Dynamic Simulation Analysis and Experiment of Large-caliber Self-propelled Pipeline Crawler Based on ADAMS

Yinlong Tang¹,*, Huadong Song¹, Yating Yu², Jun Zhang¹, Wenguang Hu¹ and Xiaoting Guo¹

¹ SINOMACH Sensing Technology Co., Ltd, Shenyang, China
² University of Electronic Science and Technology of China, Chengdu, China

*Corresponding author email: tangyinlongs@163.com

Abstract. The force states of driving wheels are different when the self-propelled pipeline crawler moves in the pipeline, so it is difficult to carry out accurate theoretical analysis and calculation on the force and output torque values of each driving wheel in horizontal, climbing and turning conditions of the crawler. Due to the complex mechanical properties of pipeline sealing and the limitation of visualization, it takes a long period and high cost to develop the robot in pipeline by experimental means. With the gradual application of virtual simulation means, the complicated dynamic analysis and solution process in the past has become relatively easy. In this paper, Solid works is used to establish a simplified model of the crawler, and ADAMS is used to analyze and simulate the dynamics of the crawler. The force of the multi-wheel driven pipeline crawler is given under the condition of horizontal, climbing 35° and turning, which provides the necessary analysis method and theoretical basis for the design optimization and improvement. Finally, the horizontal, climbing and bending motion performance of the crawler is verified by comprehensive pipeline experiment.

Keywords: The self-propelled pipeline crawler; Dynamic simulation; Force analysis; ADAMS.

1. Introduction

Before the pipeline is put into use and during use, the health of the pipeline needs to be regularly evaluated to avoid cracks, corrosion, and deformation caused by the pipeline. Defects should be repaired or replaced in time to ensure the safety of pipeline operations [1]. The traditional differential pressure-driven pipeline robot-PIG uses the fluid pressure difference between the two ends of the robot in the pipeline to provide power, overcome the friction between the pipe wall and the cup, and push the robot to walk along the pipeline [2]. Its advantages are good practicability, simple structure, and long range, but because it has no power, it cannot go reverse, the detection speed cannot be adjusted independently, and the detection cost is high, which limits its practical application [3]. The automatic pipeline robot can actively drive the inspection equipment to complete the inspection task of the pipeline. The inspection speed can be adjusted independently according to the demand. The important pipe sections can stay for detection. It can be run without a fluid push in the pipeline and enables bidirectional walking. Due to the above advantages, automatic pipeline robots have become the focus of pipeline equipment research and development.

The research of pipeline robots began in the 1950s, and pipeline robots with various drive forms appeared to meet the needs of different pipelines. IwASHINA [4] and HIROSE [5] of Tokyo Institute of Technology developed a pipeline robot based on the principle of screw driving. ZHU [6] developed a wheeled robot for sewage sampling in a straight pipe. Se-gonRoh [7] designed a pipeline robot that can select a suitable driving method according to the shape of the pipeline. Professor Deng Zongquan...
and Professor Tang Dewei of Harbin Institute of Technology have conducted research on six independent wheel drive and differential wheel pipeline robots [8-9], and the Department of Precision Instruments and Mechanics of Tsinghua University has conducted continuous and in-depth research on direct-drive wheeled pipeline robots [10]. The National University of Defense Technology has developed a peristaltic micro-pipe robot [11], and the Shenyang Institute of Automation Chinese Academy of Sciences has developed a pipe robot with axial and circumferential detection functions [12]. The pipeline robots studied above are mostly pipelines with a diameter of less than 500mm or micro-caliber pipelines. The crawler has a small traction and a short range.

