A Novel Pretreatment Method for Chamfering Contour Error in Subsea Multifunctional Operation Equipment

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Abstract **— Subsea multifunctional operation equipment can complete: i) anticorrosion layer removal of the pipeline, ii) drilling and cutting off pipes, iii) inside/outside chamfering of pipe ends, and iv) removal of weld line in underwater operations. In the chamfering operation, there are problems like: i) high cutting force, ii) contour error and iii) serious tool wear. These are caused by: i) the non-concentricity among the self-centering pipe clamping device, and ii) the cutter head and the pipe center. In this paper, a contour pretreating method is developed to predict the pipe center and chamfering contour error. In this method, self-centering clamping device, cutter head and pipe center are not concentric, and the eccentric coordinates of the pipeline center was derived through the three points on the contour line of the pipe detected by the laser sensor installed on the multifunctional operation equipment. Then standard operating position was adjusted to calibrate the difference between the standard position and the position of any other angle was the contour accuracy deviation. In the chamfering process, the cutter head is preprocessed by the contour error correction program to achieve the goal of eliminating the contour error. The subsea multifunctional operation equipment finished the chamfering experiment on 18-inch pipe end of submarine pipeline, and the experimental results validated the effectiveness of the contour error pretreating method. The method defines the relationship between the self-centering clamping device and the eccentric error of the pipe, and makes a timely correction to the contour error of pipe end groove. This solves the problem of non-uniform chamfering caused, and provides technical support for underwater chamfering operation of the equipment.**

Keywords-deep - water pipe; multifunctional operation equipment; chamfering; eccentricity; contour error; pretreating method; experiment research.

I. INTRODUCTION

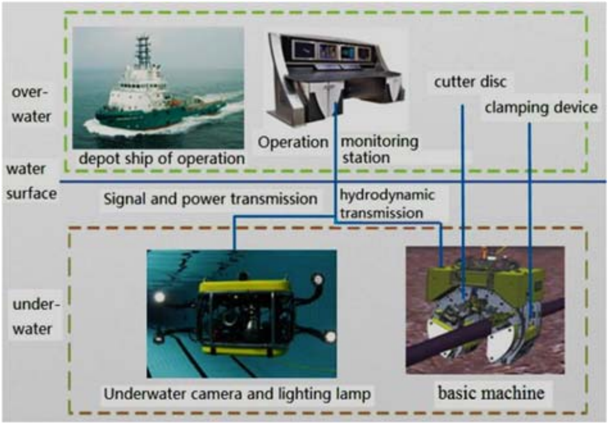
Submarine oil and gas pipelines are the important constitutional units of oil extraction equipment offshore. At present, there are more than 4000 kilometers of submarine oil pipeline in China [1-2]. Corroded by seawater, oil, hydrogen sulfide and dragged by anchor line, the damage to submarine oil and gas pipelines often happens [3-6]. There will be significant impacts if pipelines fail. Rush-repair must be taken, the underwater emergency maintenance equipment and technology arises at the historic moment [7].

Currently, most of the deep-water pipeline repair equipment have only one function, while the subsea multifunctional operation equipment is a kind of combined machine, which integrates a variety of modules of pipe repair machines into a cutter disc. It can remove pipe coating, drill on pipeline, cut off pipes, chamfer pipes internally and externally and remove pipe welds at the same time. It is the latest generation of the deep water emergency maintenance equipment. Strictly speaking, there are no deep water pipelines in China. However, with the development of the resources of the South China Sea, the laying of subsea pipelines and the maintenance technology will be an important development trend. According to the API 5L, the level of deep-water pipeline (1500 meters) is above X85. It is a single layer of steel pipe, which has no weight coating or thermal insulation layer. It only has 5-mm-thick anticorrosion layer whose material is FBE. This kind of pipeline is used on the seabed of the Gulf of Mexico (US) and the weld height is no more than 3mm.

