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Project coordinator

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Reliability and durability of Machines and Mechanisms used for Oil and Gas transportation in Black Sea Region

(RDMMOGT)

Project partners:

1. **Prof.Dr. Carsten Proppe**
Karlsruhe Institute of Technology, Karlsruhe, Germany

Task Title : *Friction, wear and reliability of piston assemblies.*

2. **Prof. Dr. Erdal Celik**
Dokuz Eylul University, Izmir, Turkiye

Task Title: *New fabrication techniques of wear resistance materials for reciprocating machines.*

3. **Prof. Dr. Nodar Davitashvili**
Georgian Technical University, Tbilisi, Georgia

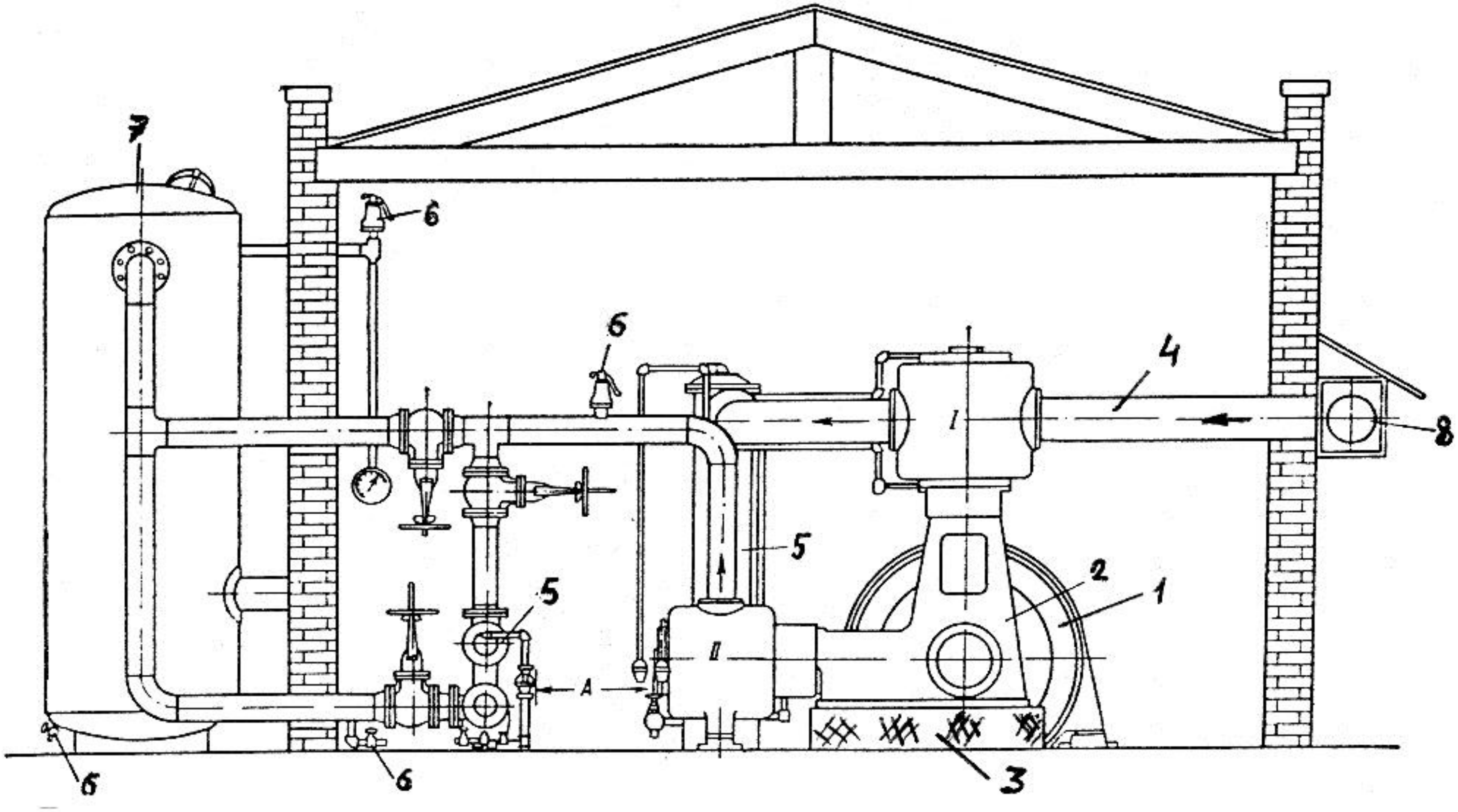
Task Title: *Research of damage intensity of various elements of crank - piston mechanisms in different technical conditions.*

Summary of Project:

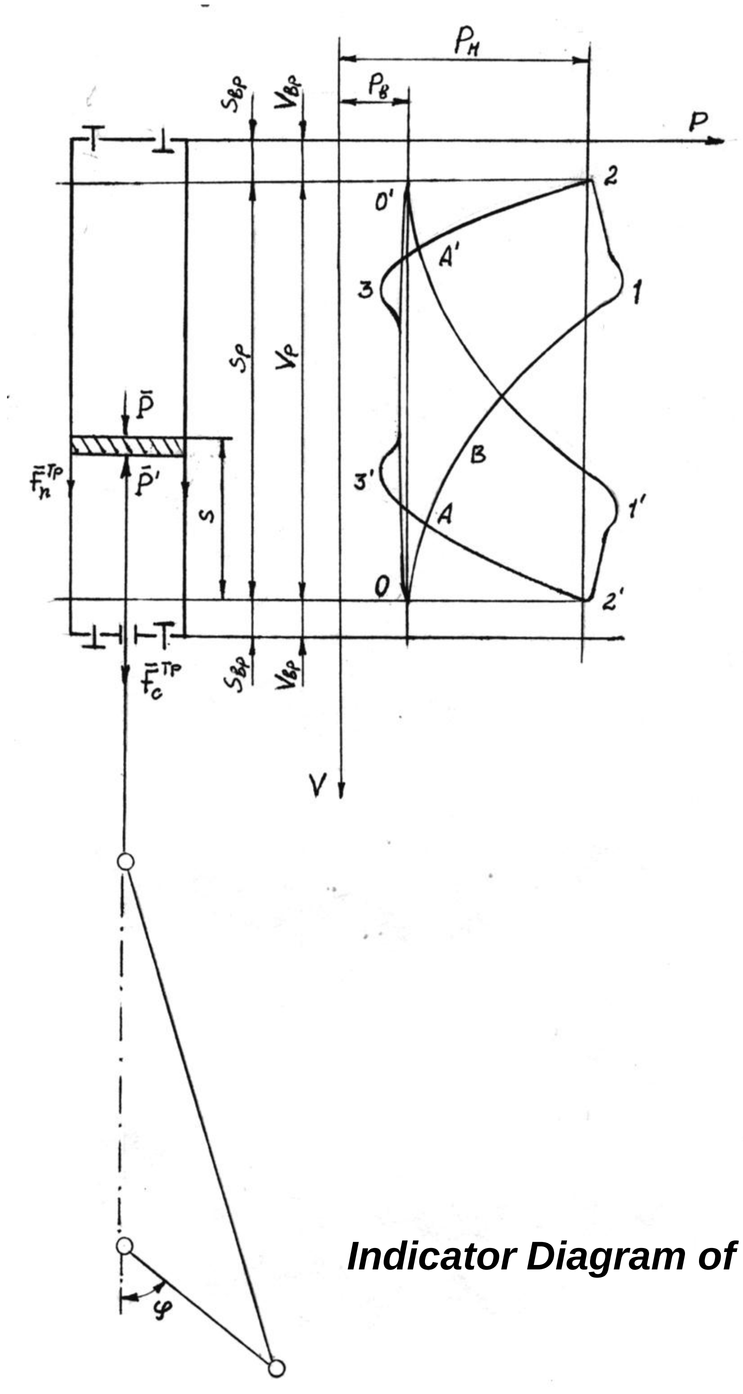
Reciprocating machines are widely used for exploration and transportation of natural resources in the Black Sea Region, for example in Baku-Tbilisi-Ceyhan Main Oil Pipeline, there are 8 pump-compressor stations (2 stations in Azerbaijan, 2 stations in Georgia and 4 stations in Turkey). Piston machines (PM) are heavy-duty systems that are still failure prone due to high stresses and wear. Increasing the reliability and durability of piston machines corresponds therefore to actual needs and political demandsof reduced environmental impacts during exploration and transportation of resources.

A multidisciplinary study on reciprocating machines for petroleum industry is proposed. The project brings together experts from Azerbaijan, Georgia, Turkey and Germany in order to develop an integrated model of the piston machine system that is then used to evaluate and improve current designs. 'Dynamical analysis of Piston Machines and increase of reliability of pump-compressor stations'(Azerbaijan team), 'Analysis and determination of the friction losses in piston assembly'(Germany team), 'New fabrication techniques of wear resistance materials for reciprocating machines'(Turkey team) and 'Research of damage intensity of various elements of crank – piston mechanisms in different technical conditions'(Georgia team) are the aspects on the agenda.

The research efforts will lead to more reliable and efficient design alternatives for reciprocating machines as are used for the transport of oil and gas and will thus contribute directly to the competitivity of a key industry in the Black Sea Region.



Compressor Station in Oil Industry
1. A drive, 2. Piston Compressor, 3. Foundation, 4. A gas pipeline, 5. An intermediate and trailer refrigerator, 6. The purge gate, 7. A receiver, 8. The filter



Indicator Diagram of Piston Machine

The differential equations of thermodynamical process of piston compressors

1.The indissolubility equation

$$\frac{\partial \rho}{\partial \tau} + div\left(\rho \overline{W}\right) = O$$

2. Energy equation

$$dq_H = di + WdW$$

3. Equation of motion

$$vdp + WdW + dL_{mp} = 0$$

4. State equation of gas

$$Pv = zRT$$

First stage:

$$P = \frac{f_n P_b V_o^{m_1}}{\left\{ V_{bP} + \left[S_P - R(1-\cos\varphi) + \frac{R^2}{2L}\sin^2\varphi \right] f_n \right\}^{m_1}}$$

$$P^1 = \frac{f_n P_H V_{bP}^{m_2}}{\left\{ V_{bP} + \left[R(1-\cos\varphi) - \frac{R^2}{2L}\sin^2\varphi \right] \cdot f_n \right\}^{m_2}}$$

Second stage:

$$P = \frac{f_n P_b V_O^{m_2}}{\left\{ V_{bP} + \left[S_p - R(1-\cos\varphi) + \frac{R^2}{2L}\sin^2\varphi \right] \cdot f_n \right\}^{m_2}} ; P^| = f_n P_b$$

3-d stage:

$$P = \frac{f_n P_H V_{bP}^{m_2}}{\left\{ V_{bP} + \left[S_P - R(1-\cos\varphi) + \frac{R^2}{2L}\sin^2\varphi \right] \cdot f_n \right\}^{m_2}}, \qquad P^1 = \frac{f_n P_b V_o^{m_1}}{\left\{ V_{bP} + \left[R(1-\cos\varphi) - \frac{R^2}{2L}\sin^2\varphi \right] f_n \right\}^{m_1}}$$

4-th stage:

$$P = f_n P_H; \qquad P^| = f_n \cdot P_b$$

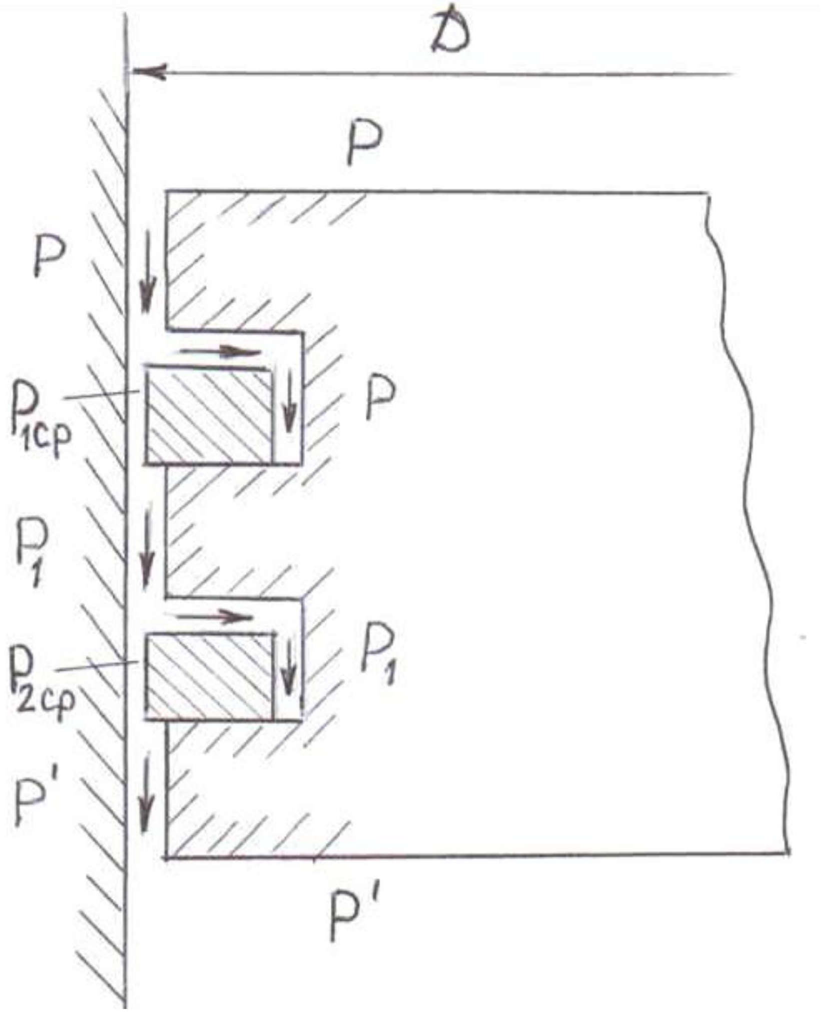
$$P^1 = \frac{f_n P_b V_o^{m_1}}{\left\{ V_{bP} + \left[R(1-\cos\varphi) - \frac{R^2}{2L}\sin^2\varphi \right] f_n \right\}^{m_1}}$$

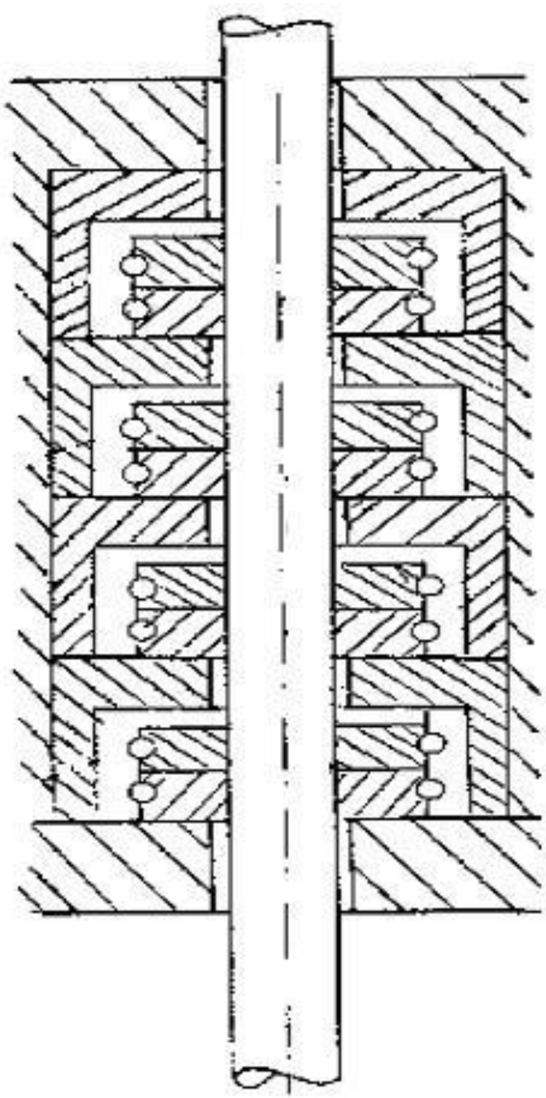
6-th stage:

$$P = f_n \cdot P_b; P^1 = f_n \cdot P_H$$

$$P = f_n \cdot P_b;$$

The scheme of Piston assemble with gas stream in clearances of piston rings and cylinder.





The scheme of Stuffing box seal

$$P_Z = P\left[1-\frac{Z}{Z_1}\left(1-\frac{\left(P'\right)^{2,5}}{P^{2,5}}\right)\right]^{\frac{1}{2,5}}$$

$$P_Z = P\left[\begin{aligned}&1-0{,}4\frac{Z}{Z_1}-0{,}12\frac{Z^2}{Z_1^2}-0{,}064\frac{Z^3}{Z_1^3}-0{,}0416\frac{Z^4}{Z_1^4}+\frac{(P')^{2,5}}{P^{2,5}}\cdot\left(0{,}4\frac{Z}{Z_1}+0{,}24\frac{Z^2}{Z_1^2}+0{,}192\frac{Z^3}{Z_1^3}+0{,}1664\frac{Z^4}{Z_1^4}\right)-\\&-\frac{(P')^5}{P^5}\left(0{,}12\frac{Z^2}{Z_1^2}+0{,}192\frac{Z^3}{Z_1^3}+0{,}2496\frac{Z^4}{Z_1^4}\right)+\frac{(P')^{7,5}}{P^{7,5}}\left(0{,}064\frac{Z^3}{Z_1^3}+0{,}1664\frac{Z^4}{Z_1^4}\right)-0{,}0416\cdot\left(\frac{Z}{Z_1}\right)^4\left(\frac{P'}{P}\right)^{10}\end{aligned}\right]$$

(1.6)

$$P_Z = P'\left[1-\frac{Z}{Z_1}\left(1-\frac{P_b^{2,5}}{\left(P'\right)^{2,5}}\right)\right]^{\frac{1}{2,5}}$$

$$P_Z = P'\left[\begin{aligned}&1-0{,}4\frac{Z}{Z_1}-0{,}12\frac{Z^2}{Z_1^2}-0{,}064\frac{Z^3}{Z_1^3}-0{,}0416\frac{Z^4}{Z_1^4}+\frac{(P_b)^{2,5}}{(P')^{2,5}}\cdot\left(0{,}4\frac{Z}{Z_1}+0{,}24\frac{Z^2}{Z_1^2}+0{,}192\frac{Z^3}{Z_1^3}+0{,}1664\frac{Z^4}{Z_1^4}\right)-\\&-\frac{(P_b)^5}{(P')^5}\left(0{,}12\frac{Z^2}{Z_1^2}+0{,}192\frac{Z^3}{Z_1^3}+0{,}2496\frac{Z^4}{Z_1^4}\right)+\frac{(P_b)^{7,5}}{(P')^{7,5}}\left(0{,}064\frac{Z^3}{Z_1^3}+0{,}1664\frac{Z^4}{Z_1^4}\right)-0{,}0416\cdot\left(\frac{Z}{Z_1}\right)^4\left(\frac{P_b}{P'}\right)^{10}\end{aligned}\right]$$

(1.7)

$$N_{г} = \pi(D-2a)bp - \pi Db\frac{P+P_1}{2} + \pi(D-2a)bP_1 - \pi Db\frac{P_1+P^{|}}{2} =$$

$$= (0,5\pi Db - 2\pi ab)P - 2\pi abP_1 - 0,5\pi DbP^{|},$$

(1.8)

$$P_1 = P\left[0,7594 + 0,388\left(\frac{P'}{P}\right)^{2,5} - 0,696\left(\frac{P'}{P}\right)^{5} + 0,0904\left(\frac{P'}{P}\right)^{7,5} - 0,0026\left(\frac{P'}{P}\right)^{10}\right]$$

$$F_n^{Tp} = \mu_n\left(N_{г} + N_{уn}\right),$$

(1.9)

$$N_{уп} = 2?\ Db\ P_{уп}\ ,$$

(1.10)

$$F_n^{tp} = 0,5\mu_n\pi b(D-4a)P - 0,5\mu_n\pi bDP' + 2\mu_n\pi bDP_{уп} -$$

$$- 2\mu_n\pi baP\left[0,7594 + 0,388\left(\frac{P'}{P}\right)^{2,5} - 0,696\left(\frac{P'}{P}\right)^{5} + 0,0904\left(\frac{P'}{P}\right)^{7,5} - 0,0026\left(\frac{P'}{P}\right)^{10}\right]$$

(1.11)

$$F_n^{tp} = \mu_n\left[2\pi ba\left(2,242P + 0,933\frac{(P')^{2,5}}{P^{1,5}} - 0,242\frac{(P')^{5}}{P^{4}} + 0,057\frac{(P')^{7,5}}{P^{6,5}} - 0,016\frac{(P')^{10}}{P^{9}}\right)\right] + \pi b(0,5D-a)P - 0,5\pi b(D-2a)P^{|} + 4\pi bDP_{уп} + M_n g\Big] +$$

$$P_{1ср} = \frac{P^{|}+P_1}{2};\quad P_{2ср} = \frac{P_1+P_2}{2},\quad P_{3ср} = \frac{P_2+P_3}{2},\quad P_{4ср} = \frac{P_3+P_в}{2},$$

$$N_{г} = 2\pi d_2 b_1(P^1 + P_1 + P_2 + P_3) - 2\pi d_1 в_1(P_{1ср} + P_{2ср} + P_{3ср} + P_{4ср} =$$

$$= 2\pi в_1(d_2 - d_1)(P_1 + P_2 + P_3) + \pi в_1(2d_2 - d_1)P^{|} - \pi d_1 в_1 P_в$$

(1.12)

$$P_1 = P'\left[0,891 + 0,118\left(\frac{P_B}{P'}\right)^{2,5} - 0,011\left(\frac{P_B}{P'}\right)^{5} + 0,002\left(\frac{P_B}{P'}\right)^{7,5} - 0,0001\left(\frac{P_B}{P'}\right)^{10}\right]$$

$$P_1 + P_2 + P_3 = 2{,}242P' + 0{,}933\frac{P_B^{2,5}}{(P')^{1,5}} - 0{,}242\frac{P_B^{5}}{(P')^{4}} + 0{,}057\frac{P_B^{7,5}}{(P')^{6,5}} - 0{,}016\frac{P_B^{10}}{(P')^{9}}$$

(1.13)

