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Moving of Inline Cleaning Units Along Submerged Crossing in Main Pipelines

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Abstract. The article analyzes the forces acting on the inline cleaning units of new design, operating on a bailer principle. In this case all cleaning products are collected in the internal cavity of the cleaning unit, which eliminates the formation of the ground plug and can significantly reduce the friction of the cleaning unit on the inner surface of the pipeline. The moving of the cleaning units of the given design within the space of a curved steel pipeline is investigated, the solution of the obtained equations and their analysis related to pipeline submerged crossing are shown.

1 Introduction

Cleaning the inner cavity of main and field pipelines is one of the main technological processes during the construction period of the oil and gas pipelines as well as their operation [1, 2, 3]. Periodic cleaning can reduce the water resistance of the pipeline and thereby significantly reduce the cost for the product pumping. This paper presents the results of the dynamics test of new design inline cleaning units taking into account their service particularities. In contrast to the previous papers, considering the moving of inline cleaning units like a motion of a material point, the cleaning units in this paper are considered as the contiguous flexible objects with distributed loads [4, 5]. Such formulation corresponds to a constructive solution of the cleaning unit data and differs significantly from the models of the previous authors [7]. The obtained results allow within the accepted assumptions to evaluate the impact of the design parameters of the materials of the cleaning units and their geometric characteristics on the moving process of the cleaning units along a spatially curved pipeline [9].

2 Research object (Model, Process, Unit, Synthesis, Experimental procedure, etc.)

Being developed method of cleaning the internal cavity of the pipelines is based on the use of cleaning units like a "bailer". The design is based on plastic pipes, which ensures the friction lowering on the internal surface of the pipeline and the possibility for a large structure length to pass sections with a small curvature [21]. In the adopted model the

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assumption for the constancy of the mass of the cleaning unit and the uniform distribution of the cleaning products on the cleaning unit was made [10].

3 Method

Cleaning unit is a plastic pipe of the length about 5 – 10 diameters, closed at one end, Figure 1.

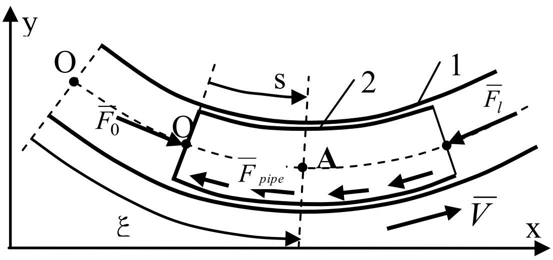

Fig. 1. Scheme of the clearing unit.

In the figure are indicated: 1 – pipeline, 2 – cleaning unit. The cleaning unit moves at a rate $\overline{V}$ under the acting force $\overline{F}_0$, generated by extreme pressure of the air injected into the pipeline. A force $\overline{F}_l$ acts on the right end of the cleaning unit (Figure 1), caused by the resistance of the being removed from the internal surface of the pipeline deposit products $\overline{F}_c$, and extreme pressure of air displaced from the pipeline [11]. The distributed over the length of the unit friction force $\overline{F}_{pipe}$, weight force and reaction forces act on the cleaning unit while moving.

The position of any arbitrary point A of the cleaning unit is defined by its coordinate s about a point O of the cleaning unit – "beginning" or coordinate ξ – about a point O′ – the beginning of the pipeline, Figure 1. The coordinate ξ depends on the time t, as well the coordinate s i.e. $\xi = \xi(s, t)$.

To derive the motion equation of the cleaning unit an element of the length ds is considered, Figure 2.

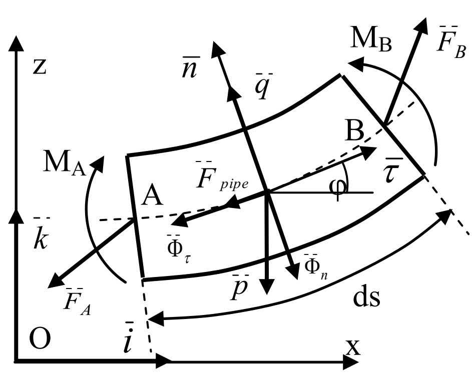

Fig. 2. An element of the clearing unit.

In Figure 2 is indicated:

$\overline{i}$, $\overline{k}$ – the unit vectors of the Cartesian coordinate system XOZ;

$\bar{\tau}$, $\bar{n}$ – ordinary vectors directed tangentially and normally to the pipe axis in the concavity direction

$\overline{F_A}$, $\overline{F_B}$ – forces acting in sections A and B, where $\overline{F} = T\bar{\tau} + N\bar{n}$;

T and N – tangential and shearing forces, respectively;

MA, MB – bending moments in the cross section A and B;

$\bar{p}$, $\bar{q}$ –weight and reaction forces acting on the element in question;

Φ_τ, Φ_n – tangential and normal inertia forces;

$\overline{F}_{pipe}$ – friction force.

