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Speed Control Characteristics and Energy Consumption Modeling for Composite Driving in-Pipe Robot*

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***Abstract* - In order to realize the long-distance inspection of the in-pipe robot, a new type of composite in-pipe robot mechanism driven by integrated the fluid medium and the motor is proposed in this paper. By analyzing the speed regulation mode of the speed-regulating mechanism of discharge flow, the dynamic equation for the fluid drive of the in-pipe robot is established, and according to the requirements of the inspection conditions of the in-pipe robot on the moving speed, the dynamic model of the speed regulation for the fast motion and deceleration drive is proposed. Furthermore, the energy consumption evaluation model of the composite driving in-pipe robot is established, the speed regulation characteristics and energy consumption variation characteristics of the in-pipe robot adapted to three kinds of the inspection conditions are studied by simulation. The energy consumption variation rule of the in-pipe robot with different moving speed and fluid pressure is analyzed and studied by using the experimental prototype of the composite driving in-pipe robot, and the valuable conclusions are obtained.**

Index Terms – in-pipe robot*, *composite driving*, *speed regulation*, *energy consumption modeling

I. Introduction

According to the driving mode of pipeline robot, it can be divided into two categories, active type and passive type. The former is suitable for pipeline operation with the small inner diameter, adopts the motor drive mode and can move actively, the representative types are mainly straight forward wheel type, screw type, inchworm type and caterpillar type [1-6]. The latter is mainly pipeline intelligent inspection PIG [7-11], relying on the pressure difference of the fluid medium in the pipe to generate the driving force and move passively, which can realize the on-line inspection. It has the advantages of long inspection distance and many inspection parameters, is the main inspection tool for the large size of the oil and gas pipelines at present, but the size of the equipment of the PIG is generally larger in volume and also complex in structure, adapt to the conveying pipelines with larger inner diameter and medium pressure, which limits the application in the small pipe diameter. With the continuous improvement of in-pipe inspection and maintenance requirements, some technical problems need to be solved for in-pipe robots that can be applied to the special environments in small-sized pipeline. For example, how to overcome the contradiction between the self-weight of the on-board limited power supply and the long-distance locomotion for the in-pipe robot operation without cable control. Therefore, the interaction ability between the in-pipe robot and the pipe environment has become an important influence factor to expand the application range of the in-pipe robot, which promotes the generation and development of the fluid medium driven in-pipe robot and the articulated structure in-pipe robot.

For the in-pipe robot with articulated structure, the multiple functional modules can be combined together, including the battery module, to facilitate autonomous moving without cable control. C. Birkenhofer [12] proposed a typical multi-segmented in-pipe robot, and in order to adapt the robot to complete the autonomous inspection task, studied the navigation method for the in-pipe robot compliant motion in unstructured dynamic environment. Young-Sik [13] proposed a design and motion planning algorithm of a caterpillar-based pipe robot with two modules, which can cooperatively navigate through difficult segments of the pipes. Edwin Dertien [14] proposed a design of a small pipe diameter inspection modular in-pipe robot with its outer diameter extends from 63 to 125mm, has a strong ability to pass through the elbow. Atsushi Kakogawa [15-17] designed a multilink-articulated in-pipe robot with omni and hemispherical wheels, and the elastic joint characteristics were studied in detail, the experimental results revealed that the robot could adapt to bent, branch, vertical, and winding pipes. Based on bio-inspired propelling concept, Fekrmandi Hadi [18] also designed a four-module crawling robot and carried out the crawling experiment in small, varying pipes within complex configurations. From the above studies, it can be seen that the in-pipe robot driven by motor is mainly applied in the environment without medium in the pipe, and its structure and adaptability to motion in the pipe are mainly studied. However, there are few researches on the in-pipe robot that needs to realize long-distance moving. Therefore, in order to tackle the aforementioned issues, this paper proposes a composite drive mode of integrated motor drive and fluid medium drive for the special environment in the pipe, and studies the driving characteristics and energy consumption modeling method for the composite driving in-pipe robot.