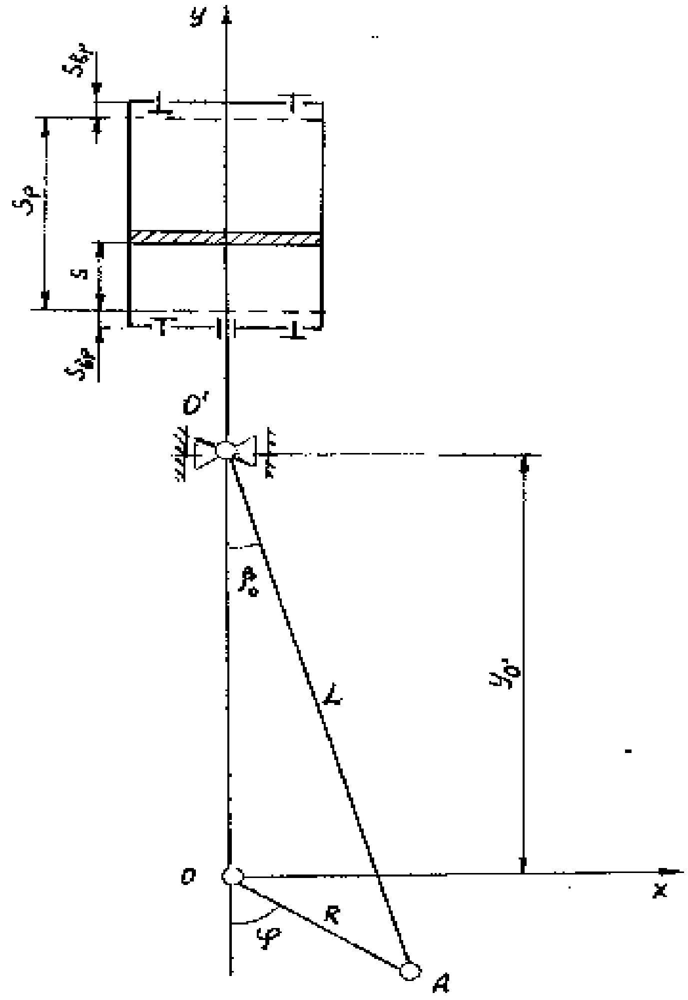
$$N_{yn} = 2\pi d_1 в_1 P_{yn} Z_1, \qquad (1.14)$$

$$F_C^{TP} = \mu_C \left(N_Г + N_{yn}\right),$$

$$F_C^{TP} = \mu_C \Big[2\pi b_1 (d_2 - d_1)\left(2{,}242P' + 0{,}933\frac{P_b^{2,5}}{(P')^{1,5}} - 0{,}242\frac{P_b^{5}}{(P')^{4}} + 0{,}057\frac{P_b^{7,5}}{(P')^{6,5}} - 0{,}016\frac{P_b^{10}}{(P')^{9}}\right.$$

$$+ \pi b_1 (2d_2 - d_1) P' + 2\pi b_1 d_1 P_{yn} z_1 - \pi b_1 d_1 P_b \Big]$$

(1.15)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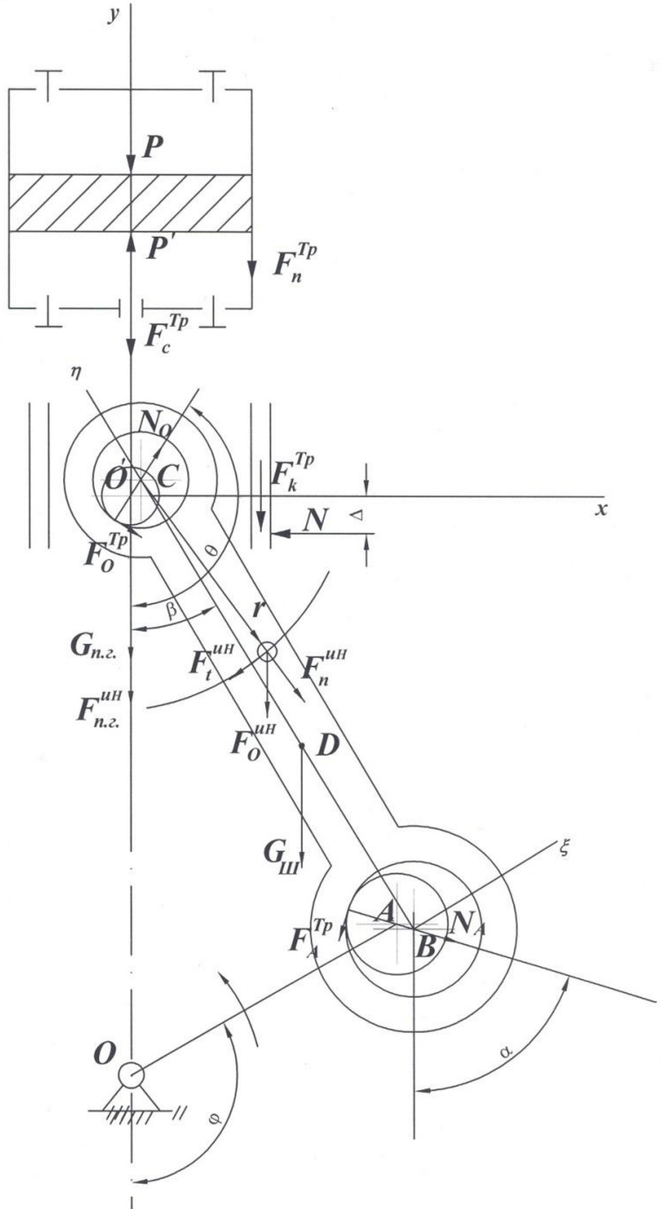


The scheme of crank-piston mechanism with acting forces

Equations of kinetostatics of Piston machine

$$-P+P^1-G_{п.г.}-G_{ш}-F_{п}^{тр}-F_{с}^{тр}-F_{К}^{тр}-F_{пг}^{ин}+\sum F_{o^1y}^{ин}+\sum F_{ty}^{ин}+\sum F_{пy}^{ин}-N_A\cos\alpha+F_A^{тр}\sin\alpha$$

$$-N+\sum F_{TX}^{ИН}+\sum F_{пх}^{UН}+N_A\sin\alpha+F_A^{TP}\cos\alpha=0$$

$$m_{O^1}\left(\overline{G}_{ш}\right)+\sum m_{O^1}\left(F_t^{ИН}\right)+m_{O^1}\left(F_{O^1}^{TP}\right)+m_{o^1}(F_A^{тр})+m_{O^1}\left(\overline{N}_A\right)-N\cdot\Delta-F_K^{TP}\cdot\delta=O$$

$$-P+P^1-G_{п\cdot Г}-F_{п}^{TP}-F_{C}^{TP}-F_{K}^{TP}-F_{пГ}^{ин}-N_{O^1}\cos\theta-F_{O^1}^{TP}\sin\theta=O$$

$$-N+N_{O^1}\sin\theta-F_{O^1}^{TP}\cos\theta=O$$

$$-N\cdot\Delta-F_K^{TP}\cdot\delta+F_{O^1}^{TP}\cdot r=0$$

Parameters of Piston Compressor 505 ВП20/18

φ	α	θ	N_A, Н	N, Н	N_o`,Н	Δ, м
0˚	4˚20`	6˚	7449	-29	15012	2,02
15˚	173˚	7˚	893	-37	340	0,12
30˚	174˚	192˚	21487	1422	14329	0,03
45˚	171˚	194˚	30338	4060	26676	0,016
60˚	163˚	196˚	32333	4693	26781	0,013
75˚	165˚	197˚	28345	4791	24494	0,011
90˚	162˚	197˚	25483	4524	23027	0,01
105˚	161˚	196˚	24239	4420	24322	0,012
120˚	165˚	195˚	31326	5611	33174	0,014
135˚	162˚	194˚	15861	2410	20229	0,024
150˚	154˚	190˚	7218	983	12894	0,043
165˚	33˚	187˚	2780	104	5492	0,02
180˚	5˚	186˚	4626	25	3613	0,058
195˚	4˚	-11˚	15215	1460	7203	0,032
210˚	6˚	-13˚	34731	3429	26286	0,021
225˚	6˚	-16˚	32129	4875	27276	0,012
240˚	5˚	-18˚	24703	4512	21448	0,008
255˚	-0˚40`	-19˚	15830	3556	14984	0,007
270˚	-3˚	-19 ˚	13676	3674	14462	0,008
286˚	5˚	-17˚	21365	5237	24781	0,009
300˚	4˚	-16˚	17092	4660	22206	0,011
315˚	1˚20`	-14˚	13324	2893	19339	0,017
330˚	0˚15`	-12˚	10051	1601	17038	0,03
345˚	1˚	-9˚	8991	864	16370	0,066
360˚	4˚	-6˚	8515	14	16076	4,35

Parameters of Piston Compressor 405 ГП15/70

φ	α	θ	N_A, Н	N, Н	$N_{o`}$,Н	Δ, м
0˚	4˚	3˚	6324	-17	23420	3,04
15˚	5˚	10˚	5213	-24	20335	0,09
30˚	162˚	181˚	8920	-980	20500	0,07
45˚	165˚	187˚	22410	-3270	23412	0,02
60˚	160˚	192˚	25423	2588	24487	0,02
75˚	158˚	190˚	23129	3920	24083	0,01
90˚	156˚	185˚	20230	4244	22483	0,01
105˚	154˚	180˚	20120	3783	24626	0,01
120˚	159˚	173˚	28931	4974	30092	0,02
135˚	160˚	170˚	12843	3427	24326	0,03
150˚	138˚	157˚	6924	1807	17129	0,04
165˚	112˚	148˚	4288	98	6218	0,03
180˚	12˚	140˚	5371	34	3780	0,08
195˚	11˚	102˚	12307	37	6893	0,04
210˚	8˚	-15˚	26420	3249	18215	0,03
225˚	7˚	-18˚	26028	4200	24326	0,01
240˚	-2˚	-20˚	22790	4035	22780	0,01
255˚	-2˚	-28˚	16370	3874	13051	0,01
270˚	-3˚	-25 ˚	13212	3780	13489	0,01
286˚	-1˚	-20˚	18448	4983	25120	0,01
300˚	6˚	-20˚	14417	4554	21112	0,01
315˚	5˚	-18˚	12370	3719	17150	0,02
330˚	3˚	-10˚	11910	2100	16015	0,02
345˚	2˚	-7˚	7486	878	16214	0,05
360˚	4˚	-2˚	6500	10	14871	3,07

$$d\left(PV/RT\right) = i_к^в dG_щ$$

(2.2)

$$VdP = d(Gi) - i_К^В i_Щ dG_Щ$$

(2.3)

$$i = C_p T \ , \ i_щ = C_p T_щ$$

(2.4)

$$i_k^в dG_щ = \alpha_щ f_щ W_щ \rho_щ i_к^в d\tau$$

(2.5)

$$PT^{\frac{m}{m-1}} = пост.$$

(2.6)

$$T_Щ = T_В \left(\frac{P}{P_В}\right)^{\frac{m-1}{m}}, \rho_щ = \rho_В \left(\frac{p}{p_В}\right)^{\frac{1}{m}},$$

(2.7)

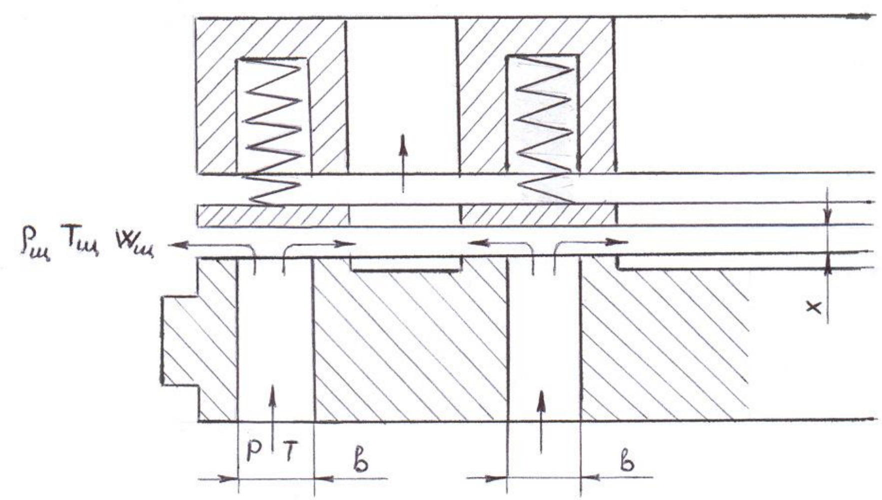
$$d\left(\frac{PV}{RT}\right) = \alpha_Щ f_Щ \rho_Щ W_Щ i_К^В d\tau$$

(2.8)

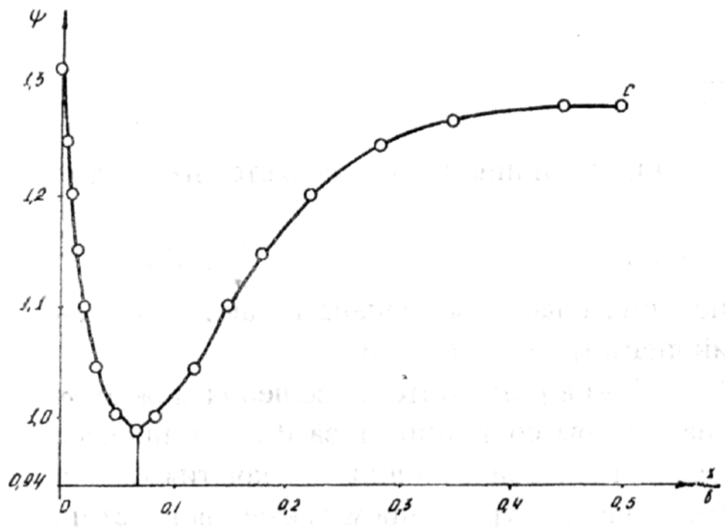
$$KPdV + VdP = KT_В \left(\frac{p}{p_в}\right)^{\frac{m-1}{m}} d\left(\frac{PV}{T}\right) = Ki_к^в \alpha_Щ f_Щ W_Щ Pd\tau$$

(2.9)

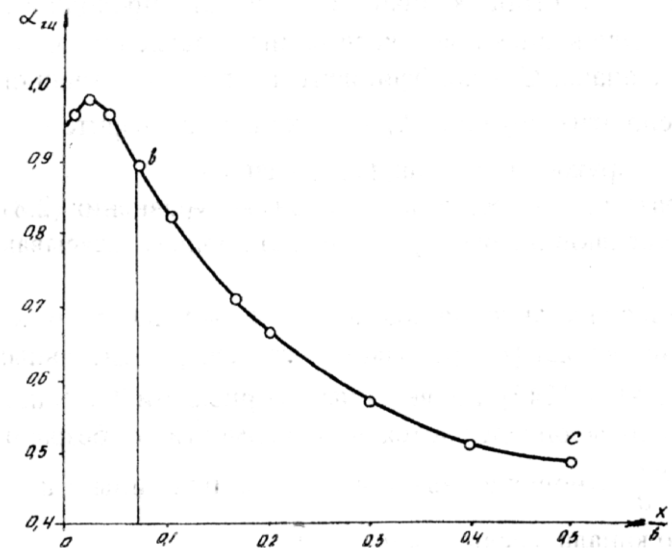
$$M\frac{d^2X}{d\tau^2} = (P_B - P) f_c \psi - C(X_o^1 + X) i_n^B \qquad (2.11)$$



The scheme of the valve of compressor



x/b



α щ

x/b

$$\alpha_{щ} = \alpha_0 + \alpha_1 \frac{x}{\text{в}} + \alpha_2 \left(\frac{x}{\text{в}}\right)^2 + \alpha_3 \left(\frac{x}{\text{в}}\right)^3$$

(2.12)

$$\psi = \psi_0 + \psi_1 \frac{x}{\text{в}} + \psi_2 \left(\frac{x}{\text{в}}\right)^2 + \psi_3 \left(\frac{x}{\text{в}}\right)^3 ,$$

(2.13)

$$KP_B \frac{dV}{d\tau} - K\Delta P_{\text{в}} \frac{dV}{d\tau} - V \frac{d(\Delta p_{\text{в}})}{d\tau} = A\alpha_0 \sqrt{\Delta p_{\text{в}}}X + A\frac{\alpha_1}{\text{в}}\sqrt{\Delta p_{\text{в}}}X^2 +$$

$$+ A\frac{\alpha_2}{\text{в}^2}\sqrt{\Delta p_{\text{в}}}X^3 + A\frac{\alpha_3}{\text{в}^3}\sqrt{\Delta p_{\text{в}}}X^4 - \frac{1{,}3A}{p_{\text{в}}}\alpha_0 \Delta p_{\text{в}}\sqrt{\Delta p_{\text{в}}}X -$$

$$- \frac{1{,}3A}{p_{\text{в}}} \cdot \frac{\alpha_1}{\text{в}} \Delta p_{\text{в}}\sqrt{\Delta p_{\text{в}}}X^2 - \frac{1{,}3A}{p_{\text{в}}} \frac{\alpha_2}{\text{в}^2} \Delta p_{\text{в}}\sqrt{\Delta p_{\text{в}}}X^3 - \frac{1{,}3A}{P_{\text{в}}} \cdot \frac{\alpha_3}{\text{в}^3} \Delta P_B \sqrt{\Delta P_{\text{в}}}X^4,$$

(2.18)

$$M\frac{d^2x}{d\tau^2} = f_c\psi_0\Delta P_в + f_c\frac{\psi_1}{в}\Delta P_в X + f_C\frac{\psi_2}{в^2}\Delta P_B X^2 + $$
$$+ f_C\cdot\frac{\psi_3}{в^3}\Delta P_{Вв}X^3 - i_n^в C X_0^1 - i_n^в C X$$

(2.19)

$$KP_H\frac{dV}{d\tau} + V\frac{d(\Delta P_H)}{d\tau} + K\Delta P_H\frac{dV}{d\tau} = -A_H\alpha_0\sqrt{\Delta P_H}X - A_H\frac{\alpha_1}{в}\sqrt{\Delta P_H}X^2 -$$
$$- A_H\frac{\alpha_2}{в^2}\sqrt{P_H}X^3 - A_H\frac{\alpha_3}{в^3}\sqrt{\Delta P_H}X^4 + \frac{A_H\lambda}{P_H}\alpha_0\Delta P_H\sqrt{\Delta P_H}X +$$
$$+ \frac{A_H\lambda}{p_H}\cdot\frac{\alpha_1}{в}\Delta P_H\sqrt{\Delta p_H}X^2 + \frac{A_H\lambda}{P_H}\cdot\frac{\alpha_2}{в_2}\Delta P_H\sqrt{\Delta P_H}X^3 + \frac{A_H\lambda}{p_H}\cdot\frac{\alpha_3}{в^3}\Delta P_H\sqrt{\Delta P_H}X^4,$$

(2.27)

$$M\frac{d^2X}{d\tau^2} = (P - P_H)f_C\psi - i_n^H C(X_0^1 + X)$$

(2.29)

$$M\frac{d^2X}{d\tau^2} = f_C\psi\Delta P_н + f_C\frac{\psi_1}{b}\Delta P_н x + f_C\frac{\psi_2}{b_2}\Delta P_н x^2 + f_C\frac{\psi_3}{b_3}\Delta P_н x^3 - i_n^н C X_0^1 - i_n^н C X$$

(2.30)

$$\sqrt{\Delta P_в} = a_0 + a_1\cos\omega\tau + a_2\sin\omega\tau + a_3\cos 2\omega\tau + a_4\sin 2\omega\tau$$

(2.32)

$$x = в_0 + в_1\cos\omega\tau + в_2\sin\omega\tau + в_3 cos 2\omega\tau + в_4\sin 2\omega\tau$$

(2.33)

$$V = H + E\cos\omega\tau + F\sin^2\omega\tau\ ,$$

(2.34)

$$r = \sqrt{R^2 + e_1^2 - 2Re_1 \cos(\varphi - \alpha)} \ ,$$

(3.1)

$$\gamma = \alpha\tau c \sin \frac{\ell_1 \sin(\varphi - \alpha)}{r} \ ,$$

(3.2)

$$\frac{O_1 B}{\sin\beta} = \frac{L}{\sin(180^0 - \varphi - \gamma)} \ ,$$

(3.3)

$$O_1 B = r - \frac{e_2 \sin\theta}{\sin(\varphi + \gamma)}$$

(3.4)

$$\beta = \arcsin\frac{1}{L}\left[\begin{array}{l}\sin\varphi\sqrt{R^2 + e_1^2 - 2Re_1\cos(\varphi-\alpha) - e_1^2\sin^2(\varphi-\alpha)} - \\ -e_1\sin(\varphi-\alpha)\cos\varphi - e_2\sin\theta\end{array}\right]$$

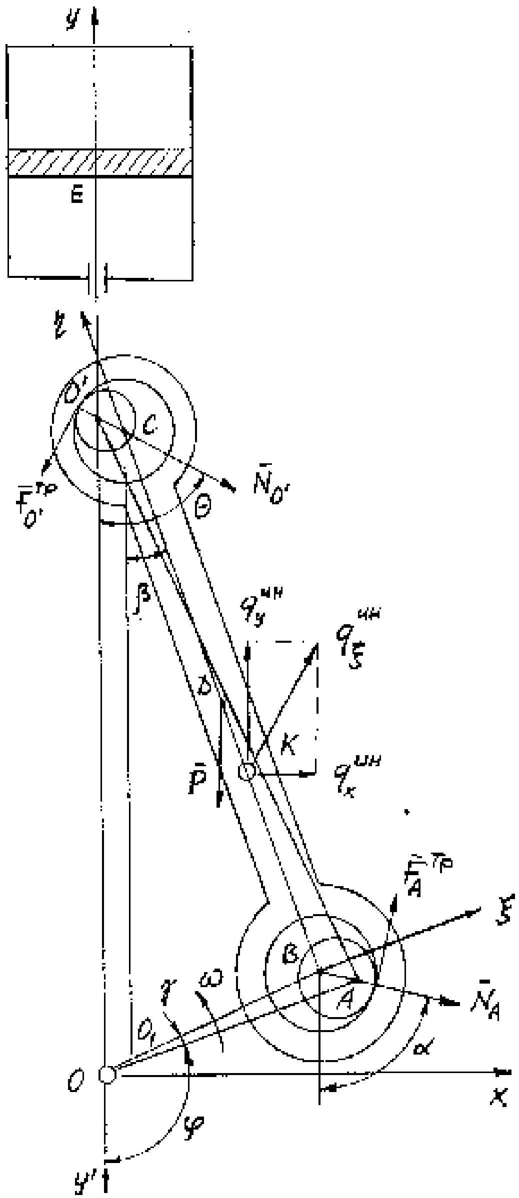
(3.5)

$$\begin{aligned} X_k &= r\sin(\varphi + \gamma) - \eta_k \sin\beta \\ Y_k &= -r\cos(\varphi + \gamma) + \eta_k \cos\beta, \end{aligned} \qquad (3.6)$$

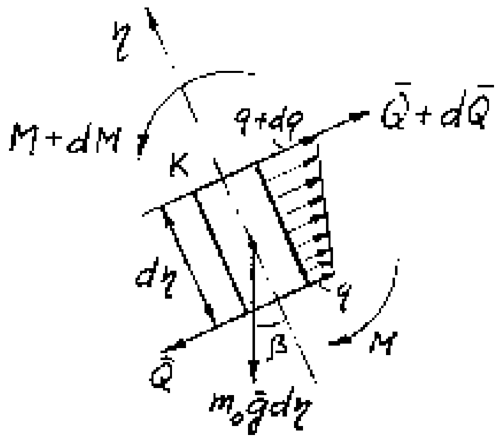
$$q_x^{ин} = m_0 \ddot{x}_k \ , \quad q_y^{ин} = m_0 \ddot{y}_к \ ,$$

$$q_\xi^{ин} = q_x^{ин}\cos\beta + q_y^{ин}\sin\beta$$

(3.7) $$m_0 d\eta \frac{\partial^2 \xi}{\partial t^2} = Q + \frac{\partial Q}{\partial \eta} d\eta - Q - m_0 g d\eta \sin\beta + q_\xi^{ин} d\eta$$



Scheme of crank-piston mechanism



Element of connecting rod

$$Q = \frac{\partial M}{\partial \eta}, \quad M = EJ\frac{\partial^2 \xi}{\partial \eta^2},$$

(3.10)

$$P = a_0^p + \sum (a_i^p \cos i\omega t + b_i^p \sin i\omega t)$$

$$q_\xi^{ин} = a_0^{ин} + \sum (a_i^{ин} \cos i\omega t + b_i^{ин} \sin i\omega t)$$

$$m_0 \frac{\partial^2 \xi}{\partial t^2} - EJ\frac{\partial^4 \xi}{\partial \eta^4} = a_0^{ин} - a_0^p + \sum [a_i^{ин} - a_i^p)\cos i\omega t + (b_i^{ин} - b_i^p)\sin i\omega t]$$

