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RESEARCH ON THE PIPELINE TRANSPORT ROBOTS ELEMENTS

In the article are reviewed constructions of the pipeline transport robots elements and scheme of new original construction is presented. The mathematical model of the pipeline transport robot is formed and its motion equations are presented.

Keywords: *a pipeline transport robot, robots elements, vibration exciter.*

1. Introduction

Robots of various types and designs are widely used for effective control and repair of gas pipelines, water pipelines or communication lines [1, 2, 5, 6]. One kind namely, the pipeline transport robots those with elastic elements is discussed here. The object of the present project is the development of an original robot with elastic elements and the investigation of its movement.

2. Designs of Robots Elements

Usually a robot consists of several transporting blocks connected with elastic elements [3] (Fig 1). The transporting blocks are equipped with elements that contact with the internal surface of the pipe in several points and ensure fixing of the block in the pipe. Because of a simple structure and sufficiently good fixation in the pipe robots with elastic elements consisting of rings, half-rings and similar easily deformable elements may be usable as well.

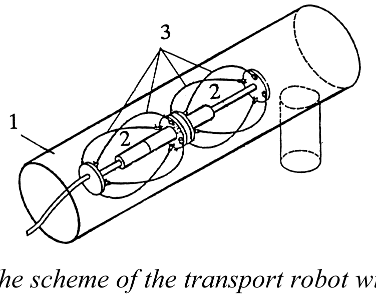

Fig. 1. The scheme of the transport robot with ring-shaped elements: 1 - pipe, 2 - transporting blocks, 3 - elastic support elements

A transporting block of such robots consists of a drive, deformable elastic elements that pay a role of block fixing supports and block connecting elements.

When one block is fixed, other blocks may turn and move along the fixed block. This enables the equipment to go round obstacles on a movement in the pipe.

However, some robots with transporting blocks of this type have some imperfections (such as large sizes, limited power supply possibilities) that cause limited possibilities of their application.

The most frequent imperfection – such robots may be used only in straight fragments of pipelines (Fig. 1) and their capability to move in sections of different diameters of pipes is limited.

So, one of newer designs providing extended possibilities of application is a robot with ring elements, consisting of transporting blocks connected with elastic elements (Figs 2, 3). Such robots consist of rings or their elements with the ends of the latter connected with elastic link elements and with each other forming blocks.

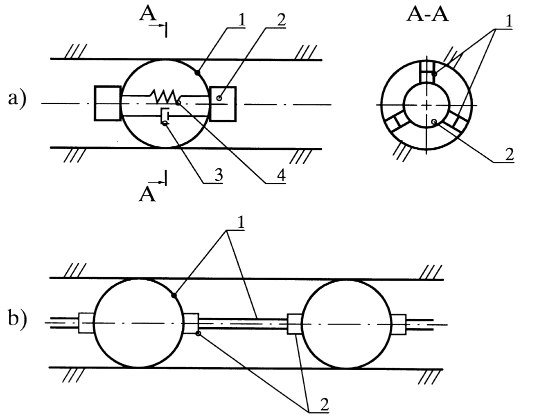

Fig. 2. The schemes of the robot block with ring elements a) and its connection b): 1 - ring-shaped elastic element, 2 - the element connecting blocks and their ring elastic elements, 3 – damper, 4 - spring

The interconnected blocks form a chain of the blocks.

In such a way an increased capability of the robot to manoeuvre and permeability of the robot on its movement in pipes is ensured.

