LOCOMOTION MECHANISM FOR PIPE INSPECTION TASKS

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Abstract: The pipe mechanisms play significant role for applications like inspections, wearing of cables, materials and other devices. The paper deals with motion analysis of pipe mechanism with shape memory effect actuator. At first, the principle of motion and design solution of experimental pipe mechanism is introduced. Then the mathematical model is established by means of Newton´s mechanics. The mechanism (robot) can be used for pipes with circular section with diameters 10 – 15 mm. For real behavior determination the experiments with robot were done. Then the experiments were compared with mathematical model. In the conclusion the advantages and disadvantages of pipe robot using SMA spring – steel spring actuator are discussed.

Keywords: friction, locomotion, mechanism, pipe

1 Introduction

There are several kinds of areas where the pipes are used which have to be researched or explored, for example nuclear power plant, heat-exchanger, etc. Often they cannot be researched by man because of its dangerous environments and conditions or its unavailability. Hence there should be used some kind of robot which is able to moves through the pipe. In the paper the in-pipe robot will be investigated, which is for small pipe diameter designed.

There are a several issues what are under the research concerning in-pipe robots like difficult task to choose suitable actuators, sensors, power supply, etc. [1] There are two basic approaches for robots motion design, namely wheeled and bristled locomotion [2][3]. Different approach is unconventional way of motion using several SMA springs creating body in square shape according to work [4].

In our study bristled in-pipe robot will be investigated. The bristled locomotion on the friction differences is based. In other words, coefficient of friction is lower in the forward direction in comparison with backward direction [5]. It can be reached by suitable design solution of bristles [6][7]. As an actuator the SMA spring in conjunction with steel spring will be used.

The paper is divided into following sections: At first mechanical design of in-pipe robot consisting of SMA and steel spring is introduced. Next section is dedicated to the mathematical model of robot motion in the pipe. Fourth chapter deals with experimental analysis of SMA spring. In the fifth chapter the experiment with robot is done in order to verification of locomotion with mathematical model can be done. In the conclusion the advantages and disadvantages of used in-pipe bristled robot are discussed.

2 Mechanical design of pipe robot

There are several issues concerning the in-pipe robots. One of them is design of their actuator. In the past there were investigated in-pipe robots with different actuators like geared DC motor, actuators based on magnetic field impact, actuators based on SMA (shape memory alloy) wires, etc. [8][9][10]

For our study unconventional approach was chosen by using actuator consisting of two subjects, namely SMA spring and steel spring. The actuator uses SME (shape memory effect) what means, that by heating of SMA spring, the spring is widen. In the next phase the SMA spring is cooling and now it becomes shapeable. In this phase the steel spring plays its role by shortening the SMA spring. So, by repeating of heating and cooling of SMA spring we can reach forward motion of robot. The principle of mentioned actuator in the Fig. 1 is shown. The red color denotes heating phase of SMA spring and blue color denotes cooling phase of SMA spring.

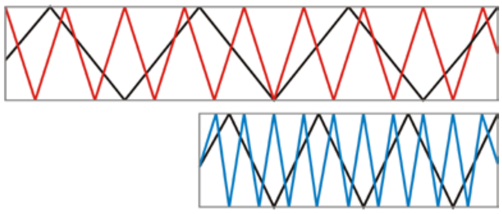

Figure 1 Heating and cooling of SMA spring

During the cooling phase the SMA spring can be shortened to 16 mm. During the heating phase the SMA can be lengthened to 30 mm with over 4 N/m force. In software SolidWorks 3D model of in-pipe robot was designed, see Figure 2.

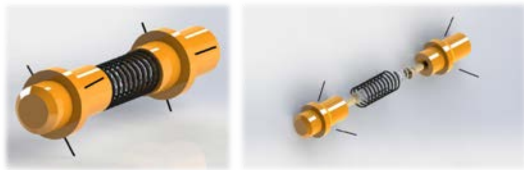

Figure 2 CAD model of in-pipe robot

To ensuring that cooled SMA spring will moves forward not backward is achieved by bristles, attached to front and back part of robot. As will be mentioned later, expected forward motion will be reached by difference of friction between forward and backward direction of bristles.

3 Mathematical model of pipe robot locomotion

The mathematical model of bristled locomotion has its foundation in the nature. The model is inspired by earthworm or inchworm, which can move by means of difference of friction causes by bristles. The sequence of motion in the Figure 3 is shown.

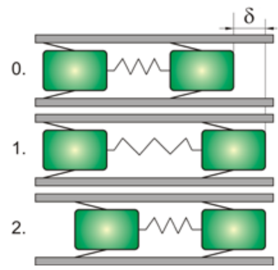

Figure 3 Sequence of in-pipe robot locomotion

The locomotion is divided into two phases. The traveled distance during one locomotion sequence is δ. By repeating of these two phases the robot performs forward motion through the pipe.

