Design and motion analysis of multi-motion mode pipeline robot

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Abstract: Aiming to improve the adaptability level of single motion form pipeline robots, a wheeled pipeline robot with multiple motion modes is designed. The overall scheme of the pipeline robot is given. The self-adaptive diameter-changing mechanism, wheel displacement mechanism, and turning mechanism are designed. The motion and mechanical models of pipeline robots during travelling are established; on this basis, the robot's main body structure is optimised.

Keywords: pipeline robot; multiple motion modes; design; kinematic analysis.

1. Introduction:
The pipeline robot is a robot that can carry out a series of operations inside and outside various kinds of pipes. Checking these pipelines’ status and integrity is challenging and has high economic costs, concluding to Christian[1]. The pipeline robot has many standard moving modes, such as the wheel, crawler, creeping, spiral, electromagnetic, etc. In Korea, Seung Kwan University[2] has successfully developed an MRINSPECT series of multi-function wheeled pipeline inspection robots. These robots mainly use clutches, multi-axis differential mechanisms to control the speed of driving wheels. Firas[3] has designed and developed a revolutionary Pipeline Inspection Gauge (PIG) for industrial pipes with tiny dimensions. Snake robots[4] are made up of numerous connection modules that may bend in one or more planes, inspired by biological snake locomotion. A fully autonomous mobile robot for pipeline exploration was proposed by designers J.R.Kim, G.Sharma[5]. It can travel in horizontal and vertical conditions involving pipelines with various accessories. The University of National Defense Science and Technology [6] has proposed a telescopic peristaltic pipe robot, suitable for pipes diameter
60~180mm. Sahari [7] developed a wheel-type robot with an adhesive system for completing inspection tasks through vertical pipes. JinweiQiao et al. [8] developed a self-locking isolated structure that allowed inchworm growing in vertical funnels with high adaptability. J. Chen Ling [9] and others developed a six-wheel-drive pipeline robot.

In summary, although researchers have developed a variety of pipeline robots, most of these robots have only one way of walking. When faced with complex working conditions such as obstacle avoidance, climbing and changing diameter in the pipeline, its adaptability is limited. As a result, a wheeled pipeline robot with multiple motion modes is proposed in this paper. The robot is mainly composed of an adaptive diameter changing mechanism, wheel displacement mechanism, turning mechanism and independently driven wheels, which can realise a variety of moving modes through the change of wheel position.

2. The structure of the multi-motion mode pipeline robot

The overall structure of the multi-mode pipeline robot is shown in figure 1. It is mainly composed of two symmetrically arranged bodies. The middle of the two bodies is a turning mechanism that controls the robot’s turning during the robot movement. Each body is composed of an adaptive diameter changing mechanism, wheel displacement mechanism and independently driven wheels. The adaptive variable diameter mechanism uses a parallel four-bar mechanism to adjust the distance between the wheel and the body to adapt to different pipe diameters. The translation characteristic of the parallel four-bar mechanism is used to maintain the contact state between the wheel and the pipe remains. At the end of the adaptive variable diameter mechanism, three independently driven wheels squeeze the pipe wall to form the forward power. There is also a wheel modification mechanism driven by the steering gear that can change the rotation direction of the wheel to realise the conversion of straight moving mode and spiral moving mode.

3. Kinematic and mechanical modelling of wheeled moving

In order to ensure the stability of the pressure between the wheel of the pipeline robot and the pipe wall, the adaptive diameter changing mechanism adopts the step screw nut mechanism to promote the structure of the four-bar mechanism, which converts the axial displacement into the radial displacement of the wheel. When the diameter needs to be changed, the stepper motor drives the screw to rotate, forward the nut seat. And then, the rod AB drives the rotation of the four-bar mechanism CDEF to increase the radial distance of the wheel, realising the diameter change. The spring at the end mainly
adapts the extrusion pressure between the wheel and the pipe wall. When the nut seat moves, the slider of the four-bar mechanism on the screw would be slid. As a result, the compression spring adjusts the pressure of the wheel to the pipe wall to realise the dynamic adjustment and self-adaptation of the pressure.

