*UDC 621.646.978: 62-799*
*DOI: 10.25140/2411-5363-2019-4(18)-36-42*

*Filip Filakovský, Ivan Virgala*

# ANYLSIS OF PIPE MECHANISM LOCOMOTION

***Urgency of the research.*** *Inspection tasks are frequently and very important from the view of safety. From this reason the topic is very actual.*

***Target setting.*** *The aim of the study is to investigate new kind of pipe mechanism based on differential frictions of bristles.*

***Actual scientific researches and issues analysis.*** *There are many mechanisms for inspection of narrow or hard-to-reach areas. Many of them are based on wheels or tank belt. This research investigates bristle-based pipe mechanism.*

***Uninvestigated parts of general matters defining.*** *Nowadays, the SMA materials or different kind of memory materials are always in the focus of researchers.*

***The research objective*** *is to develop and experimental test the new kind of mechanism based on SMA as well as steel spring mechanism.*

***The statement of basic materials.*** *The locomotion divided into two phases is introduced. Based on this locomotion the mathematical model was derived. Assuming mathematical model was developed control system for experimental pipe mechanism.*

***Conclusions.*** *The results of the experiments shows problems with cooling phase due to its long time consumption. For cooling was used external device. The cooling phase significantly decrease average velocity of pipe mechanism. The advantage of this kind of mechanism is simple control and utilization for the pipe with small diameters.*

***Keywords:*** *pipe mechanism; SMA; spring.*
*Fig.: 10. References: 11.*

**Introduction.** There are many hard-to-reach areas which need to be inspected because of detection of escaping gas or monitoring of obstacle presence etc. From this reasons the researchers develop many years the mechanisms suitable for these tasks [1]. Within this research will be investigated pipe mechanism. There are several kind of mechanisms for these purposes like wheel-based or tank-belt based mechanisms. In the research we will discuss about bristle-based mechanism. Bristle-based mechanism works on the difference of friction in forward and backward motion [2; 3]. In other words, the friction coefficient in one direction is different in comparison of friction coefficient in another direction [4]. So, by suitable designing of mechanisms bristles it can be achieved this friction differentiation [5; 6].

In our case as actuator will be used SMA spring in cooperation with conventional steel spring. There are some similar solution in the works [10][11]. The paper is divided as follows.

The second chapter deals with mechanical design of our pipe robot. Next, mathematical model is introduced. It deals with pipe mechanism motion in the narrow space like pipe. Within the paper the mechanism is investigated by experiments. The conclusion shows the results of the analyses.

**Design of mechanical parts of pipe mechanism.** One of the most important issues within the pipe mechanism designing is design of actuator. There were investigated many mechanisms in the past based on DC motor actuators or actuators based on magnetism principles. This study investigated SMA (shape memory alloy) actuator [7; 8; 9].

So, entire actuator consists of SMA as well as steel spring actuator. SMA spring behaves based on the temperature of the spring. By heating of the SMA spring, it expands. When the SMA springs is cooled, it shortens. By these two cycles can be driven mechanism based on SMA spring. Steel spring plays the role of the helper of shortening of the SMA spring.

As can be seen in the Fig. 1, the red colour represents SMA spring in heating phase and blue colour SMA spring in cooling phase. The black one represents steel spring.

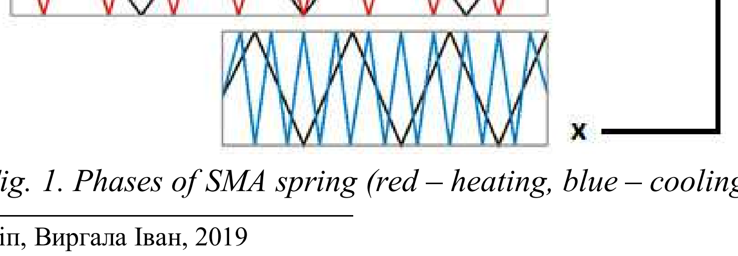


*Fig. 1. Phases of SMA spring (red – heating, blue – cooling)*

© Філаковський Філіп, Виргала Іван, 2019

Based on concrete type of used SMA spring, during cooling phase it shortens to 16 mm. On the other hand, during the heating phase, it extends to 30 mm.

