Подключение библиотек

Основные уравнения, алгоритмы, зависимости и ф-и

▶ Параметры расчета

▼ Исходные данные

Коэф. запаса: $safety = 1.3$

Степень двухконтурности: $m2 = 6$

РТ: Воздух $\qquad$ $compressor = \text{"КНД"}$

Число Маха: $M = 0$

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

Массовый расход (кг/с): $G = \begin{cases} 35.65 + 213.93 & \text{if } compressor = \text{"Вл"} \\ 35.65 & \text{if } compressor = \text{"КНД"} \\ 34.81 & \text{if } compressor = \text{"КВД"} \end{cases} = 35.65$

Полная температура на входе в К (К): $T^*_{К1} = \begin{cases} 418.2 & \text{if } compressor = \text{"КВД"} \\ 288.2 & \text{otherwise} \end{cases} = 288.2$

Полное давление на входе в К (Па): $P^*_{К1} = \begin{cases} 316.2 \cdot 10^3 & \text{if } compressor = \text{"КВД"} \\ 101325 & \text{otherwise} \end{cases} = 101.3 \cdot 10^3$

Степень повышения давления КВД: $\pi^*_{К} = \begin{cases} 1.6 & \text{if } compressor = \text{"Вл"} \\ \dfrac{3.2}{1.6} & \text{if } compressor = \text{"КНД"} \\ 9 & \text{if } compressor = \text{"КВД"} \end{cases} = 2.000$

Ожидаемый адиабатический КПД ОК: $\eta^*_K = \begin{cases} 0.86 & \text{if } compressor = \text{"Вл"} \\ 0.87 & \text{if } compressor = \text{"КНД"} \\ 0.88 & \text{if } compressor = \text{"КВД"} \end{cases} = 87.00 \cdot \%$

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

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

$0.3 \le \overline{d}_1 \le 0.6 = 0$

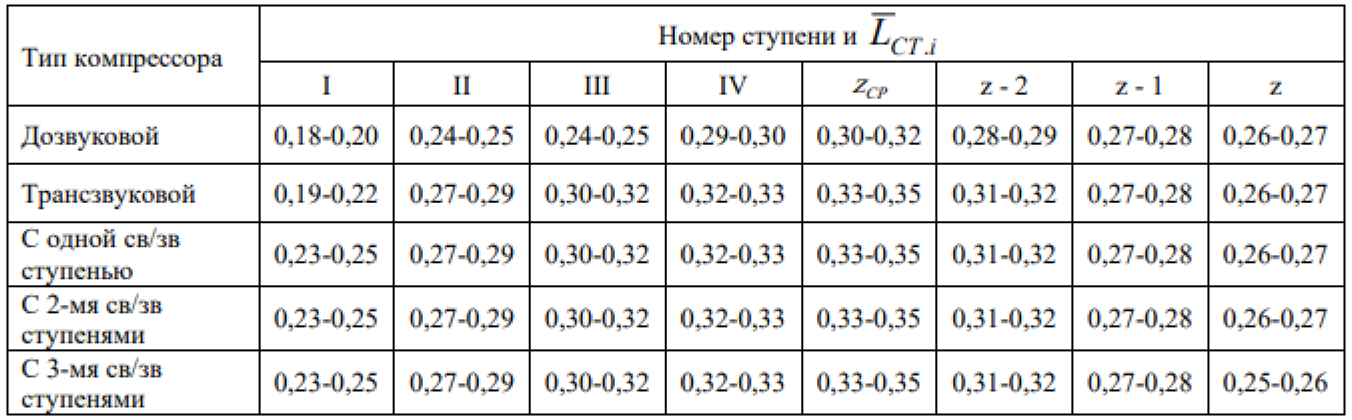
Частота вращения ротора (об/мин): $n = \dfrac{60 \cdot \omega}{2 \cdot \pi} = 5300$

Закон профилирования проточной части (ЗППЧ):

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

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:

$$R_{L\sim \text{ср}} = R_{L\sim \text{ср}} + \left|\begin{array}{l} 0.0 \ \text{ if } \ compressor = \text{"Вл"} \\ 0.1 \ \text{ if } \ compressor = \text{"КНД"} \\ 0.2 \ \text{ if } \ compressor = \text{"КВД"} \end{array}\right.$$

$$\overline{c}_{\sim a1} = \overline{c}_{\sim a1} - \left|\begin{array}{l} 0.10 \ \text{ if } \ compressor = \text{"Вл"} \\ 0.141 \ \text{ if } \ compressor = \text{"КНД"} \\ 0.213 \ \text{ if } \ compressor = \text{"КВД"} \end{array}\right.$$

увеличение несущественно увеличивает π

понижение существенно увеличивает π

$$\eta^*_{\sim} = \eta^*_{\sim} + \left|\begin{array}{l} -0.020 \ \text{ if } \ compressor = \text{"Вл"} \\ -0.028 \ \text{ if } \ compressor = \text{"КНД"} \\ -0.017 \ \text{ if } \ compressor = \text{"КВД"} \end{array}\right.$$

$$\overline{H}\sim_{T} = \overline{H}\sim_{T} + \left|\begin{array}{l} 0.0145 \ \text{ if } \ compressor = \text{"Вл"} \\ 0.0164 \ \text{ if } \ compressor = \text{"КНД"} \\ 0.0183 \ \text{ if } \ compressor = \text{"КВД"} \end{array}\right.$$

[16, с. 234]

увеличение несущественно увеличивает π

увеличение существенно увеличивает π

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

	1	2	3	4	5	6	7	8
1	0.600	0.600	0.600	0.600	0.600	0.600	0.600	0.600
2	0.990	0.980	0.970	0.960	0.950	0.950	0.950	0.950
3	0.852	0.862	0.877	0.882	0.882	0.877	0.862	0.852
4	0.294	0.284	0.274	0.264	0.254	0.244	0.234	0.224
5	0.266	0.306	0.336	0.346	0.366	0.336	0.306	0.286

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

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

$$0.18 \le \overline{H}\sim_{T}{}^{T} = (1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1)$$

$$\overline{H}\sim_{T}{}^{T} \le 0.35 = (1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 1)$$

Коэф. теор. напора "средней" ступени [14, с.11]:

$$\overline{H}_{T\text{ср}} = \frac{\displaystyle\sum_{i=1}^{rows(z_{\sim})} \overline{H}\sim_{T_i}}{rows(z_{\sim})} = 0.3189$$

$$0.25 \le \overline{H}_{T\text{ср}} \le 0.32 = 1$$

Исходные данные

Распределение основных параметров ОК по ступеням

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

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

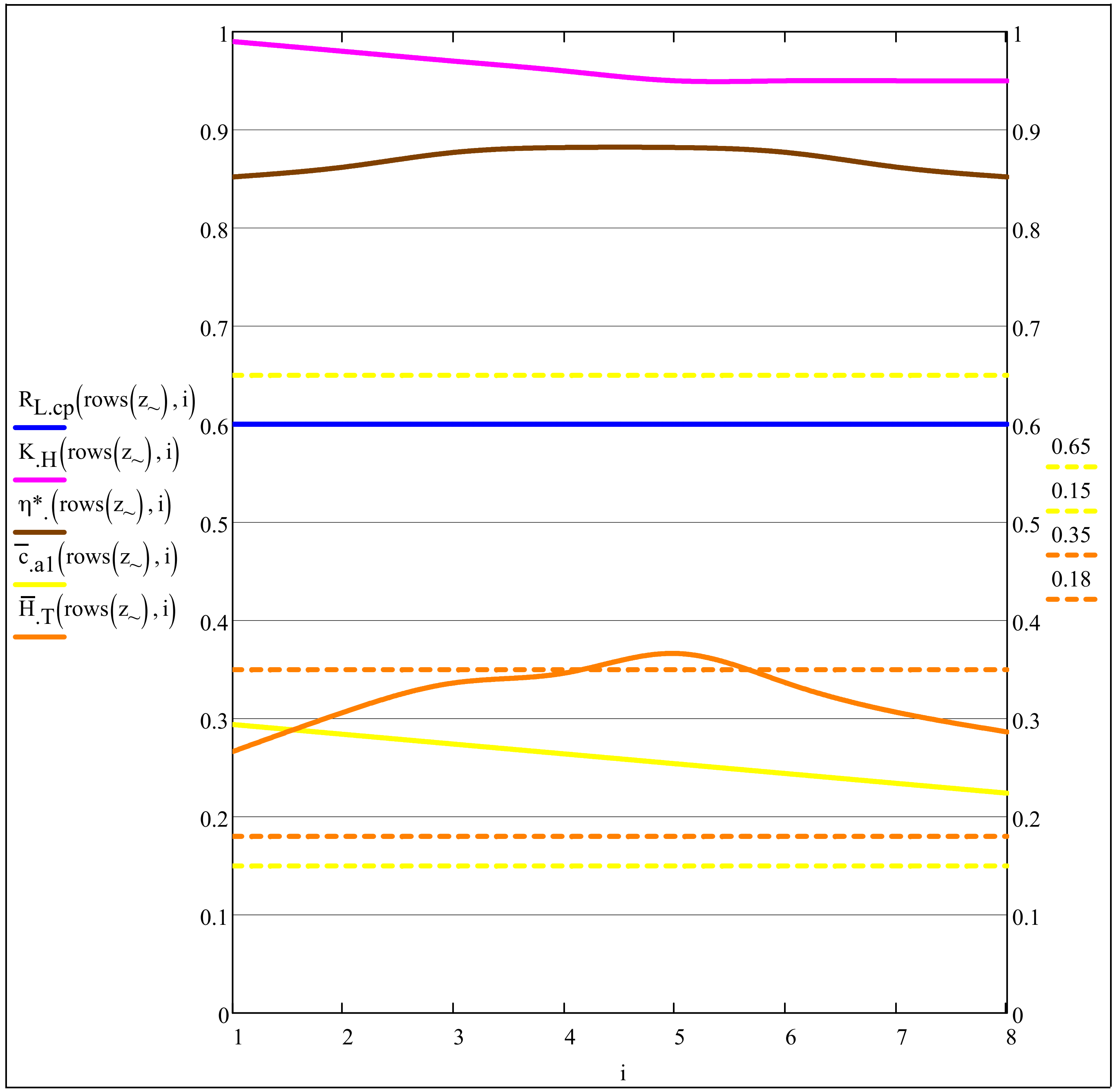
Коэф. расхода: $\bar{c}_{\sim a1}(i) = \text{interp}\left(\text{lspline}\left(\frac{z_{\sim}}{\text{rows}(z_{\sim})}, \bar{c}_{\sim a1}\right), \frac{z_{\sim}}{\text{rows}(z_{\sim})}, \bar{c}_{\sim a1}, i\right)$

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

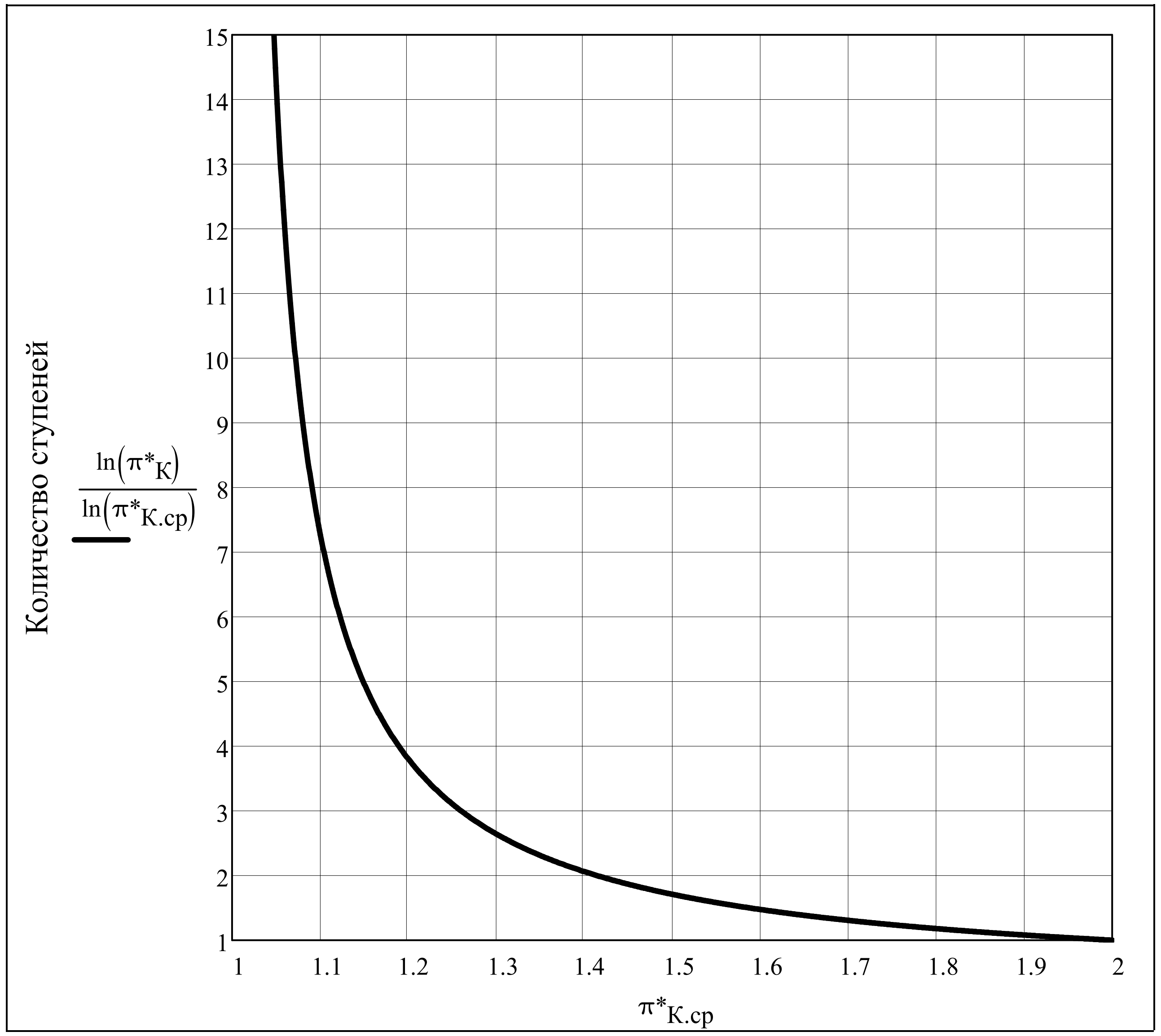
$$\begin{pmatrix} R_{L.cp} \\ K_{.H} \\ \eta^*_{.} \\ \bar{c}_{.a1} \\ \bar{H}_{.T} \end{pmatrix} = \left| \begin{array}{l} R_{L.cp}(Z,i) = \left| \begin{array}{ll} R_{L\sim cp}\left(\dfrac{1}{rows(z_{\sim})}\right) & \text{if } i < 1 \\ R_{L\sim cp}(1) & \text{if } i > Z \\ R_{L\sim cp}\left(\dfrac{i}{Z}\right)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

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

$$\begin{pmatrix} R_{L.cp}(Z_{temp}, i_{temp}) \\ K_{.H}(Z_{temp}, i_{temp}) \\ \eta^*_{.}(Z_{temp}, i_{temp}) \\ \bar{c}_{.a1}(Z_{temp}, i_{temp}) \\ \bar{H}_{.T}(Z_{temp}, i_{temp}) \end{pmatrix} = \begin{pmatrix} 0.600 \\ 0.950 \\ 0.852 \\ 0.224 \\ 0.286 \end{pmatrix}$$



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]: $P^*_{К3} = \pi^*_{К}\cdot P^*_{К1} = 203\cdot 10^{3}$

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

Количество итераций []: $iteration_3 = 1$

Полная температура после К [К]: $T^*_{К3} = 360.9$

Показатель адиаьаты после К []: $k_{К3} = 1.398$

Полная плотность перед и после К [кг/м^3]: $\begin{pmatrix} \rho^*_{К1} \\ \rho^*_{К3} \end{pmatrix} = \frac{1}{R_{в}}\cdot\begin{pmatrix} \frac{P^*_{К1}}{T^*_{К1}} \\ \frac{P^*_{К3}}{T^*_{К3}} \end{pmatrix} = \begin{pmatrix} 1.224 \\ 1.955 \end{pmatrix}$

Критические скорости перед и после К [м/с]: $\begin{pmatrix} a^*_{с.вх} \\ a^*_{с.вых} \end{pmatrix} = \begin{pmatrix} a_{кр}\left(k_{К1}, R_{в}, T^*_{К1}\right) \\ a_{кр}\left(k_{К3}, R_{в}, T^*_{К3}\right) \end{pmatrix} = \begin{pmatrix} 310.8 \\ 347.6 \end{pmatrix}$

Ср. показатель адиабаты К []: $k_{ср} = k_{ад}\left(Cp_{воздух.ср}\left(P^*_{К1}, P^*_{К3}, T^*_{К1}, T^*_{К3}\right), R_{в}\right) = 1.4$

Теоретический напор [Дж/кг]: $H_{ТК} = \frac{Cp_{воздух.ср}\left(P^*_{К1}, P^*_{К3}, T^*_{К1}, T^*_{К3}\right)\cdot T^*_{К1}\cdot\left(\pi^{*\,\frac{k_{ср}-1}{k_{ср}}}_{К} - 1\right)}{\eta^*_{К}} = 72.9\cdot 10^{3}$

```
$\begin{pmatrix} \text{iteration}_u \\ u_{1пер} \\ Z_{recomend} \\ c_{вх} \\ \lambda_{вх} \\ \rho_{К1} \end{pmatrix}$ = | $\text{iteration}_u = 0$
                                 | $\rho_{К1} = \rho*_{К1}$
                                 | while $0 < 1$
                                 |     $\text{iteration}_u = \text{iteration}_u + 1$
                                 |     trace(concat("iteration.u = ", num2str($\text{iteration}_u$)))
                                 |     $u_{1пер} = \sqrt[3]{\dfrac{\pi \cdot G \cdot n^2}{900 \cdot \overline{c}_{.a1}(1,0) \cdot \rho_{К1} \cdot \left[1 - \left(\overline{d}_1\right)^2\right]}}$
                                 |     $Z_{recomend} = \max\left(\text{round}\left(\dfrac{H_{ТК}}{\overline{H}_{Тср} \cdot {u_{1пер}}^2}\right), 1\right)$
                                 |     $c_{вх} = \overline{c}_{.a1}\left(Z_{recomend}, 0\right) \cdot u_{1пер}$
                                 |     $\lambda_{вх} = \dfrac{c_{вх}}{a*_{c.вх}}$
                                 |     $\rho'_{К1} = \rho*_{К1} \cdot ГДФ\left("\rho", \lambda_{вх}, k_{К1}\right)$
                                 |     if $\left|eps\left("rel", \rho'_{К1}, \rho_{К1}\right)\right| \le epsilon$
                                 |         $\rho_{К1} = \rho'_{К1}$
                                 |         break
                                 |     $\rho_{К1} = \rho'_{К1}$
                                 | $\begin{pmatrix} \text{iteration}_u \\ u_{1пер} \\ Z_{recomend} \\ c_{вх} \\ \lambda_{вх} \\ \rho_{К1} \end{pmatrix}$
```

Количество итераций []: $\text{iteration}_u = 2$

Окружная скорость на перифкрии перед К [м/с]: $u_{1пер} = 283.8$

Рекомендуемое количество ступеней []: $Z_{recomend} = 3$

Абс. скорость перед К [м/с]: $c_{вх} = 83.4$

Приведенная скорость перед К []: $\lambda_{вх} = 0.2685$

Плотность перед К [кг/м^3]: $\rho_{К1} = 1.188$

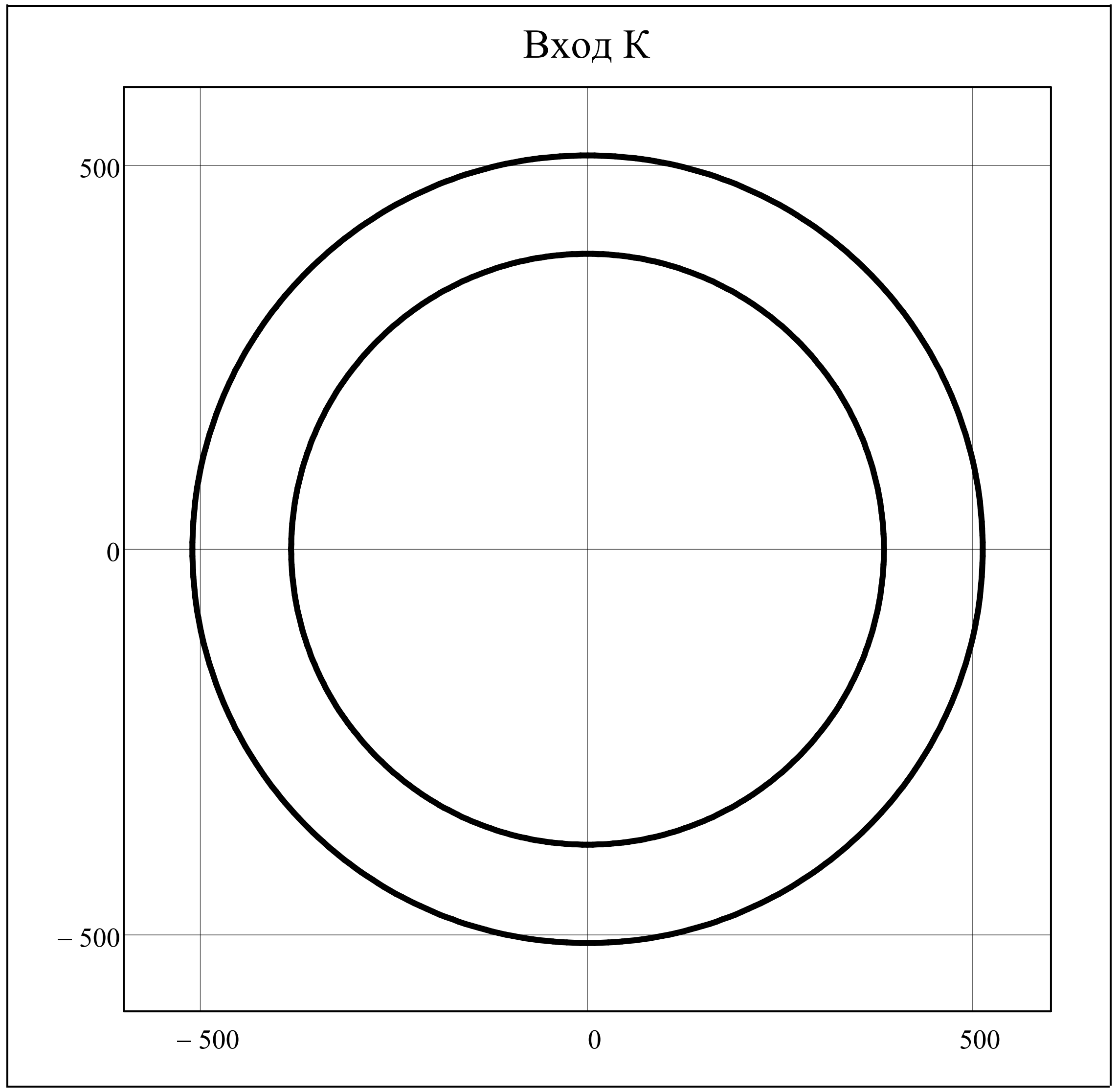
Кольцевая площадь перед К [м²]: $F_{вх} = \dfrac{G \cdot \sqrt{R_в \cdot T*_{К1}}}{m_q\left(k_{К1}\right) \cdot P*_{К1} \cdot ГДФ\left("G", \lambda_{вх}, k_{К1}\right)} = 0.3596$

$$D'_{пер1} = \frac{2 \cdot u_{1пер}}{\omega} = 1022.8 \cdot 10^{-3}$$

Диамтеры перед К [м]: $D'_{ср1} = \overline{r}_{ср}\left(\overline{d}_1\right) \cdot D'_{пер1} = 904 \cdot 10^{-3}$

$$D'_{кор1} = \overline{d}_1 \cdot D'_{пер1} = 767.1 \cdot 10^{-3}$$

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



Рекомендуемое количество ступеней []: $Z_{recomend} = 3$

Количество ступеней []: $Z = \left| \begin{array}{l} 1 \ \text{if compressor} = \text{"Вл"} \\ 3 \ \text{if compressor} = \text{"КНД"} \\ 9 \ \text{if compressor} = \text{"КВД"} \end{array} \right. = 3$

▲ Нулевые приближения

$$\text{ВНА} = \left| \begin{array}{l} 1 \ \ \text{if compressor} = \text{"КВД"} \\ 0 \ \ \text{otherwise} \end{array} \right. = 0$$

Расчет ВНА:

$$\begin{pmatrix} \alpha_{1ВНА} & \alpha_{3ВНА} \\ \sigma_{ВНА} & \sigma_{ВНА} \\ \overline{d}_{1ВНА} & \overline{d}_{3ВНА} \\ T^*{}_{1ВНА} & T^*{}_{3ВНА} \\ P^*{}_{1ВНА} & P^*{}_{3ВНА} \\ \rho^*{}_{1ВНА} & \rho^*{}_{3ВНА} \\ k_{1ВНА} & k_{3ВНА} \\ a_{кр1ВНА} & a_{кр3ВНА} \\ \overline{c}_{a1ВНА} & \overline{c}_{a3ВНА} \\ \overline{c}_{u1ВНА} & \overline{c}_{u3ВНА} \\ c_{a1ВНА} & c_{a3ВНА} \\ c_{u1ВНА} & c_{u3ВНА} \\ c_{1ВНА} & c_{3ВНА} \\ \lambda_{c1ВНА} & \lambda_{c3ВНА} \\ F_{1ВНА} & F_{3ВНА} \\ \varepsilon_{ВНА} & \varepsilon_{ВНА} \end{pmatrix} = \left| \begin{array}{l} \text{for } r \in av(N_r) \\ \quad \left| \begin{array}{l} \alpha_{1ВНА_r} = 90° \\ \overline{d}_{1ВНА} = \overline{d}_1 \\ \overline{d}_{3ВНА} = \overline{d}_{1ВНА} \\ T^*{}_{1ВНА_r} = T^*{}_{К1} \\ T^*{}_{3ВНА_r} = T^*{}_{1ВНА_r} \\ P^*{}_{1ВНА_r} = P^*{}_{К1} \\ \rho^*{}_{1ВНА_r} = \dfrac{P^*{}_{1ВНА_r}}{R_в \cdot T^*{}_{1ВНА_r}} \\ k_{1ВНА_r} = k_{ад}\left(Cp_{воздух}\left(P^*{}_{1ВНА_r}, T^*{}_{1ВНА_r}\right), R_в\right) \\ a_{кр1ВНА_r} = a_{кр}\left(k_{1ВНА_r}, R_в, T^*{}_{1ВНА_r}\right) \\ \overline{c}_{a1ВНА_r} = \overline{c}_{.a1}(Z,0) \\ \overline{c}_{u1ВНА_r} = \left| \begin{array}{l} \overline{r}_{cp}\left(\overline{d}_{1ВНА}\right)\cdot\left(1 - R_{L.cp}(Z,0)\right) - \dfrac{\overline{H}_{.T}(Z,0)}{2\cdot\overline{r}_{cp}\left(\overline{d}_{1ВНА}\right)} \ \ \text{if ВНА} = 1 \\ 0 \ \ \text{otherwise} \end{array} \right. \\ c_{a1ВНА_r} = \overline{c}_{a1ВНА_r} \cdot u_{1пер} \end{array} \right. \end{array} \right.$$

$\sigma_{ВНА} = 1.0000$

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

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

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

$\begin{pmatrix} \overline{d}_{1ВНА} \\ \overline{d}_{3ВНА} \end{pmatrix} = \begin{pmatrix} 0.7500 \\ 0.7500 \end{pmatrix}$ $\begin{pmatrix} F_{1ВНА} \\ F_{3ВНА} \end{pmatrix} = \begin{pmatrix} 0.3596 \\ 0.3596 \end{pmatrix}$

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

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

$$\lambda_{c1BHA_r} = \frac{c_{1BHA_r}}{a_{кр1BHA_r}}$$

$$\sigma_{BHA} = \begin{cases} \left[1 + \mathrm{mean}(0.03, 0.06) \cdot ГДФ\left("\rho", \lambda_{c1BHA_r}, k_{1BHA_r}\right) \cdot \frac{k_{1BHA_r}}{k_{1BHA_r} + 1} \cdot \left(\lambda_{c1BHA_r}\right)^2\right]^{-1} & \text{if } BHA = 1 \\ 1 & \text{otherwise} \end{cases}$$

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

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

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

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

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

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

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

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

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

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

$$\lambda_{c3BHA_r} = \frac{c_{3BHA_r}}{\ }$$

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

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

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

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

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

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

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

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

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

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

$$\mathrm{submatrix}\left(\overline{c}_{a1BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.294)$$

$$\mathrm{submatrix}\left(\overline{c}_{a3BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.277)$$

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

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

$$\mathrm{submatrix}\left(c_{a1BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (83.4)$$

$$\mathrm{submatrix}\left(c_{a3BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (83.4)$$

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

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

$$\mathrm{submatrix}\left(c_{1BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (83.4)$$

$$\mathrm{submatrix}\left(c_{3BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (83.4)$$

$$\mathrm{submatrix}\left(\lambda_{c1BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.268)$$

$$\mathrm{submatrix}\left(\lambda_{c3BHA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.268)$$

$\lambda_{c3ВНА_r} = \frac{}{a_{кр3ВНА_r}}$

$$\begin{pmatrix} F_{1ВНА} \\ F_{3ВНА} \end{pmatrix} = G\cdot\sqrt{R_в}\cdot\begin{pmatrix} \dfrac{\sqrt{T^*_{1ВНА_r}}}{m_q\left(k_{1ВНА_r}\right)\cdot P^*_{1ВНА_r}\cdot ГДФ\left("G", \lambda_{c1ВНА_r}, k_{1ВНА_r}\right)\cdot\sin\left(\alpha_{1ВНА_r}\right)} \\ \dfrac{\sqrt{T^*_{3ВНА_r}}}{m_q\left(k_{3ВНА_r}\right)\cdot P^*_{3ВНА_r}\cdot ГДФ\left("G", \lambda_{c3ВНА_r}, k_{3ВНА_r}\right)\cdot\sin\left(\alpha_{3ВНА_r}\right)} \end{pmatrix}$$

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

$$\begin{pmatrix} \alpha_{1ВНА} & \alpha_{3ВНА} \\ \sigma_{ВНА} & \sigma_{ВНА} \\ \overline{d}_{1ВНА} & \overline{d}_{3ВНА} \\ T^*_{1ВНА} & T^*_{3ВНА} \\ P^*_{1ВНА} & P^*_{3ВНА} \\ \rho^*_{1ВНА} & \rho^*_{3ВНА} \\ k_{1ВНА} & k_{3ВНА} \\ a_{кр1ВНА} & a_{кр3ВНА} \\ \overline{c}_{a1ВНА} & \overline{c}_{a3ВНА} \\ \overline{c}_{u1ВНА} & \overline{c}_{u3ВНА} \\ c_{a1ВНА} & c_{a3ВНА} \\ c_{u1ВНА} & c_{u3ВНА} \\ c_{1ВНА} & c_{3ВНА} \\ \lambda_{c1ВНА} & \lambda_{c3ВНА} \\ F_{1ВНА} & F_{3ВНА} \\ \varepsilon_{ВНА} & \varepsilon_{ВНА} \end{pmatrix}$$

Расчет ВНА:

Поступенчатый расчет ОК по ср. ЛТ

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

```
$D_{st(1,1),N_r} = \frac{2 \cdot u_{st(1,1),N_r}}{\omega}$
$D_{st(1,1),1} = \sqrt{\left(D_{st(1,1),N_r}\right)^2 - \frac{4 \cdot F_{st(1,1)}}{\pi}}$
$D_{st(1,1),r} = \overline{r}_{cp}\left(\frac{D_{st(1,1),1}}{D_{st(1,1),N_r}}\right) \cdot D_{st(1,1),N_r}$
$\overline{d}_{st(1,1)} = \frac{D_{st(1,1),1}}{D_{st(1,1),N_r}}$
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($iteration_{12}$)))
        $k_{12} = mean\left(k_{st(i,1),r}, k_{st(i,2),r}\right)$
        $Cp_{12} = \frac{k_{12}}{k_{12} - 1} \cdot R_в$
        $T^*_{st(i,2),r} = T^*_{st(i,1),r} + \frac{L_i}{Cp_{12}}$
        $\pi^*_i = \left(1 + \frac{L^*_i}{Cp_{12} \cdot T^*_{st(i,1),r}}\right)^{\frac{k_{12}}{k_{12}-1}}$
        $P^*_{st(i,2),r} = P^*_{st(i,1),r} \cdot \pi^*_i$
```

```
    $Cp_{st(i,2),r} = Cp_{воздух}(P^*_{st(i,2),r}, T^*_{st(i,2),r})$
    $k'_2 = k_{ад}(Cp_{st(i,2),r}, R_в)$
    if $\left|eps("rel", k_{st(i,2),r}, k'_2)\right| < epsilon$
        $k_{st(i,2),r} = k'_2$
        break
    $k_{st(i,2),r} = k'_2$
$a^*_{c_{st(i,2),r}} = a_{кр}(k_{st(i,2),r}, R_в, T^*_{st(i,2),r})$
$T^*_{st(i,3),r} = T^*_{st(i,2),r}$
$P^*_{st(i,3),r} = P^*_{st(i,2),r}$
$Cp_{st(i,3),r} = Cp_{воздух}(P^*_{st(i,3),r}, T^*_{st(i,3),r})$
$k_{st(i,3),r} = k_{ад}(Cp_{st(i,3),r}, R_в)$
$a^*_{c_{st(i,3),r}} = a_{кр}(k_{st(i,3),r}, R_в, T^*_{st(i,3),r})$
$\overline{c}_{a_{st(i,3),r}} = \overline{c}.a1(Z, i+1)$
$iteration_3 = 0$
$\begin{pmatrix}\alpha_{st(i,3),r}\\ u_{st(i,3),N_r}\end{pmatrix} = \begin{pmatrix}\alpha_{st(i,1),r}\\ u_{st(i,1),N_r}\end{pmatrix}$
$c_{a_{st(i,3),r}} = \overline{c}_{a_{st(i,3),r}} \cdot u_{st(i,3),N_r}$
$c_{st(i,3),r} = \frac{c_{a_{st(i,3),r}}}{\sin(\alpha_{st(i,3),r})}$
$\lambda_{c_{st(i,3),r}} = \frac{c_{st(i,3),r}}{a^*_{c_{st(i,3),r}}}$
$F_{st(i,3)} = \frac{F_{st(i,1)} \cdot m_q(k_{st(i,1),r}) \cdot ГДФ("G", \lambda_{c_{st(i,1),r}}, k_{st(i,1),r}) \cdot \sin(\alpha_{st(i,1),r}) \cdot P^*_{st(i,1),r} \cdot \sqrt{T^*_{st(i,3),r}}}{m_q(k_{st(i,3),r}) \cdot ГДФ("G", \lambda_{c_{st(i,3),r}}, k_{st(i,3),r}) \cdot \sin(\alpha_{st(i,3),r}) \cdot P^*_{st(i,3),r} \sqrt{T^*_{st(i,1),r}}}$
while $0 < 1$
    $iteration_3 = iteration_3 + 1$
    trace(concat("    iteration.3 = ", num2str($iteration_3$)))
    if $(ЗППЧ_i \ne "пер") \wedge (ЗППЧ_i \ne "кор") \wedge (ЗППЧ_i \ne "ср")$
        $D_{st(i,3),N_r} = D_{st(i,1),N_r} \cdot str2num(ЗППЧ_i)$
        $D_{st(i,3),1} = \sqrt{\left(D_{st(i,3),N_r}\right)^2 - \frac{4F_{st(i,3)}}{\pi}}$
    if $ЗППЧ_i = "пер"$
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        $D_{st(i,3),N_r} = D_{st(i,1),N_r}$
        $D_{st(i,3),1} = \sqrt{\left(D_{st(i,3),N_r}\right)^2 - \frac{4F_{st(i,3)}}{\pi}}$
    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} = $
        $\operatorname{atan}\left(\frac{\overline{c}_{a_{st(i,3),r}}}{\overline{c}_{u_{st(i,3),r}}}\right)$ if $\operatorname{atan}\left(\frac{\overline{c}_{a_{st(i,3),r}}}{\overline{c}_{u_{st(i,3),r}}}\right) \ge 0$
        $\operatorname{atan}\left(\frac{\overline{c}_{a_{st(i,3),r}}}{\overline{c}_{u_{st(i,3),r}}}\right) + 2\pi$ otherwise
    $u_{st(i,3),N_r} = u_{st(i,1),N_r}\cdot\frac{D_{st(i,3),N_r}}{D_{st(i,1),N_r}}$
    $c_{a_{st(i,3),r}} = \overline{c}_{a_{st(i,3),r}}\cdot u_{st(i,3),N_r}$
    $c_{st(i,3),r} = \frac{c_{a_{st(i,3),r}}}{\sin\left(\alpha_{st(i,3),r}\right)}$
    $\lambda_{c_{st(i,3),r}} = \frac{c_{st(i,3),r}}{a*_{c_{st(i,3),r}}}$
    $F'_3 = \frac{G\cdot\sqrt{R_в\cdot T*_{st(i,3),r}}}{m_q\left(k_{st(i,3),r}\right)\cdot ГДФ\left("G", \lambda_{c_{st(i,3),r}}, k_{st(i,3),r}\right)\cdot\sin\left(\alpha_{st(i,3),r}\right)\cdot P*_{st(i,3),r}}$
    break if $\left(\left|eps\left("rel", F'_3, F_{st(i,3)}\right)\right| < epsilon\right) \wedge \left(iteration_3 = 0\right)$
```

```
    $iteration_3 = -1$ if $(|eps("rel", F'_3, F_{st(i,3)})| < epsilon)$
    $F_{st(i,3)} = F'_3$
$\bar{c}_{a_{st(i,2),r}} = mean(\bar{c}_{a_{st(i,1),r}}, \bar{c}_{a_{st(i,3),r}})$
$iteration_2 = 0$
$F_{st(i,2)} = mean(F_{st(i,1)}, F_{st(i,3)})$
while $0 < 1$
    $iteration_2 = iteration_2 + 1$
    trace(concat("    iteration.2 = ", num2str($iteration_2$)))
    if $(ЗППЧ_i \neq "пер") \wedge (ЗППЧ_i \neq "кор") \wedge (ЗППЧ_i \neq "ср")$
        $D_{st(i,2),N_r} = mean(D_{st(i,1),N_r}, D_{st(i,3),N_r})$
        $\bar{d}_{st(i,2)} = \sqrt{2 \cdot mean(\bar{r}_{cp}(\bar{d}_{st(i,1)}), \bar{r}_{cp}(\bar{d}_{st(i,3)}))^2 - 1}$
        $D_{st(i,2),r} = D_{st(i,2),N_r} \cdot \bar{r}_{cp}(\bar{d}_{st(i,2)})$
        $D_{st(i,2),1} = \bar{d}_{st(i,2)} \cdot D_{st(i,2),N_r}$
    if $ЗППЧ_i = "пер"$
        $D_{st(i,2),N_r} = D_{st(i,1),N_r}$
        $\bar{d}_{st(i,2)} = \sqrt{2 \cdot mean(\bar{r}_{cp}(\bar{d}_{st(i,1)}), \bar{r}_{cp}(\bar{d}_{st(i,3)}))^2 - 1}$
        $D_{st(i,2),r} = D_{st(i,2),N_r} \cdot \bar{r}_{cp}(\bar{d}_{st(i,2)})$
        $D_{st(i,2),1} = \bar{d}_{st(i,2)} \cdot D_{st(i,2),N_r}$
    if $ЗППЧ_i = "кор"$
        $D_{st(i,2),1} = D_{st(i,1),1}$
        $\bar{d}_{st(i,2)} = \sqrt{2 \cdot mean(\bar{r}_{cp}(\bar{d}_{st(i,1)}), \bar{r}_{cp}(\bar{d}_{st(i,3)}))^2 - 1}$
        $D_{st(i,2),N_r} = \frac{D_{st(i,2),1}}{\bar{d}_{st(i,2)}}$
        $D_{st(i,2),r} = D_{st(i,2),N_r} \cdot \bar{r}_{cp}(\bar{d}_{st(i,2)})$
    if $ЗППЧ_i = "ср"$
        $D_{st(i,2),r} = D_{st(i,1),r}$
        $\bar{d}_{st(i,2)} = \sqrt{2 \cdot mean(\bar{r}_{cp}(\bar{d}_{st(i,1)}), \bar{r}_{cp}(\bar{d}_{st(i,3)}))^2 - 1}$
        $D_{st(i,2),N_r} = \frac{D_{st(i,2),r}}{\bar{r}_{cp}(\bar{d}_{st(i,2)})}$
        $D_{st(i,2),1} = \bar{d}_{st(i,2)} \cdot D_{st(i,2),N_r}$
```

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

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

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

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

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

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

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

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

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

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

for $a \in 1..3$

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

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

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

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

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

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

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

```
      $w_{u_{st(i,a),r}} = w_{st(i,a),r}\cdot\cos(\beta_{st(i,a),r})$
      $c_{u_{st(i,a),r}} = c_{st(i,a),r}\cdot\cos(\alpha_{st(i,a),r})$
      $M_{w_{st(i,a),r}} = \frac{w_{st(i,a),r}}{a_{\text{ЗВ}_{st(i,a),r}}}$
      $M_{c_{st(i,a),r}} = \frac{c_{st(i,a),r}}{a_{\text{ЗВ}_{st(i,a),r}}}$
      $h_{st(i,a)} = 0.5\cdot\left(D_{st(i,a),N_r} - D_{st(i,a),1}\right)$
      for  radius ∈ 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 ∈ 1 .. Z
    for  a ∈ 1 .. 3
      for  r ∈ 1 .. $N_r$
        $R_{st(i,a),r} = 0.5\cdot D_{st(i,a),r}$
  $\begin{pmatrix} R_L & K_H & Cp & \overline{H}_T & L^* & T^* & P^* & \rho^* & a^*_c & \lambda_c & F & D & \overline{d} & \overline{c}_a & c_a & u & c & M_c & \alpha & \varepsilon_{rotor} \\ \pi^* & \eta^* & k & H_T & L & T & P & \rho & a_{\text{зв}} & \lambda_c & F & R & h & \overline{c}_u & c_u & w_u & w & M_w & \beta & \varepsilon_{stator} \end{pmatrix}^T$
```

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

▲ Поступенчатый расчет ОК по ср. ЛТ

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

Расчет СА:

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

```
for $r \in av(N_r)$
    $\alpha_{1CA_r} = \alpha_{st(Z,3),r}$
    $\alpha_{3CA_r} = \begin{cases} 90\cdot° & \text{if } CA = 1 \\ \alpha_{1CA_r} & \text{otherwise} \end{cases}$
    $\overline{d}_{1CA} = \overline{d}_{st(Z,3)}$
    $\overline{d}_{3CA} = \overline{d}_{1CA}$
    $T^*_{1CA_r} = T^*_{st(Z,3),r}$
    $T^*_{3CA_r} = T^*_{1CA_r}$
    $P^*_{1CA_r} = P^*_{st(Z,3),r}$
    $iterarion_{CA} = 0$
    $\sigma_{CA} = 1$
    while $0 < 1$
        $iterarion_{CA} = iterarion_{CA} + 1$
        $trace(concat("iterarion.CA = ", num2str(iterarion_{CA})))$
        $P^*_{3CA_r} = P^*_{1CA_r} \cdot \sigma_{CA}$
        $\begin{pmatrix} \rho^*_{1CA_r} \end{pmatrix}$   1   $\begin{pmatrix} \frac{P^*_{1CA_r}}{T^*_{1CA_r}} \end{pmatrix}$
```

$\sigma_{CA} = 1.0000$

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

$submatrix(\alpha_{1CA}, av(N_r), av(N_r), 1, 1) = (51.49)\cdot deg$

$submatrix(\alpha_{3CA}, av(N_r), av(N_r), 1, 1) = (51.49)\cdot deg$

$$\begin{pmatrix} \overline{d}_{1CA} \\ \overline{d}_{3CA} \end{pmatrix} = \begin{pmatrix} 0.6953 \\ 0.6953 \end{pmatrix} \qquad \begin{pmatrix} F_{1CA} \\ F_{3CA} \end{pmatrix} = \begin{pmatrix} 0.3310 \\ 0.3310 \end{pmatrix}$$

$$\begin{pmatrix} \vdots \\ \rho^*{}_{3CA_r} \end{pmatrix} = \frac{1}{R_в}\cdot\begin{pmatrix} \vdots \\ \dfrac{P^*{}_{3CA_r}}{T^*{}_{3CA_r}} \end{pmatrix}$$