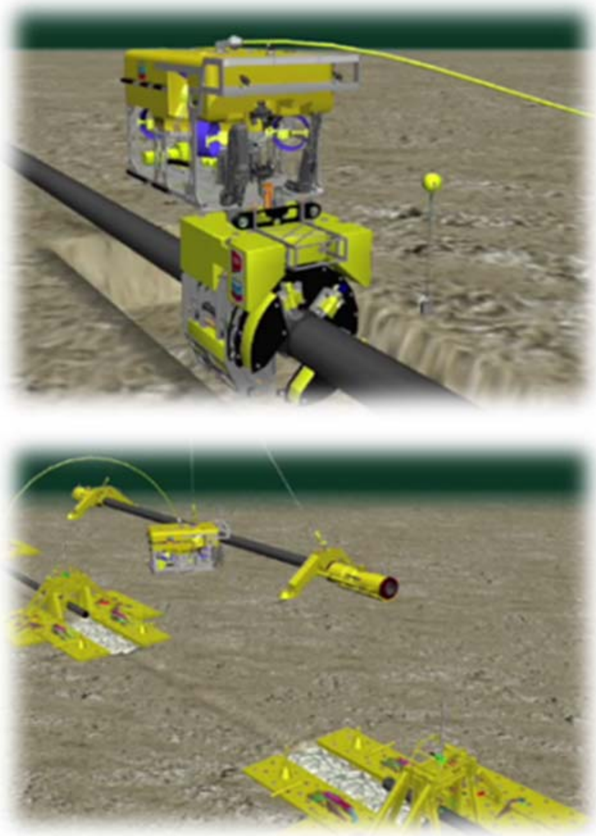
This paper targets at the chamfering operation by the subsea pipeline multifunctional operation equipment, analyzed the causes of the contour error of chamfering, and came up with a solution of error pretreating, which was verified by experiments.

II. THE CAUSES OF CHAMFERING CONTOUR ERROR

The operating system of the subsea multifunctional operation equipment is shown in Fig.1.The operating procedure is as follows: first, the ROV carrying the multifunctional equipment descends to the operation position and the ROV assists the equipment to adjust the position to above the pipeline. Then, the equipment holds itself on the pipeline per its own clamping device; the operator in the ship controls the cutter disc and the three multifunctional tool modules on the cutter disc to act in turn; a 360 - degree circumferential task can be completed thus. In the process, the clamping device can center itself so that the clamp and the cutter are concentric.



(a) The system of subsea multifunctional equipment.

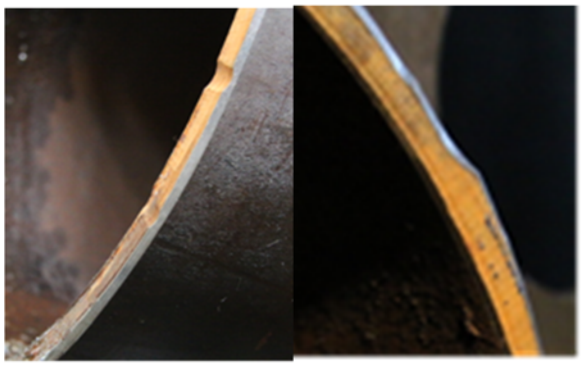


(b) Cutting submarine pipeline and slinging the damaged pipe section

Figure.1 Operation process of subsea multifunctional operation equipment

When the equipment was used to do the chamfering test, it was found that the chamfering of the pipe end surface has a great error variation. In some areas error increased gradually, while in other areas error gradually became smaller. In the locations with large variations, the error was either very big or very small, which lead to poor chamfering as shown in Fig.2.