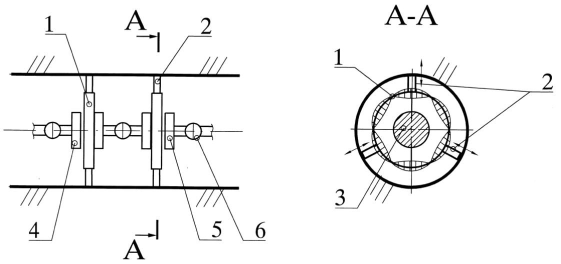

Fig. 3. The scheme of a robot blocks with ring elements located along the direction of its movement: 1 - elastic ring element, 2 - supports with excitable masses, 3,5 - electrostatic exciting elements, 4 - elastic element, 6 - hinge block jointing element

3. The Mathematical Model of the Transport Robot with Ring Elements Located Perpendicularly to the Direction of its Movement

The mathematical model of a robot is developed for the determination of its characteristics and at the beginning it may be usable in a simplified form. So, a robot with elastic ring elements situated perpendicularly to the direction of its motion (Fig 3) may be simulated by one-support dynamic model and examined as a dynamic model of one-dimensional vibration exciter with two degrees of freedom (Fig 4).

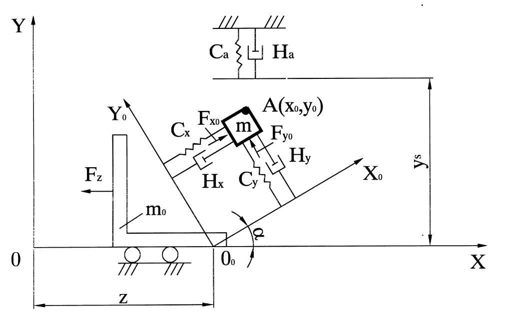

Fig. 4. The scheme of the dynamic model of the system of the one-dimensional vibration exciter with two degrees of freedom

The coordinates of the point A $(x_0; y_0)$ of the excitable mass m in the coordinate system $X_0 0_0 Y_0$ and the point $A(x, y)$ of the same mass in the coordinate system $X0Y$ are expressed by the following equations [3,4]:

$$x = z + x_0 \cos\alpha - y_0 \sin\alpha; \tag{1}$$

$$y = x_0 \sin\alpha + y_0 \cos\alpha; \tag{2}$$

$$x_0 = (x - z)\cos\alpha + y_0 \sin\alpha; \tag{3}$$

$$y_0 = -(x - z)\sin\alpha + y\cos\alpha. \tag{4}$$

The kinetic and potential energy of the system as well as its dissipative function shall be expressed as follows:

$$T = 0{,}5\left[m_0 \dot{z}^2 + m(\dot{x}^2 + \dot{y}^2)\right]. \tag{5}$$

$$\Pi = 0{,}5\left[c_x x_0^2 + c_y y_0^2 + c_a (y - y_s)^2\right]. \tag{6}$$

$$D = 0{,}5\left[H_x \dot{x}_0^2 + H_y \dot{y}_0^2 + H_a \dot{y}^2\right]. \tag{7}$$

where m – mass; x, x_0, y, y_0 – shifts of the robot and its mass; y_s – distance between support and the coordinate axel X, c_x, c_y, c_a – coefficients of stiffness; H_x, H_y, H_a – coefficients of resistance of a linear shift; f_0, f_1 – the coefficients of dry and liquid friction.

The mathematics expression of the dynamic model of the system shall be the following equations:

- when $y \le y_s$, there is no contact with the support at the point A:

$$\begin{aligned} m\ddot{x} &+ c_x\left[(x - z)\cos\alpha + y\sin\alpha\right]\cos\alpha + \\ &+ c_y\left[(x - z)\sin\alpha - y\cos\alpha\right]\sin\alpha + \\ &+ H_x\left[(\dot{x} - \dot{z})\cos\alpha + \dot{y}\sin\alpha\right]\cos\alpha + \\ &+ H_y\left[(\dot{x} - \dot{z})\sin\alpha - \dot{y}\cos\alpha\right]\sin\alpha = F_x; \end{aligned} \tag{8}$$

$$\begin{aligned} m\ddot{y} &+ c_x\left[(x - z)\cos\alpha + y\sin\alpha\right]\sin\alpha - \\ &- c_y\left[(x - z)\sin\alpha - y\cos\alpha\right]\cos\alpha + \\ &+ H_x\left[(\dot{x} - \dot{z})\cos\alpha + \dot{y}\sin\alpha\right]\sin\alpha - \\ &- H_y\left[(\dot{x} - \dot{z})\sin\alpha - \dot{y}\cos\alpha\right]\cos\alpha = F_y; \end{aligned} \tag{9}$$

