Подключение библиотек

Основные уравнения, алгоритмы, зависимости и ф-и

▶ Параметры расчета

▾ Исходные данные

Коэф. запаса: $safety = 1.3$

Степень двухконтурности: $m2 = 6$

РТ: Воздух $compressor = \text{"Вл"}$

Число Маха: $M = 0$

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

Массовый расход (кг/с):
$$G = \left| \begin{array}{l} 35.65 + 213.93 \ \text{ if } compressor = \text{"Вл"} \\ 35.65 \ \text{ if } compressor = \text{"КНД"} \\ 34.81 \ \text{ if } compressor = \text{"КВД"} \end{array} \right. = 249.58$$

Полная температура на входе в К (К):
$$T^*_{K1} = \left| \begin{array}{l} 418.2 \ \text{ if } compressor = \text{"КВД"} \\ 288.2 \ \text{ otherwise} \end{array} \right. = 288.2$$

Полное давление на входе в К (Па):
$$P^*_{K1} = \left| \begin{array}{l} 316.2 \cdot 10^3 \ \text{ if } compressor = \text{"КВД"} \\ 101325 \ \text{ otherwise} \end{array} \right. = 101.3 \cdot 10^3$$

Степень повышения давления КВД:
$$\pi^*_K = \left| \begin{array}{l} 1.6 \ \text{ if } compressor = \text{"Вл"} \\ \frac{3.2}{1.6} \ \text{ if } compressor = \text{"КНД"} \\ 9 \ \text{ if } compressor = \text{"КВД"} \end{array} \right. = 1.600$$

Ожидаемый адиабатический КПД ОК:

$$\eta^*_K = \left| \begin{array}{l} 0.86 \text{ if } compressor = \text{"Вл"} \\ 0.87 \text{ if } compressor = \text{"КНД"} \\ 0.88 \text{ if } compressor = \text{"КВД"} \end{array} \right. = 86.00\cdot\%$$

Частота вращения ротора (c^{-1}):

$$\omega = \left| \begin{array}{l} 1570.8 \text{ if } compressor = \text{"КВД"} \\ 555 \text{ otherwise} \end{array} \right. = 555.0$$

Относ. диаметр корня 1ой ступени [14, с.7]:

$$\bar{d}_1 = \left| \begin{array}{l} 0.40 \text{ if } compressor = \text{"Вл"} \\ 0.75 \text{ if } compressor = \text{"КНД"} \\ 0.65 \text{ if } compressor = \text{"КВД"} \end{array} \right. = 0.40$$

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

Частота вращения ротора (об/мин):

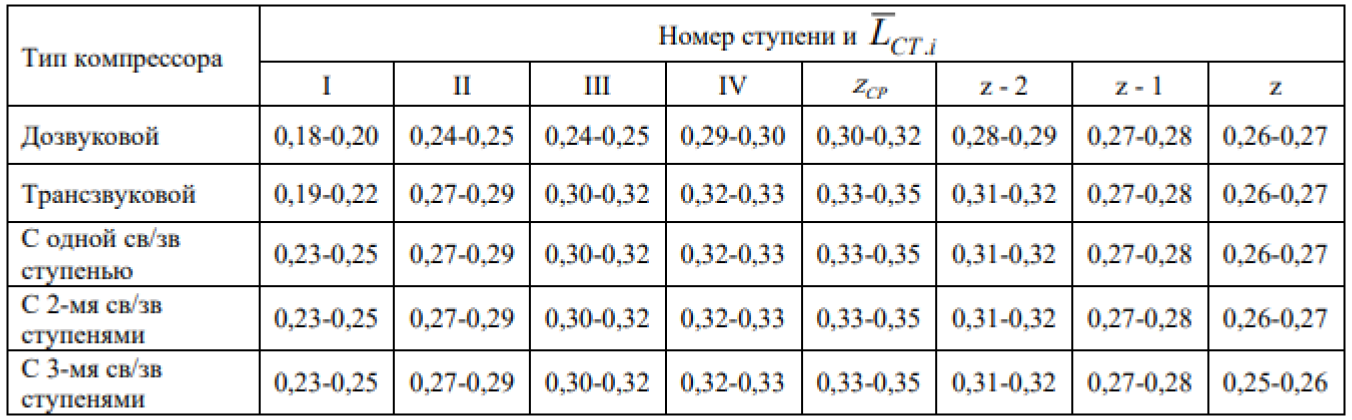
$$n = \frac{60\cdot\omega}{2\cdot\pi} = 5300$$

Закон профилирования проточной части (ЗППЧ):

$$ЗППЧ = \begin{pmatrix} \left| \begin{array}{l} \text{"пер"} \text{ if } compressor = \text{"Вл"} \\ \text{"пер"} \text{ if } compressor = \text{"КНД"} \\ \text{"ср"} \text{ if } compressor = \text{"КВД"} \end{array} \right. & \left| \begin{array}{l} \text{"пер"} \text{ if } compressor = \text{"Вл"} \\ \text{"0.96"} \text{ if } compressor = \text{"КНД"} \\ \text{"ср"} \text{ if } compressor = \text{"КВД"} \end{array} \right. & \left| \begin{array}{l} \text{"пер"} \text{ if } compressor = \text{"Вл"} \\ \text{"0.92"} \text{ if } compressor = \text{"КНД"} \\ \text{"кор"} \text{ if } compressor = \text{"КВД"} \end{array} \right. & \text{"кор"} & \text{"кор"} & \text{"кор"} & \text{"кор"} & \text{"кор"} & \text{"кор"} & \text{"пер"} & \text{"пер"} & \text{"пер"} & \text{"пер"} & \text{"пер"} & \text{"пер"} \end{pmatrix}^T$$

Относ. параметры по относительным ступеням:

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



Тип компрессора	Номер ступени и $\bar{L}_{CT.i}$							
	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:

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

увеличение несущественно увеличивает π

$$\bar{c}_{\sim a1} = \bar{c}_{\sim a1} - \left| \begin{array}{l} 0.100 \ \text{ if } \ compressor = \text{"Вл"} \\ 0.141 \ \text{ if } \ compressor = \text{"КНД"} \\ 0.203 \ \text{ if } \ compressor = \text{"КВД"} \end{array} \right.$$

понижение существенно увеличивает π

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

увеличение несущественно увеличивает π

$$\bar{H}_{\sim T} = \bar{H}_{\sim T} + \left| \begin{array}{l} 0.0145 \ \text{ if } \ compressor = \text{"Вл"} \\ 0.0164 \ \text{ if } \ compressor = \text{"КНД"} \\ 0.0173 \ \text{ if } \ compressor = \text{"КВД"} \end{array} \right.$$

[16, с. 234]

увеличение существенно увеличивает π

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

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

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

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

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

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

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

$$\bar{H}_{Tср} = \frac{\displaystyle\sum_{i=1}^{\mathrm{rows}(z_{\sim})} \bar{H}_{\sim T_i}}{\mathrm{rows}(z_{\sim})} = 0.317$$

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

Исходные данные

Распределение основных параметров ОК по ступеням

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

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

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

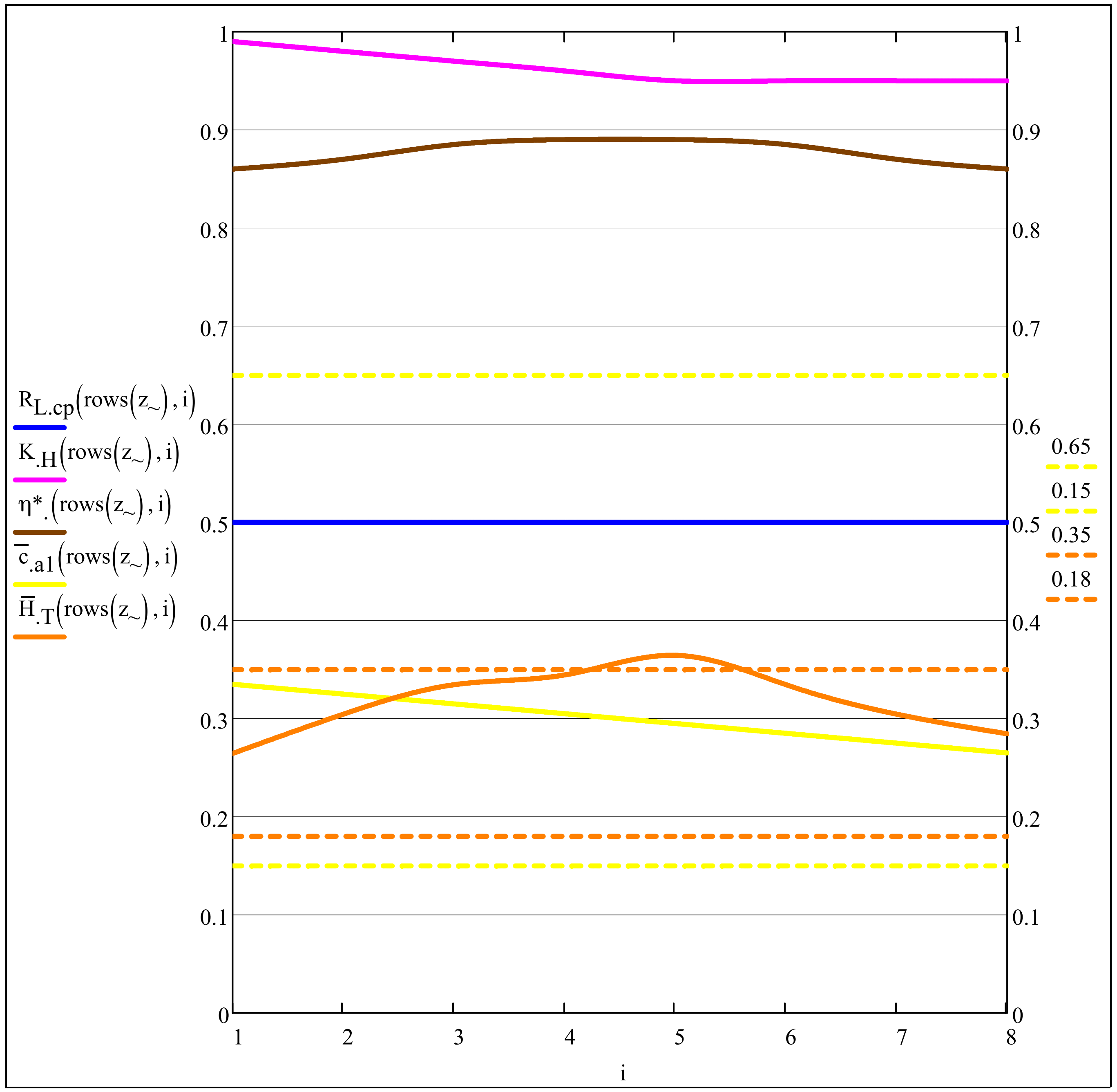
Коэф. расхода: $\bar{c}_{\sim a1}(i) = \mathrm{interp}\left(\mathrm{lspline}\left(\frac{z_{\sim}}{\mathrm{rows}(z_{\sim})}, \bar{c}_{\sim a1}\right), \frac{z_{\sim}}{\mathrm{rows}(z_{\sim})}, \bar{c}_{\sim a1}, i\right)$

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

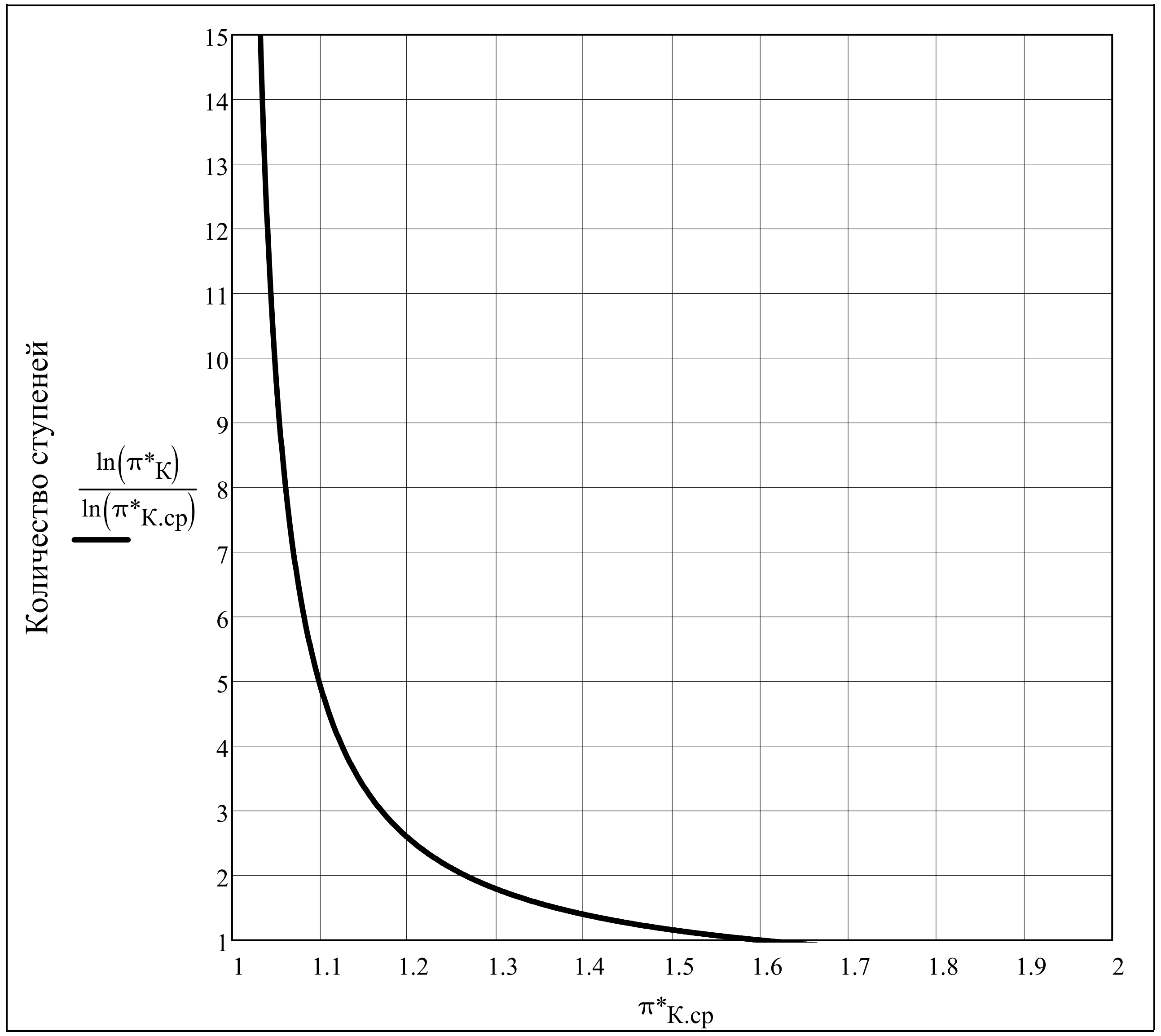
$$\begin{pmatrix} R_{L.cp} \\ K_{.H} \\ \eta^*_{.} \\ \bar{c}_{.a1} \\ \bar{H}_{.T} \end{pmatrix} = \left| \begin{array}{l} R_{L.cp}(Z,i) = \left| \begin{array}{ll} R_{L\sim cp}\left(\dfrac{1}{rows(z_\sim)}\right) & \text{if } i < 1 \\ R_{L\sim cp}(1) & \text{if } i > Z \\ R_{L\sim cp}\left(\dfrac{i}{Z}\right)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

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

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



Распределение основных параметров ОК по ступеням


Количество ступеней
ln(π*K) / ln(π*K.ср)
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
π*K.ср

Нулевые приближения

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

Полное давление после К [Па]: $P^*_{К3} = \pi^*_К \cdot P^*_{К1} = 162\cdot10^3$

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

Количество итераций []: $iteration_3 = 1$

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

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

Полная плотность перед и после К [кг/м^3]:

$$\begin{pmatrix} \rho^*_{К1} \\ \rho^*_{К3} \end{pmatrix} = \frac{1}{R_в}\cdot\begin{pmatrix} \dfrac{P^*_{К1}}{T^*_{К1}} \\ \dfrac{P^*_{К3}}{T^*_{К3}} \end{pmatrix} = \begin{pmatrix} 1.224 \\ 1.678 \end{pmatrix}$$

Критические скорости перед и после К [м/с]:

$$\begin{pmatrix} a^*_{с.вх} \\ a^*_{с.вых} \end{pmatrix} = \begin{pmatrix} a_{кр}\left(k_{К1}, R_в, T^*_{К1}\right) \\ a_{кр}\left(k_{К3}, R_в, T^*_{К3}\right) \end{pmatrix} = \begin{pmatrix} 310.8 \\ 335.7 \end{pmatrix}$$

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

Теоретический напор [Дж/кг]:

$$H_{ТК} = \frac{Cp_{воздух.ср}\left(P^*_{К1}, P^*_{К3}, T^*_{К1}, T^*_{К3}\right)\cdot T^*_{К1}\cdot\left(\pi^{*\,\frac{k_{ср}-1}{k_{ср}}}_К - 1\right)}{\eta^*_К} = 48.4\cdot10^3$$

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

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

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

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

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

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

Плотность перед К [кг/м^3]: $\rho_{\text{К1}} = 1.120$

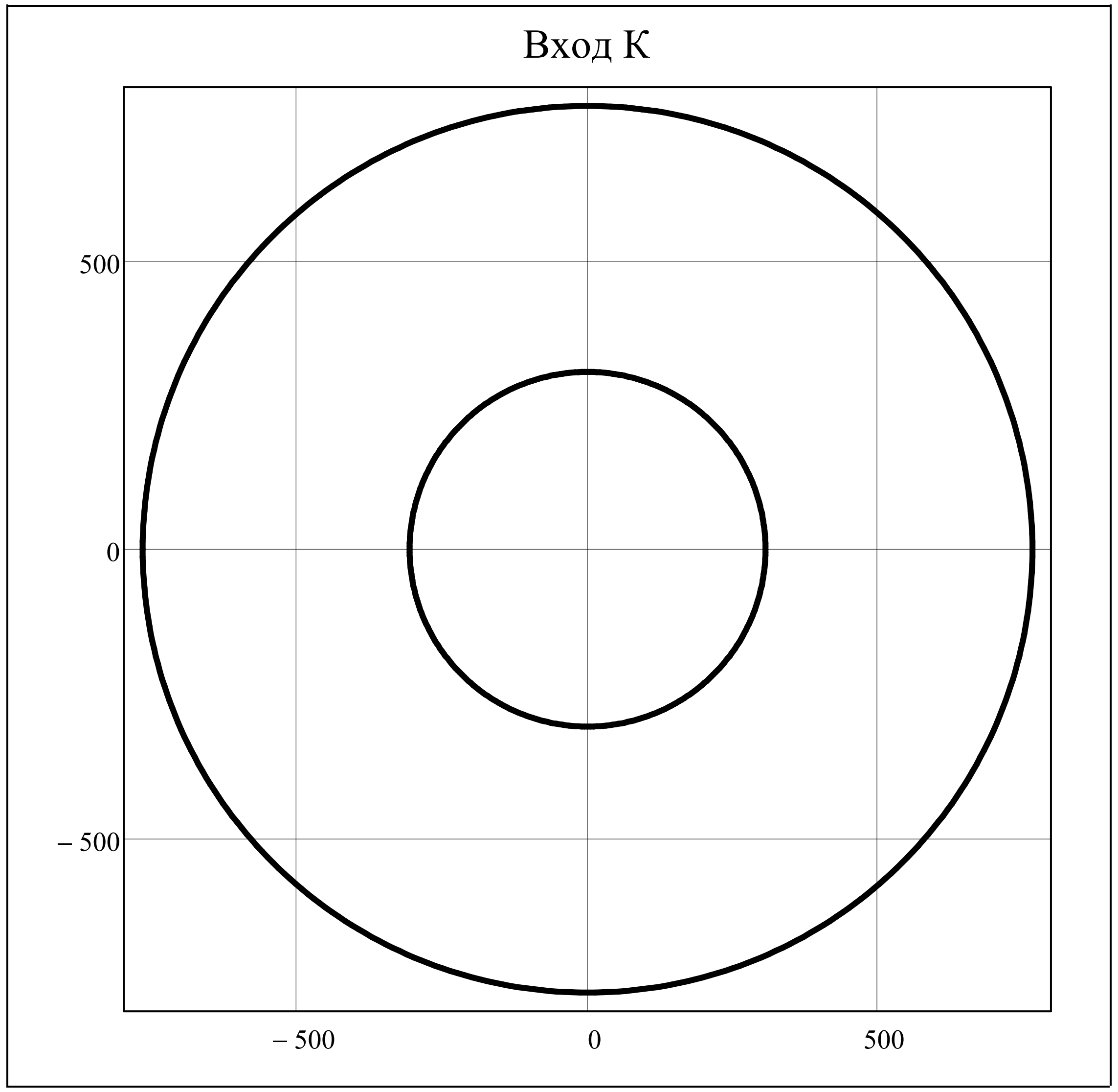
Кольцевая площадь перед К [м^2]: $F_{\text{вх}} = \dfrac{G\cdot\sqrt{R_{\text{в}}\cdot T*_{\text{К1}}}}{m_q(k_{\text{К1}})\cdot P*_{\text{К1}}\cdot\text{ГДФ}(\text{"G"},\lambda_{\text{вх}},k_{\text{К1}})} = 1.5621$

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

Диамтеры перед К [м]: $D'_{\text{ср1}} = \overline{r}_{\text{ср}}(\overline{d}_1)\cdot D'_{\text{пер1}} = 1169\cdot 10^{-3}$

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

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



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

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

▲ Нулевые приближения

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

Расчет ВНА:

$$\begin{pmatrix} \alpha_{1\text{ВНА}} & \alpha_{3\text{ВНА}} \\ \sigma_{\text{ВНА}} & \sigma_{\text{ВНА}} \\ \overline{d}_{1\text{ВНА}} & \overline{d}_{3\text{ВНА}} \\ T^*_{1\text{ВНА}} & T^*_{3\text{ВНА}} \\ P^*_{1\text{ВНА}} & P^*_{3\text{ВНА}} \\ \rho^*_{1\text{ВНА}} & \rho^*_{3\text{ВНА}} \\ k_{1\text{ВНА}} & k_{3\text{ВНА}} \\ a_{\text{кр}1\text{ВНА}} & a_{\text{кр}3\text{ВНА}} \\ \overline{c}_{a1\text{ВНА}} & \overline{c}_{a3\text{ВНА}} \\ \overline{c}_{u1\text{ВНА}} & \overline{c}_{u3\text{ВНА}} \\ c_{a1\text{ВНА}} & c_{a3\text{ВНА}} \\ c_{u1\text{ВНА}} & c_{u3\text{ВНА}} \\ c_{1\text{ВНА}} & c_{3\text{ВНА}} \\ \lambda_{c1\text{ВНА}} & \lambda_{c3\text{ВНА}} \\ F_{1\text{ВНА}} & F_{3\text{ВНА}} \\ \varepsilon_{\text{ВНА}} & \varepsilon_{\text{ВНА}} \end{pmatrix} = \ \text{for } r \in av(N_r)$$

$$\alpha_{1\text{ВНА}_r} \leftarrow 90°$$

$$\overline{d}_{1\text{ВНА}} \leftarrow \overline{d}_1$$

$$\overline{d}_{3\text{ВНА}} \leftarrow \overline{d}_{1\text{ВНА}}$$

$$T^*_{1\text{ВНА}_r} \leftarrow T^*_{\text{К}1}$$

$$T^*_{3\text{ВНА}_r} \leftarrow T^*_{1\text{ВНА}_r}$$

$$P^*_{1\text{ВНА}_r} \leftarrow P^*_{\text{К}1}$$

$$\rho^*_{1\text{ВНА}_r} \leftarrow \frac{P^*_{1\text{ВНА}_r}}{R_{\text{в}} \cdot T^*_{1\text{ВНА}_r}}$$

$$k_{1\text{ВНА}_r} \leftarrow k_{\text{ад}}\left(Cp_{\text{воздух}}\left(P^*_{1\text{ВНА}_r}, T^*_{1\text{ВНА}_r}\right), R_{\text{в}}\right)$$

$$a_{\text{кр}1\text{ВНА}_r} \leftarrow a_{\text{кр}}\left(k_{1\text{ВНА}_r}, R_{\text{в}}, T^*_{1\text{ВНА}_r}\right)$$

$$\overline{c}_{a1\text{ВНА}_r} \leftarrow \overline{c}_{.a1}(Z,0)$$

$$\overline{c}_{u1\text{ВНА}_r} \leftarrow \begin{cases} \overline{r}_{\text{ср}}\left(\overline{d}_{1\text{ВНА}}\right) \cdot \left(1 - R_{L.\text{ср}}(Z,0)\right) - \dfrac{\overline{H}_{.T}(Z,0)}{2 \cdot \overline{r}_{\text{ср}}\left(\overline{d}_{1\text{ВНА}}\right)} & \text{if } \text{ВНА} = 1 \\ 0 & \text{otherwise} \end{cases}$$

$$c_{a1\text{ВНА}_r} \leftarrow \overline{c}_{a1\text{ВНА}_r} \cdot u_{1\text{пер}}$$

$$\sigma_{\text{ВНА}} = 1.0000$$

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

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

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

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

$$c_{u1\text{ВНА}_r} = \frac{c_{a1\text{ВНА}_r}}{\tan\left(\alpha_{1\text{ВНА}_r}\right)}$$

$$c_{1\text{ВНА}_r} = \frac{c_{a1\text{ВНА}_r}}{\sin\left(\alpha_{1\text{ВНА}_r}\right)}$$

$$\lambda_{c1\text{ВНА}_r} = \frac{c_{1\text{ВНА}_r}}{a_{\text{кр}1\text{ВНА}_r}}$$

$$\sigma_{\text{ВНА}} = \left|\begin{array}{ll} \left[1 + \text{mean}(0.03, 0.06)\cdot \text{ГДФ}\left(\text{"}\rho\text{"}, \lambda_{c1\text{ВНА}_r}, k_{1\text{ВНА}_r}\right)\cdot \dfrac{k_{1\text{ВНА}_r}}{k_{1\text{ВНА}_r} + 1}\cdot\left(\lambda_{c1\text{ВНА}_r}\right)^2\right]^{-1} & \text{if } \text{ВНА} = 1 \\ 1 & \text{otherwise} \end{array}\right.$$

$$P^*_{3\text{ВНА}_r} = P^*_{1\text{ВНА}_r}\cdot\sigma_{\text{ВНА}}$$

$$\rho^*_{3\text{ВНА}_r} = \frac{P^*_{3\text{ВНА}_r}}{R_{\text{в}}\cdot T^*_{3\text{ВНА}_r}}$$

$$k_{3\text{ВНА}_r} = k_{\text{ад}}\left(Cp_{\text{воздух}}\left(P^*_{3\text{ВНА}_r}, T^*_{3\text{ВНА}_r}\right), R_{\text{в}}\right)$$

$$a_{\text{кр}3\text{ВНА}_r} = a_{\text{кр}}\left(k_{3\text{ВНА}_r}, R_{\text{в}}, T^*_{3\text{ВНА}_r}\right)$$

$$\overline{c}_{a3\text{ВНА}_r} = \left|\begin{array}{ll} \overline{c}_{.a1}(Z, 1) & \text{if } \text{ВНА} = 1 \\ \overline{c}_{a1\text{ВНА}_r} & \text{otherwise} \end{array}\right.$$

$$\overline{c}_{u3\text{ВНА}_r} = \left|\begin{array}{ll} \overline{r}_{\text{ср}}\left(\overline{d}_{3\text{ВНА}}\right)\cdot\left(1 - R_{L.\text{ср}}(Z, 1)\right) - \dfrac{\overline{H}_{.T}(Z, 1)}{2\cdot\overline{r}_{\text{ср}}\left(\overline{d}_{3\text{ВНА}}\right)} & \text{if } \text{ВНА} = 1 \\ 0 & \text{otherwise} \end{array}\right.$$

$$\alpha_{3\text{ВНА}_r} = \left|\begin{array}{ll} \text{triangle}\left(\overline{c}_{a1\text{ВНА}_r}, \overline{c}_{u1\text{ВНА}_r}\right) & \text{if } \text{ВНА} = 1 \\ \dfrac{\pi}{2} & \text{otherwise} \end{array}\right.$$

$$c_{a3\text{ВНА}_r} = \overline{c}_{a1\text{ВНА}_r}\cdot u_{1\text{пер}}$$

$$c_{u3\text{ВНА}_r} = \frac{c_{a3\text{ВНА}_r}}{\tan\left(\alpha_{3\text{ВНА}_r}\right)}$$

$$c_{3\text{ВНА}_r} = \frac{c_{a3\text{ВНА}_r}}{\sin\left(\alpha_{3\text{ВНА}_r}\right)}$$

$$\lambda_{c3\text{ВНА}_r} = \frac{c_{3\text{ВНА}_r}}{a_{\text{кр}3\text{ВНА}}}$$

