Kinematic and Dynamic Irregularities of Roller Pumps

Part I. Modeling of Kinematic and Dynamic Irregularities

Prof. MSc. Gencho POPOV PhD[1], MSc. Yuliyan ANGELOV PhD[1]

[1]University of Ruse "Angel Kanchev", Bulgaria, gspopov@uni-ruse.bg, julian@uni-ruse.bg

Abstract: *In this work generalized models for the determination of some typical irregularities in roller pumps, mainly used to work with water and water solutions, have been presented. It is concluded that when for the investigation of the kinematic characteristics of this type of pumps, the approximate equation for estimating the relative move of the rolls in the rotor's canals is used, the occurred deviation will be negligible. Some equations, which can be used for the determination of: the change of a given working camera's flow rate; the pump's total momentary flow rate; the loading of rolls, have been established. The equations describing the rotation of a given roll, has also been found.*

Keywords: *Roller pump, models of kinematic and dynamic irregularities.*

1. Introduction

The roller pumps are volumetric hydraulic machines, finding a wide range of application in crop-protective machines, used in agriculture, bio-technics, etc. They are mainly considered to work with relatively low pressures (up to 2 MPa) and specialized into the transportation of low-oil liquids, such as water and water solutions. This is the main reason for the rolls to be produced by nonmetallic antifriction materials (Teflon, naylon, different modifications of solid rubber, etc.), while both, the stator and rotor, are cast-iron details. The principle scheme of this kind of a pump is given in fig. 1.

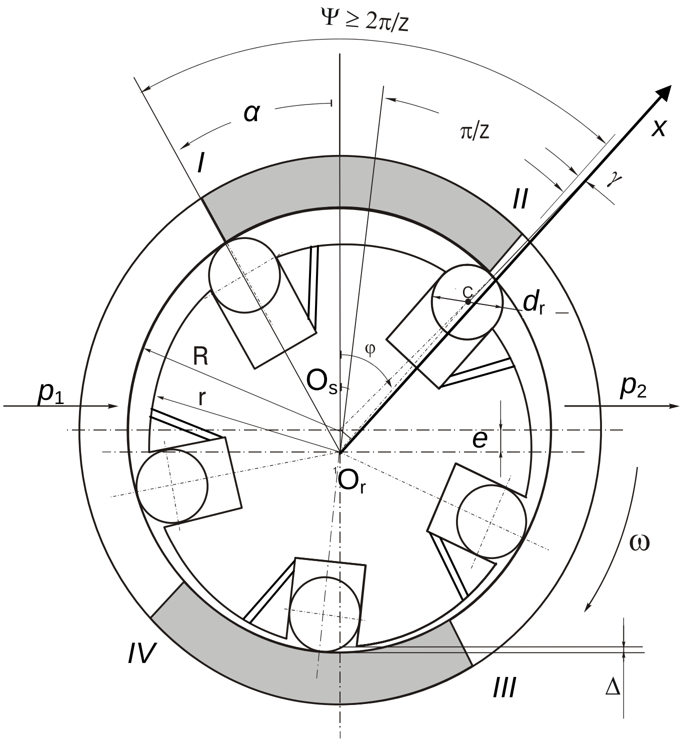

Fig.1 A scheme of a roller pump

The principle of work of this kind of machines, including different irregularities, according to their type and grade, which are determined by the processes, concerning the liquid transportation from the sucking (low pressure) zone to the zone of high pressure, as well as the features of the

kinematic and dynamic pump's working elements (the rolls). The main parameters, characterizing these processes, respectively are: the geometric volume of the pump's working cameras and its change in the range of one full rotation of the pump's shaft; the theoretical (geometric) flow rate and the grade of the flow rate's kinematic irregularity; the geometry of the liquid's distribution in the transitional sections, dividing each other the pump low and high pressure zones; the force loading of the pump's main working elements, etc.
In this work some theoretical equations, found by the authors and used for the determination of the roller pump's parameters, mentioned in the above paragraph, are being generalized.
The implemented parameters and their symbols are given in Table 1:

TABLE 1. Used parameters

Radius (diameter) of the stator's directive cylindrical surface	$R\left(D\right)$
Radius (diameter) of the rotor	$r\left(d\right)$
Radius (diameter) of the roll	$r_r\left(d_r\right)$
Roll's relative radius	$\bar{r}_r = r_r / R$
Number of rolls	z
Eccentricity of the stator with respect to the rotor	e
Relative eccentricity	$\lambda = e / R$
Rotor's width (length)	b
Relative rotor's width (length)	$\bar{b} = b / R$
Angular, determining the beginning of the transitional sections	α
Angular, determining the length of the sealing sections	ψ
Angular between two adjacent rolls	$\beta = 2\pi / z$
Angular between the radiuses of the pump's rotor and stator	$\gamma = \arcsin(\lambda \sin\varphi)$
Minimal gap between the rotor and stator	Δ
Roll's mass	m
Mass inertia torque of a roll	J
Gravity acceleration	g
Rotor's angular velocity	ω
Roll's angular velocity and acceleration	ω_r and ε_r
Slipping coefficients of friction	μ_1 and μ_2
Coefficient of resistance, when viscosity friction between the roll and working surface, is indicated	k
Force of pressure, acting on the pump's rolls	F
Force of gravity of the rolls	G
Inertia force of the transitional and relative roll's acceleration	Φ
Coriolis inertia force	F_k
Torque, occurred as a result of the resistance against the roll's (auxiliary-rotation) rotation	M_S
Roll's inertia torque	$M^{(\Phi)}$
Normal reactions, occurred in the zone of contact between the stator's directive surface and the rotor's canal's wall	N_1 and N_2
Forces of friction between the stator's directive surface and the rotor's canal's wall	T_1 and T_2

2. Kinematic irregularities modeling

The kinematic irregularity of a roller pump is due to the existing of the irregular relative roll's move, with respect to the rotor's canals, occurred in the range of one full pump shaft's rotation. The physical law, describing the roll's move into the canal, can be presented as a function of the rotor's angular of rotation - φ. As a preliminary base, used for the determination of these kinematic parameters, the equation, estimating the radius-vector of the stator's cylindrical directive surface, in respect to the axis of rotation, can be selected. This equation is equal to the equation, valid for one-acting radial-piston pumps and vane pumps, having same type of directive surfaces:

$$\rho_\varphi = R\left(\sqrt{1-\lambda^2 \sin^2\varphi} + \lambda\cos\varphi\right). \tag{1}$$

By using equation (1), the physical law, determining the relative roll's move, in respect to the rotor's canal, when its angular of rotation is φ, can be found (fig. 1):

$$x = R + e - \rho_\varphi = R\left(1 + \lambda - \lambda\cos\varphi - \sqrt{1-\lambda^2 \sin^2\varphi}\right). \tag{2}$$

For the simplification of equation (2), different methods can be used. It is a well-known fact, that best results can be achieved in case that the radical, given in brackets, is being presented according to the Newton's binomial theorem, by taking the first two articles – $\sqrt{1-\lambda^2\sin^2\varphi} \approx 1 - 0{,}5\lambda^2\sin^2\varphi$. With this approximation the physical law, describing the relative roll's move in the canal x*, can be given by the following equation:

$$x^* = R\left(\lambda - \lambda\cos\varphi + 0{,}5\lambda^2\sin^2\varphi\right). \tag{3}$$

The relative percentage deviation, between the results found by using the approximate equation (3), instead of the precise equation (2), can be evaluated by the following equation:

$$\delta = \frac{x - x^*}{x} 100, \ \%.$$

The equation, used for the estimation of the relative deviation δ, given as a function of the angular of rotation φ, for pumps having different eccentricity λ, is given in fig. 2. It can be seen that, when for the investigation of the kinematic parameters of the roll's move in the rotor's canals, the approximate equation (3) is used, the relative deviation is negligible (its value is less than 0.6 % for the high eccentricity pumps).