It is known from analysis that the chamfering error of cutting tool mainly comes from the self-centering error of the clamping device, the assembly error of the equipment and the deformation error of the equipment under force and so on. The self-centering error of the clamping device is the biggest of all. The clamp and the cutter are concentric, but the pipeline center must have deviation (affected by the pipe circularity and weld), so when the clamp holds the pipe, if the clamp and the pipeline are non-concentric, a contour error will occur when the cutter disc goes for 360 degrees. In this situation the cutter feed needs adjusting to compensate the contour error.[10-12]. In the experiment, the operator can observe the situation of chamfering through a camera in real time, adjust the position of the cutter to eliminate the large contour error timely. However, it affects the efficiency of the equipment seriously.



(a)small error (b) large error

Figure.2. Chamfering quality variation caused by tool path error

Aiming at this problem, this paper studies a kind of control strategy, the contour error in the former period will be predicted in advance, and then the tool path can be compensated beforehand according to its rule of change. By adjusting the feed rate and feed amount of the cutter automatically, we can not only ensure that the tool path is always in a certain error range, but also can improve the quality of the surface of work piece and work efficiency.

III. PRINCIPLE OF SELF-CENTERING CLAMPING DEVICE

The principle of the self-centering clamping device of the subsea multifunctional equipment is shown in Fig.3. Each clamp is composed of two clamping claws which are symmetrically arranged and the parameters are identical [13]. The clamp is a six-bar mechanism. The fulcrum of the connecting rod *D*, *D'*, *A*, *A'*, are located on the circle of the clamp center O, which coincides with the center of another circle, where the cutter is initially located. The center is the reference point of the cutter's action.

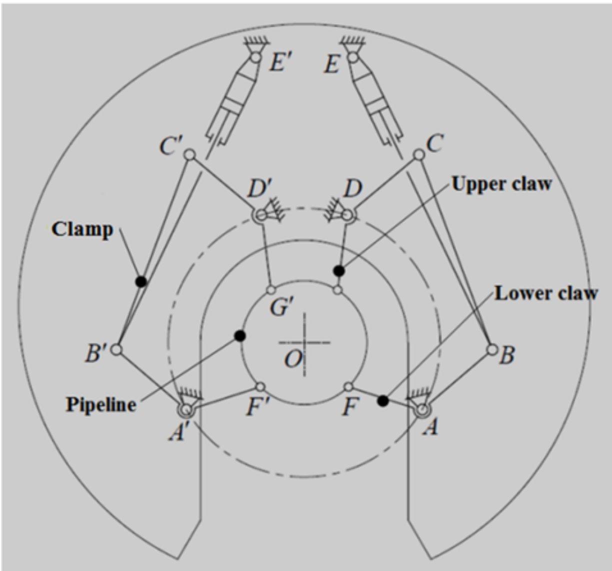


Figure.3. Schematic diagram of the Clamp

In the ideal state, if the left and right two hydraulic cylinders are in the synchronous movement in the whole chucking process, the motion displacement of the two claws will be exactly the same. In this way, it is ensured that the left and right two symmetrical claws are simultaneously contacted to the pipeline. After the clamp holding the pipeline, the pipe center and the pivot center of clamp are in superposition. And the clamp can adapt to different diameters of pipes which is the principle of self-centering of the equipment. Actually, due to assembly errors, circularity error of pipeline , manufacturing error of clamp components, the synchronization performance of hydraulic cylinder and so on, it is difficult to ensure that the circle center of the clamp and the center of the pipeline are completely coincident, which will produce certain eccentricity errors. The experiment tells that the error is generally less than 8mm. Generally, because the size of the chamfering process is relatively small, it is sensitive to error when the tool chamfered. Because of the existence of error, it has a great influence on the path accuracy of the chamfering. The experiments showed that eccentric error of the clamp is the main source of tool path error. As long as the eccentric error is eliminated, the chamfering quality can be guaranteed.

IV. PIPE ECCENTRICITY CAUSED BY CLAMPING

Figuring out the origin of the three tools and the deviation of the center of the pipe can work out the path error of the tool movement. In the plane of the tool center, a simplified model of the cutter and the pipe is shown in Fig.4.