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

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

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

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

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

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

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

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

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

$\text{submatrix}\left(a_{\text{кр}3\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (310.8)$

$\text{submatrix}\left(\overline{c}_{a1\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.335)$

$\text{submatrix}\left(\overline{c}_{a3\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.335)$

$\text{submatrix}\left(\overline{c}_{u1\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.000)$

$\text{submatrix}\left(\overline{c}_{u3\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.000)$

$\text{submatrix}\left(c_{a1\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (142.7)$

$\text{submatrix}\left(c_{a3\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (142.7)$

$\text{submatrix}\left(c_{u1\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.0)$

$\text{submatrix}\left(c_{u3\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.0)$

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

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

$\text{submatrix}\left(\lambda_{c1\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.459)$

$\text{submatrix}\left(\lambda_{c3\text{ВНА}}, \text{av}\left(N_r\right), \text{av}\left(N_r\right), 1, 1\right) = (0.459)$

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

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

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

Расчет ВНА:

Поступенчатый расчет ОК по ср. ЛТ

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

$$r = av(N_r)$$

$$T^*_{st(1,1),r} = T^*_{\text{3ВНА}_r}$$

$$P^*_{st(1,1),r} = P^*_{\text{3ВНА}_r}$$

$$\rho^*_{st(1,1),r} = \rho^*_{\text{3ВНА}_r}$$

$$Cp_{st(1,1),r} = Cp_{\text{воздух}}\left(P^*_{st(1,1),r}, T^*_{st(1,1),r}\right)$$

$$k_{st(1,1),r} = k_{\text{ад}}\left(Cp_{st(1,1),r}, R_{\text{в}}\right)$$

$$a^*_{c_{st(1,1),r}} = a_{\text{кр}}\left(k_{st(1,1),r}, R_{\text{в}}, T^*_{st(1,1),r}\right)$$

$$\overline{c}_{a_{st(1,1),r}} = \overline{c}_{\text{a3ВНА}_r}$$

$$\overline{c}_{u_{st(1,1),r}} = \overline{c}_{\text{u3ВНА}_r}$$

$$c_{a_{st(1,1),r}} = c_{\text{a3ВНА}_r}$$

$$u_{st(1,1),N_r} = u_{\text{1пер}}$$

$$\alpha_{st(1,1),r} = \alpha_{\text{3ВНА}_r}$$

$$c_{st(1,1),r} = \frac{c_{a_{st(1,1),r}}}{\sin\left(\alpha_{st(1,1),r}\right)}$$

$$\lambda_{c_{st(1,1),r}} = \frac{c_{st(1,1),r}}{a^*_{c_{st(1,1),r}}}$$

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

```
$D_{st(1,1),N_r} = \frac{2 \cdot u_{st(1,1),N_r}}{\omega}$
$D_{st(1,1),1} = \sqrt{\left(D_{st(1,1),N_r}\right)^2 - \frac{4 \cdot F_{st(1,1)}}{\pi}}$
$D_{st(1,1),r} = \overline{r}_{cp}\left(\frac{D_{st(1,1),1}}{D_{st(1,1),N_r}}\right) \cdot D_{st(1,1),N_r}$
$\overline{d}_{st(1,1)} = \frac{D_{st(1,1),1}}{D_{st(1,1),N_r}}$
for $i \in 1..Z$
    trace(concat("ступень i = ", num2str(i)))
    $\begin{pmatrix} \overline{H}_{T_i} \\ K_{H_i} \\ \eta^*_i \\ R_{L_{i,r}} \end{pmatrix} = \begin{pmatrix} \overline{H}_{.T}(Z,i) \\ K_{.H}(Z,i) \\ \eta^*_{.}(Z,i) \\ R_{L.cp}(Z,i) \end{pmatrix}$
    $H_{T_{i,r}} = \overline{H}_{T_i} \cdot \left(u_{st(i,1),N_r}\right)^2$
    $L_i = K_{H_i} \cdot H_{T_{i,r}}$
    $L^*_i = L_i \cdot \eta^*_i$
    $iteration_{12} = 0$
    $k_{st(i,2),r} = k_{st(i,1),r}$
    while $0 < 1$
        $iteration_{12} = iteration_{12} + 1$
        trace(concat("    iteration.12 = ", num2str(iteration_{12})))
        $k_{12} = mean\left(k_{st(i,1),r}, k_{st(i,2),r}\right)$
        $Cp_{12} = \frac{k_{12}}{k_{12} - 1} \cdot R_в$
        $T^*_{st(i,2),r} = T^*_{st(i,1),r} + \frac{L_i}{Cp_{12}}$
        $\pi^*_i = \left(1 + \frac{L^*_i}{Cp_{12} \cdot T^*_{st(i,1),r}}\right)^{\frac{k_{12}}{k_{12}-1}}$
        $P^*_{st(i,2),r} = P^*_{st(i,1),r} \cdot \pi^*_i$
        $Cp_{st(i,2),r} = Cp_{воздух}\left(P^*_{st(i,2),r}, T^*_{st(i,2),r}\right)$
```

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

```
    $D_{st(i,3),N_r} = D_{st(i,1),N_r}$
    $D_{st(i,3),1} = \sqrt{\left(D_{st(i,3),N_r}\right)^2 - \frac{4F_{st(i,3)}}{\pi}}$
if $\text{ЗППЧ}_i = \text{"кор"}$
    $D_{st(i,3),1} = D_{st(i,1),1}$
    $D_{st(i,3),N_r} = \sqrt{\left(D_{st(i,3),1}\right)^2 + \frac{4F_{st(i,3)}}{\pi}}$
if $\text{ЗППЧ}_i = \text{"ср"}$
    $D_{st(i,3),N_r} = \sqrt{\left(D_{st(i,1),r}\right)^2 + \frac{2F_{st(i,3)}}{\pi}}$
    $D_{st(i,3),1} = \sqrt{\left(D_{st(i,1),r}\right)^2 - \frac{2F_{st(i,3)}}{\pi}}$
$\bar{d}_{st(i,3)} = \frac{D_{st(i,3),1}}{D_{st(i,3),N_r}}$
$D_{st(i,3),r} = \bar{r}_{cp}\left(\bar{d}_{st(i,3)}\right)\cdot D_{st(i,3),N_r}$
$\bar{c}_{u_{st(i,3),r}} = \bar{r}_{cp}\left(\bar{d}_{st(i,3)}\right)\cdot\left(1 - R_{L.cp}(Z,i+1)\right) - \frac{\bar{H}_{.T}(Z,i+1)}{2\cdot\bar{r}_{cp}\left(\bar{d}_{st(i,3)}\right)}$
$\alpha_{st(i,3),r} =$
    $\operatorname{atan}\left(\frac{\bar{c}_{a_{st(i,3),r}}}{\bar{c}_{u_{st(i,3),r}}}\right)$ if $\operatorname{atan}\left(\frac{\bar{c}_{a_{st(i,3),r}}}{\bar{c}_{u_{st(i,3),r}}}\right) \ge 0$
    $\operatorname{atan}\left(\frac{\bar{c}_{a_{st(i,3),r}}}{\bar{c}_{u_{st(i,3),r}}}\right) + 2\pi$ otherwise
$u_{st(i,3),N_r} = u_{st(i,1),N_r}\cdot\frac{D_{st(i,3),N_r}}{D_{st(i,1),N_r}}$
$c_{a_{st(i,3),r}} = \bar{c}_{a_{st(i,3),r}}\cdot u_{st(i,3),N_r}$
$c_{st(i,3),r} = \frac{c_{a_{st(i,3),r}}}{\sin\left(\alpha_{st(i,3),r}\right)}$
$\lambda_{c_{st(i,3),r}} = \frac{c_{st(i,3),r}}{a*_{c_{st(i,3),r}}}$
$F'_3 = \frac{G\cdot\sqrt{R_B\cdot T*_{st(i,3),r}}}{m_q\left(k_{st(i,3),r}\right)\cdot\text{ГДФ}\left(\text{"G"},\lambda_{c_{st(i,3),r}},k_{st(i,3),r}\right)\cdot\sin\left(\alpha_{st(i,3),r}\right)\cdot P*_{st(i,3),r}}$
break if $\left(\left|\operatorname{eps}\left(\text{"rel"},F'_3,F_{st(i,3)}\right)\right| < \text{epsilon}\right) \wedge \left(\text{iteration}_3 = 0\right)$
$\text{iteration}_3 = -1$ if $\left(\left|\operatorname{eps}\left(\text{"rel"},F'_3,F_{st(i,3)}\right)\right| < \text{epsilon}\right)$
```

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

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

$$\alpha_{st(i,2),r} = \text{triangle}\left(\bar{c}_{a_{st(i,2),r}},\bar{c}_{u_{st(i,2),r}}\right)$$

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

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

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

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

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

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

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

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

for $a \in 1..3$

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

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

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

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

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

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

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

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

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

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

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

```
            $M_{c_{st(i,a),r}} = \frac{}{a_{зв_{st(i,a),r}}}$
            $h_{st(i,a)} = 0.5\cdot\left(D_{st(i,a),N_r} - D_{st(i,a),1}\right)$
            for $radius \in 1..N_r$
                $u_{st(i,a),radius} = \omega\cdot\frac{D_{st(i,a),radius}}{2}$
        $\begin{pmatrix} \varepsilon rotor_{i,av(N_r)} \\ \varepsilon stator_{i,av(N_r)} \end{pmatrix} = \begin{pmatrix} \beta_{st(i,2),av(N_r)} - \beta_{st(i,1),av(N_r)} \\ \alpha_{st(i,3),av(N_r)} - \alpha_{st(i,2),av(N_r)} \end{pmatrix}$
    for $i \in 1..Z$
        for $a \in 1..3$
            for $r \in 1..N_r$
                $R_{st(i,a),r} = 0.5\cdot D_{st(i,a),r}$
    $\begin{pmatrix} R_L & K_H & Cp & \overline{H}_T & L^* & T^* & P^* & \rho^* & a^*_c & \lambda_c & F & D & \overline{d} & \overline{c}_a & c_a & u & c & M_c & \alpha & \varepsilon_{rotor} \\ \pi^* & \eta^* & k & H_T & L & T & P & \rho & a_{зв} & \lambda_c & F & R & h & \overline{c}_u & c_u & w_u & w & M_w & \beta & \varepsilon_{stator} \end{pmatrix}^T$
```

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

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

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

$\sigma_{CA} = 1.0000$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

▲ Расчет СА:

Результаты поступенчатого расчета по ср. ЛТ

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

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

$\overline{\Delta}G^T =$

	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																

$\cdot\%$

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

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

Количество ступеней ОК: $Z = 1$

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

Дискритизация ступеней: $i = 1..Z$

$\pi*^T =$

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

[16, с 114] $\pi*^T \le 1.9 =$

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

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

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

$H_T^T =$

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

$\cdot 10^3$

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

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

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

Мощность К (Вт): $N_К = G \cdot L_К = 12.24 \cdot 10^6$

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

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

$K_H{}^T =$

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

$\eta^{*T} =$

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

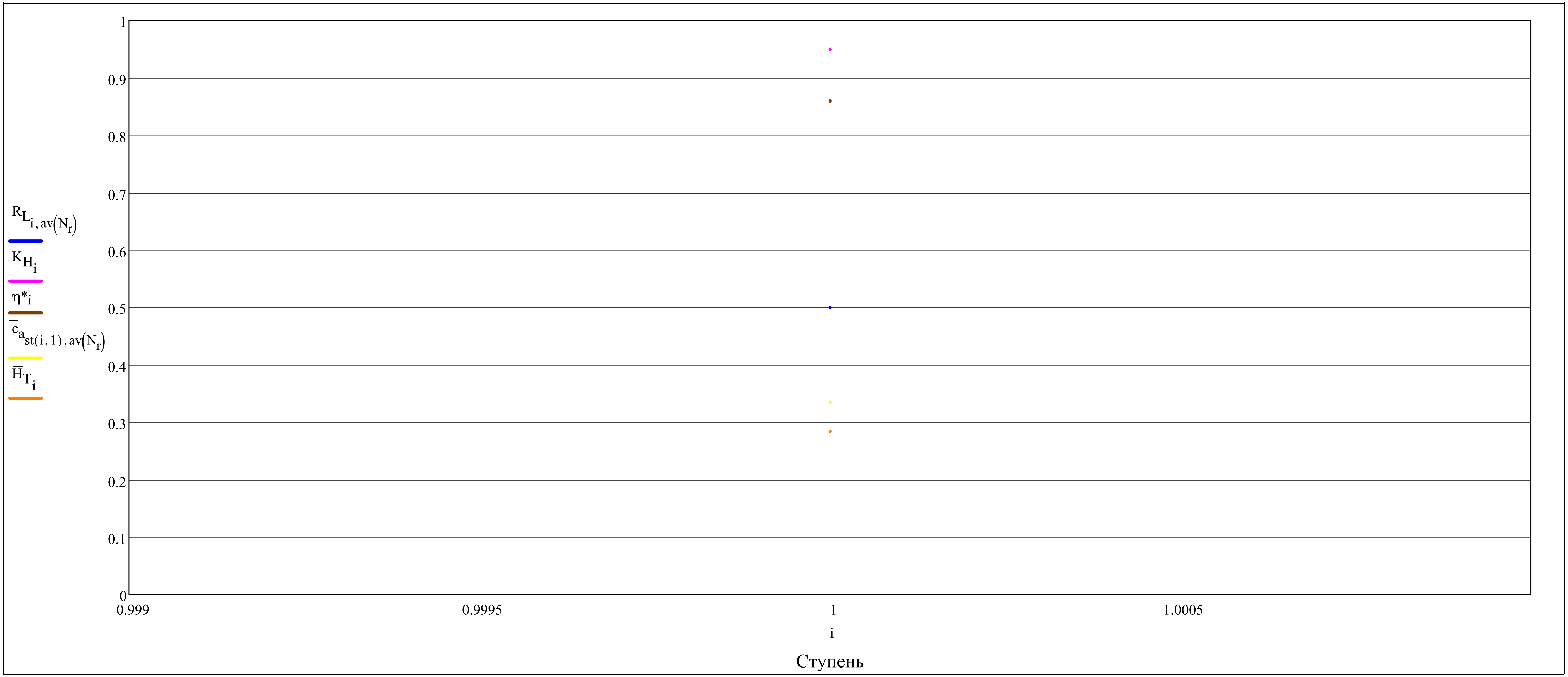
$\cdot\%$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.335	0.300	0.265																	

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

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



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

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

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

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

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

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

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	278	316.8	326.7																		

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

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

$\cdot 10^3$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	89.4	131.1	146.1															

$\cdot 10^3$

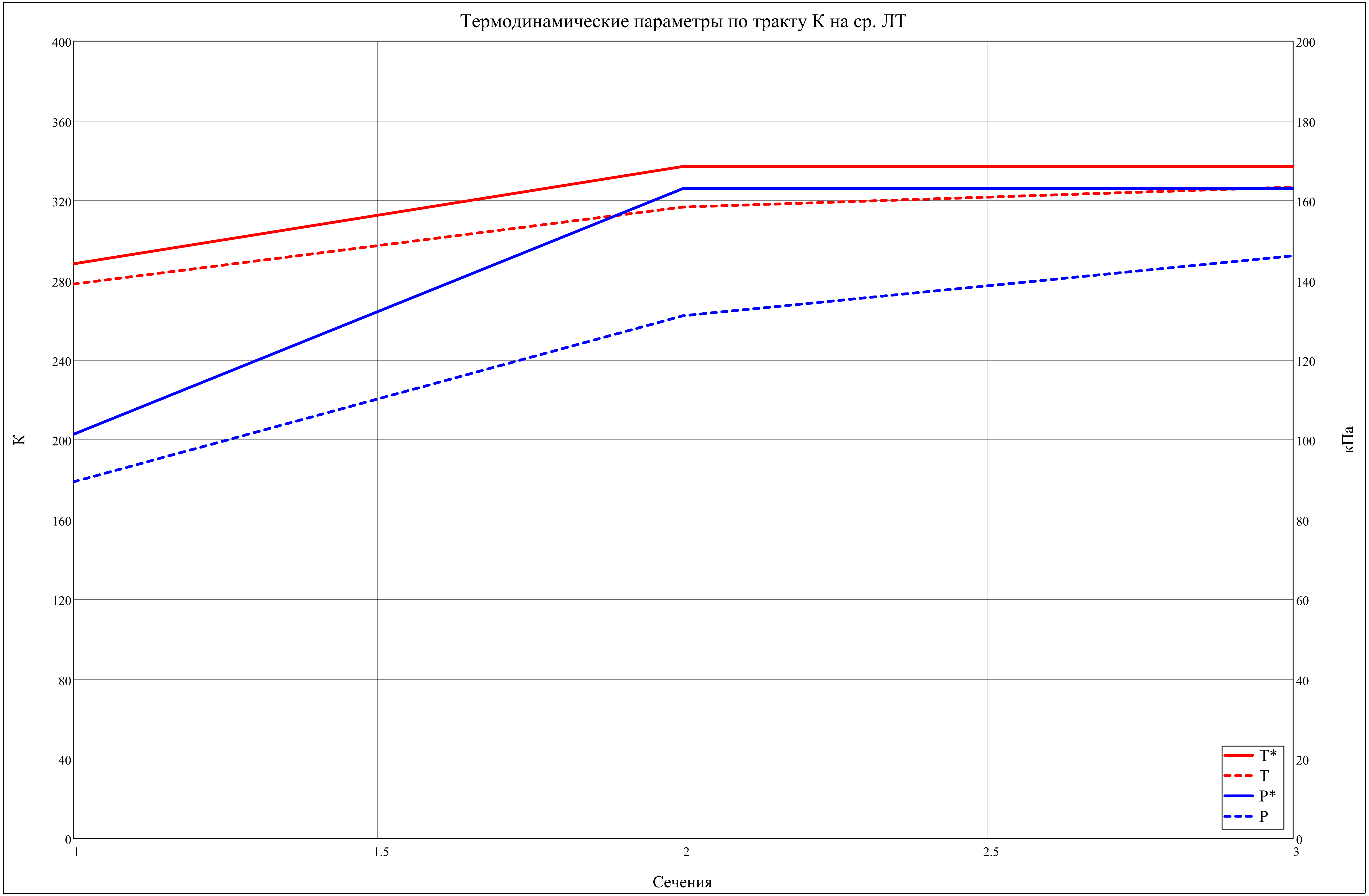
$\mathrm{submatrix}\left(\rho^*, 1, 2Z+1, av\left(N_r\right), av\left(N_r\right)\right)^T =$

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

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.12	1.441	1.558																

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


Термодинамические параметры по тракту К на ср. ЛТ
K
кПа
Сечения
400
360
320
280
240
200
160
120
80
40
0
200
180
160
140
120
100
80
60
40
20
0
1
1.5
2
2.5
3
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	1.5621	1.3551	1.4194																		

$\overline{d}^T =$

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

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

$D^T =$

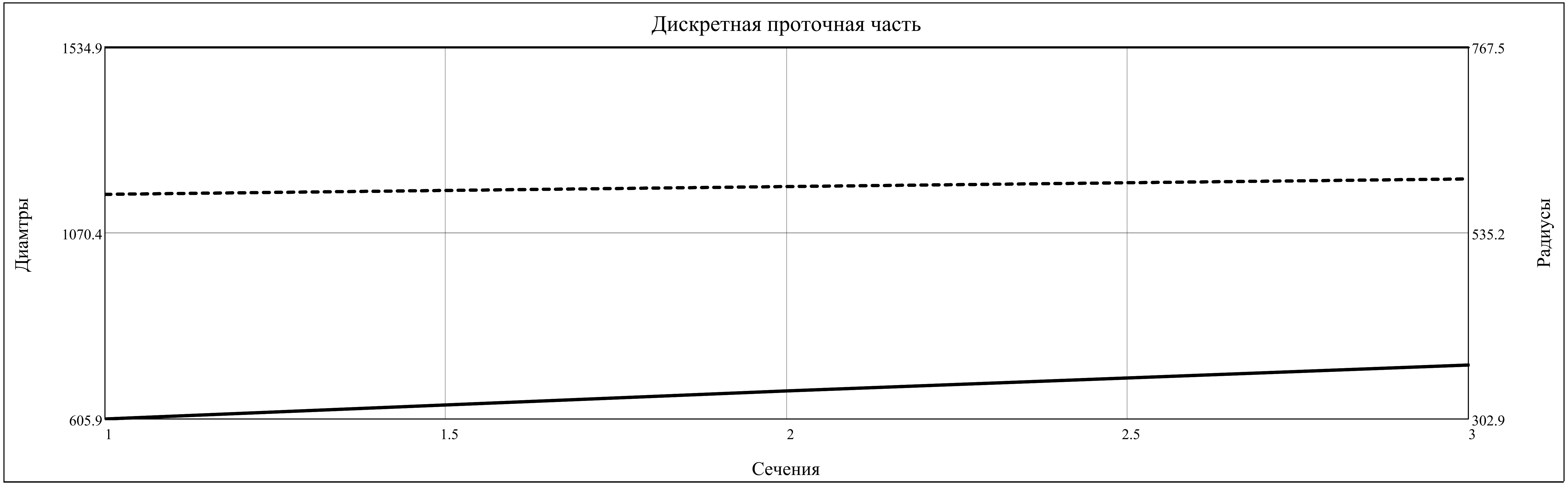
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	605.9	676.2	740.8																		
2	1166.8	1186.0	1205.1																		
3	1534.9	1534.9	1534.9																		

$\cdot 10^{-3}$

$R^T =$

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

$\cdot 10^{-3}$



$h^T =$

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

$\cdot 10^{-3}$

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

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

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	334.5	356.8	362.4																		

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	142.7	202.3	144.4																		

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	353.8	214.5																			

$u^T =$

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

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

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	142.7	127.8	112.9																		

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

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

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	323.8	172.3	244.4																		

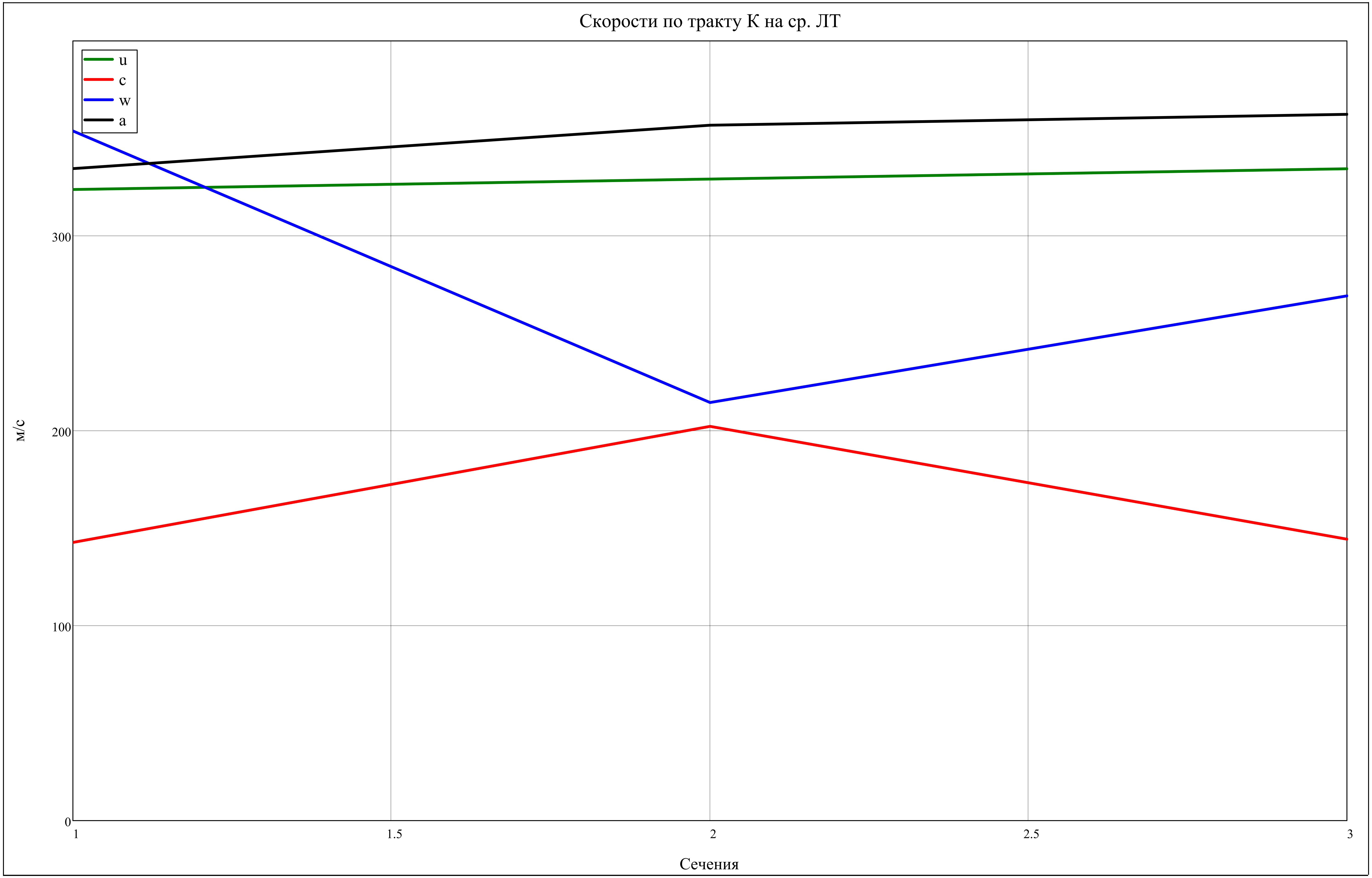
$\Delta c_{a_{i,av\left(N_r\right)}} = \left(c_{a_{st(i,2),av\left(N_r\right)}} - c_{a_{st(i,1),av\left(N_r\right)}}\right)$