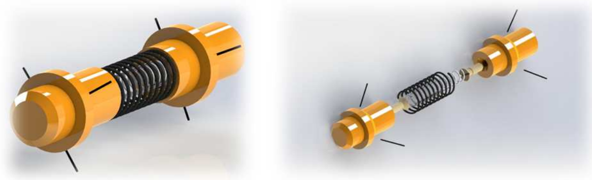

*Fig. 2. CAD model of in-pipe robot*

In the Fig. 2 the CAD model is shown.

Design of our pipe mechanism arise from the inspiration from the nature by inchworm. In the Fig. 3 is introduced the locomotion of the mechanism.

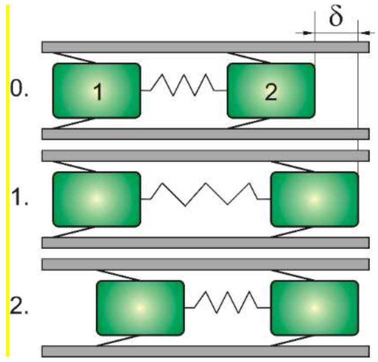


*Fig. 3. Locomotion of the pipe mechanism*

From fig. 3, zero phase is initial position of pipe mechanism. During the first phase, the first module moves forward by maximum extension. The first phase is heating phase. While the first module moves forward, the friction coefficient of this module in forward direction is smaller than friction coefficient of second module in backward motion. During the second phase, so called cooling phase, the second module moves forward while the first module is static because of friction differentiation.

$$F_S + F_{fS} - F_{SMA} = 0 \tag{1}$$

where $F_S$ is force of steel spring, $F_{fS}$ is static friction and $F_{SMA}$ is SMA spring foce, respectively. Static friction force can be set as

$$F_{fS} = \mu_S F_N \eta \tag{2}$$

where $\mu_S$ and $F_N$ are static friction coefficient and load force, respectively. Variable $\eta$ represents following function

$$\eta = \begin{Bmatrix} 0 \forall v \neq 0 \\ 1 \forall v = 0 \end{Bmatrix} \tag{3}$$

The second module motion is expressed as follows

$$F_{SMA} - F_S - F_f > 0 \tag{4}$$

where $F_{sma}$ is SMA spring force, $F_S$ is steel spring force and $F_f$ is friction force. Considering Coulomb friction model between mechanism modules and pipe, friction force is

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

where $\mu_C$ and FN are Coulomb friction coefficient and load force, respectively. Sgn(v) is signum function, described by equation (6).

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

Coulomb friction force depends on the direction of module velocity. From the equations (1) and the equation (4) we can derive

$$\mu_S = \frac{F_{SMA} - F_S}{wg\eta} \tag{7}$$

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

where $w$ is weight of pipe mechanism module. The required difference between forward and backward friction coefficients can be set by suitable design of pipe mechanism bristles.

SMA spring is cooled by external device during its second phase. In this phase, it loses its force and steel spring helps to shorten the distance between two modules.

The second phase could be described as

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

$$\mu_S = \frac{F_S}{wg\eta} \tag{10}$$

The first phase duration is

$$t_1 = \sqrt{\frac{2\delta w}{F_{SMA} - F_S - \mu_C wg \operatorname{sgn}(v)}} \tag{11}$$

The second phase duration is

$$t_2 = \sqrt{\frac{2\delta w}{F_S - \mu_C wg \operatorname{sgn}(v)}} \tag{12}$$

From both eqautions (11) and (12) can be set average velocity of pipe mechanism

$$v_A = \frac{\delta}{t_1 + t_2} \tag{13}$$

Theoretical average velocity of the pipe mechanism in the Fig. 4 is shown.

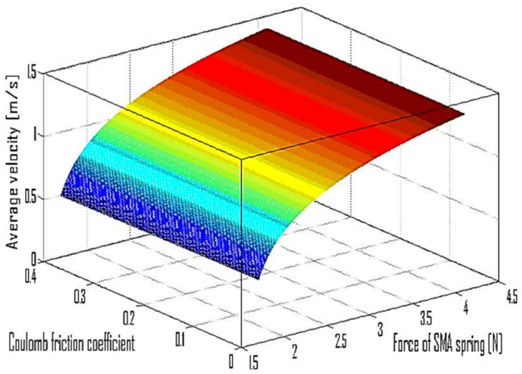


*Fig. 4. Pipe mechanism average velocity*

**Experimental on SMA spring.** As have been mentioned, SMA material changes its properties by heating or cooling it. The heating of SMA can be achieved by supplying it by electrical current. By connecting SMA to supply voltage different potentials, the current would flow through it.