3.1 First phase of locomotion

During the first phase the second mass moves forward because of difference of bristles friction. The first mass motion can be expressed by following equation

$$F_S + F_{fS} - F_{SMA} = 0 \qquad (1)$$

where *Fs*, *Ffs* and *FSMA* are force of steel spring, static friction and force of SMA spring, respectively. Static friction force is

$$F_{fS} = \mu_S F_N \eta \qquad (2)$$

where μs is static friction coefficient and FN is load force. The symbol η represents function, described by

$$\eta = \begin{Bmatrix} 0 \forall v \neq 0 \\ 1 \forall v = 0 \end{Bmatrix} \quad (3)$$

The second mass motion can be expressed by following equation

$$F_{SMA} - F_S - F_f > 0 \quad (4)$$

where *Fsma*, *FS* and *Ff* are force of SMA spring, force of steel spring and friction force, respectively. By consideration of dry friction between in-pipe robot bristle and wall of pipe, the friction force by Coulomb friction can be represented, according equation (5).

$$F_f = \mu_C F_N \operatorname{sgn}(v) \quad (5)$$

where μc is Coulomb friction coefficient and FN is load force. Sgn(v) represents signum function, which can be expressed by equation (6).

$$\operatorname{sgn}(v) = \begin{Bmatrix} 1 \forall v > 0 \\ 0 \forall v = 0 \\ -1 \forall v < 0 \end{Bmatrix} \quad (6)$$

Coulomb friction force depends only on mass velocity direction, not on velocity magnitude. From the equations (1) and (4) can be obtained terms for friction coefficients.

$$\mu_S = \frac{F_{SMA} - F_S}{wg\eta} \quad (7)$$

$$\mu_C < \frac{F_{SMA} - F_S}{wg \operatorname{sgn}(v)} \quad (8)$$

where w is weight of in-pipe robot mass. It is obvious, that the higher difference between static and Coulomb friction coefficient is, the higher average velocity the robot can reaches. The difference between these two coefficients can be reached by suitable design solution of bristles.

3.2 Second phase of locomotion

During the second phase of locomotion, the SMA spring is cooled. When SMA spring is cooled enough it loses its force and the steel spring starts pull the first mass forward. The second phase can be described by similar way as first phase and friction coefficients are

$$\mu_C < \frac{F_S}{wg \operatorname{sgn}(v)} \quad (9)$$

$$\mu_S = \frac{F_S}{wg\eta} \quad (10)$$

4 Experimental analysis of SMA spring and pipe robot bristles

As was mentioned above, the SMA spring changes its length by means of two actions, namely heating and cooling. The heating phase is reached by connecting of SMA spring ends to the voltage supply, what allows to current flowing through the spring, whereby the spring heats and its length expands. During the second phase the supply of current is prevented and during this time the SMA spring cools and its length is shortened by affecting of steel spring.

4.1 SMA spring testing

For testing of SMA spring the package of steel linear springs was used. The stiffness of each steel spring was determined and these springs were used as opposite spring to the SMA spring in order to obtain a load for SMA spring.
In the Figure 4, the displacement in dependence on current is shown.

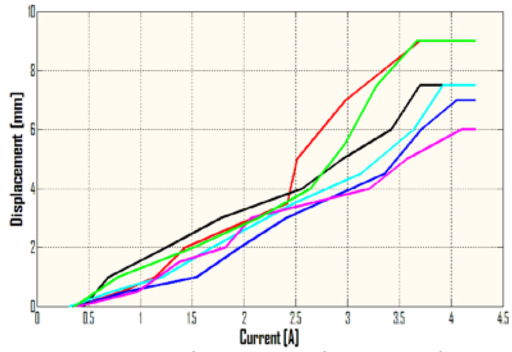

Figure 4 Displacement of SMA spring with focus on current flow

The current flowing through the SMA spring is relatively high, over 4 A for 2 V. We can see that SMA spring is very demanding for current consumption what is ineligible from the view of autonomous of system, because accumulators of small dimensions for this task are inapplicable.

4.2 Friction coefficient measuring of pipe robot bristles

Friction coefficient of in-pipe robot bristles plays very significant role for its locomotion through the pipe. The lower Coulomb friction coefficient of bristle in comparison with static friction coefficient is, the higher velocity the robot will has. The basic assumption of robot forward motion is that the friction coefficient in forward motion in lower that friction coefficient in backward motion.