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

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

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

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

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

$$\overline{c}_{u3CA_r} = \left| \begin{array}{ll} 0 & \text{if } CA = 1 \\ \overline{c}_{u1CA_r} & \text{otherwise} \end{array} \right.$$

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

$$c_{a3CA_r} = c_{a1CA_r} - \left| \begin{array}{l} 10 \ \text{ if } CA = 1 \\ 0 \ \text{ otherwise} \end{array} \right.$$

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

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

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

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

$$\text{submatrix}\left(T^*{}_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (361.5)$$

$$\text{submatrix}\left(T^*{}_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (361.5)$$

$$\text{submatrix}\left(P^*{}_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (202.7)\cdot 10^3$$

$$\text{submatrix}\left(P^*{}_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (202.7)\cdot 10^3$$

$$\text{submatrix}\left(\rho^*{}_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.952)$$

$$\text{submatrix}\left(\rho^*{}_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.952)$$

$$\text{submatrix}\left(k_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.398)$$

$$\text{submatrix}\left(k_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (1.398)$$

$$\text{submatrix}\left(a_{кр1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (347.9)$$

$$\text{submatrix}\left(a_{кр3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (347.9)$$

$$\text{submatrix}\left(\overline{c}_{a1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.224)$$

$$\text{submatrix}\left(\overline{c}_{a3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.224)$$

$$\text{submatrix}\left(\overline{c}_{u1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.178)$$

$$\text{submatrix}\left(\overline{c}_{u3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.178)$$

$$\text{submatrix}\left(c_{a1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (56.1)$$

$$\text{submatrix}\left(c_{a3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (56.1)$$

$$\text{submatrix}\left(c_{u1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (44.7)$$

$$\text{submatrix}\left(c_{u3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (44.7)$$

$$\text{submatrix}\left(c_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (71.8)$$

$$\text{submatrix}\left(c_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (71.8)$$

$$\text{submatrix}\left(\lambda_{1CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.206)$$

$$\text{submatrix}\left(\lambda_{3CA}, av\left(N_r\right), av\left(N_r\right), 1, 1\right) = (0.206)$$

```
            1   otherwise
      break if $\left(\left|eps\left("rel", \sigma'_{CA}, \sigma_{CA}\right)\right| < epsilon\right) \wedge \left(iterarion_{CA} = 0\right)$
      $iterarion_{CA} = -1$ if $\left(\left|eps\left("rel", \sigma'_{CA}, \sigma_{CA}\right)\right| < epsilon\right)$
      $\sigma_{CA} = \sigma'_{CA}$
    $\begin{pmatrix} F_{1CA} \\ F_{3CA} \end{pmatrix} = \left( \dfrac{\dfrac{F_{st(Z,3)}}{G \cdot \sqrt{R_{в} \cdot T^{*}_{3CA_{r}}}}}{m_{q}\left(k_{3CA_{r}}\right) \cdot P^{*}_{3CA_{r}} \cdot ГДФ\left("G", \lambda_{3CA_{r}}, k_{3CA_{r}}\right) \cdot \sin\left(\alpha_{3CA_{r}}\right)} \right)$
    $\varepsilon_{CA_{r}} = \alpha_{3CA_{r}} - \alpha_{1CA_{r}}$
  $\begin{pmatrix} \alpha_{1CA} & \alpha_{3CA} \\ \sigma_{CA} & \sigma_{CA} \\ \overline{d}_{1CA} & \overline{d}_{3CA} \\ T^{*}_{1CA} & T^{*}_{3CA} \\ P^{*}_{1CA} & P^{*}_{3CA} \\ \rho^{*}_{1CA} & \rho^{*}_{3CA} \\ k_{1CA} & k_{3CA} \\ a_{кр1CA} & a_{кр3CA} \\ \overline{c}_{a1CA} & \overline{c}_{a3CA} \\ \overline{c}_{u1CA} & \overline{c}_{u3CA} \\ c_{a1CA} & c_{a3CA} \\ c_{u1CA} & c_{u3CA} \\ c_{1CA} & c_{3CA} \\ \lambda_{1CA} & \lambda_{3CA} \\ F_{1CA} & F_{3CA} \\ \varepsilon_{CA} & \varepsilon_{CA} \end{pmatrix}$
```

Расчет CA:

Результаты поступенчатого расчета по ср. ЛТ

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

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

$\Delta G^T =$

	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	0.00	0.00	0.00	0.00												

$\cdot\%$

$\Delta G^T < 1\% =$

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

Количество ступеней ОК: $Z = 3$

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	1.300	1.297	1.187												

[16, с 114] $\pi^{*T} \leq 1.9 =$

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

Полученная степень повышения полного давления []: $\prod_{i=1}^{Z} \pi^*_i = 2.000$

Степень повышения давления в ЛА: $\pi^*_{ЛА} = \dfrac{P^*_{3CA_{av(N_r)}}}{P^*_{1BHA_{av(N_r)}}} = 2.000$ $\pi^*_{ЛА} \geq \pi^*_{К} = 1$

$H_T^{\,T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	26.51	29.08	21.26												
2	26.51	29.08	21.26												
3	26.51	29.08	21.26												

$\cdot 10^3$

Действительная работа К (Дж/кг): $L_K = \sum_{i=1}^{Z} L_i = 73.6 \cdot 10^3$

Адиабатная работа К [Дж/кг]: $L^*_K = \sum_{i=1}^{Z} L^*_i = 64.1 \cdot 10^3$

Адиабатная КПД К []: $\eta^*_K = \dfrac{L^*_K}{L_K} = 87.02 \cdot \%$

Мощность К (Вт): $N_K = G \cdot L_K = 2.62 \cdot 10^6$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.60	0.60	0.60												

${K_H}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.973	0.949	0.95												

$\eta^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	87.25	88.13	85.20												

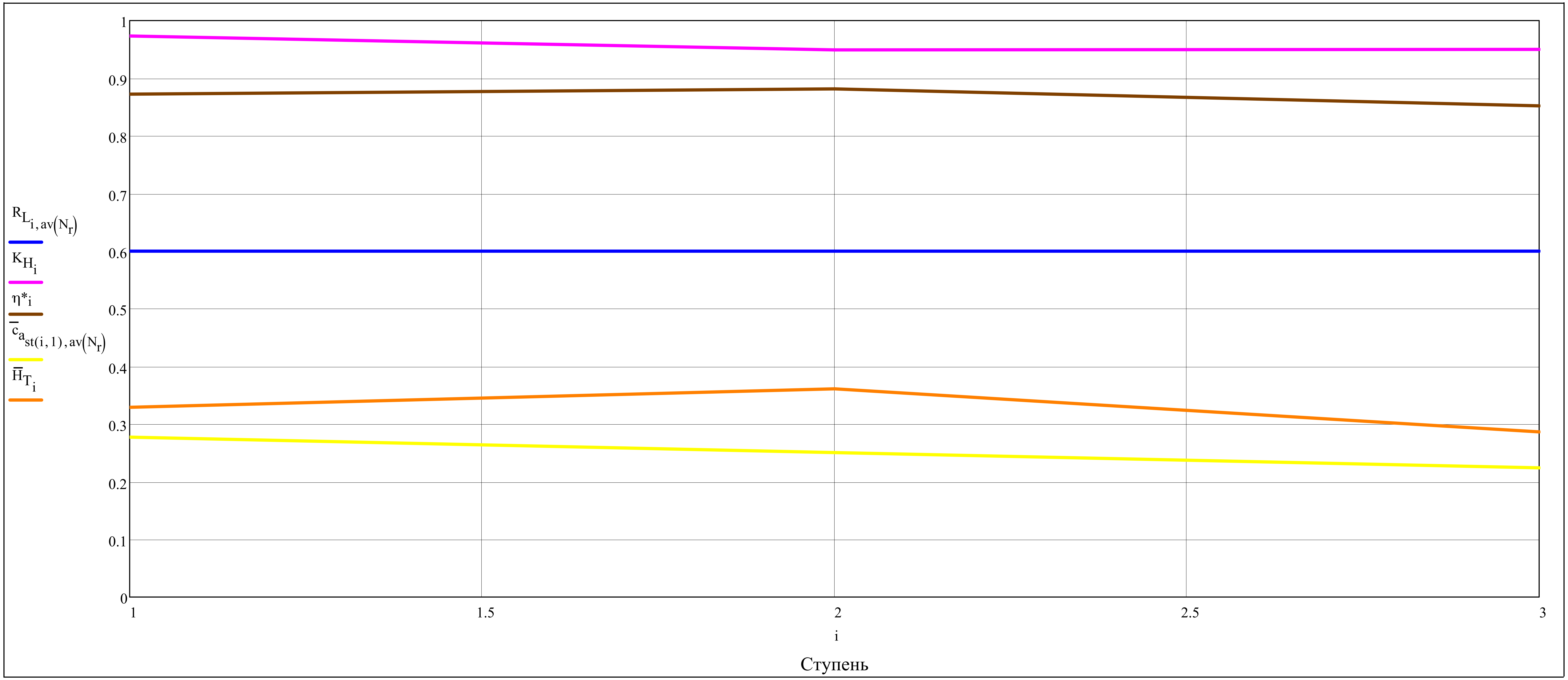
$\cdot\%$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.277	0.264	0.251	0.237	0.224	0.224	0.224													

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.33	0.36	0.29												



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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1002.6	1004.1	1004.1	1006.4	1006.4	1008.5	1008.5												

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.401	1.401	1.401	1.399	1.399	1.398	1.398														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	288.2	313.9	313.9	341.4	341.4	361.5	361.5														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	284.7	305.6	310.5	326.2	338.3	349	359														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	101.3	131.7	131.7	170.8	170.8	202.7	202.7											

$\cdot 10^3$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	97.1	119.8	126.7	145.5	165.3	179.1	197.7											

$\cdot 10^3$

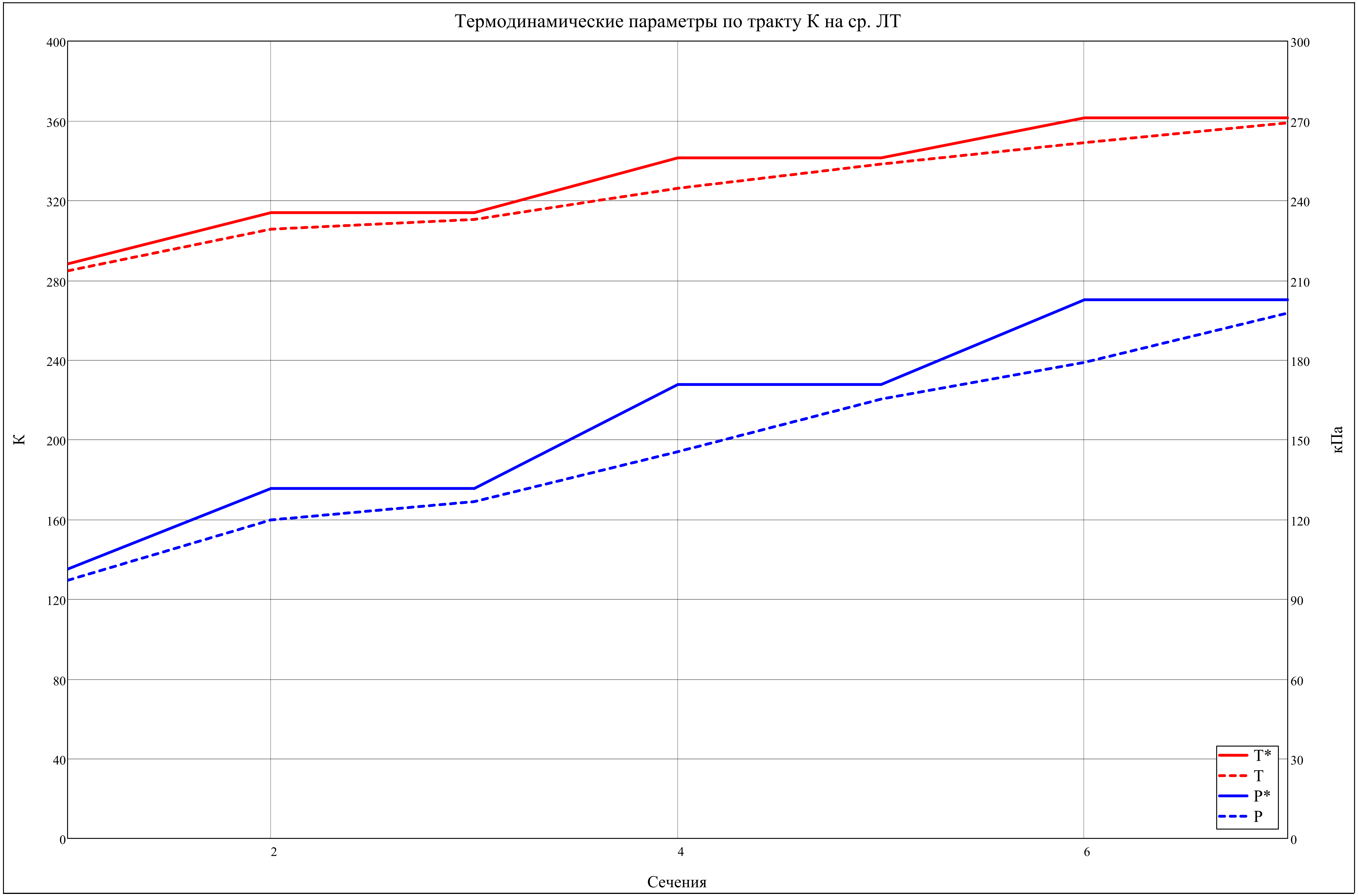
$\mathrm{submatrix}\left(\rho^*, 1, 2Z+1, av\left(N_r\right), av\left(N_r\right)\right)^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.224	1.461	1.461	1.742	1.742	1.952	1.952												

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.188	1.366	1.421	1.553	1.702	1.787	1.918												

$k_{\text{ср}} = k_{\text{ад}}\left(Cp_{\text{воздух.ср}}\left(P^*_{st(1,1),av\left(N_r\right)}, P^*_{st(Z,3),av\left(N_r\right)}, T^*_{st(1,1),av\left(N_r\right)}, T^*_{st(Z,3),av\left(N_r\right)}\right), R_{\text{в}}\right) = 1.400$


Термодинамические параметры по тракту К на ср. ЛТ
400
360
320
280
240
200
160
120
80
40
0
К
300
270
240
210
180
150
120
90
60
30
0
кПа
2
4
6
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	21
1	359639	348398	352628	347646	343267	340438	331025														

$\cdot 10^{-6}$

$\overline{d}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.7498	0.7527	0.7555	0.7474	0.7393	0.7175	0.6953																

$\overline{d}_{st(Z,3)} = 0.6953$

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

$D^T =$

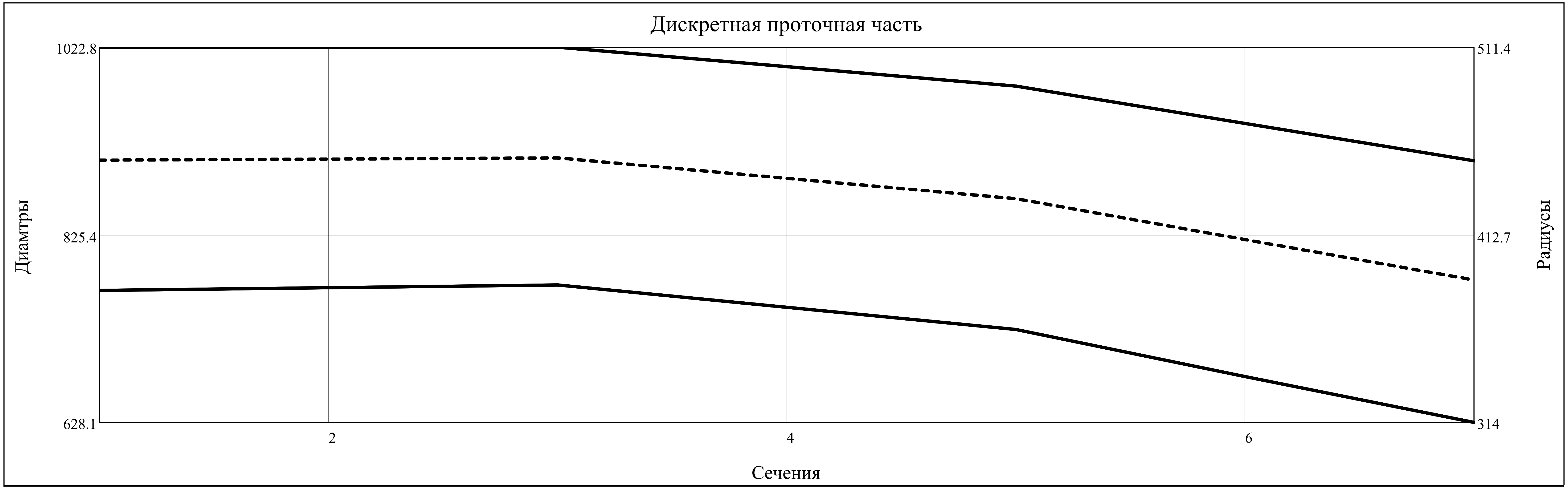
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	766.9	769.8	772.7	749.2	725.9	676.3	628.1														
2	903.9	905.2	906.4	884.8	863.4	820.3	777.9														
3	1022.8	1022.8	1022.8	1002.3	981.8	942.6	903.3														

$\cdot 10^{-3}$

$R^T =$

	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	383.4	384.9	386.3	374.6	363.0	338.2	314.0																		
2	452.0	452.6	453.2	442.4	431.7	410.2	389.0																		
3	511.4	511.4	511.4	501.1	490.9	471.3	451.6																		

$\cdot 10^{-3}$



$h^T =$

	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	127.9	126.5	125.0	126.6	128.0	133.1	137.6																		

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	310.8	324.3	324.3	338.2	338.2	347.9	347.9														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	338.5	350.6	353.4	362.0	368.7	374.3	379.6														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	83.4	129.4	83.0	175.2	79.8	158.8	71.8														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	278.7	163.8	220.5	106.2	197.8	99.2															

$u^T =$

	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	212.8	213.6	214.4	207.9	201.4	187.7	174.3																		
2	250.8	251.2	251.5	245.5	239.6	227.6	215.9																		
3	283.8	283.8	283.8	278.1	272.5	261.6	250.7																		

$c_{a_{st(Z,3),av(N_r)}} = 56.15$ $\quad c_{a_{st(Z,3),av(N_r)}} \le 130 = 1$ Для КС

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	83.4	74.9	71.1	66.0	61.0	58.6	56.1														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	105.6	42.8	162.3	51.5	147.6	44.7														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	265.9	145.6	208.7	83.3	188.1	80.1	171.2														

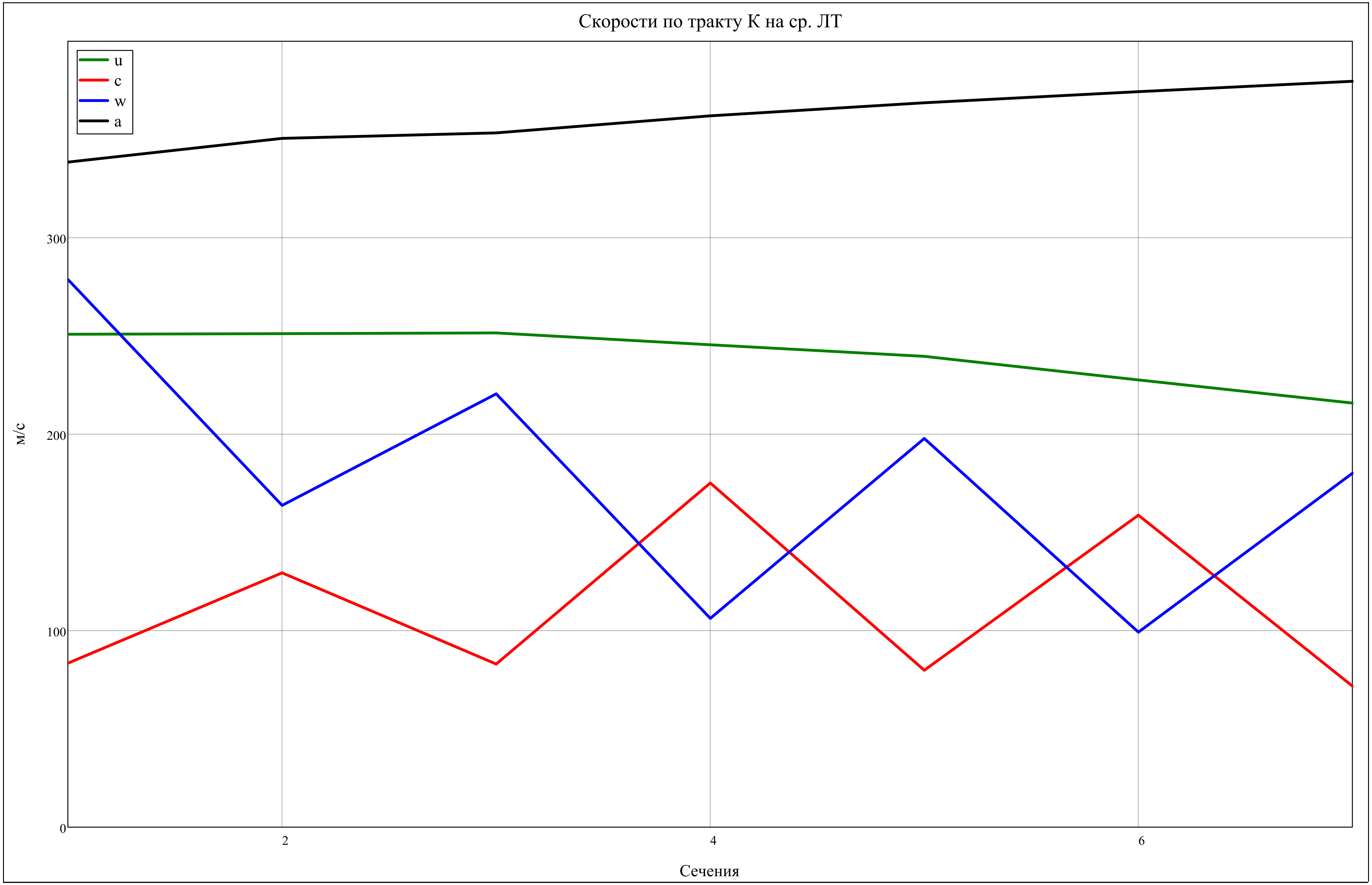
$$\Delta c_{a_{i,av(N_r)}} = \left(c_{a_{st(i,2),av(N_r)}} - c_{a_{st(i,1),av(N_r)}}\right)$$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	-8.51	-5.13	-2.44																		

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

	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	1	1	1																											


Скорости по тракту К на ср. ЛТ
u
c
w
a
м/с
300
200
100
0
2
4
6
Сечения

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	90.00	35.37	58.97	22.13	49.86	21.65	51.49														

$\cdot ^{\circ}$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	17.42	27.23	18.82	38.41	17.97	36.19	18.16														

$\cdot ^{\circ}$

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

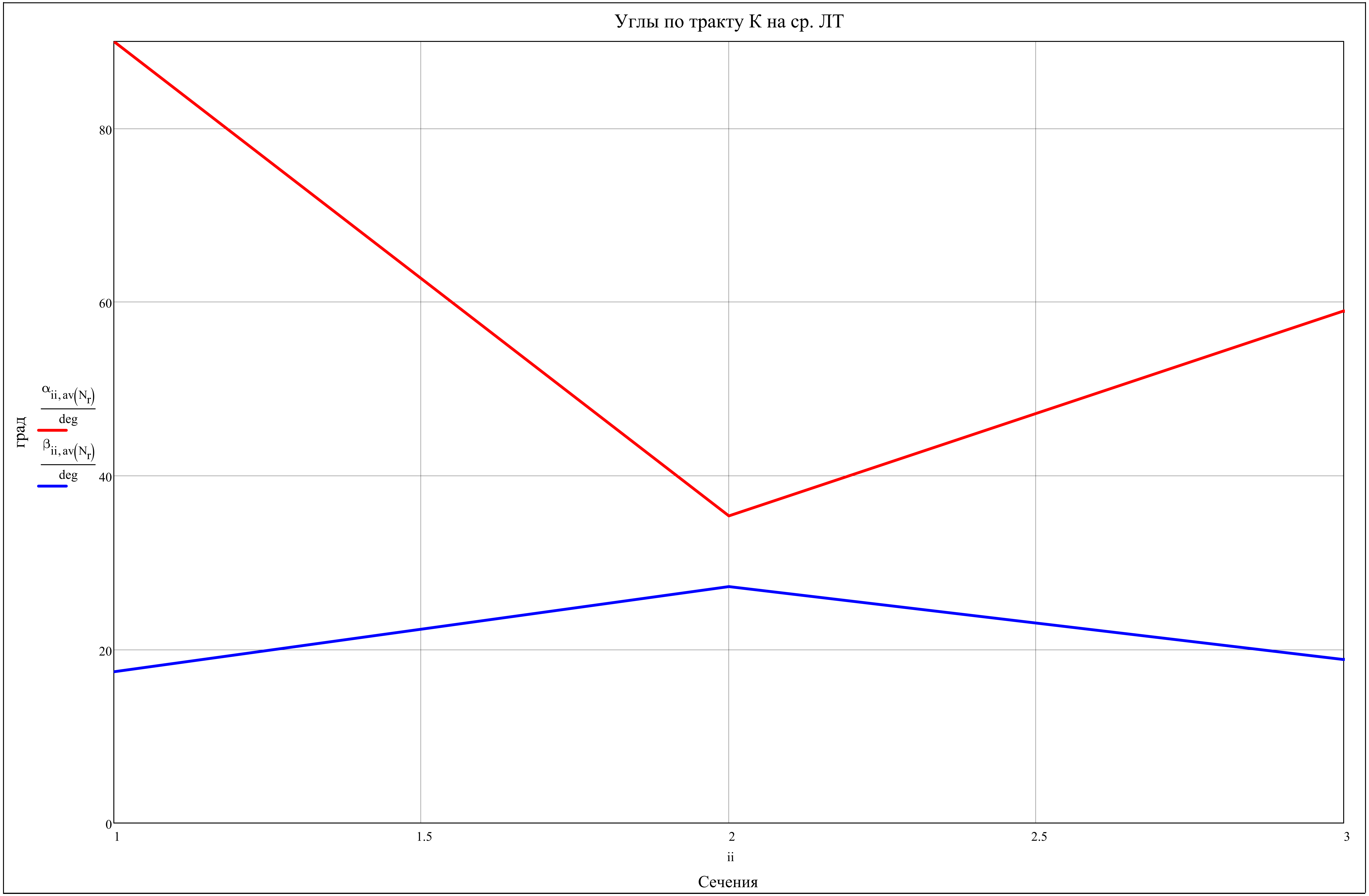
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	9.81	19.59	18.22																		

$\cdot ^{\circ}$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	23.61	27.72	29.84																		

$\cdot ^{\circ}$


Углы по тракту К на ср. ЛТ
град
$\frac{\alpha_{ii,av(N_r)}}{deg}$
$\frac{\beta_{ii,av(N_r)}}{deg}$
0
20
40
60
80
1
1.5
2
2.5
3
ii
Сечения

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.2685	0.3991	0.2560	0.5181	0.2361	0.4564	0.2062												

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

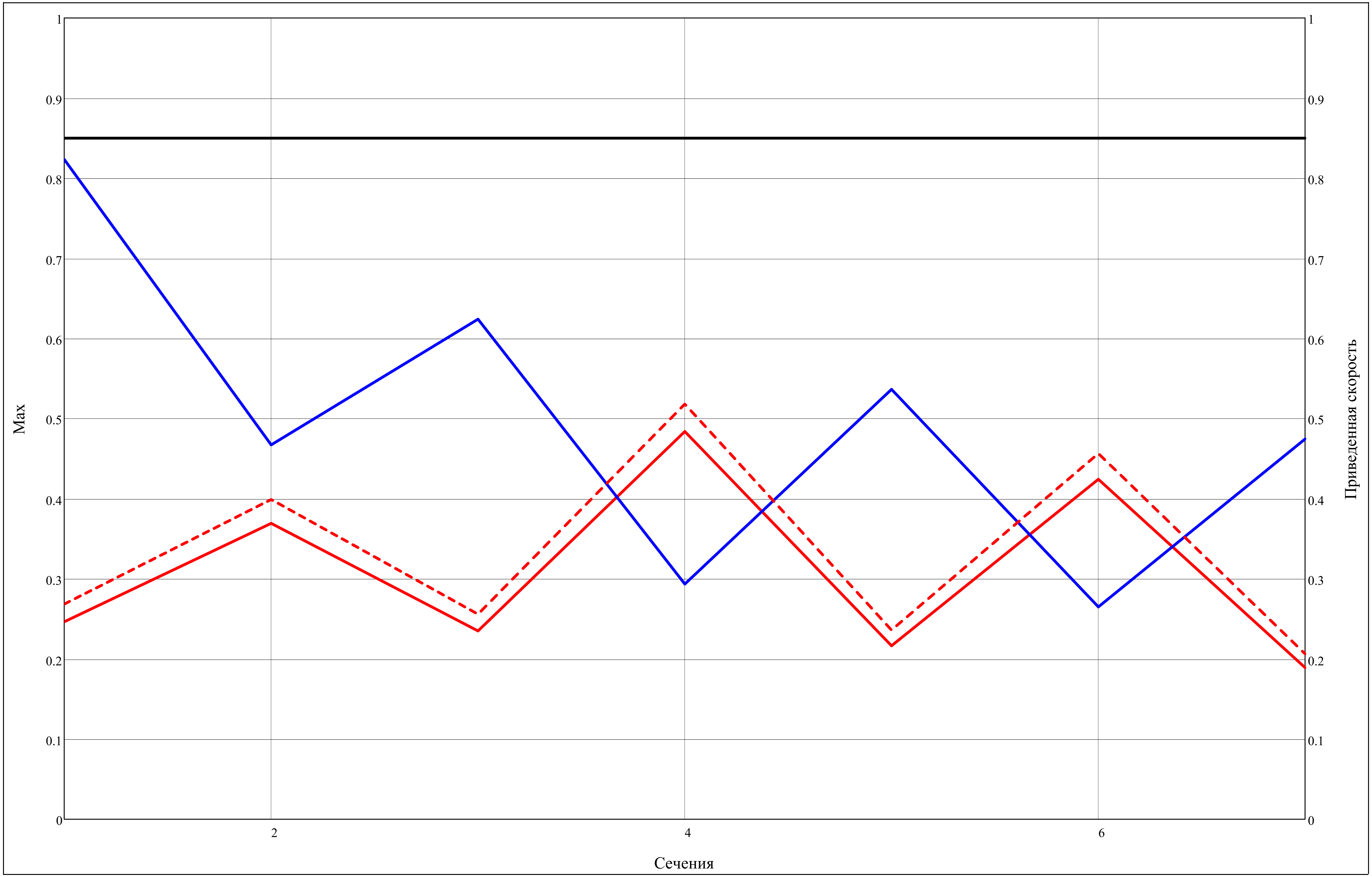
	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.8234	0.4672	0.6241	0.2935	0.5365	0.2651													

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.2465	0.3693	0.2349	0.4840	0.2166	0.4242	0.1890												


Max
Приведенная скорость
Сечения
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
4
6

⏶ 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]

$$\begin{pmatrix} \bar{d}_{m2\text{Ц}} \\ \bar{d}_{R2m} \end{pmatrix} = \begin{pmatrix} 0.7 \\ 0.3 \end{pmatrix}$$

$$m := \left| \begin{array}{l} \text{for } i \in 1..Z \\ \quad m_i \leftarrow \left| \begin{array}{ll} -1 & \text{if } \bar{d}_{st(i,1)} \le \bar{d}_{R2m} \\ 1 & \text{if } \bar{d}_{st(i,1)} \ge \bar{d}_{m2\text{Ц}} \\ -1 + \dfrac{1-(-1)}{\bar{d}_{m2\text{Ц}} - \bar{d}_{R2m}} \cdot \left(\bar{d}_{st(i,1)} - \bar{d}_{R2m} \right) & \text{otherwise} \end{array} \right. \\ m \end{array} \right.$$

$$m_i := \left| \begin{array}{l} 0.73 \ \text{ if } compressor = \text{"Вл"} \\ m_i \ \text{ otherwise} \end{array} \right.$$

$m^T =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	1.000	1.000	1.000									

$$\begin{pmatrix} T^*{}_{1BHA} & T^*{}_{3BHA} \\ P^*{}_{1BHA} & P^*{}_{3BHA} \\ \rho^*{}_{1BHA} & \rho^*{}_{3BHA} \\ Cp_{1BHA} & Cp_{3BHA} \\ k_{1BHA} & k_{3BHA} \\ a^*{}_{c1BHA} & a^*{}_{c3BHA} \\ c_{u1BHA} & c_{u3BHA} \\ c_{a1BHA} & c_{a3BHA} \\ \alpha_{1BHA} & \alpha_{3BHA} \\ c_{1BHA} & c_{3BHA} \\ \lambda_{c1BHA} & \lambda_{c3BHA} \\ \varepsilon_{BHA} & \varepsilon_{BHA} \end{pmatrix} =$$

```
for $i \in 1$
  for $r \in 1 .. N_r$
    $\begin{pmatrix} T^*1BHA_r \\ T^*3BHA_r \end{pmatrix} \leftarrow \begin{pmatrix} T^*1BHA_{av(N_r)} \\ T^*3BHA_{av(N_r)} \end{pmatrix}$
    $\begin{pmatrix} P^*1BHA_r \\ P^*3BHA_r \end{pmatrix} \leftarrow \begin{pmatrix} P^*1BHA_{av(N_r)} \\ P^*3BHA_{av(N_r)} \end{pmatrix}$
    $\begin{pmatrix} \rho^*1BHA_r \\ \rho^*3BHA_r \end{pmatrix} \leftarrow \begin{pmatrix} \rho^*1BHA_{av(N_r)} \\ \rho^*3BHA_{av(N_r)} \end{pmatrix}$
    $\begin{pmatrix} Cp_{1BHA_r} \\ Cp_{3BHA_r} \end{pmatrix} \leftarrow \begin{pmatrix} Cp_{воздух}\left(P^*1BHA_r, T^*1BHA_r\right) \\ Cp_{воздух}\left(P^*3BHA_r, T^*3BHA_r\right) \end{pmatrix}$
    $\begin{pmatrix} k_{1BHA_r} \\ k_{3BHA_r} \end{pmatrix} \leftarrow \begin{pmatrix} k_{ад}\left(Cp_{1BHA_r}, R_в\right) \\ k_{ад}\left(Cp_{3BHA_r}, R_в\right) \end{pmatrix}$
    $\begin{pmatrix} a^*{}_{c1BHA_r} \\ a^*{}_{c3BHA_r} \end{pmatrix} \leftarrow \begin{pmatrix} \sqrt{\frac{2 \cdot k_{1BHA_r}}{k_{1BHA_r} + 1} \cdot R_в \cdot T^*1BHA_r} \\ \sqrt{\frac{2 \cdot k_{3BHA_r}}{k_{3BHA_r} + 1} \cdot R_в \cdot T^*3BHA_r} \end{pmatrix}$
    $A \leftarrow \left(1 - R_{L_{i, av(N_r)}}\right) \cdot \omega \cdot \left(R_{st(i,1), av(N_r)}\right)^{m_i + 1}$
    $B \leftarrow \frac{H_{T_{i, av(N_r)}}}{2 \cdot \omega}$
    $\Bigg[ \; c_{u1BHA_{av(N_r)}}$
```

$$\begin{pmatrix} c_{u1BHA_r} \\ c_{u3BHA_r} \end{pmatrix} = \begin{cases} \dfrac{A}{\left(R_{st(i,1),r}\right)^{m_i}} - \dfrac{B}{\left(R_{st(i,1),r}\right)} & \text{if } BHA = 1 \\ c_{u1BHA_{av(N_r)}} & \text{otherwise} \end{cases}$$

$$c_{a1BHA_{av(N_r)}}$$

$$\begin{pmatrix} c_{a1BHA_r} \\ c_{a3BHA_r} \end{pmatrix} = \begin{cases} \sqrt{\left(c_{a3BHA_{av(N_r)}}\right)^2 + 2\cdot A^2\cdot\left[\left(R_{st(i,1),av(N_r)}\right)^2 - \left(R_{st(i,1),r}\right)^2\right] + 4\cdot A\cdot B\cdot\left(\ln\left(R_{st(i,1),r}\right) - \ln\left(R_{st(i,1),av(N_r)}\right)\right)} & \text{if } m_i = -1 \\ \sqrt{\left(c_{a3BHA_{av(N_r)}}\right)^2 + 2\cdot A^2\cdot\ln\left(R_{st(i,1),av(N_r)}\right) - 2\cdot A^2\cdot\ln\left(R_{st(i,1),r}\right) - \dfrac{2\cdot A\cdot B}{R_{st(i,1),r}} + \dfrac{2\cdot A\cdot B}{R_{st(i,1),av(N_r)}}} & \text{if } m_i = 0 \\ \sqrt{\left(c_{a3BHA_{av(N_r)}}\right)^2 + \dfrac{A\cdot\left(m_i - 1\right)\cdot\left[A\cdot\left[\left(R_{st(i,1),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,1),av(N_r)}\right) - \left(R_{st(i,1),r}\right)\cdot\left(R_{st(i,1),av(N_r)}\right)^{2\cdot m_i+1}\right] - 2\cdot B\cdot m_i\cdot\left[\left(R_{st(i,1),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,1),av(N_r)}\right)^{m_i} - (R_{st(i,}\right.\right.}{m_i\cdot\left(m_i + 1\right)\cdot(R_{st(i,1),r}\cdot R_{st(i,1),av(N_r)}}} \end{cases}$$

$$\begin{pmatrix} \alpha_{1BHA_r} \\ \alpha_{3BHA_r} \end{pmatrix} = \begin{pmatrix} \text{triangle}\left(c_{a1BHA_r}, c_{u1BHA_r}\right) \\ \text{triangle}\left(c_{a3BHA_r}, c_{u3BHA_r}\right) \end{pmatrix}$$

$$\begin{pmatrix} c_{1BHA_r} \\ c_{3BHA_r} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{a1BHA_r}}{\sin\left(\alpha_{1BHA_r}\right)} \\ \dfrac{c_{a3BHA_r}}{\sin\left(\alpha_{3BHA_r}\right)} \end{pmatrix}$$

$$\begin{pmatrix} \lambda_{c1BHA_r} \\ \lambda_{c3BHA_r} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{1BHA_r}}{a^*_{c1BHA_r}} \\ \dfrac{c_{3BHA_r}}{a^*_{c3BHA_r}} \end{pmatrix}$$

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

$$\begin{pmatrix} T^*_{1BHA} & P^*_{1BHA} & \rho^*_{1BHA} & Cp_{1BHA} & k_{1BHA} & a^*_{c1BHA} & c_{u1BHA} & c_{a1BHA} & \alpha_{1BHA} & c_{1BHA} & \lambda_{c1BHA} & \varepsilon_{BHA} \\ T^*_{3BHA} & P^*_{3BHA} & \rho^*_{3BHA} & Cp_{3BHA} & k_{3BHA} & a^*_{c3BHA} & c_{u3BHA} & c_{a3BHA} & \alpha_{3BHA} & c_{3BHA} & \lambda_{c3BHA} & \varepsilon_{BHA} \end{pmatrix}^T$$

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

```
for $i \in 1..Z$
  for $a \in 1..3$
    for $r \in 1..N_r$
      $T^*_{st(i,a),r} = T^*_{st(i,a),av(N_r)}$
      $P^*_{st(i,a),r} = P^*_{st(i,a),av(N_r)}$
      $\rho^*_{st(i,a),r} = \rho^*_{st(i,a),av(N_r)}$
      $Cp_{st(i,a),r} = Cp_{воздух}(P^*_{st(i,a),r}, T^*_{st(i,a),r})$
      $k_{st(i,a),r} = k_{ад}(Cp_{st(i,a),r}, R_в)$
      $a^*c_{st(i,a),r} = \sqrt{\frac{2\cdot k_{st(i,a),r}}{k_{st(i,a),r}+1}\cdot R_в\cdot T^*_{st(i,a),r}}$
      if $\Delta H_{Tmax} = 0$
        $A_{st(i,a),r} = \left(1 - R_{L_{i,av(N_r)}}\right)\cdot\omega\cdot\left(R_{st(i,a),av(N_r)}\right)^{m_i+1}$
        $B_{st(i,a),r} = \frac{H_{T_{i,av(N_r)}}}{2\cdot\omega}$
        $c_{u_{st(i,a),r}} =$
          $\frac{A_{st(i,a),r}}{\left(R_{st(i,a),r}\right)^{m_i}} + \frac{B_{st(i,a),r}}{\left(R_{st(i,a),r}\right)}$  if $a = 2$
          $\frac{A_{st(i,a),r}}{\left(R_{st(i,a),r}\right)^{m_i}} - \frac{B_{st(i,a),r}}{\left(R_{st(i,a),r}\right)}$  otherwise
        $c_{a_{st(i,a),r}} =$
          if $m_i = -1$
            $\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left[\left(R_{st(i,a),av(N_r)}\right)^2 - \left(R_{st(i,a),r}\right)^2\right] - 4\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}\cdot\left(\ln\left(R_{st(i,a),r}\right) - \ln\left(R_{st(i,a),av(N_r)}\right)\right)}$  if $a = 2$
            $\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left[\left(R_{st(i,a),av(N_r)}\right)^2 - \left(R_{st(i,a),r}\right)^2\right] + 4\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}\cdot\left(\ln\left(R_{st(i,a),r}\right) - \ln\left(R_{st(i,a),av(N_r)}\right)\right)}$  otherwise
          if $m_i = 0$
            $\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),av(N_r)}\right) - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),r}\right) + \frac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{} - \frac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{}}$  if $a = 2$
```

$R_{st(i,a),r}$ $\quad R_{st(i,a),av(N_r)}$

$$\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),av(N_r)}\right) - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\ln\left(R_{st(i,a),r}\right) - \frac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{R_{st(i,a),r}} + \frac{2\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}}{R_{st(i,a),av(N_r)}}} \quad \text{otherwise}$$

otherwise

$$\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + \frac{A_{st(i,a),r}\cdot\left(m_i-1\right)\cdot\Bigl[A_{st(i,a),r}\cdot\left[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,a),av(N_r)}\right) - \left(R_{st(i,a),r}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\right] + 2\cdot B_{st(i,a),r}\cdot m_i\cdot\Bigl[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\bigl(R_s}{m_i\cdot\left(m_i+1\right)\cdot\bigl(R_{st(i,a),}}}$$

$$\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + \frac{A_{st(i,a),r}\cdot\left(m_i-1\right)\cdot\Bigl[A_{st(i,a),r}\cdot\left[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,a),av(N_r)}\right) - \left(R_{st(i,a),r}\right)\cdot\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i+1}\right] - 2\cdot B_{st(i,a),r}\cdot m_i\cdot\Bigl[\left(R_{st(i,a),r}\right)^{2\cdot m_i+1}\cdot\bigl(R_s}{m_i\cdot\left(m_i+1\right)\cdot\bigl(R_{st(i,a),}}}$$

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

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

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

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

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

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

$$c_{a_{st(i,a),r}} = \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2 - \left(R_{st(i,a),av(N_r)}\right)^2\right] - \left(6\cdot\frac{A_{st(i,a),r}}{\omega} - 2\right)\cdot k_{HT}\cdot\left(R_{st(i,a),r} - R_{st(i,a),av(N_r)}\right) - 2\cdot\frac{k_{HT}}{\omega}\cdot\left(B_{st(i,a),r} + \frac{b_{HT}}{\omega}\right)\cdot\frac{R_{st(i,a),r} - R_s}{R_{st(i,a),r}\cdot R_{st}}}$$

$$\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 - 2\cdot\left(A_{st(i,a),r}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2 - \left(R_{st(i,a),av(N_r)}\right)^2\right] - 4\cdot A_{st(i,a),r}\cdot B_{st(i,a),r}\cdot\ln\left(\frac{R_{st(i,a),r}}{R_{st(i,a),av(N_r)}}\right)} \quad \text{otherwise}$$

