Cyclic deformation of separating tape in electromagnetic rolling pump

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Abstract. The purpose of the paper is to justify a substantiation of the possibilities of trouble-free operation of de-axial pump based on the Rolamite mechanism with rolling bodies. The use of an electromagnet as a drive makes it possible to transfer the rotation into a closed space as well as abandon bearings and seals. The flexible tape allows reducing the slip friction and getting separate cameras with the possibilities to pump two substances at a time. The structure of the strain cycle of combined stretching and bending during rotation is investigated in details for the separating tape. The thickness of the tape which provides the specified durability of operation is determined.

1. Introduction
Accelerated development of high-tech industries of human activity puts new demands on product improvement for designers of pumping equipment. There is an urgent need to transport not only water but also other liquid materials, different in their physical and chemical qualities and characteristics, in particular, oil and petroleum products.

Volumetric rotary pumps, which operate on the principle of displacement, work by changing the volume of the working chamber [1, 2]. The efficiency of such pumps depends on two components – hydraulic and mechanical. For example, in a gear pump, the hydraulic component is affected by fluid loss due to radial gaps between the cylindrical surfaces of the body and the outer surfaces of the gear teeth heads, as well as due to leaks between the teeth. The value of the radial gap is determined by the possible gap in the bearings and their misalignment, as well as the eccentricity of the gears in the body pads. Such losses account for up to 75–80% of the total losses in the pump. The influence of mechanical losses on the efficiency of the pump is determined by the type of bearings, the design of the seal and the accuracy of the friction surfaces. The complexity and high cost of the design are due to the need for careful sealing of the working chambers of the pump, fitting and grinding of the contact parts, etc. In the case of gapless engagement, there is unwanted fluid compression, which causes heavy loads on the gears, leads to increased wear of the teeth and overheating of the shaft and bearings.
Traditional methods of combating hydraulic losses, compression or vibration [2–5] lead to the complexity of pump designs.

D. Wilkes [6] recently patented the Rolamite mechanism. This mechanism consists of two rollers held on opposite sides of the S-shaped metal tape. Because the tape and rollers move at the same speed, there is no sliding between them and therefore almost no friction. The device is quite versatile and can function as a switch, valve, pump, fuse, thermostat, amplifier, coupling, speed change device, brake, pressure sensor, electromagnet, fire alarm etc. [7]. In the course of further experiments, it was found that due to the tension of the flexible tape, the sliding of the rollers is practically eliminated, i.e. the sliding friction turns into almost pure rolling [6, 8]. It is important that this happens without the use of lubricant.

The low coefficients of friction, various combinations that can be created by changing the size of the rollers and tape, have led to the use of this mechanism in many fields of technology. In [9] the application of Rolamite principles for the creation of upper limb prostheses is described, work [10] gives an example of the application of this mechanism in dentistry. The article [11] analyses the Rolamite architecture exploiting shape-memory alloys as power element to obtain a solid-state actuator.

Basically, pumps built on the Rolamite mechanism were of the parietal type [12]. The gas meter mechanism belongs to the constructions in which the free space between the working and distribution rollers began to be used [13]. It is also interesting to use the Rolamite mechanism in two mutually perpendicular planes [14].

In order to avoid a negative impact of these shortcomings on the quality of existing rotary volumetric hydraulic pumps, the authors proposed a fundamentally new deaxial rotary hydraulic rolling pump [15, 16]. It uses an advanced eccentric Rolamite mechanism with an electromagnetic drive. Analytical calculation of chambers volumes is provided and the coefficient of liquid compression is determined [16]. The most important element that determines the durability of the proposed structure is a closed separating tape, which undergoes cyclic deformation of bending and tension.

Previously [7], experiments showed that the beryllium copper strips used in Rolamite were so strong that they showed no signs of metal fatigue after $10^6$ bends. The issues of theoretical analysis of the durability of cyclically deformed tape remain unresolved today. Only some problems of the mechanics of fracture of thin boundless plates during bending were considered, taking into account the closure of single cracks [17–20], as well as systems of collinear [21–24] and parallel [25–28] defects. Cases of combined bending and tension [17, 29] and cyclic bending [30] of cracked plates were also considered. The effect of the geometric parameters of the rubber-rop e belt on its stress-strain state on the driving drum winder is investigated [31, 32].

The aim of the paper is to justify a substantiation of the possibilities of trouble-free operation of deaxial pump based on the Rolamite mechanism with rolling bodies. At the same time it is necessary to describe regularities of cyclic deformations of tension and bending of a separating tape in order to establish relations between design parameters of the pump and its durability.

2. Rolling pump design

The proposed design of the electromagnetic rolling pump [15, 16] is shown in figure 1. The rolling pump has an electromagnetic drive 1, body 2 with inlet B and b and outlet C and c windows in the end wall of the body, end cover 3, thin elastic non-magnetic closed tape 4, three distributions 5 and three working 6 rollers. Each of the working rollers 6 is made with an external radius, three times smaller than the radius of the inner surface of the body and one of them 8 is ferromagnetic. In the body 2, the spike 7 is made with eccentricity. The tape 4 with its inner surface covers the distribution rollers 5, and with the outer surface – working rollers 6. The rollers are able to move: distribution 5 move along the axis 7, and working ones 6 move on the inner surface of the body 2. Between inlet B and b and outlet C and c windows there are jumpers with a distance twice less than the distance between adjacent rollers.
The rolling hydraulic pump works as follows. When you activate the drive 1 there is a running magnetic field, which causes the ferromagnetic roller 8 to move along the inner cylindrical guide of the body 2. Due to the kinematic connection of this roller with other rollers, with the help of tape 4, they will begin rolling: the working rollers will roll along the cylindrical surface of the body 2, and the distributing ones – along the spike 7. Since the axis 7 is eccentric, the volume of space between the rollers will begin to change. In this case, the volume of liquid between two adjacent working 6 and distribution 5 rollers will begin to decrease from the injection cavities to the suction cavities. In the suction zone, the volumes that increase between the rollers are filled with liquid, which enters under the action of atmospheric pressure from the tank through the holes B and b. As the volume between the rollers decreases the liquid will be pushed into the pressure line through the windows C and c.