Derivation of the motion equations is carried out as usual. We assume

$$\overline{F_B} = -\overline{F_A} + d\overline{F}, \quad d\overline{F} = \frac{d\overline{F}}{ds}ds = \frac{d}{ds}\left(T\bar{\tau} + N\bar{n}\right)ds. \tag{1}$$

Derivatives of vectors $\bar{\tau}$ and $\bar{n}$ are equal respectively [6]:

$$\frac{d\bar{\tau}}{ds} = \chi\bar{n}, \qquad \frac{d\bar{n}}{ds} = -\chi\bar{\tau}, \tag{2}$$

where $\chi = \dfrac{1}{R}$ – the curvature of the pipe axis.

Taking into account these designations we obtain:

$$d\overline{F} = \left(\frac{dT}{ds} + \chi N\right)\bar{\tau}ds + \left(\frac{dN}{ds} - \chi T\right)\bar{n}ds \tag{3}$$

The bending moment M is a scalar value, so

$$M_B = -M_A + \frac{dM}{ds}ds, \tag{4}$$

$$\overline{Q} = qds\bar{n}, \tag{5}$$

where q – the distributed reaction force. The weight of element of the length ds is equal

$$\overline{P} = -gdm\bar{k} = -g\gamma\, ds\bar{k}, \tag{6}$$

γ - mass of a length unit.

The vector $\bar{k}$ is decomposed into components, directed along the axes $\bar{\tau}$ and $\bar{n}$:

$$\bar{k} = \sin\varphi \cdot \bar{\tau} \pm \cos\varphi \cdot \bar{n}, \tag{7}$$

The "+" – if the bulge is upward, "-" – if it is down, then the vector

$$\bar{P} = -g\gamma \sin\varphi ds\bar{\tau} \pm g\gamma \cos\varphi ds\bar{n}, \tag{8}$$

friction force

$$\bar{F}_{pipe} = -f|q|ds\bar{\tau}, \tag{9}$$

f – the friction coefficient.

The considered element of the repairing insert moves with acceleration. Therefore, the inertia force acts on it in accordance with the principle of d'Alembert [12]. Taking this into account we obtain

$$\begin{cases} -\gamma a_\tau - \gamma g \sin\varphi + \dfrac{dT}{ds} - \chi N - f|q| = 0 \\ -\gamma a_n \pm \gamma g \cos\varphi - \chi T + \dfrac{dN}{ds} + q = 0 \\ \dfrac{dM}{ds} + N = 0. \end{cases}, \tag{10}$$

The unknowns in these equations are accelerations a_τ and a_n, forces T and N, and the reaction force q. The bending moment M can be considered as known, because the shape of the curved pipe axis is considered as acquainted [14]. The total number of unknowns – more than three, therefore, the problem in this formulation is statically indeterminate.

We denote u(s, t) – moving the point of the repairing insert along the axis of the pipeline with coordinate s at the time moment t. Axial deformation at the point s:

$$\varepsilon = \frac{\partial u}{\partial s}, \tag{11}$$

then the tangential force T

$$T = EA \cdot \varepsilon = EA\frac{\partial u}{\partial s}, \tag{12}$$

where A – the sectional area of the pipe of the cleaning unit; E –elasticity modulus of the pipe material.

Bending moment is

$$M = EJ\chi, \tag{13}$$

where J – the inertia moment of the cleaning unit section, the curvature χ is assumed to be acquainted at each point of the pipeline.

The rate of the point with the coordinate s

$$v(s,t)=\frac{\partial u}{\partial t}, \tag{14}$$

Tangential and normal accelerations are

$$a_\tau=\frac{\partial^2 u}{\partial t^2}, \quad a_n=\chi v^2=\chi\left(\frac{\partial u}{\partial t}\right)^2. \tag{15}$$

The moving rate of the cleaning unit is about 3-5 m / s. At such rates, the normal inertial force has no significant impact on the moving of the repairing insert, so it will not be taken into account [13].

