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# Journal of Vibroengineering

2000 No4 (5)

ISSN 1392-8716

## Contents

73-100 Proceedings of the 2<sup>nd</sup> International Anniversary Conference VIBROENGINEERING-2000 1-143

## **Aims and Scope**

Original papers dealing with modern developments in the areas of theory and applications of mechanical, mechatronic and biomechatronic system are welcomed. The following subjects are indicated as principal topics:

- vibroacoustic and wave processes
- analysis and synthesis of nonlinear vibration systems
- generation of vibrations and waves
- vibrostabilization and control of motions
- transformation of motion by vibrations and waves
- technology of vibrations and waves
- vibration measurement, vibro-identification, vibro-diagnostics and monitoring

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## **J. Vibroengineering is supported by**

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**ALL PUBLISHED MATERIALS ARE REVIEWED**

# Pipe Crawling Robots With Vibratory Drives

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**ABSTRACTS.** In the article the classification of pipe crawling robots with vibratory drives is presented, their advantages and imperfections are reviewed. The schemes of the construction of a pipe crawling robot with a vibratory shock drive or vibratory drives. The dynamic models of a robot with a vibratory shock drive and a one-dimensional vibration exciter with two degrees of freedom were developed and the equations of their movement were formed and written.

**KEYWORDS:** a pipe crawling robot, a vibratory drive, a vibratory shock drive, an exciter

## NOTATION

$m_x, m_0, m$  – masses

$x, x_0, y, y_0, y_s$  – shifts of the robot and its masses

$C, c_x, c_y, c_a$  – coefficients of stiffness

$H, H_x, H_y, H_a$  – coefficients of resistance of a linear shift

$z^+, x^+$  – the speed and the shift after a shock, respectively

$z^-, x^-$  – the speed and the shift before a shock, respectively

$f_0, f_1$  – the coefficients of dry and liquid friction

## 1. INTRODUCTION

The pipe transport is widely used for a transportation of homogenous substances (such as water, gas, oil and its products, various chemicals and so on). In Republic of Lithuania the length of pipes for transportation oil only is over 400 km. In a course of time a pipe wears out, i.e. the inner surface of the pipe is covered by corrosion coating, the welding seams of the pipes lose their tightness, defects in the structure of the pipe's material appear and on a transportation of various sticky substances a layer of thin coating is formed on the inner surface of the pipe, thus reducing the capacity of the pipe (Only on a transportation of oil and its products this thin coating constitutes to 70% of the diameter of the pipe). So, special technical means are necessary to control pipes. Lately robots are world-widely used for a control of the inner part of pipes.

## 2. THE CLASSIFICATION OF PIPE CRAWLING ROBOTS

Piping systems for transportation of substances are classified according to the diameters of pipes, lengths of pipes, transportable substances, radii of pipe bending and so on. Many various robots are developed for a control of inner surface of cylindrical pipes. They are divided into groups according to the manner of driving of the robot in the pipe:

- self-propelled;

- drawn with a rope or chain;
- moving together with the transported substance;
- of a combined type.

According to their functional purpose robots are classified to:

- diagnostic
- cleaning
- combined (diagnostic and cleaning)

In their turn, self-propelled pipe crawling robots are classified:

1. according to periodicity of movement:

- step movement;
  - continuous movement
2. according to the type of the drive:
- electric;
  - hydraulic;
  - pneumatic;
  - magnetic;
  - combined.

3. according to the interaction with the surface of support:

- interacting with a plane;
- interacting with a deformation-proof pipe;
- interacting with deformable media.

In their turn, step movement pipe crawling robots are classified according to the type of control to:

- programmed control;
- biotechnical;
- intellectual.

According to the method of cleaning of pipes the pipe crawling robots are classified to:

- mechanical;
- chemical;
- combined (mechanical and chemical).

A self-propelled pipe crawling robot consists of an open kinematic circuit, which links are connected to each other with kinematic couples. Crawling contact surface is formed by rollers, cater-pillar tracks and so on of the corresponding shapes. All self-propelled continuous

The Journal was received on 3 July 2000 and was accepted for publication on 28 August 2000.

movement pipe crawling robots may be divided into two groups according to their design.

