Sensors & Transducers, Vol. 172, Issue 6, June 2014, pp. 308-312

Sensors & Transducers

Numerical Simulation for Inspection Robot Movement in Downhill Pipeline

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Received: 31 March 2014 /Accepted: 31 May 2014 /Published: 30 June 2014

Abstract: The downhill running of robot in vertical pipe is a special case for robot running inside the whole “U” type pipe, in which case the speed variation fluctuates greatly. The thesis makes a specific analysis of the force situation of the robot running downhill in the inclined pipe, carries out analog simulation of the fluid pressure and speed change of robot with the dynamic grid technique of Fluent, and finally gets the fluid pressure and speed change rules, thus providing theoretical basis for further effective means in the robot speed control. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Pipeline robot, Downhill Pipeline, Speed fluctuation, Fluent, Numerical simulation.

1. Introduction

At present, there are 93000 km pipelines in China, and the oil and gas pipeline network covering the whole China has preliminarily formed. It is expected that, in 2015, China's oil and gas pipeline mileage will reach 150,000 km [1].Generally, long oil and gas pipelines are built along with the terrain. With the different elevations and horizontal winding of land surfaces, pipelines often have many bending and tilting parts. As shown in Fig. 1, a-b, e-f, i-j are horizontal parts of the pipe, b-c, d-e, f-g, h-i, c-d, g-h are inclined parts. The whole pipeline presents a “U” glyph in the vertical cross section, called the “U” type pipe.

Studies on the motion law of inspection robot in horizontal pipeline are described in [2-5]. The paper [6] analysis the factors influencing the speed of differential-pressure-driven in-pipe inspection robot in horizontal pipeline, and carried out numerical simulation of robot`s speed fluctuation processes, based on previous similar researches, with the help of dynamic grid technique by Fluent software, then the laws of influence of various factors on robot`s velocity fluctuation process are summarized, and the causes of robot`s velocity fluctuation is illustrated [6].

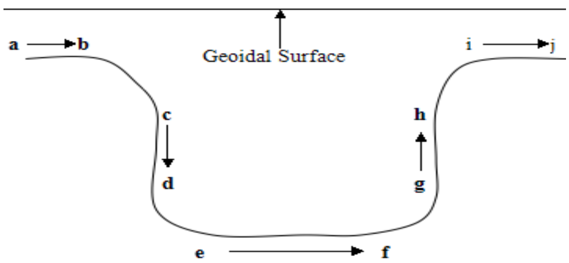

Fig. 1. Diagram of Oil and Gas Pipeline in Ramp Section.

But, the study on the robot movement in inclined pipeline, especially in vertical pipeline is very rarely. When the robot getting into and out of the inclined or vertical pipelines, the friction between robot and the pipe inner walls will change, and the axial force of

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robot will vary too, which causes change of robot`s driving force and speed.

In particular, too fast speed of the robot running in downhill pipe, will not only lead to unsatisfactory collection of defect signals or failure of signal detection. What`s worse, due to the excessive running speed, the pipeline and operation equipment may be easily impacted and the robot will be damaged. Therefore, analysis of the running speed of robot in downhill pipe, study of its speed changing rules, and control to its speed with targeted and effective means, are premises for the improvement of defect detection accuracy and reduction of safety accidents.

2. Dynamics Analysis of Robot in Downhill Pipeline

Fig. 2 shows the model of the physical map of the pipeline robot, it has the shell, flanges, end caps, sports wheels and supporting frame of five parts. Consider the support frame removed, the robot simplified to a cylinder, the robot with the pipe becomes a symmetrical axis of rotation, so that the robot run in the pipeline can be simplified to a two-dimensional axisymmetric problem further.

Fig. 2. Figure of Robot Model in Pipeline.

Compared with horizontal straight pipe, the inclined pipe has a tilt angle θ. The following Fig. 3 describes the running of robot in medium-filled inclined pipe.

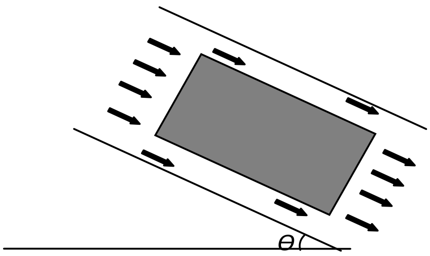

Fig. 3. Diagram of Robot Running in the Medium-filled Inclined Pipe.