(3.12)

$$\xi = \sum [\phi_i(\eta)\cos i\omega t + H_i(\eta)\sin i\omega t],$$

(3.13)

$$m_0\omega^2 \sum i^2[\phi_i(\eta)\cos i\omega t + H_i(\eta)\sin i\omega t] - EJ\sum [\phi_i^{IV}(\eta)\cos i\omega t + H_i^{IV}(\eta)\sin i\omega$$
$$= a_0^{ин} - a_0^p + \sum [a_i^{ин} - a_i^p)\cos i\omega t + (b_i^{ин} - b_i^p)\sin i\omega t]$$

$$\Phi_i(\eta) = e^{\frac{\sqrt{2}}{2}k\eta}(C_1\cos\tfrac{\sqrt{2}}{2}k\eta + C_2\sin\tfrac{\sqrt{2}}{2}k\eta) + e^{-\frac{\sqrt{2}}{2}k\eta}(C_3\cos\tfrac{\sqrt{2}}{2}k\eta + C_4\sin\tfrac{\sqrt{2}}{2}k\eta) - \frac{a_i^{ин} - a_i^p}{m_0\omega^2 i^2}$$

$$H_i(\eta) = e^{\frac{\sqrt{2}}{2}k\eta}(D_1\cos\tfrac{\sqrt{2}}{2}k\eta + D_2\sin\tfrac{\sqrt{2}}{2}k\eta) + e^{-\frac{\sqrt{2}}{2}k\eta}(D_3\cos\tfrac{\sqrt{2}}{2}k\eta + +D_4\sin\tfrac{\sqrt{2}}{2}k\eta) - \frac{b_i^{ин} - b_i^p}{m_0\omega^2 i^2}$$

(3.14)

$\eta = 0,$

а) $$EJ\frac{\partial^2 \xi}{\partial \eta^2} = M_A = fN_A r_A,$$

$$EJ\frac{\partial^3 \xi}{\partial \eta^3} = N_{A\xi} = N_A\sin(\alpha - \beta) + fN_A\cos(\alpha - \beta)$$

$\eta = L,$

б) $$EJ\frac{\partial^2 \xi}{\partial \eta^2} = M_{o'} = fN_0 r_0,$$

$$EJ\frac{\partial^3 \xi}{\partial \eta^3} = N_{o'\xi} = N_{o'}\sin(\alpha - \beta) + fN_{0'}\cos(\alpha - \beta)$$

(3.15)

$$M_A = a_0^{шм} + \sum (a_i^{шм} \cos i\omega t + b_i^{шм} \sin i\omega t)$$

$$M_{0'} = a_0^{пм} + \sum (a_i^{пм} \cos i\omega t + b_i^{пм} \sin i\omega t)$$

$$N_{A\xi} = a_0^{шс} + \sum (a_i^{шс} \cos i\omega t + b_i^{шс} \sin i\omega t)$$

$$N_{0'\xi} = a_0^{пс} + \sum (a_i^{пс} \cos i\omega t + b_i^{пс} \sin i\omega t)$$

$$q_\eta^{ин} = -q_x^{ин} \sin\beta + q_y^{ин} \cos\beta ,$$

(3.16)

$$m_0 d\eta \frac{\partial^2 u}{\partial t^2} = -N + N + N\frac{\partial N}{\partial \eta} - q_\eta^{ин} d\eta - m_0 g d\eta \cos\beta$$

$$\frac{\partial^2 u}{\partial t^2} = \frac{1}{m_0}\frac{\partial N}{\partial \eta} - \frac{1}{m_0} q_\eta^{ин} - g\cos\beta ,$$

(3.17)

$$\frac{1}{\rho F} q_\eta^{ин} + g\cos\beta = a_0 + \sum (a_i \cos i\omega t + b_i \sin i\omega t)$$

(3.21)

$$c^2 \frac{\partial^2 u}{\partial \eta^2} - \frac{\partial^2 u}{\partial t^2} = \alpha_0 + \sum (a_i \cos i\omega t + b_i \sin i\omega t)$$

(3.22)

при h\` =0, $EF\frac{\partial u}{\partial \eta} = N_{A\eta} = -N_A \cos(\alpha - \beta) + F_A^{тр} \sin(\alpha - \beta)$

при h =L, $EF\frac{\partial u}{\partial \eta} = N_{д\eta} = -N_д \cos(\theta - \beta) + F_д^{тр} \sin(\theta - \beta),$

(3.23)

$$N_{A\eta} = A_O^{ш} + \sum \left(A_i^{ш} \cos i\omega t + B_i^{ш} \sin i\omega t\right)$$

$$N = A_O^n + \sum \left(A_i^n \cos i\omega t + B_i^n \sin i\omega t\right)$$

$$U(\eta,t)=\sum\left[P_i(\eta)\cos i\omega t+S_i(\eta)\sin i\omega t\right],$$

(3.24)

$$c^2\sum[P_i^{||}(\eta)\cos i\omega t+S_i^{||}(\eta)\sin i\omega t]+\omega^2\sum i^2[P_i(\eta)\cos i\omega t+S_i(\eta)\sin i\omega t]=$$
$$=a_0+\sum\left(a_i\cos i\omega t+b_i\sin i\omega t\right)$$

$$\left.\begin{aligned}P_i(\eta)&=C_1\cos k\eta+C_2\sin k\eta+\frac{a_i}{k^2c^2}\\ S_i(\eta)&=D_1\cos k\eta+D_2\sin k\eta+\frac{b_i}{k^2c^2}\end{aligned}\right\}$$

(3.25)

$$EF\sum[P_i^{|}(0)\cos i\omega t+S_i^{|}(0)\sin i\omega t]=A_0^{ш}+\sum\left(A_i^{ш}\cos i\omega t+B_i^{ш}\sin i\omega t\right)$$
$$EF\sum[P_i^{|}(L)\cos i\omega t+S_i^{|}(L)\sin i\omega t]=A_0^{n}+\sum\left(A_i^{n}\cos i\omega t+B_i^{n}\sin i\omega t\right)$$

$$EFP_i^{|}(0)=A_i^{ш},\qquad EFP_i^{|}(L)=A_i^{n}$$
$$EFS_i^{|}(0)=B_i^{ш},\qquad EFS_i^{|}(L)=B_i^{n}$$

$$C_1=\frac{A_i^{ш}\cos kL-A_i^{n}}{kEF\sin kL},\quad C_2=\frac{A_i^{ш}}{kEF},$$

$$D_1=\frac{B_i^{ш}\sin kL-B_i^{n}}{kEF\sin kL},\quad D_2=\frac{B_i^{ш}}{kEF}$$

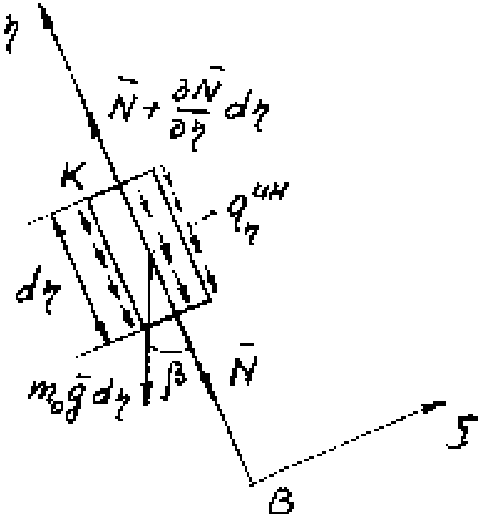
$$\mathrm{u}(\eta,t)=\sum\Big[\Big(\frac{A_i^{ш}\cos kL-A_i^{n}}{kEF\sin kL}\cos k\eta+\frac{A_i^{ш}}{kEF}\sin k\eta+\frac{a_i}{k^2c^2}\Big)\cos i\omega t+$$
$$+\Big(\frac{B_i^{ш}\cos kL-B_i^{n}}{kEF\sin kL}\cos k\eta+\frac{B_i^{ш}}{kEF}\sin k\eta+\frac{b_i}{k^2c^2}\Big)\sin i\omega t\Big]$$

(3.26)

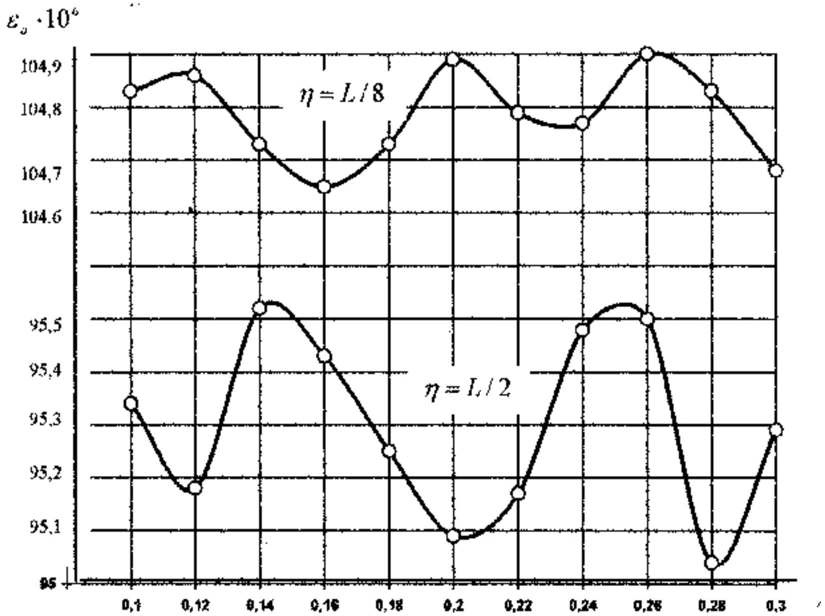
$$\sigma=E\frac{\partial u}{\partial\eta}\quad \text{и}\quad \varepsilon=\frac{\sigma}{E}=\frac{\partial u}{\partial\eta}$$

$$\varepsilon_a=\sqrt{\Big(\frac{A_i^{ш}\cos kL+A_i^{n}}{EF\sin kL}\sin k\eta+\frac{A_i^{ш}}{EF}\cos k\eta\Big)^2+\Big(\frac{B_i^{ш}\sin kL+B_i^{n}}{EF\sin kL}\sin k\eta+\frac{B_i^{ш}}{EF}\cos k\eta\Big)^2}$$

(3.27)

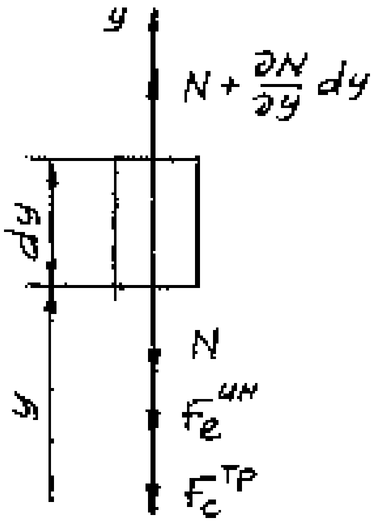


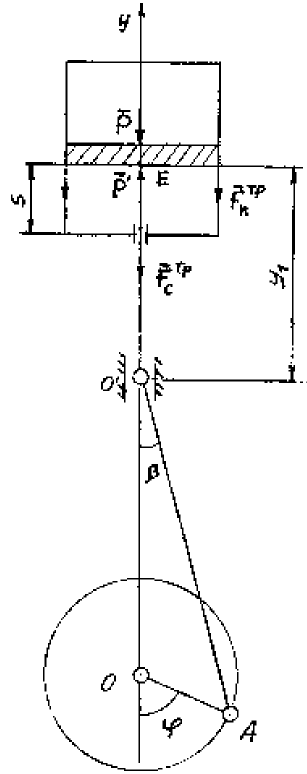
Element of connecting rod



Unit longitudinal deformation of “floating connecting rod”

Analysis of oscillation of piston rod of Piston machine





Element of piston rod with acting forces

$$\rho F\frac{\partial^2 u}{\partial t^2}dy = N + \frac{\partial N}{\partial y}dy - N + \frac{F_{cy}^{TP}}{S_P}dy - \rho F W_{O'y}dy$$

(3.28)

$$\frac{\partial^2 u}{\partial t^2} = C^2\frac{\partial^2 u}{\partial y^2} + \frac{F_c^{TP}}{S_P \rho F} - W_{O'} ,$$

(3.30)

$$F_c^{TP} = a_0^c + \sum\left(a_s^c \cos S\omega t + b_s^c \sin S\omega t\right)$$

(3.31)

$$W_{O'} = a_o^y + \sum\left(a_s^y \cos S\omega t + b_s^y \sin S\omega t\right)$$

(3.32)

	F_n^{mp}		F_c^{mp}		$F_y^{ин}$		$P^{/} - P$	
	a_S^n	b_S^n	a_S^C	b_s^C	a_S^y	b_s^y	a_S^{∂}	b_S^{∂}
	2,05	0	23,3	0	-359,2	0	6672,5	0
	-13,35	-121,4	-19,05	-105,05	-619,6	-1160,65	-9593	112,5
	-4,35	-1,05	-28,95	-29,95	-2693,95	-4273,05	10608	135,0
	-67,9	-36,65	-48,33	-31,65	10041,9	12540,75	9284,5	-312,5
	3,95	-1,8	-22,29	-6,15	3245,3	3520,4	8262	192,5
	-53,76	-5,25	-36,35	-9,1	2024,3	4167,5	3448,5	-144
	-1,25	-0,0001	-18,3	0,00025	3526,8	-0,1	5826,5	-0,001
	-53,76	5,25	-36,35	9,1	2024,15	-4168,05	3448,5	144,5
	3,95	1,8	-22,29	6,15	3245,3	3520,5	8262	-192,5
0	-67,9	36,65	-48,3	31,65	10041,4	-12541	9284,5	312,5
1	-4,35	1,1	-28,95	29,95	-2693,85	4273,4	10608	-135
2	-13,3	121,4	-19,05	105,05	-619,6	1160,77	-9593,5	-112,5

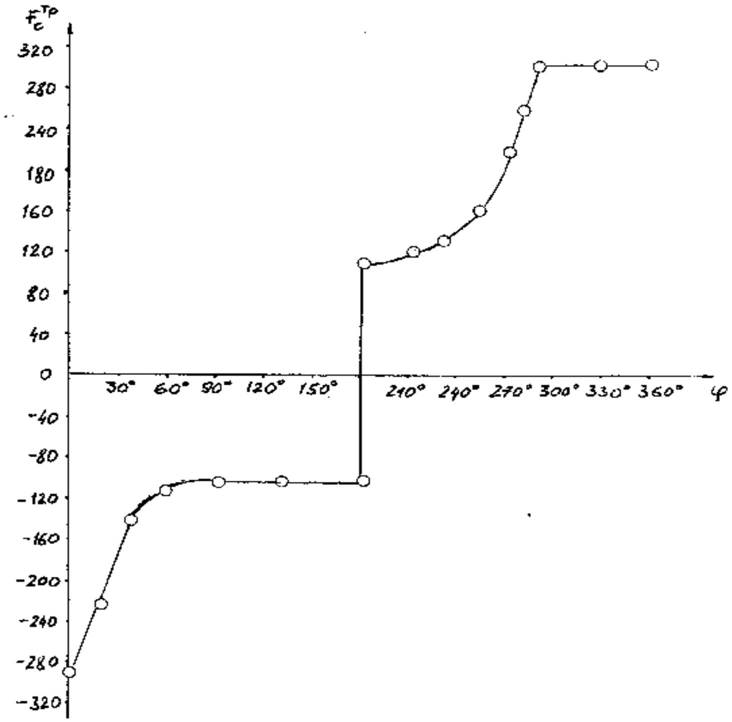


Diagram of friction forces in oil- seal

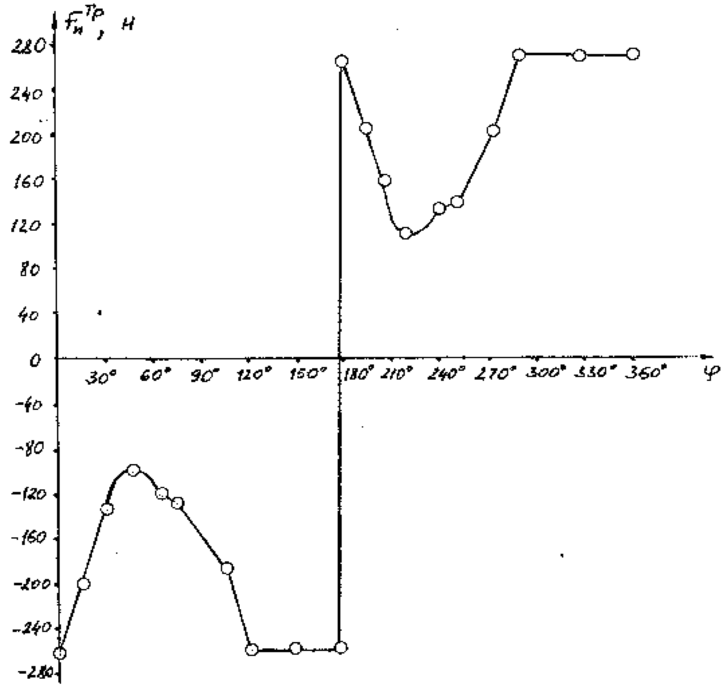


Diagram of friction forces in piston assemble

$$\frac{\partial^2 u}{\partial t^2} = C^2 \frac{\partial^2 u}{\partial y^2} + A_O + \sum \left(A_S \cos S\omega t + B_S \sin S\omega t \right)$$

(3.33)

$$u = \sum \left[\varphi_S(y) \cos S\omega t + \psi_S(y) \sin S\omega t \right]$$

(3.34)

$$\frac{\partial u}{\partial t} = \omega \sum S \left[\psi_S(y) \cos S\omega t - \varphi_S(y) \sin S\omega t \right],$$

$$\frac{\partial^2 u}{\partial t^2} = -\omega^2 \sum S^2 \left[\varphi_S(y) \cos S\omega t - \psi_S(y) \sin S\omega t \right],$$

$$\frac{\partial u}{\partial y} = \sum \left[\varphi_S(y) \cos S\omega t - \psi_S(y) \sin S\omega t \right],$$

$$\frac{\partial^2 u}{\partial y^2} = \sum \left[\dot{\varphi}_S(y) \cos S\omega t - \dot{\psi}_S(y) \sin S\omega t \right],$$

$$-\omega^2 \sum S^2 \left[\varphi_S(y) \cos S\omega t - \psi_S(y) \sin S\omega t \right] = C^2 \sum \left[\ddot{\varphi}_S(y) \cos S\omega t + \dot{\psi}_S(y) \sin S\omega t \right] +$$
$$+ A_O + \sum \left(A_S \cos S\omega t + B_S \sin S\omega t \right)$$

$$\left. \begin{aligned} -\omega^2 S^2 \varphi_S(y) &= C^2 \dot{\varphi}_S(y) + A_S \\ -\omega^2 S^2 \psi_S(y) &= C^2 \dot{\psi}_S(y) + B_S \end{aligned} \right\}$$

(3.35)

$$\dot{\rho}_S(y) + \frac{S^2 \omega^2}{C^2} \rho_S(y) = 0$$

$$\dot{Q}_S(y) + \frac{S^2 \omega^2}{C^2} Q_S(y) = 0$$

$$\rho_S(y) = C_1 \cos \frac{s\omega}{c} y + C_2 \sin \frac{s\omega}{c} y$$

$$Q_S(y) = D_1 \cos \frac{s\omega}{c} y + D_2 \sin \frac{s\omega}{c} y$$

$$\varphi_S(y) = C_1 \cos \frac{S\omega}{C} y + C_2 \sin \frac{S\omega}{C} y - \frac{A_S}{S^2 \omega^2}$$

$$\psi_S(y) = D_1 \cos \frac{S\omega}{C} y + D_2 \sin \frac{S\omega}{C} y - \frac{B_S}{S^2 \omega^2} \qquad (3.37)$$

при $y=0$ $u(y,t)=0$,

при $y=y_1$
$$EF \left. \frac{\partial u}{\partial y} \right/_{y=y_1} = -M_{\Pi} \frac{\partial^2 u}{\partial t^2} + F_n^{TP} - M_{\Pi} W_{O'} + (P' - P), \qquad (3.38)$$

$$F_n^{TP} = a_o^n + \sum\left(a_S^n \cos S\omega t + b_S^n \sin S\omega t\right)$$

(3.39)

$$P^{|} - P = a_o^{\partial} + \sum\left(a_S^{\partial} \cos S\omega t + b_S^{\partial} \sin S\omega t\right)$$

(3.40)

$$\varphi_S(o) = C_1 - \frac{A_S}{S^2\omega^2} = 0; \qquad \psi_S(o) = D_1 - \frac{B_S}{S^2\omega^2} = 0$$

$$C_1 = \frac{A_S}{S^2\omega^2}; \qquad D_1 = \frac{B_S}{S^2\omega^2}$$

(3.41)

$$EF\sum\left[\dot{\varphi}_S(y_1)\cos S\omega t + \dot{\psi}_S(y_1)\sin S\omega t\right] = M_{\Pi}\omega^2\sum S^2\left[\varphi_S(y_1)\cos S\omega t + \psi_S(y_1)\sin S\alpha\right.$$

$$a_o^{\Pi} + \sum\left(a_S^{\Pi}\cos S\omega t + b_S^{\Pi}\sin S\omega t\right) + a_o^{u} + \sum\left(a_S^{u}\cos S\omega t + b_S^{u}\sin S\omega t\right) + a_o^{\partial} +$$

$$\sum\left(a_S^{\partial}\cos S\omega t + b_S^{\partial}\sin S\omega t\right)$$

где $a_S^u = -M_{\Pi}a_S^y$; $b_S^u = -M_{\Pi}b_S^y$

$$\left.\begin{aligned} EF\dot{\varphi}_S(y_1) &= M_{\Pi}\omega^2 S^2\varphi_S(y_1) + a_S^{\Pi} + a_S^{U} + a_S^{\partial} \\ EF\dot{\psi}_S(y_1) &= M_{\Pi}\omega^2 S^2\psi_S(y_1) + b_S^{\Pi} + b_S^{U} + B_S^{\partial} \end{aligned}\right\}$$

(3.42)

$$\dot{\varphi}_S(y_1) = C_2\frac{S\omega}{C}\cos\frac{S\omega}{C}y_1 - C_1\frac{S\omega}{C}\sin\frac{S\omega}{C}y_1$$

$$\dot{\psi}_S(y_1) = D_2\frac{S\omega}{C}\cos\frac{S\omega}{S}y_1 - D_1\frac{S\omega}{C}\sin\frac{S\omega}{C}y_1$$

$$C_2EF\frac{S\omega}{C}\cos\frac{S\omega}{C}y_1 - EFC_1\frac{S\omega}{C}\sin\frac{S\omega}{C}y_1 = M_{\Pi}S^2\omega^2C_1\cos\frac{S\omega}{C}y_1 +$$

$$+M_{\Pi}S^2\omega^2C_2\sin\frac{S\omega}{C}y_1 - M_{\Pi}A_S + a_S^{\Pi} + a_S^{U} + a_S^{\partial}$$

