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In-pipe Minimachine and Principles of its Motion and Control

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BIOGRAPHICAL NOTES

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KEY WORDS

minimachine, in-pipe movement, bristle, adhesive force, control

ABSTRACT

The paper deals with the minimachine designed to move within the pipes with inner diameter less than 25 mm. The minimachine consists of two modules connected by a link of variable length enabling to change their mutual distance. Motion is based on inchworm principle known from biology. In motion sequence one of the modules is anchored to the inner surface of the pipe, while the second is released and moved forward by change of the link length. The principle of the link length change consists in transformation of the actuator rotary movement to the linear motion. Problem of anchoring the modules by flexible metal bristles is analyzed in the paper.

INTRODUCTION

Nowadays the mobile machines for motion within pipes represent a promising area of research. Their utilization is oriented towards detection of defects on the inner pipe surface, the repair of localized defects, monitoring and maintenance of pipes and last, but not least, their utilization is oriented towards drawing new cables through old and unused pipe systems [8]. The utilization of motion principles by means of classic wheel and crawling traction for design of in-pipe minimachine is limited by a small pipe inner diameter [7]. For this reason for positioning and motion of the minimachine there are used bristles in the form of flexible beams. They are strained towards the pipe inner surface under a precise angle that causes friction difference between the bristle and pipe wall. Next chapters deals with concept, design, motion and control such a machine.

CONCEPT OF MINIMACHINE

The in-pipe minimachine as shown on (Fig. 1) consists of three modules, where the outer modules (the front and back ones) consist of rotary electromagnetic actuators to provide strain of the bristles, then a screw, nut and bristles [2]. The middle module developing the own movement has a rotary electromagnetic actuator, screw and nut (Fig. 2). The principle of the movement is based on transforming the actuator rotary movement through the screw and nut into the straight motion.

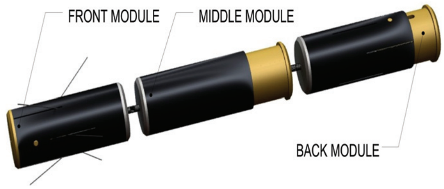

Fig. 1 *3D model of the in-pipe minimachine*

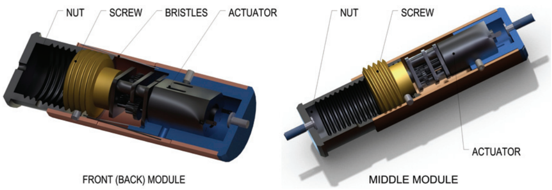

Fig. 2 *Cut-away view of the in-pipe minimachine modules*

This motion causes change of distance between the minimachine front and back modules. The direction of the minimachine movement within a pipe depends on pressing the concerned bristles and their pressing to the inner wall of the pipe is ensured by a screw and nut.

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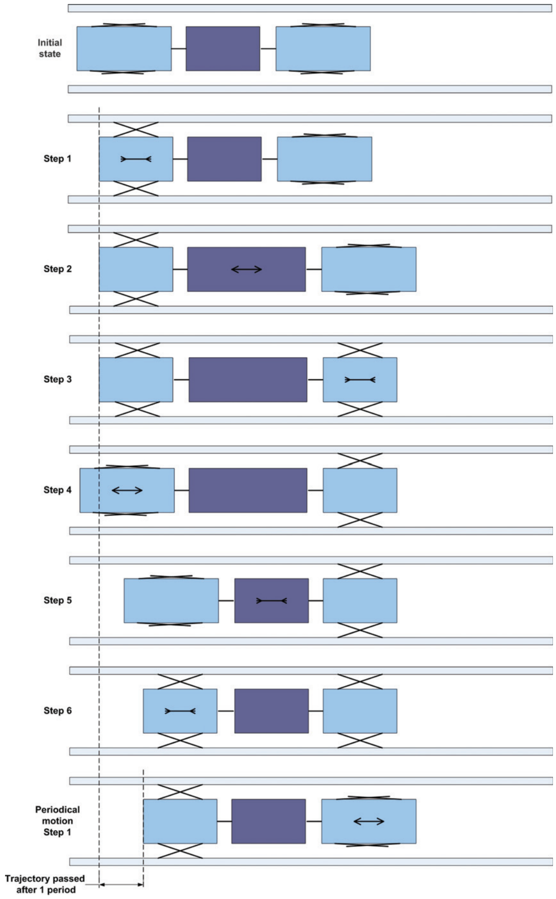

Fig. 3 *Motion sequence of the minimachine*

The direction of the minimachine movement within a pipe depends on pressing the concerned bristles in the outer modules to the pipe wall. Pushing forward the bristles and their pressing to the inner wall of the pipe is ensured by a screw and nut.

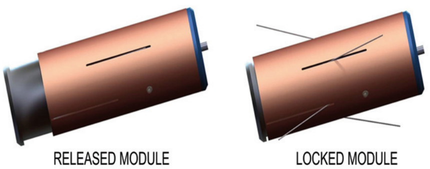

Fig. 4 *Model of the front (back) in-pipe minimachine module*

The control system of the minimachine ensures its cyclic repeating of the change in direction of the linear movement [1, 3].
The protopype as shown on (Fig. 5) was created for verification and testing purpose of actuator and motion principle of the designed in-pipe minimachine [1].

