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# Calculation Models Regarding the Dynamics of the Arms of Concrete Pumps Mounted on Truck

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## Abstract

*The article relates to the stability of four articulated sections arms for concrete pumps, mounted on truck, taking into account the transport of concrete pumped in pipelines to the pump with two cylinders, according to the schedule of pressure pumping. Model calculations are analysed for the articulated arm oscillations in analysis working in stretched position, in the vertical-longitudinal an horizontal plan, and independent oscillations of the top section at which the masses of concrete transportation pipes were reduced. They are indicated the graphs of pressure pumping and transport speed of the concrete plug formed inside the pipe on a horizontally and tilted path.*

**Key words:** *cylinder, concrete pump, articulated arm pump, slurry pump*

## General Remarks

The constructive complexity of the concrete pump mounted on truck with the functional parameters required to transport concrete; pump flow rate, pressure, horizontal and vertical transport distance of concrete, the structure of the concrete mixtures transported and ensuring a complex trail to transport the concrete in the event of obstacles on the construction site, which requires a certain configuration of the arm sections positioning.

The structure of the articulated arm is a foldable, detachable unit which can be mounted at the top of a tower and for working in the fixed point on the construction site.

Parallel to the structure of the arm (fig. 1,a) it is mounted a column of concrete transport consisting of pipes and fittings, which ends with a hose that is manipulated by the operator at pouring of concrete into the formwork on the site (fig. 1,b) [4].

The concrete pumping is ensured in the pipeline, by the flow of the formed buffer, which is separated from the walls of the pipe by a layer of lubricant consisting of grout. The water in the grout is hydraulic connected to the spaces between the particles of rock that can be found in the formed concrete plug (fig. 2,a) [1].

With the hydraulic theory to the flow velocity of the plug into the pipe, in the vertical plan speed is constant on the plugs height.

In marginal areas, speed through the layer of lubrication is zero at the contact with the walls of the pipe. The speed of the concrete plug is shown in Figure 2,b.

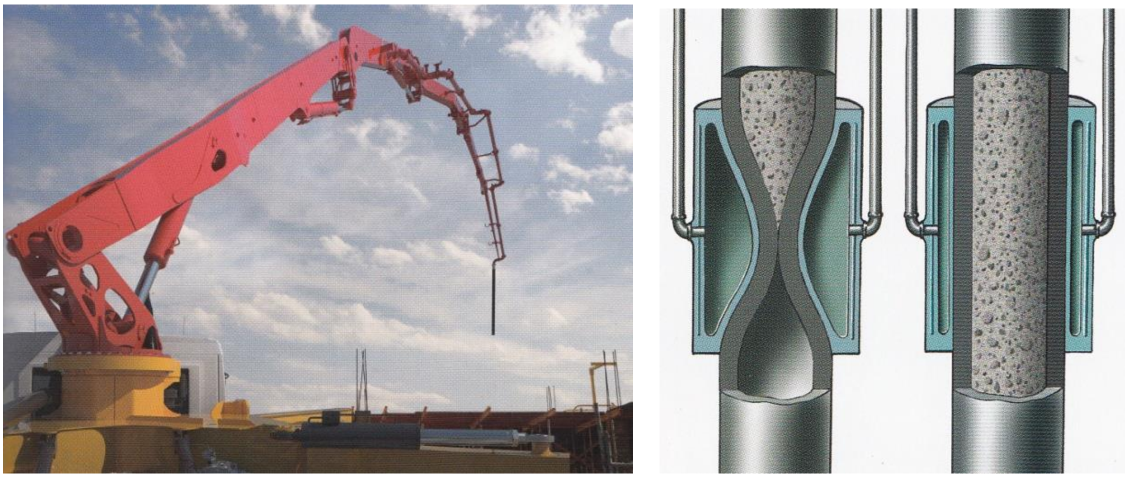

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**Fig. 1.** The holding arm of concrete pump (**a**) with the hose end (**b**).

