Research on Impact and Steering Mechanism of the Puncturing Mud Robot

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Abstract. The purpose of this paper was to propose an automatic device based on a trenchless underground perforation and a path planning method to learn. Based on conservation of mechanical energy, the authors propose a pneumatic impact mechanism. Through the establishment of dynamic analysis of mathematical Model, the authors point out the relationship between the displacement of the piston segments, mass and output parameters. Through the development of its test system, the parameters and path correlation curves are acquired to point out the mutual connection and restrictive relationship. Several data and experimental analyses are described, showing that puncturing mud robot can realize steering and its impact reaches the level of trenchless laying pipes technology at home and abroad. With the proposed approach, it is possible for puncturing mud robot to squeeze the surrounding soil layer to form a circular hole and lay the trenchless pipeline to improve perforation performance.

1. Introduction

There are mainly five kinds of methods on trenchless pipe laying in China, including pipe jacking, ramming method, impact spear, vibration squeeze soil, horizontal directional drilling technology. [1-2] Research of the Puncturing mud robot drew lessons from the working principles of impact spear, which paths can be controlled being researched by the Research Institutes at home and abroad [3-4]. The robot ideal state can overcome the resistance in the soil to walk independently. Its structure is consist of tapered bit, knuckle mechanic, impact mechanism and other units. It can realize the PE or PVC pipe, cable and other small diameter pipelines underground trenchless laying. It can finish perforated underground operation with distance about 30~60m. The curve perforation is different from the impact spear which the path can be controlled. Puncturing mud robot can rotates with its rotating mechanism through transferring torque to influence mechanism. [5-7] This is the same principle as the study by Yang et al. the ontology appearance of Puncturing mud robot looks like two long rods with ribs [8]. Xv et al. proposed that SDH-70 Pneumatic Impact Trajectory Controlled Puncher can change the working state of the bistable head through making flexible rod relative bistable head rotating 180 degrees [9]. The research of Wang et al. [10] revealed the change rule of the KCM-130 controlled impact spear's drilling trajectory, and designed the structure of impact spear.

At present, foreign puncturing mud robots (underground perforating equipment) are manipulated on land by manual operation, and can’t be operated automatically. The impact spear can have
independent motion characteristics. After it is installed steering mechanism, it can be controlled the trajectory of impact motion curve. However, the article of the robot research and experimentation, the special rotation mechanism of the robot body can achieve the rotation driven. The generated torque is transferred to the robot body, and the autonomous movement of the robot soil is realized.

2. Impact force test method and system composition

According to the test principle, the test system is composed of impacting spear, force sensor, transmitter, power supply and oscilloscope, single chip sampling system and computer system, as showed in Figure 1(a-d).

![Figure 1. Test system components](image)

Notes: (a) Impact force transduce; (b) single chip sampling system; (c) power supply and oscilloscope; (d) computer system

1) Transmitter BK-2F force sensor measured voltage signal is 0-22mv, if the voltage signal is directly used as a microcontroller system A/D input, it will causes the large measurement error. So it must be amplified with a transmitter line to 0-5v of the voltage signal.

2) Sampling system analog voltage signal output from the pressure sensor is amplified by the transmitter and sent to the A/D converter. The conversion results by AT89C51 via a serial port to a computer in interrupt mode.

3) The computer system mainly includes microprocessors, keyboard, printers, CRT display terminal, I/O interface and a wealth of system software and application software. Through using the computer system and Visual C++ language programming, it completes serial data and data processing to accept the work.

3. Design method and analysis of impact and steering mechanism

3.1. Mathematical model establishment of pneumatic impact mechanism

The pneumatic impact mechanism of Puncturing mud robot is shown in Figure 2.

![Figure 2. Structure diagram of impacting machine](image)

1-short connection of the front, 2-cylinder, 3-Impact piston, 4-support ring, 5-valve rod core, 6-piston ring, 7-valve rod block, 8-cylinder rear-end plate, 9-intake pipe joints

Under a certain pressure, piston moves backwards and forwards in the cylinder, it can be divided into piston power stroke and return stroke. There are three kinds of motions in the power stroke, those are uniformly accelerating motion, variable accelerating motion and slowdown impact which are shown as piston displacement $S_1$, $S_2$ and $S_3$ accordingly. Return stroke can regard as the inverse
process of the power stroke, that is, returning uniformly accelerating motion \( S_3 \), variable accelerating motion \( S_2 \), slowdown impact \( S_1 \). Then, after piston starting, piston will impact the cylinder front end cover and rear end cover respectively with certain velocity, which forms a kind of self-induced vibration which has certain velocity and frequency. Then, we will build its dynamic process mathematics model by taking the case of the impact process, its mathematical model is given by the following equations [11-12]:

\[
W = \frac{m_pv^2}{2}
\]

(1)

\[
a_1 = \left( \frac{\pi}{4} (d^2 - P_0 - D^2 \cdot P_t) - f_{\mu} \right) / m
\]

(2)

\[
t_1 = \sqrt{\frac{2S_1}{a_1}}
\]