$$\begin{aligned} m_0\ddot{z} &- c_x\left[(x - z)\cos\alpha + y\sin\alpha\right]\cos\alpha - \\ &- c_y\left[(x - z)\sin\alpha - y\cos\alpha\right]\sin\alpha - \\ &- H_x\left[(\dot{x} - \dot{z})\cos\alpha + \dot{y}\sin\alpha\right]\cos\alpha - \\ &- H_y\left[(\dot{x} - \dot{z})\sin\alpha - \dot{y}\cos\alpha\right]\sin\alpha = F_z; \end{aligned} \tag{10}$$

- when $y \ge y_s$, there is a contact with the support at the point A and the following forces appear.

Along the axis $0Y$:

$$F_{so} = H_a\dot{y} + c_a(y - y_s). \tag{11}$$

Along the axis $0X$:

$$F_f = f_0 N sign\dot{x} + f_1\dot{x}. \tag{12}$$

The normalized force of pressure:

$$N = F_{so}; \tag{13}$$

$$m\ddot{x}+c_x\left[(x-z)\cos\alpha+y\sin\alpha\right]\cos\alpha+$$
$$+c_y\left[(x-z)\sin\alpha-y\cos\alpha\right]\sin\alpha+$$
$$+H_x\left[(\dot{x}-\dot{z})\cos\alpha+\dot{y}\sin\alpha\right]\cos\alpha+$$
$$+H_y\left[(\dot{x}-\dot{z})\sin\alpha-\dot{y}\cos\alpha\right]\sin\alpha+F_f=F_x; \quad (14)$$

$$m\ddot{y}+c_x\left[(x-z)\cos\alpha+y\sin\alpha\right]\sin\alpha-$$
$$+c_y\left[(x-z)\sin\alpha-y\cos\alpha\right]\cos\alpha+$$
$$+H_x\left[(\dot{x}-\dot{z})\cos\alpha+\dot{y}\sin\alpha\right]\sin\alpha-$$
$$-H_y\left[(\dot{x}-\dot{z})\sin\alpha-\dot{y}\cos\alpha\right]\cos\alpha+F_{so}=F_y; \quad (15)$$

$$m_0\ddot{z}-c_x\left[(x-z)\cos\alpha+y\sin\alpha\right]\cos\alpha-$$
$$-c_y\left[(x-z)\sin\alpha-y\cos\alpha\right]\sin\alpha-$$
$$-H_x\left[(\dot{x}-\dot{z})\cos\alpha+\dot{y}\sin\alpha\right]\cos\alpha-$$
$$-H_y\left[(\dot{x}-\dot{z})\sin\alpha-\dot{y}\cos\alpha\right]\sin\alpha=F_z. \quad (16)$$