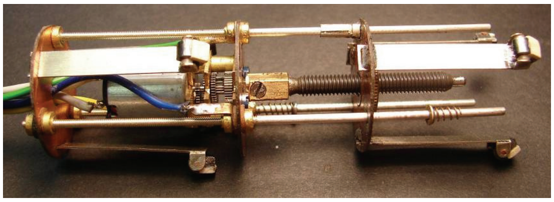

Fig. 5 *Prototype of the in-pipe minimachine*

Motion of the designed in-pipe minimachine is based on inchworm principle known from biology. The motion can be divided into individual steps as shown on (Fig. 3). Order these steps define the direction the final motion.

FORCES ACTING ON MINIMACHINE BRISTLE

The kinematic scheme in Fig. 6 represents the middle part of the module and includes an actuator (M). Its motion is defined by angular velocity ωM that is transmitted through the clutch to the screw. The movement of the back module of the mechanism is expressed by the parameter x as a result of the nut rotation.

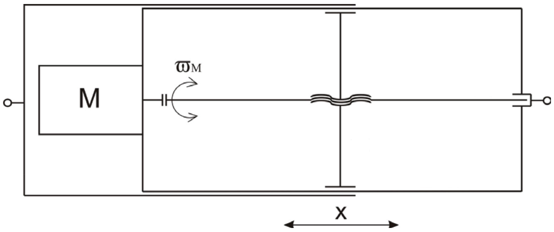

Fig. 6 *Kinematic scheme of the middle module of the in-pipe minimachine*

The motion in the pipe is enabled by friction forces acting between bristles and pipe wall [4]. For design of the minimachine, it is necessary to define reactions of pipe wall as a function of parameters defining the bristle elastic properties in order to ensure sufficient adhesive forces. Geometric parameters are bristle length L and diameter D, further parameters are inner radius R of the pipe, radius a of the minimachine outer surface and bristle angle α, see Fig. 7.

Material parameters are modulus of elasticity E and design strength of the bristle material σ_d.
Up to now, spring steel has been used as material for bristles. In following study, diameter D = 0,3 mm, modulus of elasticity E = $2{,}1.10^5$ MPa and design strength σ_d = 600 MPa were considered.

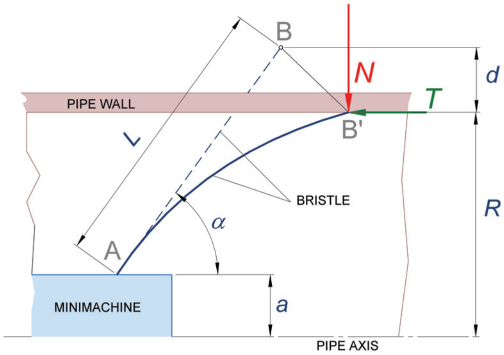

Fig. 7 *Geometry and deflection of the bristle*

Adhesive force $T \leq fNT$ (see Fig. 7) depends on coefficient of friction ***f*** and compressive force N, force N is function of bristle deflection defined by displacement

$$d = a + L\sin\alpha - R. \quad (1)$$

Derivation of ***N*** as a function of displacement ***d*** can be done by use of theory of elastica. This concept was adopted by many authors for solution of similar problems, e.g. for contact of flexible elastic beams with rigid walls [9]. Anyway, it should be noted that solution of equations obtained from theory of elastica is complex and use of a numerical method to solve them is practically inevitable. The result is loss of the main advantage of analytical solution that is derivation of closed form formulas. As numerical solution can not be avoided, another possibility is use numerical solution from the beginning as offered by Finite Element Method (FEM). Utilization of the method for study of bristle-pipe wall interaction is described in following text.
The bristle was modeled by geometric nonlinear 2D beam elements used in most of commercially available FEM programs. Pipe wall was modeled by four node planar elements; placement of the bristle inside the pipe was modeled by displacement ***d*** of the wall in radial direction. Computational model

with presentation of typical results is shown in Fig. 8. Bristle consisted of 20 beam elements was initially in its straight, undeformed configuration and then gradually bent by moving walls. Analyses were undertaken as geometric nonlinear with consideration of frictional contact among nodes of beam elements and outline of planar elements.

Courses of compressive forces ***N*** as functions of non-dimensional parameter ***v/d*** where v is actual displacement and ***d*** is displacement calculated from equation (1) for various lengths of the bristle are shown in Fig. 9. It is interesting that functions differ very little from straight lines. This indicates that for sets of parameters considered, only small difference from results that could be obtained by common linear theory of bending. It should be noted that with increase value of coefficient of friction, courses of compressive forces became more nonlinear.

Courses for bristle lengths of 28 and 32 mm have breaks indicating that a part of the bristle touched-down on the pipe inner surface. This sort of contact is shown in Fig. 10.