The first group [11] consists of a carrying frame with the robot moving a drive mounted on it, the end link of the drive being a roller, connected with another roller or caterpillar track in a kinematic way. On the top of the robot a support link is mounted, which is connected in a kinematic way with the carrying frame via a cylindrical reductor and a screw-nut drive. The support link is used to ensure the stability of the robot. The support link with a support roller mounted on its end may hinge by an angle to  $90^\circ$  and move around the axle of fitting. This ensures a stability of movement of the robot on changes of the diameter of the pipe.

The principle of movement of mechanisms of this group is the following: the pipe crawling robot moving drive via the kinematic link transfers a rotational movement to the driving roller, which rotates the roller or caterpillar, contacting with the inner surface of the pipe. The position of the support link alters dependently on the diameter of the pipe and on changes of the latter the changes of the position take place as well.

The advantages of this group of designs of pipe crawling robots are the following:

1. Self-propelling
2. Good control of the speed of movement and the force of cohesion with the contact surface.
3. A good capacity of piping, where diameters of pipes are different.
4. Sufficient capacity in bent fragments of piping.

The imperfections of this group of designs of pipe crawling robots are the following:

1. They may be used only after a termination of supply of the transported substance
2. Limited possibilities of power supply
3. Rotational movement on the contact with the pipe.

The second group of continuous movement pipe crawling robots includes "rotating" mechanisms [12]. Such mechanism consists of a stator with a rotor, put on it. A brake is fitted between the stator and rotor. Cuts may be provided in the rotor for an injection of the substance for cleaning the inner surface of the pipe. The substance may be held in the rotor mechanism itself or supplied by hoses. The principle of operation of the pipe crawling robot is the following: when the rotor with spiral-shaped notches, which enter into contact with the pipe, is rotating on the stator, the robot is moving forward or backward dependently on the direction of rotation of the rotor. If several such rotors are connected, the mobility of robots of this group increases considerably in bent fragments of the piping.

The advantages of this group of designs of pipe crawling robots are the following:

1. Self-propelling
2. Good control of the speed of movement and the force of cohesion with the contact surface

The imperfections of this group of constructions of pipe crawling robots are the following:

1. They may be used only after a termination of supply of the transported substance
2. Limited possibilities of power supply
3. Limited capacity in bent fragments of piping
4. Rotational movement on the contact with the pipe.
5. Limited capacity of piping with different diameters of pipes.

Self-propelled step movement pipe crawling robots also consists of an open kinematic circuit, which links are connected to each other with kinematic couples and in the drive of power supply a supplemental movement transforming equipment is provided. According to peculiarities of designs all the self-propelled step movement pipe crawling robots may be divided into three groups.

Pipe crawling robots of the first group [4] consist of links, connected with cylindrical inter-link hinge joints. Each hinge joint is connected to electric engine via the worm reductor and one-side clutch. An angle meter for a measurement of the angle between links is mounted into each hinge joint. One of the middle links consists of two parts connected with a hinge joint. These parts are also connected with a cylindrical hinge joint, which is connected in a kinematic way with self-stopping worm reductor and electric engine. A rotation angle measuring device is mounted into the inter-link hinge joint. The axle of this joint is perpendicular to the axles of the inter-link cylindrical hinge joints and parallel to the longitudinal axle of the pipe.

The principle of operation of the construction of this group is the following: the movement of links around the cylindrical hinge joint, perpendicular to the longitudinal axle of the piping, enables the drive of each link to change positions of links of the robot in the longitudinal plane of the pipe in order to form bent elbows. In such case the support pressure on the contact ensures the sufficient friction force (on rest) to achieve an immobility of the bent elbow and free movement of other links. Because the length of the bent elbow is less than the one of the straightened links, forming the elbow, the bending and straightening of the elbow make to move the pipe crawling robot. Such pipe crawling robot may move according to the principle of "running wave", when the functions of a formation of bent elbow and change of its length are bound and the bent elbows are formed in succession along the total length of the mechanism. Such mechanism may also move with the fixed front and end bent elbows and to change the lengths of the middle links on changes of the fixation.

The advantages of this group of designs of pipe crawling robots are the following:

1. Self-propelling
2. No motion on the contact with the pipe.
3. Good control of the speed of movement and the force of cohesion with the contact surface
4. Good capacity in bent fragments of piping.

