Research on Pipeline Robots with Obstacle Crossing and Turning Ability

Hangxin Wei1*, Panghu Cheng1, Xiaorong Wang2 and Xinai Song3

1 School of Mechanical Engineering, Xi'an ShiYou University, Xi'an City, Shanxi Province, 710065, China
2 Oil and Gas Technology Research Institute, Changqing Oilfield, Xi'an City, Shanxi Province, 710018, China
3 School of Computer Science, Xi'an ShiYou University, Xi'an City, Shanxi Province, 710065, China
*Corresponding author’s e-mail: weihangxin@xsyu.edu.cn

Abstract. The pipeline robot will encounter complex conditions of turning, obstacles and pipe diameter changes when it works. Therefore, cornering performance, obstacle crossing performance, and diameter changing ability are important indicators of the pipeline robot performance. A multi-axis differential adaptive pipeline robot is designed. The multi-axis differential mechanism is used to realize the smooth turning of the robot. The pre-tightening and reducing mechanism is used to achieve the obstacle crossing of the robot and the ability to adapt to different pipe diameters. The overall structure of the pipeline robot, the transmission mechanism, and the pre-tightening and reducing mechanism are introduced. The kinematics model of the robot is studied when it crosses obstacles. Using the maximum height of the pipeline robot passing through obstacles as an indicator, an equation of the pipeline robot obstacle crossing is established. The ADAMS software is used to simulate the kinematics of the turning process of the pipeline robot. Through the simulation experiments, the following conclusions are obtained: (1) The larger the adhesion coefficient between the pipe wall and the wheel, the stronger the obstacle crossing ability of the pipeline robot. The larger the diameter of the wheel, the stronger the ability to overcome obstacles. (2) By tracking the changes in the angular velocity of the three driving wheels, it is shown that the pipeline robot can pass through the curve smoothly and has anti-motion interference performance.

1. Introduction
With its many advantages such as safety, economy, and efficiency, pipeline transportation has established an important position. However, with the extension of the service life of the pipeline, factors such as chemical corrosion, foreign body blockage, and extrusion deformation will affect the normal use of the pipeline. Therefore, safety inspection and maintenance of pipelines must be carried out in time. Most pipes are buried underground or embedded in buildings, and traditional methods are not conducive to maintaining the pipes. Pipeline robots can solve such problems [1][2]. It can enter the inside of the pipeline to detect and maintain the inner wall of the pipeline[3]. Therefore, the research on pipeline robots has a great significance.

For more than half a century, pipeline robot technology has developed rapidly. There are various types of pipeline robots. According to the driving method, pipeline robots can be divided into: tube-
media driven[4], wheel-driven, leg-driven, crawler-driven, bionic creep-driven[5], screw-driven[6]. According to the type of power, pipeline robots can be divided into: medium pressure differential drive type, mobile power drive type, cable drive type, and hydraulic drive type. These pipeline robots are used in specific working conditions according to their respective advantages.

Obstacle crossing ability[7] and turning ability[8] are important characteristics of pipeline robots. Firstly, when obstacles are encountered in the pipeline, the robot may be blocked and cannot move. Secondly, when the pipe is bent, the driving wheels of the robot are not synchronized due to different curvatures of the pipe wall. In addition, when the inner diameter of the pipe changes, the driving force of the robot also change [9]. Therefore, a new type of robot is designed in this paper, which can solve these problems. The robot has the ability to overcome obstacles and adapt to changes in pipe diameter. At the same time, a differential mechanism is used, and the rotation speeds of different driving wheels of the robot at the bend of the pipeline are coordinated. So the robot can smoothly pass through the bend of the pipeline.

2. Overall structure of pipeline robot

The structure of the pipeline robot is shown in Fig.1. It mainly includes differential module, drive module and reducing module. The differential module can solve the problem of motion interference caused by different speeds of the inside and outside of the robot during turning [10][11]. The reducing module can solve the problem of the pressure change between the pipeline robot wheel and the pipe wall caused by the pipe diameter change.

In Fig.1, the pipeline robot has a total of 6 group wheels. Three wheels on the left are driving wheels to drive the robot. These wheel spaces are spaced 120° from each other on three axes. Three wheels on the right are free wheels, which have no power and move freely, and are only used to maintain the attitude of the pipeline robot. These wheels are also spaced 120° apart from each other. Since the pipeline robot mainly works on long-distance oil pipelines, there are certain requirements for the pipeline robot's movement speed and distance. Therefore, the power component is an electric motor and is electrically driven.

The working principle of the robot is as follows: the motor is the power source of the robot. The output speed of the motor is high and the speed is reduced by the speed reducer. Then the movement is distributed to the gear 12 by the gear 10 and gear 11. The gear 12 can change the rotation direction of motion. Finally, the movement is transmitted to the driving wheels through the chain transmission pair 13 to drive the pipeline robot to move.

When the pipe diameter changes, the limit switches 1 at both ends of the spring are triggered by the expansion and contraction of the spring in the front wheel support rod. The signal from the switch is fed back to the single-chip microcomputer (MCU)[12][13]. MCU controls the electromagnetic clutch 5 to close and the screw 3 to rotate. In this way, the back-and-forth movement of the adjusting nut 4 can be adjusted to change the opening degree of the driving wheel.

When the pipeline robot approaches the curved pipe, the distance measuring sensor at the front end of the robot feeds back the detection signal to the MCU. The MCU controls the drive motor to slow down, allowing the pipe-line robot to enter the curve at a smaller speed. At the same time, the MCU controls three electromagnetic clutches 6, so that power is transmitted to only two of the wheels, and the remaining one moves freely. Then in the next second, power was switched to the other two wheels. And so on, until the robot completely leaves the curve. After the distance measure sensor detects that the robot has left the pipeline, it transmits power to all three wheels simultaneously. In this way, the robot can avoid motion interference when passing through the pipe.