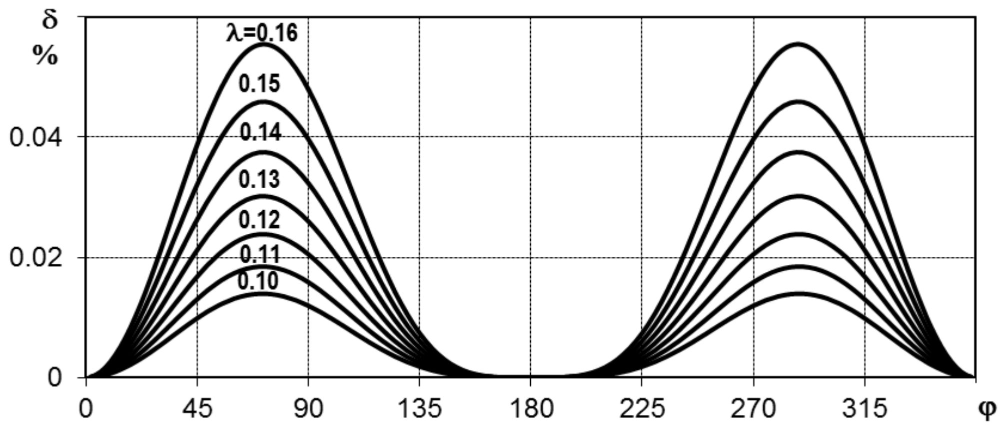

Fig. 2. Change of the relative deviation, when for the determination of the roll's move the approximate equation is used

The relative velocity and relative acceleration of the roll's move, in the radial canal of the rotor, can be determined by using the approximate equation (3):

$$\upsilon = \frac{dx}{dt} = \frac{dx}{d\varphi}\frac{d\varphi}{dt} = \omega R^3\, \bar{r}_r\, \bar{b}\, \lambda(\sin\varphi + 0{,}5\,\lambda\, \sin 2\varphi), \tag{4}$$

$$a = \frac{d\upsilon}{dt} = \frac{d\upsilon}{d\varphi}\frac{d\varphi}{dt} = -\,\omega^2 R^3\, \bar{r}_r\, \bar{b}\, \lambda(\cos\varphi + \lambda\cos 2\varphi). \tag{5}$$

The kinematic irregularity of the pump's flow rate is due to the irregular move of the rolls in the rotor's canals. To investigate this irregularity, first it is necessary for the change of the volume of the pump's working cameras, given as a function of the angular of rotation [5], to be determined. The equation, used for the estimation of the volume of a working camera, is given in a dimensionless order:

$$\begin{aligned}\overline{V}_\varphi = \frac{V_\varphi}{\bar{b}R^3} = 0{,}5\Big\{ \lambda\Big[\sin(\varphi+\beta)\sqrt{1-\lambda^2\sin^2(\varphi+\beta)} - \sin\varphi\sqrt{1-\lambda^2\sin^2\varphi}\Big] + \\ + \arcsin\lambda\sin(\varphi+\beta) - \arcsin\lambda\sin\varphi + 0{,}5\lambda^2\left[\sin 2(\varphi+\beta) - \sin 2\varphi\right] - \\ - 2\bar{r}_r\Big[\sqrt{1-\lambda^2\sin(\varphi+\beta)} - \sqrt{1-\lambda^2\sin^2\varphi}\Big] - 2\lambda\bar{r}_r\left[\cos(\varphi+\beta) - \cos\varphi\right]\Big\} + A,\end{aligned} \tag{6}$$

where A has a constant value, independent by φ.

