Multilink Micro Robots Designed for Inspection in Pipes of Small Diameters

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Abstract: The importance of designing robotic platforms for pipes of small diameters inspection is connected with necessity of efficiency improvement in technical diagnostics of pipelines of different use, especially in mechanical engineering. This paper is devoted to in-pipe micro robot design. Different techniques of the robot's motion inside a pipeline have been discussed. The proposed design of the in-pipe robot may be used in experimental investigation of different inspection techniques. The method of determining the speed of micro robot allows finding the speed of micro robot when it moves in different environments with different viscosity under the absence and presence of excessive pressure in the piping system.

1 INTRODUCTION

Research and development of miniature robots for movement in pipes is actively conducted in the UK, Sweden, Italy, Germany, USA, Arab Emirates, China and Japan. Robotics operations for inspection and repair of pipelines are based on international and national R&D programs.

There are many papers devoted to R&D of miniature robots and control systems for them (Valdastri et al., 2009; Becker et al., 2010). We apply our design for pipes of small diameters (4-10mm) only. The importance of designing robotic platforms for pipes of small diameters inspection is connected with necessity of efficiency improvement in technical diagnostics of pipelines of different use, especially in mechanical engineering. Especially such robotic platforms are useful in coolant pipes for steamers in nuclear energy systems.

One of the main methods of moving inside curved pipelines arbitrarily located in space is stepping method. Tracks and wheeled chassis with clamping wheel to the surface are also used for moving inside pipes (Gradetsky et al., 1998; Gradetsky et al., 2005).

To move in pipelines filled with liquid (water, oil, flammable substances and polymer solutions) the robotic platform should create mechanical waves along its hull. In order to provide such waves these robotic platforms are equipped with piezo drives. Each drive consists of thin ceramic plates, which are able to bend themselves under certain voltage and returns to the original state under voltage outage. Another technique of obtaining waves along the robot's hull is application of polypyrrole as organic conductive polymer able to contract under voltage (Gradetsky et al., 2003; Gradetsky et al., 2005).

All robotic platforms mentioned above have moving elements outside the hull. Therefore reliability of such robots is decreased due to constant interaction between moving hull elements and surface of the pipeline.

2 THE IN-PIPE ROBOT WITH MOVEMENT BASED ON MICRO IMPACTS

The current level of development of mechatronic devices for technological operations is aimed at the intellectualization of all processes in mechatronic system. The first place is given to control of functional movements of robots. For micro robots this means the increasing autonomy of their behavior, the possibility to operate in offline mode, the transmission of diagnostic information to the operator in a convenient visual and graphical form.

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The in-pipe robotic module (Figure 1) consists of middle link – mover 1 and two terminal links – brakes 2. The mover is electromagnetic unit made of solenoid coil 3 and ferromagnetic core 4. The ferromagnetic core has a recoil spring 5. Two terminal links have solenoid coil 6, ferromagnetic core 7 and recoil spring 5. The ferromagnetic core 7 is supplied with adjustable brake element 9. It provides brake effect during robot's motion inside the pipeline. The adjustable brake element 9 includes two lamellar elastic retainers 10 and 11 which are designed to provide significant brake force in desired direction depending on ferromagnetic core 7 position. The links are interconnected by swivels 12. It provides turning of the robot in pipeline bending. Such kind of robotic design provides inspection of small diameter pipes with sufficient speed and it can be used in such environment as liquid.

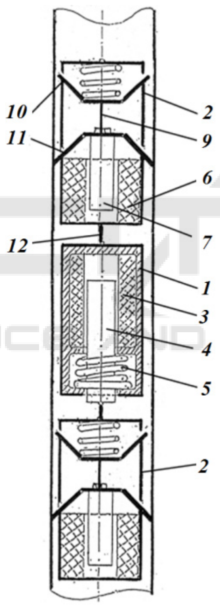

Figure 1: The in-pipe robot with modules.

The design of each robotic module involves the use of standard elements. The power supply system consists of common micro batteries.

The principle of the robot's movement is as follows. The electromagnetic core is moving inside the robot's hull. It strikes the frontal part of the hull and sends an impulse to it (Chaschukhin, 2008; Rizzotto et al., 2003). Thus the hull starts moving forward. After full stop of the hull the ferromagnetic core returns back slowly. Meanwhile the hull stands still due to friction force. The cycle then repeats.

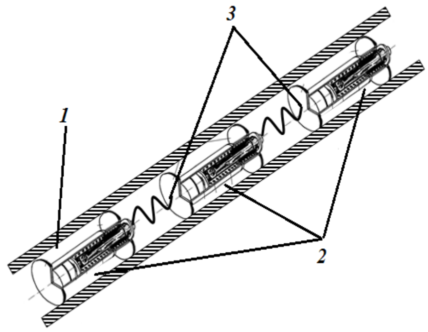

Figure 2: The multilink in-pipe micro robot design: 1 – pipe, 2 – robotic modules, 3 - interconnections.