When the robot runs in the downhill pipe, its gravity along the axial component $mg\sin\theta$ is in the same direction with the robot's movement, thus increasing the driving force in case of the robot's running. The driving force will thus facilitate its forward movement and will increase with the increased angle. At the same time, the friction produced by robot's radial component force $mg\cos\theta$ to the pipe wall also changes, decreasing with the increased angle.

Therefore, the force situation of the robot becomes complicated, and is closely related to the angle θ. According to Newton's second law, the dynamics equation of the robot is:

$$m\frac{dv}{dt} = \frac{\pi D^2}{4}(P_a - P_b + P_d) + mg\sin\theta - \mu(N_0 + mg\cos\theta) \tag{1}$$

v: Speed of robot;

P_d: Fluid dynamic pressure effect on the robot positive side;

P_a-P_b: Differential pressure between the both ends of the robot;

m: Mass of robot;

μ: Friction coefficient;

N_0: The pressure between wheels and tube wall;

θ: Inclination angle of pipe ($-90^o \leq \theta \leq 90^o$)

It can be seen from the above equation:

1) When the Angle θ is small, $mg\sin\theta < \mu(N_o + mg\cos\theta)$, the axial component of the gravity is also small, and the driving effect on robot is relatively small. With the increase of Angle θ, the driving force on the robot is bigger and bigger, the frictional resistance is smaller and smaller, and so the robot gets accelerated velocity and speeds ahead. With the increase of robot's speed, the differential pressure P_a-P_b+P_d at both ends of the robot decreases, the differential driving force on the robot decreases, and the robot can achieve a new state of uniform speed. The greater the Angle θ is, the faster the robot will run.

2) With further increase of Angle θ until the robot's velocity v increases to be the same with the fluid velocity u, no throttle is between the fluid and robot, at that moment, P_a=P_b, $P_d = \frac{1}{2}C\rho(u^2 - v^2)$=0, therefore, $P_a - P_b + P_d$=0. Then, $mg\sin\theta = \mu(N_0 + mg\cos\theta)$.

3) As the Angle θ continues to increase, $mg\sin\theta > \mu(N_0 + mg\cos\theta)$, the driving force on the robot increases, and the robot speeds up. At this point, the robot's speed v is greater than the fluid speed u, and the pressure difference P_a-P_b+P_d on the robot is negative, hindering the forward movement of the robot. The pressure drag increases as the acceleration of the robot, leading to a new running state with uniform speed for the robot.

4) When θ=90°, that is, robot runs downhill in the vertical pipeline, equation (1) can be transformed into:

$$m\frac{dv}{dt}=\frac{\pi D^2}{4}(P_a-P_b+P_d)+mg-\mu N_0, \quad (2)$$

As shown in the equation, as the robot's gravity is all transformed into driving force, the robot gets the biggest driving force and smallest resistance when other conditions are the same, and the variation in the speed of the robot is the largest. In order to obtain enough driving force, under the condition of horizontal pipeline, $mg>\mu N_o$. Therefore, after the robot enters into vertical slope, its speed will increase, and only when the robot speed v is greater than the fluid velocity u, and P_a-P_b+P_d is negative, can $m\frac{dv}{dt}$ be equal to 0 and can the robot move forward with uniform speed. If robot runs too fast or even reaches or exceeds the fluid velocity, not only the precision of the pipeline defect detection will be affected, but also impact will be easily caused with the bottom of inclined pipe to damage the robot's components.

3. Velocity Simulation of Robot Running Downhill the Vertical Pipeline

Vertical pipe is one of limit conditions when the robot runs through pipes with different angles, so the simulation of running situation of the robot in the vertical pipeline can be considered.

In Gambit software, the two-dimensional projection of a vertical pipeline can be established as the flow field area in the process of robot running. The computational domain of robot can select a bar area of 0.2 m upstream and 1 m downstream, the origin of which is the robot's centroid. The fluid direction is from top to bottom and fluid velocity is 0.8 m/s. Since the pipe angle cannot change, and the friction between robot and the pipe wall can be adjusted through other means, therefore, the main focus of this study is the influence of the friction on the robot speed in the vertical pipe. The author chooses the robot with D=120 mm, sets different frictions respectively as 5 N, 10 N, 20 N, 30 N, 40 N, and simulates the robot running in the pipe. As normally the robot has initial velocity when it enters into the vertical pipeline, it will be more practical to set the initial velocity of the robot the same as its steady speed when running in a horizontal pipeline with the same parameters when the downhill running of robot in the vertical pipe is simulated.