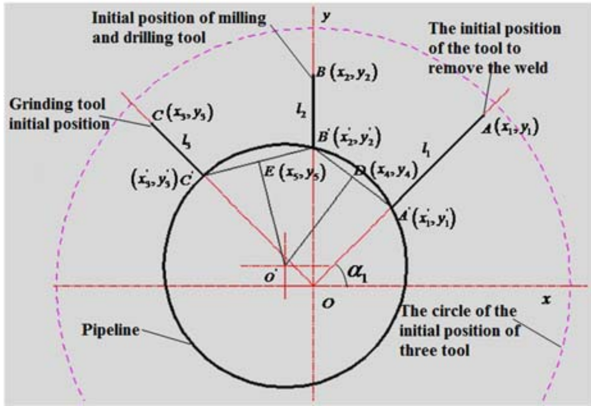


Figure.4. Simplified model of cutter and pipe in the mid-plane of tool

The coordinate system is established with the tool reference point *O* as the origin, the eccentricity of the center of the tool which is relative to the center of the pipeline is calculated. In the 4 coordinate system, *A*, *B*, and *C* are all known, while *AA'*, *BB'*, *CC'* can be measured by displacement sensor. In this way, this can be obtained by the following formula that three cutters to the coordinates of the points $A'(x_1', y_1')$, $B'(x_1', y_1')$, $C'(x_1', y_1')$, on the pipe surface.

$$\begin{cases} x_n' = x_n - l_n \cos\alpha_n \\ y_n' = y_n - l_n \sin\alpha_n \end{cases} \quad (1)$$

Where: n=1, 2, 3; α_n is the intersection angle between the initial position of three cutters and the X axis of coordinate system. α_1=45°, α_2=90°, α_3=135°; *A*(404.46, 404.46), *B*(0, 572), *C*(-404.46, 404.46).

In Figure 4, Point *D* is the midpoint of the chord *A'B'* on Circle *O'*. According to the inference of Vertical Theorem: The diameter that split the chord in the middle is perpendicular to the chord, hereby we can get $O'D \perp A'B'$. Therefore, the slope of the straight line *O'D* can be calculated:

$$k_1 = -\frac{x_1' - x_2'}{y_1' - y_2'} \quad (2)$$

Thus, the equation for the straight line *O'D* can be obtained:

$$y - y_4 = k_1\left(x - x_4\right) \quad (3)$$

Where, $x_4 = \dfrac{x_1' + x_2'}{2}$, $y_4 = \dfrac{y_1' + y_2'}{2}$.

In the similar way, the equation for the straight line *O'E* can be obtained:

$$y - y_5 = k_2\left(x - x_5\right) \quad (4)$$

Where $k_2 = -\dfrac{x_2^{'} - x_3^{'}}{y_2^{'} - y_3^{'}}$, $x_5 = \dfrac{x_2^{'} + x_3^{'}}{2}$, $y_5 = \dfrac{y_2^{'} + y_3^{'}}{2}$.

Unite formula(1), (3), (4), we can work out the eccentric position of the pipe center.

$$\begin{cases} x_0^{'} = \dfrac{y_4 - y_5 + k_2 x_5 - k_1 x_4}{k_2 - k_1} \\ y_0^{'} = y_4 - k_1 x_4 + k_1 \dfrac{y_4 - y_5 + k_2 x_5 - k_1 x_4}{k_2 - k_1} \end{cases} \quad (5)$$

Without error correction, the status of the cutter after running angle β is shown in Fig. 5. Set the origin of the coordinate as the center, draw a circle with radius R which is the distance from the initial position of the cutter to the center. This circle is the actual tool path without error correction.

