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Machines for In-Pipe Inspection

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Abstract The paper deals with in-pipe machines based on directional friction and inertial stepping principle. Both type are developed for inner pipe with diameter 11 mm. The main purpose is inspection of inner pipe wall as prevention of cracks.

Keywords: *In-pipe, machine, locomotion, insert, template*

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1. Introduction

In-pipe micromachines are able to move in the pipe to inspect or to repair the pipe or other special tasks. Pipe is as confined space i.e. this is constraint for micromachine dimensions, degrees of freedom etc. There are a lot of interdisciplinary problems in design and realisation of in-pipe micromachine. It is difficult to choose suitable actuators, sensors, and power supply etc.

In term of biological analogy, it is possible to divide ways of locomotion into two main groups (Figure 1) [1-20]:

- artificial locomotion,
- biological inspired locomotion.

In term of physical principle, we can divide both these groups into several basic locomotion ways (see Figure 1). It is important to say that it is not final and changeless dividing.

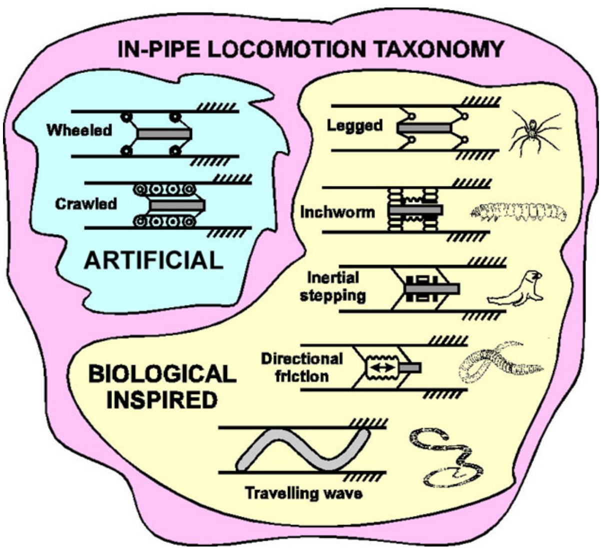

Figure 1. Ways of in-pipe machine locomotion

Wheeled locomotion principle: Wheels are standard synthetic components, which are very often used for locomotion purposes. However inner pipe wall is not perfect. There are a lot of obstacles, which have various characters. When inner pipe wall is dirty, wheels tend to slipping.

Crawled locomotion principle: Tracks is also unfinished rotating element. It is most adaptable to surface then wheels but it is not so often used as wheels.

Legged locomotion principle: Legs are components, which have inspiration in biology (e.g. spider, cockroach etc.). Many biological organisms are able to locomote via legs and reach high speed. These organisms overcome difficult obstacles and there are fascinating for designers.

Inchworm-like principle: The inchworm strategy comes from biological example. The inchworm is capable of manoeuvring in extremely small spaces, it can do so in arbitrary orientations to gravity and can withstand substantial external forces attempting to diverge it from its intended course. It can do these things because its mobility system is governed by a simple rule: "Never let go of what you're holding until you're holding something else!".

Inertial stepping locomotion principle: The principle based on fact that a part of device (inertial mass) oscillates with suitable frequency. Backward tendency of motion is damped.

Worm-like locomotion principle: The locomotion uses difference characteristic of friction between device and pipe wall. Forward friction force is less then backward friction force. It causes that device locomotes in forward direction.

Travelling wave locomotion principle: Device has articulated body and generates travelling wave from head to tail [4,5,6,7].

2. In-pipe Machine Based on Directional Friction

Subject of the article is in-pipe micromachine which locomotes via worm-like principle based on directional friction. Motive forces must be generated internally and then the system will use friction and constraints and shape changes to move. With humans, the frictional forces are isotropic, i.e., sliding a foot forward cause the other foot to slide backwards. That is why we must lift one foot to reposition it while the other foot remains static. But snakes and worms remain in contact with the ground and can have anisotropic frictional forces because of their scales [21].