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

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

$c_{st(i,a),r}$

```
        $\lambda_{c_{st(i,a),r}} = \frac{\;_{st(i,a),r}}{a^*_{c_{st(i,a),r}}}$
        $\begin{pmatrix} T_{st(i,a),r} \\ P_{st(i,a),r} \\ \rho_{st(i,a),r} \end{pmatrix} = \begin{pmatrix} T^*_{st(i,a),r} \cdot ГДФ\left(\text{"T"}, \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \\ P^*_{st(i,a),r} \cdot ГДФ\left(\text{"P"}, \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \\ \rho^*_{st(i,a),r} \cdot ГДФ\left(\text{"}\rho\text{"}, \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \end{pmatrix}$
        $a_{зв_{st(i,a),r}} = \sqrt{k_{st(i,a),r} \cdot R_в \cdot T_{st(i,a),r}}$
        $\beta_{st(i,a),r} = \text{triangle}\left(c_{a_{st(i,a),r}}, u_{st(i,a),r} - c_{u_{st(i,a),r}}\right)$
        $w_{st(i,a),r} = \frac{c_{a_{st(i,a),r}}}{\sin\left(\beta_{st(i,a),r}\right)}$
        $w_{u_{st(i,a),r}} = w_{st(i,a),r} \cdot \cos\left(\beta_{st(i,a),r}\right)$
        $\begin{pmatrix} M_{w_{st(i,a),r}} \\ M_{c_{st(i,a),r}} \end{pmatrix} = \frac{1}{a_{зв_{st(i,a),r}}} \cdot \begin{pmatrix} w_{st(i,a),r} \\ c_{st(i,a),r} \end{pmatrix}$
    for $r \in 1 .. N_r$
        $R_{L_{i,r}} = 1 - \frac{c_{u_{st(i,1),r}} + c_{u_{st(i,2),r}}}{u_{st(i,1),r} + u_{st(i,2),r}}$
        $\begin{pmatrix} \varepsilon_{rotor_{i,r}} \\ \varepsilon_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \beta_{st(i,2),r} - \beta_{st(i,1),r} \\ \alpha_{st(i,3),r} - \alpha_{st(i,2),r} \end{pmatrix}$
$\begin{pmatrix} T^* & P^* & \rho^* & Cp & a^*_c & c_u & \alpha & c & \lambda_c & M_w & R_L & \varepsilon_{rotor} \\ T & P & \rho & k & a_{зв} & c_a & \beta & w & w_u & M_c & R_L & \varepsilon_{stator} \end{pmatrix}^T$
```

$$\begin{pmatrix} T^*_{1CA} & T^*_{3CA} \\ P^*_{1CA} & P^*_{3CA} \\ \rho^*_{1CA} & \rho^*_{3CA} \\ Cp_{1CA} & Cp_{3CA} \\ k_{1CA} & k_{3CA} \\ a^*_{c1CA} & a^*_{c3CA} \\ c_{u1CA} & c_{u3CA} \\ c_{a1CA} & c_{a3CA} \\ \alpha_{1CA} & \alpha_{3CA} \\ c_{1CA} & c_{3CA} \\ \lambda_{c1CA} & \lambda_{c3CA} \\ \varepsilon_{CA} & \varepsilon_{CA} \end{pmatrix} =$$

```
for  $i \in Z$
  for  $r \in 1 .. N_r$
    $\begin{pmatrix} T^*_{1CA_r} \\ T^*_{3CA_r} \end{pmatrix} = \begin{pmatrix} T^*_{st(i,3),r} \\ T^*_{3CA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} P^*_{1CA_r} \\ P^*_{3CA_r} \end{pmatrix} = \begin{pmatrix} P^*_{st(i,3),r} \\ P^*_{3CA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} \rho^*_{1CA_r} \\ \rho^*_{3CA_r} \end{pmatrix} = \begin{pmatrix} \rho^*_{st(i,3),r} \\ \rho^*_{3CA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} Cp_{1CA_r} \\ Cp_{3CA_r} \end{pmatrix} = \begin{pmatrix} Cp_{воздух}\left(P^*_{1CA_r}, T^*_{1CA_r}\right) \\ Cp_{воздух}\left(P^*_{3CA_r}, T^*_{3CA_r}\right) \end{pmatrix}$
    $\begin{pmatrix} k_{1CA_r} \\ k_{3CA_r} \end{pmatrix} = \begin{pmatrix} k_{ад}\left(Cp_{1CA_r}, R_в\right) \\ k_{ад}\left(Cp_{3CA_r}, R_в\right) \end{pmatrix}$
    $\begin{pmatrix} a^*_{c1CA_r} \\ a^*_{c3CA_r} \end{pmatrix} = \begin{pmatrix} \sqrt{\dfrac{2 \cdot k_{1CA_r}}{k_{1CA_r} + 1} \cdot R_в \cdot T^*_{1CA_r}} \\ \sqrt{\dfrac{2 \cdot k_{3CA_r}}{k_{3CA_r} + 1} \cdot R_в \cdot T^*_{3CA_r}} \end{pmatrix}$
    $A \leftarrow \left(1 - R_{L_{i,av(N_r)}}\right) \cdot \omega \cdot \left(R_{st(i,3),av(N_r)}\right)^{m_i + 1}$
    $B \leftarrow \dfrac{H_{T_{i,av(N_r)}}}{2 \cdot \omega}$
    $\begin{pmatrix} c_{u1CA_r} \\ \end{pmatrix} = \begin{pmatrix} c_{u_{st(i,3),r}} \\ c_{u3CA} \quad \text{if } CA = 1 \end{pmatrix}$
```

$$\begin{pmatrix} c_{u3CA_r} \end{pmatrix} \quad \begin{cases} \ldots\ \mathrm{av}(N_r) & \\ c_{u_{st(i,3),r}} & \text{otherwise} \end{cases}$$

$$c_{a_{st(i,3),r}}$$

$$\begin{pmatrix} c_{a1CA_r} \\ c_{a3CA_r} \end{pmatrix} = \begin{cases} \sqrt{\left(c_{a3CA_{av(N_r)}}\right)^2 + 2\cdot A^2\cdot\left[\left(R_{st(i,3),av(N_r)}\right)^2 - \left(R_{st(i,3),r}\right)^2\right] + 4\cdot A\cdot B\cdot\left(\ln\left(R_{st(i,3),r}\right) - \ln\left(R_{st(i,3),av(N_r)}\right)\right)} & \text{if } m_i = -1 \\ \sqrt{\left(c_{a3CA_{av(N_r)}}\right)^2 + 2\cdot A^2\cdot\ln\left(R_{st(i,3),av(N_r)}\right) - 2\cdot A^2\cdot\ln\left(R_{st(i,3),r}\right) - \dfrac{2\cdot A\cdot B}{R_{st(i,3),r}} + \dfrac{2\cdot A\cdot B}{R_{st(i,3),av(N_r)}}} & \text{if } m_i = 0 \\ \sqrt{\left(c_{a3CA_{av(N_r)}}\right)^2 + \dfrac{A\cdot\left(m_i - 1\right)\cdot\left[A\cdot\left[\left(R_{st(i,3),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,3),av(N_r)}\right) - \left(R_{st(i,3),r}\right)\cdot\left(R_{st(i,3),av(N_r)}\right)^{2\cdot m_i+1}\right] - 2\cdot B\cdot m_i\cdot\left[\left(R_{st(i,3),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,3),av(N_r)}\right)^{m_i} - \left(R_{st(i,3),r}\right)^{m}\right.}{m_i\cdot\left(m_i + 1\right)\cdot\left(R_{st(i,3),r}\cdot R_{st(i,3),av(N_r)}\right)^{2\cdot m_i+1}}} & \end{cases}$$

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

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

$$\begin{pmatrix} \lambda_{c1CA_r} \\ \lambda_{c3CA_r} \end{pmatrix} = \begin{pmatrix} \dfrac{c_{1CA_r}}{a^*_{c1CA_r}} \\ \dfrac{c_{3CA_r}}{a^*_{c3CA_r}} \end{pmatrix}$$

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

$$\begin{pmatrix} T^*_{1CA} & P^*_{1CA} & \rho^*_{1CA} & Cp_{1CA} & k_{1CA} & a^*_{c1CA} & c_{u1CA} & c_{a1CA} & \alpha_{1CA} & c_{1CA} & \lambda_{c1CA} & \varepsilon_{CA} \\ T^*_{3CA} & P^*_{3CA} & \rho^*_{3CA} & Cp_{3CA} & k_{3CA} & a^*_{c3CA} & c_{u3CA} & c_{a3CA} & \alpha_{3CA} & c_{3CA} & \lambda_{c3CA} & \varepsilon_{CA} \end{pmatrix}^T$$

▲ Расчет параметров потока по высоте Л

▼ Результаты расчета параметров потока по высоте Л

$$T^*_{1BHA} = \begin{pmatrix} 288.2 \\ 288.2 \\ 288.2 \end{pmatrix} \qquad T^*_{3BHA} = \begin{pmatrix} 288.2 \\ 288.2 \\ 288.2 \end{pmatrix} \qquad a^*_{c1BHA} = \begin{pmatrix} 310.78 \\ 310.78 \\ 310.78 \end{pmatrix} \qquad a^*_{c3BHA} = \begin{pmatrix} 310.78 \\ 310.78 \\ 310.78 \end{pmatrix} \qquad \alpha_{1BHA} = \begin{pmatrix} 90.00 \\ 90.00 \\ 90.00 \end{pmatrix} \cdot ° \qquad \alpha_{3BHA} = \begin{pmatrix} 90.00 \\ 90.00 \\ 90.00 \end{pmatrix} \cdot °$$

$$P^*_{1BHA} = \begin{pmatrix} 101.3 \\ 101.3 \\ 101.3 \end{pmatrix} \cdot 10^3 \qquad P^*_{3BHA} = \begin{pmatrix} 101.3 \\ 101.3 \\ 101.3 \end{pmatrix} \cdot 10^3 \qquad c_{1BHA} = \begin{pmatrix} 83.4 \\ 83.4 \\ 83.4 \end{pmatrix} \qquad c_{3BHA} = \begin{pmatrix} 83.4 \\ 83.4 \\ 83.4 \end{pmatrix} \qquad \varepsilon_{BHA} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot °$$

$$\rho^*_{1BHA} = \begin{pmatrix} 1.224 \\ 1.224 \\ 1.224 \end{pmatrix} \qquad \rho^*_{3BHA} = \begin{pmatrix} 1.224 \\ 1.224 \\ 1.224 \end{pmatrix} \qquad c_{u1BHA} = \begin{pmatrix} 0.0 \\ 0.0 \\ 0.0 \end{pmatrix} \qquad c_{u3BHA} = \begin{pmatrix} 0.0 \\ 0.0 \\ 0.0 \end{pmatrix}$$

$$Cp_{1BHA} = \begin{pmatrix} 1002.6 \\ 1002.6 \\ 1002.6 \end{pmatrix} \qquad Cp_{3BHA} = \begin{pmatrix} 1002.6 \\ 1002.6 \\ 1002.6 \end{pmatrix} \qquad c_{a1BHA} = \begin{pmatrix} 83.4 \\ 83.4 \\ 83.4 \end{pmatrix} \qquad c_{a3BHA} = \begin{pmatrix} 83.4 \\ 83.4 \\ 83.4 \end{pmatrix} \qquad \lambda_{c1BHA} = \begin{pmatrix} 0.268 \\ 0.268 \\ 0.268 \end{pmatrix} \qquad \lambda_{c3BHA} = \begin{pmatrix} 0.268 \\ 0.268 \\ 0.268 \end{pmatrix}$$

$$k_{1BHA} = \begin{pmatrix} 1.401 \\ 1.401 \\ 1.401 \end{pmatrix} \qquad k_{3BHA} = \begin{pmatrix} 1.401 \\ 1.401 \\ 1.401 \end{pmatrix}$$

$T^{*T} =$

	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	313.9	313.9	341.4	341.4	361.5	361.5																		
2	288.2	313.9	313.9	341.4	341.4	361.5	361.5																		
3	288.2	313.9	313.9	341.4	341.4	361.5	361.5																		

$T^{T} =$

	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	283.2	295.0	310.2	322.1	337.7	346.0	358.9																		
2	283.6	299.4	310.5	327.0	338.3	350.4	359.3																		
3	283.8	302.0	310.7	329.7	338.6	352.7	359.4																		

$P^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	101.3	131.7	131.7	170.8	170.8	202.7	202.7														
2	101.3	131.7	131.7	170.8	170.8	202.7	202.7														
3	101.3	131.7	131.7	170.8	170.8	202.7	202.7														

$\cdot 10^3$

$P^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	95.3	105.9	126.2	139.2	164.3	173.7	197.6														
2	95.8	111.6	126.7	146.7	165.3	181.6	198.3														
3	96.1	115.0	127.0	151.0	165.8	185.8	198.6														

$\cdot 10^3$

$\rho^{*T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.224	1.461	1.461	1.742	1.742	1.952	1.952														
2	1.224	1.461	1.461	1.742	1.742	1.952	1.952														
3	1.224	1.461	1.461	1.742	1.742	1.952	1.952														

$\rho^{T} =$

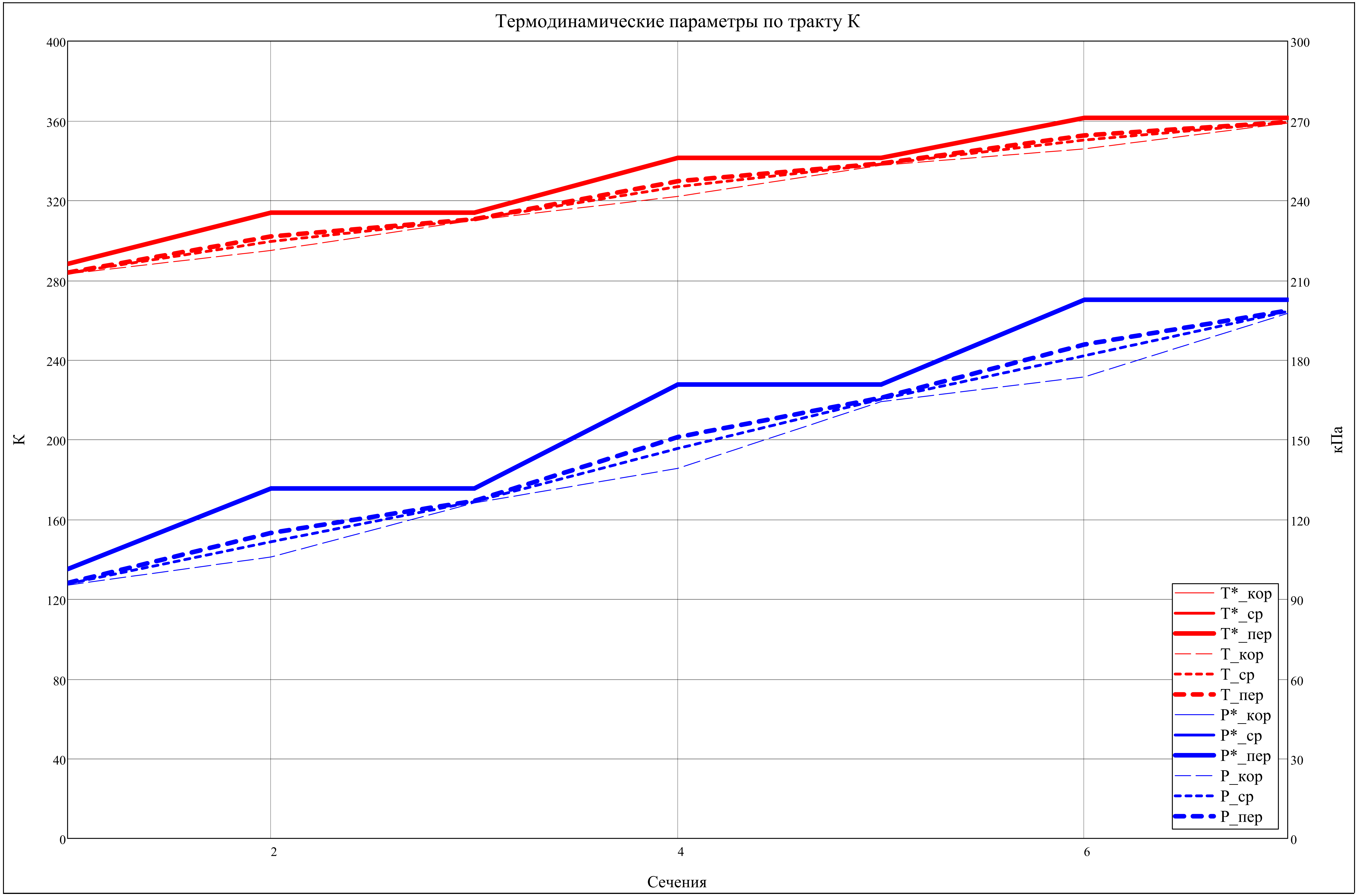
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.172	1.250	1.417	1.505	1.695	1.748	1.917														
2	1.176	1.298	1.421	1.563	1.702	1.805	1.922														
3	1.179	1.326	1.423	1.595	1.705	1.835	1.925														

$Cp^{T} =$

	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	1004	1004	1006	1006	1009	1009																		
2	1003	1004	1004	1006	1006	1009	1009																		
3	1003	1004	1004	1006	1006	1009	1009																		

$k^{T} =$

	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	1.401	1.401	1.399	1.399	1.398	1.398																		
2	1.401	1.401	1.401	1.399	1.399	1.398	1.398																		
3	1.401	1.401	1.401	1.399	1.399	1.398	1.398																		


Термодинамические параметры по тракту К
400
360
320
280
240
200
160
120
80
40
0
300
270
240
210
180
150
120
90
60
30
0
К
кПа
2
4
6
Сечения
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	324.3	324.3	338.2	338.2	347.9	347.9																		
2	310.8	324.3	324.3	338.2	338.2	347.9	347.9																		
3	310.8	324.3	324.3	338.2	338.2	347.9	347.9																		

$a_{зв}^T =$

	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	337.6	344.4	353.2	359.7	368.4	372.7	379.6																		
2	337.8	347.0	353.4	362.4	368.7	375.0	379.8																		
3	338.0	348.5	353.5	363.9	368.8	376.3	379.9																		

$c^T =$

	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	100.5	195.2	87.1	197.3	86.4	177.1	72.6																		
2	96.0	170.6	83.0	170.7	79.8	149.7	67.3																		
3	93.4	154.9	80.6	153.9	76.0	133.4	64.6																		

$w^T =$

	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	177.7	82.0	179.0	69.6	152.9	62.1	140.1																		
2	219.8	123.3	220.5	110.1	197.8	107.3	187.4																		
3	255.8	166.1	256.0	154.0	235.3	153.3	225.8																		

$u^T =$

	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	212.8	213.6	214.4	207.9	201.4	187.7	174.3																		
2	250.8	251.2	251.5	245.5	239.6	227.6	215.9																		
3	283.8	283.8	283.8	278.1	272.5	261.6	250.7																		

$c_a^T =$

	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	83.4	74.9	71.1	66.0	61.0	58.6	56.1																		
2	83.4	74.9	71.1	66.0	61.0	58.6	56.1																		
3	83.4	74.9	71.1	66.0	61.0	58.6	56.1																		

$c_u^T =$

	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	56.0	180.2	50.2	186.0	61.2	167.1	46.0																		
2	47.5	153.3	42.8	157.4	51.5	137.8	37.1																		
3	42.0	135.6	37.9	139.0	45.3	119.9	32.0																		

$w_u^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	156.8	33.4	164.2	21.9	140.2	20.6	128.3																		
2	203.4	97.9	208.7	88.1	188.1	89.9	178.8																		
3	241.8	148.2	245.9	139.1	227.2	141.7	218.7																		

```
$\Delta c_a$ = | for $i \in 1..Z$
               |   for $a \in 2..3$
               |     for $r \in 1..N_r$
               |       $\Delta c_{a_{st(i,a),r}} = c_{a_{st(i,a),r}} - c_{a_{st(i,a-1),r}}$
               | $\Delta c_a$
```

$\Delta c_a^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0.00	-8.51	-3.78	-5.13	-4.98	-2.44	-2.44														
2	0.00	-8.51	-3.78	-5.13	-4.98	-2.44	-2.44														
3	0.00	-8.51	-3.78	-5.13	-4.98	-2.44	-2.44														

[16, c. 81]

$\Delta c_a^T \ge -25 =$

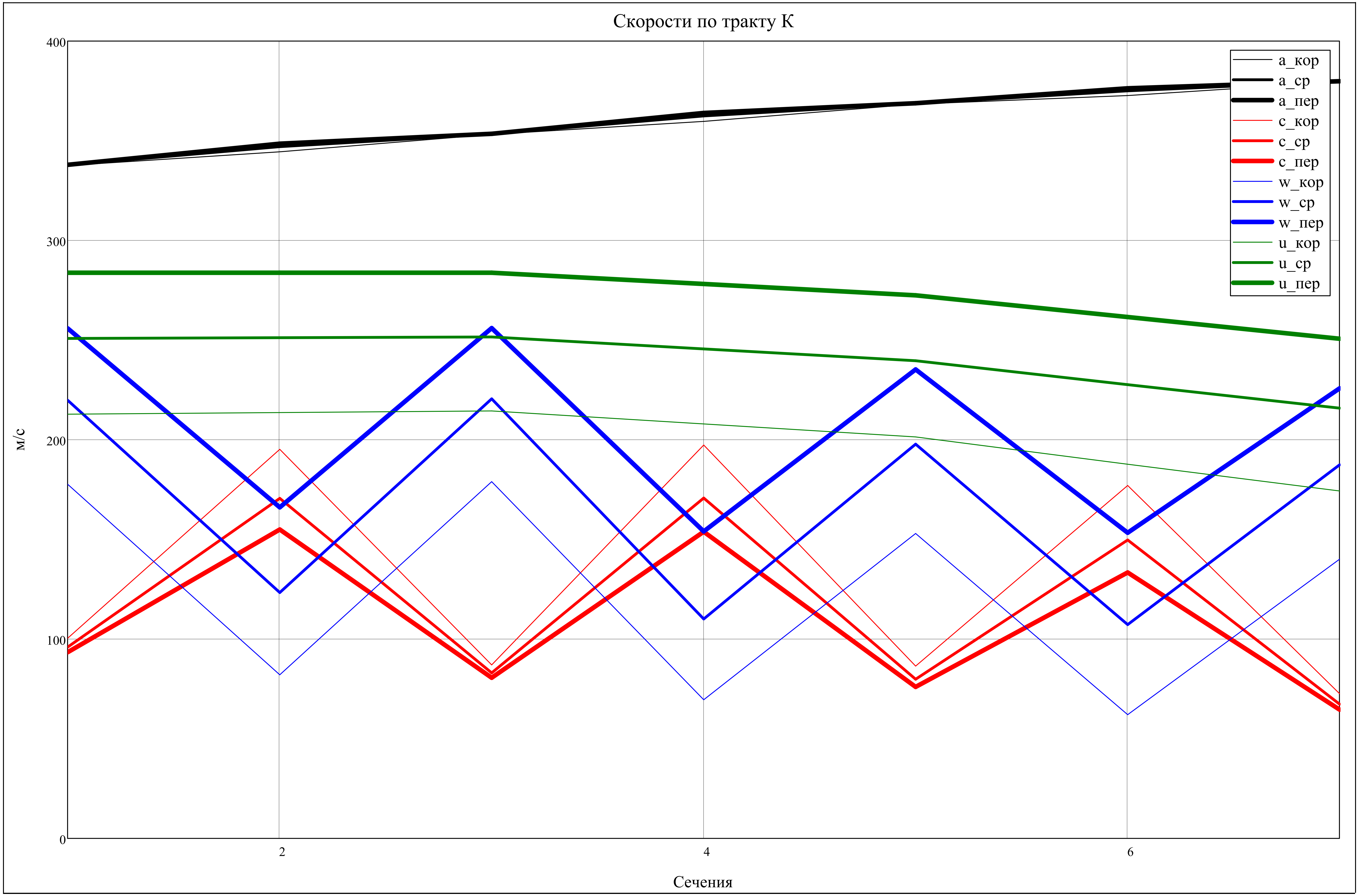
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	1	1	1	1	1	1																		
2	1	1	1	1	1	1	1																		
3	1	1	1	1	1	1	1																		

$R_L^T =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.4462	0.4408	0.4133									
2	0.6001	0.5972	0.5950									
3	0.6871	0.6852	0.6907									

$R_L^T \ge 0 =$

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


Скорости по тракту К
400
300
200
100
0
м/с
2
4
6
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	56.15	22.58	54.79	19.54	44.91	19.32	50.69																		
2	60.36	26.05	58.97	22.75	49.86	23.04	56.54																		
3	63.30	28.92	61.94	25.40	53.44	26.04	60.35																		

$\cdot°$

$\beta^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	28.01	65.96	23.42	71.62	23.52	70.63	23.63														
2	22.31	37.42	18.82	36.84	17.97	33.10	17.44														
3	19.04	26.82	16.14	25.38	15.04	22.47	14.40														

$\cdot°$

$\beta^T \le 91\cdot° =$

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

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

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

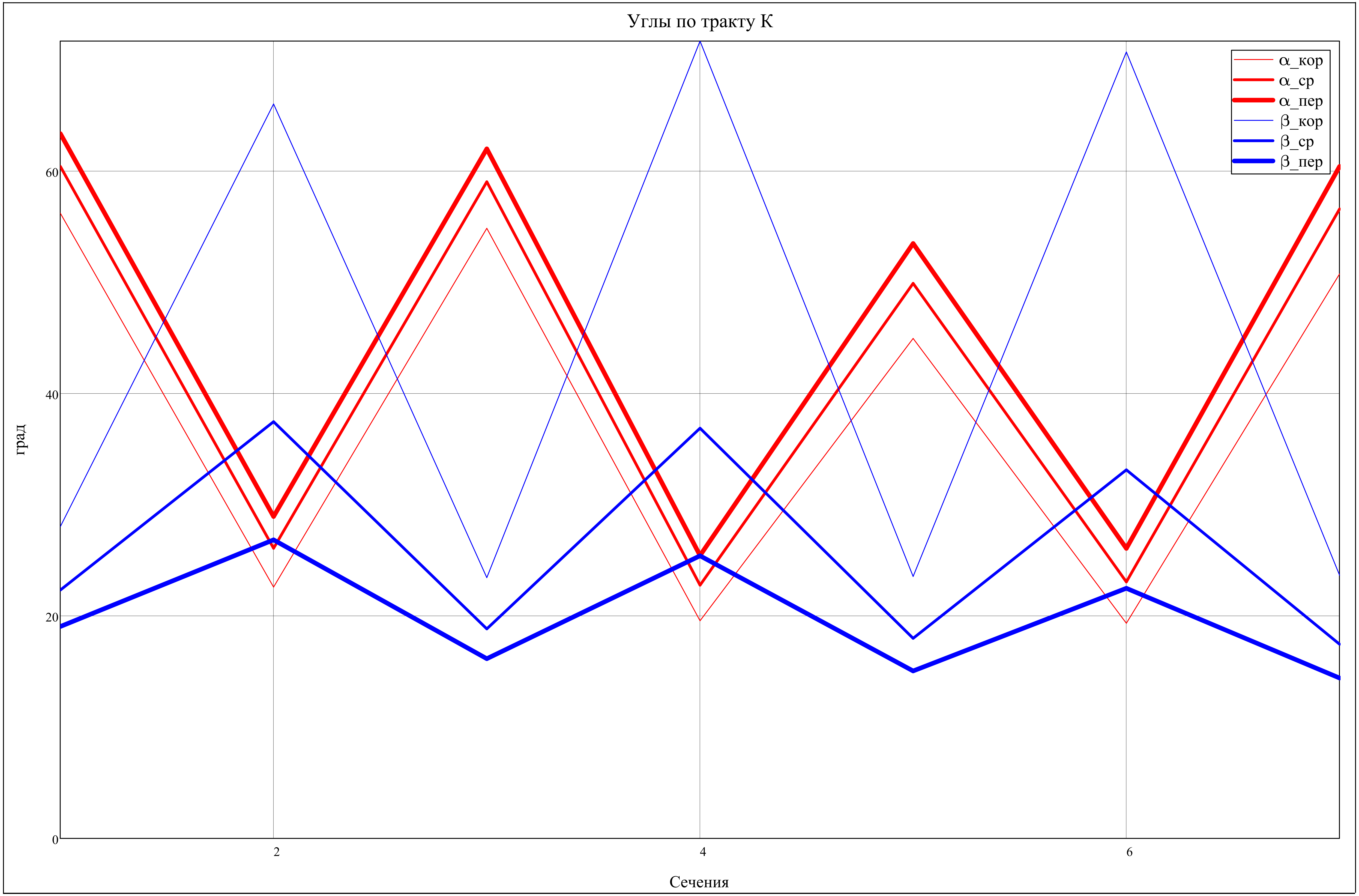
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	37.95	48.19	47.11												
2	15.11	18.02	15.12												
3	7.79	9.24	7.43												

$\cdot°$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	29.12	36.05	31.37												
2	29.99	37.32	33.50												
3	30.26	37.74	34.31												

$\cdot°$

Углы по тракту К
град
60
40
20
0
2
4
6
Сечения
α_кор
α_ср
α_пер
β_кор
β_ср
β_пер

$\lambda_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.3233	0.6017	0.2685	0.5835	0.2556	0.5089	0.2086																
2	0.3089	0.5260	0.2560	0.5048	0.2361	0.4303	0.1935																
3	0.3005	0.4778	0.2486	0.4550	0.2247	0.3836	0.1857																

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

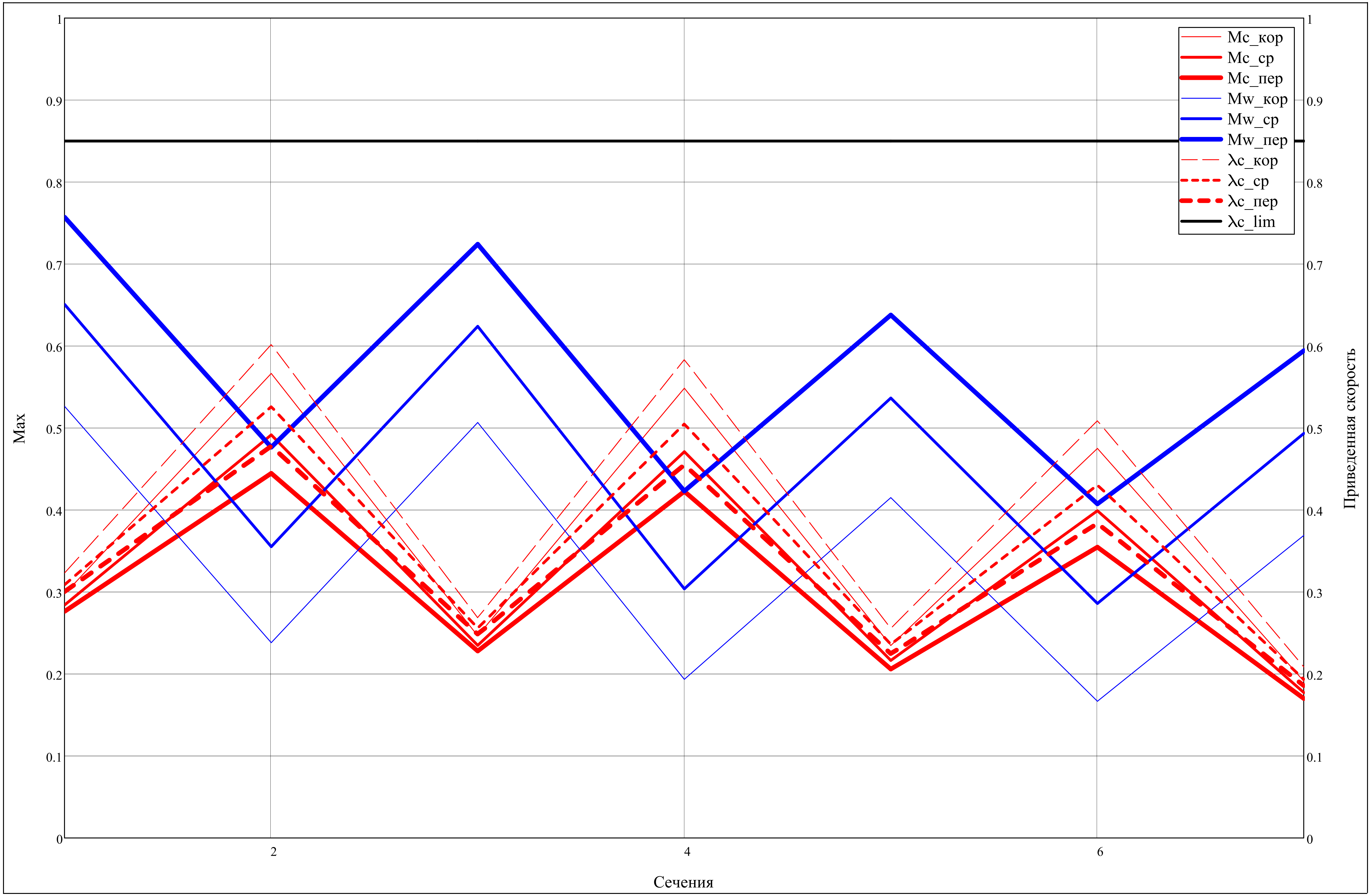
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1	1	1	1	1	1	1												
2	1	1	1	1	1	1	1												
3	1	1	1	1	1	1	1												

$M_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.2977	0.5666	0.2465	0.5485	0.2347	0.4751	0.1912																
2	0.2842	0.4916	0.2349	0.4710	0.2166	0.3991	0.1772																
3	0.2764	0.4446	0.2281	0.4228	0.2060	0.3546	0.1701																

$M_w^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.5263	0.2382	0.5068	0.1934	0.4152	0.1667	0.3690																
2	0.6507	0.3553	0.6241	0.3037	0.5365	0.2861	0.4934																
3	0.7570	0.4765	0.7242	0.4232	0.6379	0.4075	0.5944																



Max
Приведенная скорость
Сечения
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
4
6
Mc_кор
Mc_ср
Mc_пер
Mw_кор
Mw_ср
Mw_пер
λc_кор
λc_ср
λc_пер
λc_lim

$$T^*_{1CA} = \begin{pmatrix} 361.5 \\ 361.5 \\ 361.5 \end{pmatrix} \qquad T^*_{3CA} = \begin{pmatrix} 361.5 \\ 361.5 \\ 361.5 \end{pmatrix} \qquad a^*_{c1CA} = \begin{pmatrix} 347.9 \\ 347.9 \\ 347.9 \end{pmatrix} \qquad a^*_{c3CA} = \begin{pmatrix} 347.9 \\ 347.9 \\ 347.9 \end{pmatrix} \qquad \alpha_{1CA} = \begin{pmatrix} 50.69 \\ 56.54 \\ 60.35 \end{pmatrix} \cdot ^\circ \qquad \alpha_{3CA} = \begin{pmatrix} 50.69 \\ 56.54 \\ 60.35 \end{pmatrix} \cdot ^\circ$$

$$P^*_{1CA} = \begin{pmatrix} 202.7 \\ 202.7 \\ 202.7 \end{pmatrix} \cdot 10^3 \qquad P^*_{3CA} = \begin{pmatrix} 202.7 \\ 202.7 \\ 202.7 \end{pmatrix} \cdot 10^3 \qquad c_{1CA} = \begin{pmatrix} 72.6 \\ 67.3 \\ 64.6 \end{pmatrix} \qquad c_{3CA} = \begin{pmatrix} 72.6 \\ 67.3 \\ 64.6 \end{pmatrix} \qquad \varepsilon_{CA} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot ^\circ$$

$$\rho^*_{1CA} = \begin{pmatrix} 1.952 \\ 1.952 \\ 1.952 \end{pmatrix} \qquad \rho^*_{3CA} = \begin{pmatrix} 1.952 \\ 1.952 \\ 1.952 \end{pmatrix} \qquad c_{u1CA} = \begin{pmatrix} 46.0 \\ 37.1 \\ 32.0 \end{pmatrix} \qquad c_{u3CA} = \begin{pmatrix} 46.0 \\ 37.1 \\ 32.0 \end{pmatrix}$$

$$Cp_{1CA} = \begin{pmatrix} 1008.5 \\ 1008.5 \\ 1008.5 \end{pmatrix} \qquad Cp_{3CA} = \begin{pmatrix} 1008.5 \\ 1008.5 \\ 1008.5 \end{pmatrix} \qquad c_{a1CA} = \begin{pmatrix} 56.1 \\ 56.1 \\ 56.1 \end{pmatrix} \qquad c_{a3CA} = \begin{pmatrix} 56.1 \\ 56.1 \\ 56.1 \end{pmatrix} \qquad \lambda_{c1CA} = \begin{pmatrix} 0.209 \\ 0.193 \\ 0.186 \end{pmatrix} \qquad \lambda_{c3CA} = \begin{pmatrix} 0.209 \\ 0.193 \\ 0.186 \end{pmatrix}$$

$$k_{1CA} = \begin{pmatrix} 1.398 \\ 1.398 \\ 1.398 \end{pmatrix} \qquad k_{3CA} = \begin{pmatrix} 1.398 \\ 1.398 \\ 1.398 \end{pmatrix}$$

▲ Результаты расчета параметров потока по высоте Л

Вывод результатов расчета параметров потока по высоте Л

Рассматриваемая ступень:

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

Построение треугольников скоростей в 3х сечениях

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

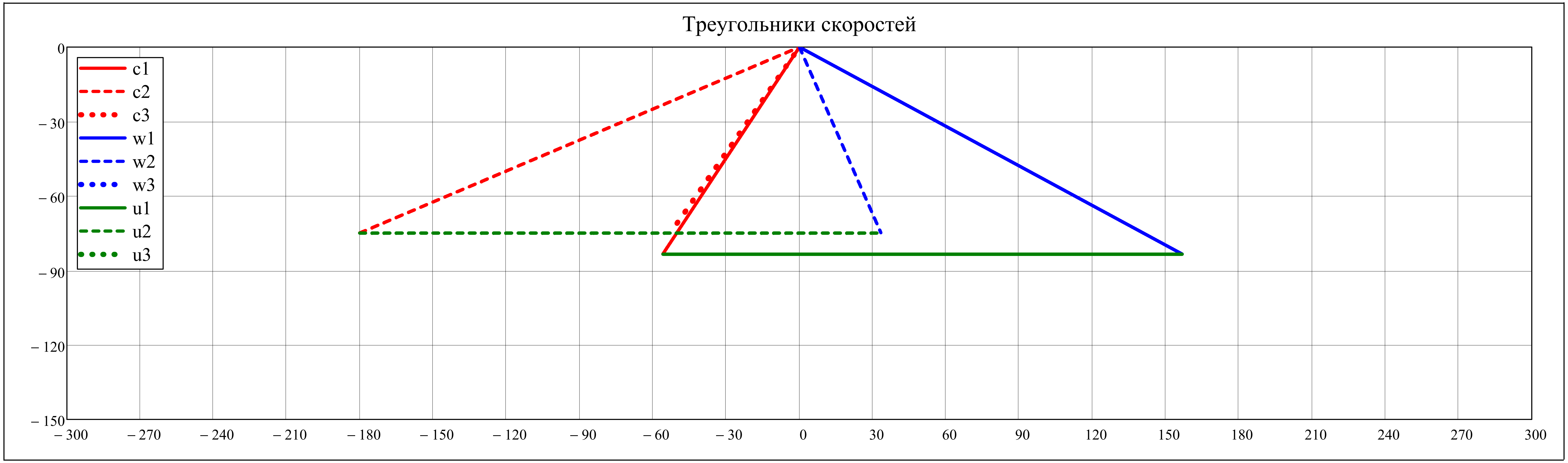
$$\Delta_w(v,i,j,r) := \left| \begin{array}{l} -\tan\left(\beta_{st(i,j),r}\right)\cdot v \ \text{ if } \left(-\tan\left(\beta_{st(i,j),r}\right) \ge 0\right) \wedge \left(-\left|w_{st(i,j),r}\cdot\cos\left(\beta_{st(i,j),r}\right)\right| \le v \le 0\right) \wedge (j \ne 3) \\ -\tan\left(\beta_{st(i,j),r}\right)\cdot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

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

$$v_{lim} := \text{ceil}\left(\frac{\max(c,w,u)}{10^2}\right)\cdot 10^2 = 300$$

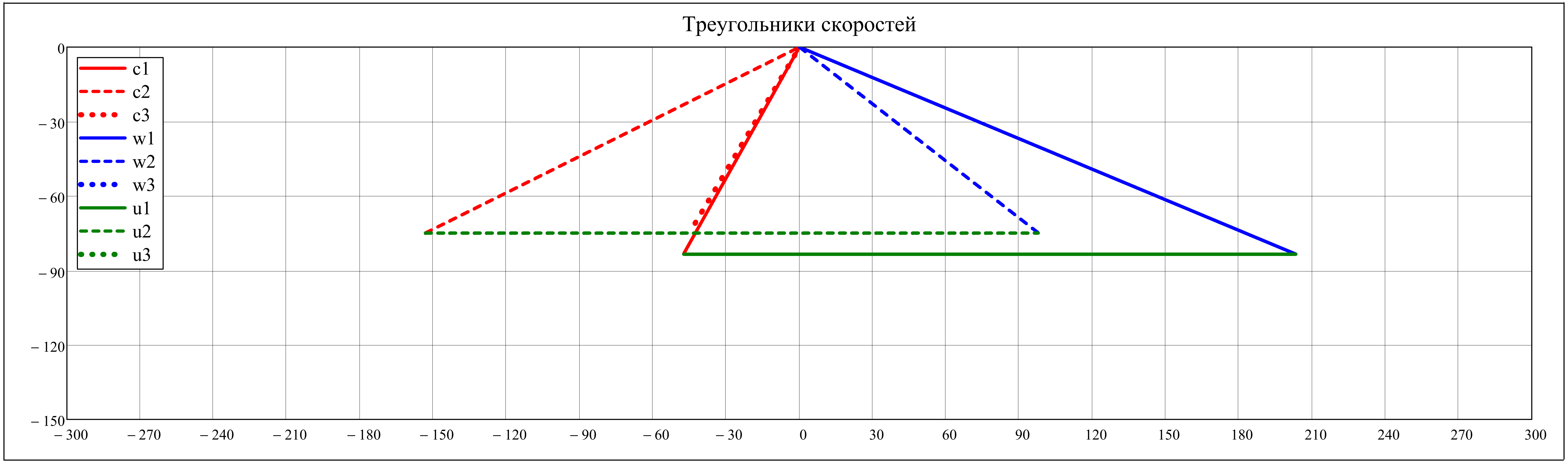
Дискретизация скорости: $v := -v_{lim}, -v_{lim} + \frac{v_{lim}}{3000} .. v_{lim}$

$r = 1$

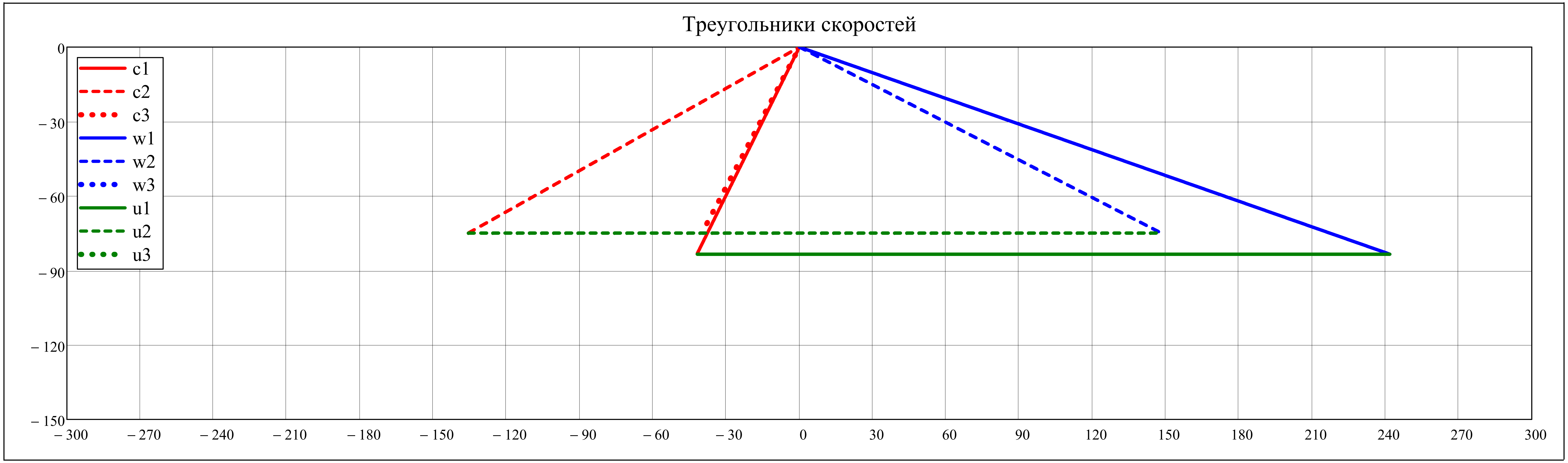


Треугольники скоростей
c1
c2
c3
w1
w2
w3
u1
u2
u3
0
– 30
– 60
– 90
– 120
– 150
– 300
– 270
– 240
– 210
– 180
– 150
– 120
– 90
– 60
– 30
0
30
60
90
120
150
180
210
240
270
300