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

	1	2	3	4	5	6	7	8	9	10	11	12
1	-14.91											

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

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



Скорости по тракту К на ср. ЛТ

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	90.00	39.17	51.42																		

·°

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	23.78	36.56	24.79																		

·°

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

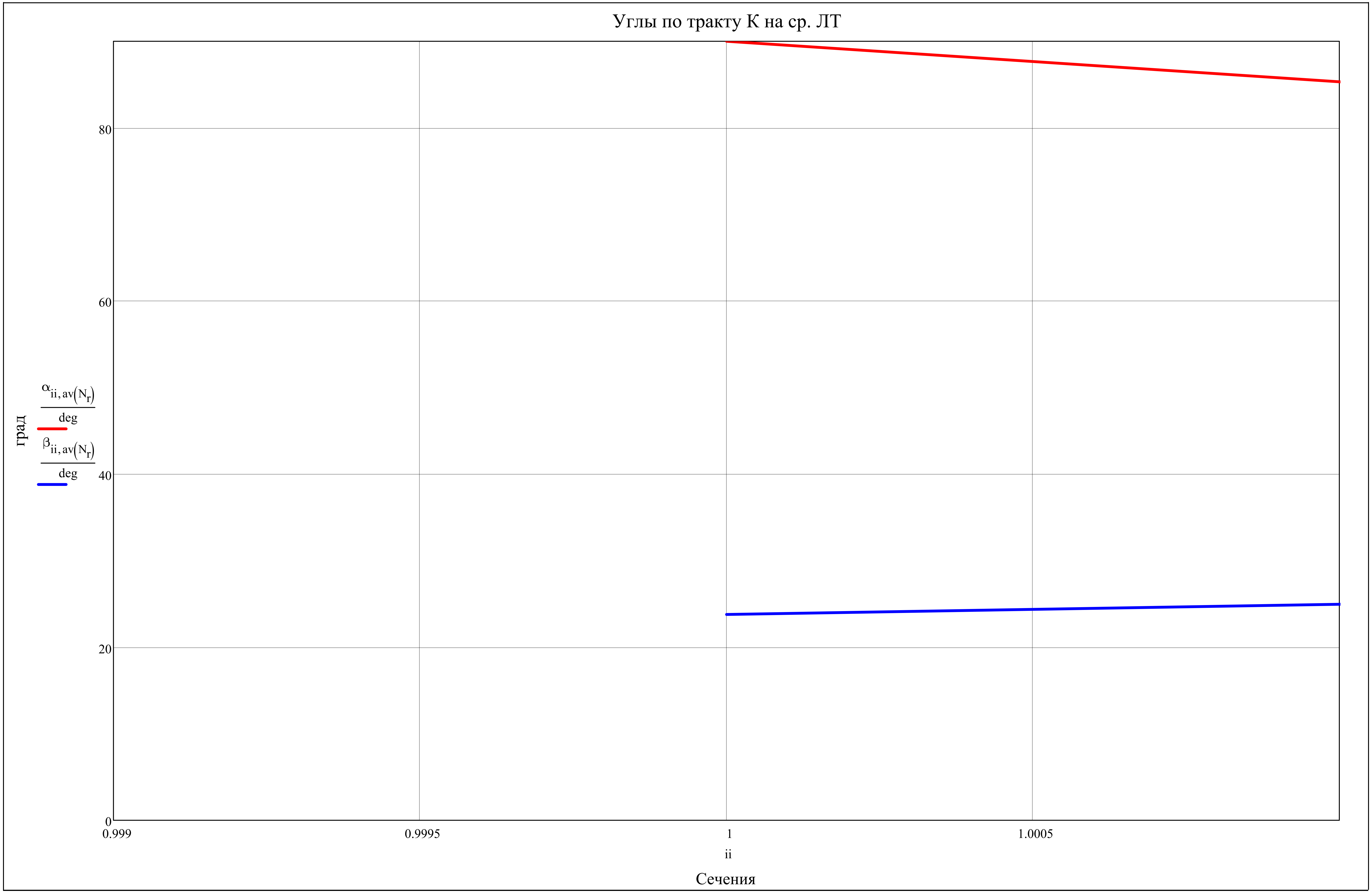
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	12.78																				

·°

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	12.25																				

·°



Углы по тракту К на ср. ЛТ

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.4591	0.6020	0.4297																

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

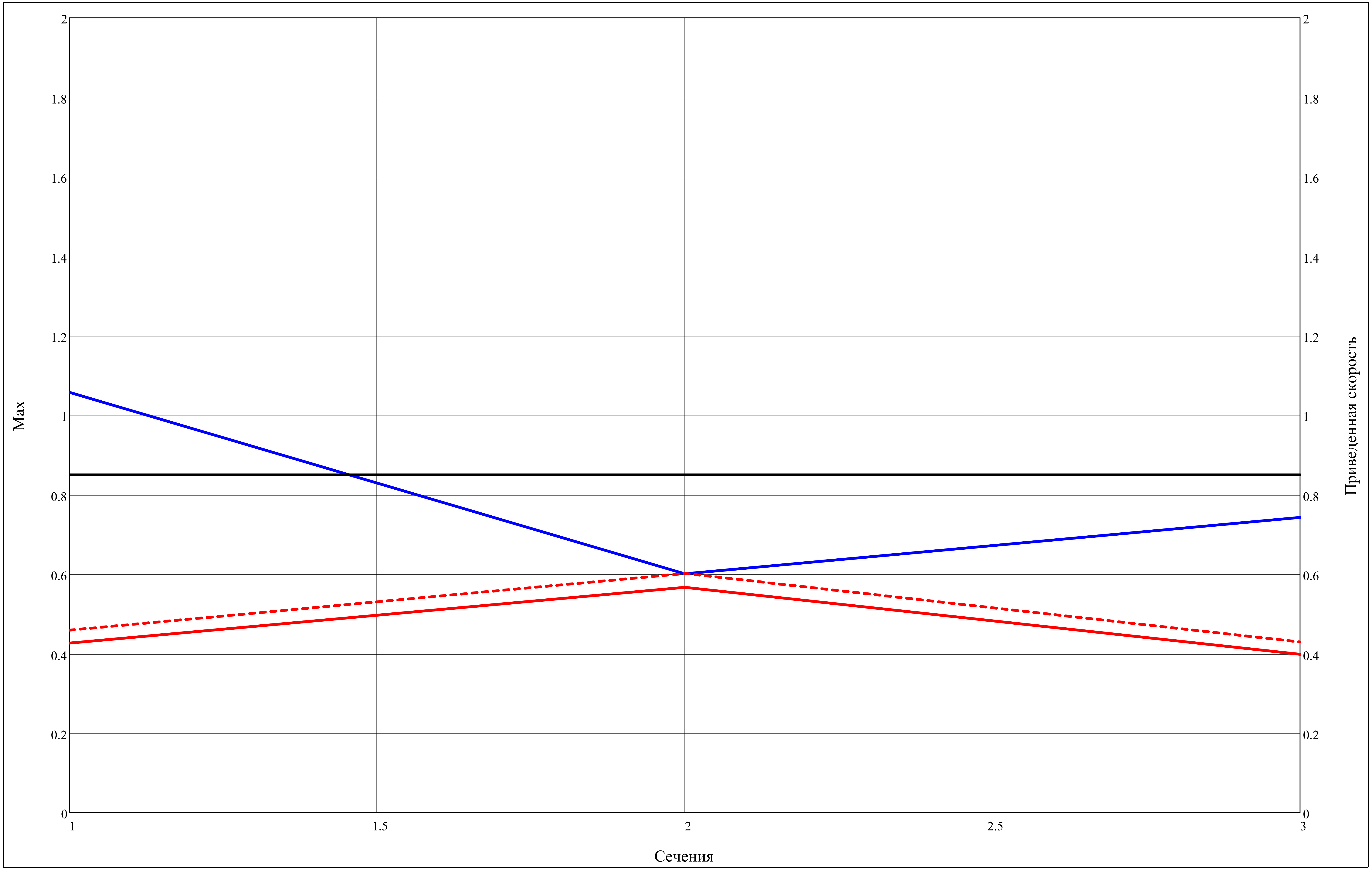
	1	2	3
1	1	1	1

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.0579	0.6012																	

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.4266	0.5670	0.3985																


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

Результаты поступенчатого расчета по ср. ЛТ

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

Расчет параметров потока по высоте Л

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

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

```
m = | for i ∈ 1 .. Z
    |     m_i = | −1  if  $\bar{d}_{st(i,1)} \le \bar{d}_{R2m}$
    |           | 1  if  $\bar{d}_{st(i,1)} \ge \bar{d}_{m2Ц}$
    |           | $-1 + \frac{1-(-1)}{\bar{d}_{m2Ц} - \bar{d}_{R2m}} \cdot \left(\bar{d}_{st(i,1)} - \bar{d}_{R2m}\right)$  otherwise
    | m
```

```
m_i = | 0.73  if  compressor = "Вл"
      | m_i  otherwise
```

$m^T =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.730											

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

```
for $i \in 1$
  for $r \in 1..N_r$
    $\begin{pmatrix} T^*_{1BHA_r} \\ T^*_{3BHA_r} \end{pmatrix} = \begin{pmatrix} T^*_{1BHA_{av(N_r)}} \\ T^*_{3BHA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} P^*_{1BHA_r} \\ P^*_{3BHA_r} \end{pmatrix} = \begin{pmatrix} P^*_{1BHA_{av(N_r)}} \\ P^*_{3BHA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} \rho^*_{1BHA_r} \\ \rho^*_{3BHA_r} \end{pmatrix} = \begin{pmatrix} \rho^*_{1BHA_{av(N_r)}} \\ \rho^*_{3BHA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} Cp_{1BHA_r} \\ Cp_{3BHA_r} \end{pmatrix} = \begin{pmatrix} Cp_{воздух}\left(P^*_{1BHA_r}, T^*_{1BHA_r}\right) \\ Cp_{воздух}\left(P^*_{3BHA_r}, T^*_{3BHA_r}\right) \end{pmatrix}$
    $\begin{pmatrix} k_{1BHA_r} \\ k_{3BHA_r} \end{pmatrix} = \begin{pmatrix} k_{ад}\left(Cp_{1BHA_r}, R_в\right) \\ k_{ад}\left(Cp_{3BHA_r}, R_в\right) \end{pmatrix}$
    $\begin{pmatrix} a^*_{c1BHA_r} \\ a^*_{c3BHA_r} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2 \cdot k_{1BHA_r}}{k_{1BHA_r}+1} \cdot R_в \cdot T^*_{1BHA_r}} \\ \sqrt{\frac{2 \cdot k_{3BHA_r}}{k_{3BHA_r}+1} \cdot R_в \cdot T^*_{3BHA_r}} \end{pmatrix}$
    $A = \left(1 - R_{L_{i,av(N_r)}}\right) \cdot \omega \cdot \left(R_{st(i,1),av(N_r)}\right)^{m_i+1}$
    $B = \frac{H_{T_{i,av(N_r)}}}{2 \cdot \omega}$
    $\left( c_{u1BHA} \right. = \left[ c_{u1BHA_{av(N_r)}} \quad A \quad B \right.$
```

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

$$\begin{pmatrix} c_{a1BHA_r} \\ c_{a3BHA_r} \end{pmatrix} = \begin{bmatrix} c_{a1BHA_{av(N_r)}} \\ \left| \begin{array}{l} \text{if } BHA = 1 \\ \quad \left| \begin{array}{ll} \sqrt{\left(c_{a3BHA_{av(N_r)}}\right)^2 - 2\cdot A^2\cdot\left[\left(R_{st(i,1),r}\right)^2 - \left(R_{st(i,1),av(N_r)}\right)^2\right] + 4\cdot A\cdot B\cdot\ln\left(\dfrac{R_{st(i,1),r}}{R_{st(i,1),av(N_r)}}\right)} & \text{if } m_i = -1 \\ \sqrt{\left(c_{a3BHA_{av(N_r)}}\right)^2 - 2\cdot A^2\cdot\ln\left(\dfrac{R_{st(i,1),r}}{R_{st(i,1),av(N_r)}}\right) - 2\cdot A\cdot B\cdot\left(\dfrac{1}{R_{st(i,1),r}} - \dfrac{1}{R_{st(i,1),av(N_r)}}\right)} & \text{if } m_i = 0 \\ \sqrt{\left(c_{a3BHA_{av(N_r)}}\right)^2 + \dfrac{A\cdot\left(m_i - 1\right)\cdot\left[\begin{array}{l} -A\cdot\left(m_i + 1\right)\cdot\left[\dfrac{1}{\left(R_{st(i,1),r}\right)^{2\cdot m_i}} - \dfrac{1}{\left(R_{st(i,1),av(N_r)}\right)^{2\cdot m_i}}\right] \ldots \\ +2\cdot B\cdot m_i\cdot\left[\dfrac{1}{\left(R_{st(i,1),r}\right)^{m_i+1}} - \dfrac{1}{\left(R_{st(i,1),av(N_r)}\right)^{m_i+1}}\right] \end{array}\right]}{m_i\cdot\left(m_i + 1\right)}} & \text{otherwise} \end{array} \right. \\ c_{a1BHA_{av(N_r)}} \quad \text{otherwise} \end{array} \right. \end{bmatrix}$$

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

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

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

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

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

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

```
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 $\Delta H_{Tmax} = 0$
                $A_{st(i,a)} = \left(1 - R_{L_{i,av(N_r)}}\right)\cdot\omega\cdot\left(R_{st(i,a),av(N_r)}\right)^{m_i+1}$
                $B_{st(i,a)} = \frac{H_{T_{i,av(N_r)}}}{2\cdot\omega}$
                $c_{u_{st(i,a),r}} =$
                    $c_{u_{st(i,a-1),r}}\cdot\frac{R_{st(i,a),r}}{R_{st(i,a-1),r}} + \frac{H_{T_{i,av(N_r)}}}{\omega\cdot R_{st(i,a),r}}$  if $a = 2$
                    otherwise
                        $0$  if $(a = 1) \wedge (i = 1) \wedge (BHA = 0)$
                        $\frac{A_{st(i,a)}}{\left(R_{st(i,a),r}\right)^{m_i}} - \frac{B_{st(i,a)}}{\left(R_{st(i,a),r}\right)}$  otherwise
                $c_{a_{st(i,a),r}} =$
                    $c_{a3BHA_r}$  if $(a = 1) \wedge (i = 1) \wedge (BHA = 1)$
                    $\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 - 2\cdot\left(A_{st(i,a)}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2 - \left(R_{st(i,a),av(N_r)}\right)^2\right] + 4\cdot A_{st(i,a)}\cdot B_{st(i,a)}\cdot\ln\left(\frac{R_{st(i,a),r}}{R_{st(i,a),av(N_r)}}\right)}\cdot$ | $-1$ if $a = 2$ ; $1$ otherwise |   if $m_i = -1$
                    $\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 - 2\cdot\left(A_{st(i,a)}\right)^2\cdot\ln\left(\frac{R_{st(i,a),r}}{R}\right) - 2\cdot A_{st(i,a)}\cdot B_{st(i,a)}\cdot\left(\frac{1}{R} - \frac{1}{R}\right)}\cdot$ | $-1$ if $a = 2$   if $m_i = 0$
```

$$\sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 + \frac{A_{st(i,a)}\cdot(m_i-1)\cdot\left[-A_{st(i,a)}\cdot(m_i+1)\cdot\left[\frac{1}{\left(R_{st(i,a),r}\right)^{2\cdot m_i}} - \frac{1}{\left(R_{st(i,a),av(N_r)}\right)^{2\cdot m_i}}\right]\ldots + 2\cdot B_{st(i,a)}\cdot m_i\cdot\left[\frac{1}{\left(R_{st(i,a),r}\right)^{m_i+1}} - \frac{1}{\left(R_{st(i,a),av(N_r)}\right)^{m_i+1}}\right]\cdot\left|\begin{array}{l} -1 \text{ if } a = 2 \\ 1 \text{ otherwise}\end{array}\right.\right]}{m_i\cdot(m_i+1)}} \quad \text{otherwise}$$

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

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

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

$$c_{u_{st(i,a),r}} = \left|\begin{array}{l} A_{st(i,a)}\cdot R_{st(i,a),r} + \frac{B_{st(i,a)}}{R_{st(i,a),r}} + \frac{H_{T_{i,r}}}{\omega\cdot R_{st(i,a),r}} \quad \text{if } a = 2 \\ \text{otherwise} \\ \quad\left|\begin{array}{l} 0 \quad \text{if } (a = 1) \wedge (i = 1) \wedge (BHA = 0) \\ A_{st(i,a)}\cdot R_{st(i,a),r} + \frac{B_{st(i,a)}}{R_{st(i,a),r}} \quad \text{otherwise}\end{array}\right.\end{array}\right.$$

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

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

$$c_{a_{st(i,a),r}} = \left|\begin{array}{l} c_{a3BHA_r} \quad \text{if } (a = 1) \wedge (i = 1) \wedge (BHA = 1) \\ \sqrt{\begin{array}{l}\left(c_{a_{st(i,a),av(N_r)}}\right)^2 - 2\cdot\left(A_{st(i,a)}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2 - \left(R_{st(i,a),av(N_r)}\right)^2\right]\ldots \\ + -\left(6\cdot\frac{A_{st(i,a)}}{\omega} - 2\right)\cdot k_{HT}\cdot\left(R_{st(i,a),r} - R_{st(i,a),av(N_r)}\right)\ldots \\ + -2\cdot\frac{k_{HT}}{\omega}\cdot\left(B_{st(i,a)} + \frac{b_{HT}}{\omega}\right)\cdot\frac{R_{st(i,a),r} - R_{st(i,a),av(N_r)}}{R_{st(i,a),r}\cdot R_{st(i,a),av(N_r)}} - 2\cdot\left[2\cdot A_{st(i,a)}\cdot\left(B_{st(i,a)} + \frac{b_{HT}}{\omega}\right) + \frac{k_{HT}^{\,2}}{\omega^2}\right]\cdot\ln\left(\frac{R_{st(i,a),r}}{R_{st(i,a),av(N_r)}}\right)\end{array}} \quad \text{if } a = 2 \\ \sqrt{\left(c_{a_{st(i,a),av(N_r)}}\right)^2 - 2\cdot\left(A_{st(i,a)}\right)^2\cdot\left[\left(R_{st(i,a),r}\right)^2 - \left(R_{st(i,a),av(N_r)}\right)^2\right] - 4\cdot A_{st(i,a)}\cdot B_{st(i,a)}\cdot\ln\left(\frac{R_{st(i,a),r}}{R_{st(i,a),av(N_r)}}\right)} \quad \text{otherwise}\end{array}\right.$$

```
            $\alpha_{st(i,a),r} = \text{triangle}\left(c_{a_{st(i,a),r}}, c_{u_{st(i,a),r}}\right)$
            $c_{st(i,a),r} = \frac{c_{a_{st(i,a),r}}}{\sin\left(\alpha_{st(i,a),r}\right)}$
            $\lambda_{c_{st(i,a),r}} = \frac{c_{st(i,a),r}}{a^*_{c_{st(i,a),r}}}$
            $\begin{pmatrix} T_{st(i,a),r} \\ P_{st(i,a),r} \\ \rho_{st(i,a),r} \end{pmatrix} = \begin{pmatrix} T^*_{st(i,a),r} \cdot ГДФ\left("T", \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \\ P^*_{st(i,a),r} \cdot ГДФ\left("P", \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \\ \rho^*_{st(i,a),r} \cdot ГДФ\left("\rho", \lambda_{c_{st(i,a),r}}, k_{st(i,a),r}\right) \end{pmatrix}$
            $a_{зв_{st(i,a),r}} = \sqrt{k_{st(i,a),r} \cdot R_в \cdot T_{st(i,a),r}}$
            $\beta_{st(i,a),r} = \text{triangle}\left(c_{a_{st(i,a),r}}, u_{st(i,a),r} - c_{u_{st(i,a),r}}\right)$
            $w_{st(i,a),r} = \frac{c_{a_{st(i,a),r}}}{\sin\left(\beta_{st(i,a),r}\right)}$
            $w_{u_{st(i,a),r}} = w_{st(i,a),r} \cdot \cos\left(\beta_{st(i,a),r}\right)$
            $\begin{pmatrix} M_{w_{st(i,a),r}} \\ M_{c_{st(i,a),r}} \end{pmatrix} = \frac{1}{a_{зв_{st(i,a),r}}} \cdot \begin{pmatrix} w_{st(i,a),r} \\ c_{st(i,a),r} \end{pmatrix}$
        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  $r \in 1..N_r$
    $\begin{pmatrix} T^*{}_{1CA_r} \\ T^*{}_{3CA_r} \end{pmatrix} = \begin{pmatrix} T^*{}_{st(i,3),r} \\ T^*{}_{3CA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} P^*{}_{1CA_r} \\ P^*{}_{3CA_r} \end{pmatrix} = \begin{pmatrix} P^*{}_{st(i,3),r} \\ P^*{}_{3CA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} \rho^*{}_{1CA_r} \\ \rho^*{}_{3CA_r} \end{pmatrix} = \begin{pmatrix} \rho^*{}_{st(i,3),r} \\ \rho^*{}_{3CA_{av(N_r)}} \end{pmatrix}$
    $\begin{pmatrix} Cp_{1CA_r} \\ Cp_{3CA_r} \end{pmatrix} = \begin{pmatrix} Cp_{воздух}\left(P^*{}_{1CA_r}, T^*{}_{1CA_r}\right) \\ Cp_{воздух}\left(P^*{}_{3CA_r}, T^*{}_{3CA_r}\right) \end{pmatrix}$
    $\begin{pmatrix} k_{1CA_r} \\ k_{3CA_r} \end{pmatrix} = \begin{pmatrix} k_{ад}\left(Cp_{1CA_r}, R_в\right) \\ k_{ад}\left(Cp_{3CA_r}, R_в\right) \end{pmatrix}$
    $\begin{pmatrix} a^*{}_{c1CA_r} \\ a^*{}_{c3CA_r} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2 \cdot k_{1CA_r}}{k_{1CA_r} + 1} \cdot R_в \cdot T^*{}_{1CA_r}} \\ \sqrt{\frac{2 \cdot k_{3CA_r}}{k_{3CA_r} + 1} \cdot R_в \cdot T^*{}_{3CA_r}} \end{pmatrix}$
    $A = \left(1 - R_{L_{i,av(N_r)}}\right) \cdot \omega \cdot \left(R_{st(i,3),av(N_r)}\right)^{m_i+1}$
    $B = \frac{H_{T_{i,av(N_r)}}}{2 \cdot \omega}$
    $\begin{pmatrix} c_{u1CA_r} \\ c_{u3CA} \end{pmatrix} = \begin{pmatrix} c_{u_{st(i,3),r}} \\ c_{u3CA_{av(N_r)}} \ \text{ if } CA = 1 \end{pmatrix}$
```

$$\begin{pmatrix} c_{u3CA_r} \end{pmatrix} \quad \begin{pmatrix} c_{u_{st(i,3),r}} \quad \text{otherwise} \end{pmatrix}$$

$$\begin{pmatrix} c_{a1CA_r} \\ c_{a3CA_r} \end{pmatrix} = \begin{bmatrix} c_{a_{st(i,3),r}} \\ \left| \begin{array}{l} \text{if } CA = 1 \\ \quad \left| \begin{array}{ll} \sqrt{\left(c_{a3CA_{av(N_r)}}\right)^2 - 2\cdot A^2\cdot\left[\left(R_{st(i,3),r}\right)^2 - \left(R_{st(i,3),av(N_r)}\right)^2\right] + 4\cdot A\cdot B\cdot \ln\left(\dfrac{R_{st(i,3),r}}{R_{st(i,3),av(N_r)}}\right)} & \text{if } m_i = -1 \\ \sqrt{\left(c_{a3CA_{av(N_r)}}\right)^2 - 2\cdot A^2\cdot \ln\left(\dfrac{R_{st(i,3),r}}{R_{st(i,3),av(N_r)}}\right) - 2\cdot A\cdot B\cdot\left(\dfrac{1}{R_{st(i,3),r}} - \dfrac{1}{R_{st(i,3),av(N_r)}}\right)} & \text{if } m_i = 0 \\ \sqrt{\left(c_{a3CA_{av(N_r)}}\right)^2 + \dfrac{A\cdot\left(m_i - 1\right)\cdot\left[\begin{array}{l} -A\cdot\left(m_i + 1\right)\cdot\left[\dfrac{1}{\left(R_{st(i,3),r}\right)^{2\cdot m_i}} - \dfrac{1}{\left(R_{st(i,3),av(N_r)}\right)^{2\cdot m_i}}\right] \ldots \\ + 2\cdot B\cdot m_i\cdot\left[\dfrac{1}{\left(R_{st(i,3),r}\right)^{m_i+1}} - \dfrac{1}{\left(R_{st(i,3),av(N_r)}\right)^{m_i+1}}\right] \end{array}\right]}{m_i\cdot\left(m_i + 1\right)}} & \text{otherwise} \end{array} \right. \\ c_{a_{st(i,3),r}} \quad \text{otherwise} \end{array} \right. \end{bmatrix}$$

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

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

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

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

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

▲ Расчет параметров потока по высоте Л

▼ Результаты расчета параметров потока по высоте Л

$T^*_{1ВНА} = \begin{pmatrix} 288.2 \\ 288.2 \\ 288.2 \end{pmatrix}$ $T^*_{3ВНА} = \begin{pmatrix} 288.2 \\ 288.2 \\ 288.2 \end{pmatrix}$ $a^*_{c1ВНА} = \begin{pmatrix} 310.78 \\ 310.78 \\ 310.78 \end{pmatrix}$ $a^*_{c3ВНА} = \begin{pmatrix} 310.78 \\ 310.78 \\ 310.78 \end{pmatrix}$ $\alpha_{1ВНА} = \begin{pmatrix} 90.00 \\ 90.00 \\ 90.00 \end{pmatrix} \cdot °$ $\alpha_{3ВНА} = \begin{pmatrix} 90.00 \\ 90.00 \\ 90.00 \end{pmatrix} \cdot °$

$P^*_{1ВНА} = \begin{pmatrix} 101.3 \\ 101.3 \\ 101.3 \end{pmatrix} \cdot 10^3$ $P^*_{3ВНА} = \begin{pmatrix} 101.3 \\ 101.3 \\ 101.3 \end{pmatrix} \cdot 10^3$ $c_{1ВНА} = \begin{pmatrix} 142.7 \\ 142.7 \\ 142.7 \end{pmatrix}$ $c_{3ВНА} = \begin{pmatrix} 142.7 \\ 142.7 \\ 142.7 \end{pmatrix}$ $\varepsilon_{ВНА} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot °$

$\rho^*_{1ВНА} = \begin{pmatrix} 1.224 \\ 1.224 \\ 1.224 \end{pmatrix}$ $\rho^*_{3ВНА} = \begin{pmatrix} 1.224 \\ 1.224 \\ 1.224 \end{pmatrix}$ $c_{u1ВНА} = \begin{pmatrix} 0.0 \\ 0.0 \\ 0.0 \end{pmatrix}$ $c_{u3ВНА} = \begin{pmatrix} 0.0 \\ 0.0 \\ 0.0 \end{pmatrix}$

$Cp_{1ВНА} = \begin{pmatrix} 1002.6 \\ 1002.6 \\ 1002.6 \end{pmatrix}$ $Cp_{3ВНА} = \begin{pmatrix} 1002.6 \\ 1002.6 \\ 1002.6 \end{pmatrix}$ $c_{a1ВНА} = \begin{pmatrix} 142.7 \\ 142.7 \\ 142.7 \end{pmatrix}$ $c_{a3ВНА} = \begin{pmatrix} 142.7 \\ 142.7 \\ 142.7 \end{pmatrix}$ $\lambda_{c1ВНА} = \begin{pmatrix} 0.459 \\ 0.459 \\ 0.459 \end{pmatrix}$ $\lambda_{c3ВНА} = \begin{pmatrix} 0.459 \\ 0.459 \\ 0.459 \end{pmatrix}$

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

$T^{*T} =$

	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	337.1	337.1																						
2	288.2	337.1	337.1																						
3	288.2	337.1	337.1																						

$T^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	274.5	281.8	321.8																						
2	278.0	316.8	326.7																						
3	278.9	324.0	328.5																						

$P^{*T} =$

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

$\cdot 10^3$

$P^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	85.5	87.0	138.5																		
2	89.4	131.1	146.1																		
3	90.3	141.9	148.9																		