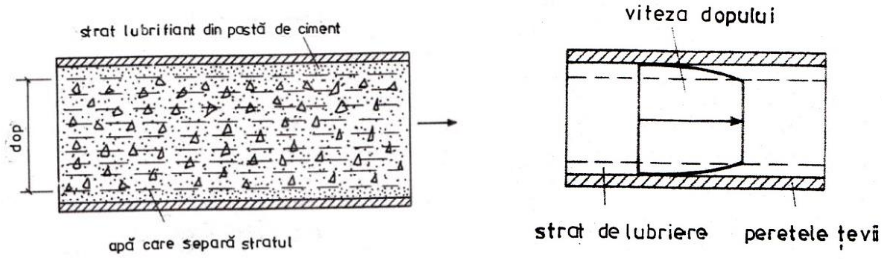


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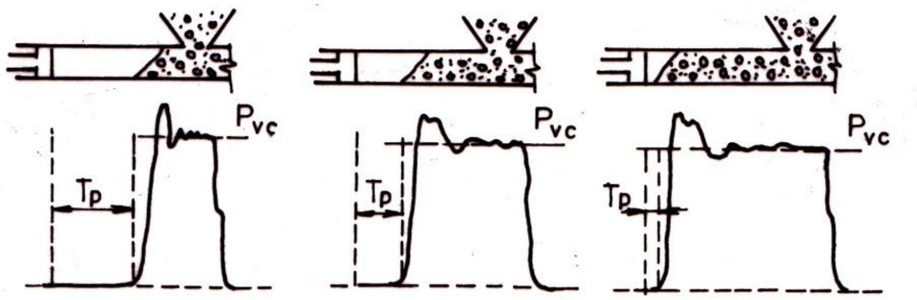
**Fig. 2.** Transportation of concrete through the pipe (**a**) and the speed of the formed plug (**b**)

The effect of workability, pumping and efficiency of the concrete pump can be expressed according to the shape of the pressure pump graph (fig. 3), that takes during the pump testing [1].




a b c

**Fig. 3.** The effect of workability and and pumping of the pump according to the pump pressure diagram.

In Figure 3, we can distinguish the following situations [2]:

Case a) if $T_p$ is high, noted here with $T_{pI}$, has poor workability: low efficiency of water accumulation, lean material through installation, high resistance to flow (fig. 3,a);

Case b) if $T_{pII} < P_{pI}$, workability is average, increases the effectiveness of water accumulation, it reduces the flow resistance (fig. 3,b);

Case c) if $T_{pIII} < T_{pII} < T_{pII}$, workability is good, the accumulation of water in the material is good, a large amount of material is passed through the facility and the pumping resistance is low (fig. 3,c). Notations: $P_{vc}$ – the concrete pressure at constant speed and $T_p$ – the corresponding time for the pump piston to hit the material.

In Figure 4 is shown the chart to record the working parameters to test the functioning of a pump with two cylinders engine working in tandem equipped with a Putzmeister S switching tube [2].

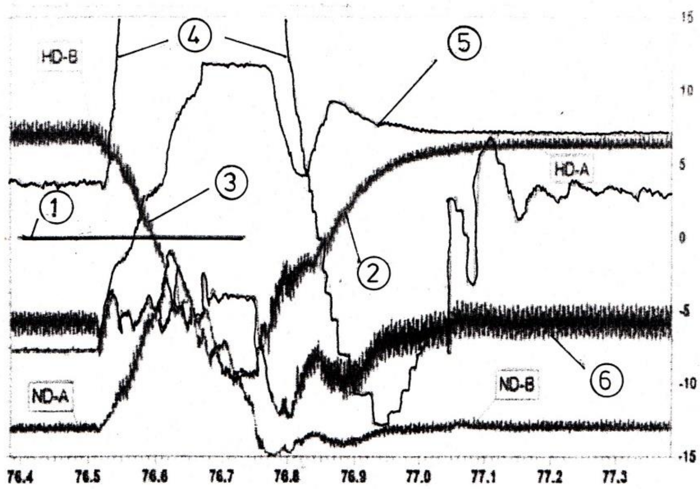



**Fig. 4.** The parameters registered in the concrete pump operation:
1 – the adjustment to zero of the transmission mechanism; 2 – cylinder pressure A; 3 – cylinder pressure B; 4 – current coil to the valve of oil; 5 – square plate turntable; 6 – power pressure.

Choosing appropriate piping (with double walls) working at a high pumping pressure is just as important as the choice of concrete pump and an appropriate arm.

## The Calculation Model for the Analysis of Oscillations Made by the Articulated Arm in the Vertical-Longitudinal Plan

The modeling of the folding arm composed of four articulated sections that is fixed at the head of the revolving tower mounted on the chassis of the truck is shown in Figure 5. The four articulated sections, provided each with a hydraulic cylinder for independent tipping are in a horizontal working position.