For experimental testing was SMA spring connected to supply voltage from 0.2 V up to 2 V. The results in the Fig. 5 are shown.

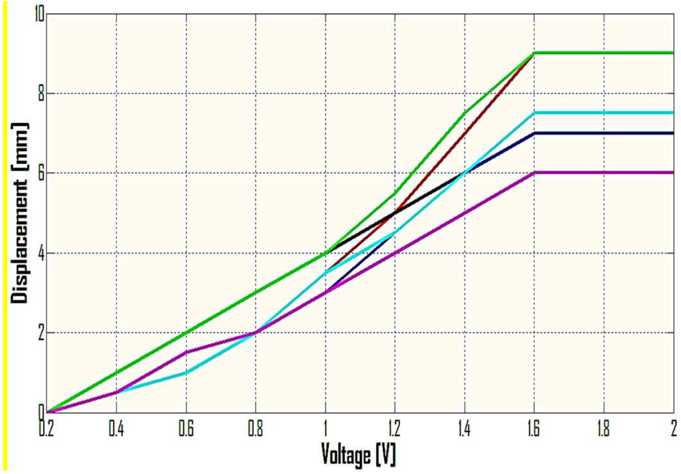


*Fig. 5. SMA spring extensions based on different voltage level*

From the Fig. 5 it is clear, the higher supply voltage is the more extension of SMA spring occurs. The load force for measurements were gained by different steel springs.

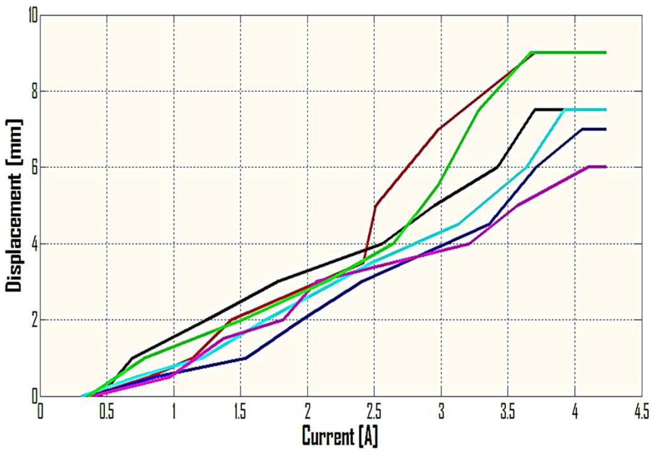


*Fig. 6. SMA spring and electrical current*

The current flowing through the SMA is too high. For the voltage 2 V it is roughly 4 A. As have been mentioned, friction force is very important for this kind of mechanism. Design of the bristles is important task. Friction coefficient in the forward as well as backward direction can be determined by tribometer.

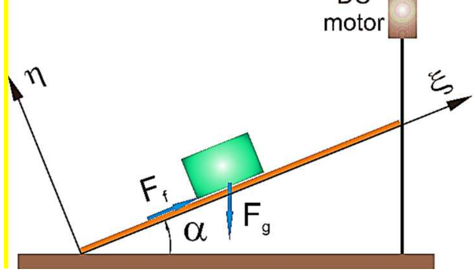


*Fig. 7. Friction coefficient measuring stand*

By any kind of motor with screw the angle of inclined surface can be changed, (see Fig. 7).

$$F_f - wg\sin\alpha = 0 \tag{14}$$

$$F_N - wg\cos\alpha = 0 \tag{15}$$

The static friction coefficient can be set by following term

$$\mu_S = tg\alpha \tag{16}$$

From measuring of friction there were found following values

$$\mu_{Forward} = 0.449 \tag{17}$$

$$\mu_{Backward} = 0.589 \tag{18}$$

As can be seen, the friction coefficient in forward direction is lower than friction if backward direction. By this difference the forward motion is achieved.