$r = av(N_r)$


Треугольники скоростей
c1
c2
c3
w1
w2
w3
u1
u2
u3
0
− 30
− 60
− 90
− 120
− 150
− 300
− 270
− 240
− 210
− 180
− 150
− 120
− 90
− 60
− 30
0
30
60
90
120
150
180
210
240
270
300

$r = N_r$



▲ Построение треугольников скоростей в 3х сечениях

Определение степени повышения полного давлеия по 2ум контурам

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

Кольцевые площади (м^2):

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0514	0.0509	0.0504	0.0497	0.0490	0.0484	0.0473												
2	0.3083	0.3053	0.3023	0.2985	0.2942	0.2902	0.2837												
3	0.3596	0.3484	0.3526	0.3476	0.3433	0.3404	0.3310												

Радиус и диаметр двухконтурности (м):

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	404.2	405.4	406.6	395.2	383.9	360.2	337.1												
2	808.4	810.8	813.1	790.3	767.7	720.4	674.3												

$\cdot 10^{-3}$

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

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

	1	2	3	4	5	6	7	8	9	10	11	12
1	1.300	1.297	1.187									
2	1.300	1.297	1.187									

$\prod_{i=1}^{Z} \pi^*_{I_i} = 2.000$

$\prod_{i=1}^{Z} \pi^*_{II_i} = 2.000$

Определение степени повышения полного давлеия по 2ум контурам

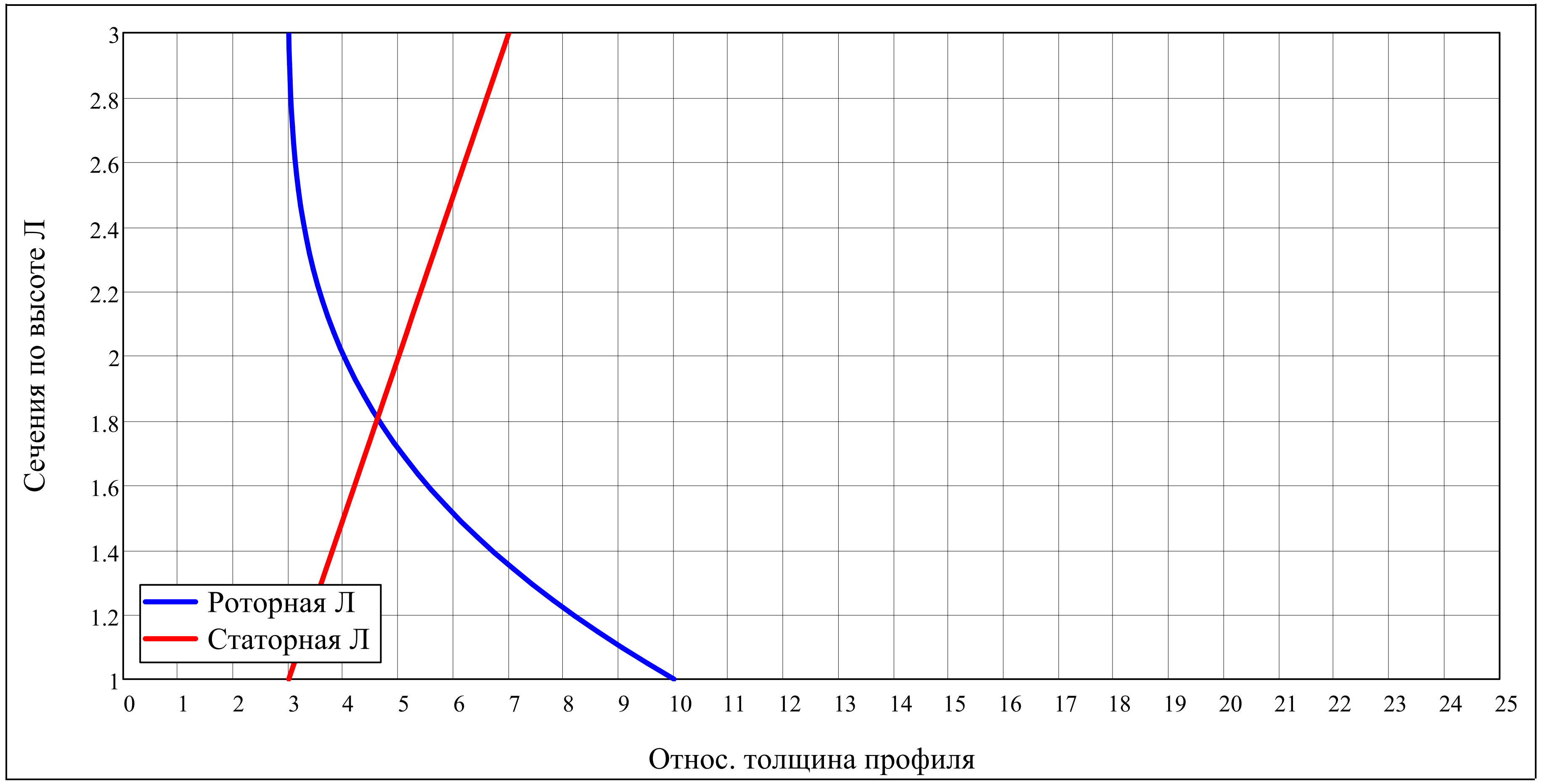
Относ. толщины и радиусы профилей

Относ. толщины Л РК и СА:

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

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

$$\overline{c}_{stator.}(r) = interp\left[cspline\left[\begin{pmatrix}1\\ av\left(N_r\right)\\ N_r\end{pmatrix}, \begin{pmatrix}3\\5\\7\end{pmatrix}\%\right], \begin{pmatrix}1\\ av\left(N_r\right)\\ N_r\end{pmatrix}, \begin{pmatrix}3\\5\\7\end{pmatrix}\%, r\right]$$



```
$\overline{c}_{BHA}$ = | for $r \in 1..N_r$
                       |   $\overline{c}_{BHA_r} = \overline{c}_{stator.}(r)$
                       | $\overline{c}_{BHA}$
```

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

	1
1	3.00
2	5.00
3	7.00

$\cdot\%$

```
$\begin{pmatrix}\overline{c}_{stator}\\ \overline{c}_{rotor}\end{pmatrix}$ = | for $i \in 1..Z$
                                                                                |   for $r \in 1..N_r$
                                                                                |     $\begin{pmatrix}\overline{c}_{stator_{i,r}}\\ \overline{c}_{rotor_{i,r}}\end{pmatrix} = \begin{pmatrix}\overline{c}_{stator.}(r)\\ \overline{c}_{rotor.}(r)\end{pmatrix}$
                                                                                | $\begin{pmatrix}\overline{c}_{stator}\\ \overline{c}_{rotor}\end{pmatrix}$
```

$\overline{c}_{stator}^{\,T} =$

	1	2	3
1	3.00	3.00	3.00
2	5.00	5.00	5.00
3	7.00	7.00	7.00

$\cdot\%$

$\overline{c}_{rotor}^{\,T} =$

	1	2	3
1	10.00	10.00	10.00
2	4.00	4.00	4.00
3	3.00	3.00	3.00

$\cdot\%$

```
$\overline{c}_{CA}$ = | for $r \in 1..N_r$
                      |   $\overline{c}_{CA_r} = \overline{c}_{stator.}(r)$
                      | $\overline{c}_{CA}$
```

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

	1
1	3.00
2	5.00
3	7.00

$\cdot\%$

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

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

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

$\overline{r}\_\mathrm{inlet}_{BHA} = 0.000\cdot\%$

$\overline{r}\_\mathrm{inlet}_{stator}{}^{T} =$

	1	2	3
1	0.600	0.600	0.600
2	1.000	1.000	1.000
3	1.400	1.400	1.400

$\cdot\%$

$\overline{r}\_\mathrm{outlet}_{stator}{}^{T} =$

	1	2	3
1	0.300	0.300	0.300
2	0.500	0.500	0.500
3	0.700	0.700	0.700

$\cdot\%$

$\overline{r}\_\mathrm{outlet}_{BHA} = 0.000\cdot\%$

$\overline{r}\_\mathrm{inlet}_{CA} = 0.000\cdot\%$

$\overline{r}\_\mathrm{inlet}_{rotor}{}^{T} =$

	1	2	3
1	2.000	2.000	2.000
2	0.800	0.800	0.800
3	0.600	0.600	0.600

$\cdot\%$

$\overline{r}\_\mathrm{outlet}_{rotor}{}^{T} =$

	1	2	3
1	1.000	1.000	1.000
2	0.400	0.400	0.400
3	0.300	0.300	0.300

$\cdot\%$

$\overline{r}\_\mathrm{outlet}_{CA} = 0.000\cdot\%$

▲ Относ. толщины и радиусы профилей

Распределение параметров по высоте Л

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

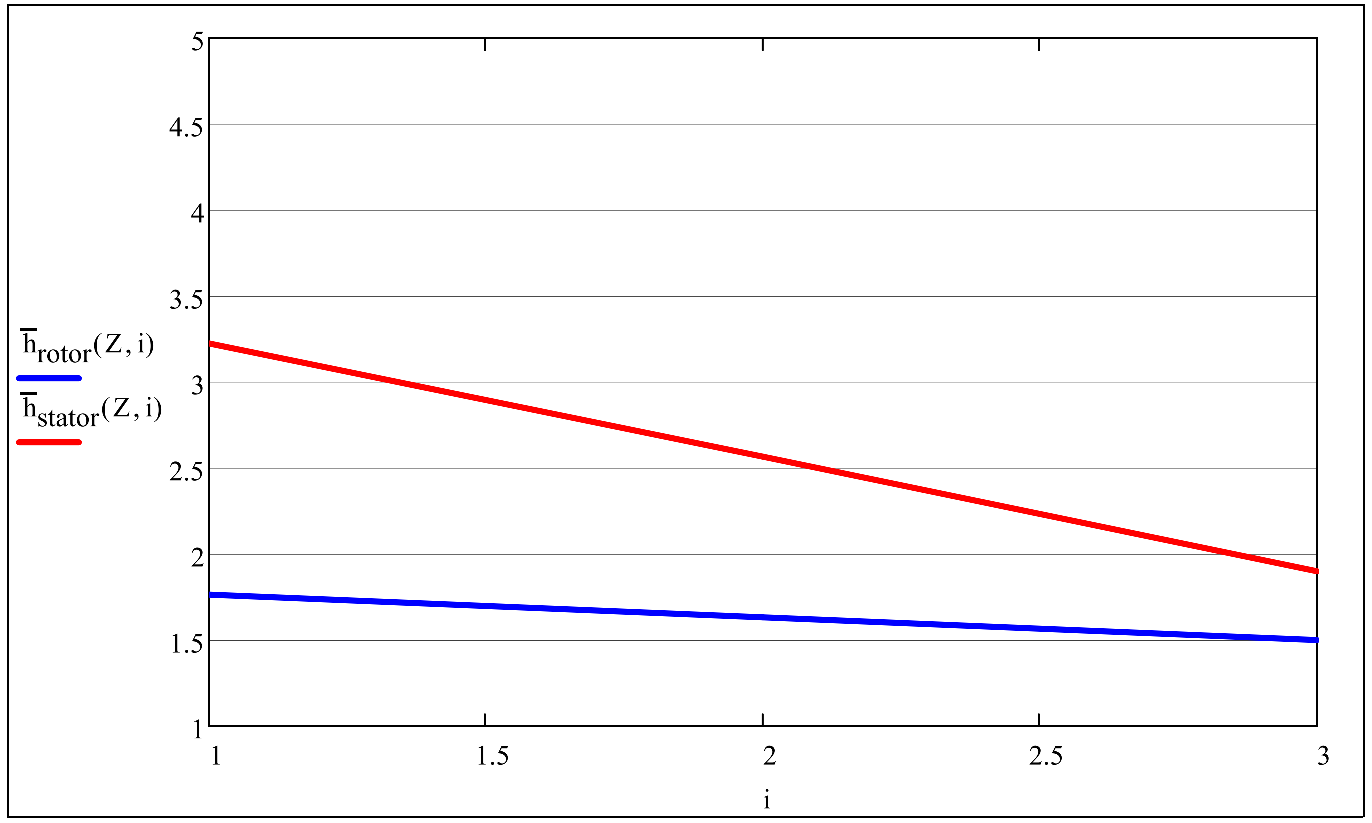
$$\overline{h}_{\sim rotor} = (2\ \ 1.9\ \ 1.85\ \ 1.8\ \ 1.75\ \ 1.7\ \ 1.65\ \ 1.6)^T + \left| \begin{array}{l} 1.1 \ \text{ if } \ compressor = \text{"Вл"} \\ -0.1 \ \text{ if } \ compressor = \text{"КНД"} \\ -0.55 \ \text{ if } \ compressor = \text{"КВД"} \end{array} \right.$$

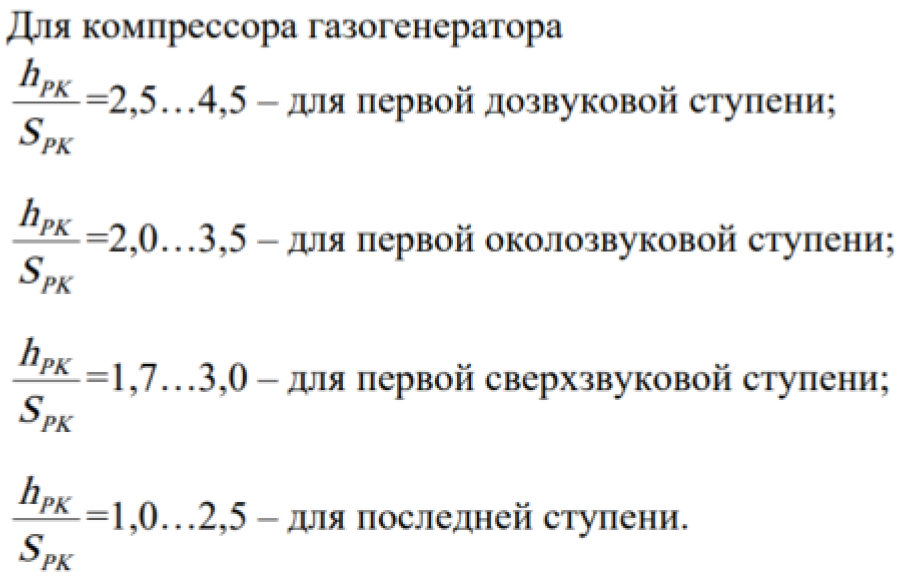
$$\overline{h}_{\sim stator} = (4\ \ 3.5\ \ 3.25\ \ 3\ \ 2.75\ \ 2.5\ \ 2.25\ \ 2)^T + \left| \begin{array}{l} 1.1 \ \text{ if } \ compressor = \text{"Вл"} \\ -0.1 \ \text{ if } \ compressor = \text{"КНД"} \\ -0.7 \ \text{ if } \ compressor = \text{"КВД"} \end{array} \right.$$

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

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

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




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

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

```
$\begin{pmatrix} chord_{rotor} & chord_{stator} \end{pmatrix} =$
    for $i \in 1..Z$
        $\begin{pmatrix} chord_{rotor_{i,av(N_r)}} \\ chord_{stator_{i,av(N_r)}} \end{pmatrix} = \begin{pmatrix} \dfrac{mean(h_{st(i,1)}, h_{st(i,2)})}{\overline{h}_{rotor}(Z,i)} \\ \dfrac{mean(h_{st(i,2)}, h_{st(i,3)})}{\overline{h}_{stator}(Z,i)} \end{pmatrix}$
        $sail = \dfrac{R_{st(i,2),N_r} - R_{st(i,2),1}}{R_{st(i,2),av(N_r)} - R_{st(i,2),1}}$
        for $r \in 1..N_r$
            $b_{РКкор} = \dfrac{chord_{rotor_{i,av(N_r)}} \cdot sail}{sail_{rotor} - 1 + sail}$
            $b_{НАкор} = \dfrac{chord_{stator_{i,av(N_r)}} \cdot sail}{sail_{stator} - 1 + sail}$
            $\begin{pmatrix} b_{РКпер} \\ b_{НАпер} \end{pmatrix} = \begin{pmatrix} b_{РКкор} \cdot sail_{rotor} \\ b_{НАкор} \cdot sail_{stator} \end{pmatrix}$
            $chord_{rotor.}(z) = interp\left[ cspline\left[ \begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{РКкор} \\ chord_{rotor_{i,av(N_r)}} \\ b_{РКпер} \end{pmatrix} \right], \begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{РКкор} \\ chord_{rotor_{i,av(N_r)}} \\ b_{РКпер} \end{pmatrix}, z \right]$
            $chord_{stator.}(z) = interp\left[ cspline\left[ \begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{НАкор} \\ chord_{stator_{i,av(N_r)}} \\ b_{НАпер} \end{pmatrix} \right], \begin{pmatrix} R_{st(i,2),1} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),N_r} \end{pmatrix}, \begin{pmatrix} b_{НАкор} \\ chord_{stator_{i,av(N_r)}} \\ b_{НАпер} \end{pmatrix}, z \right]$
            $chord_{rotor_{i,r}} = chord_{rotor.}(R_{st(i,2),r})$
            $chord_{stator_{i,r}} = chord_{stator.}(R_{st(i,2),r})$
    $\begin{pmatrix} chord_{rotor} & chord_{stator} \end{pmatrix}$
```

```
$chord_{CA} =$  for $i \in Z$                                                  if $CA = 1$
    $chordCA_{av(N_r)} = \frac{h_{st(i,3)}}{\overline{h}_{stator}(Z, Z+1)}$
    $sail = \frac{R_{st(1,1),N_r} - R_{st(1,1),1}}{R_{st(1,1),av(N_r)} - R_{st(1,1),1}}$
    for $r \in 1..N_r$
        $b_{CAкор} = \frac{chordCA_{av(N_r)} \cdot sail}{sail_{stator} - 1 + sail}$
        $b_{CAпер} = b_{CAкор} \cdot sail_{stator}$
        $b_{CA.}(z) = interp\left[cspline\left[\begin{pmatrix} R_{st(i,1),1} \\ R_{st(i,1),av(N_r)} \\ R_{st(i,1),N_r} \end{pmatrix}, \begin{pmatrix} b_{CAкор} \\ chordCA_{av(N_r)} \\ b_{CAпер} \end{pmatrix}\right], \begin{pmatrix} R_{st(i,1),1} \\ R_{st(i,1),av(N_r)} \\ R_{st(i,1),N_r} \end{pmatrix}, \begin{pmatrix} b_{CAкор} \\ chordCA_{av(N_r)} \\ b_{CAпер} \end{pmatrix}, z\right]$
        $chordCA_r = b_{CA.}(R_{st(i,1),r})$
    $chord_{CA}$
```

▲ Расчет длин хорд по высоте Л

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

$\bar{x}_f = 0.5$

Определение количества Л РК и НА

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

```
if BHA = 1
    for $r \in av(N_r)$
        $\varepsilon_{BHA(b/t)=1_r} \leftarrow \varepsilon_{(b/t)=1}(\alpha_{3BHA_r})$
        $b/t_{BHA_r} \leftarrow b/t{=}1\left(\frac{\varepsilon_{BHA_r}}{\varepsilon_{BHA(b/t)=1_r}}\right)$
        $t_{BHA_r} \leftarrow \frac{chord_{BHA_r}}{b/t_{BHA_r}}$
        $Z_{BHA} \leftarrow$
            $round\left(\frac{\pi\cdot D_{st(1,1),r}}{t_{BHA_r}}\right)$ if $mod\left(round\left(\frac{\pi\cdot D_{st(1,1),r}}{t_{BHA_r}}\right),2\right) = 0$
            $round\left(\frac{\pi\cdot D_{st(1,1),r}}{t_{BHA_r}}\right) + 1$ otherwise
    for $r \in 1..N_r$
        $(r\_inlet_{BHA_r}\ \ r\_outlet_{BHA_r}) \leftarrow chord_{BHA_r}\cdot(\overline{r\_inlet}_{BHA_r}\ \ \overline{r\_outlet}_{BHA_r})$
        $t_{BHA_r} \leftarrow \frac{D_{st(1,1),r}}{Z_{BHA}}$
        $i_{BHA_r} \leftarrow 2.5\cdot\left(\frac{chord_{BHA_r}}{t_{BHA_r}} - 2\right)\cdot°$
        $m_{BHA_r} \leftarrow 0.23\cdot(2\cdot\bar{x}_f)^2 + 0.18 - \frac{0.002}{}\cdot(\alpha_{3BHA_r})$
```

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

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

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

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

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

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

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

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

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

```
for  $i \in 1..Z$
    for  $r \in av(N_r)$
        $\begin{pmatrix} \varepsilon_{РК(b/t)=1_{i,r}} \\ \varepsilon_{НА(b/t)=1_{i,r}} \end{pmatrix} = \begin{pmatrix} \varepsilon_{(b/t)=1}(\beta_{st(i,2),r}) \\ \varepsilon_{(b/t)=1}(\alpha_{st(i,3),r}) \end{pmatrix}$
        $\begin{pmatrix} b/t_{РК_{i,r}} \\ b/t_{НА_{i,r}} \end{pmatrix} = \begin{pmatrix} b/t{=}1\left(\dfrac{\varepsilon_{rotor_{i,r}}}{\varepsilon_{РК(b/t)=1_{i,r}}}\right) \\ b/t{=}1\left(\dfrac{\varepsilon_{stator_{i,r}}}{\varepsilon_{НА(b/t)=1_{i,r}}}\right) \end{pmatrix}$
        $\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{b/t_{РК_{i,r}}} \\ \dfrac{chord_{stator_{i,r}}}{b/t_{НА_{i,r}}} \end{pmatrix}$
        $\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \frac{2}{3}\begin{pmatrix} chord_{rotor_{i,r}} \cdot \cos(\beta_{st(i,1),r}) \\ chord_{stator_{i,r}} \cdot \cos(\alpha_{st(i,2),r}) \end{pmatrix}$
        $Z_{stator_i} =$ | $round\left(\dfrac{\pi \cdot mean(D_{st(i,2),r}, D_{st(i,3),r})}{t_{stator_{i,r}}}\right)$  if  $mod\left(round\left(\dfrac{\pi \cdot mean(D_{st(i,2),r}, D_{st(i,3),r})}{t_{stator_{i,r}}}\right), 2\right) = 0$
                       | $round\left(\dfrac{\pi \cdot mean(D_{st(i,2),r}, D_{st(i,3),r})}{t_{stator_{i,r}}}\right) + 1$  otherwise
        $Z_{rotor_i} =$ | $Z_{rotor_i} = round\left(\dfrac{\pi \cdot mean(D_{st(i,1),r}, D_{st(i,2),r})}{t_{rotor_{i,r}}}\right)$
```

```
            while $\gcd\left(Z_{rotor_i}, Z_{stator_i}\right) \neq 1$
                $Z_{rotor_i} = Z_{rotor_i} + 1$
    for $r \in 1 .. N_r$
        $\begin{pmatrix} r\_inlet_{stator_{i,r}} & r\_outlet_{stator_{i,r}} \\ r\_inlet_{rotor_{i,r}} & r\_outlet_{rotor_{i,r}} \end{pmatrix} = \begin{pmatrix} \overline{r\_inlet}_{stator_{i,r}} \cdot chord_{stator_{i,r}} & \overline{r\_outlet}_{stator_{i,r}} \cdot chord_{stator_{i,r}} \\ \overline{r\_inlet}_{rotor_{i,r}} \cdot chord_{rotor_{i,r}} & \overline{r\_outlet}_{rotor_{i,r}} \cdot chord_{rotor_{i,r}} \end{pmatrix}$
        $\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \pi \cdot \begin{pmatrix} \dfrac{\mathrm{mean}\left(D_{st(i,1),r}, D_{st(i,2),r}\right)}{Z_{rotor_i}} \\ \dfrac{\mathrm{mean}\left(D_{st(i,2),r}, D_{st(i,3),r}\right)}{Z_{stator_i}} \end{pmatrix}$
        $\begin{pmatrix} i_{rotor_{i,r}} \\ i_{stator_{i,r}} \end{pmatrix} = 2.5 \cdot \begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{t_{rotor_{i,r}}} - 1 \\ \dfrac{chord_{stator_{i,r}}}{t_{stator_{i,r}}} - 2 \end{pmatrix} \cdot {}^\circ$
        $\begin{pmatrix} m_{rotor_{i,r}} \\ m_{stator_{i,r}} \end{pmatrix} = 0.23 \cdot \left(2 \cdot \overline{x}_f\right)^2 + 0.18 - \dfrac{0.002}{deg} \cdot \begin{pmatrix} \beta_{st(i,2),r} \\ \alpha_{st(i,3),r} \end{pmatrix}$
        $\begin{pmatrix} \theta_{rotor_{i,r}} \\ \theta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{\varepsilon_{rotor_{i,r}} - i_{rotor_{i,r}}}{1 - m_{rotor_{i,r}} \cdot \sqrt{\dfrac{t_{rotor_{i,r}}}{chord_{rotor_{i,r}}}}} \\ \dfrac{\varepsilon_{stator_{i,r}} - i_{stator_{i,r}}}{1 - m_{stator_{i,r}} \cdot \sqrt{\dfrac{t_{stator_{i,r}}}{chord_{stator_{i,r}}}}} \end{pmatrix}$
        $\begin{pmatrix} \delta_{rotor_{i,r}} \\ \delta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} m_{rotor_{i,r}} \cdot \theta_{rotor_{i,r}} \cdot \sqrt{\dfrac{t_{rotor_{i,r}}}{chord_{rotor_{i,r}}}} \\ m_{stator_{i,r}} \cdot \theta_{stator_{i,r}} \cdot \sqrt{\dfrac{t_{stator_{i,r}}}{chord_{stator_{i,r}}}} \end{pmatrix}$
        $\begin{pmatrix} \chi_{rotor_{i,r}} \\ \chi_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \theta_{rotor_{i,r}} \\ \theta_{stator_{i,r}} \end{pmatrix} \cdot \dfrac{1 + 2 \cdot \left(1 - 2 \cdot \overline{x}_f\right)}{2}$
        $\begin{pmatrix} \upsilon_{rotor} \end{pmatrix} \quad \begin{pmatrix} \chi_{rotor} + \beta_{st(i,1),r} + i_{rotor} \end{pmatrix}$
```

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

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

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

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

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

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

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

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

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

```
$\begin{pmatrix} \varepsilon_{CA(b/t)=1} \\ Z_{CA} \\ r\_inlet_{CA} \\ r\_outlet_{CA} \\ t_{CA} \\ i_{CA} \\ m_{CA} \\ \theta_{CA} \\ \delta_{CA} \\ \chi_{CA} \\ \upsilon_{CA} \\ R_{СЛ.CA} \\ K_{CA} \\ D_{CA} \end{pmatrix}$ = 
  if CA = 1
    for $r \in av(N_r)$
      $\varepsilon_{CA(b/t)=1_r} = \varepsilon_{(b/t)=1}(\alpha_{3CA_r})$
      $b/t_{CA_r} = b/t{=}1\left(\frac{\varepsilon_{CA_r}}{\varepsilon_{CA(b/t)=1_r}}\right)$
      $t_{CA_r} = \frac{chord_{CA_r}}{b/t_{CA_r}}$
      $Z_{CA} =$
        $round\left(\frac{\pi \cdot D_{st(Z,3),r}}{t_{CA_r}}\right)$  if  $mod\left(round\left(\frac{\pi \cdot D_{st(Z,3),r}}{t_{CA_r}}\right), 2\right) = 0$
        $round\left(\frac{\pi \cdot D_{st(Z,3),r}}{t_{CA_r}}\right) + 1$  otherwise
    for $r \in 1..N_r$
      $(r\_inlet_{CA_r} \;\; r\_outlet_{CA_r}) = chord_{CA_r} \cdot (\overline{r}\_inlet_{CA_r} \;\; \overline{r}\_outlet_{CA_r})$
      $t_{CA_r} = \frac{D_{st(Z,3),r}}{Z_{CA}}$
      $i_{CA_r} = 2.5 \cdot \left(\frac{chord_{CA_r}}{t_{CA_r}} - 2\right) \cdot °$
      $m_{CA_r} = 0.23 \cdot (2 \cdot \overline{x}_f)^2 + 0.18 - \frac{0.002}{deg} \cdot (\alpha_{3CA_r})$
      $\theta_{CA_r} = \frac{\varepsilon_{CA_r} - i_{CA_r}}{1 - m_{CA_r} \cdot \sqrt{\frac{t_{CA_r}}{chord_{CA_r}}}}$
```

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

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

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

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

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

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

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

▲ Определение количества Л РК и НА

Результаты расчета количества Л и параметров решеток РК и НА

Длина хорды Л (м):

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

$chord_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	62.10	66.35	74.88												
2	72.07	77.02	87.03												
3	80.73	86.26	97.34												

$\cdot 10^{-3}$

$chord_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	35.22	44.78	64.29												
2	38.99	49.58	71.24												
3	42.27	53.74	77.15												

$\cdot 10^{-3}$

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

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	2	3
1	1.24	1.33	1.50
2	0.58	0.62	0.70
3	0.48	0.52	0.58

$\cdot 10^{-3}$

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

	1	2	3
1	0.62	0.66	0.75
2	0.29	0.31	0.35
3	0.24	0.26	0.29

$\cdot 10^{-3}$

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

	1	2	3
1	0.21	0.27	0.39
2	0.39	0.50	0.71
3	0.59	0.75	1.08

$\cdot 10^{-3}$

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

	1	2	3
1	0.11	0.13	0.19
2	0.19	0.25	0.36
3	0.30	0.38	0.54

$\cdot 10^{-3}$

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

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

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

Угол поворота потока:

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	10.13	9.95	8.82												

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	19.44	14.94	18.16												

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

$\frac{chord_{BHA}}{t_{BHA}} = ▮$

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	-315.659	-424.321	-1051.790												
2	288.710	387.361	956.340												
3	1.926	2.868	8.574												

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

	1	2	3
1	68.783	90.392	154.460
2	-63.250	-83.302	-143.804
3	8.424	11.159	19.786

$\frac{chord_{CA}}{t_{CA}} = ▮$

$Z_{BHA} = 0$

Количество Л:

$Z_{rotor}^{\;T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	65	59	49												

$Z_{stator}^{\;T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	122	90	58												

$Z_{CA} = 0$

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

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

$t_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	37.14	40.52	44.95												
2	43.72	47.69	53.98												
3	49.43	53.91	61.69												

$\cdot 10^{-3}$

Шаг решетки (м):

$t_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	19.86	25.74	35.33												
2	23.32	30.51	43.29												
3	26.34	34.63	49.99												

$\cdot 10^{-3}$

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

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

$i_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.681	1.594	1.664												
2	1.621	1.538	1.531												
3	1.583	1.500	1.445												

$\cdot {}^{\circ}$

Угол атаки:

$i_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	-0.566	-0.652	-0.450												
2	-0.821	-0.938	-0.885												
3	-0.988	-1.121	-1.142												

$\cdot {}^{\circ}$

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

$m_{BHA} = 0.0000$

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	0.2781	0.2668	0.2687												
2	0.3352	0.3363	0.3438												
3	0.3564	0.3592	0.3651												

$m_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.3004	0.3202	0.3086												
2	0.2921	0.3103	0.2969												
3	0.2861	0.3031	0.2893												

$m_{CA} = 0.0000$

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

Угол изгиба ср. линии профиля:

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	46.20	58.87	57.39												
2	18.25	22.42	18.64												
3	8.60	10.82	8.44												

$\cdot ^{\circ}$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	38.33	48.47	41.26												
2	39.80	50.56	44.74												
3	40.36	51.36	46.21												

$\cdot ^{\circ}$

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

Угол отставания:

$\delta_{BHA} = 0.000\cdot°$

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

	1	2	3
1	9.935	12.273	11.951
2	4.765	5.933	5.047
3	2.399	3.072	2.453

$\cdot°$

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

	1	2	3
1	8.647	11.766	9.439
2	8.991	12.308	10.354
3	9.115	12.497	10.761

$\cdot°$

$\delta_{CA} = 0.000\cdot°$

Угол установки Л:

$\upsilon_{BHA} = 0.00\cdot°$

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

	1	2	3
1	52.80	54.45	53.88
2	33.06	31.57	28.82
3	24.92	23.04	20.70

$\cdot°$

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

	1	2	3
1	41.18	43.13	39.50
2	45.14	47.09	44.52
3	48.11	49.96	48.01

$\cdot°$

$\upsilon_{CA} = 0.00\cdot°$

$R_{СЛ.ВНА} = 0.00 \cdot 10^{-3}$

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	79.14	67.50	77.97												
2	227.18	198.10	268.69												
3	538.16	457.64	661.42												

$\cdot 10^{-3}$

$R_{СЛ.stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	53.64	54.55	91.24												
2	57.27	58.05	93.61												
3	61.26	62.00	98.30												

$\cdot 10^{-3}$

$R_{СЛ.СА} = 0.00 \cdot 10^{-3}$

$K_{ВНА} = 0.0000$

Фактор диффузорности решетки:

$K_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.8980	0.9279	0.9600												
2	0.8980	0.9279	0.9600												
3	0.8980	0.9279	0.9600												

$K_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.9495	0.9246	0.9583												
2	0.9495	0.9246	0.9583												
3	0.9495	0.9246	0.9583												

$K_{СА} = 0.0000$

$D_{BHA} = 0.0000$

Диффузорность решетки:

$D_{rotor}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.7459	0.8541	0.8287												
2	0.5845	0.6702	0.6115												
3	0.4630	0.5287	0.4635												

$D_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.7416	0.7436	0.7781												
2	0.7070	0.7234	0.7546												
3	0.6762	0.7025	0.7293												

$D_{CA} = 0.0000$

$D_{BHA} \leq 0.6 = 1$

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

	1	2	3
1	0	0	0
2	1	0	0
3	1	1	1

[18, с. 71]

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

	1	2	3
1	0	0	0
2	0	0	0
3	0	0	0

$D_{CA} \leq 0.6 = 1$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.1673	0.2205	0.2090												
2	0.1434	0.1916	0.1716												
3	0.1235	0.1616	0.1412												

Коэф. потерь полного давления:

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.1956	0.2235	0.2381												
2	0.1570	0.1805	0.1854												
3	0.1320	0.1531	0.1538												

$quality_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	7.554	6.371	6.795												
2	7.869	7.214	8.352												
3	7.909	8.024	9.582												

Качество профилей решеток РК и НА:

$quality_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	7.077	6.313	6.233												
2	8.314	7.367	7.521												
3	9.434	8.269	8.628												

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	75.49	71.96	71.94												
2	76.73	73.61	74.78												
3	75.48	73.43	74.91												

$\cdot\%$

▲ 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 сверхзвуковой профиль.xlsx

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

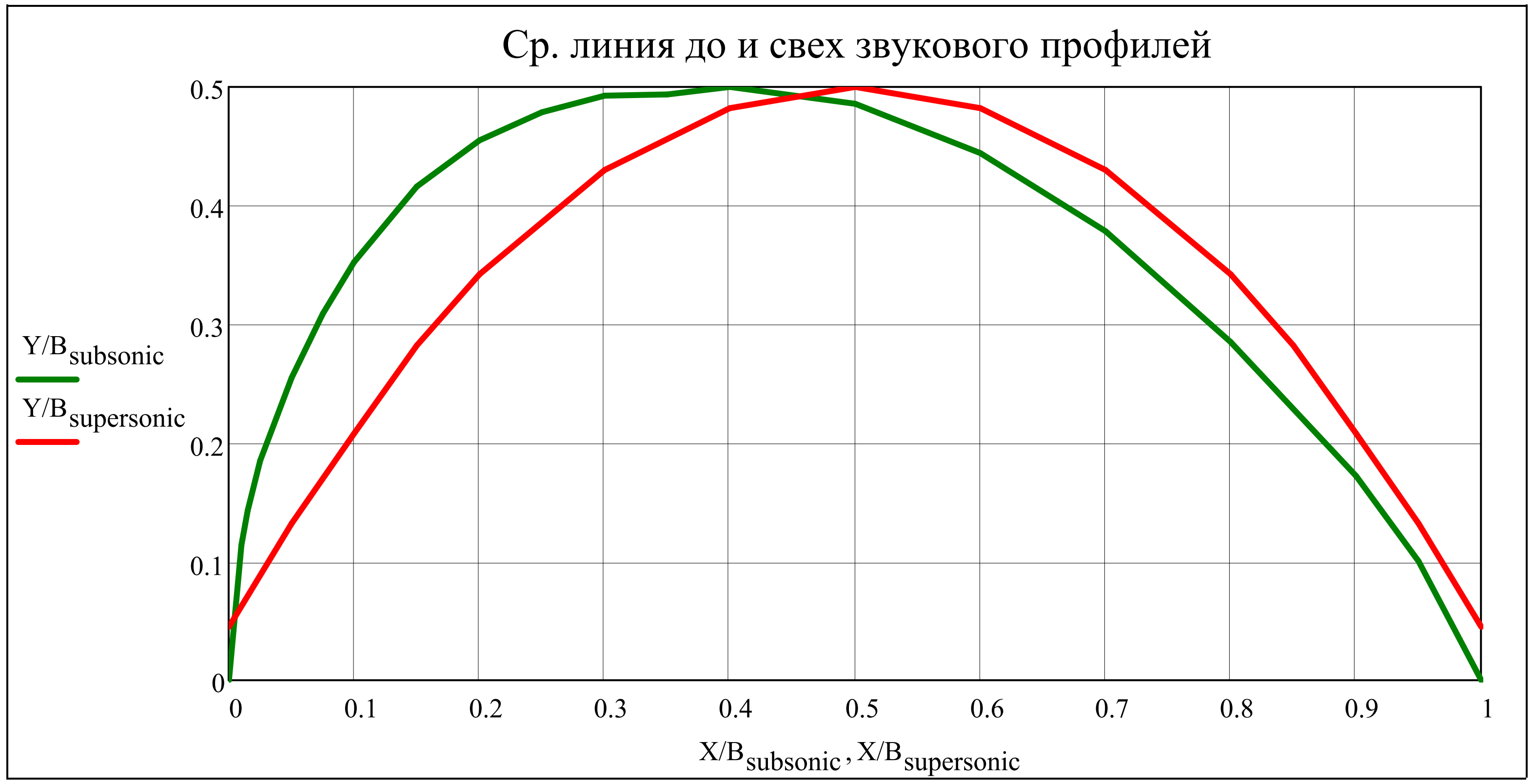
$$Y/B_{supersonic} := \mathrm{submatrix}\left(EXCEL_{AIRFOIL.supersonic}, 2, \mathrm{rows}\left(EXCEL_{AIRFOIL.supersonic}\right), ORIGIN + 1, ORIGIN + 1\right)$$

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

	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

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

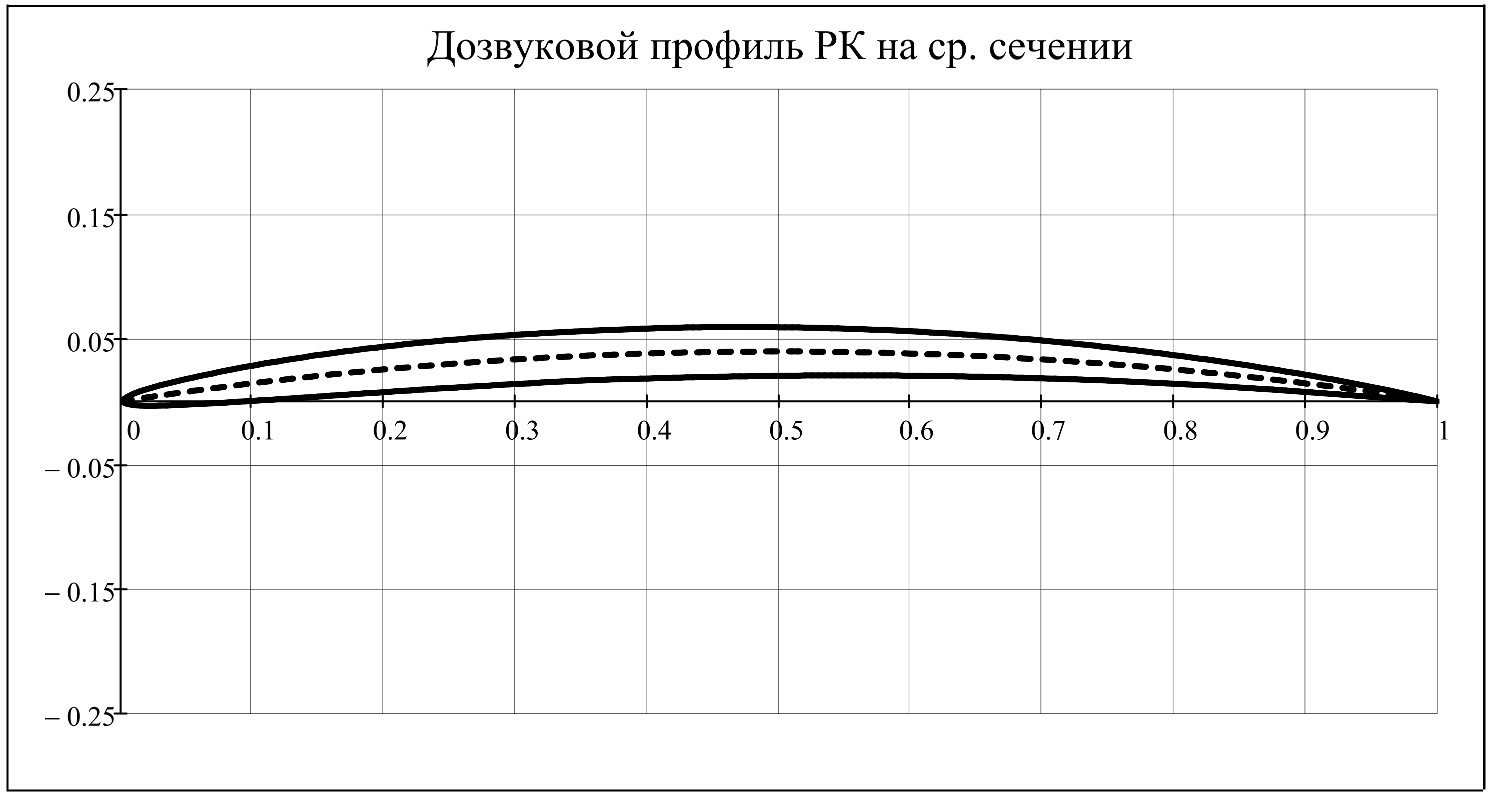
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.000	0.050	0.100	0.150	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.850	0.900	0.950	1.000
2	0.045	0.132	0.208	0.282	0.342	0.430	0.482	0.500	0.482	0.430	0.342	0.282	0.208	0.132	0.045