Expressing the shear force N taken into account the expressions (11) – (15) from the last equation of the system (10) we obtain:

$$\begin{cases} \gamma\dfrac{\partial^2 u}{\partial t^2}+\gamma g\sin\varphi-EA\dfrac{\partial^2 u}{\partial s^2}-EJ\chi\dfrac{d\chi}{ds}+f|q|=0, \\ \pm\gamma g\cos\varphi-EA\chi\dfrac{\partial u}{\partial s}+EJ\dfrac{d^2\chi}{ds^2}-q=0. \end{cases}$$

Finally, expressing q from the second equation and substituting it in the first one, we obtain:

$$\gamma\frac{\partial^2 u}{\partial t^2}-EA\frac{\partial^2 u}{\partial s^2}-EJ\chi\frac{d\chi}{ds}+\gamma g\sin\varphi+f\left|EJ\frac{d^2\chi}{ds^2}-EA\chi\frac{\partial u}{\partial s}\pm\gamma g\cos\varphi\right|=0 \tag{16}$$

The values φ and χ in the equation are different at different points of the trajectory, and they should be considered as a function of ξ (but not s). Therefore, the derivatives dx/ds and d2x/ds2 in the equation (16) should be replaced by dx/dξ and d2x/dξ2. The coordinate ξ is expressed in terms of s and u as follows:

$$\xi=s+u(s,t) \tag{17}$$

Therefore

$$\varphi=\varphi(s+u(s,t)), \quad \chi=\chi(s+u(s,t)). \tag{18}$$

The obtained equation (16) is a nonlinear differential equation in partial derivatives [15]. The initial and boundary conditions are for the considered problem as follows:

$$\begin{cases} u(s,0)=0, \quad v(s,0)=0, \\ T(0,t)=EA\dfrac{\partial u}{\partial s}\Big|_{S=0}=T_0, \; T(l,t)=EA\dfrac{\partial u}{\partial s}\Big|_{S=l}=-T_l, \end{cases} \tag{19}$$

where l – length of the cleaning unit, T0 = PL·S, T1 = PR·S, PL – the pressure on the left of the cleaning unit (Fig. 1), PR – the pressure on the right, S – the cross-sectional area of the pipeline.

The pressure on the left PL and PR depends on the moving rate of the cleaning unit v, on the length LL = u(0,t) of the pipeline on the left from the cleaning unit and on the length LR = L – u(0,t) on the right from the cleaning unit. Furthermore, the pressure drop depends on the thermodynamic air parameters [16]. Loss of pressure on the left and on the right from the cleaning unit is determined by expressions [8]:

$$P_L = \frac{P_{IN}}{\sqrt{1+\lambda \dfrac{L_L}{d} \cdot \dfrac{v^2}{RT}}}, \qquad P_R = \frac{P_0}{\sqrt{1-\lambda \dfrac{L_R}{d} \cdot \dfrac{v^2}{RT}}} \tag{20}$$

where PIN – the inlet pressure in the pipeline; P0 – the outlet pressure in the pipeline (atmospheric pressure); λ – coefficient of hydraulic friction; d – the inner pipeline diameter, R – gas constant for air; T – absolute temperature. The coefficient of hydraulic friction is determined by the formula of Altshul [18].

Solution of the motion equations. The analytical solution of the problem (16), (19) is not possible. The finite difference method for the solution is applicable.

We write the motion equation (16) as a system of two differential first-order equations with the variable t:

$$\begin{cases} \dfrac{\partial v}{\partial t} = \dfrac{EA}{\gamma}\dfrac{\partial^2 u}{\partial s^2} + \dfrac{EJ}{\gamma}\chi\dfrac{d\chi}{ds} - g\sin\varphi - f\left|\dfrac{EJ}{\gamma}\dfrac{d^2\chi}{ds^2} - \dfrac{EA}{\gamma}\chi\dfrac{\partial u}{\partial s} \pm g\cos\varphi\right|, \\ v = \dfrac{\partial u}{\partial t}. \end{cases} \tag{21}$$

We apply the simplest difference scheme. Approximation of the derivatives is taken as follows

$$\frac{\partial v_j^{i+1}}{\partial t} \approx \frac{v_j^{i+1} - v_j^i}{\Delta t}, \quad \frac{\partial u_j^i}{\partial s} \approx \frac{u_{j+1}^i - u_{j-1}^i}{2\Delta s}, \quad \frac{\partial^2 u_j^i}{\partial s^2} \approx \frac{u_{j+1}^i - 2u_j^i + u_{j-1}^i}{(\Delta s)^2}.$$