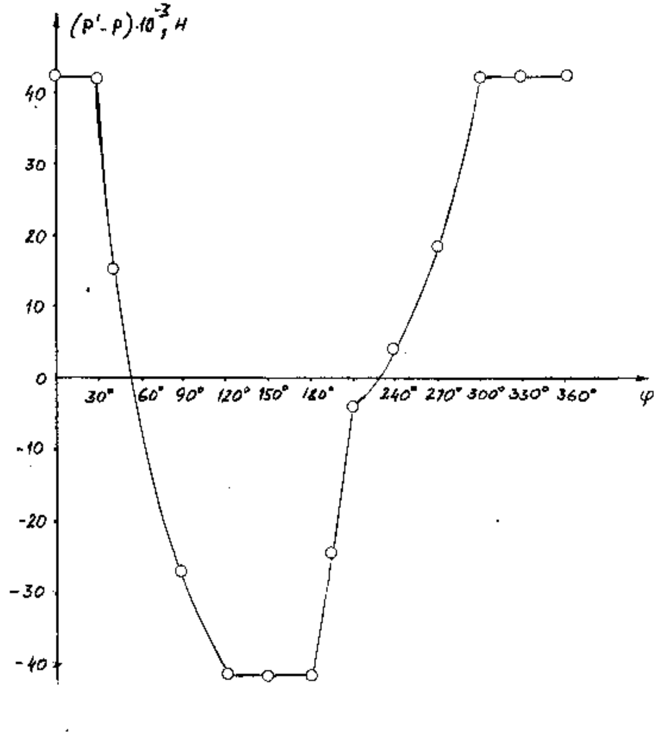


Рис.3.9. График силы давления газа, действующие на поршень

$$C_2 = \frac{A_S\left(\frac{EF}{C}\sin\frac{S\omega}{C}y_1 + M_П S\omega\cos\frac{S\omega}{C}y_1\right) + S\omega\left(a_S^П + a_S^U + a_S^д - M_П A_S\right)}{S^2\omega^2\left(\frac{EF}{C}\cos\frac{S\omega}{C}y_1 - M_П S\omega\sin\frac{S\omega}{C}y_1\right)}$$

$$D_2 = \frac{B_S\left(\frac{EF}{C}\sin\frac{S\omega}{C}y_1 + M_П S\omega\cos\frac{S\omega}{C}y_1\right) + S\omega\left(b_S^П + b_S^U - b_s^д - M_П B_S\right)}{S^2\omega^2\left(\frac{EF}{C}\cos\frac{S\omega}{C}y_1 - M_П S\omega\sin\frac{S\omega}{C}y_1\right)}$$

$$y = y_o + u = r(1-\cos\omega t) - \frac{r^2}{2L}\sin^2\omega t + \sum\left[\varphi_s(y)\cos s\omega t + \psi_s(y)\sin s\omega t\right]$$

$$N = EF\frac{\partial u}{\partial y}\Big|_{y=y_1} = EF\sum\left[\dot{\varphi}_s(y_1)\cos s\omega t + \dot{\psi}_s(y_1)\sin s\omega t\right]$$

$$N = \sum(a_s \cos s\omega t + b_s \sin s\omega t)$$

(3.43)

$$\frac{\partial^4 x}{\partial y^4} - \frac{N}{EJ}\cdot\frac{\partial^2 x}{\partial y^2} + \frac{m}{EJ}\cdot\frac{\partial^2 x}{\partial t^2} = 0,$$

(3.44)

$$x(y,t) = \sum\left[\phi_s(y)\cos\frac{s\omega t}{2} + H_s(y)\sin\frac{s\omega t}{2}\right],$$

(3.45)

при $y = 0$, $x(y,t) = 0$; $\frac{\partial x}{\partial y} = 0$,

(3.46)

при $y = y_1$, $x(y,t) = 0$; $\frac{\partial x}{\partial y} = 0$

$$N = a_1 \cos\omega t + в_1 \sin\omega t + a_2 \cos 2\omega t + в_2 \sin 2\omega t$$

$$X(y,t) = \Phi_1(y)\cos\frac{\omega t}{2} + H_1(y)\sin\frac{\omega t}{2} + \Phi_2(y)\cos\omega t + H_2(y)\sin\omega t$$

(3.47)

$$\left.\begin{aligned} -\frac{\omega^2}{4}\Phi_1 - \frac{a_1}{2m}\Phi_1^{11} - \frac{в_1}{2m}H_1^{11} + \frac{EJ}{m}\Phi_1^{1V} = 0 \\ -\frac{\omega^2}{4}H_1 + \frac{a_1}{2m}H_1^{11} - \frac{в_1}{2m}\Phi_1^{11} + \frac{EJ}{m}H_1^{1V} = 0 \end{aligned}\right\}$$

(3.48)

$$\left.\begin{aligned} -\omega^2\Phi_2 - \frac{a_2}{2m}\Phi_2^{11} - \frac{в_2}{2m}H_2^{11} + \frac{EJ}{m}\Phi_2^{1V} = 0 \\ -\omega^2 H_2 + \frac{a_2}{2m}H_2^{11} - \frac{в_2}{2m}\phi_2^{11} + \frac{EJ}{m}\phi_2^{1V} = 0 \end{aligned}\right\}$$

(3.49)

$$\Phi_1^{VIII}(y) + p_1\Phi_1^{IV}(y) + q_1\Phi_1(y) = 0$$

(3.50)

$$P_1 = -\frac{m\omega^2}{2EJ} - \frac{a_1^2}{4(EJ)^2} - \frac{b_1^2}{4(EJ)^2}\ ;\ \ q_1 = \frac{m^2\omega^2}{16(EJ)^2}$$

(3.51)

$$H_1(y) = \alpha_1 L_1 e^{r_1 y} + \alpha_1 L_2 e^{-r_1 y} + \alpha_2 L_3 \cos r_1 y + \alpha_2 L_4 \sin r_1 y + \alpha_3 L_5 e^{r_2 y} +$$
$$+ \alpha_3 L_6 e^{-r_2 y} + \alpha_4 L_7 \cos r_2 y + \alpha_4 L_8 \sin r_2 y,$$

(3.53)

$$\alpha_1 = \frac{1}{2b_1\omega^2 m}\left[\left(-\omega^2 m - 2r_1^2 a_1 + 4r_1^4 EJ\right)\left(2a_1 + 4r_1^2 EJ\right) - 4b_1^2 r_1^2\right]$$

$$\alpha_2 = \frac{1}{2b_1\omega^2 m}\left[\left(-\omega^2 m + 2r_1^2 a_1 + 4r_1^4 EJ\right)\left(2a_1 - 4r_1^2 EJ\right) + 4b_1^2 r_1^2\right]$$

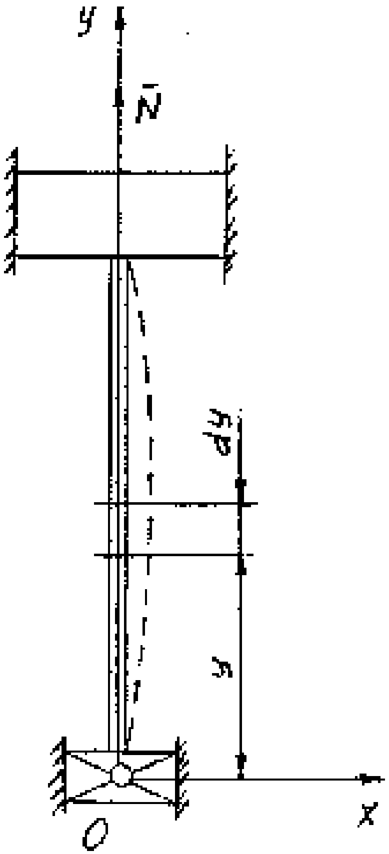
$$\alpha_3 = \frac{1}{2b_1\omega^2 m}\left[\left(-\omega^2 m - 2r_2^2 a_1 + 4r_2^4 EJ\right)\left(2a_1 + 4r_2^2 EJ\right) - 4b_1^2 r_2^2\right]$$

$$\alpha_4 = \frac{1}{2b_1\omega^2 m}\left[\left(-\omega^2 m + 2r_2^2 a_1 + 4r_2^4 EJ\right)\left(2a_1 - 4r_2^2 EJ\right) + 4b_1^2 r_2^2\right]$$

$$\Phi_2(y) = M_1 e^{k_1 y} + M_2 e^{-k_1 y} + M_3 \cos k_1 y + M_4 \sin k_1 y + M_5 e^{k_2 y} +$$
$$+ M_6 e^{-k_2 y} + M_7 \cos k_2 y + M_8 \sin k_2 y$$

(3.54)

$$H_2(y) = \beta_1 M_1 e^{k_1 y} + \beta_1 M_2 e^{-k_1 y} + \beta_2 M_3 \cos k_1 y + \beta_2 M_4 \sin k_1 y +$$
$$+ \beta_3 M_5 e^{k_2 y} + \beta_3 M_6 e^{-k_2 y} + \beta_4 M_7 \cos k_2 y + \beta_4 M_8 \sin k_2 y.$$



The scheme of Piston group

$$L_i = \frac{m_1}{m_1 - 1} P_в \left(V_P + Vв_P\right) \left[\left(\frac{p_H}{P_в} \right)^{\frac{m_1 - 1}{m_1}} - 1 \right] - \frac{m_2}{m_2 - 1} p_H V_{вP} \left[1 - \left(\frac{P_в}{P_H} \right)^{\frac{m_2 - 1}{m_2}} \right]$$

(4.1)

$$dL_{п.ц.} = F_n^{mp} ds,$$

(4.2)

$$L_{п.ц.} = \mu_n \int_0^s \left[\begin{array}{l} 0{,}5\pi b(D - 4a)P - 0{,}5\pi bDP' + 2\pi bDP_{yn} - \\ - 2\pi baP\left[0{,}75 + 0{,}38\left(\frac{P'}{P}\right)^{2,5} - 0{,}69\left(\frac{P'}{P}\right)^{5} + 0{,}09\left(\frac{P'}{P}\right)^{7,5} - 0{,}002\left(\frac{P'}{P}\right)^{10} \right] \end{array} \right] dS$$

(4.3)

$$dL_C = F_c^{mp} ds$$

(4.4)

$$L_c = \mu_c \pi b_1 \int_0^s \left[\begin{array}{l} 2\left(d_2 - d_1\right)\left(2{,}242 P^| + 0{,}933 \frac{P_b^{2,5}}{\left(P^|\right)^{1,5}} - 0{,}242 \frac{P_b^{5}}{\left(P^|\right)^{4}} + 0{,}057 \frac{P_b^{7,5}}{\left(P^1\right)^{6,5}} - 0{,}016 \frac{P_b^{10}}{(P')^{9}} \right) + \\ + \left(2d_2 - d_1\right)P^| + 2\mathrm{d}_1 \mathrm{P}_{\mathrm{yn}} \mathrm{z}_1 - \mathrm{d}_1 P_b \end{array} \right] dS$$

(4.5)

$$L_{F_{o'}^{mp}} = \mu_{кn} r_{o'} \int N_{o'} d\theta, \qquad (4.6)$$

$$L_{F_A^{mp}} = \int \mu_ш r_A N_A d(\alpha + \varphi) = \mu_ш r_A \int N_A d\alpha + \mu_ш r_A \int N_A d\varphi$$

(4.7)

$$L_{F_K^{mp}} = \int \mu_к N \, ds = \mu_k \int_0^{S_p} N ds - \mu_k \int_{S_p}^0 N ds$$

(4.8)

$$L к.п. = 2 \; \pi \mathrm{M} \quad ,$$

$$\mathrm{M} = \frac{39}{4} \pi\mu \, ab_3 e^4 + \pi\mu \, ae^2 \left(5b_1 + 6b_2 a + 7b_3 a^2\right) +$$

$$2\pi\mu \, a \mathrm{T}(t)\left(c_1 a + 2c_2 a^2 + 3c_3 a^3\right) - \pi\mu \, ae^2 \mathrm{T}(t)\left(2c_2 + 15 c_3 a\right)$$

$$L_{mp} = L_{п.ц.} + L_c + L_{F_к^{mp}} + L_{F_{o^|}^{mp}} + L_{F_A^{mp}} + L_{k.n}$$

$r_B = a + h,$

h =? +e cos? .

r_B= a +? +e cos? =в+e cos?

$$\frac{\partial P}{\partial \theta} = \mu r\left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r^2}\cdot\frac{\partial^2 V_\theta}{\partial \theta^2} + \frac{1}{r}\frac{\partial V_\theta}{\partial r} - \frac{V_\theta}{r^2}\right)$$

(4.9)

$$\frac{\partial V_r}{\partial r} + \frac{1}{r}\cdot\frac{\partial V_\theta}{\partial \theta} + \frac{Vr}{r} = 0,$$

(4.10) u

При $r=a$, $V_?$ = , V_r=0

При $r=r_B$, $V_?$ =0, V_r=0

(4.11)

V_θ =u ? (r)? ? (?)+? (r), (4.12)

$$\psi(\theta) = C_O + C_1\cos\theta + C_2\cos 2\theta\ ,$$

(4.13)

$$\left.\begin{aligned}\varphi(r) &= a_0 + a_1 r + a_2 r^2\\ \tau(r) &= в_0 + в_1 r + в_2 r^2\end{aligned}\right\}$$

(4.14)

$$u\,\varphi(a).\psi(\theta) + \tau(a) = u$$
$$u\,\varphi(r_B)\psi(\theta) + \tau(r_B) = 0$$

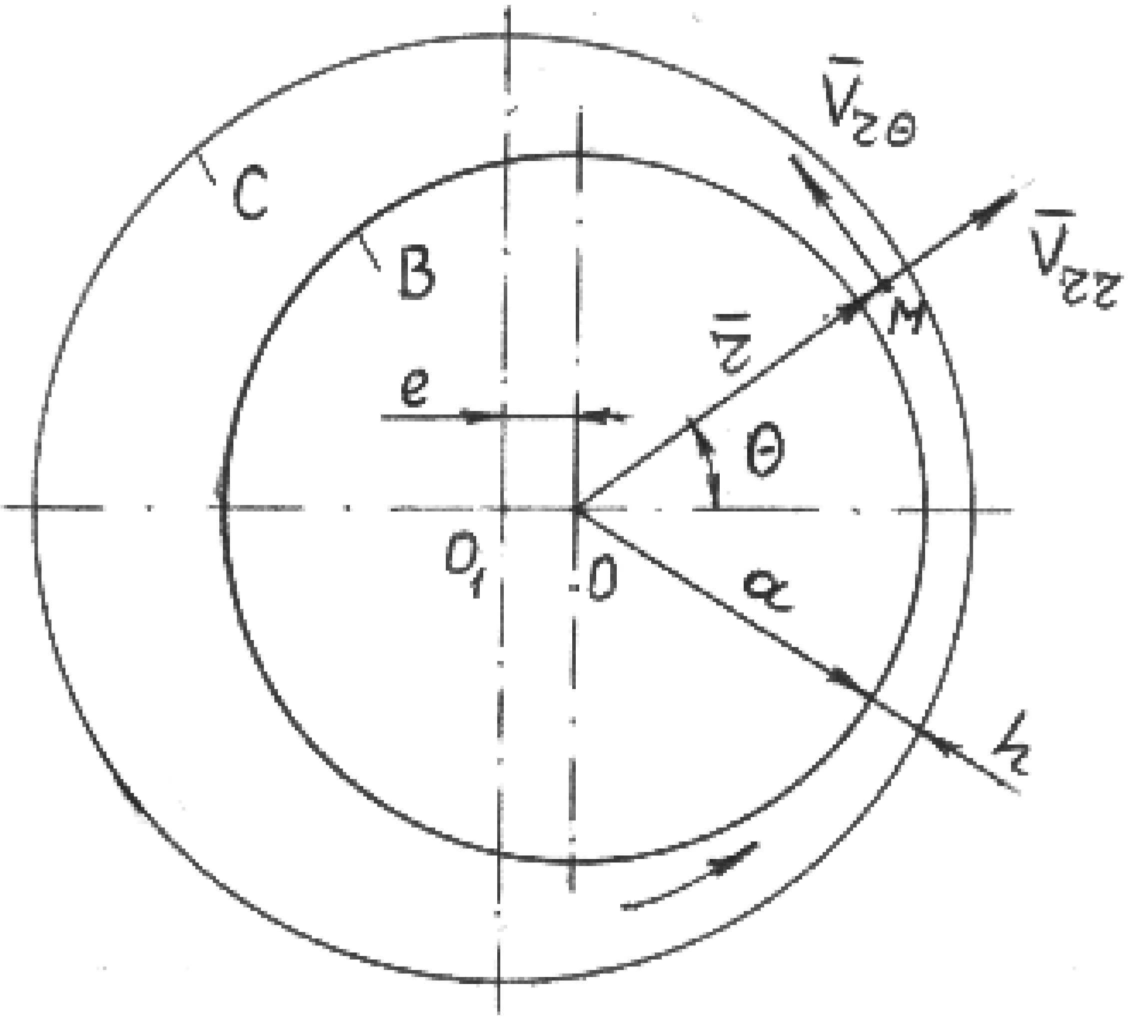
$$\varphi(a) = 0,\quad \tau(a) = u$$

(4.15)

$$u\varphi(r_B)\psi(\theta) + \tau(r_B) = o$$

(4.16)

$$\int_a^{r_c} V_\theta dr = C,$$



The scheme of sliding bearing of piston machine

$$\int_0^{2\pi} \frac{\partial P}{\partial \theta} d\theta = 0 \qquad (4.19)$$

$$\frac{\partial P}{\partial \theta}\Big|_{r=a} = \mu\left[a u \varphi''(a) + u\varphi'(a) - \frac{u}{a}\varphi(a)\right]\psi(\theta) + \mu\frac{u}{a}\varphi(a)\psi''(a) + \mu\tau'(a) - \mu\frac{1}{a}\tau(a)$$

(4.20)

$$uC_0\left[a\varphi''(a) + \varphi'(a) - \frac{1}{a}\varphi(a)\right] + \left[a\tau''(a) + \tau'(a) - \frac{1}{a}\tau(a)\right] = 0$$

(4.21)

$$M = \int_0^{2\pi} P_{r\theta}\Big|_{r=a} a^2 d\theta,$$

(4.22)

$$P_{r\theta}\Big|_{r=a} = \mu\left(\frac{1}{r}\cdot\frac{\partial V_r}{\partial \theta}\Big|_{r=a} + \frac{\partial V_\theta}{\partial r}\Big|_{r=a} - \frac{V_\theta}{r}\right)$$

$r = a, V_r = 0$ и $V_\theta = u$, то $\frac{\partial V_r}{\partial \theta}\Big|_{r=a} = 0$

$$P_{r\theta} = \mu\left(\frac{\partial V_\theta}{\partial r}\Big|_{r=a} - \frac{u}{a}\right)$$

$$M = a^2 \mu u \varphi^1(a) \int_0^{2\pi} \psi(\theta) d\theta + 2\pi \mu a^2 \tau^1(a) - 2\pi a \mu u = 2\pi a^2 \mu \left[u \varphi^1(a) C_0 + \tau^1(a) \right] - 2\pi a \mu u =$$

$$= 2\pi a^2 \mu \left[u C_0 a a_1 + 2u C_0 a^2 a_2 + a b_1 + 2a^2 b_2 - u \right] \quad (4.23)$$

$$Q = a \int_0^{2\pi} \left[\mu \left(\frac{\partial V_\theta}{\partial r} \Big|_{r=a} - \frac{u}{a} \right) - \frac{\partial P}{\partial \theta} \Big|_{r=a} \right] \cos\theta d\theta$$

(4.25)

$$Q = \pi a^2 \mu \varphi^1(a) C_1 - \pi a \mu u C_1 \left[\varphi^{11}(a) + \varphi^1(a) - \frac{2}{a} \varphi(a) \right] =$$

$$= \pi \mu C_1 \left(a^2 a_1 + 2a^3 a_2 - 2a u a_2 - a u a_1 - 2a^2 u a_2 + 2u a_0 + 2a u a_1 + 2a^2 u a_2 \right)$$

(4.26)

Тепловой расчет подшипника скольжения ПК

$$q = q_1 + q_2,$$

$$t_M = t_{вх} + \frac{fQu}{2(c\rho V + kA)} \le [t_M],$$

$$t_M = t_{вх} + \frac{f\pi\mu u C_1\left[a^2\varphi'(a) - ua\varphi''(a) + ua\varphi'(a) - 2u\varphi(a)\right]}{2(c\rho V + kA)} \le [t_M] \ .$$

4.4. Методика определения момента трения в подшипнике скольжения ПК под действием переменной нагрузки

$$P = P_1 + P_0 \sin(\omega t + \delta), \qquad (4.27)$$

$$e = e_1 + e_0 \sin(\omega t + \delta_1), \qquad (4.28)$$

$$r_c = a + e\cos\theta \qquad (4.29)$$

$$\frac{\partial V_\theta}{\partial t} = -\frac{1}{\rho r}\cdot\frac{\partial P}{\partial \theta} + \nu\left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r^2}\cdot\frac{\partial^2 V_\theta}{\partial \theta^2} + \frac{1}{r}\cdot\frac{\partial V_\theta}{\partial r} + \frac{2}{r^2}\cdot\frac{\partial V_r}{\partial \theta} - \frac{V_\theta}{r^2}\right) \qquad (4.30)$$

$$\frac{\partial V_r}{\partial t} = -\frac{1}{\rho}\cdot\frac{\partial P}{\partial r} + \nu\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r^2}\cdot\frac{\partial^2 V_r}{\partial \theta^2} + \frac{1}{r}\cdot\frac{\partial V_r}{\partial r} - \frac{2}{r^2}\cdot\frac{\partial V_\theta}{\partial \theta} - \frac{V_r}{r^2}\right) \qquad (4.31)$$

$$\frac{\partial V_r}{\partial r} + \frac{1}{r}\cdot\frac{\partial V_\theta}{\partial \theta} + \frac{V_r}{r} = 0, \qquad (4.32)$$

при $r = r_c$ $V_\theta = V_{C\theta}$, $V_r = V_{Cr}$

при $r = r_B$ $V_\theta = 0$, $V_r = 0$

(4.33)

$$V_r = \varphi(r)e(t)\cos\theta + \psi(r)e(t)\sin\theta$$

(4.35)

$$\varphi(r) = a_O + a_1 r + a_2 r^2 + a_3 r^3$$

(4.36)

$$\psi(r) = b_O + b_1 r + b_2 r^2 + b_3 r^3$$

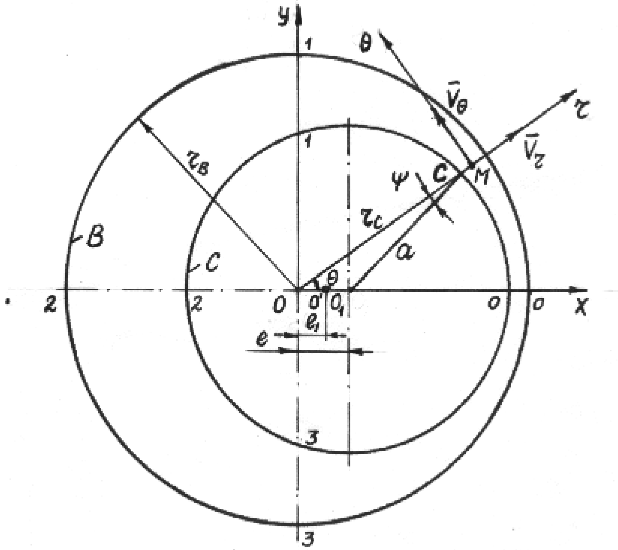
(4.37)

$$V_\theta = e(t)\psi_1(r)\cos\theta - e(t)\varphi_1(r)\sin\theta + \tau(r)T(t),$$

(4.38)

$$\tau(r) = C_O + C_1 r + C_2 r^2 + C_3 r^3,$$

(4.40)