The proposed design of the miniature robot has no any moving parts outside the robot's hull thus it has increased reliability. The outer diameter of the hull is smaller than the inner diameter of the pipe. The figure 2 shows that the multilink micro robot consists of several basic modules. The calculation technique for the proposed design is based on energy conservation law (Bolotnik et al., 2014). The process of impacting the ferromagnetic core on the frontal part of the robot's hull is described as follows.

$$\begin{cases} mv + MV = mv_0 \\ \frac{mv^2}{2} + \frac{MV^2}{2} + Q = \frac{mv_0^2}{2}, \end{cases} \quad (1)$$

Here m and M are masses of the ferromagnetic core and the hull; v and V are velocities of the ferromagnetic core and the hull after impact; Q is thermal energy which is known for the certain design.

The solution for the system mentioned above is:

$$\begin{cases} v = \frac{m}{m+M}\left(v_0 - \frac{m+M}{m}\sqrt{v_0^2 - \left(1 + \frac{m}{M}\right)\frac{2}{m}Q}\right) \\ V = \frac{m}{m+M}\left(v_0 + \sqrt{v_0^2 - \left(1 + \frac{m}{M}\right)\frac{2}{m}Q}\right) \end{cases}, \quad (2)$$

Here we can see that velocity of the hull grows with $Q \to 0, \frac{m}{M} \to \infty$ Let us estimate the system after impact. Let the ferromagnetic core has the position coordinate along x_1 axis, and the hull has the position coordinate along x_2 axis. The stiffness coefficient of the spring let be k, and the friction force between adjustable brake element and the pipeline inner surface let be F_{fr}. Then the equations of the system's motion are the following.

$$\begin{cases} m\ddot{x}_1 = -k(x_1 - x_2) \\ M\ddot{x}_2 = -k(x_2 - x_1) + F_{fr}, \end{cases} \quad (3)$$

The solution for the system will be the following:

$$\begin{cases} x_1(t) = C_1 + C_2 t + F_{fr}\frac{1}{2(m+M)}t^2 + \\ \quad +C_3\cos(\omega t) + C_4\sin(\omega t) \\ x_2(t) = C_1 + \frac{m}{k(m+M)}F_{fr} + C_2 t + \\ +F_{fr}\frac{1}{2(m+M)}t^2 - C_3\frac{m}{M}\cos(\omega t) - \\ \quad -C_4\frac{m}{M}\sin(\omega t) \end{cases}, \qquad (4)$$

Here $\omega = \sqrt{k\frac{m+M}{mM}}$; $C_1 \dots C_4$ are constants.

If we suppose the system below to be the initial condition

$$\begin{cases} x_1(0) = x_0 \\ \dot{x}_1(0) = v \\ x_2(0) = y_0 \\ \dot{x}_2(0) = V \end{cases}, \qquad (5)$$

then for $C_1 \dots C_4$ constants we can obtain the next result

$$\begin{cases} C_1 = \frac{M}{m+M}\left(\frac{m}{M}x_0 + y_0 - \frac{m}{k(m+M)}F_{fr}\right) \\ \quad C_2 = \frac{M}{m+M}\left(\frac{m}{M}V - v\right) \\ C_3 = \frac{M}{m+M}\left(\frac{m}{M}x_0 - y_0 + \frac{m}{k(m+M)}F_{fr}\right) \\ \quad C_4 = \frac{M}{m+M}\frac{1}{\omega}(v - V) \end{cases}, \qquad (6)$$

The use of these equations requires experimental clarification. But it can provide the evaluative calculation of movement modes for different design types of the robot.

3 THE IN-PIPE IMPACTLESS MICRO ROBOTS

There is another way of motion for in-pipe micro robots with the design mentioned above (Gradetsky et al., 2011; Gradetsky et al., 2012; Virk, 2012). It does not need any impacts to move (Figure 3).

The design of such type of in-pipe robot includes the Inner rod 1 and the Outer hull 2. The Inner rod has the spring 3 that pushes the rod outside the hull after voltage cut off in the electromagnetic coil 4. The Inner rod and the Outer hull have their own adjustable brake elements 5. Each brake element has friction anisotropy (Pan, 2003.).