(3)

\[
v_1 = \frac{ds_1}{dt} = \sqrt{2 \cdot S_1 \cdot a_1}
\]

(4)

\[
P_t = P_{i} \left( \frac{V_{i}}{V_{i} - A_{i} \cdot s} \right)^{k}
\]

(5)

\[
a_s = \frac{(P_0 \cdot A_0 - P_s \cdot A_i - f_{\mu})}{m}
\]

(6)

\[
A_0 = \frac{\pi}{4} \cdot d^2 \cdot A_i = \frac{\pi}{4} \cdot D^2
\]

(7)

\[
a_3 = \frac{\pi}{4} (D^2 - d^2) \cdot P_0 \cdot f_{\mu}
\]

(8)

\[
v_3 = v_2 - a_3 \cdot t_3
\]

(9)

\[
S_3 = v_2 \cdot t - 0.5 \cdot a_3 \cdot t_3^2
\]

(10)

\[
v' = \frac{(m_p - m_w \cdot e)}{m_p + m_w} \cdot v_3
\]

(11)

\[
u = \frac{(1 + e)m_p}{(m_p + m_w)} \cdot v_3
\]

(12)

Where: \( W \) is the impact work, \( Nm \); \( m_p \) is the quality of impact piston, \( kg \); \( v \) is the piston impact velocity, \( m/s \); \( P_1 \) is the pressure before the air chamber, \( MPa \); \( f_{\mu} \) is the friction, \( N \); \( S_1 \), is the piston uniform acceleration, \( S_2 \) is the variable acceleration, \( S_3 \) is the deceleration impact displacement; \( m \); \( a_1 \), and \( a_3 \) are the piston acceleration in displacement \( S_1,S_2,S_3 \); \( a_1 \cdot t_1, a_3 \cdot t_3 \) are the time of displacement \( S_1,S_2,S_3 \); After displacement \( S_1,S_2,S_3 \), the velocity are \( v_1,v_2,v_3 \), \( m/s \); \( d,D \) are the cross-sectional diameter of after or before the gas chamber, \( m \); \( A_0,A_i \) are the Sectional area of after or before the gas chamber, \( m^2 \); \( P_s \) is the a gas chamber pressure when the displacement of the piston is \( s \), \( MPa \); \( V_i \) is the initial volume of the former chamber, \( m^3 \); \( s \) is the piston displacement, \( m \); \( a_s \) is the piston acceleration in displacement \( s \), \( m/s^2 \); \( k \) is the adiabatic coefficient, \( k=1.41 \); \( v' \) is the speed after the piston hit, \( m/s \); \( u \) is the impact mechanism forward speed, \( m/s \); \( m_w \) is the total mass of impact mechanism apart from the quality of piston, \( kg \); \( e \) is the coefficient of restitution, for steel to steel impact, \( e=0.56 \).

The formulas (2) - (4) are the uniform acceleration process, the equations (5) - (7) are the accelerating processes, and the equations (8) - (10) are the deceleration impact processes. We can get a differential equation (13) from Equation (5) - (7), such as:

\[
\frac{d^2s}{dt^2} = a_s = \left( \frac{\pi}{4} (P_0 \cdot d^2 - P_i \left( \frac{V_i}{V_i - \frac{\pi}{4} \cdot D^2 \cdot s} \right)^{k} \cdot D^2 \right) - f_{\mu} \right) / m
\]

(13)

Initial conditions: \( t_0=0, \ s_0=0, \ v_i=v_1 \); Ultimate displacement: \( s=S_2 \). It is difficult that an algebraic solution is worked out from this differential equation. So, the fourth-order Runge-Kutta method was
used for the numerical solution. Equation (13) can be turned into a first order differential equation respectively with mathematical transformation as followed.

\[ s' = V \]

\[ V' = s'' = \left( \frac{\pi}{4} \left( P_s - d^2 - P \left( \frac{V}{V_1} \right)^\phi \cdot d^2 \right) - f' \right) / m \]

Where:

\[ s'' = a_s = \frac{d^2 s}{dt^2} \]

\[ s' = V = \frac{ds}{dt} \]

First-order differential equation \( y' = f(x, y) \) of the Runge-Kutta method was involved in, then:

\[ y_{n+1} = y_n + \Delta y_n = y_n + \frac{1}{6} (K_1 + 2K_2 + 2K_3 + K_4) \]

\[ K_1 = f(x_n, y_n) \cdot h \]

\[ K_2 = f(x_n + h/2, y_n + K_1/2) \cdot h \]

\[ K_3 = f(x_n + h/2, y_n + K_2/2) \cdot h \]

\[ K_4 = f(x_n + h, y_n + K_3) \cdot h \]

Where: \( K_1, K_2, K_3, K_4 \) is the coefficient; \( x_n, y_n \) is the first n-point independent variables and variables; \( h \) is the step size. After the establishment, the mathematical model can simulate the dynamic process of pneumatic impact mechanism.