The scheme of sliding bearing with components of velocities of oil stream

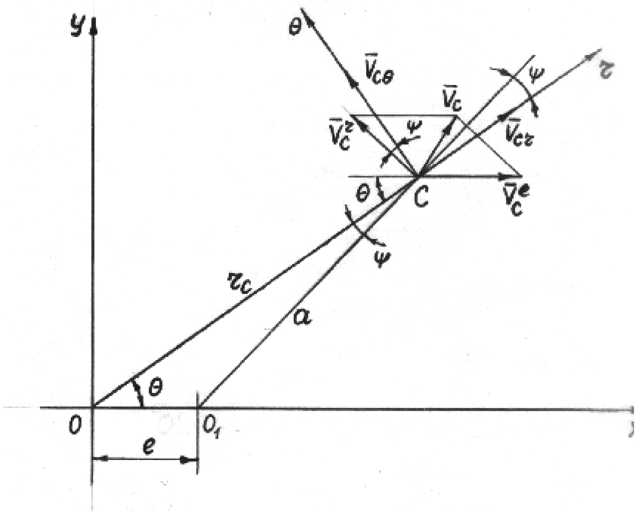


Diagram of velocities of particles of lubrication

$$\int_O^{2\pi} \frac{\partial P}{\partial \theta} d\theta = O$$

(4.57)

$$\frac{\partial P}{\partial \theta} = \rho r \nu \left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r^2} \times \frac{\partial^2 V_\theta}{\partial \theta^2} + \frac{1}{r} \times \frac{\partial V_\theta}{\partial r} + \frac{2}{r^2} \times \frac{\partial V_r}{\partial \theta} - \frac{V_\theta}{r^2} \right) - \frac{\partial V_\theta}{\partial t} \rho r$$

$$\frac{\partial P}{\partial \theta} = \rho \nu \left[e(t) r \ddot{\psi}_1(r) \cos\theta - \dot{e}(t) r \ddot{\varphi}_1(r) \sin\theta + r \ddot{\tau}(r) T(t) - \right.$$
$$2\dot{\psi}(r) e(t) \cos\theta + 2\dot{e}(t) \dot{\varphi}(r) \sin\theta + e(t) \dot{\psi}_1(r) \cos\theta - \dot{e}(t) \dot{\varphi}_1(r) \sin\theta +$$
$$\left. \dot{\tau}(r) T(t) - \frac{1}{r} \tau(r) T(t) \right] - \rho \dot{e}(t) r \psi_1(r) \cos\theta + \rho \ddot{e}(t) r \varphi_1(r) \sin\theta - \rho r \tau(r) T(t)$$

$$T(t) \left[\ddot{\tau}(r_B) + \frac{1}{r_B} \tau(r_B) - \frac{1}{r_B^2} \tau(r_B) \right] - \frac{1}{\nu} \tau(r_B) T(t) = 0$$

$$\dot{\tau}(r_B) + \frac{1}{r_B} \tau(r_B) + \frac{1}{r_B^2} \tau(r_B) = 0$$

(4.58)

$$Q_X = \int_O^{2\pi} P_{rr} \Big/_{r = r_C} r_c \cos\theta d\theta - \int_O^{2\pi} P_{r\theta} \Big/_{r = r_c} r_c \sin\theta d\theta \ ,$$

(4.59)

$$Q_y = \int_0^{2\pi} P_{rr} \Big/_{r = r_C} r_c \sin\theta d\theta + \int_0^{2\pi} P_{r\theta} \Big/_{r = r_c} r_c \cos\theta d\theta \ ,$$

(4.60)

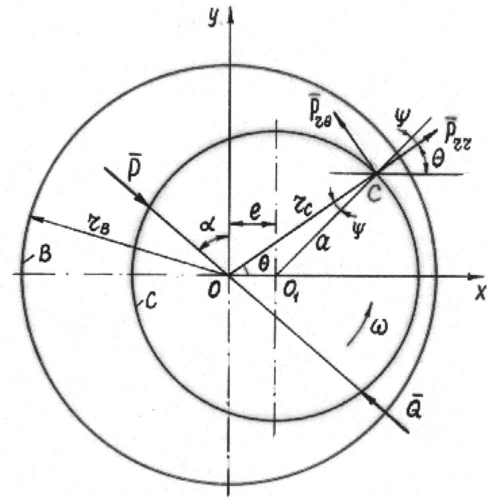


Рис.4.4. Диаграмма расположения сил действующих на цапфу вала

$$M = a\int_0^{2\pi} P_{r\theta} r_c \cos\psi d\theta - a\int_0^{2\pi} P_{rr} r_c \sin\psi d\theta$$

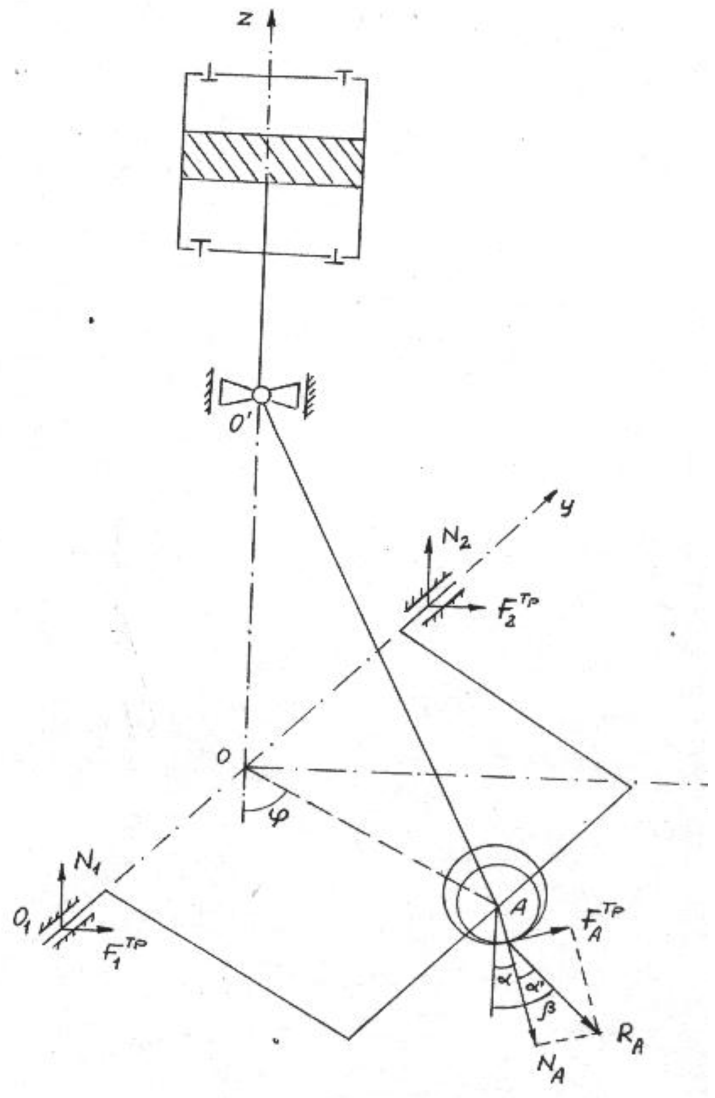
$$M = a\int_0^{2\pi} P_{r\theta}\Big|_{r=rc} \cdot r_c d\theta - e(t)\int_0^{2\pi} P_{rr}\Big|_{r=rc} \cdot r_c \sin\theta d\theta$$

$$M = a\mu\int_0^{2\pi} \left(\frac{\partial V_r}{\partial\theta}\Big|_{r=r_c} + r_c\frac{\partial V_\theta}{\partial r}\Big|_{r=r_c} - v_\theta\right)d\theta + e\int_0^{2\pi} r_c P\sin\theta d\theta - e\int_0^{2\pi} 2\mu\frac{\partial V_r}{\partial r}\Big|_{r=r_c} \cdot r_c \sin$$

$$M = \frac{39}{4}\pi\mu\, ab_3e^4 + \pi\mu\, ae^2\left(5b_1 + 6b_2a + 7b_3a^2\right) +$$
$$2\pi\mu\, aT(t)\left(c_1a + 2c_2a^2 + 3c_3a^3\right) - \pi\mu\, ae^2T(t)\left(2c_2 + 15c_3a\right)$$

$$l = \frac{36}{\omega}\left(\frac{k_д}{\kappa_б Q}\right)^{3,33},$$

4.5. Методика расчета механических потерь в коренных подшипниках коленчатого вала поршневых компрессоров



The scheme of crank-piston mechanism

$$\beta = \alpha - \alpha' = \alpha - arctg\,\mu_{ш},$$

$$\omega' = \frac{d\beta}{dt} = \frac{d\alpha}{dt} = \frac{d\alpha}{d\varphi}\frac{d\varphi}{dt} = \frac{d\alpha}{d\varphi}\omega_0 \;, \quad \frac{\omega'}{\omega_0} = \frac{d\alpha}{d\varphi} \;,$$

(4.72)

$$\left.\begin{aligned}
\Sigma F_{iz} &= N_1 + N_2 - R_A\cos\beta - 2m_1\omega_0^2\frac{R}{2}\cos\varphi - m_2\omega_0^2 R\cos\varphi = 0 \\
\Sigma F_{ix} &= F_1^{тр} + F_2^{тр} - R_A\sin\beta + 2m_1\omega_0^2\frac{R}{2}\sin\varphi - m_2\omega_0^2 R\sin\varphi = 0 \\
\Sigma m_y(F_i) &= R_A\cos\beta R\sin\varphi + R_A\sin\beta R\cos\varphi - \left(F_1^{тр} + F_2^{тр}\right)r = 0
\end{aligned}\right\}$$

$$R_A = \frac{\omega_0^2(m_1 + m_2)Rr\sin\varphi}{r\sin\beta - R\sin(\beta + \varphi)}$$

(4.75)

$$W_{тр} = \left|W\left(F^{тр}\right)\right| + \left|W\left(F'^{тр}\right)\right| = \mu_k N\omega_0 r + \mu_k N'\omega' r = \mu_k Nr\left(\omega_0 + \omega'\right)$$

(4.76)

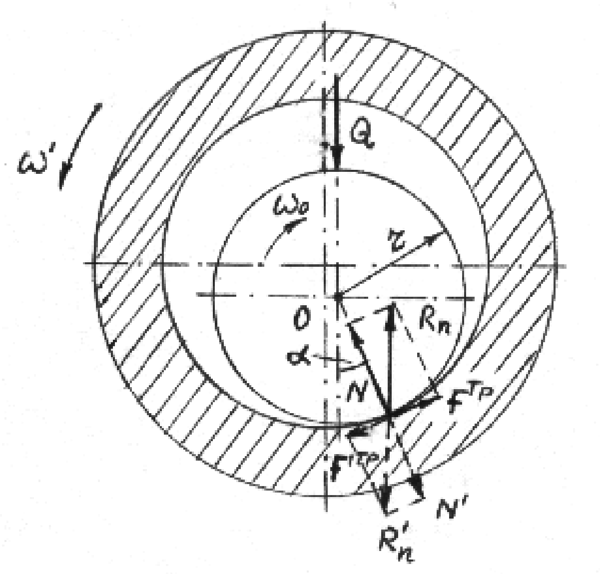
$$W_{дв} = R_A\sin(\alpha - \beta)R\omega_0$$

(4.77)

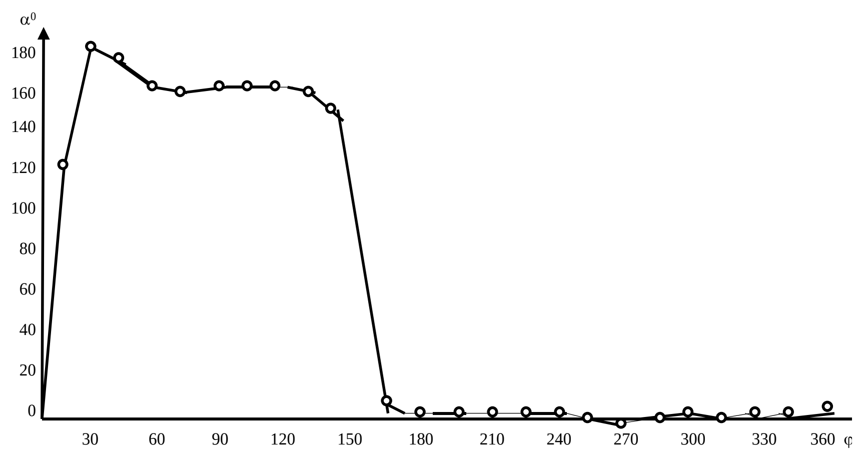
$$f = \frac{W_{тр}}{W_{дв}} = \mu_k\left(1 + \frac{\omega'}{\omega_0}\right)\frac{tg\,\varphi\cos\beta + \sin\beta - k\sin(\beta + \varphi)}{ktg\,\varphi\sin\left(arctg\,\mu_{ш}\right)}$$

(4.78)

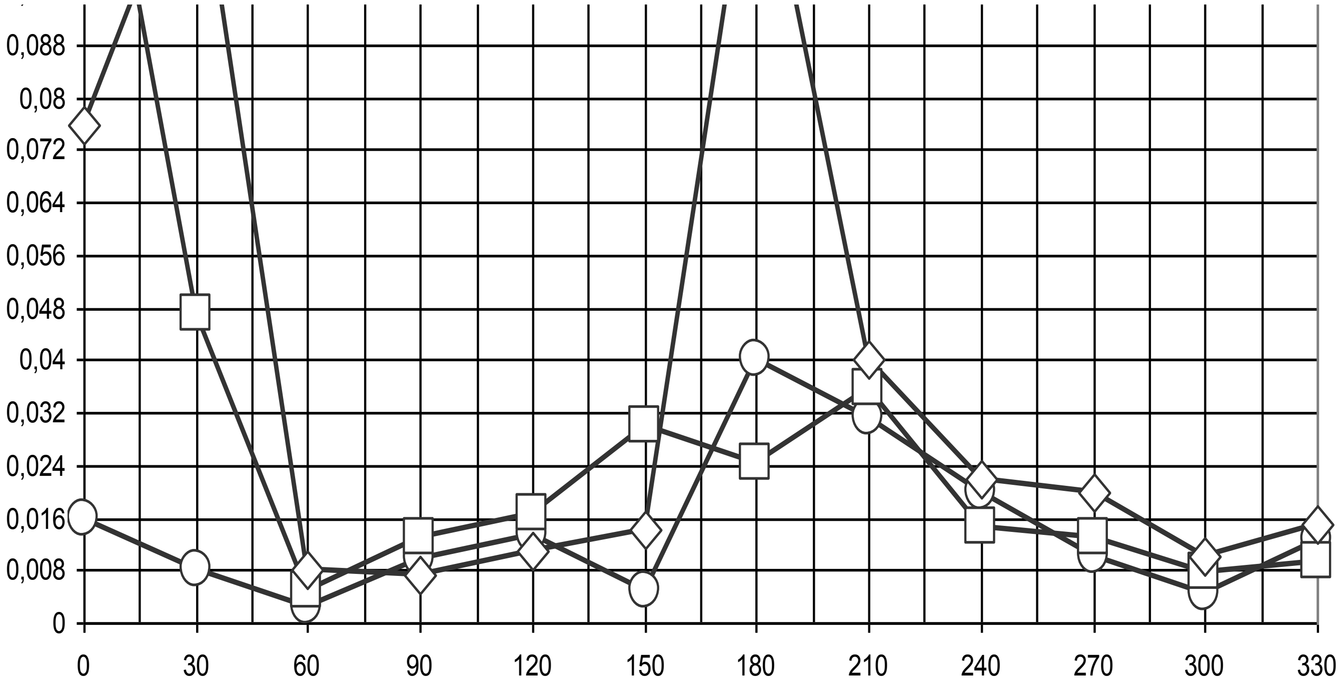
$$\frac{\omega'}{\omega_0} = \frac{d\alpha}{d\varphi}$$



Main bearing of crankshaft

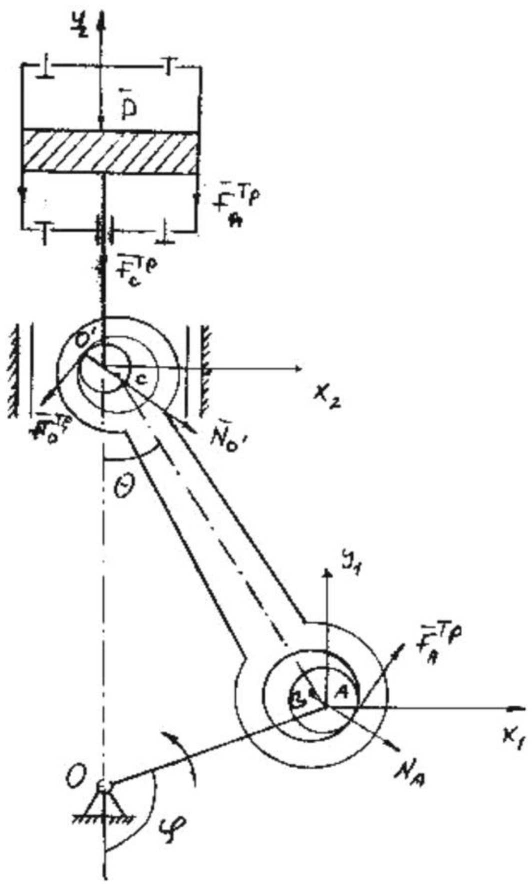


φ^0	φ^0	f к=1,2	f к=1,46	f к=1,92	f к=2	f к=2,6	f к=2,5
0^0	-10^0	0,2556	0,139	0,015	0	0,088	0,076
30^0	$169^0 30^{\vert}$	0,008	0,047	0,008	0,093	0,1232	0,12
60^0	$158^0 30$	-0,007	0,004	0,002	0,002	0,0004	0,0006
90^0	$157^0 30^{\vert}$	-0,015	0,0127	0,0096	0,0097	0,0072	0,0074
120^0	$160^0 30^{\vert}$	0,0201	0,0168	0,0132	0,0128	0,0104	0,0108
150^0	$149^0 30^{\vert}$	0,0532	0,0297	0,0048	0,0015	0,0164	0,0138
180^0	$0^0 30^{\vert}$	0,0156	0,0242	0,0826	0,0892	0,131	0,1254
210^0	$1^0 30^{\vert}$	0,0238	0,0356	0,0312	0,0176	0,0272	0,028
240^0	$0^0 30^{\vert}$	0,0155	0,0226	0,0176	0,0181	0,017	0,0172
270^0	$-7^0 30^{\vert}$	0,0154	0,0128	0,0058	0,0094	0,0072	0,0074
300^0	$-0^0 30^{\vert}$	0,0104	0,0076	0,0046	0,0041	0,0019	0,0022
330^0	$-4^0 15^{\vert}$	0,006	0,0091	0,0126	0,0131	0,0154	0,0152



Relationship between coefficient of losses and angle of rotation of crankshaft
1. к=1,92; 2.к=1,46; 3. к=2,5

Oscillation processes in Piston machine
Accuracy and reliability of piston machines



? = $f_1(t) = \omega$ t

(5.1)

$\alpha = f_2(t),$

(5.2)

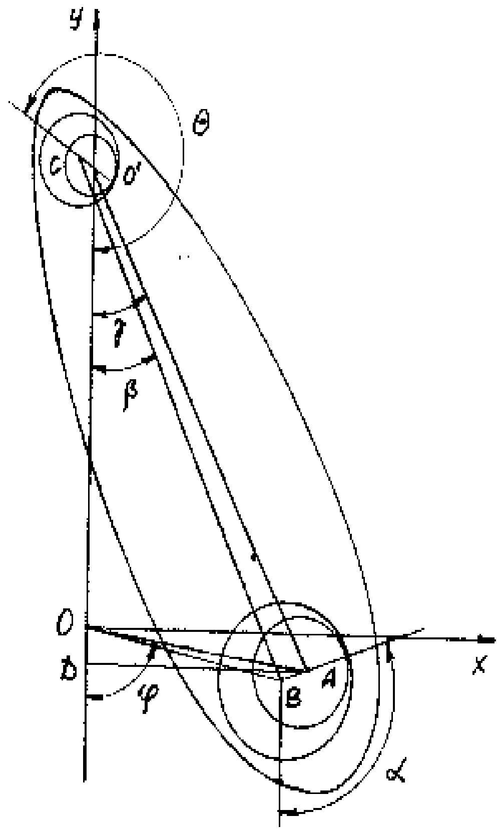
$\theta = f_3(t),$

(5.3)

$$AO^{|}\sin\gamma + O^{|}C\sin\theta + CB\sin\beta + BA\sin\alpha = 0$$

$$AO^{|}\cos\gamma - O^{|}C\cos\theta - CB\cos\beta - BA\cos\alpha = 0$$

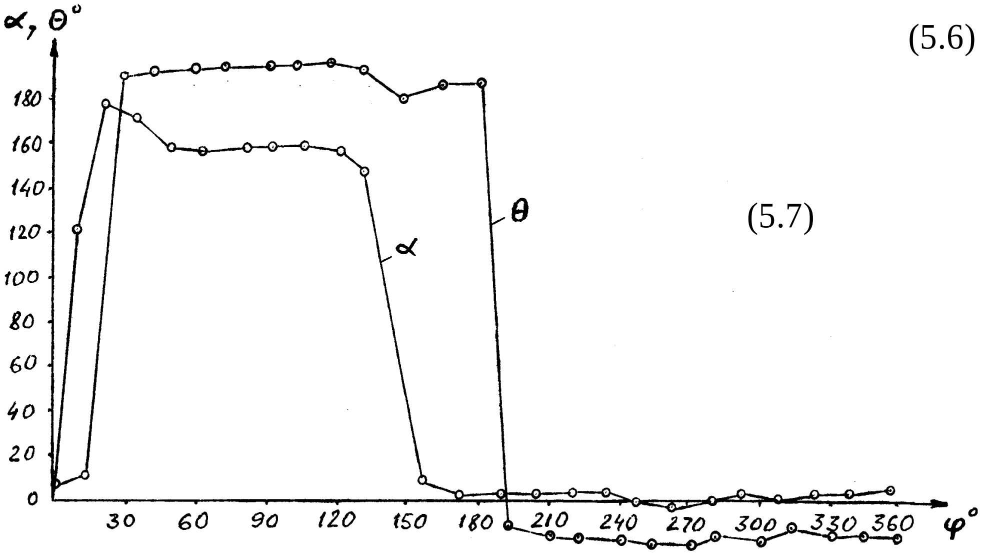
(5.4)



CB=L, AB=e_1, $O^{|}C$=e_2,

$AO^{|}\sin\gamma = r\sin\varphi,$ $AO^{|}\cos\gamma = O^{|}D = Y_{o^{|}} + r\cos$

$$-r\sin\varphi + e_2\sin\theta + L\sin\beta + e_1\sin\alpha = 0$$



$$Y_{O^{|}} + R\cos\varphi - e_2\cos\theta - L\cos\beta - e_1\cos\alpha = 0$$

(5.6)

$$\sin\beta = \frac{1}{L}(R\sin\varphi - e_2\sin\theta - e_1\sin\alpha)$$

(5.7)

$$Y_{O^{|}} = e_2\cos\theta - R\cos\varphi + L\cos\beta + e_1\cos\alpha$$

$$\overline{OB} = \overline{OA} + \overline{AB}$$

$$X_B = OA\sin\varphi - AB\cos(\alpha - 90^0)$$

$$Y_B = OA\cos(180^0 - \varphi) - AB\cos(180^0 - \alpha)$$

$$\left.\begin{aligned} X_B &= R\sin\varphi - e_1\sin\alpha = R\sin\omega t - e_1\sin[f_2(t)] \\ Y_B &= e_1\cos\alpha - R\cos\varphi = e_1\cos[f_2(t)] - R\cos\omega t \end{aligned}\right\}$$

(5.9)

$$X_B = R\sin\omega t - e_1\sin[f_2(t)],$$

(5.10)

$$Y_B = e_1\cos[f_2(t)]) - R\cos\omega t,$$

(5.11)

$$\sin\beta = \frac{1}{L}\{R\sin\omega t - e_2\sin[f_3(t)] - e_1\sin[f_2(t)]\}$$

(5.12)

$$Y_{o}^{|} = - R\cos? \ + y_{?} + L\cos ? \ + e_{2} \cos\theta \ .$$

$$y_{O^{|}}^{O} = -R\cos ? \ + L\cos ?_{o},$$

$$\Delta Y_{0^1} = Y_{0^1} - Y_{o^|}^{O} - e_2 = Y_B + e_2\cos\theta + L(\cos\beta - \cos\beta_0) - e_2 .$$

(5.13)

$$\overline{00^1} = \overline{OA} + \overline{AB} + \overline{BC} + \overline{CO} \ .$$

(5.14)

$$R\sin? \ - x_{?} - L\sin? \ - e_2\sin\theta = O$$

$$x_{?} = R\sin? \ - L\sin ? \ - e_2 \sin\theta \ .$$

$$Y_B = \frac{X_B}{tg\alpha} = R\frac{\sin\varphi}{tg\alpha} - L\frac{\sin\beta}{tg\alpha} - e_2\frac{\sin\theta}{tg\alpha}$$

(5.15)

$$\left.\begin{aligned} \sin\beta_0 &= \frac{R}{L}\sin\varphi \\ \sin\beta &= \frac{1}{L}(R\sin\varphi - e_1\sin\alpha - e_2\sin\theta) \end{aligned}\right\}$$