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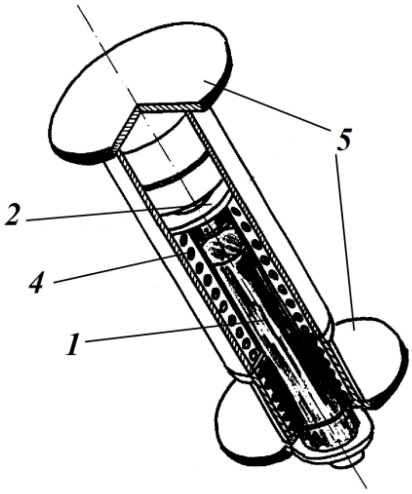

Figure 3: The in-pipe impactless micro robot.

elements are designed to prevent backward moving. Meanwhile the friction between the surface of the pipe and the brake element is not enough to stop the micro robot when it moves forward. When the robot receives a task for moving it adjusts its brake elements according to the desired direction. Then a bunch of square impulses from the control unit come to the electromagnetic coil. The cycle repeats in a short time. Thus the robot moves under pulling and pushing cycles.

The calculation technique for the motion parameters of the robot is based on assumption that it moves in rectilinear pipe which axis has an angle β with the horizon. Let $x_i (i = 1,2)$ be absolute coordinates of the Inner rod and the Outer hull along that axis; $m_i (i = 1,2)$ be masses of the Inner rod and the Outer hull accordingly; the factor *k* be the stiffness factor of the spring. The *g* is acceleration of gravity. Initial points have been chosen with the assumption that the spring is not deformed when $x_1 = x_2 = 0$. The Inner rod is pulled inside the electromagnetic coil under electromagnetic force *F*. The elastic force of the spring $k|x_2 - x_1|$ is acting on the Inner rod and the Outer hull. The other forces acting on the system are gravity $m_i g$ and reaction forces N_i in brakes. The force of dry friction F_{fri} and the resistance force of the environment $D_i\dot{x}_i$ are also acting on the robot. Here *D* stands for the resistance factor of the environment that may vary for different parts of the micro robot. Thus equations of motion for the robot given as a system with two masses are the following:

$$\begin{cases} m_1\ddot{x}_1 = -F + k(x_2 - x_1) - \\ -m_1 g\sin(\beta) - F_{fr1} - D_1\dot{x}_1 \\ m_2\ddot{x}_2 = F - k(x_2 - x_1) - \\ -m_2 g\sin(\beta) - F_{fr2} - D_2\dot{x}_2 \end{cases}, \qquad (7)$$

$$F_{fri} = \begin{cases} \mu^+ N_i, (\dot{x}_i < 0 \; and \; R_i > \mu^+ N_i) \\ -\mu^- N_i, (\dot{x}_i < 0 \; and \; R_i < -\mu^- N_i) \\ R_i, (\dot{x}_i = 0 \; and \; -\mu^- N_i \le R_i \le \mu^+ N_i) \end{cases}, \quad (8)$$

$$R_i = (-1)^i [F - k(x_2 - x_1)] - \\ -m_i g \sin(\beta) - D_i \dot{x}_i, \;\; i = 1,2, \quad (9)$$

Here μ^+ is the friction factor for brake element under its moving along robot's desired direction; μ^- is the friction factor for brake element moving in opposite robot's desired direction.

The electromagnetic coil receives square impulses periodically. The electromagnetic force F can be described as:

$$F = \frac{dW}{dx} = \frac{1}{2}\frac{dL}{dx} I^2, \quad (10)$$

Here W is the electromagnetic power, L is the coil inductance, I is the current in the coil.

Using these equations is essential in motion simulation and parametric optimization of the in-pipe robot of impactless type of different design.

4 THE DESIGN AND TECHNOLOGICAL EQUIPMENT OF IN-PIPE ROBOTS

Micro robots designed for moving in pipes can be equipped with different technological equipment like sensors for pipes diagnostic and inspection, cameras with standard or infrared optics, communication units and different tools for cleaning, drilling, welding and cable pulling. Such robots can inspect many environmental parameters like humidity, temperature, radiation and so on.

The figure 4 shows the example of applying micro camera to the designed robot.

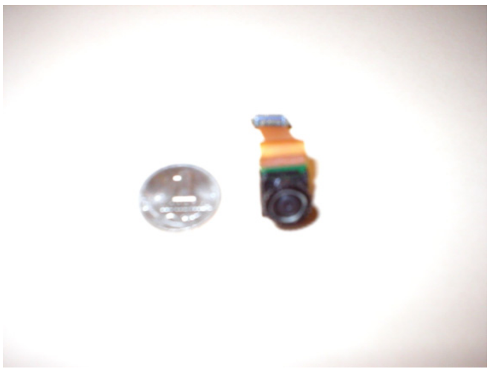

Figure 4: Digital camera for in-pipe micro robot.

