Подключение библиотек

Основные уравнения, алгоритмы, зависимости и ф-и

Параметры расчета

Исходные данные

Коэф. запаса: $safety = 1.3$

Степень двухконтурности: $m2 = 6$

РТ: Воздух

$compressor = "Вл"$

Число Маха: $M = 0$

Геометрическая высота работы (м): $H = 0$

Массовый расход (кг/с):

$$G = \begin{vmatrix} 35.65 + 213.93 \ \text{if compressor} = "Вл" \\ 35.65 \ \text{if compressor} = "КНД" \\ 34.81 \ \text{if compressor} = "КВД" \end{vmatrix} = 249.58$$

Полная температура на входе в К (К):

$$T^*_{K1} = \begin{vmatrix} 418.2 \ \text{if compressor} = "КВД" \\ 288.2 \ \text{otherwise} \end{vmatrix} = 288.2$$

Полное давление на входе в К (Па):

$$P^*_{K1} = \begin{vmatrix} 316.2 \cdot 10^3 \ \text{if compressor} = "КВД" \\ 101325 \ \text{otherwise} \end{vmatrix} = 101.3 \cdot 10^3$$

Степень повышения давления КВД:

$$\pi^*_K = \begin{vmatrix} 1.6 \ \text{if compressor} = "Вл" \\ \frac{3.2}{1.6} \ \text{if compressor} = "КНД" \\ 9 \ \text{if compressor} = "КВД" \end{vmatrix} = 1.600$$

Ожидаемый адиабатический КПД ОК: $\eta^*_K = \begin{vmatrix} 0.86 \text{ if compressor} = \text{"Вл"} \\ 0.87 \text{ if compressor} = \text{"КНД"} \\ 0.88 \text{ if compressor} = \text{"КВД"} \end{vmatrix} = 86.00 \cdot \%$

Частота вращения ротора (с$^{-1}$): $\omega = \begin{vmatrix} 1570.8 \text{ if compressor} = \text{"КВД"} \\ 555 \text{ otherwise} \end{vmatrix} = 555.0$

Относ. диаметр корня 1ой ступени [14, с.7]: $\overline{d}_1 = \begin{vmatrix} 0.40 \text{ if compressor} = \text{"Вл"} \\ 0.75 \text{ if compressor} = \text{"КНД"} \\ 0.65 \text{ if compressor} = \text{"КВД"} \end{vmatrix} = 0.40$

$0.3 \le \overline{d}_1 \le 0.6 = 1$

Частота вращения ротора (об/мин): $n = \dfrac{60 \cdot \omega}{2 \cdot \pi} = 5300$

Закон профилирования проточной части (ЗППЧ):

$$\text{ЗППЧ} = \left(\begin{vmatrix} \text{"пер" if compressor = "Вл"} \\ \text{"пер" if compressor = "КНД"} \\ \text{"ср" if compressor = "КВД"} \end{vmatrix} \;\; \begin{vmatrix} \text{"пер" if compressor = "Вл"} \\ \text{"0.96" if compressor = "КНД"} \\ \text{"ср" if compressor = "КВД"} \end{vmatrix} \;\; \begin{vmatrix} \text{"пер" if compressor = "Вл"} \\ \text{"0.92" if compressor = "КНД"} \\ \text{"кор" if compressor = "КВД"} \end{vmatrix} \;\; \text{"кор" "кор" "кор" "кор" "кор" "кор" "пер" "пер" "пер" "пер" "пер" "пер"} \right)^T$$

Относ. параметры по относительным ступеням:

$$\begin{pmatrix} z_{\sim} \\ R_{L\sim cp} \\ K_{\sim H} \\ \eta^*_{\sim} \\ \overline{c}_{\sim a1} \\ \overline{H}_{\sim T} \end{pmatrix} = \begin{bmatrix} (1\ 2\ 3\ 4\ 5\ 6\ 7\ 8)^T \\ (0.5\ 0.5\ 0.5\ 0.5\ 0.5\ 0.5\ 0.5\ 0.5)^T \\ (0.99\ 0.98\ 0.97\ 0.96\ 0.95\ 0.95\ 0.95\ 0.95)^T \\ (0.88\ 0.89\ 0.905\ 0.91\ 0.91\ 0.905\ 0.89\ 0.88)^T \\ (0.435\ 0.425\ 0.415\ 0.405\ 0.395\ 0.385\ 0.375\ 0.365)^T \\ (0.25\ 0.29\ 0.32\ 0.33\ 0.35\ 0.32\ 0.29\ 0.27)^T \end{bmatrix}$$

Тип компрессора	Номер ступени и $\overline{L}_{CT.i}$							
	I	II	III	IV	z_{CP}	z - 2	z - 1	z
Дозвуковой	0,18-0,20	0,24-0,25	0,24-0,25	0,29-0,30	0,30-0,32	0,28-0,29	0,27-0,28	0,26-0,27
Трансзвуковой	0,19-0,22	0,27-0,29	0,30-0,32	0,32-0,33	0,33-0,35	0,31-0,32	0,27-0,28	0,26-0,27
С одной св/зв ступенью	0,23-0,25	0,27-0,29	0,30-0,32	0,32-0,33	0,33-0,35	0,31-0,32	0,27-0,28	0,26-0,27
С 2-мя св/зв ступенями	0,23-0,25	0,27-0,29	0,30-0,32	0,32-0,33	0,33-0,35	0,31-0,32	0,27-0,28	0,26-0,27
С 3-мя св/зв ступенями	0,23-0,25	0,27-0,29	0,30-0,32	0,32-0,33	0,33-0,35	0,31-0,32	0,27-0,28	0,25-0,26

[16, с. 60]

[18, с. 24]

Уточнение параметров:

$$R_{L\sim cp} = R_{L\sim cp} + \begin{vmatrix} 0.0 & \text{if compressor} = \text{"Вл"} \\ 0.1 & \text{if compressor} = \text{"КНД"} \\ 0.2 & \text{if compressor} = \text{"КВД"} \end{vmatrix}$$

увеличение несущественно увеличивает π

$$\bar{c}_{\sim a1} = \bar{c}_{\sim a1} - \begin{vmatrix} 0.10 & \text{if compressor} = \text{"Вл"} \\ 0.141 & \text{if compressor} = \text{"КНД"} \\ 0.213 & \text{if compressor} = \text{"КВД"} \end{vmatrix}$$

понижение существенно увеличивает π

$$\eta^*_\sim = \eta^*_\sim + \begin{vmatrix} -0.020 & \text{if compressor} = \text{"Вл"} \\ -0.028 & \text{if compressor} = \text{"КНД"} \\ -0.017 & \text{if compressor} = \text{"КВД"} \end{vmatrix}$$

увеличение несущественно увеличивает π

$$\bar{H}_{\sim T} = \bar{H}_{\sim T} + \begin{vmatrix} 0.0145 & \text{if compressor} = \text{"Вл"} \\ 0.0164 & \text{if compressor} = \text{"КНД"} \\ 0.0183 & \text{if compressor} = \text{"КВД"} \end{vmatrix}$$

[16, с. 234]

увеличение существенно увеличивает π

$$\text{stack}\left(R_{L\sim cp}{}^T, K_{\sim H}{}^T, \eta^*_\sim{}^T, \bar{c}_{\sim a1}{}^T, \bar{H}_{\sim T}{}^T\right) =$$

	1	2	3	4	5	6	7	8
1	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
2	0.990	0.980	0.970	0.960	0.950	0.950	0.950	0.950
3	0.860	0.870	0.885	0.890	0.890	0.885	0.870	0.860
4	0.335	0.325	0.315	0.305	0.295	0.285	0.275	0.265
5	0.265	0.305	0.335	0.345	0.365	0.335	0.305	0.285

$$0.15 \le \bar{c}_{\sim a1}{}^T = (1\ 1\ 1\ 1\ 1\ 1\ 1\ 1)$$

$$\bar{c}_{\sim a1}{}^T \le 0.65 = (1\ 1\ 1\ 1\ 1\ 1\ 1\ 1)$$

$$0.18 \le \bar{H}_{\sim T}{}^T = (1\ 1\ 1\ 1\ 1\ 1\ 1\ 1)$$

$$\bar{H}_{\sim T}{}^T \le 0.35 = (1\ 1\ 1\ 1\ 0\ 1\ 1\ 1)$$

Коэф. теор. напора "средней" ступени [14, с. 11]:
$$\bar{H}_{Tcp} = \frac{\sum_{i=1}^{\text{rows}(z_\sim)} \bar{H}_{\sim T_i}}{\text{rows}(z_\sim)} = 0.317$$

$$0.25 \le \bar{H}_{Tcp} \le 0.32 = 1$$

Исходные данные

Распределение основных параметров ОК по ступеням

Кинематическая степень реактивности: $R_{L\sim cp}(i) = \text{interp}\left(\text{lspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, R_{L\sim cp}\right), \frac{z_\sim}{\text{rows}(z_\sim)}, R_{L\sim cp}, i\right)$

Коэф. уменьшения теор. напора: $K_{\sim H}(i) = \text{interp}\left(\text{lspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, K_{\sim H}\right), \frac{z_\sim}{\text{rows}(z_\sim)}, K_{\sim H}, i\right)$

Изоэнтропический КПД: $\eta^*_\sim(i) = \text{interp}\left(\text{lspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, \eta^*_\sim\right), \frac{z_\sim}{\text{rows}(z_\sim)}, \eta^*_\sim, i\right)$

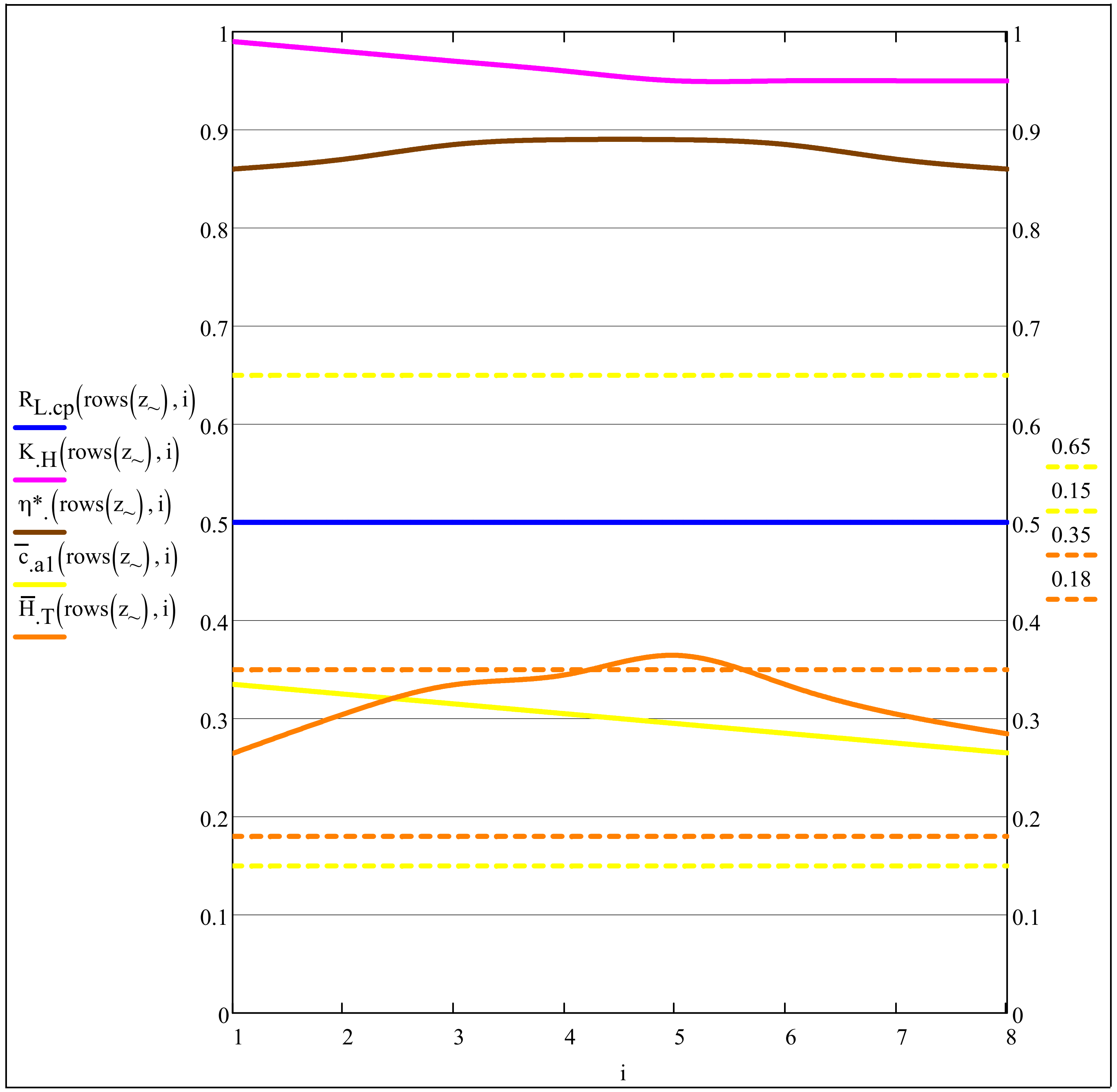
Коэф. расхода: $\bar{c}_{\sim a1}(i) = \text{interp}\left(\text{lspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, \bar{c}_{\sim a1}\right), \frac{z_\sim}{\text{rows}(z_\sim)}, \bar{c}_{\sim a1}, i\right)$

Коэф. напора: $\bar{H}_{\sim T}(i) = \text{interp}\left(\text{lspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, \bar{H}_{\sim T}\right), \frac{z_\sim}{\text{rows}(z_\sim)}, \bar{H}_{\sim T}, i\right)$

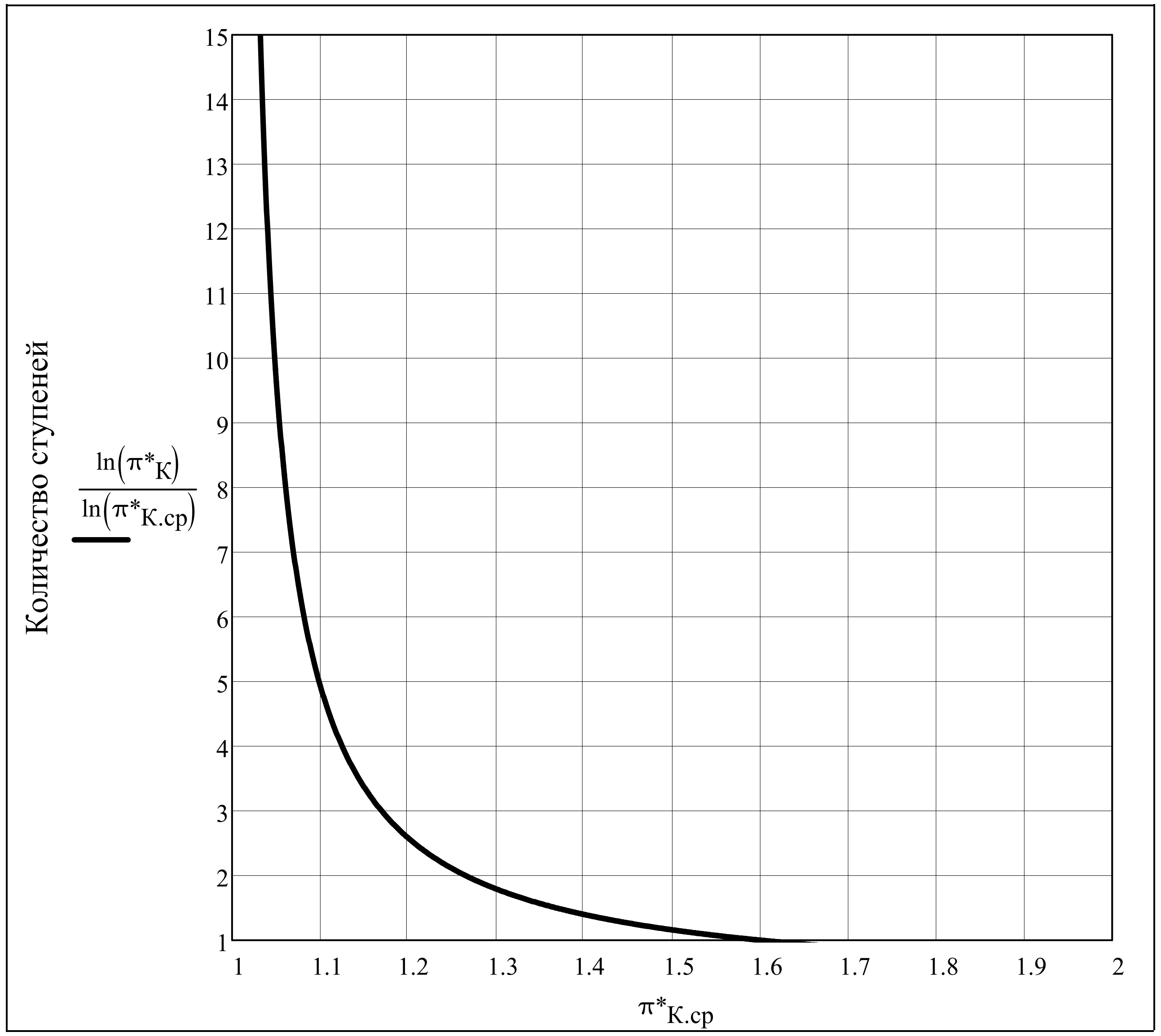
$$\begin{pmatrix} R_{L.cp} \\ K_{.H} \\ \eta^*_{.} \\ \overline{c}_{.a1} \\ \overline{H}_{.T} \end{pmatrix} = \left| \begin{array}{l}
R_{L.cp}(Z,i) = \left| \begin{array}{ll} R_{L\sim cp}\left(\dfrac{1}{rows(z_{\sim})}\right) & \text{if } i < 1 \\ R_{L\sim cp}(1) & \text{if } i > Z \\ R_{L\sim cp}\left(\dfrac{i}{Z}\right) & \text{otherwise} \end{array} \right. \\
K_{.H}(Z,i) = \left| \begin{array}{ll} K_{\sim H}\left(\dfrac{1}{rows(z_{\sim})}\right) & \text{if } i < 1 \\ K_{\sim H}(1) & \text{if } i > Z \\ K_{\sim H}\left(\dfrac{i}{Z}\right) & \text{otherwise} \end{array} \right. \\
\eta^*_{.}(Z,i) = \left| \begin{array}{ll} \eta^*_{\sim}\left(\dfrac{1}{rows(z_{\sim})}\right) & \text{if } i < 1 \\ \eta^*_{\sim}(1) & \text{if } i > Z \\ \eta^*_{\sim}\left(\dfrac{i}{Z}\right) & \text{otherwise} \end{array} \right. \\
\overline{c}_{.a1}(Z,i) = \left| \begin{array}{ll} \overline{c}_{\sim a1}\left(\dfrac{1}{rows(z_{\sim})}\right) & \text{if } i < 1 \\ \overline{c}_{\sim a1}(1) & \text{if } i > Z \\ \overline{c}_{\sim a1}\left(\dfrac{i}{Z}\right) & \text{otherwise} \end{array} \right. \\
\overline{H}_{.T}(Z,i) = \left| \begin{array}{ll} \overline{H}_{\sim T}\left(\dfrac{1}{rows(z_{\sim})}\right) & \text{if } i < 1 \\ \overline{H}_{\sim T}(1) & \text{if } i > Z \\ \overline{H}_{\sim T}\left(\dfrac{i}{Z}\right) & \text{otherwise} \end{array} \right. \\
\left(R_{L.cp} \;\; K_{.H} \;\; \eta^*_{.} \;\; \overline{c}_{.a1} \;\; \overline{H}_{.T}\right)^{T}
\end{array} \right.$$

$$\begin{pmatrix} Z_{temp} \\ i_{temp} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} R_{L.cp}(Z_{temp}, i_{temp}) \\ K_{.H}(Z_{temp}, i_{temp}) \\ \eta^*_{.}(Z_{temp}, i_{temp}) \\ \overline{c}_{.a1}(Z_{temp}, i_{temp}) \\ \overline{H}_{.T}(Z_{temp}, i_{temp}) \end{pmatrix} = \begin{pmatrix} 0.500 \\ 0.950 \\ 0.860 \\ 0.265 \\ 0.285 \end{pmatrix}$$



Распределение основных параметров ОК по ступеням



Количество ступеней
$\frac{\ln(\pi^*_K)}{\ln(\pi^*_{K.cp})}$
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
$\pi^*_{K.cp}$

Нулевые приближения

Показатель адиаьаты перед К []: $k_{К1} = k_{ад}\left(Cp_{воздух}\left(P*_{К1}, T*_{К1}\right), R_в\right) = 1.401$

Полное давление после К [Па]: $P*_{К3} = \pi*_К \cdot P*_{К1} = 162 \cdot 10^3$

$$\begin{pmatrix} iteration_3 \\ T*_{К3} \\ k_{К3} \end{pmatrix} = \left| \begin{array}{l} iteration_3 = 0 \\ k_{К3} = k_{К1} \\ \text{while } 0 < 1 \\ \quad \left| \begin{array}{l} iteration_3 = iteration_3 + 1 \\ trace\left(\text{"iteration.3 = "}, num2str\left(iteration_3\right)\right) \\ k_{ср} = mean\left(k_{К1}, k_{К3}\right) \\ T*_{К3} = T*_{К1} \cdot \left(1 + \dfrac{\pi*_К^{\frac{k_{ср}-1}{k_{ср}}} - 1}{\eta*_К}\right) \\ Cp_{К3} = Cp_{воздух}\left(P*_{К3}, T*_{К3}\right) \\ k'_{К3} = k_{ад}\left(Cp_{К3}, R_в\right) \\ \text{if } \left|eps\left(\text{"rel"}, k_{К3}, k'_{К3}\right)\right| \le epsilon \\ \quad \left| \begin{array}{l} k_{К3} = k'_{К3} \\ break \end{array} \right. \\ k_{К3} = k'_{К3} \end{array} \right. \\ \begin{pmatrix} iteration_3 \\ T*_{К3} \\ k_{К3} \end{pmatrix} \end{array} \right.$$

Количество итераций []: $iteration_3 = 1$

Полная температура после К [К]: $T*_{К3} = 336.5$

Показатель адиаьаты после К []: $k_{К3} = 1.399$

Полная плотность перед и после К [кг/м^3]: $\begin{pmatrix} \rho*_{К1} \\ \rho*_{К3} \end{pmatrix} = \dfrac{1}{R_в} \cdot \begin{pmatrix} \dfrac{P*_{К1}}{T*_{К1}} \\ \dfrac{P*_{К3}}{T*_{К3}} \end{pmatrix} = \begin{pmatrix} 1.224 \\ 1.678 \end{pmatrix}$

Критические скорости перед и после К [м/с]: $\begin{pmatrix} a*_{с.вх} \\ a*_{с.вых} \end{pmatrix} = \begin{pmatrix} a_{кр}\left(k_{К1}, R_в, T*_{К1}\right) \\ a_{кр}\left(k_{К3}, R_в, T*_{К3}\right) \end{pmatrix} = \begin{pmatrix} 310.8 \\ 335.7 \end{pmatrix}$

Ср. показатель адиабаты К []: $k_{ср} = k_{ад}\left(Cp_{воздух.ср}\left(P*_{К1}, P*_{К3}, T*_{К1}, T*_{К3}\right), R_в\right) = 1.401$

Теоретический напор [Дж/кг]: $H_{ТК} = \dfrac{Cp_{воздух.ср}\left(P*_{К1}, P*_{К3}, T*_{К1}, T*_{К3}\right) \cdot T*_{К1} \cdot \left(\pi*_К^{\frac{k_{ср}-1}{k_{ср}}} - 1\right)}{\eta*_К} = 48.4 \cdot 10^3$

$$\begin{pmatrix} iteration_u \\ u_{1пер} \\ Z_{recomend} \\ c_{вх} \\ \lambda_{вх} \\ \rho_{K1} \end{pmatrix} = \left| \begin{array}{l} iteration_u \leftarrow 0 \\ \rho_{K1} \leftarrow \rho^*_{K1} \\ \text{while } 0 < 1 \\ \quad \left| \begin{array}{l} iteration_u \leftarrow iteration_u + 1 \\ trace\left(concat\left(\text{"iteration.u = "}, num2str\left(iteration_u\right)\right)\right) \\ u_{1пер} \leftarrow \sqrt[3]{\dfrac{\pi \cdot G \cdot n^2}{900 \cdot \overline{c}_{.a1}(1,0) \cdot \rho_{K1} \cdot \left[1 - \left(\overline{d}_1\right)^2\right]}} \\ Z_{recomend} \leftarrow \max\left(round\left(\dfrac{H_{TK}}{\overline{H}_{Tcp} \cdot u_{1пер}^2}\right), 1\right) \\ c_{вх} \leftarrow \overline{c}_{.a1}\left(Z_{recomend}, 0\right) \cdot u_{1пер} \\ \lambda_{вх} \leftarrow \dfrac{c_{вх}}{a^*_{c.вх}} \\ \rho'_{K1} \leftarrow \rho^*_{K1} \cdot ГДФ\left(\text{"ρ"}, \lambda_{вх}, k_{K1}\right) \\ \text{if } \left|eps\left(\text{"rel"}, \rho'_{K1}, \rho_{K1}\right)\right| \le epsilon \\ \quad \left| \begin{array}{l} \rho_{K1} \leftarrow \rho'_{K1} \\ break \end{array} \right. \\ \rho_{K1} \leftarrow \rho'_{K1} \end{array} \right. \\ \begin{pmatrix} iteration_u \\ u_{1пер} \\ Z_{recomend} \\ c_{вх} \\ \lambda_{вх} \\ \rho_{K1} \end{pmatrix} \end{array} \right.$$

Количество итераций []: $iteration_u = 2$

Окружная скорость на перифкрии перед К [м/с]: $u_{1пер} = 425.9$

Рекомендуемое количество ступеней []: $Z_{recomend} = 1$

Абс. скорость перед К [м/с]: $c_{вх} = 142.7$

Приведенная скорость перед К []: $\lambda_{вх} = 0.4591$

Плотность перед К [кг/м^3]: $\rho_{K1} = 1.120$

Кольцевая площадь перед К [м^2]: $F_{вх} = \dfrac{G \cdot \sqrt{R_в \cdot T^*_{K1}}}{m_q\left(k_{K1}\right) \cdot P^*_{K1} \cdot ГДФ\left(\text{"G"}, \lambda_{вх}, k_{K1}\right)} = 1.5621$

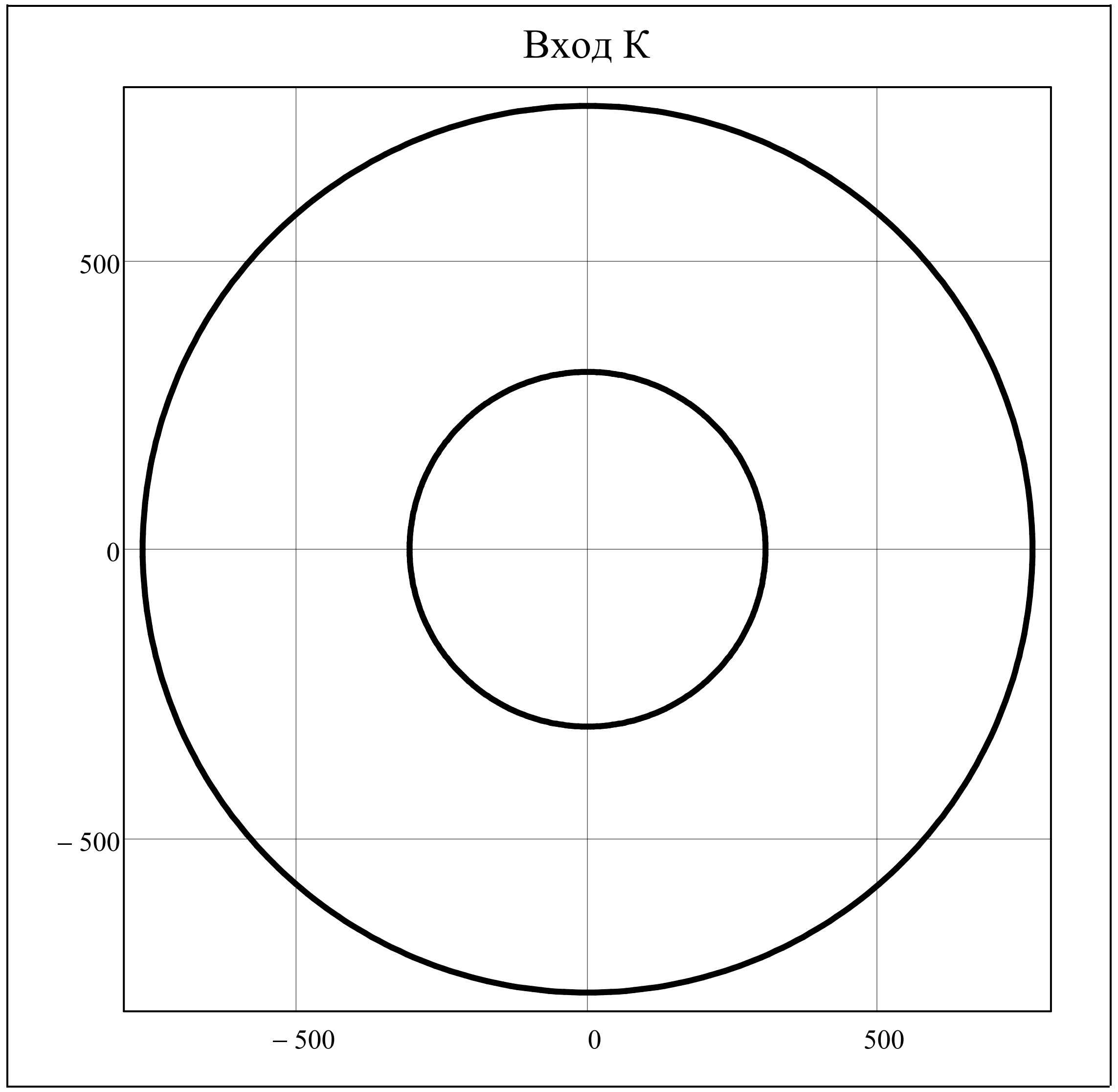
Диамтеры перед К [м]:

$$D'_{пер1} = \frac{2 \cdot u_{1пер}}{\omega} = 1534.9 \cdot 10^{-3}$$

$$D'_{ср1} = \overline{r}_{ср}\left(\overline{d}_1\right) \cdot D'_{пер1} = 1169 \cdot 10^{-3}$$

$$D'_{кор1} = \overline{d}_1 \cdot D'_{пер1} = 614 \cdot 10^{-3}$$

$$\varphi := 0, \frac{2\cdot\pi}{360} .. 2\cdot\pi$$



Рекомендуемое количество ступеней []: $Z_{recomend} = 1$

Количество ступеней []:
$$Z := \begin{vmatrix} 1 \text{ if } compressor = \text{"Вл"} \\ 3 \text{ if } compressor = \text{"КНД"} \\ 9 \text{ if } compressor = \text{"КВД"} \end{vmatrix} = 1$$

Нулевые приближения

$$BHA = \begin{cases} 1 & \text{if } compressor = \text{"КВД"} \\ 0 & \text{otherwise} \end{cases} = 0$$

Расчет ВНА:

$$\begin{pmatrix} \alpha_{1BHA} & \alpha_{3BHA} \\ \sigma_{BHA} & \sigma_{BHA} \\ \overline{d}_{1BHA} & \overline{d}_{3BHA} \\ T^*_{1BHA} & T^*_{3BHA} \\ P^*_{1BHA} & P^*_{3BHA} \\ \rho^*_{1BHA} & \rho^*_{3BHA} \\ k_{1BHA} & k_{3BHA} \\ a_{кр1BHA} & a_{кр3BHA} \\ \overline{c}_{a1BHA} & \overline{c}_{a3BHA} \\ \overline{c}_{u1BHA} & \overline{c}_{u3BHA} \\ c_{a1BHA} & c_{a3BHA} \\ c_{u1BHA} & c_{u3BHA} \\ c_{1BHA} & c_{3BHA} \\ \lambda_{1BHA} & \lambda_{3BHA} \\ F_{1BHA} & F_{3BHA} \\ \varepsilon_{BHA} & \varepsilon_{BHA} \end{pmatrix} = \left| \begin{array}{l} \text{for } r \in av(N_r) \\ \quad \left| \begin{array}{l} \alpha_{1BHA_r} \leftarrow 90° \\ \overline{d}_{1BHA} \leftarrow \overline{d}_1 \\ \overline{d}_{3BHA} \leftarrow \overline{d}_{1BHA} \\ T^*_{1BHA_r} \leftarrow T^*_{K1} \\ T^*_{3BHA_r} \leftarrow T^*_{1BHA_r} \\ P^*_{1BHA_r} \leftarrow P^*_{K1} \\ \rho^*_{1BHA_r} \leftarrow \dfrac{P^*_{1BHA_r}}{R_в \cdot T^*_{1BHA_r}} \\ k_{1BHA_r} \leftarrow k_{ад}\left(Cp_{воздух}\left(P^*_{1BHA_r}, T^*_{1BHA_r}\right), R_в\right) \\ a_{кр1BHA_r} \leftarrow a_{кр}\left(k_{1BHA_r}, R_в, T^*_{1BHA_r}\right) \\ \overline{c}_{a1BHA_r} \leftarrow \overline{c}_{.a1}(Z,0) \\ \overline{c}_{u1BHA_r} \leftarrow \begin{cases} \overline{r}_{cp}\left(\overline{d}_{1BHA}\right)\cdot\left(1 - R_{L.cp}(Z,0)\right) - \dfrac{\overline{H}_{.T}(Z,0)}{2\cdot\overline{r}_{cp}\left(\overline{d}_{1BHA}\right)} & \text{if } BHA = 1 \\ 0 & \text{otherwise} \end{cases} \\ c_{a1BHA_r} \leftarrow \overline{c}_{a1BHA_r} \cdot u_{1пер} \end{array} \right. \end{array} \right.$$

$\sigma_{BHA} = 1.0000$

$submatrix\left(\varepsilon_{BHA}, av(N_r), av(N_r), 1, 1\right) = (0.00)\cdot deg$

$submatrix\left(\alpha_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (90.00)\cdot deg$

$submatrix\left(\alpha_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (90.00)\cdot deg$

$\begin{pmatrix} \overline{d}_{1BHA} \\ \overline{d}_{3BHA} \end{pmatrix} = \begin{pmatrix} 0.4000 \\ 0.4000 \end{pmatrix}$ $\begin{pmatrix} F_{1BHA} \\ F_{3BHA} \end{pmatrix} = \begin{pmatrix} 1.5621 \\ 1.5621 \end{pmatrix}$

$$c_{u1BHA_r} = \frac{c_{a1BHA_r}}{\tan\left(\alpha_{1BHA_r}\right)}$$

$$c_{1BHA_r} = \frac{c_{a1BHA_r}}{\sin\left(\alpha_{1BHA_r}\right)}$$

$$\lambda_{1BHA_r} = \frac{c_{1BHA_r}}{a_{кр1BHA_r}}$$

$$\sigma_{BHA} = \begin{cases} \left[1 + \text{mean}(0.03, 0.06)\cdot \text{ГДФ}\left("\rho", \lambda_{1BHA_r}, k_{1BHA_r}\right)\cdot \frac{k_{1BHA_r}}{k_{1BHA_r}+1}\cdot\left(\lambda_{1BHA_r}\right)^2\right]^{-1} & \text{if } BHA = 1 \\ 1 & \text{otherwise} \end{cases}$$

$$P^*_{3BHA_r} = P^*_{1BHA_r}\cdot\sigma_{BHA}$$

$$\rho^*_{3BHA_r} = \frac{P^*_{3BHA_r}}{R_в\cdot T^*_{3BHA_r}}$$

$$k_{3BHA_r} = k_{ад}\left(Cp_{воздух}\left(P^*_{3BHA_r}, T^*_{3BHA_r}\right), R_в\right)$$

$$a_{кр3BHA_r} = a_{кр}\left(k_{3BHA_r}, R_в, T^*_{3BHA_r}\right)$$

$$\overline{c}_{a3BHA_r} = \overline{c}_{.a1}(Z,1)$$

$$\overline{c}_{u3BHA_r} = \begin{cases} \overline{r}_{cp}\left(\overline{d}_{3BHA}\right)\cdot\left(1 - R_{L.cp}(Z,1)\right) - \frac{\overline{H}_{.T}(Z,1)}{2\cdot\overline{r}_{cp}\left(\overline{d}_{3BHA}\right)} & \text{if } BHA = 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\alpha_{3BHA_r} = \begin{cases} \text{atan}\left(\frac{\overline{c}_{a1BHA_r}}{\overline{c}_{u1BHA_r}}\right) & \text{if } BHA = 1 \\ \frac{\pi}{2} & \text{otherwise} \end{cases}$$

$$c_{a3BHA_r} = c_{a1BHA_r} - \begin{cases} 10 & \text{if } BHA = 1 \\ 0 & \text{otherwise} \end{cases}$$

$$c_{u3BHA_r} = \frac{c_{a3BHA_r}}{\tan\left(\alpha_{3BHA_r}\right)}$$

$$c_{3BHA_r} = \frac{c_{a3BHA_r}}{\sin\left(\alpha_{3BHA_r}\right)}$$

$$\lambda_{3BHA_r} = \frac{c_{3BHA_r}}{\ldots}$$

$\text{submatrix}\left(T^*_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (288.2)$

$\text{submatrix}\left(T^*_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (288.2)$

$\text{submatrix}\left(P^*_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (101.3)\cdot 10^3$

$\text{submatrix}\left(P^*_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (101.3)\cdot 10^3$

$\text{submatrix}\left(\rho^*_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (1.224)$

$\text{submatrix}\left(\rho^*_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (1.224)$

$\text{submatrix}\left(k_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (1.401)$

$\text{submatrix}\left(k_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (1.401)$

$\text{submatrix}\left(a_{кр1BHA}, av(N_r), av(N_r), 1, 1\right) = (310.8)$

$\text{submatrix}\left(a_{кр3BHA}, av(N_r), av(N_r), 1, 1\right) = (310.8)$

$\text{submatrix}\left(\overline{c}_{a1BHA}, av(N_r), av(N_r), 1, 1\right) = (0.335)$

$\text{submatrix}\left(\overline{c}_{a3BHA}, av(N_r), av(N_r), 1, 1\right) = (0.265)$

$\text{submatrix}\left(\overline{c}_{u1BHA}, av(N_r), av(N_r), 1, 1\right) = (0.000)$

$\text{submatrix}\left(\overline{c}_{u3BHA}, av(N_r), av(N_r), 1, 1\right) = (0.000)$

$\text{submatrix}\left(c_{a1BHA}, av(N_r), av(N_r), 1, 1\right) = (142.7)$

$\text{submatrix}\left(c_{a3BHA}, av(N_r), av(N_r), 1, 1\right) = (142.7)$

$\text{submatrix}\left(c_{u1BHA}, av(N_r), av(N_r), 1, 1\right) = (0.0)$

$\text{submatrix}\left(c_{u3BHA}, av(N_r), av(N_r), 1, 1\right) = (0.0)$

$\text{submatrix}\left(c_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (142.7)$

$\text{submatrix}\left(c_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (142.7)$

$\text{submatrix}\left(\lambda_{1BHA}, av(N_r), av(N_r), 1, 1\right) = (0.459)$

$\text{submatrix}\left(\lambda_{3BHA}, av(N_r), av(N_r), 1, 1\right) = (0.459)$

$$\lambda_{3ВНА_r} = \frac{\ldots}{a_{кр3ВНА_r}}$$

$$\begin{pmatrix} F_{1ВНА} \\ F_{3ВНА} \end{pmatrix} = G\cdot\sqrt{R_в}\cdot\begin{pmatrix} \dfrac{\sqrt{T^*_{1ВНА_r}}}{m_q\left(k_{1ВНА_r}\right)\cdot P^*_{1ВНА_r}\cdot ГДФ\left("G", \lambda_{1ВНА_r}, k_{1ВНА_r}\right)\cdot\sin\left(\alpha_{1ВНА_r}\right)} \\ \dfrac{\sqrt{T^*_{3ВНА_r}}}{m_q\left(k_{3ВНА_r}\right)\cdot P^*_{3ВНА_r}\cdot ГДФ\left("G", \lambda_{3ВНА_r}, k_{3ВНА_r}\right)\cdot\sin\left(\alpha_{3ВНА_r}\right)} \end{pmatrix}$$

$$\varepsilon_{ВНА_r} = -1\cdot\left(\alpha_{3ВНА_r} - \alpha_{1ВНА_r}\right)$$

$$\begin{pmatrix} \alpha_{1ВНА} & \alpha_{3ВНА} \\ \sigma_{ВНА} & \sigma_{ВНА} \\ \overline{d}_{1ВНА} & \overline{d}_{3ВНА} \\ T^*_{1ВНА} & T^*_{3ВНА} \\ P^*_{1ВНА} & P^*_{3ВНА} \\ \rho^*_{1ВНА} & \rho^*_{3ВНА} \\ k_{1ВНА} & k_{3ВНА} \\ a_{кр1ВНА} & a_{кр3ВНА} \\ \overline{c}_{a1ВНА} & \overline{c}_{a3ВНА} \\ \overline{c}_{u1ВНА} & \overline{c}_{u3ВНА} \\ c_{a1ВНА} & c_{a3ВНА} \\ c_{u1ВНА} & c_{u3ВНА} \\ c_{1ВНА} & c_{3ВНА} \\ \lambda_{1ВНА} & \lambda_{3ВНА} \\ F_{1ВНА} & F_{3ВНА} \\ \varepsilon_{ВНА} & \varepsilon_{ВНА} \end{pmatrix}$$

Расчет ВНА:

Поступенчатый расчет ОК по ср. ЛТ

$$
\begin{pmatrix}
R_L & \pi^* \\
K_H & \eta^* \\
Cp & k \\
\overline{H}_T & H_T \\
L^* & L \\
T^* & T \\
P^* & P \\
\rho^* & \rho \\
a^*_c & a_{зв} \\
\lambda_c & \lambda_c \\
F & F \\
D & R \\
\overline{d} & h \\
\overline{c}_a & \overline{c}_u \\
c_a & c_u \\
u & w_u \\
c & w \\
M_c & M_w \\
\alpha & \beta \\
\varepsilon_{rotor} & \varepsilon_{stator}
\end{pmatrix}
=
\left|
\begin{array}{l}
r = av(N_r) \\
T^*_{st(1,1),r} = T^*_{ЗВНА_r} \\
P^*_{st(1,1),r} = P^*_{ЗВНА_r} \\
\rho^*_{st(1,1),r} = \rho^*_{ЗВНА_r} \\
Cp_{st(1,1),r} = Cp_{воздух}\left(P^*_{st(1,1),r}, T^*_{st(1,1),r}\right) \\
k_{st(1,1),r} = k_{ад}\left(Cp_{st(1,1),r}, R_в\right) \\
a^*_{c_{st(1,1),r}} = a_{кр}\left(k_{st(1,1),r}, R_в, T^*_{st(1,1),r}\right) \\
\overline{c}_{a_{st(1,1),r}} = \overline{c}_{aЗВНА_r} \\
\overline{c}_{u_{st(1,1),r}} = \overline{c}_{uЗВНА_r} \\
c_{a_{st(1,1),r}} = c_{aЗВНА_r} \\
u_{st(1,1),N_r} = u_{1пер} \\
\alpha_{st(1,1),r} = \alpha_{ЗВНА_r} \\
c_{st(1,1),r} = \dfrac{c_{a_{st(1,1),r}}}{\sin\left(\alpha_{st(1,1),r}\right)} \\
\lambda_{c_{st(1,1),r}} = \dfrac{c_{st(1,1),r}}{a^*_{c_{st(1,1),r}}} \\
F_{st(1,1)} = \dfrac{G\cdot\sqrt{R_в\cdot T^*_{st(1,1),r}}}{m\left(k_{st(1,1)\ldots}\right)\cdot ГДФ\left("G", \lambda \ldots k_{st(1,1)\ldots}\right)\cdot\sin\left(\alpha_{st(1,1)\ldots}\right)\cdot P^*_{st(1,1)\ldots}}
\end{array}
\right.
$$

$$m_q(k_{st(1,1),r})\cdot ГДФ\left(G, \lambda c_{st(1,1),r}, k_{st(1,1),r}\right)\cdot \sin(\alpha_{st(1,1),r})\cdot P^*_{st(1,1),r}$$

$$D_{st(1,1),N_r} = \frac{2\cdot u_{st(1,1),N_r}}{\omega}$$

$$D_{st(1,1),1} = \sqrt{\left(D_{st(1,1),N_r}\right)^2 - \frac{4\cdot F_{st(1,1)}}{\pi}}$$

$$D_{st(1,1),r} = \overline{r}_{cp}\left(\frac{D_{st(1,1),1}}{D_{st(1,1),N_r}}\right)\cdot D_{st(1,1),N_r}$$

$$\overline{d}_{st(1,1)} = \frac{D_{st(1,1),1}}{D_{st(1,1),N_r}}$$

for $i \in 1..Z$

trace(concat("ступень i = ", num2str(i)))

$$\begin{pmatrix} \overline{H}_{T_i} \\ K_{H_i} \\ \eta^*_i \\ R_{L_{i,r}} \end{pmatrix} = \begin{pmatrix} \overline{H}_{.T}(Z,i) \\ K_{.H}(Z,i) \\ \eta^*_{.}(Z,i) \\ R_{L.cp}(Z,i) \end{pmatrix}$$

$$H_{T_{i,r}} = \overline{H}_{T_i}\cdot\left(u_{st(i,1),N_r}\right)^2$$

$$L_i = K_{H_i}\cdot H_{T_{i,r}}$$

$$L^*_i = L_i\cdot\eta^*_i$$

$$iteration_{12} = 0$$

$$k_{st(i,2),r} = k_{st(i,1),r}$$

while $0 < 1$

$$iteration_{12} = iteration_{12} + 1$$

trace(concat("   iteration.12 = ", num2str(iteration$_{12}$)))

$$k_{12} = mean\left(k_{st(i,1),r}, k_{st(i,2),r}\right)$$

$$Cp_{12} = \frac{k_{12}}{k_{12}-1}\cdot R_{в}$$

$$T^*_{st(i,2),r} = T^*_{st(i,1),r} + \frac{L_i}{Cp_{12}}$$

$$\pi^*_i = \left(1 + \frac{L^*_i}{Cp_{12}\cdot T^*_{st(i,1),r}}\right)^{\frac{k_{12}}{k_{12}-1}}$$

$$P^*_{st(i,2),r} = P^*_{st(i,1),r}\cdot\pi^*_i$$

$$Cp_{st(i,2),r} = Cp_{воздух}\left(P^*_{st(i,2),r}, T^*_{st(i,2),r}\right)$$

$$k'_2 = k_{ад}\left(Cp_{st(i,2),r}, R_в\right)$$

$$\text{if } \left|eps\left(\text{"rel"}, k_{st(i,2),r}, k'_2\right)\right| < epsilon$$

$$k_{st(i,2),r} = k'_2$$

break

$$k_{st(i,2),r} = k'_2$$

$$a^*_{c_{st(i,2),r}} = a_{кр}\left(k_{st(i,2),r}, R_в, T^*_{st(i,2),r}\right)$$

$$T^*_{st(i,3),r} = T^*_{st(i,2),r}$$

$$P^*_{st(i,3),r} = P^*_{st(i,2),r}$$

$$Cp_{st(i,3),r} = Cp_{воздух}\left(P^*_{st(i,3),r}, T^*_{st(i,3),r}\right)$$

$$k_{st(i,3),r} = k_{ад}\left(Cp_{st(i,3),r}, R_в\right)$$

$$a^*_{c_{st(i,3),r}} = a_{кр}\left(k_{st(i,3),r}, R_в, T^*_{st(i,3),r}\right)$$

$$\overline{c}_{a_{st(i,3),r}} = \overline{c}.a1(Z, i+1)$$

$$iteration_3 = 0$$

$$\begin{pmatrix} \alpha_{st(i,3),r} \\ u_{st(i,3),N_r} \end{pmatrix} = \begin{pmatrix} \alpha_{st(i,1),r} \\ u_{st(i,1),N_r} \end{pmatrix}$$

$$c_{a_{st(i,3),r}} = \overline{c}_{a_{st(i,3),r}} \cdot u_{st(i,3),N_r}$$

$$c_{st(i,3),r} = \frac{c_{a_{st(i,3),r}}}{\sin\left(\alpha_{st(i,3),r}\right)}$$

$$\lambda_{c_{st(i,3),r}} = \frac{c_{st(i,3),r}}{a^*_{c_{st(i,3),r}}}$$

$$F_{st(i,3)} = \frac{F_{st(i,1)} \cdot m_q\left(k_{st(i,1),r}\right) \cdot ГДФ\left(\text{"G"}, \lambda_{c_{st(i,1),r}}, k_{st(i,1),r}\right) \cdot \sin\left(\alpha_{st(i,1),r}\right) \cdot P^*_{st(i,1),r} \cdot \sqrt{T^*_{st(i,3),r}}}{m_q\left(k_{st(i,3),r}\right) \cdot ГДФ\left(\text{"G"}, \lambda_{c_{st(i,3),r}}, k_{st(i,3),r}\right) \cdot \sin\left(\alpha_{st(i,3),r}\right) \cdot P^*_{st(i,3),r} \sqrt{T^*_{st(i,1),r}}}$$

$$\text{while } 0 < 1$$

$$iteration_3 = iteration_3 + 1$$

$$trace\left(concat\left(\text{"   iteration.3 = "}, num2str\left(iteration_3\right)\right)\right)$$

$$\text{if } \left(ЗППЧ_i \neq \text{"пер"}\right) \wedge \left(ЗППЧ_i \neq \text{"кор"}\right) \wedge \left(ЗППЧ_i \neq \text{"ср"}\right)$$

$$D_{st(i,3),N_r} = D_{st(i,1),N_r} \cdot str2num\left(ЗППЧ_i\right)$$

$$D_{st(i,3),1} = \sqrt{\left(D_{st(i,3),N_r}\right)^2 - \frac{4 F_{st(i,3)}}{\pi}}$$

$$\text{if } ЗППЧ_i = \text{"пер"}$$

$$D_{st(i,3),N_r} = D_{st(i,1),N_r}$$

$$D_{st(i,3),1} = \sqrt{\left(D_{st(i,3),N_r}\right)^2 - \frac{4F_{st(i,3)}}{\pi}}$$

if $ЗППЧ_i$ = "кор"

$$D_{st(i,3),1} = D_{st(i,1),1}$$

$$D_{st(i,3),N_r} = \sqrt{\left(D_{st(i,3),1}\right)^2 + \frac{4F_{st(i,3)}}{\pi}}$$

if $ЗППЧ_i$ = "ср"

$$D_{st(i,3),N_r} = \sqrt{\left(D_{st(i,1),r}\right)^2 + \frac{2F_{st(i,3)}}{\pi}}$$

$$D_{st(i,3),1} = \sqrt{\left(D_{st(i,1),r}\right)^2 - \frac{2F_{st(i,3)}}{\pi}}$$

$$\overline{d}_{st(i,3)} = \frac{D_{st(i,3),1}}{D_{st(i,3),N_r}}$$

$$D_{st(i,3),r} = \overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)\cdot D_{st(i,3),N_r}$$