The flow rate - $Q_{1,\varphi}$, ensured by a working camera, can be estimated by the following equation [4]:

$$Q_{\varphi,1} = \frac{dV}{dt} = \omega\frac{dV}{d\varphi}$$

Using the equation of estimation the flow rate $Q_{1,\varphi}$, given in [4], the dimensionless value of the flow rate for a given pump's working camera, can be determinate by the following equation:

$$\begin{aligned}\overline{Q}_{1,\varphi} = \frac{Q_{1,\varphi}}{\omega\bar{b}R^3} = \lambda\Big\{\cos\varphi\sqrt{1-\lambda^2\sin^2\varphi} - \cos(\varphi+\beta)\sqrt{1-\lambda^2\sin^2(\varphi+\beta)} + \lambda\left[\cos^2\varphi - \cos^2(\varphi+\beta)\right] + \\ + \bar{r}_r\left[\sin\varphi - \sin(\varphi+\beta)\right] + 0{,}5\bar{r}_r\lambda\left[\frac{\sin 2\varphi}{\sqrt{1-\lambda^2\sin^2\varphi}} - \frac{\sin 2(\varphi+\beta)}{\sqrt{1-\lambda^2\sin^2(\varphi+\beta)}}\right]\Big\}.\end{aligned} \tag{7}$$

Equation (7) indicates that the flow rate, ensured by a working camera, changes according to a complicate trigonometric mathematical function, which can be recognized as a typical feature, concerning all hydraulic machines with similar kinematic of driving to their main working elements.

The momentary pump's flow rate can be determined by summing of all the separate flow rates, ensured by each of the working cameras, which are connected to the high pressure canal:

$$Q_\varphi = \sum_{m=1}^{k-1} Q_{1,\varphi},$$

where k is the number of the same time connected to the pump's high pressure zone cameras.

By using equation (9), indicating the fact that (usually) for the roller pumps $\lambda \le 0{,}1$ and assuming that $\sqrt{1-\lambda^2\sin^2\varphi} \approx \sqrt{1-\lambda^2\sin^2(\varphi+\beta)} \approx 1$, some simplifications can be accomplished. In this case the value of the dimensionless momentary flow rate can be estimated by the following equation:

$$\begin{aligned}\overline{Q}_\varphi = \frac{Q_\varphi}{\omega\bar{b}R^3} = \lambda\Big\{\sum_{m=0}^{k-1}\left[\cos(\varphi+m\beta) - \cos(\varphi+\beta+m\beta)\right] + \lambda\sum_{m=0}^{k-1}\left[\cos^2(\varphi+m\beta) - \cos^2(\varphi+\beta+m\beta)\right] + \\ + \bar{r}_r\sum_{m=0}^{k-1}\left[\sin(\varphi+m\beta) - \sin(\varphi+\beta+m\beta)\right] + 0{,}5\bar{r}_r\,\lambda\sum_{m=0}^{k-1}\left[\sin 2(\varphi+\beta) - \sin 2(\varphi+\beta+m\beta)\right]\Big\},\end{aligned} \tag{8}$$

where after the above equation is being mathematically transformed, it can be given in the following way:

$$\overline{Q}_{\varphi} = \lambda\{\cos\varphi - \cos(\varphi + k\beta) + \lambda[\cos^2\varphi - \cos^2(\varphi + k\beta)] + \\ + \bar{r}_r[\sin\varphi - \sin(\varphi + k\beta)] + 0{,}5\bar{r}_r\lambda[\sin 2\varphi - \sin 2(\varphi + k\beta)]\}. \qquad (9)$$

It is well-known that for pumps with an even number of rolls $k = z/2$ and respectively - $k\beta = \pi$. For those with an odd number of rolls, the number of cameras k, belonging to the pump's high pressure zone at the same time, depends on the angular of the rotor's rotation - φ. Within the range of an angular step ($\beta = 2\pi/z$) it changes from $k = (z+1)/2$, in the first half of the rotation, to $k = (z-1)/2$ - during the second half of it.

