{\partial q^0}$, $\frac{\partial f^0}{\partial l^0}$ and $\frac{\partial f^0}{\partial x^0}$ are values of the partial derivatives on $(\mathbf{q}^0, \mathbf{l}^0, \mathbf{x}^0)$, which are not relative to errors of $(\Delta \mathbf{q}, \Delta \mathbf{l}, \Delta \mathbf{x})$.

Obviously, the positional error of the follower of disc storing mechanism is a linear combination of the original error. Each item in formulate is the position error of each one corresponding to the original error. The Eq. (9) can be written as follows using matrix.

$$\mathbf{D}_q^0 \Delta \mathbf{q} + \mathbf{D}_l^0 \Delta \mathbf{l} + \mathbf{D}_x^0 \Delta \mathbf{x} = 0 \quad (i=1,2,\dots,n) \quad (10)$$

Hence, the positional error of the follower can be written as:

$$\Delta \mathbf{x} = -\mathbf{D}_x^{0-1} \mathbf{D}_q^0 \Delta \mathbf{q} - \mathbf{D}_x^{0-1} \mathbf{D}_l^0 \Delta \mathbf{l} \quad (11)$$

where, $\mathbf{D}_x = \left(\frac{\partial \mathbf{f}_i}{\partial \mathbf{x}_j}\right)_{n \times n}$ is the $n \times n$ dimensional partial matrix

of $\mathbf{f}(\mathbf{q}, \mathbf{l}, \mathbf{x})$ to \mathbf{x} . $\mathbf{D}_q = \left(\frac{\partial \mathbf{f}_i}{\partial q_k}\right)_{n \times c}$ is the $n \times c$ dimensional

partial matrix of $\mathbf{f}(\mathbf{q}, \mathbf{l}, \mathbf{x})$ to \mathbf{q} . $\mathbf{D}_l = \left(\frac{\partial \mathbf{f}_i}{\partial l_s}\right)_{n \times m}$ is the $n \times m$ dimensional partial matrix of $\mathbf{f}(\mathbf{q}, \mathbf{l}, \mathbf{x})$ to \mathbf{l} .

The positional error of the follower can be obtained by solving Eq. (11).

3.2. Positional Accuracy Model of Disc Storing Mechanism

The coordinate is built as shown in Fig. (2) shown. In the disc storing mechanism, α_3 is the angle of frame AB and reference axis x , l_1 is the length of rod OA, l_2 is the cylinder length, and l_3 is the distance of point O and B. θ_i ($i=1,2$) is the angle of rods to reference axis x . According to the vector calculation rule, the positional equation for disc storing mechanism can be described as:

$$l_1 e^{j\theta_1} + l_2 e^{j\theta_2} = l_3 e^{j\alpha_3} \quad (12)$$

The real and imaginary part of complex is equivalent, respectively, and the positional equation of disc storing mechanism can be equivalent to follow [10, 11].

$$\begin{cases} f_1 = l_1 \cos \theta_1 + l_2 \cos \theta_2 - l_3 \cos \alpha_3 = 0 \\ f_2 = l_1 \sin \theta_1 + l_2 \sin \theta_2 - l_3 \sin \alpha_3 = 0 \end{cases} \quad (13)$$

In the disc storing mechanism, the cylinder is the driver. The vector of relative position is expressed as \mathbf{l} , $\mathbf{l} = (l_1, l_3, \alpha_1)^T$. The imputing vector of the mechanism is expressed as \mathbf{q} , $\mathbf{q} = l_2$. The vector for position of the follower is expressed as \mathbf{x} , $\mathbf{x} = (\theta_1, \theta_2)^T$. Hence, the dimensional error of components can be expressed as $\Delta \mathbf{l}$, $\Delta \mathbf{l} = (\Delta l_1, \Delta l_3, \Delta \alpha_1)^T$, the positional error of driver to ideal mechanism can be expressed as $\Delta \mathbf{q}$, $\Delta \mathbf{q} = \Delta l_2$, and the position error of the follower can be written as $\Delta \mathbf{x}$, $\Delta \mathbf{x} = (\Delta \theta_1, \Delta \theta_2)^T$. According to Eq. (11), the output error of the disc storing mechanism can be expressed as

$$\begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \end{bmatrix} = \begin{bmatrix} -l_1 \sin \theta_1 & -l_2 \sin \theta_2 \\ l_1 \cos \theta_1 & l_2 \cos \theta_2 \end{bmatrix}^{-1} \begin{bmatrix} \cos \theta_1 \\ \sin \theta_2 \end{bmatrix} \Delta l_2 \quad (14)$$

$$+ \begin{bmatrix} -l_1 \sin \theta_1 & -l_2 \sin \theta_2 \\ l_1 \cos \theta_1 & l_2 \cos \theta_2 \end{bmatrix}^{-1} \begin{bmatrix} \cos \theta_1 & \cos \alpha_1 & l_3 \sin \alpha_1 \\ \sin \theta_1 & -\sin \theta_1 & -l_3 \cos \alpha_1 \end{bmatrix} \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta \alpha_1 \end{bmatrix}$$