$$\overline{c}_{u_{st(i,3),r}} = \overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)\cdot\left(1 - R_{L.cp}(Z,i+1)\right) - \frac{\overline{H}_{.T}(Z,i+1)}{2\cdot\overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)}$$

$$\alpha_{st(i,3),r} = \begin{cases} \operatorname{atan}\left(\dfrac{\overline{c}_{a_{st(i,3),r}}}{\overline{c}_{u_{st(i,3),r}}}\right) & \text{if } \operatorname{atan}\left(\dfrac{\overline{c}_{a_{st(i,3),r}}}{\overline{c}_{u_{st(i,3),r}}}\right) \ge 0 \\ \operatorname{atan}\left(\dfrac{\overline{c}_{a_{st(i,3),r}}}{\overline{c}_{u_{st(i,3),r}}}\right) + 2\pi & \text{otherwise} \end{cases}$$

$$u_{st(i,3),N_r} = u_{st(i,1),N_r}\cdot\frac{D_{st(i,3),N_r}}{D_{st(i,1),N_r}}$$

$$c_{a_{st(i,3),r}} = \overline{c}_{a_{st(i,3),r}}\cdot u_{st(i,3),N_r}$$

$$c_{st(i,3),r} = \frac{c_{a_{st(i,3),r}}}{\sin\left(\alpha_{st(i,3),r}\right)}$$

$$\lambda_{c_{st(i,3),r}} = \frac{c_{st(i,3),r}}{a^*_{c_{st(i,3),r}}}$$

$$F'_3 = \frac{G\cdot\sqrt{R_в\cdot T^*_{st(i,3),r}}}{m_q\left(k_{st(i,3),r}\right)\cdot ГДФ\left(\text{"G"},\lambda_{c_{st(i,3),r}},k_{st(i,3),r}\right)\cdot\sin\left(\alpha_{st(i,3),r}\right)\cdot P^*_{st(i,3),r}}$$

$$\text{break if } \left(\left|eps\left(\text{"rel"},F'_3,F_{st(i,3)}\right)\right| < epsilon\right) \wedge \left(iteration_3 = 0\right)$$

$$iteration_3 = -1 \ \text{if} \ \left(\left|eps\left("rel", F'_3, F_{st(i,3)}\right)\right| < epsilon\right)$$

$$F_{st(i,3)} = F'_3$$

$$\overline{c}_{a_{st(i,2),r}} = mean\left(\overline{c}_{a_{st(i,1),r}}, \overline{c}_{a_{st(i,3),r}}\right)$$

$$iteration_2 = 0$$

$$F_{st(i,2)} = mean\left(F_{st(i,1)}, F_{st(i,3)}\right)$$

while $0 < 1$

$$iteration_2 = iteration_2 + 1$$

$$trace\left(concat\left(" \quad iteration.2 = ", num2str\left(iteration_2\right)\right)\right)$$

if $\left(ЗППЧ_i \neq "пер"\right) \wedge \left(ЗППЧ_i \neq "кор"\right) \wedge \left(ЗППЧ_i \neq "ср"\right)$

$$D_{st(i,2),N_r} = mean\left(D_{st(i,1),N_r}, D_{st(i,3),N_r}\right)$$

$$\overline{d}_{st(i,2)} = \sqrt{2 \cdot mean\left(\overline{r}_{cp}\left(\overline{d}_{st(i,1)}\right), \overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)\right)^2 - 1}$$

$$D_{st(i,2),r} = D_{st(i,2),N_r} \cdot \overline{r}_{cp}\left(\overline{d}_{st(i,2)}\right)$$

$$D_{st(i,2),1} = \overline{d}_{st(i,2)} \cdot D_{st(i,2),N_r}$$

if $ЗППЧ_i = "пер"$

$$D_{st(i,2),N_r} = D_{st(i,1),N_r}$$

$$\overline{d}_{st(i,2)} = \sqrt{2 \cdot mean\left(\overline{r}_{cp}\left(\overline{d}_{st(i,1)}\right), \overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)\right)^2 - 1}$$

$$D_{st(i,2),r} = D_{st(i,2),N_r} \cdot \overline{r}_{cp}\left(\overline{d}_{st(i,2)}\right)$$

$$D_{st(i,2),1} = \overline{d}_{st(i,2)} \cdot D_{st(i,2),N_r}$$

if $ЗППЧ_i = "кор"$

$$D_{st(i,2),1} = D_{st(i,1),1}$$

$$\overline{d}_{st(i,2)} = \sqrt{2 \cdot mean\left(\overline{r}_{cp}\left(\overline{d}_{st(i,1)}\right), \overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)\right)^2 - 1}$$

$$D_{st(i,2),N_r} = \frac{D_{st(i,2),1}}{\overline{d}_{st(i,2)}}$$

$$D_{st(i,2),r} = D_{st(i,2),N_r} \cdot \overline{r}_{cp}\left(\overline{d}_{st(i,2)}\right)$$

if $ЗППЧ_i = "ср"$

$$D_{st(i,2),r} = D_{st(i,1),r}$$

$$\overline{d}_{st(i,2)} = \sqrt{2 \cdot mean\left(\overline{r}_{cp}\left(\overline{d}_{st(i,1)}\right), \overline{r}_{cp}\left(\overline{d}_{st(i,3)}\right)\right)^2 - 1}$$

$$D_{st(i,2),N_r} = \frac{D_{st(i,2),r}}{\overline{r}_{cp}\left(\overline{d}_{st(i,2)}\right)}$$

$$D_{st(i,2),1} = \overline{d}_{st(i,2)} \cdot D_{st(i,2),N_r}$$

$$\bar{c}_{u_{st(i,2),r}} = \frac{1}{\bar{r}_{cp}\left(\bar{d}_{st(i,2)}\right)}\left(\frac{D_{st(i,1),N_r}}{D_{st(i,2),N_r}}\right)^2\cdot\left(\bar{H}_{T_i} + \bar{c}_{u_{st(i,1),r}}\cdot\frac{D_{st(i,1),r}}{D_{st(i,1),N_r}}\right)$$

$$\alpha_{st(i,2),r} = \begin{cases} \operatorname{atan}\left(\dfrac{\bar{c}_{a_{st(i,2),r}}}{\bar{c}_{u_{st(i,2),r}}}\right) & \text{if } \operatorname{atan}\left(\dfrac{\bar{c}_{a_{st(i,2),r}}}{\bar{c}_{u_{st(i,2),r}}}\right) \ge 0 \\ \operatorname{atan}\left(\dfrac{\bar{c}_{a_{st(i,2),r}}}{\bar{c}_{u_{st(i,2),r}}}\right) + 2\pi & \text{otherwise} \end{cases}$$

$$u_{st(i,2),N_r} = u_{st(i,1),N_r}\cdot\frac{D_{st(i,2),N_r}}{D_{st(i,1),N_r}}$$

$$c_{a_{st(i,2),r}} = \bar{c}_{a_{st(i,2),r}}\cdot u_{st(i,2),N_r}$$

$$c_{st(i,2),r} = \frac{c_{a_{st(i,2),r}}}{\sin\left(\alpha_{st(i,2),r}\right)}$$

$$\lambda_{c_{st(i,2),r}} = \frac{c_{st(i,2),r}}{a^*_{c_{st(i,2),r}}}$$

$$F'_2 = \frac{G\cdot\sqrt{R_B\cdot T^*_{st(i,2),r}}}{m_q\left(k_{st(i,2),r}\right)\cdot \text{ГДФ}\left(\text{"G"},\lambda_{c_{st(i,2),r}},k_{st(i,2),r}\right)\cdot\sin\left(\alpha_{st(i,2),r}\right)\cdot P^*_{st(i,2),r}}$$

$$\text{break if } \left(\left|\text{eps}\left(\text{"rel"},F'_2,F_{st(i,2)}\right)\right| < \text{epsilon}\right)\wedge\left(\text{iteration}_2 = 0\right)$$

$$\text{iteration}_2 = -1 \text{ if } \left(\left|\text{eps}\left(\text{"rel"},F'_2,F_{st(i,2)}\right)\right| < \text{epsilon}\right)$$

$$F_{st(i,2)} = F'_2$$

for $a \in 1..3$

$$\rho^*_{st(i,a),r} = \frac{P^*_{st(i,a),r}}{R_B\cdot T^*_{st(i,a),r}}$$

$$T_{st(i,a),r} = T^*_{st(i,a),r}\cdot \text{ГДФ}\left(\text{"T"},\lambda_{c_{st(i,a),r}},k_{st(i,a),r}\right)$$

$$P_{st(i,a),r} = P^*_{st(i,a),r}\cdot \text{ГДФ}\left(\text{"P"},\lambda_{c_{st(i,a),r}},k_{st(i,a),r}\right)$$

$$\rho_{st(i,a),r} = \rho^*_{st(i,a),r}\cdot \text{ГДФ}\left(\text{"}\rho\text{"},\lambda_{c_{st(i,a),r}},k_{st(i,a),r}\right)$$

$$a_{зв_{st(i,a),r}} = \sqrt{k_{st(i,a),r}\cdot R_B\cdot T_{st(i,a),r}}$$

$$\beta_{st(i,a),r} = \operatorname{atan}\left(\frac{\bar{c}_{a_{st(i,a),r}}}{\bar{r}_{cp}\left(\bar{d}_{st(i,a)}\right) - \bar{c}_{u_{st(i,a),r}}}\right)$$

$$w_{st(i,a),r} = \frac{c_{a_{st(i,a),r}}}{\sin\left(\beta_{st(i,a),r}\right)}$$

$$w_{u_{st(i,a),r}} = w_{st(i,a),r} \cdot \cos\left(\beta_{st(i,a),r}\right)$$

$$c_{u_{st(i,a),r}} = c_{st(i,a),r} \cdot \cos\left(\alpha_{st(i,a),r}\right)$$

$$M_{w_{st(i,a),r}} = \frac{w_{st(i,a),r}}{a_{зв_{st(i,a),r}}}$$

$$M_{c_{st(i,a),r}} = \frac{c_{st(i,a),r}}{a_{зв_{st(i,a),r}}}$$

$$h_{st(i,a)} = 0.5 \cdot \left(D_{st(i,a),N_r} - D_{st(i,a),1}\right)$$

for $radius \in 1 .. N_r$

$$u_{st(i,a),radius} = \omega \cdot \frac{D_{st(i,a),radius}}{2}$$

$$\begin{pmatrix} \varepsilon_{rotor_{i,av(N_r)}} \\ \varepsilon_{stator_{i,av(N_r)}} \end{pmatrix} = \begin{pmatrix} \beta_{st(i,2),av(N_r)} - \beta_{st(i,1),av(N_r)} \\ \alpha_{st(i,3),av(N_r)} - \alpha_{st(i,2),av(N_r)} \end{pmatrix}$$

for $i \in 1 .. Z$

for $a \in 1 .. 3$

for $r \in 1 .. N_r$

$$R_{st(i,a),r} = 0.5 \cdot D_{st(i,a),r}$$

$$\begin{pmatrix} R_L & K_H & Cp & \overline{H}_T & L^* & T^* & P^* & \rho^* & a^*_c & \lambda_c & F & D & \overline{d} & \overline{c}_a & c_a & u & c & M_c & \alpha & \varepsilon_{rotor} \\ \pi^* & \eta^* & k & H_T & L & T & P & \rho & a_{зв} & \lambda_c & F & R & h & \overline{c}_u & c_u & w_u & w & M_w & \beta & \varepsilon_{stator} \end{pmatrix}^T$$

$$
\begin{pmatrix} H_T \\ R_L \end{pmatrix} = \left|
\begin{array}{l}
\text{for } i \in 1..Z \\
\quad \left|
\begin{array}{l}
H_{T.}(r) = \text{interp}\left[\text{pspline}\left[\begin{pmatrix} 1 \\ av(N_r) \\ N_r \end{pmatrix}, \begin{pmatrix} H_{T_{i,av(N_r)}} - \dfrac{\Delta H_T\left(\overline{d}_{st(i,2)}\right)}{2} \\ H_{T_{i,av(N_r)}} \\ H_{T_{i,av(N_r)}} + \dfrac{\Delta H_T\left(\overline{d}_{st(i,2)}\right)}{2} \end{pmatrix}\right], \begin{pmatrix} 1 \\ av(N_r) \\ N_r \end{pmatrix}, \begin{pmatrix} H_{T_{i,av(N_r)}} - \dfrac{\Delta H_T\left(\overline{d}_{st(i,2)}\right)}{2} \\ H_{T_{i,av(N_r)}} \\ H_{T_{i,av(N_r)}} + \dfrac{\Delta H_T\left(\overline{d}_{st(i,2)}\right)}{2} \end{pmatrix}, r\right] \\
R_{L.}(r) = \text{interp}\left[\text{pspline}\left[\begin{pmatrix} 1 \\ av(N_r) \\ N_r \end{pmatrix}, \begin{pmatrix} R_{L_{i,av(N_r)}} - \dfrac{\Delta R_L\left(\overline{d}_{st(i,2)}\right)}{2} \\ R_{L_{i,av(N_r)}} \\ R_{L_{i,av(N_r)}} + \dfrac{\Delta R_L\left(\overline{d}_{st(i,2)}\right)}{2} \end{pmatrix}\right], \begin{pmatrix} 1 \\ av(N_r) \\ N_r \end{pmatrix}, \begin{pmatrix} R_{L_{i,av(N_r)}} - \dfrac{\Delta R_L\left(\overline{d}_{st(i,2)}\right)}{2} \\ R_{L_{i,av(N_r)}} \\ R_{L_{i,av(N_r)}} + \dfrac{\Delta R_L\left(\overline{d}_{st(i,2)}\right)}{2} \end{pmatrix}, r\right] \\
\text{for } r \in 1..N_r \\
\quad \left| \begin{array}{l} H_{T_{i,r}} = H_{T.}(r) \\ R_{L_{i,r}} = R_{L.}(r) \end{array} \right.
\end{array}
\right. \\
\begin{pmatrix} H_T \\ R_L \end{pmatrix}
\end{array}
\right.
$$

▲ Поступенчатый расчет ОК по ср. ЛТ

$$CA := \begin{cases} 1 & \text{if } compressor = "КВД" \\ 0 & \text{otherwise} \end{cases} = 0$$

Расчет CA:

$$\begin{pmatrix} \alpha_{1CA} & \alpha_{3CA} \\ \sigma_{CA} & \sigma_{CA} \\ \overline{d}_{1CA} & \overline{d}_{3CA} \\ T^*_{1CA} & T^*_{3CA} \\ P^*_{1CA} & P^*_{3CA} \\ \rho^*_{1CA} & \rho^*_{3CA} \\ k_{1CA} & k_{3CA} \\ a_{кр1CA} & a_{кр3CA} \\ \overline{c}_{a1CA} & \overline{c}_{a3CA} \\ \overline{c}_{u1CA} & \overline{c}_{u3CA} \\ c_{a1CA} & c_{a3CA} \\ c_{u1CA} & c_{u3CA} \\ c_{1CA} & c_{3CA} \\ \lambda_{1CA} & \lambda_{3CA} \\ F_{1CA} & F_{3CA} \\ \varepsilon_{CA} & \varepsilon_{CA} \end{pmatrix} := \left| \begin{array}{l} \text{for } r \in av(N_r) \\ \quad \alpha_{1CA_r} \leftarrow \alpha_{st(Z,3),r} \\ \quad \alpha_{3CA_r} \leftarrow \begin{cases} 90\cdot° & \text{if } CA = 1 \\ \alpha_{1CA_r} & \text{otherwise} \end{cases} \\ \quad \overline{d}_{1CA} \leftarrow \overline{d}_{st(Z,3)} \\ \quad \overline{d}_{3CA} \leftarrow \overline{d}_{1CA} \\ \quad T^*_{1CA_r} \leftarrow T^*_{st(Z,3),r} \\ \quad T^*_{3CA_r} \leftarrow T^*_{1CA_r} \\ \quad P^*_{1CA_r} \leftarrow P^*_{st(Z,3),r} \\ \quad iterarion_{CA} \leftarrow 0 \\ \quad \sigma_{CA} \leftarrow 1 \\ \quad \text{while } 0 < 1 \\ \quad\quad iterarion_{CA} \leftarrow iterarion_{CA} + 1 \\ \quad\quad trace(concat("iterarion.CA = ", num2str(iterarion_{CA}))) \\ \quad\quad P^*_{3CA_r} \leftarrow P^*_{1CA_r} \cdot \sigma_{CA} \\ \quad\quad \begin{pmatrix} \rho^*_{1CA_r} \\ \ldots \end{pmatrix} \leftarrow \ldots \begin{pmatrix} \dfrac{P^*_{1CA_r}}{T^*_{1CA_r}} \\ \ldots \end{pmatrix} \end{array} \right.$$

$\sigma_{CA} = 1.0000$

$submatrix(\varepsilon_{CA}, av(N_r), av(N_r), 1, 1) = (0.00)\cdot deg$

$submatrix(\alpha_{1CA}, av(N_r), av(N_r), 1, 1) = (51.42)\cdot deg$

$submatrix(\alpha_{3CA}, av(N_r), av(N_r), 1, 1) = (51.42)\cdot deg$

$\begin{pmatrix} \overline{d}_{1CA} \\ \overline{d}_{3CA} \end{pmatrix} = \begin{pmatrix} 0.4826 \\ 0.4826 \end{pmatrix}$ $\quad$ $\begin{pmatrix} F_{1CA} \\ F_{3CA} \end{pmatrix} = \begin{pmatrix} 1.4194 \\ 1.4195 \end{pmatrix}$

$$\left(\rho^*_{3CA_r}\right) = \frac{1}{R_в}\cdot\left(\frac{P^*_{3CA_r}}{T^*_{3CA_r}}\right)$$

$$\begin{pmatrix} k_{1CA_r} \\ k_{3CA_r} \end{pmatrix} = \begin{pmatrix} k_{ад}\left(Cp_{воздух}\left(P^*_{1CA_r}, T^*_{1CA_r}\right), R_в\right) \\ k_{ад}\left(Cp_{воздух}\left(P^*_{3CA_r}, T^*_{3CA_r}\right), R_в\right) \end{pmatrix}$$

$$\begin{pmatrix} a_{кр1CA_r} \\ a_{кр3CA_r} \end{pmatrix} = \begin{pmatrix} a_{кр}\left(k_{1CA_r}, R_в, T^*_{1CA_r}\right) \\ a_{кр}\left(k_{3CA_r}, R_в, T^*_{3CA_r}\right) \end{pmatrix}$$

$$\overline{c}_{a1CA_r} = \overline{c}_{a_{st(Z,3),r}}$$

$$\overline{c}_{a3CA_r} = \overline{c}_{.a1}(Z, Z+1)$$

$$\overline{c}_{u1CA_r} = \overline{c}_{u_{st(Z,3),r}}$$

$$\overline{c}_{u3CA_r} = \begin{cases} 0 & \text{if } CA = 1 \\ \overline{c}_{u1CA_r} & \text{otherwise} \end{cases}$$

$$c_{a1CA_r} = \overline{c}_{a3CA_r}\cdot u_{st(Z,3),N_r}$$

$$c_{a3CA_r} = c_{a1CA_r} - \begin{cases} 10 & \text{if } CA = 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{pmatrix} c_{u1CA_r} \\ c_{u3CA_r} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{a1CA_r}}{\tan\left(\alpha_{1CA_r}\right)} \\ \dfrac{c_{a3CA_r}}{\tan\left(\alpha_{3CA_r}\right)} \end{pmatrix}$$

$$\begin{pmatrix} c_{1CA_r} \\ c_{3CA_r} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{a1CA_r}}{\sin\left(\alpha_{1CA_r}\right)} \\ \dfrac{c_{a3CA_r}}{\sin\left(\alpha_{3CA_r}\right)} \end{pmatrix}$$

$$\begin{pmatrix} \lambda_{1CA_r} \\ \lambda_{3CA_r} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{1CA_r}}{a_{кр1CA_r}} \\ \dfrac{c_{3CA_r}}{a_{кр3CA_r}} \end{pmatrix}$$

$$\sigma'_{CA} = \left| 1 - \mathrm{mean}(0.25, 0.5)\cdot ГДФ\left("\rho", \lambda_{3CA_r}, k_{3CA_r}\right)\cdot\frac{k_{3CA_r}}{k_{3CA_r}+1}\cdot\left(\lambda_{3CA_r}\right)^2 \quad \text{if } CA = 1\right.$$

$$\mathrm{submatrix}\left(T^*_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (337.1)$$

$$\mathrm{submatrix}\left(T^*_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (337.1)$$

$$\mathrm{submatrix}\left(P^*_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (163.0)\cdot 10^3$$

$$\mathrm{submatrix}\left(P^*_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (163.0)\cdot 10^3$$

$$\mathrm{submatrix}\left(\rho^*_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.684)$$

$$\mathrm{submatrix}\left(\rho^*_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.684)$$

$$\mathrm{submatrix}\left(k_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.399)$$

$$\mathrm{submatrix}\left(k_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.399)$$

$$\mathrm{submatrix}\left(a_{кр1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (336.0)$$

$$\mathrm{submatrix}\left(a_{кр3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (336.0)$$

$$\mathrm{submatrix}\left(\overline{c}_{a1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.265)$$

$$\mathrm{submatrix}\left(\overline{c}_{a3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.265)$$

$$\mathrm{submatrix}\left(\overline{c}_{u1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.211)$$

$$\mathrm{submatrix}\left(\overline{c}_{u3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.211)$$

$$\mathrm{submatrix}\left(c_{a1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (112.9)$$

$$\mathrm{submatrix}\left(c_{a3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (112.9)$$

$$\mathrm{submatrix}\left(c_{u1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (90.0)$$

$$\mathrm{submatrix}\left(c_{u3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (90.0)$$

$$\mathrm{submatrix}\left(c_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (144.4)$$

$$\mathrm{submatrix}\left(c_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (144.4)$$

$$\mathrm{submatrix}\left(\lambda_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.430)$$

$$\mathrm{submatrix}\left(\lambda_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.430)$$

$1 \quad \text{otherwise}$

$\text{break if } \left(\left|\text{eps}\left("\text{rel}", \sigma'_{CA}, \sigma_{CA}\right)\right| < \text{epsilon}\right) \wedge \left(\text{iterarion}_{CA} = 0\right)$

$\text{iterarion}_{CA} = -1 \quad \text{if } \left(\left|\text{eps}\left("\text{rel}", \sigma'_{CA}, \sigma_{CA}\right)\right| < \text{epsilon}\right)$

$\sigma_{CA} = \sigma'_{CA}$

$$\begin{pmatrix} F_{1CA} \\ F_{3CA} \end{pmatrix} = \left(\frac{\dfrac{F_{st(Z,3)}}{G \cdot \sqrt{R_B \cdot T^*_{3CA_r}}}}{m_q\left(k_{3CA_r}\right) \cdot P^*_{3CA_r} \cdot \text{ГДФ}\left("G", \lambda_{3CA_r}, k_{3CA_r}\right) \cdot \sin\left(\alpha_{3CA_r}\right)} \right)$$

$\varepsilon_{CA_r} = \alpha_{3CA_r} - \alpha_{1CA_r}$

$$\begin{pmatrix} \alpha_{1CA} & \alpha_{3CA} \\ \sigma_{CA} & \sigma_{CA} \\ \overline{d}_{1CA} & \overline{d}_{3CA} \\ T^*_{1CA} & T^*_{3CA} \\ P^*_{1CA} & P^*_{3CA} \\ \rho^*_{1CA} & \rho^*_{3CA} \\ k_{1CA} & k_{3CA} \\ a_{кр1CA} & a_{кр3CA} \\ \overline{c}_{a1CA} & \overline{c}_{a3CA} \\ \overline{c}_{u1CA} & \overline{c}_{u3CA} \\ c_{a1CA} & c_{a3CA} \\ c_{u1CA} & c_{u3CA} \\ c_{1CA} & c_{3CA} \\ \lambda_{1CA} & \lambda_{3CA} \\ F_{1CA} & F_{3CA} \\ \varepsilon_{CA} & \varepsilon_{CA} \end{pmatrix}$$

Расчет СА:

Результаты поступенчатого расчета по ср. ЛТ

Относ. погрешность расчета по массовому расходу (кг/с):

$$\bar{\Delta}G = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } a \in 1..3 \\ \quad\quad \bar{\Delta}G_{st(i,a)} = \left| eps\left("rel", G, \rho_{st(i,a),av(N_r)} \cdot ca_{st(i,a),av(N_r)} \cdot F_{st(i,a)}\right)\right| \\ \bar{\Delta}G \end{array} \right.$$

$\bar{\Delta}G^T =$ (·%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.00	0.00	0.01																

$\bar{\Delta}G^T < 1\% =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1	1	1																

Количество ступеней ОК: $Z = 1$

Дискритизация сечений: $ii := 1..2Z + 1$

Дискритизация ступеней: $i := 1..Z$

$\pi^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.609														

[16, с 114] $\pi^{*T} \le 1.9 =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1														

Полученная степень повышения полного давления []: $\prod_{i=1}^{Z} \pi^*_i = 1.609$

Степень повышения давления в ЛА: $\pi^*_{ЛА} := \dfrac{P^*_{3СА_{av(N_r)}}}{P^*_{1ВНА_{av(N_r)}}} = 1.609$ $\quad \pi^*_{ЛА} \ge \pi^*_{К} = 1$

$H_T^{\,T} =$ (×10³)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	51.62														
2	51.62														
3	51.62														

Действительная работа К (Дж/кг): $L_K = \sum_{i=1}^{Z} L_i = 49 \cdot 10^3$

Адиабатная работа К [Дж/кг]: $L^*_K = \sum_{i=1}^{Z} L^*_i = 42.2 \cdot 10^3$

Адиабатная КПД К []: $\eta^*_K = \frac{L^*_K}{L_K} = 86.00 \cdot \%$

Мощность К (Вт): $N_K = G \cdot L_K = 12.24 \cdot 10^6$

$\text{submatrix}\left(R_L, 1, Z, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.50														

$K_H{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.95														

$\eta^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	86.00														

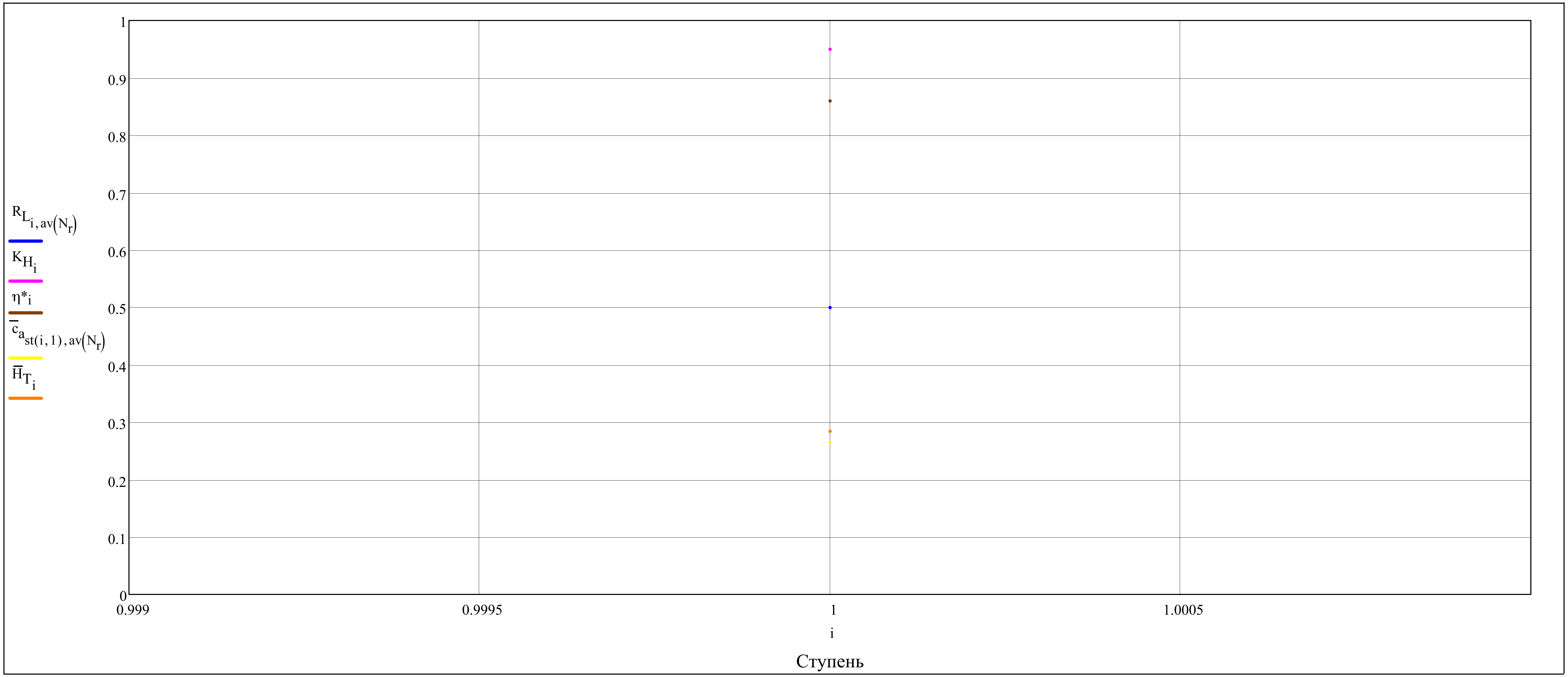
$\cdot\%$

$\text{submatrix}\left(\bar{c}_a, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.265	0.265	0.265																	

$\bar{H}_T{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.28														



$submatrix\left(Cp, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1002.6	1006.0	1006.0																

$submatrix\left(k, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.401	1.399	1.399																		

$submatrix\left(T^*, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	288.2	337.1	337.1																		

$submatrix\left(T, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	278	318.6	326.7																		

$submatrix\left(P^*, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	101.3	163	163															

$\cdot 10^3$

$submatrix\left(P, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	89.4	133.7	146.1															

$\cdot 10^3$

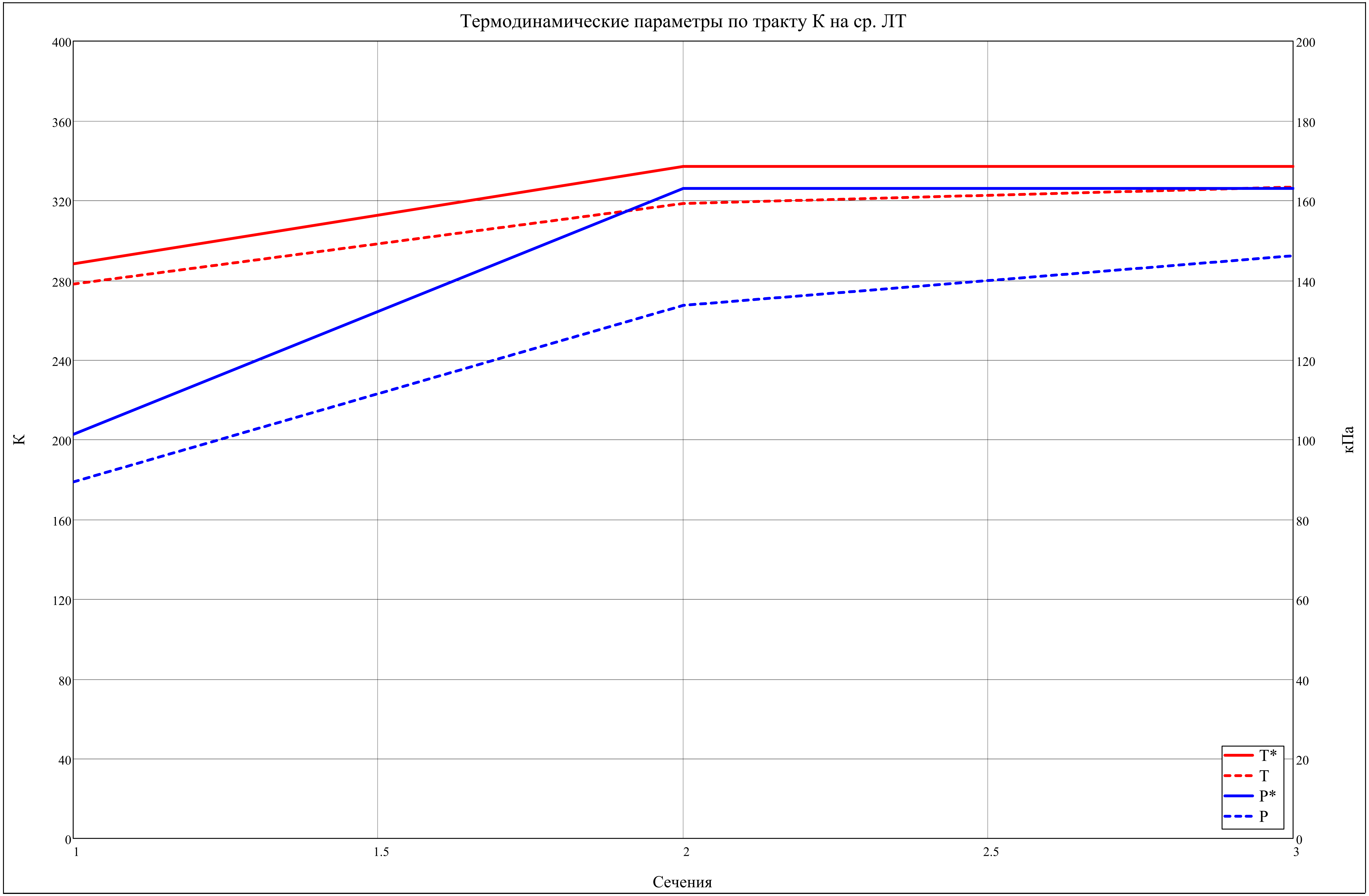
$submatrix\left(\rho^*, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.224	1.684	1.684																

$submatrix\left(\rho, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.12	1.462	1.558																

$$k_{ср} = k_{ад}\left(Cp_{воздух.ср}\left(P^*_{st(1,1),av(N_r)}, P^*_{st(Z,3),av(N_r)}, T^*_{st(1,1),av(N_r)}, T^*_{st(Z,3),av(N_r)}\right), R_{в}\right) = 1.401$$



Термодинамические параметры по тракту К на ср. ЛТ
400
360
320
280
240
200
160
120
80
40
0
К
200
180
160
140
120
100
80
60
40
20
0
кПа
1
1.5
2
2.5
3
Сечения
T*
T
P*
P

$F^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1562068	1512686	1419368																	

$\overline{d}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.3947	0.4405	0.4826																				

$\overline{d}_{st(Z,3)} = 0.4826$ $\qquad$ $\overline{d}_{st(Z,3)} \le 0.9 = 1$

$D^T =$

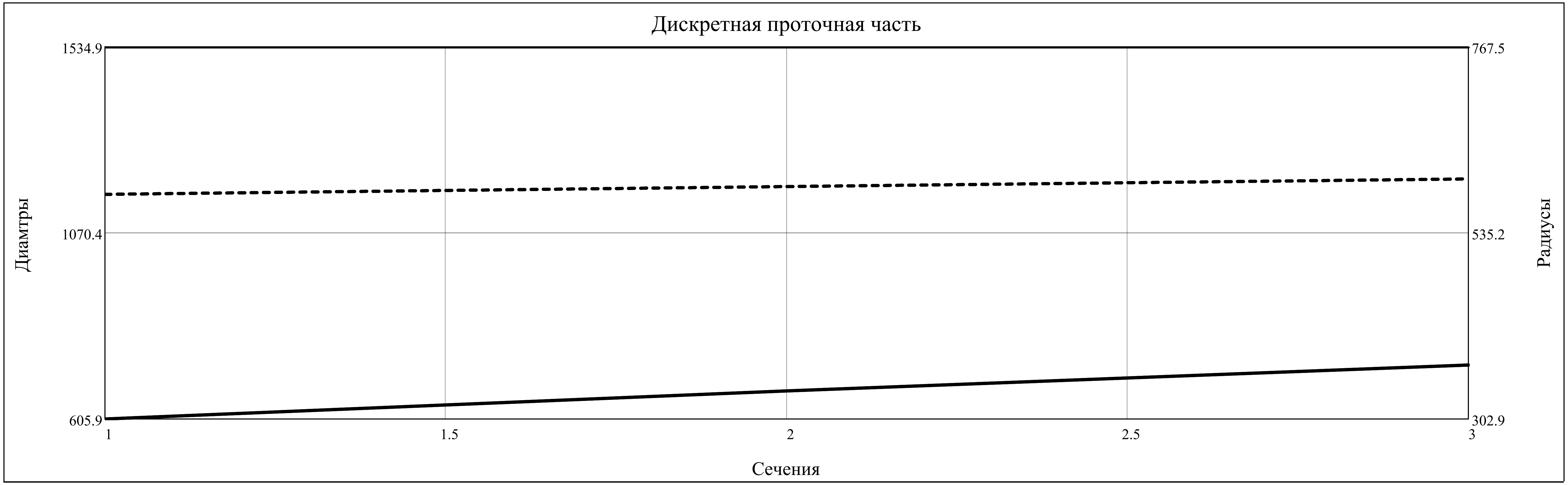
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	605.9	676.2	740.8																		
2	1166.8	1186.0	1205.1																		
3	1534.9	1534.9	1534.9																		

$\cdot 10^{-3}$

$R^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	302.9	338.1	370.4																						
2	583.4	593.0	602.6																						
3	767.5	767.5	767.5																						

$\cdot 10^{-3}$



$h^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	464.5	429.4	397.1																						

$\cdot 10^{-3}$

$\mathrm{submatrix}\left(a^*_c, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	310.8	336.0	336.0																		

$\mathrm{submatrix}\left(a_{зв}, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	334.5	357.8	362.4																		

$\mathrm{submatrix}\left(c, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	142.7	193.2	144.4																		

$\mathrm{submatrix}\left(w, 1, 2Z, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	433.5	206																			

$u^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	168.1	187.6	205.6																						
2	323.8	329.1	334.4																						
3	425.9	425.9	425.9																						

$c_{a_{st(Z,3), av(N_r)}} = 112.87$ $\quad c_{a_{st(Z,3), av(N_r)}} \le 130 = 1$ $\quad$ Для КС

$\mathrm{submatrix}\left(c_a, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	142.7	112.9	112.9																		

$\mathrm{submatrix}\left(c_u, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	156.8	90																		

$\mathrm{submatrix}\left(w_u, 1, 2Z+1, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	409.3	172.3	244.4																		

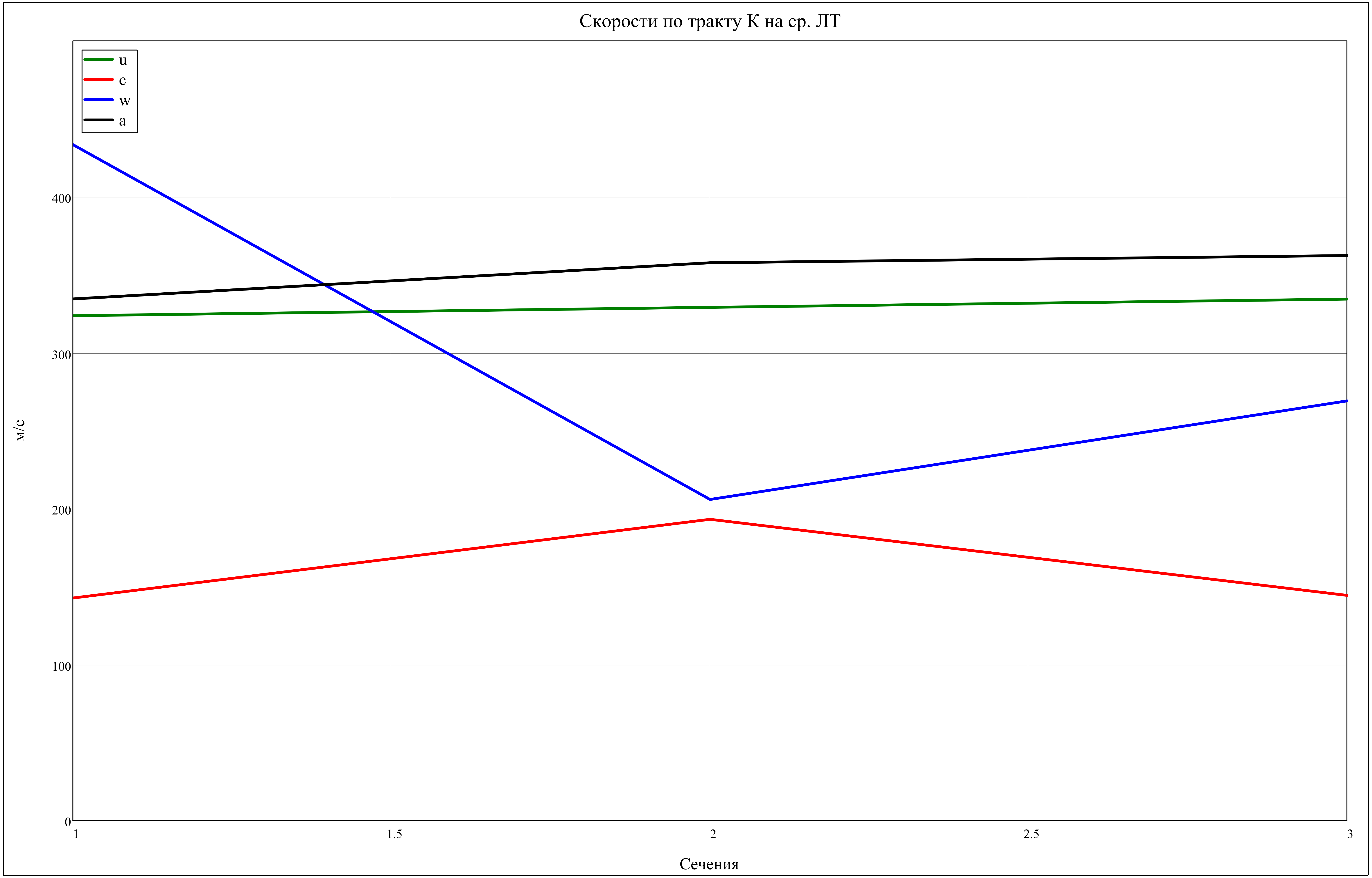
$$\Delta c_{a_{i, av(N_r)}} = \left(c_{a_{st(i,2), av(N_r)}} - c_{a_{st(i,1), av(N_r)}}\right)$$

$\mathrm{submatrix}\left(\Delta c_a, 1, Z, av(N_r), av(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1	-29.82																				

$\mathrm{submatrix}\left(\Delta c_a, 1, Z, av(N_r), av(N_r)\right)^T \ge -12 =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0																													



Скорости по тракту К на ср. ЛТ
u
c
w
a
м/с
400
300
200
100
0
1
1.5
2
2.5
3
Сечения

$$\mathrm{submatrix}\left(\alpha,1,2\cdot Z+1,\mathrm{av}\left(N_r\right),\mathrm{av}\left(N_r\right)\right)^T =$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	90.00	35.74	51.42																		

$\cdot{}^\circ$

$$\mathrm{submatrix}\left(\beta,1,2\cdot Z+1,\mathrm{av}\left(N_r\right),\mathrm{av}\left(N_r\right)\right)^T =$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	19.22	33.23	24.79																		

$\cdot{}^\circ$

$$\mathrm{submatrix}\left(\varepsilon_{rotor},1,Z,\mathrm{av}\left(N_r\right),\mathrm{av}\left(N_r\right)\right)^T =$$

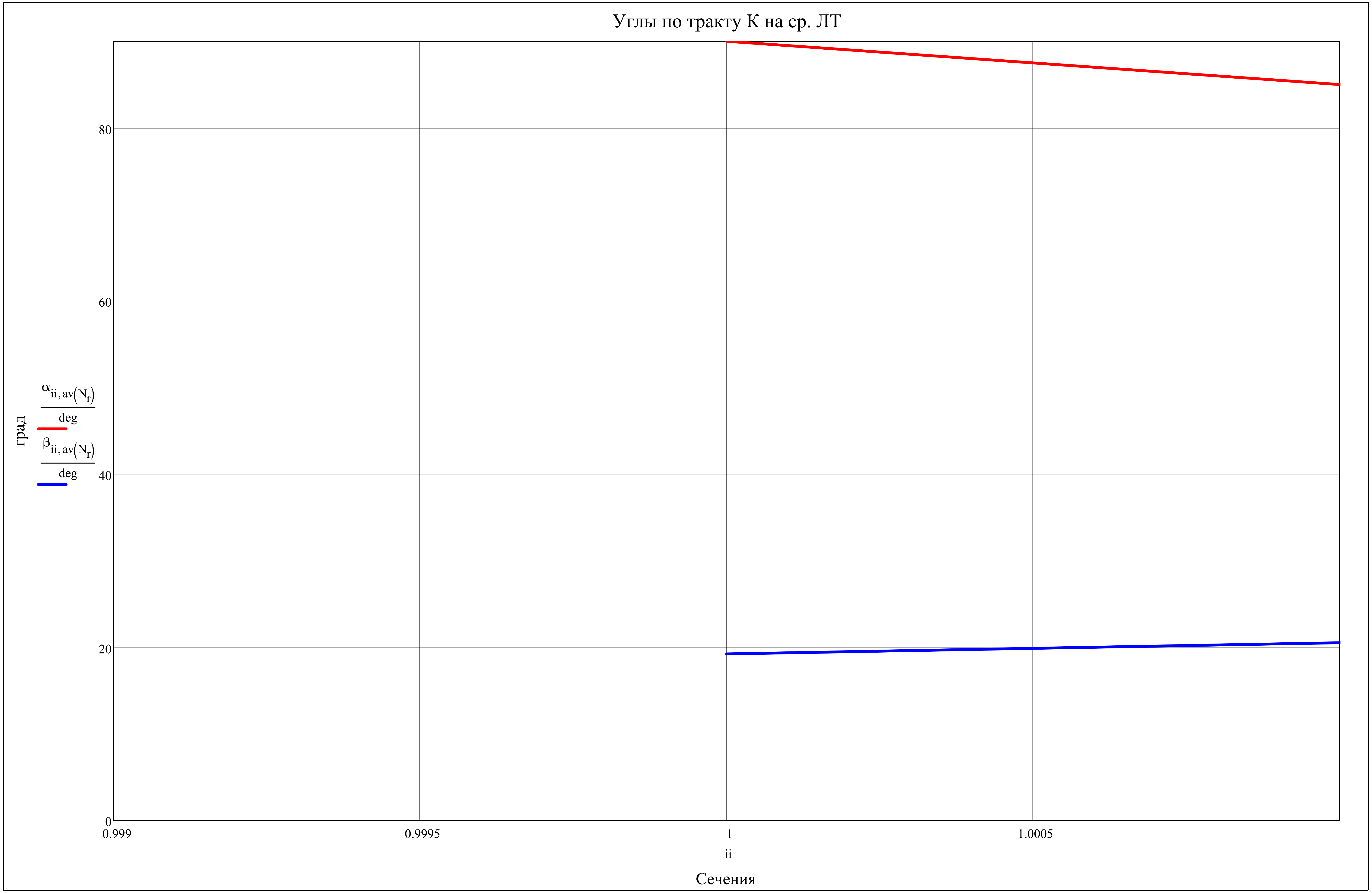
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	14.01																				

$\cdot{}^\circ$

$$\mathrm{submatrix}\left(\varepsilon_{stator},1,Z,\mathrm{av}\left(N_r\right),\mathrm{av}\left(N_r\right)\right)^T =$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	15.68																				

$\cdot{}^\circ$



Углы по тракту К на ср. ЛТ
80
60
40
20
0
0.999
0.9995
1
1.0005
ii
Сечения
град
$\frac{\alpha_{ii,av(N_r)}}{deg}$
$\frac{\beta_{ii,av(N_r)}}{deg}$

$\mathrm{submatrix}\left(\lambda_c, 1, 2Z+1, \mathrm{av}(N_r), \mathrm{av}(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.4591	0.5750	0.4297																

[16, c. 87] $\mathrm{submatrix}\left(\lambda_c, 1, 2Z+1, \mathrm{av}(N_r), \mathrm{av}(N_r)\right)^T \le 0.85 =$

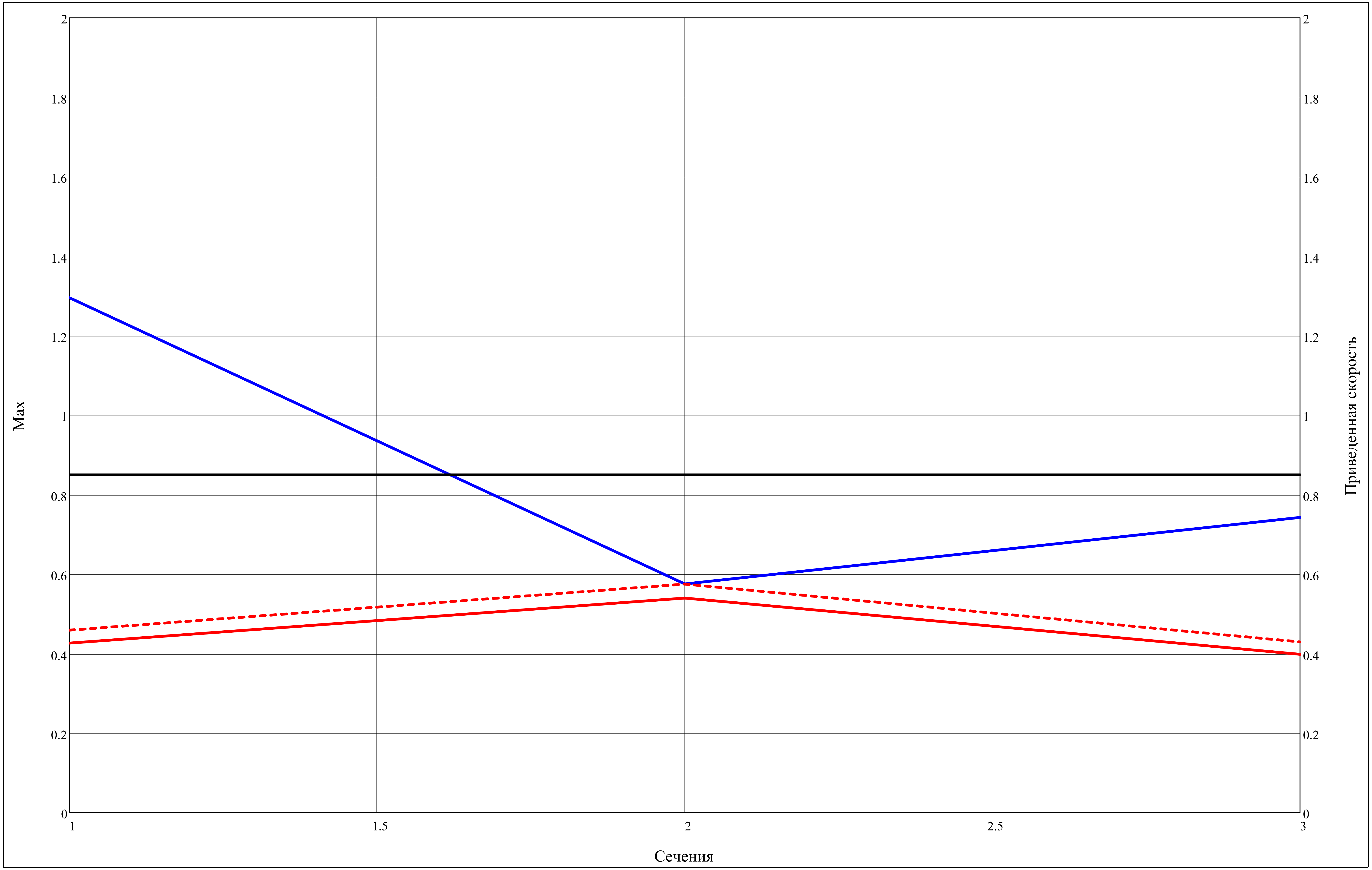
	1	2	3
1	1	1	1

$\mathrm{submatrix}\left(M_w, 1, 2Z, \mathrm{av}(N_r), \mathrm{av}(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.296	0.5757																	