When sliding forward the frictional forces are minimal, but when a body segment slides backward, the scales dig in and the frictional force becomes very large. Worm can be substituted with one spring, two masses (Figure 2). When the spring is expanded (l increases) scale B slides over the ground and scale A grips the ground. Then the spring is contracted and scale A slides and scale B digs in and grips.

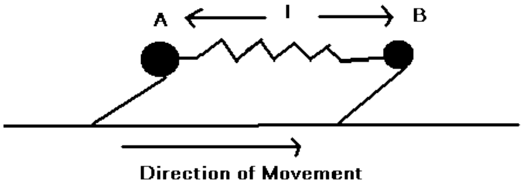

Figure 2. Worm-like in-pipe locomotion principle – directional friction principle

So changing (oscillating) the spring length will result in forward motion. A real worm consists of many segments like the above (Figure 2). To prevent having only one scale gripping, the worm sends a wave of compression from its head to its tail. In a real worm, the wave is a square wave. However, with the simple spring-mass model, a square wave creates shape distortions and a sine wave works better describes the locomotion [21].

The in-pipe micromachine (Figure 3) locomotes via worm-like principle described above. It consists of a piezoactuator (1), which converts electrical energy form to mechanical energy form. Just piezoactuator transformation cannot provide in-pipe locomotion. So there is a need of other mechanical parts – bristle plate (2, 3) and bristles (4). These mechanical parts add another function to piezoactuator. Energy transformation can be controlled with any microcomputer. Finally, locomotion can be obtained with this synergic integration.

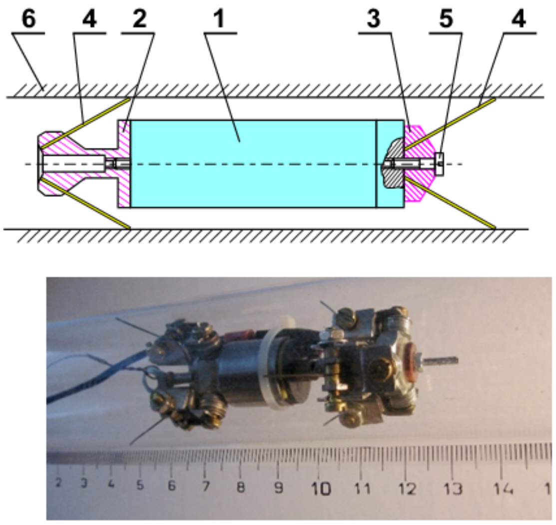

Figure 3. Worm-like in-pipe machine based on directional friction principle. 1 – piezoactuator, linear motor; 2 – head bristle plate; 3 – back bristle plate; 4 – bristles; 5 – screw; 6 – pipe

Mechanical parts provide force coupling with inner pipe wall and diagonally attached bristles, which cause anisotropic character of friction force between bristle tip and pipe wall.

The control system, which generates suitably modulated voltage, provide actuator controlling. There is a need of organs and parts optimisation for effective utilisation of energy transformation. Hence, mechatronics design approach is necessary. It means that actuator is supported with mechanical part. Another possible way of improving is to add another function to bristles. So, implementation of another actuator gives to bristles new function. Another actuator is able to drive bristle parameters, and these bristles become an intelligent “smart bristles”. Bristle properties cannot be improved, moreover, by classic design approach, so there is a place for intelligence integration. Finally, the integration gives better properties to system, which becomes competitive in this class of micromachine.

Bristle is simple one leaf spring with constant cross-section. Bristles are attached as cantilevers to a bristle plate diagonally. A characteristic property is bigger deformability, which is typical for springs. High deformability is ensured with using of material with high compliance otherwise with using of material with high stiffness which is suitable shaped.

Bristles are unloaded if micromachine is out of the pipe. Bristles are designed with parameters which secure that bristle tip span are bigger than inner pipe diameter. So, after in-pipe micromachine application into pipe, bristles are deformed. Let’s assume that deformations of pipe are negligible. Deformations of bristles depend on geometrical deviations of inner pipe diameter and roundness deviation. It means that, bristle tip span has to equal with inner pipe diameter.