Friction coefficient in both direction by means of tribometer is determined. Friction coefficient from the next equations in obtained.

$$F_f - wg \sin\alpha = 0 \quad (14)$$

$$F_N - wg \cos\alpha = 0 \quad (15)$$

By next adjustment the static friction coefficient is expressed by equation (16):

$$\mu_S = tg\alpha \quad (16)$$

Tribometer is connected to the linear potentiometer in vertical axis. The output from potentiometer through the measuring I/O card MF624 is recorded in Matlab / Simulink which cooperates with measuring card by Real Time Toolbox. The output from Simulink is measured coefficient of friction. From measuring of friction coefficient was found that

$$\mu_{Forward} = 0.449 \quad (17)$$

$$\mu_{Backward} = 0.589 \quad (18)$$

Friction coefficient in forward direction is lower than friction coefficient in backward direction, whereby the forward motion is achieved. Friction coefficient in forward direction can of course be reduced by suitable mechanical modification according to user need.

5 Experimental analysis of pipe robot locomotion

For experiment the glass pipe with circular section with diameter 13 mm is used. The first aim of experiment is find out the differences between the real model and mathematical model. The second aim is analysis of power consumption which is necessary to robot locomotion. The third aim of experiment is to analyze SMA spring as actuator, its advantages and disadvantages for these purposes.

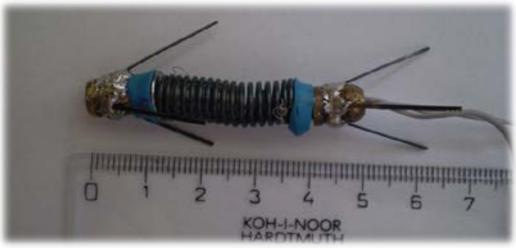

Figure 5 In-pipe robot in the pipe

In the third chapter was mentioned that one motion cycles consists of two phases. But difference between real and theoretical model is that SMA spring heats and cools the time which is significantly higher than the time which was considered in mathematical model. From the view of mathematical model the average velocity of in-pipe robot can be increased by suitable design solution of bristles what causes higher difference between static and Coulomb friction coefficient. In the reality this difference between these two coefficients is not very significant, rather negligible. This is caused because the time, necessary to heat the SMA spring and the time, necessary to cool, is very high. For example, when the current flow to the SMA spring is prevented, it takes a significant time while SMA spring cools and its force is lower in comparison with force of steel spring, which shortens SMA spring.

Connection and disconnection SMA spring to the voltage supply was automatized by means of 32-bit microcontroller BasicAtom Pro-28M. The problem with long time for cooling was partly solved by blower, which was directed to the heated place. Because of microcontroller dimensions, it could not be part of robot and it is placed out of the pipe.

Next point of experimental part is investigation of electric power consumption by actuator SMA spring – steel spring. The electric current and electric power consumption by means of MF624 were measured according to scheme, which in Matlab / Simulink was created.

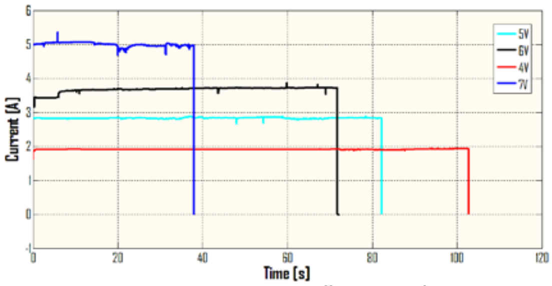

Figure 6 First phase duration caused by different value of current input

As can be seen in the Fig. 11, the higher current input is, the lower time the first phase lasts. In other words, by higher current we can achieved faster heating of SMA spring and then first phase duration lasts lower time. Nevertheless, the time of heating is still too high even if we use higher value of current for heating. Given results are results that were obtained using blower for faster cooling phase.

The highest disadvantage of this kind of in-pipe robot is SMA spring heating and cooling phase which takes a lot of time what causes very slow locomotion, in our case only 2 mm/min.

6 Conclusion

In the paper motion analysis of in-pipe robot moving in the pipe with circular section with 13 mm diameter was investigated. At first mechanical design of experimental in-pipe robot is introduced. From the mathematical model the coefficients of friction in both directions are expressed.

In-pipe robot using actuator SMA spring – steel spring has advantages like very simple control, low weight, small dimensions. In spite of these advantages its disadvantages are very significant. One of the most disadvantage is the duration of heating and cooling phase. They can be a little bit modified but this modification is highly limited.

The system is autonomous in the straight pipes through the microcontroller BasicAtom Pro28-M. The next disadvantage of SMA spring is that it required high electric power consumption, whereby classical battery utilization becomes useless.

In the future the SMA spring – steel spring actuator should be modified by suitable solution of SMA spring cooling. For the tasks where does not matter on the velocity of robot and application time this kind of robot can be useful.

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