To evaluate the pump's flow rate irregularity, it is recommended for the coefficient of the flow rate's irregularity to be used:

$$\delta = \frac{Q_{max} - Q_{min}}{Q_T} 100, \quad \%, \qquad (10)$$

where Q_{max} and Q_{min} are the maximal and minimal values of the pump's momentary flow rate and Q_T is the average value of the theoretical flow rate, which can be estimated by the following equation:

$$Q_T = 2eDb\left(\pi k_z - \bar{r}_r z \cos\frac{\pi}{z}\right)n \qquad (11)$$

where $k_z = \frac{\sin\pi/z}{\pi/z}$ is a coefficient, indicating the number of rolls.

For an even number of rolls the coefficient of the flow rate's irregularity can be estimated by the following equation:

$$\delta = \frac{1}{k_z}\left[\frac{1 - \cos(\alpha + \operatorname{arctg}\bar{r}_r)}{\cos(\alpha + \operatorname{arctg}\bar{r}_r - \frac{\pi}{z})}\right] \cdot 100, \quad \%. \qquad (12)$$

The estimation of the angular α (fig. 1), determining the beginning of the transitional sections, located between the low and high pressure zones, can be done by using the following equation [5]:

$$\alpha = \frac{\pi}{z} - 2\lambda\frac{r_r}{r_{r,min}}. \qquad (13)$$

Using the condition of non-allowing any blocking, the minimal value of the roll's radius - $r_{r,min}$, can be determined by the following equation:

$$r_{r,min} = R\left(\frac{1+\lambda}{2} - \sqrt{\left(\frac{1-\lambda}{2}\right)^2 - \lambda(1-\overline{\Delta}) - \overline{\Delta}}\right), \qquad (14)$$

where $\overline{\Delta} = \Delta/R$ is the relative minimal value of the gap between the rotor and stator.

Equation (9), used to estimate the pump's momentary flow rate in case of an odd number of rolls, has no exact solution in respect to its minimum and maximum. This is the main reason for the irregularity δ to be found by using an empirical equation, indicating the impact of the main geometric parameters on the flow rate's irregularity:

$$\delta = \frac{125}{z^2}\left(1 + 2{,}55 \cdot z^{0{,}87} \cdot \lambda^{z^{0{,}15}}\right), \quad \%. \qquad (15)$$

The established equations, presented in the above paragraphs, ensuring for the impact of some of the main geometric and constructive parameters on the kinematic irregularities in roller pumps, in respect to their: change of the flow rate of the working cameras; momentary and theoretical flow rates and their irregularities, etc., to be investigated and analyzed.

3. Dynamic irregularities modeling

Theoretical deterministic models, described by equations referred to Mathematics and Mechanics, of the given object, are mainly used to investigate the existing unsteady processes. Based on this, in [1, 2 and 3] a method for the determination of the force loading on the rolls and a generalized model for the investigation of the periodical dynamic processes of these rolls, are being presented. In [4 and 5] it is paid attention to other irregularities, typical for these machines, concerning the geometry of the liquid's distribution and the pump's flow rate. As a source of excitation for the existing dynamic processes, having different characteristics, the forces, occurred in the main pump's working elements, can be considered. The forces acting on the rolls are respectively: the force F, which is a result from the difference between the pressures in the low and high pressure zones - $\Delta p = p_2 - p_1$ (fig. 1); the force of gravity of the rolls – G; the forces of reaction, occurred in the zones of contact between the roll and stator - N_1 and T_1, and between the rolls and the surfaces of the rotor canals – N_2 and T_2; the inertia forces, occured as a result of the existing roll's transmission and relative accelerations - Φ, as well as the Coriolis inertia force - F_k; the torque - M_S, which is a result of the viscosity resistance, occurred because of the roll's rotation (with $M^{(\Phi)}$ it is indicated the roll's inertia torque).