Difference equations will be as follows:

$$\begin{cases} v_0^{i+1} = v_0^i + \dfrac{\Delta t\cdot EA}{\gamma}\dfrac{2(u_1^i-u_0^i)}{(\Delta s)^2} + \dfrac{\Delta t\cdot EJ}{\gamma}\chi(u_0^i)\dfrac{d\chi(u_0^i)}{ds} - \Delta t\cdot g\sin\varphi(u_0^i) - f\Delta t\cdot\left|\dfrac{EJ}{\gamma}\dfrac{d^2\chi(u_0^i)}{ds^2} \pm g\cos\varphi(u_0^i)\right| \\ v_j^{i+1} = v_j^i + \dfrac{\Delta t\cdot EA}{\gamma}\cdot\dfrac{u_{j+1}^i - 2u_j^i + u_{j-1}^i}{(\Delta s)^2} + \dfrac{\Delta t\cdot EJ}{\gamma}\chi(j\Delta s + u_j^i)\dfrac{d\chi(j\Delta s+u_j^i)}{ds} - \Delta t\cdot g\cdot\sin\varphi(j\Delta s + u_j^i) - \\ \qquad - f\Delta t\cdot\left|\dfrac{EJ}{\gamma}\cdot\dfrac{d^2\chi(j\Delta s+u_j^i)}{ds^2} - \dfrac{EA}{\gamma}\chi(j\Delta s+u_j^i)\dfrac{u_{j+1}^i - u_{j-1}^i}{2\Delta s} \pm g\cos\varphi(j\Delta s+u_j^i)\right|,\quad j=1,2,...n-1; \\ v_n^{i+1} = v_n^i + \dfrac{\Delta t 2EA}{\gamma}\cdot\dfrac{u_{n-1}^i - 2u_n^i}{(\Delta s)^2} + \dfrac{2\Delta t T}{\gamma\Delta s} + \dfrac{\Delta t EJ}{\gamma}\chi(n\Delta s+u_n^i)\dfrac{d\chi(n\Delta s+u_n^i)}{ds} - \Delta t\cdot g\cdot\sin\varphi(n\Delta s+u_n^i) - \\ \qquad - f\Delta t\cdot\left|\dfrac{EJ}{\gamma}\cdot\dfrac{d^2\chi(n\Delta s+u_n^i)}{ds^2} - \dfrac{T}{\gamma}\chi(n\Delta s+u_n^i) \pm g\cos\varphi(n\Delta s+u_n^i)\right| \quad . \end{cases}$$

From the stability conditions $\Delta t \le \Delta s\sqrt{\dfrac{\gamma}{EA}}$ should be chosen.

From these equations for i = 0 we find v_j^1, then we find u_j^{i+1} from the equation $u_j^{i+1} = u_j^i + \Delta t\cdot v_j^{i+1}$ $(j = 0, 1, \ldots, n)$ and return again to the equations (22).

4 Results and Discussion

The obtained equations allow us to calculate the moving of the cleaning unit for pipeline submerged crossing of any profile. To do this, it is necessary to determine the spatial position of the pipeline axis and to approximate the axis by any functions.

As an example, the results of calculation of the submerged crossing profile are given, shown in Figure 3. The submerged crossing length is conditionally divided into three sections [17].

Sections L_1, L_3 are submerged crossing areas with distinctive variable curvature, characterized by the presence of differential of the elevation marks. The section L_2 is a straight portion of the river bed of the submerged crossing. It is characterized by the absence of the curvature of the pipeline axis.

The cleaning element starts moving from the start-receiver pig chamber, (initial point of section L_1) passes the area L_1, where the rolling force $F_{ск}$ accelerates the moving. The rolling force is absent on a straight section. The rolling force has a retarding impact on the moving of the repairing insert on the section L_3.

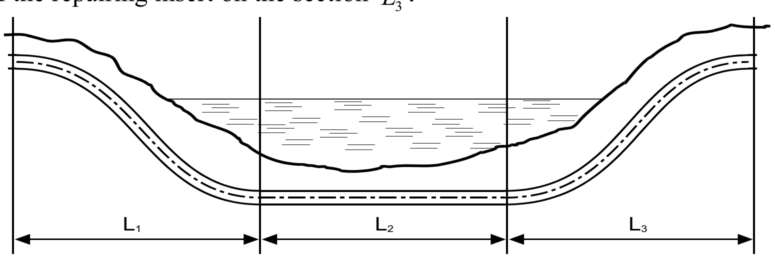

Fig. 3. Profile of submerged crossing.

The moving of the cleaning unit is carried out by the force T_B created by air pressure acting on the section of the cleaning unit. The air supply Q is carried out by the compressor, while it remains constant in the throughout time interval of moving [20].

Typical graphs on the calculation results of the cleaning unit moving dynamics ($v(t)$ – change in moving speed; $P(t)$ – change in the air pressure) for the submerged crossing corresponding to the profile Figure 2.