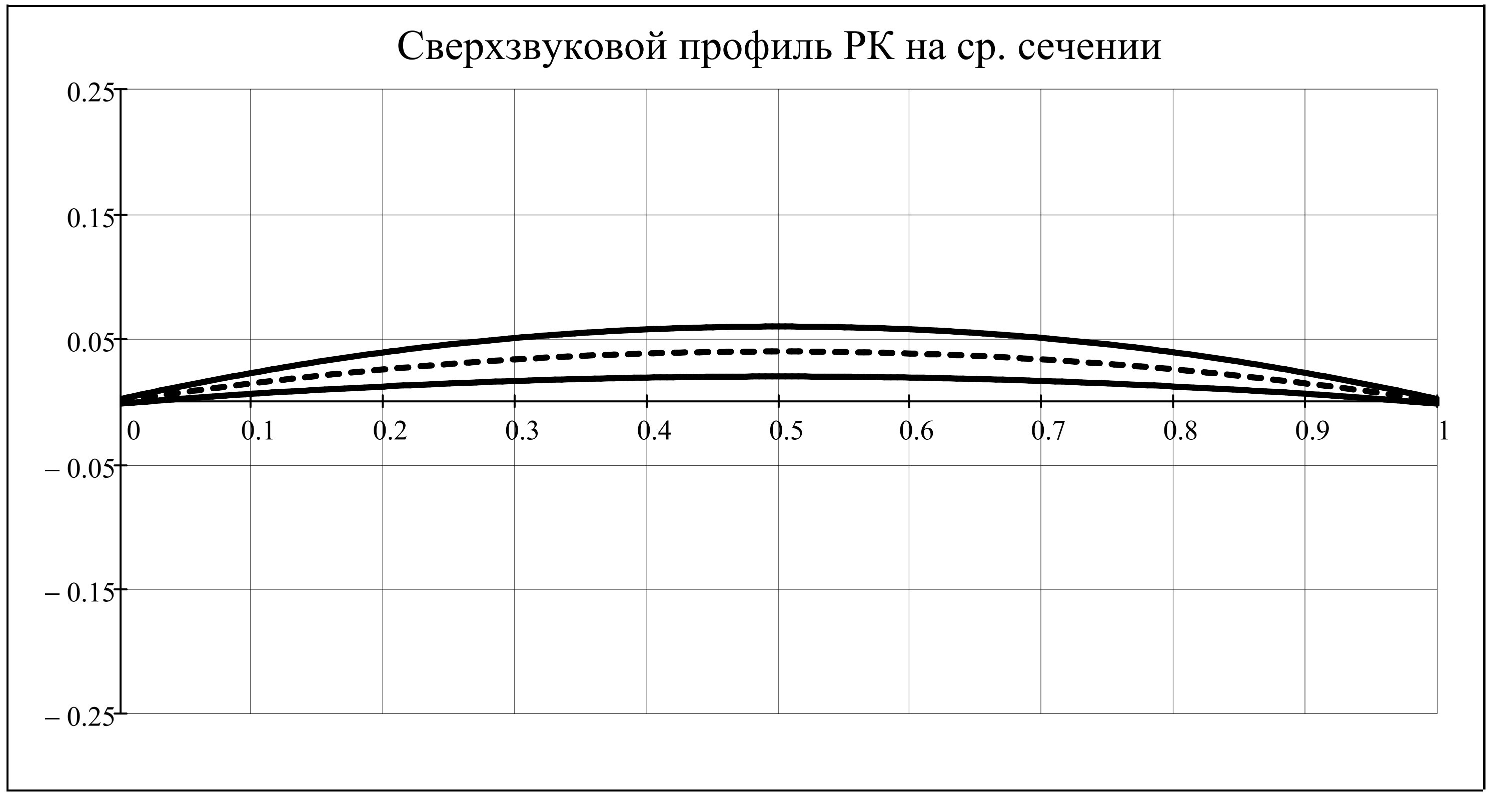
$$\text{AIRFOIL}_{\text{subsonic}}(x,\text{line},\overline{c},\theta) = \left|\begin{array}{l} \text{if } 0 \le x \le 1 \\ \quad \left|\begin{array}{l} \text{interp}\left(\text{cspline}\left(X/B_{\text{subsonic}}, y/b_{\text{ср.л}}\left(X/B_{\text{subsonic}},\theta\right) + Y/B_{\text{subsonic}}\cdot\overline{c}\right),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

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

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



Дозвуковой профиль РК на ср. сечении



Сверхзвуковой профиль РК на ср. сечении

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

$$l\_upper_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 35.84 & 45.87 & 65.55 \\ 2 & 39.92 & 51.18 & 73.21 \\ 3 & 43.55 & 55.87 & 79.87 \end{array} \cdot 10^{-3}$$

$$l\_lower_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 35.45 & 45.27 & 64.79 \\ 2 & 39.19 & 50.04 & 71.74 \\ 3 & 42.46 & 54.15 & 77.61 \end{array} \cdot 10^{-3}$$

$$area_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 27.22 & 44.00 & 90.69 \\ 2 & 55.60 & 89.89 & 185.62 \\ 3 & 91.47 & 147.83 & 304.72 \end{array} \cdot 10^{-6}$$

$$Sx_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 46.8 & 119.6 & 307.2 \\ 2 & 109.1 & 280.4 & 744.9 \\ 3 & 196.3 & 505.6 & 1356.9 \end{array} \cdot 10^{-9}$$

$$Sy_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 433.1 & 889.8 & 2633.2 \\ 2 & 979.2 & 2012.8 & 5972.5 \\ 3 & 1746.1 & 3587.6 & 10617.2 \end{array} \cdot 10^{-9}$$

$$x0_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 15.91 & 20.22 & 29.04 \\ 2 & 17.61 & 22.39 & 32.18 \\ 3 & 19.09 & 24.27 & 34.84 \end{array} \cdot 10^{-3}$$

$$y0_{stator}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1.72 & 2.72 & 3.39 \\ 2 & 1.96 & 3.12 & 4.01 \\ 3 & 2.15 & 3.42 & 4.45 \end{array} \cdot 10^{-3}$$

$$l\_upper_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 65.31 & 70.89 & 79.86 \\ 2 & 72.70 & 77.84 & 87.78 \\ 3 & 81.01 & 86.60 & 97.66 \end{array} \cdot 10^{-3}$$

$$l\_lower_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 62.53 & 67.14 & 75.72 \\ 2 & 72.15 & 77.14 & 87.12 \\ 3 & 80.77 & 86.30 & 97.38 \end{array} \cdot 10^{-3}$$

$$area_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 282.07 & 321.98 & 410.06 \\ 2 & 151.96 & 173.54 & 221.57 \\ 3 & 143.01 & 163.24 & 207.90 \end{array} \cdot 10^{-6}$$

$$Sx_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1121.3 & 1751.4 & 2458.0 \\ 2 & 275.9 & 402.0 & 486.2 \\ 3 & 149.7 & 216.7 & 250.4 \end{array} \cdot 10^{-9}$$

$$Sy_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 7911.0 & 9648.4 & 13867.0 \\ 2 & 4946.1 & 6036.3 & 8708.5 \\ 3 & 5214.2 & 6359.3 & 9139.7 \end{array} \cdot 10^{-9}$$

$$x0_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 28.05 & 29.97 & 33.82 \\ 2 & 32.55 & 34.78 & 39.30 \\ 3 & 36.46 & 38.96 & 43.96 \end{array} \cdot 10^{-3}$$

$$y0_{rotor}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 3.98 & 5.44 & 5.99 \\ 2 & 1.82 & 2.32 & 2.19 \\ 3 & 1.05 & 1.33 & 1.20 \end{array} \cdot 10^{-3}$$

$$Jx_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 90 & 362 & 1163 \\ 2 & 248 & 994 & 3425 \\ 3 & 511 & 2025 & 7174 \end{array} \cdot 10^{-12}$$

$$Jy_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 8814 & 23022 & 97817 \\ 2 & 22061 & 57660 & 245859 \\ 3 & 42645 & 111393 & 473297 \end{array} \cdot 10^{-12}$$

$$Jxy_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 775 & 2515 & 9272 \\ 2 & 1998 & 6526 & 24916 \\ 3 & 3896 & 12753 & 49147 \end{array} \cdot 10^{-12}$$

$$Jx0_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 9.78 & 36.60 & 122.70 \\ 2 & 33.91 & 118.89 & 436.13 \\ 3 & 90.12 & 295.71 & 1131.83 \end{array} \cdot 10^{-12}$$

$$Jy0_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1925 & 5027 & 21360 \\ 2 & 4817 & 12591 & 53687 \\ 3 & 9313 & 24327 & 103364 \end{array} \cdot 10^{-12}$$

$$Jxy0_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 29.54 & 95.59 & 353.26 \\ 2 & 76.16 & 247.88 & 948.31 \\ 3 & 148.52 & 484.29 & 1869.75 \end{array} \cdot 10^{-12}$$

$$\alpha\_major_{stator}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 0.88 & 1.10 & 0.95 \\ 2 & 0.91 & 1.14 & 1.02 \\ 3 & 0.92 & 1.15 & 1.05 \end{array} \cdot \circ$$

$$Jx_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 5553 & 11302 & 17546 \\ 2 & 628 & 1124 & 1336 \\ 3 & 223 & 383 & 439 \end{array} \cdot 10^{-12}$$

$$Jy_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 283876 & 369905 & 599965 \\ 2 & 205969 & 268621 & 437896 \\ 3 & 243225 & 316934 & 514049 \end{array} \cdot 10^{-12}$$

$$Jxy_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 32688 & 54536 & 86376 \\ 2 & 9339 & 14540 & 19872 \\ 3 & 5675 & 8779 & 11445 \end{array} \cdot 10^{-12}$$

$$Jx0_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1095.16 & 1774.68 & 2812.20 \\ 2 & 126.62 & 192.64 & 269.39 \\ 3 & 66.63 & 95.15 & 137.87 \end{array} \cdot 10^{-12}$$

$$Jy0_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 61996 & 80784 & 131027 \\ 2 & 44976 & 58657 & 95620 \\ 3 & 53111 & 69207 & 112249 \end{array} \cdot 10^{-12}$$

$$Jxy0_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1239.06 & 2053.22 & 3254.61 \\ 2 & 357.80 & 556.68 & 761.35 \\ 3 & 217.68 & 336.69 & 439.04 \end{array} \cdot 10^{-12}$$

$$\alpha\_major_{rotor}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1.17 & 1.49 & 1.45 \\ 2 & 0.46 & 0.55 & 0.46 \\ 3 & 0.24 & 0.28 & 0.22 \end{array} \cdot \circ$$

$$\mathrm{Ju}_{\mathrm{stator}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 9.32 & 34.77 & 116.82 \\ 2 & 32.70 & 113.97 & 419.24 \\ 3 & 87.73 & 285.95 & 1097.64 \end{array} \cdot 10^{-12}$$

$$\mathrm{Jv}_{\mathrm{stator}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1925 & 5029 & 21366 \\ 2 & 4818 & 12596 & 53704 \\ 3 & 9316 & 24337 & 103398 \end{array} \cdot 10^{-12}$$

$$\mathrm{Juv}_{\mathrm{stator}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 0.00 & -0.00 & 0.00 \\ 2 & -0.00 & -0.00 & 0.00 \\ 3 & 0.00 & 0.00 & 0.00 \end{array} \cdot 10^{-12}$$

$$\mathrm{Jp}_{\mathrm{stator}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1934 & 5064 & 21482 \\ 2 & 4851 & 12710 & 54123 \\ 3 & 9403 & 24623 & 104496 \end{array} \cdot 10^{-12}$$

$$\mathrm{Wp}_{\mathrm{stator}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 99.7 & 205.0 & 606.5 \\ 2 & 225.9 & 464.4 & 1378.1 \\ 3 & 404.0 & 830.0 & 2456.4 \end{array} \cdot 10^{-9}$$

$$\mathrm{stiffness}_{\mathrm{stator}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 7.39 & 19.31 & 82.06 \\ 2 & 51.41 & 134.37 & 572.95 \\ 3 & 194.78 & 508.78 & 2161.75 \end{array} \cdot 10^{-12}$$

$$\mathrm{Ju}_{\mathrm{rotor}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1069.96 & 1721.36 & 2729.64 \\ 2 & 123.77 & 187.34 & 263.31 \\ 3 & 65.74 & 93.51 & 136.15 \end{array} \cdot 10^{-12}$$

$$\mathrm{Jv}_{\mathrm{rotor}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 62021 & 80838 & 131110 \\ 2 & 44979 & 58662 & 95626 \\ 3 & 53112 & 69209 & 112251 \end{array} \cdot 10^{-12}$$

$$\mathrm{Juv}_{\mathrm{rotor}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & -0.00 & 0.00 & 0.00 \\ 2 & 0.00 & 0.00 & 0.00 \\ 3 & -0.00 & 0.00 & 0.00 \end{array} \cdot 10^{-12}$$

$$\mathrm{Jp}_{\mathrm{rotor}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 63091 & 82559 & 133839 \\ 2 & 45103 & 58850 & 95890 \\ 3 & 53178 & 69302 & 112387 \end{array} \cdot 10^{-12}$$

$$\mathrm{Wp}_{\mathrm{rotor}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1840.2 & 2244.1 & 3225.4 \\ 2 & 1140.0 & 1391.3 & 2007.2 \\ 3 & 1200.9 & 1464.6 & 2104.9 \end{array} \cdot 10^{-9}$$

$$\mathrm{stiffness}_{\mathrm{rotor}}{}^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 2646.10 & 3448.00 & 5592.45 \\ 2 & 307.19 & 400.64 & 653.10 \\ 3 & 204.05 & 265.89 & 431.26 \end{array} \cdot 10^{-12}$$

$$CPx_{stator}^{T} = \begin{array}{|c|c|c|c|} \hline & 1 & 2 & 3 \\ \hline 1 & 12.328 & 15.673 & 22.502 \\ \hline 2 & 13.648 & 17.353 & 24.936 \\ \hline 3 & 14.794 & 18.807 & 27.002 \\ \hline \end{array} \cdot 10^{-3}$$

$$CPx_{rotor}^{T} = \begin{array}{|c|c|c|c|} \hline & 1 & 2 & 3 \\ \hline 1 & 21.736 & 23.223 & 26.207 \\ \hline 2 & 25.225 & 26.956 & 30.459 \\ \hline 3 & 28.256 & 30.189 & 34.069 \\ \hline \end{array} \cdot 10^{-3}$$

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

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

Результат расчета абсолютных геометрических характеристик сечений Л

Вывод результатов расчета геометрических хар-к сечений Л

Профилирование решеток

Абс. координаты профиля:

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

Профилирование решеток

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

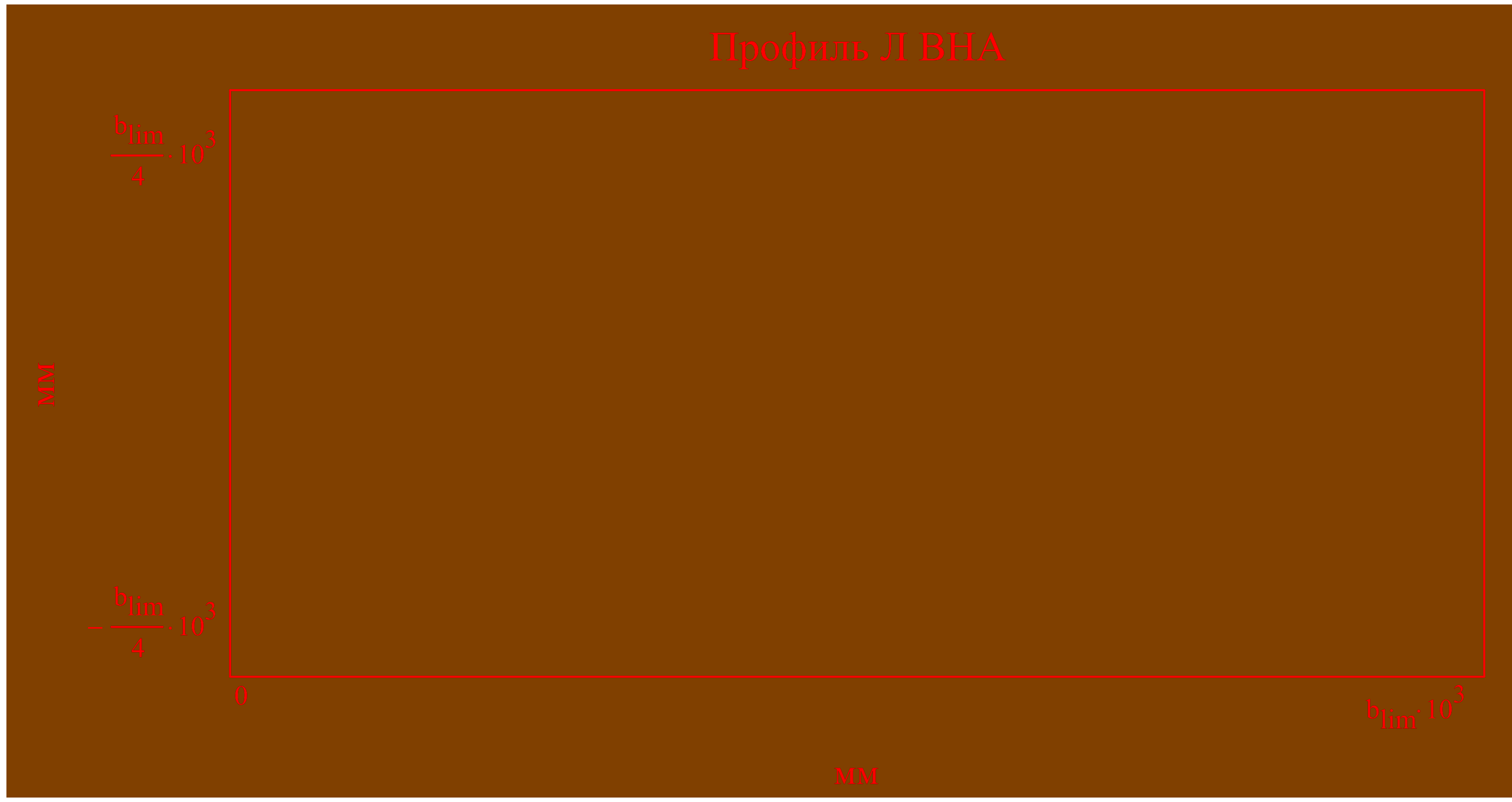
▼ Построение профилей Л РК и НА

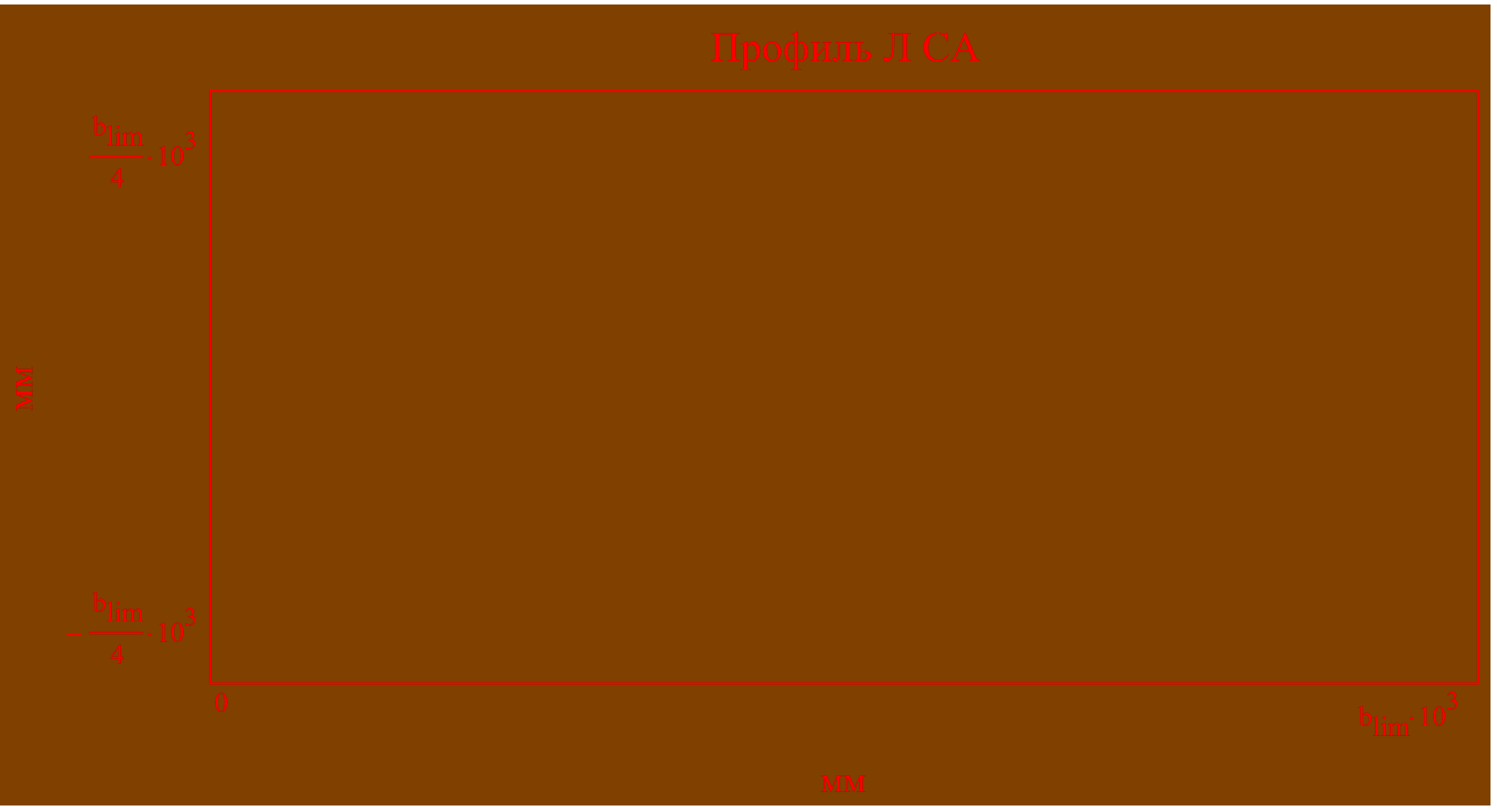
$$\mathrm{AXLE0}(type, x, i, r) = \left| \begin{array}{ll} \dfrac{y0_{rotor_{i,r}}}{chord_{rotor_{i,r}}} + \tan\left(\alpha\_major_{rotor_{i,r}}\right) \cdot \left(x - \dfrac{x0_{rotor_{i,r}}}{chord_{rotor_{i,r}}} \right) & \text{if } type = \text{"rotor"} \\ \dfrac{y0_{stator_{i,r}}}{chord_{stator_{i,r}}} + \tan\left(\alpha\_major_{stator_{i,r}}\right) \cdot \left(x - \dfrac{x0_{stator_{i,r}}}{chord_{stator_{i,r}}} \right) & \text{if } type = \text{"stator"} \\ \mathrm{NaN} & \text{otherwise} \end{array} \right.$$

$$b_{lim} = \frac{\mathrm{ceil}\left(\max\left(chord_{rotor_{j, N_r}}, chord_{stator_{j, N_r}} \right) \cdot 10^{2} \right)}{10^{2}} = 90 \cdot 10^{-3}$$

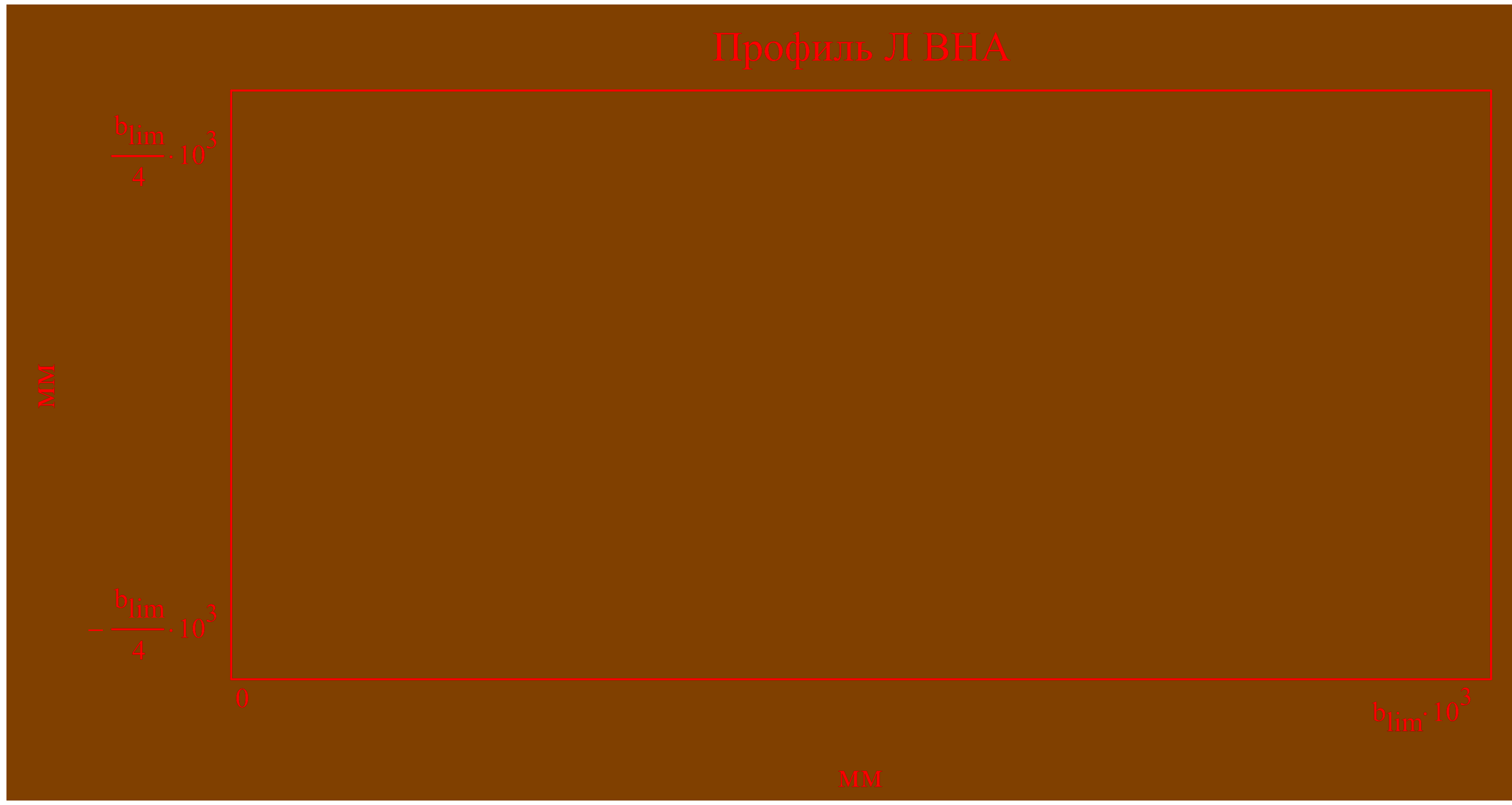
$$\mathrm{AXLE90}(type, x, i, r) = \left| \begin{array}{ll} \dfrac{y0_{rotor_{i,r}}}{chord_{rotor_{i,r}}} + \tan\left(\alpha\_major_{rotor_{i,r}} + \dfrac{\pi}{2}\right) \cdot \left(x - \dfrac{x0_{rotor_{i,r}}}{chord_{rotor_{i,r}}} \right) & \text{if } (type = \text{"rotor"}) \wedge \left|\alpha\_major_{rotor_{i,r}}\right| \geq 1 \cdot {}^{\circ} \\ \dfrac{y0_{stator_{i,r}}}{chord_{stator_{i,r}}} + \tan\left(\alpha\_major_{stator_{i,r}} + \dfrac{\pi}{2}\right) \cdot \left(x - \dfrac{x0_{stator_{i,r}}}{chord_{stator_{i,r}}} \right) & \text{if } (type = \text{"stator"}) \wedge \left|\alpha\_major_{stator_{i,r}}\right| \geq 1 \cdot {}^{\circ} \\ \mathrm{NaN} & \text{otherwise} \end{array} \right.$$

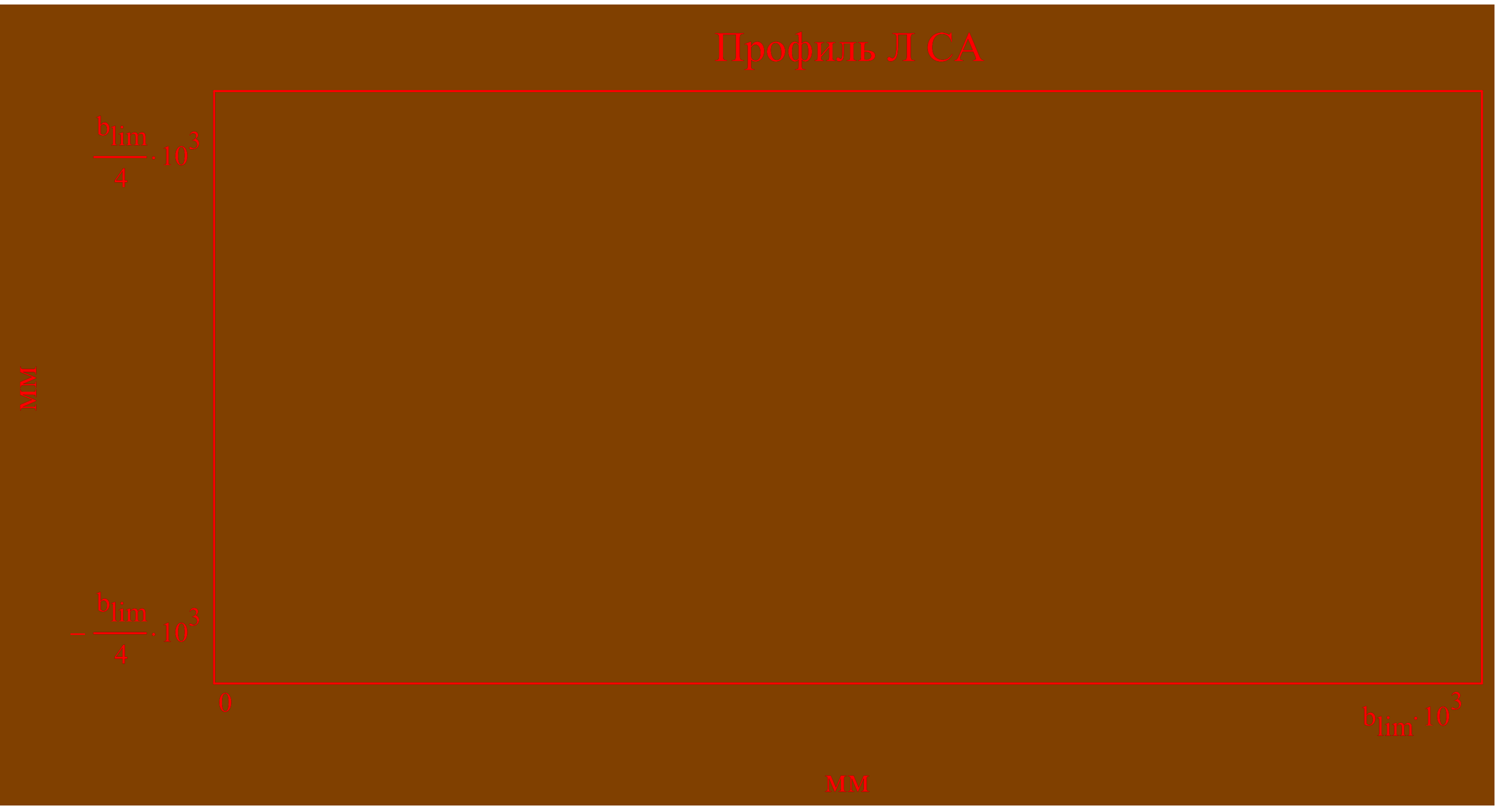
$r = 1$


Профиль Л ВНА

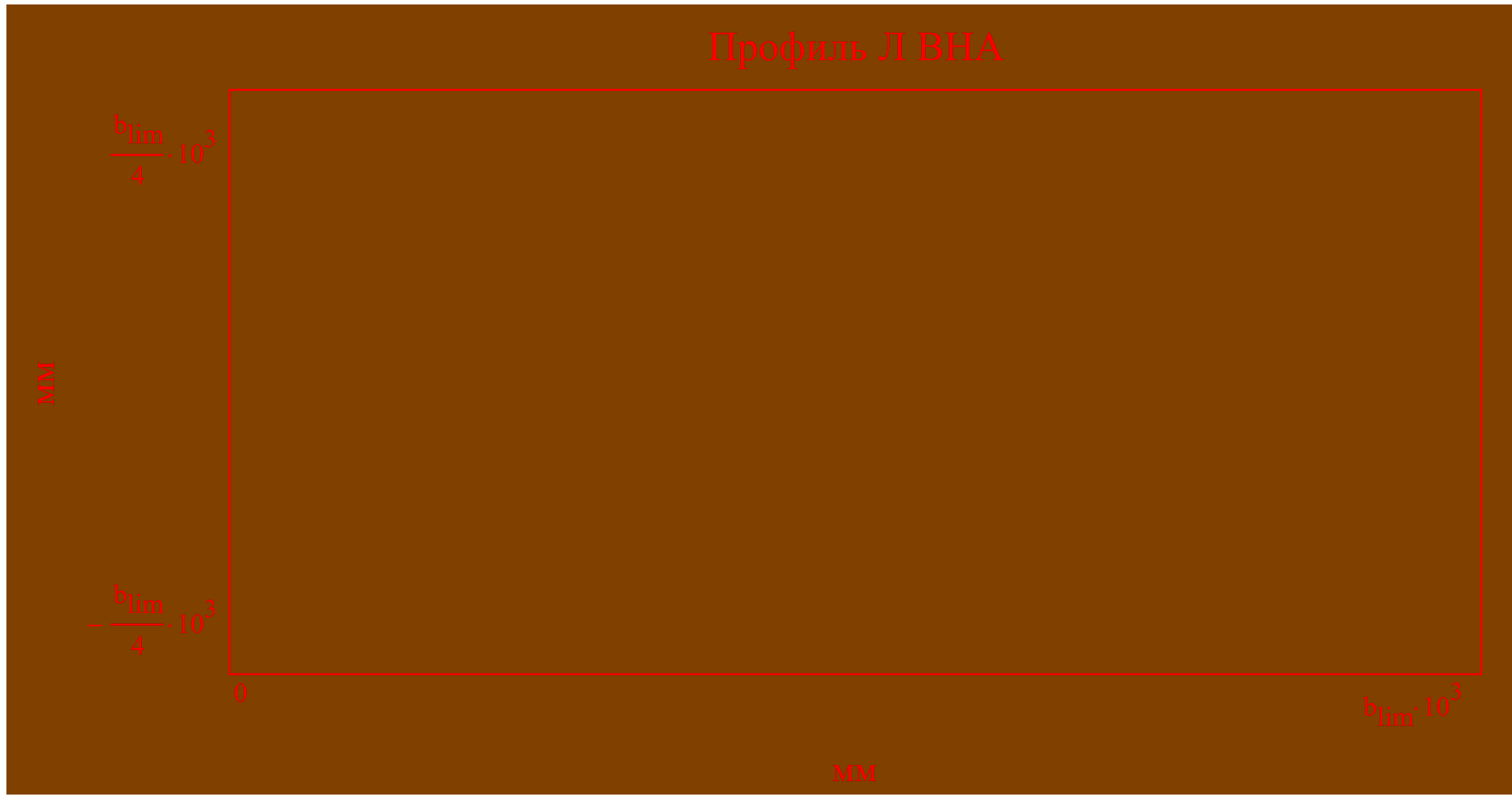

Профиль Л СА

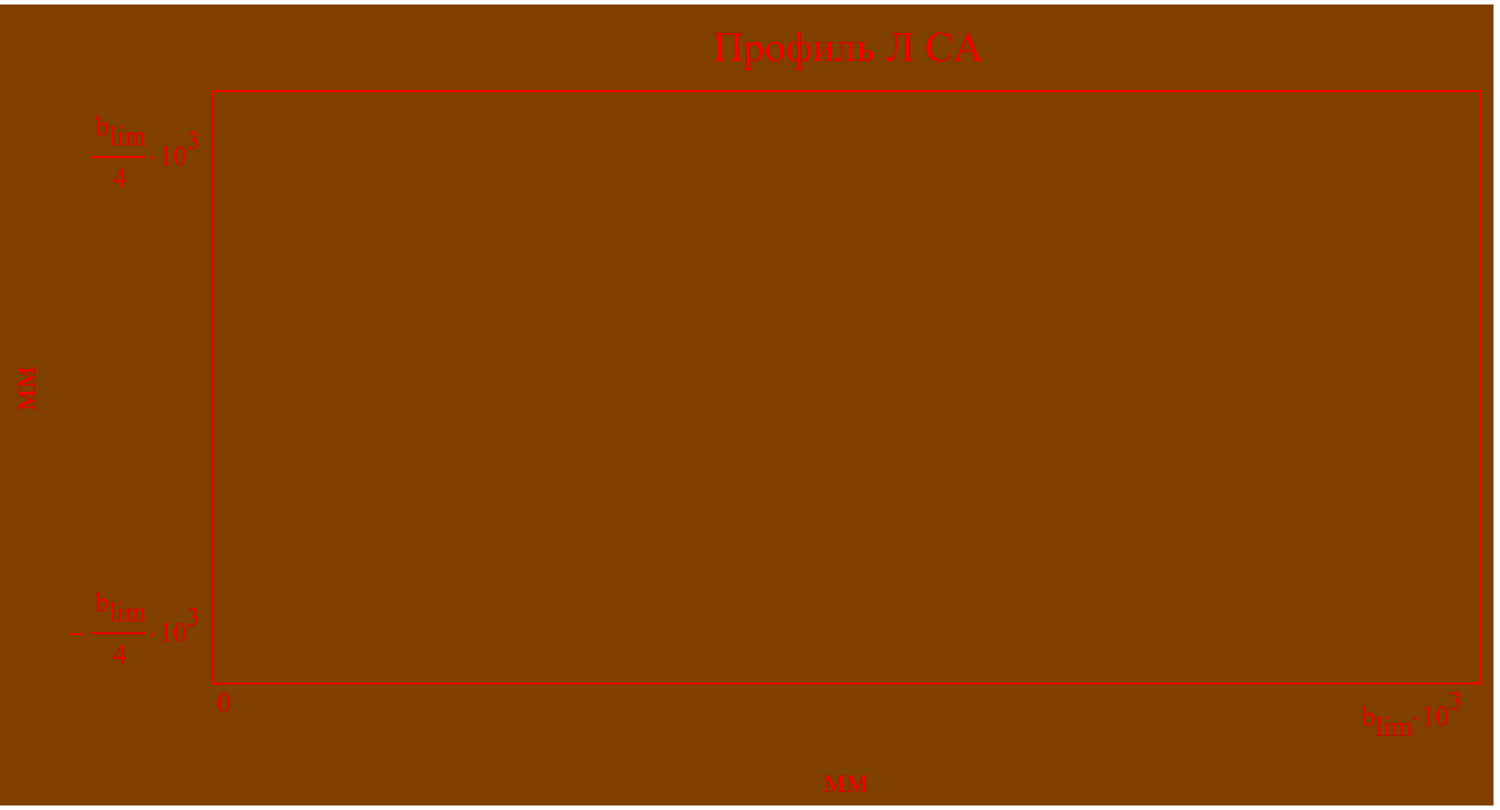
$r = av(N_r)$


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

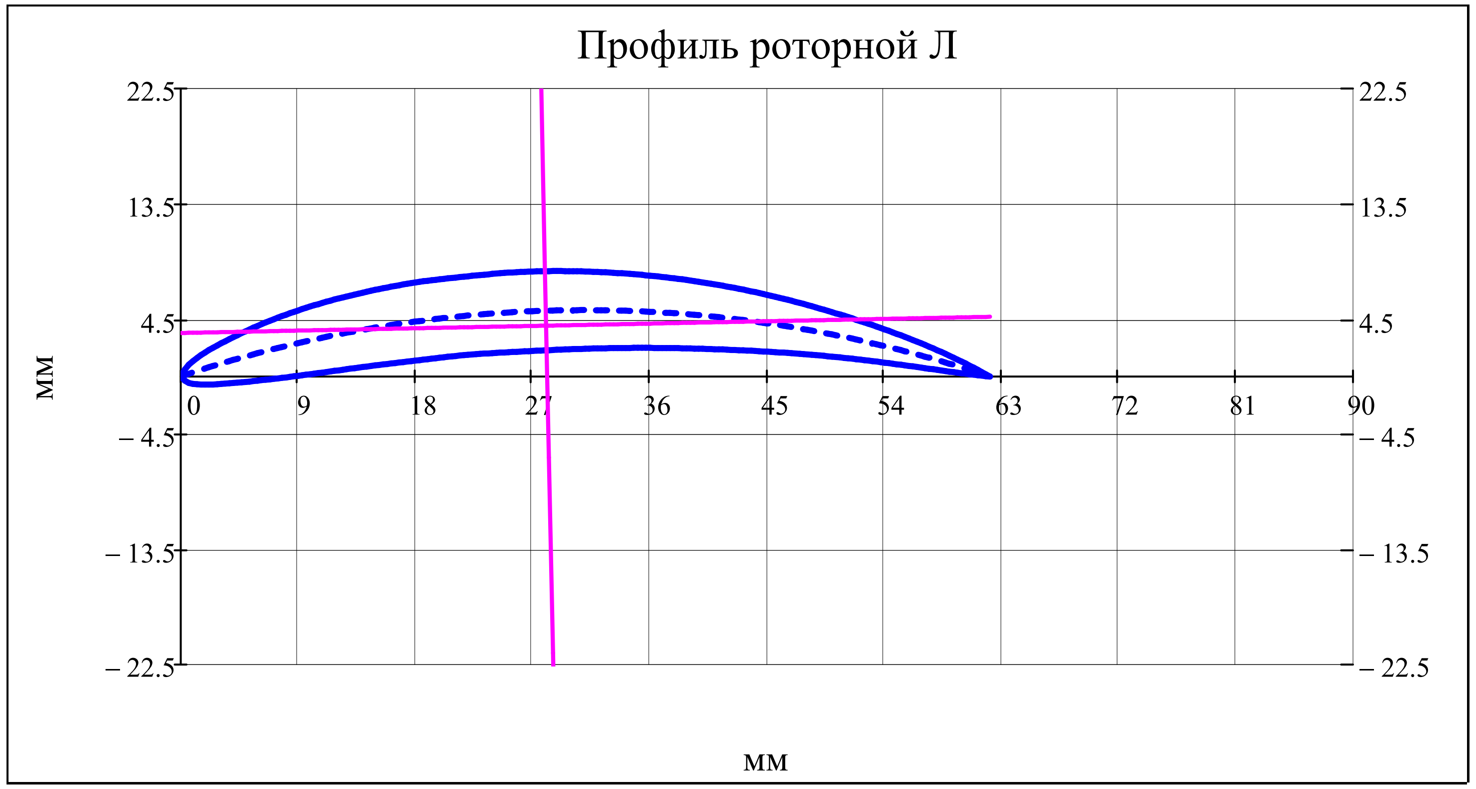

Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
мм
$-\frac{b_{lim}}{4} \cdot 10^3$
0
$b_{lim} \cdot 10^3$
мм