With the development of computer simulation technology, simulation methods are widely used in the product design process, which can effectively shorten the design and development cycle and reduce the cost of experimentation. The virtual prototype modeling technology, ADAMS (Automatic Dynamic Analysis of Mechanical Systems) is widely used. Engineers can use the software to conveniently perform kinematics and dynamics analysis on virtual mechanical systems for predicting mechanical systems. The performance, range of motion, collision detection, peak load, and understanding of the motion state and performance of complex mechanical system designs. Existing crawlers are more suitable for small and medium-caliber pipes, and self-propelled crawlers for larger pipes are relatively rare. Starting from the overall composition and structural design of the crawler, this paper uses Solid works modeling software to carry out the structural design, combined with the ADAMS virtual prototype simulation method to carry out the dynamic simulation analysis of the large-caliber self-propelled pipeline crawler. The focus is on the structure and composition of the large-caliber self-propelled pipeline crawler. The dynamics simulates the load situation and torque of the crawler when leveling, climbing and turning, which provides a basis for the design of the large-caliber self-propelled pipeline crawler.

2. The Composition and Working Principle of the Pipeline Crawler

The design goal of the pipeline crawler described in this article is to adapt to the detection of oil and gas pipelines with a diameter of more than 1000mm before being put into production. Relying on its own active drive, it achieves a 35° climbing function, has a range of 30km, can drive forward and backward in both directions, and can carry a certain quality task load for pipeline inspection. The traveling speed is 1m/s, and it can pass through curved pipes.

![Figure 1. Self-propelled pipeline crawler.](image_url)
driving wheel and the supporting wheel form a group corresponding to the front and rear, and the circumferential angle of each group of wheels is 60°, as shown in Figure 1.

3. Dynamic Analysis of Pipeline Crawler Based on ADAMS

ADAMS is used to analyze the dynamics of the crawler in the horizontal and inclined pipelines. Obtain the pressure of the driving wheel on the tube wall and the radial force of the driving wheel, and the required torque of the driving wheel can be obtained. Provide a certain basis for the design of the crawler, the selection and optimization of the driving wheel.

Figure 2. ADAMS Dynamics simulation flow chart.

Figure 2 is a block diagram of the ADAMS dynamics simulation process of the self-propelled pipeline crawler, including model simplification, import, simulation settings, model property settings, contact force settings, simulation solution settings, post-processing. The driving force of the crawler in the pipeline comes from the friction between the support wheels and the pipe wall. The magnitude of the friction depends on the positive pressure on the pipeline. The greater the pressure, the greater the friction. Due to the deformation of the pipe wall and the welding seam, the crawler produces a clock attitude deflection during the traveling process, and the positive pressure will change.

Now for a simplified analysis of the model (Figure 3), the three sets of support wheels are evenly distributed in contact with the pipe wall. The gravity of the crawler is represented by G. Assuming that the initial state of crawling is that the arm 3 coincides with the y-axis, the crawler deflects after a period of walking. \( \gamma \) is the attitude angle (-60°<\( \gamma \)<60°).

![Figure 3. Support force analysis.](image)

Regardless of the attitude angle of the crawler, the two sets of supporting wheels support the gravity G. N1, N2, and N3 are the supporting pressures on the driving wheels caused by the crawler's gravity G on the inner wall of the pipeline. The supporting force of the top driving wheel due to the gravity of the crawler is 0, and the balance equation is listed:

\[
\begin{align*}
N_1 \cos(60 - \gamma) + N_2 \cos(60 + \gamma) &= G \\
N_1 \sin(60 - \gamma) - N_2 \sin(60 + \gamma) &= 0
\end{align*}
\]  

(1)

Solving formula (1):

\[
N_1 = \frac{2\sqrt{3}G \sin(60^\circ + \gamma)}{3}
\]
\[ N_2 = \frac{2\sqrt{3}G \sin(60^\circ \gamma)}{3} \]

Considering that the pipeline is not only horizontal, but also has a slope \( \phi \), the total supporting force is:

\[ \sum N = N_1 + N_2 = 2G \cos \gamma \cos \phi \]  \tag{2}

\( \gamma \) changes in the range of \(-60^\circ \sim 60^\circ\), when the slope \( \phi = 0 \), \( \sum N \) in formula (2) is the largest. When the crawler is walking in the pipeline, the output traction is maximum when the attitude angle \( \gamma = 0^\circ \). Adams is used to perform dynamic simulation of the attitude angle state in Figure 4 (a) and (b). It is concluded that in state (a), the sum of the supporting forces of the crawler driving wheels is the smallest, and the traction is the smallest. In the state (b), the total support force of the crawler driving wheels is the largest, and the traction force is the largest.