3.1. Kinematic model

![Figure 2](image)

**Figure 2.** Principle of adaptive variable diameter mechanism

The mechanism of the adaptive variable diameter mechanism is shown in figure 2. From this diagram, it can be seen that the length of the bar AB, BC, CD and the initial position of the nut seat are significant for the form of the mechanism. Because it determines the variable diameter range and force of the variable diameter mechanism. In order to avoid the strange position in the operation of the mechanism, the length of the distance slider of the nut seat should be greater than the length of the rod BC, and the length of the rod AB should be larger than the length of the rod CD. In order to obtain the quantitative relationship between the length of each rod and the change of pipe diameter. A coordinate system with the centre of the nut seat as the origin is established: the rod length and critical attitude angle of each rod are established, and the initial wheel is located at the midpoint of the rod BF. From the geometric relationship between the diameter-changing mechanisms, the wheel centre coordinates can be obtained as follows:

\[ \begin{align*}
    x_0 &= l_1 \cos \theta_1 + l_2 \cos \theta_2 + l_4 + \Delta x \\
    y_0 &= l_2 \sin \theta_2 + l_6
\end{align*} \]

(1)

\( \Delta x \) is the compression amount of the spring.

The attitude angle of the rod AB and the rod CD also satisfies the following relationship:

\[ l_2 = \frac{l_1 \sin \theta_1}{\sin \theta_2} \]

(2)

By combining the above equations, the relationship between the nut seat displacement can be obtained. Then, use MatLab to display the diameter change figure of the diameter changing mechanism. The changing trend diagram is shown in figure 3; it can be seen from the figure that the relationship between the nut seat displacement and the mechanism diameter change is monotonously increasing. However, the trend slows down with the increase of the displacement, meaning that with the increase of the attitude
angle of the rod AB, the nut seat displacement increment and the mechanism diameter change increment are in a downward trend. It concludes that the variation range of attitude angle should not be too extensive to obtain an extensive range of diameter change.

![Figure 3. Relationship between horizontal displacement and attitude angle](image)

3.2. Mechanical model
The wheel's driving force determines the robot's load ability. Under the constant friction coefficient, the driving force of the wheel positively depends on the pressure between the wheel and the pipe wall. Therefore, a stable and sizeable positive pressure is the basis for the stable movement of the robot. The pressure is provided together by the spring and thrust of the nut seat. So, it can be actively adjusted by the movement of the nut seat to change the spring compression.

![Figure 4. Stress relationship of variable diameter mechanism](image)

Because of the tardy diameter changing process of the diameter changing mechanism, only consider the static analysis of the mechanism. Furthermore, the mass of the bar and the friction force at the hinge of the member are ignored. The force of each rod is shown in figure 4. According to the relationship between the forces and the principle of static balance, combined with Newton’s Third Law of Motion-Force and Acceleration, the following simplified equations can be obtained:
\[
\begin{align*}
F_1 \cos \theta &= (F_2 + F_3) \cos \alpha \\
F_1 \sin \theta + (F_2 + F_3) \sin \alpha &= F_N \\
l_1 \sin \alpha &= l_1 \sin \theta \\
l_4 \cdot F_1 \sin \theta + F_N \cdot \frac{l_2}{2} &= F_3 \sin \alpha \cdot l_3
\end{align*}
\]  

(3)

By simplifying the above equation, the wall pressure of the tube can be obtained.

\[
F_t = \frac{F_N (\cos \theta \cdot \cos \alpha)}{\sin (\alpha + \theta)}
\]

(4)

It can be concluded that the horizontal force is only related to the rod lengths \(l_1\) and \(l_2\).