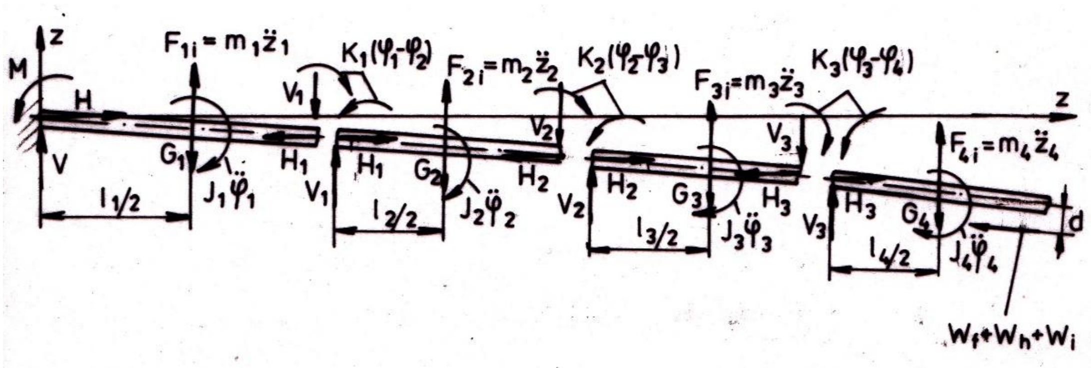


**Fig. 5.** The calculation scheme of the arm with four sections in vertical plan

Into the analysed calculation model, the base (I) is represented by a bar at one end and is considered recessed to the tower, where we have two reactions in the vertical-longitudinal plan *V* and *H* and a point M determined by the action of the tipping cylinder.

In the centre of gravity of the base section acts the vertical force of inertia $m_1\ddot{Z}_1$ and the moment of inertia $J_1\ddot{\varphi}_1$, and at the other end of the bar acting force $V_1$, $H_1$ and the moment of elastic embedment. After that, the charging scheme repeats itself and the other three sections of the articulated arm. The system of equations (1) was written for the four articulated sections, it is the mechanical calculation model described by the articulated arm together with the transport of concrete column.

The general system of equations for the articulated arm structure in the vertical-longitudinal plan results of the form:

Section I:

$$V + m_1\frac{l_1}{2}\ddot{y}_1 - V_1 - G_1 = 0;$$
$$H = H_1$$
$$-\frac{1}{6}m_1 l_1^2\ddot{\varphi}_1 + V_1 \cdot l_1 + H_1 \cdot l_1 \cdot \varphi_1 + K_1(\varphi_1 - \varphi_2) = 0$$

Section II:

$$V_1 + m_2\frac{l_2}{2}\ddot{\varphi}_2 - V_2 - G_2 = 0; \qquad H_1 = H_2$$
$$-\frac{1}{6}m_2 l_2^2\ddot{\varphi}_2 + V_2 \cdot l_2 + H_2 l_2 \cdot \varphi_2 + K_2(\varphi_2 - \varphi_3) = 0; \tag{1}$$

Section III:

$$V_2 + m_3\frac{l_3}{2}\ddot{\varphi}_3 - V_3 - G_3 = 0; \quad H_2 = H_3;$$
$$-\frac{1}{6}m_3 l_3^2\ddot{\varphi}_3 + V_3 l_3 + H_3 l_3\varphi_3 + K_3(\varphi_3 - \varphi_2) = 0;$$

Section IV:

$$V_3 + m_4\frac{l_4}{2}\ddot{\varphi}_4 - G_4 = 0;$$
$$H_3 = F_p = W_f + W_h + W_i;$$
$$-\frac{1}{6}m_4 l_4^2\ddot{\varphi}_4 + F_p \cdot l_4\varphi_4 = 0,$$

where: $\varphi_i$ ($i$ =1...,4) represents the rotations in vertical plan of each section in part;
$G_i = m_i\, g$ ; $l_i$ – weights, and lengths of each section of the arm;
$V_i$ – the force in the vertical plan on the direction of cut-cylinder tipping mechanism in this case;
$H_1 = H_2 = H_3 = H_4 = F_p$ – it is considered the horizontal reaction of the arm sections that equals the force of thrust of the concrete by pump cylinders;
$m_i$, $J_i$ – the masses respectively the moments of inertia of the first three articulated sections;

Note:

$$m_4 = m_4' + m_{bc},$$
$$J_4 = J_4' + J_{bc}, \tag{2}$$

in which $m_4$ is the total mass of the tip base consisting of $m_4$' and the concrete mass and contained in the transport pipe reduced to section IV;

$J_4$ – the total moment of inertia of the peak section made of its own moment of inertia $J_4$' and the moment of inertia of the concrete content in the pipeline transport reduced to section IV.