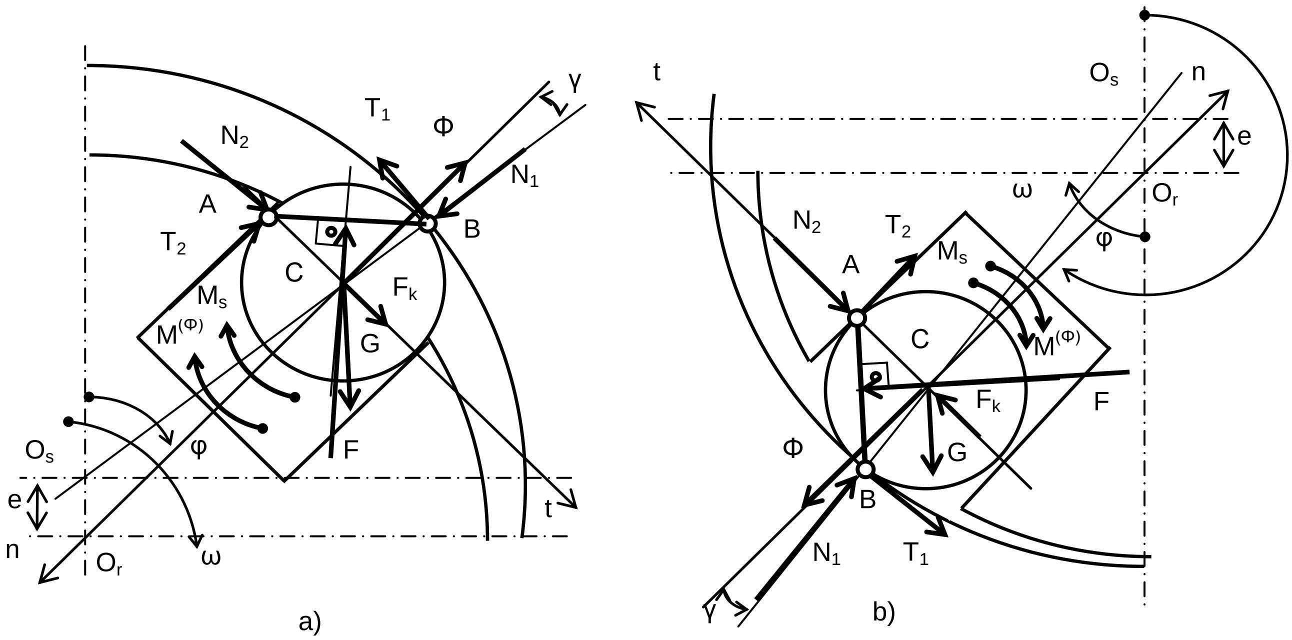

Fig.3 A scheme of roll's loading in the sealing sections:
a) in the high pressure zone;
b) in the low pressure zone.

The boundaries of the sealing sections – high pressure „I-II" and low pressure „III-IV", can be defined by the following intervals:

$$\varphi_{I,II} \in [-\alpha \div (\beta - \alpha)] \text{ and } \varphi_{III,IV} \in [(\pi - \alpha) \div (\pi + \beta - \alpha)]. \quad (16)$$

The angular α (fig. 1), determining the beginning of the transitional sections – between the low and high pressure pump zones, can be estimated by (13) and (14).
The length of the sealing sections can be determined by implementing the condition, indicating the necessity for at least one roll to belong them incessantly, so that the low and high pressure zones to be permanently separated each other (fig. 1). This can be formalized by the following inequality: $\psi \geq \beta$, where β is the angular between any two adjacent rolls.

The acting of the force of pressure F on the rolls is valid only for the intervals (1) and its magnitude depends of the roll surface's size (the part of the total surface, where the pressure difference Δp is acting), and it is known that the force will be directed from the high to the low pressure zone (fig. 3):

$$F = \Delta p b \overline{AB} = 2\Delta p b r_r \sin\left(\frac{\gamma+\beta}{2}\right), \tag{17}$$

where: $\overline{AB} = 2r_r \sin(\pi/4+\gamma/2)$ is the chorda's length, determining this part of the roll's surface, where the pressure difference is acting.
The rolls belonging to the high and low pressure cameras, determined by the intervals:

$$\varphi \in [(\beta-\alpha) \div (\pi-\alpha)] \text{ and } \varphi \in [(\pi+\beta-\alpha) \div (2\pi-\alpha)], \tag{18}$$

get into isobaric environment, as a result of which $F = 0$. For a given correct interpretation of these processes (fig. 3) different schemes of calculation, consistent with the following intervals:

$$\varphi_a \in [-\alpha \div (\pi-\alpha)] \text{ and } \varphi_b \in [(\pi-\alpha) \div (2\pi-\alpha)], \tag{19}$$

are being formulated.
For each of these schemes it has been applied the principle of d'Alambert, as well as the relevant kineto-static equations, in respect to the axes of the flat rolling movable coordinate system – C*nt*, are established. For the scheme, given in fig. 3a, it can be given the following equations:

$$\vec{F}_n^{(e)} + \overrightarrow{\Phi_n} = \vec{0}; \quad G\cos\varphi - F\cos(\pi/4-\gamma/2) + N_1\cos\gamma - T_1\sin\gamma - T_2 - \Phi = 0,$$
$$\vec{F}_t^{(e)} + \overrightarrow{\Phi_t} = \vec{0}; \quad G\sin\varphi - F\sin(\pi/4-\gamma/2) - N_1\sin\gamma - T_1\cos\gamma + N_2 + F_k = 0,$$

and for the scheme in fig. 3b:

$$\vec{F}_n^{(e)} + \overrightarrow{\Phi_n} = \vec{0}; \quad -G\cos(\pi+\varphi) - F\cos(\pi/4-\gamma/2) + N_1\cos\gamma + T_1\sin\gamma + T_2 - \Phi = 0,$$
$$\vec{F}_t^{(e)} + \overrightarrow{\Phi_t} = \vec{0}; \quad -G\sin(\pi-\varphi) + F\sin(\pi/4-\gamma/2) + N_1\sin\gamma - T_1\cos\gamma - N_2 + F_k = 0.$$

Indicating the restrictions, given in (17), (18) and (19), and transforming them in respect to the normal reactions N_1 and N_2, the following equations, valid only for the intervals (20) and (21), can be given:

- for $\varphi_a \in [-\alpha \div (\pi-\alpha)]$:

$$N_1 = \frac{F[\cos(\pi/4-\gamma/2) + \mu_2\sin(\pi/4-\gamma/2)] - G(\cos\varphi + \mu_2\sin\varphi) - \mu_2 F_k + \Phi}{\cos\gamma(1-\mu_1\mu_2) - \sin\gamma(\mu_1+\mu_2)},$$
$$N_2 = F\sin(\pi/4-\gamma/2) + N_1(\sin\gamma + \mu_1\cos\gamma) - G\sin\varphi - F_k,$$
$$F = 0 \text{ for } \varphi \in [(\beta-\alpha) \div (\pi-\alpha)]; \tag{20}$$

- for $\varphi_b \in [(\pi-\alpha) \div (2\pi-\alpha)]$:

$$N_1 = \frac{F[\cos(\pi/4-\gamma/2) - \mu_2\sin(\pi/4-\gamma/2)] - G(\cos\varphi + \mu_2\sin\varphi) - \mu_2 F_k + \Phi}{\cos\gamma(1-\mu_1\mu_2) + \sin\gamma(\mu_1+\mu_2)},$$
$$N_2 = F\sin(\pi/4-\gamma/2) + N_1(\sin\gamma - \mu_1\cos\gamma) + G\sin\varphi + F_k,$$
$$F = 0, \text{ for } \varphi \in [(\pi+\beta-\alpha) \div (2\pi-\alpha)]. \tag{21}$$

For the structuring of the model, representing the forces and torques, acting on the rolls, it is also necessary for the equations, given in [1], to be applied:

$$\Phi = m\omega^2 R\left[1 - r_1/2R - \lambda^2/4 + 2\lambda\cos\varphi + 5\lambda^2\cos(2\varphi)/4\right],$$
$$F_k = 2m\lambda\omega^2 R[\sin\varphi + \lambda\sin(2\varphi)/2], \tag{22}$$
$$G = mg, \; T_1 = \mu_1 N_1, \; T_2 = \mu_2 N_2, \; M_S = k\omega_r, \; M^{(\Phi)} = J\varepsilon_r,$$