4. POSITIONAL ACCURACY ANALYSIS OF DISC STORING MECHANISM FOR BENTHIC CORING DRILL

4.1. Analyzing Parameters

According to the length of rods and the tolerance requirements for disc storing mechanism, the analyzing parameters are shown as follows. The length of disc handle device is $l_1 = 148 \pm 1 \text{ mm}$. The initial length of cylinder is $l_2 = 474 \pm 2 \text{ mm}$. The distance of joint O and B is $l_3 = 474 \pm 2 \text{ mm}$. The angle of frame AB and reference axis x is $\alpha_1 = 47 \pm 0.5^\circ$. In initial condition, the evaluated angle of disc handle device and reference axis x is $\theta_1 = 100^\circ$, and the evaluated angle of cylinder and reference axis x is $\theta_2 = 33^\circ$.

4.2. Numerical Solution Method

According to Eq. (13), the solution of θ_1 and θ_2 is obtained using Neton-Simpson solving method. The variable θ_i is described as the sum of estimates of solutions $\bar{\theta}_i$ and tiny correction factor $\Delta \theta_i$ for the difference between prediction values and estimate values.

Expand Eq. (13) using Taylor series, the Eq. (13) is changed to

$$\begin{bmatrix} f_1(\bar{\theta}_1, \bar{\theta}_2) \\ f_2(\bar{\theta}_1, \bar{\theta}_2) \end{bmatrix} + \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} \Big|_{\bar{\theta}_1, \bar{\theta}_2} & \frac{\partial f_1}{\partial \theta_2} \Big|_{\bar{\theta}_1, \bar{\theta}_2} \\ \frac{\partial f_2}{\partial \theta_1} \Big|_{\bar{\theta}_1, \bar{\theta}_2} & \frac{\partial f_2}{\partial \theta_2} \Big|_{\bar{\theta}_1, \bar{\theta}_2} \end{bmatrix} \begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (15)$$

Therefore, tiny correction factor $\Delta\theta_i$ for the difference between prediction values and estimate values can be expressed as:

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \end{bmatrix} = - \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} & \frac{\partial f_1}{\partial \theta_2} \\ \frac{\partial f_2}{\partial \theta_1} & \frac{\partial f_2}{\partial \theta_2} \end{bmatrix}^{-1} \begin{bmatrix} f_1(\bar{\theta}_1, \bar{\theta}_2) \\ f_2(\bar{\theta}_1, \bar{\theta}_2) \end{bmatrix} \quad (16)$$

Reset the estimates of solutions $\bar{\theta}_i$ and iterate repeatedly. When the tiny correction factor $\Delta\theta_i$ for the difference between prediction values and estimate values, reaches to the set accuracy, the solution completes and the estimates of solutions $\bar{\theta}_i$ are the equivalent solution θ_i of the equation [12, 13].

Solving Eq. (14), gives the positional error of disc storing mechanism. The whole numerical solving scheme is shown as Fig. (3).

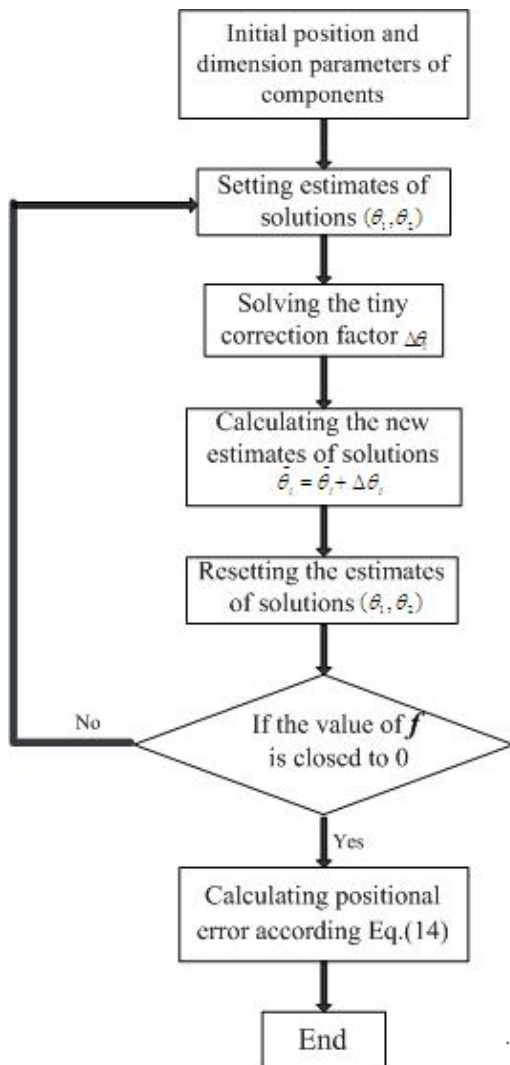


Fig. (3). Whole numerical solving scheme.