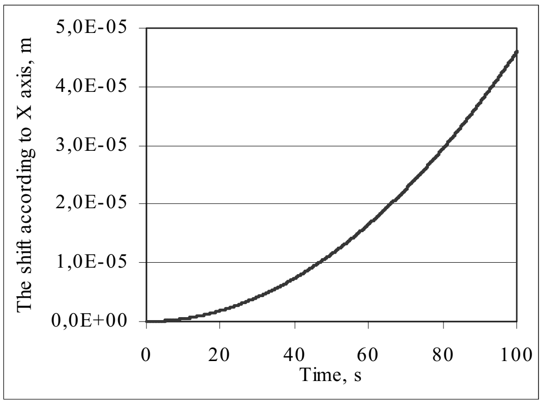

Fig. 5. The shifts of the exciter according to X *axis dependence upon the time*

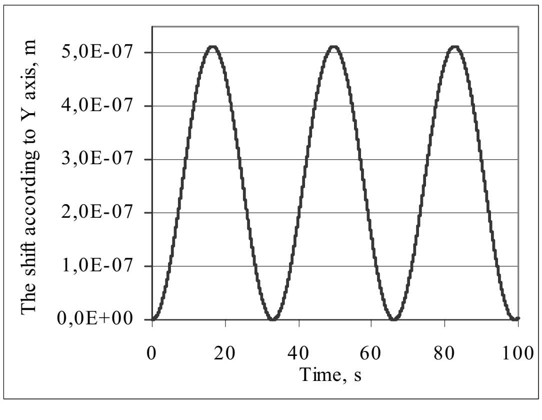

Fig. 6. The shifts of the exciter according to Y *axis dependence upon the time*

After the solution of the above-presented equations we find the characteristics of the dynamic model of the one-dimensional vibration exciter with two degrees of freedom (Figs 5, 6).

On the further analysis of the obtained solution and the optimization of the parameters of the dynamic models it was concluded that the design of the robot requires improvement. The obtained shifts of the vibration exciter were very small increasing the exciting force. So in order to ensure more effective dynamic characteristics of the robot it was decided to change its design for the one where deformable rings are deformed in the direction of the movement of the robot (Figs 2, 7).

4. The Mathematical Model of the Transport Robot with Ring Elements Situated Along the Direction of its Movement

Developing a mathematical model of a robot with elastic ring-shaped elements (Figs 2, 7) some changes are introduced to simplify the calculations. Points of a ring element may be singled out and their coordinates may be used for the description of the model or the ring elements may be replaced with solid members.

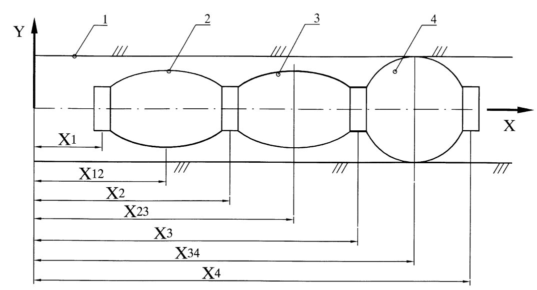

Fig. 7. The scheme of a robot with ring elements 1-pipe, 2, 3, 4 - the blocks formed of elastic elements and united into the chain

The coordinates of the points of the simplified model of a robot (Fig 8) [4] may be written as follows:

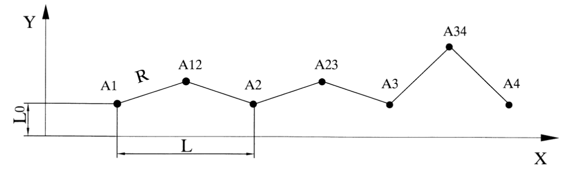

Fig. 8. The simplified scheme of a robot calculation

$$A_{i,j+1}\left(X_{i,j+1}, L_0 + Y_{i,j+1}\right); \quad (17)$$

$$X_{i,i+1} = \frac{1}{2}\left(X_i + X_{i+1}\right); \quad (18)$$

$$Y_{i,i+1} = \sqrt{R^2 - \frac{1}{4}\left(X_i - X_{i+1}\right)^2}\ ; \quad (19)$$

here R-the length of a section;

$$\dot{X}_{i,i+1} = \frac{1}{2}\left(\dot{X}_i + \dot{X}_{i+1}\right); \quad (20)$$

$$\dot{Y}_{i,i+1} = -\frac{X_i - X_{i+1}}{4Y_{i,i+1}}\left(\dot{X}_i - \dot{X}_{i+1}\right); \quad (21)$$

here $\dot{} = \frac{d}{dt}$.