Figure 4. Crawler traction minimum, maximum two states.

3.1. Horizontal Driving Dynamics Simulation

Because the model is complex, the model is simplified and then imported into ADAMS [13-14]. The model in Figure 4(a) is used for simulation to ensure that the traction can be met even when the traction is minimal. In the ADAMS simulation environment, 12 wheel rotation pairs, 12 rotation pairs at the support arm joints, 1 pipe fixed constraint, and contact attributes, friction coefficient, gravity direction, crawler quality, driving wheel material, pipe material, and driving parameters are set. The specific parameters are shown in Table 1. The software setting interface is shown in Figure 5.

| Crawler quality | Direction of gravity | Wheel diameter | Wheel body material | Suspension stiffness |
|-----------------|----------------------|----------------|---------------------|---------------------|
| 410kg           | Y forward            | 220mm          | rubber              | 120N/mm             |
| Number of driving wheels | Driving wheel speed | Contact stiffness | Exponent | Damping |
| 6               | 520°/s               | 2855           | 1.1                 | 0.57                |
| Penetration depth | static friction coeff | dynamic friction coeff | static friction velocity | dynamic friction velocity |
| 0.1             | 0.3                  | 0.25           | 0.1                 | 10                  |

Figure 5. Setup of crawler simulation environment.
Figure 6. Torque/time curves of six driving wheels in horizontal state.

Figure 6 shows the output torque curves of the six driving wheels. The average value of the torque motion1 of the driving wheel 1 is 12N•m after being stable. The torque curves of drive wheel 2 and drive wheel 6 coincide with the average value of 9N•m. The torque curves of driving wheel 3 and driving wheel 5 coincide with the average value of 7N•m. The average value of the torque curve of the driving wheel 4 is 5N•m.

Figure 7. Contact force curves of six driving wheels and pipe wall in horizontal state.

Figure 7 shows the results of the contact force of the driving wheels. The contact force contact1 between the driving wheel 1 and the pipe is the largest, with an average value of about 1890N. The contact force curves of driving wheel 2 (contact 2) and driving wheel 6 (contact 6) coincide with an average value of about 1740N. The contact force curves of driving wheel 3 (contact 3) and driving wheel 5 (contact 5) almost coincide with an average value of about 1350N. The contact force of driving wheel 4 (contact 4) is the smallest, and the average value of the curve is about 1140N.

Figure 8. Force/time curves of suspension spring under six driving wheels in horizontal state.

Figure 8 shows the results of the contact force of the driving wheels. The contact force contact1 between the driving wheel 1 and the pipe is the largest, with an average value of about 1890N. The contact force curves of driving wheel 2 (contact 2) and driving wheel 6 (contact 6) coincide with an average value of about 1740N. The contact force curves of driving wheel 3 (contact 3) and driving wheel 5 (contact 5) almost coincide with an average value of about 1350N. The contact force of driving wheel 4 (contact 4) is the smallest, and the average value of the curve is about 1140N.

In Figure 8, the spring suspension under the driving wheel 1 has a maximum force of 3560N. When designing the crawler structure, the load capacity of the spring suspension should be greater than 3560N. At the same time, considering the existence of deformation in the pipeline, the crawler has a certain amount of deformation, and the spring suspension must have excess load-bearing capacity and deformation to ensure the crawler’s performance. The amount of deformation is usually 10% of the inner diameter of the pipe.
3.2. Dynamic Simulation of Climbing State

In Figure 10, the crawler and the pipeline model are rotated by 35°, and the other parameter settings are the same as the horizontal simulation parameters. The climbing state of the crawler is simulated, and the output torque and contact force results of the crawler are obtained.

Figure 9. Speed/time curve of horizontal crawler.
Figure 9 shows the speed curve of the crawler. After 0.3 seconds of acceleration, the horizontal moving speed of the crawler is stable and maintained at 1m/s.