The peculiar feature of this design is also that this pump allows (if necessary) to work simultaneously with two different types of fluid. This advantage is achieved through a system of two independent working chambers, which are formed by working and distribution rollers, as well as distribution rollers and a spike. The running magnetic field, which acts on the ferromagnetic roller,
allows the rolling elements to perform a dual function – as rolling bearings and cutting off a portion of the liquid. In addition, we get the rotational movement of the working elements in an enclosed space, which solves the problem of sealing the working area and eliminates the loss of instantaneous flow through the radial gaps.

3. Analysis of cyclic deformation of the separating tape

The thin separating tape undergoes intense cyclic deformation and is therefore the most vulnerable element of the pump. On the other hand, the importance of this link is difficult to overestimate; in fact, the failure of the tape inevitably leads to pump failure.

Let us construct quantitative analytical estimates of the deformation of the belt per revolution of the pump $0^\circ \leq \phi \leq 360^\circ$.

We introduce the following values: $r$ is spike radius, $R_1, R_2$ are the radii of the working and distribution rollers, respectively, $R$ is the radius of the inner surface of the body, $e$ is distance between the axes of the spike and the body (eccentricity), and $h$ is tape thickness.

By solving the planimetry problem, we approximated the current value of the tape length:

$$L(\phi) = \frac{L_{\text{max}} + L_{\text{min}}}{2} - \frac{L_{\text{max}} - L_{\text{min}}}{2} \cos \left( \frac{\pi}{60} \phi \right);$$ \hspace{1cm} (1)

$$L_{\text{max}} = 2\pi R_2 + 2(R_1 + R_2)(2\pi - \alpha^+ - 2\beta^+), \quad L_{\text{min}} = 2\pi R_2 + 2(R_1 + R_2)(2\pi - \alpha^- - 2\beta^-),$$

$$\alpha^+ = \arccos \frac{(r + R_1)^2 + (R_1 + R_2)^2 - (R - R_1 + e)^2}{2(r + R_2)(R_1 + R_2)};$$

$$\beta^+ = \arccos \frac{(r + R_1 + e)^2 + (R_1 + R_2)^2 - (R - R_1)^2}{2(r + R_1 + e)(R_1 + R_2)}.$$  \hspace{1cm} (2)

Then the membrane deformation of the middle surface of the tape caused by eccentricity will be:

$$\varepsilon_m(\phi) = \frac{(L(\phi) - L_{\text{min}})}{L_{\text{min}}}. \hspace{1cm} (3)$$

Bending deformation of the tape occurs due to curvature during the alternate coverage of the inner and outer rollers by the tape. Its value on the outer and inner surfaces of the tape is proportional to the curvature of the corresponding roller and changes abruptly 3 times per revolution:

$$\varepsilon_{bo}(\phi) = \left( -\frac{h}{2R_2} \right) \arccos \left( 1 - \frac{h}{2R_2} \right), \quad \varepsilon_{bo}(\phi) = \left( \frac{h}{2R_1} \right) \arccos \left( 1 - \frac{h}{2R_1} \right).$$

We found the total deformation of the outer and inner surfaces of the tape as the sum of membrane and bending deformations:

$$\varepsilon_\circ(\phi) = \varepsilon_m(\phi) + \varepsilon_{bo}(\phi), \quad \varepsilon_\circ(\phi) = \varepsilon_m(\phi) + \varepsilon_{bo}(\phi).$$ \hspace{1cm} (4)

The results of calculations performed by formulas (1)–(4) for $r = 15\,\text{mm}$, $R_1 = 40\,\text{mm}$, $R_2 = 29.6\,\text{mm}$, $R = 120\,\text{mm}$, $e = 10\,\text{mm}$, $h = 0.1\,\text{mm}$ are shown in figures 2–7. The outer surface of the tape (figure 6) has a better chance of fatigue damage, as it has longer contact with smaller diameter rollers. The amplitude of the cycle is:

$$\varepsilon_a = \frac{1}{2} \left( \varepsilon_m(\phi) + \varepsilon_\circ(\phi) \right) = \frac{1}{2} \left( \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{min}}} + \frac{h}{2R_1} + \frac{h}{2R_2} \right) \approx 1.83 \cdot 10^{-3}.$$ \hspace{1cm} (5)

Using the Weller diagram for beryllium bronze, by the amplitude (5) we can determine the number of cycles to failure.
4. Conclusions
The proposed design of the pump makes it possible to get rid of rotary supports outside the working area; pump two substances at the same time, as well as significantly increase the efficiency by reducing the forces of sliding friction.

An additional advantage of this pump is the magnetization of the liquid, which reduces corrosion of metal elements of the pump and pipelines, slows down the formation of scale, as well as prevents the deposition of resins and paraffin on the walls of oilfield equipment.
The detailed theoretical analysis of the cyclic deformation of the separating tape allows to estimate the durability of the structure, as well as to solve the inverse problem – to perform a design calculation of the structure for a given service life.

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