The force required for the plunger's pump must be greater than the sum of the resistance of the sum of the resistance of the concrete forwarding from the pipeline [5]:

$$F_p \geq W_f + W_h + W_i \tag{3}$$

where $F_p = p \cdot \frac{\pi Dp^2}{4}$ is the force pushing the piston pump;

$W_f$ – the frictions resistance between concrete and pipe:

$$W_f = P_p \cdot \frac{\pi Dc^2}{4}, \tag{4}$$

in which $P_p$ pressure loss due to the frictions on the pipeline;
$D_c$ – the diameter of the pipe, $p$ – pump pressure and $D_p$ – the diameter of the pump cylinder.

$$P_p = \frac{l}{R}\left(\frac{V}{K}\right)^{\frac{1}{n}}, \tag{5}$$

where : $l$ – the total pipeline length equivalent;
$R$ – hydraulic radius of the pipeline $R = \frac{D_c}{4}$;
$V$ – velocity of displacement of the concrete plug;
$K$ – coefficient which decreases with the increase of the consistency of concrete, factor A/C (water/cement) and the dosage of cement;
$n$ - coefficient which increases with the consistency of concrete;
$W_h$ – the strength of the vertical column pressure:

$$W_h = \gamma_b \cdot H \cdot \frac{\pi Dc^2}{4}, \tag{6}$$

in which: $\gamma_b$ – the mass volume of the fresh concrete;
$H$ – the height of the vertical column;
$W_i$ – the strength due to concrete inertia:

$$W_i = \rho \cdot L' \cdot a \cdot \frac{\pi D c^2}{4} \tag{7}$$

ρ – the specific mass of the concrete;
$L'$ – the length of the column of concrete subjected to acceleration in the growth period of the piston from zero speed to $V_{max}$;
$a$ – the concrete acceleration.

**Table 1.** Specific initial friction values $\tau_0$ and $K$ and $n$ coefficients [5].

| The type of cement | $\tau_0$ in gf/ inches$^2$ | $K$ | $n$ |
|---|---|---|---|
| Potland cement with normal consistency 25% | 0.15 - 0.35 | 0.7 - 2.5 | 1.27 - 1.70 |
| Potland cement with normal consistency 28 % | 0.15 - 0.50 | 0.7 - 7.0 | 1.60 - 2.20 |

It is considered the specific resistance at shearing of the form $\tau = (V/K)^{1/n} + \tau_0$ , which $\tau_0$ is the specific initial friction to start slipping in cement milk along the pipeline.

$$\begin{aligned}
\ddot{\varphi}_1 &= \frac{2}{m_1 l_1}(V_1 + G_1 - V); \\
\ddot{\varphi}_2 &= \frac{2}{m_2 l_2}(V_2 + G_2 - V_1); \\
\ddot{\varphi}_3 &= \frac{2}{m_3 l_3}(V_3 + G_3 - V_2); \\
\ddot{\varphi}_4 &= \frac{2}{m_4 l_4}(-V_3 + G_4).
\end{aligned} \tag{8}$$

The masses and the lengths of the four sections were chosen arbitrarily by the form: $m_1$ = 6300 kg; $m_2$ = 4500 kg; $m_3$ = 2160 kg; $m_4$ = 1440 kg; $l_1$ = 12 metres; $l_2$ = 11 metres; $l_3$ = 9 metres and $l_4$ = 8 metres.

The calculation of the cylindrical stiffness constants at bending from the elastic connections of the arm sections $K_i$ ($i$ =1, ...,3) is composed from the expression of the characteristic equation coefficients obtained from the equalization with zero matrix of the determinant of the system of ordinary differential equations (1) which applies a general solution of the form $\varphi_i = e^{\bar{K}it}$. As a result of the calculation results the determinant of the system:

$$\begin{vmatrix} -\frac{1}{6}m_1l_1^2\bar{K}^2+(H_0l_1+K_1) & -K & 0 & 0 \\ 0 & -\frac{1}{6}m_2l_2^2\bar{K}^2+(H_0l_2+K_2) & -K_2 & 0 \\ 0 & 0 & -\frac{1}{6}m_3l_3^2\bar{K}^2+(H_0l_3+K_3) & -K_3 \\ 0 & 0 & 0 & -\frac{1}{6}m_4l_4^2\bar{K} \end{vmatrix} = 0$$

representing the stability condition of oscillation in static conditions in longitudinal-vertical plan of the articulated arm.