This paper is organized as follows. The overall mechanism of the composite driving in-pipe robot and the speed regulating mechanism for the fluid driving unit are

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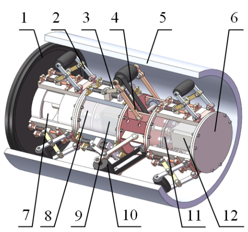
introduced in Section II. The fluid driving force modeling of the outlet angle of the speed regulating mechanism for the composite driving in-pipe robot is presented in Section III. The speed regulation planning of the in-pipe robot is analyzed, the energy consumption model is established and the simulation results are given in Section IV. The experimental validations on the fabricated principle prototype are followed in Section V. Finally, the influence of the speed regulation characteristics on the motion of the composite driving in-pipe robot and the future research work are summarized in Section VI.

II. THE OVERALL MECHANISM OF THE IN-PIPE ROBOT

The in-pipe robot is composed of two driving units, motor and fluid, and the two driving units are respectively arranged at the front and rear ends of the two segments of the in-pipe robot body. and the robot is equipped with two cylindrical sealed cylinders, which are mainly used for installing motor and driver, control circuit and power supply. Three groups of driving wheels are arranged in phase 120° around the body of the in-pipe robot, the power is transferred from one driving motor to three groups of driving wheels through the transmission system, forming the motor driving unit, as shown in Fig.1.

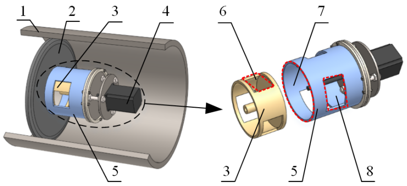


1-driving cup, 2-spring slide support mechanism, 3-switching mechanism, 4-belt drive, 5-pipe, 6-motor box, 7-drain outlet;8-flow-discharging mechanism, 9-drain drive motor, 10-drive wheel, 11-transmission gear train, 12- drive motor

Fig. 1 Schematic diagram of composite driving in-pipe robot mechanism.

The fluid driving unit consists of two parts: the driving cup and the speed regulating mechanism of the flow discharge, and its structure diagram is shown in Fig.2. The outer edge of the cup is attached to the pipe wall, which can effectively close the fluid in the pipe and can be used as the supporting pressure surface of the fluid driving force. The speed regulation mechanism of the flow discharge can change the pressure difference between the front and rear of the in-pipe robot by regulating the discharge of the fluid in the pipe to control the moving speed of the robot.

The speed regulating mechanism is mainly composed of a speed regulating cylinder, a flow discharge motor and a body barrel, in which the body barrel is a body structure with one end open and the other end closed, and the opening end is an inlet port. The rectangular outer slot and inner slot are respectively opened at a circumferential interval of 120° on the surface of the body barrel and the speed regulating cylinder, and the speed regulating cylinder is nested inside the body barrel and its end is connected to the flow discharge motor. When the flow discharge motor drives the speed regulating cylinder to rotate, the overlapping area of the inner slot and the outer slot changes, and the purpose of controlling the moving speed of the in-pipe robot is realized by the change of the discharge flow of the regulating fluid.



1-pipe wall, 2-driving cup, 3-speed regulating cylinder, 4-flow discharge motor, 5-body barrel, 6- internal opening, 7-fluid inlet, 8- external opening

Fig. 2 Schematic of the structure of the fluid driving unit.

III. THE FLUID DRIVING FORCE MODELING OF IN-PIPE ROBOT

In order to analyze the motion of the in-pipe robot under the fluid force, the fluid driving force model in the pipe was established, as shown in Fig. 3.

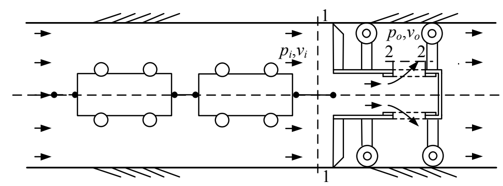


Fig. 3 The model of the fluid driving force of in-pipe robot.