Figure 10. Simulation model of climbing movement.

Figure 11. Torque/time curves of six driving wheels in climbing state.
Figure 11 shows the torque/time variation curve of the driving wheels. The torque of the driving wheel 1 has the largest average value, which is about 63N•m. The torque curves of the driving wheel 2 and the driving wheel 6 almost coincide with an average value of about 52N•m. The torque curves of the driving wheel 3 and the driving wheel 5 almost coincide with an average value of about 36N•m. The driving wheel 4 is the smallest, and the average torque curve is 29N•m.
Figure 12. Contact force/time curves of six driving wheels and pipe wall in climbing state.
In Figure 12, the contact force contact1 between the driving wheel 1 and the pipe is the largest with an average value of about 2300N. The contact force curves of driving wheel 2 (contact2) and driving wheel 6 (contact6) almost coincide with an average value of about 2000N. The contact force curves of driving wheel 3 (contact 3) and driving wheel 5 (contact 5) coincide with an average value of about 1420N. The contact force of driving wheel 4 (contact4) is the smallest, and the average value of the curve is about 1100N.

3.3. Dynamic Simulation of Cornering State
No matter what kind of pipeline robot is walking in the pipeline, the bend must be paid attention to. Because the cornering ability is an important indicator of the pipeline robot. The main influencing factors are the limit geometric size of the robot unit and the deformability of the walking wheels [15-16]. This article is concerned with whether the crawler drive wheel is suspended and loses its driving ability when passing a bend. A model with a turning radius of 7m is established and simulated. The virtual prototype model of the pipeline crawler is shown in Figure 13.

Figure 13. Analysis of crawler contact force for bending condition.

Figure 14. Contact force/time curves of six driving wheels and pipe wall in bending state.
Figure 14 is the contact force/time curve of the drive wheel and the pipe wall in the state of the crawler passing the bend. It can be concluded from the graph that the sum of the six contact forces is relatively stable, the force value does not have an obvious downward trend, and there is no situation where the contact force is zero. It shows that the driving wheel has not lost its driving force.
4. Crawler Experiment

Based on the above structural parameters and simulation results, a prototype of a 1219mm large-caliber crawler was manufactured. Completed horizontal and climbing pipe section experiments. The actual performance of the crawler was tested in the integrated pipe section on site.

4.1. Crawler Running Horizontally, Climbing Experiment, Cornering Experiment

The crawler has carried out crawling experiments on the long straight pipe section and the inclined pipe section. Figure 16(a) is the horizontal test of the crawler, Figure 16 (b) is the experimental site of a section of 8m-long inclined 35-degree pipeline, and Figure 16 (c) is a section of 7m radius bend.

- Limited by the length of the pipeline, the crawler was set to reciprocate in the pipeline to test the stability and endurance of the crawler. Experiments show that the crawler ran at a speed of 1m/s, and the energy consumption was about one-third of the total power after 3 hours of continuous operation.
- An 8m-long pipe section was used for the climbing experiment, and the inclination angle of the pipe was gradually increased by a crane. The crawler successfully completed the 25° and 35° pipeline climbing, and the detected data showed that the current of the drive wheel motor did not exceed the rated current and remained within the safe value range.
- In the bending experiment, a 6m-long bend with a turning radius of 7m was used for the test. The six driving wheels could be in close contact with the pipe, and the crawler passed through the bend smoothly.

4.2. Running Experiment on Actual Pipe Section of Crawler

In Figure17, the crawler was tested on the actual pipe section at a construction site. The pipe section is about 1km long and contains an upslope section of about 20°. When the crawler walked in the pipeline, it steadily passed through all pipe sections, including horizontal and uphill. The entire speed is maintained at 1m/s. After the equipment was picked out of the tube, the structure of the whole machine was intact, and the support arm, drive motor, drive wheel body and power supply were normal.
Data analysis was carried out on the current of the crawler drive motor. Figure 18 shows the total current curve of the drive motor during the crawler's traveling process. The abscissa is the running mileage and the ordinate is the total current of the drive motor. The current at 300m in the curve increases, corresponding to the uphill section of the pipe section, and the motor needs to be driven to increase the current to increase the output torque and complete the uphill.