(5.16)

$$\Delta Y_{0^1} = e_1 \cos\alpha + e_2 \cos\theta - e_2 + \frac{\text{Re}_1}{L} \sin\varphi \sin\alpha +$$
$$+ \frac{\text{Re}_2}{L} \sin\varphi \sin\theta - \frac{e_1^2}{2L} \sin^2\alpha - \frac{e_2^2}{2L} \sin^2\theta - \frac{e_1 e_2}{L} \sin\alpha \sin\theta$$

(5.18)

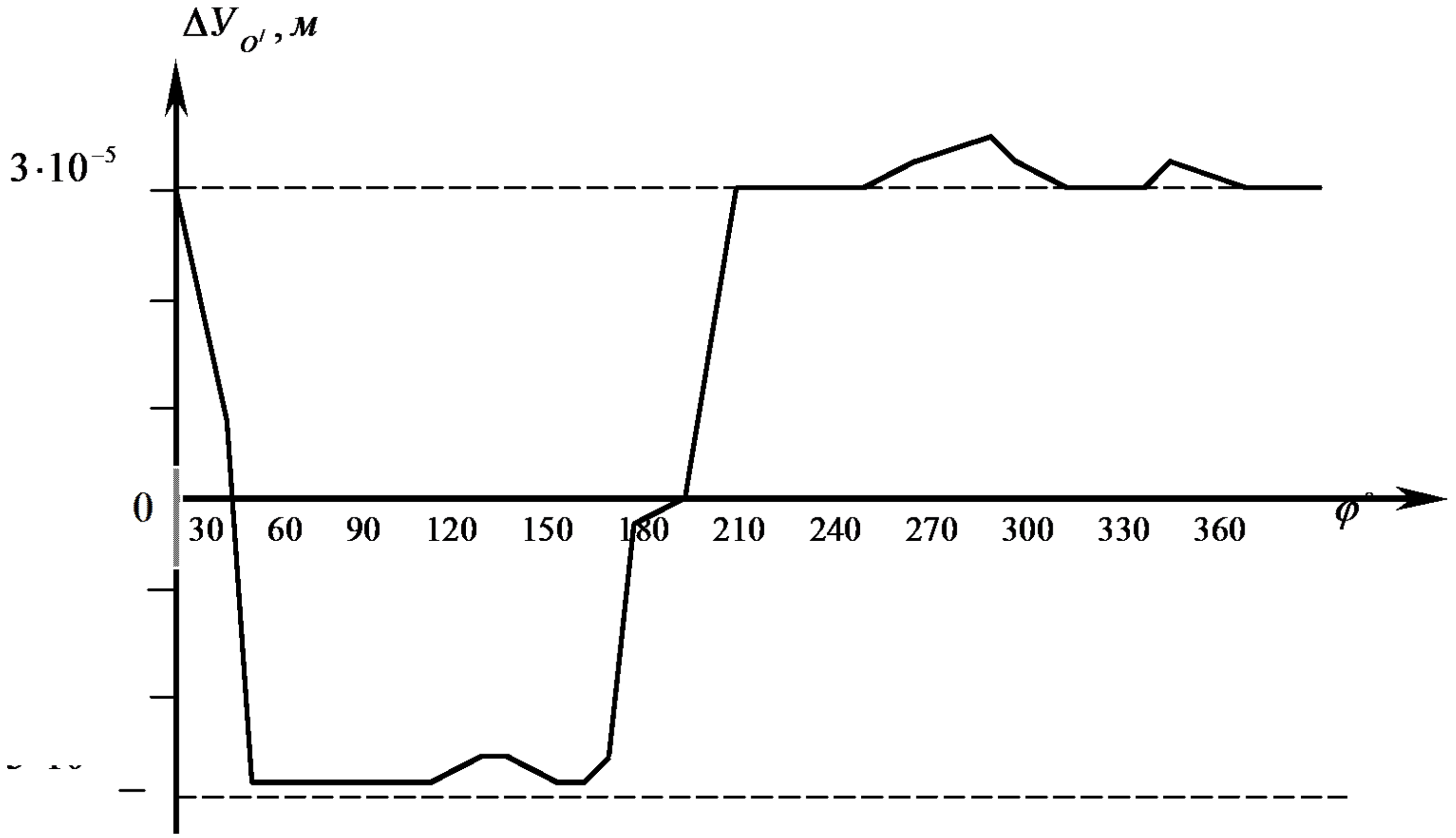
$$\Delta \dot{Y}_{0^1} = -e_1\omega_1 \sin\alpha - e_2\omega_2 \sin\theta + \frac{\text{Re}_1}{L}(\omega \cos\varphi \sin\alpha + \omega_1 \sin\varphi \cos\alpha) +$$
$$+ \frac{\text{Re}_2}{L}(\omega \cos\varphi \sin\theta + \omega_2 \sin\varphi \cos\theta)$$

(5.19)

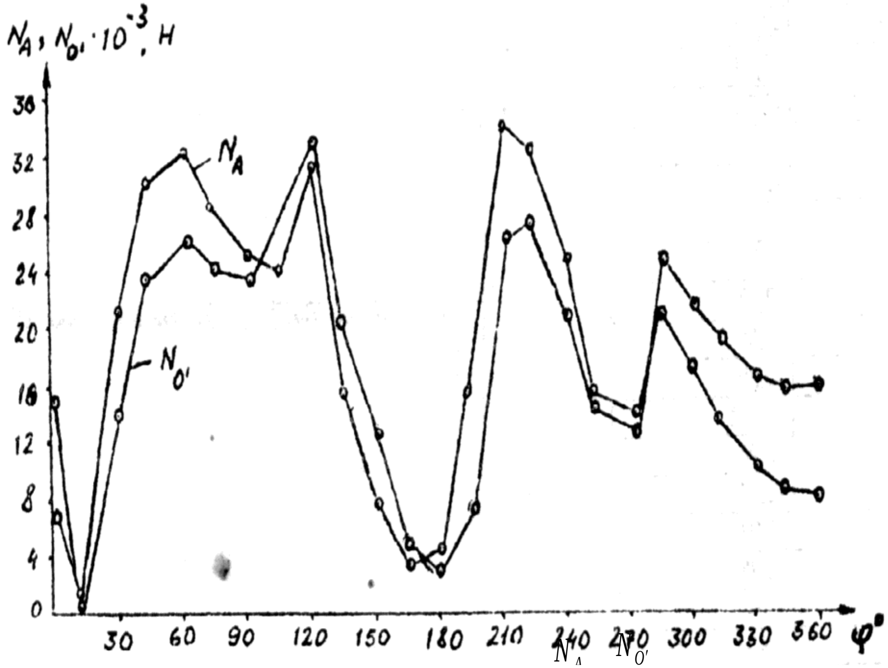
$$\Delta \ddot{Y}_{0^1} = -e_1\left(\omega_1^2 \cos\alpha + \varepsilon_1 \sin\alpha\right) - e_2\left(\omega_2^2 \cos\theta + \varepsilon_2 \sin\theta\right) -$$
$$- \frac{\text{Re}_1}{L}\left(\omega^2 + \omega_1^2\right)\sin\varphi \sin\alpha - \frac{\text{Re}_2}{L}\left(\omega^2 + \omega_2^2\right)\sin\varphi \sin\theta +$$
$$+ \frac{2\,\text{Re}_1}{L}\omega\omega_1 \cos\vartheta \cos\alpha + \frac{2\,\text{Re}_2}{L}\omega\omega_2 \cos\varphi \cos\theta,$$

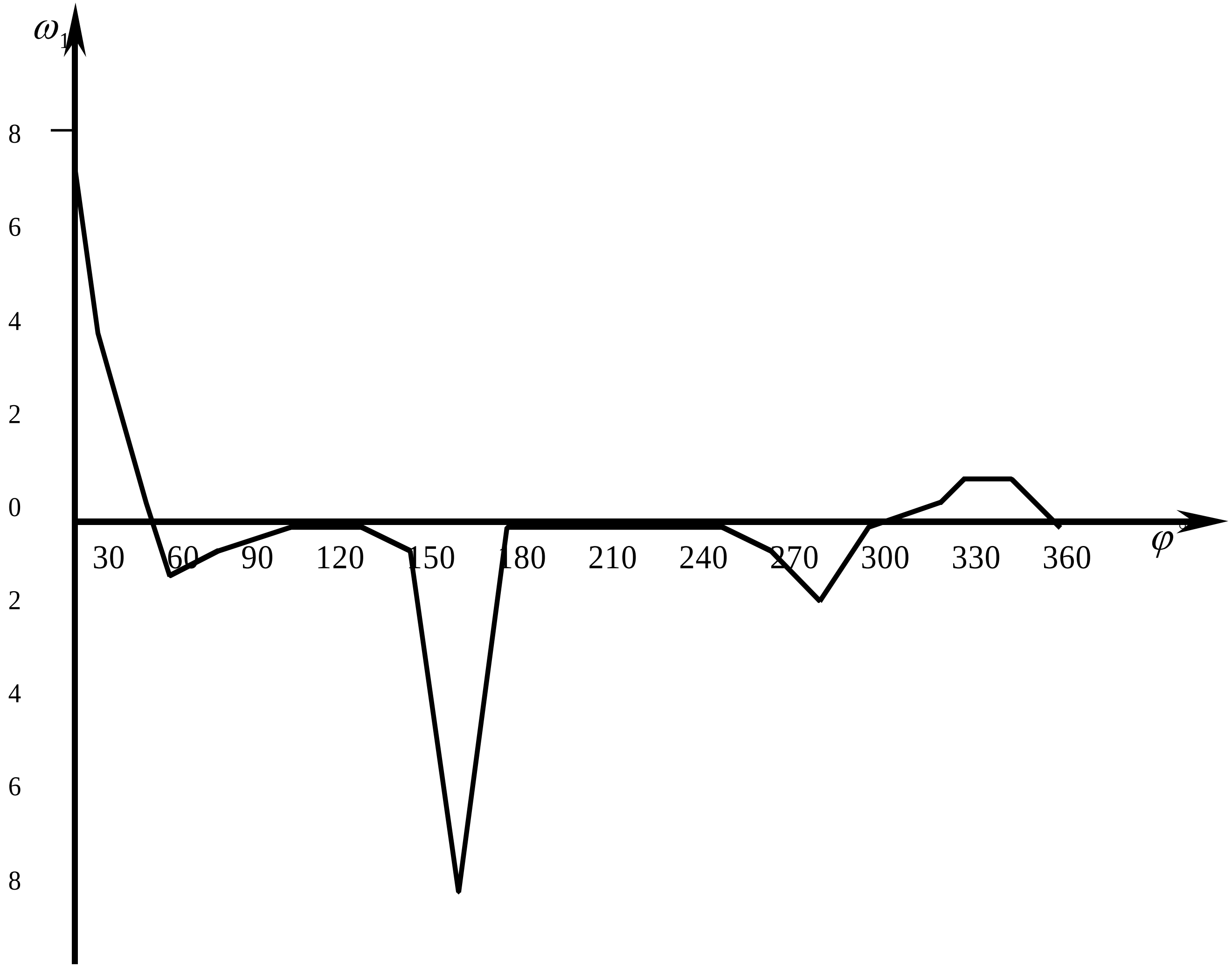
(5.20)

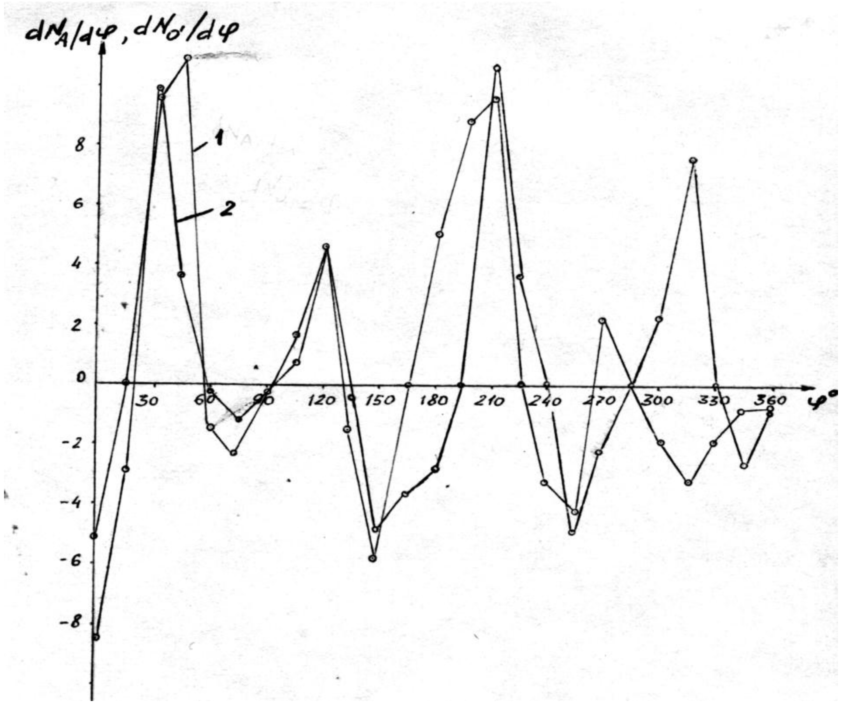
?	? y_0
00	2.98
150	0.61
30	-2.82
45	-2.78
60	-2.76
75	-2.79
90	-2.73
105	-2.67
120	-2.79
135	-2.73
150	-2.55
165	-0.39
180	-0.005
195	-2.96
210	-2.94
225	-2.93
240	-2.98
255	3.04
270	3.35
285	2.97
300	2.99
315	3.005
330	2.99
345	2.98
360	2.97



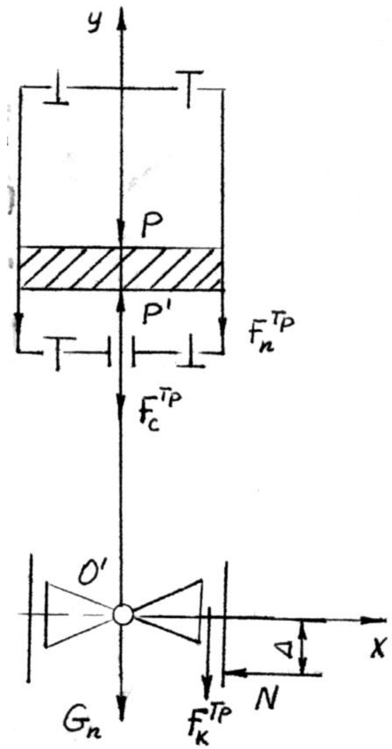
$\Delta Y_{o'}, м$
$3\cdot10^{-5}$
0
30
60
90
120
150
180
210
240
270
300
330
360
φ°


$N_A, N_{0'} \cdot 10^{-3}$, H
0
4
8
12
16
20
24
28
32
36
30
60
90
120
150
180
210
240
270
300
330
360
φ°
N_A
$N_{0'}$

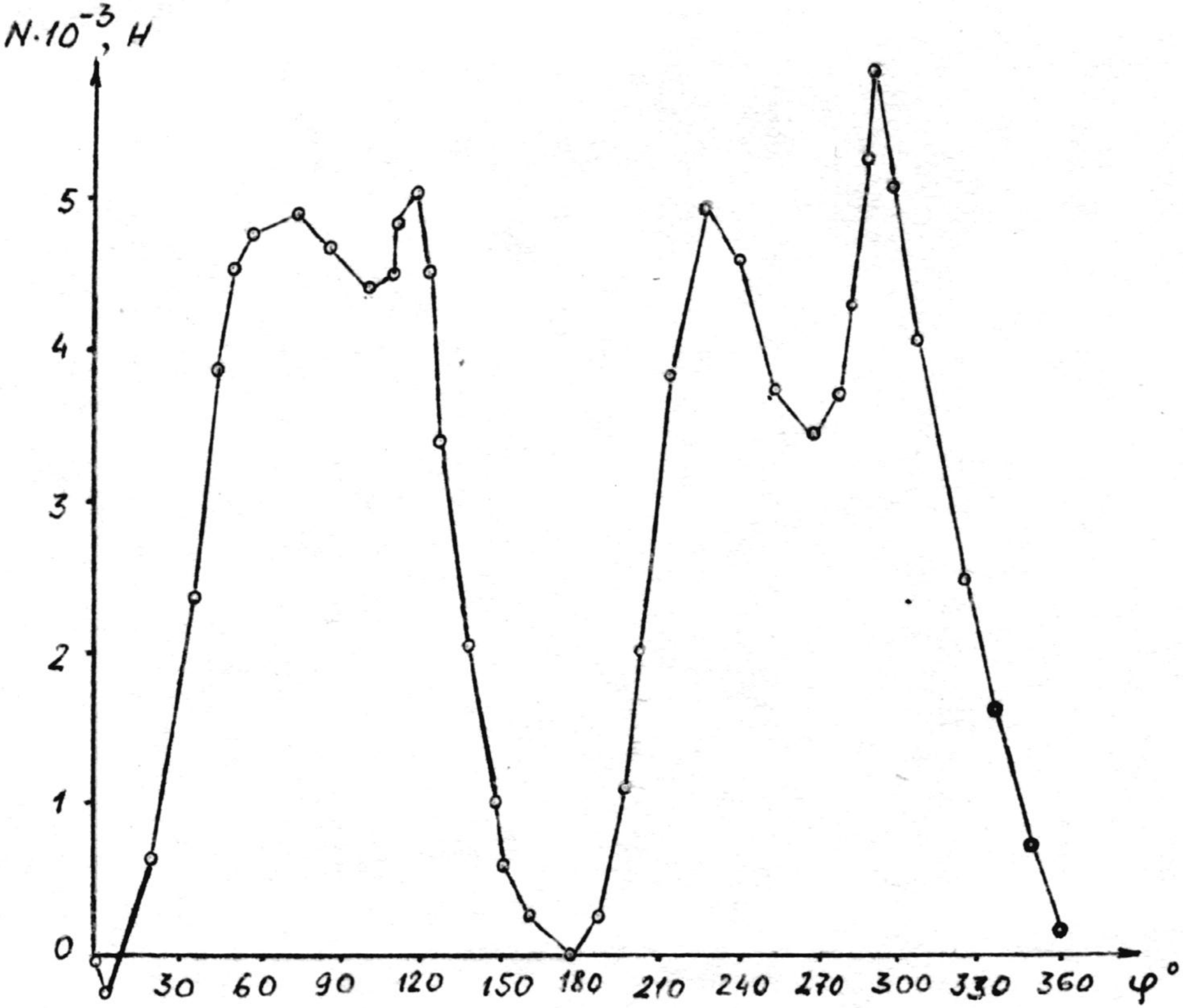

ω_1
8
6
4
2
0
2
4
6
8
30
60
90
120
150
180
210
240
270
300
330
360
φ



Frequencies of loads



The scheme of piston assemble with crosshead



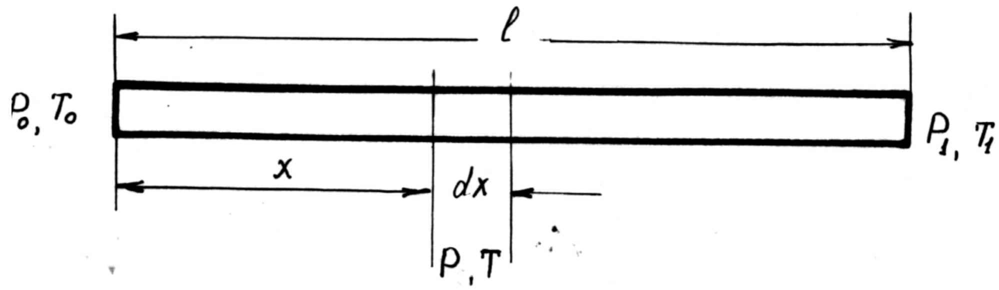
N·10^-3, Н
5
4
3
2
1
0
30
60
90
120
150
180
210
240
270
300
330
360
φ°

φ	$dN_A/d\varphi$	$dN_{O'}/d\varphi$		ω_1
0	-500	-854		7,46
15	0	-294		4
30	794	956		1,07
45	986	3568		-0,53
60	-147	-74		-0,25
75	-220	-118		0
90	-30	-28		0
105	177	74		0
120	441	470		0
135	-150	-44		-0,4
150	-588	-515		-6,93
165	0	-368		0
180	500	-294		0
195	883	0		0
210	950	1074		0
225	0	368		0
240	-324	0		0
255	-426	442		-0,26
270	220	-220		-0,66
285	0	0		0
300	-191	235		0,26
315	-324	765		0,4
330	-191	0		0,53
345	-74	-265		0
360	-60	-74		0

1.Уравнением состояния

$$\frac{P}{\rho} = RT$$

(6.1)



2.Уравнением неразрывности

$$G = \rho W f$$

(6.2)

3.Уравнением движения в виде уравнения Бернулли в дифференциальной форме

$$\frac{dP}{\rho} + WdW + dL_{тр} = 0$$

(6.3)

$$dL_{тр} = \xi \frac{W^2}{2} \cdot \frac{dx}{D}$$

(6.4)

$$\xi = 0{,}0032 + \frac{0{,}221}{\mathrm{Re}^{0{,}237}} \qquad (6.5)$$

$$\mathrm{Re} = \frac{\rho W D}{\mu}$$

(6.6)

$$W = \frac{GRT}{Pf}$$

(6.7)

$$dW = -\frac{GRT}{P^2 f} dp$$

(6.8)

$$RTPdP - \frac{G^2 R^2 T^2}{f^2} \cdot \frac{dp}{p} + \xi \frac{G^2 R^2 T^2}{2Df^2} dx = 0$$

$$\frac{RT}{2}(P^2 - P_0^2) - \frac{G^2 R^2 T^2}{f^2} \ln \frac{p}{p_0} + \xi \frac{G^2 R^2 T^2}{2 f^2 D} X = 0$$

(6.9)

P_0=4,905 МПа, T_0=300К, G_0=2кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
49	1,56? 10^3	4,57? 10^3	11,044? 10^3	23,26? 10^3	44,273? 10^3
48	3,09? 10^3	9057,43	21865,85	46659,32	87653,23
47	4595,18	13447,47	32464,07	68383,96	130138,21
46	6063,75	17745,1	42839,18	90238,68	171728,93
45	7500,69	2195028	52991,16	111623,3	212425,5
44	8906,03	26063,01	62919,93	132537,9	252227,54
43	10279,78	383,32	72625,62	152982,6	291134,04
42	11621,92	34011,15	82108,12	172957,1	329146,79
41	12932,46	37846,54	37842,18	192467,4	366265,11
40	14211,33	41589,49	100403,8	211496,12	402488,96

P_0=7,3575 МПа, T_0=300К, G_0=2кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
74	2353,205	6885,88	16622,97	35015,01	66634,94
73	4674,81	13679,31	33022,77	69559,93	132375,3
72	6964,85	20380,36	49045,21	103635,1	197221,8
71	9223,27	26988,94	65153,14	137240,1	261173,5
70	11450,11	33504,64	80883,58	170375,17	324230,8
69	13645,35	399928,79	96390,89	203040,17	386393,6
68	15808,49	46260,06	111675,05	253253,15	447662,03
67	17941,11	52498,22	126736,11	287408,14	508036
66	20041,51	58645,31	141574	298215,11	567515,52
65	22110,37	64699,25	156188,74	329000,04	626100,5

P_0=9,81 МПа, T_0=300К, G_0=2кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
99	3143,02	9196,76	22201,38	46765,31	88996,06
98	6254,44	18301,09	44179,62	93060,6	177098,47
97	9334,29	27312,99	65934,74	138885,9	264304,86
96	12382,53	36232,45	87466.69	184241,16	350617,66
95	15399,18	45059,48	108775,54	229126,44	465285,89
94	18384,24	53794,05	129861,23	273541,68	555480,16
93	21337,72	62436,21	150723,76	317486,92	644719,14
92	24259,59	70985,95	171363,24	360962,18	686924,15
91	27149,61	79443,24	191779,54	403967,4	768764,7
90	30008,57	87808,09	211972,71	446502,64	849710,79