Different from the previous design of the pipeline robot, an intelligent control system has been added into the pipeline robot, which are composed of a MCU and sensors. Give full play to the advantages of combining machinery and electronics to make pipeline robots more flexible and controllable when working.
3. Analysis of the obstacle crossing and turning performance

3.1 Obstacle crossing performance

Obstacle crossing performance refers to the ability of pipeline robots to pass obstacles without activating the reducing module [14][15]. The index is the height $h_{\text{max}}$ through which the highest obstacle passes. When the robot moves in the pipeline and encounters an obstacle, the force acting on it is shown in Fig. 2.

When the driving wheel just contacts an obstacle, the angle between the positive pressure of the obstacle on the driving wheel and the vertical direction is defined as the obstacle angle $\alpha$. The higher the obstacle, the larger the obstacle angle $\alpha$, and the more difficult passing the obstacle.

From Fig. 2, the following equations can be deduced:

$$F_D + F_D \cdot \cos \alpha + F_D \cdot \sin \alpha - \sum F_B > F_T$$  \hspace{1cm} (1)

Where,

- $F_D$ is the frictional force between the pipeline robot driving wheel $i$ and the pipe wall or obstacle, $i = 1, 2, 3$.
- $F_N$ is the pressure of the obstacle driven by the pipeline robot driving wheel 2.
- $F_B$ is the resistance of the tube wall to the rear wheel $i$, $i = 1, 2, 3$.
- $F_T$ is the drag force on the pipeline robot.

When the robot moves, the driving force on the three driving wheels is the same. It means:

$$F_D = F_D = F_D = \rho \cdot F_N$$  \hspace{1cm} (2)

Where, $\rho$ is the adhesion coefficient between the pipeline robot wheel and the pipe wall.

According force analysis on the vertical direction, it can be deduced:

$$F_N \cdot \cos \alpha + F_D \cdot \sin \alpha = \frac{1}{3} k_1 \cdot F_t = F_N = F_N$$  \hspace{1cm} (3)

$$F_D = \frac{1}{3} \rho \cdot k_1 \cdot F_t$$  \hspace{1cm} (4)

Where $k_1$ is a force amplification factor of the closed mechanism. $F_t$ is the spring force. From Eq.(1)-Eq.(4), the maximum obstacle crossing angle $\alpha_{\text{max}}$ can be calculated. The maximum height $h_{\text{max}}$ is:

$$h_{\text{max}} = r \cdot (1 - \cos \alpha_{\text{max}})$$  \hspace{1cm} (5)

Where: $r$ is the radius of the wheel of the robot.
According to Eq.(2) and Eq.(5), it can be seen that the larger the adhesion coefficient between the pipe wall and the wheel, the stronger the obstacle crossing ability of the pipeline robot. And the larger the diameter of the wheel, the stronger the ability to overcome obstacles.

3.2 Turning performance

The 3D solid model of the robot established in Pro/E software is imported into the ADAMS software to simulate a pipeline robot passing through a curved pipe. The angular velocity of each driving wheel is recorded to judge the differential driving performance of the pipeline robot.

When $\beta$ is equal to $0^\circ$, $30^\circ$, and $60^\circ$, the real-time angular velocities of the three driving wheels are tracked and recorded with ADAMS software, as is shown in Fig.3.

(a) When $\beta=0^\circ$, the angular velocity of the three driving wheels is shown in the Fig.4. From Fig.4, it can be seen that the angular velocity of the driving wheel 1 remains substantially unchanged. The driving wheel 2 is faster than the driving wheel 1 because it lies on the outside of the curve. Because the driving wheel 3 is located on the inside of the curve, its angular velocity is lower than the angular velocity of the driving wheel 1. So, the robots can pass through bends.

(2) When $\beta=30^\circ$, the angular velocity of the three driving wheels is shown in the Fig.5. It can be seen that the angular velocity of the driving wheels 1 and 3 are basically the same, and are less than
the average value of the angular speeds of the three driving wheels. The driving wheel 2 is at the outermost side of the curve, so its angular velocity is the largest. So, the robots can pass through bends.

(3) When $\beta=60^\circ$, the angular velocity of the three driving wheels is shown in the Fig.6. The direction of the driving wheel 3 is vertically downward, so its angular velocity remains unchanged. The driving wheel 2 is located outside the curve, so its angular velocity is larger than the driving wheel 3. In contrast, the driving wheel 1 is located inside the curve, so its angular velocity is lower than that of the driving wheel 3. So, the robots can pass through bends.

4. Conclusions
A cyclic differential adaptive pipeline robot is proposed. A virtual prototype model of the pipeline robot is established. The feasibility of the design is verified with the help of ADAMS software. Finally, the obstacle crossing performance and turning performance of the robot are studied. Conclusion can be obtained as follows:

(1) According to the working environment of the pipeline robot, the relevant design parameters of the pipeline robot are determined. The Pro/E software is used to build a three-dimensional model of the pipeline robot.

(2) The established virtual prototype is simulated, and the results prove that the mechanism does not have motion interference.

(3) The ADAMS software was used to simulate the pipeline robot passing through a bend. The simulation results proved that the design of the pipeline robot differential turning system is feasible.

(4) A mathematical model for obstacle crossing of pipeline robots was established. Analysis shows that the larger the adhesion coefficient between the pipe wall and the wheel, the stronger the obstacle crossing ability of the pipeline robot. And the larger the diameter of the wheel, the stronger the ability to overcome obstacles.

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