5. Good capacity of piping, where diameters of pipes are different.

The imperfections of this group of constructions of pipe crawling robots are the following:

1. They may be used only after a termination of supply of the transported substance
2. Limited possibilities of power supply
3. Limited movement when the layer of coating on the inner surface of the pipe is too thick.

The second group of step movement pipe crawling robots includes robots with a pneumatic drive [9] (See Fig. 1).

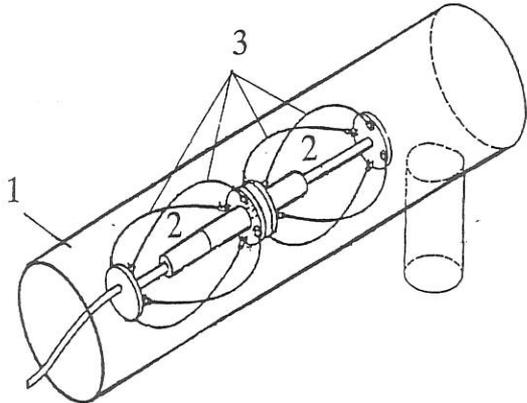


Fig. 1 The scheme of transporting blocks of a crawling robot with deformable pressing elements:  
1 – the pipe, 2 – the transporting blocks, 3 – the deformable pressing elements

The advantages of this group of designs of pipe crawling robots are the following:

1. Self-propelling
2. No motion on the contact with the pipe.
3. Good control of the speed of movement and the force of cohesion with the contact surface

The imperfections of this group of constructions of pipe crawling robots are the following:

1. They may be used only after a termination of supply of the transported substance
2. Limited possibilities of power supply
3. Limited movement when the layer of coating on the inner surface of the pipe is too thick.
4. Limited capacity in bent fragments of piping
5. Limited capacity of piping with different diameters of pipes

The third group of step movement pipe crawling robots includes robots with an electric drive [2, 3, 7]. Their constituent parts are the following: a central body with electric engines mounted on it, which are connected with the movement supports. The number of the supports is no less than six, i.e. three supports in one plane and three supports in the other plane. In this way a stability of movement of the robot is ensured. The number of the

supports may be increased in order to improve a permeability of the robot, when the layer of coating on the inner part of the pipe is too thick.

The principle of operation is following: the electric engine, mounted on the central body, activates a step movement of the supports and thus enables the pipe crawling robot to move forward or backward.

The advantages of this group of constructions of pipe crawling robots are the following:

1. Self-propelling
2. No motion on the contact with the pipe
3. Good control of the speed of movement and the force of cohesion with the contact surface

The imperfections of this group of constructions of pipe crawling robots are the following:

1. They may be used only after a termination of supply of the transported substance
2. Limited possibilities of power supply
3. Limited movement when the layer of coating on the inner surface of the pipe is too thick
4. Limited capacity in bent fragments of piping
5. Limited capacity of piping with different diameters of pipes

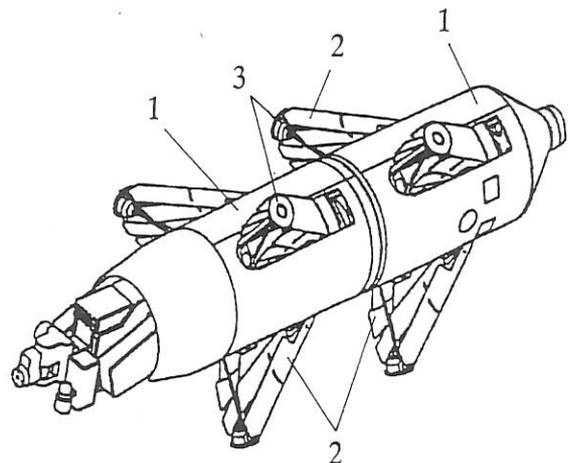


Fig. 2. The scheme of transporting blocks of crawling robots with unbendable feet:  
1 - the transporting blocks, 2 – the unbendable feet, 3 – special surfaces

### 3. NEW SCHEMES OF DESIGNS OF PIPE CRAWLING ROBOTS

After an analysis of the peculiarities of the designs of the pipe crawling robots, described in the Section 2, it was decided to develop new schemes of designs of the robots, preserving good permeability of the robots in bent fragments of piping and when the diameters of pipes are different as well as other features of the existing pipe crawling robots. The new schemes are presented in Fig. 3.