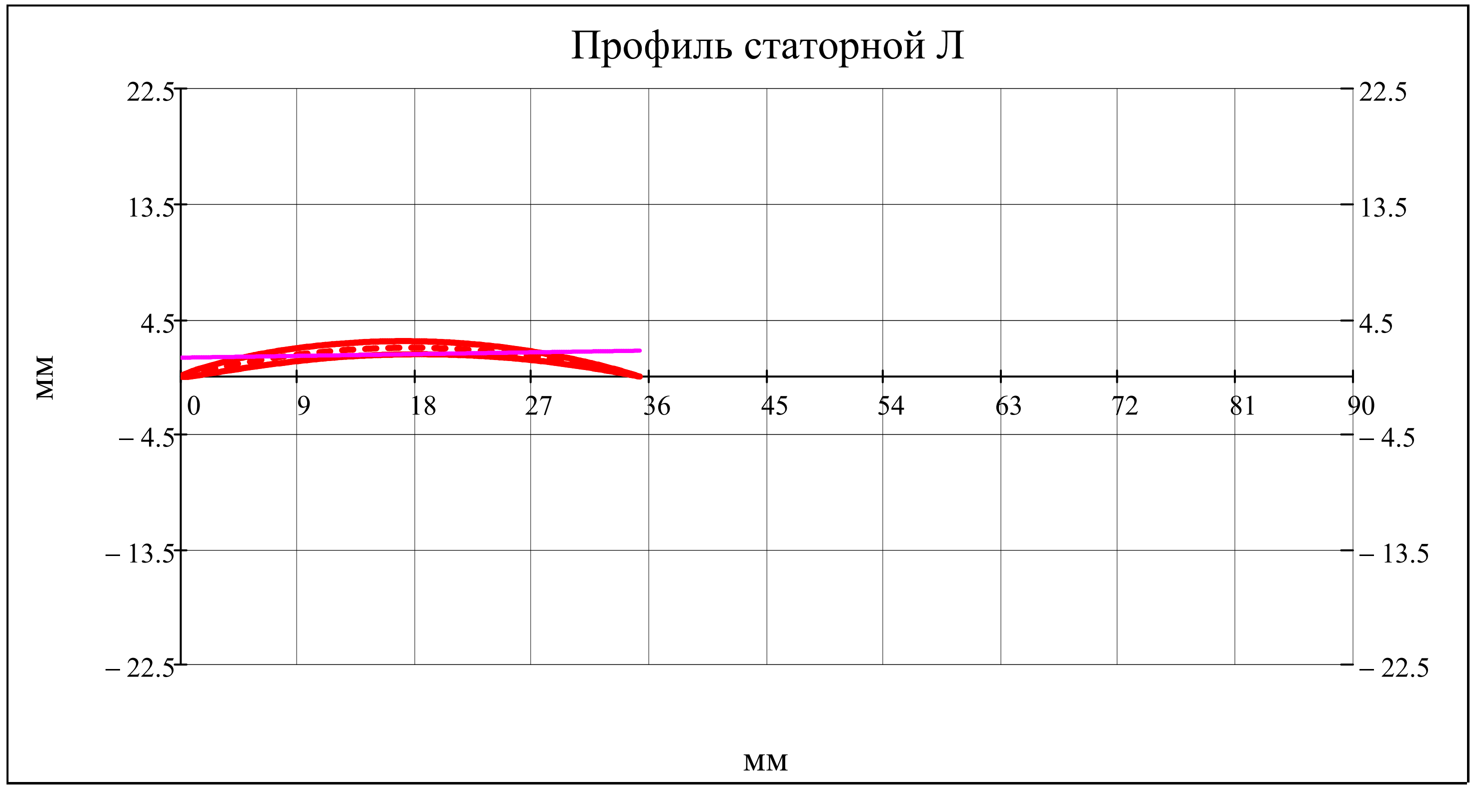
$r = N_r$


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

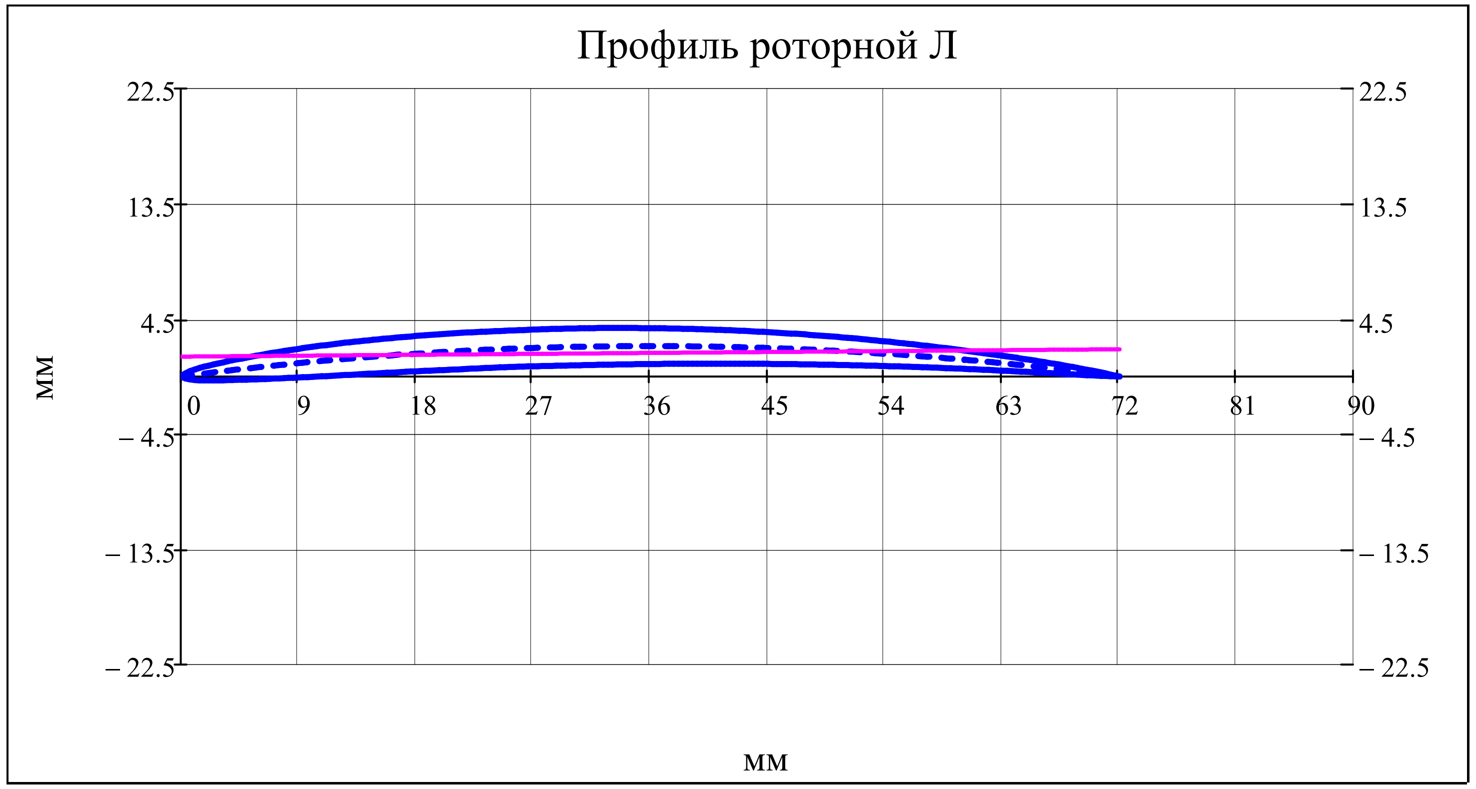

Профиль Л СА
мм
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
0
$b_{lim} \cdot 10^3$
мм

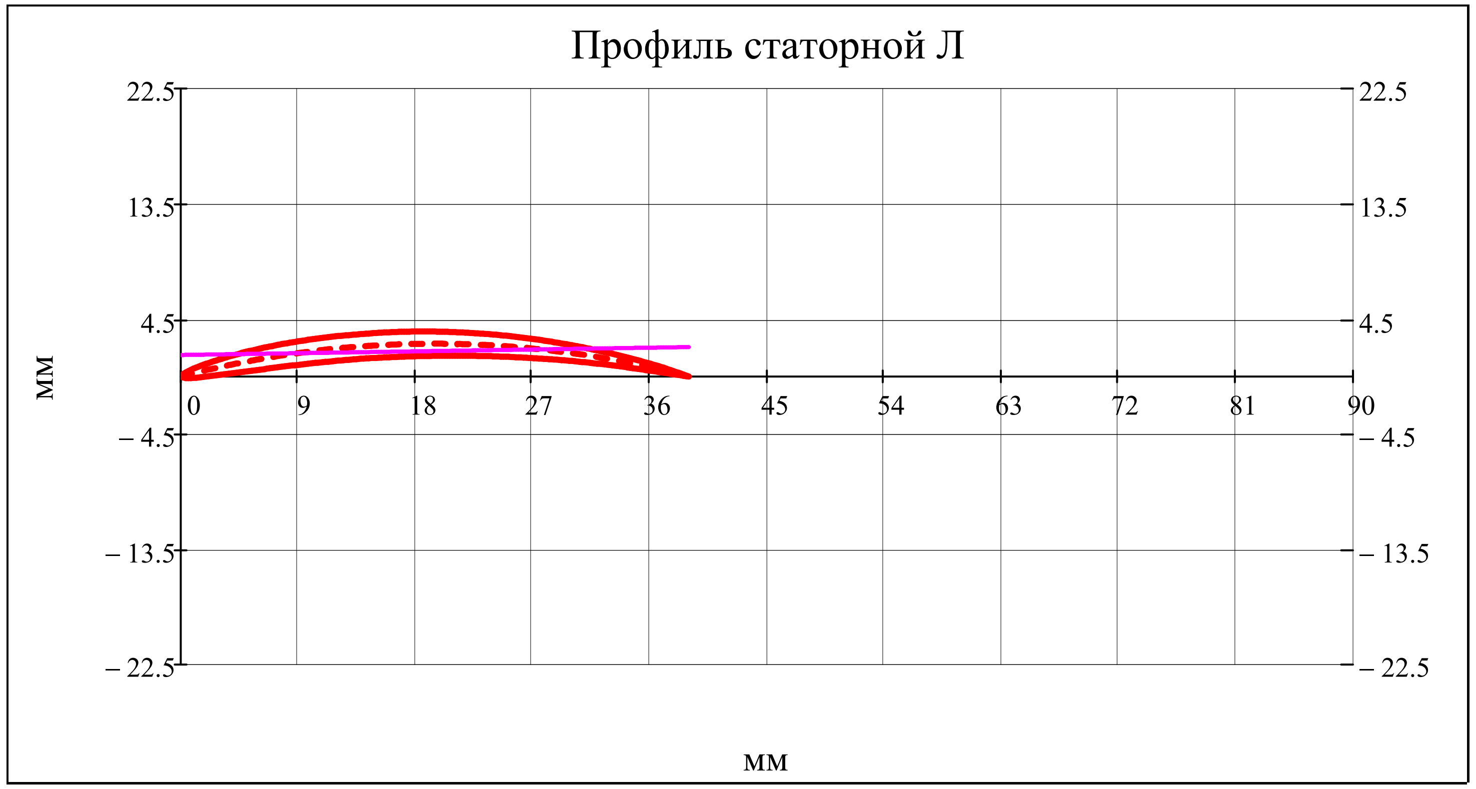
r = 1


Профиль роторной Л
22.5
13.5
4.5
– 4.5
– 13.5
– 22.5
0
9
18
27
36
45
54
63
72
81
90
мм
мм

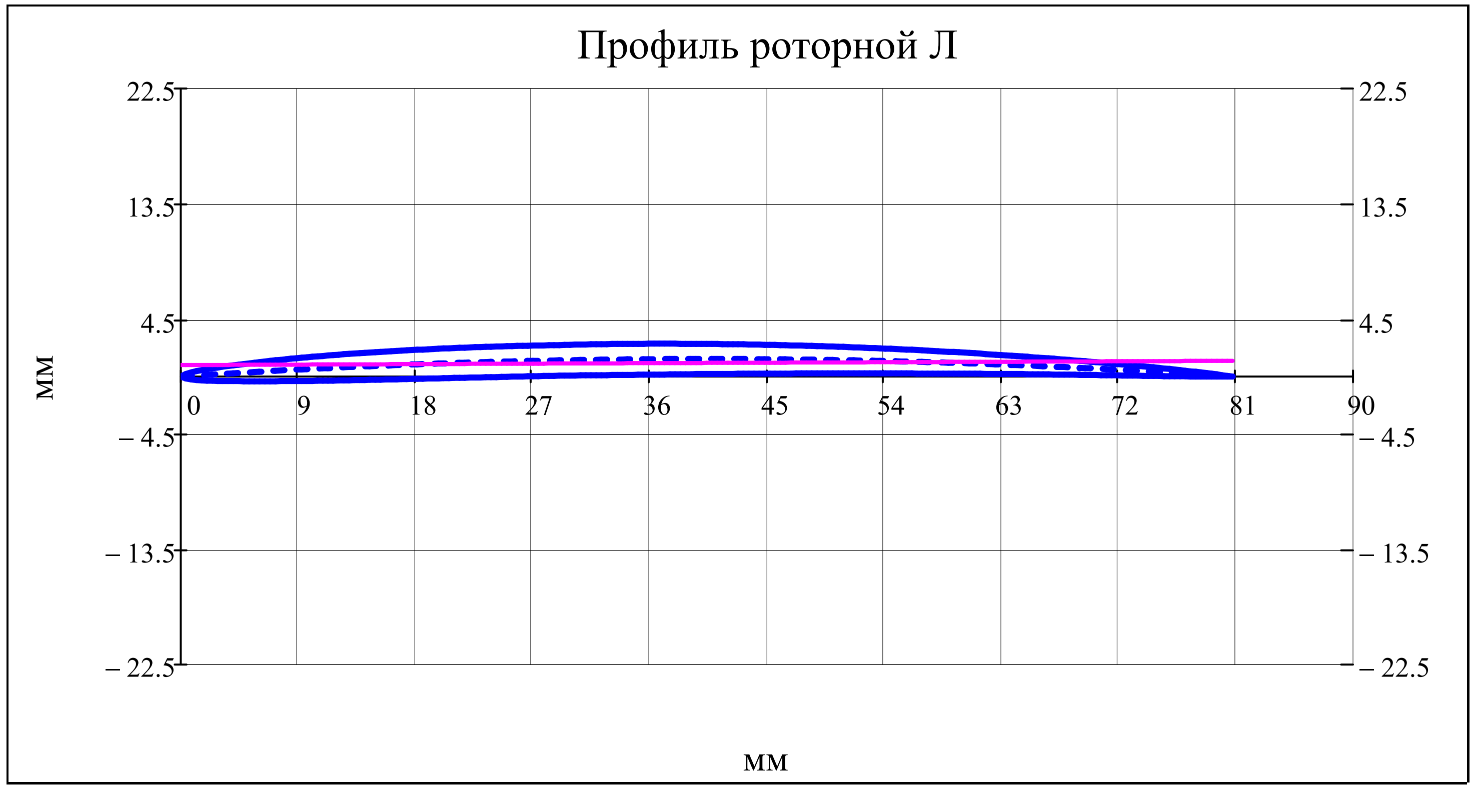

Профиль статорной Л
22.5
13.5
4.5
– 4.5
– 13.5
– 22.5
0
9
18
27
36
45
54
63
72
81
90
мм
мм

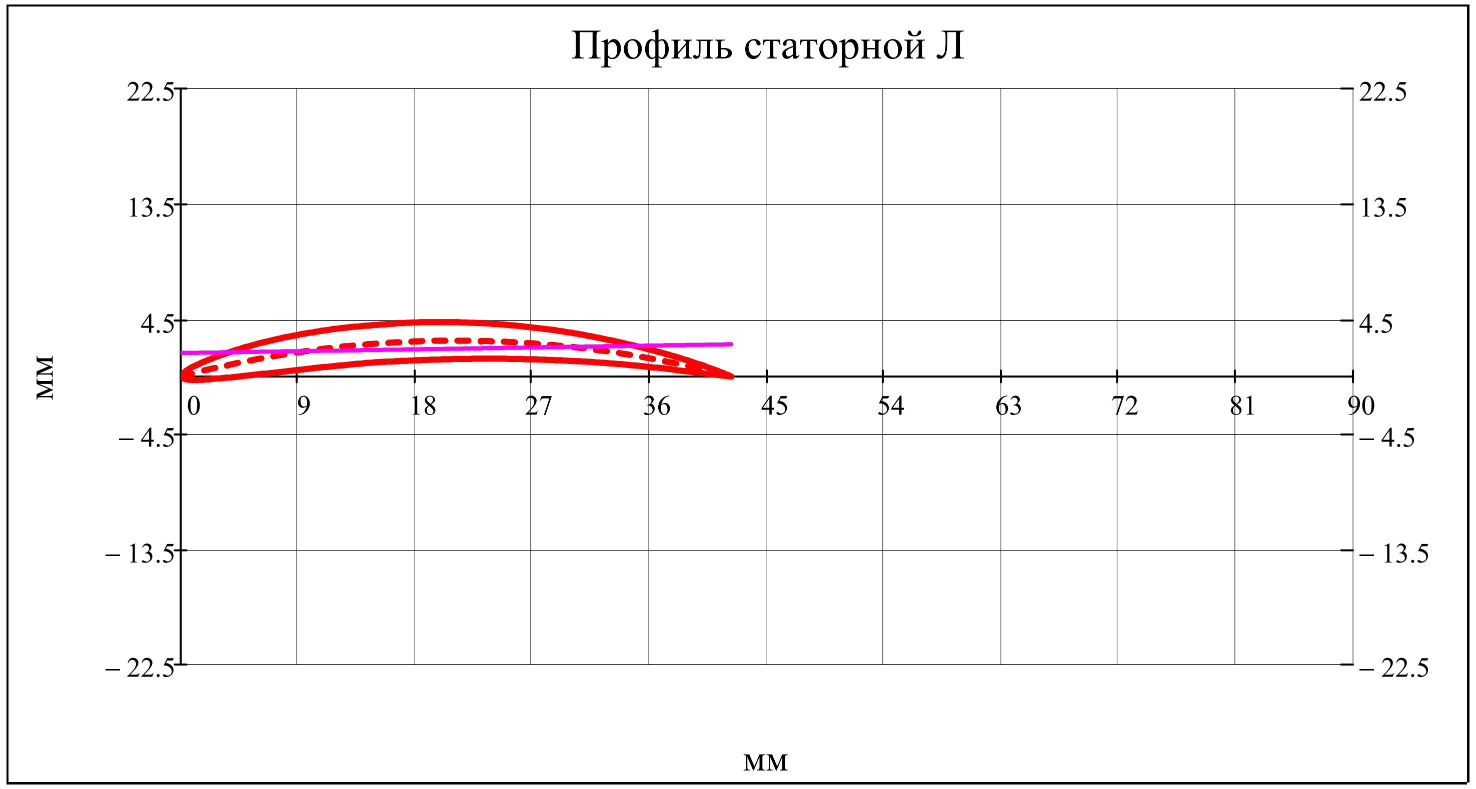
$r = av(N_r)$


Профиль роторной Л
22.5
13.5
4.5
– 4.5
– 13.5
– 22.5
0
9
18
27
36
45
54
63
72
81
90
мм
мм


Профиль статорной Л
22.5
13.5
4.5
– 4.5
– 13.5
– 22.5
0
9
18
27
36
45
54
63
72
81
90
мм
мм

$r = N_r$





Построение профилей Л РК и НА

Вывод координат для построения профиля Л

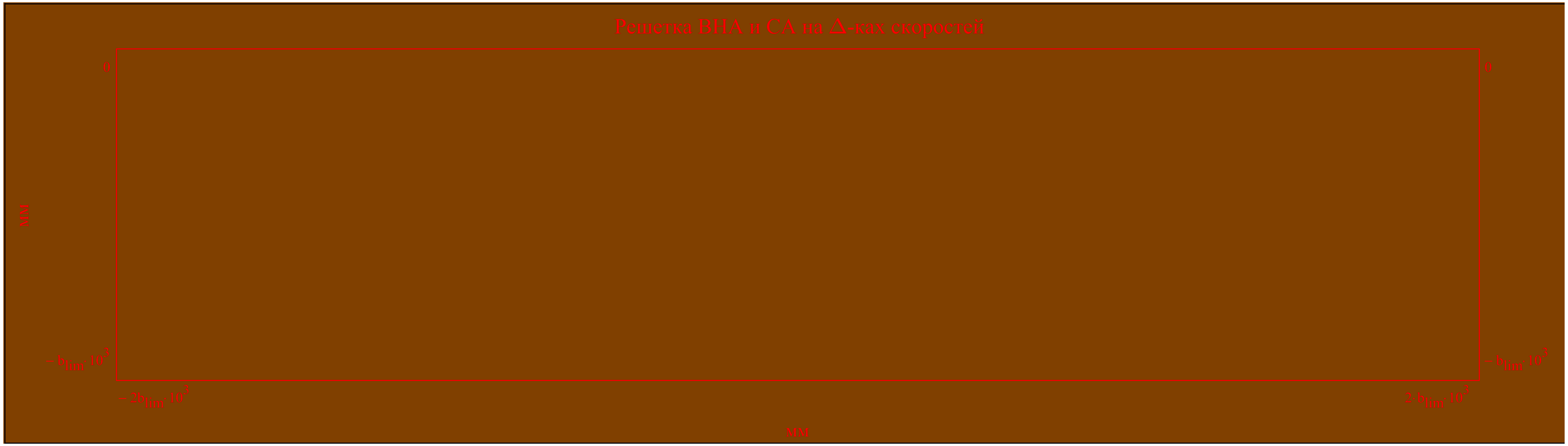
Рассматриваемая ступень:

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

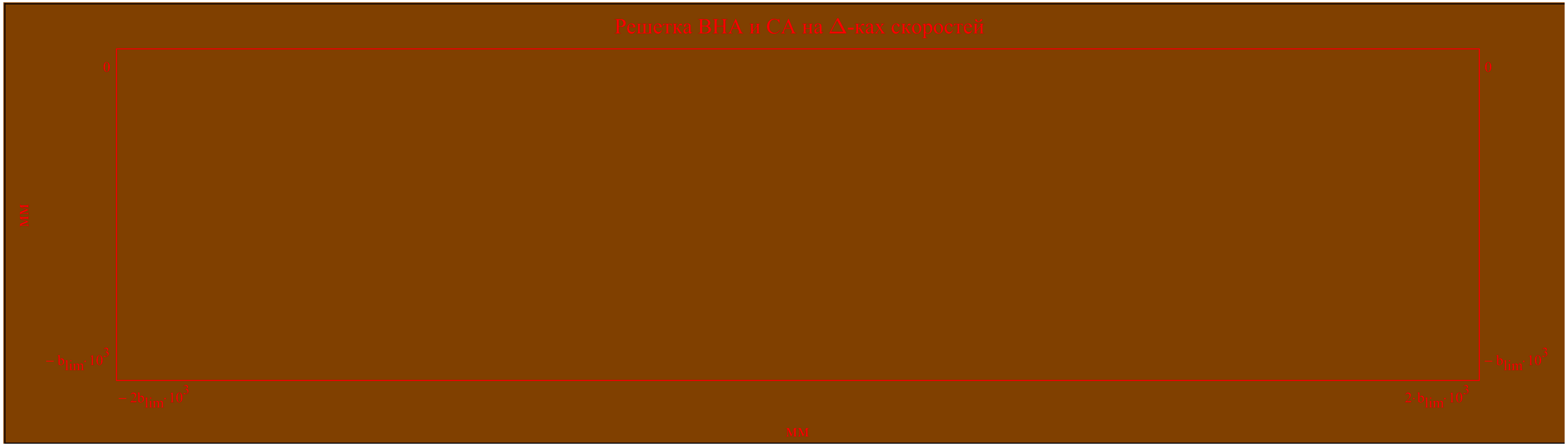
$$b_{lim} := \frac{\text{ceil}\left(\max\left(\text{chord}_{\text{rotor}_{j,N_r}}, \text{chord}_{\text{stator}_{j,N_r}}\right) \cdot 10^2\right)}{10^2} = 90 \cdot 10^{-3}$$

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

$r := 1$

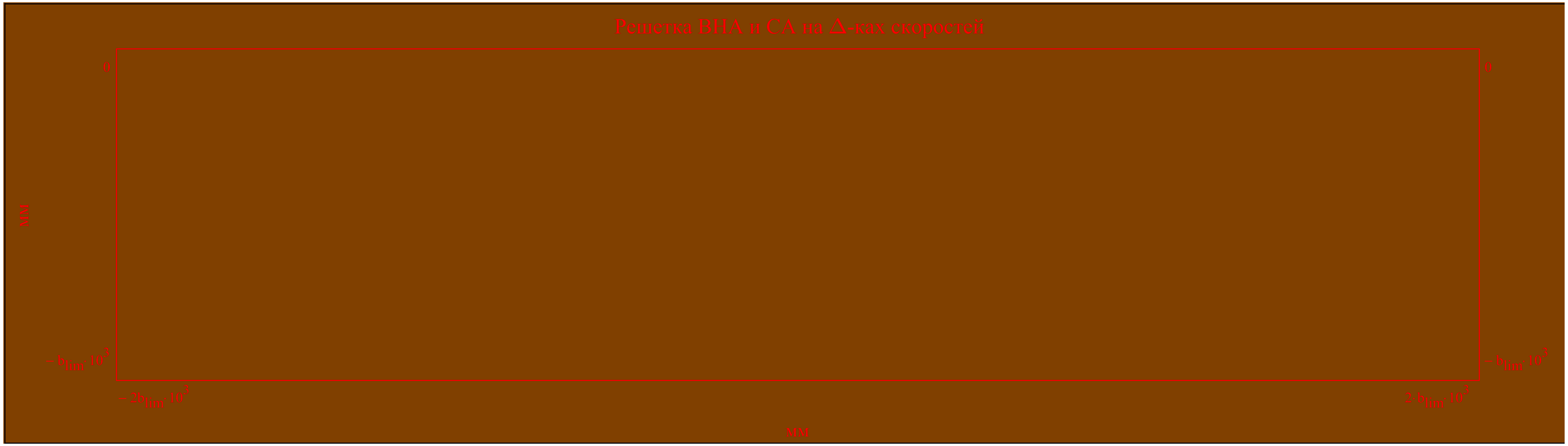


$r = av(N_r)$



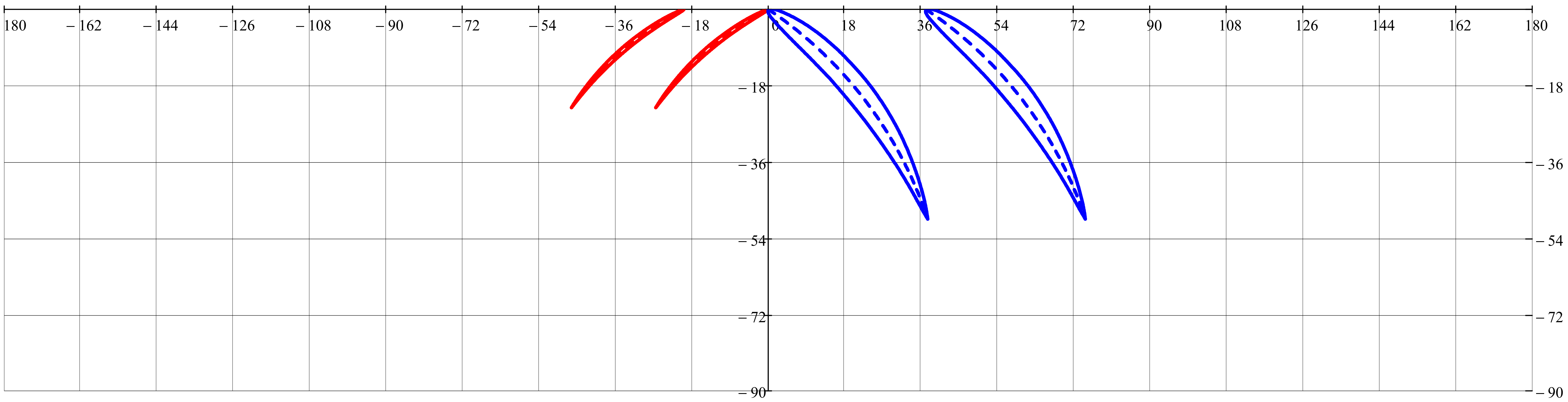
Решетка ВНА и СА на Δ-ках скоростей
0
0
мм
$-b_{lim} \cdot 10^3$
$-b_{lim} \cdot 10^3$
$-2b_{lim} \cdot 10^3$
$2 \cdot b_{lim} \cdot 10^3$
мм

$r = N_r$

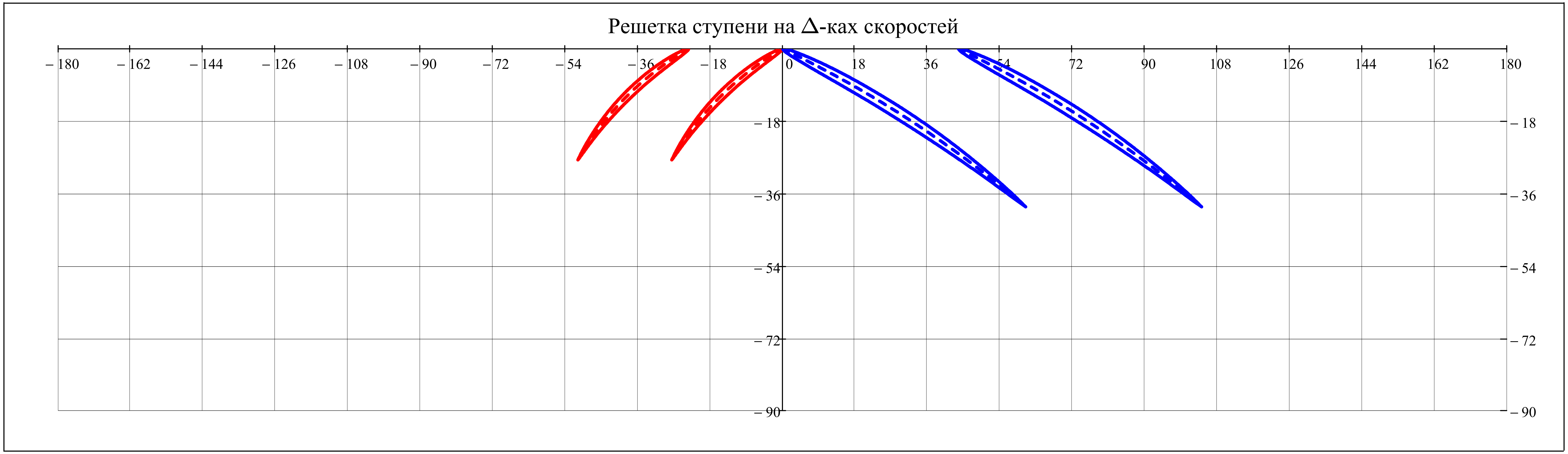

Решетка ВНА и СА на Δ-ках скоростей
0
0
$-b_{lim}\cdot 10^3$
$-b_{lim}\cdot 10^3$
мм
$-2b_{lim}\cdot 10^3$
$2\cdot b_{lim}\cdot 10^3$
мм

$r = 1$

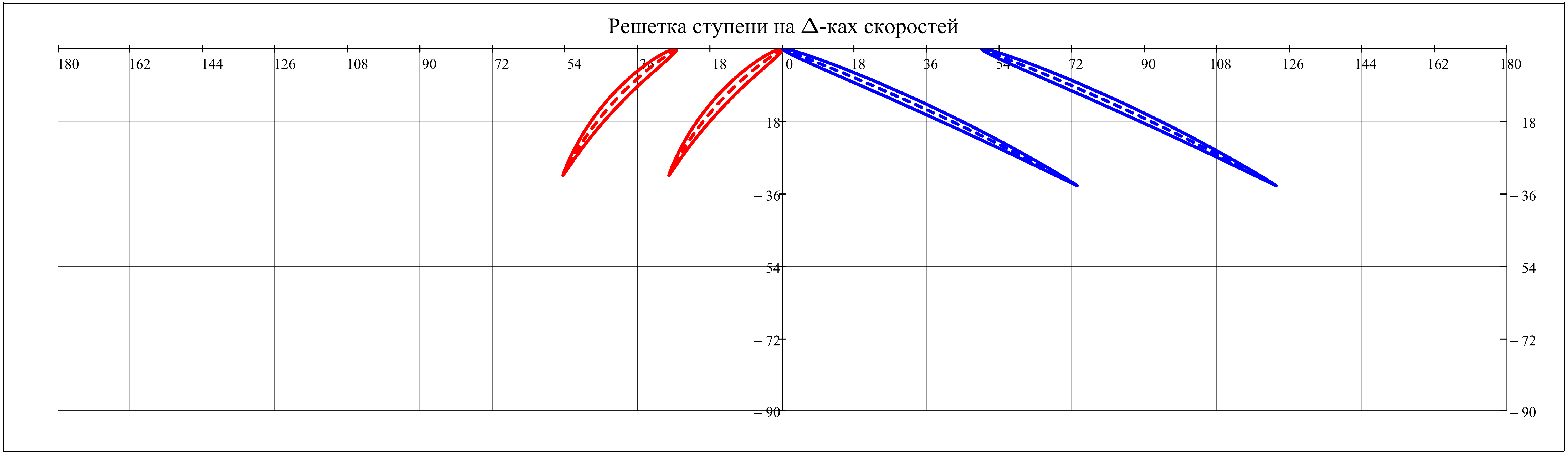
Решетка ступени на Δ-ках скоростей



$r = av(N_r)$


Решетка ступени на Δ-ках скоростей
– 180
– 162
– 144
– 126
– 108
– 90
– 72
– 54
– 36
– 18
0
18
36
54
72
90
108
126
144
162
180
– 18
– 36
– 54
– 72
– 90

$r = N_r$


Решетка ступени на Δ-ках скоростей

▲ 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]:

$\overline{\Delta}r = 0.0025$

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

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

$$\Delta_r^{\,T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 2.56 & 2.51 & 2.36 \end{array} \cdot 10^{-3}$$

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

$\overline{\Delta}a = 0.17$

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

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

$$\Delta a^{T} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 12.25 & 13.09 & 14.79 \end{array} \cdot 10^{-3}$$

Односторонний осевой зазор (м):

$$\frac{\Delta a^{T}}{2} = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 6.13 & 6.55 & 7.40 \end{array} \cdot 10^{-3}$$

Длина ОК (м):

$$Length = \left[\Delta a_1 + \begin{cases} chord_{BHA_{av(N_r)}} \cdot \sin\left(\upsilon_{BHA_{av(N_r)}}\right) & \text{if } BHA = 1 \\ 0 & \text{otherwise} \end{cases} \ldots \\ + \sum_{i=1}^{Z} \left(chord_{rotor_{i,av(N_r)}} \cdot \sin\left(\upsilon_{rotor_{i,av(N_r)}}\right)\right) + 2 \cdot \sum_{i=1}^{Z} \Delta a_i + \sum_{i=1}^{Z} \left(chord_{stator_{i,av(N_r)}} \cdot \sin\left(\upsilon_{stator_{i,av(N_r)}}\right)\right) \ldots \\ + \begin{cases} chord_{CA_{av(N_r)}} \cdot \sin\left(\upsilon_{CA_{av(N_r)}}\right) & \text{if } CA = 1 \\ 0 & \text{otherwise} \end{cases} + \Delta a_Z \right] = 342.8 \cdot 10^{-3}$$

Радиальные и осевые зазоры и длина К

Проточная часть

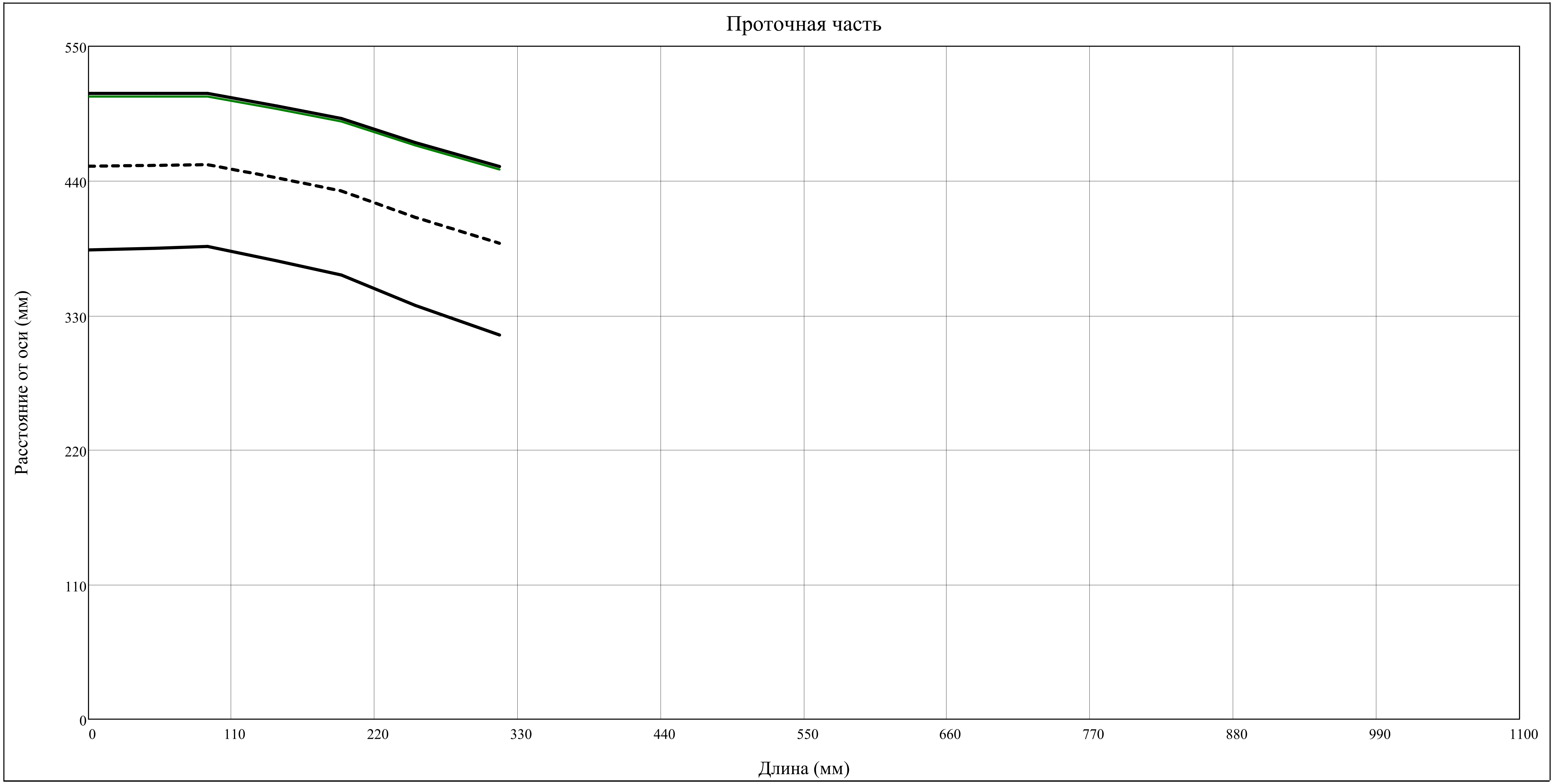
```
$\begin{pmatrix} x_{\text{ПЧ}} \\ y_{\text{ПЧпер}} \\ y_{\text{ПЧср}} \\ y_{\text{ПЧкор}} \\ y_{\text{Лпер}} \end{pmatrix} =$
    $c = 1$
    $x_{\text{ПЧ}_c} =$
        $chord_{BHA_{av(N_r)}} \cdot \sin\left(\upsilon_{BHA_{av(N_r)}}\right)$  if  $BHA = 1$
        $0$  otherwise
    $y_{\text{ПЧпер}_c} = R_{st(c,1),N_r}$
    $y_{\text{Лпер}_c} = y_{\text{ПЧпер}_c} - \Delta_{r_c}$
    $y_{\text{ПЧср}_c} = R_{st(c,1),av(N_r)}$
    $y_{\text{ПЧкор}_c} = R_{st(c,1),ORIGIN}$
    for  $i \in 1..Z$
        $c = c + 1$
        $x_{\text{ПЧ}_c} = x_{\text{ПЧ}_{c-1}} + 0.5 \cdot \Delta a_i + chord_{rotor_{i,av(N_r)}} \cdot \sin\left(\upsilon_{rotor_{i,av(N_r)}}\right) + 0.5 \cdot \Delta a_i$
        $\begin{pmatrix} y_{\text{ПЧпер}_c} \\ y_{\text{ПЧср}_c} \\ y_{\text{ПЧкор}_c} \end{pmatrix} = \begin{pmatrix} R_{st(i,2),N_r} \\ R_{st(i,2),av(N_r)} \\ R_{st(i,2),ORIGIN} \end{pmatrix}$
        $y_{\text{Лпер}_c} = y_{\text{ПЧпер}_c} - \Delta_{r_i}$
        $c = c + 1$
        $x_{\text{ПЧ}_c} = x_{\text{ПЧ}_{c-1}} + 0.5 \cdot \Delta a_i + chord_{stator_{i,av(N_r)}} \cdot \sin\left(\upsilon_{stator_{i,av(N_r)}}\right) + 0.5 \cdot \Delta a_i$
        $\begin{pmatrix} y_{\text{ПЧпер}_c} \\ y_{\text{ПЧср}_c} \\ y_{\text{ПЧкор}_c} \end{pmatrix} = \begin{pmatrix} R_{st(i,3),N_r} \\ R_{st(i,3),av(N_r)} \\ R_{st(i,3),ORIGIN} \end{pmatrix}$
        $y_{\text{Лпер}_c} = y_{\text{ПЧпер}_c} - \Delta_{r_i}$
    $\left(x_{\text{ПЧ}} \;\; y_{\text{ПЧпер}} \;\; y_{\text{ПЧср}} \;\; y_{\text{ПЧкор}} \;\; y_{\text{Лпер}}\right)^T$
```

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

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

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

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



▲ Проточная часть

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

▼ Поперечная часть ступени

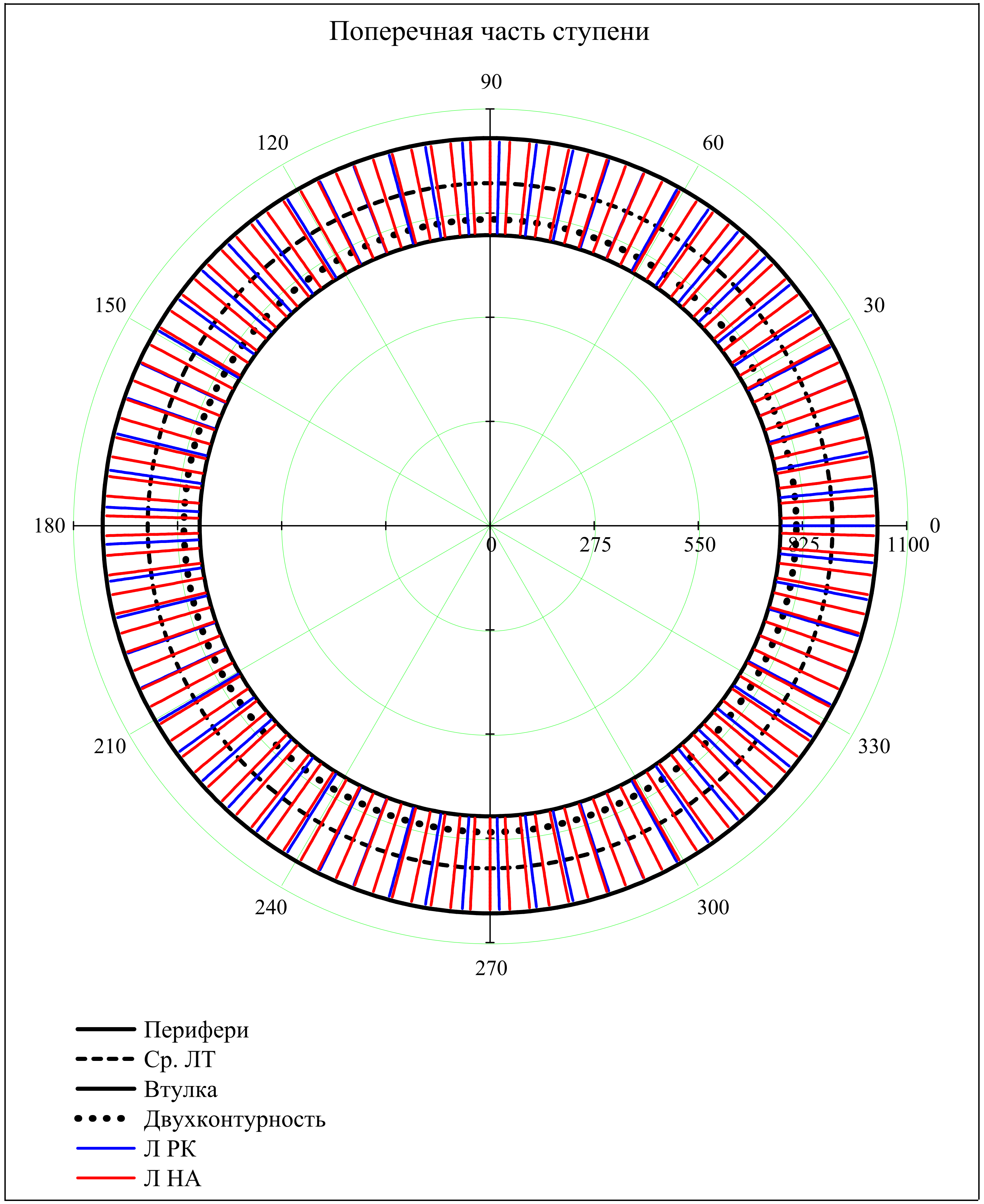
$$r = \min(D), \min(D) + \frac{\max(D) - \min(D)}{N_{dis}} .. \max(D)$$

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

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

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

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



▲ Поперечная часть ступени

Выбор материала Л

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

Выбранный материал Л:

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

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

Плотность материала Л (кг/м^3):

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

Предел длительной прочности Л РК (Па):

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

Коэф. формы: $k_n = 6.8$

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

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

$material\_blade^T =$

	1	2	3	4	5	6	7	8	9
1	"ВТ6"	"ВТ6"	"ВТ6"						

$\rho\_blade^T =$

	1	2	3
1	4430	4430	4430

$\sigma\_blade\_long^T =$

	1	2	3
1	210.0	210.0	210.0

$\cdot 10^6$

Выбор материала Л

Расчет собственных частот колебаний Л

$$\begin{pmatrix} \nu0_{\text{изг.stator}} & \nu0_{\text{изг.rotor}} \\ \nu0_{\text{угл.stator}} & \nu0_{\text{угл.rotor}} \\ \nu0_{\text{угл.stator\_bondage}} & \nu0_{\text{угл.rotor\_bondage}} \end{pmatrix} =$$

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

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	874	862	811	693	700	675												
2	2622	2587	2434	2078	2100	2025												
3	4369	4312	4057	3463	3501	3374												
4	6117	6037	5680	4848	4901	4724												
5	7865	7762	7302	6233	6301	6074												
6	9612	9487	8925	7618	7702	7424												