If the in-pipe micromachine doesn’t locomote, there is only normal force, which is applied to inner pipe wall. The normal force depends on bristle deflection, bristle stiffness and assembling bristle angle. When excitation force will be applied and it will be continuously increased, if micromachine starts locomotion, value of the excitation force will be equal to adhesive part of friction force Fto.

Bristles are also used as part for creating force coupling with inner pipe wall in [17,18,19,20,21]. Diagonally bristle attaching is suitable because of anisotropic character of friction between bristle tip and pipe wall. The friction force in forward direction is less than friction force in backward direction. The difference of these friction forces causes the forward locomotion of in-pipe micromachine. Work [17] doesn’t deal with other details about this phenomenon and doesn’t specify conditions, which is necessary for the phenomena. Bristles are substituted with fins and blades in [17,18,19,20,21].

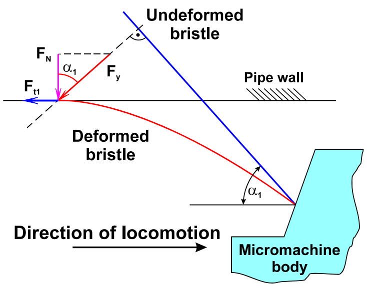

Figure 4. Forces on bristle tip in forward locomotion

Friction force between inner pipe wall (Figure 4) and bristle tip can be described with equation:

$$F_{t1} = \frac{F_{N1} \cdot f}{1 + f \cdot tg\alpha_1} \quad (1)$$

Analogical, it is also possible to derive friction force for moving in backward (Figure 5) direction and it is given as:

$$F_{t2} = \frac{F_{N2} \cdot f}{1 - f \cdot tg\alpha_1} \quad (2)$$

where:

F_{t1} – friction force between bristle tip and pipe wall in forward direction

F_{t2} – friction force between bristle tip and pipe wall in backward direction

f – adhesive coefficient of friction

α_1 – bristle angle to angle of body

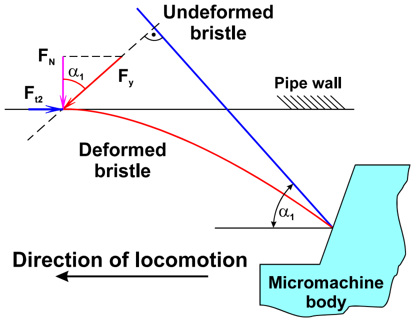

Figure 5. Forces on bristle tip in backward locomotion

If we will assume that normal force will not change, we can write equations (1) and (2) into one common equation:

$$F_{t1,2} = \frac{F_N \cdot f}{1 \pm f \cdot tg\alpha_1} \quad (3)$$

As we can see from equation (3), friction force in forward direction is still less than friction force in backward direction.

If the value of coefficient of friction f will converge to cotgα_1, then friction force in backward direction will converge to infinity, so micromachine will be automatically locked.

The self-locking mechanism causes forward locomotion of most worms and snakes. It is very difficult to influence of friction coefficient value, so we have to find different way of bristle optimisation. The criterion of optimisation is the maximal difference between forward and backward friction force.

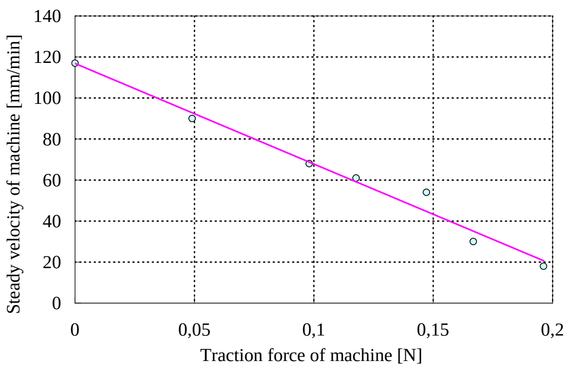

Figure 6. Machine velocity versus traction force of machine

Figure 6 shows the machine velocity dependence on traction force of in-pipe machine.