Assuming that the pressure and velocity corresponding to the flow cross section 1-1 and 2-2 are p_i, v_i and p_o, v_o, respectively, and based on the theory of fluid mechanics, the fluid driving force F of the in-pipe robot can be expressed as

$$F(\psi_r) = \kappa D^4 (1-\lambda^2) \left(\frac{v_i - v_r}{\lambda l \psi} \right)^2 \tag{1}$$

with

$$\begin{cases} \kappa = 112.5\pi\rho C_i \xi_r \\ \lambda = d / D \end{cases} \tag{2}$$

Where, D is the inner diameter of the pipe, d is the inner diameter of the barrel, and l is the length, ρ is the fluid density, C_i is the surface coefficient, ξ_r is the local resistance coefficient, v_i is the fluid medium velocity, v_r is the robot moving speed, and ψ is the discharge opening angle. The moving speed of in-pipe robot directly depends on the opening angle of the outlet and the velocity of the fluid, therefore, the fluid driving speed of the in-pipe robot is controlled mainly based on the parameters ψ.

IV. SPEED REGULATION PLANNING AND ENERGY CONSUMPTION MODELING FOR IN-PIPE ROBOT

In-pipe robot usually requires fast moving and low speed inspection when performing inspecting tasks, therefore, it is necessary for in-pipe robot to have strong speed control capability to ensure the inspection quality and reduce the driving energy consumption.

A. Speed Control of the in-Pipe Robot Moving Fast

Under the rapid inspection condition, the driving force for the robot moving in the pipe is the fluid kinetic energy and the static pressure energy, the moving speed of the robot is adjusted by the discharge speed regulation mechanism, the differential equation of the fast motion of the robot is

$$m\frac{\mathrm{d}v_{rapid}}{\mathrm{d}t}=F(\psi_{rapid})-\mu_\theta G \tag{3}$$

with

$$\mu_\theta = 2\mu_f - \mathrm{sgn}(\varepsilon)\cdot\sin\theta \tag{4}$$

Where, v_{rapid} is the running speed of the in-pipe robot in the fast moving phase, μ_f is the adhesion coefficient between the support wheels and pipe wall, G is the gravity of the in-pipe robot, θ is the pipe inclination angle, $\mathrm{sgn}(\varepsilon)$ is the symbolic function, with +1 is the downhill motion, 0 is the horizontal motion, and -1 is the uphill motion. Therefore, when the speed control for the in-pipe robot driven by the fluid force is realized by changing the value of the parameter ψ, the driving energy consumption for the robot moving in the pipe is mainly energy consumption of speed regulation of discharge motor.

B. Speed Control for Slow Down Drive

In the low speed inspection condition, the in-pipe robot must undergo a deceleration process in advance in order to transition from the rapid inspection condition to the low speed inspection condition, at this time, the deceleration speed is much smaller than the fast running speed, that is $v_{slow} < v_{rapid}$. Assume that the maximum distance that allows the in-pipe robot to slow down in advance is $x_{\max}$, when the in-pipe robot moves at constant speed under the condition of fast moving, $dv_{rapid}/dt=0$, according to (3), The minimum moving speed that the in-pipe robot can be obtained by the speed regulation of the discharge mechanism is

$$(v_{rapid})_{\min}=v_i-\frac{\lambda l\psi_{\max}}{D^2}\sqrt{\frac{\mu_\theta G}{\kappa(1-\lambda^2)}} \tag{5}$$

During the speed regulation process of the discharge mechanism, the moving distance of the in-pipe robot is

$$x_{down}=\int v_{rapid}dt \tag{6}$$

For the in-pipe robot runs under the condition of deceleration transition, when $(v_{rapid})_{\min}\le v_{slow}$ and $x_{down}\le x_{\max}$ only through the speed regulation of the discharge mechanism can meet the speed requirements for the in-pipe robot in the low speed inspection conditions before it reaches the area to be inspected. When $(v_{rapid})_{\min} > v_{slow}$ or $x_{down} > x_{\max}$, the parameters $\mathrm{sgn}(\varepsilon)$, θ and v_i have a significant effect on the moving speed of the robot, which exceeds the deceleration ability of the discharge mechanism. Therefore, the driving wheel braking mode is considered to ensure the controllable speed of the robot under the condition of deceleration transition.