Using micro camera inside different pipes the operator can receive desired information about the inner condition of the pipe and presence of extraneous objects.

Figure 5: View from the robot's camera inside the pipeline.

The figure 5 shows the camera view with different objects in sight. These extraneous objects can be deleted from the pipe with the robot.

The movement speed of the designed in-pipe micro robot depends on impulses frequency controlled by control system (Basem et al., 2012). For the example the designed robot moves with the speed of 6 sm/sec under impulses with frequency of *f* equals 10 Hz. And for *f* equals 15 Hz the absolute movement speed of the robot was 9 sm/sec. It took 2 minutes to pass 10 meters inside a pipe for the robot. Characteristics of different in-pipe robots design are shown on the table 1.

Table 1: In-pipe robot's parameters.

Parameter	Ver.1	Ver.2	Ver.3
Pipe diameter, mm	5	10	20
Motor type	Electromagnetic		
Supply voltage, V	6-10	10-15	15-20
Current, A	0.4	1.0	1.5
Impulse frequency, Hz	4-20	4-30	4-70
Power consumption, W	3.2-4.0	10-15	22.5-30.0
Movement speed, mm/sec	4-10	6-20	6-30
Position error, mm	0.5	0.7	0.8
Fillet radius of the pipe, mm	100	400	600
Movement range, m	10	50	70
Payload, N	0.05	0.5	2.0

The dynamics research of the designed robot showed that its motion inside of pipelines of different diameters is aperiodic in nature.

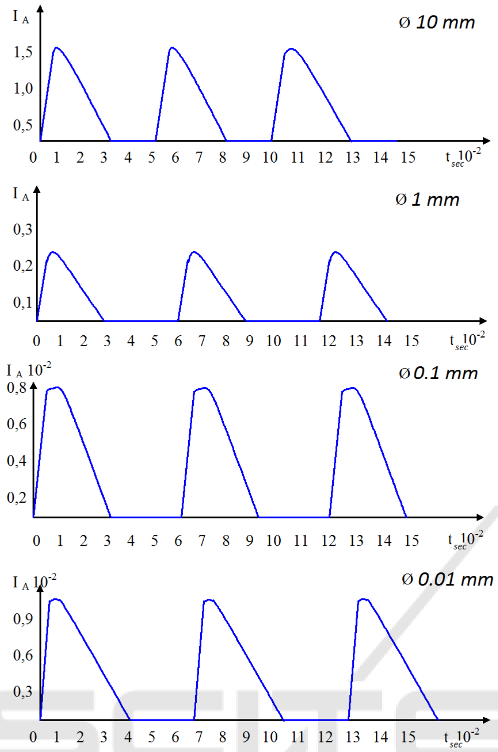

Figure 6: View from the robot's camera inside the pipeline.

Figure 6 shows control signals form depending on different electromagnetic core diameters inside the coil.

Research of the speed of micro robots in pipes of small diameters was conducted under different environmental conditions like absence and presence of excess pressure in the system.

The use of high precision sensors onboard the robot allows to obtain information about the environment inside a pipe with high accuracy.

In the designed in-pipe micro robot is controlled in supervision mode. The information obtained by the sensors and camera is transmitted to the operator on the control panel. The operator takes a decision and sends a command to the signal line by a time–pulse coding. The use of this form of transmission of control signals enables one signal wire to transmit up to eight commands.

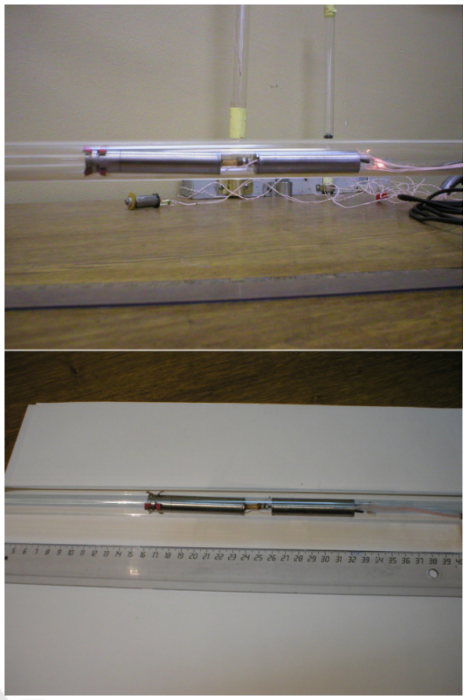

Figure 7: overview of the designed robotic modules.

5 CONCLUSIONS

The proposed design of the in-pipe robot may be used in experimental investigation of different inspection techniques. The method of determining the speed of micro robot allows finding the speed of micro robot when it moves in different environments with different viscosity under the absence and presence of excessive pressure in the piping system.

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