4.3. Calculation Results of Positional Error

In working process, the length of cylinder l_2 for disc storing mechanism is changed from 474 mm to 550 mm. Increasing the cylinder length Δl_2 and setting at 5.43 mm, the positional error on each position is shown in Table 1, and the curve of positional error to cylinder length changes is shown as Fig. (4). In Table 1, $l_2 = l_{20} + i\Delta l_2$.

Table 1. Positional error of disc storing mechanism.

i	$\theta_1 / ^\circ$	$\theta_2 / ^\circ$	$\Delta\theta_1 / ^\circ$	$\Delta\theta_2 / ^\circ$
0	99.7948	32.6001	0.8127	-0.6805
1	102.0550	32.3424	0.7507	-0.6293
2	104.2792	32.1194	0.6827	-0.5752
3	106.4735	31.9286	0.6180	-0.5235
4	108.6429	31.7679	0.5617	-0.4773
5	110.7920	31.6354	0.5163	-0.4377
6	112.9249	31.5296	0.4825	-0.4051
7	115.0453	31.4491	0.4604	-0.3790
8	117.1566	31.3928	0.4494	-0.3589
9	119.2621	31.3597	0.4488	-0.3441
10	121.3647	31.3490	0.4582	-0.3339
11	123.4673	31.3598	0.4773	-0.3277
12	125.5727	31.3917	0.5058	-0.3250
13	127.6837	31.4440	0.5438	-0.3254
14	129.8030	31.5165	0.5914	-0.3284

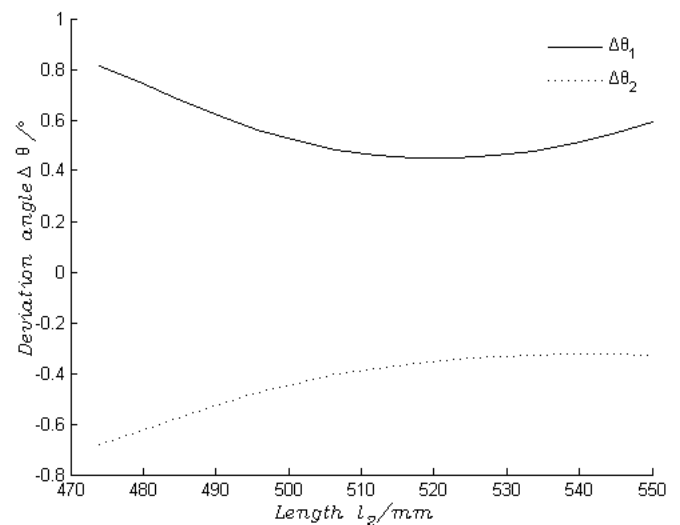


Fig. (4). Positional error to cylinder length changes.

The results show that, the crank rotating angle errors caused by length parameters are positive, which ranges from 0.4488 mm to 0.8127 mm. The errors of angle for cylinder and reference axis x are negative in the working process, which ranges from -0.6805 mm to -0.3250 mm. The

maximum crank rotating angle error appears on initial position, $l_2 = 474$ mm, and $\theta_1 = 99.7948^\circ$, $\theta_2 = 32.6001^\circ$. There is an inflection point on curve for crank rotating angle error to cylinder length. When cylinder length l_2 is less than 517.44 mm, the crank rotating angle errors decrease with the increase of the cylinder length. However, the crank rotating angle errors increase with the increase of the cylinder length, when cylinder length l_2 is larger than 517.44 mm. The maximum angle error $\Delta\theta_2$ of cylinder to reference axis x also appears on initial position, $l_2 = 474$ mm, and the angle error of cylinder to reference axis x decreases with the increase of the cylinder length.

CONCLUSION

The mathematical model of positional accuracy for disc storing mechanism is established using complex vector and matrix analyzing method. The crank rotating angle positional accuracy is analyzed using the model, which supports an important theory, leading to tolerance design for dimensional parameters of disc storing mechanism. The results acquired through the analysis are shown as follows:

- 1) The crank rotating angle errors caused by length parameters are positive, however, the errors of angle for cylinder and reference axis x are negative in the working process.
- 2) The maximum positional error for angle of crank rotating angle and cylinder to reference axis x both appear at initial position, $l_2 = 474$ mm.
- 3) When cylinder length l_2 is less than 517.44 mm, the crank rotating angle errors decrease with the increase of the cylinder length. However, the crank rotating angle errors increase with the increase of the cylinder length, when cylinder length l_2 is larger than 517.44 mm.
- 4) The angle error of cylinder to reference axis x decreases with the increase of the cylinder length.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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