The characteristic equation is of the form:

$$ax^4 + bx^3 + cx^2 + dx + e = 0 \tag{10}$$

With the roots of the equation

$x_1 = 7{,}969 + i6{,}84$; $x_2 = 7{,}969 - i \cdot 6{,}84$; $x_3 = -4{,}719 + i6{,}34$; $x_4 = -4{,}719 - i \cdot 6{,}34$

The nature of the roots of the characteristic equation we show whether the system behaves in stable or unstable mod during the operation.

The cylindrical stiffness at bending is calculated from the conditions provided by the characteristic equation coefficients:

$$\frac{a}{e} > 0; \frac{b}{e} > 0; \frac{c}{e} > 0; \frac{d}{e} > 0 \tag{11}$$

For the calculation model adopted in Figure 1 with the features above, resulted the cylindrical stiffness values at bending: $K_1$ = -376514 daNm; $K_2$ = -666050 daNm; $K_3$ = -522193 daNm.

The general solution of the oscillation arm reduced to the base section $\varphi_1$ from the condition of ensuring stability, with transitional arrangements of oscillation:

$$\varphi(j\bar{K},\omega,t) = \frac{A+jB}{C+jB}\cos\bar{K}_1t + \frac{D}{C+jB}\cos\bar{K}_3t + \frac{e j\omega t}{m_e(\omega^4+a_1j\omega^3+b_1\omega^2+\theta^2 \ldots)} \tag{12}$$

with initial conditions:

$\ddot{\varphi}_1$ = -2.479; $\ddot{\varphi}_1$ = 12.676 and $\ddot{\varphi}_3$ = -7.014; and $\varphi_1$ = 0, $\varphi_3$ = -0.254 ;

The transient component contained in the general solution of the rotation $\varphi_1$ is negligible while the integration constants from (12) are:

$$A_1 = \frac{A+jB}{C+jB} = \frac{-120{,}32 + i163{,}12}{39{,}43 + i163{,}12}; \quad C_1 = \frac{D}{C+jB} = \frac{29{,}569}{39{,}43 + i163{,}12}.$$

The resulting calculations:

$$\bar{K}_1 = 7{,}969 + i6{,}48; \bar{K}_3 = -4{,}719 + i6{,}48, \tag{13}$$
$$\varphi_1 = 9{,}761 \cdot \varphi_3 - 2{,}479;$$

for
$$\varphi_3 = 0; \varphi_1 = -2{,}479, \ddot{\varphi}_1 = 25{,}048$$
$$a_1 = 6{,}502; b_1 = 17{,}51; \omega_{ne}^2 = -2138{,}65$$
$$\Theta_{ne} = \sqrt{\frac{Kc}{mc}} = \sqrt{\frac{K_1 \cdot K_2 \cdot K_3}{m_1 \cdot m_2 \cdot m_3}} = i \cdot 46{,}245 \text{ și } me = 6{,}12 \cdot 10^{10}$$
$$\omega_1 = 3{,}251 + i \cdot 4{,}184;\ \omega_2 = 3{,}251 - i \cdot 4{,}184;\ \omega_3 = 202{,}33;\ \omega_4 = -87{,}54$$

You can study the stationary or transient regimes for different assumptions concerning the depreciation system, or the nature of the excitation forces and their static characteristics in the hypothesis of the Sorokin oscillations depreciation. The arm held system mostly acts of in conditions of indifferent stability. The size of the output rotation system with 4 degrees of freedom, excited by a force stationary random noted $F_{ij} \rightarrow X_i\ (t)$, $i = 1, \ldots, 4$, during the transitional process, is an unstable process that presents a great importance to qualitative appreciation of the system especially for reliability studies. For such a study, it is necessary to determine the characteristic frequencies of the system in the transitional arrangements $\Phi(j\omega t)$, which in this case is a function of time. The law of oscillation of the structure of the arm in the vertical-longitudinal plan in stability conditions is shown in Figure 6.