$\cdot 10^3$

$\rho^{*T} =$

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

$\rho^{T} =$

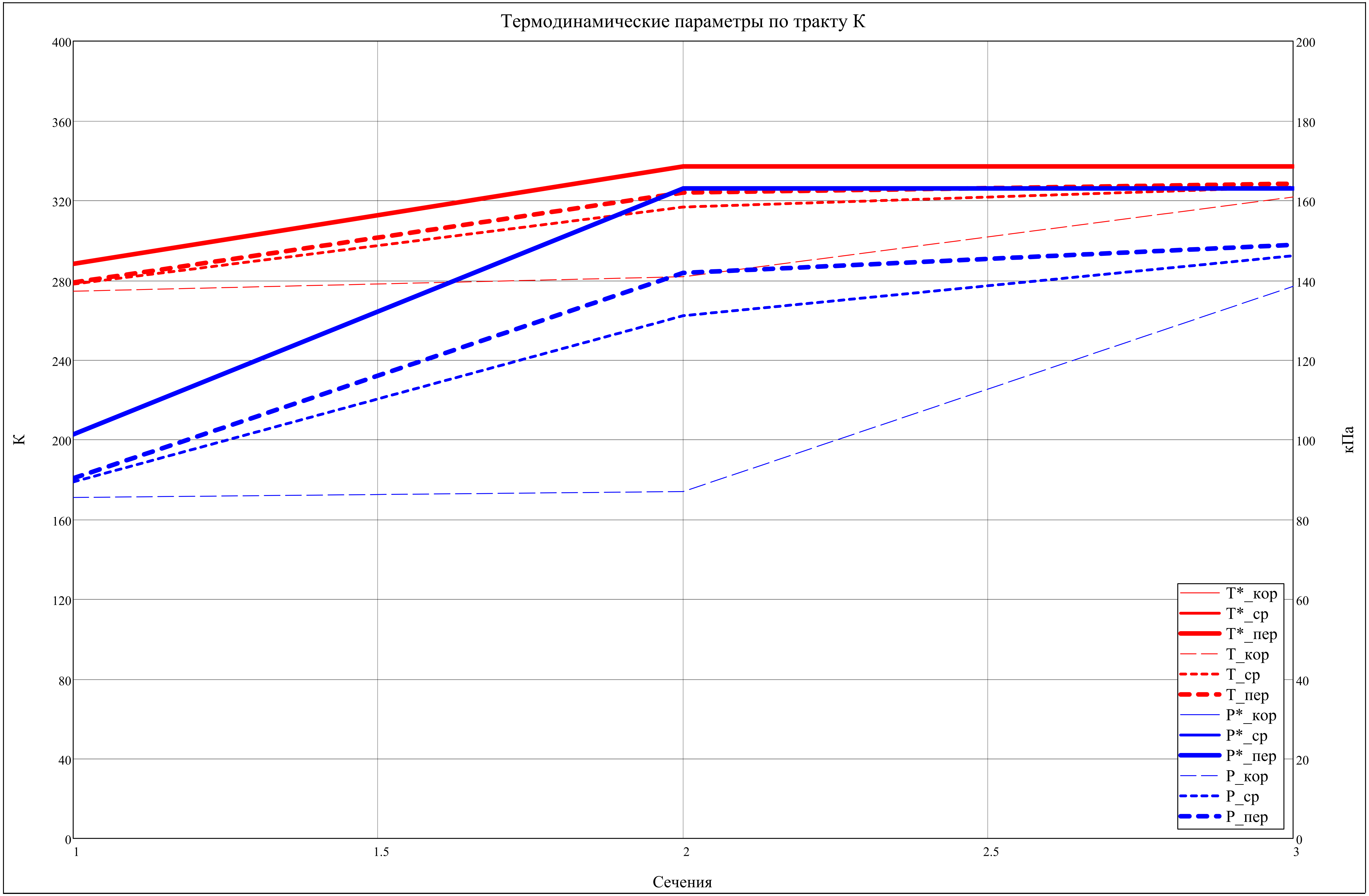
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.085	1.075	1.499																		
2	1.120	1.441	1.558																		
3	1.128	1.525	1.578																		

$Cp^{T} =$

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

$k^{T} =$

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


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

$a^*{}_c{}^T =$

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

$a_{зв}{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	332.4	336.5	359.6																						
2	334.5	356.8	362.4																						
3	335.0	360.8	363.3																						

$c^T =$

	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	165.6	333.7	175.8																						
2	142.7	202.3	144.4																						
3	136.7	162.5	131.8																						

$w^T =$

	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	236.0	208.2	163.4																						
2	353.8	214.5	269.2																						
3	447.3	323.4	362.0																						

$u^T =$

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

$c_a{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	165.6	188.9	134.6																						
2	142.7	127.8	112.9																						
3	136.7	108.3	105.1																						

$c_u{}^T =$

	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	0.0	275.1	113.0																						
2	0.0	156.8	90.0																						
3	0.0	121.2	79.6																						

$w_u{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	168.1	-87.4	92.6																					
2	323.8	172.3	244.4																					
3	425.9	304.8	346.4																					

```
$\Delta c_a =$ | 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	23.31	-54.27																		
2	0.00	-14.91	-14.91																		
3	0.00	-28.35	-3.26																		

[16, c. 81]

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

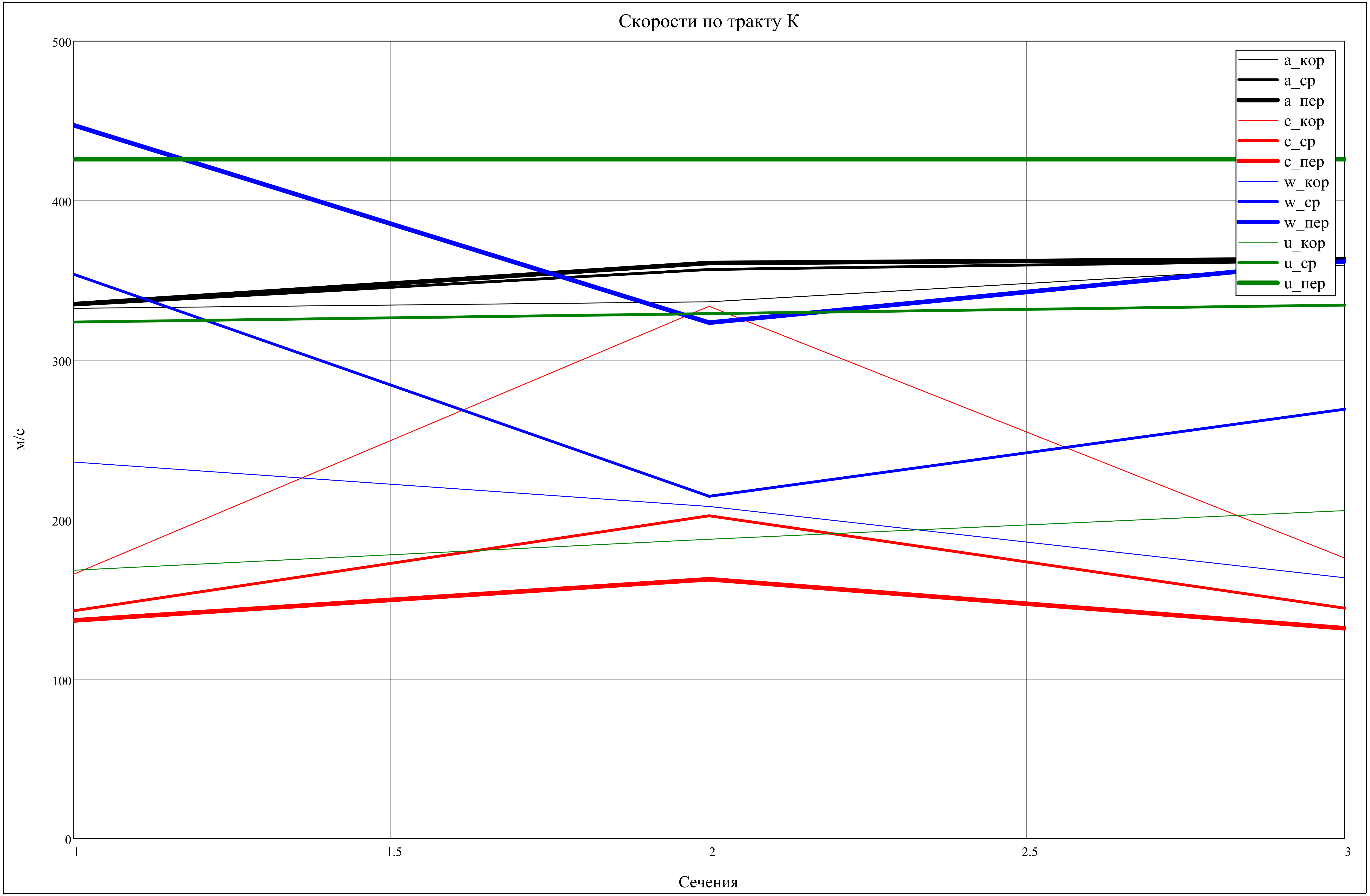
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	1	0																						
2	1	1	1																						
3	1	0	1																						

$R_L^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.2268											
2	0.7598											
3	0.8578											

$R_L^{T} \geq 0 =$

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


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

$\alpha^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	90.00	34.48	49.99																						
2	90.00	39.17	51.42																						
3	90.00	41.80	52.87																						

$\cdot°$

$\beta^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	44.56	114.84	55.48																		
2	23.78	36.56	24.79																		
3	17.79	19.57	16.88																		

$\cdot°$

$\beta^{T} \le 91\cdot° =$

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

$\beta.2 > 91 \Rightarrow$ поменять з-н профилирования

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

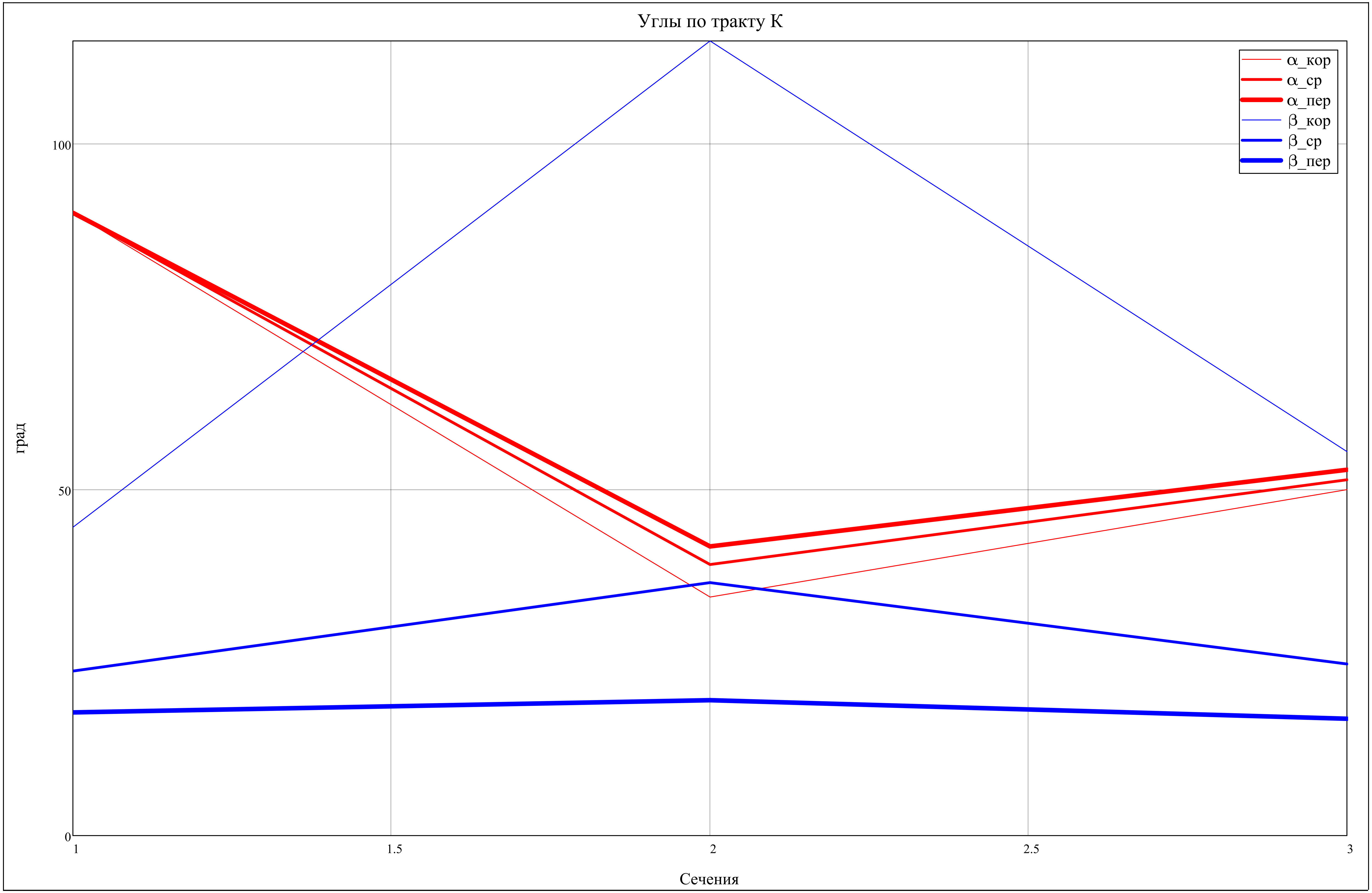
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	70.28														
2	12.78														
3	1.78														

$\cdot°$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	15.52														
2	12.25														
3	11.07														

$\cdot°$


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

$\lambda_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.5328	0.9931	0.5231																				
2	0.4591	0.6020	0.4297																				
3	0.4398	0.4837	0.3922																				

[16, c. 87]

$\lambda_c^T \le 0.85 =$

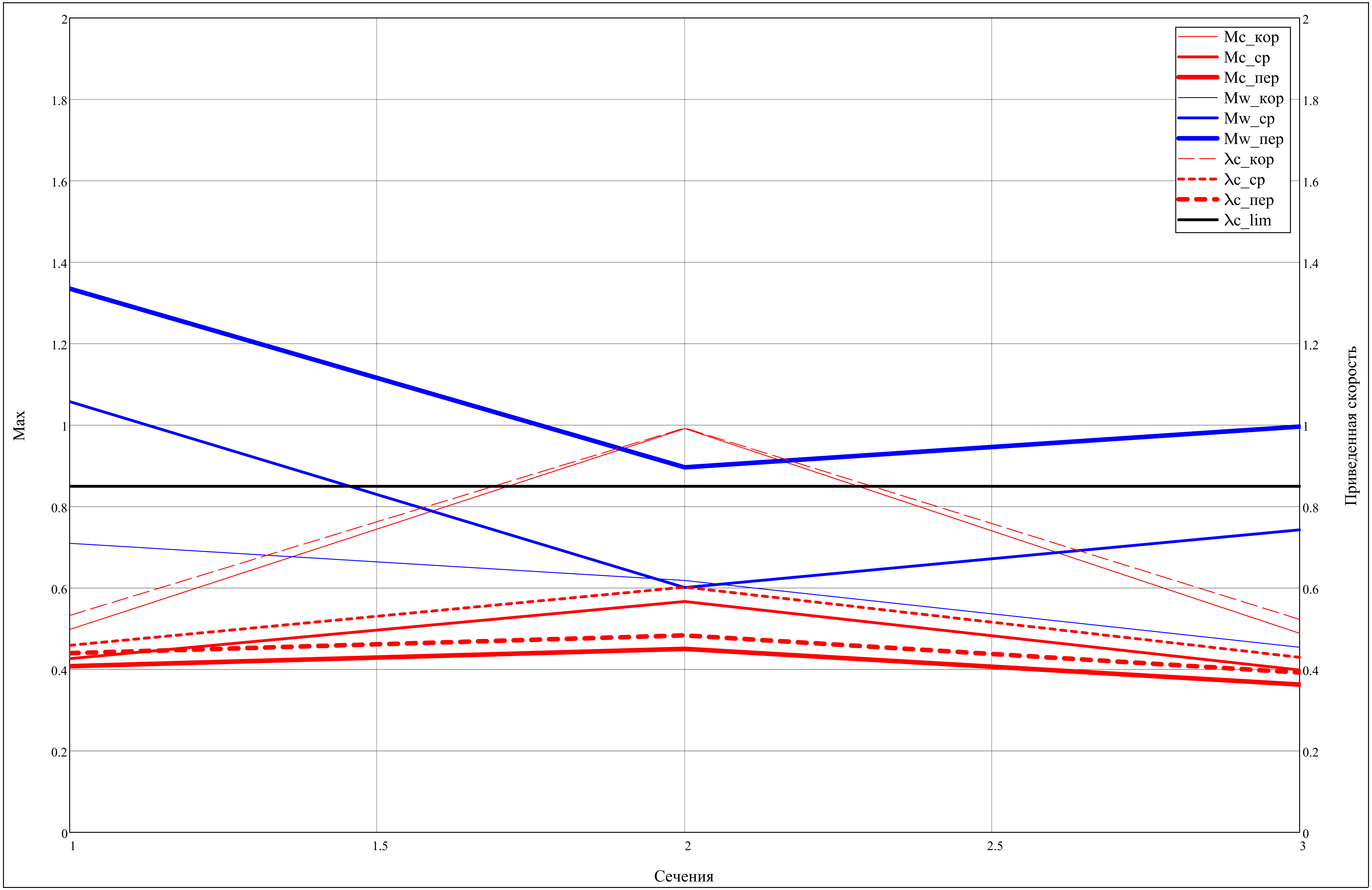
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1	0	1																
2	1	1	1																
3	1	1	1																

$M_c^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.4982	0.9917	0.4888																				
2	0.4266	0.5670	0.3985																				
3	0.4080	0.4505	0.3628																				

$M_w^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.7100	0.6186	0.4544																				
2	1.0579	0.6012	0.7429																				
3	1.3354	0.8964	0.9963																				


Mc_кор
Mc_ср
Mc_пер
Mw_кор
Mw_ср
Mw_пер
λc_кор
λc_ср
λc_пер
λc_lim
Мах
Приведенная скорость
Сечения
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1
1.5
2
2.5
3

$$T^*_{1CA} = \begin{pmatrix} 337.1 \\ 337.1 \\ 337.1 \end{pmatrix} \qquad T^*_{3CA} = \begin{pmatrix} 337.1 \\ 337.1 \\ 337.1 \end{pmatrix} \qquad a^*_{c1CA} = \begin{pmatrix} 336.0 \\ 336.0 \\ 336.0 \end{pmatrix} \qquad a^*_{c3CA} = \begin{pmatrix} 336.0 \\ 336.0 \\ 336.0 \end{pmatrix} \qquad \alpha_{1CA} = \begin{pmatrix} 49.99 \\ 51.42 \\ 52.87 \end{pmatrix} \cdot ° \qquad \alpha_{3CA} = \begin{pmatrix} 49.99 \\ 51.42 \\ 52.87 \end{pmatrix} \cdot °$$

$$P^*_{1CA} = \begin{pmatrix} 163.0 \\ 163.0 \\ 163.0 \end{pmatrix} \cdot 10^3 \qquad P^*_{3CA} = \begin{pmatrix} 163.0 \\ 163.0 \\ 163.0 \end{pmatrix} \cdot 10^3 \qquad c_{1CA} = \begin{pmatrix} 175.8 \\ 144.4 \\ 131.8 \end{pmatrix} \qquad c_{3CA} = \begin{pmatrix} 175.8 \\ 144.4 \\ 131.8 \end{pmatrix} \qquad \varepsilon_{CA} = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot °$$

$$\rho^*_{1CA} = \begin{pmatrix} 1.684 \\ 1.684 \\ 1.684 \end{pmatrix} \qquad \rho^*_{3CA} = \begin{pmatrix} 1.684 \\ 1.684 \\ 1.684 \end{pmatrix} \qquad c_{u1CA} = \begin{pmatrix} 113.0 \\ 90.0 \\ 79.6 \end{pmatrix} \qquad c_{u3CA} = \begin{pmatrix} 113.0 \\ 90.0 \\ 79.6 \end{pmatrix}$$

$$Cp_{1CA} = \begin{pmatrix} 1006.0 \\ 1006.0 \\ 1006.0 \end{pmatrix} \qquad Cp_{3CA} = \begin{pmatrix} 1006.0 \\ 1006.0 \\ 1006.0 \end{pmatrix} \qquad c_{a1CA} = \begin{pmatrix} 134.6 \\ 112.9 \\ 105.1 \end{pmatrix} \qquad c_{a3CA} = \begin{pmatrix} 134.6 \\ 112.9 \\ 105.1 \end{pmatrix} \qquad \lambda_{c1CA} = \begin{pmatrix} 0.523 \\ 0.430 \\ 0.392 \end{pmatrix} \qquad \lambda_{c3CA} = \begin{pmatrix} 0.523 \\ 0.430 \\ 0.392 \end{pmatrix}$$

$$k_{1CA} = \begin{pmatrix} 1.399 \\ 1.399 \\ 1.399 \end{pmatrix} \qquad k_{3CA} = \begin{pmatrix} 1.399 \\ 1.399 \\ 1.399 \end{pmatrix}$$

▲ Результаты расчета параметров потока по высоте Л

Вывод результатов расчета параметров потока по высоте Л

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

Построение треугольников скоростей в 3х сечениях

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

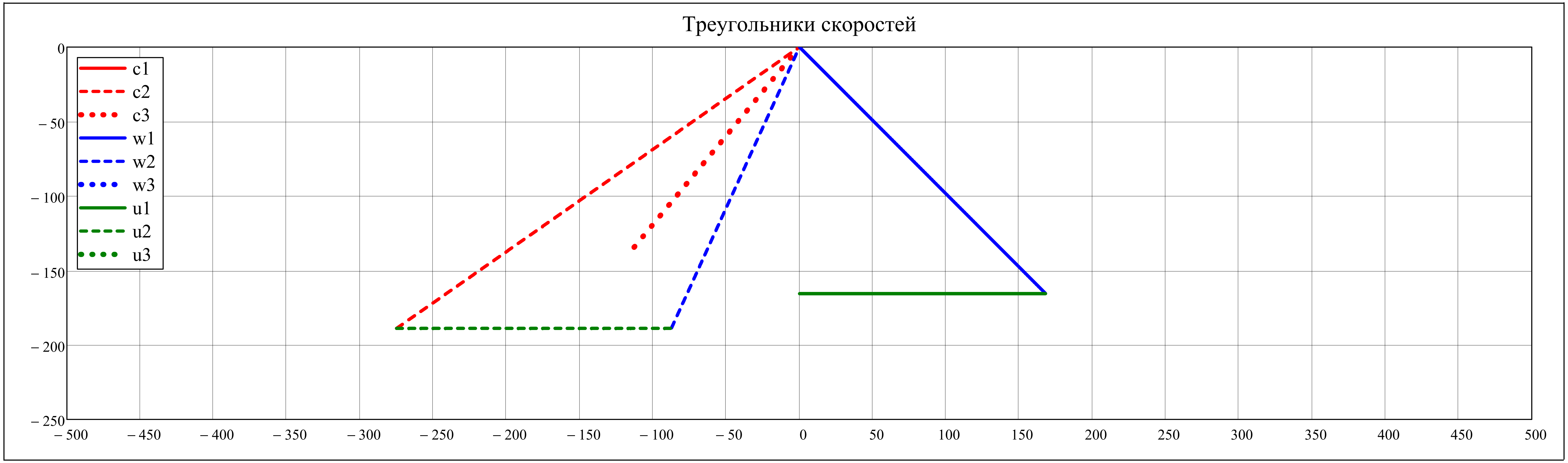
$$\Delta_w(v,i,j,r) = \left| \begin{array}{l} -\tan\left(\beta_{st(i,j),r}\right)\cdot v \;\; \text{if } \left(-\tan\left(\beta_{st(i,j),r}\right) \ge 0\right) \wedge \left(-\left|w_{st(i,j),r}\cdot\cos\left(\beta_{st(i,j),r}\right)\right| \le v \le 0\right) \wedge (j \ne 3) \\ -\tan\left(\beta_{st(i,j),r}\right)\cdot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

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

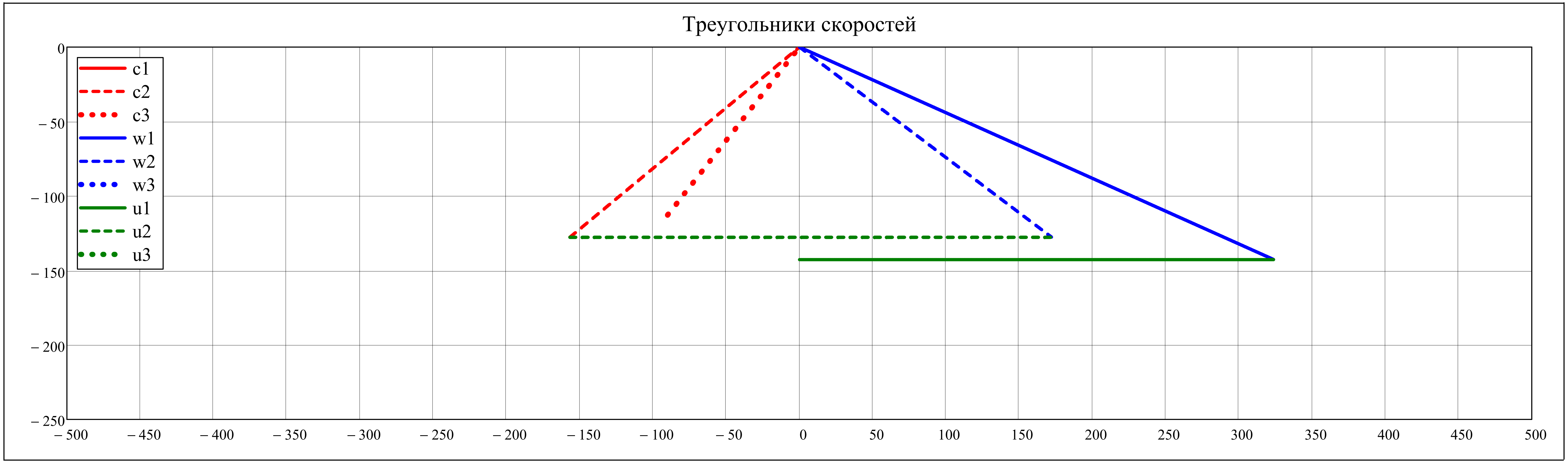
$$v_{lim} = \text{ceil}\left(\frac{\max(c,w,u)}{10^2}\right)\cdot 10^2 = 500$$

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

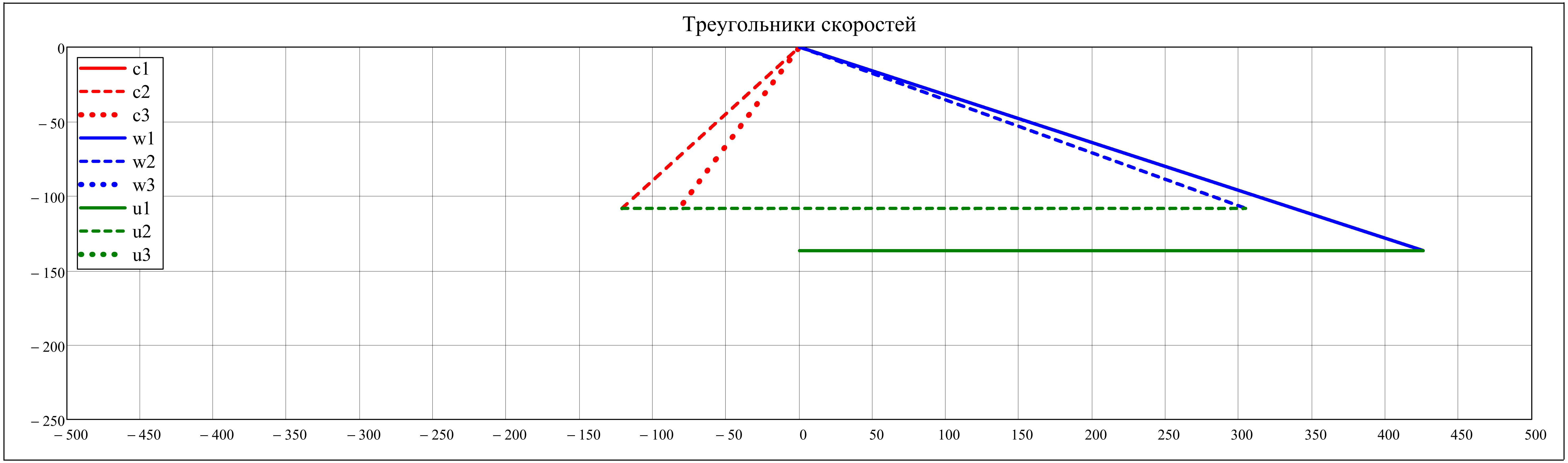
r = 1


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

$r = av(N_r)$


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

$r = N_r$



▲ Построение треугольников скоростей в 3х сечениях

Определение степени повышения полного давлеия по 2ум контурам

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

Кольцевые площади (м^2):

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.2232	0.2130	0.2028																
2	1.3389	1.2783	1.2166																
3	1.5621	1.3551	1.4194																

Радиус и диаметр двухконтурности (м):

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	403.5	426.7	449.2																
2	807.0	853.5	898.3																

$\cdot 10^{-3}$

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

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

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

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

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

▲ Определение степени повышения полного давлеия по 2ум контурам

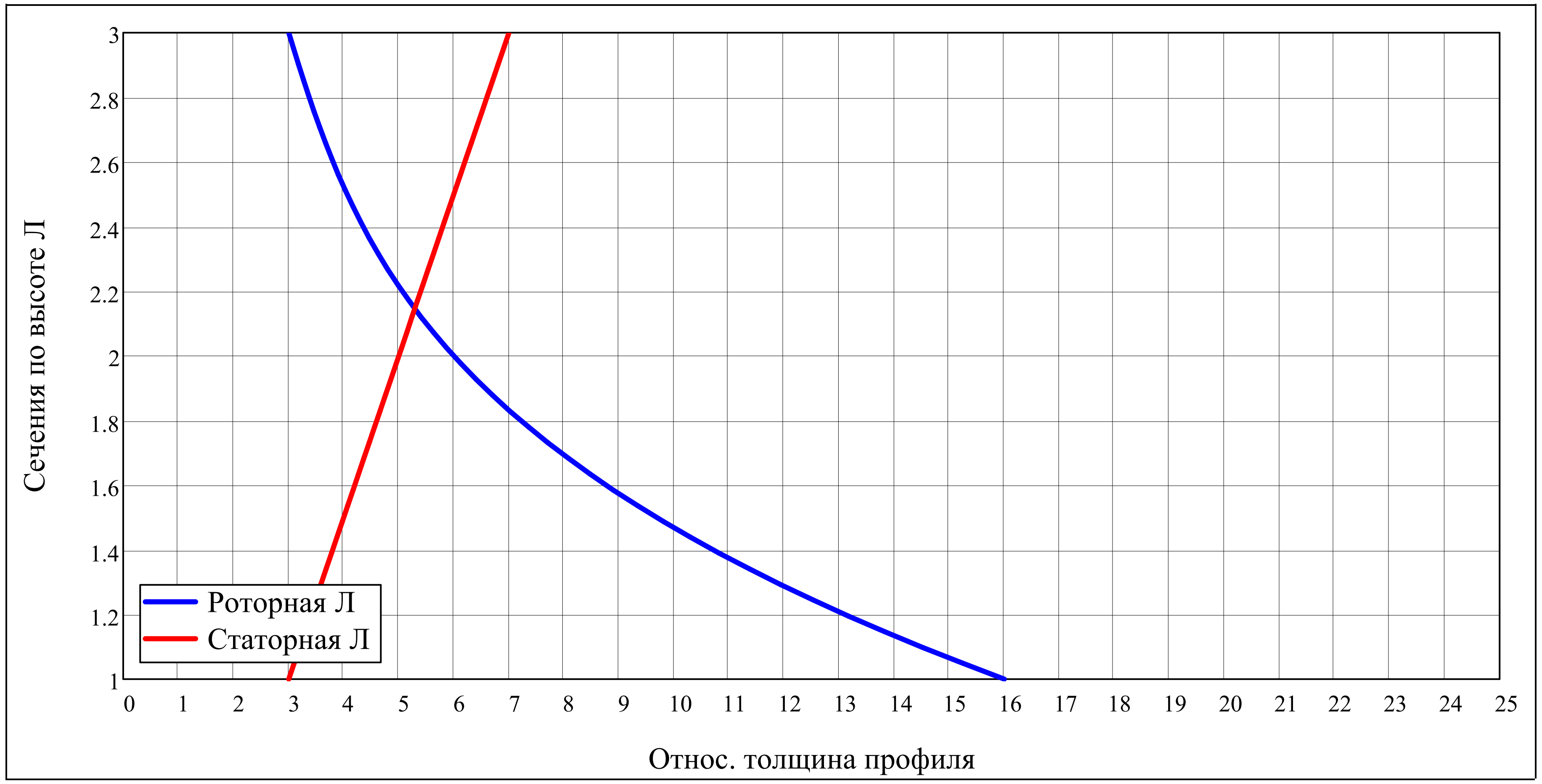
Относ. толщины и радиусы профилей

Относ. толщины Л РК и СА:

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

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

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



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

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

	1
1	3.00
2	5.00
3	7.00

$\cdot\%$

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

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

	1
1	3.00
2	5.00
3	7.00

$\cdot\%$

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

	1
1	16.00
2	6.00
3	3.00

$\cdot\%$

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

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

	1
1	3.00
2	5.00
3	7.00

$\cdot\%$

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

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

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

$$\overline{r\_inlet}_{stator}^{\,T} = \begin{array}{c|c} & 1 \\ \hline 1 & 0.600 \\ 2 & 1.000 \\ 3 & 1.400 \end{array}\cdot\%$$

$$\overline{r\_outlet}_{stator}^{\,T} = \begin{array}{c|c} & 1 \\ \hline 1 & 0.300 \\ 2 & 0.500 \\ 3 & 0.700 \end{array}\cdot\%$$

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

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

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

$$\overline{r\_inlet}_{rotor}^{\,T} = \begin{array}{c|c} & 1 \\ \hline 1 & 3.200 \\ 2 & 1.200 \\ 3 & 0.600 \end{array}\cdot\%$$

$$\overline{r\_outlet}_{rotor}^{\,T} = \begin{array}{c|c} & 1 \\ \hline 1 & 1.600 \\ 2 & 0.600 \\ 3 & 0.300 \end{array}\cdot\%$$

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

▲ Относ. толщины и радиусы профилей

▼ Распределение параметров по высоте Л

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

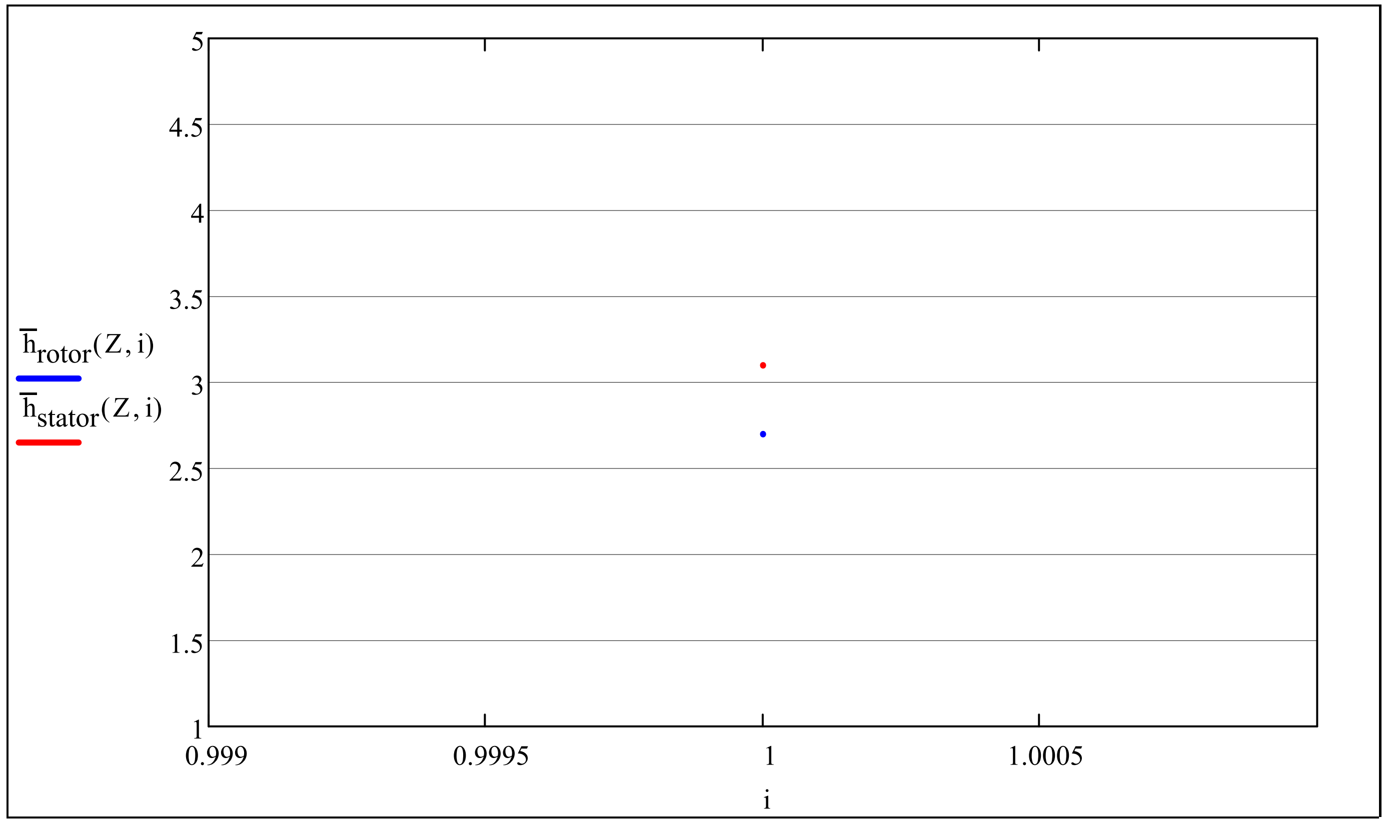
$$\overline{h}_{\sim rotor} = (2\ \ 1.9\ \ 1.85\ \ 1.8\ \ 1.75\ \ 1.7\ \ 1.65\ \ 1.6)^{T} + \left| \begin{array}{l} 1.1\ \ \text{if compressor = "Вл"} \\ -0.1\ \ \text{if compressor = "КНД"} \\ -0.55\ \ \text{if compressor = "КВД"} \end{array} \right.$$

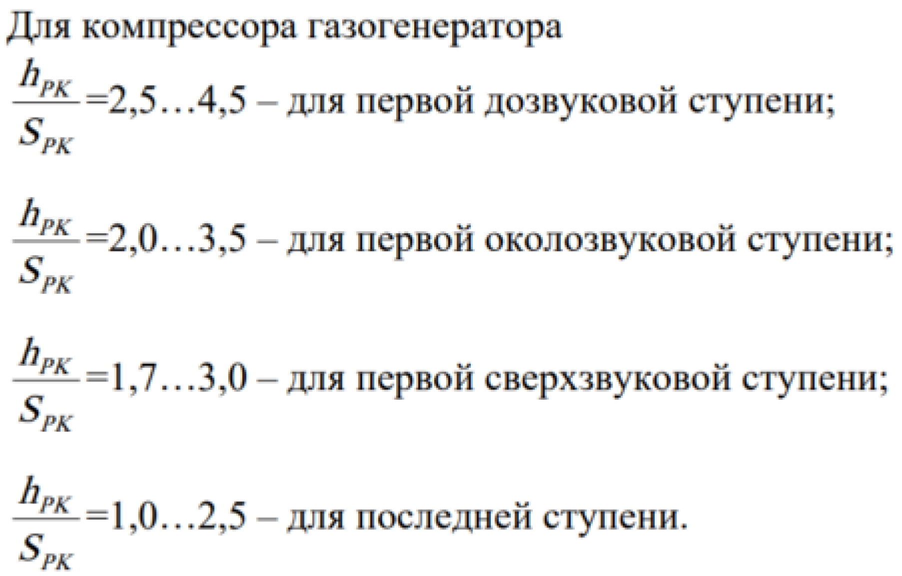
$$\overline{h}_{\sim stator} = (4\ \ 3.5\ \ 3.25\ \ 3\ \ 2.75\ \ 2.5\ \ 2.25\ \ 2)^{T} + \left| \begin{array}{l} 1.1\ \ \text{if compressor = "Вл"} \\ -0.1\ \ \text{if compressor = "КНД"} \\ -0.7\ \ \text{if compressor = "КВД"} \end{array} \right.$$

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

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

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





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

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

Расчет длин хорд по высоте Л

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

$\overline{x}_f = 0.5$

Определение количества Л РК и НА

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

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

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

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

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

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

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

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

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

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

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