A robot with vibratory drives in its transporting block is classified as a robot of a newer type. A drive of the

transporting block of such robot consists of excitable masses, elastic elements and electrostatic exciting elements, which excite vibrations of the transporting blocks (Fig. 3). So, the transporting block may be called the exciting and transporting block. The electrostatic exciting elements via the elastic elements vibrate the excitable masses, which develop a friction force on a contact with the support and push the transporting block. Because of this the transporting block starts to move. Robots with transporting block of this type may be of smaller dimensions, they are more mobile, so their field of application is more various and wider.

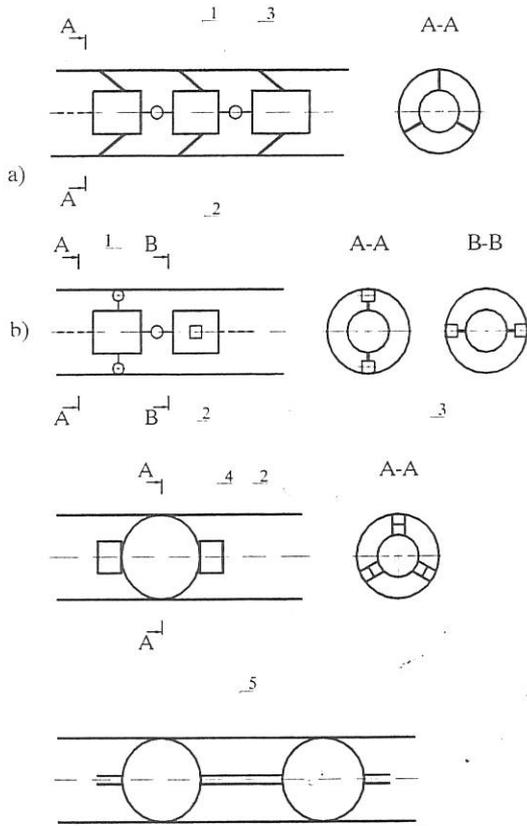


Fig. 3. The schemes of crawling robots for curved pipes: a) the principal scheme of the drive, b) the fragments of the drive's element 1 – the element of the vibratory drive, 2 – the elastic hinge joints, 3 – the hinge joint elastic contact supports, 4 – segments of the cylinder, 5 – rings

### 3.1. PIPE CRAWLING ROBOTS WITH VIBRATORY SHOCK DRIVE

The robot (see Fig. 4) consists of the body 1 with three supports 2 fitted on it, forming an angle of 120°. In order to ensure a movement of the robot in one direction the elastic element 3 is inserted between the body 1 and the support 2. In the end part of the body an alternating electromagnet 4 is mounted with the elastic element 5 and damper 6 fitted to it. A moving mass (permanent magnet)

is connected to the elastic element 5 and damper 6. Various diagnostic and cleaning equipment may be connected to the robot.

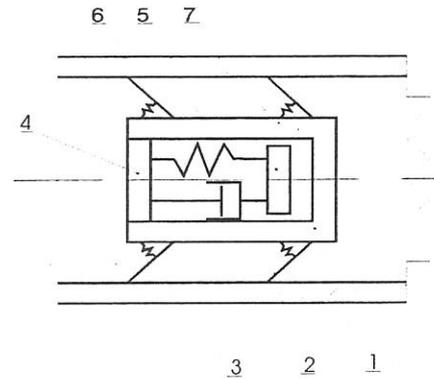


Fig. 4. The scheme of the design of the original step movement robot with a vibratory shock drive. 1 – the body, 2 – the movement support, 3, - the elastic elements, 4 – the alternating-current electromagnet, 5 – the elastic element, 6 – the damper, 7 – the moving mass (permanent magnet).