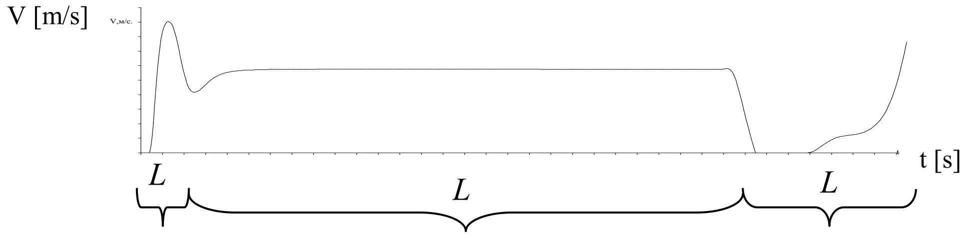

Fig. 4. Change in moving rate of the cleaning element in the submerged crossing.

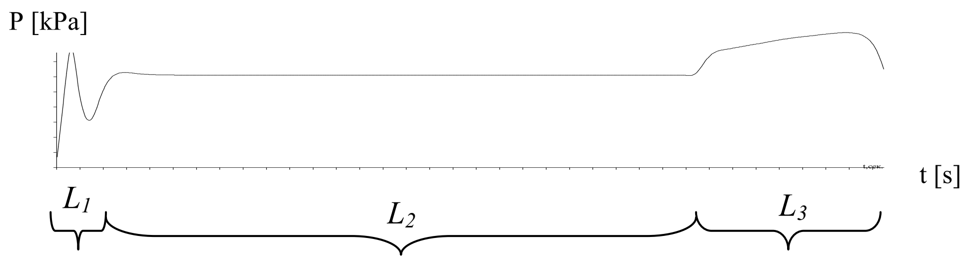

Fig. 5. Time pressure changes character.

From the graphs the moving parameters character of the cleaning unit can be seen.

The initial time t = 0 corresponds to the air feed release. Until the time moment t1 the overpressure increases from 0 up to values at which the force acting on the cleaning unit reaches a friction force value. After that, it begins to move. When this pressure continues to increase because the speed of the leaning unit increases slower than the pressure increases [19]. But the acceleration of the cleaning unit also increases (because the pressure increases). At the time moment t2 rate of the cleaning unit reaches such value that the volume on the left of the cleaning unit starts to increase faster than the air is injected. At this time, the pressure Pmax is maximal. The speed continues to increase because the rolling force acts on the cleaning unit together with the pressure. At the point t3 the rate reaches a maximum value and the pressure – the minimum one, i.e. the speed and pressure change are shifted in phase. After some fluctuations in the section L1 the cleaning unit enters the straight portion L2. The rate and pressure in the straight section are almost constant. While reaching the curved section L3 the rate decreases sharply, because as the resistance force increases sharply and the rolling force occurs, retarding moving. At the time t4 a stop occurs, continuing until the pressure reaches the value necessary to start the moving.

Thus, in general, the moving rate of the cleaning unit has an uneven character and is determined by the profile of the submerged crossing.

3 Conclusion

It should be noted that basic elements of HSC DSS have been implemented in the software product the System of Remote Monitoring of Parameters (SRMP), there is a Certificate of state registration of the software (Appendix No. 1), co-authors are Razboynikov A.A. and Vashchilin V. V. Within a calculation method approbation of a residual resource pump stations' equipment, on the basis of stationary monitoring systems of vibration parameters, on the CPS-4 object of the Ust-Balyksky field, the implementation measures of the residual resource calculation method on three pump units SRP-240 on the basis of the permanently installed monitoring systems of vibration characteristics (PIMSVC) "Vibrobit-300" of LLC OPP "Vibrobit" production were held. The protocol of successfully carried out results after pilot tests has been signed (Appendix No. 2). According to the conducted researches, a comprehensive application of the developed methodology and software operation system of the main equipment of pumping stations by the technical state described in this work will allow to:

- to provide accident-free operation of an oil and gas complex equipment (in particular-pumping stations);
- to withdraw the defective aggregate from operation promptly, thereby preventing an emergency situation and serious damage to the equipment units;
- to define an aggregate residual resource effectively;
- to optimize an aggregate operating mode;
- to reduce the repair cost, through targeted funding aggregates according to the actual state;
- to increase the efficiency of repair work planning by identifying defects at an early development stage;
- to estimate the preliminary cost of repair work.

The expected results from implementation of the above-stated developments and improvements fully corresponds to the Strategy of innovative development of the Russian Federation theses till 2030.

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