For the interval - $\varphi \in [-\alpha \div (2\pi-\alpha)]$, using the torque kineto-static equation, in respect to the axis of the roll's rotation:

$$\overrightarrow{M_c}^{(e)} + \vec{M}_c^{(\Phi)} = \vec{0}; \qquad T_1 r_P - T_2 r_P - M^{(\Phi)} - M_c = 0$$

its acceleration can be estimated:

$$\varepsilon_r = \frac{2(\mu_1 N_1 r_r - \mu_2 N_2 r_r - k\omega_r)}{m r_r^{\ 2}}. \tag{23}$$

Equation (23) is a second order linear inhomogeneous differential equation, having constant values of its coefficients. Finding a solution of this equation, when its zero initial conditions have been selected, ensuring for the physical law of its rotation and speed of rotation to be found:

$$\varphi_r = (T_1 - T_2)\frac{J r_r}{k^2}\left(e^{-\frac{k}{J}t} + \frac{k}{J} - 1\right), \tag{24}$$

$$\omega_r = (T_1 - T_2)\frac{r_r}{k}\left(1 - e^{-\frac{k}{J}t}\right), \tag{25}$$

where $t = \varphi / \omega$ is the current time.

Conclusions

Analyzing the presented generalized models, used to determine the typical irregularities in roller pumps, the following more important conclusions can be given:

- Comparing the results found by using the approximate equation (3) for estimating the relative roll's rotation in the rotor's canals, instead of the precise equation – (2), it can be seen that the occurred deviation is negligible (less than 0,06%);
- The established equations, describing the change of the pump's volume (6) and the flow rate of a given working camera (7), as well as the total momentary theoretical flow rate (8) or (9), ensuring good possibilities for the investigation of the kinematic irregularities of roller pumps;
- The established model of force loading of a pump's rolls and its intervals of validation (20) and (21), have been strictly defined.
- The physical law (24), describing the rotation of a given roll, which also can be used for the investigation of the phase characteristics of the roll's rotation, is found.

References

[1] Angelov Y., G. Popov Dynamics of the rollers of a roller pump, Part I. Modeling of force load. PROCEEDINGS of the UNIVERSITY OF RUSE "Angel Kanchev" Volume 53, book 2 Mechanics, Mechanical and Manufacturing Engineering, ISBN 1311-3321, Ruse, 2014, 111-115 p.

[2] Angelov Y., I. Nikolaev Dynamics of the rolls of a roller pump, Part II. Numerical study of the dynamics of rolls. PROCEEDINGS of the UNIVERSITY OF RUSE "Angel Kanchev" Volume 53, book 2 Mechanics, Mechanical and Manufacturing Engineering, ISBN 1311-3321, Ruse, 2014, 116-120 p.

[3] Batsov T, G. Popov, Y. Angelov A model for forces racting upon rollers of a roller pump investigation. Mechanika na mashinite, year XIII, book 1, Varna, 2005.

[4] Popov G., P. Russev. Irregularities in a roller pump's flow rate. PROCEEDINGS of the UNIVERSITY OF RUSE "Angel Kanchev" Volume 37, ser. 9, ISBN 1311-3321, Ruse, 1999, 102-105 p.

[5] Popov G., P. Russev. About the geometry of the flow rate's distribution in roller pumps. PROCEEDINGS of the UNIVERSITY OF RUSE "Angel Kanchev" Volume 37, ser. 9, ISBN 1311-3321, Ruse, 1999, 106-110 p.

[6] Popov G., P. Russev, Iv. Nikolaev. Investigation of the force loading on the vanes and determination of the mechanical loses in one-acting vane pumps. Mechanika na mashinite 39, book 1, Varna, 2002, pp. 50-53.