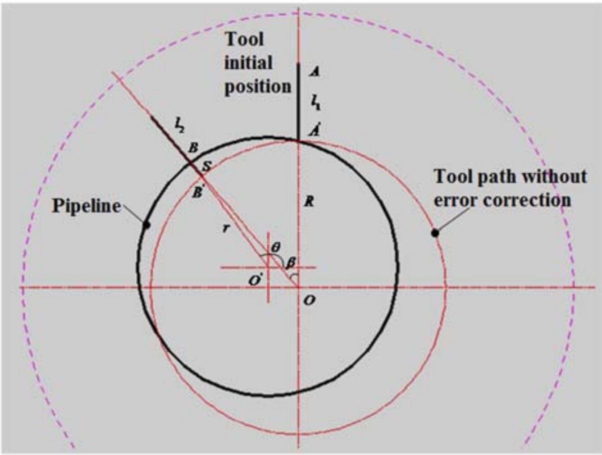


Figure.5. Schematic diagram of tool path model without correction

In fact, the motion of the eccentric mechanism can be simplified as a model of 2-stage rod group which has one sliding pair[14-16]. Therefore, according to the method of solving the rod group, the tool path deviation value S can be found. The following equations are obtained according to the geometric relations:

$$\begin{cases} f(\beta, \mathrm{S}) = (S + R)\cos\beta - x_0^{'} - r\cos\theta \\ f(\beta, \mathrm{S}) = (S + R)\sin\beta - y_0^{'} - r\sin\theta \end{cases} \quad (6)$$

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In the formula: β is turning angle of the cutter; θ is the angle between X axis forward and pipe radius which is at the intersection point of the cutter and pipe; R is the radius of the tool path which is not corrected. In initial position, $R=l_{OA}-l_1$; $x_0^{'}$ is the position of the pipeline center in the X direction in the coordinate system; $y_0^{'}$ is the position of the pipeline center in the Y direction in coordinate system; R is the diameter of pipe, $S=l_{BB'}$, it is the tool path error at the angle of β.

After calculating, the path error of the tool after turning β is:

$$S = \frac{-u_1 + \sqrt{u_1^2 - 4u_2}}{2} \quad (7)$$

Where:

$u_1 = 2\left(R - x_0^{'}\cos\beta - y_0^{'}\sin\beta\right)$;

$u_2 = x_0^{'2} + y_0^{'2} + R^2 - 2R\left(x_0^{'}\cos\beta + y_0^{'}\sin\beta\right) - r^2$.

V. ALGORITHM OF TOOL PATH ERROR ELIMINATION

The effect of chamfering is handling the burr of the pipe end incision, making the pipeline ready for the next step of the non-welded connection, so it doesn't have too high requirements on the accuracy of chamfering. According to the condition of chamfering tool and the purpose of chamfering, it is reasonable to ensure the tool path error plus/minus 2mm. According to the tool path error by the previous calculation, the design of algorithm in eliminating chamfering tool path error in this paper is shown in Fig.6.

First of all, in the initial position of the tool, the distance between the cutter and the pipe will be measured by laser displacement sensors which are installed on three cutters. By Formula (5), the eccentric coordinates of the pipeline center can be calculated. Adjust the chamfering tool to the working position, the distance between the tool and the pipe which is measured by displacement sensor is now treated as a standard value, the difference between the position of the tool in any angle and the standard value is the path deviation.