3. In-pipe Machine Based on Inertial Stepping Principle

Figure 7 shows the outlook photograph of the developed micromachine. Dimensions are 10 mm in diameter, 45 mm in length, 10 g in weight.

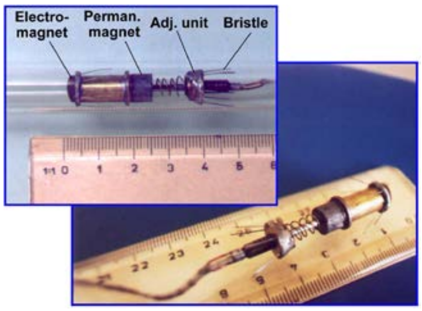

Figure 7. In-pipe machine based on inertial stepping principle

The micromachine is composed of these units: a electromagnet, a adjusting unit, a permanent magnet, a guide rod, a damping spring and bristles. The bristles serve as a clamping element which contacts the pipe wall to hold the weight of machine both in horizontal pipe and in the vertical pipe [22].

Figure 8 shows the mobile principle of the micromachine. When the repulsive force produced by a magnetic field of the electromagnet effects on the permanent magnet, the magnet moves from the electromagnet. During the contact of magnet with the damping spring, the repulsive force is finished. As result, the magnet returns to electromagnet. In the moment of impact of the magnet with electromagnet, the micromachine moves forward, because impact force exceeds the maximum static friction force of the micromachine bristle tip with pipe wall. Consequently, by repeating this cycle the micromachine moves forward. In addition, the spring function of the bristle enables to move in-pipe whose diameter is little of variety.

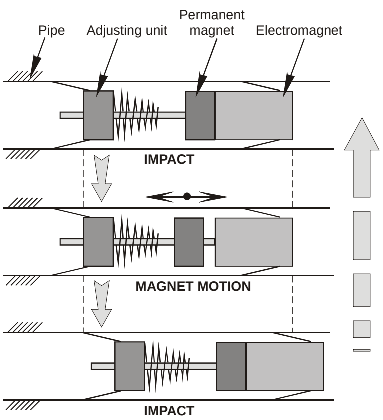

Figure 8. Simplified motion cycle of in-pipe machine based on inertial stepping principle

The speed of the micromachine depends on the distance electromagnet from the spring and the repulsive force duration. The maximum speed was 20 mm/s in the horizontal direction and 15 mm/s in the vertical direction in the glass pipe, at 10-12 ms repulsive force duration and at 1,5 – 2 mm of the distance the spring from the magnet (in while of turned off electromagnet). Figure 9 shows speed versus load characteristic.

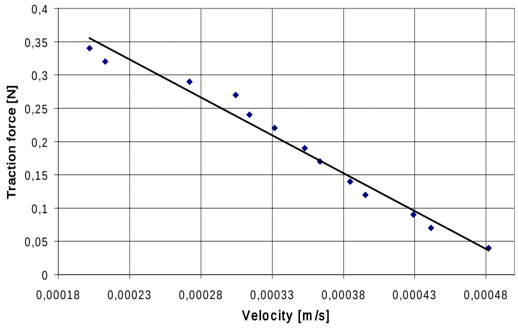

Figure 9. Speed versus load characteristic

4. Conclusion

In-pipe machines are able to locomote inside pipes and they are used mainly for inspection tasks of pipe systems like steam generators, heat exchangers, pipeline for gas, oil, water etc. Inside pipe are technologic remainders in elbows, fittings, reductions. Also inner diameter are not constant, cross-section of pipe has big deviation of roundness. Roundness on inner pipe wall varies and pipe wall are very dirty and very often pipe wall is covered with sediments. Pipe is constrained space and all these factors are affecting the design of the in-pipe machines [23,24,25,26,27,28].

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