The braking effect of three groups of driving wheels of the robot on the motion of the robot in braking mode can be equivalent to a total driving wheel, the total braking torque produced by the speed reduction control is as follows

$$\begin{aligned}T_1 &= (F(\psi_{down})-\mu_\theta G)r\\ &-\mu_w\sum N_{adjust}-\left(\frac{mr^2+3J}{r}\right)\cdot\frac{\mathrm{d}v_{down}}{\mathrm{d}t}\end{aligned} \tag{7}$$

Where, J is the moment of inertia of a single driving wheel, m is the mass of the driving wheel, r is the radius of the driving wheel, μ_w is the rolling friction coefficient of the driving wheel, and $\sum N_{adjust}$ is the sum of the adjustable closed force when the driving wheel meets the braking. Equation (7) shows that the braking torque required for robot speed reduction and control is related to pipeline inclination angle θ and robot real-time speed v_{down}. When the moving speed of the in-pipe robot meets the requirements of constant low speed inspection, there is $dv_{rapid}/dt = dv_{slow}/dt = 0$, the total braking torque of the DC motor under low speed inspection condition can be given as

$$T_{slow}=(F(\psi_{slow})-\mu_\theta G)r-\mu_w\sum N_{adjust} \tag{8}$$

C. Energy Consumption Model of Composite Drive

In the composite driving process of the in-pipe robot, the moving speed of the in-pipe robot is adjusted by the fluid driving force, so it is necessary to establish the energy consumption model of the driving unit about the fluid speed regulation. According to the structure composition of the fluid driving unit system shown in Fig. 2, the discharge motor transmits its torque to the speed regulating cylinder through the primary transmission coupling. Using the equivalent inertia theory, based on the Lagrange equation, the equivalent dynamic equation of the DC motor shaft is established as follows

$$\tau_{motor}=\left(\frac{J_2+J_{load}}{g_T^2}+J_1\right)\ddot{\theta}_1+\tau_{f1}+\frac{1}{g_T}(T+\tau_{f2}) \tag{9}$$

with

$$g_T=\frac{\dot{\theta}_1(t)}{\dot{\theta}(t)} \tag{10}$$

Where, τ_{motor} is the output torque of discharge motor shaft, J_1 is the moment of inertia of the motor output shaft and the coupling high speed shaft, J_2 is the moment of inertia of the low speed shaft of the coupling, J_{load} is the moment of inertia of the speed regulating cylinder, $\dot{\theta}_1$ and $\ddot{\theta}_1$ are the angular velocity and angular acceleration of the high speed axis respectively, and $\ddot{\theta}_1 = d\dot{\theta}_1(t)/dt$, $\dot{\theta}$ is the angular velocity of the low speed axis, τ_{f1} is the friction torque on motor shaft and coupling high speed shaft, and the LuGre computing model is usually adopted, τ_{f2} is the friction torque of the low speed axis, g_T is the reduction ratio of the coupling, T is the resistance moment generated by gravity and friction of the speed regulating cylinder.

In addition, the power consumption of the discharge motor mainly includes two parts, one is the effective work output of the motor, the other is the heat loss of the motor and the friction heat of the machine, given as follows

$$P = \frac{\tau_{motor}\ddot{\theta}_1}{\eta_1} + \left(\frac{\tau_{motor}}{K_T g_T \eta_1}\right)^2 R_z \tag{11}$$

Where, η_1 is the transmission efficiency of discharge motor, K_T is the torque constant coefficient, R_z is the armature resistance of the discharge motor.

Therefore, the total energy consumption of the motor speed regulation of the fluid drive unit is given as follows

$$E(t) = \int P dt \tag{12}$$

D. Numerical Simulation of Energy Consumption

In order to reduce driving energy consumption and improve the utilization rate of the limited energy, based on the established composite driving speed regulation mode and the driving energy consumption model, the combined simulation analysis is carried out by using the virtual prototype technology and the MATLAB software.

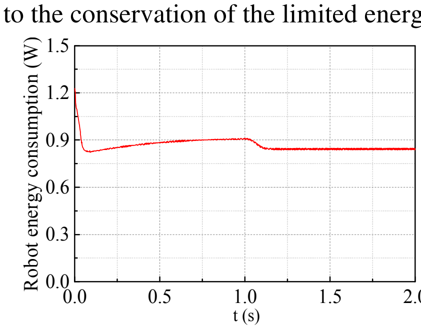
If the heat dissipation loss of the motor is ignored, the calculation model of the energy consumption performance objective function of the composite driving in-pipe robot can be given as

$$P_e = \frac{\sum_{i=1}^{n}\int_0^t T_i \dot{\theta}_i \mathrm{d}t}{t} \tag{13}$$