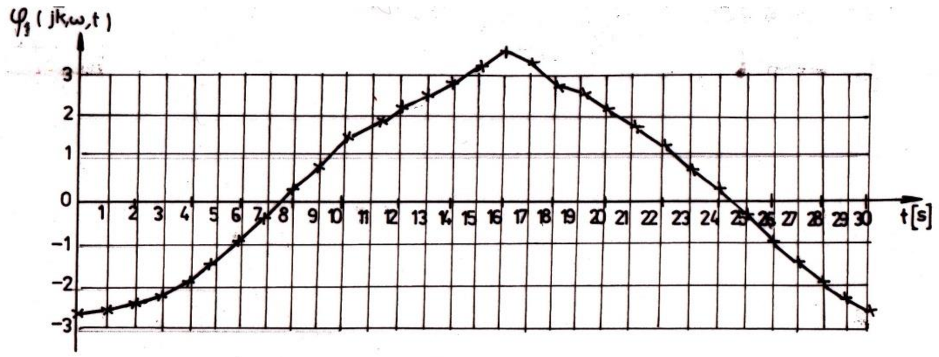
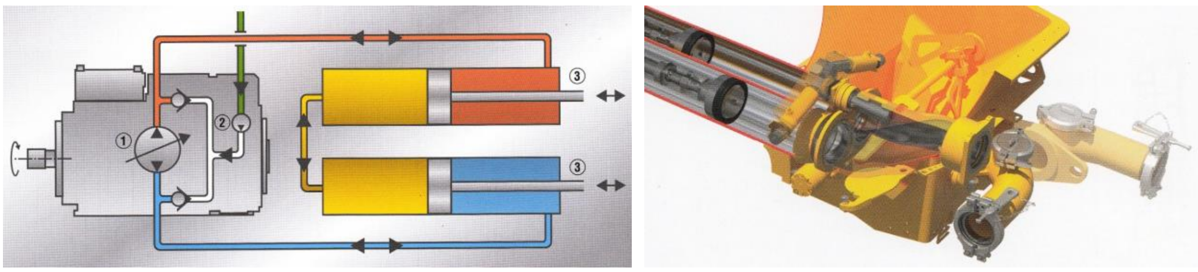



**Fig. 6.** Vertical oscillations of the arm.

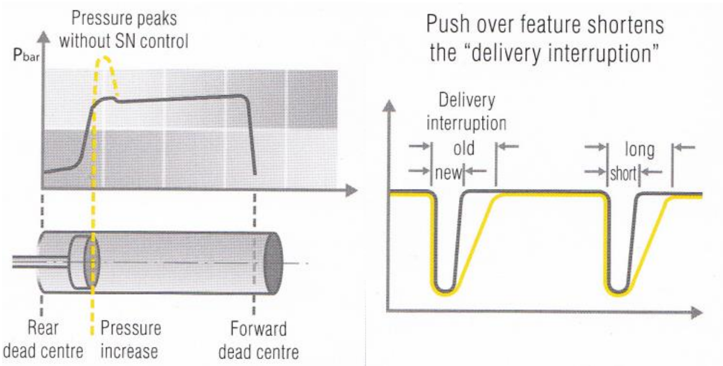
In Figure 7, it is presented the principle scheme of operation of the hydraulic cylinders functioning which acts through their rods, cylinders with piston of the concrete pump (fig. 7 b), which are pumping succesively the concrete in the column of carriage mounted on the arm.




a b

**Fig. 7.** The operating scheme of hydraulic cylinders of the pump (a), with the action of the pumping concrete cylinders (b) [1]: 1-main pump with variable flow; 2-pump power supply; 3-motion cylinders. Legend colours: red – high pressure; blue – low pressure; yellow – oil in motion; green – suction side of the oil pressure pump supply.

A convenient and economical operation of the concrete pumps with control of SN( Source Neutraliser) that refers to the value of the high pressure to push the concrete over the cylinders characteristic (fig. 8). New Putzmeister pumps are designed for smoothing the knockback concrete into the column. Peak pressure intensity increases the lifetime in the delivery of the concrete without wearing of the pump cylinder [4].




**a** **b**

**Fig. 8.** Diagram of pressure in the pumping cylinders [4]

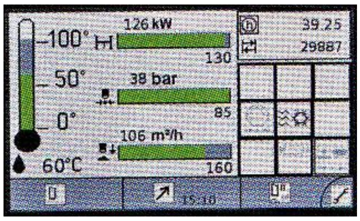
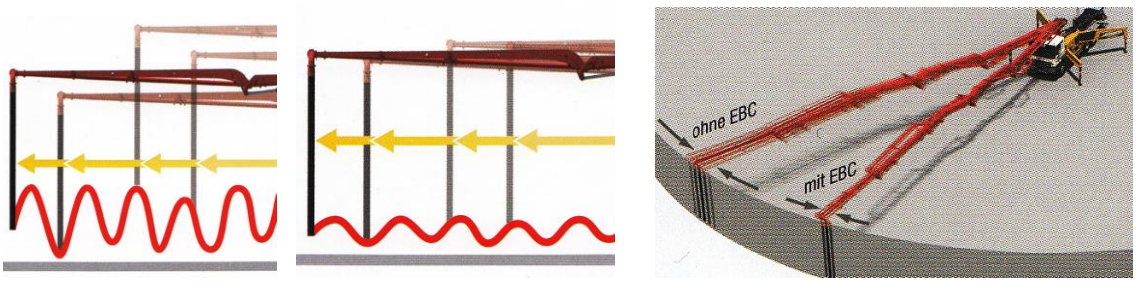