```
for  $i \in 1..Z$
    for  $r \in av(N_r)$
        $\begin{pmatrix} \varepsilon_{РК(b/t)=1_{i,r}} \\ \varepsilon_{НА(b/t)=1_{i,r}} \end{pmatrix} = \begin{pmatrix} \varepsilon_{(b/t)=1}(\beta_{st(i,2),r}) \\ \varepsilon_{(b/t)=1}(\alpha_{st(i,3),r}) \end{pmatrix}$
        $\begin{pmatrix} b/t_{РК_{i,r}} \\ b/t_{НА_{i,r}} \end{pmatrix} = \begin{pmatrix} b/t{=}1\left(\dfrac{\varepsilon_{rotor_{i,r}}}{\varepsilon_{РК(b/t)=1_{i,r}}}\right) \\ b/t{=}1\left(\dfrac{\varepsilon_{stator_{i,r}}}{\varepsilon_{НА(b/t)=1_{i,r}}}\right) \end{pmatrix}$
        $\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{b/t_{РК_{i,r}}} \\ \dfrac{chord_{stator_{i,r}}}{b/t_{НА_{i,r}}} \end{pmatrix}$
        $\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \dfrac{2}{3}\begin{pmatrix} chord_{rotor_{i,r}} \cdot \cos(\beta_{st(i,1),r}) \\ chord_{stator_{i,r}} \cdot \cos(\alpha_{st(i,2),r}) \end{pmatrix}$
        $Z_{stator_i} =$
            $round\left(\dfrac{\pi \cdot mean(D_{st(i,2),r}, D_{st(i,3),r})}{t_{stator_{i,r}}}\right)$  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 $r \in 1..N_r$
    $\begin{pmatrix} r\_inlet_{stator_{i,r}} & r\_outlet_{stator_{i,r}} \\ r\_inlet_{rotor_{i,r}} & r\_outlet_{rotor_{i,r}} \end{pmatrix} = \begin{pmatrix} \overline{r}\_inlet_{stator_{i,r}} \cdot chord_{stator_{i,r}} & \overline{r}\_outlet_{stator_{i,r}} \cdot chord_{stator_{i,r}} \\ \overline{r}\_inlet_{rotor_{i,r}} \cdot chord_{rotor_{i,r}} & \overline{r}\_outlet_{rotor_{i,r}} \cdot chord_{rotor_{i,r}} \end{pmatrix}$
    $\begin{pmatrix} t_{rotor_{i,r}} \\ t_{stator_{i,r}} \end{pmatrix} = \pi \cdot \begin{pmatrix} \dfrac{\text{mean}\left(D_{st(i,1),r}, D_{st(i,2),r}\right)}{Z_{rotor_i}} \\ \dfrac{\text{mean}\left(D_{st(i,2),r}, D_{st(i,3),r}\right)}{Z_{stator_i}} \end{pmatrix}$
    $\begin{pmatrix} i_{rotor_{i,r}} \\ i_{stator_{i,r}} \end{pmatrix} = 2.5 \cdot \begin{pmatrix} \dfrac{chord_{rotor_{i,r}}}{t_{rotor_{i,r}}} - 1 \\ \dfrac{chord_{stator_{i,r}}}{t_{stator_{i,r}}} - 2 \end{pmatrix} \cdot {}^{\circ}$
    $\begin{pmatrix} m_{rotor_{i,r}} \\ m_{stator_{i,r}} \end{pmatrix} = 0.23 \cdot \left(2 \cdot \overline{x}_f\right)^2 + 0.18 - \dfrac{0.002}{deg} \cdot \begin{pmatrix} \beta_{st(i,2),r} \\ \alpha_{st(i,3),r} \end{pmatrix}$
    $\begin{pmatrix} \theta_{rotor_{i,r}} \\ \theta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{\varepsilon_{rotor_{i,r}} - i_{rotor_{i,r}}}{1 - m_{rotor_{i,r}} \cdot \sqrt{\dfrac{t_{rotor_{i,r}}}{chord_{rotor_{i,r}}}}} \\ \dfrac{\varepsilon_{stator_{i,r}} - i_{stator_{i,r}}}{1 - m_{stator_{i,r}} \cdot \sqrt{\dfrac{t_{stator_{i,r}}}{chord_{stator_{i,r}}}}} \end{pmatrix}$
    $\begin{pmatrix} \delta_{rotor_{i,r}} \\ \delta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} m_{rotor_{i,r}} \cdot \theta_{rotor_{i,r}} \cdot \sqrt{\dfrac{t_{rotor_{i,r}}}{chord_{rotor_{i,r}}}} \\ m_{stator_{i,r}} \cdot \theta_{stator_{i,r}} \cdot \sqrt{\dfrac{t_{stator_{i,r}}}{chord_{stator_{i,r}}}} \end{pmatrix}$
    $\begin{pmatrix} \chi_{rotor_{i,r}} \\ \chi_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \theta_{rotor_{i,r}} \\ \theta_{stator_{i,r}} \end{pmatrix} \cdot \dfrac{1 + 2 \cdot \left(1 - 2 \cdot \overline{x}_f\right)}{2}$
    $\begin{pmatrix} \upsilon_{rotor_{i,r}} \end{pmatrix} = \begin{pmatrix} \chi_{rotor_{i,r}} + \beta_{st(i,1),r} + i_{rotor_{i,r}} \end{pmatrix}$
```

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

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

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

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

$$\begin{pmatrix} \zeta_{rotor_{i,r}} \\ \zeta_{stator_{i,r}} \end{pmatrix} = \begin{pmatrix} \dfrac{\text{ζ•sin(β3)/(2b/t)}\ \left(D_{rotor_{i,r}}\right)\cdot 2\cdot\dfrac{chord_{rotor_{i,r}}}{t_{rotor_{i,r}}}}{\sin\left(\beta_{st(i,2),r}\right)} \\ \dfrac{\text{ζ•sin(β3)/(2b/t)}\ \left(D_{stator_{i,r}}\right)\cdot 2\cdot\dfrac{chord_{stator_{i,r}}}{t_{stator_{i,r}}}}{\sin\left(\alpha_{st(i,3),r}\right)} \end{pmatrix}$$

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

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

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

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

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

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

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

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

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

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

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

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

▲ Определение количества Л РК и НА

▾ Результаты расчета количества Л и параметров решеток РК и НА

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

Длина хорды Л (м):

$chord_{rotor}^{T} =$

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

$\cdot 10^{-3}$

$chord_{stator}^{T} =$

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

$\cdot 10^{-3}$

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

Радисы входных и выходных кромок профилей Л (мм):

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

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

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

	1
1	4.50
2	1.99
3	1.10

$\cdot 10^{-3}$

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

	1
1	2.25
2	0.99
3	0.55

$\cdot 10^{-3}$

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

	1
1	0.71
2	1.33
3	2.00

$\cdot 10^{-3}$

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

	1
1	0.36
2	0.67
3	1.00

$\cdot 10^{-3}$

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

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

Угол поворота потока:

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

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	9.86														

·°

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	15.65														

·°

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

Густота решетки:

$\dfrac{chord_{BHA}}{t_{BHA}}$ = ▮

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

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

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

	1
1	2.998
2	1.987
3	1.660

$\dfrac{chord_{CA}}{t_{CA}}$ = ▮

Количество Л:

$Z_{BHA} = 0$

$Z_{rotor}{}^T =$

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

$Z_{stator}{}^T =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	56														

$Z_{CA} = 0$

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	54.43														
2	99.89														
3	130.33														

$\cdot 10^{-3}$

Шаг решетки (м):

$t_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	39.75														
2	67.07														
3	86.11														

$\cdot 10^{-3}$

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