On an examination of the pipe crawling robot the following dynamic model of this scheme was developed:

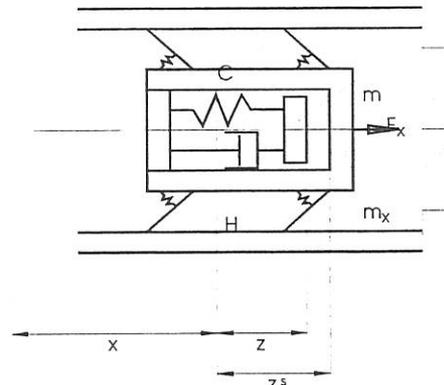


Fig. 5. The dynamic model of the original pipe crawling robot:  $m_s$  – the moving mass,  $m_x$  – the mass of the body,  $x$  – the shift of the robot,  $z$  – the shift of the moving mass,  $C$  – the coefficient of stiffness,  $H$  – the coefficient of resistance of linear shift

The mathematical expression of the dynamic model of the system shall be the following system of equation [1, 5, 6, 8]:

$$\text{When } z < z_s, \begin{cases} x'' + z'' + hz' + h_2z = f_0 \sin \omega t; \\ \mu x'' + f_f - hz' - h_2z = f_f; \end{cases} \quad (1)$$

$$\text{When } z = z_s, \begin{cases} z'^+ = Rz'^-; \\ x'^+ = x'^- + \frac{HR}{1 + \mu} z'^-; \end{cases} \quad (2)$$

$$0 < R < 1; \mu = \frac{m_x}{m}; h = \frac{H}{m}; h_2 = \frac{C}{m}; f_0 = \frac{F_0}{m};$$

$$f_f = \frac{F_f}{m}; f_x = \frac{F_x}{m}. \quad (3)$$

The dynamic parameters of the system shall be found on a solution of these system of equations.

4. THE ROBOTS WITH A VIBRATORY DRIVE

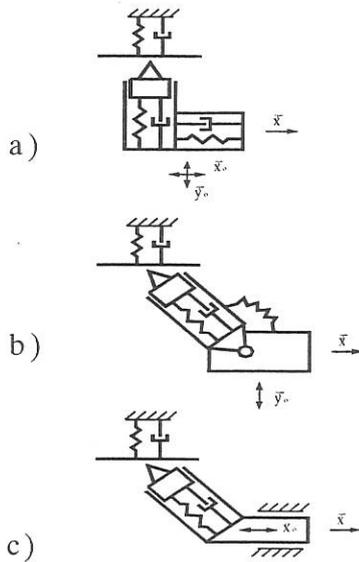


Fig. 6. A vibratory drive:  
a) two-dimensional motion;  
b) and c) - one-dimensional motions,  $x_0, y_0$  - external excitation  
 $X$  - the caused motion

The following dynamic model of the system of the one-dimensional vibration exciter with two degrees of freedom is developed:

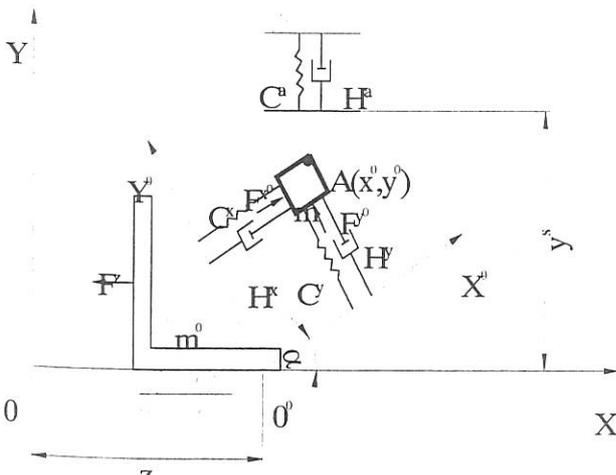


Fig. 7. The scheme of the dynamic model of the system of the one-dimensional vibration exciter with two degrees of freedom.