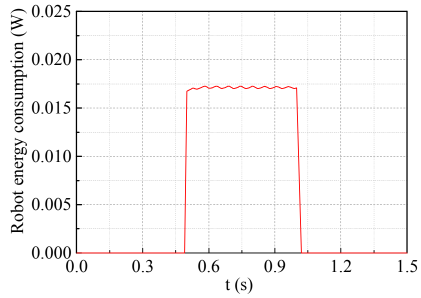
Where, P_e is the average driving power consumption of the in-pipe robot, T_i is the torque of driving wheel in each movement stage, $\dot{\theta}_i$ is the angular velocity of the driving wheel in each movement stage, and t is the total running time.

The driving mode of the composite driving in-pipe robot is the superposition of the motor drive and the fluid drive, and according to the needs of the inspection, the composite driving conditions of the in-pipe robot can be divided into three types. The first working condition is based on the combined driving of the motor and the fluid during the low-speed inspection process of the in-pipe robot, and the moving speed of the in-pipe robot is regulated by the fluid driving unit to meet the inspection speed requirement. The second working condition indicates that the composite driving in-pipe robot is driven by the separate fluid and the opening of the discharge outlet is controlled to achieve the purpose of regulating the speed of the robot's locomotion. The third working condition corresponds to the deceleration transition stage of the in-pipe robot from the fast moving condition to the low-speed inspection condition, and in this stage, in order to reach the fluid driving speed of the in-pipe robot to meet the requirements of the low-speed inspection condition, the energy consumption braking is adopted for deceleration control.

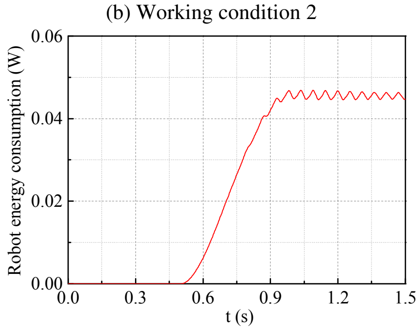
Figure 4a shows that the moving speed of the in-pipe robot is adjusted by the fluid driving unit, and when the fluid driving force increases, the driving power consumption will decrease. Figure 4b shows that the requirements of moving speed regulation can be realized by controlling the opening of the discharge outlet with independent fluid driving, and the energy consumption of the discharge motor increases in the process of speed regulation. As shown in Fig. 4c, the energy consumption of the in-pipe robot increases continuously after the adoption of energy consumption braking, compared with the fluid driving speed regulation scheme in the second working condition, the driving energy consumption of the in-pipe robot increases significantly and the in-pipe robot needs to constantly consume the limited energy in order to keep moving at a low speed. Therefore, the fluid driving speed should be adjusted to the maximum in the transition stage of deceleration, if the moving speed of the in-pipe robot is still unable to meet the speed requirements of the low-speed inspection, the deceleration should be carried out by connecting the motor braking. Obviously, this is not conducive to the conservation of the limited energy.



(a) Working condition 1



(b) Working condition 2



(c) Working condition 3

Fig. 4 Energy consumption of composite driving in-pipe robot

V. Energy Consumption Experiment of the Composite Driving in-Pipe Robot

A. Experimental Setup and in-Pipe Robot Prototype

The experimental setup and the in-pipe robot experimental prototype are shown in Fig. 5. The inspection pipe is made of acrylic material, with an inner diameter of 190mm and a length of 1200mm, there are three sections in total, each section is connected by a flange, and both ends are sealed by rubber, the inlet and outlet are arranged respectively, and water is used as the fluid medium. The submersible pump head 13m, flow 1.5m^3/h, rated power 550W. In addition, the experimental setup also includes water storage bucket, PPR tube, ball valve and corresponding seals. By adjusting the ball valve at the inlet and outlet, the pressure at the inlet can be maintained constant when the fluid flows steadily in the pipe. The total weight of the in-pipe robot experimental prototype is 2.52kg, and the total length of the body is 270mm.