In the process of simulation, the boundary conditions and calculation method are the same with those in the case of horizontal pipeline, and dynamic grid is adopted to make grid dispersing. The computational field of the flow field where the robot with D=120 mm stays is dispersed with quadrilateral grid, as shown in the Fig. 4.

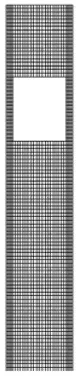

Fig. 4. Figure of discrete grid.

3.1. Flow Field Pressure Variation in the Downhill Running of Robot in Vertical Pipeline

The author, using fluid mechanics simulation software Fluent and dynamic grid technique, writes a user-defined function, and establishes a grade pipeline flow field model with a diameter of 120 mm, fluid velocity of 0.8 m/s and the friction of 5 N for the robot. Partial map of the robot's running state is shown in Fig. 5.

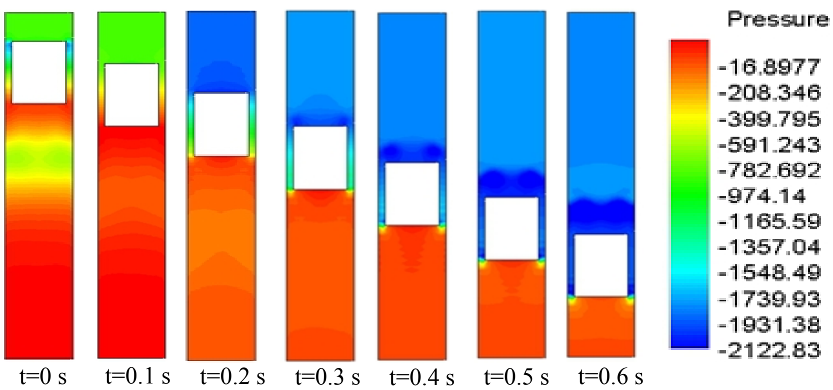

Fig. 5. Local figure of robot running state.

3.2. Analysis of Fluid Field Gage Pressure Affected by Different Friction

Pipeline fluid velocity is set as 0.8 m/s, the quality of the robot 3 kg, and frictions 5 N and 40 N. In the simulation, the author substitutes the stable speed of the robot in horizontal pipeline under different friction conditions into the initial velocity of the robot downhill the vertical pipeline, intercepts the gauge pressure cloud pictures of robot on both ends at stable running, and reads the gauge pressure at the both ends. As shown in the Fig. 6. Different flow field situations of the robot in the pipeline can be seen when the frictions are respectively 40 N and 5 N. And the gauge pressure difference on both ends can be seen when the frictions are respectively 5 N and 40 N in the Table 1 below.

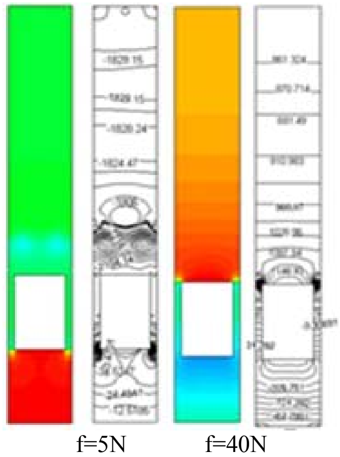

Fig. 6. The flow stress of robot at stable runtime under the conditional of two kinds of friction.

Table 1. The pressure size between both ends of robot at stable runtime under the two kinds of frictions.

	Gauge pressure for robot back-end (Pa)	Gauge pressure for robot front-end (Pa)	Pressure difference (Pa)	Differential pressure force (N)
f=5 N	-2014.1	-24.5	-1989.6	-22.5
f=40 N	1211.9	-265.8	1477.7	16.7

As shown in the Fig. 6 and Table 1:

1) When the robot runs downhill in the vertical pipe, the value of friction force can affect the variation of pipeline flow field.