Graphs in Fig. 9 are valid for hypothetic material without elastic limits only. For a real material, maximum stress in the bristle should not exceed value of design stress,

$$\frac{R_x + R_y}{A} + \frac{M_z}{W} \leq \sigma_d \qquad (2)$$

where R_x and R_y are horizontal and vertical reactions respectively, M is bending moment at fixed point of the bristle, A is cross-sectional area and W is section modulus. Values of reactions and bending moment are directly obtained by FEM. Limit values of displacement ***d*** for bristle parameters considered are shown in Fig. 11.

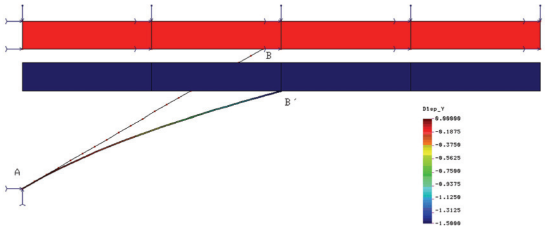

Fig. 8 *Computational model and deformed configuration*

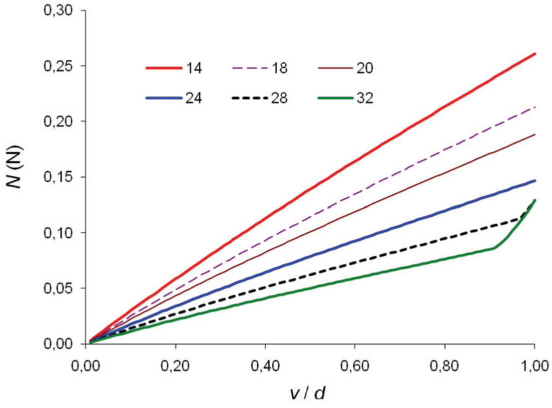

Fig. 9 *Compressive forces as functions of deflection parameter*

Fig. 10 *Contact outside the bristle tip*

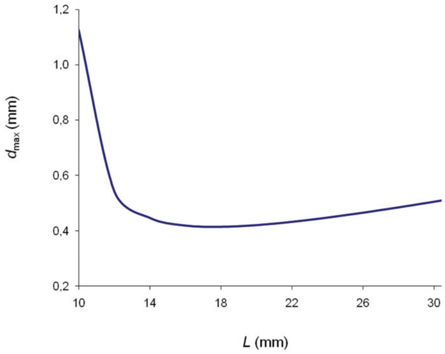

Fig. 11 *Limit values of displacement for various bristle lengths*

THE CONCEPT OF MINIMACHINE CONTROL

In this in-pipe minimachine design [5], there is not enough free space for embedded control electronics. The use of limit switches of actuating units in the marginal points of its trajectories needs also the spatial interest, whose creation should have significant influence on the construction and dimensions of the minimachine. Therefore, the electrical control and power supply components are designed externally near by the minimachine service [6].

It is known that the mechanical burden affecting the load of electric motor increases its current consumption. The maximal current consumption rises from short-term deadlock of the electric motor's output shaft. In the designed in-pipe minimachine, the limit switches are replaced by the control module of the actuating units' current consumption. This module compares current consumption of the particular actuating units with the predetermined limiting values of consumption. If the current consumption achieves the limiting values, the module informs the minimachine's control about achieved state.

The minimachine actuating units are power supplied directly through the line wire (Fig. 12). The power supply, which is the part of the control unit, supplies the in-pipe minimachine and its control by the energy. The control unit monitors the succession of every single step, which altogether create the final movement of the minimachine. The control module mainly consists of the programmable integrated circuit (PIC). The control module of the current consumption of its individual actuating units informs the control module about the achieved limiting value of current consumption.

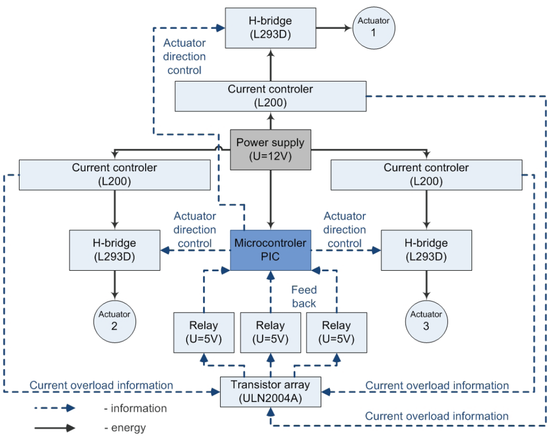

Fig. 12 *Scheme of electric connection of the in-pipe minimachine control*

CONCLUSIONS

The particular stages of the design and mechatronics concept of the in-pipe minimachine were described in this paper. The minimachine developed at the authors' working place is capable to move within the tubes of diameter about 25 mm. The average speed of movement is up to 120 mm/min. and it can be controlled by change of the actuator contractions frequency. Ability of movement in slanting and vertical pipes depends on adhesive forces that are defined by coefficient of friction and compressive forces of bristles. The paper describes possibilities of assessment of these forces by finite element analysis.

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