$\mathrm{submatrix}\left(M_c, 1, 2Z+1, \mathrm{av}(N_r), \mathrm{av}(N_r)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.4266	0.5401	0.3985																


Max
Приведенная скорость
Сечения
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1
1.5
2
2.5
3

Результаты поступенчатого расчета по ср. ЛТ

Вывод результатов поступенчатого расчета по ср. ЛТ ОК в EXCEL:

Расчет параметров потока по высоте Л

Относ. диаметр корня при увеличении которого меняется з-н профилирования Л
с промежуточного на Ц = const:
с R = const на промежуточный:
[16, с.94-99]

$$\begin{pmatrix} \bar{d}_{m2Ц} \\ \bar{d}_{R2m} \end{pmatrix} = \begin{pmatrix} 0.7 \\ 0.3 \end{pmatrix}$$

$$m = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad m_i = \left| \begin{array}{ll} -1 & \text{if } \bar{d}_{st(i,1)} \le \bar{d}_{R2m} \\ 1 & \text{if } \bar{d}_{st(i,1)} \ge \bar{d}_{m2Ц} \\ -1 + \dfrac{1-(-1)}{\bar{d}_{m2Ц} - \bar{d}_{R2m}} \cdot \left(\bar{d}_{st(i,1)} - \bar{d}_{R2m}\right) & \text{otherwise} \end{array} \right. \\ m \end{array} \right.$$

$$m_i = \left| \begin{array}{ll} 0.4 & \text{if compressor = "Вл"} \\ m_i & \text{otherwise} \end{array} \right.$$

$m^T =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.400											

$$\begin{pmatrix} T^* & T \\ P^* & P \\ \rho^* & \rho \\ Cp & k \\ a^*_c & a_{зв} \\ c_u & c_a \\ \alpha & \beta \\ c & w \\ \lambda_c & w_u \\ M_w & M_c \\ R_L & R_L \\ \varepsilon_{rotor} & \varepsilon_{stator} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } a \in 1..3 \\ \quad\quad \text{for } r \in 1..N_r \\ \quad\quad\quad T^*_{st(i,a),r} = T^*_{st(i,a),av(N_r)} \\ \quad\quad\quad P^*_{st(i,a),r} = P^*_{st(i,a),av(N_r)} \\ \quad\quad\quad \rho^*_{st(i,a),r} = \rho^*_{st(i,a),av(N_r)} \\ \quad\quad\quad Cp_{st(i,a),r} = Cp_{воздух}\left(P^*_{st(i,a),r}, T^*_{st(i,a),r}\right) \\ \quad\quad\quad k_{st(i,a),r} = \dfrac{Cp_{воздух}\left(P^*_{st(i,a),r}, T^*_{st(i,a),r}\right)}{Cp_{воздух}\left(P^*_{st(i,a),r}, T^*_{st(i,a),r}\right) - R_B} \\ \quad\quad\quad a^*c_{st(i,a),r} = \sqrt{\dfrac{2 \cdot k_{st(i,a),r}}{k_{st(i,a),r}+1} \cdot R_B \cdot T^*_{st(i,a),r}} \\ \quad\quad\quad \text{if } \Delta H_{Tmax} = 0 \end{array} \right.$$

$$A_{st(i,a),r} = \left(1 - R_{L_{i,av(N_r)}}\right)\cdot\omega\cdot\left(R_{st(i,a),av(N_r)}\right)$$

$$B_{st(i,a),r} = \frac{H_{T_{i,av(N_r)}}}{2\cdot\omega}$$

$$c_{u_{st(i,a),r}} = \begin{cases} c_{u_{st(i,a),av(N_r)}} & \text{if } (a = 1) \\ \dfrac{A_{st(i,a),r}}{\left(R_{st(i,a),r}\right)^{m_i}} + \dfrac{B_{st(i,a),r}}{\left(R_{st(i,a),r}\right)} & \text{if } (a = 2) \\ \dfrac{A_{st(i,a),r}}{\left(R_{st(i,a),r}\right)^{m_i}} - \dfrac{B_{st(i,a),r}}{\left(R_{st(i,a),r}\right)} & \text{if } (a = 3) \end{cases}$$

$c_{a_{st(i,a),r}} =$ if $m_i = -1$

$$\begin{cases} c_{a_{st(i,a),av(N_r)}} & \text{if } (a = 1) \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left(R_{st(i,a),av(N_r)}\right)^2 - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left(R_{st(i,a),r}\right)^2 - 4\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}\cdot\left(\ln\left(R_{st(i,a),r}\right) - \ln\left(R_{st(i,a),av(N_r)}\right)\right)} & \text{if } (a = 2) \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left(R_{st(i,a),av(N_r)}\right)^2 - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left(R_{st(i,a),r}\right)^2 + 4\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}\cdot\left(\ln\left(R_{st(i,a),r}\right) - \ln\left(R_{st(i,a),av(N_r)}\right)\right)} & \text{if } (a = 3) \end{cases}$$

if $m_i = 0$

$$\begin{cases} c_{a_{st(i,a),av(N_r)}} & \text{if } (a = 1) \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),av(N_r)}\right) - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),r}\right) + \dfrac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{R_{st(i,a),r}} - \dfrac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{R_{st(i,a),av(N_r)}}} & \text{if } (a = 2) \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),av(N_r)}\right) - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),r}\right) - \dfrac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{R_{st(i,a),r}} + \dfrac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{R_{st(i,a),av(N_r)}}} & \text{if } (a = 3) \end{cases}$$

otherwise

$$\begin{cases} c_{a_{st(i,a),av(N_r)}} & \text{if } (a = 1) \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + \dfrac{A_{st(i,a),r}\cdot\left(m_i - 1\right)\cdot\left[A_{st(i,a),r}\cdot\left[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,a),av(N_r)}\right) - \left(R_{st(i,a),r}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\right] + 2\cdot B_{st(i,a),r}\cdot m_i\cdot\left[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{s}\right.\right.}{m_i\cdot\left(m_i+1\right)\cdot\left(R_{st(i,a),r}\right.}} \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + \dfrac{A_{st(i,a),r}\cdot\left(m_i - 1\right)\cdot\left[A_{st(i,a),r}\cdot\left[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,a),av(N_r)}\right) - \left(R_{st(i,a),r}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\right] - 2\cdot B_{st(i,a),r}\cdot m_i\cdot\left[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{s}\right.\right.}{m_i\cdot\left(m_i+1\right)\cdot\left(R_{st(i,a),r}\right.}} \end{cases}$$

if $\Delta H_{Tmax} \neq 0$

$$A_{st(i,a),r} = \frac{1}{\left(R_{st(i,a),av(N_r)}\right)^2 - \left(R_{st(i,a),1}\right)^2}\cdot\left[\omega\cdot\left(R_{st(i,a),av(N_r)}\right)^2\cdot\left(1 - R_{L_{i,av(N_r)}}\right) - \omega\cdot\left(R_{st(i,a),1}\right)^2\cdot\left(1 - R_{L_{i,1}}\right) + \frac{H_{T_{i,1}} - H_{T_{i,av(N_r)}}}{2\cdot\omega}\right]$$

$$B_{st(i,a),r} = \frac{\left(R_{st(i,a),1}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)}{\left(R_{st(i,a),av(N_r)}\right)^2-\left(R_{st(i,a),1}\right)^2}\cdot\left[\omega\cdot R_{st(i,a),1}\cdot R_{st(i,a),av(N_r)}\cdot\left(1-R_{L_{i,1}}\right)-\omega\cdot R_{st(i,a),av(N_r)}\cdot R_{st(i,a),1}\cdot\left(1-R_{L_{i,av(N_r)}}\right)-\frac{1}{2\cdot\omega}\cdot\left(\frac{H_{T_{i,1}}\cdot R_{st(i,a),av(N_r)}}{R_{st(i,a),1}}-\frac{H_{T_{i,av(N_r)}}\cdot R_{st(i,a)}}{R_{st(i,a),av(N_r)}}\right.\right.$$

$$c_{u_{st(i,a),r}} = \begin{cases} c_{u_{st(i,a),av(N_r)}} & \text{if } (a=1) \\ A_{st(i,a),r}\cdot R_{st(i,a),r}+\dfrac{B_{st(i,a),r}}{R_{st(i,a),r}}+\dfrac{H_{T_{i,r}}}{\omega\cdot R_{st(i,a),r}} & \text{if } (a=2) \\ A_{st(i,a),r}\cdot R_{st(i,a),r}+\dfrac{B_{st(i,a),r}}{R_{st(i,a),r}} & \text{if } (a=3) \end{cases}$$

$$k_{HT} = \frac{H_{T_{i,av(N_r)}}-H_{T_{i,1}}}{R_{st(i,a),av(N_r)}-R_{st(i,a),1}}$$

$$b_{HT} = H_{T_{i,av(N_r)}}-k_{HT}\cdot R_{st(i,a),av(N_r)}$$

$$c_{a_{st(i,a),r}} = \begin{cases} c_{a_{st(i,a),av(N_r)}} & \text{if } (a=1) \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2-2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2-\left(R_{st(i,a),av(N_r)}\right)^2\right]-\left(6\cdot\dfrac{A_{st(i,a),r}}{\omega}-2\right)\cdot k_{HT}\cdot\left(R_{st(i,a),r}-R_{st(i,a),av(N_r)}\right)-2\cdot\dfrac{k_{HT}}{\omega}\cdot\left(B_{st(i,a),r}+\dfrac{b_{HT}}{\omega}\right)\cdot\dfrac{R_{st(i,a),r}-R_{s}}{R_{st(i,a),r}\cdot R_{st}}} & \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2-2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2-\left(R_{st(i,a),av(N_r)}\right)^2\right]-4\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}\cdot\ln\left(\dfrac{R_{st(i,a),r}}{R_{st(i,a),av(N_r)}}\right)} & \text{if } (a=3) \end{cases}$$

$$\alpha_{st(i,a),r} = \text{triangle}\left(c_{a_{st(i,a),r}}, c_{u_{st(i,a),r}}\right)$$

$$c_{st(i,a),r} = \frac{c_{a_{st(i,a),r}}}{\sin\left(\alpha_{st(i,a),r}\right)}$$

$$\lambda_{c_{st(i,a),r}} = \frac{c_{st(i,a),r}}{a^*_{c_{st(i,a),r}}}$$

$$\begin{pmatrix} T_{st(i,a),r} \\ P_{st(i,a),r} \\ \rho_{st(i,a),r} \end{pmatrix} = \begin{pmatrix} T^*_{st(i,a),r}\cdot \text{ГДФ}\left(\text{"T"}, \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \\ P^*_{st(i,a),r}\cdot \text{ГДФ}\left(\text{"P"}, \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \\ \rho^*_{st(i,a),r}\cdot \text{ГДФ}\left(\text{"}\rho\text{"}, \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \end{pmatrix}$$

$$a_{зв_{st(i,a),r}} = \sqrt{k_{st(i,a),r}\cdot R_{в}\cdot T_{st(i,a),r}}$$

$$\beta_{st(i,a),r} = \text{triangle}\left(c_{a_{st(i,a),r}}, u_{st(i,a),r}-c_{u_{st(i,a),r}}\right)$$

$$w_{st(i,a),r} = \frac{c_{a_{st(i,a),r}}}{\sin\left(\beta_{st(i,a),r}\right)}$$

$$w_{u_{st(i,a),r}} = w_{st(i,a),r} \cdot \cos(\beta_{st(i,a),r})$$

$$\begin{pmatrix} M_{w_{st(i,a),r}} \\ M_{c_{st(i,a),r}} \end{pmatrix} = \frac{1}{a_{зв_{st(i,a),r}}} \cdot \begin{pmatrix} w_{st(i,a),r} \\ c_{st(i,a),r} \end{pmatrix}$$

for $r \in 1 .. N_r$

$$R_{L_{i,r}} = 1 - \frac{c_{u_{st(i,1),r}} + c_{u_{st(i,2),r}}}{u_{st(i,1),r} + u_{st(i,2),r}}$$

$$\begin{pmatrix} \varepsilon_{rotor_{i,r}} \\ \varepsilon_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \beta_{st(i,2),r} - \beta_{st(i,1),r} \\ \alpha_{st(i,3),r} - \alpha_{st(i,2),r} \end{pmatrix}$$

$$\begin{pmatrix} T^* & P^* & \rho^* & Cp & a^*_c & c_u & \alpha & c & \lambda_c & M_w & R_L & \varepsilon_{rotor} \\ T & P & \rho & k & a_{зв} & c_a & \beta & w & w_u & M_c & R_L & \varepsilon_{stator} \end{pmatrix}^T$$

$$
\begin{pmatrix} c_{u1BHA} & c_{u3BHA} \\ c_{a1BHA} & c_{a3BHA} \\ \alpha_{1BHA} & \alpha_{3BHA} \\ \varepsilon_{BHA} & \varepsilon_{BHA} \end{pmatrix} = \left|
\begin{array}{l}
\text{for } i \in 1 \qquad\qquad\qquad\qquad \text{if } BHA = 1 \\
\quad \text{for } r \in 1 .. N_r \\
\qquad \begin{pmatrix} c_{u1BHA_r} \\ c_{u3BHA_r} \end{pmatrix} = \begin{pmatrix} c_{u1BHA_{av(N_r)}} \\ c_{u_{st(i,1),r}} \end{pmatrix} \\
\qquad \begin{pmatrix} c_{a1BHA_r} \\ c_{a3BHA_r} \end{pmatrix} = \begin{pmatrix} c_{a1BHA_{av(N_r)}} \\ c_{a_{st(i,1),r}} \end{pmatrix} \\
\qquad \begin{pmatrix} \alpha_{1BHA_r} \\ \alpha_{3BHA_r} \end{pmatrix} = \begin{pmatrix} 90\cdot{}^\circ \\ \alpha_{st(1,1),r} \end{pmatrix} \\
\qquad \varepsilon_{BHA_r} = -1\cdot\left(\alpha_{3BHA_r} - \alpha_{1BHA_r}\right) \\
\begin{pmatrix} c_{u1BHA} & c_{u3BHA} \\ c_{a1BHA} & c_{a3BHA} \\ \alpha_{1BHA} & \alpha_{3BHA} \\ \varepsilon_{BHA} & \varepsilon_{BHA} \end{pmatrix}
\end{array}\right.
$$

$$
\begin{pmatrix} c_{u1CA} & c_{u3CA} \\ c_{a1CA} & c_{a3CA} \\ \alpha_{1CA} & \alpha_{3CA} \\ \varepsilon_{CA} & \varepsilon_{CA} \end{pmatrix} = \left|
\begin{array}{l}
\text{for } i \in Z \qquad\qquad\qquad\qquad \text{if } CA = 1 \\
\quad \text{for } r \in 1 .. N_r \\
\qquad \begin{pmatrix} c_{u1CA_r} \\ c_{u3CA_r} \end{pmatrix} = \begin{pmatrix} c_{u_{st(i,3),r}} \\ c_{u3CA_{av(N_r)}} \end{pmatrix} \\
\qquad \begin{pmatrix} c_{a1CA_r} \\ c_{a3CA_r} \end{pmatrix} = \begin{pmatrix} c_{a_{st(i,3),r}} \\ c_{a3CA_{av(N_r)}} \end{pmatrix} \\
\qquad \begin{pmatrix} \alpha_{1CA_r} \\ \alpha_{3CA_r} \end{pmatrix} = \begin{pmatrix} \alpha_{st(i,3),r} \\ 90\cdot{}^\circ \end{pmatrix} \\
\qquad \varepsilon_{CA_r} = \left(\alpha_{3CA_r} - \alpha_{1CA_r}\right) \\
\begin{pmatrix} c_{u1CA} & c_{u3CA} \\ c_{a1CA} & c_{a3CA} \\ \alpha_{1CA} & \alpha_{3CA} \\ \varepsilon_{CA} & \varepsilon_{CA} \end{pmatrix}
\end{array}\right.
$$

$c_{u1BHA} = \begin{pmatrix} 0.00 \\ 0.00 \end{pmatrix}$

$c_{u1CA} = 0.00$

$c_{u3BHA} = 0.00$

$c_{u3CA} = \begin{pmatrix} 0.00 \\ 90.04 \end{pmatrix}$

$c_{a1BHA} = \begin{pmatrix} 0.00 \\ 142.69 \end{pmatrix}$

$c_{a1CA} = 0.00$

$c_{a3BHA} = 0.00$

$c_{a3CA} = \begin{pmatrix} 0.00 \\ 112.87 \end{pmatrix}$

$\alpha_{1BHA} = 0.00 \cdot °$

$\alpha_{1CA} = 0.00 \cdot °$

$\alpha_{3BHA} = 0.00 \cdot °$

$\alpha_{3CA} = 0.00 \cdot °$

$\varepsilon_{BHA} = 0.00 \cdot °$

$\varepsilon_{CA} = 0.00 \cdot °$

Расчет параметров потока по высоте Л

Результаты расчета параметров потока по высоте Л

$T^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	288.2	337.1	337.1																						
2	288.2	337.1	337.1																						
3	288.2	337.1	337.1																						

$T^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	278.0	252.6	324.7																						
2	278.0	300.0	328.2																						
3	278.0	311.5	331.6																						

$p^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	101.3	163.0	163.0																		
2	101.3	163.0	163.0																		
3	101.3	163.0	163.0																		

$\cdot 10^{3}$

$p^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	89.4	59.3	142.9																		
2	89.4	108.3	148.4																		
3	89.4	123.7	153.9																		

$\cdot 10^{3}$

$\rho^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.224	1.684	1.684																		
2	1.224	1.684	1.684																		
3	1.224	1.684	1.684																		

$\rho^{T} =$

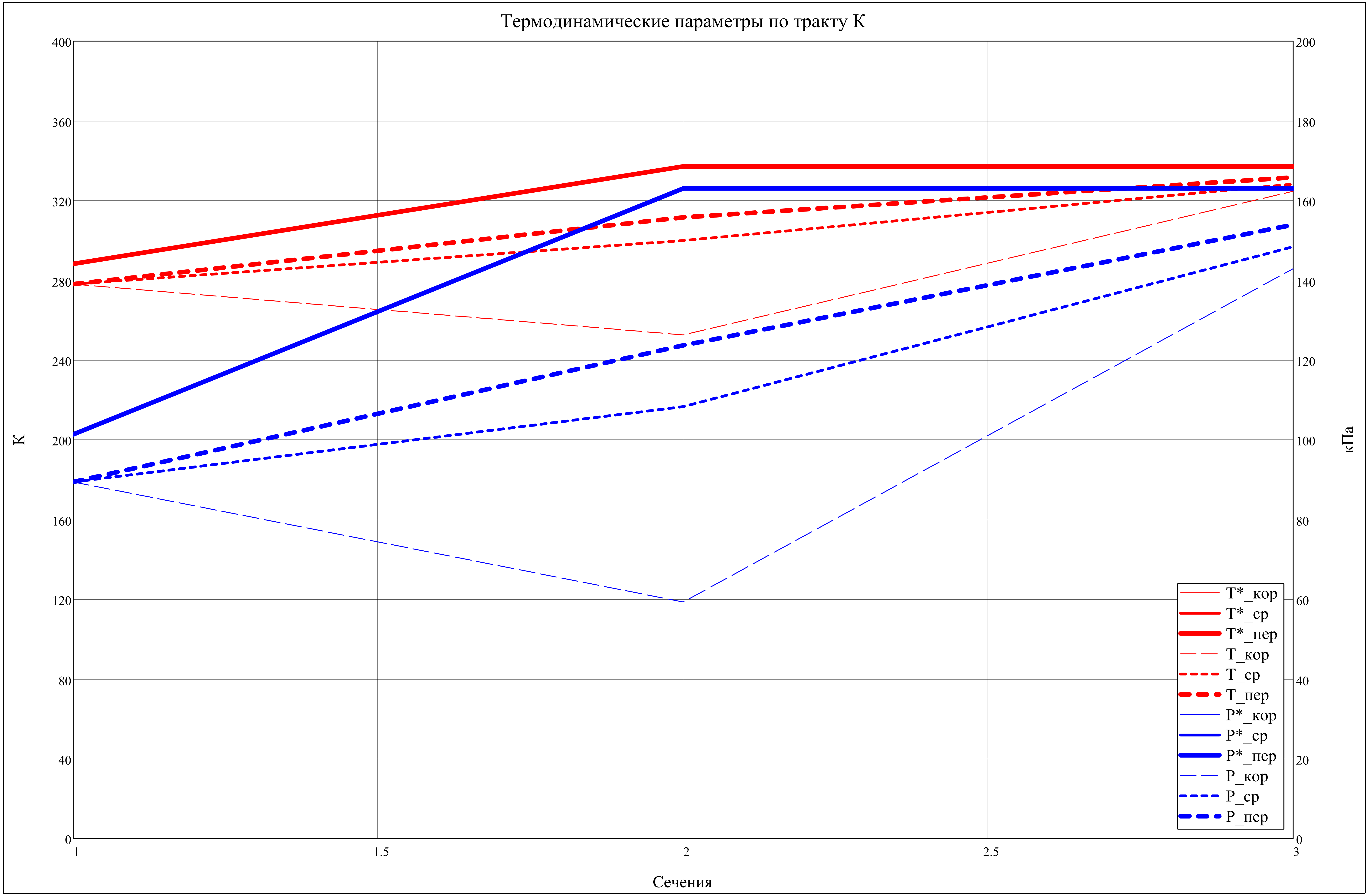
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.120	0.818	1.533																		
2	1.120	1.257	1.575																		
3	1.120	1.382	1.616																		

$Cp^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1003	1006	1006																						
2	1003	1006	1006																						
3	1003	1006	1006																						

$k^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1.401	1.399	1.399																						
2	1.401	1.399	1.399																						
3	1.401	1.399	1.399																						


Термодинамические параметры по тракту К
К
кПа
Сечения
0
40
80
120
160
200
240
280
320
360
400
0
20
40
60
80
100
120
140
160
180
200
1
1.5
2
2.5
3
T*_кор
T*_ср
T*_пер
T_кор
T_ср
T_пер
P*_кор
P*_ср
P*_пер
P_кор
P_ср
P_пер

$a^*{}_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	310.8	336.0	336.0																						
2	310.8	336.0	336.0																						
3	310.8	336.0	336.0																						

$a_{зв}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	334.5	318.6	361.2																						
2	334.5	347.2	363.2																						
3	334.5	353.8	365.0																						

$c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	142.7	412.4	158.2																						
2	142.7	273.4	134.0																						
3	142.7	226.8	105.2																						

$w^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	220.5	276.3	188.1																						
2	353.8	152.1	263.8																						
3	449.2	234.1	338.8																						

$u^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	168.1	187.6	205.6																						
2	323.8	329.1	334.4																						
3	425.9	425.9	425.9																						

$c_a^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	142.7	228.0	137.9																						
2	142.7	125.4	99.2																						
3	142.7	88.1	52.4																						

$c_u^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0.0	343.6	77.6																						
2	0.0	243.0	90.0																						
3	0.0	209.0	91.2																						

$w_u^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	168.1	-155.9	128.0																					
2	323.8	86.1	244.4																					
3	425.9	216.9	334.7																					

$$\Delta c_a = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } a \in 2..3 \\ \quad\quad \text{for } r \in 1..N_r \\ \quad\quad\quad \Delta c_{a_{st(i,a),r}} = c_{a_{st(i,a),r}} - c_{a_{st(i,a-1),r}} \\ \Delta c_a \end{array}\right.$$

$\Delta c_a{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0.00	85.34	-90.18																		
2	0.00	-17.32	-26.16																		
3	0.00	-54.54	-35.79																		

[16, c. 81]

$\Delta c_a{}^T \geq -25 =$

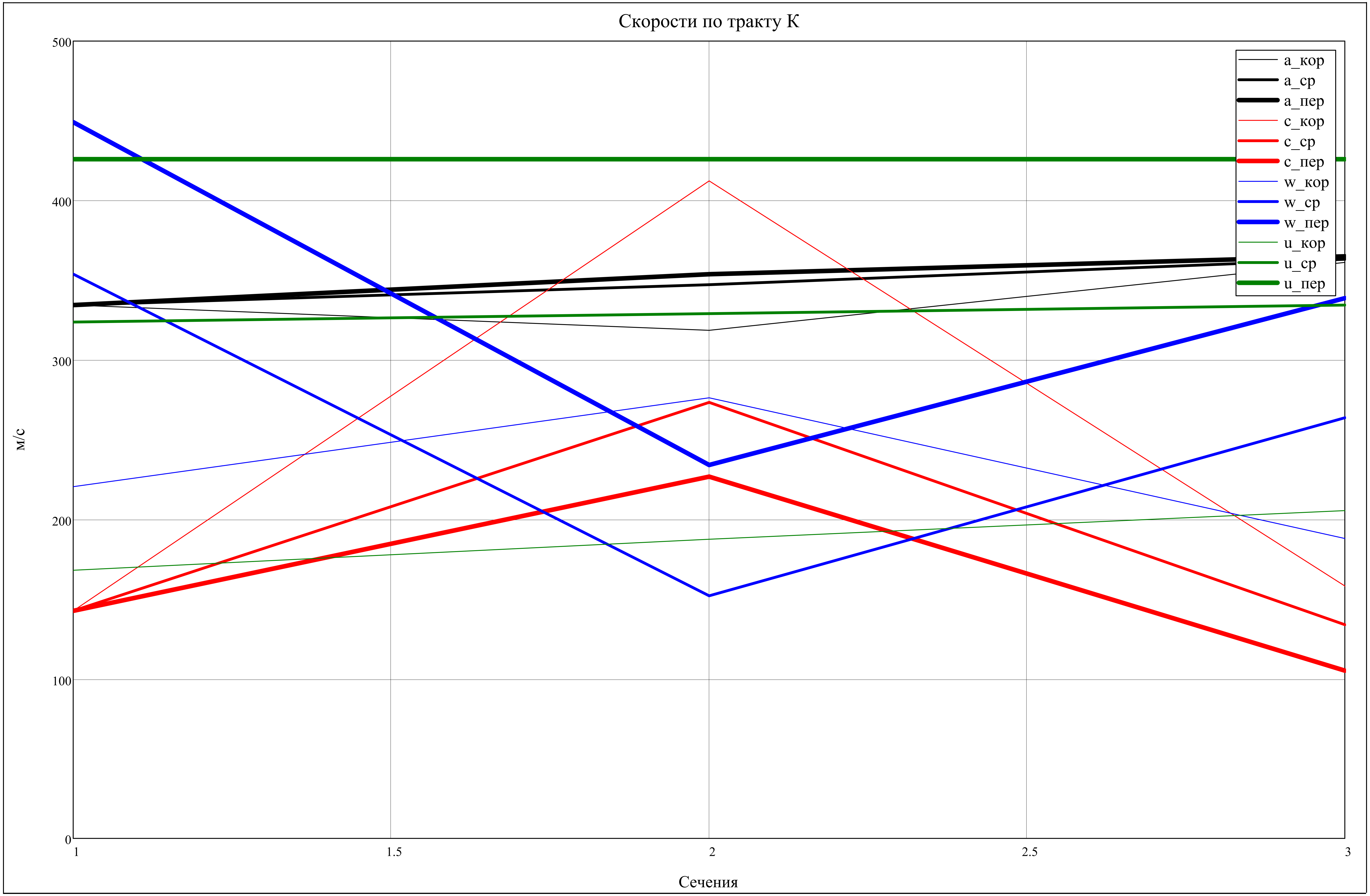
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	1	0																		
2	1	1	0																		
3	1	0	0																		

$R_L{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.0343											
2	0.6279											
3	0.7546											

$R_L{}^T \geq 0 =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	1											
2	1											
3	1											



Скорости по тракту К
500
400
300
200
100
0
м/с
1
1.5
2
2.5
3
Сечения
a_кор
a_ср
a_пер
c_кор
c_ср
c_пер
w_кор
w_ср
w_пер
u_кор
u_ср
u_пер

$\alpha^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	90.00	33.57	60.62																						
2	90.00	27.29	47.77																						
3	90.00	22.87	29.86																						

$\cdot°$

$\beta^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	40.32	124.36	47.13																		
2	23.78	55.51	22.09																		
3	18.52	22.11	8.89																		

$\cdot°$

$\beta^T \le 91\cdot° =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	0	1																		
2	1	1	1																		
3	1	1	1																		

β.2 > 91 => поменять з-н профилирования

$\varepsilon_{rotor}{}^T =$

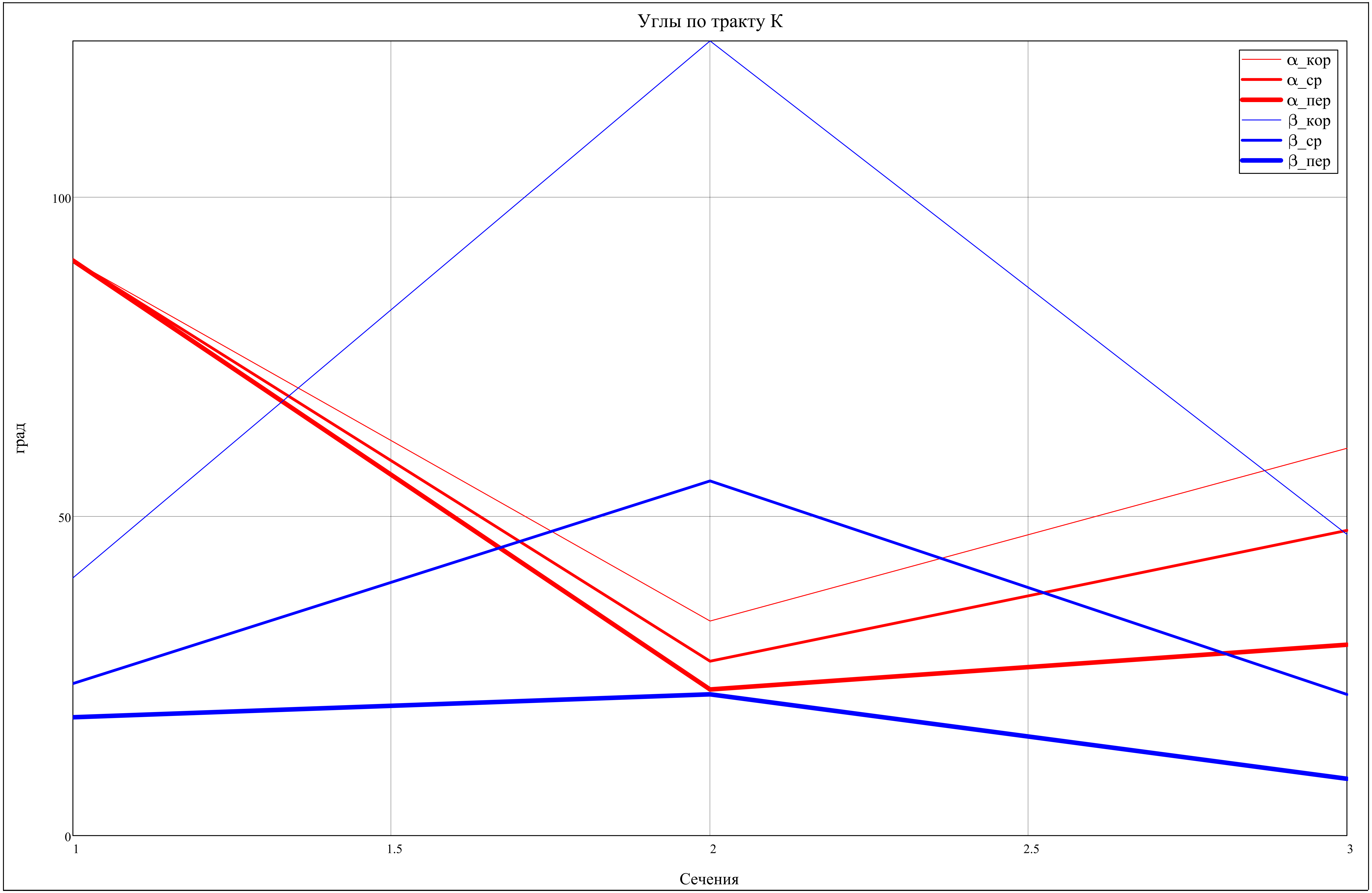
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	84.04														
2	31.73														
3	3.59														

$\cdot°$

$\varepsilon_{stator}{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	27.05														
2	20.48														
3	6.99														

$\cdot°$



Углы по тракту К
α_кор
α_ср
α_пер
β_кор
β_ср
β_пер
град
100
50
0
1
1.5
2
2.5
3
Сечения

$\lambda_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.4591	1.2272	0.4708																				
2	0.4591	0.8137	0.3987																				
3	0.4591	0.6751	0.3130																				

[16, c. 87] $\lambda_c^T \le 0.85 =$

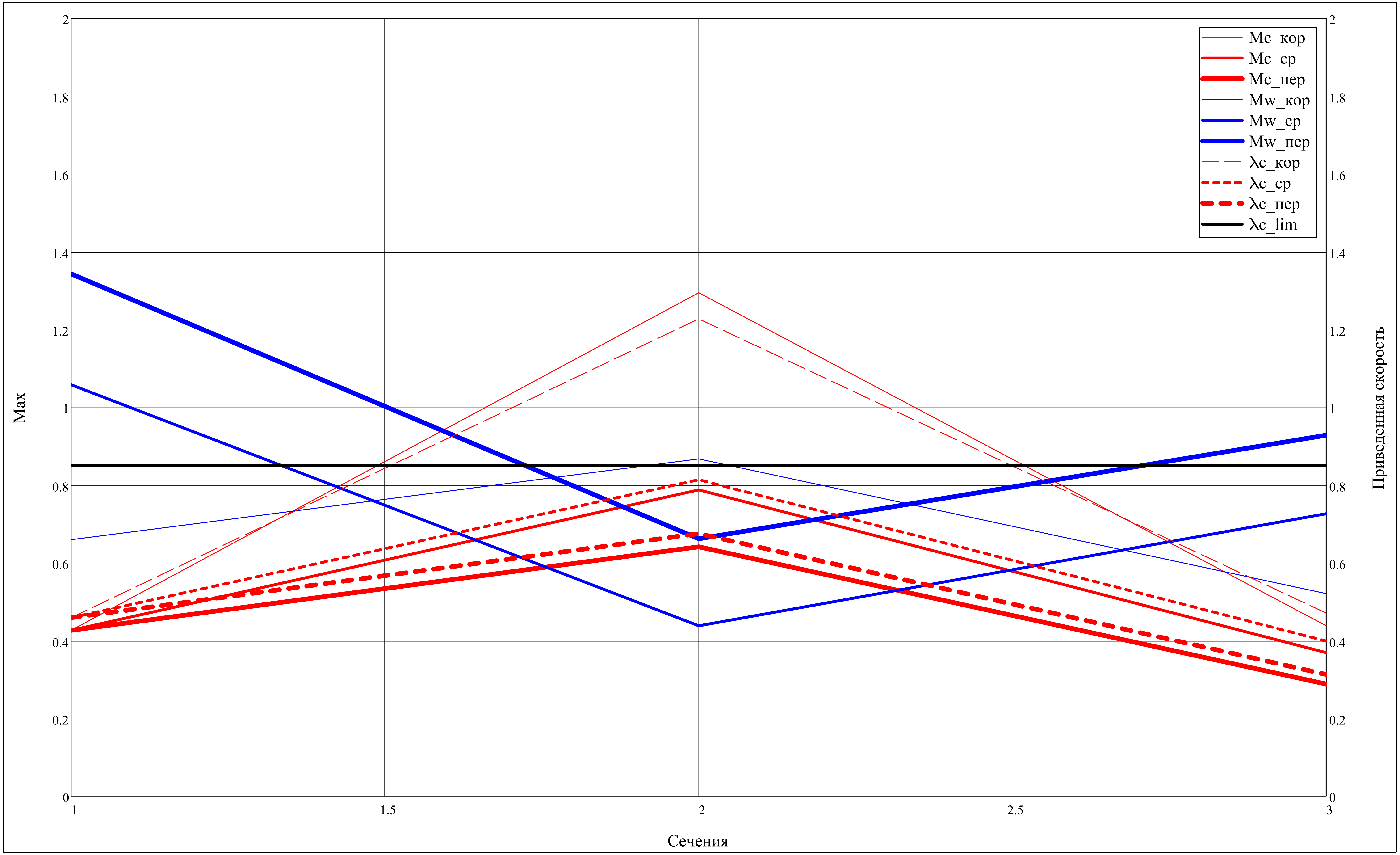
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1	0	1																
2	1	1	1																
3	1	1	1																

$M_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.4266	1.2943	0.4380																				
2	0.4266	0.7875	0.3689																				
3	0.4266	0.6411	0.2881																				

$M_w^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.6593	0.8671	0.5207																				
2	1.0579	0.4381	0.7263																				
3	1.3430	0.6618	0.9281																				



Результаты расчета параметров потока по высоте Л

Вывод результатов расчета параметров потока по высоте Л

Рассматриваемая ступень: $j = \left| \begin{array}{l} j = 1 \\ j = \left| \begin{array}{ll} \text{"Такой ступени не существует!"} & \text{if } (j < 1) \vee (j > Z) \\ j & \text{otherwise} \end{array} \right. \end{array} \right. = 1$

Построение треугольников скоростей в 3х сечениях

$$\Delta_c(v,i,j,r) = \left| \begin{array}{ll} \tan\left(\alpha_{st(i,j),r}\right)\cdot v & \text{if } \left(\tan\left(\alpha_{st(i,j),r}\right) \ge 0 \wedge -\left|c_{st(i,j),r}\cdot\cos\left(\alpha_{st(i,j),r}\right)\right| \le v \le 0\right) \\ \tan\left(\alpha_{st(i,j),r}\right)\cdot v & \text{if } \left(\tan\left(\alpha_{st(i,j),r}\right) < 0 \wedge 0 \le v \le \left|c_{st(i,j),r}\cdot\cos\left(\alpha_{st(i,j),r}\right)\right|\right) \end{array} \right.$$

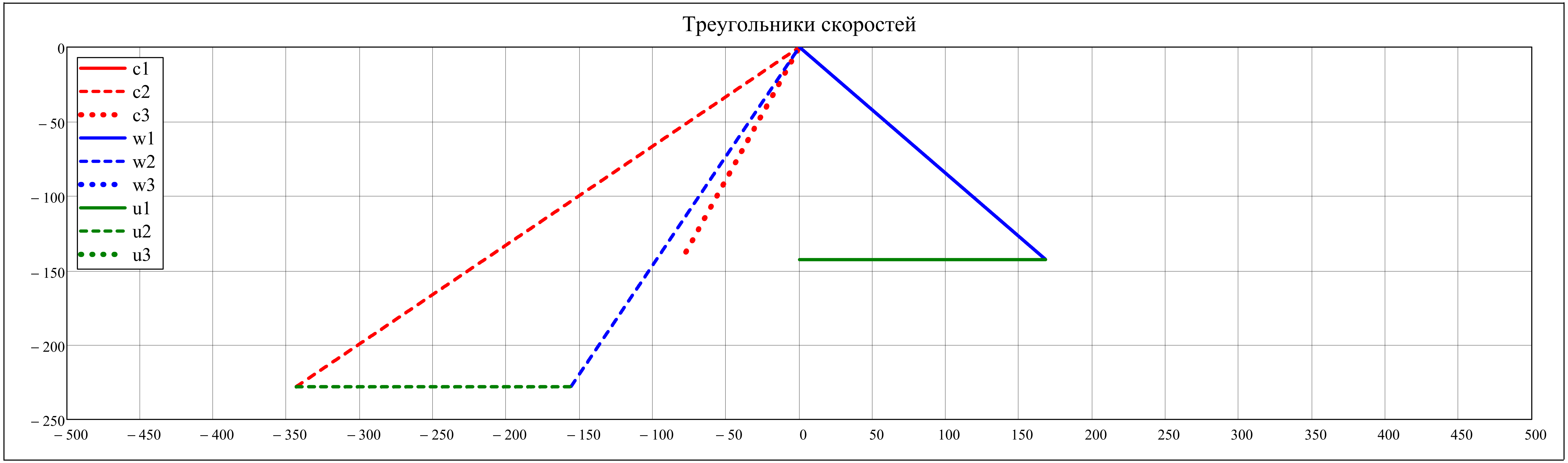
$$\Delta_w(v,i,j,r) = \left| \begin{array}{ll} -\tan\left(\beta_{st(i,j),r}\right)\cdot v & \text{if } \left(-\tan\left(\beta_{st(i,j),r}\right) \ge 0\right) \wedge \left(-\left|w_{st(i,j),r}\cdot\cos\left(\beta_{st(i,j),r}\right)\right| \le v \le 0\right) \wedge (j \ne 3) \\ -\tan\left(\beta_{st(i,j),r}\right)\cdot v & \text{if } \left(-\tan\left(\beta_{st(i,j),r}\right) < 0\right) \wedge \left(0 \le v \le \left|w_{st(i,j),r}\cdot\cos\left(\beta_{st(i,j),r}\right)\right|\right) \wedge (j \ne 3) \end{array} \right.$$

$$\Delta_u(v,i,j,r) = \left| \begin{array}{ll} -c_{a_{st(i,j),r}} & \text{if } \left(-c_{st(i,j),r}\cdot\cos\left(\alpha_{st(i,j),r}\right) \le v \le w_{st(i,j),r}\cdot\cos\left(\beta_{st(i,j),r}\right)\right) \wedge (j \ne 3) \\ \text{NaN} & \text{otherwise} \end{array} \right.$$

$$v_{lim} = \text{ceil}\left(\frac{\max(c,w,u)}{10^2}\right)\cdot 10^2 = 500$$

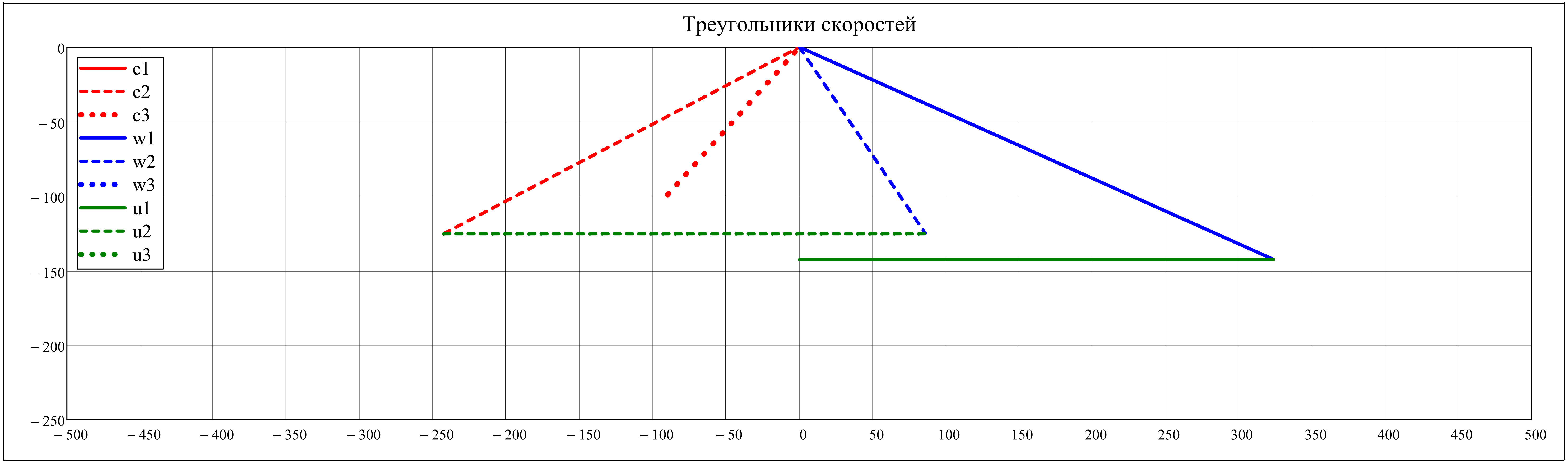
Дискретизация скорости: $v = -v_{lim}, -v_{lim} + \frac{v_{lim}}{3000} .. v_{lim}$

r = 1



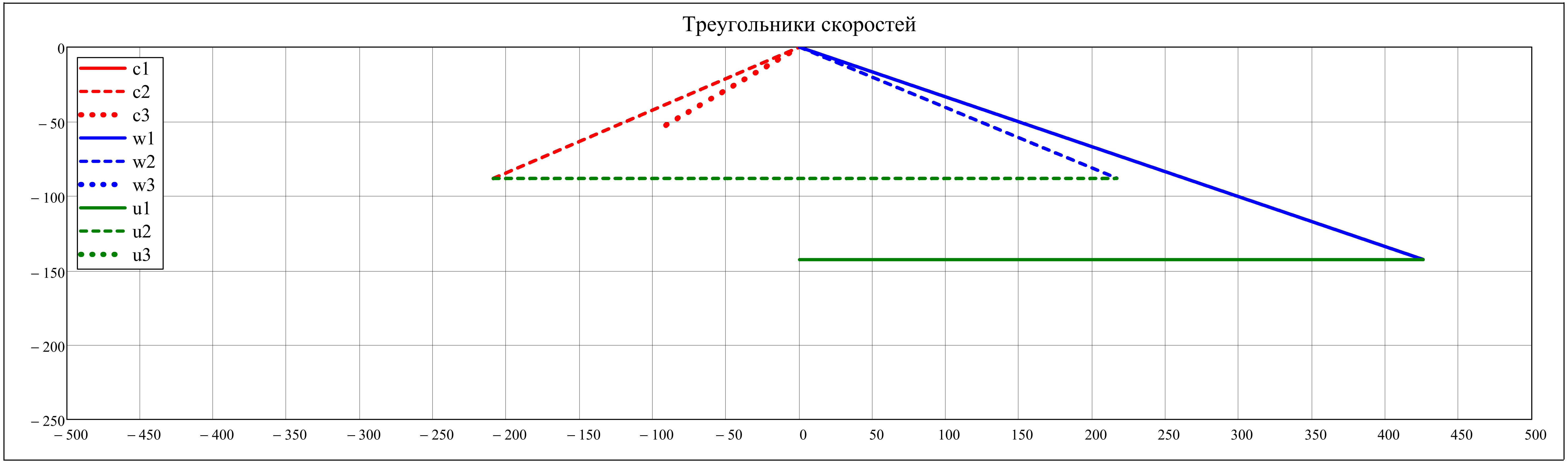
Треугольники скоростей
c1
c2
c3
w1
w2
w3
u1
u2
u3
0
− 50
− 100
− 150
− 200
− 250
− 500
− 450
− 400
− 350
− 300
− 250
− 200
− 150
− 100
− 50
0
50
100
150
200
250
300
350
400
450
500

$r := av(N_r)$



Треугольники скоростей
c1
c2
c3
w1
w2
w3
u1
u2
u3
0
− 50
− 100
− 150
− 200
− 250
− 500
− 450
− 400
− 350
− 300
− 250
− 200
− 150
− 100
− 50
0
50
100
150
200
250
300
350
400
450
500

$r = N_r$



Построение треугольников скоростей в 3х сечениях

Определение степени повышения полного давлеия по 2ум контурам

$$\begin{pmatrix} F_I & F_{II} \\ D2 & R2 \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } a \in 1..3 \\ \quad\quad \rho_{.}(z) \leftarrow \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(\rho, st(i,a), st(i,a), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(\rho, st(i,a), st(i,a), 1, N_r\right)^T, z\right) \\ \quad\quad c_{a.}(z) \leftarrow \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(c_a, st(i,a), st(i,a), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(c_a, st(i,a), st(i,a), 1, N_r\right)^T, z\right) \\ \quad\quad R2 \leftarrow \sqrt{\dfrac{\left(R_{st(i,a), N_r}\right)^2 + m2 \cdot \left(R_{st(i,a), 1}\right)^2}{1 + m2}} \\ \quad\quad R2_{st(i,a)} \leftarrow \mathrm{root}\left[\dfrac{\rho_{.}(R2) \cdot c_{a.}(R2) \cdot \pi \cdot \left[\left(R_{st(i,a), N_r}\right)^2 - (R2)^2\right]}{\rho_{.}(R2) \cdot c_{a.}(R2) \cdot \pi \cdot \left[(R2)^2 - \left(R_{st(i,a), 1}\right)^2\right]} - m2, R2\right] \\ \quad\quad D2_{st(i,a)} \leftarrow 2 \cdot R2_{st(i,a)} \\ \quad\quad \begin{pmatrix} F_{II_{st(i,a)}} \\ F_{I_{st(i,a)}} \end{pmatrix} \leftarrow \pi \cdot \begin{bmatrix} \left(R_{st(i,a), N_r}\right)^2 - \left(R2_{st(i,a)}\right)^2 \\ \left(R2_{st(i,a)}\right)^2 - \left(R_{st(i,a), 1}\right)^2 \end{bmatrix} \\ \begin{pmatrix} F_I & F_{II} \\ D2 & R2 \end{pmatrix} \end{array} \right.$$

Кольцевые площади (м^2):

$$\mathrm{stack}\left(F_I^T, F_{II}^T, F^T\right) =$$

	1	2	3
1	0.2232	0.2130	0.2028
2	1.3389	1.2783	1.2166
3	1.5621	1.5127	1.4194

Радиус и диаметр двухконтурности (м):

$$\mathrm{stack}\left(R2^T, D2^T\right) =$$

	1	2	3
1	403.5	426.7	449.2
2	807.0	853.5	898.3

$\cdot 10^{-3}$

$$\begin{pmatrix} \pi^*_{II} \\ \pi^*_{I} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } a \in 1 \\ \quad\quad Cp_{.}(z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(Cp, st(i,a), st(i,a), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(Cp, st(i,a), st(i,a), 1, N_r\right)^T, z\right) \\ \quad\quad k_{.}(z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(k, st(i,a), st(i,a), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(k, st(i,a), st(i,a), 1, N_r\right)^T, z\right) \\ \quad\quad T^*_{.}(z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(T^*, st(i,a), st(i,a), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(T^*, st(i,a), st(i,a), 1, N_r\right)^T, z\right) \\ \quad\quad H_{T.}(z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(H_T, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,a), st(i,a), 1, N_r\right)^T, \mathrm{submatrix}\left(H_T, i, i, 1, N_r\right)^T, z\right) \\ \quad\quad \pi^*_{II_i} = \left| \begin{array}{l} 1 \quad \text{if } m2 = 0 \\ \dfrac{2\cdot\pi}{F_{II_{st(i,a)}}} \cdot \displaystyle\int_{R2_{st(i,a)}}^{R_{st(i,a),N_r}} \left(1 + \dfrac{K_{H_i}\cdot\eta^*_i\cdot H_{T.}(r)}{Cp_{.}(r)\cdot T^*_{.}(r)}\right)^{\frac{k_{.}(r)}{k_{.}(r)-1}} \cdot r\,dr \quad \text{otherwise} \end{array} \right. \\ \quad\quad \pi^*_{I_i} = \dfrac{2\cdot\pi}{F_{I_{st(i,a)}}} \cdot \displaystyle\int_{R_{st(i,a),1}}^{R2_{st(i,a)}} \left(1 + \dfrac{K_{H_i}\cdot\eta^*_i\cdot H_{T.}(r)}{Cp_{.}(r)\cdot T^*_{.}(r)}\right)^{\frac{k_{.}(r)}{k_{.}(r)-1}} \cdot r\,dr \\ \begin{pmatrix} \pi^*_{II} \\ \pi^*_{I} \end{pmatrix} \end{array} \right.$$

$$\mathrm{stack}\left({\pi^*_I}^T, {\pi^*_{II}}^T\right) =$$

	1	2	3	4	5	6	7	8	9	10	11	12
1	1.609											
2	1.609											

$$\prod_{i=1}^{Z} \pi^*_{I_i} = 1.609 \qquad \prod_{i=1}^{Z} \pi^*_{II_i} = 1.609$$