**Fig. 9.** Registered parameters [4]

In Figure 8, the pressure peaks are shown without control SN thus, behind the dead point of the piston pressure increases and further changes to neutral until the dead end of the race of the piston. In Figure 8,b it is shown the pushing action over short interruptions in the delivery of concrete in the pipeline. Transport characteristics of the concrete in the pipeline can be viewed on the display in Figure 9, where they are shown: the working power supplied from the engine, in kW; the concrete pumping pressure, in bar; and the pumping flow, in $m^3$/h. In Figure 10,a,b and c it is shown the manner of depreciation from the arm vibrations of Putzmeister pumps in order to improve the productivity of pumping concrete into the column. This is done with the help of EBC system (Ergonic Boom Control), which is a control system for peaceful and safe operation of the arm. With the EBC is reduced the vertical oscillation of the arm with approximately 1/3 of the amplitude of the oscillation, so is limited at the same time and the arrow at the end of the hose in all directions (fig. 10, b and c) [2, 4].




**a** **b** **c**

**Fig. 10.** Arm's own oscillations in the vertical plan (**a**), and depreciated oscillations registered with the EBM system in the vertical and horizontal plane (**b** and **c**) [4].

## Independent Oscillations of the Arm Section to the Pumping Concrete into the Column

The rotation equation $\varphi_4$ the construction of the peak section is:

$$-\frac{1}{6}m_4 l_4^2\ddot{\varphi}_4 - F_p\cdot l_4\cdot\varphi_4 = 0. \qquad (14)$$

Here

$$H_3 = F_p = W_f + W_h + W_i;$$

or:

$$p = \frac{1}{i^2}\left[\frac{4l}{D_c}\left(\frac{V}{K}\right)^{\frac{1}{n}} + \gamma_b \cdot H + \rho L \frac{dv}{dt}\right], \tag{15}$$

We consider for the concrete speed a solution of the form $V = V_0 e^{\bar{K} v\, t}$ and for the pressure an increase caused by the need of pushing the concrete plug of the form: $p = p_0 e^{\frac{4\mu}{D_c} \cdot x}$,

from which:

$$\bar{K}_v = \frac{p_0 e^{\frac{4\mu}{D_c} \cdot x} - \frac{1}{i^2}\gamma_b \cdot H - \frac{1}{i^2}\frac{4 \cdot l}{D_c}\left(\frac{V_0}{K}\right)^{\frac{1}{n}} + \tau_0}{\rho L V_0^{\frac{1}{n}}} \tag{16}$$

in which $p$ - is the maximum pressure;
$p_0$ – initial pressure ($p_0 = 0.14\, L\, \mu$) horizontally and $p_0 = 0.14\, H$ vertically;
$x$ – the length of the concrete plug;
$\mu$ – friction coefficient, $\mu = 0.2\text{-}0.4$;
$\gamma_b$ – weight by volume of the fresh concrete.

The change in velocity of the concrete plug in the pipeline transportation $V = V_0 \cos \bar{K} vt$ is given in the graph in Figure 12.

The law of rotation of the top section:

$$\varphi_4 = A_4 cos\bar{K}_{4,1} \quad t + B_4 \sin \bar{K}_{4,2} + C_4 \tag{17}$$

The expression of their own throb $\bar{K}_4^2$ of the form:

$$\bar{K}_{4(1,2)} = \pm i\sqrt{\frac{F_p}{\frac{1}{6}m_4 l_4}} = \pm\, i\sqrt{\frac{p_0 e^{\frac{4\mu}{D_c} \cdot x} \cdot \frac{\pi \cdot D_p^2}{4}}{\frac{1}{6}m_4 l_4}}, \tag{18}$$

which corresponds to an increase in pressure to push the plug of the concrete with the initial conditions:

$$tg\varphi_4 = \frac{F \cdot l^2}{2K_3} \quad \text{and} \quad \ddot{\varphi}_1 = \frac{2}{m_4 l_4}(-V_3 + G_4)$$

For the problem under review, it follows the law of rotation of the top section for the transport of the concrete through the pipe form:

$$\varphi_4 = A_4 cos\bar{K}_{4,1} + C_4, \quad . \tag{19}$$

given in the graph in Figure 11, where: $\bar{K}_{(4)\,1,2} = \pm\, i\, 0.52$; $A_4 = 1.005$; $C_4 = -3.527$.