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	187	268	316	215	253	246												
2	1171	1679	1980	1347	1585	1545												
3	3279	4700	5545	3771	4439	4325												
4	6429	9218	10875	7395	8705	8482												
5	10624	15231	17969	12219	14384	14016												
6	15866	22747	26836	18249	21482	20932												

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1748	1725	1623	1385	1400	1350												
2	3495	3450	3246	2770	2801	2699												
3	5243	5175	4868	4155	4201	4049												
4	6991	6900	6491	5540	5601	5399												
5	8738	8625	8114	6926	7001	6749												
6	10486	10349	9737	8311	8402	8098												

▲ 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

$$\begin{pmatrix} R0_{rotor} & area0_{rotor} \\ N0_{rotor} & \sigma0\_z_{rotor} \\ area_{rotor.} & area_{stator.} \\ N_{rotor} & \sigma\_z_{rotor} \\ P_1 & \rho_1 \\ P_2 & \rho_2 \\ P_3 & \rho_3 \\ c_{a1} & c_{u1} \\ c_{a2} & c_{u2} \\ c_{a3} & c_{u3} \\ qx_{rotor} & qx_{stator} \\ qy_{rotor} & qy_{stator} \\ Mx_{rotor} & Mx_{stator} \\ My_{rotor} & My_{stator} \\ shift\_x_{rotor} & shift\_y_{rotor} \\ x0_{rotor.} & x0_{stator.} \\ y0_{rotor.} & y0_{stator.} \\ \alpha\_major_{rotor.} & \alpha\_major_{stator.} \\ Ju_{rotor.} & Ju_{stator.} \\ Jv_{rotor.} & Jv_{stator.} \\ CPx_{rotor.} & CPx_{stator.} \\ CPy_{rotor.} & CPy_{stator.} \\ CPx_{rotor.axis} & CPx_{stator.axis} \\ CPy_{rotor.axis} & CPy_{stator.axis} \end{pmatrix} =$$

$$\chi_{rotor}(i,z) = \frac{area_{rotor_{i,N_r}}}{area_{rotor_{i,1}}}$$

$$R0_{rotor}(i,z) = \frac{1}{\sqrt{1-\ln(\chi_{rotor}(i,z))}} \cdot \begin{vmatrix} \sqrt{mean\left(R_{st(i,1),1}, R_{st(i,2),1}\right)^2 - mean\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right)^2 \cdot \ln(\chi_{rotor}(i,z))} & \text{if type = "compressor"} \\ \sqrt{mean\left(R_{st(i,2),1}, R_{st(i,3),1}\right)^2 - mean\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right)^2 \cdot \ln(\chi_{rotor}(i,z))} & \text{if type = "turbine"} \end{vmatrix}$$

$$\sigma0_{rotor.max}(i,z) = \frac{\rho\_blade_i \cdot \omega^2}{2} \cdot \begin{vmatrix} \left[mean\left(R_{st(i,1),N_r}, R_{st(i,2),N_r}\right)^2 - \left(R0_{rotor}(i,z)\right)^2\right] & \text{if type = "compressor"} \\ \left[mean\left(R_{st(i,2),N_r}, R_{st(i,3),N_r}\right)^2 - \left(R0_{rotor}(i,z)\right)^2\right] & \text{if type = "turbine"} \end{vmatrix}$$

$$\rho\_blade_i \cdot \omega^2 \quad \int^{R0_{rotor}(i,z)}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\mathrm{M}\tau_{\mathrm{rotor}}(i,z) = \int_{z}^{\left|\begin{array}{ll}\mathrm{mean}\left(R_{\mathrm{st}(i,1),N_r},R_{\mathrm{st}(i,2),N_r}\right) & \text{if type="compressor"}\\ \mathrm{mean}\left(R_{\mathrm{st}(i,2),N_r},R_{\mathrm{st}(i,3),N_r}\right) & \text{if type="turbine"}\end{array}\right.} \left(\mathrm{qx}_{\mathrm{rotor}}(i,z1)\cdot\mathrm{CPy}_{\mathrm{rotor.axis}}(i,z1) - \mathrm{qy}_{\mathrm{rotor}}(i,z1)\cdot\mathrm{CPx}_{\mathrm{rotor.axis}}(i,z1)\right)\,dz1$$

$$\mathrm{M}\tau_{\mathrm{stator}}(i,z) = \int_{z}^{\left|\begin{array}{ll}\mathrm{mean}\left(R_{\mathrm{st}(i,2),1},R_{\mathrm{st}(i,3),1}\right) & \text{if type="compressor"}\\ \mathrm{mean}\left(R_{\mathrm{st}(i,1),1},R_{\mathrm{st}(i,2),1}\right) & \text{if type="turbine"}\end{array}\right.} \left(\mathrm{qx}_{\mathrm{stator}}(i,z1)\cdot\mathrm{CPy}_{\mathrm{stator.axis}}(i,z1) - \mathrm{qy}_{\mathrm{stator}}(i,z1)\cdot\mathrm{CPx}_{\mathrm{stator.axis}}(i,z1)\right)\,dz1$$

$$\tau_{\mathrm{rotor}}(i,z) = \frac{\mathrm{M}\tau_{\mathrm{rotor}}(i,z)}{\mathrm{Wp}_{\mathrm{rotor.}}(i,z)}$$

$$\tau_{\mathrm{stator}}(i,z) = \frac{\mathrm{M}\tau_{\mathrm{stator}}(i,z)}{\mathrm{Wp}_{\mathrm{stator.}}(i,z)}$$

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

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

$$\mathrm{Mu}_{\mathrm{rotor}}(i,z) = \mathrm{axis}_x\left(\mathrm{Mx}_{\mathrm{rotor}}(i,z),\mathrm{My}_{\mathrm{rotor}}(i,z),0,0,\varphi\_\mathrm{uv}_{\mathrm{rotor}}(i,z),1\right)$$

$$\mathrm{Mu}_{\mathrm{stator}}(i,z) = \mathrm{axis}_x\left(\mathrm{Mx}_{\mathrm{stator}}(i,z),\mathrm{My}_{\mathrm{stator}}(i,z),0,0,\varphi\_\mathrm{uv}_{\mathrm{stator}}(i,z),1\right)$$

$$\mathrm{Mv}_{\mathrm{rotor}}(i,z) = \mathrm{axis}_y\left(\mathrm{Mx}_{\mathrm{rotor}}(i,z),\mathrm{My}_{\mathrm{rotor}}(i,z),0,0,\varphi\_\mathrm{uv}_{\mathrm{rotor}}(i,z),1\right)$$

$$\mathrm{Mv}_{\mathrm{stator}}(i,z) = \mathrm{axis}_y\left(\mathrm{Mx}_{\mathrm{stator}}(i,z),\mathrm{My}_{\mathrm{stator}}(i,z),0,0,\varphi\_\mathrm{uv}_{\mathrm{stator}}(i,z),1\right)$$

$$\varphi\_\mathrm{neutral}_{\mathrm{rotor}}(i,z) = \left|\begin{array}{ll}\mathrm{atan}\left(\dfrac{\mathrm{Mv}_{\mathrm{rotor}}(i,z)\cdot\mathrm{Ju}_{\mathrm{rotor.}}(i,z)}{\mathrm{Mu}_{\mathrm{rotor}}(i,z)\cdot\mathrm{Jv}_{\mathrm{rotor.}}(i,z)}\right) & \text{if } \mathrm{Mu}_{\mathrm{rotor}}(i,z)\cdot\mathrm{Jv}_{\mathrm{rotor.}}(i,z)\neq 0\\ \dfrac{\pi}{2} & \text{otherwise}\end{array}\right.$$

$$\varphi\_\mathrm{neutral}_{\mathrm{stator}}(i,z) = \left|\begin{array}{ll}\mathrm{atan}\left(\dfrac{\mathrm{Mv}_{\mathrm{stator}}(i,z)\cdot\mathrm{Ju}_{\mathrm{stator.}}(i,z)}{\mathrm{Mu}_{\mathrm{stator}}(i,z)\cdot\mathrm{Jv}_{\mathrm{stator.}}(i,z)}\right) & \text{if } \mathrm{Mu}_{\mathrm{stator}}(i,z)\cdot\mathrm{Jv}_{\mathrm{stator.}}(i,z)\neq 0\\ \dfrac{\pi}{2} & \text{otherwise}\end{array}\right.$$

$$\left(\begin{array}{cc}\mathrm{R0}_{\mathrm{rotor}} & \mathrm{area0}_{\mathrm{rotor}}\\ \mathrm{N0}_{\mathrm{rotor}} & \sigma0\_z_{\mathrm{rotor}}\\ \mathrm{area}_{\mathrm{rotor.}} & \mathrm{area}_{\mathrm{stator.}}\\ N_{\mathrm{rotor}} & \sigma\_z_{\mathrm{rotor}}\end{array}\right.$$

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

▲ Расчет Л на прочность

$$\text{neutral\_line}(\text{type}, x, i, r) = \left| \begin{array}{ll} \dfrac{y0_{\text{rotor}_{i,r}}}{\text{chord}_{\text{rotor}_{i,r}}} + \tan\left(\left(\alpha\_\text{major}_{\text{rotor}_{i,r}} + \varphi\_\text{neutral}_{\text{rotor}}\left(i, R_{\text{st}(i,2),r}\right)\right)\right) \cdot \left(x - \dfrac{x0_{\text{rotor}_{i,r}}}{\text{chord}_{\text{rotor}_{i,r}}}\right) & \text{if type} = \text{"rotor"} \\ \dfrac{y0_{\text{stator}_{i,r}}}{\text{chord}_{\text{stator}_{i,r}}} + \tan\left(\left(\alpha\_\text{major}_{\text{stator}_{i,r}} + \varphi\_\text{neutral}_{\text{stator}}\left(i, R_{\text{st}(i,2),r}\right)\right)\right) \cdot \left(x - \dfrac{x0_{\text{stator}_{i,r}}}{\text{chord}_{\text{stator}_{i,r}}}\right) & \text{if type} = \text{"stator"} \end{array} \right.$$

$$\text{epure}(\text{type}, x, i, r) = \left| \begin{array}{ll} \dfrac{y0_{\text{rotor}_{i,r}}}{\text{chord}_{\text{rotor}_{i,r}}} + \dfrac{-1}{\tan\left(\alpha\_\text{major}_{\text{rotor}_{i,r}} + \varphi\_\text{neutral}_{\text{rotor}}\left(i, R_{\text{st}(i,2),r}\right) - \dfrac{\pi}{4}\right)} \cdot \left(x - \dfrac{x0_{\text{rotor}_{i,r}}}{\text{chord}_{\text{rotor}_{i,r}}}\right) & \text{if type} = \text{"rotor"} \\ \dfrac{y0_{\text{stator}_{i,r}}}{\text{chord}_{\text{stator}_{i,r}}} + \dfrac{-1}{\tan\left(\alpha\_\text{major}_{\text{stator}_{i,r}} + \varphi\_\text{neutral}_{\text{stator}}\left(i, R_{\text{st}(i,2),r}\right) - \dfrac{\pi}{4}\right)} \cdot \left(x - \dfrac{x0_{\text{stator}_{i,r}}}{\text{chord}_{\text{stator}_{i,r}}}\right) & \text{if type} = \text{"stator"} \end{array} \right.$$

▶ 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	-12.869	-8.632	-6.369						
2	-0.812	-0.808	-0.816						
3	-0.897	-0.929	-0.931						

$\cdot 10^{-3}$

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

	1	2	3
1	5.554	5.189	4.787
2	1.980	2.082	1.978
3	36.465	1.578	1.506

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	32.400	32.610	33.132						
2	39.494	39.486	39.498						
3	-1.228	44.263	-28.394						

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	-11.216	-11.055	-9.312						
2	-2.338	-2.734	-2.267						
3	-44.267	-1.520	-1.240						

$\cdot 10$

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

	1	2	3	4	5	6	7	8	9
1	0.312	0.319	0.314						
2	-0.037	-0.025	-0.031						
3	-0.030	-0.013	-0.021						

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	1.035	1.155	1.074						
2	1.550	1.690	1.617						
3	2.107	2.262	2.191						

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	19.285	19.266	19.279						
2	21.345	21.321	21.335						
3	23.135	23.105	23.120						

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	-2.034	-2.548	-2.199						
2	-2.334	-2.944	-2.623						
3	-2.573	-3.259	-2.940						

$\cdot 10^{-3}$

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

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

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

	1	2	3	4	5	6	7	8	9
1	-4.46	-5.26	-4.36						
2	-12.02	-16.11	-14.53						
3	0.00	-0.21	-0.53						

$\cdot 10^{6}$

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

	1	2	3	4	5	6	7	8	9
1	0.01	0.39	0.65						
2	46.82	26.96	12.71						
3	81.04	44.66	18.78						

$\cdot 10^{6}$

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

	1	2	3
1	1	1	1
2	1	1	1
3	1	1	1

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

	1	2	3
1	1	1	1
2	1	1	1
3	0	1	1

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

	1	2	3	4	5	6	7	8	9
1	9.71	12.96	10.20						
2	15.41	22.59	17.60						
3	0.00	0.21	0.43						

$\cdot 10^{6}$

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

	1	2	3	4	5	6	7	8	9
1	-0.03	-0.88	-1.35						
2	-71.44	-48.03	-20.98						
3	-101.06	-66.39	-25.87						

$\cdot 10^{6}$

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

	1	2	3
1	1	1	1
2	1	1	1
3	1	1	1

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

	1	2	3
1	1	1	1
2	1	1	1
3	1	1	1

```
$\begin{pmatrix}\sigma_{rotor}\\ \sigma_{stator}\end{pmatrix} =$
    for $i \in 1..Z$
        for $r \in 1..N_r$
            $\sigma_{rotor_{i,r}} = \sqrt{\left(\sigma\_z_{rotor}\left(i, R_{st(i,2),r}\right) + \max\left(\sigma\_p_{rotor_{i,r}}, \sigma\_n_{rotor_{i,r}}\right)\right)^2 + \tau_{rotor}\left(i, R_{st(i,2),r}\right)^2}$
            $\sigma_{stator_{i,r}} = \sqrt{\left(0 + \max\left(\sigma\_p_{stator_{i,r}}, \sigma\_n_{stator_{i,r}}\right)\right)^2 + \tau_{stator}\left(i, R_{st(i,2),r}\right)^2}$
    $\begin{pmatrix}\sigma_{rotor}\\ \sigma_{stator}\end{pmatrix}$
```

```
$\begin{pmatrix}\sigma_{rotor.}\\ \sigma_{stator.}\end{pmatrix} =$
    for $i \in 1..Z$
        $\sigma_{rotor.}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\sigma_{rotor}, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\sigma_{rotor}, i, i, 1, N_r\right)^T, z\right)$
        $\sigma_{stator.}(i,z) = \mathrm{interp}\left(\mathrm{lspline}\left(\mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\sigma_{stator}, i, i, 1, N_r\right)^T\right), \mathrm{submatrix}\left(R, st(i,2), st(i,2), 1, N_r\right)^T, \mathrm{submatrix}\left(\sigma_{stator}, i, i, 1, N_r\right)^T, z\right)$
    $\begin{pmatrix}\sigma_{rotor.}\\ \sigma_{stator.}\end{pmatrix}$
```

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

	1	2	3	4	5	6	7	8	9
1	56.86	60.87	58.39						
2	50.87	60.61	57.47						
3	0.00	3.77	6.96						

$\cdot 10^6$

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

	1	2	3	4	5	6	7	8	9
1	0.02	0.40	0.66						
2	46.82	26.97	12.72						
3	81.04	44.67	18.78						

$\cdot 10^6$

```
$\begin{pmatrix} safety_{rotor} \\ safety_{stator} \end{pmatrix} =$
  for $i \in 1..Z$
    for $r \in 1..N_r$
      $safety_{rotor_{i,r}} = \begin{cases} \dfrac{\sigma\_blade\_long_i}{\sigma_{rotor_{i,r}}} & \text{if } \sigma_{rotor_{i,r}} \neq 0 \\ \infty & \text{otherwise} \end{cases}$
      $safety_{stator_{i,r}} = \begin{cases} \dfrac{\sigma\_blade\_long_i}{\sigma_{stator_{i,r}}} & \text{if } \sigma_{stator_{i,r}} \neq 0 \\ \infty & \text{otherwise} \end{cases}$
  $\begin{pmatrix} safety_{rotor} \\ safety_{stator} \end{pmatrix}$
```

$safety_{rotor}{}^{T} =$

	1	2	3	4	5	6
1	3.69	3.45	3.6			
2	4.13	3.46	3.65			
3	00000000000000000000000000000000	55.66	30.18			

$safety_{rotor}{}^{T} \geq safety =$

	1	2	3
1	1	1	1
2	1	1	1
3	1	1	1

$safety_{stator}{}^{T} =$

	1	2	3	4	5
1	12142.81	520.95	315.95		
2	4.49	7.79	16.51		
3	2.59	4.7	11.18		

$safety_{stator}{}^{T} \geq safety =$

	1	2	3
1	1	1	1
2	1	1	1
3	1	1	1

Рассматриваемая ступень:

$$j = \left| \begin{array}{l} j = \left| \begin{array}{l} 1 \ \text{ if } \ type = \text{"compressor"} \\ Z \ \text{ if } \ type = \text{"turbine"} \end{array} \right. \\ j = \left| \begin{array}{l} \text{"Такой ступени не существует!"} \ \text{ if } \ (j < 1) \vee (j > Z) \\ j \ \text{ otherwise} \end{array} \right. \end{array} \right. = 1$$

$$b_{lim} = \frac{\text{ceil}\left(\max\left(chord_{rotor_{j,N_r}}, chord_{stator_{j,N_r}}\right) \cdot 10^2\right)}{10^2} = 90 \cdot 10^{-3}$$

Расстояния от оси ЛМ до рассматриваемой ступени (м):

$$Rj = \text{submatrix}\left(R, 2 \cdot j - 1, 2 \cdot j + 1, 1, N_r\right) =$$

	1	2	3
1	383.4	452.0	511.4
2	384.9	452.6	511.4
3	386.3	453.2	511.4

$\cdot 10^{-3}$

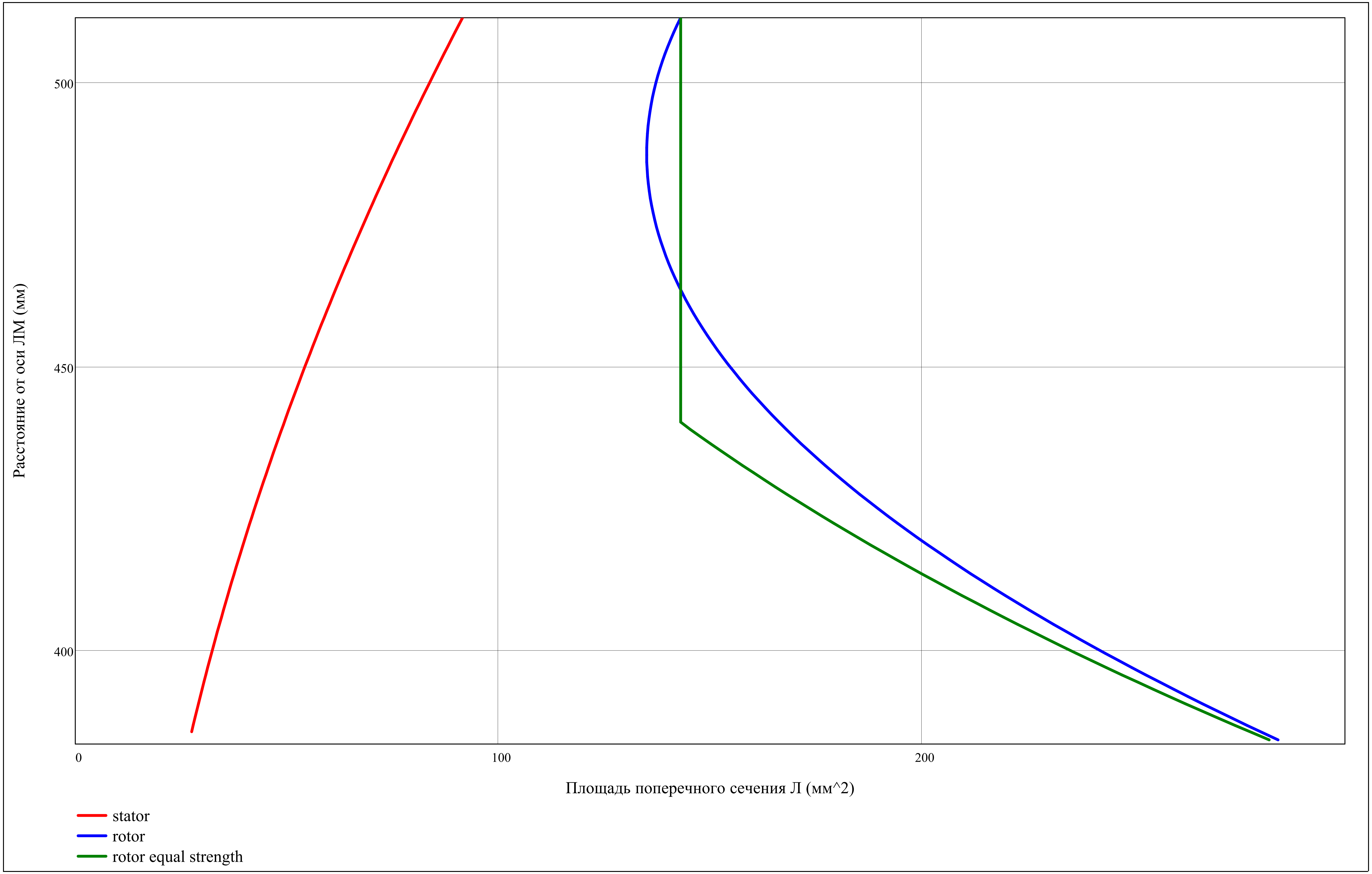
Дискретизация по высоте Л:

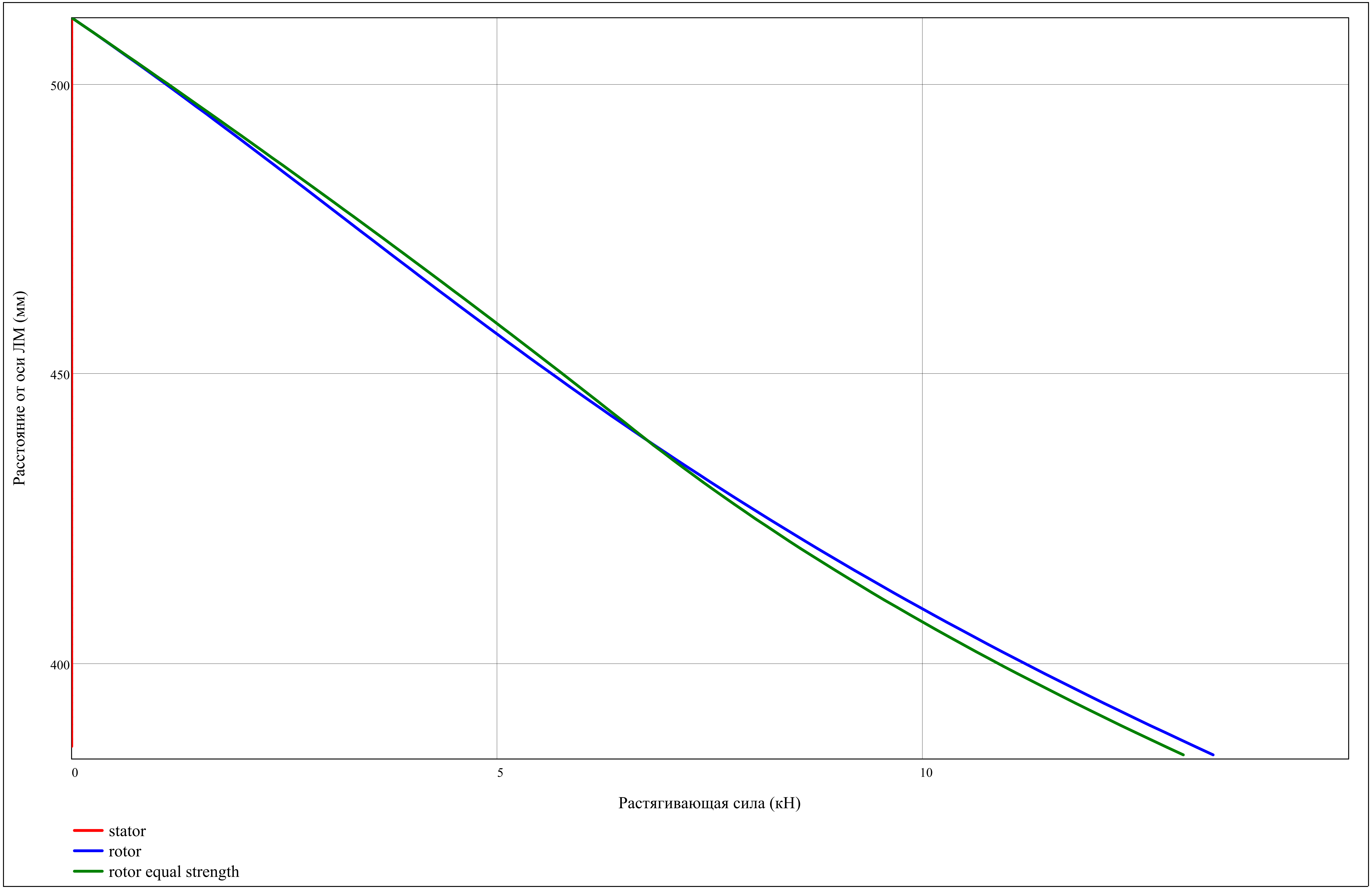
$$z = \min(Rj), \min(Rj) + \frac{\max(Rj) - \min(Rj)}{100} \, .. \, \max(Rj)$$

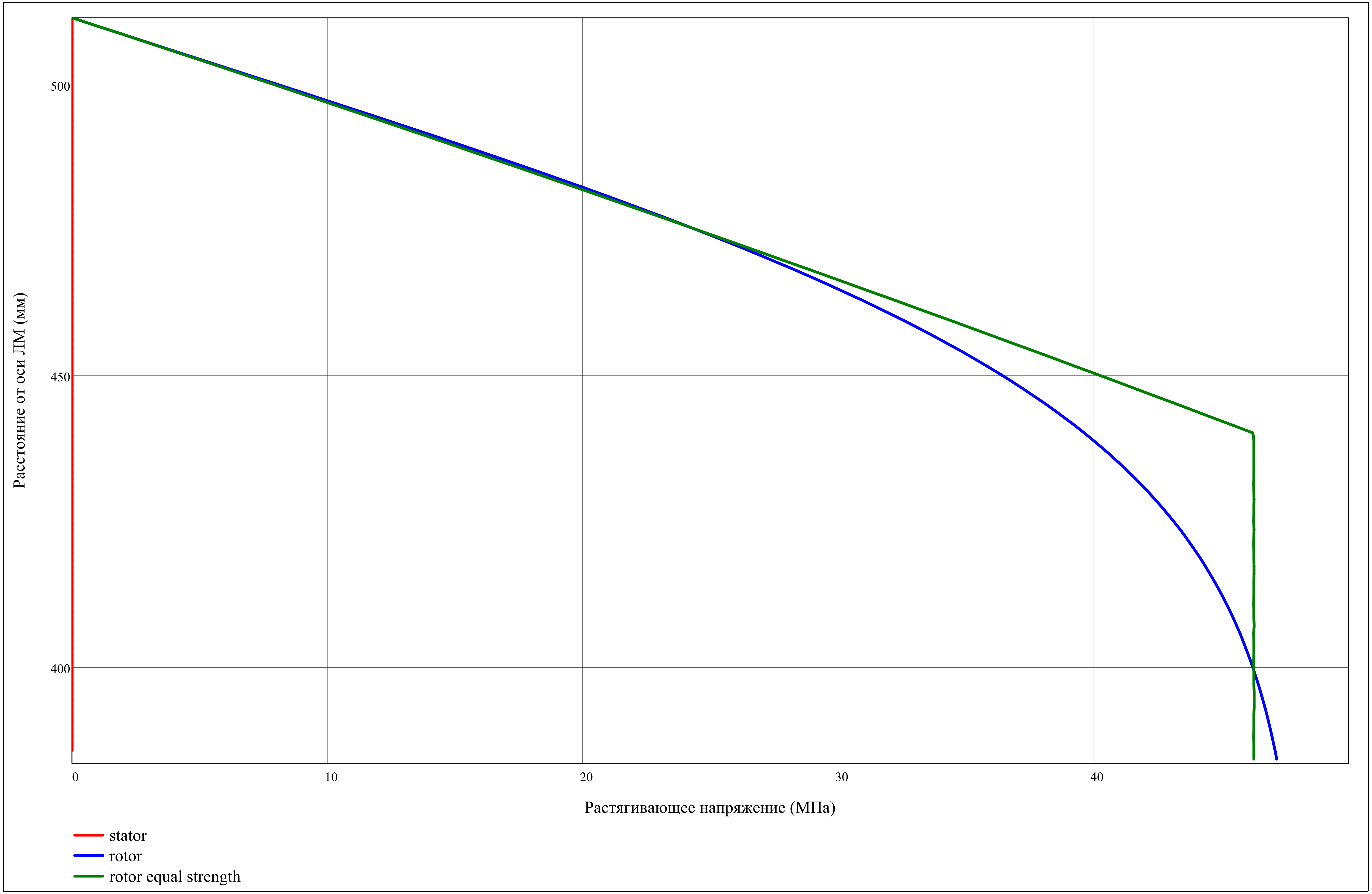
$$z_{rotor} = \left| \begin{array}{l} \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right), \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right) + \dfrac{\text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) - \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right)}{100} \, .. \, \text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) \ \text{ if } \ type = \text{"compressor"} \\ \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right), \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right) + \dfrac{\text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) - \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right)}{100} \, .. \, \text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) \ \text{ if } \ type = \text{"turbine"} \end{array} \right.$$

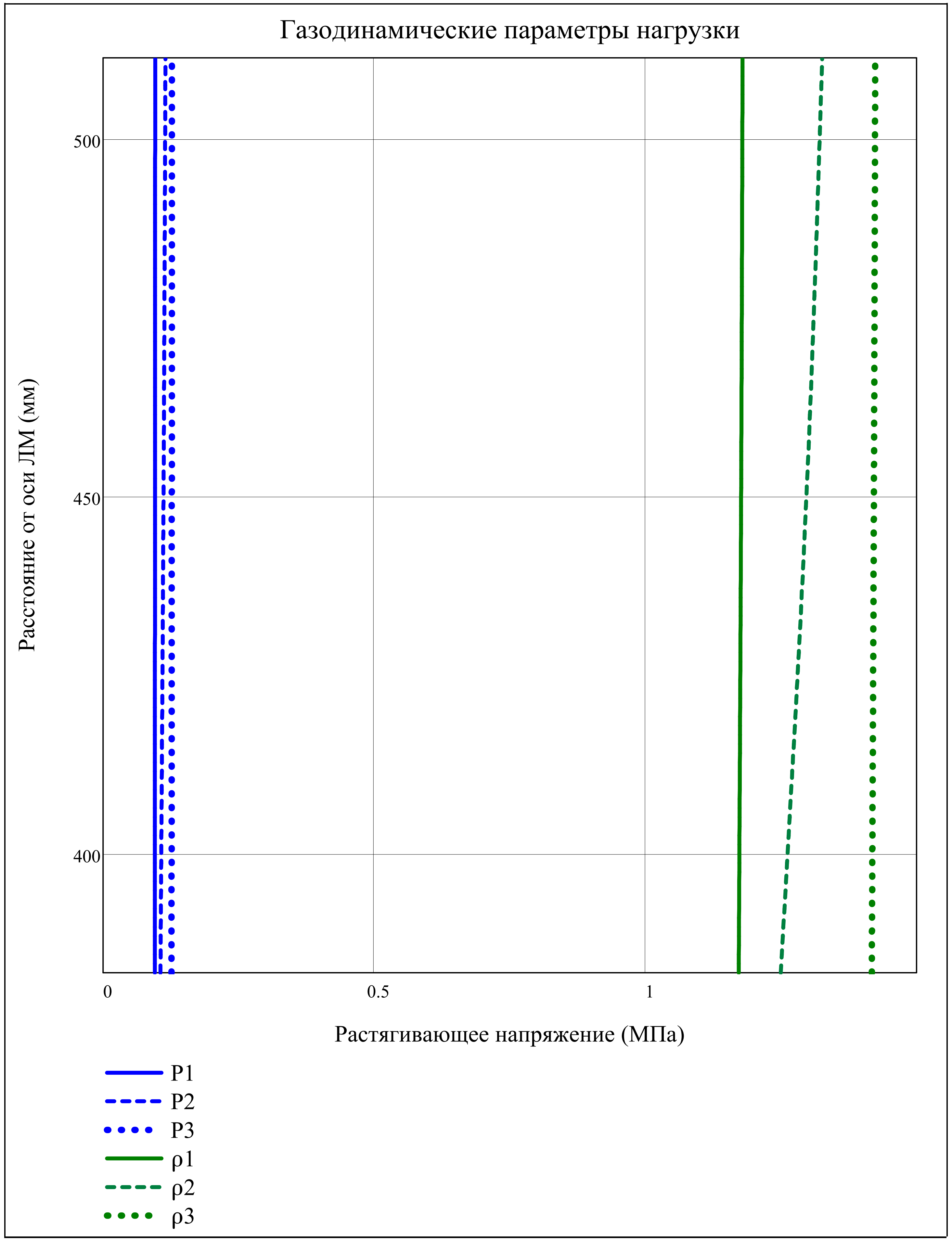
$$z_{stator} = \left| \begin{array}{l} \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right), \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right) + \dfrac{\text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) - \text{mean}\left(Rj_{2,1}, Rj_{3,1}\right)}{100} \, .. \, \text{mean}\left(Rj_{2,N_r}, Rj_{3,N_r}\right) \ \text{ if } \ type = \text{"compressor"} \\ \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right), \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right) + \dfrac{\text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) - \text{mean}\left(Rj_{1,1}, Rj_{2,1}\right)}{100} \, .. \, \text{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) \ \text{ if } \ type = \text{"turbine"} \end{array} \right.$$

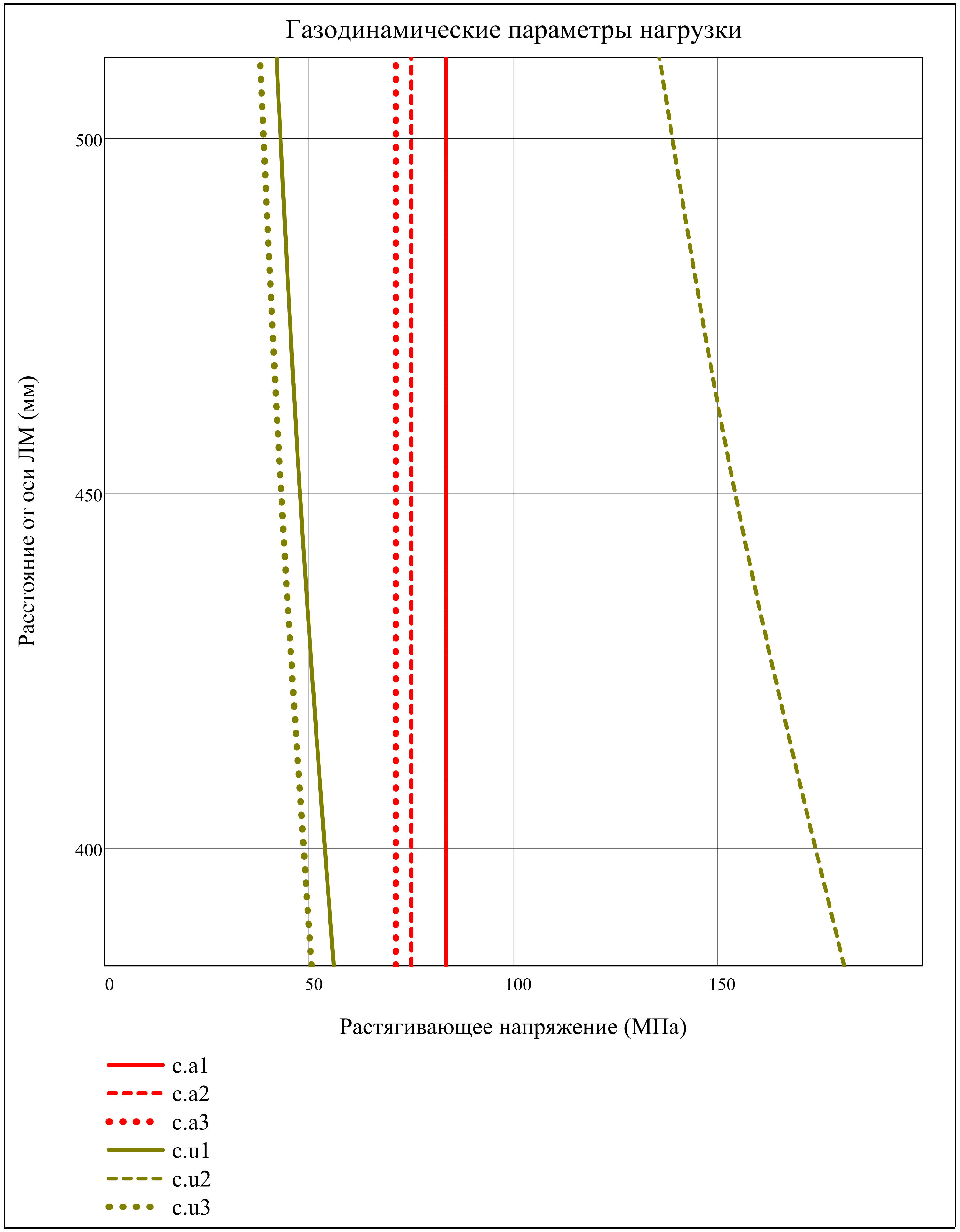
▾ Результаты расчета на прочность Л

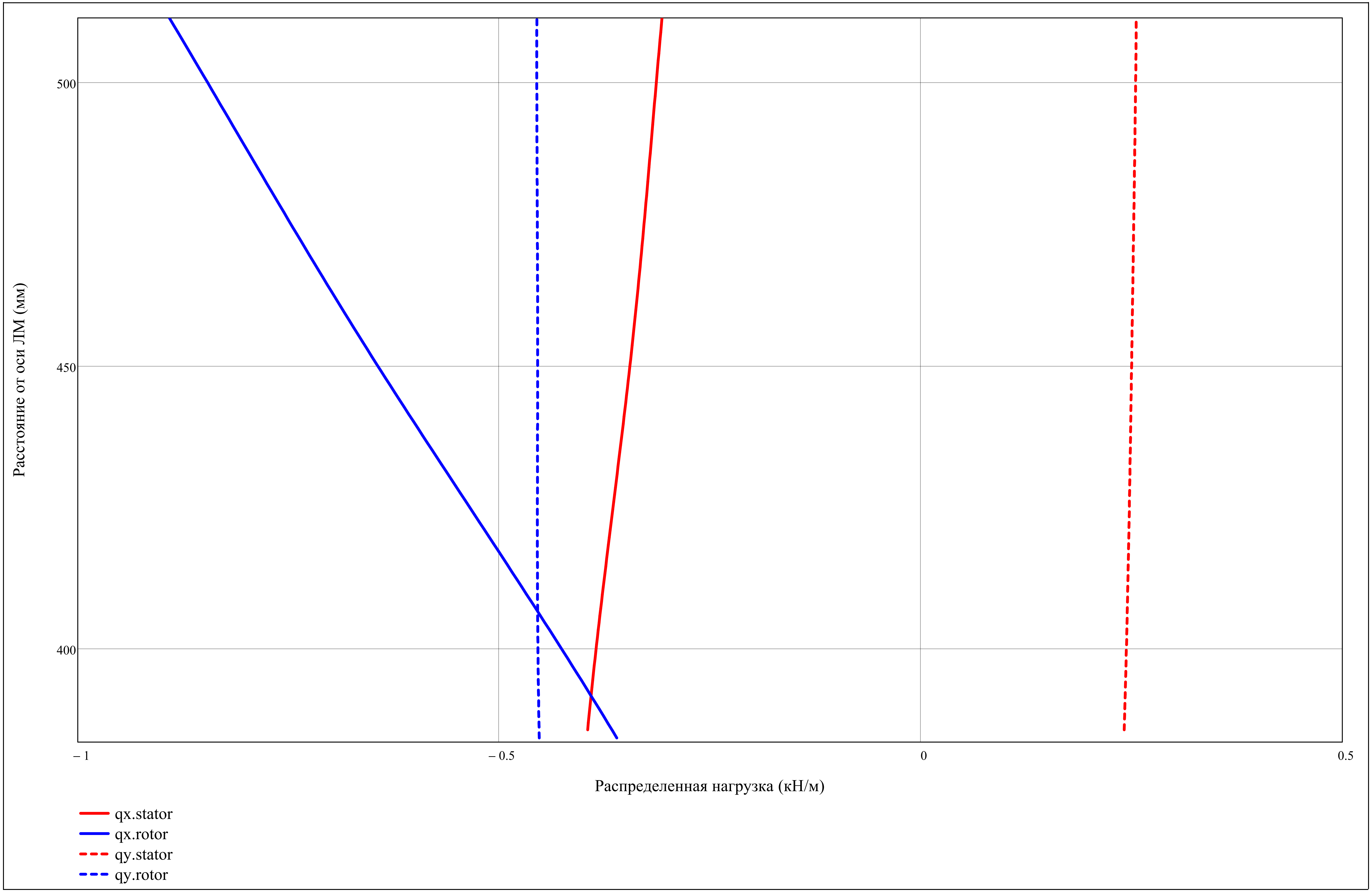

500
450
400
Расстояние от оси ЛМ (мм)
0
100
200
Площадь поперечного сечения Л (мм^2)
stator
rotor
rotor equal strength

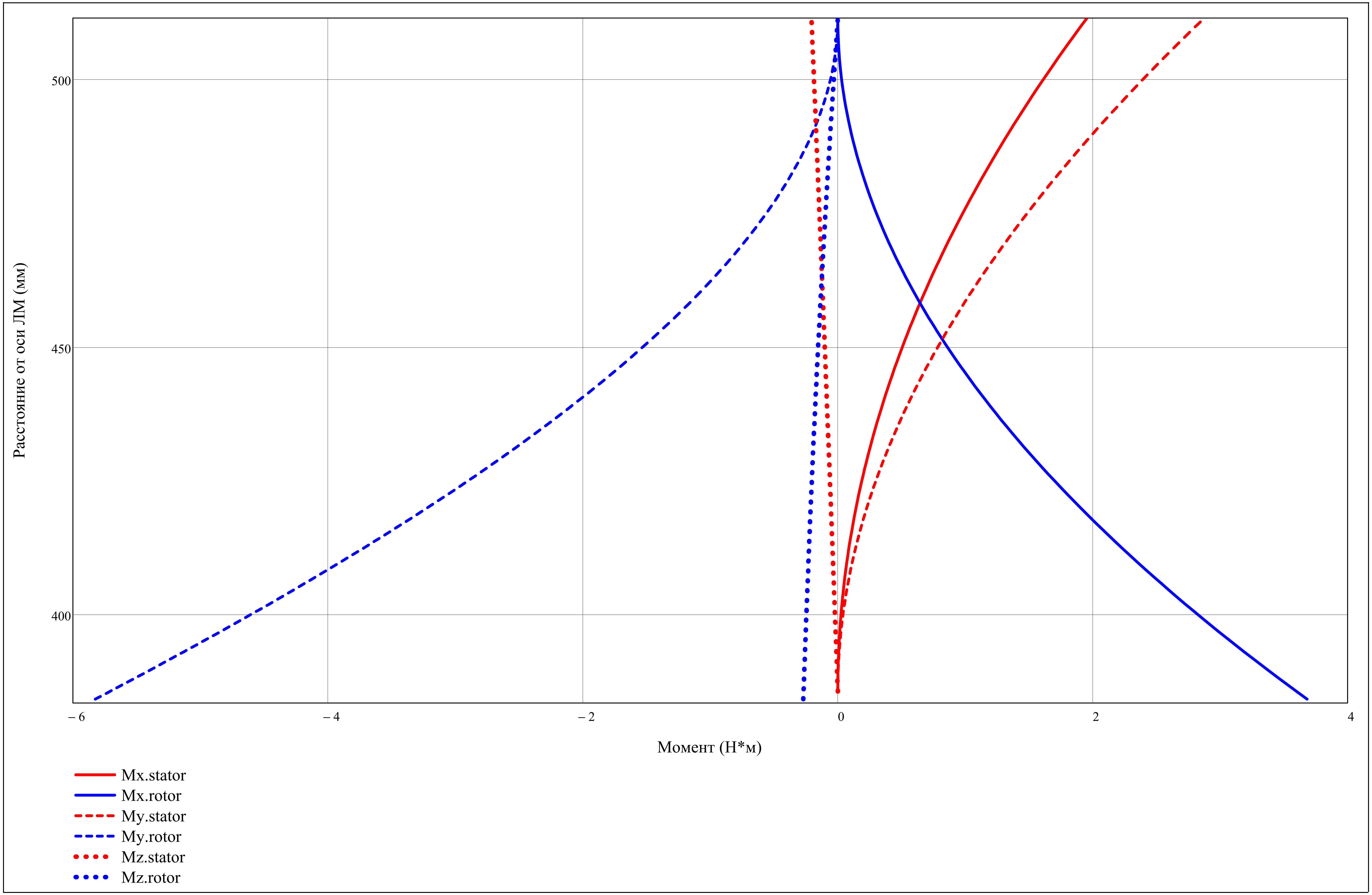

Расстояние от оси ЛМ (мм)
500
450
400
0
5
10
Растягивающая сила (кН)
stator
rotor
rotor equal strength