**Experimental analysis with pipe mechanism.** According to CAD model mentioned above was designed pipe mechanism for experimental purposes. The mechanism is designed for 13 mm diameter of the pipe, see Fig. 8.

*Fig. 8. Experimental pipe mechanism*

During the experiments the electrical current consumption was measured. The measurements were done by input/output measuring cad MF624 connected with MATLAB / Simulnik, see Fig. 9.

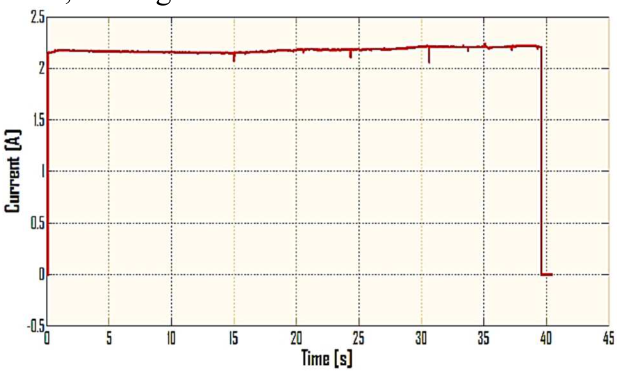


*Fig. 9. Electric current consumption during the first phase of locomotion*

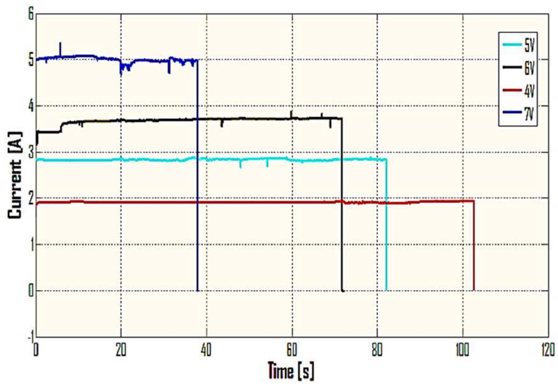


*Fig. 10. First phase of locomotion for several supply voltage levels*

It can be seen, the first phase of locomotion characterized by SMA spring heating, last roughly 40 seconds.

The Fig. 10 shows, that the higher current flowing through the SMA spring is, the lower time it takes. The second phase, cooling phase, was takes a long time. From this reason was used blower for faster cooling phase.

The significant disadvantage of this kind of mechanism is SMA spring heating but especially cooling phase which takes a lot of time what causes very slow locomotion, in our case only 2 mm/min.

**Conclusion.** The paper dealt with motion analysis of pipe mechanism in the pipe with diameter 13 mm. At first mathematical model of locomotion was designed. From mathematical model of both phases the average velocity of mechanism was derived. Then SMA spring was experimentally tested in cooperation with steel spring. In the conclusion, there was designed pip mechanism according to CAD model mentioned in the beginning of the paper. The experiments were done with this experimental pipe mechanism. The results show problems especially with cooling phase which takes a lot of time. From this reason is this kind of mechanism very slow. The advantage of the mechanism is very simple control system, small weight and possibility to use the robot in very small diameters of pipe.