In Figure 11 is drawn the oscillation of the section is considered independent from the tip of the arm, for the transport of concrete through the column. The speed graph in the concrete pipe plug is given in Figure 12.

## Conclusions

If you follow the graphs oscillations plotted to arm structure and for the pump system parameters, i.e. pressure and velocity of the concrete plug in pipeline transportation, within the period of 60 s, the following are found:

a) graphs expressing the oscillations structure $\varphi(t)$, figure 6, and $\psi(t)$, figure 16, taken in a short span of time, they match the general air of oscillations given by Putzmeister in [4], in vertical, longitudinal and transverse plan, oscillations which are written off with EBC control system, acting on the hydraulic tilting facility of sections (fig. 10, a, b, and c);

b) the oscillation chart of the top section $\varphi_4$ considered independently, (fig. 11), indicates a strong rotation with negative value, that happens under the action of pumping concrete into the column transportation. that was considered to be represented in this section;

c) the change in velocity of the concrete plug transported in the pipeline can be found on the positive branch in this time frame (fig. 12). Is determined by the increasing pressure of pumping and pushing the concrete and of its inertia in motion, for a transmission ratio given by the pump/pipe diameters $i = D_p/D_c = 2$.

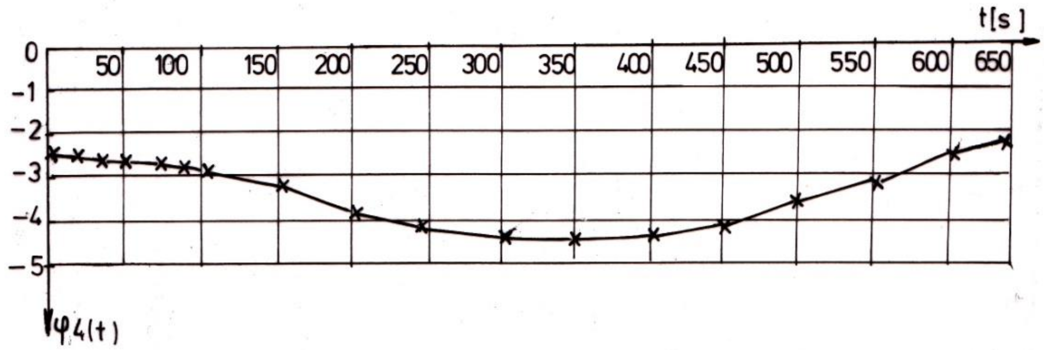



**Fig. 11.** Independent oscillation of the calculated peak

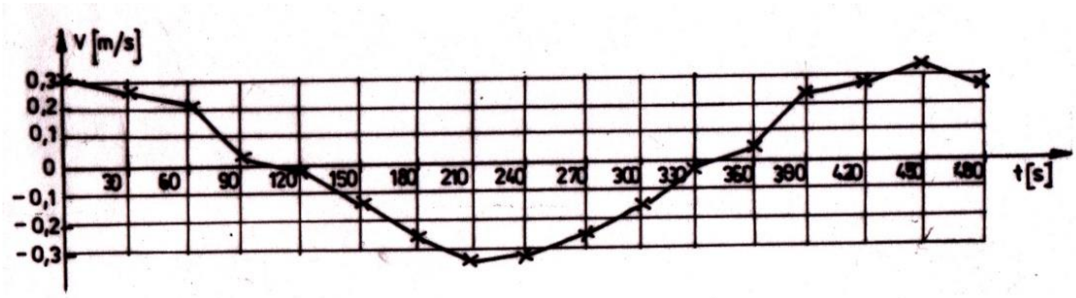



**Fig. 12.** The velocity oscillation calculated on the pipeline route

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# Modele de calcul privind braţele pompelor de beton montate pe camion


## Rezumat

*Articolul se referă la stabilitatea braţelor cu patru tronsoane articulate pentru pompele de beton montate pe camion, ţinând seama de transportul betonului pompat în conducte de către pompa cu doi cilindrii, conform graficului presiunii de pompare. Sunt analizate modelele de calcul pentru analiza oscilaţiilor braţului articulat în poziţia de lucru întins, în plan vertical –longitudinal şi orizontal, şi oscilaţiile independente ale tronsonului de vârf la care s-au fost reduse masele conductelor de transport cu beton. Sunt indicate graficele presiunii de pompare şi vitezei de transport a dopului de beton format în interiorul conductei pe un traseu orizontal şi înclinat.*