The coordinates of the point A ( $x_0; y_0$ ) of the excitable mass  $m$  in the coordinate system  $X_0O_0Y_0$  and the point A( $x, y$ ) of the same mass in the coordinate system  $XOY$  are expressed by the following equations [1, 5, 6, 8]:

$$x = z + x_0 \cos \alpha - y_0 \sin \alpha; \quad (4)$$

$$y = x_0 \sin \alpha + y_0 \cos \alpha; \quad (5)$$

$$x_0 = (x - z) \cos \alpha + y_0 \sin \alpha; \quad (6)$$

$$y_0 = -(x - z) \sin \alpha + y \cos \alpha; \quad (7)$$

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

$$T = 0,5[m_0 z'^2 + m(x'^2 + y'^2)]; \quad (8)$$

$$n = 0,5[c_x x_0^2 + c_y y_0^2 + c_a (y - y_s)^2]; \quad (9)$$

$$D = 0,5[H_x x_0'^2 + H_y y_0'^2 + H_a y'^2]; \quad (10)$$

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

- when  $y \leq y_s$ , there is no contact with the support on the point A

$$m x'' + c_x [(x - z) \cos \alpha + y \sin \alpha] \cos \alpha + c_y [(x - z) \sin \alpha - y \cos \alpha] \sin \alpha + H_x [(x' - z') \cos \alpha + y' \sin \alpha] \cos \alpha + H_y [(x' - z') \sin \alpha - y' \cos \alpha] \sin \alpha = F_x; \quad (11)$$

$$m y'' + c_x [(x - z) \cos \alpha + y \sin \alpha] \sin \alpha - c_y [(x - z) \sin \alpha - y \cos \alpha] \cos \alpha + H_x [(x' - z') \cos \alpha + y' \sin \alpha] \sin \alpha - H_y [(x' - z') \sin \alpha - y' \cos \alpha] \cos \alpha = F_y; \quad (12)$$

$$m_0 z'' - c_x [(x - z) \cos \alpha + y \sin \alpha] \cos \alpha - c_y [(x - z) \sin \alpha - y \cos \alpha] \sin \alpha - H_x [(x' - z') \cos \alpha + y' \sin \alpha] \cos \alpha - H_y [(x' - z') \sin \alpha - y' \cos \alpha] \sin \alpha = F_z; \quad (13)$$

- when  $y \geq y_s$ , there is a contact with the support on the point A and the following forces appear:  
Along the axis OY:

$$F_{so} = H_a y'' + c_a (y - y_s); \quad (14)$$

Along the axis OX:

$$F_f = f_0 N \text{sign} x' + f_1 x'; \quad (15)$$

The normalized force of pressure:

$$N = F_{s0}; \quad (16)$$

$$\begin{aligned} & mx'' + c_x[(x-z)\cos\alpha + y\sin\alpha]\cos\alpha + \\ & c_y[(x-z)\sin\alpha - y\cos\alpha]\sin\alpha + \\ & + H_x[(x'-z')\cos\alpha + y'\sin\alpha]\cos\alpha + \\ & + H_y[(x'-z')\sin\alpha - y'\cos\alpha]\sin\alpha + F_f = F_x; \end{aligned} \quad (17)$$

$$\begin{aligned} & my'' + c_x[(x-z)\cos\alpha + y\sin\alpha]\sin\alpha - \\ & c_y[(x-z)\sin\alpha - y\cos\alpha]\cos\alpha + \\ & + H_x[(x'-z')\cos\alpha + y'\sin\alpha]\sin\alpha - \\ & - H_y[(x'-z')\sin\alpha - y'\cos\alpha]\cos\alpha + F_{s0} = F_y; \end{aligned} \quad (18)$$

$$\begin{aligned} & m_0 z'' - c_x[(x-z)\cos\alpha + y\sin\alpha]\cos\alpha - \\ & c_y[(x-z)\sin\alpha - y\cos\alpha]\sin\alpha - \\ & - H_x[(x'-z')\cos\alpha + y'\sin\alpha]\cos\alpha - \\ & - H_y[(x'-z')\sin\alpha - y'\cos\alpha]\sin\alpha = F_z. \end{aligned} \quad (19)$$

After a solution of these equations and analysis of the solutions as well as an optimization of the parameters of the dynamic model it will be possible to present the optimum design of the activator of vibrations.

## 5. CONCLUSIONS

The review of designs of pipe crawling robots moving by curved trajectories and several new schemes of them are presented.

The model of the robot with vibratory shock drive with its dynamic characteristics was developed.

The model of the system of the one-dimensional vibration exciter with two degrees of freedom with its dynamic characteristics was developed.

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