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

$i_{rotor}{}^{T} =$

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

$\cdot {}^{\circ}$

Угол атаки:

$i_{stator}{}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.494														
2	-0.032														
3	-0.849														

$\cdot {}^{\circ}$

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

$m_{\text{ВНА}} = 0.0000$

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	0.1803														
2	0.3369														
3	0.3709														

$m_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.3100														
2	0.3072														
3	0.3043														

$m_{\text{СА}} = 0.0000$

$\theta_{\text{ВНА}} = 0.00 \cdot {}^\circ$

Угол изгиба ср. линии профиля:

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	74.71														
2	15.09														
3	1.13														

$\cdot {}^\circ$

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	15.86														
2	15.70														
3	15.61														

$\cdot {}^\circ$

$\theta_{\text{СА}} = 0.00 \cdot {}^\circ$

Угол отставания:

$\delta_{BHA} = 0.000\cdot°$

$\delta_{rotor}{}^{T} =$ $\cdot°$

	1
1	8.384
2	3.948
3	0.353

$\delta_{stator}{}^{T} =$ $\cdot°$

	1
1	2.840
2	3.421
3	3.685

$\delta_{CA} = 0.000\cdot°$

Угол установки Л:

$\upsilon_{BHA} = 0.00\cdot°$

$\upsilon_{rotor}{}^{T} =$ $\cdot°$

	1
1	85.87
2	32.97
3	19.36

$\upsilon_{stator}{}^{T} =$ $\cdot°$

	1
1	44.90
2	46.99
3	48.75

$\upsilon_{CA} = 0.00\cdot°$

$R_{СЛ.ВНА} = 0.00 \cdot 10^{-3}$

Радиус дуги ср. линии (м):

$R_{СЛ.rotor}^{T} =$ … $\cdot 10^{-3}$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	115.79														
2	630.45														
3	9298.59														

$R_{СЛ.stator}^{T} =$ … $\cdot 10^{-3}$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	431.76														
2	488.01														
3	526.55														

$R_{СЛ.СА} = 0.00 \cdot 10^{-3}$

$K_{ВНА} = 0.0000$

Фактор диффузорности решетки:

$K_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.1408														
2	0.8955														
3	0.7926														

$K_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.7127														
2	0.8833														
3	0.9699														

$K_{СА} = 0.0000$

$D_{BHA} = 0.0000$

Диффузорность решетки:

$D_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.3277														
2	0.5230														
3	0.3736														

$D_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.5543														
2	0.3693														
3	0.2663														

$D_{CA} = 0.0000$

$D_{BHA} \le 0.6 = 1$

[18, с. 71]

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

	1
1	1
2	1
3	1

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

	1
1	1
2	1
3	1

$D_{CA} \le 0.6 = 1$

Коэф. потерь полного давления:

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0604														
2	0.1180														
3	0.1038														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.1858														
2	0.0622														
3	0.0365														

Качество профилей решеток РК и НА:

$quality_{rotor}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	25.284														
2	8.472														
3	1.765														

$quality_{stator}^{T} =$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3.347														
2	9.696														
3	15.434														

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	57.04														
2	77.63														
3	39.01														

$\cdot\%$

▲ 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

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

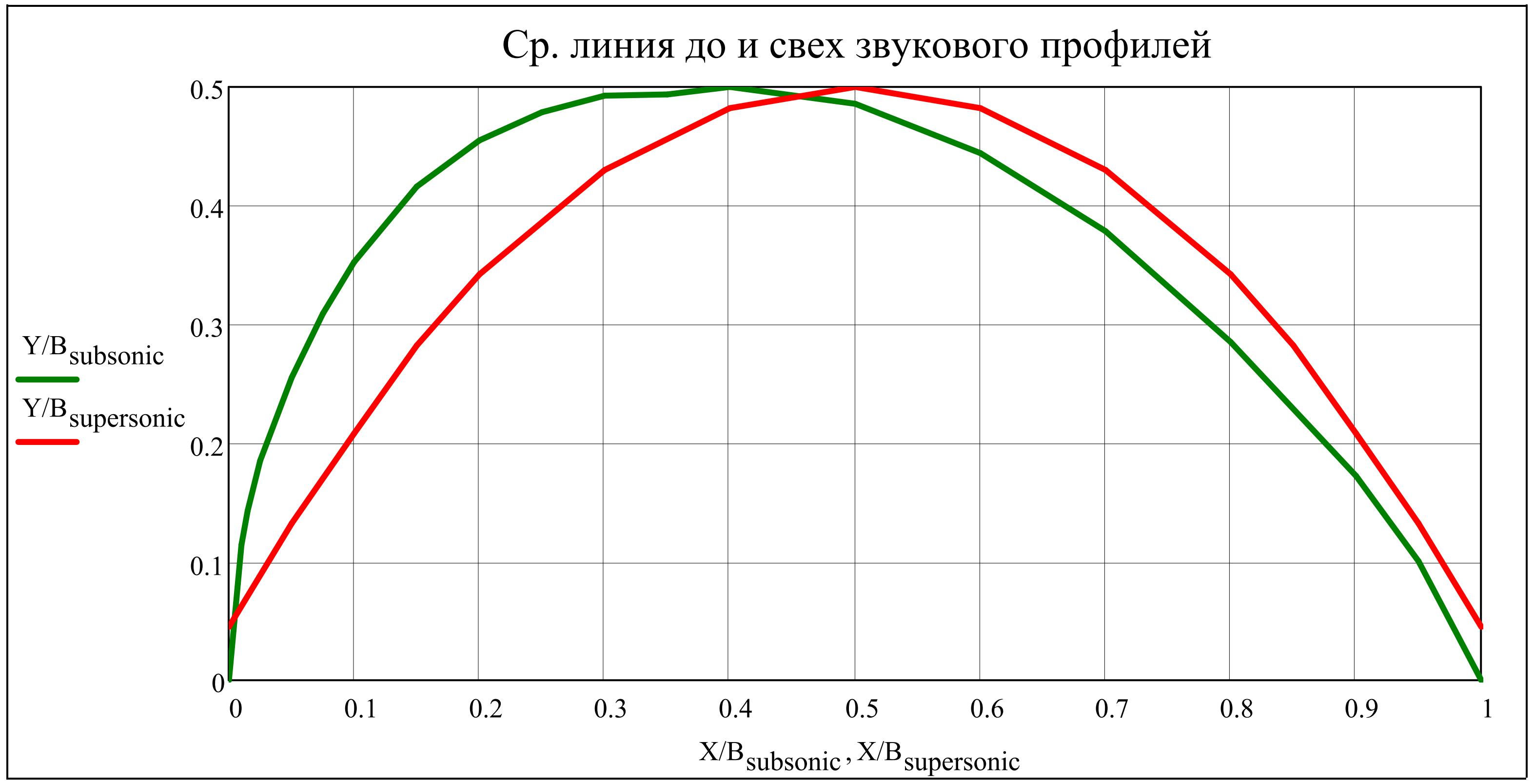
$$Y/B_{supersonic} := \mathrm{submatrix}\left(EXCEL_{AIRFOIL.supersonic}, 2, \mathrm{rows}\left(EXCEL_{AIRFOIL.supersonic}\right), ORIGIN + 1, ORIGIN + 1\right)$$

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

	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

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

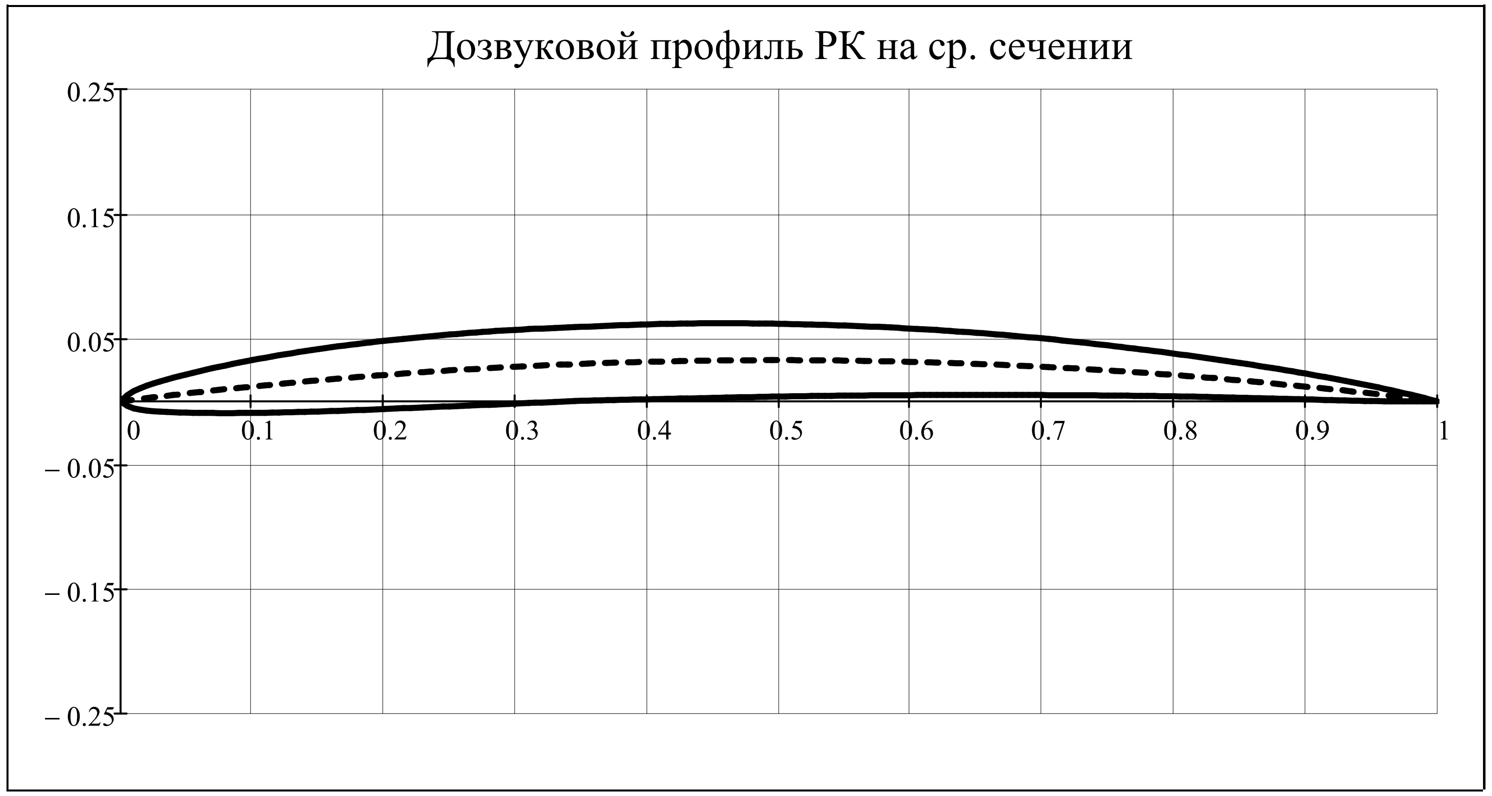
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.000	0.050	0.100	0.150	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.850	0.900	0.950	1.000
2	0.045	0.132	0.208	0.282	0.342	0.430	0.482	0.500	0.482	0.430	0.342	0.282	0.208	0.132	0.045

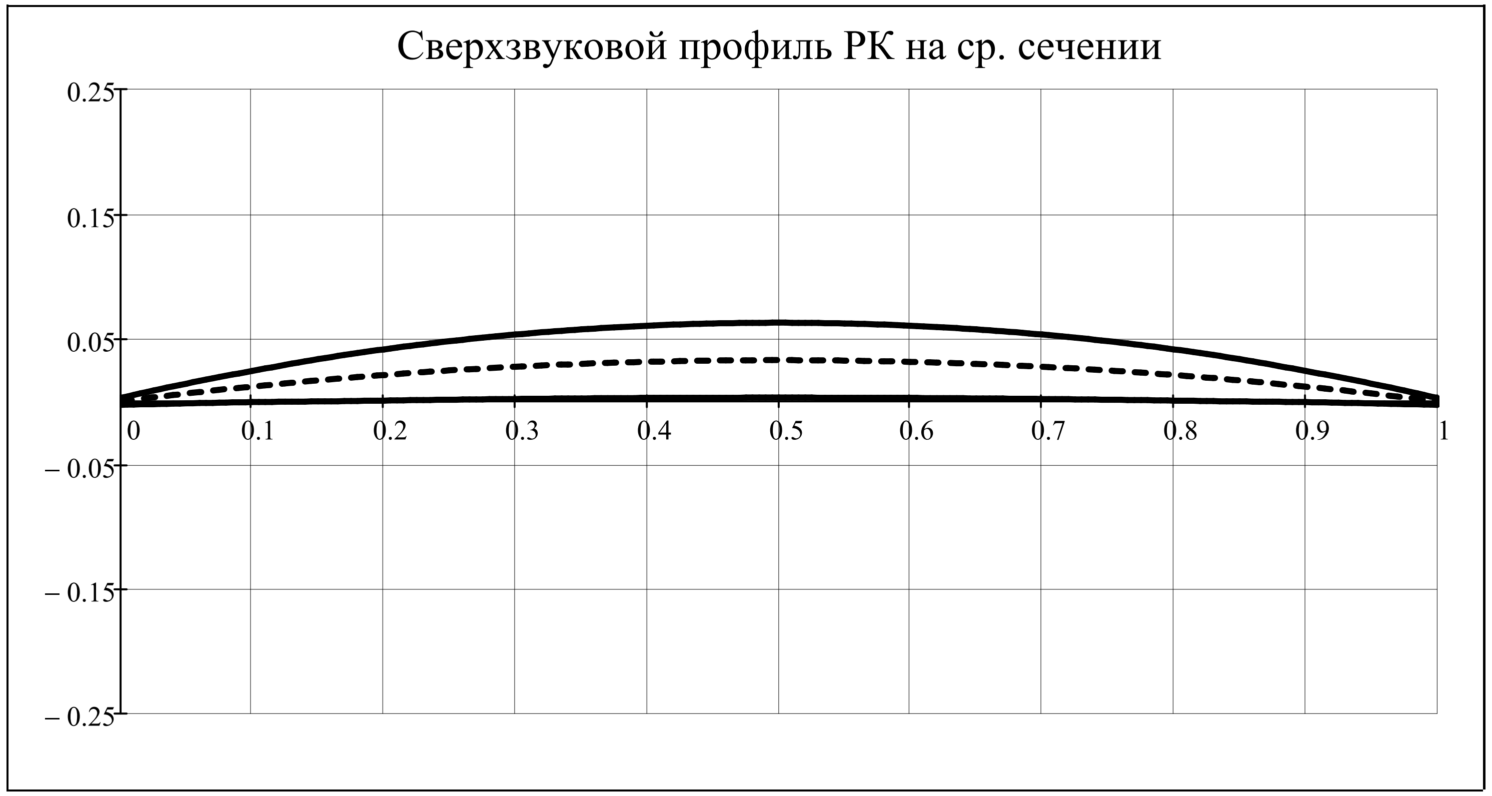

Ср. линия до и свех звукового профилей

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

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

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


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

$$l\_upper_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 120.00 \\ \hline 2 & 134.48 \\ \hline 3 & 144.74 \\ \hline \end{array} \cdot 10^{-3}$$

$$l\_lower_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 119.30 \\ \hline 2 & 133.46 \\ \hline 3 & 143.38 \\ \hline \end{array} \cdot 10^{-3}$$

$$area_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 311.49 \\ \hline 2 & 649.75 \\ \hline 3 & 1046.61 \\ \hline \end{array} \cdot 10^{-6}$$

$$Sx_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 960.3 \\ \hline 2 & 1767.3 \\ \hline 3 & 2759.9 \\ \hline \end{array} \cdot 10^{-9}$$

$$Sy_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 16761.6 \\ \hline 2 & 39115.4 \\ \hline 3 & 67582.7 \\ \hline \end{array} \cdot 10^{-9}$$

$$x0_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 53.81 \\ \hline 2 & 60.20 \\ \hline 3 & 64.57 \\ \hline \end{array} \cdot 10^{-3}$$

$$y0_{stator}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 3.08 \\ \hline 2 & 2.72 \\ \hline 3 & 2.64 \\ \hline \end{array} \cdot 10^{-3}$$

$$l\_upper_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 161.30 \\ \hline 2 & 166.88 \\ \hline 3 & 182.81 \\ \hline \end{array} \cdot 10^{-3}$$

$$l\_lower_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 143.99 \\ \hline 2 & 165.54 \\ \hline 3 & 182.71 \\ \hline \end{array} \cdot 10^{-3}$$

$$area_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 2310.37 \\ \hline 2 & 1151.87 \\ \hline 3 & 701.28 \\ \hline \end{array} \cdot 10^{-6}$$

$$Sx_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 39814.7 \\ \hline 2 & 4165.0 \\ \hline 3 & 388.4 \\ \hline \end{array} \cdot 10^{-9}$$

$$Sy_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 146612.4 \\ \hline 2 & 95338.5 \\ \hline 3 & 64049.4 \\ \hline \end{array} \cdot 10^{-9}$$

$$x0_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 63.46 \\ \hline 2 & 82.77 \\ \hline 3 & 91.33 \\ \hline \end{array} \cdot 10^{-3}$$

$$y0_{rotor}{}^{T} = \begin{array}{|c|c|}\hline & 1 \\ \hline 1 & 17.23 \\ \hline 2 & 3.62 \\ \hline 3 & 0.55 \\ \hline \end{array} \cdot 10^{-3}$$

$Jx_{stator}^{T} =$

	1
1	3497
2	7040
3	14379

$\cdot 10^{-12}$

$Jy_{stator}^{T} =$

	1
1	1153935
2	3012608
3	5583399

$\cdot 10^{-12}$

$Jxy_{stator}^{T} =$

	1
1	53733
2	110632
3	185320

$\cdot 10^{-12}$

$Jx0_{stator}^{T} =$

	1
1	536.41
2	2233.62
3	7101.42

$\cdot 10^{-12}$