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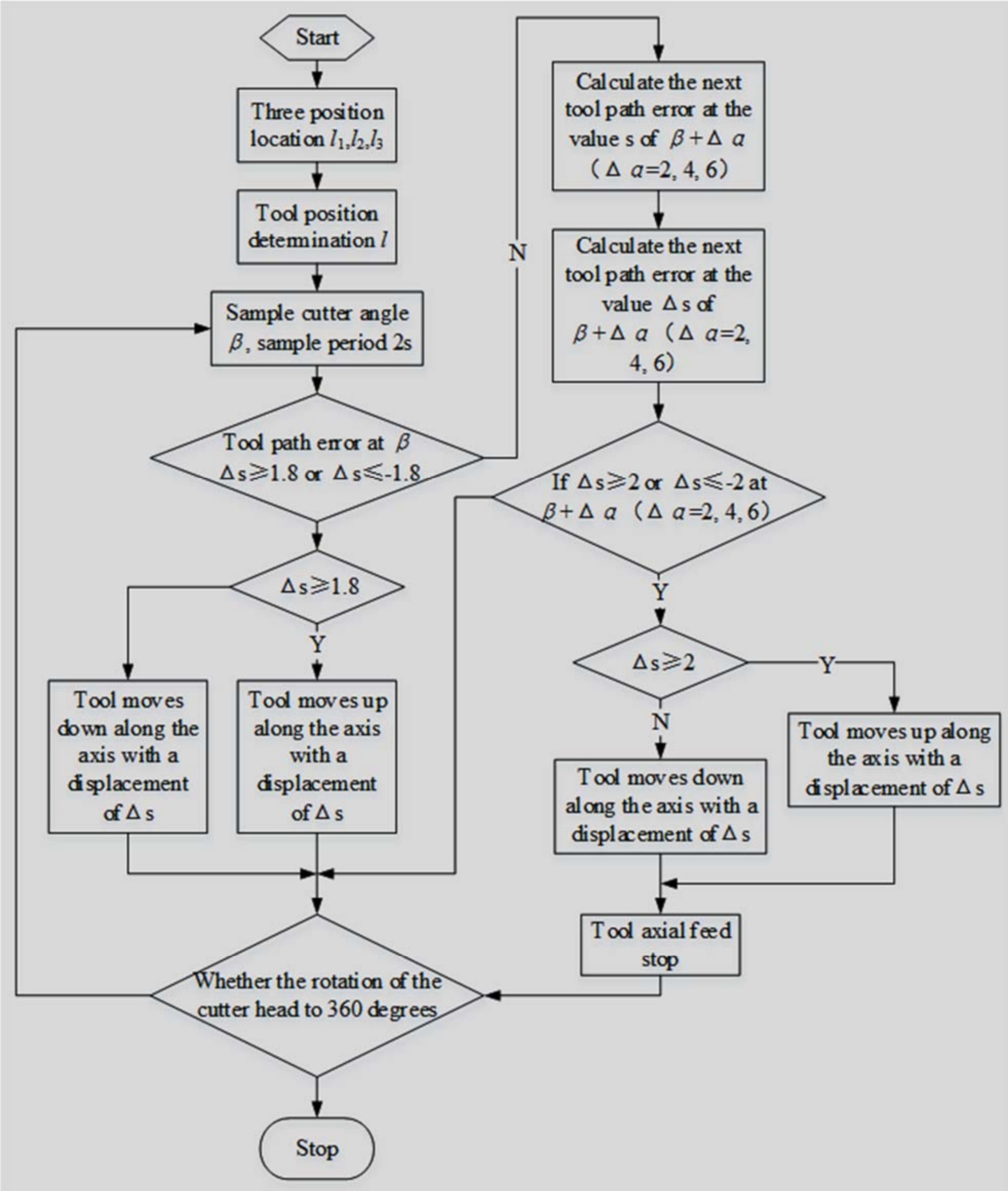


Figure.6. The flow-process of tool path error correction program.

When calculating the error, we firstly calculate the path error of the tool at angle β. At this time if the path error is greater than 1.8mm, judge the direction of error, then let the tool carry out an axial movement to adjust the error to zero. The specific method is: Control the axial feed of the tool; then compare the value which is transmitted back by the displacement sensor in real time with the original value. Do not stop the tool feed until the distance from the tool to the pipe reaches the initial value. So the distance from the tool after each error compensation to the pipeline is the same as that at the beginning. If the actual error at the angle β of the tool is not up to 1.8mm, in the next 6 degrees, use the tool displacement error Formula (7) to calculate the error trend of the tool. In the next 6 degrees, collect the value of 2nd, 4th, 6th point to calculate the position error. If the error of any point is greater than 2mm, it illustrates that it will reach the maximum error position. Let the tool start error compensation. Each time the error calculation program is executed, the working schedule of the tool needs calculating. If the tool has completed a 360-degree operation, the error compensation procedure is no more performed.