Figure 17. 1km comprehensive experiment section.

![Drive wheel motor current curve](image)

Figure 18. Drive wheel motor current curve.

5. Conclusion
(1) In this paper, Solidworks is used to establish a simplified crawler model, and the crawler dynamics analysis simulation solution is carried out through ADAMS. The force, driving torque and spring suspension force of the crawler under the conditions of horizontal, climbing 35° and turning are obtained.
(2) The torque results show that the output torque of the driving wheel in horizontal driving state is small, which mainly overcomes the rolling friction. When climbing, the gravity component and rolling friction along the slope are overcome, and the output torque increases.
(3) When the crawler passes through the bend, the contact force between the driving wheel and the pipe wall always exists. There is no drop in the driving force caused by the suspension of the driving wheel.
(4) The motion performance of the crawler has been verified by the comprehensive pipe section experiment. The field test effect reached the design expectations.

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References
[1] Bruschi, R., et al., Pipe technology and installation equipment for frontier deep water projects. Ocean Engineering, 2015. 108: 369-392.
[2] S.T.Tolmasquim, A.O.Niecke. Design and control of pig operations through pipelines. Journal of Petroleum Science and Engineering, 2008(62):102-110.
[3] Dr. Florien Rah. Optimizing the active speed control unit for in-line inspection tools in gas. Canada: ROSEN Technology &Research Center, 2006.
[4] IWASHINA S, HAYASHI I, IWATSUKI N, et al. Development of in-pipe operation micro robots//Proceedings International Symposium on Micro Machine and Human Science, Oct. 2-4, 1994, Nagoya, Japan. Nagoya:IEEE, 1994:41-45.
[5] HIROSE S, OHNO H, MITSUI T, et al. Design of in-pipe inspection vehicles for φ25, φ50, φ150 pipes// Proceedings of IEEE International Conference on Robotics and Automation, May 10-15, 1999, Detroit, USA. Detroit:IEEE, 1999:2309-2314.

[6] ZHU Chi. In-pipe robot for inspection and sampling tasks. Industrial Robot:An International Journal, 2007, 34(1):39-45.

[7] Se-gon Roh, Do Wan Kim, Jung-Sub Lee, et al..International Journal of Control, Automation, and Systems (2009) 7(1):105-112.

[8] DENG Zongquan, CHEN Jun, JIANG Shengyuan, et al. Traction robot driven by six independent wheels for inspection inside pipeline. Chinese Journal of Mechanical Engineering, 2005, 41(9):67-72.

[9] TANG Dewei, LI Qingkai, LIANG Tao, et al. Mechanical self-adaptive drive technology of triaxial differential pipe-robot. Chinese Journal of Mechanical Engineering, 2008, 44(9):128-133.

[10] ZHANG Xiuli, ZHENG Haojun, ZHAO Liyao. A small pipe-inspection robot. Robot, 2001, 23(7):626-629.

[11] XIE Xuhui, WANG Honggang, XU Congqi. Journal of National University of Defense Technology, 2007, 29(6):98-101.

[12] LI Peng, MA Shugen, LI Bin, WANG Yuechao. Screw Drive In-pipe Robot with Axial and Circum-directional Inspection Ability. Chinese Journal of Mechanical Engineering, 2010, 46(21):19-28.

[13] GUO Yu. Design and analysis of the micro screw locomotion in-pipe robot. Changsha :National University of Defense Technology, 2006.

[14] Chen Huan. Research on Four-wheeled Full-drive Pipeline Robot. Hefei University of Technology, 2017.

[15] XU Fengping, DENG Zongquan. Research on Traveling-capability of Pipeline Robot in Elbow. ROBOT, 2004(3):155-160.

[16] WANG Xiuxin. Research on the Bending Control of the Pipe Detection Robot. North China University of Science and Technology, 2018.