$Jy0_{stator}^{T} =$

	1
1	251977
2	657843
3	1219368

$\cdot 10^{-12}$

$Jxy0_{stator}^{T} =$

	1
1	2058.42
2	4240.94
3	7105.43

$\cdot 10^{-12}$

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

	1
1	0.47
2	0.37
3	0.34

$\cdot \circ$

$Jx_{rotor}^{T} =$

	1
1	819752
2	22926
3	1449

$\cdot 10^{-12}$

$Jy_{rotor}^{T} =$

	1
1	11903414
2	9610401
3	7124382

$\cdot 10^{-12}$

$Jxy_{rotor}^{T} =$

	1
1	2623407
2	344732
3	35473

$\cdot 10^{-12}$

$Jx0_{rotor}^{T} =$

	1
1	133622.41
2	7865.54
3	1234.18

$\cdot 10^{-12}$

$Jy0_{rotor}^{T} =$

	1
1	2599607
2	1719392
3	1274619

$\cdot 10^{-12}$

$Jxy0_{rotor}^{T} =$

	1
1	96824.41
2	-0.99
3	-0.10

$\cdot 10^{-12}$

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

	1
1	2.25
2	-0.00
3	-0.00

$\cdot \circ$

$Ju_{stator}^{T} =$

	1
1	519.56
2	2206.19
3	7059.77

$\cdot 10^{-12}$

$Jv_{stator}^{T} =$

	1
1	251994
2	657871
3	1219410

$\cdot 10^{-12}$

$Juv_{stator}^{T} =$

	1
1	0.00
2	0.00
3	0.00

$\cdot 10^{-12}$

$Jp_{stator}^{T} =$

	1
1	252513
2	660077
3	1226469

$\cdot 10^{-12}$

$Wp_{stator}^{T} =$

	1
1	3860.4
2	9024.0
3	15633.8

$\cdot 10^{-9}$

$stiffness_{stator}^{T} =$

	1
1	968.09
2	7020.61
3	25501.84

$\cdot 10^{-12}$

$Ju_{rotor}^{T} =$

	1
1	129826.54
2	7865.54
3	1234.18

$\cdot 10^{-12}$

$Jv_{rotor}^{T} =$

	1
1	2603403
2	1719392
3	1274619

$\cdot 10^{-12}$

$Juv_{rotor}^{T} =$

	1
1	0.00
2	0.00
3	0.00

$\cdot 10^{-12}$

$Jp_{rotor}^{T} =$

	1
1	2733229
2	1727257
3	1275853

$\cdot 10^{-12}$

$Wp_{rotor}^{T} =$

	1
1	34617.3
2	20848.7
3	13969.1

$\cdot 10^{-9}$

$stiffness_{rotor}^{T} =$

	1
1	284045.72
2	26233.50
3	4861.85

$\cdot 10^{-12}$

$CPx_{stator}^{T} =$

	1
1	41.702
2	46.654
3	50.042

$\cdot 10^{-3}$

$CPx_{rotor}^{T} =$

	1
1	49.179
2	57.938
3	63.932

$\cdot 10^{-3}$

$CPy_{stator}^{T} =$

	1
1	0.0000
2	0.0000
3	0.0000

$\cdot 10^{-3}$

$CPy_{rotor}^{T} =$

	1
1	0.0000
2	0.0000
3	0.0000

$\cdot 10^{-3}$

▲ Результат расчета абсолютных геометрических характеристик сечений Л

Вывод результатов расчета геометрических хар-к сечений Л

Профилирование решеток

Абс. координаты профиля:

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

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

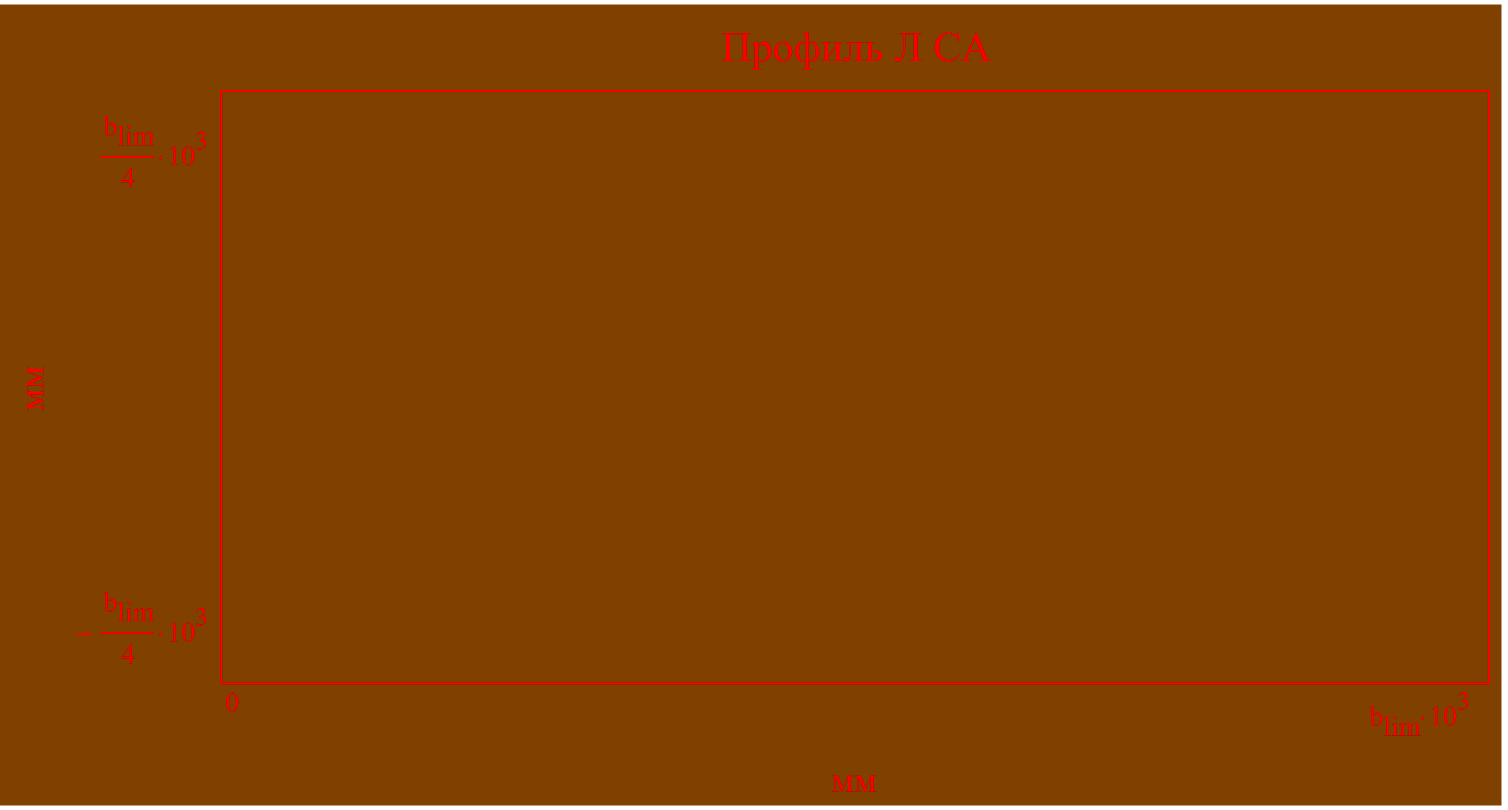
$$AXLE0(type, x, i, r) = \left| \begin{array}{ll} \dfrac{y0rotor_{i,r}}{chord_{rotor_{i,r}}} + \tan\left(\alpha\_major_{rotor_{i,r}}\right) \cdot \left(x - \dfrac{x0rotor_{i,r}}{chord_{rotor_{i,r}}}\right) & \text{if } type = \text{"rotor"} \\ \dfrac{y0stator_{i,r}}{chord_{stator_{i,r}}} + \tan\left(\alpha\_major_{stator_{i,r}}\right)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

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

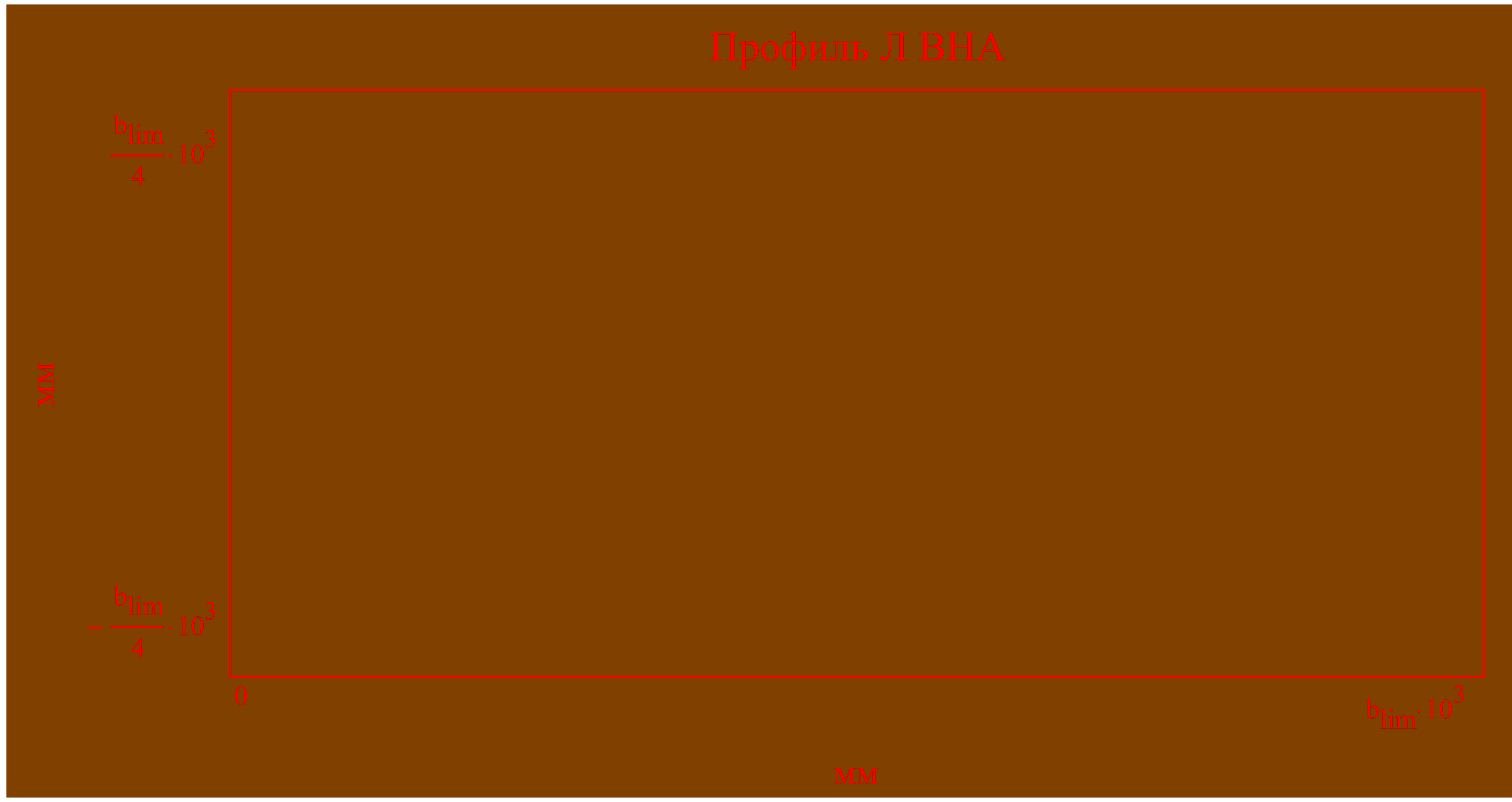
$$AXLE90(type, x, i, r) = \left| \begin{array}{ll} \dfrac{y0rotor_{i,r}}{chord_{rotor_{i,r}}} + \tan\left(\alpha\_major_{rotor_{i,r}} + \dfrac{\pi}{2}\right) \cdot \left(x - \dfrac{x0rotor_{i,r}}{chord_{rotor_{i,r}}}\right) & \text{if } (type = \text{"rotor"}) \wedge \left|\alpha\_major_{rotor_{i,r}}\right|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

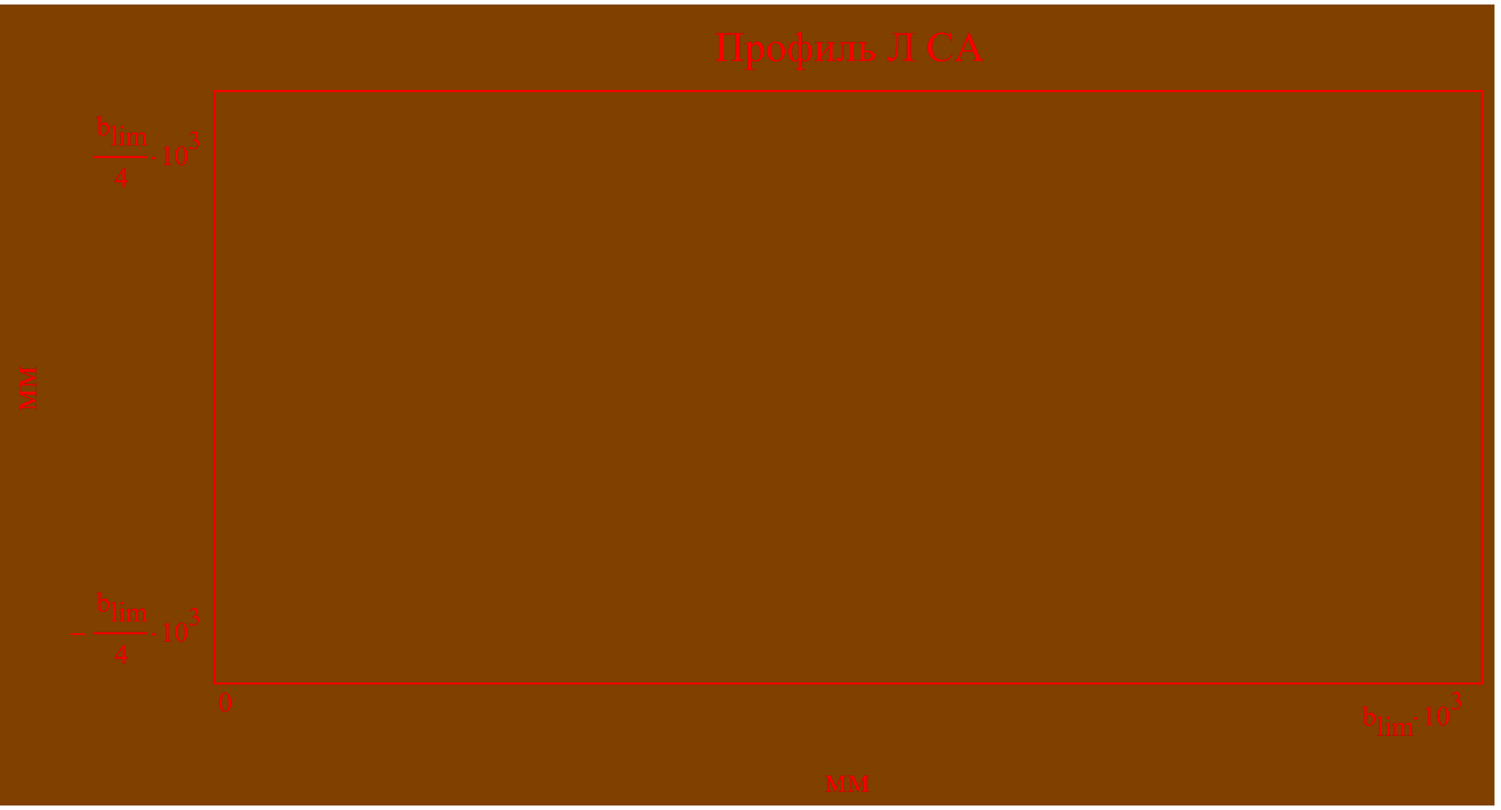
$r = 1$


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

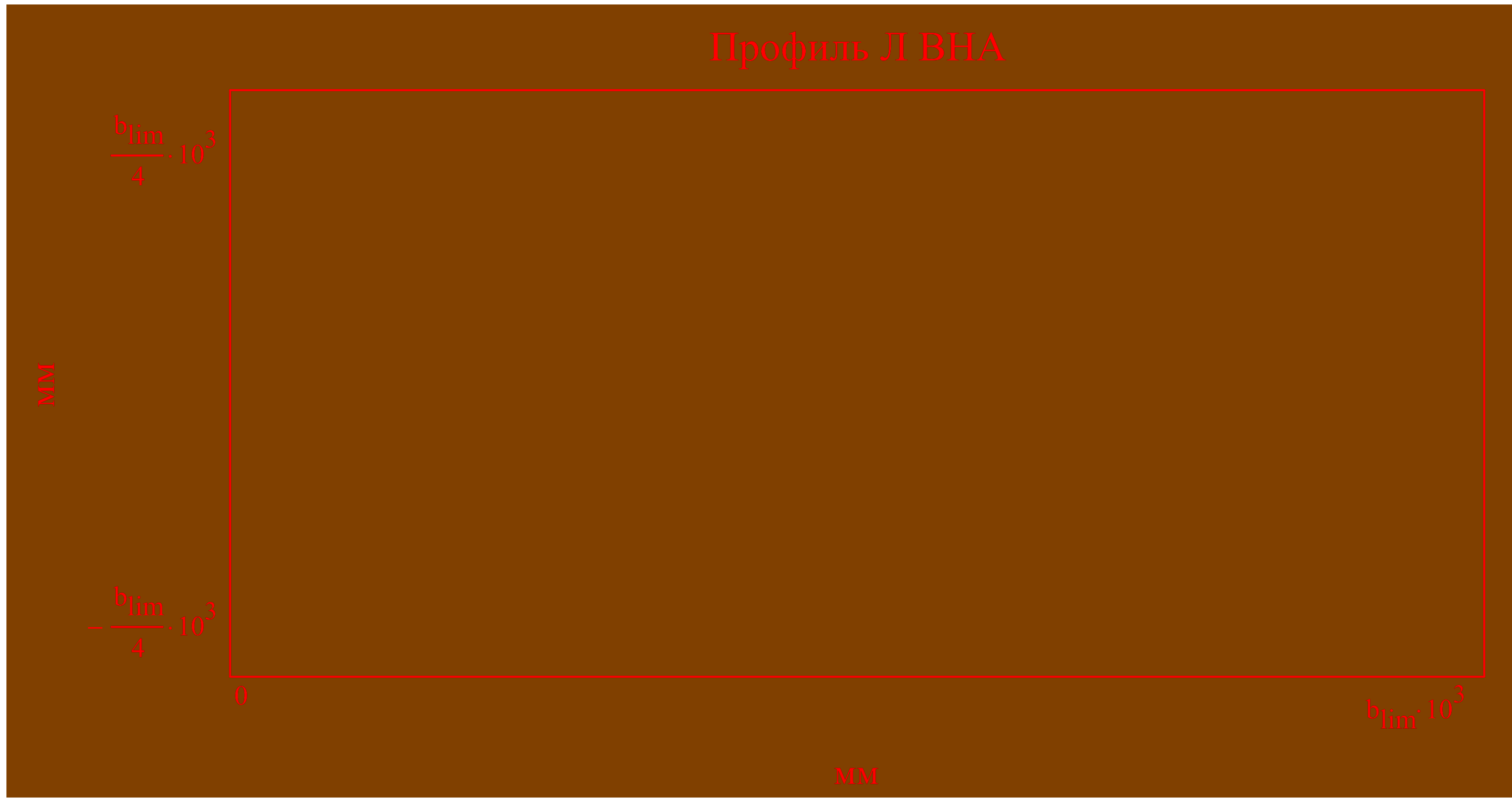

Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм

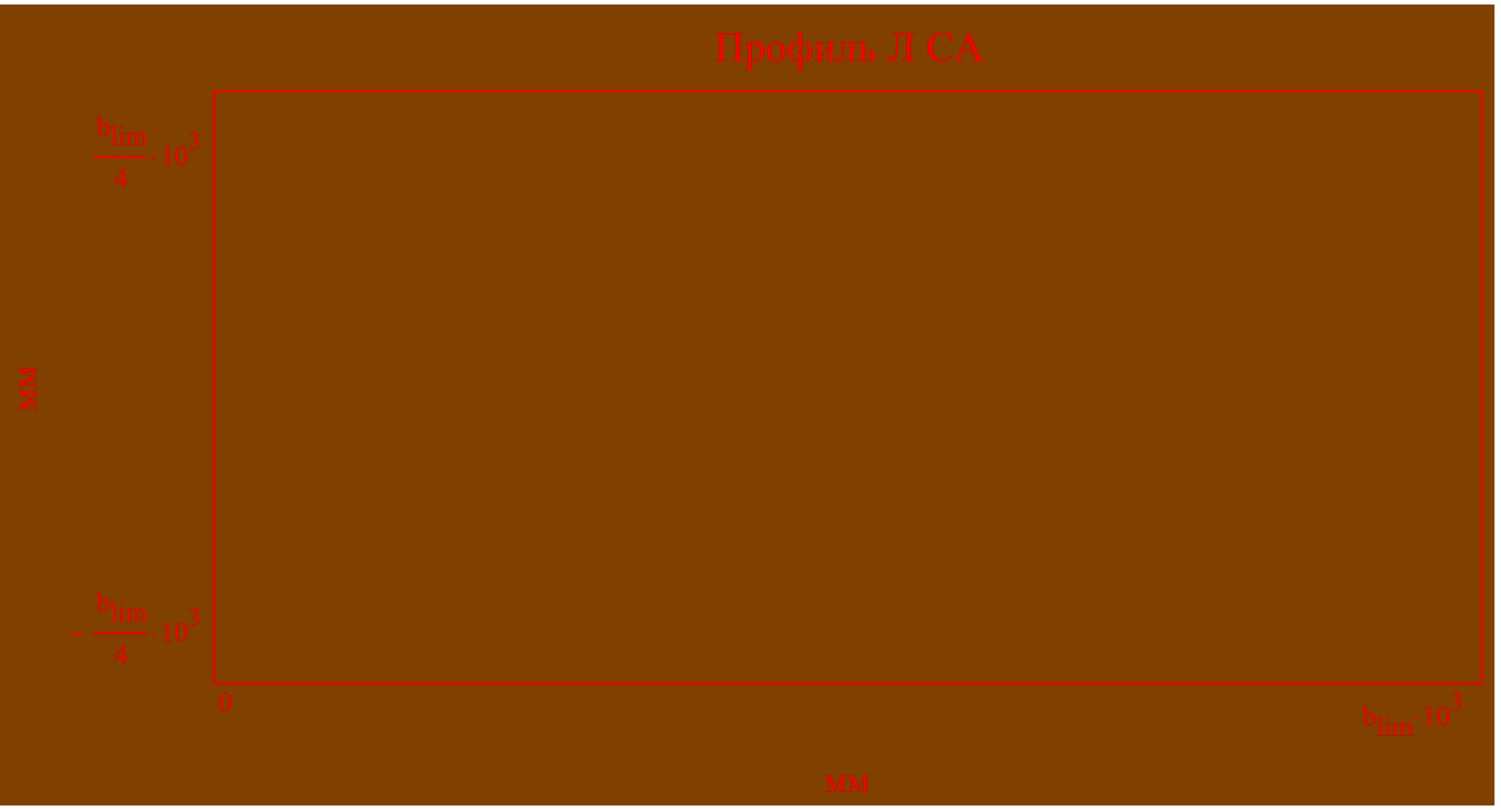
$r = av(N_r)$


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

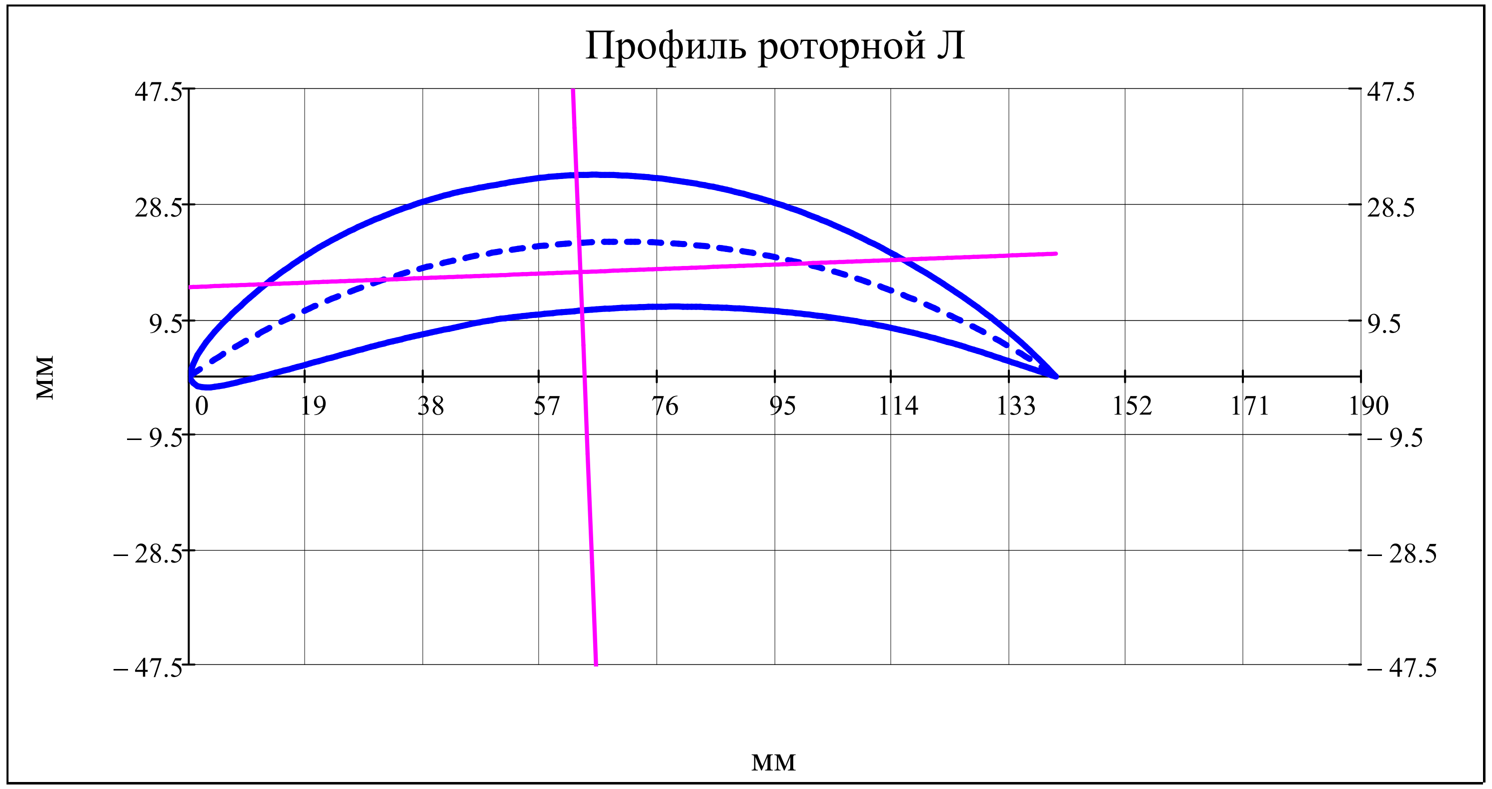

Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
$-\frac{b_{lim}}{4} \cdot 10^3$
мм
0
$b_{lim} \cdot 10^3$
мм

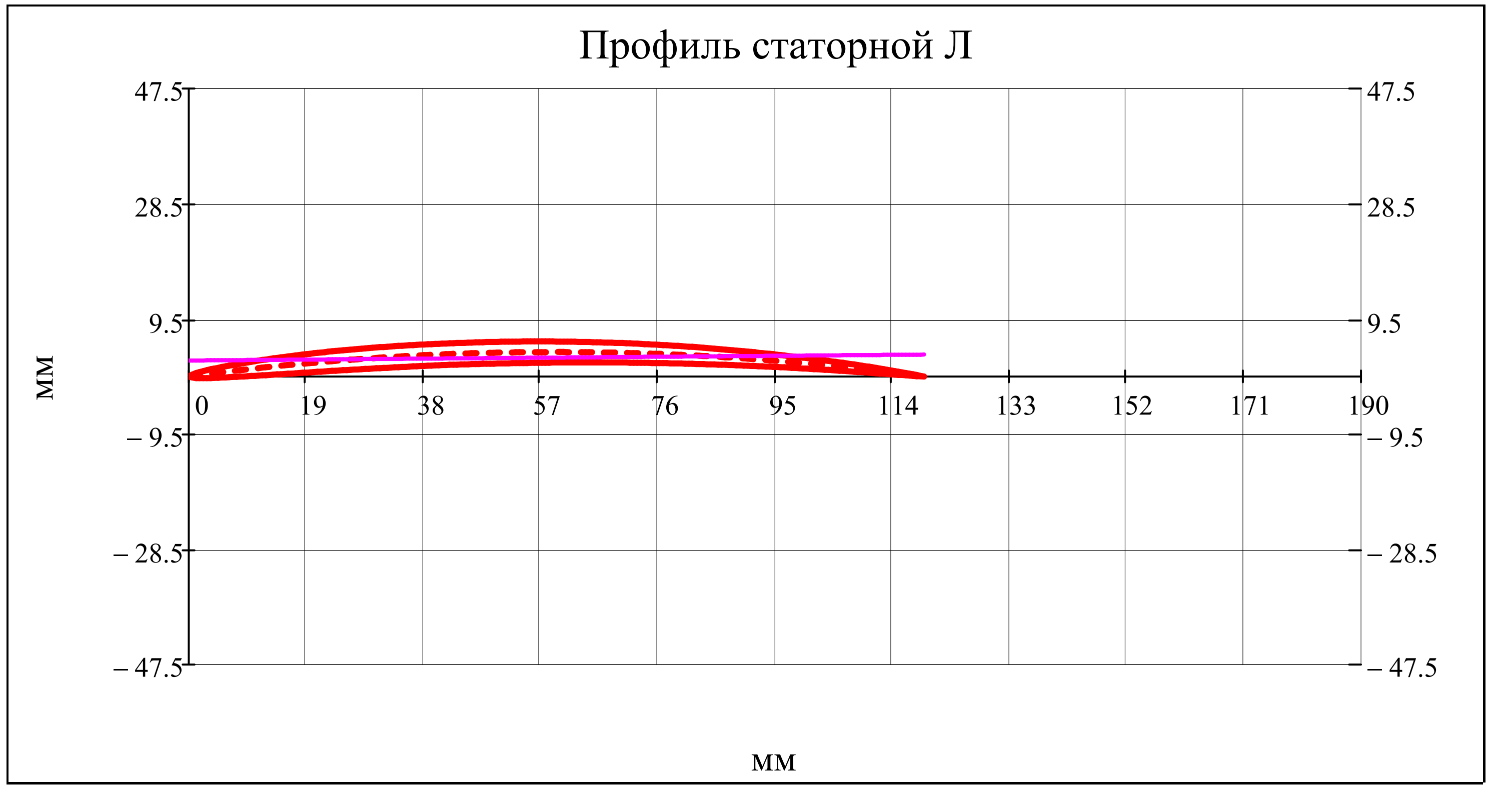
$r = N_r$


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

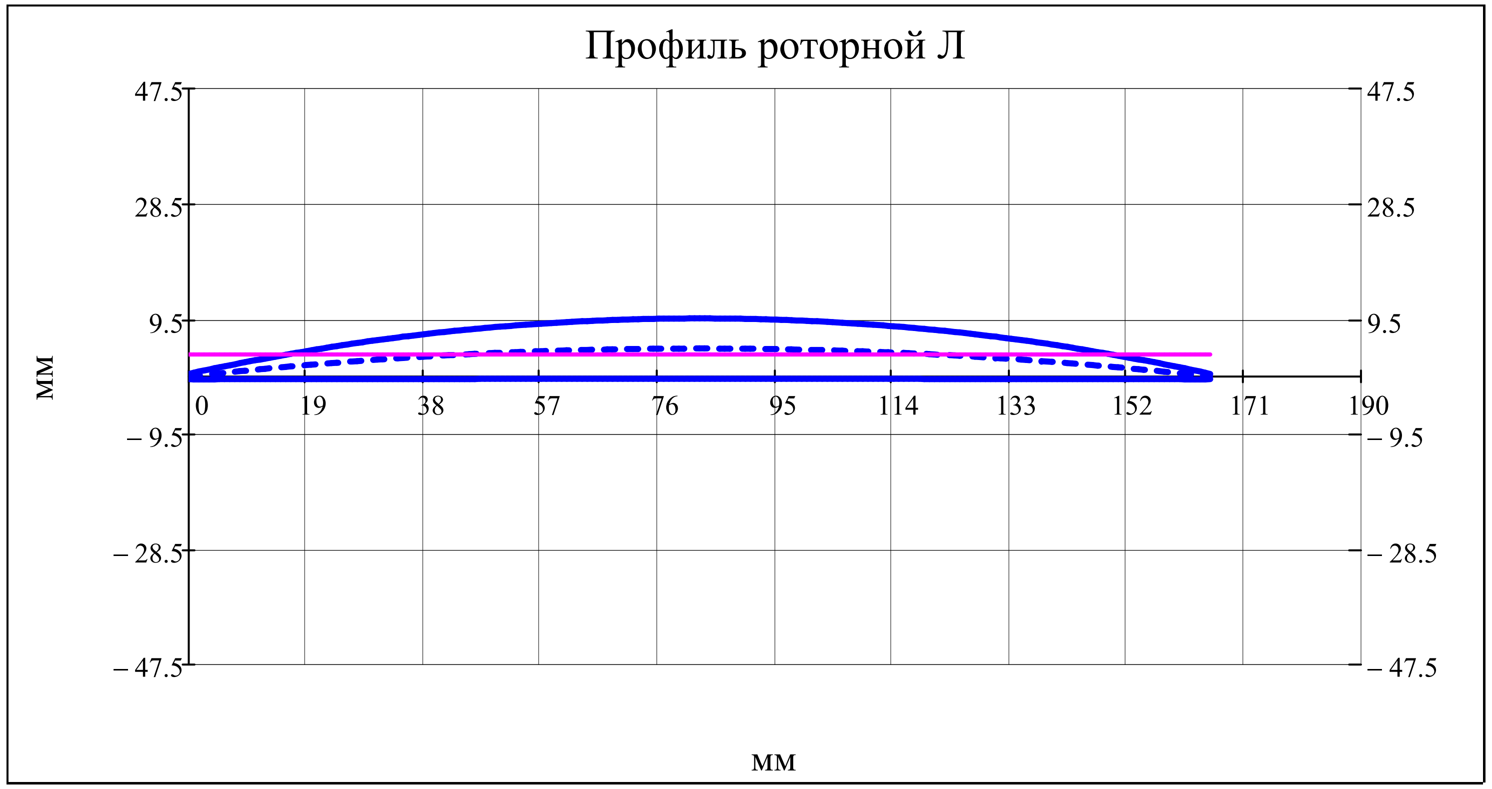

Профиль Л СА
$\frac{b_{lim}}{4} \cdot 10^3$
мм
$-\frac{b_{lim}}{4} \cdot 10^3$
0
$b_{lim} \cdot 10^3$
мм

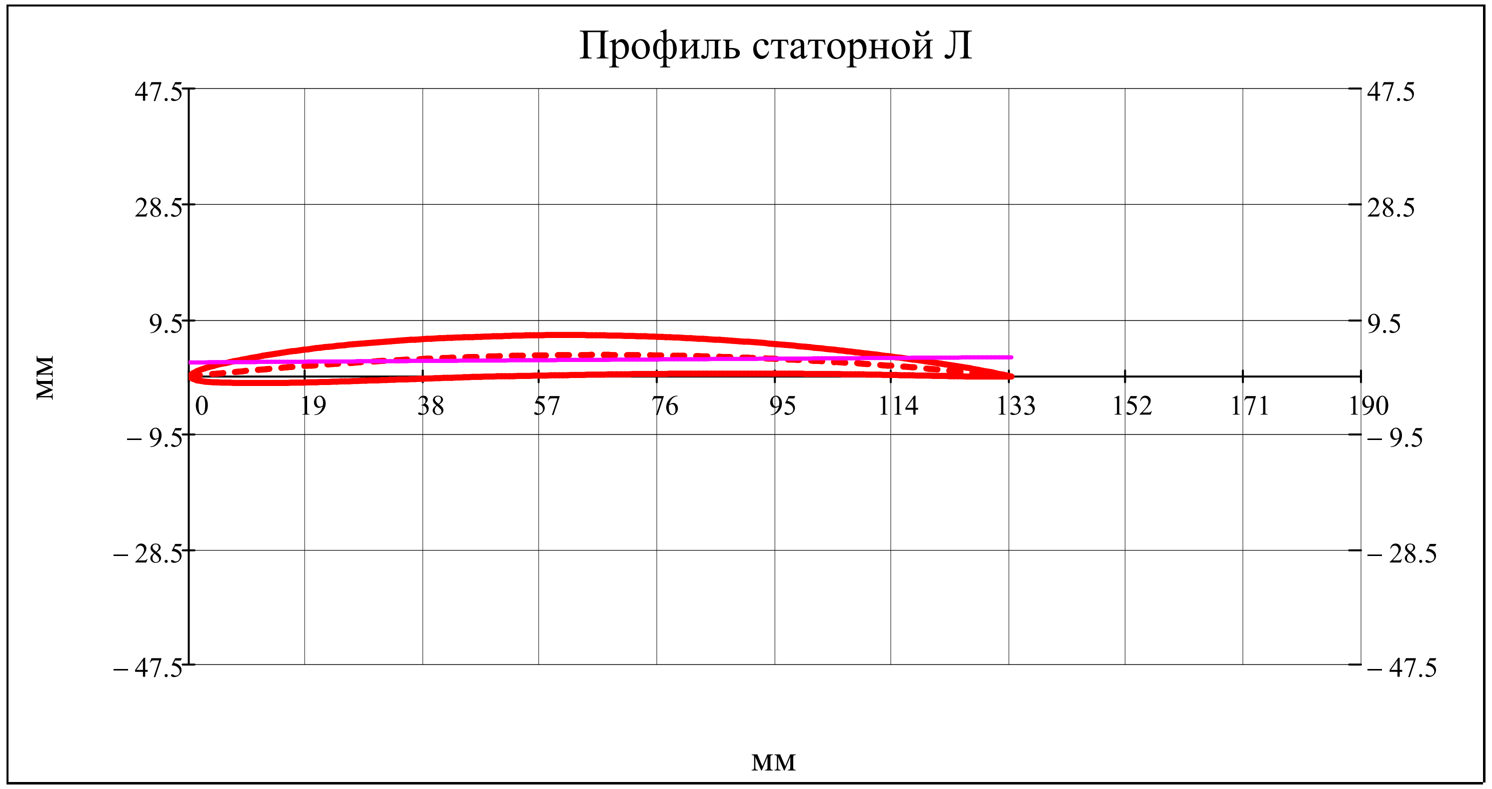
r = 1


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

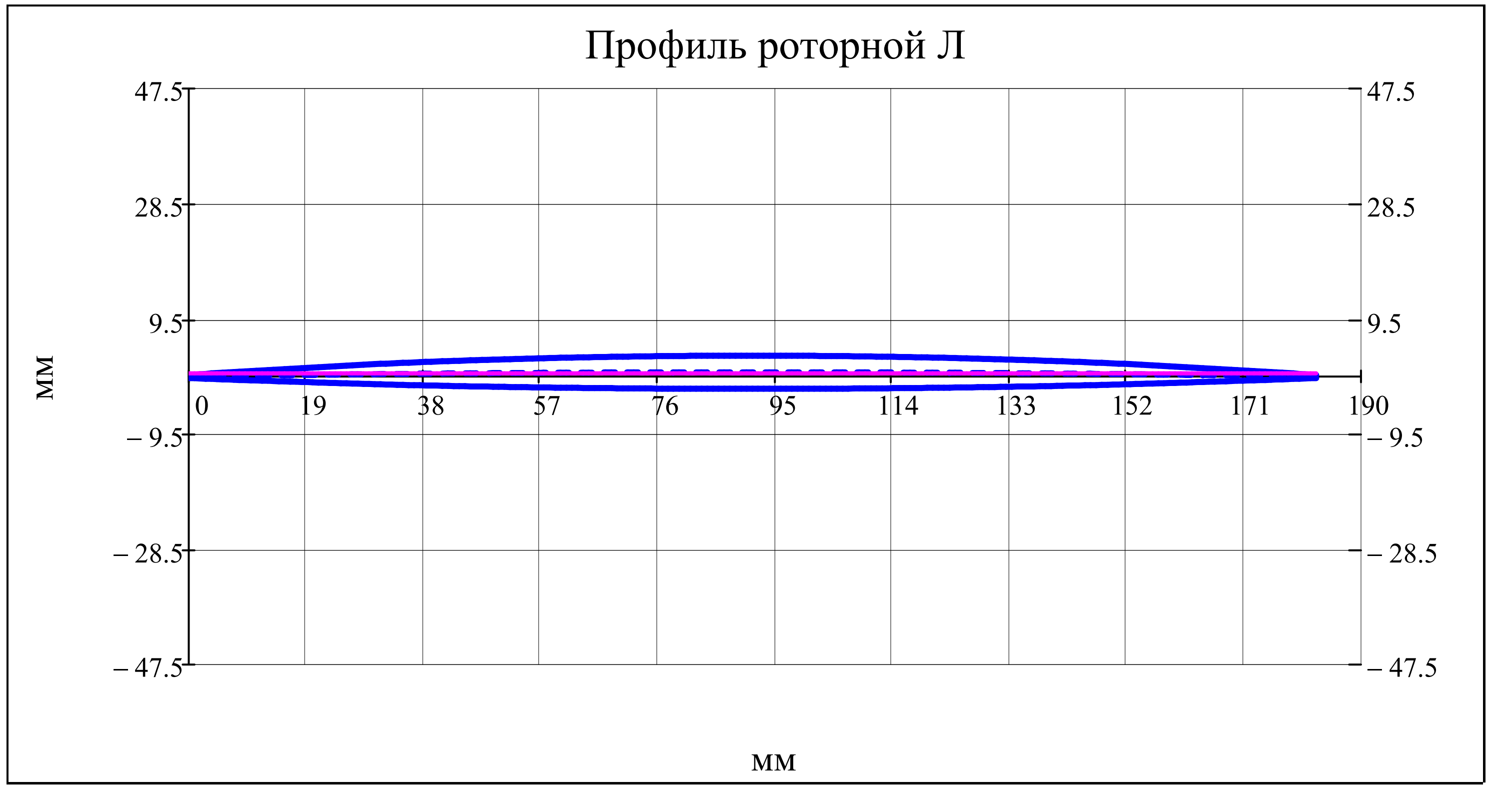

Профиль статорной Л
47.5
28.5
9.5
– 9.5
– 28.5
– 47.5
0
19
38
57
76
95
114
133
152
171
190
мм
мм

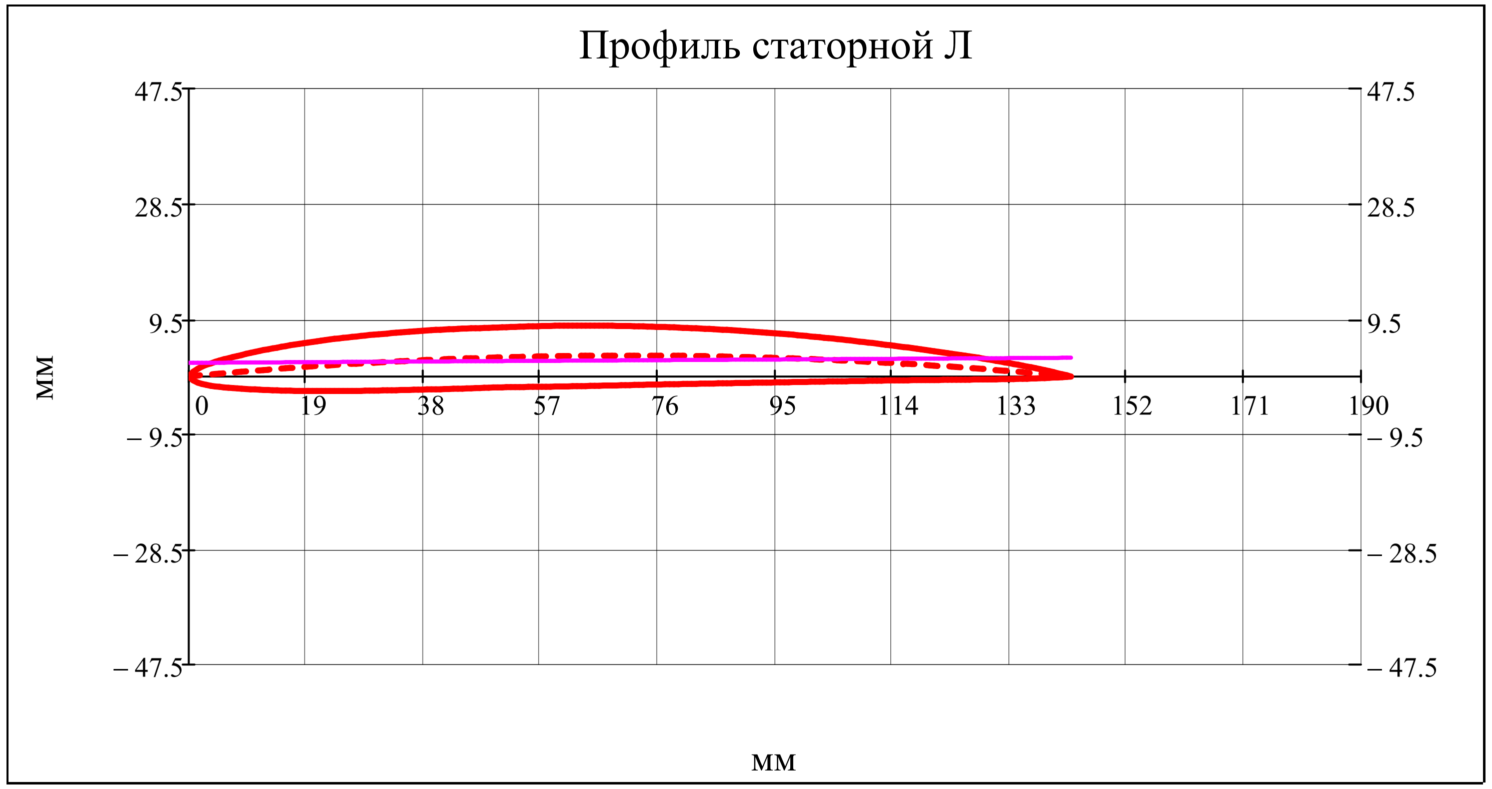
$r = av(N_r)$


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


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

$r = N_r$





Построение профилей Л РК и НА

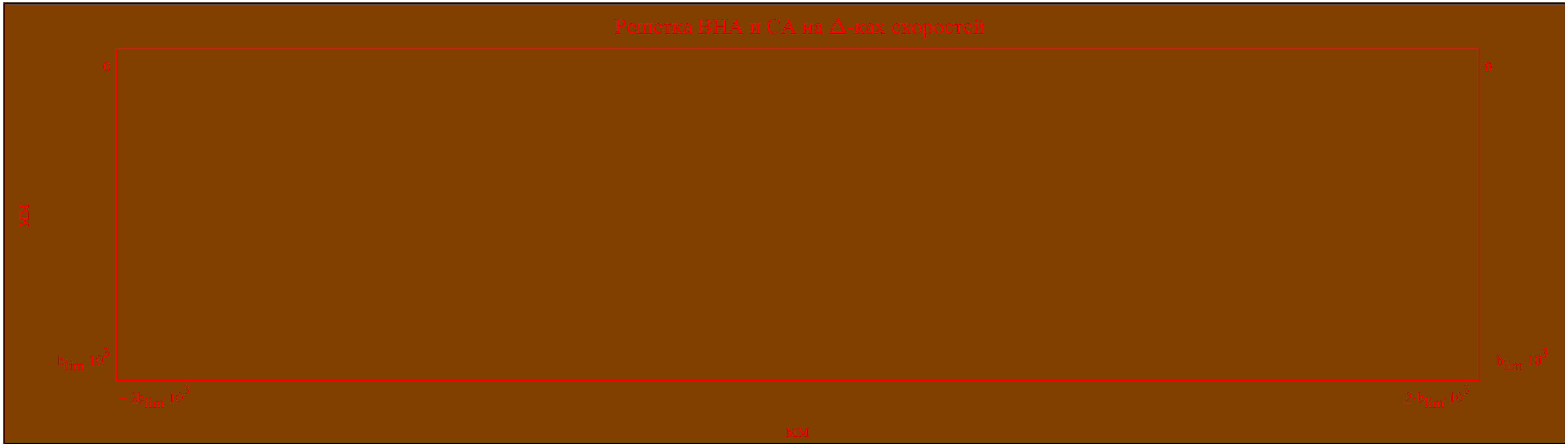
Вывод координат для построения профиля Л

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

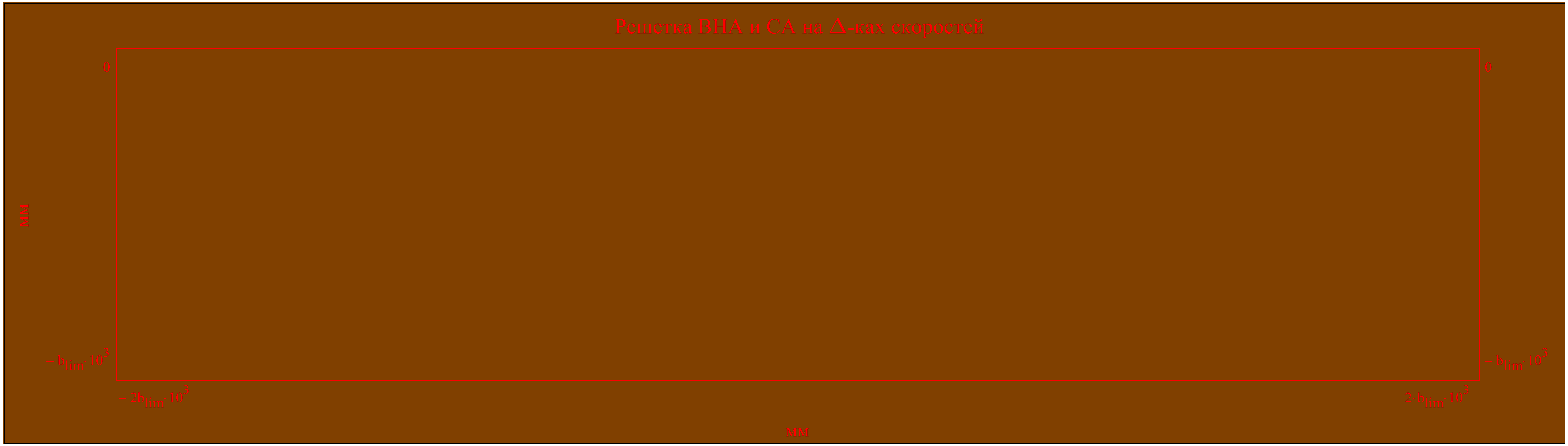
$$b_{lim} := \frac{\mathrm{ceil}\left(\max\left(chord_{rotor_{j,N_r}}, chord_{stator_{j,N_r}}\right) \cdot 10^2\right)}{10^2} = 190 \cdot 10^{-3}$$

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

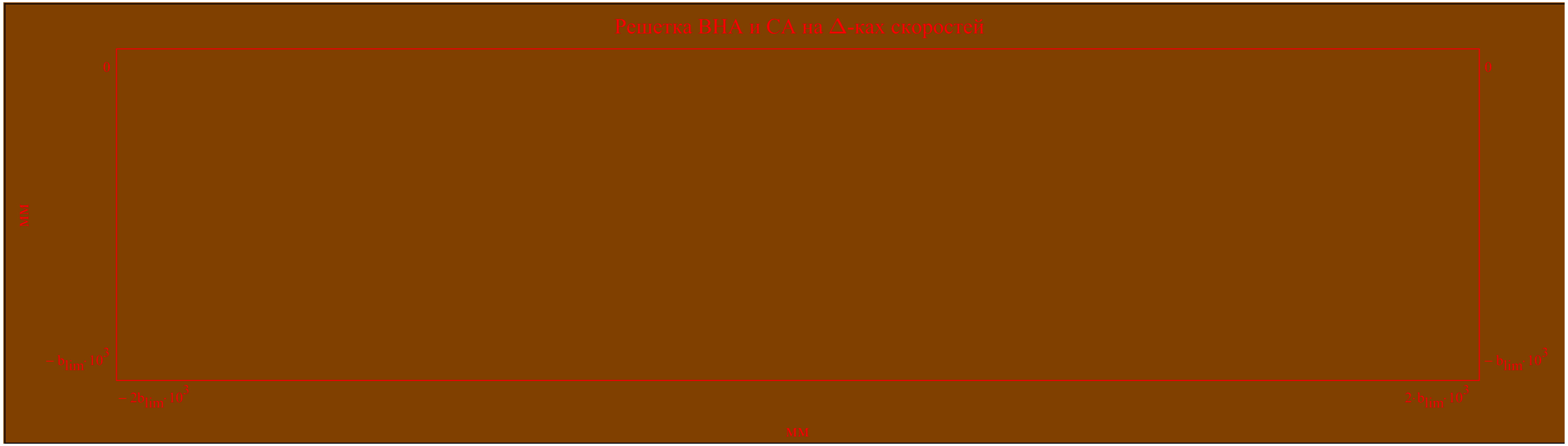
$r := 1$



$r = av(N_r)$

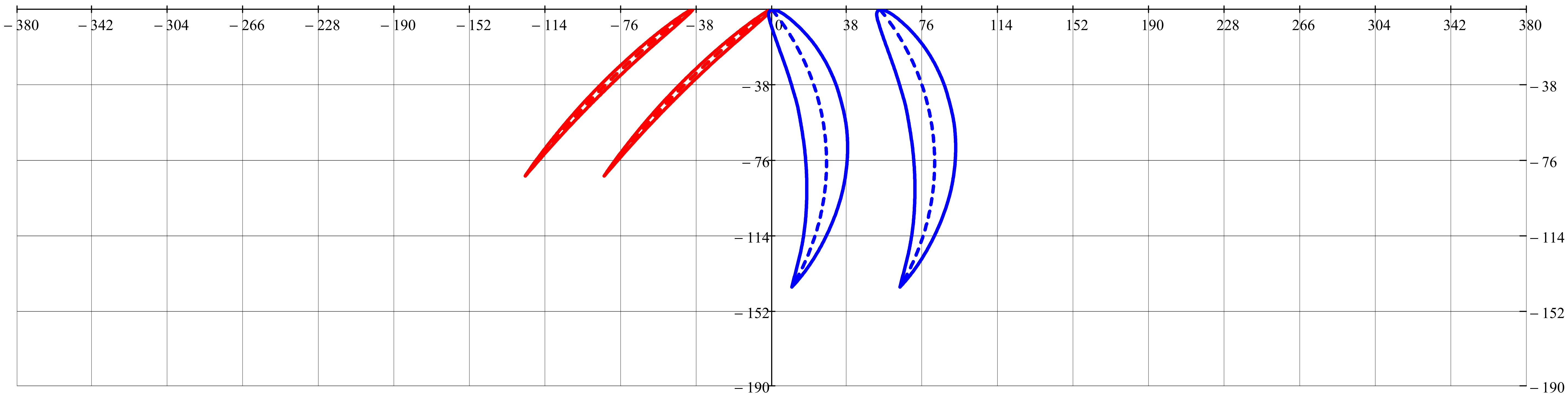

Решетка ВНА и СА на Δ-ках скоростей
0
0
мм
$-b_{lim} \cdot 10^3$
$-b_{lim} \cdot 10^3$
$-2b_{lim} \cdot 10^3$
$2 \cdot b_{lim} \cdot 10^3$
мм

$r = N_r$


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

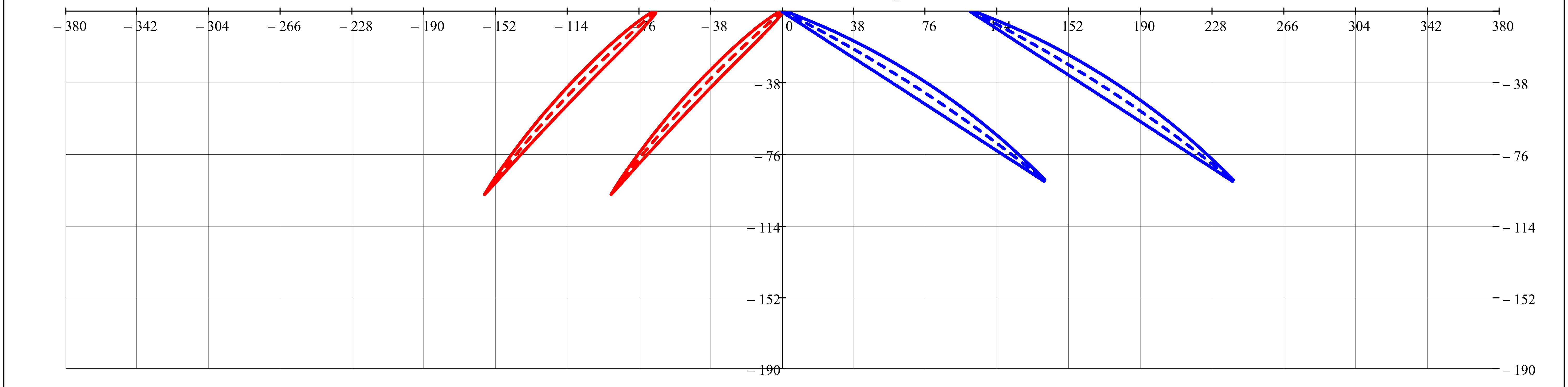
$r = 1$

Решетка ступени на Δ-ках скоростей

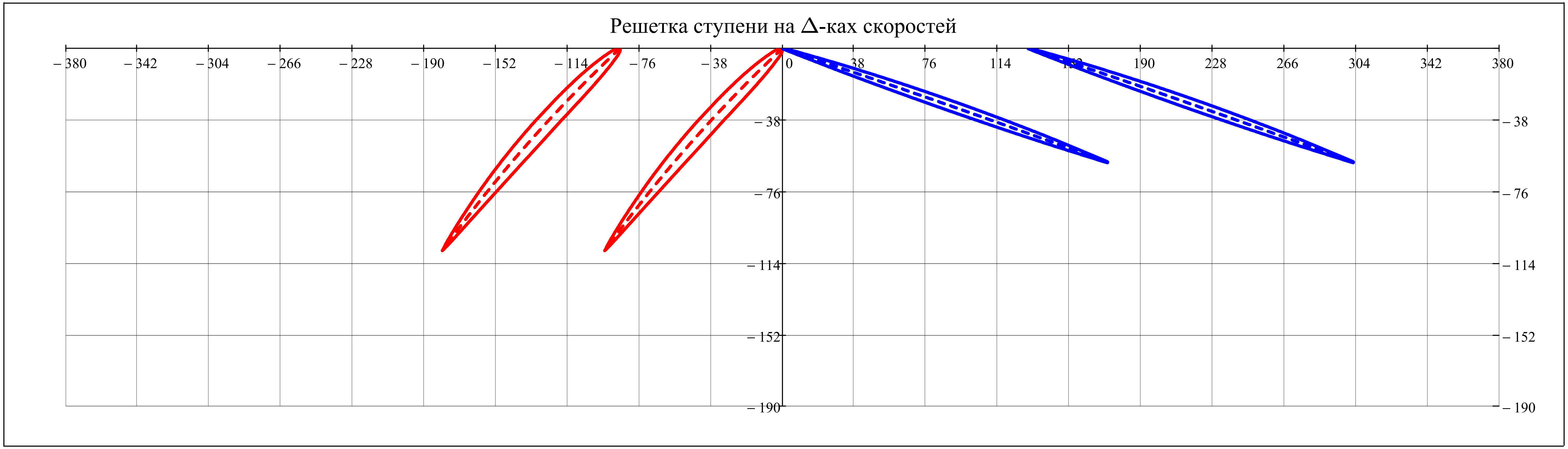


$r = av(N_r)$

Решетка ступени на Δ-ках скоростей



$r = N_r$



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]:

$\overline{\Delta}r = 0.0025$

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

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

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

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

$\overline{\Delta}a = 0.17$

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

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

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

Односторонний осевой зазор (м):

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

Длина ОК (м):

$$Length = \left[\Delta a_1 + \begin{cases} chord_{BHA_{av(N_r)}} \cdot \sin\left(\upsilon_{BHA_{av(N_r)}}\right) & \text{if } BHA = 1 \\ 0 & \text{otherwise} \end{cases} \ldots \\ + \sum_{i=1}^{Z} \left(chord_{rotor_{i,av(N_r)}} \cdot \sin\left(\upsilon_{rotor_{i,av(N_r)}}\right)\right) + 2 \cdot \sum_{i=1}^{Z} \Delta a_i + \sum_{i=1}^{Z} \left(chord_{stator_{i,av(N_r)}} \cdot \sin\left(\upsilon_{stator_{i,av(N_r)}}\right)\right) \ldots \\ + \begin{cases} chord_{CA_{av(N_r)}} \cdot \sin\left(\upsilon_{CA_{av(N_r)}}\right) & \text{if } CA = 1 \\ 0 & \text{otherwise} \end{cases} + \Delta a_Z\right] = 300.1 \cdot 10^{-3}$$

Радиальные и осевые зазоры и длина К

Проточная часть

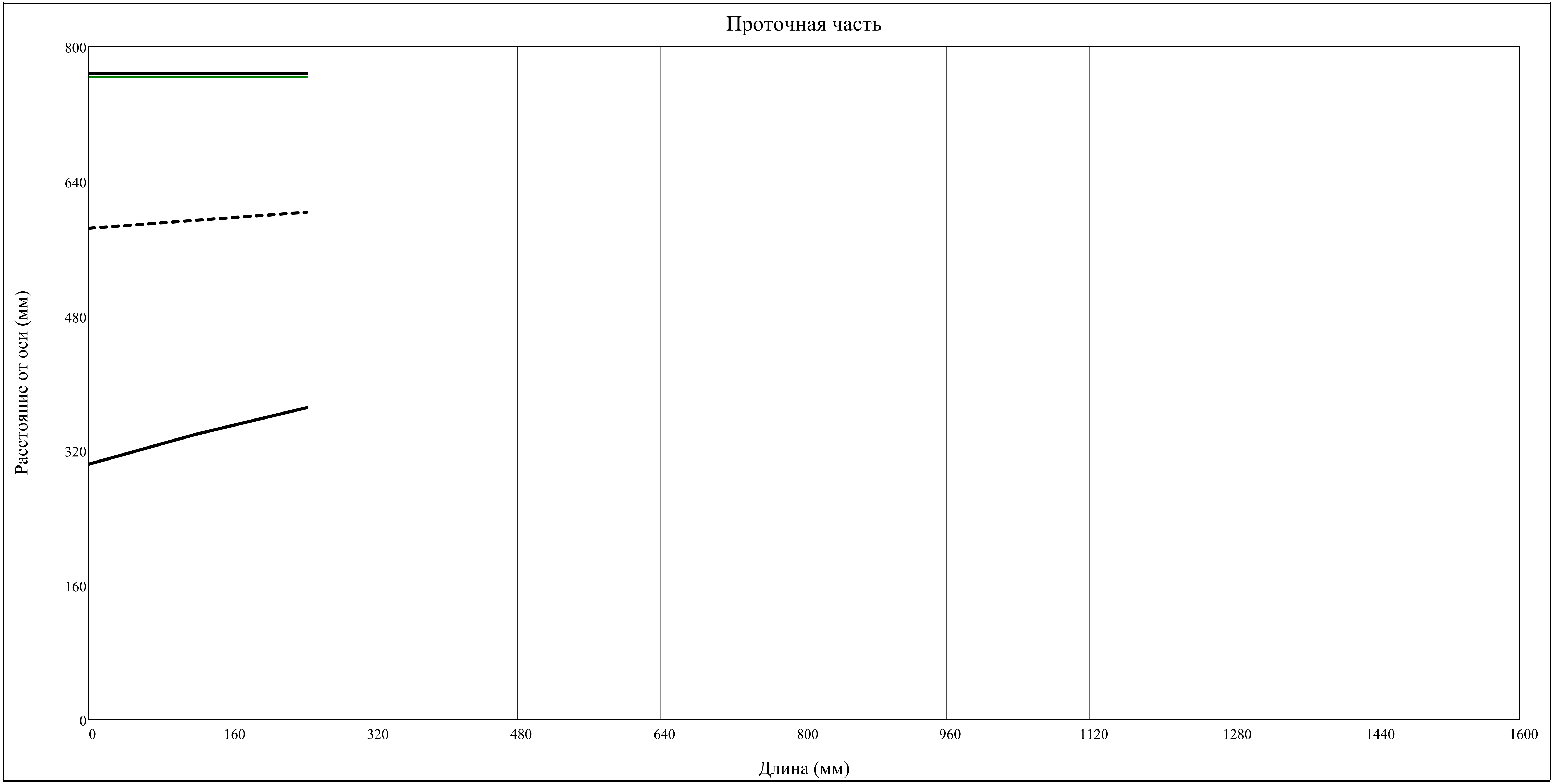
```
$\begin{pmatrix} x_{ПЧ} \\ y_{ПЧпер} \\ y_{ПЧср} \\ y_{ПЧкор} \\ y_{Лпер} \end{pmatrix} =$
    $c = 1$
    $x_{ПЧ_c} =$
        $chord_{BHA_{av(N_r)}} \cdot \sin\left(\upsilon_{BHA_{av(N_r)}}\right)$  if  $BHA = 1$
        $0$  otherwise
    $y_{ПЧпер_c} = R_{st(c,1),N_r}$
    $y_{Лпер_c} = y_{ПЧпер_c}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