Определение степени повышения полного давлеия по 2ум контурам

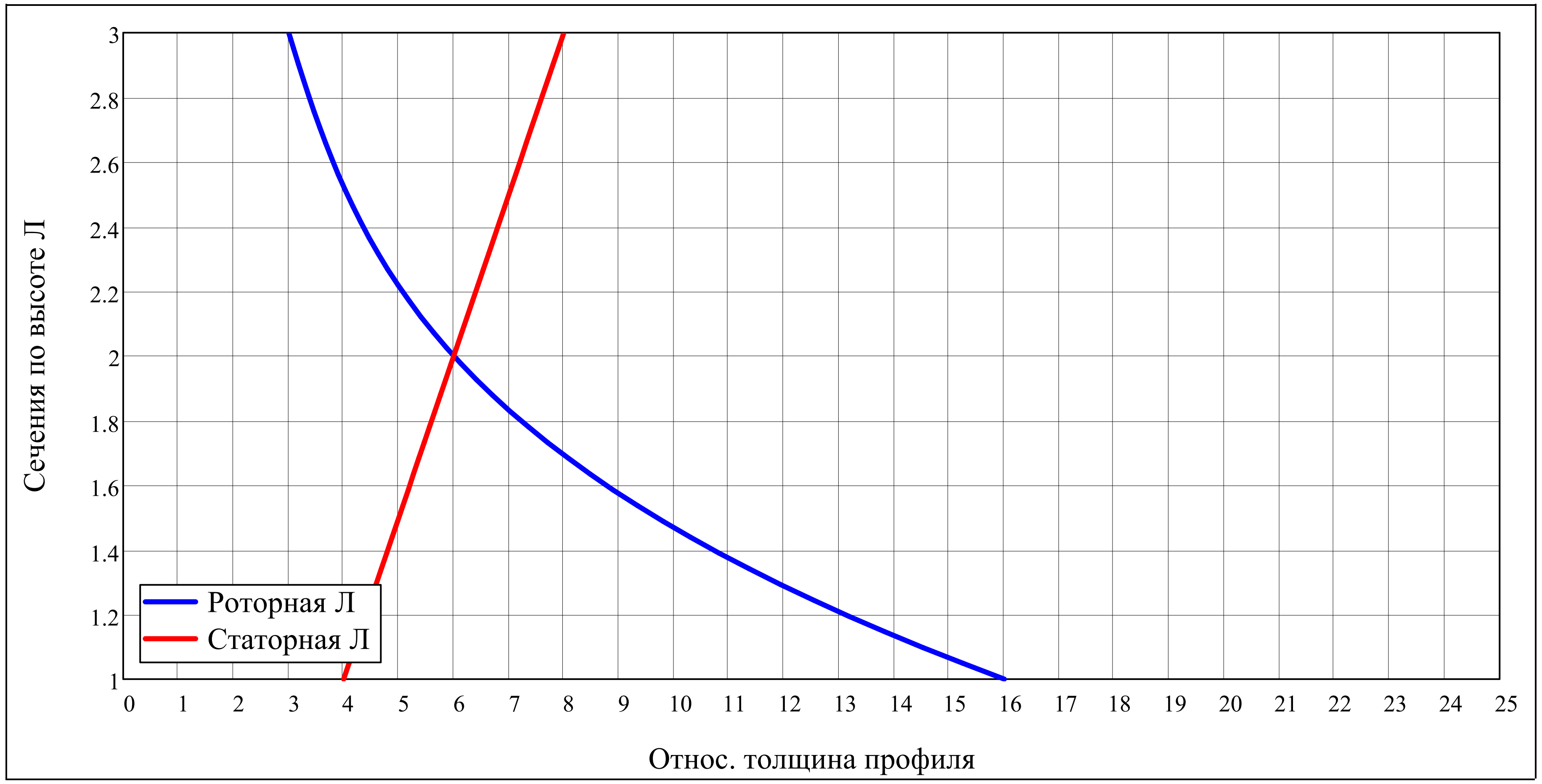
Относ. толщины и радиусы профилей

Относ. толщины Л РК и СА:

$$\overline{c}_{rotor.}(r) := \mathrm{interp}\left[\mathrm{cspline}\left[\begin{pmatrix}1\\ av(N_r)\\ N_r\end{pmatrix}, \begin{pmatrix}13 + \begin{vmatrix}3 & \text{if compressor} = \text{"Вл"}\\ -3 & \text{if compressor} = \text{"КНД"}\\ 0 & \text{otherwise}\end{vmatrix}\\ 5 + \begin{vmatrix}1 & \text{if compressor} = \text{"Вл"}\\ -1 & \text{if compressor} = \text{"КНД"}\\ 0 & \text{otherwise}\end{vmatrix}\\ 3\end{pmatrix}\%\right], \begin{pmatrix}1\\ av(N_r)\\ N_r\end{pmatrix}, \begin{pmatrix}13 + \begin{vmatrix}3 & \text{if compressor} = \text{"Вл"}\\ -3 & \text{if compressor} = \text{"КНД"}\\ 0 & \text{otherwise}\end{vmatrix}\\ 5 + \begin{vmatrix}1 & \text{if compressor} = \text{"Вл"}\\ -1 & \text{if compressor} = \text{"КНД"}\\ 0 & \text{otherwise}\end{vmatrix}\\ 3\end{pmatrix}\%, r\right]$$

$$r := ORIGIN, ORIGIN + \frac{N_r - ORIGIN}{N_{dis}} .. N_r$$

$$\overline{c}_{stator.}(r) := \mathrm{interp}\left[\mathrm{cspline}\left[\begin{pmatrix}1\\ av(N_r)\\ N_r\end{pmatrix}, \begin{pmatrix}4\\ 6\\ 8\end{pmatrix}\%\right], \begin{pmatrix}1\\ av(N_r)\\ N_r\end{pmatrix}, \begin{pmatrix}4\\ 6\\ 8\end{pmatrix}\%, r\right]$$



$$\bar{c}_{BHA} = \left| \begin{array}{l} \text{for } r \in 1..N_r \\ \quad \bar{c}_{BHA_r} = \bar{c}_{stator.}(r) \\ \bar{c}_{BHA} \end{array} \right.$$

$\bar{c}_{BHA} =$

	1
1	4.00
2	6.00
3	8.00

$\cdot\%$

$$\begin{pmatrix} \bar{c}_{stator} \\ \bar{c}_{rotor} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } r \in 1..N_r \\ \quad\quad \begin{pmatrix} \bar{c}_{stator_{i,r}} \\ \bar{c}_{rotor_{i,r}} \end{pmatrix} = \begin{pmatrix} \bar{c}_{stator.}(r) \\ \bar{c}_{rotor.}(r) \end{pmatrix} \\ \begin{pmatrix} \bar{c}_{stator} \\ \bar{c}_{rotor} \end{pmatrix} \end{array} \right.$$

$\bar{c}_{stator}{}^{T} =$

	1
1	4.00
2	6.00
3	8.00

$\cdot\%$

$\bar{c}_{rotor}{}^{T} =$

	1
1	16.00
2	6.00
3	3.00

$\cdot\%$

$$\bar{c}_{CA} = \left| \begin{array}{l} \text{for } r \in 1..N_r \\ \quad \bar{c}_{CA_r} = \bar{c}_{stator.}(r) \\ \bar{c}_{CA} \end{array} \right.$$

$\bar{c}_{CA} =$

	1
1	4.00
2	6.00
3	8.00

$\cdot\%$

$$\begin{pmatrix}\overline{r}\text{\_inlet}_{BHA}\\ \overline{r}\text{\_outlet}_{BHA}\end{pmatrix} = \left|\begin{array}{l}\text{for } r \in 1..N_r \\ \quad \begin{pmatrix}\overline{r}\text{\_inlet}_{BHA_r}\\ \overline{r}\text{\_outlet}_{BHA_r}\end{pmatrix} = \begin{pmatrix}0.2\\ 0.1\end{pmatrix}\cdot\overline{c}_{stator.}(r) \\ \begin{pmatrix}\overline{r}\text{\_inlet}_{BHA}\\ \overline{r}\text{\_outlet}_{BHA}\end{pmatrix}\end{array}\right. \quad \text{if } BHA = 1$$

$$\begin{pmatrix}\overline{r}\text{\_inlet}_{CA}\\ \overline{r}\text{\_outlet}_{CA}\end{pmatrix} = \left|\begin{array}{l}\text{for } r \in 1..N_r \\ \quad \begin{pmatrix}\overline{r}\text{\_inlet}_{CA_r}\\ \overline{r}\text{\_outlet}_{CA_r}\end{pmatrix} = \begin{pmatrix}0.2\\ 0.1\end{pmatrix}\cdot\overline{c}_{stator.}(r) \\ \begin{pmatrix}\overline{r}\text{\_inlet}_{CA}\\ \overline{r}\text{\_outlet}_{CA}\end{pmatrix}\end{array}\right. \quad \text{if } CA = 1$$

$$\begin{pmatrix}\overline{r}\text{\_inlet}_{rotor} & \overline{r}\text{\_inlet}_{stator}\\ \overline{r}\text{\_outlet}_{rotor} & \overline{r}\text{\_outlet}_{stator}\end{pmatrix} = \left|\begin{array}{l}\text{for } i \in 1..Z \\ \quad \text{for } r \in 1..N_r \\ \quad\quad \left|\begin{array}{l}\begin{pmatrix}\overline{r}\text{\_inlet}_{stator_{i,r}}\\ \overline{r}\text{\_outlet}_{stator_{i,r}}\end{pmatrix} = \begin{pmatrix}0.2\\ 0.1\end{pmatrix}\cdot\overline{c}_{stator.}(r) \\ \begin{pmatrix}\overline{r}\text{\_inlet}_{rotor_{i,r}}\\ \overline{r}\text{\_outlet}_{rotor_{i,r}}\end{pmatrix} = \begin{pmatrix}0.2\\ 0.1\end{pmatrix}\cdot\overline{c}_{rotor.}(r)\end{array}\right. \\ \begin{pmatrix}\overline{r}\text{\_inlet}_{rotor} & \overline{r}\text{\_inlet}_{stator}\\ \overline{r}\text{\_outlet}_{rotor} & \overline{r}\text{\_outlet}_{stator}\end{pmatrix}\end{array}\right.$$

$\overline{r}\text{\_inlet}_{BHA} = 0.000\cdot\%$

$\overline{r}\text{\_inlet}_{CA} = 0.000\cdot\%$

$\overline{r}\text{\_inlet}_{stator}{}^{T} =$ (table below) $\cdot\%$

	1
1	0.800
2	1.200
3	1.600

$\overline{r}\text{\_inlet}_{rotor}{}^{T} =$ (table below) $\cdot\%$

	1
1	3.200
2	1.200
3	0.600

$\overline{r}\text{\_outlet}_{stator}{}^{T} =$ (table below) $\cdot\%$

	1
1	0.400
2	0.600
3	0.800

$\overline{r}\text{\_outlet}_{rotor}{}^{T} =$ (table below) $\cdot\%$

	1
1	1.600
2	0.600
3	0.300

$\overline{r}\text{\_outlet}_{BHA} = 0.000\cdot\%$

$\overline{r}\text{\_outlet}_{CA} = 0.000\cdot\%$

Относ. толщины и радиусы профилей

▾ Распределение параметров по высоте Л

Относ. удлинение Л РК и НА: [16, с. 244]

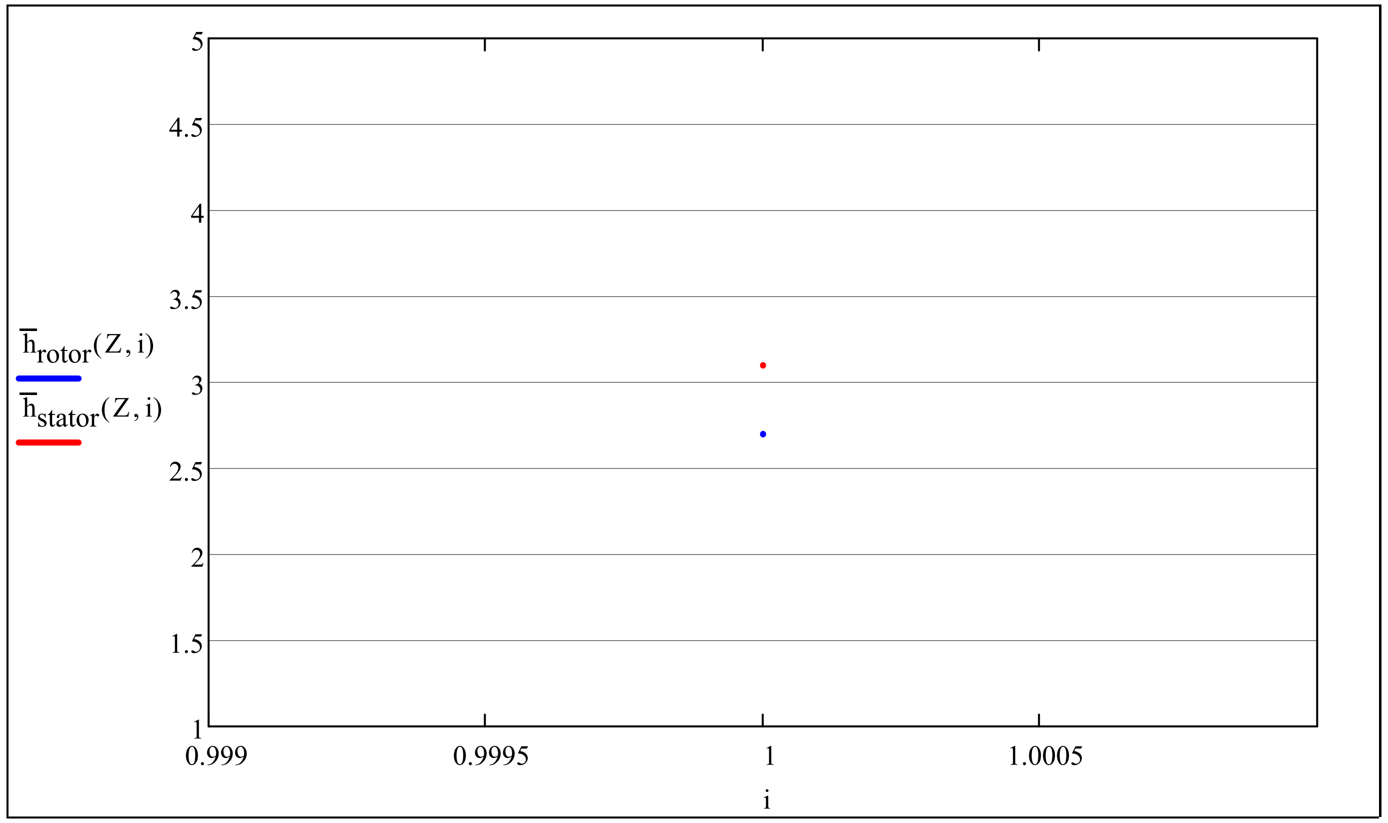
$$\overline{h}_{\sim rotor} = (2\ \ 1.9\ \ 1.85\ \ 1.8\ \ 1.75\ \ 1.7\ \ 1.65\ \ 1.6)^T + \begin{vmatrix} 1.1 \ \text{if compressor = "Вл"} \\ -0.1 \ \text{if compressor = "КНД"} \\ -0.55 \ \text{if compressor = "КВД"} \end{vmatrix}$$

$$\overline{h}_{\sim stator} = (4\ \ 3.5\ \ 3.25\ \ 3\ \ 2.75\ \ 2.5\ \ 2.25\ \ 2)^T + \begin{vmatrix} 1.1 \ \text{if compressor = "Вл"} \\ -0.1 \ \text{if compressor = "КНД"} \\ -0.7 \ \text{if compressor = "КВД"} \end{vmatrix}$$

$$\overline{h}_{\sim rotor}(i) = \text{interp}\left(\text{cspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, \overline{h}_{\sim rotor}\right), \frac{z_\sim}{\text{rows}(z_\sim)}, \overline{h}_{\sim rotor}, i\right)$$

$$\overline{h}_{\sim stator}(i) = \text{interp}\left(\text{cspline}\left(\frac{z_\sim}{\text{rows}(z_\sim)}, \overline{h}_{\sim stator}\right), \frac{z_\sim}{\text{rows}(z_\sim)}, \overline{h}_{\sim stator}, i\right)$$

$$\overline{h}_{rotor}(Z,i) = \begin{vmatrix} \overline{h}_{\sim rotor}\left(\frac{1}{\text{rows}(z_\sim)}\right) \ \text{if } i < 1 \\ \overline{h}_{\sim rotor}(1) \ \text{if } i > Z \\ \overline{h}_{\sim rotor}\left(\frac{i}{Z}\right) \ \text{otherwise} \end{vmatrix} \qquad \overline{h}_{stator}(Z,i) = \begin{vmatrix} \overline{h}_{\sim stator}\left(\frac{1}{\text{rows}(z_\sim)}\right) \ \text{if } i < 1 \\ \overline{h}_{\sim stator}(1) \ \text{if } i > Z \\ \overline{h}_{\sim stator}\left(\frac{i}{Z}\right) \ \text{otherwise} \end{vmatrix}$$



Для компрессора газогенератора

$\frac{h_{PK}}{S_{PK}}$=2,5…4,5 – для первой дозвуковой ступени;

$\frac{h_{PK}}{S_{PK}}$=2,0…3,5 – для первой околозвуковой ступени;

$\frac{h_{PK}}{S_{PK}}$=1,7…3,0 – для первой сверхзвуковой ступени;

$\frac{h_{PK}}{S_{PK}}$=1,0…2,5 – для последней ступени.

[16, с. 83-84]

▴ Распределение параметров по высоте Л

Парусность: $\begin{pmatrix} sail_{rotor} \\ sail_{stator} \end{pmatrix} = \begin{pmatrix} 1.3 \\ 1.2 \end{pmatrix}$

Расчет длин хорд по высоте Л

$$
chord_{BHA} = \left| \begin{array}{l}
\text{for } i \in 1 \\
\quad \left| \begin{array}{l}
chord_{BHA_{av(N_r)}} = \dfrac{h_{st(i,1)}}{\overline{h}_{stator}(Z,0)} \\
sail = \dfrac{R_{st(1,1),N_r} - R_{st(1,1),1}}{R_{st(1,1),av(N_r)} - R_{st(1,1),1}} \\
\text{for } r \in 1..N_r \\
\quad \left| \begin{array}{l}
b_{BHAкор} = \dfrac{chord_{BHA_{av(N_r)}} \cdot sail}{sail_{stator} - 1 + sail} \\
b_{BHAпер} = b_{BHAкор} \cdot sail_{stator} \\
b_{BHA.}(z) = interp\left[cspline\left[\begin{pmatrix} R_{st(i,1),1} \\ R_{st(i,1),av(N_r)} \\ R_{st(i,1),N_r} \end{pmatrix}, \begin{pmatrix} b_{BHAкор} \\ chord_{BHA_{av(N_r)}} \\ b_{BHAпер} \end{pmatrix}\right], \begin{pmatrix} R_{st(i,1),1} \\ R_{st(i,1),av(N_r)} \\ R_{st(i,1),N_r} \end{pmatrix}, \begin{pmatrix} b_{BHAкор} \\ chord_{BHA_{av(N_r)}} \\ b_{BHAпер} \end{pmatrix}, z\right] \\
chord_{BHA_r} = b_{BHA.}(R_{st(i,1),r})
\end{array} \right.
\end{array} \right. \\
chord_{BHA}
\end{array} \right. \quad \text{if } BHA = 1
$$

$$
\begin{pmatrix} \mathrm{chord}_{rotor} & \mathrm{chord}_{stator} \end{pmatrix} =
\left|
\begin{array}{l}
\text{for } i \in 1..Z \\
\quad \left|
\begin{array}{l}
\begin{pmatrix} \mathrm{chord}_{rotor_{i,av(N_r)}} \\ \mathrm{chord}_{stator_{i,av(N_r)}} \end{pmatrix} = \begin{pmatrix} \dfrac{\mathrm{mean}\left(h_{st(i,1)}, h_{st(i,2)}\right)}{\overline{h}_{rotor}(Z,i)} \\[2ex] \dfrac{\mathrm{mean}\left(h_{st(i,2)}, h_{st(i,3)}\right)}{\overline{h}_{stator}(Z,i)} \end{pmatrix} \\[4ex]
\mathrm{sail} = \dfrac{R_{st(i,2),N_r} - R_{st(i,2),1}}{R_{st(i,2),av(N_r)} - R_{st(i,2),1}} \\[3ex]
\text{for } r \in 1..N_r \\
\quad \left|
\begin{array}{l}
b_{\text{РКкор}} = \dfrac{\mathrm{chord}_{rotor_{i,av(N_r)}}{}^{\cdot \mathrm{sail}}}{\mathrm{sail}_{rotor} - 1 + \mathrm{sail}} \\[3ex]
b_{\text{НАкор}} = \dfrac{\mathrm{chord}_{stator_{i,av(N_r)}}{}^{\cdot \mathrm{sail}}}{\mathrm{sail}_{stator} - 1 + \mathrm{sail}} \\[3ex]
\begin{pmatrix} b_{\text{РКпер}} \\ b_{\text{НАпер}} \end{pmatrix} = \begin{pmatrix} b_{\text{РКкор}}{}^{\cdot \mathrm{sail}_{rotor}} \\ b_{\text{НАкор}}{}^{\cdot \mathrm{sail}_{stator}} \end{pmatrix} \\[3ex]
\mathrm{chord}_{rotor.}(z) = \mathrm{interp}\left[\mathrm{cspline}\left[\begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{\text{РКкор}} \\ \mathrm{chord}_{rotor_{i,av(N_r)}} \\ b_{\text{РКпер}} \end{pmatrix}\right], \begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{\text{РКкор}} \\ \mathrm{chord}_{rotor_{i,av(N_r)}} \\ b_{\text{РКпер}} \end{pmatrix}, z\right] \\[5ex]
\mathrm{chord}_{stator.}(z) = \mathrm{interp}\left[\mathrm{cspline}\left[\begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{\text{НАкор}} \\ \mathrm{chord}_{stator_{i,av(N_r)}} \\ b_{\text{НАпер}} \end{pmatrix}\right], \begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{\text{НАкор}} \\ \mathrm{chord}_{stator_{i,av(N_r)}} \\ b_{\text{НАпер}} \end{pmatrix}, z\right] \\[5ex]
\mathrm{chord}_{rotor_{i,r}} = \mathrm{chord}_{rotor.}\left(R_{st(i,2),r}\right) \\[1ex]
\mathrm{chord}_{stator_{i,r}} = \mathrm{chord}_{stator.}\left(R_{st(i,2),r}\right)
\end{array}
\right.
\end{array}
\right. \\
\begin{pmatrix} \mathrm{chord}_{rotor} & \mathrm{chord}_{stator} \end{pmatrix}
\end{array}
\right.
$$

$$
chord_{CA} = \left| \begin{array}{l} \text{for } i \in Z \\ \quad \left| \begin{array}{l} chord_{CA_{av(N_r)}} = \dfrac{h_{st(i,3)}}{\overline{h}_{stator}(Z, Z+1)} \\ sail = \dfrac{R_{st(1,1),N_r} - R_{st(1,1),1}}{R_{st(1,1),av(N_r)} - R_{st(1,1),1}} \\ \text{for } r \in 1..N_r \\ \quad \left| \begin{array}{l} b_{CAкор} = \dfrac{chord_{CA_{av(N_r)}} \cdot sail}{sail_{stator} - 1 + sail} \\ b_{CAпер} = b_{CAкор} \cdot sail_{stator} \\ b_{CA.}(z) = interp\left[cspline\left[\begin{pmatrix} R_{st(i,1),1} \\ R_{st(i,1),av(N_r)} \\ R_{st(i,1),N_r} \end{pmatrix}, \begin{pmatrix} b_{CAкор} \\ chord_{CA_{av(N_r)}} \\ b_{CAпер} \end{pmatrix}\right], \begin{pmatrix} R_{st(i,1),1} \\ R_{st(i,1),av(N_r)} \\ R_{st(i,1),N_r} \end{pmatrix}, \begin{pmatrix} b_{CAкор} \\ chord_{CA_{av(N_r)}} \\ b_{CAпер} \end{pmatrix}, z\right] \\ chord_{CA_r} = b_{CA.}\left(R_{st(i,1),r}\right) \end{array} \right. \end{array} \right. \\ chord_{CA} \end{array} \right. \quad \text{if } CA = 1
$$

Расчет длин хорд по высоте Л

Ср. линия профиля:
0.5 - дуга окружности
0.45 - парабола

$\overline{x}_f = 0.5$

Определение количества Л РК и НА

$$
\begin{pmatrix}
\varepsilon_{BHA(b/t)=1} \\
Z_{BHA} \\
r\_inlet_{BHA} \\
r\_outlet_{BHA} \\
t_{BHA} \\
i_{BHA} \\
m_{BHA} \\
\theta_{BHA} \\
\delta_{BHA} \\
\chi_{BHA} \\
\upsilon_{BHA} \\
R_{СЛ.BHA} \\
K_{BHA} \\
D_{BHA}
\end{pmatrix}
=
\begin{array}{|l}
\text{if } BHA = 1 \\
\quad \begin{array}{|l}
\text{for } r \in av(N_r) \\
\quad \begin{array}{|l}
\varepsilon_{BHA(b/t)=1_r} = \varepsilon_{(b/t)=1}\left(\alpha_{3BHA_r}\right) \\
b/t_{BHA_r} = b/t{=}1\left(\dfrac{\varepsilon_{BHA_r}}{\varepsilon_{BHA(b/t)=1_r}}\right) \\
t_{BHA_r} = \dfrac{chord_{BHA_r}}{b/t_{BHA_r}} \\
Z_{BHA} = \begin{array}{|l}
round\left(\dfrac{\pi \cdot D_{st(1,1),r}}{t_{BHA_r}}\right) \text{ if } mod\left(round\left(\dfrac{\pi \cdot D_{st(1,1),r}}{t_{BHA_r}}\right), 2\right) = 0 \\
round\left(\dfrac{\pi \cdot D_{st(1,1),r}}{t_{BHA_r}}\right) + 1 \text{ otherwise}
\end{array}
\end{array} \\
\text{for } r \in 1..N_r \\
\quad \begin{array}{|l}
\left(r\_inlet_{BHA_r} \;\; r\_outlet_{BHA_r}\right) = chord_{BHA_r} \cdot \left(\overline{r}\_inlet_{BHA_r} \;\; \overline{r}\_outlet_{BHA_r}\right) \\
t_{BHA_r} = \dfrac{D_{st(1,1),r}}{Z_{BHA}} \\
i_{BHA_r} = 2.5 \cdot \left(\dfrac{chord_{BHA_r}}{t_{BHA_r}} - 2\right) \cdot {}^\circ \\
m_{BHA_r} = 0.23 \cdot \left(2 \cdot \overline{x}_f\right)^2 + 0.18 - \dfrac{0.002}{deg} \cdot \left(\alpha_{3BHA_r}\right)
\end{array}
\end{array}
\end{array}
$$

$$\theta_{BHA_r} = \frac{\varepsilon_{BHA_r} - i_{BHA_r}}{1 - m_{BHA_r} \cdot \sqrt{\dfrac{t_{BHA_r}}{chord_{BHA_r}}}}$$

$$\delta_{BHA_r} = m_{BHA_r} \cdot \theta_{BHA_r} \cdot \sqrt{\frac{t_{BHA_r}}{chord_{BHA_r}}}$$

$$\chi_{BHA_r} = \theta_{BHA_r} \cdot \frac{1 + 2 \cdot \left(1 - 2 \cdot \overline{x}_f\right)}{2}$$

$$\upsilon_{BHA_r} = \chi_{BHA_r} + \alpha_{1BHA_r} + i_{BHA_r}$$

$$R_{СЛ.BHA_r} = \frac{chord_{BHA_r}}{2 \cdot \sin\left(0.5 \cdot \theta_{BHA_r}\right)}$$

$$K_{BHA_r} = \frac{c_{a3BHA_r}}{c_{a1BHA_r}}$$

$$D_{BHA_r} = \left(1 - K_{BHA_r} \cdot \frac{\sin\left(\alpha_{1BHA_r}\right)}{\sin\left(\alpha_{3BHA_r}\right)}\right) + \left(\frac{1}{\tan\left(\alpha_{1BHA_r}\right)} - K_{BHA_r} \cdot \frac{1}{\tan\left(\alpha_{3BHA_r}\right)}\right) \cdot \frac{\sin\left(\alpha_{1BHA_r}\right)}{2 \cdot \dfrac{chord_{BHA_r}}{t_{BHA_r}}}$$

$$\left(\varepsilon_{BHA(b/t)=1} \;\; Z_{BHA} \;\; r\_inlet_{BHA} \;\; r\_outlet_{BHA} \;\; t_{BHA} \;\; i_{BHA} \;\; m_{BHA} \;\; \theta_{BHA} \;\; \delta_{BHA} \;\; \chi_{BHA} \;\; \upsilon_{BHA} \;\; R_{СЛ.BHA} \;\; K_{BHA} \;\; D_{BHA}\right)^T$$

$$
\begin{pmatrix}
\varepsilon_{РК(b/t)=1} & \varepsilon_{НА(b/t)=1} \\
Z_{rotor} & Z_{stator} \\
r\_inlet_{rotor} & r\_inlet_{stator} \\
r\_outlet_{rotor} & r\_outlet_{stator} \\
t_{rotor} & t_{stator} \\
i_{rotor} & i_{stator} \\
m_{rotor} & m_{stator} \\
\theta_{rotor} & \theta_{stator} \\
\delta_{rotor} & \delta_{stator} \\
\chi_{rotor} & \chi_{stator} \\
\upsilon_{rotor} & \upsilon_{stator} \\
R_{СЛ.rotor} & R_{СЛ.stator} \\
K_{rotor} & K_{stator} \\
D_{rotor} & D_{stator} \\
\zeta_{rotor} & \zeta_{stator} \\
quality_{rotor} & quality_{stator} \\
\eta_{stage} & \eta_{stage}
\end{pmatrix}
=
$$

$\text{for } i \in 1..Z$

$\quad \text{for } r \in av(N_r)$

$$
\begin{pmatrix} \varepsilon_{РК(b/t)=1_{i,r}} \\ \varepsilon_{НА(b/t)=1_{i,r}} \end{pmatrix}
=
\begin{pmatrix} \varepsilon_{(b/t)=1}\left(\beta_{st(i,2),r}\right) \\ \varepsilon_{(b/t)=1}\left(\alpha_{st(i,3),r}\right) \end{pmatrix}
$$

$$
\begin{pmatrix} b/t_{РК_{i,r}} \\ b/t_{НА_{i,r}} \end{pmatrix}
=
\begin{pmatrix} b/t{=}1\left(\dfrac{\varepsilon_{rotor_{i,r}}}{\varepsilon_{РК(b/t)=1_{i,r}}}\right) \\ b/t{=}1\left(\dfrac{\varepsilon_{stator_{i,r}}}{\varepsilon_{НА(b/t)=1_{i,r}}}\right) \end{pmatrix}
$$

$$
\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix}
=
\begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{b/t_{РК_{i,r}}} \\ \dfrac{chord_{stator_{i,r}}}{b/t_{НА_{i,r}}} \end{pmatrix}
$$

$$
\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix}
=
\frac{2}{3}
\begin{pmatrix} chord_{rotor_{i,r}} \cdot \cos\left(\beta_{st(i,1),r}\right) \\ chord_{stator_{i,r}} \cdot \cos\left(\alpha_{st(i,2),r}\right) \end{pmatrix}
$$

$$
Z_{stator_i} = \left|
\begin{array}{l}
round\left(\dfrac{\pi \cdot mean\left(D_{st(i,2),r}, D_{st(i,3),r}\right)}{t_{stator_{i,r}}}\right) \text{ if } mod\left(round\left(\dfrac{\pi \cdot mean\left(D_{st(i,2),r}, D_{st(i,3),r}\right)}{t_{stator_{i,r}}}\right), 2\right) = 0 \\
round\left(\dfrac{\pi \cdot mean\left(D_{st(i,2),r}, D_{st(i,3),r}\right)}{t_{stator_{i,r}}}\right) + 1 \text{ otherwise}
\end{array}
\right.
$$

$$
Z_{rotor_i} = \left|
\begin{array}{l}
Z_{rotor_i} = round\left(\dfrac{\pi \cdot mean\left(D_{st(i,1),r}, D_{st(i,2),r}\right)}{t_{rotor_{i,r}}}\right)
\end{array}
\right.
$$

$$\text{while } \gcd\left(Z_{rotor_i}, Z_{stator_i}\right) \neq 1$$

$$Z_{rotor_i} = Z_{rotor_i} + 1$$

for $r \in 1 .. N_r$

$$\begin{pmatrix} r\_inlet_{stator_{i,r}} & r\_outlet_{stator_{i,r}} \\ r\_inlet_{rotor_{i,r}} & r\_outlet_{rotor_{i,r}} \end{pmatrix} = \begin{pmatrix} \overline{r\_inlet}_{stator_{i,r}} \cdot chord_{stator_{i,r}} & \overline{r\_outlet}_{stator_{i,r}} \cdot chord_{stator_{i,r}} \\ \overline{r\_inlet}_{rotor_{i,r}} \cdot chord_{rotor_{i,r}} & \overline{r\_outlet}_{rotor_{i,r}} \cdot chord_{rotor_{i,r}} \end{pmatrix}$$

$$\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \pi \cdot \begin{pmatrix} \dfrac{\mathrm{mean}\left(D_{st(i,1),r}, D_{st(i,2),r}\right)}{Z_{rotor_i}} \\ \dfrac{\mathrm{mean}\left(D_{st(i,2),r}, D_{st(i,3),r}\right)}{Z_{stator_i}} \end{pmatrix}$$

$$\begin{pmatrix} i_{rotor_{i,r}} \\ i_{stator_{i,r}} \end{pmatrix} = 2.5 \cdot \begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{t_{rotor_{i,r}}} - 1 \\ \dfrac{chord_{stator_{i,r}}}{t_{stator_{i,r}}} - 2 \end{pmatrix} \cdot \circ$$

$$\begin{pmatrix} m_{rotor_{i,r}} \\ m_{stator_{i,r}} \end{pmatrix} = 0.23 \cdot \left(2 \cdot \overline{x}_f\right)^2 + 0.18 - \frac{0.002}{deg} \cdot \begin{pmatrix} \beta_{st(i,2),r} \\ \alpha_{st(i,3),r} \end{pmatrix}$$

$$\begin{pmatrix} \theta_{rotor_{i,r}} \\ \theta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{\varepsilon_{rotor_{i,r}} - i_{rotor_{i,r}}}{1 - m_{rotor_{i,r}} \cdot \sqrt{\dfrac{t_{rotor_{i,r}}}{chord_{rotor_{i,r}}}}} \\ \dfrac{\varepsilon_{stator_{i,r}} - i_{stator_{i,r}}}{1 - m_{stator_{i,r}} \cdot \sqrt{\dfrac{t_{stator_{i,r}}}{chord_{stator_{i,r}}}}} \end{pmatrix}$$

$$\begin{pmatrix} \delta_{rotor_{i,r}} \\ \delta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} m_{rotor_{i,r}} \cdot \theta_{rotor_{i,r}} \cdot \sqrt{\dfrac{t_{rotor_{i,r}}}{chord_{rotor_{i,r}}}} \\ m_{stator_{i,r}} \cdot \theta_{stator_{i,r}} \cdot \sqrt{\dfrac{t_{stator_{i,r}}}{chord_{stator_{i,r}}}} \end{pmatrix}$$

$$\begin{pmatrix} \chi_{rotor_{i,r}} \\ \chi_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \theta_{rotor_{i,r}} \\ \theta_{stator_{i,r}} \end{pmatrix} \cdot \frac{1 + 2 \cdot \left(1 - 2 \cdot \overline{x}_f\right)}{2}$$

$$\left(\upsilon_{rotor_{i,r}} \right) \quad \left(\chi_{rotor_{i,r}} + \beta_{st(i,1),r} + i_{rotor_{i,r}} \right)$$

$$\begin{pmatrix} \upsilon_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \chi_{stator_{i,r}} + \alpha_{st(i,2),r} + i_{stator_{i,r}} \end{pmatrix}$$

$$\begin{pmatrix} R_{СЛ.rotor_{i,r}} \\ R_{СЛ.stator_{i,r}} \end{pmatrix} = \frac{1}{2}\cdot\begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{\sin\left(0.5\cdot\theta_{rotor_{i,r}}\right)} \\ \dfrac{chord_{stator_{i,r}}}{\sin\left(0.5\cdot\theta_{stator_{i,r}}\right)} \end{pmatrix}$$

$$\begin{pmatrix} K_{rotor_{i,r}} \\ K_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{a_{st(i,2),r}}}{c_{a_{st(i,1),r}}} \\ \dfrac{c_{a_{st(i,3),r}}}{c_{a_{st(i,2),r}}} \end{pmatrix}$$

$$\begin{pmatrix} D_{rotor_{i,r}} \\ D_{stator_{i,r}} \end{pmatrix} = \begin{bmatrix} \left(1 - K_{rotor_{i,r}}\cdot\dfrac{\sin\left(\beta_{st(i,1),r}\right)}{\sin\left(\left|\beta_{st(i,2),r}\right|\right)}\right) + \left(\dfrac{1}{\tan\left(\beta_{st(i,1),r}\right)} - K_{rotor_{i,r}}\cdot\dfrac{1}{\tan\left(\beta_{st(i,2),r}\right)}\right)\cdot\dfrac{\sin\left(\beta_{st(i,1),r}\right)}{2\cdot\dfrac{chord_{rotor_{i,r}}}{t_{rotor_{i,r}}}} \\ \left(1 - K_{stator_{i,r}}\cdot\dfrac{\sin\left(\alpha_{st(i,2),r}\right)}{\sin\left(\alpha_{st(i,3),r}\right)}\right) + \left(\dfrac{1}{\tan\left(\alpha_{st(i,2),r}\right)} - K_{stator_{i,r}}\cdot\dfrac{1}{\tan\left(\alpha_{st(i,3),r}\right)}\right)\cdot\dfrac{\sin\left(\alpha_{st(i,2),r}\right)}{2\cdot\dfrac{chord_{stator_{i,r}}}{t_{stator_{i,r}}}} \end{bmatrix}$$

$$\begin{pmatrix} \zeta_{rotor_{i,r}} \\ \zeta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{\zeta\bullet\sin(\beta3)/(2b/t)\left(D_{rotor_{i,r}}\right)\cdot 2\cdot\dfrac{chord_{rotor_{i,r}}}{t_{rotor_{i,r}}}}{\sin\left(\beta_{st(i,2),r}\right)} \\ \dfrac{\zeta\bullet\sin(\beta3)/(2b/t)\left(D_{stator_{i,r}}\right)\cdot 2\cdot\dfrac{chord_{stator_{i,r}}}{t_{stator_{i,r}}}}{\sin\left(\alpha_{st(i,3),r}\right)} \end{pmatrix}$$

$$\begin{pmatrix} \beta_{cp_{i,r}} \\ \alpha_{cp_{i,r}} \end{pmatrix} = \begin{pmatrix} \operatorname{atan}\left(\dfrac{c_{a_{st(i,1),r}}}{\operatorname{mean}\left(w_{u_{st(i,1),r}}, w_{u_{st(i,2),r}}\right)}\right) \\ \operatorname{atan}\left(\dfrac{c_{a_{st(i,2),r}}}{\operatorname{mean}\left(c_{u_{st(i,2),r}}, c_{u_{st(i,3),r}}\right)}\right) \end{pmatrix}$$

$$\begin{pmatrix} quality_{rotor_{i,r}} \\ quality_{stator_{i,r}} \end{pmatrix} = \begin{bmatrix} \dfrac{2}{\zeta_{rotor_{i,r}}}\cdot\left(\dfrac{1}{\tan\left(\beta_{st(i,1),r}\right)} - \dfrac{1}{\tan\left(\beta_{st(i,2),r}\right)}\right)\cdot\left(\dfrac{\sin\left(\beta_{st(i,1),r}\right)}{\sin\left(\beta_{cp_{i,r}}\right)}\right)^2 - \dfrac{1}{\tan\left(\beta_{cp_{i,r}}\right)} \\ \dfrac{2}{\zeta_{stator_{i,r}}}\cdot\left(\dfrac{1}{\tan\left(\alpha_{st(i,2),r}\right)} - \dfrac{1}{\tan\left(\alpha_{st(i,3),r}\right)}\right)\cdot\left(\dfrac{\sin\left(\alpha_{st(i,2),r}\right)}{\sin\left(\alpha_{cp_{i,r}}\right)}\right)^2 - \dfrac{1}{\tan\left(\alpha_{cp_{i,r}}\right)} \end{bmatrix}$$

$$\eta_{stage_{i,r}} = 1 - \left[\frac{\left(\frac{c_{a_{st(i,1),r}}}{u_{st(i,1),r}}\right)^2 + \left(R_{L_{i,r}}\right)^2}{quality_{rotor_{i,r}} \cdot \frac{c_{a_{st(i,1),r}}}{u_{st(i,1),r}} + R_{L_{i,r}}} + \frac{\left(\frac{c_{a_{st(i,2),r}}}{u_{st(i,2),r}}\right)^2 + \left(1 - R_{L_{i,r}}\right)^2}{quality_{stator_{i,r}} \cdot \frac{c_{a_{st(i,2),r}}}{u_{st(i,2),r}} + \left(1 - R_{L_{i,r}}\right)} \right]$$

$$\begin{pmatrix} \varepsilon_{PK(b/t)=1} & Z_{rotor} & r\_inlet_{rotor} & r\_outlet_{rotor} & t_{rotor} & i_{rotor} & m_{rotor} & \theta_{rotor} & \delta_{rotor} & \chi_{rotor} & \upsilon_{rotor} & R_{СЛ.rotor} & K_{rotor} & D_{rotor} & \zeta_{rotor} & quality_{rotor} & \eta_{stage} \\ \varepsilon_{HA(b/t)=1} & Z_{stator} & r\_inlet_{stator} & r\_outlet_{stator} & t_{stator} & i_{stator} & m_{stator} & \theta_{stator} & \delta_{stator} & \chi_{stator} & \upsilon_{stator} & R_{СЛ.stator} & K_{stator} & D_{stator} & \zeta_{stator} & quality_{stator} & \eta_{stage} \end{pmatrix}^T$$

$$
\begin{pmatrix}
\varepsilon_{CA(b/t)=1} \\
Z_{CA} \\
r\_inlet_{CA} \\
r\_outlet_{CA} \\
t_{CA} \\
i_{CA} \\
m_{CA} \\
\theta_{CA} \\
\delta_{CA} \\
\chi_{CA} \\
\upsilon_{CA} \\
R_{СЛ.CA} \\
K_{CA} \\
D_{CA}
\end{pmatrix}
=
$$

if $CA = 1$

for $r \in av(N_r)$

$$\varepsilon_{CA(b/t)=1_r} \leftarrow \varepsilon_{(b/t)=1}\left(\alpha_{3CA_r}\right)$$

$$b/t_{CA_r} \leftarrow b/t{=}1\left(\frac{\varepsilon_{CA_r}}{\varepsilon_{CA(b/t)=1_r}}\right)$$

$$t_{CA_r} \leftarrow \frac{chord_{CA_r}}{b/t_{CA_r}}$$

$$Z_{CA} \leftarrow \begin{cases} round\left(\dfrac{\pi \cdot D_{st(Z,3),r}}{t_{CA_r}}\right) & \text{if } mod\left(round\left(\dfrac{\pi \cdot D_{st(Z,3),r}}{t_{CA_r}}\right), 2\right) = 0 \\ round\left(\dfrac{\pi \cdot D_{st(Z,3),r}}{t_{CA_r}}\right) + 1 & \text{otherwise} \end{cases}$$

for $r \in 1 .. N_r$

$$\left(r\_inlet_{CA_r} \;\; r\_outlet_{CA_r}\right) \leftarrow chord_{CA_r} \cdot \left(\overline{r}\_inlet_{CA_r} \;\; \overline{r}\_outlet_{CA_r}\right)$$

$$t_{CA_r} \leftarrow \frac{D_{st(Z,3),r}}{Z_{CA}}$$

$$i_{CA_r} \leftarrow 2.5 \cdot \left(\frac{chord_{CA_r}}{t_{CA_r}} - 2\right) \cdot {}^\circ$$

$$m_{CA_r} \leftarrow 0.23 \cdot \left(2 \cdot \overline{x}_f\right)^2 + 0.18 - \frac{0.002}{deg} \cdot \left(\alpha_{3CA_r}\right)$$

$$\theta_{CA_r} \leftarrow \frac{\varepsilon_{CA_r} - i_{CA_r}}{1 - m_{CA_r} \cdot \sqrt{\dfrac{t_{CA_r}}{chord_{CA_r}}}}$$

$$\delta_{CA_r} = m_{CA_r}\cdot\theta_{CA_r}\cdot\sqrt{\frac{t_{CA_r}}{chord_{CA_r}}}$$

$$\chi_{CA_r} = \theta_{CA_r}\cdot\frac{1+2\cdot\left(1-2\cdot\bar{x}_f\right)}{2}$$

$$\upsilon_{CA_r} = \chi_{CA_r} + \alpha_{1CA_r} + i_{CA_r}$$

$$R_{СЛ.CA_r} = \frac{chord_{CA_r}}{2\cdot\sin\left(0.5\cdot\theta_{CA_r}\right)}$$

$$K_{CA_r} = \frac{c_{a3CA_r}}{c_{a1CA_r}}$$

$$D_{CA_r} = \left(1 - K_{CA_r}\cdot\frac{\sin\left(\alpha_{1CA_r}\right)}{\sin\left(\alpha_{3CA_r}\right)}\right) + \left(\frac{1}{\tan\left(\alpha_{1CA_r}\right)} - K_{CA_r}\cdot\frac{1}{\tan\left(\alpha_{3CA_r}\right)}\right)\cdot\frac{\sin\left(\alpha_{1CA_r}\right)}{2\cdot\frac{chord_{CA_r}}{t_{CA_r}}}$$

$$\left(\varepsilon_{CA(b/t)=1}\ \ Z_{CA}\ \ r\_inlet_{CA}\ \ r\_outlet_{CA}\ \ t_{CA}\ \ i_{CA}\ \ m_{CA}\ \ \theta_{CA}\ \ \delta_{CA}\ \ \chi_{CA}\ \ \upsilon_{CA}\ \ R_{СЛ.CA}\ \ K_{CA}\ \ D_{CA}\right)^T$$

Определение количества Л РК и НА

Результаты расчета количества Л и параметров решеток РК и НА

$chord_{BHA} = 0.00 \cdot 10^{-3}$

Длина хорды Л (м):

$chord_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	140.51														
2	165.54														
3	182.66														

$\cdot 10^{-3}$

$chord_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	119.15														
2	133.30														
3	142.98														

$\cdot 10^{-3}$

$chord_{CA} = 0.00 \cdot 10^{-3}$

Радисы входных и выходных кромок профилей Л (мм):

$r\_inlet_{BHA} = 0.00 \cdot 10^{-3}$ $r\_outlet_{BHA} = 0.00 \cdot 10^{-3}$

$r\_inlet_{rotor}^{T} =$

	1
1	4.50
2	1.99
3	1.10

$\cdot 10^{-3}$

$r\_outlet_{rotor}^{T} =$

	1
1	2.25
2	0.99
3	0.55

$\cdot 10^{-3}$

$r\_inlet_{stator}^{T} =$

	1
1	0.95
2	1.60
3	2.29

$\cdot 10^{-3}$

$r\_outlet_{stator}^{T} =$

	1
1	0.48
2	0.80
3	1.14

$\cdot 10^{-3}$

$r\_inlet_{CA} = 0.00 \cdot 10^{-3}$ $r\_outlet_{CA} = 0.00 \cdot 10^{-3}$

$\varepsilon_{BHA(b/t)=1_{av(N_r)}} = ■\cdot°$

Угол поворота потока:

$\text{submatrix}\left(\varepsilon_{PK(b/t)=1}, 1, Z, av(N_r), av(N_r)\right)^T =$ (table below) $\cdot°$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	17.63														

$\text{submatrix}\left(\varepsilon_{HA(b/t)=1}, 1, Z, av(N_r), av(N_r)\right)^T =$ (table below) $\cdot°$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	14.02														

$\varepsilon_{CA(b/t)=1_{av(N_r)}} = ■\cdot°$

$\frac{chord_{BHA}}{t_{BHA}} = ■$

Густота решетки:

$\left(\frac{chord_{rotor}}{t_{rotor}}\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.582														
2	1.657														
3	1.402														

$\left(\frac{chord_{stator}}{t_{stator}}\right)^T =$

	1
1	2.570
2	1.703
3	1.423

$\frac{chord_{CA}}{t_{CA}} = ■$

$Z_{BHA} = 0$

Количество Л:

$Z_{rotor}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	37														

$Z_{stator}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	48														

$Z_{CA} = 0$

Значения округляются до целого в большую сторону так, чтобы при разъемном корпусе количество Л НА было четным, а количества Л РК и НА были взаимно простыми

$t_{BHA} = 0.00 \cdot 10^{-3}$

$t_{rotor}^{T} =$ (values $\cdot 10^{-3}$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	54.43														
2	99.89														
3	130.33														

Шаг решетки (м):

$t_{stator}^{T} =$ (values $\cdot 10^{-3}$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	46.37														
2	78.25														
3	100.46														

$t_{CA} = 0.00 \cdot 10^{-3}$

$i_{BHA} = 0.000 \cdot {}^{\circ}$

$i_{rotor}^{T} =$ (values $\cdot {}^{\circ}$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3.954														
2	1.643														
3	1.004														

Угол атаки:

$i_{stator}^{T} =$ (values $\cdot {}^{\circ}$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.424														
2	-0.741														
3	-1.442														

$i_{CA} = 0.000 \cdot {}^{\circ}$

$m_{BHA} = 0.0000$

Коэф. формы ср. линии профиля по Ховеллу:

$m_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.1613														
2	0.2990														
3	0.3658														

$m_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.2888														
2	0.3145														
3	0.3503														

$m_{CA} = 0.0000$

$\theta_{BHA} = 0.00 \cdot ^\circ$

Угол изгиба ср. линии профиля:

$\theta_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	89.03														
2	39.18														
3	3.75														

$\cdot ^\circ$

$\theta_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	31.26														
2	27.96														
3	11.94														

$\cdot ^\circ$

$\theta_{CA} = 0.00 \cdot ^\circ$

$\delta_{BHA} = 0.000 \cdot {}^\circ$

Угол отставания:

$\delta_{rotor}{}^{T} =$

	1
1	8.936
2	9.100
3	1.158

$\cdot {}^\circ$

$\delta_{stator}{}^{T} =$

	1
1	5.630
2	6.735
3	3.506

$\cdot {}^\circ$

$\delta_{CA} = 0.000 \cdot {}^\circ$

$\upsilon_{BHA} = 0.00 \cdot {}^\circ$

Угол установки Л:

$\upsilon_{rotor}{}^{T} =$

	1
1	88.79
2	45.02
3	21.40

$\cdot {}^\circ$

$\upsilon_{stator}{}^{T} =$

	1
1	50.63
2	40.53
3	27.39

$\cdot {}^\circ$

$\upsilon_{CA} = 0.00 \cdot {}^\circ$

$R_{СЛ.ВНА} = 0.00 \cdot 10^{-3}$

Радиус дуги ср. линии (м):

$R_{СЛ.rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	100.21														
2	246.84														
3	2792.96														

$\cdot 10^{-3}$

$R_{СЛ.stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	221.14														
2	275.93														
3	687.29														

$\cdot 10^{-3}$

$R_{СЛ.СА} = 0.00 \cdot 10^{-3}$

$K_{ВНА} = 0.0000$

Фактор диффузорности решетки:

$K_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.5981														
2	0.8786														
3	0.6178														

$K_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.6045														
2	0.7913														
3	0.5940														

$K_{СА} = 0.0000$

$D_{BHA} = 0.0000$

Диффузорность решетки:

$D_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0319														
2	0.7728														
3	0.6447														

$D_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.7419														
2	0.6742														
3	0.7189														

$D_{CA} = 0.0000$

$D_{BHA} \le 0.6 = 1$

$D_{rotor}^{T} \le 0.6 =$

	1
1	1
2	0
3	0

[18, с. 71]

$D_{stator}^{T} \le 0.6 =$

	1
1	0
2	0
3	0

$D_{CA} \le 0.6 = 1$

Коэф. потерь полного давления:

$\zeta_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0329														
2	0.2002														
3	0.2428														

$\zeta_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.2659														
2	0.1659														
3	0.2392														

Качество профилей решеток РК и НА:

$quality_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	47.400														
2	6.438														
3	0.393														

$quality_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3.098														
2	5.892														
3	1.396														

КПД элементарной ступени: $\eta_{stage}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	47.27														
2	72.18														
3	3.81														

$\cdot\%$

Результаты расчета количества Л и параметров решеток РК и НА

Вывод параметров решеток

Подключение симметричного профиля

$EXCEL_{AIRFOIL.subsonic} =$ ...\A40.xlsx

$$X/B_{subsonic} = \mathrm{submatrix}\left(EXCEL_{AIRFOIL.subsonic}, 2, \mathrm{rows}\left(EXCEL_{AIRFOIL.subsonic}\right), ORIGIN + 0, ORIGIN + 0\right)$$

$$Y/B_{subsonic} = \mathrm{submatrix}\left(EXCEL_{AIRFOIL.subsonic}, 2, \mathrm{rows}\left(EXCEL_{AIRFOIL.subsonic}\right), ORIGIN + 1, ORIGIN + 1\right)$$

$EXCEL_{AIRFOIL.supersonic} =$ ...\Емин сверхзв...ой профиль.xlsx

$$X/B_{supersonic} = \mathrm{submatrix}\left(EXCEL_{AIRFOIL.supersonic}, 2, \mathrm{rows}\left(EXCEL_{AIRFOIL.supersonic}\right), ORIGIN + 0, ORIGIN + 0\right)$$

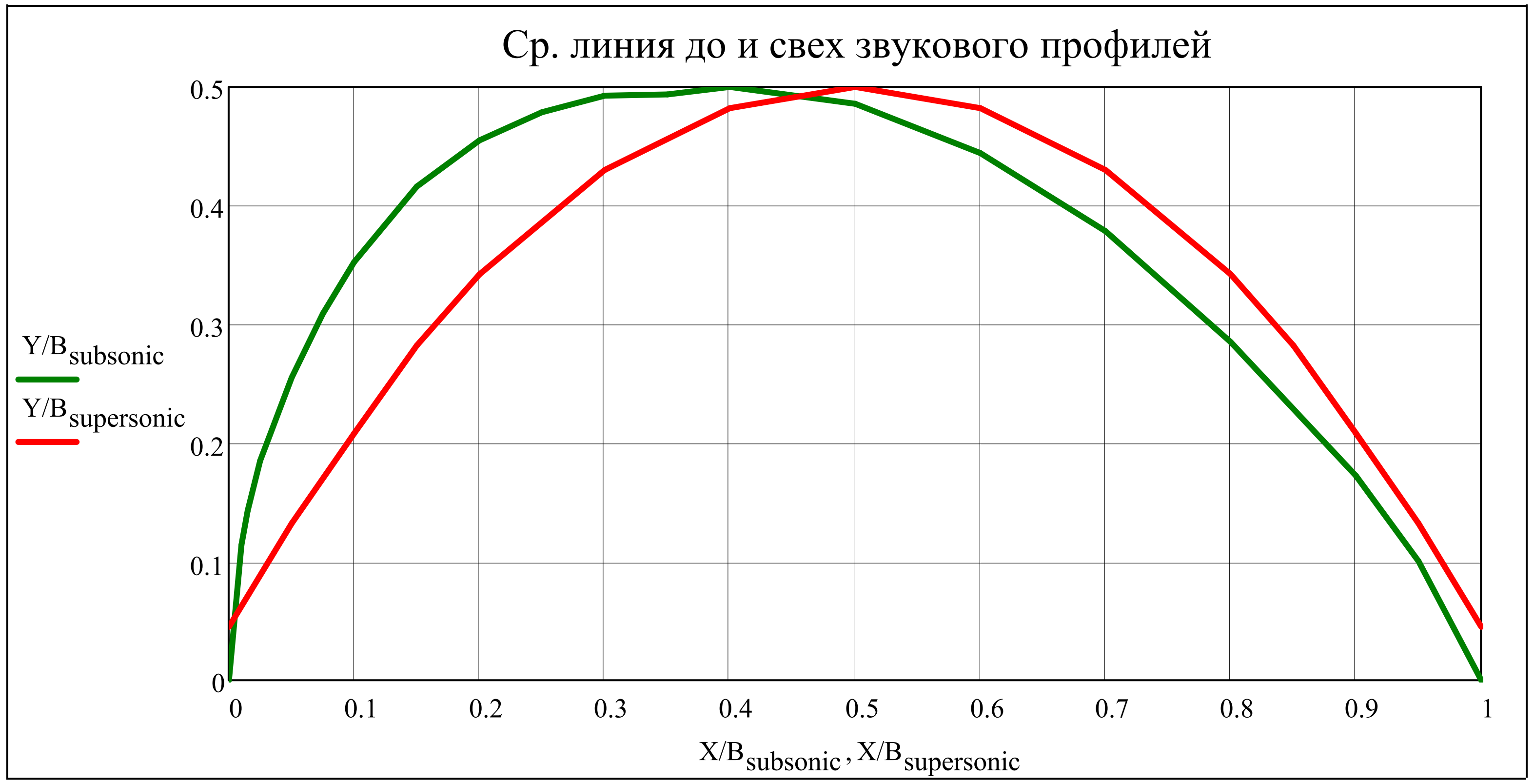
$$Y/B_{supersonic} = \mathrm{submatrix}\left(EXCEL_{AIRFOIL.supersonic}, 2, \mathrm{rows}\left(EXCEL_{AIRFOIL.supersonic}\right), ORIGIN + 1, ORIGIN + 1\right)$$

$\mathrm{augment}\left(X/B_{subsonic}, Y/B_{subsonic}\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.000	0.010	0.015	0.025	0.050	0.075	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.500	0.600	0.700	0.800	0.900	0.950	1.000
2	0.000	0.114	0.143	0.185	0.255	0.309	0.352	0.416	0.455	0.479	0.493	0.494	0.500	0.486	0.444	0.378	0.285	0.172	0.100	0.000

$\mathrm{augment}\left(X/B_{supersonic}, Y/B_{supersonic}\right)^T =$

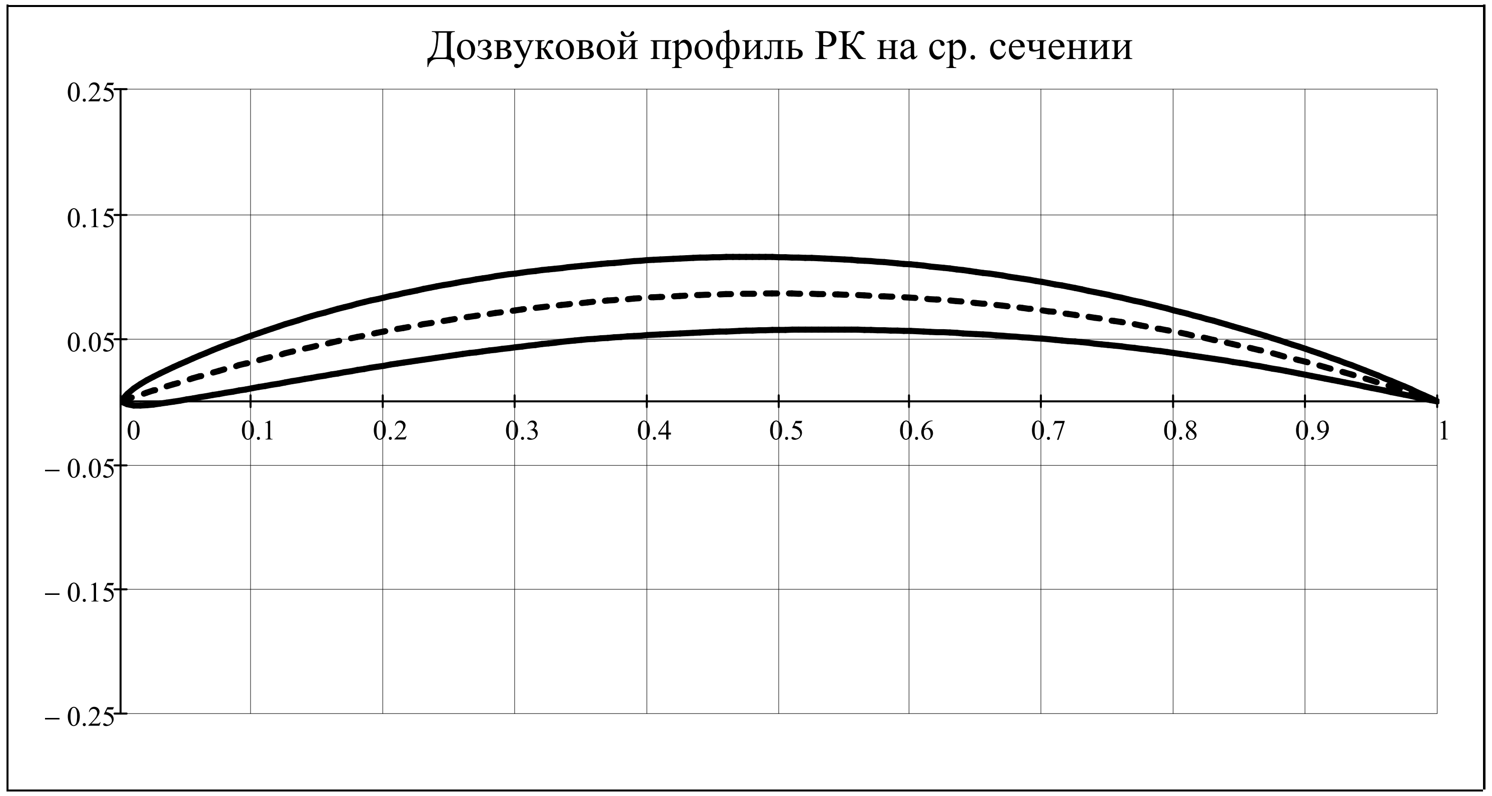
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.000	0.050	0.100	0.150	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.850	0.900	0.950	1.000
2	0.045	0.132	0.208	0.282	0.342	0.430	0.482	0.500	0.482	0.430	0.342	0.282	0.208	0.132	0.045

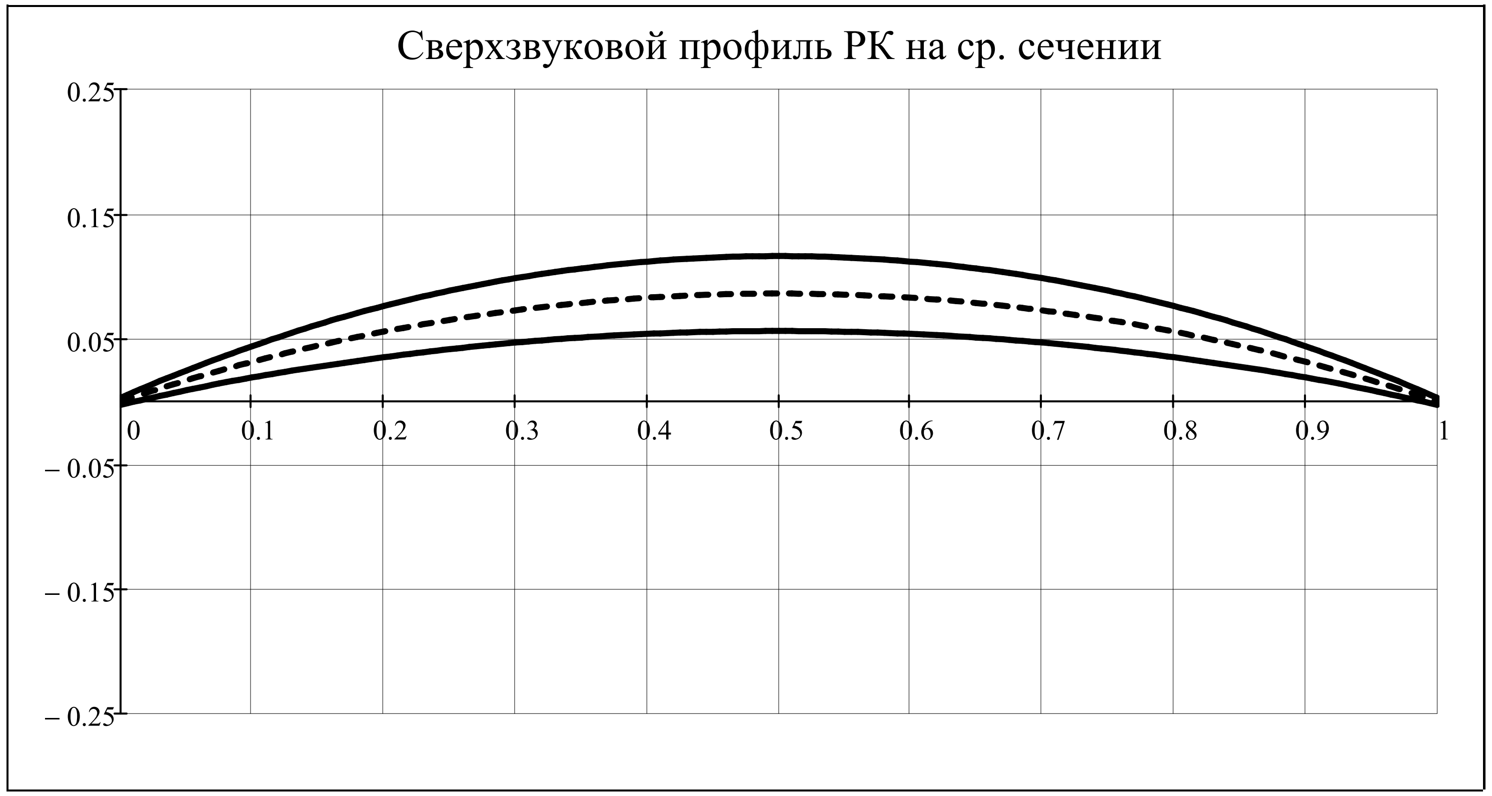


$$AIRFOIL_{subsonic}(x, line, \overline{c}, \theta) = \begin{cases} \begin{cases} interp\left(cspline\left(X/B_{subsonic}, y/b_{ср.л}(X/B_{subsonic}, \theta) + Y/B_{subsonic} \cdot \overline{c}\right), X/B_{subsonic}, y/b_{ср.л}(X/B_{subsonic}, \theta) + Y/B_{subsonic} \cdot \overline{c}, x\right) & \text{if } line = \text{"+"} \\ interp\left(cspline\left(X/B_{subsonic}, y/b_{ср.л}(X/B_{subsonic}, \theta)\right), X/B_{subsonic}, y/b_{ср.л}(X/B_{subsonic}, \theta), x\right) & \text{if } line = \text{"0"} \\ interp\left(cspline\left(X/B_{subsonic}, y/b_{ср.л}(X/B_{subsonic}, \theta) - Y/B_{subsonic} \cdot \overline{c}\right), X/B_{subsonic}, y/b_{ср.л}(X/B_{subsonic}, \theta) - Y/B_{subsonic} \cdot \overline{c}, x\right) & \text{if } line = \text{"-"} \end{cases} & \text{if } 0 \le x \le 1 \\ NaN & \text{otherwise} \end{cases}$$

$$AIRFOIL_{supersonic}(x, line, \overline{c}, \theta) = \begin{cases} \begin{cases} interp\left(cspline\left(X/B_{supersonic}, y/b_{ср.л}(X/B_{supersonic}, \theta) + Y/B_{supersonic} \cdot \overline{c}\right), X/B_{supersonic}, y/b_{ср.л}(X/B_{supersonic}, \theta) + Y/B_{supersonic} \cdot \overline{c}, x\right) & \text{if } line = \text{"+"} \\ interp\left(cspline\left(X/B_{supersonic}, y/b_{ср.л}(X/B_{supersonic}, \theta)\right), X/B_{supersonic}, y/b_{ср.л}(X/B_{supersonic}, \theta), x\right) & \text{if } line = \text{"0"} \\ interp\left(cspline\left(X/B_{supersonic}, y/b_{ср.л}(X/B_{supersonic}, \theta) - Y/B_{supersonic} \cdot \overline{c}\right), X/B_{supersonic}, y/b_{ср.л}(X/B_{supersonic}, \theta) - Y/B_{supersonic} \cdot \overline{c}, x\right) & \text{if } line = \text{"-"} \end{cases} & \text{if } 0 \le x \le 1 \\ NaN & \text{otherwise} \end{cases}$$

$x = 0, 0.005 .. 1$ $\qquad$ $j = 1$





Подключение симметричного профиля

Определение относительных геометрических характеристик сечений Л

Результат расчета абсолютных геометрических характеристик сечений Л

Определение абсолютных геометрических характеристик сечений Л

Результат расчета абсолютных геометрических характеристик сечений Л

$l\_upper_{stator}{}^{T} =$

	1
1	121.04
2	135.60
3	144.67

$\cdot 10^{-3}$

$l\_upper_{rotor}{}^{T} =$

	1
1	166.68
2	169.63
3	182.89

$\cdot 10^{-3}$

$l\_lower_{stator}{}^{T} =$

	1
1	119.68
2	133.58
3	143.70

$\cdot 10^{-3}$

$l\_lower_{rotor}{}^{T} =$

	1
1	146.22
2	166.33
3	182.68

$\cdot 10^{-3}$

$area_{stator}{}^{T} =$

	1
1	397.84
2	779.71
3	1196.12

$\cdot 10^{-6}$

$area_{rotor}{}^{T} =$

	1
1	2310.37
2	1151.87
3	701.28

$\cdot 10^{-6}$

$Sx_{stator}{}^{T} =$

	1
1	2202.7
2	3555.2
3	1990.7

$\cdot 10^{-9}$

$Sx_{rotor}{}^{T} =$

	1
1	48635.3
2	10418.2
3	785.6

$\cdot 10^{-9}$

$Sy_{stator}{}^{T} =$

	1
1	23701.0
2	46938.5
3	77237.4

$\cdot 10^{-9}$

$Sy_{rotor}{}^{T} =$

	1
1	146612.4
2	95338.5
3	64049.4

$\cdot 10^{-9}$

$x0_{stator}{}^{T} =$

	1
1	59.57
2	60.20
3	64.57

$\cdot 10^{-3}$

$x0_{rotor}{}^{T} =$

	1
1	63.46
2	82.77
3	91.33

$\cdot 10^{-3}$

$y0_{stator}{}^{T} =$

	1
1	5.54
2	4.56
3	1.66

$\cdot 10^{-3}$

$y0_{rotor}{}^{T} =$

	1
1	21.05
2	9.04
3	1.12

$\cdot 10^{-3}$

$Jx_{stator}^T =$

	1
1	13765
2	20850
3	13161

$\cdot 10^{-12}$

$Jy_{stator}^T =$

	1
1	1719636
2	3615129
3	6381028

$\cdot 10^{-12}$

$Jxy_{stator}^T =$

	1
1	131222
2	222539
3	133676

$\cdot 10^{-12}$

$Jx0_{stator}^T =$

	1
1	1570.01
2	4639.78
3	9847.62

$\cdot 10^{-12}$

$Jy0_{stator}^T =$

	1
1	307659
2	789412
3	1393563

$\cdot 10^{-12}$

$Jxy0_{stator}^T =$

	1
1	-0.38
2	8514.03
3	5128.05

$\cdot 10^{-12}$

$\alpha\_major_{stator}^T =$

	1
1	-0.00
2	0.62
3	0.21

$\cdot \circ$

$Jx_{rotor}^T =$

	1
1	1184467
2	108851
3	2172

$\cdot 10^{-12}$

$Jy_{rotor}^T =$

	1
1	11903414
2	9610401
3	7124382

$\cdot 10^{-12}$

$Jxy_{rotor}^T =$

	1
1	3202279
2	862298
3	71753

$\cdot 10^{-12}$

$Jx0_{rotor}^T =$

	1
1	160649.15
2	14621.64
3	1292.04

$\cdot 10^{-12}$

$Jy0_{rotor}^T =$

	1
1	2599607
2	1719392
3	1274619

$\cdot 10^{-12}$

$Jxy0_{rotor}^T =$

	1
1	115952.83
2	-2.47
3	-0.21

$\cdot 10^{-12}$

$\alpha\_major_{rotor}^T =$

	1
1	2.72
2	-0.00
3	-0.00

$\cdot \circ$

$Ju_{stator}^{T} = \cdot 10^{-12}$

	1
1	1570.01
2	4547.42
3	9828.61

$Jv_{stator}^{T} = \cdot 10^{-12}$

	1
1	307659
2	789504
3	1393582

$Juv_{stator}^{T} = \cdot 10^{-12}$

	1
1	0.00
2	-0.00
3	0.00

$Jp_{stator}^{T} = \cdot 10^{-12}$

	1
1	309229
2	794052
3	1403411

$Wp_{stator}^{T} = \cdot 10^{-9}$

	1
1	5168.4
2	10842.1
3	17895.4

$stiffness_{stator}^{T} = \cdot 10^{-12}$

	1
1	2086.26
2	12131.62
3	38066.88

$Ju_{rotor}^{T} = \cdot 10^{-12}$

	1
1	155148.93
2	14621.64
3	1292.04

$Jv_{rotor}^{T} = \cdot 10^{-12}$

	1
1	2605107
2	1719392
3	1274619

$Juv_{rotor}^{T} = \cdot 10^{-12}$

	1
1	0.00
2	0.00
3	0.00

$Jp_{rotor}^{T} = \cdot 10^{-12}$

	1
1	2760256
2	1734013
3	1275911

$Wp_{rotor}^{T} = \cdot 10^{-9}$

	1
1	34556.9
2	20826.2
3	13969.0

$stiffness_{rotor}^{T} = \cdot 10^{-12}$

	1
1	284045.72
2	26233.50
3	4861.85

$$CPx_{stator}^{T} = \begin{array}{c|c} & 1 \\ \hline 1 & 41.702 \\ 2 & 46.654 \\ 3 & 50.042 \end{array} \cdot 10^{-3}$$

$$CPx_{rotor}^{T} = \begin{array}{c|c} & 1 \\ \hline 1 & 49.179 \\ 2 & 57.938 \\ 3 & 63.932 \end{array} \cdot 10^{-3}$$

$$CPy_{stator}^{T} = \begin{array}{c|c} & 1 \\ \hline 1 & 0.0000 \\ 2 & 0.0000 \\ 3 & 0.0000 \end{array} \cdot 10^{-3}$$

$$CPy_{rotor}^{T} = \begin{array}{c|c} & 1 \\ \hline 1 & 0.0000 \\ 2 & 0.0000 \\ 3 & 0.0000 \end{array} \cdot 10^{-3}$$

Результат расчета абсолютных геометрических характеристик сечений Л

Вывод результатов расчета геометрических хар-к сечений Л

Профилирование решеток

Абс. координаты профиля:

$$
\mathrm{Airfoil}(type, x, line, i, r) = \begin{cases}
\text{if } type = \text{"BHA"} \\
\quad \begin{cases} \mathrm{AIRFOIL}_{subsonic}\left(x, line, \overline{c}_{BHA_r}, \varepsilon_{BHA_r}\right) & \text{if } M_{c_{st(1,1),r}} < 1 \\ \mathrm{AIRFOIL}_{supersonic}\left(x, line, \overline{c}_{BHA_r}, \varepsilon_{BHA_r}\right) & \text{otherwise} \end{cases} \\
\text{if } type = \text{"rotor"} \\
\quad \begin{cases} \mathrm{AIRFOIL}_{subsonic}\left(x, line, \overline{c}_{rotor_{i,r}}, \varepsilon_{rotor_{i,r}}\right) & \text{if } M_{w_{st(i,1),r}} < 1 \\ \mathrm{AIRFOIL}_{supersonic}\left(x, line, \overline{c}_{rotor_{i,r}}, \varepsilon_{rotor_{i,r}}\right) & \text{otherwise} \end{cases} \\
\text{if } type = \text{"stator"} \\
\quad \begin{cases} \mathrm{AIRFOIL}_{subsonic}\left(x, line, \overline{c}_{stator_{i,r}}, \varepsilon_{stator_{i,r}}\right) & \text{if } M_{c_{st(i,2),r}} < 1 \\ \mathrm{AIRFOIL}_{supersonic}\left(x, line, \overline{c}_{stator_{i,r}}, \varepsilon_{stator_{i,r}}\right) & \text{otherwise} \end{cases} \\
\text{if } type = \text{"CA"} \\
\quad \begin{cases} \mathrm{AIRFOIL}_{subsonic}\left(x, line, \overline{c}_{CA_r}, \varepsilon_{CA_r}\right) & \text{if } M_{c_{st(Z,3),r}} < 1 \\ \mathrm{AIRFOIL}_{supersonic}\left(x, line, \overline{c}_{CA_r}, \varepsilon_{CA_r}\right) & \text{otherwise} \end{cases}
\end{cases}
$$

Профилирование решеток

Рассматриваемая ступень: $j = \left| \begin{array}{l} j = 1 \\ j = \left| \begin{array}{ll} \text{"Такой ступени не существует!"} & \text{if } (j < 1) \vee (j > Z) \\ j & \text{otherwise} \end{array} \right. \end{array} \right. = 1$

Построение профилей Л РК и НА

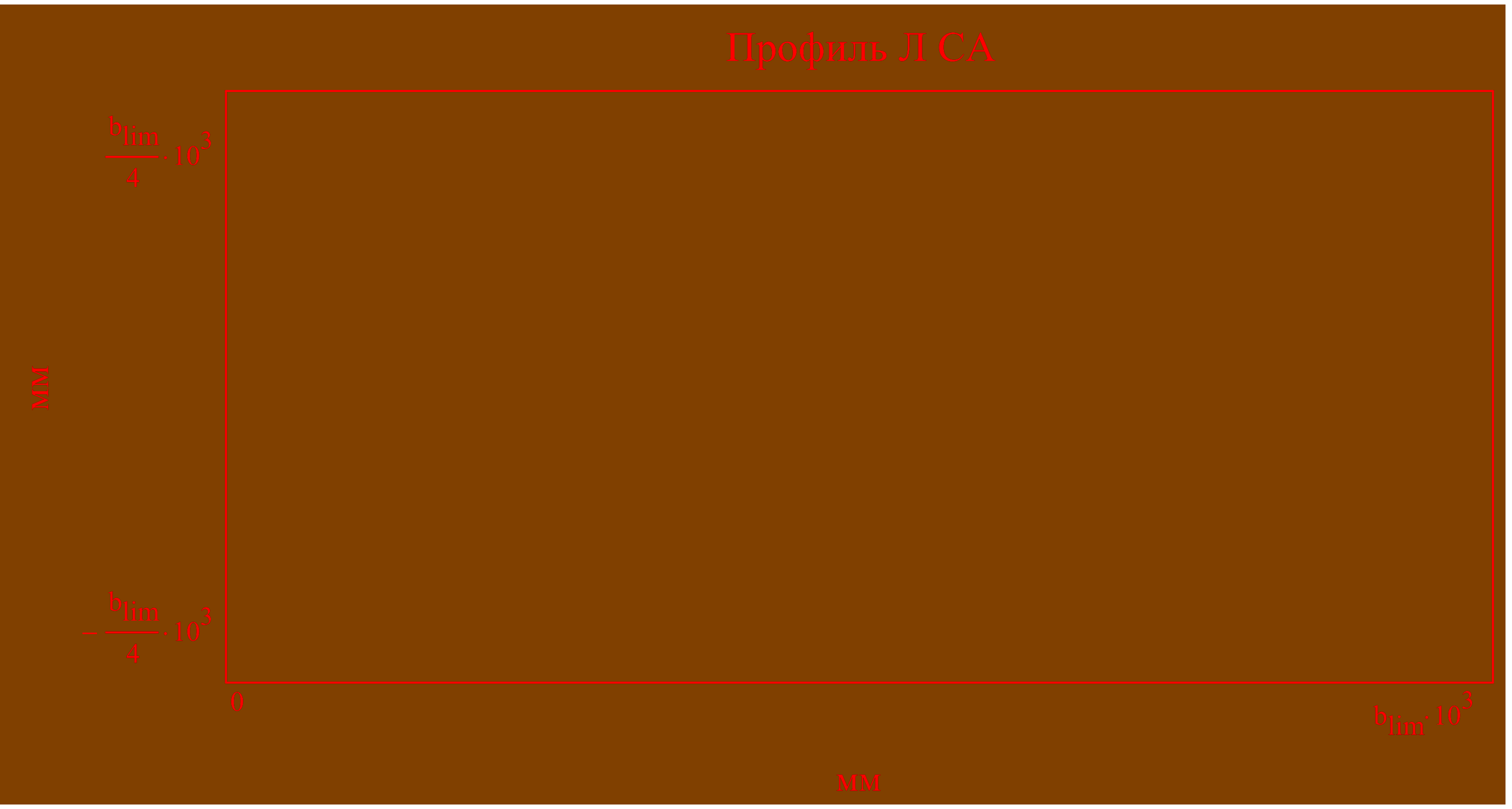
$$AXLE0(type, x, i, r) = \left| \begin{array}{ll} \dfrac{y0rotor_{i,r}}{chord_{rotor_{i,r}}} + \tan\left(\alpha\_major_{rotor_{i,r}}\right)\cdot\left(x - \dfrac{x0rotor_{i,r}}{chord_{rotor_{i,r}}}\right) & \text{if } type = \text{"rotor"} \\ \dfrac{y0stator_{i,r}}{chord_{stator_{i,r}}} + \tan\left(\alpha\_major_{stator_{i,r}}\right)\cdot\left(x - \dfrac{x0stator_{i,r}}{chord_{stator_{i,r}}}\right) & \text{if } type = \text{"stator"} \\ NaN & \text{otherwise} \end{array} \right.$$

$$b_{lim} = \frac{\text{ceil}\left(\max\left(chord_{rotor_{j,N_r}}, chord_{stator_{j,N_r}}\right)\cdot 10^2\right)}{10^2} = 190\cdot 10^{-3}$$

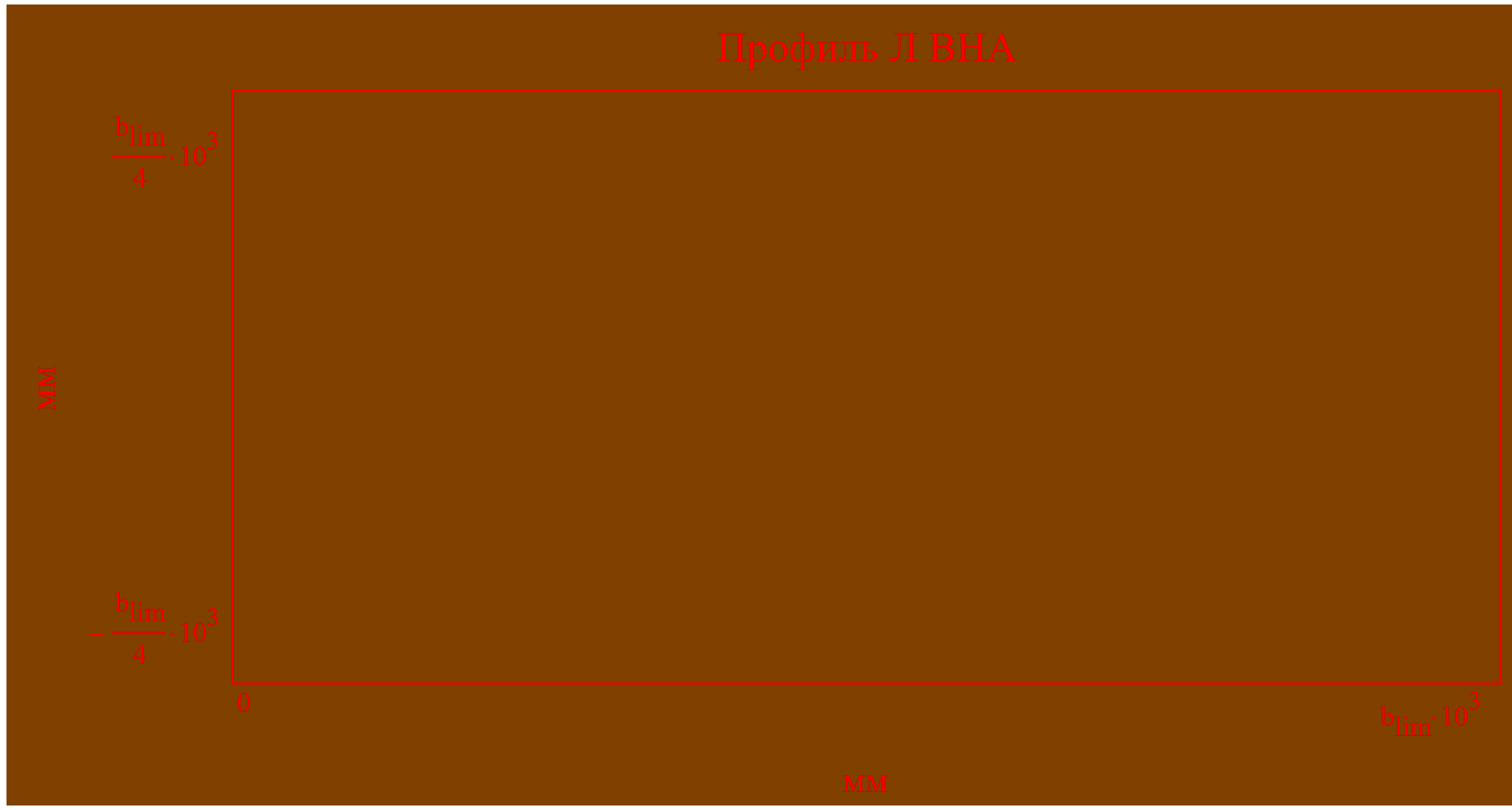
$$AXLE90(type, x, i, r) = \left| \begin{array}{ll} \dfrac{y0rotor_{i,r}}{chord_{rotor_{i,r}}} + \tan\left(\alpha\_major_{rotor_{i,r}} + \dfrac{\pi}{2}\right)\cdot\left(x - \dfrac{x0rotor_{i,r}}{chord_{rotor_{i,r}}}\right) & \text{if } (type = \text{"rotor"}) \wedge \left|\alpha\_major_{rotor_{i,r}}\right| \geq 1\cdot° \\ \dfrac{y0stator_{i,r}}{chord_{stator_{i,r}}} + \tan\left(\alpha\_major_{stator_{i,r}} + \dfrac{\pi}{2}\right)\cdot\left(x - \dfrac{x0stator_{i,r}}{chord_{stator_{i,r}}}\right) & \text{if } (type = \text{"stator"}) \wedge \left|\alpha\_major_{stator_{i,r}}\right| \geq 1\cdot° \\ NaN & \text{otherwise} \end{array} \right.$$

r = 1

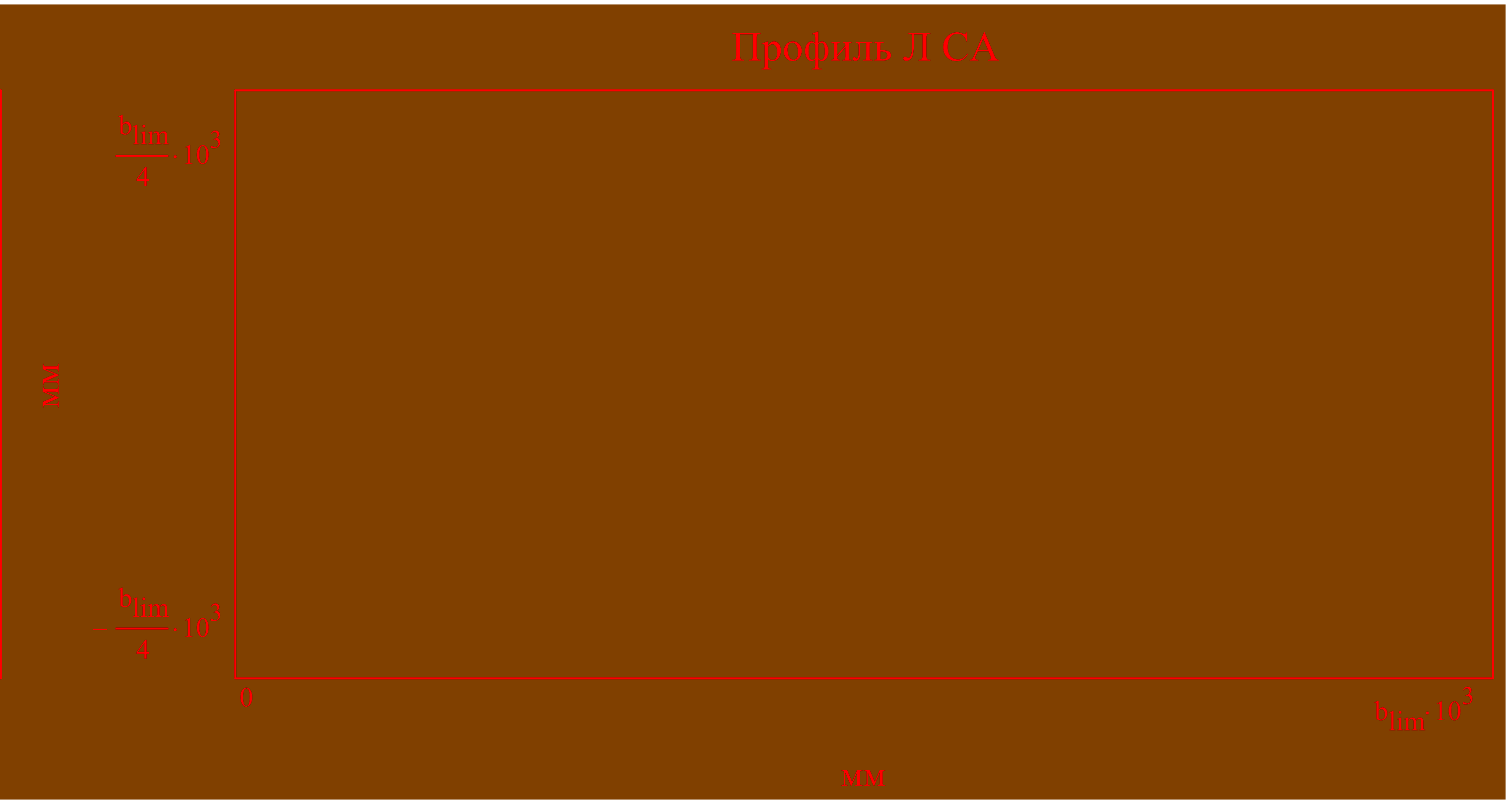

Профиль Л ВНА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм


Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм

$r := av(N_r)$



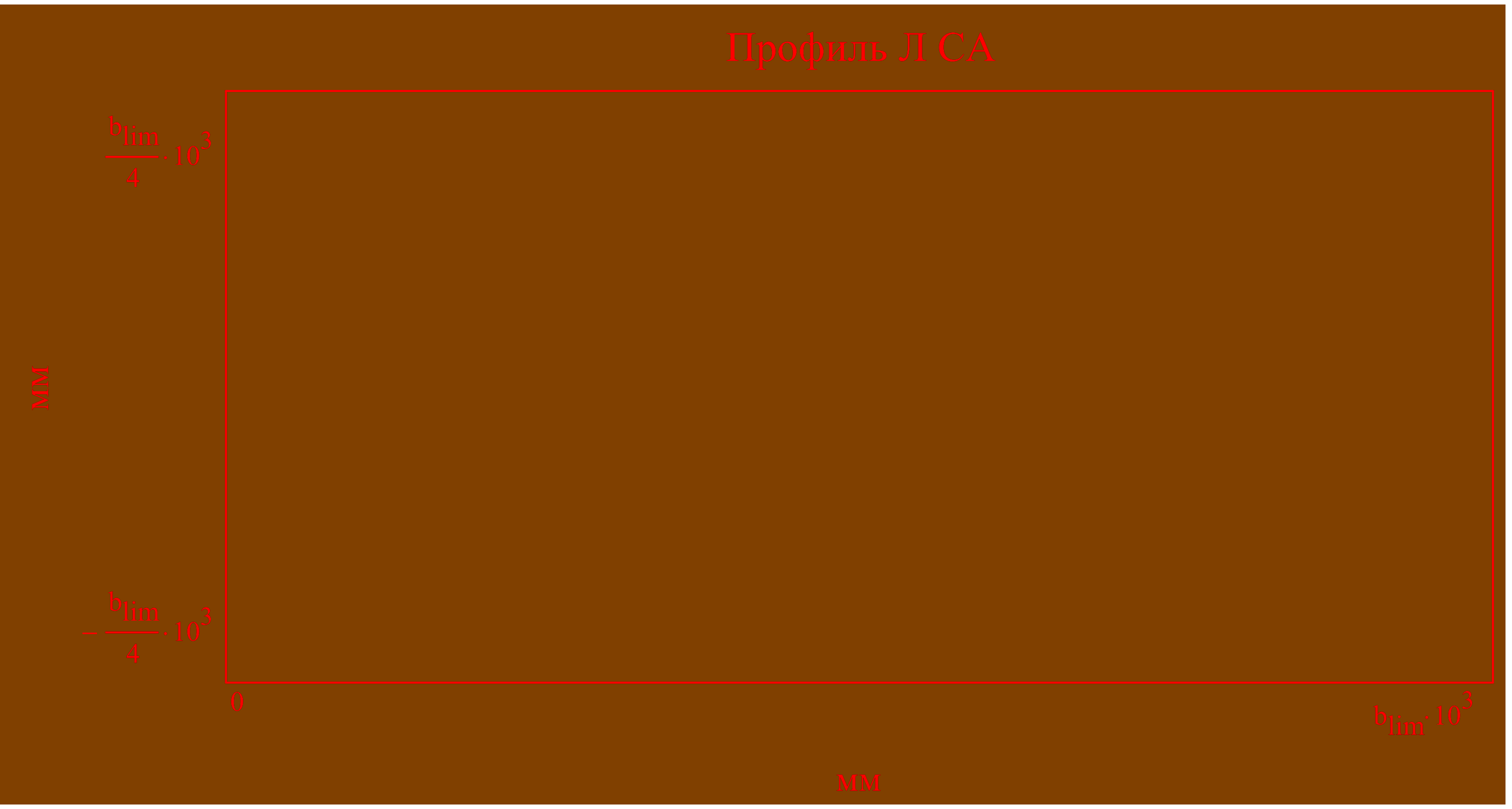
Профиль Л ВНА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм



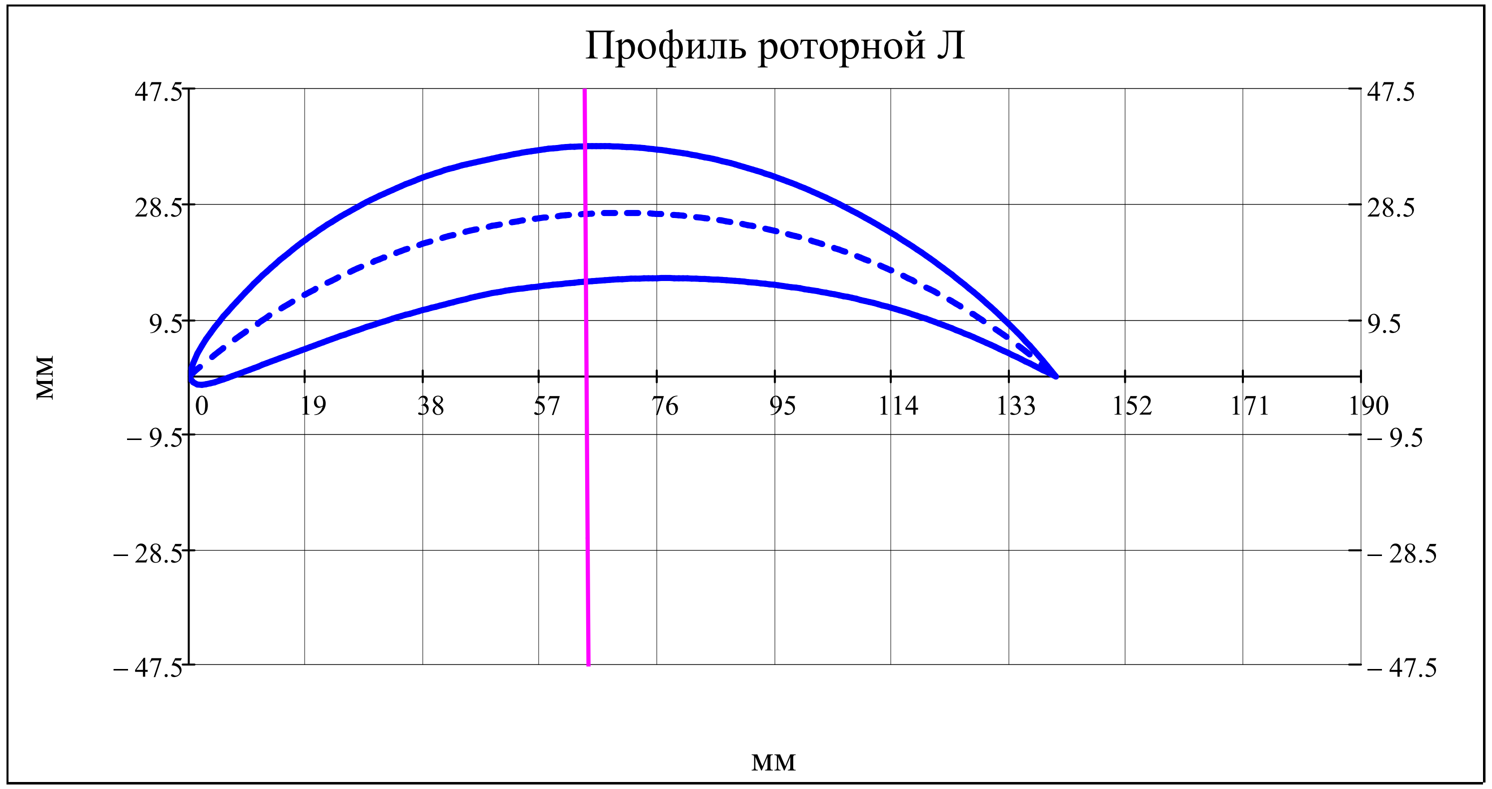
Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм

$r := N_r$

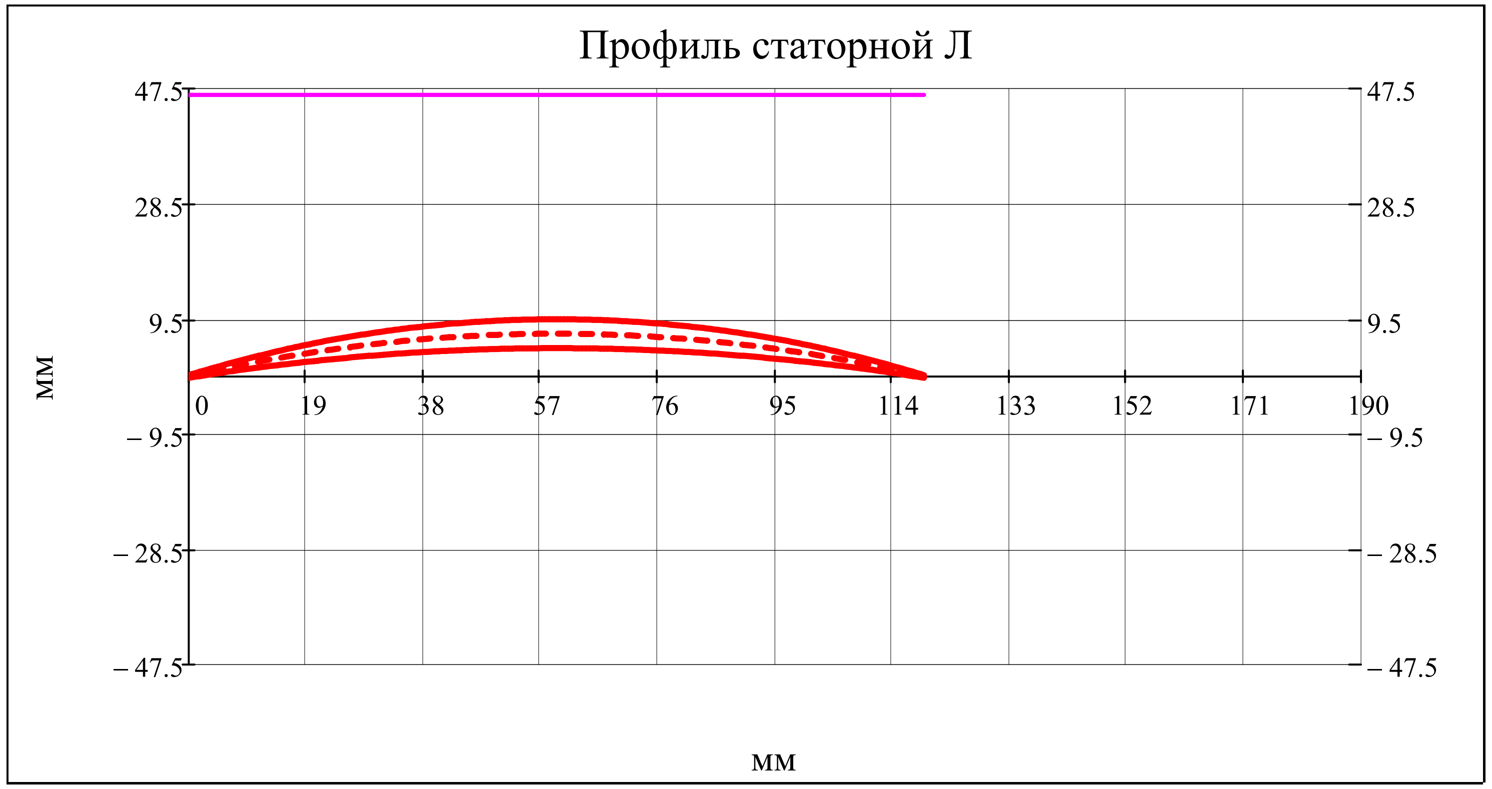

Профиль Л ВНА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм


Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм

$r = 1$

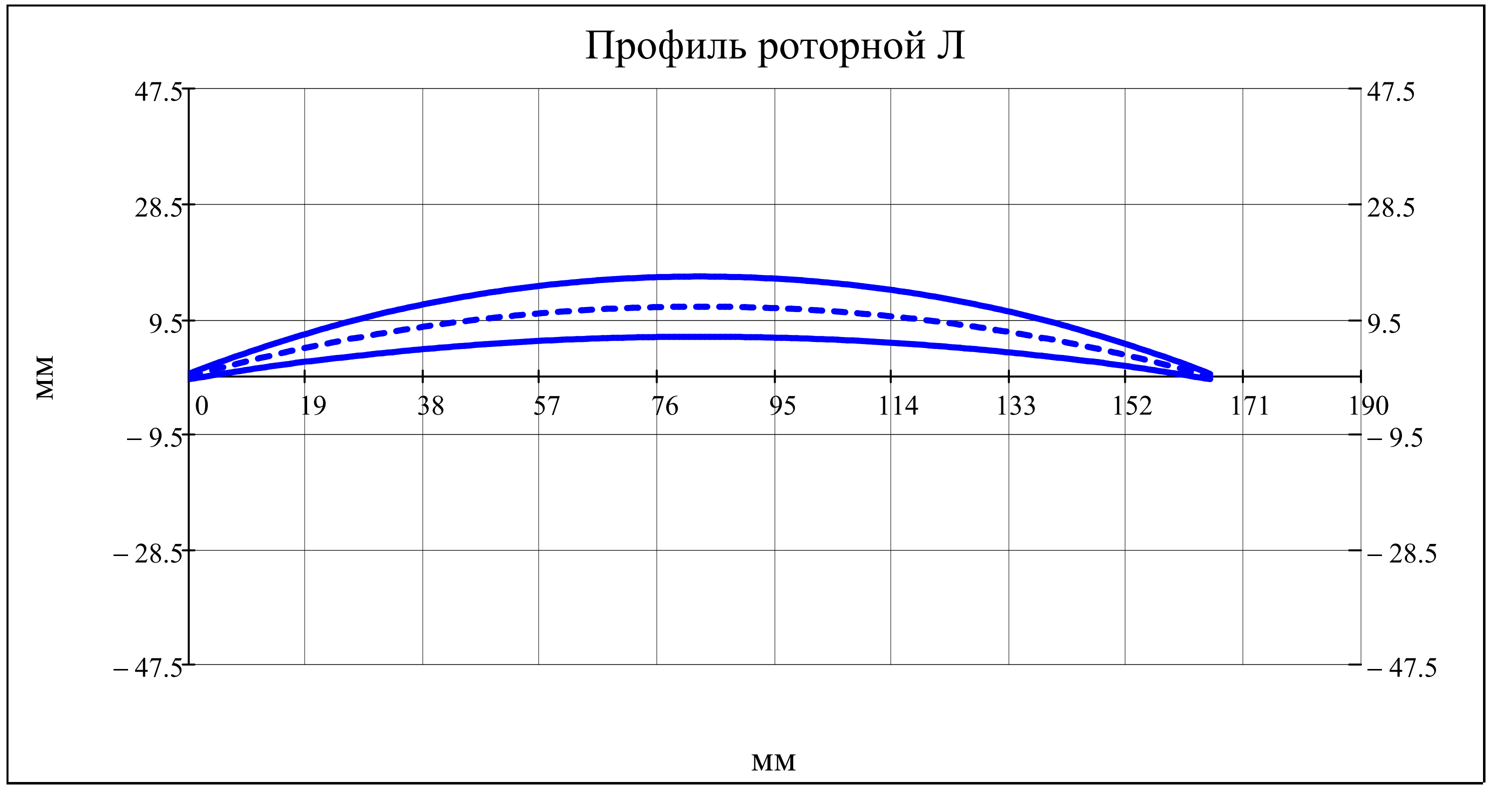


Профиль роторной Л
47.5
28.5
9.5
− 9.5
− 28.5
− 47.5
0
19
38
57
76
95
114
133
152
171
190
мм
мм

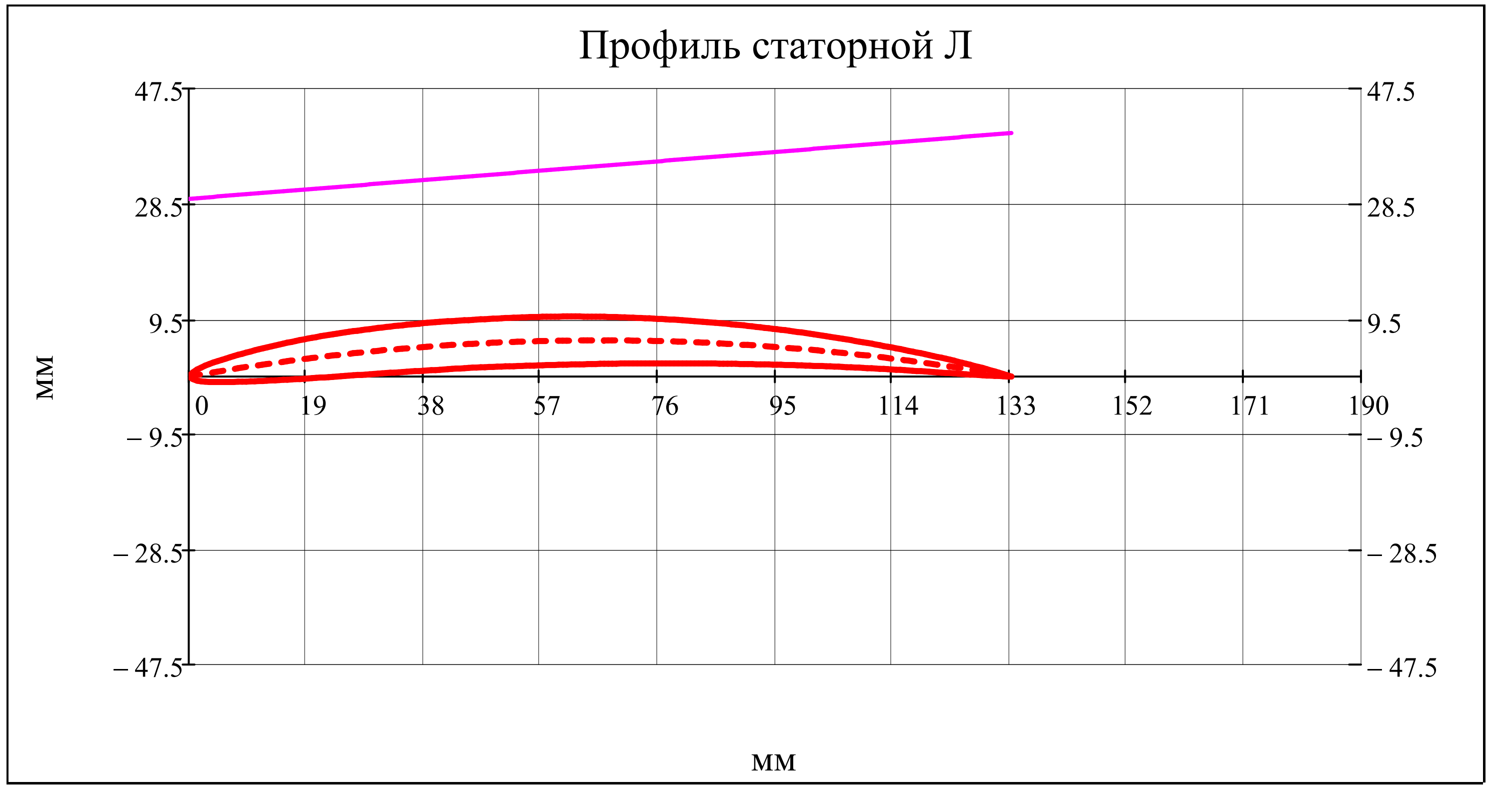


Профиль статорной Л
47.5
28.5
9.5
− 9.5
− 28.5
− 47.5
0
19
38
57
76
95
114
133
152
171
190
мм
мм

$r = av(N_r)$

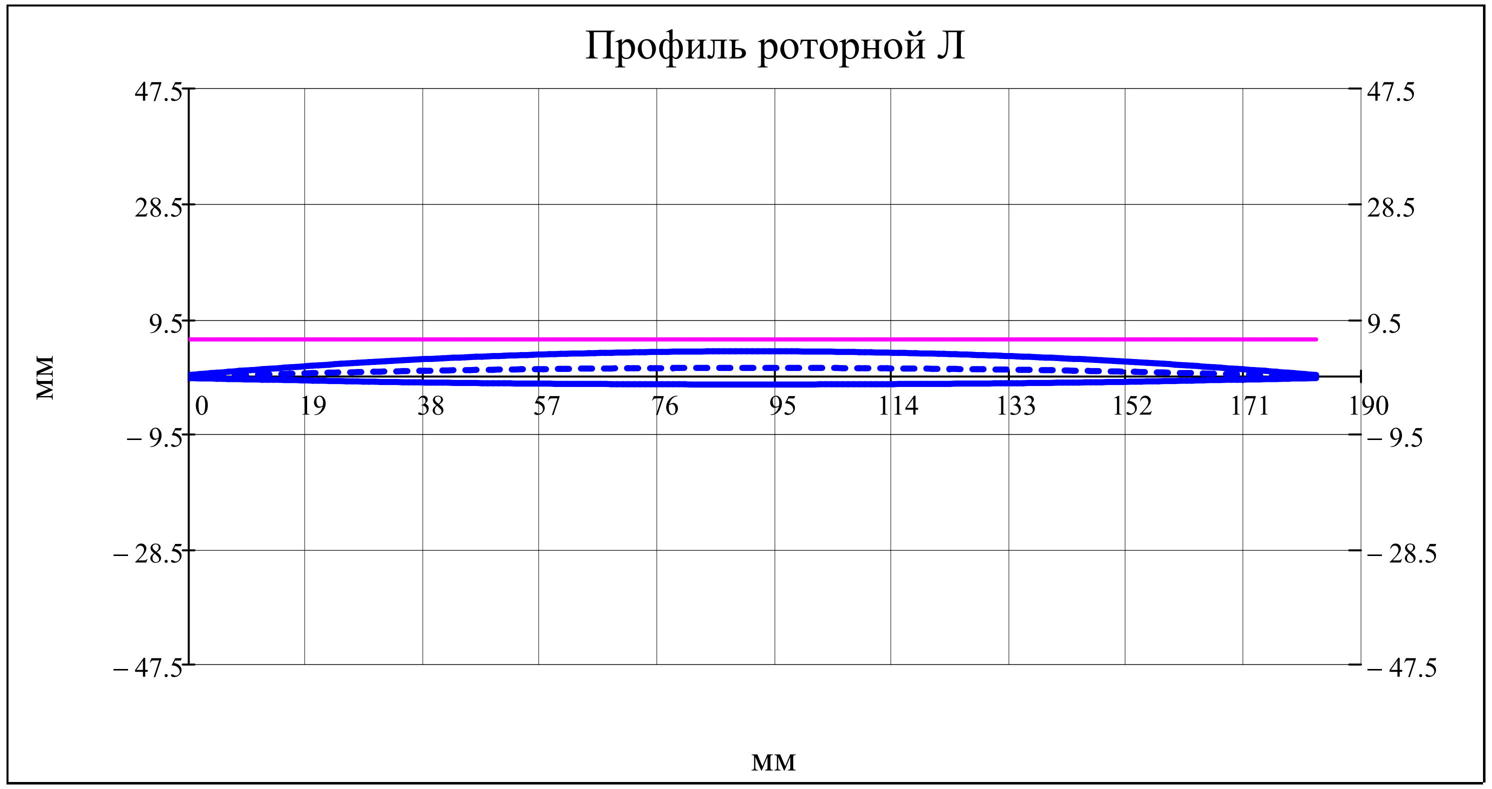


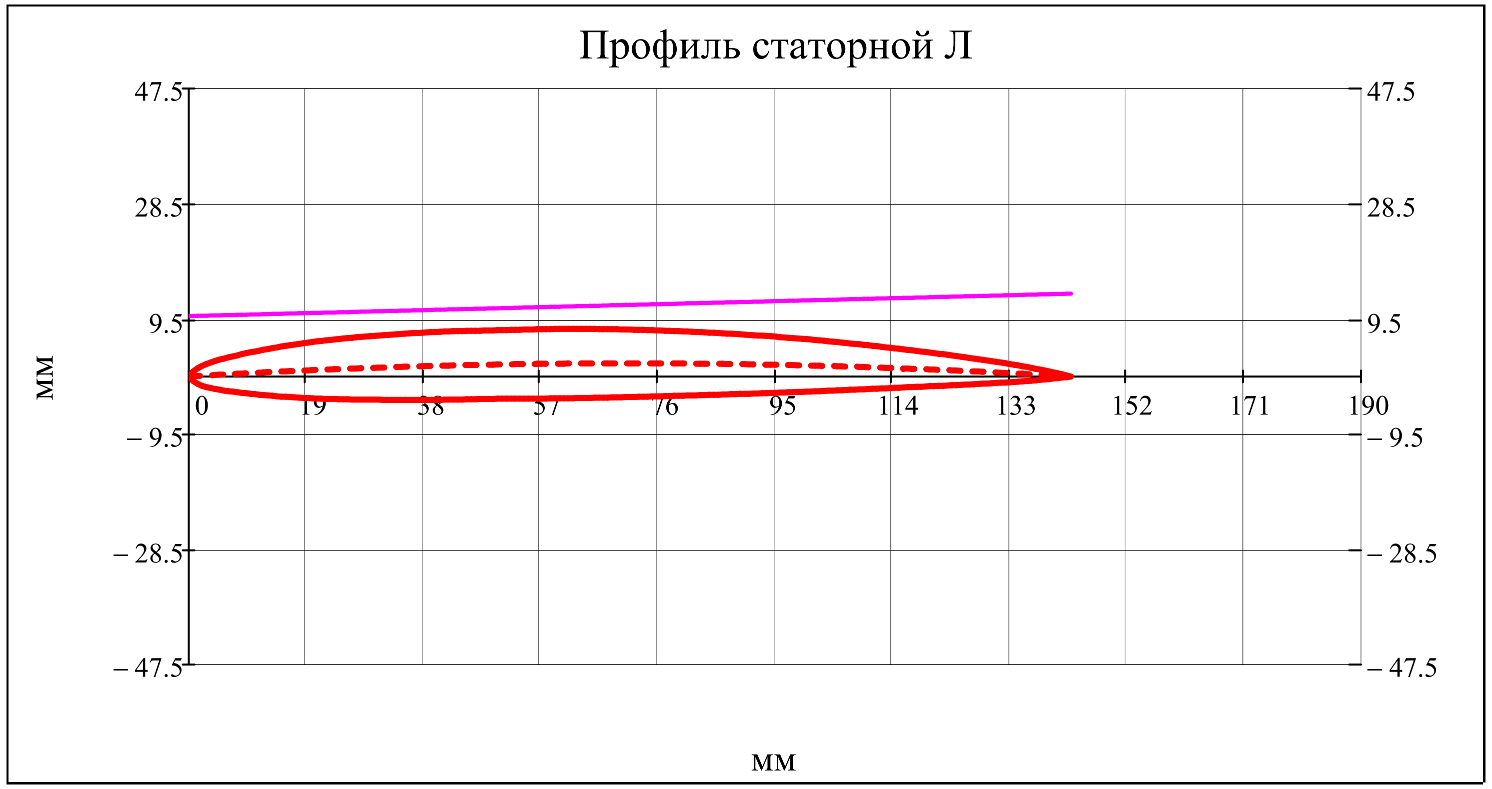
Профиль роторной Л
47.5
28.5
9.5
− 9.5
− 28.5
− 47.5
0
19
38
57
76
95
114
133
152
171
190
мм
мм



Профиль статорной Л
47.5
28.5
9.5
− 9.5
− 28.5
− 47.5
0
19
38
57
76
95
114
133
152
171
190
мм
мм

$r = N_r$





Построение профилей Л РК и НА

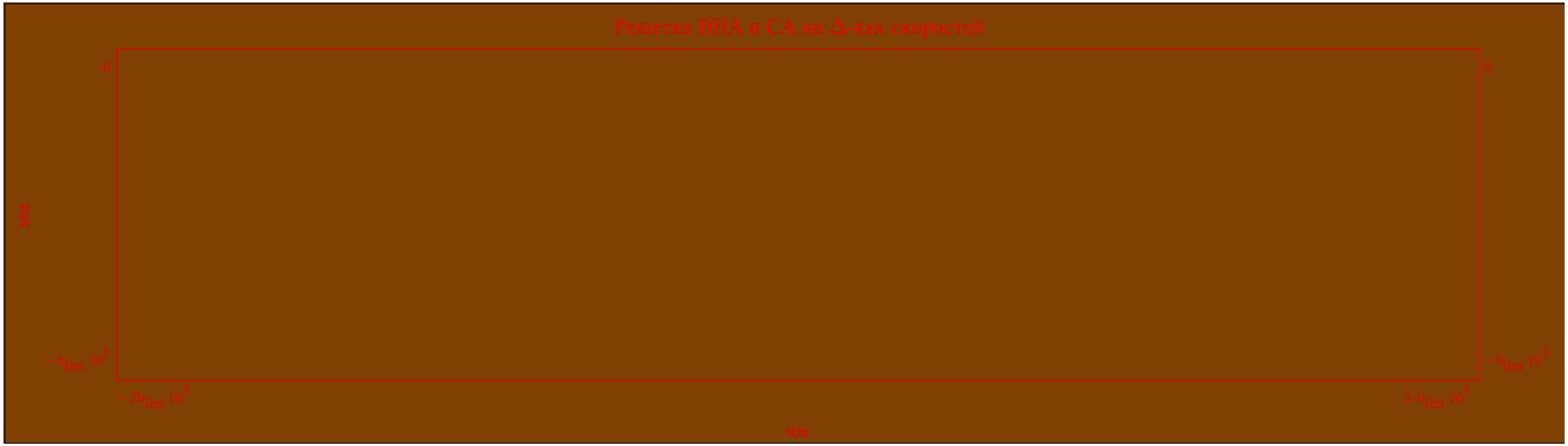
Вывод координат для построения профиля Л

Рассматриваемая ступень: $j = \left| \begin{array}{l} j = 1 \\ j = \left| \begin{array}{ll} \text{"Такой ступени не существует!"} & \text{if } (j < 1) \vee (j > Z) \\ j & \text{otherwise} \end{array} \right. \end{array} \right. = 1$

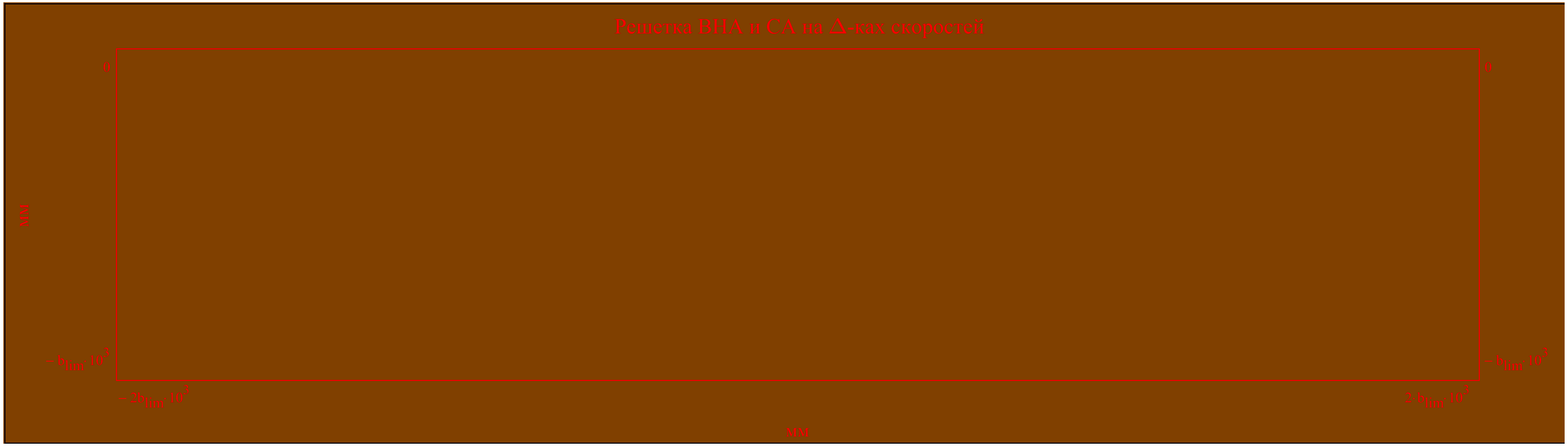
$$b_{lim} = \frac{\mathrm{ceil}\left(\max\left(chord_{rotor_{j,N_r}}, chord_{stator_{j,N_r}}\right)\cdot 10^2\right)}{10^2} = 190\cdot 10^{-3}$$

Построение плоских решеток профилей Л РК и НА (+ ВНА и СА) на треугольниках скоростей

$r = 1$

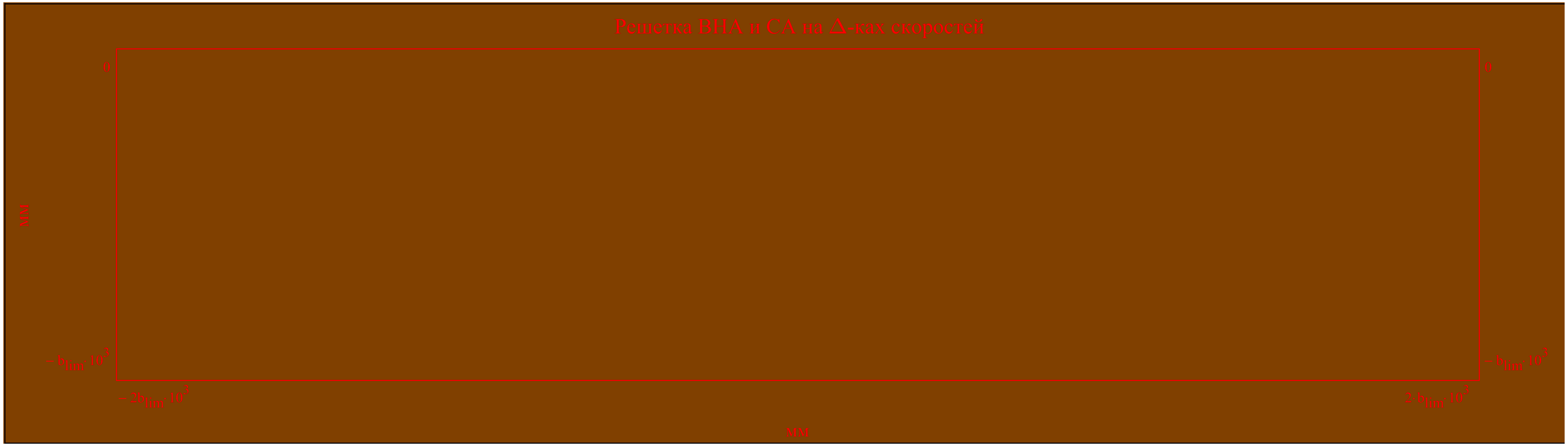


$r := av(N_r)$

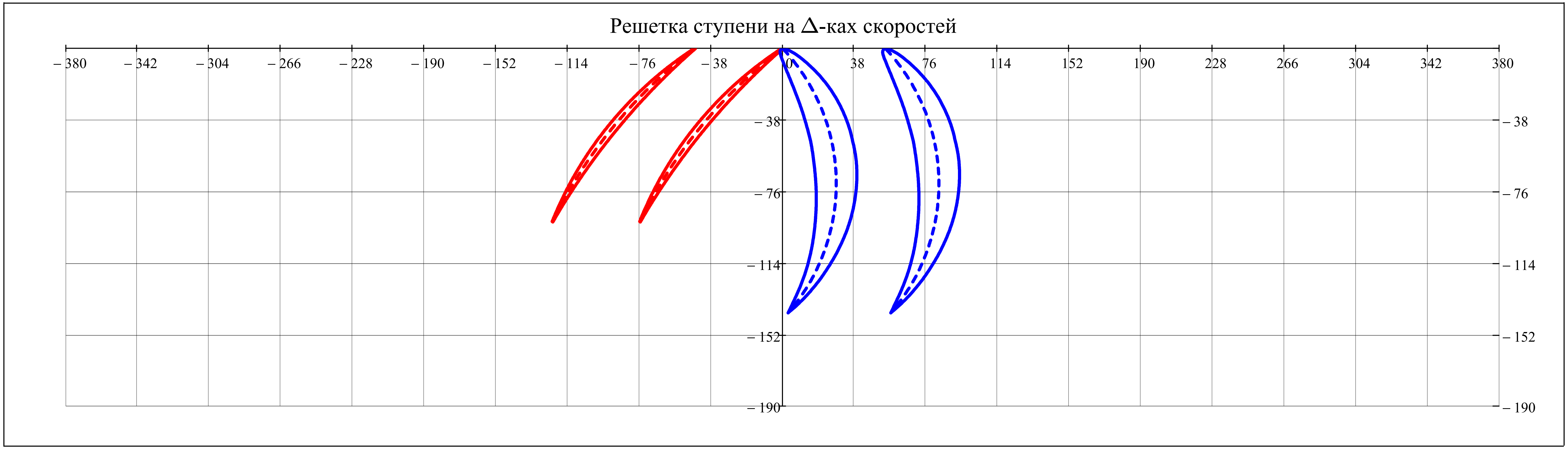


Решетка ВНА и СА на Δ-ках скоростей
0
0
мм
− b_lim·10^3
− b_lim·10^3
− 2b_lim·10^3
2·b_lim·10^3
мм

$r = N_r$

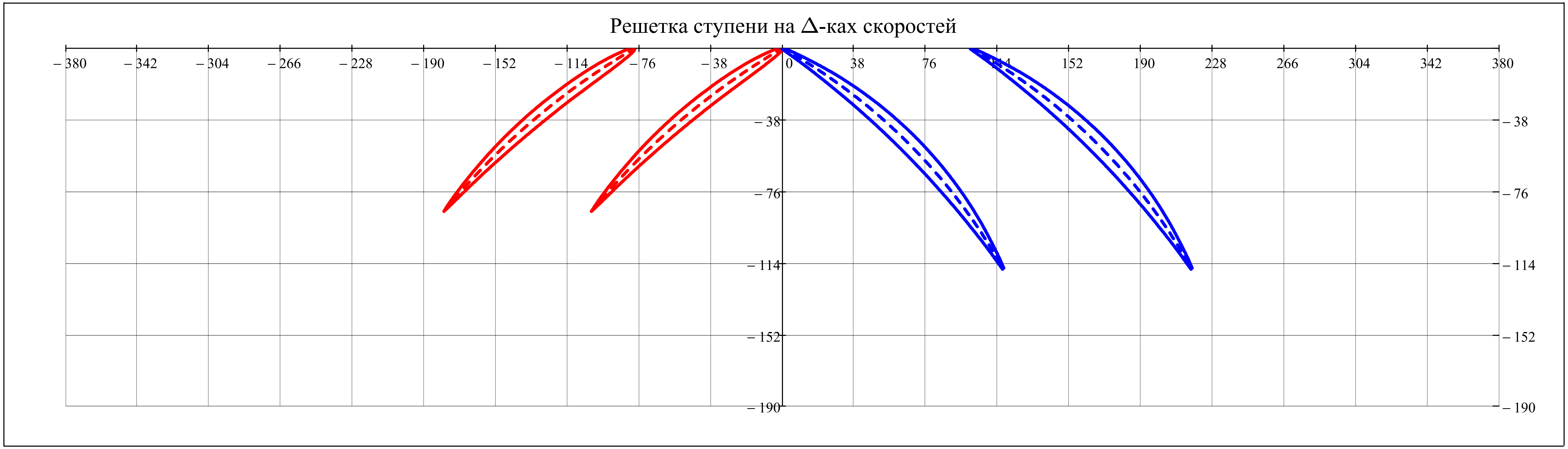

Решетка ВНА и СА на Δ-ках скоростей
0
0
мм
$-b_{lim} \cdot 10^3$
$-b_{lim} \cdot 10^3$
$-2b_{lim} \cdot 10^3$
$2 \cdot b_{lim} \cdot 10^3$
мм

$r = 1$

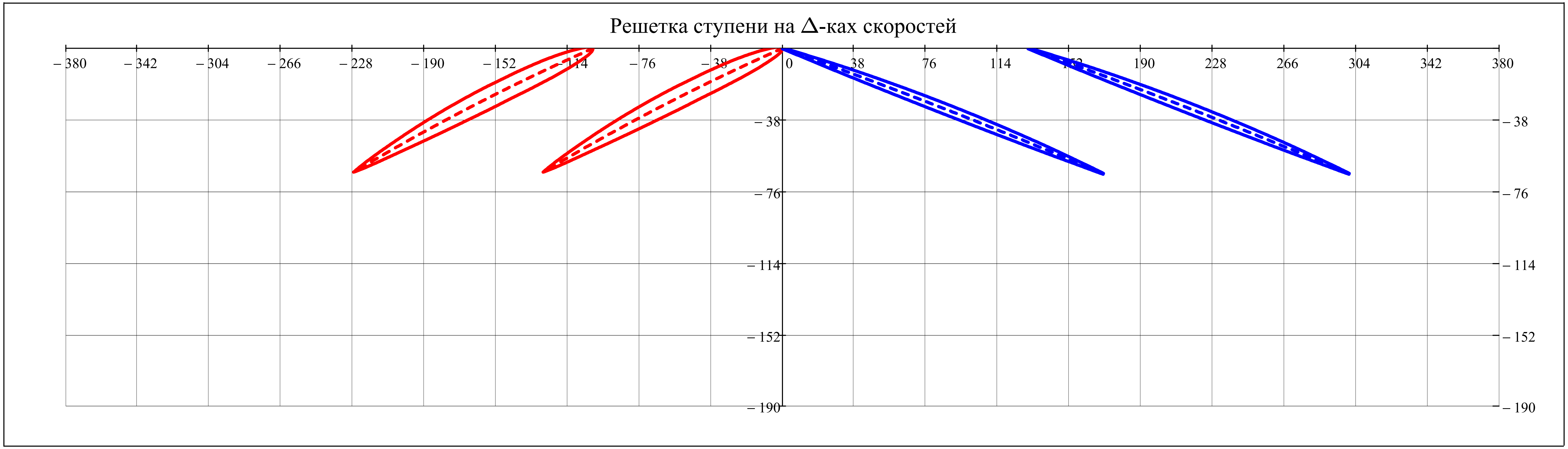


Решетка ступени на Δ-ках скоростей
– 380
– 342
– 304
– 266
– 228
– 190
– 152
– 114
– 76
– 38
0
38
76
114
152
190
228
266
304
342
380
– 38
– 76
– 114
– 152
– 190

$r = av(N_r)$


Решетка ступени на Δ-ках скоростей
– 380
– 342
– 304
– 266
– 228
– 190
– 152
– 114
– 76
– 38
0
38
76
114
152
190
228
266
304
342
380
– 38
– 76
– 114
– 152
– 190

$r = N_r$



Построение плоских решеток профилей Л РК и НА (+ ВНА и СА) на треугольниках скоростей

Вывод данных по построению профиля Л rotor и stator на треугольниках скоростей

Радиальные и осевые зазоры и длина К

Радиальный зазор (м)
[с.64 казаджан]:

$\bar{\Delta}r = 0.0025$

$0.0015 \le \bar{\Delta}r \le 0.0035 = 1$

$$\Delta_{r_i} = \bar{\Delta}r \cdot D_{st(i,2),N_r}$$

$$\Delta_r^T = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 3.84 \\ \hline\end{array} \cdot 10^{-3}$$

Относительный осевой зазор () [16,с. 245]:

$\bar{\Delta}a = 0.17$

$0.1 \le \bar{\Delta}a \le 0.2 = 1$

Осевой зазор (м): $\Delta a_i = \bar{\Delta}a \cdot chord_{rotor_{i,av(N_r)}}$

$$\Delta a^T = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 28.14 \\ \hline\end{array} \cdot 10^{-3}$$

Односторонний осевой зазор (м):

$$\frac{\Delta a^T}{2} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 14.07 \\ \hline\end{array} \cdot 10^{-3}$$

Длина ОК (м):

$$Length = \left[\Delta a_1 + \left|\begin{array}{l} chord_{BHA_{av(N_r)}} \cdot \sin\left(\upsilon_{BHA_{av(N_r)}}\right) \text{ if } BHA = 1 \\ 0 \text{ otherwise}\end{array}\right. \ldots \\ + \sum_{i=1}^{Z}\left(chord_{rotor_{i,av(N_r)}} \cdot \sin\left(\upsilon_{rotor_{i,av(N_r)}}\right)\right) + 2\cdot\sum_{i=1}^{Z}\Delta a_i + \sum_{i=1}^{Z}\left(chord_{stator_{i,av(N_r)}} \cdot \sin\left(\upsilon_{stator_{i,av(N_r)}}\right)\right) \ldots \\ + \left|\begin{array}{l} chord_{CA_{av(N_r)}} \cdot \sin\left(\upsilon_{CA_{av(N_r)}}\right) \text{ if } CA = 1 \\ 0 \text{ otherwise}\end{array}\right. + \Delta a_Z\right] = 316.3 \cdot 10^{-3}$$

Радиальные и осевые зазоры и длина К

Проточная часть

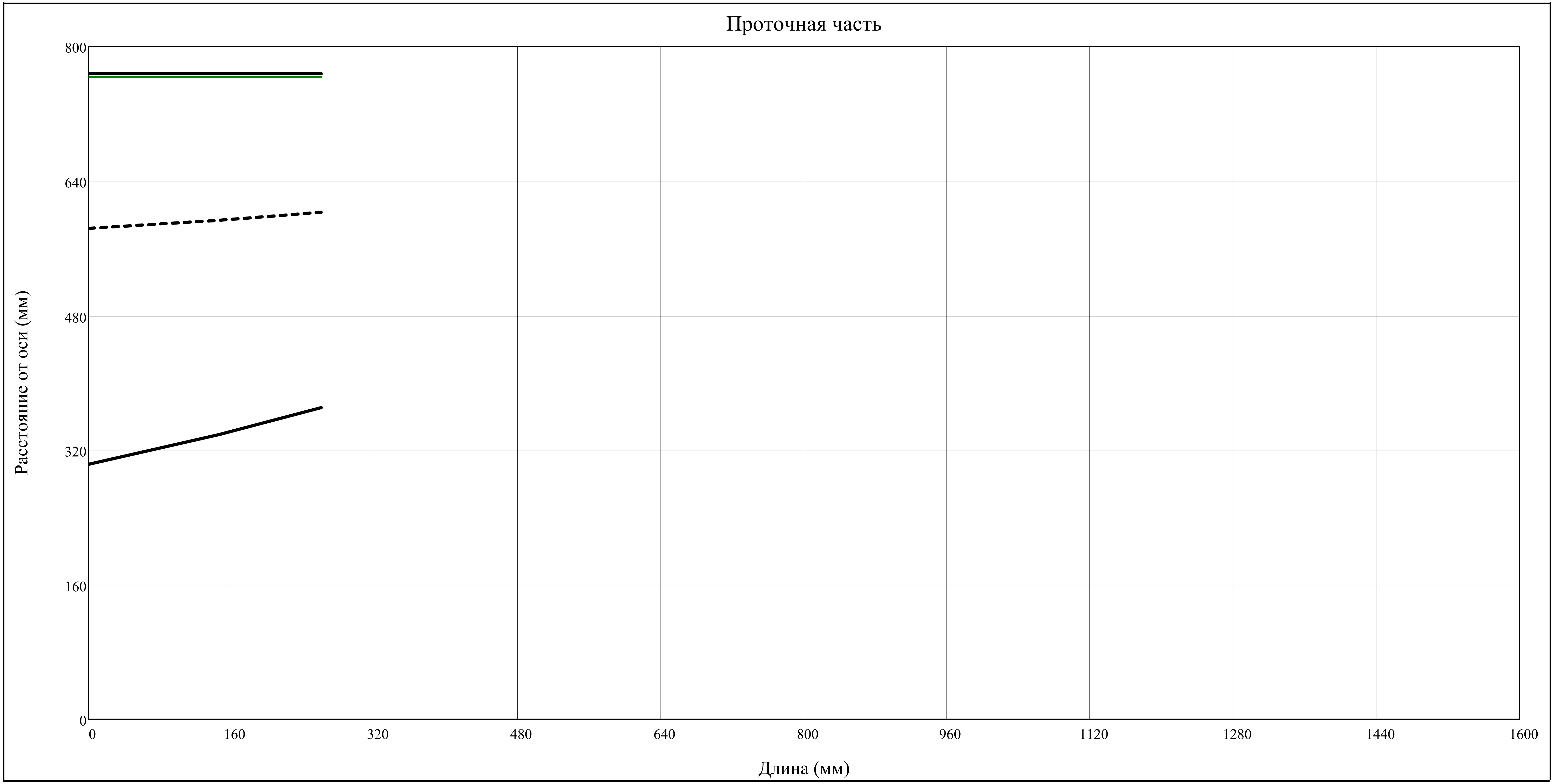
$$\begin{pmatrix} x_{ПЧ} \\ y_{ПЧпер} \\ y_{ПЧср} \\ y_{ПЧкор} \\ y_{Лпер} \end{pmatrix} = \left| \begin{array}{l} c \leftarrow 1 \\ x_{ПЧ_c} \leftarrow \left| \begin{array}{ll} chord_{BHA_{av(N_r)}} \cdot \sin\left(\upsilon_{BHA_{av(N_r)}}\right) & \text{if } BHA = 1 \\ 0 & \text{otherwise} \end{array} \right. \\ y_{ПЧпер_c} \leftarrow R_{st(c,1),N_r} \\ y_{Лпер_c} \leftarrow y_{ПЧпер_c} - \Delta_{r_c} \\ y_{ПЧср_c} \leftarrow R_{st(c,1),av(N_r)} \\ y_{ПЧкор_c} \leftarrow R_{st(c,1),ORIGIN} \\ \text{for } i \in 1..Z \\ \quad \left| \begin{array}{l} c \leftarrow c+1 \\ x_{ПЧ_c} \leftarrow x_{ПЧ_{c-1}} + 0.5 \cdot \Delta a_i + chord_{rotor_{i,av(N_r)}} \cdot \sin\left(\upsilon_{rotor_{i,av(N_r)}}\right) + 0.5 \cdot \Delta a_i \\ \begin{pmatrix} y_{ПЧпер_c} \\ y_{ПЧср_c} \\ y_{ПЧкор_c} \end{pmatrix} \leftarrow \begin{pmatrix} R_{st(i,2),N_r} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),ORIGIN} \end{pmatrix} \\ y_{Лпер_c} \leftarrow y_{ПЧпер_c} - \Delta_{r_i} \\ c \leftarrow c+1 \\ x_{ПЧ_c} \leftarrow x_{ПЧ_{c-1}} + 0.5 \cdot \Delta a_i + chord_{stator_{i,av(N_r)}} \cdot \sin\left(\upsilon_{stator_{i,av(N_r)}}\right) + 0.5 \cdot \Delta a_i \\ \begin{pmatrix} y_{ПЧпер_c} \\ y_{ПЧср_c} \\ y_{ПЧкор_c} \end{pmatrix} \leftarrow \begin{pmatrix} R_{st(i,3),N_r} \\ R_{st(i,3),av(N_r)} \\ R_{st(i,3),ORIGIN} \end{pmatrix} \\ y_{Лпер_c} \leftarrow y_{ПЧпер_c} - \Delta_{r_i} \end{array} \right. \\ \left(x_{ПЧ} \; y_{ПЧпер} \; y_{ПЧср} \; y_{ПЧкор} \; y_{Лпер} \right)^T \end{array} \right.$$

$$y_{ПЧпер}(l) := interp\left(cspline\left(x_{ПЧ}, y_{ПЧпер}\right), x_{ПЧ}, y_{ПЧпер}, l\right)$$

$$y_{ПЧср}(l) := interp\left(cspline\left(x_{ПЧ}, y_{ПЧср}\right), x_{ПЧ}, y_{ПЧср}, l\right)$$

$$y_{ПЧкор}(l) := interp\left(cspline\left(x_{ПЧ}, y_{ПЧкор}\right), x_{ПЧ}, y_{ПЧкор}, l\right)$$

$$y_{Лпер}(l) := interp\left(cspline\left(x_{ПЧ}, y_{Лпер}\right), x_{ПЧ}, y_{Лпер}, l\right)$$



Проточная часть

Рассматриваемая ступень: $j := \left| \begin{array}{l} j \leftarrow 1 \\ j \leftarrow \left| \begin{array}{ll} \text{"Такой ступени не существует!"} & \text{if } (j < 1) \vee (j > Z) \\ j & \text{otherwise} \end{array} \right. \end{array} \right. = 1$

Поперечная часть ступени

$$r := \min(D), \min(D) + \frac{\max(D) - \min(D)}{N_{dis}} .. \max(D)$$

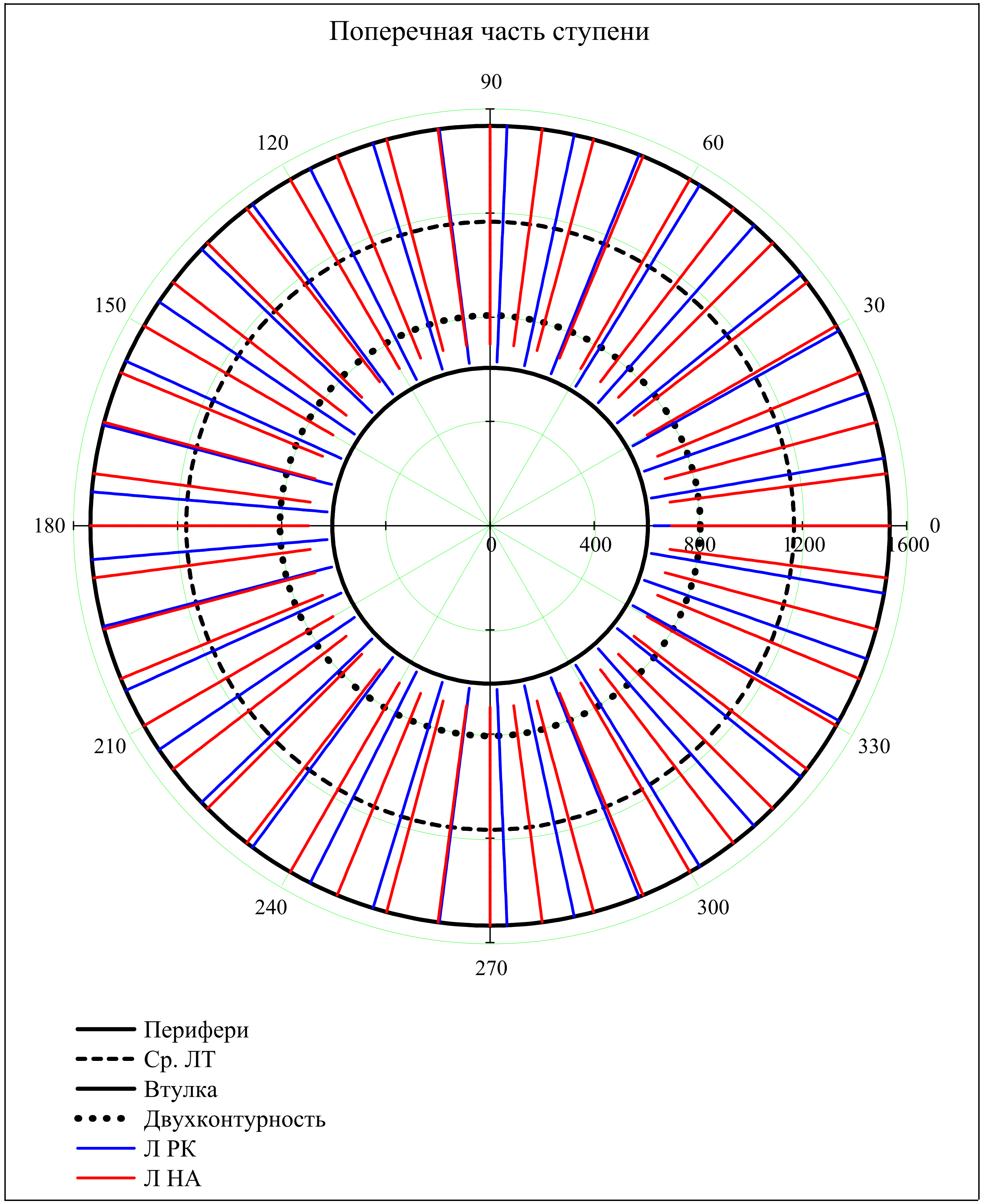
$$i_{rotor} := 1 .. Z_{rotor_j}$$

$$i_{stator} := 1 .. Z_{stator_j}$$

$$Л_{РК}(r,j) := \left| \begin{array}{ll} \dfrac{2\cdot\pi}{Z_{rotor_j}} & \text{if } D_{st(j,1),1} < r < D_{st(j,1),N_r} \\ \text{NaN} & \text{otherwise} \end{array} \right.$$

$$Л_{НА}(r,j) := \left| \begin{array}{ll} \dfrac{2\cdot\pi}{Z_{stator_j}} & \text{if } D_{st(j,2),1} < r < D_{st(j,2),N_r} \\ \text{NaN} & \text{otherwise} \end{array} \right.$$

Поперечная часть ступени



Поперечная часть ступени

Выбор материала Л

Запас по температуре (К): $\Delta T_{safety} = 50$

Выбранный материал Л:

$$material\_blade_i = \begin{cases} "ЖС\text{-}6К" & \text{if } 1123 \le T^*_{st(i,2),av(N_r)} + \Delta T_{safety} \\ "ВТ41" & \text{if } 873 \le T^*_{st(i,2),av(N_r)} + \Delta T_{safety} < 1123 \\ "ВТ25" & \text{if } 753 \le T^*_{st(i,2),av(N_r)} + \Delta T_{safety} < 873 \\ "ВТ9" & \text{otherwise} \end{cases}$$

$$material\_blade_i = \begin{cases} "ВТ23" & \text{if } compressor = "Вл" \\ "ВТ6" & \text{if } compressor = "КНД" \\ material\_blade_i & \text{otherwise} \end{cases}$$

Плотность материала Л (кг/м^3):

$$\rho\_blade_i = \begin{cases} 8393 & \text{if } material\_blade_i = "ЖС\text{-}6К" \\ 7900 & \text{if } material\_blade_i = "ВТ41" \\ 4500 & \text{if } material\_blade_i = "ВТ25" \\ 4570 & \text{if } material\_blade_i = "ВТ23" \\ 4510 & \text{if } material\_blade_i = "ВТ9" \\ 4430 & \text{if } material\_blade_i = "ВТ6" \\ NaN & \text{otherwise} \end{cases}$$

Коэф. формы: $k_n = 6.8$

Модуль Юнга I рода материала Л (Па): $E\_blade = 210 \cdot 10^9$

Коэф. Пуассона материала Л (): $\mu\_steel = 0.3$

Предел длительной прочности Л РК (Па):

$$\sigma\_blade\_long_i = 10^6 \cdot \begin{cases} 125 & \text{if } material\_blade_i = "ЖС\text{-}6К" \\ 123 & \text{if } material\_blade_i = "ВТ41" \\ 150 & \text{if } material\_blade_i = "ВТ25" \\ 230 & \text{if } material\_blade_i = "ВТ23" \\ 200 & \text{if } material\_blade_i = "ВТ9" \\ 210 & \text{if } material\_blade_i = "ВТ6" \\ NaN & \text{otherwise} \end{cases}$$

$material\_blade^T =$

	1	2	3	4	5	6	7	8	9
1	"ВТ23"								

$\rho\_blade^T =$

	1
1	4570

$\sigma\_blade\_long^T =$

	1
1	230.0

$\cdot 10^6$

Выбор материала Л

Расчет собственных частот колебаний Л

$$\begin{pmatrix} \nu0_{изг.stator} & \nu0_{изг.rotor} \\ \nu0_{угл.stator} & \nu0_{угл.rotor} \\ \nu0_{угл.stator\_bondage} & \nu0_{угл.rotor\_bondage} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } r \in av(N_r) \\ \quad\quad \text{for } mode \in 1..6 \\ \quad\quad\quad \nu0_{изг.stator_{i,mode}} = \nu0_{изгиб}\left(mode, mean\left(h_{st(i,2)}, h_{st(i,3)}\right), E\_blade, \rho\_blade_i, area_{stator_{i,r}}, Ju_{stator_{i,r}}\right) \\ \quad\quad\quad \nu0_{изг.rotor_{i,mode}} = \nu0_{изгиб}\left(mode, mean\left(h_{st(i,1)}, h_{st(i,2)}\right), E\_blade, \rho\_blade_i, area_{rotor_{i,r}}, Ju_{rotor_{i,r}}\right) \\ \quad\quad\quad \nu0_{угл.stator_{i,mode}} = \nu0_{угл}\left(mode, 0, mean\left(h_{st(i,2)}, h_{st(i,3)}\right), Jung(2, \mu\_steel, E\_blade), \rho\_blade_i, stiffness_{stator_{i,r}}, Jp_{stator_{i,r}}\right) \\ \quad\quad\quad \nu0_{угл.rotor_{i,mode}} = \nu0_{угл}\left(mode, 0, mean\left(h_{st(i,1)}, h_{st(i,2)}\right), Jung(2, \mu\_steel, E\_blade), \rho\_blade_i, stiffness_{rotor_{i,r}}, Jp_{rotor_{i,r}}\right) \\ \quad\quad\quad \nu0_{угл.stator\_bondage_{i,mode}} = \nu0_{угл}\left(mode, 1, mean\left(h_{st(i,2)}, h_{st(i,3)}\right), Jung(2, \mu\_steel, E\_blade), \rho\_blade_i, stiffness_{stator_{i,r}}, Jp_{stator_{i,r}}\right) \\ \quad\quad\quad \nu0_{угл.rotor\_bondage_{i,mode}} = \nu0_{угл}\left(mode, 1, mean\left(h_{st(i,1)}, h_{st(i,2)}\right), Jung(2, \mu\_steel, E\_blade), \rho\_blade_i, stiffness_{rotor_{i,r}}, Jp_{rotor_{i,r}}\right) \\ \begin{pmatrix} \nu0_{изг.stator} & \nu0_{изг.rotor} \\ \nu0_{угл.stator} & \nu0_{угл.rotor} \\ \nu0_{угл.stator\_bondage} & \nu0_{угл.rotor\_bondage} \end{pmatrix} \end{array} \right.$$

Частота собственных изгибных колебаний (Гц) [9, с.240]:

$\mathrm{stack}\left(\nu0_{\text{угл.stator}}, \nu0_{\text{угл.rotor}}\right)^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	314	289																
2	943	868																
3	1572	1446																
4	2201	2025																
5	2829	2603																
6	3458	3182																

Частота собственных угловых колебаний (Гц) [9, с.243] без и с бандажом:

$\mathrm{stack}\left(\nu0_{\text{изг.stator}}, \nu0_{\text{изг.rotor}}\right)^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	54	68																
2	336	424																
3	942	1187																
4	1846	2328																
5	3051	3847																
6	4556	5746																

$\mathrm{stack}\left(\nu0_{\text{угл.stator\_bondage}}, \nu0_{\text{угл.rotor\_bondage}}\right)^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	629	578																
2	1258	1157																
3	1886	1735																
4	2515	2314																
5	3144	2892																
6	3773	3471																

Расчет собственных частот колебаний Л

Вывод результатов расчета собственных частот колебаний Л

Расчетный узел: type = "compressor"

Объем бандажной полки ($м^3$): $V_{бп} = 0$

Радиус положения ЦМ бандажной полки (м): $R_{бп} = 0$

Расчет Л на прочность

$$\begin{pmatrix} R0_{rotor} & area0_{rotor} \\ N0_{rotor} & \sigma0\_z_{rotor} \\ area_{rotor.} & area_{stator.} \\ N_{rotor} & \sigma\_z_{rotor} \\ P_1 & \rho_1 \\ P_2 & \rho_2 \\ P_3 & \rho_3 \\ c_{a1} & c_{u1} \\ c_{a2} & c_{u2} \\ c_{a3} & c_{u3} \\ qx_{rotor} & qx_{stator} \\ qy_{rotor} & qy_{stator} \\ Mx_{rotor} & Mx_{stator} \\ My_{rotor} & My_{stator} \\ shift\_x_{rotor} & shift\_y_{rotor} \\ x0_{rotor.} & x0_{stator.} \\ y0_{rotor.} & y0_{stator.} \\ \alpha\_major_{rotor.} & \alpha\_major_{stator.} \\ Ju_{rotor.} & Ju_{stator.} \\ Jv_{rotor.} & Jv_{stator.} \\ CPx_{rotor.} & CPx_{stator.} \\ CPy_{rotor.} & CPy_{stator.} \\ CPx_{rotor.axis} & CPx_{stator.axis} \\ CPy_{rotor.axis} & CPy_{stator.axis} \end{pmatrix} = \left| \begin{array}{l} \chi_{rotor}(i,z) = \dfrac{area_{rotor_{i,N_r}}}{area_{rotor_{i,1}}} \\ R0_{rotor}(i,z) = \dfrac{1}{\sqrt{1-\ln(\chi_{rotor}(i,z))}} \cdot \left| \begin{array}{ll} \sqrt{mean\left(R_{st(i,1),1}, R_{st(i,2),1}\right)^2 - mean\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right)^2 \cdot \ln(\chi_{rotor}(i,z))} & \text{if type = "compressor"} \\ \sqrt{mean\left(R_{st(i,2),1}, R_{st(i,3),1}\right)^2 - mean\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right)^2 \cdot \ln(\chi_{rotor}(i,z))} & \text{if type = "turbine"} \end{array} \right. \\ \sigma0_{rotor.max}(i,z) = \dfrac{\rho\_blade_i \cdot \omega^2}{2} \cdot \left| \begin{array}{ll} \left[mean\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right)^2 - \left(R0_{rotor}(i,z)\right)^2\right] & \text{if type = "compressor"} \\ \left[mean\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right)^2 - \left(R0_{rotor}(i,z)\right)^2\right] & \text{if type = "turbine"} \end{array} \right. \\ \left| \left(\dfrac{\rho\_blade_i \cdot \omega^2}{\ldots} \int^{R0_{rotor}(i,z)} \ldots \right) \right. \end{array} \right.$$

$$\begin{pmatrix} \varphi_{rotor.axis} & \varphi_{stator.axis} \\ Wp_{rotor.} & Wp_{stator.} \\ M\tau_{rotor} & M\tau_{stator} \\ \tau_{rotor} & \tau_{stator} \\ \varphi\_uv_{rotor} & \varphi\_uv_{stator} \\ Mu_{rotor} & Mu_{stator} \\ Mv_{rotor} & Mv_{stator} \\ \varphi\_neutral_{rotor} & \varphi\_neutral_{stator} \end{pmatrix}$$

$$area0_{rotor}(i,z) = area_{rotor_{i,N_r}} \cdot \begin{vmatrix} e^{\left(\frac{\cdots}{\sigma0_{rotor.max}(i,z)} \cdot \int_z \cdots z\,dz\right)} & \text{if } z \le R0_{rotor}(i,z) \\ 1 & \text{otherwise} \end{vmatrix}$$

$$N0_{rotor}(i,z) = \rho\_blade_i \cdot \omega^2 \cdot \begin{vmatrix} \left(\int_z^{mean\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right)} area0_{rotor}(i,z) \cdot z\,dz + V_{бп} \cdot R_{бп}\right) & \text{if type = "compressor"} \\ \left(\int_z^{mean\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right)} area0_{rotor}(i,z) \cdot z\,dz + V_{бп} \cdot R_{бп}\right) & \text{if type = "turbine"} \end{vmatrix}$$

$$\sigma0\_z_{rotor}(i,z) = \frac{N0_{rotor}(i,z)}{area0_{rotor}(i,z)}$$

$$area_{rotor.}(i,z) = interp\left(pspline\left(submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(area_{rotor}, i, i, 1, N_r\right)^T\right), submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(area_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$area_{stator.}(i,z) = interp\left(pspline\left(submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(area_{stator}, i, i, 1, N_r\right)^T\right), submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(area_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$N_{rotor}(i,z) = \rho\_blade_i \cdot \omega^2 \cdot \begin{vmatrix} \left(\int_z^{mean\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right)} area_{rotor.}(i,z) \cdot z\,dz + V_{бп} \cdot R_{бп}\right) & \text{if type = "compressor"} \\ \left(\int_z^{mean\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right)} area_{rotor.}(i,z) \cdot z\,dz + V_{бп} \cdot R_{бп}\right) & \text{if type = "turbine"} \end{vmatrix}$$

$$\sigma\_z_{rotor}(i,z) = \frac{N_{rotor}(i,z)}{area_{rotor.}(i,z)}$$

$$\rho_1(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(\rho, st(i,1), st(i,1), 1, N_r\right)^T\right), submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(\rho, st(i,1), st(i,1), 1, N_r\right)^T, z\right)$$

$$\rho_2(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(\rho, st(i,2), st(i,2), 1, N_r\right)^T\right), submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(\rho, st(i,2), st(i,2), 1, N_r\right)^T, z\right)$$

$$\rho_3(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,3), st(i,3), 1, N_r\right)^T, submatrix\left(\rho, st(i,3), st(i,3), 1, N_r\right)^T\right), submatrix\left(R, st(i,3), st(i,3), 1, N_r\right)^T, submatrix\left(\rho, st(i,3), st(i,3), 1, N_r\right)^T, z\right)$$

$$P_1(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(P, st(i,1), st(i,1), 1, N_r\right)^T\right), submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(P, st(i,1), st(i,1), 1, N_r\right)^T, z\right)$$

$$P_2(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(P, st(i,2), st(i,2), 1, N_r\right)^T\right), submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(P, st(i,2), st(i,2), 1, N_r\right)^T, z\right)$$

$$P_3(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,3), st(i,3), 1, N_r\right)^T, submatrix\left(P, st(i,3), st(i,3), 1, N_r\right)^T\right), submatrix\left(R, st(i,3), st(i,3), 1, N_r\right)^T, submatrix\left(P, st(i,3), st(i,3), 1, N_r\right)^T, z\right)$$

$$c_{a1}(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(c_a, st(i,1), st(i,1), 1, N_r\right)^T\right), submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(c_a, st(i,1), st(i,1), 1, N_r\right)^T, z\right)$$

$$c_{a2}(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(c_a, st(i,2), st(i,2), 1, N_r\right)^T\right), submatrix\left(R, st(i,2), st(i,2), 1, N_r\right)^T, submatrix\left(c_a, st(i,2), st(i,2), 1, N_r\right)^T, z\right)$$

$$c_{a3}(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,3), st(i,3), 1, N_r\right)^T, submatrix\left(c_a, st(i,3), st(i,3), 1, N_r\right)^T\right), submatrix\left(R, st(i,3), st(i,3), 1, N_r\right)^T, submatrix\left(c_a, st(i,3), st(i,3), 1, N_r\right)^T, z\right)$$

$$c_{u1}(i,z) = interp\left(lspline\left(submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(c_u, st(i,1), st(i,1), 1, N_r\right)^T\right), submatrix\left(R, st(i,1), st(i,1), 1, N_r\right)^T, submatrix\left(c_u, st(i,1), st(i,1), 1, N_r\right)^T, z\right)$$

$$c_{u2}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(c_u, st(i,2), st(i,2), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(c_u, st(i,2), st(i,2), 1, N_r\right)^T, z\right)$$

$$c_{u3}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,3), st(i,3), 1, N_r\right)^T, \mathrm{submatrix}\left(c_u, st(i,3), st(i,3), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,3), st(i,3), 1, N_r\right)^T, \mathrm{submatrix}\left(c_u, st(i,3), st(i,3), 1, N_r\right)^T, z\right)$$

$$w_{u1}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,1), st(i,1), 1, N_r\right)^T, \mathrm{submatrix}\left(w_u, st(i,1), st(i,1), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,1), st(i,1), 1, N_r\right)^T, \mathrm{submatrix}\left(w_u, st(i,1), st(i,1), 1, N_r\right)^T, z\right)$$

$$w_{u2}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(w_u, st(i,2), st(i,2), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(w_u, st(i,2), st(i,2), 1, N_r\right)^T, z\right)$$

$$w_{u3}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,3), st(i,3), 1, N_r\right)^T, \mathrm{submatrix}\left(w_u, st(i,3), st(i,3), 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,3), st(i,3), 1, N_r\right)^T, \mathrm{submatrix}\left(w_u, st(i,3), st(i,3), 1, N_r\right)^T, z\right)$$

$$qx_{rotor}(i,z) = -\frac{2\pi z}{Z_{rotor_i}} \cdot \left| \begin{array}{ll} \left[\left(P_2(i,z) - P_1(i,z)\right) + \rho_1(i,z)\cdot c_{a1}(i,z)\cdot\left(c_{a2}(i,z) - c_{a1}(i,z)\right)\right] & \text{if type = "compressor"} \\ \left[\left(P_3(i,z) - P_2(i,z)\right) + \rho_2(i,z)\cdot c_{a2}(i,z)\cdot\left(c_{a3}(i,z) - c_{a2}(i,z)\right)\right] & \text{if type = "turbine"} \end{array} \right.$$

$$qx_{stator}(i,z) = -\frac{2\pi z}{Z_{stator_i}} \cdot \left| \begin{array}{ll} \left[\left(P_3(i,z) - P_2(i,z)\right) + \rho_2(i,z)\cdot c_{a2}(i,z)\cdot\left(c_{a3}(i,z) - c_{a2}(i,z)\right)\right] & \text{if type = "compressor"} \\ \left[\left(P_2(i,z) - P_1(i,z)\right) + \rho_1(i,z)\cdot c_{a1}(i,z)\cdot\left(c_{a2}(i,z) - c_{a1}(i,z)\right)\right] & \text{if type = "turbine"} \end{array} \right.$$

$$qy_{rotor}(i,z) = \frac{2\pi z}{Z_{rotor_i}} \cdot \left| \begin{array}{ll} \left[\rho_1(i,z)\cdot c_{a1}(i,z)\cdot\left(w_{u2}(i,z) - w_{u1}(i,z)\right)\right] & \text{if type = "compressor"} \\ \left[\rho_2(i,z)\cdot c_{a2}(i,z)\cdot\left(w_{u3}(i,z) - w_{u2}(i,z)\right)\right] & \text{if type = "turbine"} \end{array} \right.$$

$$qy_{stator}(i,z) = -\frac{2\pi z}{Z_{stator_i}} \cdot \left| \begin{array}{ll} \left[\rho_2(i,z)\cdot c_{a2}(i,z)\cdot\left(c_{u3}(i,z) - c_{u2}(i,z)\right)\right] & \text{if type = "compressor"} \\ \left[\rho_1(i,z)\cdot c_{a1}(i,z)\cdot\left(c_{u2}(i,z) - c_{u1}(i,z)\right)\right] & \text{if type = "turbine"} \end{array} \right.$$

$$Mx_{rotor}(i,z) = -\int_z^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right) & \text{if type="turbine"} \end{array} \right.} qy_{rotor}(i,z1)\cdot(z1 - z)\, dz1$$

$$Mx_{stator}(i,z) = \int_z^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,2),1}, R_{st(i,3),1}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,1),1}, R_{st(i,2),1}\right) & \text{if type="turbine"} \end{array} \right.} qy_{stator}(i,z1)\cdot(z1 - z)\, dz1$$

$$My_{rotor}(i,z) = \int_z^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right) & \text{if type="turbine"} \end{array} \right.} qx_{rotor}(i,z1)\cdot(z1 - z)\, dz1$$

$$My_{stator}(i,z) = -\int_z^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,2),1}, R_{st(i,3),1}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,1),1}, R_{st(i,2),1}\right) & \text{if type="turbine"} \end{array} \right.} qx_{stator}(i,z1)\cdot(z1 - z)\, dz1$$

$$\int^{z} \int^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right) & \text{if type="turbine"} \end{array} \right.} qx_{rotor}(i,z)\, dz$$

$$\text{shift\_x}_{rotor}(i,z) = \int_{\begin{cases}\text{mean}\left(R_{st(i,1),1}, R_{st(i,2),1}\right) & \text{if type="compressor"}\\ \text{mean}\left(R_{st(i,2),1}, R_{st(i,3),1}\right) & \text{if type="turbine"}\end{cases}} \frac{\int_{z} qx_{rotor}(i,z)\,dz}{N_{rotor}(i,z)}\,dz$$

$$\text{shift\_y}_{rotor}(i,z) = z\cdot\int_{\begin{cases}\text{mean}\left(R_{st(i,1),1}, R_{st(i,2),1}\right) & \text{if type="compressor"}\\ \text{mean}\left(R_{st(i,2),1}, R_{st(i,3),1}\right) & \text{if type="turbine"}\end{cases}}^{z} \frac{\int_{z}^{\begin{cases}\text{mean}\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right) & \text{if type="compressor"}\\ \text{mean}\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right) & \text{if type="turbine"}\end{cases}} \left(qy_{rotor}(i,z)\cdot z\right)dz}{N_{rotor}(i,z)\cdot z^2}\,dz$$

$$x0_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(x0_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(x0_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$x0_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(x0_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(x0_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$y0_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(y0_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(y0_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$y0_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(y0_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(y0_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$\alpha\text{\_major}_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\alpha\text{\_major}_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\alpha\text{\_major}_{rotor}, i, i, 1, N_r\right)^T\right.$$

$$\alpha\text{\_major}_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\alpha\text{\_major}_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\alpha\text{\_major}_{stator}, i, i, 1, N_r\right.\right.$$

$$Ju_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Ju_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Ju_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$Ju_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Ju_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Ju_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$Jv_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Jv_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Jv_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$Jv_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Jv_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(Jv_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$CPx_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPx_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPx_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$CPx_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPx_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPx_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$CPy_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPy_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPy_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$CPy_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPy_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(CPy_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$CPx_{rotor.axis}(i,z) = \text{axis}_x\left(CPx_{rotor.}(i,z), CPy_{rotor.}(i,z), x0_{rotor.}(i,z), y0_{rotor.}(i,z), \alpha\text{\_major}_{rotor.}(i,z), 1\right)$$

$$CPx_{stator.axis}(i,z) = \text{axis}_x\left(CPx_{stator.}(i,z), CPy_{stator.}(i,z), x0_{stator.}(i,z), y0_{stator.}(i,z), \alpha\text{\_major}_{stator.}(i,z), 1\right)$$

$$CPy_{rotor.axis}(i,z) = \text{axis}_y\left(CPx_{rotor.}(i,z), CPy_{rotor.}(i,z), x0_{rotor.}(i,z), y0_{rotor.}(i,z), \alpha\text{\_major}_{rotor.}(i,z), 1\right)$$

$$CPy_{stator.axis}(i,z) = \text{axis}_y\left(CPx_{stator.}(i,z), CPy_{stator.}(i,z), x0_{stator.}(i,z), y0_{stator.}(i,z), \alpha\text{\_major}_{stator.}(i,z), 1\right)$$

$$Wp_{rotor.}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(Wp_{rotor}, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(Wp_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$Wp_{stator.}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(Wp_{stator}, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(Wp_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$M\tau_{rotor}(i,z) = \int_z^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right) & \text{if type="turbine"} \end{array} \right.} \left(qx_{rotor}(i,z1)\cdot CPy_{rotor.axis}(i,z1) - qy_{rotor}(i,z1)\cdot CPx_{rotor.axis}(i,z1)\right) dz1$$

$$M\tau_{stator}(i,z) = \int_z^{\left| \begin{array}{ll} \mathrm{mean}\left(R_{st(i,2),1}, R_{st(i,3),1}\right) & \text{if type="compressor"} \\ \mathrm{mean}\left(R_{st(i,1),1}, R_{st(i,2),1}\right) & \text{if type="turbine"} \end{array} \right.} \left(qx_{stator}(i,z1)\cdot CPy_{stator.axis}(i,z1) - qy_{stator}(i,z1)\cdot CPx_{stator.axis}(i,z1)\right) dz1$$

$$\tau_{rotor}(i,z) = \frac{M\tau_{rotor}(i,z)}{Wp_{rotor.}(i,z)}$$

$$\tau_{stator}(i,z) = \frac{M\tau_{stator}(i,z)}{Wp_{stator.}(i,z)}$$

$$\varphi\_uv_{rotor}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\frac{\pi}{2} - \upsilon_{rotor}, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\frac{\pi}{2} - \upsilon_{rotor}, i, i, 1, N_r\right)^T, z\right)$$

$$\varphi\_uv_{stator}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\frac{\pi}{2} - \upsilon_{stator}, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\frac{\pi}{2} - \upsilon_{stator}, i, i, 1, N_r\right)^T, z\right)$$

$$Mu_{rotor}(i,z) = \mathrm{axis}_x\left(Mx_{rotor}(i,z), My_{rotor}(i,z), 0, 0, \varphi\_uv_{rotor}(i,z), 1\right)$$

$$Mu_{stator}(i,z) = \mathrm{axis}_x\left(Mx_{stator}(i,z), My_{stator}(i,z), 0, 0, \varphi\_uv_{stator}(i,z), 1\right)$$

$$Mv_{rotor}(i,z) = \mathrm{axis}_y\left(Mx_{rotor}(i,z), My_{rotor}(i,z), 0, 0, \varphi\_uv_{rotor}(i,z), 1\right)$$

$$Mv_{stator}(i,z) = \mathrm{axis}_y\left(Mx_{stator}(i,z), My_{stator}(i,z), 0, 0, \varphi\_uv_{stator}(i,z), 1\right)$$

$$\varphi\_neutral_{rotor}(i,z) = \left| \begin{array}{ll} \mathrm{atan}\left(\dfrac{Mv_{rotor}(i,z)\cdot Ju_{rotor.}(i,z)}{Mu_{rotor}(i,z)\cdot Jv_{rotor.}(i,z)}\right) & \text{if } Mu_{rotor}(i,z)\cdot Jv_{rotor.}(i,z) \neq 0 \\ \dfrac{\pi}{2} & \text{otherwise} \end{array} \right.$$

$$\varphi\_neutral_{stator}(i,z) = \left| \begin{array}{ll} \mathrm{atan}\left(\dfrac{Mv_{stator}(i,z)\cdot Ju_{stator.}(i,z)}{Mu_{stator}(i,z)\cdot Jv_{stator.}(i,z)}\right) & \text{if } Mu_{stator}(i,z)\cdot Jv_{stator.}(i,z) \neq 0 \\ \dfrac{\pi}{2} & \text{otherwise} \end{array} \right.$$

$$\begin{pmatrix} R0_{rotor} & area0_{rotor} \\ N0_{rotor} & \sigma0\_z_{rotor} \\ area_{rotor.} & area_{stator.} \\ N_{rotor} & \sigma\_z_{rotor} \end{pmatrix}$$

$$
\begin{array}{cc}
P_1 & \rho_1 \\
P_2 & \rho_2 \\
P_3 & \rho_3 \\
c_{a1} & c_{u1} \\
c_{a2} & c_{u2} \\
c_{a3} & c_{u3} \\
qx_{rotor} & qx_{stator} \\
qy_{rotor} & qy_{stator} \\
Mx_{rotor} & Mx_{stator} \\
My_{rotor} & My_{stator} \\
shift\_x_{rotor} & shift\_y_{rotor} \\
x0_{rotor.} & x0_{stator.} \\
y0_{rotor.} & y0_{stator.} \\
\alpha\_major_{rotor.} & \alpha\_major_{stator.} \\
Ju_{rotor.} & Ju_{stator.} \\
Jv_{rotor.} & Jv_{stator.} \\
CPx_{rotor.} & CPx_{stator.} \\
CPy_{rotor.} & CPy_{stator.} \\
CPx_{rotor.axis} & CPx_{stator.axis} \\
CPy_{rotor.axis} & CPy_{stator.axis} \\
Wp_{rotor.} & Wp_{stator.} \\
M\tau_{rotor} & M\tau_{stator} \\
\tau_{rotor} & \tau_{stator} \\
\varphi\_uv_{rotor} & \varphi\_uv_{stator} \\
Mu_{rotor} & Mu_{stator} \\
Mv_{rotor} & Mv_{stator} \\
\varphi\_neutral_{rotor} & \varphi\_neutral_{stator}
\end{array}
\right)
$$

Расчет Л на прочность

$$
\mathrm{neutral\_line}(\mathrm{type},x,i,r) = \begin{cases} \dfrac{y0_{rotor_{i,r}}}{chord_{rotor_{i,r}}} + \tan\left(\left(\alpha\_major_{rotor_{i,r}} + \varphi\_neutral_{rotor}\left(i, R_{st(i,2),r}\right)\right)\right)\cdot\left(x - \dfrac{x0_{rotor_{i,r}}}{chord_{rotor_{i,r}}}\right) & \text{if type = "rotor"} \\ \dfrac{y0_{stator_{i,r}}}{chord_{stator_{i,r}}} + \tan\left(\left(\alpha\_major_{stator_{i,r}} + \varphi\_neutral_{stator}\left(i, R_{st(i,2),r}\right)\right)\right)\cdot\left(x - \dfrac{x0_{stator_{i,r}}}{chord_{stator_{i,r}}}\right) & \text{if type = "stator"} \end{cases}
$$

$$
\mathrm{epure}(\mathrm{type},x,i,r) = \begin{cases} \dfrac{y0_{rotor_{i,r}}}{chord_{rotor_{i,r}}} + \dfrac{-1}{\tan\left(\alpha\_major_{rotor_{i,r}} + \varphi\_neutral_{rotor}\left(i, R_{st(i,2),r}\right) - \dfrac{\pi}{4}\right)}\cdot\left(x - \dfrac{x0_{rotor_{i,r}}}{chord_{rotor_{i,r}}}\right) & \text{if type = "rotor"} \\ \dfrac{y0_{stator_{i,r}}}{chord_{stator_{i,r}}} + \dfrac{-1}{\tan\left(\alpha\_major_{stator_{i,r}} + \varphi\_neutral_{stator}\left(i, R_{st(i,2),r}\right) - \dfrac{\pi}{4}\right)}\cdot\left(x - \dfrac{x0_{stator_{i,r}}}{chord_{stator_{i,r}}}\right) & \text{if type = "stator"} \end{cases}
$$

Определение координат точек профиля Л, наиболее удаленных от НЛ

Наиболее удаленные точки от НЛ (мм):

$u\_u_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9
1	1.472								
2	7.963								
3	-0.874								

$\cdot 10^{-3}$

$v\_u_{rotor}^{T} =$

	1
1	16.913
2	7.634
3	91.332

$\cdot 10^{-3}$

$u\_l_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9
1	76.672								
2	-82.297								
3	-1.367								

$\cdot 10^{-3}$

$v\_l_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9
1	-22.396								
2	-12.954								
3	-91.332								

$\cdot 10$

$u\_u_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9
1	0.005								
2	-0.157								
3	-3.076								

$\cdot 10^{-3}$

$v\_u_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9
1	3.911								
2	5.336								
3	6.204								

$\cdot 10^{-3}$

$u\_l_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9
1	59.567								
2	73.040								
3	-25.983								

$\cdot 10^{-3}$

$v\_l_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9
1	-5.825								
2	-5.379								
3	-5.433								

$\cdot 10^{-3}$

$$\begin{pmatrix} \sigma\_p_{rotor} & \sigma\_n_{rotor} \\ \sigma\_p_{stator} & \sigma\_n_{stator} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } r \in 1..N_r \\ \qquad \begin{pmatrix} \sigma\_p_{rotor_{i,r}} & \sigma\_n_{rotor_{i,r}} \\ \sigma\_p_{stator_{i,r}} & \sigma\_n_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \frac{Mu_{rotor}(i, R_{st(i,2)}, r)}{Ju_{rotor_{i,r}}} \cdot v\_u_{rotor_{i,r}} - \frac{Mv_{rotor}(i, R_{st(i,2)}, r)}{Jv_{rotor_{i,r}}} \cdot u\_u_{rotor_{i,r}} & \frac{Mu_{rotor}(i, R_{st(i,2)}, r)}{Ju_{rotor_{i,r}}} \cdot v\_l_{rotor_{i,r}} - \frac{Mv_{rotor}(i, R_{st(i,2)}, r)}{Jv_{rotor_{i,r}}} \cdot u\_l_{rotor_{i,r}} \\ \frac{Mu_{stator}(i, R_{st(i,2)}, r)}{Ju_{stator_{i,r}}} \cdot v\_u_{stator_{i,r}} - \frac{Mv_{stator}(i, R_{st(i,2)}, r)}{Jv_{stator_{i,r}}} \cdot u\_u_{stator_{i,r}} & \frac{Mu_{stator}(i, R_{st(i,2)}, r)}{Ju_{stator_{i,r}}} \cdot v\_l_{stator_{i,r}} - \frac{Mv_{stator}(i, R_{st(i,2)}, r)}{Jv_{stator_{i,r}}} \cdot u\_l_{stator_{i,r}} \end{pmatrix} \\ \begin{pmatrix} \sigma\_p_{rotor} & \sigma\_n_{rotor} \\ \sigma\_p_{stator} & \sigma\_n_{stator} \end{pmatrix} \end{array} \right.$$

$$\begin{pmatrix} \sigma\_p_{rotor.} & \sigma\_p_{stator.} \\ \sigma\_n_{rotor.} & \sigma\_n_{stator.} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \left| \begin{array}{l} \sigma\_p_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_p_{rotor}, i, i, 1, N_r)^T\right), \text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_p_{rotor}, i, i, 1, N_r)^T, z\right) \\ \sigma\_p_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_p_{stator}, i, i, 1, N_r)^T\right), \text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_p_{stator}, i, i, 1, N_r)^T, z\right) \\ \sigma\_n_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_n_{rotor}, i, i, 1, N_r)^T\right), \text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_n_{rotor}, i, i, 1, N_r)^T, z\right) \\ \sigma\_n_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_n_{stator}, i, i, 1, N_r)^T\right), \text{submatrix}(R, st(i,1), st(i,1), 1, N_r)^T, \text{submatrix}(\sigma\_n_{stator}, i, i, 1, N_r)^T, z\right) \end{array} \right. \\ \begin{pmatrix} \sigma\_p_{rotor.} & \sigma\_p_{stator.} \\ \sigma\_n_{rotor.} & \sigma\_n_{stator.} \end{pmatrix} \end{array} \right.$$

$\sigma\_p_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9
1	39.83								
2	8.30								
3	0.00								

$\cdot 10^{6}$

$\sigma\_p_{rotor}{}^{T} \le 70 \cdot 10^{6} =$

	1
1	1
2	1
3	1

$\sigma\_n_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9
1	-47.22								
2	-17.09								
3	0.00								

$\cdot 10^{6}$

$\sigma\_n_{rotor}{}^{T} \le 70 \cdot 10^{6} =$

	1
1	1
2	1
3	1

$\sigma\_p_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9
1	1.18								
2	125.79								
3	193.43								

$\cdot 10^{6}$

$\sigma\_p_{stator}{}^{T} \le 70 \cdot 10^{6} =$

	1
1	1
2	0
3	0

$\sigma\_n_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9
1	-1.78								
2	-127.43								
3	-170.34								

$\cdot 10^{6}$

$\sigma\_n_{stator}{}^{T} \le 70 \cdot 10^{6} =$

	1
1	1
2	1
3	1

$$\begin{pmatrix}\sigma_{rotor}\\ \sigma_{stator}\end{pmatrix} = \left|\begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } r \in 1..N_r \\ \quad\quad \left|\begin{array}{l} \sigma_{rotor_{i,r}} = \sqrt{\left(\sigma\_z_{rotor}\left(i, R_{st(i,2),r}\right) + \max\left(\sigma\_p_{rotor_{i,r}}, \sigma\_n_{rotor_{i,r}}\right)\right)^2 + \tau_{rotor}\left(i, R_{st(i,2),r}\right)^2} \\ \sigma_{stator_{i,r}} = \sqrt{\left(0 + \max\left(\sigma\_p_{stator_{i,r}}, \sigma\_n_{stator_{i,r}}\right)\right)^2 + \tau_{stator}\left(i, R_{st(i,2),r}\right)^2} \end{array}\right. \\ \begin{pmatrix}\sigma_{rotor}\\ \sigma_{stator}\end{pmatrix} \end{array}\right.$$

$$\begin{pmatrix}\sigma_{rotor.}\\ \sigma_{stator.}\end{pmatrix} = \left|\begin{array}{l} \text{for } i \in 1..Z \\ \quad \left|\begin{array}{l} \sigma_{rotor.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\sigma_{rotor}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\sigma_{rotor}, i, i, 1, N_r\right)^T, z\right) \\ \sigma_{stator.}(i,z) = \text{interp}\left(\text{lspline}\left(\text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\sigma_{stator}, i, i, 1, N_r\right)^T\right), \text{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \text{submatrix}\left(\sigma_{stator}, i, i, 1, N_r\right)^T, z\right) \end{array}\right. \\ \begin{pmatrix}\sigma_{rotor.}\\ \sigma_{stator.}\end{pmatrix} \end{array}\right.$$

$\sigma_{rotor}{}^T =$

	1	2	3	4	5	6	7	8	9
1	222.22								
2	137.93								
3	0.00								

$\cdot 10^6$

$\sigma_{stator}{}^T =$

	1	2	3	4	5	6	7	8	9
1	1.19								
2	125.80								
3	193.44								

$\cdot 10^6$

$$\begin{pmatrix} safety_{rotor} \\ safety_{stator} \end{pmatrix} = \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad \text{for } r \in 1..N_r \\ \quad\quad \left| \begin{array}{l} safety_{rotor_{i,r}} = \left| \begin{array}{ll} \dfrac{\sigma\_blade\_long_i}{\sigma_{rotor_{i,r}}} & \text{if } \sigma_{rotor_{i,r}} \neq 0 \\ \infty & \text{otherwise} \end{array} \right. \\ safety_{stator_{i,r}} = \left| \begin{array}{ll} \dfrac{\sigma\_blade\_long_i}{\sigma_{stator_{i,r}}} & \text{if } \sigma_{stator_{i,r}} \neq 0 \\ \infty & \text{otherwise} \end{array} \right. \end{array} \right. \\ \begin{pmatrix} safety_{rotor} \\ safety_{stator} \end{pmatrix} \end{array} \right.$$

$safety_{rotor}{}^{T} =$

	1	2	3	4	5	6	
1	1.03						
2	1.67						
3	000000000000000000000000000000000						

$safety_{rotor}{}^{T} \geq safety =$

	1
1	0
2	1
3	1

$safety_{stator}{}^{T} =$

	1	2	3	4	5
1	192.88				
2	1.83				
3	1.19				

$safety_{stator}{}^{T} \geq safety =$

	1
1	1
2	1
3	0

Рассматриваемая ступень: $j := \left| \begin{array}{l} j \leftarrow \left| \begin{array}{l} 1 \ \text{if } type = \text{"compressor"} \\ Z \ \text{if } type = \text{"turbine"} \end{array} \right. \\ j \leftarrow \left| \begin{array}{l} \text{"Такой ступени не существует!"} \ \text{if } (j < 1) \vee (j > Z) \\ j \ \text{otherwise} \end{array} \right. \end{array} \right. = 1$

$$b_{lim} := \frac{\text{ceil}\left(\max\left(chord_{rotor_{j,N_r}}, chord_{stator_{j,N_r}}\right) \cdot 10^2\right)}{10^2} = 190 \cdot 10^{-3}$$

Расстояния от оси ЛМ до рассматриваемой ступени (м): $Rj := \text{submatrix}(R, 2 \cdot j - 1, 2 \cdot j + 1, 1, N_r) =$

	1	2	3
1	302.9	583.4	767.5
2	338.1	593.0	767.5
3	370.4	602.6	767.5

$\cdot 10^{-3}$

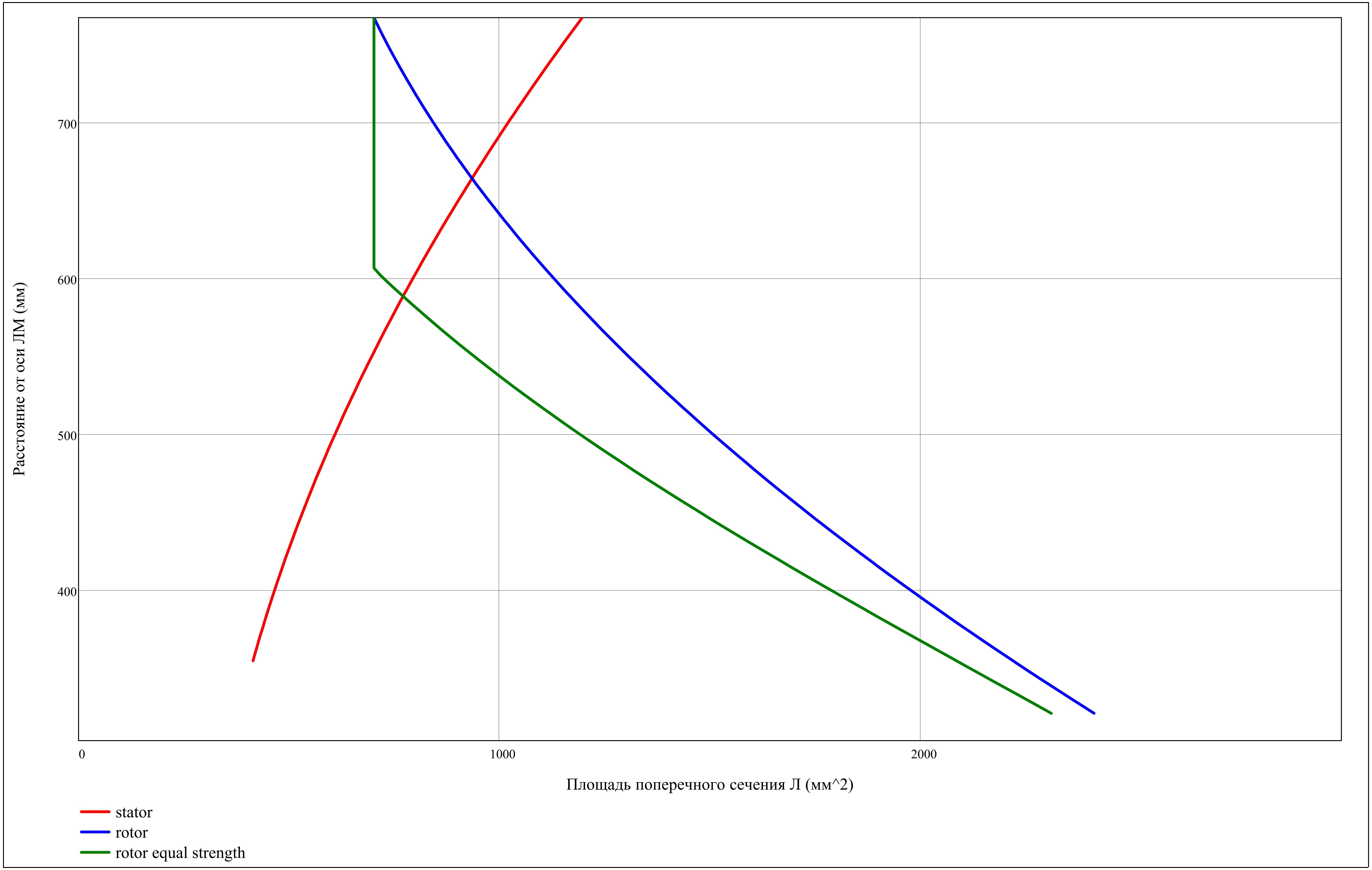
Дискретизация по высоте Л:

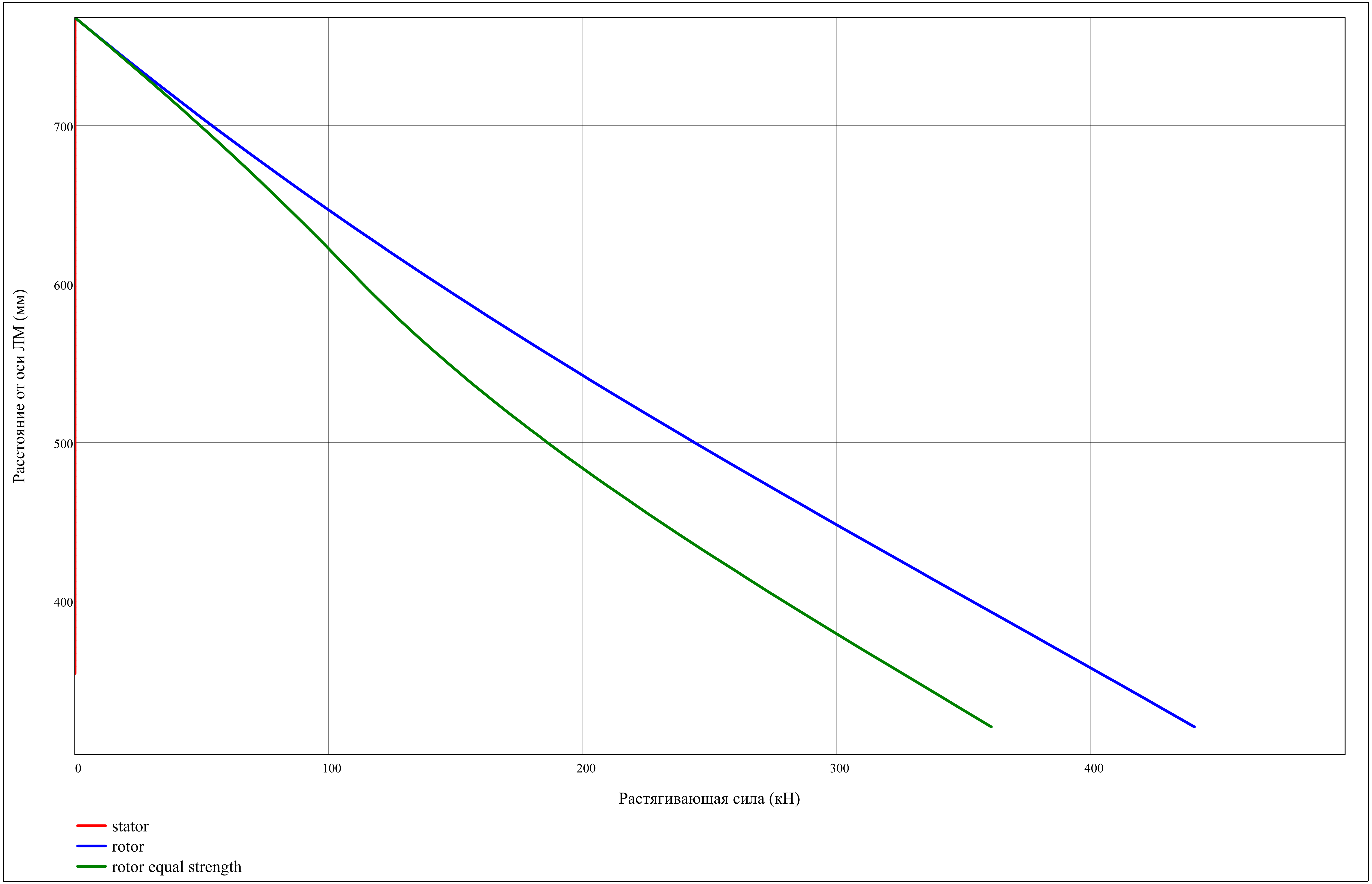
$$z := \min(Rj), \min(Rj) + \frac{\max(Rj) - \min(Rj)}{100} .. \max(Rj)$$

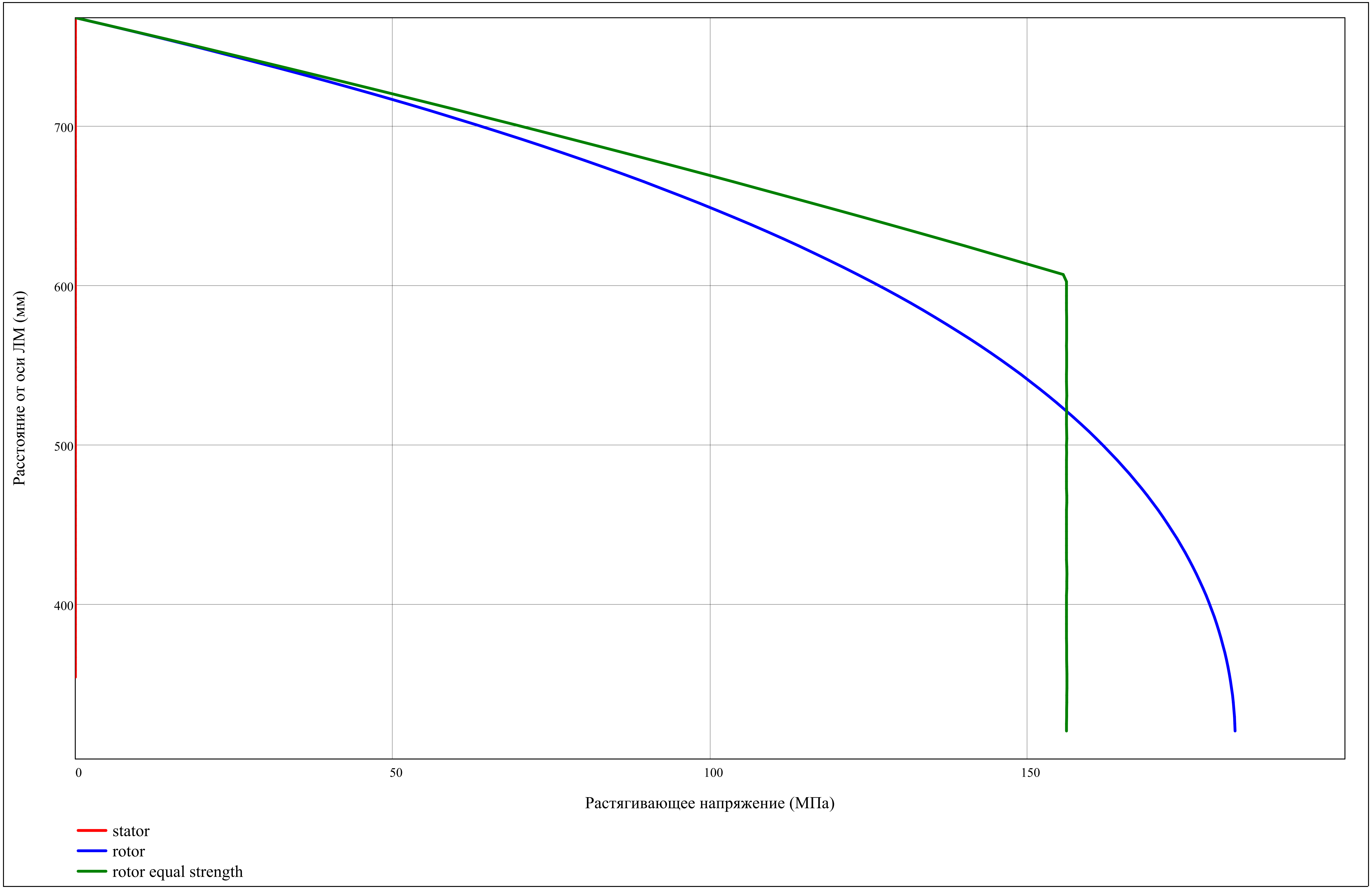
$$z_{rotor} := \left| \begin{array}{l} \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right), \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right) + \frac{\text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) - \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right)}{100} .. \text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) \ \text{if } type = \text{"compressor"} \\ \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right), \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right) + \frac{\text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) - \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right)}{100} .. \text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) \ \text{if } type = \text{"turbine"} \end{array} \right.$$

$$z_{stator} := \left| \begin{array}{l} \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right), \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right) + \frac{\text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) - \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right)}{100} .. \text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) \ \text{if } type = \text{"compressor"} \\ \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right), \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right) + \frac{\text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) - \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right)}{100} .. \text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) \ \text{if } type = \text{"turbine"} \end{array} \right.$$

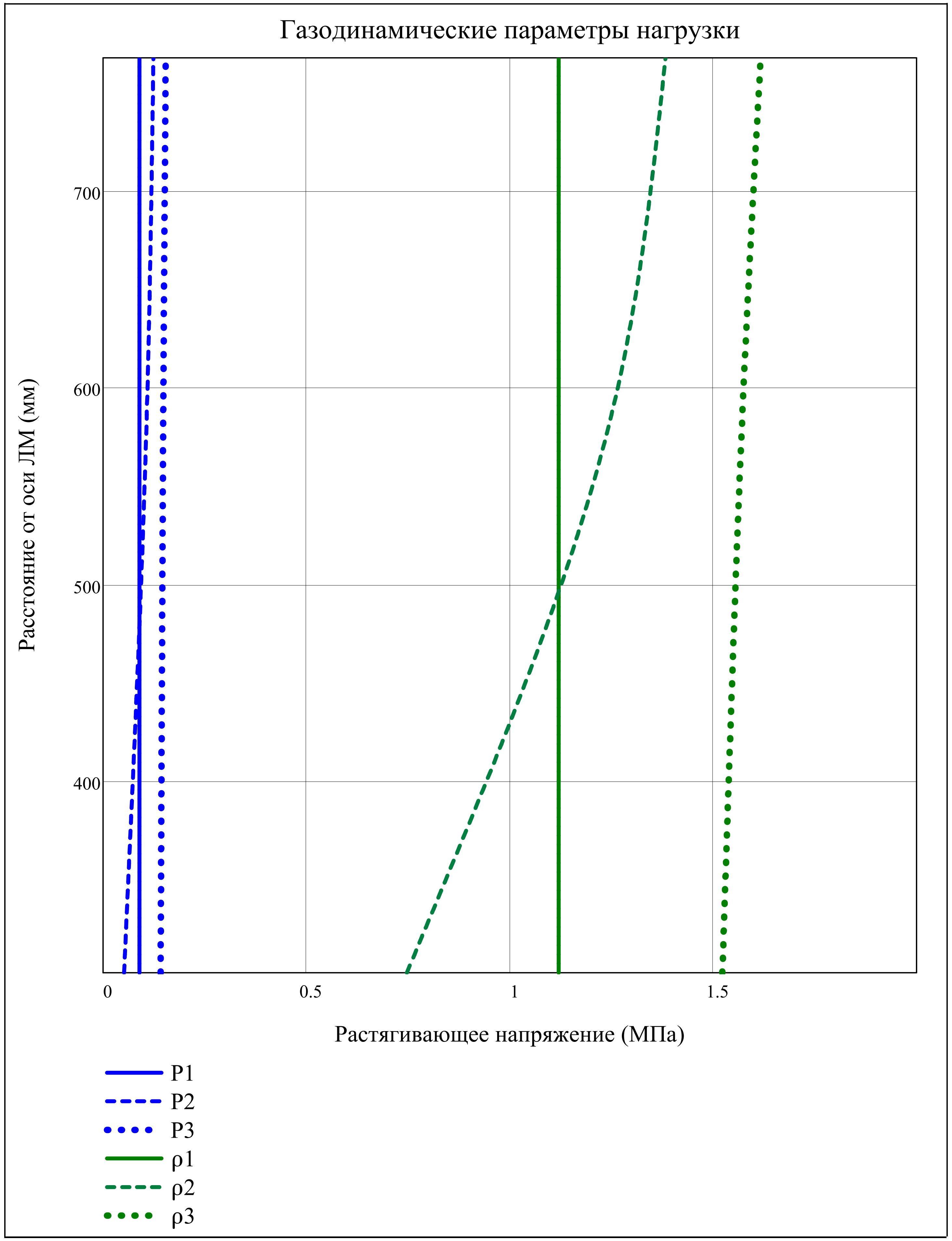
Результаты расчета на прочность Л


Расстояние от оси ЛМ (мм)
700
600
500
400
0
1000
2000
Площадь поперечного сечения Л (мм^2)
stator
rotor
rotor equal strength

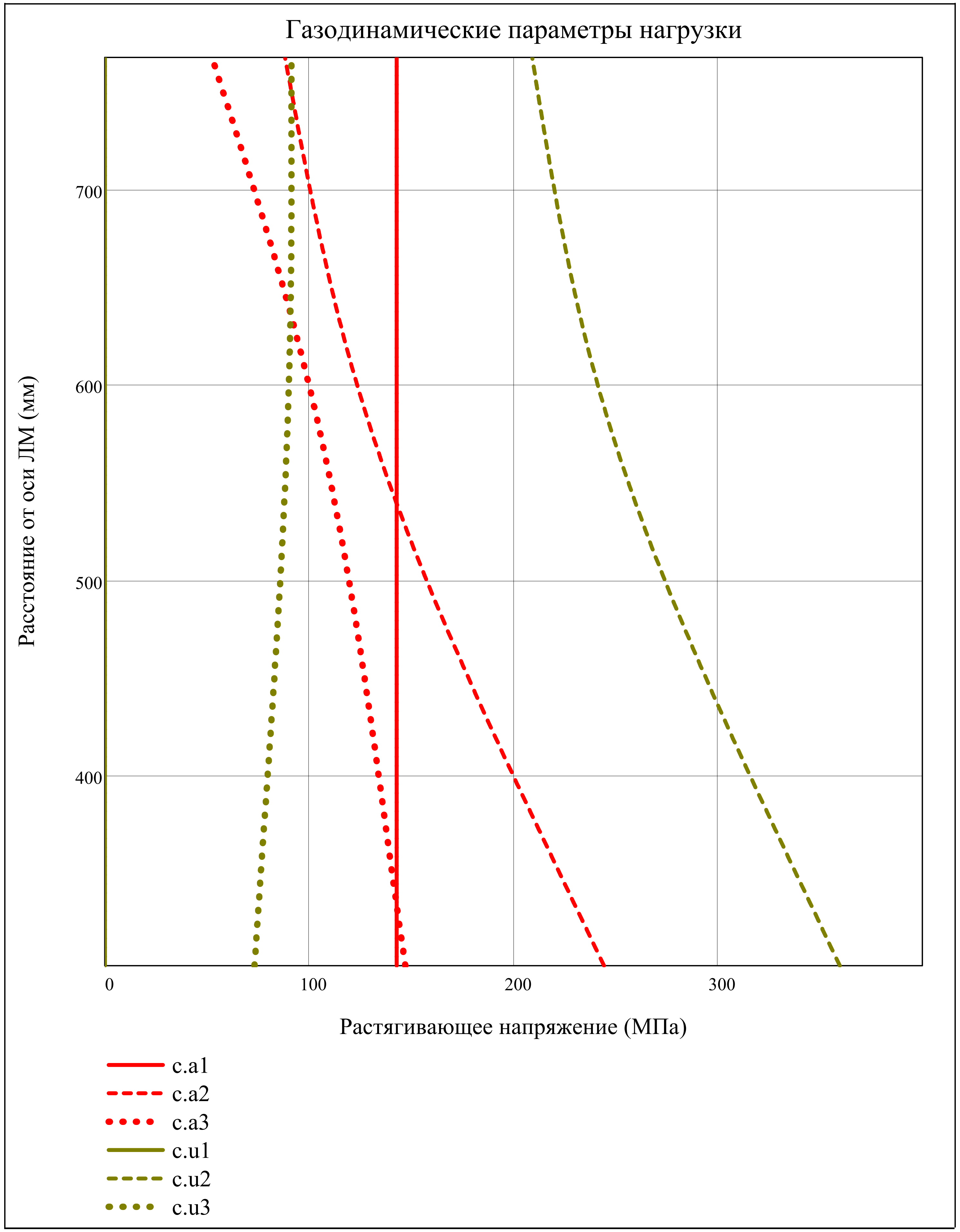

Расстояние от оси ЛМ (мм)
700
600
500
400
0
100
200
300
400
Растягивающая сила (кН)
stator
rotor
rotor equal strength