**Acknowledgement.** The authors would like to thank to Slovak Grant Agency – project VEGA 1/0872/16.

## References

1. Gmiterko, A., Dovica, M., Kelemen, M., Fedák, V., Mlýnková, Z. (2002). "In-pipe Bristled Micromachine", IEEE 7th International Workshop on Advanced motion control, pp. 599–603 [in English].
2. Kelemenová, T., Kelemen, M., Miková, Ľ. & Baláž, R. (2012). "Bristled In-pipe Machine Inside Pipe With Geometric Deviations", Procedia Engineering – Elsevier / International Conference on Modeling Mechanic and Mechatronic systems, pp. 287–294 [in English].
3. Tatar, O., Mandru, D., Ardelean, I. (2007). "Development of mobile nimirobots for in pipe inspection tasks", Mechanika, 60-64, 6 (68), ISSN 1392- 1207 [in English].
4. Wang, Z., "A Bristled-Based Pipeline Robot for I11-Constraint Pipes", IEEE / ASME Transaction on Mechatronics, Vol. 13, No. 3, June 2008 [in English].
5. Yu, H., Ma, P., Cao, Ch., "A Novel In-Pipe Worming Robot Based on SMA", Proceedings of the IEEE International Conference on Mechatronics & Automation, pp. 923–927, Niagara Falls, Canada, 2005 [in English].
6. Choi, H. R., Roh, S., "In-pipe Robot with Active Steering Capability for Moving Inside of Pipelines", Bioinspiration and Robotics: Walking and Climbing Robots, ISBN 978-3-902613-15-8, pp. 375–402, Austria 2007 [in English].
7. Li, P., Ma, S., "Self-Rescue Mechanism for Screw Drive In-pipe Robots", IEEE International Conference on Intelligent Robots and Systems, pp. 2843 – 2849, Taiwan 2010 [in English].
8. Yaguchi, H., Izumikawa, T., "Performance of Cableless Magnetic In-Piping Actuator Capable of High-Speed Movement by Means of Inertial Force", Advances in Mechanical Engineering, pp. 1–9, 2001 [in English].
9. Yaguchi, H., Kamata, K., "In-piping Magnetic Actuator Capable of Inspection in a Thin Complex Pipe", Mechanical Engineering Research, Vol. 2, No. 2, 2012 [in English].
10. Kim, S., Hawkes, E., Cho, K., Jolda, M., Foley, J., Wood, R., "Micro artificial muscle fiber using NiTi spring for soft robotics", IEEE International Conference on Intelligent Robots and Systems, pp. 2228–2234, USA, 2009 [in English].
11. Koh, J., Cho, K., "Omega-Shaped Inchworm-Inspired Crawling Robot with Large-Index-and-Pitch (LIP) SMA Spring Actuators", IEEE Transactions on Mechatronics, vol. 18, no. 2, 2013 [in English].

*УДК 621.646.978: 62-799*

*Філіп Філаковський, Іван Віргала*

## АНАЛІЗ ПЕРЕМІЩЕННЯ ТРУБОПРОВІДНОГО МЕХАНІЗМУ

***Актуальність теми дослідження.*** *Інспекційні завдання часті і дуже важливі з точки зору безпеки. З цієї причини тема дуже актуальна.*

***Постановка проблеми.*** *Метою роботи є дослідження нового типу трубного механізму на основі диференціального тертя щетинок.*

***Аналіз останніх досліджень і публікацій.*** *Існує багато механізмів огляду вузьких або важкодоступних місць. Більшість з них мають колісну або гусеничну базу. В цій роботі досліджується трубопровідний механізм з поверхнею у вигляді щетини.*

***Виділення недосліджених частин загальної проблеми.*** *У наш час SMA матерыали або різного роду запам'ятовуючі матеріали завжди знаходяться у центрі уваги дослідників*

***Постановка завдання*** *полягає в розробці та експериментальному випробуванні нового типу механізму на основі SMA, а також сталевого пружинного механізму.*

***Виклад основного матеріалу.*** *Переміщення механізму розділене на дві фази. На основі цього переміщення було виведено математичну модель. Використовуючи математичну модель, була розроблена система управління експериментальним трубним механізмом.*

***Висновки відповідно до статті.*** *Результати експериментів показують проблеми з фазою охолодження через тривалу експлуатацію. Для охолодження використовувався зовнішній пристрій. Фаза охолодження значно знижує середню швидкість трубного механізму. Перевага цього механізму полягає в простому керуванні та використанні для труби невеликих діаметрів.*

***Ключові слова:*** *трубний механізм; SMA; пружина.*
*Рис.: 10. Бібл.: 11.*

**Filip Filakovsky** – PhD student, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenskeho 8, 04200 Košice, Slovak Republic).
**Філіп Філаковський** – аспірант, Технічний університет Кошице (Park Komenskeho 8, 04200 Košice, Slovak Republic).
**E-mail:** filip.filakovsky@tuke.sk

**Ivan Virgala** – Associate Professor, Ph.D. of Technical Sciences, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenskeho 8, 04200 Košice, Slovak Republic).
**Іван Виргала** – доцент, кандидат технічних наук, Технічний університет Кошице (Park Komenskeho 8, 04200 Košice, Slovak Republic).
**E-mail:** ivan.virgala@tuke.sk