Таблица 6.4

P_0=4,905 МРа, T_0=300К, G_0=3кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
49	738,149	2171,59	5242,49	11041,84	21064,52
48	1461,38	4299,3	10379,07	21860,6	41703,49
47	2169,69	6383,13	15409,72	32456,27	61916,89
46	2862,76	84423,08	20334,45	42828,87	81704,74
45	3539,2	10418,91	25152,99	52978,8	101066,68
44	4204,9	12371,1	29865,88	62904,51	120003,4
43	4853,53	14279,41	34472,85	72607,87	138514,56
42	5487,24	16143,84	38973,9	82088,15	156600,17
41	6106,03	17964,39	43369,04	91345,34	174260,2
40	6710,0	19741,29	47658,52	100379,8	191495,04

P_0=7,3575 МПа, T_0=300К, G_0=3кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
74	1111,34	3268,82	7890,77	16619,15	31703,87
73	2207,57	6493,53	15675,34	33014,91	62981,84
72	3289,08	9674,598	23354,27	49187,9	93834,59
71	4355,47	12811,55	30926,99	65137,49	124261,44
70	5407,13	15904,85	38394,08	80864,32	154263,07
69	6443,88	18954,28	45755,25	96368,07	183839,14
68	7465,51	21959,59	53010,22	111648,43	212989,3
67	8472,41	24921,25	60159,55	126706,02	241714,26
66	9464,2	27838,8	67202,68	141540,22	270013,3
65	10441,27	30712,71	74140,17	156151,65	297887,13

Таблица 6.6

P_0=9,81 МПа, T_0=300К, G_0=3кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
99	1484,35	4365,83	10538,77	22196,15	42342,87
98	2953,77	8687,77	20971,61	44169,22	84260,18
97	4408,27	12965,83	31298,54	65919,21	125751,94
96	5847,86	17200,02	41519,55	87446,12	166818,13
95	7272,52	21390,32	51634,63	108749,95	207458,76
94	8682,27	25536,75	61643,8	129830,7	247673,84
93	10077,09	29639,29	71547,04	150688,37	287463,35
92	11456,99	33697,96	81344,37	171322,95	328827,3
91	12821,98	37712,74	91035,78	191734,46	365765,69
90	14172,05	41683,65	100621,27	211922,89	404278,52

Таблица 6.7

P_0=4,905 МПа, T_0=300К, G_0=5кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
49	437,172	1293,435	3116,933	6511,566	12497,027
48	865,504	2560,728	6170,884	12891,57	24741,57
47	1284,996	3801,882	9161,856	19140,018	36733,64
46	1695,648	5016,896	12089,85	25256,9	48473,23
45	2097,3	6205,5	14954,58	31241,98	59959,96
44	2490,23	7368,27	17756,6	37095,67	71194,59
43	2874,36	8504,85	20495,66	42817,88	82176,74
42	3249,65	9615,304	23171,73	48408,52	92906,4
41	3616,104	10699,62	25784,82	53867,61	103383,59
40	3973,	11758,04	28335,22	59195,46	113608,66

Таблица 6.8

P_0=7,3575 МРа, T_0=300К, G_0=4кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
74	658,38	1947,18	4691,72	9800,893	18809,393
73	1307,72	3867,976	9320,173	19469,89	37365,94
72	1948,42	5762,878	13885,93	29007,67	55670,37
71	2580,08	7631,39	18388,43	38413,56	73721,96
70	3203,1	9474,02	22828,22	47688,21	91521,43
69	3817,25	11290,496	27205,05	56831,304	109068,43
68	4422,38	130080,5	31518,6	65842,51	126362,57
67	5018,88	14844,79	35969,46	74722,48	143404,6
66	5606,33	16582,61	39957,05	83470,57	160193,79
65	6185,144	18294,53	44081,95	92087,42	176730,87

Таблица 6.9

P_0=4,905 МПа, T_0=300К, G_0=5кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
99	879,33	2600,68	6266,22	13089,89	25121,39
98	1749,91	5175,32	12469,5	26048,23	49990,31
97	2611,61	7723,63	18609,7	38874,9	74606,74
96	3464,48	10245,8	24687,0	51570,2	98970,69
95	4308,5	12742,01	30701,3	64133,87	123082,17
94	5143,66	15211,99	36652,63	76565,96	146941,16
93	5969,99	17655,83	42540,97	88866,5	170547,68
92	6787,49	20073,54	48366,33	101035,47	193901,71
91	7596,14	22465,1	54128,71	113072,9	217003,26
90	8395,96	24830,52	59828,11	124978,73	239852,33

Таблица 6.10

P_0=4,905 МПа, T_0=300К, G_0=5кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
49	291,626	853,858	2073,45	4320,67	8212,285
48	577,352	1690,456	4105	8554,04	16258,625
47	857,178	2509,794	6094,65	12700,1	24139,09
46	1131,104	3311,872	8042,4	24801,28	31853,62
45	1398,918	4096,434	9947,95	20730,01	39401,85
44	1661,044	4863,992	11811,9	24614,18	46784,53
43	1917,27	5614,29	13633,95	28411,05	54001,3
42	2167,596	6347,328	15414,1	32120,62	61052,15
41	2412,022	7063,106	17152,35	35742,89	67937,07
40	2650,76	7761,88	18849	39278,2	74656,46

Таблица 6.11

P_0=7,3575 МПа, T_0=300К, G_0=5кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
74	439,338	1285,614	3121,25	6503,51	12360,66
73	872,564	2553,712	6200,3	12919,38	24555,02
72	1300,102	3804,806	9237,75	19248,29	36583,85
71	1721,528	5038,384	12233,0	25489,56	48446,37
70	2137,266	6254,958	15186,65	31643,87	60143,36
69	2547,104	7454,272	18098,4	37710,88	71674,42
68	2950,83	8535,97	20967,95	43690,25	83039,19
67	3348,868	9800,864	23795,9	49582,66	94238,41
66	3740,794	10948,142	26581,65	56565,98	105271,3
65	4127,032	12078,416	29325,8	61105,24	116138,7

Таблица 6.12

P_0=9,81 МПа, T_0=300К, G_0=5кг/с					
D / 10,2P	0,100	0,125	0,150	0,175	0,200
99	586,838	1717,114	4168,75	8686,01	5608,663
98	1167,776	3416,968	8295,6	17284,72	32851,4
97	1742,814	5099,562	12380,55	25796,13	49028,22
96	2311,952	6764,896	16423,6	34220,24	65039,13
95	2875,19	8412,97	20424,75	42557,05	80884,11
94	3432,528	10043,78	24384,0	50806,56	96563,17
93	3983,966	11657,338	28301,35	58968,77	112076,3
92	4529,504	13253,63	32176,8	67043,68	127423,5
91	5069,142	14832,66	36010,3	75031,29	142604,8
90	5602,88	16394,44	3982,3	82931,6	157620,2

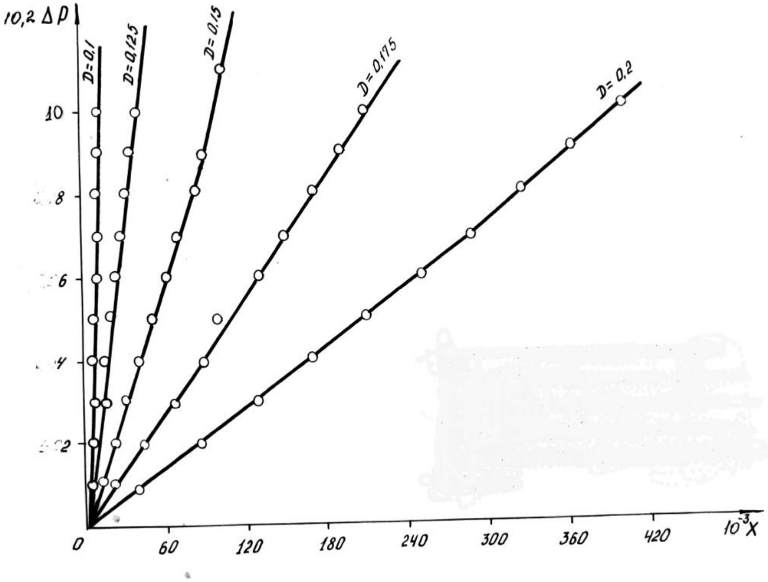


Рис.6.2 Кривые зависимости потери давления ΔP воздуха от длины X трубопровода при различных его диаметрах D для начальных параметров воздуха P_0=4,905МПа, G_0=2кг/с

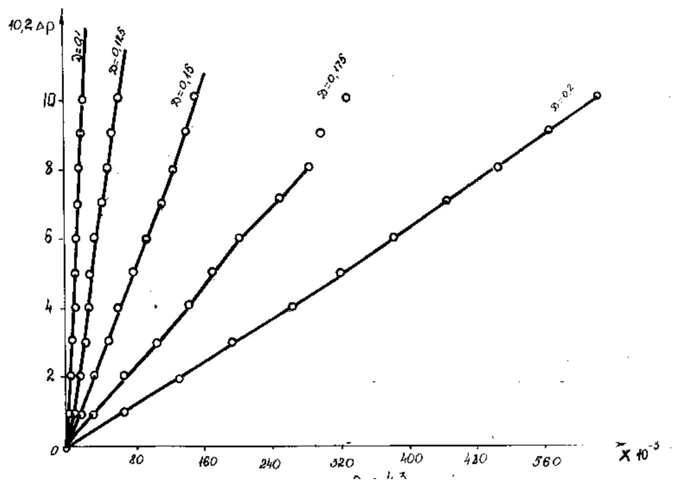


Рис.6.3. Кривые зависимости потери давления воздуха от длины X трубопровода при различных его диаметрах D для начальных параметров воздуха P_0=7,35МПа, G_0=2кг/с

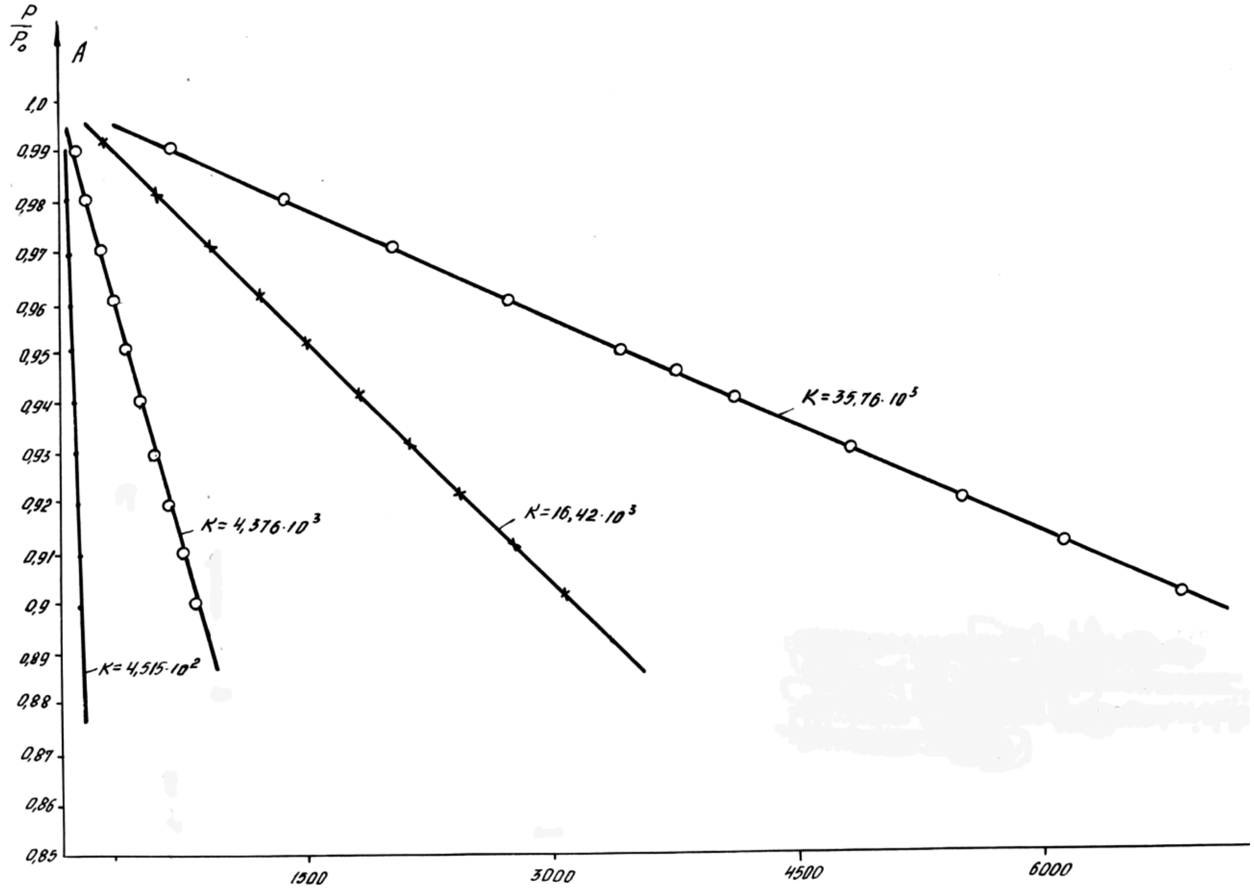


Рис. 6.14. Кривые зависимости безразмерных давления от безразмерной длины трубопровода при различных значениях параметра K.

$$\frac{f^2 P_0^2}{2G^2 RT}\left(1-\frac{P^2}{P_0^2}\right)+\ln\frac{P}{P_0}-\frac{\xi x}{2D}=0$$

$$K\left(1-\frac{P^2}{P_0^2}\right)+\ln\frac{P}{P_0}-\frac{\xi x}{2D}=0$$

6.2. Методика определения параметров движения газового потока при политропном процессе его течения по трубопроводу

1.Уравнение неразрывности

$$G = \frac{Wf}{v} = const \quad ,$$

(6.11)

2.Уравнение движения

$$vdp+WdW+dLmp=0 \ ,$$

(6.12)

3.Уравнение энергии

$$dq_{н}=di+wdw$$

(6.13)

4.Уравнение состояние

$$Pv=zRT,$$

(6.14)

$$z=1+ap+вp^2,$$

$$a=a_0+a_1T+a_2T^2, \quad в=в_0+в_1T+в_2T^2,$$

$(a_0= -527,93; \ a_1=2,5; \ a_2= -0,2767 \cdot 10^{-2}; \ в_0=14,154 \cdot 10^4;$

$в_1= -601,39; \ в_2=0,6548 \ )$

$$dL_{тр} = \xi \frac{W^2}{2} \cdot \frac{dx}{D}$$

$$\xi = 0{,}0032 + \frac{0{,}221}{Re^{0{,}237}} \; ; \quad Re = \frac{\rho w D}{2\mu} \; ; \quad \rho = \frac{1}{v} \; ,$$

$$di = C_p dT + [v - T(\frac{\partial v}{\partial v})_p] \, dp,$$

(6.15)

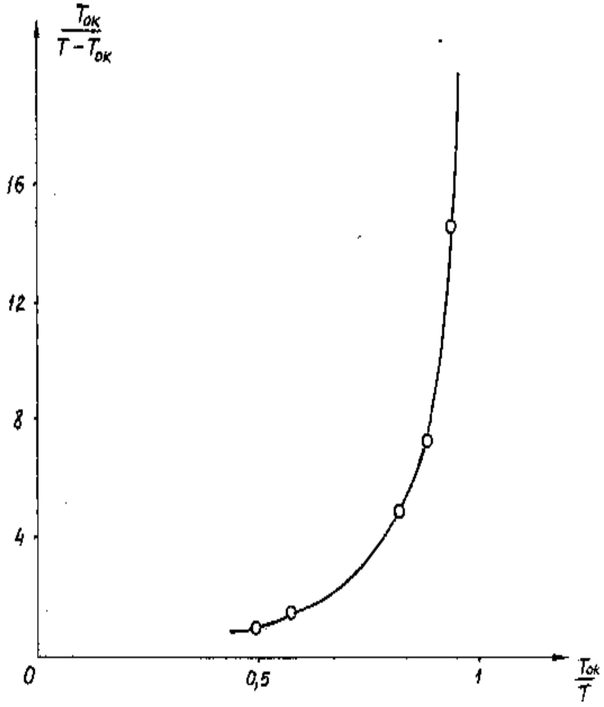
$$-dq_н = \frac{4\kappa}{D\rho}(T - T_{ок})dt = \frac{4\kappa}{DC_1}(T - T_{OK})dx \, ,$$

(6.16)

$$T = T_0 (\frac{P}{P_0})^{\frac{m-1}{m}} \, ,$$

(6.17)

$$di = C_p dt + vdp - \frac{RT^2}{P} \; [\, (a_1 + 2a_2 T)P + (в_1 + 2в_2 T)P^2]dp - \frac{RT}{P} \; (1 + ap + вp^2)dp \qquad (6.18)$$



$$\frac{T_{ок}}{T - T_{ок}} = A_1 \cdot \frac{T_{ок}}{T} + A_2 \frac{T_{ок}^2}{T^2} + A_3 \frac{T_{ок}^3}{T^3} + \ldots.$$

(6.20)

$$\frac{4\kappa}{DC_1} dx = C_p \left(\frac{A_1}{T} + \frac{A_2 Tok}{T^2} + \frac{A_3 T_{ок}^2}{T^3} \right) dT + \beta \left(N_o P^{\frac{m-1}{m}} + + N_1 P^{\frac{6m-1}{m}} + N_2 P^{\frac{5m-1}{m}} + N_3 P \right.$$
$$+ N_4 P^{\frac{3m-1}{m}} + N_5 P^{\frac{2m-1}{m}} + N_6 P^{-\frac{1}{m}} + + N_7 P^{-\frac{m+1}{m}} + N_8 P^{-\frac{2m+1}{m}} + N_9 P^{-\frac{3m+1}{m}} + N_{10} P$$
$$\left. + N_{11} P + N_{12} P^{\frac{m+1}{m}} + + N_{13} P^{\frac{m-2}{m}} + N_{14} P^{\frac{m-3}{m}} + N_{15} P^{\frac{m-4}{m}} + N_{16} P^{\frac{m-5}{m}} \right) dP$$

(6.21)

$$\frac{4K}{DC_1}X = \Bigg| C_P A_1 \ell n\left(\beta P^{\frac{m-1}{m}}\right) - C_P A_2 T_{ok} \beta^{-1} P^{\frac{1-m}{m}} - \frac{1}{2} C_P A_3 T_{ok}^2 \beta^{-2} P^{\frac{2(1-m)}{m}} +$$

$$m\beta\left(\frac{N_o}{2m-1}\cdot P^{\frac{2m-1}{m}} + \frac{N_1}{7m-1}\cdot P^{\frac{7m-1}{m}} + \frac{N_2}{6m-1}\cdot P^{\frac{6m-1}{m}} + \frac{N_3}{5m-1}\cdot P^{\frac{5m-1}{m}} + \frac{N_4}{4m-1}\cdot P^{\frac{4m-1}{m}} + \right.$$

$$\frac{N_5}{3m-1}\cdot P^{\frac{3m-1}{m}} + \frac{N_6}{m-1}\cdot P^{\frac{m-1}{m}} - N_7\cdot P^{-\frac{1}{m}} - \frac{N_8}{m+1}\cdot P^{-\frac{m+1}{m}} - \frac{N_9}{2m+1}\cdot P^{-\frac{(2m+1)}{m}} -$$

$$\frac{N_{10}}{3m+1}\cdot P^{-\frac{3m+1}{m}} + \frac{N_{11}}{2m} P^2 + \frac{N_{12}}{2m+1}\cdot P^{\frac{2m+1}{m}} + \frac{N_{13}}{2m-1}\cdot P^{\frac{2m-2}{m}} + \frac{N_{14}}{2m-3}\cdot P^{\frac{2m-3}{m}} +$$

$$\left.\frac{N_{15}}{2m-1}\cdot P^{\frac{2m-4}{m}} + \frac{N_{16}}{2m-5}\cdot P^{\frac{2m-5}{m}}\right)\Bigg|_{P_O}^{P},$$

(6.22)

$$w = \frac{G}{f}v$$

(6.23)

$$\frac{f}{G}dp + dw + \frac{\xi RG}{8kf^2}\left(\frac{T}{p} + a_0 T + a_1 T^2 + a_2 T^3 + b_0 pT + b_1 T^2 p + b_2 T^3 p\right)\times$$

$$\times\left[\begin{array}{l} cp\left(\frac{A_1}{T} + \frac{A_2 T_{0k}}{T^2} + \frac{a_3 T_{0k}^2}{T^3} + \right)dT + \\ + \beta\left(\begin{array}{l} N_0 p^{\frac{m-1}{m}} + N_1 p^{\frac{6m-1}{m}} + N_2 p^{\frac{5m-1}{m}} + N_3 p^{\frac{4m-1}{m}} + N_4 p^{\frac{3m-1}{m}} + N_5 p^{\frac{2m-1}{m}} + \\ + N_6 p^{-\frac{1}{m}} + N_7 p^{-\frac{m+1}{m}} + N_8 p^{-\frac{2m+1}{m}} + \\ + N_9 p^{-\frac{3m+1}{m}} + N_{10} p^{-\frac{4m+1}{m}} + N_{11} p + N_{12} p^{\frac{m+1}{m}} + N_{13} p^{\frac{m-2}{m}} + \\ + N_{14} p^{\frac{m-3}{m}} + N_{15} p^{\frac{m-4}{m}} + N_{16} p^{\frac{m-5}{m}} \end{array}\right) dp \end{array}\right] = 0$$

$$v = \frac{f}{G}\ W$$

(6.26)

$$T = \frac{Pv}{ZR} = \frac{f}{GR}\cdot\frac{PW}{Z} \qquad (6.27)$$

$$m = \frac{\lg P - \lg P_0}{\lg(PT_0) - \lg(P_0 T)} \qquad (6.28)$$

6.3. Методика определения силы натяжения гибкого весомого клиновидного ремня

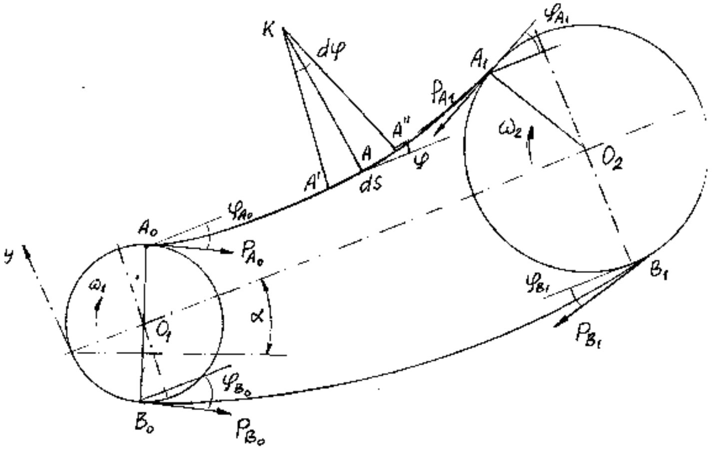


Рис. 6.16. Клиновидная гибкая связь.