2) When the friction force is relatively small, the front gauge pressure is bigger than that in back-end, pressure difference formed by which is in the opposite direction of the robot movement.

3) When the friction force is relatively large, the front gauge pressure is smaller than that in back-end, pressure difference formed by which is in the same direction of the robot movement.

3.3. Analysis of Robot's Speed under Different Frictions

Pipeline fluid velocity is set as 0.8 m/s, and the quality of the robot 3 kg. The author substitutes the stable speed of the robot in the horizontal pipeline under different friction conditions into initial velocity of the robot downhill the vertical pipeline, observes variations of the robot speed, as shown in the Fig. 7, and records the stabile speed of the robot downhill the vertical pipe, as shown in the Table 2. And the stable speeds of the robot under different frictions are drawn into curve, as shown in the Fig. 8.

As shown in the Table 2 and Fig. 8:

1) Friction between the robot and the pipeline wall affects the stability of the robot speed. The greater the friction is, the smaller the stable speed of the robot is.

2) When the friction force is relatively small, the speed of the robot running downhill increases rapidly and exceeds the fluid velocity, so it will run stably with higher speed than the fluid velocity.

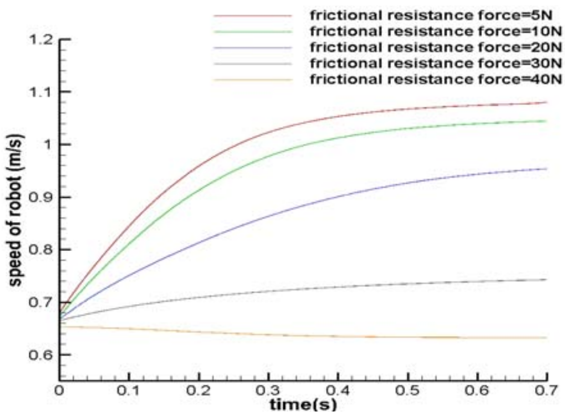

Fig. 7. The stable speeds curve of robot under different frictions.

Table 2. The relationship between frictional resistance and robot's stable speed when robot downhill in vertical pipeline.

Frictional force(N)	Speed of robot (m/s)
5	1.128
10	1.045
20	0.983
30	0.762
40	0.597

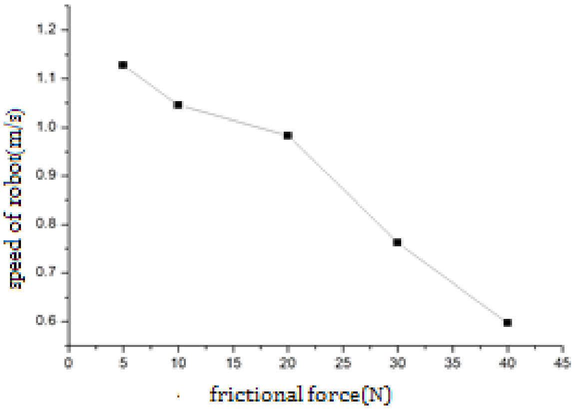

Fig. 8. The relationship curve between frictional resistance and robot's stable speed when robot downhill in vertical pipeline.

3) When the friction force is relatively large, the speed of the robot running downhill decreases rapidly, running with lower speed than that of the robot running stably in the pipeline.

To sum up, when the robot runs downhill, the robot speed can be effectively controlled by adjusting the friction force between the robot and the pipeline wall.

4. Conclusion

In this thesis, the author makes detailed analysis of the force situation of the robot running downhill in the pipeline under different inclined angles, and conducts numerical simulation of the movement of robot running downhill in vertical pipeline with dynamic grid technique of Fluent software. Simulation results show that: under the condition of small friction, the front-end gauge pressure is bigger than the back-end pressure, and the differential pressure force and robot movement are in opposite directions; under the condition of large friction, the front-end gauge pressure is smaller than the back-end pressure, and the differential pressure force and robot movement are in the same direction; the greater the friction is, the smaller the stable speed of the robot is. In conclusion, when the robot runs downhill, the robot speed can be effectively controlled by adjusting the friction force between the robot and the pipeline wall.

Acknowledgements

The project is supported by the People Libration Army General Logistics Department of China (Oil 20040207).

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