4. Optimal Design of Adaptive variable diameter Mechanism

Both diameter-changing range and force of the diameter-changing mechanism are closely related to the rod length, so a reasonable bar length is the focus of the design of the diameter-changing mechanism. In this paper, ADAMS software is used to solve the rod length.

4.1. Adams Parametric modelling

A motion model of variable diameter mechanism is built in the ADAMS software. The geometric modelling toolset creates the key points and moving components. Using variables and constants to represent the coordinates of the critical points. Eventually, they are all combined by the constraint Toolset. A rotary drive is added to the rotating pair between the screw and the earth as the power source for motions analysis. Adjust the spring between the trimming slider and the front positioning plate (elastic coefficient \(K=100\text{N/mm}\), the damping coefficient \(C = 1\text{N} \cdot \text{s/mm}\)). The small vertical downward force is applied to the end of the supporting rod, equipping the supporting force \(F_t\). The model of the variable diameter mechanism established in ADAMS is shown in figure 5. After the establishment, the objective function is determined by the measurement tool provided by ADAMS. Right-clicking the rotation pair between the screw and the earth, select Measure, measure the horizontal force of the rotation pair, and input formula (2) to a dialogue box to complete the creation of the objective function.

![Figure 5. Parametric modelling](image)
During the simulation process, it is found that the forces of \( l_2 \) and \( l_3 \) change with the dip angle transformation, and their initial direction is opposite. When passing through a certain Angle, it is found that \( l_2 \) force \( F_2 \) changes from tension to pressure and begins to bear the load together with \( l_3 \). The variation curve is shown in figure 6.

![Figure 6. Variation curve of force \( F_2 \)](image)

Therefore, under reasonable circumstances, the length of each force bar should be adjusted so that the tilt Angle \( \alpha \) of \( l_2 \) at the initial working point of the mechanism is equal to or exceeds the turning point of the force. This is conducive to the more reasonable distribution of force load of the bar in the process of movement. As a result, the point of force transformation is selected as the optimisation target.

### 4.2. Rod length optimisation

According to the design requirements, the force point is at the halfway point of \( l_4 \), \( l_4 = l_5 \). Under this condition, the force analysis can deduce the expression of force \( F_2 \):

\[
F_2 = \frac{F_N \cdot \sin \theta}{\sin(\alpha + \theta)} \left( \frac{1}{\tan \theta} - \frac{1}{\tan \alpha} \right) = \frac{F_N}{2 \cdot \sin \alpha}
\]

If the formula is equal to 0, even if the mechanism is in the critical state of \( F_2 \) direction change, and this state is taken as the starting operating point, the constraint relation between the Angle of \( \alpha \) and \( \theta \) can be obtained \( \tan \alpha = 3 \cdot \tan \theta \).

![Figure 7. The relation between Angle \( \alpha \) and Angle \( \theta \)](image)
Select the target value of the optimisation refers to the above curve generated through MATLAB. Since the working radius has been determined at the starting working point, the mechanism is starting height h=100mm. So, it just needs to select appropriate coordinate points on this curve and calculate the lengths of rod $l_2$ and $l_1$.

Adapt Not only the moderate length of $l_1$ and $l_2$ rod but also control the horizontal thrust $F_t$ of the mechanism not too large at the initial working point. Therefore, the initial $\theta=20^\circ$, $\alpha=48^\circ$ are selected to calculate the rod length $l_1=292mm$, $l_2=134mm$.

According to Formula (4), $F_2$ only relates to the rod length of $l_2$ and $l_1$. As a result, the length of remain rods can be reasonably selected according to the structure size.

After optimised calculation, the dimensions of each component are determined. Combined with 3D printing technology, the model of the robot is made, as shown in figure 8.

![Figure 8. Multiple motions of real robot](image)

5. Conclusion:
This paper proposes a multiple motion modes pipeline robot design and optimises the adaptive reducer's rod length, laying a foundation for further optimising and controlling the system design of a multi-mode pipeline flaw detection robot.

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