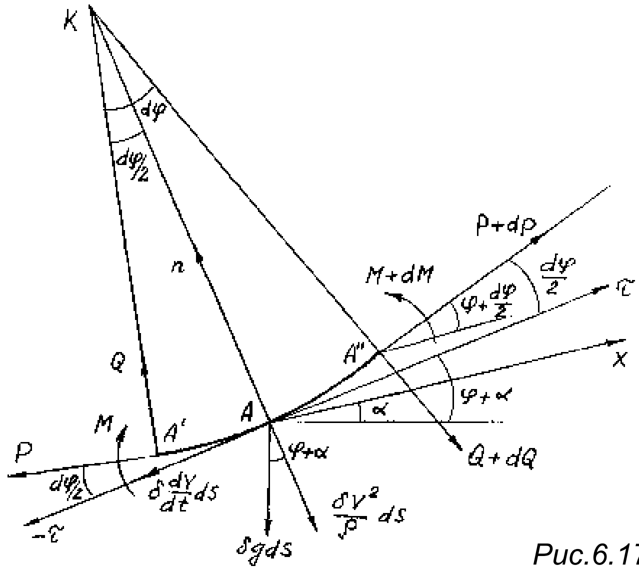


Рис.6.17. Элемент гибкого клиновидного ремня

$$-P\cos\frac{d\varphi}{2}-\delta\frac{dV}{dt}dS-\delta g ds\sin(\varphi+\alpha)+(P+dP)\cos\frac{d\varphi}{2}+Q\sin\frac{d\varphi}{2}+(Q+dQ)\sin\frac{d\varphi}{2}=0$$

(6.29)

$$P\sin\frac{d\varphi}{2}+Q\cos\frac{d\varphi}{2}-\delta g ds\cos(\varphi+\alpha)-$$

$$-(Q+dQ)\cos\frac{d\varphi}{2}-\frac{\delta V^2}{\rho}ds+(P+dP)\sin\frac{d\varphi}{2}=0$$

(6.30)

$$-P\frac{ds}{2}\sin\frac{d\varphi}{4}+(P+dP)\frac{ds}{2}\sin\frac{d\varphi}{4}-Q\frac{ds}{2}\cos\frac{d\varphi}{4}-$$

$$-(Q+dQ)\frac{ds}{2}\cos\frac{d\varphi}{4}-M+(M+dM)=0$$

(6.31)

$$M=\frac{EJ}{\rho}=EJ\frac{d\varphi}{ds},$$

$$Q=\frac{dM}{ds}=EJ\frac{d^2\varphi}{ds^2};\frac{dQ}{ds}=EJ\frac{d^3\varphi}{ds^3}$$

$$\left.\begin{aligned}\frac{dP}{ds}-\delta V\frac{dV}{ds}+EJ\frac{d\varphi}{ds}\cdot\frac{d^2\varphi}{ds^2}&=\delta g\sin(\varphi+\alpha)\\ P\frac{d\varphi}{ds}-\frac{\delta V^2}{\rho}-EJ\frac{d^3\varphi}{ds^3}&=\delta g\cos(\varphi+\alpha)\end{aligned}\right\}\qquad(6.33)$$

$$ds = (1+\Delta\varepsilon)ds_o = \left(1+\frac{P-P_o}{EF}\right)ds_o$$

$$V = \left(1+\frac{P-P_o}{EF}\right)V_o \quad , \qquad \delta = \frac{\delta_o}{\left(1+\frac{P-P_o}{EF}\right)}$$

$$A\frac{dP}{ds}+BP\frac{dP}{ds}+DEJ\frac{d\varphi}{ds}\cdot\frac{d^2\varphi}{ds^2}+\frac{J}{F}P\frac{d\varphi}{ds}\cdot\frac{d^2\varphi}{ds^2} = g\delta_o(\cos\alpha\sin\varphi+\sin\alpha\cos\varphi)$$

(6.39)

$$DEJ\frac{d^3\varphi}{ds^3}+\frac{J}{F}P\frac{d^3\varphi}{ds^3}+H\frac{d\varphi}{ds}-CP\frac{d\varphi}{ds}-BP^2\frac{d\varphi}{ds} = g\delta_o(\cos\alpha\sin\varphi-\sin\alpha\cos\varphi)$$

(6.40)

где: $A = \left(1-\frac{P_o}{EF}\right)\left(1-\frac{\delta_o V_o^2}{EF}\right); \quad B = \frac{1}{EF}\left(1-\frac{\delta_o V_o^2}{EF}\right);$

$$C = \left(1-\frac{P_o}{EF}\right)\left(1-\frac{2\delta_o V_o^2}{EF}\right); \quad D = 1-\frac{P_o}{EF}; \qquad H = \delta_o V_o^2\left(1-\frac{P_o}{EF}\right)^2;$$

$$P = a_o + a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4 ,$$

(6.41)

$$\varphi = b_o + b_1 s + b_2 s^2 + b_3 s^3 + b_4 s^4 ,$$

(6.42)

при $S = S_o$ $P = P_{A_O}$ и $\varphi = \varphi_{A_O}$

при $S = S_1$ $P = P_{A_1}$ и $\varphi = \varphi_{A_1}$

$$\varphi_{A_O} = \frac{\pi}{2} - \frac{S_O}{R_1}$$

(6.45)

$$\left.\begin{aligned}
P_{A_o} &= a_o + a_1 s_o + a_2 s_o^2 + a_3 s_o^3 + a_4 s_o^4 \\
\varphi_{A_o} &= b_o + b_1 s_o + b_2 s_o^2 + b_3 s_o^3 + b_4 s_o^4 \\
P_{A_1} &= a_o + a_1 s_1 + a_2 s_1^2 + a_3 s_1^3 + a_4 s_1^4 \\
\varphi_{A_1} &= b_o + b_1 s_1 + b_2 s_1^2 + b_3 s_1^3 + b_4 s_1^4
\end{aligned}\right\}$$

(6.46)

$$\left(1 - \frac{1}{2} b_o^2\right)(S_1 - S_o) - \frac{b_o b_1}{2}\left(S_1^2 - S_o^2\right) - \frac{1}{3}\left(2b_o b_2 + b_1^2\right)\left(S_1^3 - S_O^3\right) - \frac{1}{4}\left(b_o b_3 + b_1 b_2\right) \times$$

$$\times \left(S_1^4 - S_o^4\right) - \frac{1}{10}\left(2b_o b_4 + 2b_1 b_3 + b_2^2\right)\left(S_1^5 - S_O^5\right) = R_1 \sin\varphi_{A_o} + 0_1 0_2 - R_2 \sin\varphi_{A_1}$$

(6.47)

$$b_o\left(S_1 - S_o\right) - \frac{b_1}{2}\left(S_1^2 - S_O^2\right) + \frac{b_2}{3}\left(S_1^3 - S_O^3\right) + \frac{b_3}{4}\left(S_1^4 - S_O^4\right) + \frac{b_4}{5}\left(S_1^5 - S_O^5\right) = R_2 \cos\varphi_{A_1} - R_1 \cos\varphi_{A_o}$$

(6.48)

$$P_{B_1} = P_{A_1} + Q$$

$$-P_{A_O} V_{A_O} + P_{B_O} V_{B_O} - N_{TP_1} = -P_{A_1} V_{A_1} + P_{B_1} V_{B_1} - N_{TP_2}$$

(6.49)

6.4. Методика определения натяжения клиновидного ремня на участке обхвата шкивов гибкой передачи

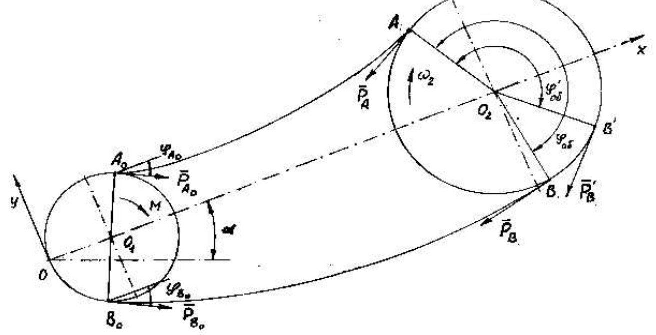


Рис. 6.18.Схема клиноременной передачи

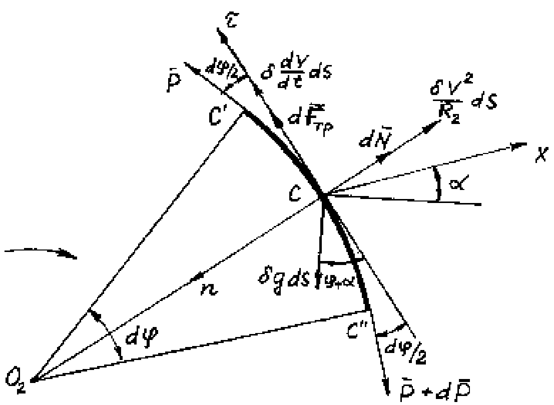


Рис.6.19.Элемент гибкого ремня на участке обхвата шкива

$$dF_{mp} - (P + dP)\cos\frac{d\varphi}{2} + \delta\frac{dv}{dt}ds + P\cos\frac{d\varphi}{2} - \delta g ds(\varphi + \alpha) = 0$$

(6.50)

$$\delta g ds\, sin(\varphi + \alpha) + (P + dP)\, sin\frac{d\varphi}{2} + P\, sin\frac{d\varphi}{2} - \frac{\delta v^2}{R_2}ds - dN = 0$$

(6.51)

$$\Delta\varepsilon = \frac{P - P_A}{EF}, ds = \left(1 + \frac{P - P_A}{EF}\right)ds_A, v = \left(1 + \frac{P - P_A}{EF}\right)v_A, dv = \frac{v_A}{EF}dP, \delta = \frac{\delta_A}{1 + \frac{P - P_A}{EF}}$$

(6.52)

$$adP - f(aP - b)d\varphi + \frac{g\delta_A R_2}{1 + \frac{P - P_A}{EF}} \times [f\sin(\varphi + \alpha) + \cos(\varphi + \alpha)]d\varphi = 0$$

(6.54)

где $a = 1 - \frac{\delta_A v_A{}^2}{EF}, b = \delta_A v_A{}^2\left(1 - \frac{P_A}{EF}\right)$

$$\frac{adP}{aP - b} = fd\varphi \; .$$

$$P=\frac{b}{a}+\left(P_A-\frac{b}{a}\right)e^{f\varphi}.$$

(6.56)

$$a\left(1-\frac{P_A}{EF}\right)dP+\frac{a}{EF}PdP-de^{f\varphi}\left(1-c+e^{f\varphi}\right)d\varphi+g\delta_A R_2\left[f\sin(\varphi+\alpha)+\cos(\varphi+\alpha)\right]d\varphi=0,$$

где ,
$$d=f\left(aP_A-b\right),c=\frac{1}{EF}\left(P_A-\frac{b}{a}\right).$$

$$a\left(1-\frac{P}{EF}\right)(P-P_A)+\frac{a}{2EF}\left(P^2-P_A{}^2\right)-\frac{d(1-c)}{f}\left(e^{f\varphi}-1\right)-\frac{cd}{2f}\left(e^{2f\varphi}-1\right)-$$
$$fg\delta_A R_2\left[\cos(\varphi+\alpha)-\cos\alpha\right]+g\delta_A R_2\left[\sin(\varphi+a)-\sin\alpha\right]=0$$

(6.57)

$$\Delta\varepsilon = \frac{P - P_A}{EF} = \frac{b}{aEF} + \left(P_A - \frac{b}{a}\right)\frac{1}{EF}e^{f\varphi} - \frac{P_A}{EF} = c\left(e^{f\varphi} - 1\right)$$

$$\Delta l_2 = \int_0^{s`_{об}} \frac{\Delta\varepsilon}{1+\Delta\varepsilon}ds = \int_0^{\varphi'_{об}} \frac{cR_2 e^{f\varphi}d\varphi}{1 - c - ce^{f\varphi}} - \int_0^{\varphi`_{об}} \frac{cR_2 d\varphi}{1 - c + ce^{f\varphi}} =$$

$$= \frac{R_2}{f(1-c)}\ln\left(1 - c + e^{f\varphi'_{об}}\right) - \frac{cR_2\varphi`_{об}}{1-c}$$

$$d^2A_{mp} = dF_{mp}.\Delta\varepsilon.ds_A = dF_{mp}\frac{P - P_A}{EF}ds_A.$$

(6.59)

$$dF_{mp} = adP + g\delta ds\cos(\varphi + \alpha).$$

$$d^2A_{mp} = ads_A\frac{P - P_A}{EF}dP + g\delta_A R_2 ds_A\frac{ce^{f\varphi} - c}{1 + ce^{f\varphi} - c}\cos(\varphi + \alpha)d\varphi.$$

$$dA_{mp} = \frac{ads_A}{2EF}(P_B - P_A)^2 - g\delta_A R_2 ds_A c(1+c)\times$$
$$\times\left[\sin\left(\varphi'_{об} + \alpha\right) - \sin\alpha\right] - g\delta_A R_2 ds_A c(1+2c)\times$$

$$\times \sin\alpha\left[\frac{e^{f\varphi_o'}}{f^2+1}\left(f\sin\varphi_{об}'-\cos\varphi_{об}'\right)+\frac{1}{f^2+1}\right]+g\delta_A R_2 ds_A c(1+2c)\times$$

$$\times\cos\alpha\left[\frac{e^{f\varphi_{об}'}}{f^2+1}\left(f\cos\varphi_{об}'+\sin\varphi_{об}'\right)-\frac{f}{f^2+1}\right]+g\delta_A R_2 ds_A c^2\sin\alpha\left[\frac{e^{2f\varphi_o'}}{4f^2+1}\times\right.$$

$$\left.\times\left(2f\sin\varphi_{об}'-\cos\varphi_{об}'\right)+\frac{1}{4f^2+1}\right]-g\delta_A R_2 ds_A c^2\times$$

$$\times\cos\alpha\left[\frac{e^{2f\varphi_o'}}{4f^2+1}\left(2f\cos\varphi_{об}'+\sin\varphi_{об}'\right)-\frac{2f}{4f^2+1}\right]$$

$$N_{mp}=\frac{av_A}{2EF}(P_B-P_A)^2-g\delta_A R_2 v_A c(1+c)\left[\sin\left(\varphi_{об}'+\alpha\right)-\sin\alpha\right]-g\delta_A R_2 v_A c(1+2c)\times$$

$$\times\sin\alpha\left[\frac{e^{f\varphi_o'}}{f^2+1}\left(f\sin\varphi_{об}'-\cos\varphi_{об}'\right)+\frac{1}{f^2+1}\right]+g\delta_A R_2 v_A c(1+2c)\times$$

$$\times\cos\alpha\left[\frac{e^{f\varphi_{об}'}}{f^2+1}\left(f\cos\varphi_{об}'+\sin\varphi_{об}'\right)-\frac{f}{f^2+1}\right]+g\delta_A R_2 v_A c^2\sin\alpha\left[\frac{e^{2f\varphi_{об}'}}{4f^2+1}\times\right.$$

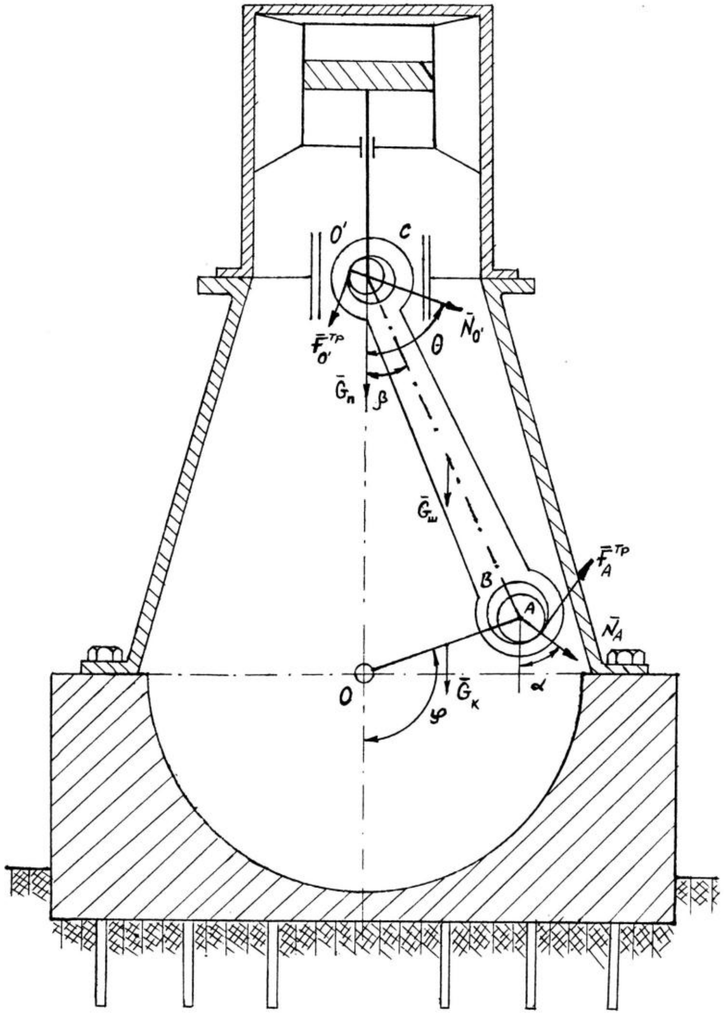
$$\left.\times\left(2f\sin\varphi_{об}'-\cos\varphi_{об}'\right)+\frac{1}{4f^2+1}\right]-g\delta_A R_2 v_A c^2\times$$

$$\times\cos\alpha\left[\frac{e^{2f\varphi_{об}'}}{4f^2+1}\left(2f\cos\varphi_{об}'+\sin\varphi_{об}'\right)-\frac{2f}{4f^2+1}\right]$$

$$
\begin{aligned}
N_{mp_1} &= \frac{aV_{b0}}{2EF}(P_{A_0} - P_{B_0})^2 - g\delta_{B_0} R_1 V_{B_O} C_1 (1 + C_1) \times \\
&\times \left[\sin(\varphi^{|}_{об} + \alpha) - \sin\alpha\right] - -g\delta_{B_0} R_1 V_{B_0} C_1 (1 + 2C_1)\sin\alpha \times \\
&\times \left[\frac{e^{-f\varphi^{|}_{об}}}{f^2+1}(-f\sin\varphi^{|}_{об} + \cos\varphi^{|}_{об}) + \frac{1}{f^2+1}\right] + g\delta_{B_0} R_1 V_{B_0} C_1 (1 + 2C_1)\cos\alpha \times \\
&\times \left[\frac{e^{-f\varphi^{|}_{об}}}{f^2+1}(-f\cos\varphi^{|}_{об} - \sin\varphi^{|}_{об}) + \frac{1}{f^2+1}\right] + g\delta_{B_0} R_1 V_{B_0} C_1^2 \sin\alpha \times \\
&\times \left[\frac{e^{-2f\varphi^{|}_{об}}}{4f^2+1}(-2f\sin\varphi^{|}_{об} - \cos\varphi^{|}_{об}) + \frac{1}{4f^2+1}\right] + g\delta_{B_0} R_1 V_{B_0} C_1^2 \cos\alpha \times \\
&\times \left[\frac{e^{-2f\varphi^{|}_{об}}}{4f^2+1}(-2f\cos\varphi^{|}_{об} + \sin\varphi^{|}_{об}) + \frac{2f}{4f^2+1}\right]
\end{aligned}
\qquad (6.61)
$$

$$
V_{A0} = \left(1 + \frac{P_{A0} - p_{в0}}{EF}\right)V_{B0},\ V_{A1} = \left(1 + \frac{P_{A1} - p_{B0}}{EF}\right)V_{B0},
$$

$$
V_{B1} = \left(1 + \frac{P_{B1} - p_{B0}}{EF}\right)V_{B0},
$$



O'
C
$\bar{N}_{O'}$
$\bar{F}^{TP}_{O'}$
θ
$\bar{G}_n$
β
$\bar{G}_ш$
$\bar{F}^{TP}_A$
B
A
$\bar{N}_A$
O
$\bar{G}_K$
φ
α

$$M\frac{d^2Y_c}{dt^2} = -c\xi \ ,$$

(6.62)

$$У_с = \frac{1}{M}\{2m_1'\ [\frac{1}{2}r\sin(\varphi - 90^0) + a + \xi] + m_1''[r\sin(\varphi - 90^0) +$$
$$a + \xi] + m_2(y_ш + \xi) + m_3(y_{o'} + \xi) + (m_k + m_ф)\cdot\xi\}$$

(6.63)

$$Y_ш = r\cos(180^0 - \varphi) \ + y_{AB} + 0{,}5l\cos\beta + a$$

$$Y_{o'} = -r\cos\varphi + y_{AB} + l\cos\beta + \Delta_2\cos\theta + a$$

(6.64)

$$Y_{AB} = r\frac{\sin\varphi}{tg\alpha} - l\frac{\sin\beta}{tg\alpha} - \Delta_2\frac{\sin\theta}{tg\alpha} \qquad Sin\beta = \frac{1}{l}(r\ \sin\varphi - \Delta_1\sin\alpha - \Delta_2\sin($$

$$Y_c = 1/M\ [M\xi - (m_1 + m_2 + m_3)r\cos\varphi - (m_2 + m_3)r^2\sin^2\varphi/4l + (m_2 + m_3)r(\Delta_1\sin\alpha + \Delta_2\sin\theta)\sin\varphi/2l + (m_2 + m_3)\Delta_1\cos\alpha + m_3\Delta_2\cos\theta + (m_1' + m_1 + m_2 + m_3)a + (0{,}5m_2 + m_3)l]$$

$$M\ddot{\xi} + C\xi = -[(m_1 + m_2 + m_3)r\omega^2 + r\omega/l(m_2 + m_3)(\Delta_1\dot{\alpha}\cos\alpha + \Delta_2\dot{\theta}\cos\theta)]\cos\omega t - r/l(m_2 + m_3)(\Delta_1\ddot{\alpha}\cos\alpha - \Delta_1\dot{\alpha}^2\sin\alpha + \Delta_2\ddot{\theta}\cos\theta - \Delta_2\dot{\theta}^2\sin\theta - \Delta_1\omega^2\sin\alpha - \Delta_2\omega^2\sin\theta)\sin\omega t + 0{,}5r^2\omega^2/l(m_2 + m_3)\cos2\omega t + (m_2 + m_3)(\Delta_1\ddot{\alpha}\sin\alpha + \Delta_1\dot{\alpha}^2\cos\alpha) +$$

(6.66)

$m_3\Delta_2(\ddot{\theta}\sin\theta + \dot{\theta}^2\cos\theta)$

$\xi = A_1(\alpha,\theta)\ \sin\omega t + B_1(\alpha,\theta)\cos\omega t + A_2(\alpha,\theta)\ \sin_2\omega t + B_2(\alpha,\theta)\cos_2\omega t + C(\alpha,\theta)$ (6.67)

$MA_1\omega^2\sin\omega t - MB_1\omega^2\cos\omega t - 4MA_2\omega^2\sin 2\omega t - 4MB_2\omega^2\cos 2\omega t + cA_1\sin\omega t + cB_1\cos\omega t + cA_2\sin 2\omega t + cB_2\cos 2\omega t + C(\alpha,\theta)c = -[(m_1 + m_2 + m_3)r\omega^2 + r\omega/l(m_2+m_3)(\Delta_1\dot{\alpha}\cos\alpha + \Delta_2\dot{\theta}\cos\theta)]\cos\omega t - r/l(m_2+m_3)(\Delta_1\ddot{\alpha}\cos\alpha - \Delta_1\dot{\alpha}^2\sin\alpha + \Delta_2\ddot{\theta}\cos\theta - \Delta_2\dot{\theta}^2\sin\theta - \Delta_1\omega^2\sin\alpha - \Delta_2\omega^2\sin\theta)\sin\omega t + 0{,}5r^2\omega^2/l(m_2+m_3)\cos 2\omega t + (m_2+m_3)(\Delta_1\ddot{\alpha}\sin\alpha + \Delta_1\dot{\alpha}^2\cos\alpha) + m_3\Delta_2(\ddot{\theta}\sin\theta + \dot{\theta}^2\cos\theta)$

$$\xi = A(\alpha,\theta)\sin(\omega t + \gamma_1) + B(\alpha,\theta)\sin(2\omega t + \gamma_2) + C(\alpha,\theta)$$

$$A(\alpha,\theta) = \frac{r}{1 - \dfrac{c}{M\omega^2}} \cdot \frac{m_1 + m_2 + m_3}{M} \cdot \left(1 - \frac{\Delta_1}{\ell} \cdot \frac{\dot{\alpha}}{\omega}\cos\alpha - \frac{\Delta_2}{\ell} \cdot \frac{\dot{\theta}}{\omega}\cos\theta\right)$$

Thank you for your attentions!