The kinetic energy of the system:

$$T = \frac{1}{2} m \sum_{i=1}^{q}\left(\dot{X}^2_{i,i+1} + \dot{Y}^2_{i,i+1}\right) + \frac{1}{2} m_0 \sum_{i=1}^{q+1}\left(\dot{X}_i^2\right); \quad (22)$$

here $q=1,2,\ldots n;$
where

$$\dot{X}^2_{i,i+1} + \dot{Y}^2_{i,i+1} = \frac{1}{4}\left(\dot{X}_i + \dot{X}_{i+1}\right)^2 + \frac{1}{4}K_{i,i+1}\left(\dot{X}_i - \dot{X}_{i+1}\right)^2\ ; \quad (23)$$

$$K_{i,i+1} = \frac{1}{4}\left(\frac{X_i - X_{i+1}}{Y_{i,i+1}}\right)^2 = K_{i,i+1}\left(X_i - X_{i+1}\right); \quad (24)$$

$$\begin{aligned} T = \frac{m}{8}\Big[& \left(1+K_{12}\right)\left(\dot{X}_1^2 + \dot{X}_2^2\right)^2 + 2\left(1-K_{12}\right)\dot{X}_1\dot{X}_2 + \\ & + \left(1+K_{23}\right)\left(\dot{X}_2^2 + \dot{X}_3^2\right)^2 + 2\left(1-K_{23}\right)\dot{X}_2\dot{X}_3 + \\ & + \left(1+K_{34}\right)\left(\dot{X}_3^2 + \dot{X}_4^2\right)^2 + 2\left(1-K_{34}\right)\dot{X}_3\dot{X}_4 + \\ & \left(1+K_{45}\right)\left(\dot{X}_4^2 + \dot{X}_5^2\right)^2 + 2\left(1-K_{45}\right)\dot{X}_4\dot{X}_5 \Big] + \\ & + m_0\left(\dot{X}_1^2 + \dot{X}_2^2 + \dot{X}_3^2 + \dot{X}_4^2 + \dot{X}_5^2\right). \end{aligned} \quad (25)$$

The forces of inertia are found:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{X}_i} - \frac{\partial T}{\partial X_i} = I\left(X_i\right); \quad (26)$$

$$I\left(X_1\right) = \frac{m}{4}\left[\left(1+K_{12}\right)\ddot{X}_1 + \left(1-K_{12}\right)\ddot{X}_2 + \frac{1}{2}\left(K_{12}\right)'_{X_1}\left(\dot{X}_1 - \dot{X}_2\right)^2\right] + m_0\ddot{X}_1\ ;$$

$$\begin{aligned} I\left(X_j\right) = \frac{m}{4}\Big[& \left(1+K_{j-1,j}\right)\ddot{X}_j + \left(1-K_{j-1,j}\right)\ddot{X}_{j-1} + \left(1+K_{j,j+1}\right)\ddot{X}_j - \\ & - \left(1-K_{j,j+1}\right)\ddot{X}_{j+1} - \frac{1}{2}\left(K_{j-1,j}\right)'_{X_{j-1}}\left(\dot{X}_{j-1} - \dot{X}_j\right)^2 + \\ & + \frac{1}{2}\left(K_{j,j+1}\right)'_{X_j}\left(\dot{X}_j - \dot{X}_{j+1}\right)^2\Big] + m_0\ddot{X}_j\ ; \end{aligned} \quad (27)$$

here $j=2,\ldots,q-1$

$$I\left(X_q\right) = \frac{m}{4}\left[\left(1+K_{q-1,q}\right)\ddot{X}_q + \left(1-K_{q-1,q}\right)\ddot{X}_{q-1} - \frac{1}{2}\left(K_{q-1,q}\right)'_{X_{q-1}}\left(\dot{X}_{q-1} - \dot{X}_q\right)^2\right] + m_0\ddot{X}_q\ . \quad (28)$$

The potential energy of the system:

$$\Pi'_{X_1} = C\left(X_1 - X_2 + L\right); \quad (29)$$

$$\Pi'_{Xj} = C\left(2X_j - X_{j-1} - X_{j+1}\right); \quad (30)$$

$$\Pi'_{X_q} = C\left(X_q - X_{q-1} - L\right). \quad (31)$$

The dissipative function:

$$D = \frac{H}{2}\left[\left(\dot{X}_1 - \dot{X}_2\right)^2 + \left(\dot{X}_2 - \dot{X}_3\right)^2 + \ldots + \left(\dot{X}_{q-1} - \dot{X}_q\right)^2\right]\ ; \quad (32)$$