Расстояние от оси ЛМ (мм)
500
450
400
0
10
20
30
40
Растягивающее напряжение (МПа)
stator
rotor
rotor equal strength

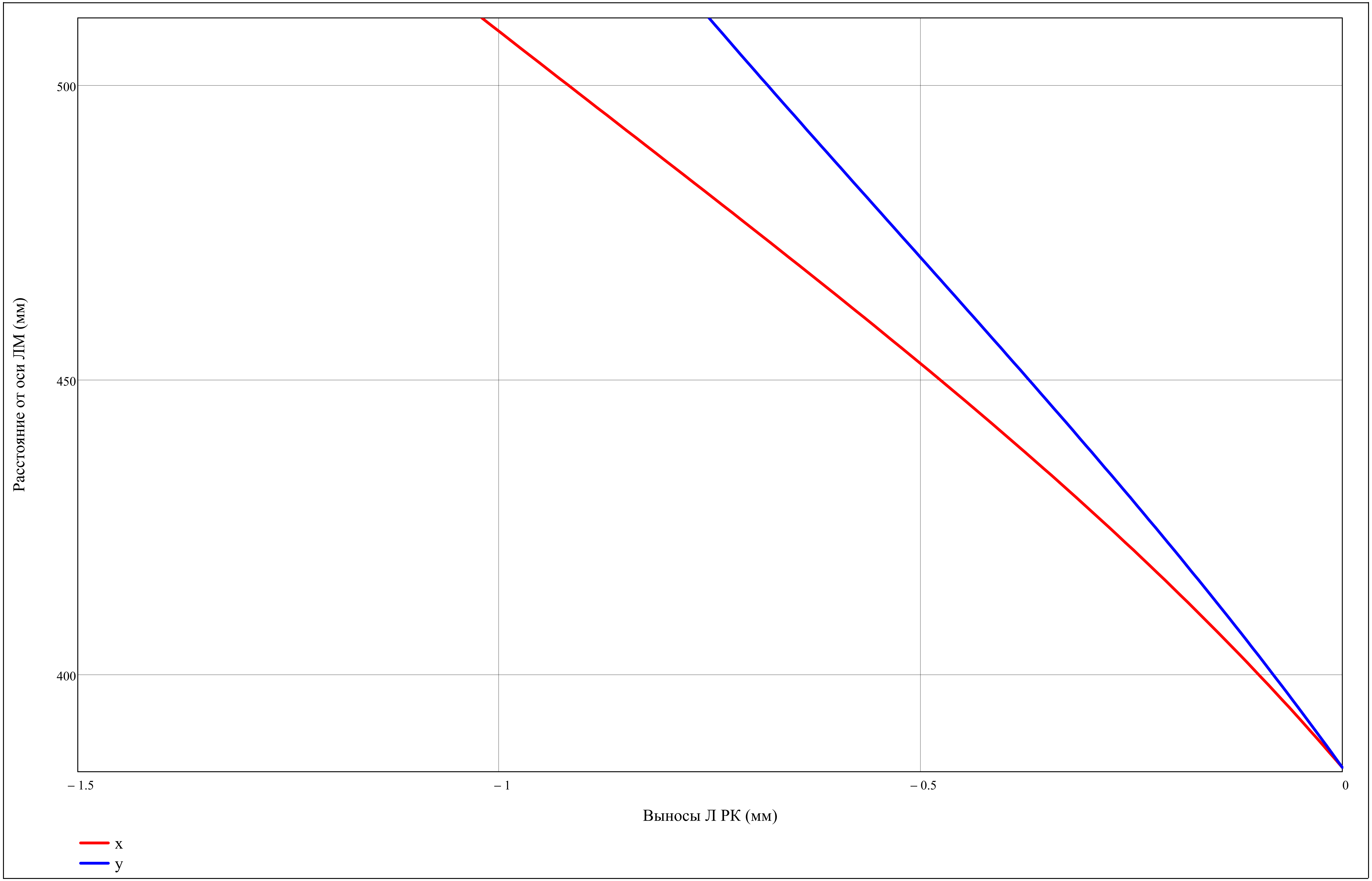

Газодинамические параметры нагрузки
Расстояние от оси ЛМ (мм)
500
450
400
0
0.5
1
Растягивающее напряжение (МПа)
P1
P2
P3
ρ1
ρ2
ρ3

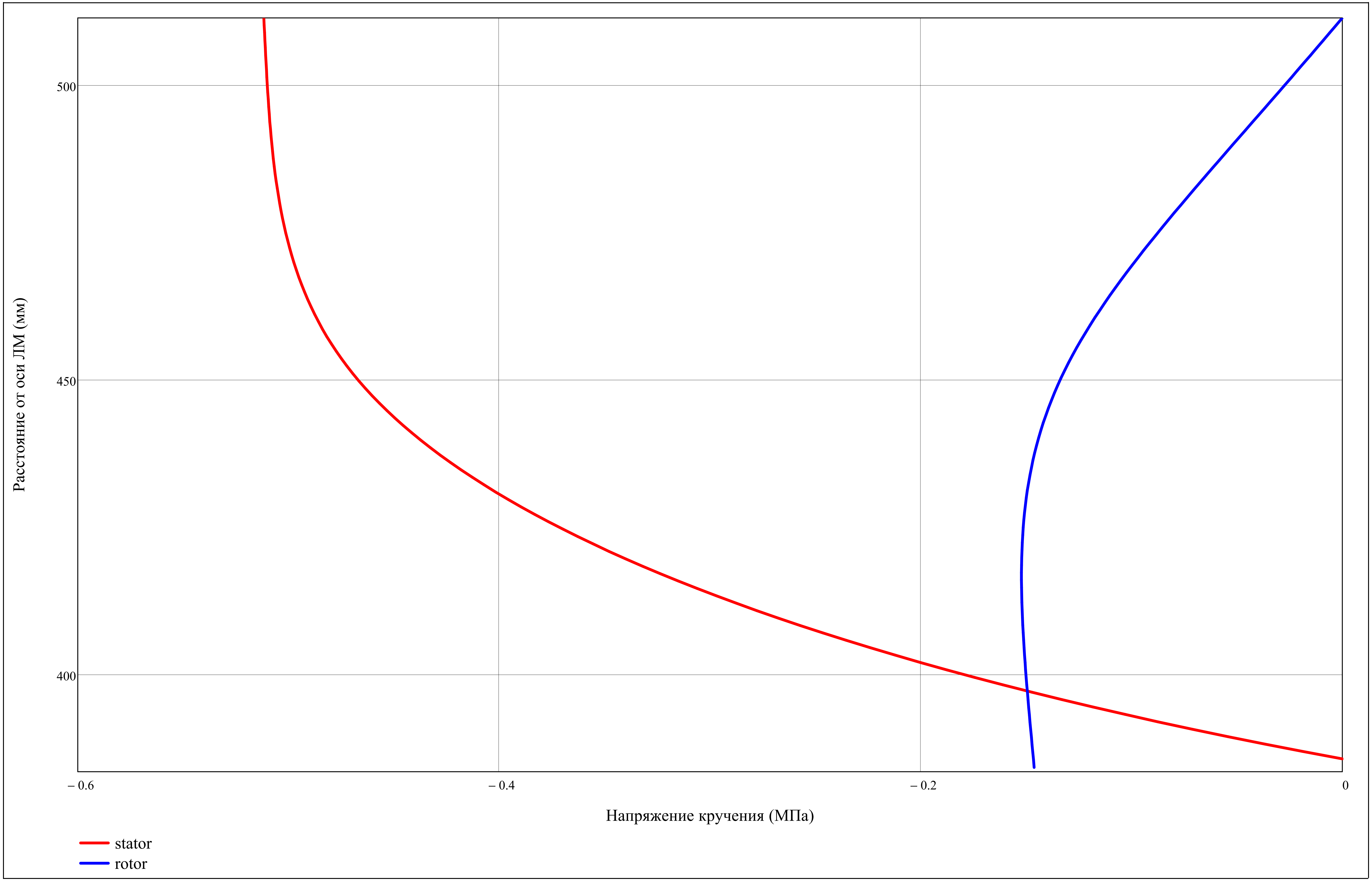

Газодинамические параметры нагрузки
Расстояние от оси ЛМ (мм)
500
450
400
0
50
100
150
Растягивающее напряжение (МПа)
c.a1
c.a2
c.a3
c.u1
c.u2
c.u3


500
450
400
Расстояние от оси ЛМ (мм)
– 1
– 0.5
0
0.5
Распределенная нагрузка (кН/м)
qx.stator
qx.rotor
qy.stator
qy.rotor

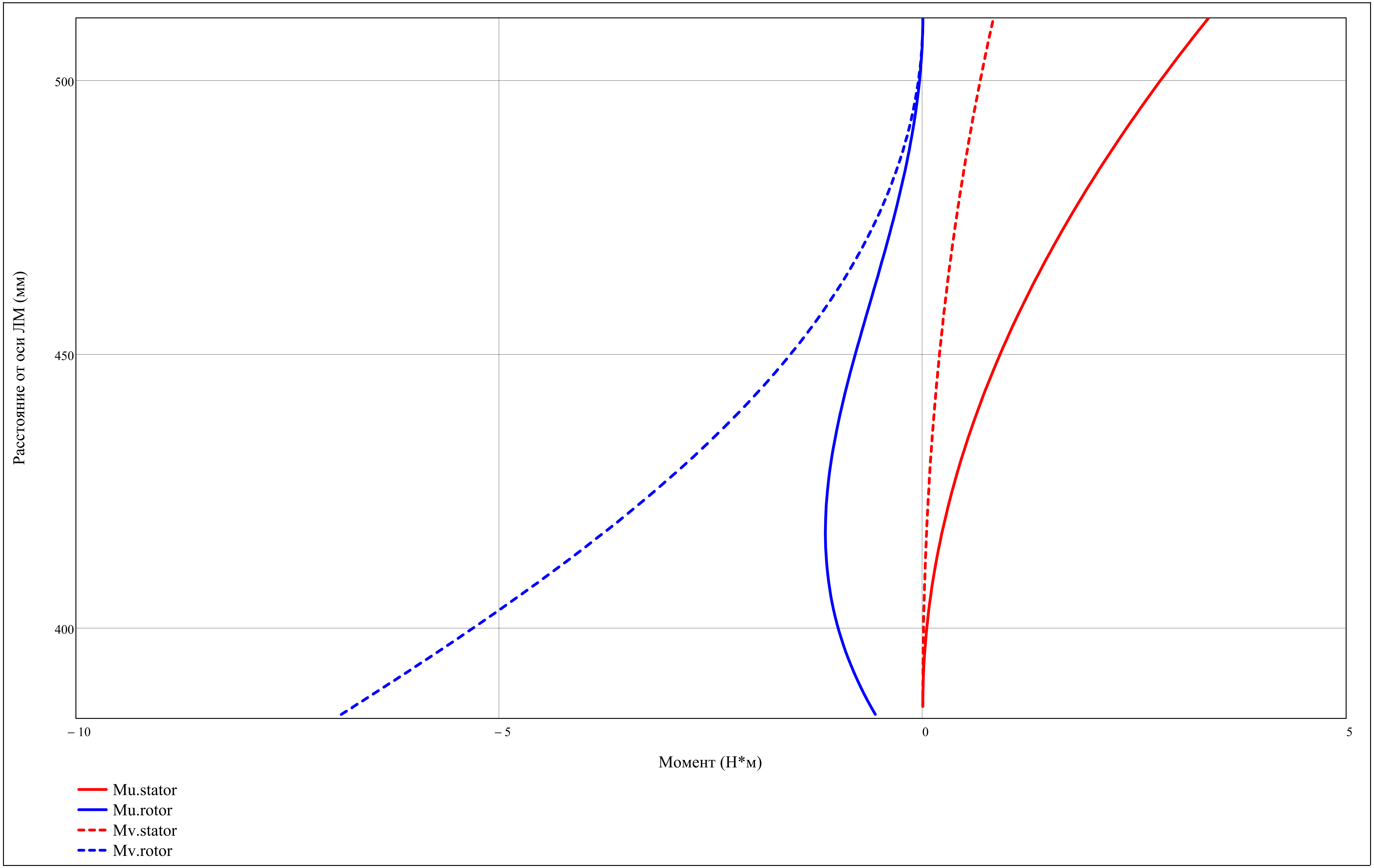


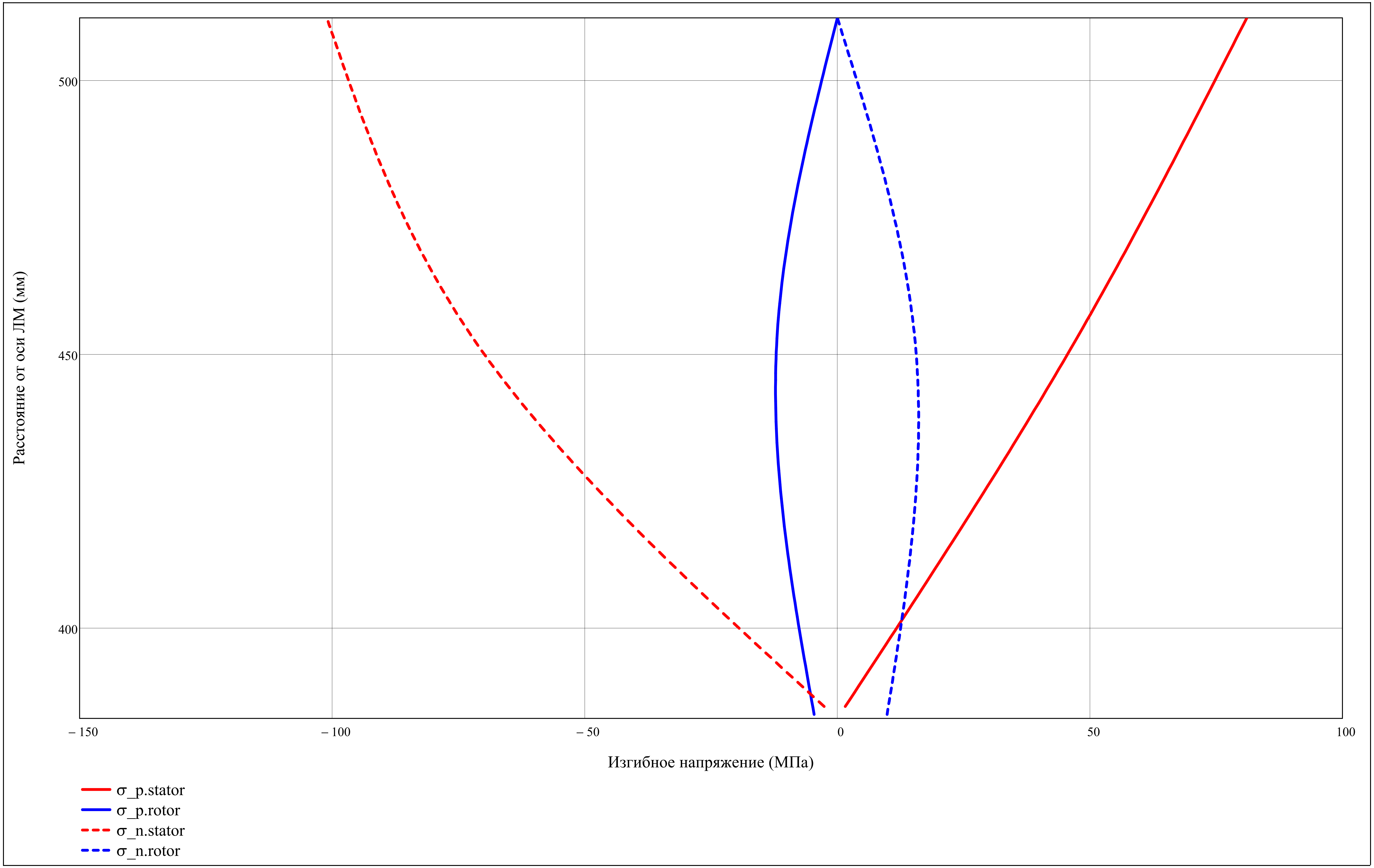
500
450
400
Расстояние от оси ЛМ (мм)
– 6
– 4
– 2
0
2
4
Момент (Н*м)
Mx.stator
Mx.rotor
My.stator
My.rotor
Mz.stator
Mz.rotor

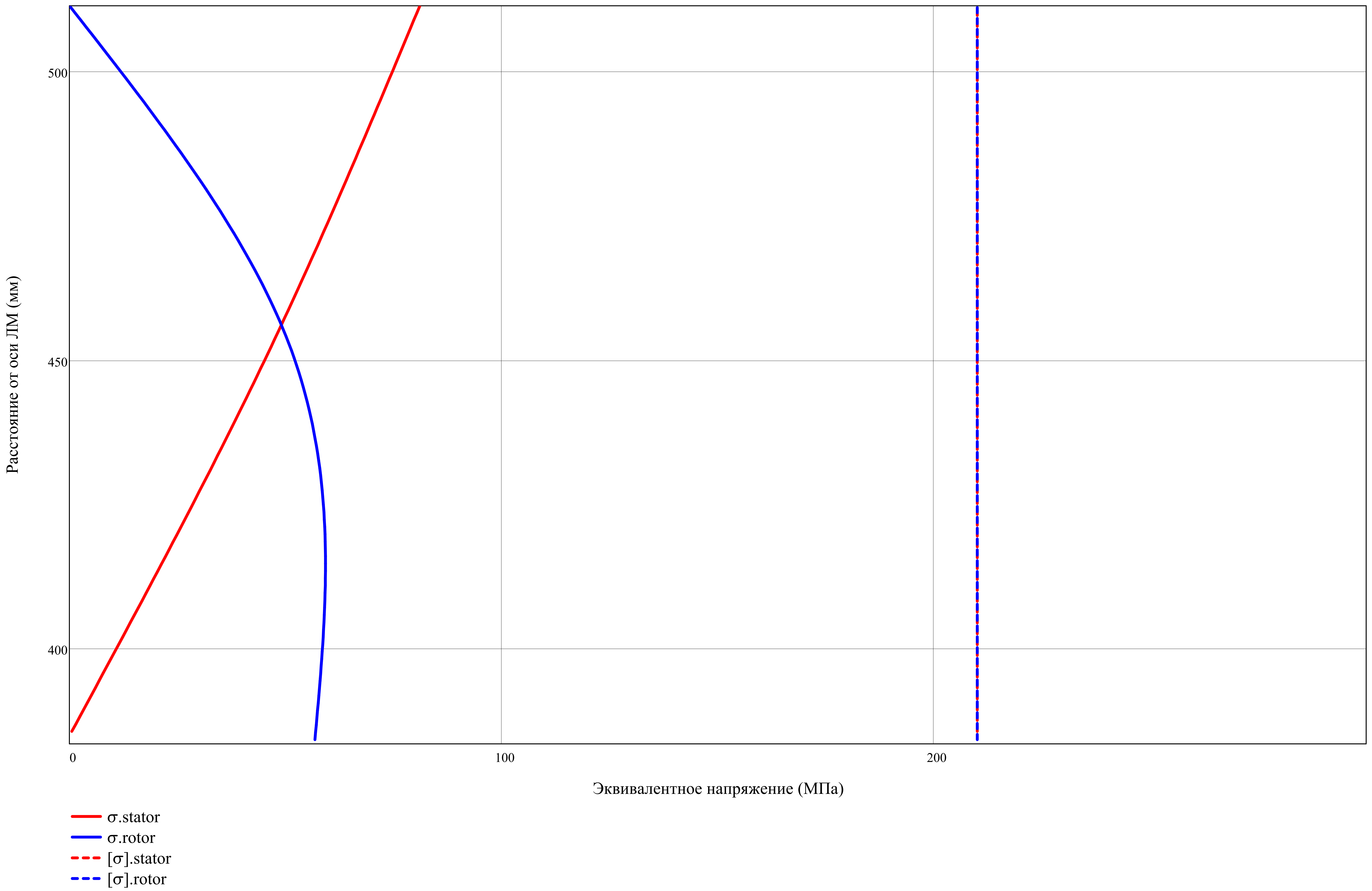

500
450
400
Расстояние от оси ЛМ (мм)
– 1.5
– 1
– 0.5
0
Выносы Л РК (мм)
x
y



500
450
400
Расстояние от оси ЛМ (мм)
– 0.6
– 0.4
– 0.2
0
Напряжение кручения (МПа)
stator
rotor


Расстояние от оси ЛМ (мм)
500
450
400
– 10
– 5
0
5
Момент (Н*м)
Mu.stator
Mu.rotor
Mv.stator
Mv.rotor


500
450
400
Расстояние от оси ЛМ (мм)
– 150
– 100
– 50
0
50
100
Изгибное напряжение (МПа)
σ_p.stator
σ_p.rotor
σ_n.stator
σ_n.rotor

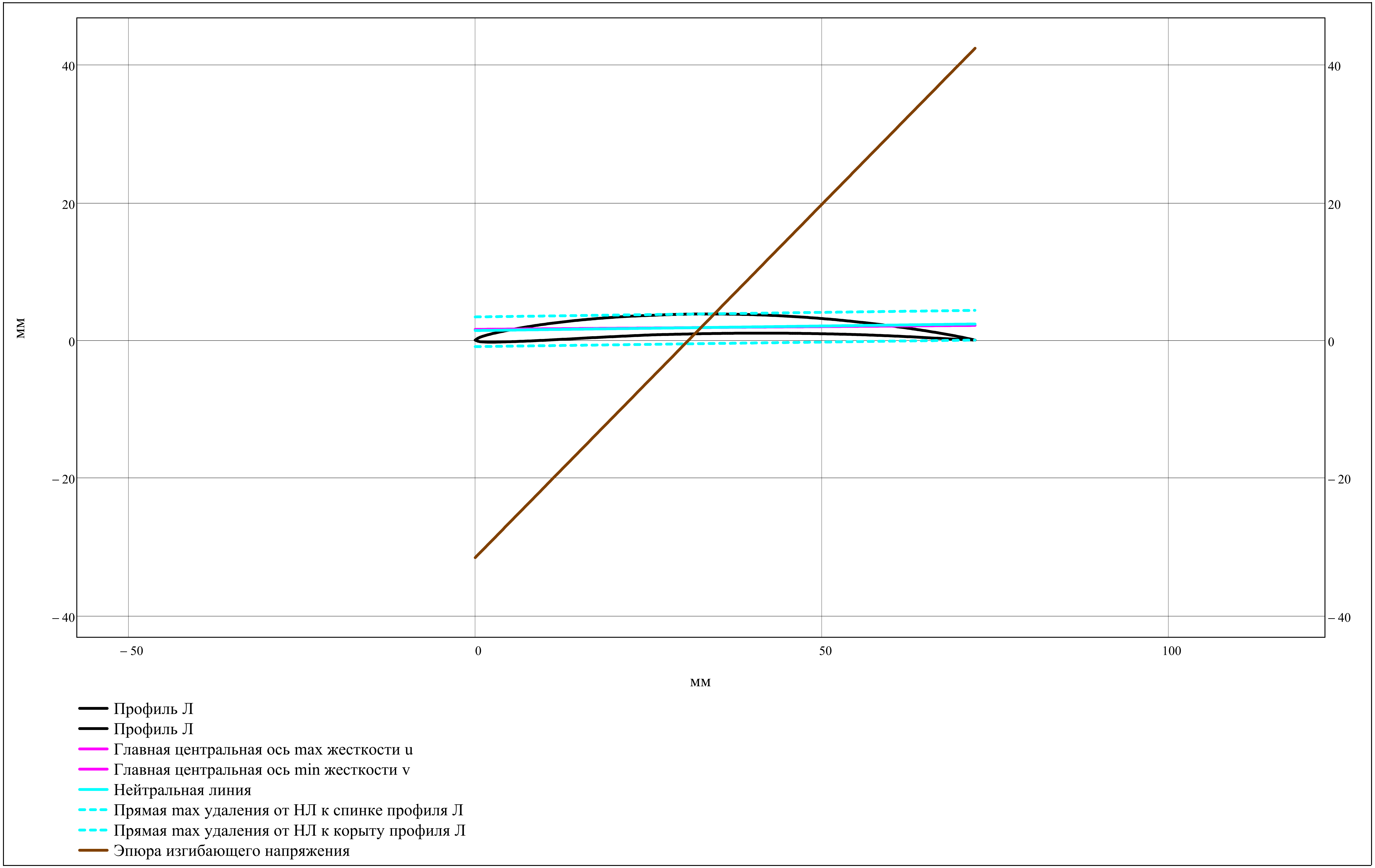

500
450
400
Расстояние от оси ЛМ (мм)
0
100
200
Эквивалентное напряжение (МПа)
σ.stator
σ.rotor
[σ].stator
[σ].rotor

$$\begin{pmatrix} \text{blade} \\ r \end{pmatrix} = \begin{pmatrix} \text{"rotor"} \\ 2 \end{pmatrix}$$

$$\begin{pmatrix} v\_p \\ v\_n \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} v\_u_{rotor_{j,r}} \\ v\_l_{rotor_{j,r}} \end{pmatrix} & \text{if blade} = \text{"rotor"} \\ \begin{pmatrix} v\_u_{stator_{j,r}} \\ v\_l_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. = \begin{array}{|c|r|} \hline & 1 \\ \hline 1 & 1.980 \\ \hline 2 & -2.338 \\ \hline \end{array} \cdot 10^{-3}$$

$$\begin{pmatrix} x0 \\ y0 \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} x0_{rotor_{j,r}} \\ y0_{rotor_{j,r}} \end{pmatrix} & \text{if blade} = \text{"rotor"} \\ \begin{pmatrix} x0_{stator_{j,r}} \\ y0_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. = \begin{array}{|c|r|} \hline & 1 \\ \hline 1 & 32.549 \\ \hline 2 & 1.816 \\ \hline \end{array} \cdot 10^{-3}$$

$$\text{chord} = \left| \begin{array}{ll} \text{chord}_{rotor_{j,r}} & \text{if blade} = \text{"rotor"} \\ \text{chord}_{stator_{j,r}} & \text{if blade} = \text{"stator"} \end{array} \right. = 72 \cdot 10^{-3}$$


40
20
0
− 20
− 40
40
20
0
− 20
− 40
мм
− 50
0
50
100
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	-0.81	1.98
2	39.49	-2.34
3	-0.04	1.55
4	21.35	-2.33

$\cdot 10^{-3}$

$$\begin{pmatrix} \sigma\_p_{rotor_{j,r}} & \sigma\_p_{stator_{j,r}} \\ \sigma\_n_{rotor_{j,r}} & \sigma\_n_{stator_{j,r}} \end{pmatrix} = \begin{pmatrix} -12.02 & 46.82 \\ 15.41 & -71.44 \end{pmatrix} \cdot 10^{6}$$

$$\begin{pmatrix} \sigma_{stator_{j,r}} \\ \sigma_{rotor_{j,r}} \end{pmatrix} = \begin{pmatrix} 46.82 \\ 50.87 \end{pmatrix} \cdot 10^{6}$$

$$\begin{pmatrix} safety_{stator_{j,r}} \\ safety_{rotor_{j,r}} \end{pmatrix} =$$

	1
1	4.485
2	4.128

▲ 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:

$$material\_disk_i = \left| \begin{array}{l} \text{"ВТ23"} \ \ \text{if } compressor = \text{"Вл"} \\ \text{"ВТ6"} \ \ \text{if } compressor = \text{"КНД"} \\ \text{"ВТ9"} \ \ \text{if } compressor = \text{"КВД"} \end{array} \right.$$

Плотность материала Д (кг/м^3):

$$\rho\_disk_i = \left| \begin{array}{l} 8266 \ \ \text{if } material\_disk_i = \text{"ВЖ175"} \\ 8320 \ \ \text{if } material\_disk_i = \text{"ЭП742"} \\ 8393 \ \ \text{if } material\_disk_i = \text{"ЖС-6К"} \\ 7900 \ \ \text{if } material\_disk_i = \text{"ВТ41"} \\ 4500 \ \ \text{if } material\_disk_i = \text{"ВТ25"} \\ 4570 \ \ \text{if } material\_disk_i = \text{"ВТ23"} \\ 4510 \ \ \text{if } material\_disk_i = \text{"ВТ9"} \\ 4430 \ \ \text{if } material\_disk_i = \text{"ВТ6"} \\ NaN \ \ \text{otherwise} \end{array} \right.$$

Предел длительной прочности Д (Па):

$$\sigma\_disk\_long_i = 10^6 \cdot \left| \begin{array}{l} 620 \ \ \text{if } material\_disk_i = \text{"ВЖ175"} \\ 680 \ \ \text{if } material\_disk_i = \text{"ЭП742"} \\ 125 \ \ \text{if } material\_disk_i = \text{"ЖС-6К"} \\ 123 \ \ \text{if } material\_disk_i = \text{"ВТ41"} \\ 150 \ \ \text{if } material\_disk_i = \text{"ВТ25"} \\ 230 \ \ \text{if } material\_disk_i = \text{"ВТ23"} \\ 200 \ \ \text{if } material\_disk_i = \text{"ВТ9"} \\ 210 \ \ \text{if } material\_disk_i = \text{"ВТ6"} \\ NaN \ \ \text{otherwise} \end{array} \right.$$

$material\_disk^T =$

	1	2	3	4	5	6	7	8	9
1	"ВТ6"	"ВТ6"	"ВТ6"						

$\rho\_disk^T =$

	1	2	3
1	4430	4430	4430

$\sigma\_disk\_long^T =$

	1	2	3
1	210	210	210

$\cdot 10^6$

▲ Выбор материала Д

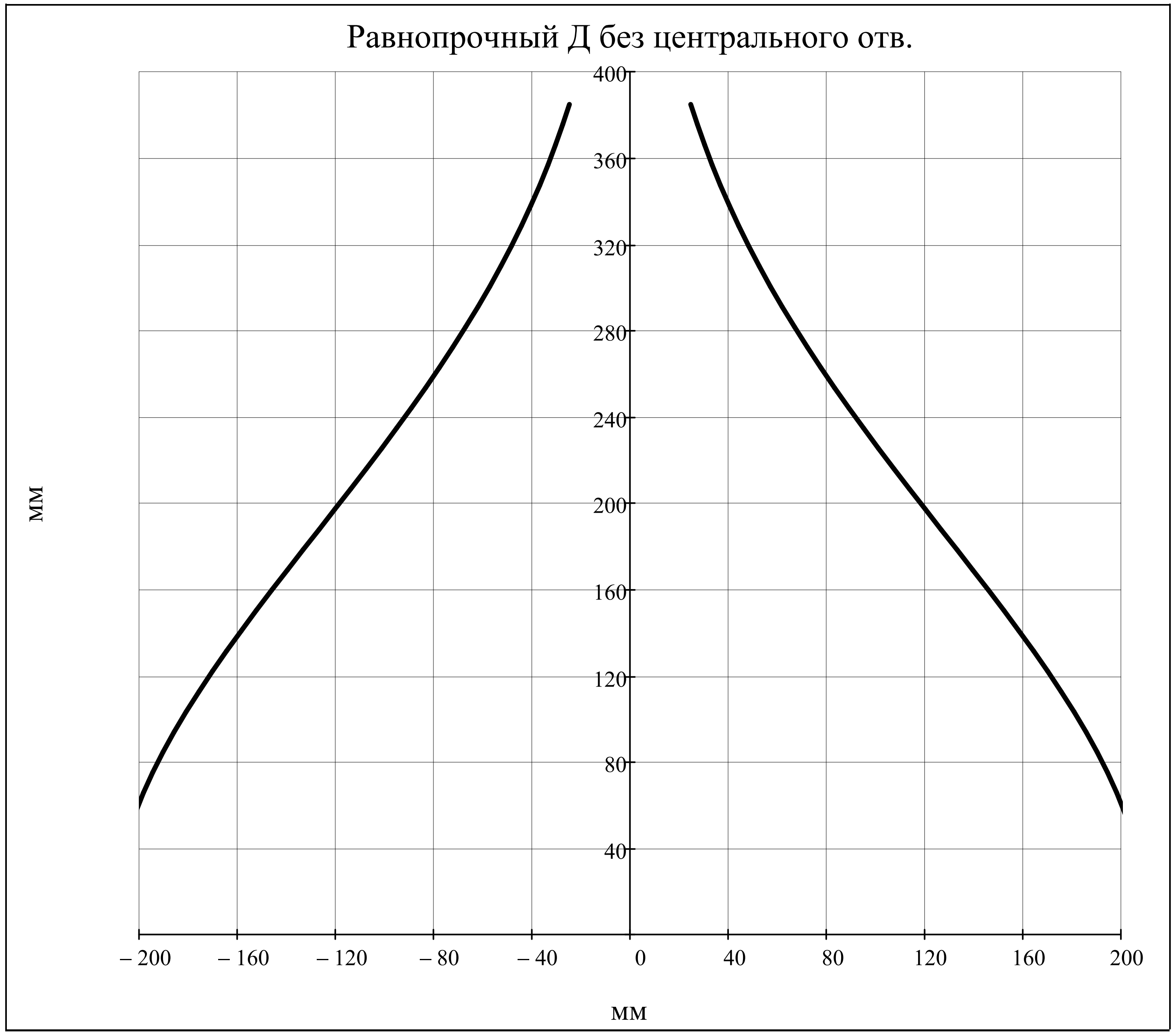
Рассматриваемая ступень:

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

Профилирование равнопрочного Д без центрального отв.

$$h(i,z) := \left| \begin{array}{ll} \left(\text{chord}_{\text{rotor}_{i,\text{ORIGIN}}} \cdot \sin\left(\upsilon_{\text{rotor}_{i,\text{ORIGIN}}}\right)\right) \cdot e^{\frac{\rho\_\text{disk}_i \cdot \omega^2}{2} \cdot \frac{1}{\sigma\_z_{\text{rotor}}\left(i, R_{\text{st}(i,2),\text{ORIGIN}}\right)} \cdot \left[\left(R_{\text{st}(i,2),\text{ORIGIN}}\right)^2 - z^2\right]} & \text{if } z \le R_{\text{st}(i,2),\text{ORIGIN}} \\ \text{NaN} & \text{otherwise} \end{array} \right.$$

$$z := 0, \frac{R_{\text{st}(j,2),\text{ORIGIN}}}{N_{\text{dis}}} .. R_{\text{st}(j,2),\text{ORIGIN}}$$



Профилирование равнопрочного Д без центрального отв.

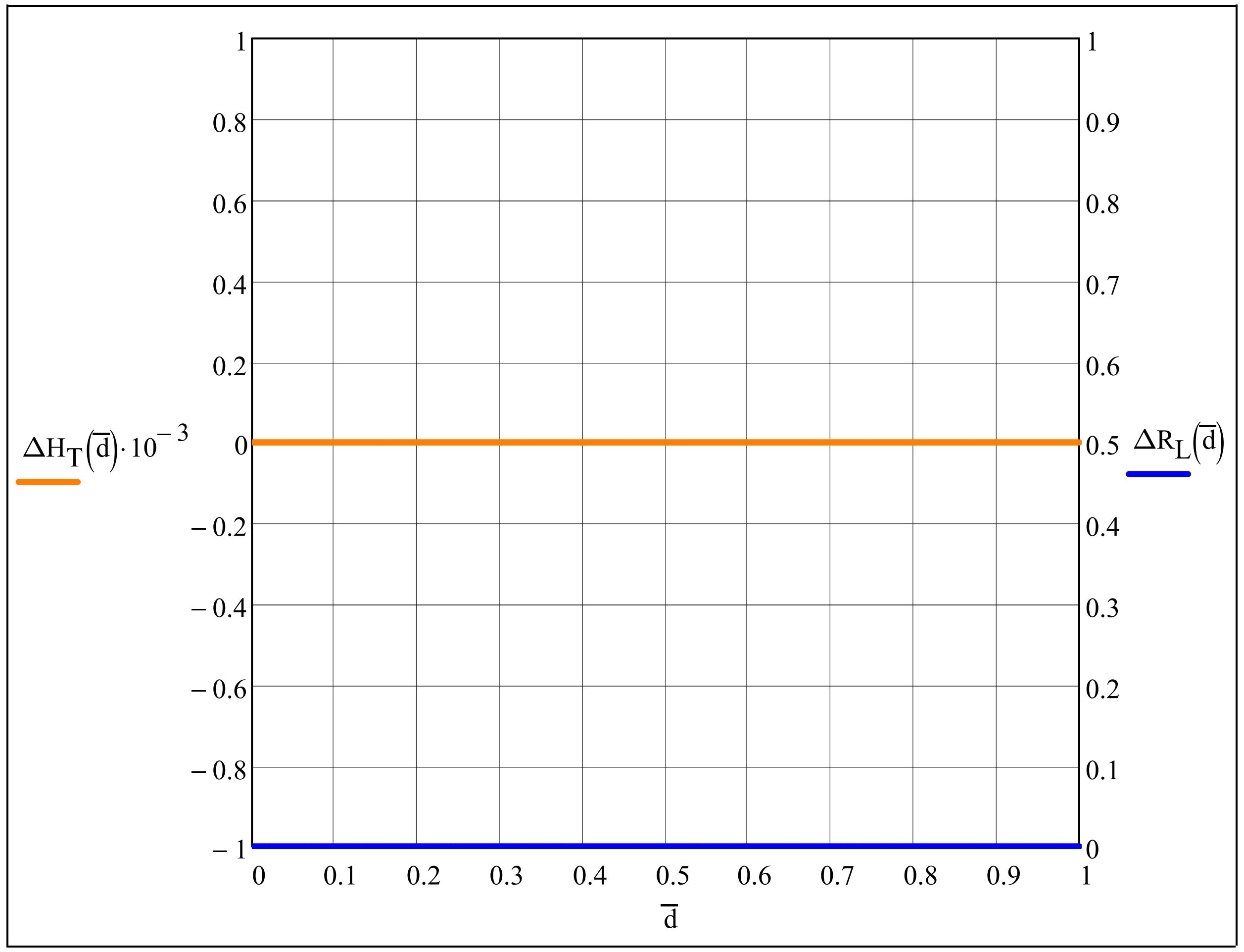
Max разница теор. напора ступени и реактивности
от периферии к корню по высоте Л (Дж/кг)
[16, с.118-119]:

$\Delta H_{Tmax} = 0\cdot 10^3$

$\Delta R_{Lmax} = 0.0$

$\Delta H_T(\overline{d}) = -\Delta H_{Tmax}\cdot\overline{d} + \Delta H_{Tmax}$

$\Delta R_L(\overline{d}) = -\Delta R_{Lmax}\cdot\overline{d} + \Delta R_{Lmax}$



$$\frac{,1),r)^{m_i}\cdot\Big(R_{st(i,1),av(N_r)}\Big)^{2\cdot m_i+1}\Big] + A\cdot m_i\cdot\Big[\Big(R_{st(i,1),r}\Big)^{2\cdot m_i+1}\cdot\Big(R_{st(i,1),av(N_r)}\Big) - \Big(R_{st(i,1),r}\Big)\cdot\Big(R_{st(i,1),av(N_r)}\Big)^{2\cdot m_i+1}\Big]\Big]}{\Big)^{2\cdot m_i+1}} \quad \text{otherwise}$$

$$\frac{\mathrm{st}(i,a),\mathrm{av}(N_r)\Big)\Big)^{m_i} - \left(R_{\mathrm{st}(i,a),r}\right)^{m_i}\cdot\left(R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\right)^{2\cdot m_i+1}\Big] + A_{\mathrm{st}(i,a),r}\cdot m_i\cdot\Big[\left(R_{\mathrm{st}(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\right) - \left(R_{\mathrm{st}(i,a),r}\right)\cdot\left(R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\right)^{2\cdot m_i+1}\Big]\Big]}{r\cdot R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\Big)^{2\cdot m_i+1}} \quad \text{if } a = 2$$

$$\frac{\mathrm{st}(i,a),\mathrm{av}(N_r)\Big)\Big)^{m_i} - \left(R_{\mathrm{st}(i,a),r}\right)^{m_i}\cdot\left(R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\right)^{2\cdot m_i+1}\Big] + A_{\mathrm{st}(i,a),r}\cdot m_i\cdot\Big[\left(R_{\mathrm{st}(i,a),r}\right)^{2\cdot m_i+1}\cdot\left(R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\right) - \left(R_{\mathrm{st}(i,a),r}\right)\cdot\left(R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\right)^{2\cdot m_i+1}\Big]\Big]}{r\cdot R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}\Big)^{2\cdot m_i+1}} \quad \text{otherwise}$$

$$\frac{,1}{\quad}\Big)\Big)\Big]$$

$$\frac{\mathrm{st}(i,a),\mathrm{av}(N_r)}{(i,a),\mathrm{av}(N_r)} - 2\cdot\left[2\cdot A_{\mathrm{st}(i,a),r}\cdot\left(B_{\mathrm{st}(i,a),r} + \frac{b_{HT}}{\omega}\right) + \frac{{k_{HT}}^2}{\omega^2}\right]\cdot\ln\left(\frac{R_{\mathrm{st}(i,a),r}}{R_{\mathrm{st}(i,a),\mathrm{av}(N_r)}}\right) \quad \text{if } a = 2$$

$$ {}_{i}\cdot\left(R_{st(i,3),av\left(N_r\right)}\right)^{2\cdot m_i+1}\Bigg] + A\cdot m_i\cdot\Bigg[\left(R_{st(i,3),r}\right)^{2\cdot m_i+1}\cdot\left(R_{st(i,3),av\left(N_r\right)}\right) - \left(R_{st(i,3),r}\right)\cdot\left(R_{st(i,3),av\left(N_r\right)}\right)^{2\cdot m_i+1}\Bigg]\Bigg] \quad \text{otherwise} $$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 100.47 \\ 195.16 \\ 87.07 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 83.44 \\ 74.93 \\ 71.14 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 177.66 \\ 82.04 \\ 178.97 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 56.15 \\ 22.58 \\ 54.79 \end{pmatrix} \cdot ^{\circ}$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 212.81 \\ 213.62 \\ 214.42 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 28.01 \\ 65.96 \\ 23.42 \end{pmatrix} \cdot ^{\circ}$$

$$\varepsilon_{stator_{j,r}} = 29.12 \cdot ^{\circ}$$

$$\varepsilon_{rotor_{j,r}} = 37.95 \cdot ^{\circ}$$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 96.01 \\ 170.59 \\ 83.02 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 83.44 \\ 74.93 \\ 71.14 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 219.81 \\ 123.3 \\ 220.52 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 60.36 \\ 26.05 \\ 58.97 \end{pmatrix} \cdot {}^\circ$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 250.84 \\ 251.18 \\ 251.52 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 22.31 \\ 37.42 \\ 18.82 \end{pmatrix} \cdot {}^\circ$$

$$\varepsilon_{stator_{j,r}} = 29.99 \cdot {}^\circ$$

$$\varepsilon_{rotor_{j,r}} = 15.11 \cdot {}^\circ$$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 93.40 \\ 154.95 \\ 80.62 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 83.44 \\ 74.93 \\ 71.14 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 255.84 \\ 166.05 \\ 255.98 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 63.3 \\ 28.92 \\ 61.94 \end{pmatrix} \cdot ^{\circ}$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 283.81 \\ 283.81 \\ 283.81 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 19.04 \\ 26.82 \\ 16.14 \end{pmatrix} \cdot ^{\circ}$$

$$\varepsilon_{stator_{j,r}} = 30.26 \cdot ^{\circ}$$

$$\varepsilon_{rotor_{j,r}} = 7.79 \cdot ^{\circ}$$

MM

MM

$,z\big)$

$\big)^{T},z\big)$

$^{-3}$

7	8	9