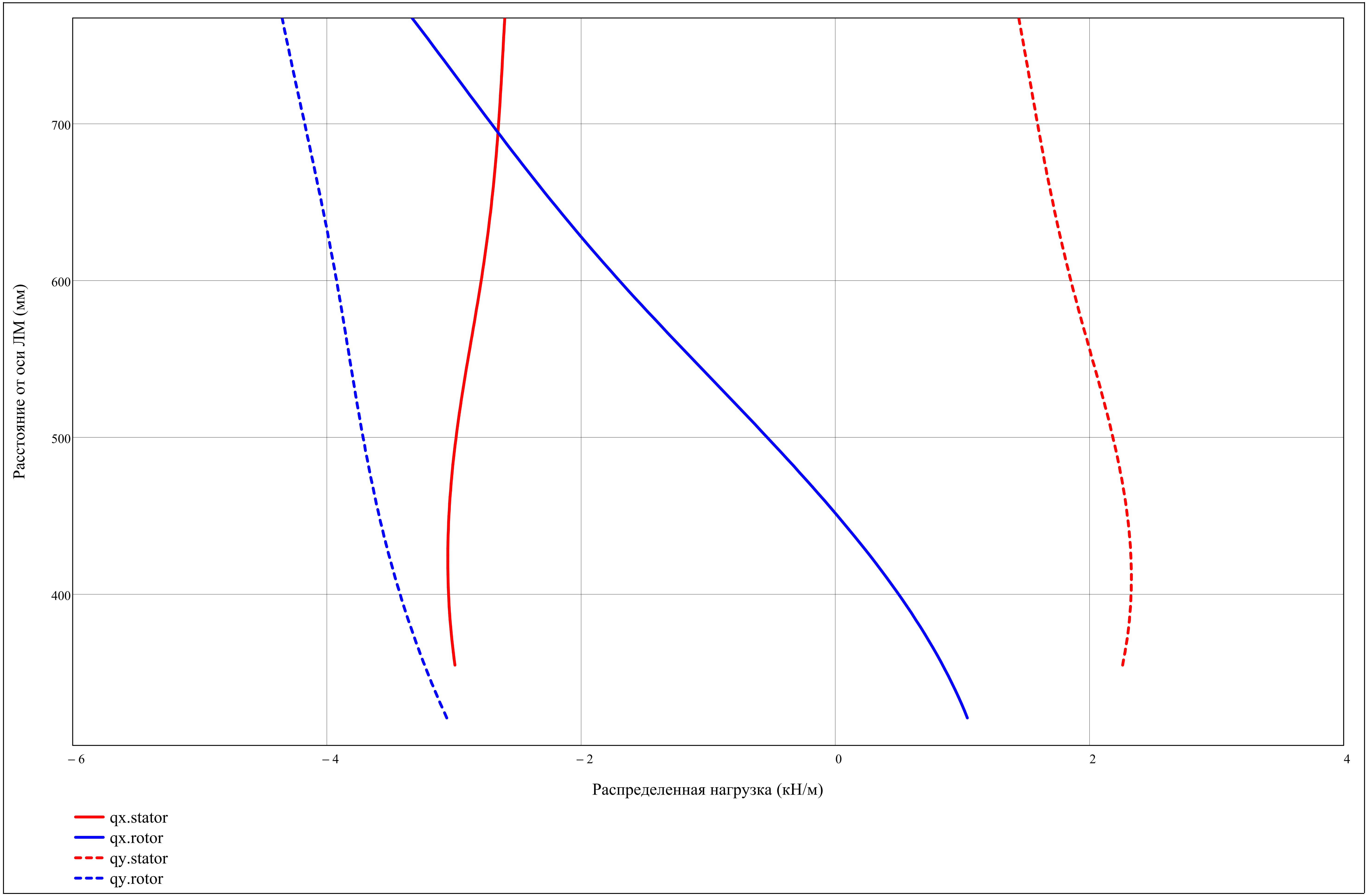
700
600
500
400
Расстояние от оси ЛМ (мм)
0
50
100
150
Растягивающее напряжение (МПа)
stator
rotor
rotor equal strength



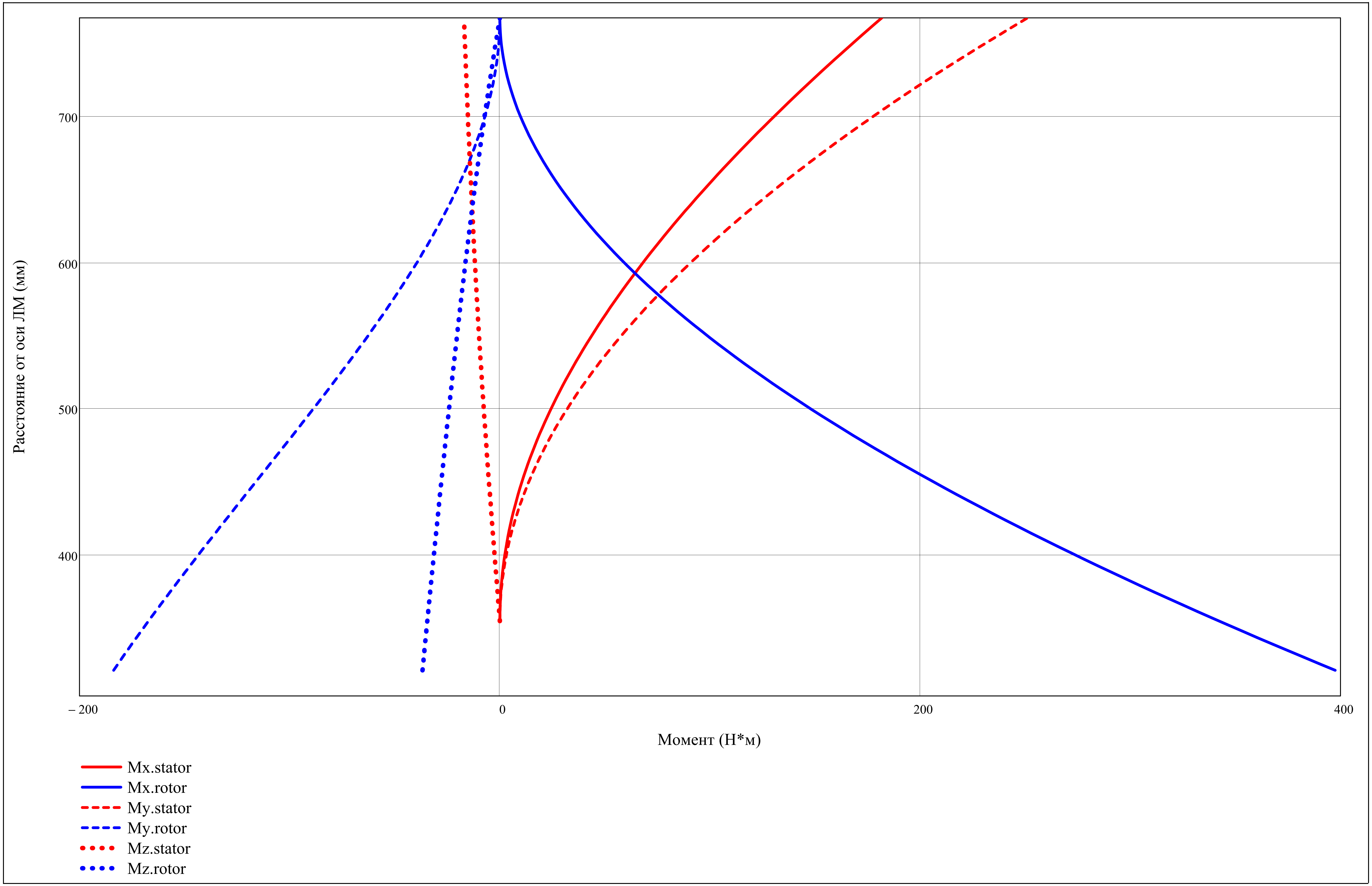
Газодинамические параметры нагрузки
Расстояние от оси ЛМ (мм)
700
600
500
400
0
0.5
1
1.5
Растягивающее напряжение (МПа)
P1
P2
P3
ρ1
ρ2
ρ3



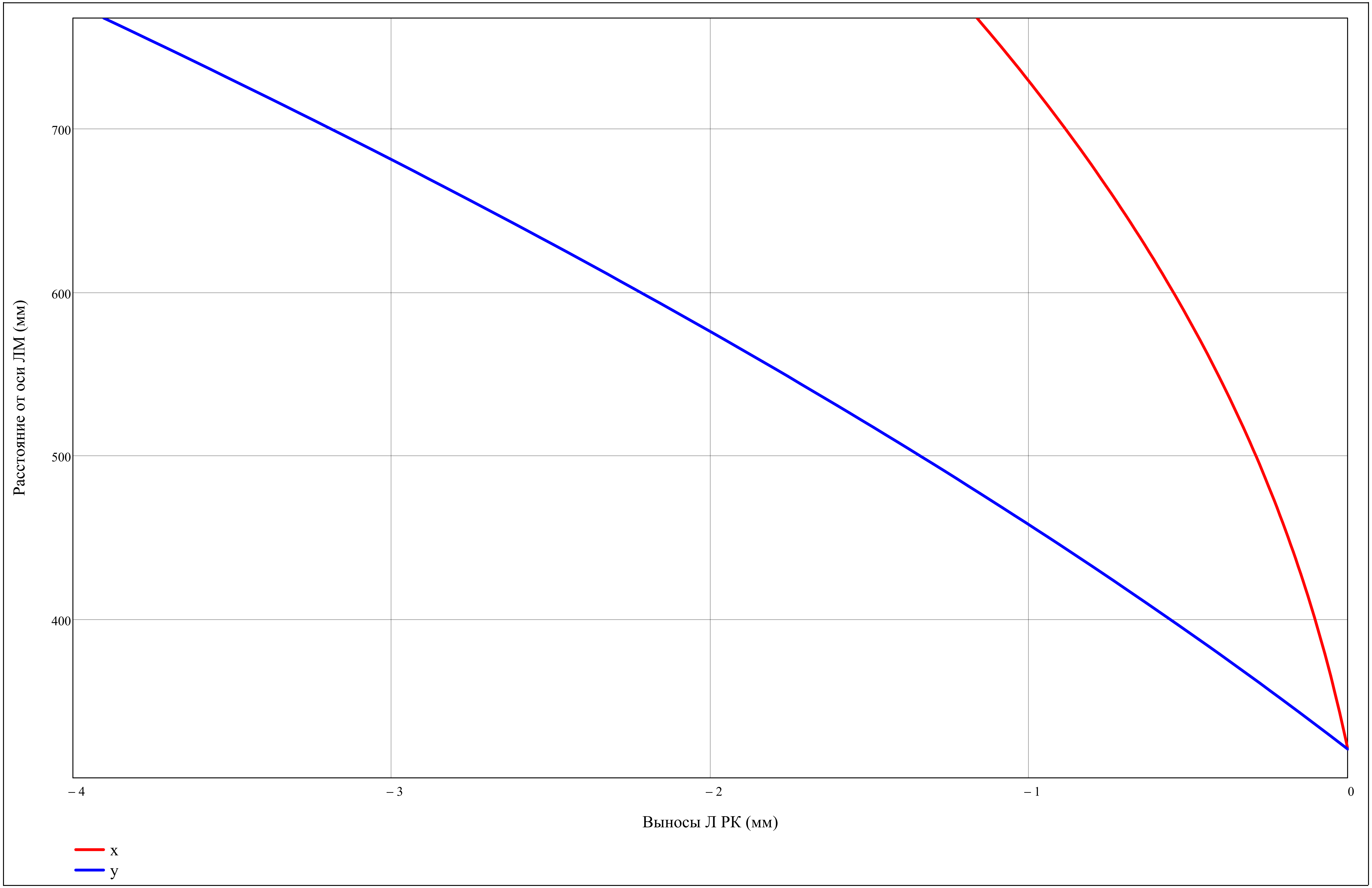
Газодинамические параметры нагрузки
Расстояние от оси ЛМ (мм)
700
600
500
400
0
100
200
300
Растягивающее напряжение (МПа)
c.a1
c.a2
c.a3
c.u1
c.u2
c.u3



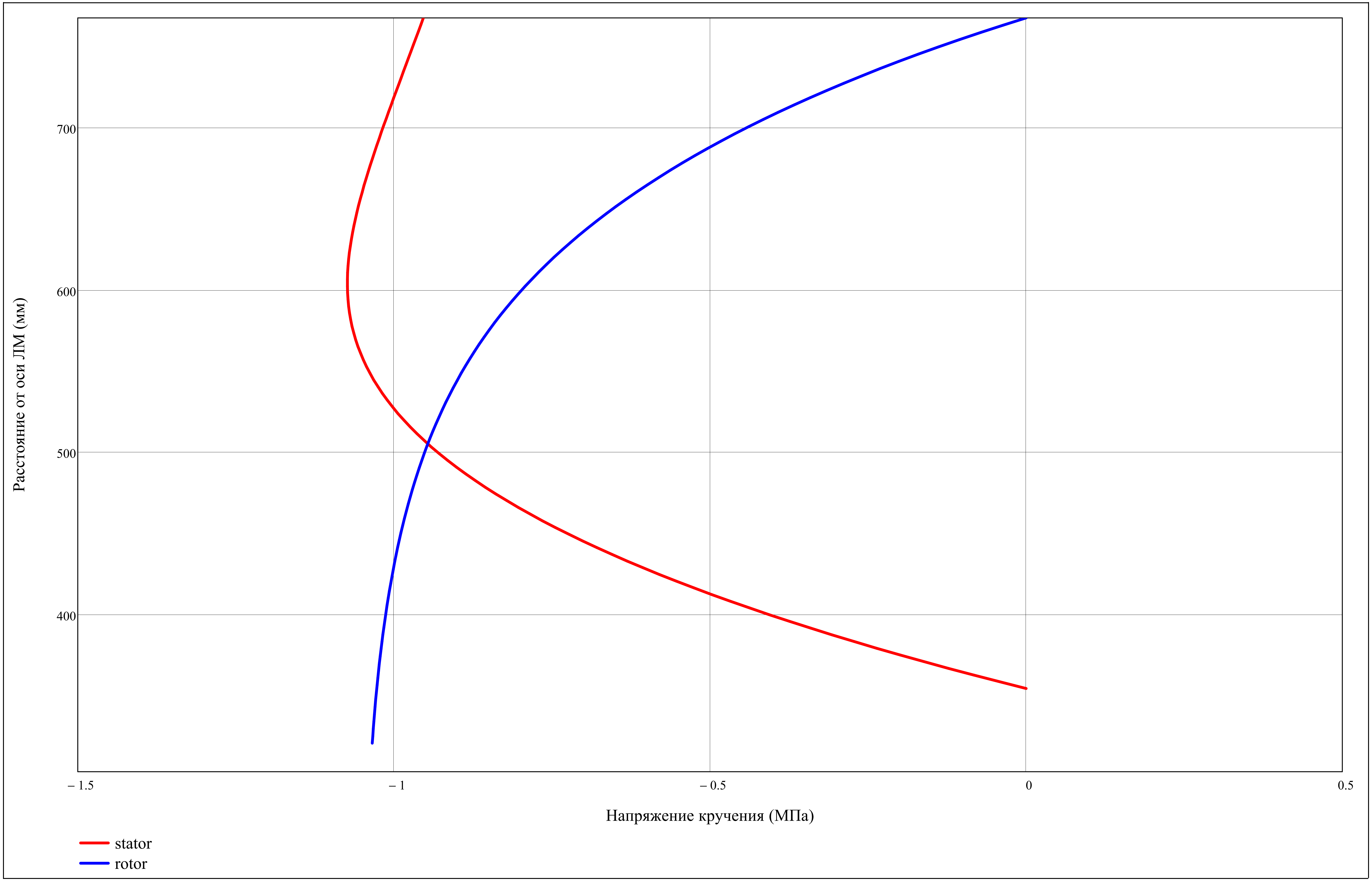
Расстояние от оси ЛМ (мм)
700
600
500
400
– 6
– 4
– 2
0
2
4
Распределенная нагрузка (кН/м)
qx.stator
qx.rotor
qy.stator
qy.rotor



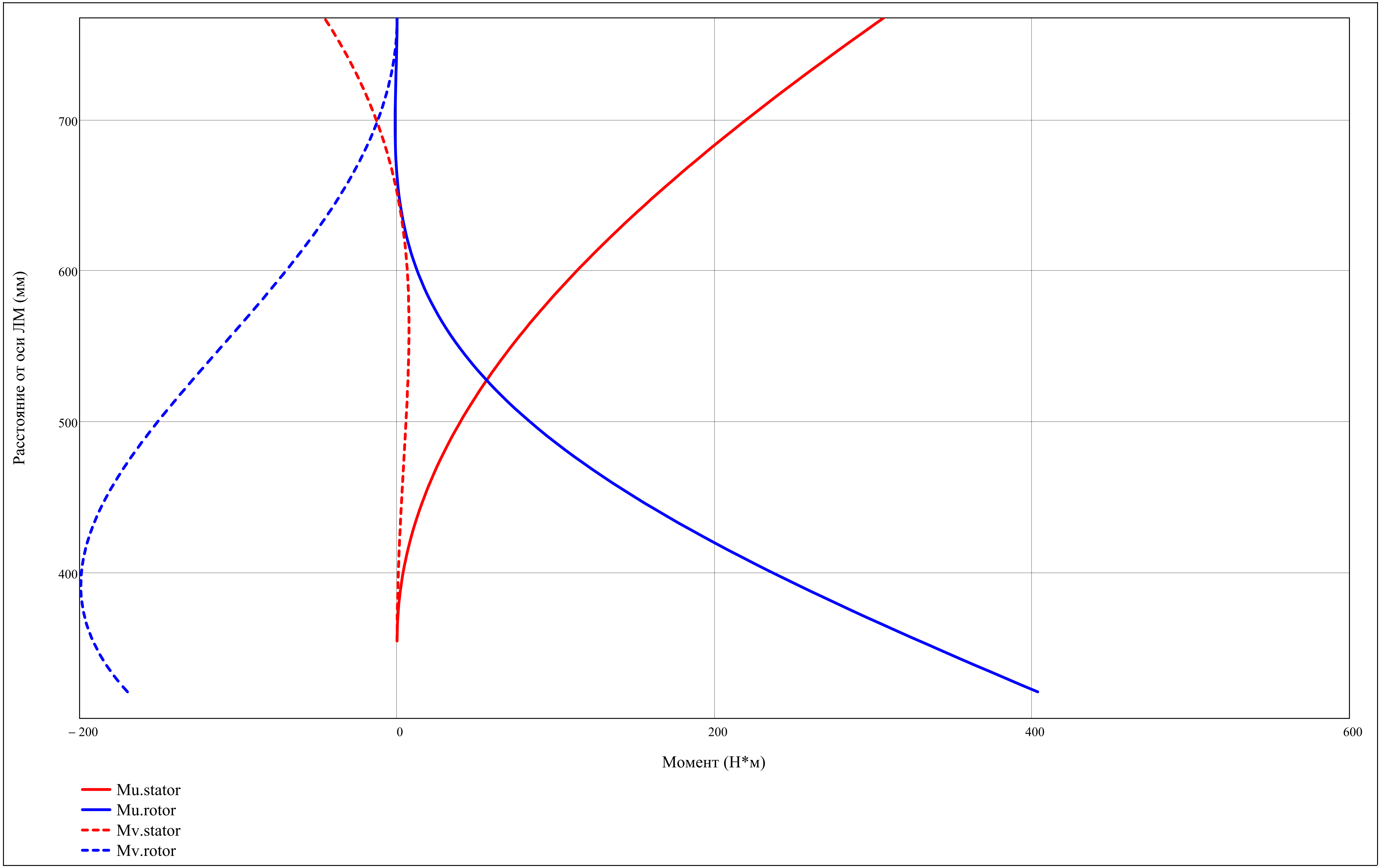
700
600
500
400
Расстояние от оси ЛМ (мм)
– 200
0
200
400
Момент (Н*м)
Mx.stator
Mx.rotor
My.stator
My.rotor
Mz.stator
Mz.rotor

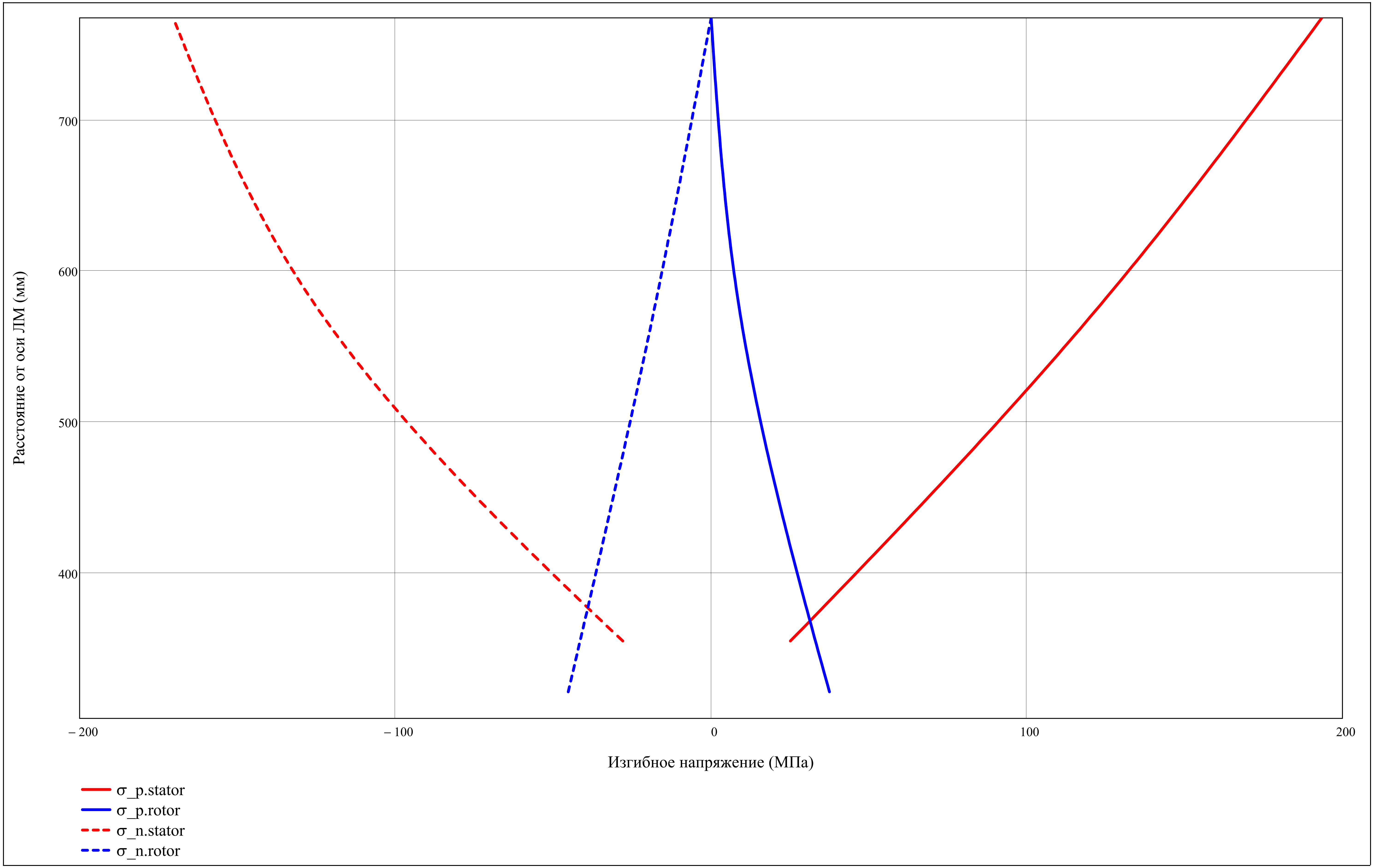


Расстояние от оси ЛМ (мм)
700
600
500
400
– 4
– 3
– 2
– 1
0
Выносы Л РК (мм)
x
y

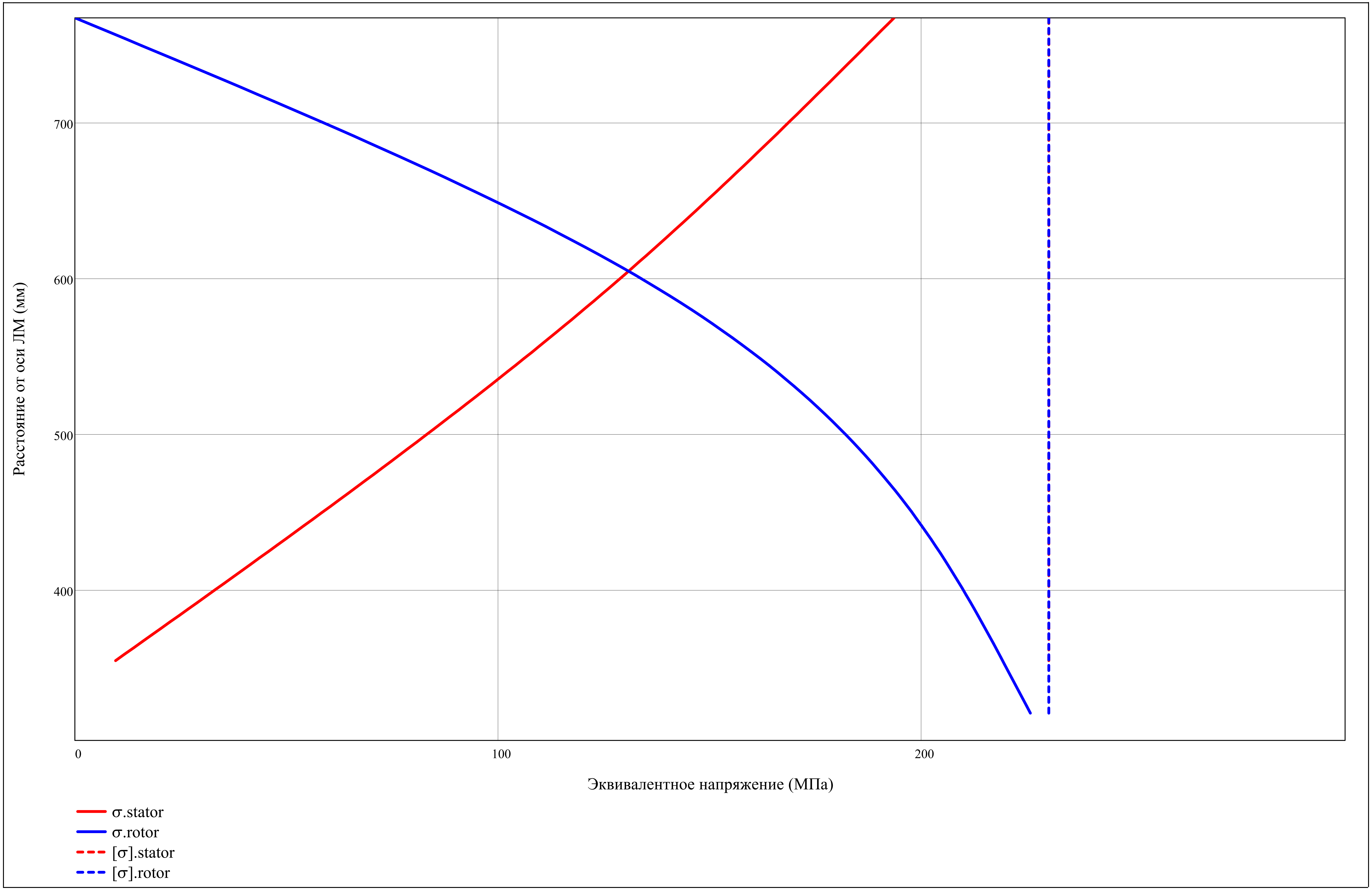


700
600
500
400
– 1.5
– 1
– 0.5
0
0.5
Расстояние от оси ЛМ (мм)
Напряжение кручения (МПа)
stator
rotor


700
600
500
400
Расстояние от оси ЛМ (мм)
– 200
0
200
400
600
Момент (Н*м)
Mu.stator
Mu.rotor
Mv.stator
Mv.rotor



700
600
500
400
Расстояние от оси ЛМ (мм)
– 200
– 100
0
100
200
Изгибное напряжение (МПа)
σ_p.stator
σ_p.rotor
σ_n.stator
σ_n.rotor



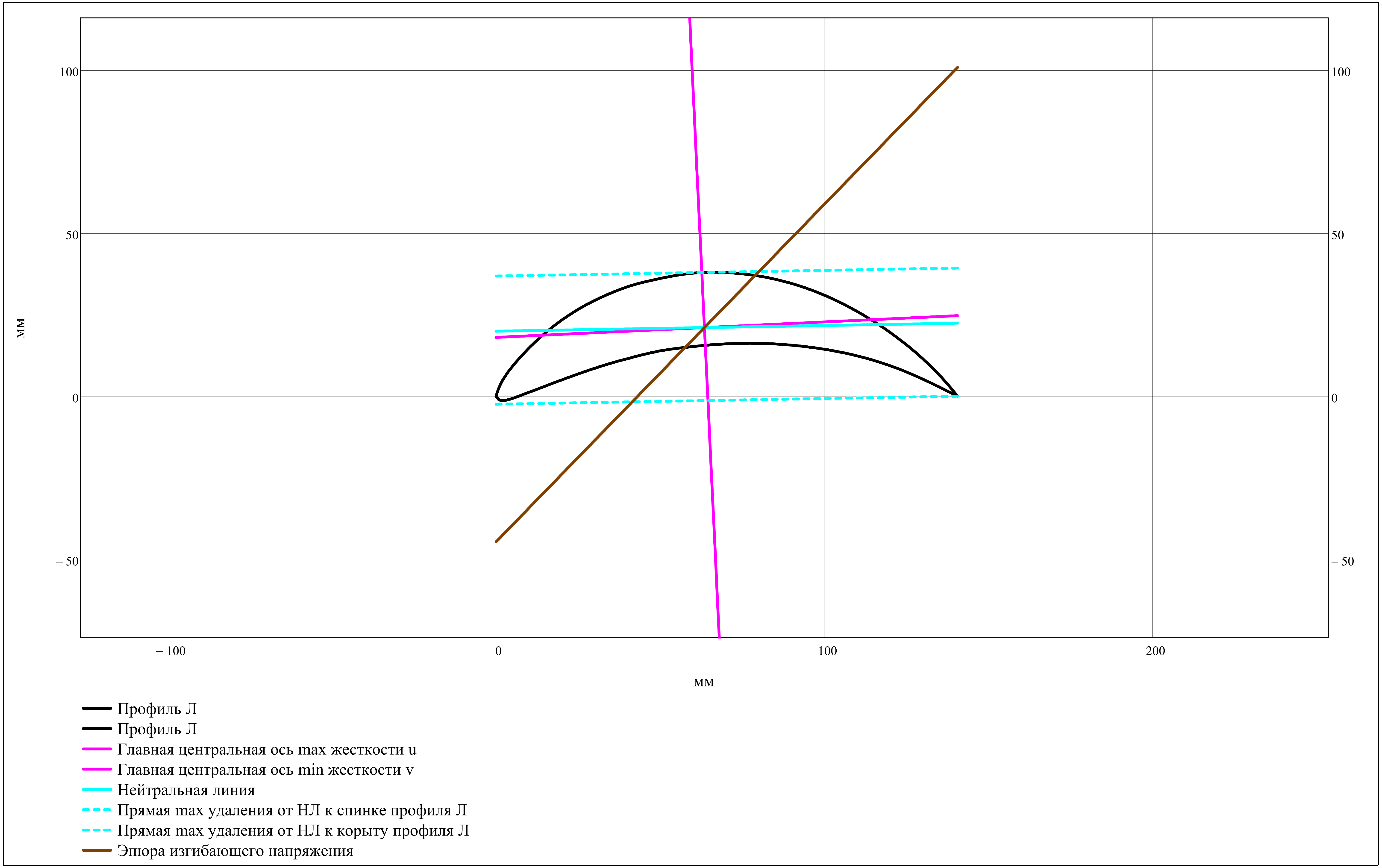
Расстояние от оси ЛМ (мм)
700
600
500
400
0
100
200
Эквивалентное напряжение (МПа)
σ.stator
σ.rotor
[σ].stator
[σ].rotor

$$\begin{pmatrix} blade \\ r \end{pmatrix} = \begin{pmatrix} \text{"rotor"} \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} v\_p \\ v\_n \end{pmatrix} = \left| \begin{array}{l} \begin{pmatrix} v\_u_{rotor_{j,r}} \\ v\_l_{rotor_{j,r}} \end{pmatrix} \text{ if } blade = \text{"rotor"} \\ \begin{pmatrix} v\_u_{stator_{j,r}} \\ v\_l_{stator_{j,r}} \end{pmatrix} \text{ otherwise} \end{array} \right. = \begin{array}{c|c} & 1 \\ \hline 1 & 16.913 \\ 2 & -22.396 \end{array} \cdot 10^{-3}$$

$$\begin{pmatrix} x0 \\ y0 \end{pmatrix} = \left| \begin{array}{l} \begin{pmatrix} x0_{rotor_{j,r}} \\ y0_{rotor_{j,r}} \end{pmatrix} \text{ if } blade = \text{"rotor"} \\ \begin{pmatrix} x0_{stator_{j,r}} \\ y0_{stator_{j,r}} \end{pmatrix} \text{ otherwise} \end{array} \right. = \begin{array}{c|c} & 1 \\ \hline 1 & 63.459 \\ 2 & 21.051 \end{array} \cdot 10^{-3}$$

$$chord = \left| \begin{array}{l} chord_{rotor_{j,r}} \text{ if } blade = \text{"rotor"} \\ chord_{stator_{j,r}} \text{ if } blade = \text{"stator"} \end{array} \right. = 141 \cdot 10^{-3}$$



100
50
0
– 50
100
50
0
– 50
мм
– 100
0
100
200
мм
Профиль Л
Профиль Л
Главная центральная ось max жесткости u
Главная центральная ось min жесткости v
Нейтральная линия
Прямая max удаления от НЛ к спинке профиля Л
Прямая max удаления от НЛ к корыту профиля Л
Эпюра изгибающего напряжения

Наиболее удаленные точки от НЛ (мм):

$$\begin{pmatrix} u\_u_{rotor_{j,r}} & v\_u_{rotor_{j,r}} \\ u\_l_{rotor_{j,r}} & v\_l_{rotor_{j,r}} \\ u\_u_{stator_{j,r}} & v\_u_{stator_{j,r}} \\ u\_l_{stator_{j,r}} & v\_l_{stator_{j,r}} \end{pmatrix} =$$

	1	2
1	1.47	16.91
2	76.67	-22.40
3	0.00	3.91
4	59.57	-5.82

$\cdot 10^{-3}$

$$\begin{pmatrix} \sigma\_p_{rotor_{j,r}} & \sigma\_p_{stator_{j,r}} \\ \sigma\_n_{rotor_{j,r}} & \sigma\_n_{stator_{j,r}} \end{pmatrix} = \begin{pmatrix} 39.83 & 1.18 \\ -47.22 & -1.78 \end{pmatrix} \cdot 10^{6}$$

$$\begin{pmatrix} \sigma_{stator_{j,r}} \\ \sigma_{rotor_{j,r}} \end{pmatrix} = \begin{pmatrix} 1.19 \\ 222.22 \end{pmatrix} \cdot 10^{6}$$

$$\begin{pmatrix} safety_{stator_{j,r}} \\ safety_{rotor_{j,r}} \end{pmatrix} =$$

	1
1	192.884
2	1.035

Результаты расчета на прочность Л

Вывод результатов расчета Л на прочность

Выбор материала Д

Запас по температуре (К): $\Delta T_{safety} = 0$

Выбранный материал Д:

$$material\_disk_i = \begin{cases} "ВТ23" & \text{if } compressor = "Вл" \\ "ВТ6" & \text{if } compressor = "КНД" \\ "ВТ9" & \text{if } compressor = "КВД" \end{cases}$$

Плотность материала Д (кг/м^3):

$$\rho\_disk_i = \begin{cases} 8266 & \text{if } material\_disk_i = "ВЖ175" \\ 8320 & \text{if } material\_disk_i = "ЭП742" \\ 8393 & \text{if } material\_disk_i = "ЖС-6К" \\ 7900 & \text{if } material\_disk_i = "ВТ41" \\ 4500 & \text{if } material\_disk_i = "ВТ25" \\ 4570 & \text{if } material\_disk_i = "ВТ23" \\ 4510 & \text{if } material\_disk_i = "ВТ9" \\ 4430 & \text{if } material\_disk_i = "ВТ6" \\ NaN & \text{otherwise} \end{cases}$$

Предел длительной прочности Д (Па):

$$\sigma\_disk\_long_i = 10^6 \cdot \begin{cases} 620 & \text{if } material\_disk_i = "ВЖ175" \\ 680 & \text{if } material\_disk_i = "ЭП742" \\ 125 & \text{if } material\_disk_i = "ЖС-6К" \\ 123 & \text{if } material\_disk_i = "ВТ41" \\ 150 & \text{if } material\_disk_i = "ВТ25" \\ 230 & \text{if } material\_disk_i = "ВТ23" \\ 200 & \text{if } material\_disk_i = "ВТ9" \\ 210 & \text{if } material\_disk_i = "ВТ6" \\ NaN & \text{otherwise} \end{cases}$$

$material\_disk^T =$

	1	2	3	4	5	6	7	8	9
1	"ВТ23"								

$\rho\_disk^T =$

	1
1	4570

$\sigma\_disk\_long^T =$

	1
1	230

$\cdot 10^6$

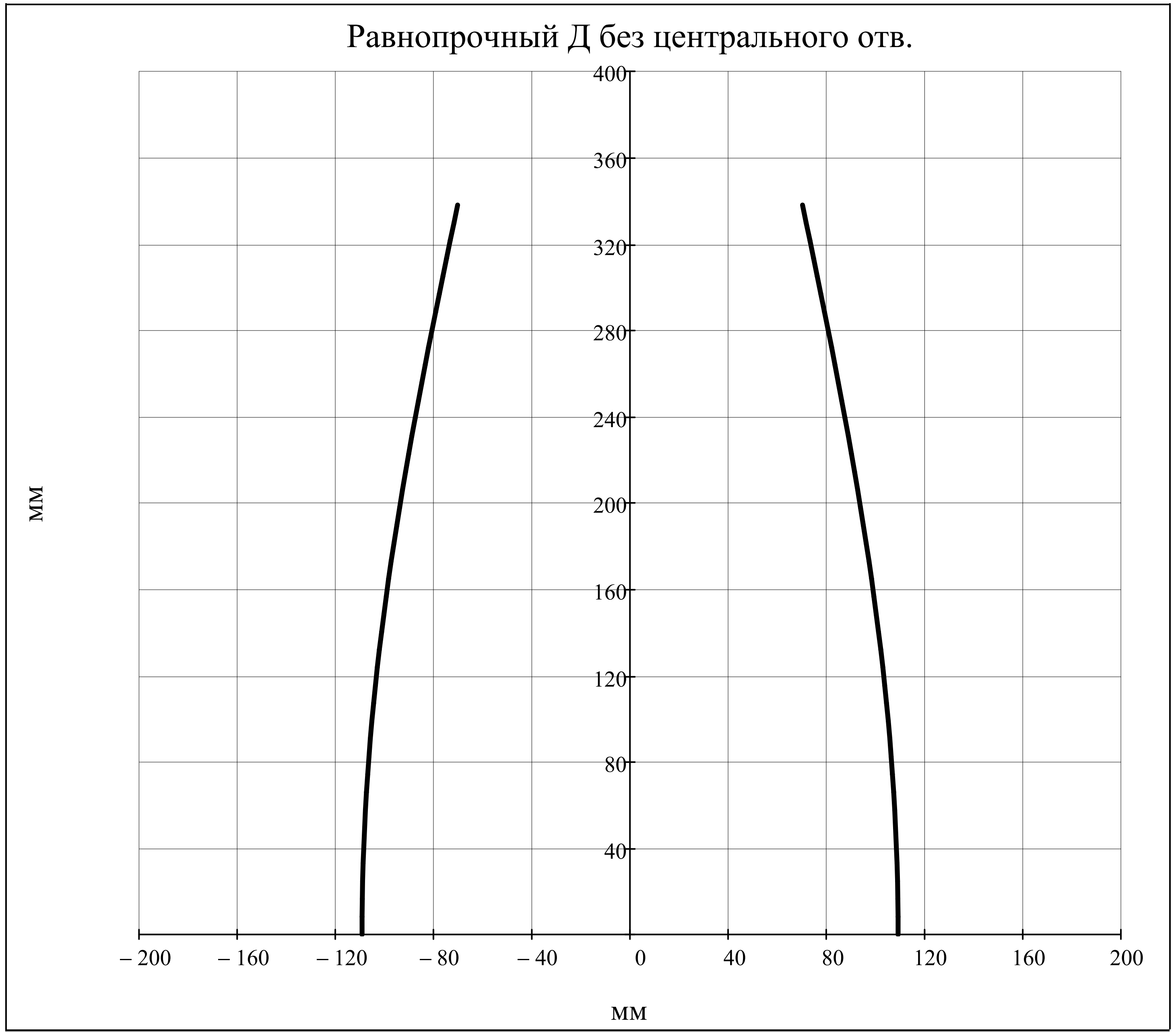
Выбор материала Д

Рассматриваемая ступень: $j := \left| \begin{array}{l} j = 1 \\ j = \left| \begin{array}{ll} \text{"Такой ступени не существует!"} & \text{if } (j < 1) \vee (j > Z) \\ j & \text{otherwise} \end{array} \right. \end{array} \right. = 1$

Профилирование равнопрочного Д без центрального отв.

$$h(i,z) := \left| \begin{array}{ll} \left(chord_{rotor_{i,ORIGIN}} \cdot \sin\left(\upsilon_{rotor_{i,ORIGIN}}\right)\right) \cdot e^{\frac{\rho\_disk_i \cdot \omega^2}{2} \cdot \frac{1}{\sigma\_z_{rotor}\left(i, R_{st(i,2),ORIGIN}\right)} \cdot \left[\left(R_{st(i,2),ORIGIN}\right)^2 - z^2\right]} & \text{if } z \le R_{st(i,2),ORIGIN} \\ NaN & \text{otherwise} \end{array} \right.$$

$$z := 0, \frac{R_{st(j,2),ORIGIN}}{N_{dis}} .. R_{st(j,2),ORIGIN}$$



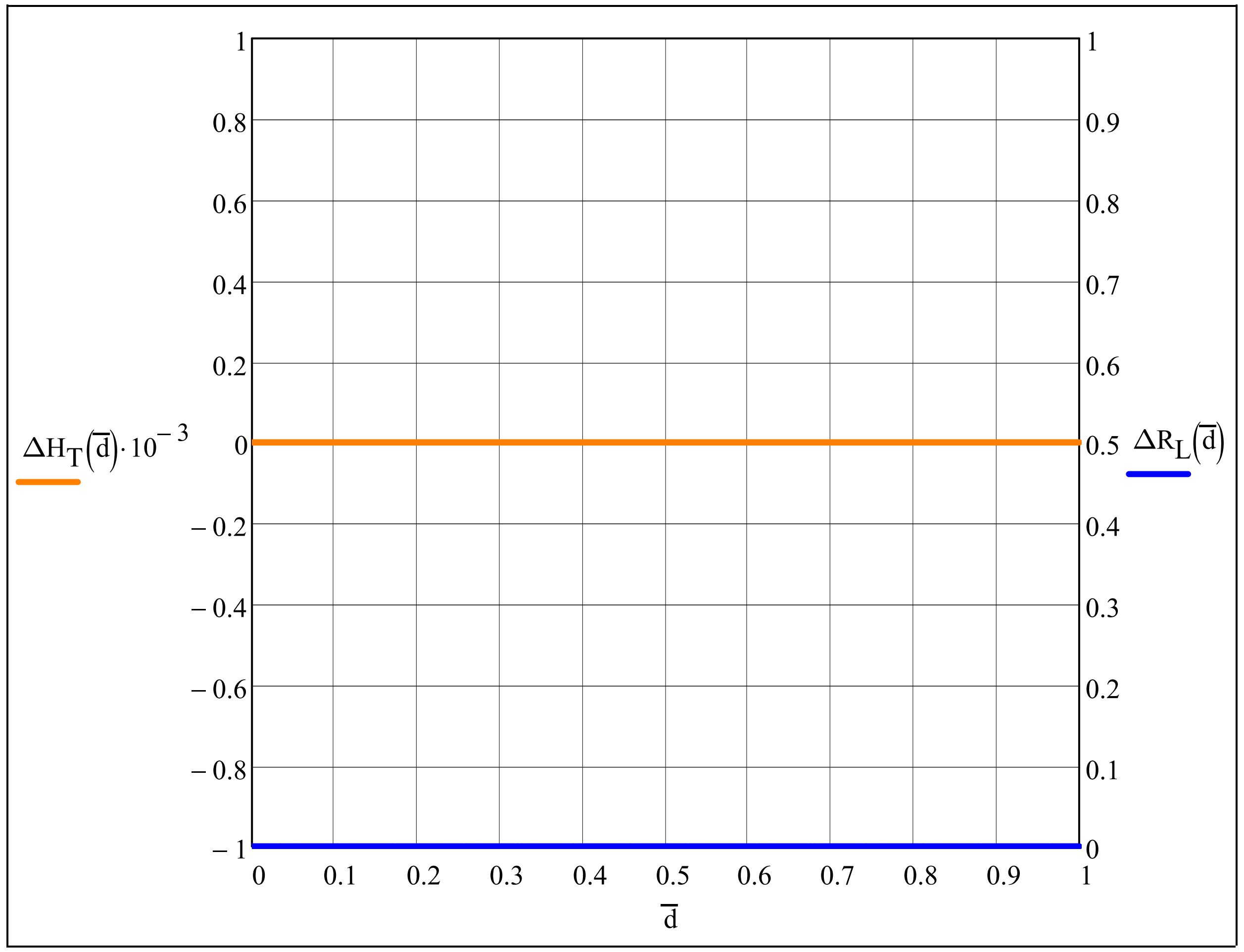
Профилирование равнопрочного Д без центрального отв.

Max разница теор. напора ступени и реактивности от периферии к корню по высоте Л (Дж/кг) [16, с.118-119]:

$\Delta H_{Tmax} = 0\cdot 10^3$

$\Delta R_{Lmax} = 0.0$

$$\Delta H_T(\overline{d}) = -\Delta H_{Tmax}\cdot\overline{d} + \Delta H_{Tmax} \qquad \Delta R_L(\overline{d}) = -\Delta R_{Lmax}\cdot\overline{d} + \Delta R_{Lmax}$$



21

$\cdot 10^{-6}$

21

$$\frac{{}_{st(i,a),av(N_r)}\Big) - \left(R_{st(i,a),r}\right)^{m_i}\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\Big] + A_{st(i,a),r}\cdot m_i\cdot\Big[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,a),av(N_r)}\right) - \left(R_{st(i,a),r}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\Big]\Big]}{\cdot R_{st(i,a),av(N_r)}\Big)^{2\cdot m_i+1}} \quad \text{if } (a = 2)$$

$$\frac{{}_{st(i,a),av(N_r)}\Big) - \left(R_{st(i,a),r}\right)^{m_i}\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\Big] + A_{st(i,a),r}\cdot m_i\cdot\Big[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,a),av(N_r)}\right) - \left(R_{st(i,a),r}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\Big]\Big]}{\cdot R_{st(i,a),av(N_r)}\Big)^{2\cdot m_i+1}} \quad \text{if } (a = 3)$$

$$\left.\left.{}_{,1}\right)\right]$$

$$\frac{\ldots_{st(i,a),av(N_r)}}{\ldots_{(i,a),av(N_r)}} - 2\cdot\left[2\cdot A_{st(i,a),r}\cdot\left(B_{st(i,a),r} + \frac{b_{HT}}{\omega}\right) + \frac{{k_{HT}}^2}{\omega^2}\right]\cdot\ln\left(\frac{R_{st(i,a),r}}{R_{st(i,a),av(N_r)}}\right) \quad \text{if } (a = 2)$$

25

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 142.7 \\ 412.4 \\ 158.2 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 142.7 \\ 228 \\ 137.9 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 220.5 \\ 276.3 \\ 188.1 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 90 \\ 33.57 \\ 60.62 \end{pmatrix} \cdot {}^\circ$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 168.1 \\ 187.6 \\ 205.6 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 40.32 \\ 124.36 \\ 47.13 \end{pmatrix} \cdot {}^\circ$$

$$\varepsilon_{stator_{j,r}} = 27.05 \cdot {}^\circ$$

$$\varepsilon_{rotor_{j,r}} = 84.04 \cdot {}^\circ$$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 142.7 \\ 273.4 \\ 134 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 142.7 \\ 125.4 \\ 99.2 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 353.8 \\ 152.1 \\ 263.8 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 90 \\ 27.29 \\ 47.77 \end{pmatrix} \cdot {}^\circ$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 323.8 \\ 329.1 \\ 334.4 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 23.78 \\ 55.51 \\ 22.09 \end{pmatrix} \cdot {}^\circ$$

$$\varepsilon_{stator_{j,r}} = 20.48 \cdot {}^\circ$$

$$\varepsilon_{rotor_{j,r}} = 31.73 \cdot {}^\circ$$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 142.7 \\ 226.8 \\ 105.2 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 142.7 \\ 88.1 \\ 52.4 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 449.2 \\ 234.1 \\ 338.8 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 90 \\ 22.87 \\ 29.86 \end{pmatrix} \cdot ^\circ$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 425.9 \\ 425.9 \\ 425.9 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 18.52 \\ 22.11 \\ 8.89 \end{pmatrix} \cdot ^\circ$$

$$\varepsilon_{stator_{j,r}} = 6.99 \cdot ^\circ$$

$$\varepsilon_{rotor_{j,r}} = 3.59 \cdot ^\circ$$

MM

MM

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$,z\big)$

$\big)^{T},z\big)$

$)^{-3}$

7	8	9