According to the actual working condition of the tool and the change rule of the error, in order to reduce the load of the computer, the program executed once per 5s is more reasonable.

The calculation method of the tool path error in any position is shown in Fig.7.

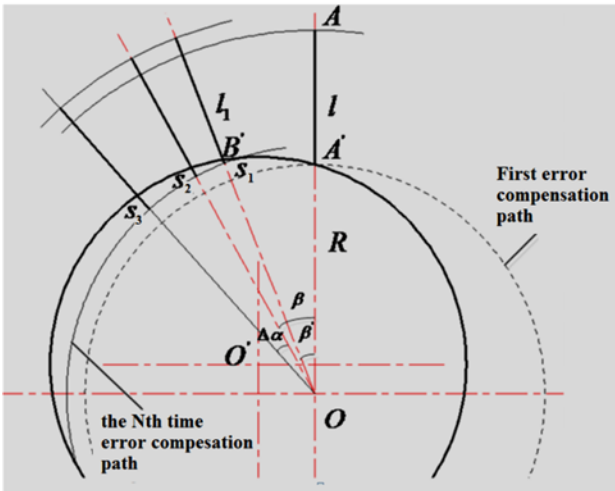


Figure.7. Schematic diagram of tool path error in any position

It is assumed that a compensation of error is completed at angle β', then the tool moves along the new circular path, the circle radius of the new path is:

$$R' = R + s_1 \tag{8}$$

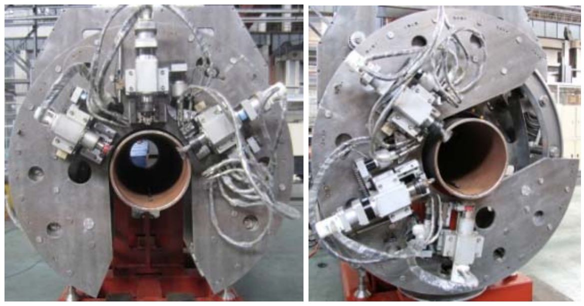
In the formula: R is the circle radius of the tool error path when the error compensation is performed at the first time; S_1 is the contour error of the tool's error path at angle β' at the first time. R was adapted after error compensation each time. The path error of the tool in any position can be calculated according to Formula (7). At this point the position of zero changed to β-β' degrees.

VI. EXPERIMENTAL VERIFICATION

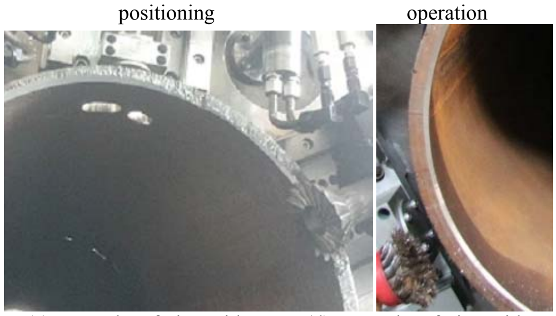
The subsea multifunctional operation equipment is used to conduct an experiment on land which is the inner and outer chamfering with the cutter to test the effectiveness of the error compensation algorithm of tool path. The experiment is shown in Fig.8.

Experimental pipelines are 18-inch deep water pipelines which meet the standard of API 5L, whose material level is X80, with a 32-mm-thick wall, with a 5-mm-thick FBE anti-corrosion layer, and with the weld height of no more than 2 mm. The pipelines were from CNOOC Branch.

Observe the cutter disc when it was operating. The cutter disc turned 360 degrees clockwise along the pipe and after the completion of operation, the cutter returned to its initial position counter clockwise.