3.2. The effect of main parameters of impact mechanism on performance

Output performance of impact mechanisms (impact energy, impact frequency etc.) are affected by operating pressure \( P_0 \), the quality of impact piston \( m_p \), displacement parameters of the acceleration \( S_I, S_2, S_3 \) etc. Then the effect will be analyzed by changing the parameters, while the other parameters cannot be changed. According to the impact mechanism of the external diameter of \( \phi 60 \text{ mm} \), the impact energy \( E \geq 20 \text{ J} \) design conditions to initially determine the main parameters: impact piston quality \( m_p = 5 \text{ kg} \), cylinder bore is \( \phi 50 \text{ mm} \), piston stroke \( s = 133 \text{ mm} \), operating pressure \( P_0 = 0.6 \text{ MPa} \).

As depicted in the Figure 3, impact energy and impact velocity are increased with the increasing of \( S_I \) and \( S_2 \). Impact frequency and reverse impact velocity are decreased with the increasing of \( S_I \) and \( S_2 \).

![Figure 3. The effect of \( S_I \) and \( S_2 \) on \( E, F, V_c \) and \( V_d \)](image)

Analysed from Figure 3 (a), \( S_I \) decides the amount of reverse impact velocity, while a greater impact on reverse impact velocity from \( S_2 \) is shown when \( S_I \) is larger, and there is space in the increasing of velocity. So, to ensure certain reverse impact velocity, \( S_I \) will be less than a certain amount, about \( S_I \leq 58 \text{ mm} \) as showed in the Figure 3. The effect on the returning impact velocity is the maximum when \( S_2 \geq 90 \text{ mm} \); When impact energy and impact velocity are the maximum as shown in the Figure3(b and c), it can conclude from Figure3(d) that returning impact velocity will be zero, that
is, piston can’t reverse impact. So, the choice of $S_1$ and $S_2$ should make the impact energy and impact velocity maximum. Other effects on the performance like composition change of $S_2$ and $S_3$, $S_1$ and $S_3$ are similar to the above.

3.3. Design of impact steering mechanism
The steering mechanism of the robot body adopts the structure of the double-piston cylinder design. The reciprocating motion of the piston drives the tooth clutch to be engaged and separated, so that the head rotates and realizes the curve and linear motion. The mechanism diagram is shown in Figure 4.

![Figure 4. Structure diagram of turning machine](image)

1. Tapered bit 2. Rotating sleeve 3. Compressed spring 4. Front clutch 5. Clutch bases 6. After the clutch 7. Piston 8. Cylinder 9. Front piston 10. After the piston 11. Cylinder back cover

When the trajectory of the curved drilling hole needs to be adjusted, the attitude of the robot is feed backed by the testing part, and the steering mechanism is rotated to a fixed angle according to the posture, so that the inclination angle of the conical drill bit is adjusted to the direction of the adjustment path. Only the impact does not rotate, then drill out of the path along the direction of the deviation angle of the drill, that is, to achieve the curve drilling.

In the drilling process, according to the feedback of the robot’s attitude, at any time to adjust the drilling direction, curve prototype can be achieved in the soil track control drilling operation, therefore, it can be called real “puncturing mud dragon” Robot prototype.

4. Experiment and analysis

4.1. Impact mechanism performance experiments
Computer system was used for dealing with the test data. The data processing system is mainly composed of an interactive interface, data curve display, the relevant parameter setting, impact energy and frequency calculation. The test data are shown in Table 1 and Figure 5. Table 1 showed the optimize design result. It reached the specifications of the same kind products and means that it can finish perforation operation.

![Figure 5. The measured curve of impact force](image)
### Table 1 Testing of main performance parameters of puncturing mud robot

| Gas pressure (MPa) | 0.4 | 0.5 | 0.6 | 0.65 | 0.80 |
|-------------------|-----|-----|-----|------|------|
| Impact frequency (Hz) | 4.49 | 5.20 | 5.98 | 6.04 | 6.08 |
| Impact force (N) | 7480 | 9351 | 11221 | 11525 | 13113 |
| Impact energy (N·m) | 14.9 | 22.4 | 32.2 | 34.1 | 50.9 |

4.2. **Rotational experiment of steering mechanism of curve prototype**

The robot works as shown in Figure 6(a). Before the experiment, we will plan its trajectory. When the angle of the drill bit of the prototype is 7.5 °, the experimental data of the drill bit impacting soil are recorded and the drilling trajectory is measured. The results show that the experiment can achieve the expected trajectory trend, as showed in Figure 6(b). Impact body with drilled bit can be drilled in the soil and be able to drill the macro-curve trajectory.

![Figure 6](image)

(a) State of curve prototype drilling out of soil at some curvature
(b) Dotted line: trajectory planning
Solid Line: The actual trajectory

5. **Conclusion**

This paper introduces a method of testing the pneumatic impact performance, the impact force is taken as the direct measurement object, and the design of the impact and the steering mechanism is studied. The influence of the impact mechanism parameters on the performance is analyzed by energy conservation method. Experiments demonstrate that the impact force of the robot has reached the performance index of similar products at home and abroad. The designed steering mechanism can drive the rotation of the impacting head in the soil and control the perforation in the soil curve to realize the autonomy movement of the robot.

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