(a) Experimental platform (b) In-pipe robot prototype

Fig. 5 The experimental setup

B. Analysis of the Experimental Results

The output pressure of the controlled pump is 0.1 MPa, 0.15 MPa, 0.2 MPa, 0.25 MPa, and 0.3MPa respectively, and the driving wheel passes through the pipe at a uniform velocity of 0.4 m/s, 0.3 m/s and 0.2 m/s, respectively. The main driving force of the in-pipe robot comes from the fluid pressure, when driven by the motor, the in-pipe robot moves at a low speed, generates less heat loss and is difficult to measure, so it can be ignored. Therefore, in the experiment, the main current in each cycle is measured by the current sensor, and the average current of the in-pipe robot moving in the whole pipe is calculated, as shown in Table I. In this way, the average energy consumption of the composite driving in-pipe robot can be obtained as shown in Table II.

According to the data shown in Table II, we can draw and fit the energy consumption change curve of the composite driving in-pipe robot under different output pressures, as shown in Fig. 6. It can be seen that under different motor driving speeds, when the output pressure is higher, the energy consumption of the corresponding composite driving is lower, and the control effect of energy-saving motion of the robot is more significant. The higher the motor driving speed, the lower the opening of the outlet can effectively improve the efficiency of the robot's limited energy. Therefore, the regulation mode of fluid drive can significantly reduce the energy consumption of the composite drive, but the fluid driving force has a non-linear relationship with the energy consumption of the composite drive.

TABLE I
Average Main Current

Robot velocity [m/s]	Fluid pressure [MPa]				
	0.10	0.15	0.20	0.25	0.30
0.4	0.151	0.143	0.126	0.097	0.061
0.3	0.131	0.122	0.105	0.084	0.058
0.2	0.113	0.104	0.093	0.079	0.056

TABLE II
Average Power of Compound Driving

Robot velocity [m/s]	Fluid pressure [MPa]				
	0.10	0.15	0.20	0.25	0.30
0.4	3.632	3.442	3.034	2.336	1.440
0.3	3.152	2.932	2.515	2.022	1.392
0.2	2.709	2.501	2.232	1.919	1.344

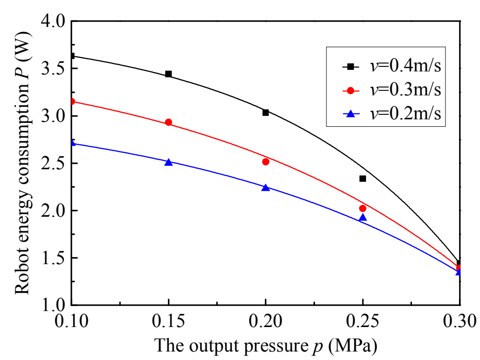


Fig. 6 Energy consumption change under different output pressures

VI. Conclusion

In this paper, a kind of composite driving mode of in-pipe robot which can superimpose fluid driving and motor driving is proposed. By establishing the fluid dynamics model of the speed adjustment mechanism, the speed regulation characteristics are analyzed, and the energy consumption model is further established, the energy consumption law of the composite driving under the robot inspection condition is studied, and the following conclusions are obtained.

By switching the speed-regulating mechanism of the flow discharge, the rapid moving of the composite driving in-pipe robot under the action of superimposed fluid driving force, its energy consumption is mainly the energy consumption of the motor and transmission system of the speed-regulating mechanism, and is affected by the speed-regulating mode, which can be used as the basis for evaluating the rationality of the structural design of the speed-regulating mechanism.

The relative motion speed between the in-pipe robot and the fluid medium affects the driving ability of the fluid, and it is related to the opening degree of the speed-regulating mechanism of the flow discharge. Both the low speed and high speed fluid are adverse to the motion of the in-pipe robot, which cannot realize the advantage of the composite drive and is not conducive for the in-pipe robot to the long-distance locomotion and inspection.

The composite driving in-pipe robot with fluid as the main driving force can reduce the restriction of the closing force on the driving ability of the supporting mechanism of the in-pipe robot, thus reducing the energy consumption caused by moving friction resistance and saving the limited energy.

The composite driving in-pipe robot needs to be sealed reliably, excessive fluid pressure increases the difficulty of the motor sealing and the driving efficiency loss caused by the sealed motor. Moreover, the lengthening of the in-pipe robot body size due to the sealing will affect its passing through the curved pipe with small curvature. Therefore, further research is needed in the future.

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