(a) Chamfering tool positioning (b) Chamfering tool operation



(c) Inner chamfering without error compensation (d) Inner chamfering with error compensation

Figure.8. Chamfering experiments

The value of the displacement sensor was recorded during the experiment. It can be drawn from the analysis of the distance data from the inner chamfering tool in operation process to the pipeline:

In the whole inner chamfering process, position adjustment was carried out 11 times . The data of the adjustment of the inner chamfering tool position were processed as shown in Table 1. The initial position of the tool was 209.07mm, which was the measured value of the laser sensor at the outside radius of the pipe at 12 o'clock direction.

TABLE 1. THE STATISTICS OF CHAMFERING TOOL PATH ERROR COMPENSATION

	Start Position and End Position of error compensation					
	Start position	End position	Start position	End position	Start position	End position
Angle degree	14.3	21.5	31.2	32.5	59.9	61.4
distance mm	1.45	0.06	1.55	0.03	1.81	0.04
Angle degree	129.2	130.5	149.7	150.9	167.8	171.0
distance mm	-1.51	-0.06	-1.41	-0.05	-1.44	-0.01
Angle degree	189.6	191.1	210.1	211.5	238.8	240.3
distance mm	-1.81	-0.05	-1.82	-0.06	-1.81	-0.02
Angle degree	320.8	322.2	339.6	340.9	——	——
distance mm	1.46	0.03	1.62	0.05	——	——

According to the statistical results in Table 1, the path error of the tool was compensated within 2mm, and the final error which was compensated each time was less than 0.1mm; the effect of error compensation was good. It can be seen from Table 1 that there were 7 times that compensation began under 1.8 and 4 times that compensation began from 8 in 11 times of error compensations. It is indicated that the error variation tendency which was predicted by path pretreating program was correct in some paths. On the whole the error pretreating program reduced the path error. The effect of tool error compensation process of this experiment is shown in Fig.9.

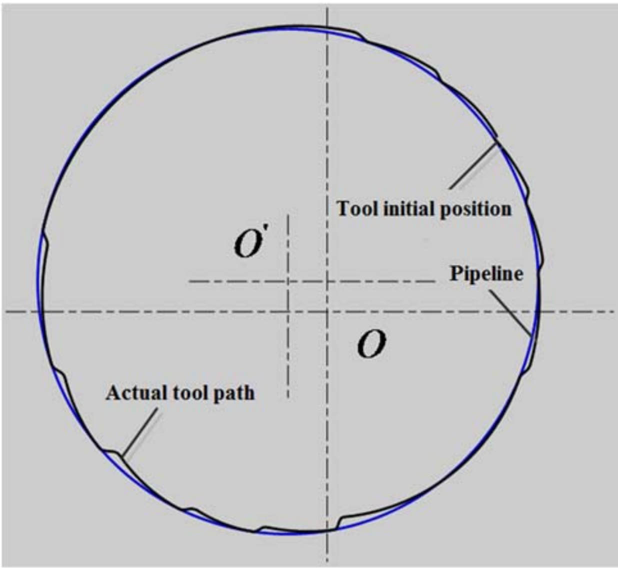


Figure 9. Schematic diagram of inner chamfering tool's error compensation path

VII. Conclusions

In view of the problems that its error of chamfering path precision is big and its quality is non-uniform in the pipe end chamfering process of marine pipeline by the subsea multifunctional operation equipment, whose errors are analyzed, the calculation formula for error between the center of the cutter and the center of the pipe caused by the eccentric clamping of self-centering clamp have been established; the changing path error trend of the tool after turning a certain angle is predicted. The path pretreating algorithm is used to adjust feed amount of a cutting tool and eliminate the path error in time. The effectiveness of the method is verified by inner chamfering experiments and the quality of pipe end chamfering is guaranteed. The method used in the multifunctional operation equipment can conveniently obtain the tool position and predict the tool path, solve the problem of non-uniform chamfering by the multifunctional equipment, technical support for the design of multifunctional equipment and the maintenance operation of underwater pipeline is provided.

Acknowledgments

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