$$D'_{\dot{X}_1} = H\left(\dot{X}_1 - \dot{X}_2\right); \quad (33)$$

$$D'_{\dot{X}_{j1}} = H\left(2\dot{X}_j - \dot{X}_{j-1} - \dot{X}_{j+1}\right); \quad (34)$$

$$D'_{\dot{X}_q} = H\left(\dot{X}_q - \dot{X}_{q-1}\right). \quad (35)$$

The differential equations of the movement of the system

$$I\left(X_1\right) + \Pi'_{X_1} + D'_{\dot{X}_1} + F_{f_{12}} = F_{12}\ ; \quad (36)$$

$$I(X_j) + \Pi'_{X_j} + D'_{\dot{X}_j} + F_{f_{j,j-1}} + F_{f_{j,j+1}} = \\ = -F_{j,j-1} + F_{j,j+1}\,; \qquad (37)$$

$$I(X_q) + \Pi'_{X_q} + D'_{\dot{X}_q} + F_{f_{q,q-1}} = -F_{q,q-1} - F_n\,; \qquad (38)$$

here F_n – the useful resistance force.

The friction force in the point $A_{j,j+1}$ is equal to

$$F_{f_{j,j-1}} = \frac{1}{2} N_{j,j-1} f_0 sign(\dot{X}_j + \dot{X}_{j-1}); \qquad (39)$$

here $N_{j,j-1}$ – the normalised force at the point $A_{j,j-1}$ acting between the immovable surface of support and the robot's ring element point $A_{j,j-1}$; f_0 – dry friction coefficient.

At the point $A_{j,}$ the external exciting force is equal to:

$$F_s = -F_{j,j-1} + F_{j,j+1}\,; \qquad (40)$$

$$sign(\dot{X}_j + \dot{X}_{j-1}) = \begin{cases} +1, kai\dot{X}_j + \dot{X}_{j-1} > 0, \\ -1, kai\dot{X}_j + \dot{X}_{j-1} < 0, \\ (-1,+1), kai\dot{X}_j + \dot{X}_{j-1} = 0. \end{cases} \qquad (41)$$

When $Y_{j,j-1}=Y_a$, i.e. to the distance to the support, in the equations $F_{f\,j,j-1}q0$. And when $Y_{j,j-1}<Y_a$, then $F_{f\,j,j-1}=0$.

The solution of these equations and a further analysis of the obtained results as well as the optimization of parameters of the mathematical model allow to improve the design of the robot and to develop its optimal variant.

5. Conclusions

Designs of pipeline transport robots elements are reviewed and the scheme of a new original construction is presented. Mathematical models of robots with elastic elements are developed and their dynamic equations are written.

6. References

[1] Komori M., Suyama K.: *Inspection robots for gas pipelines of Tokyo Gas*. Advanced Robotics, Vol 15, No 3, 2001, p. 365 - 370.

[2] Choi H.R., Ryew S.M.: *Robotic system with active steering capability for internal inspection of urban gas pipelines*. Mechatronics, Vol 12, Issue 5. 2002, p. 713-736.

[3] Kulvietis G., Mištinas V., Matuliauskas A., Ragulskis K., Spruogis B.: *Dynamic Parameter Investigation of Pipe Robots*. Journal of Vibroengineering No 2 (7). 2001, p. 55 - 58.

[4] Timoshenko S.P., Yang D.Kh., Weaver W.: *Vibrations in engineering (Колебание в инженерном деле)*. Mashinostrojenije, 1985. 472 p. (in Russian).

[5] Matuliauskas A., Spruogis B.: *Pipeline Robots With Elastic Elements*. TRANSPORT. Vilnius: Technika, 2002, XVII t. Nr.5, p. 177-181.

[6] Spruogis B., Ragulskis K., Bogdevičius M., Ragulskis M., Matuliauskas A., Mištinas V.: *In pipeline walking robot*. Patent of Lithuania (Vamzdyno viduje žingsniuojantis robotas. Lietuvos patentas) LT4968B.-Vilnius, 2000. (in Lithuanian).

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