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

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

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

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



▲ Проточная часть

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

Поперечная часть ступени

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

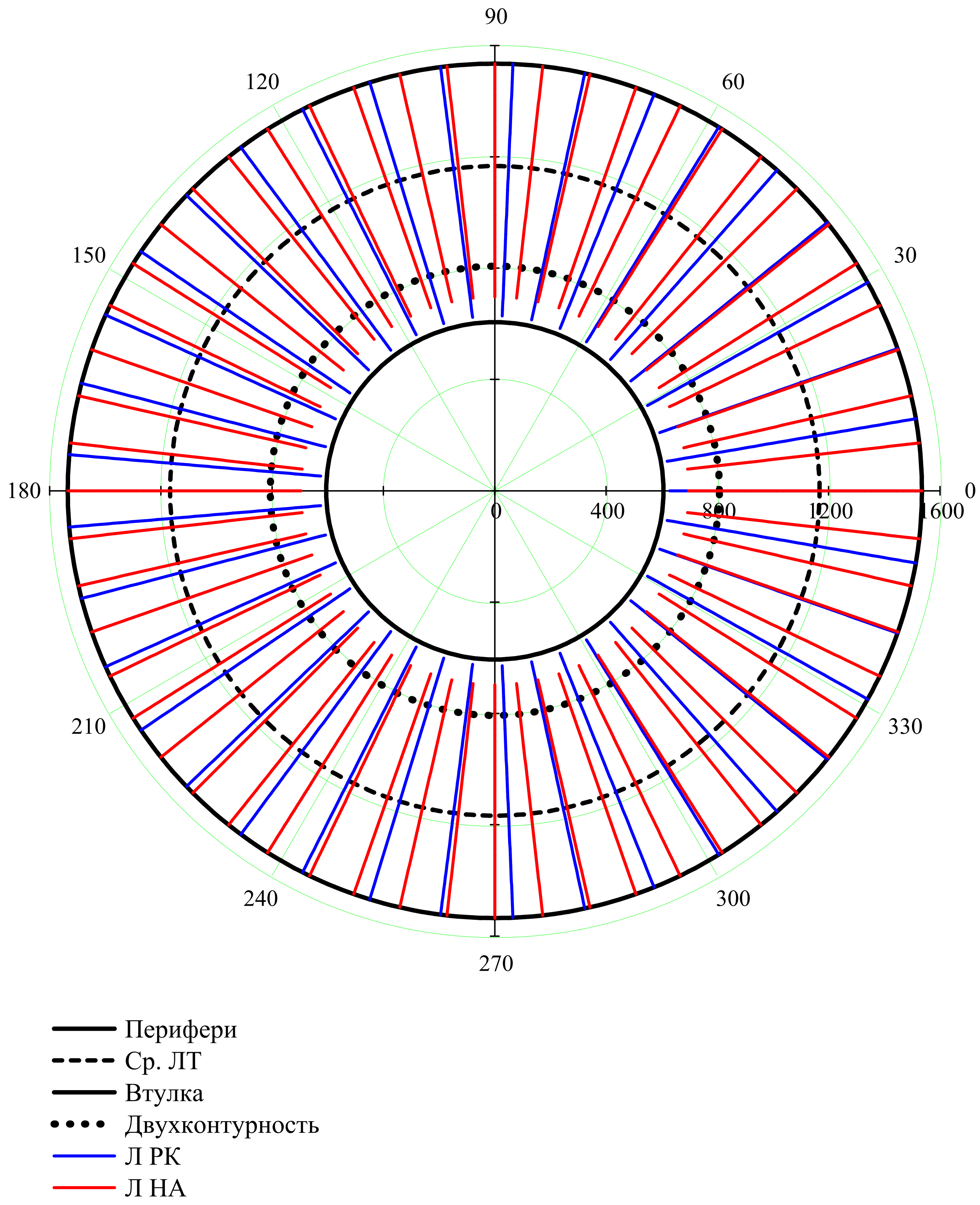
$$i_{rotor} = 1 .. Z_{rotor_j}$$

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

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

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

Поперечная часть ступени



▲ Поперечная часть ступени

▼ Выбор материала Л

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

Выбранный материал Л:

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

$$material\_blade_i = \left| \begin{array}{l} \text{"ВТ23"} \quad \text{if } compressor = \text{"Вл"} \\ \text{"ВТ6"} \quad \text{if } compressor = \text{"КНД"} \\ material\_blade_i \quad \text{otherwise} \end{array} \right.$$

Плотность материала Л (кг/м^3):

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

Предел длительной прочности Л РК (Па):

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

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	"ВТ23"								

$\rho\_blade^T =$

	1
1	4570

$\sigma\_blade\_long^T =$

	1
1	230.0

$\cdot 10^6$

▲ Выбор материала Л

Расчет собственных частот колебаний Л

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

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

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	262	290																
2	787	869																
3	1312	1449																
4	1836	2029																
5	2361	2608																
6	2885	3188																

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	41	50																
2	257	311																
3	718	871																
4	1409	1708																
5	2328	2822																
6	3477	4214																

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	525	580																
2	1049	1159																
3	1574	1739																
4	2098	2318																
5	2623	2898																
6	3148	3478																

▲ 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

▲ Расчет Л на прочность

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

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

▶ Определение координат точек профиля Л, наиболее удаленных от НЛ

Наиболее удаленные точки от НЛ (мм):

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

	1	2	3	4	5	6	7	8	9
1	7.216								
2	-3.269								
3	-0.307								

$\cdot 10^{-3}$

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

	1
1	16.326
2	5.980
3	91.332

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	-59.370								
2	82.737								
3	-0.800								

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	-22.714								
2	-4.647								
3	-91.332								

$\cdot 10$

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

	1	2	3	4	5	6	7	8	9
1	-0.171								
2	-1.522								
3	-3.055								

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	2.698								
2	4.132								
3	5.778								

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	65.310								
2	-46.896								
3	-40.299								

$\cdot 10^{-3}$

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

	1	2	3	4	5	6	7	8	9
1	-3.631								
2	-3.463								
3	-4.764								

$\cdot 10^{-3}$

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

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

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

	1	2	3	4	5	6	7	8	9
1	26.78								
2	-37.79								
3	0.00								

$\cdot 10^{6}$

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

	1	2	3	4	5	6	7	8	9
1	1.31								
2	92.34								
3	106.71								

$\cdot 10^{6}$

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

	1
1	1
2	1
3	1

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

	1
1	1
2	0
3	0

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

	1	2	3	4	5	6	7	8	9
1	-45.07								
2	32.94								
3	0.00								

$\cdot 10^{6}$

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

	1	2	3	4	5	6	7	8	9
1	-1.77								
2	-77.00								
3	-87.42								

$\cdot 10^{6}$

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

	1
1	1
2	1
3	1

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

	1
1	1
2	1
3	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	209.18								
2	162.56								
3	0.00								

$\cdot 10^6$

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

	1	2	3	4	5	6	7	8	9
1	1.31								
2	92.34								
3	106.72								

$\cdot 10^6$

```
$\begin{pmatrix} safety_{rotor} \\ safety_{stator} \end{pmatrix} =$
    for $i \in 1..Z$
        for $r \in 1..N_r$
            $safety_{rotor_{i,r}} \leftarrow$
                $\dfrac{σ\_blade\_long_i}{σ_{rotor_{i,r}}}$  if $σ_{rotor_{i,r}} \neq 0$
                $\infty$  otherwise
            $safety_{stator_{i,r}} \leftarrow$
                $\dfrac{σ\_blade\_long_i}{σ_{stator_{i,r}}}$  if $σ_{stator_{i,r}} \neq 0$
                $\infty$  otherwise
    $\begin{pmatrix} safety_{rotor} \\ safety_{stator} \end{pmatrix}$
```

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

	1	2	3	4	5	6	
1	1.1						
2	1.41						
3	0000000000000000000000000000000						

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

	1
1	0
2	1
3	1

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

	1	2	3	4	5
1	175.34				
2	2.49				
3	2.16				

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

	1
1	1
2	1
3	1

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

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

Расстояния от оси ЛМ до рассматриваемой ступени (м): $Rj := \operatorname{submatrix}(R, 2 \cdot j - 1, 2 \cdot j + 1, 1, N_r) =$

	1	2	3
1	302.9	583.4	767.5
2	338.1	593.0	767.5
3	370.4	602.6	767.5

$\cdot 10^{-3}$

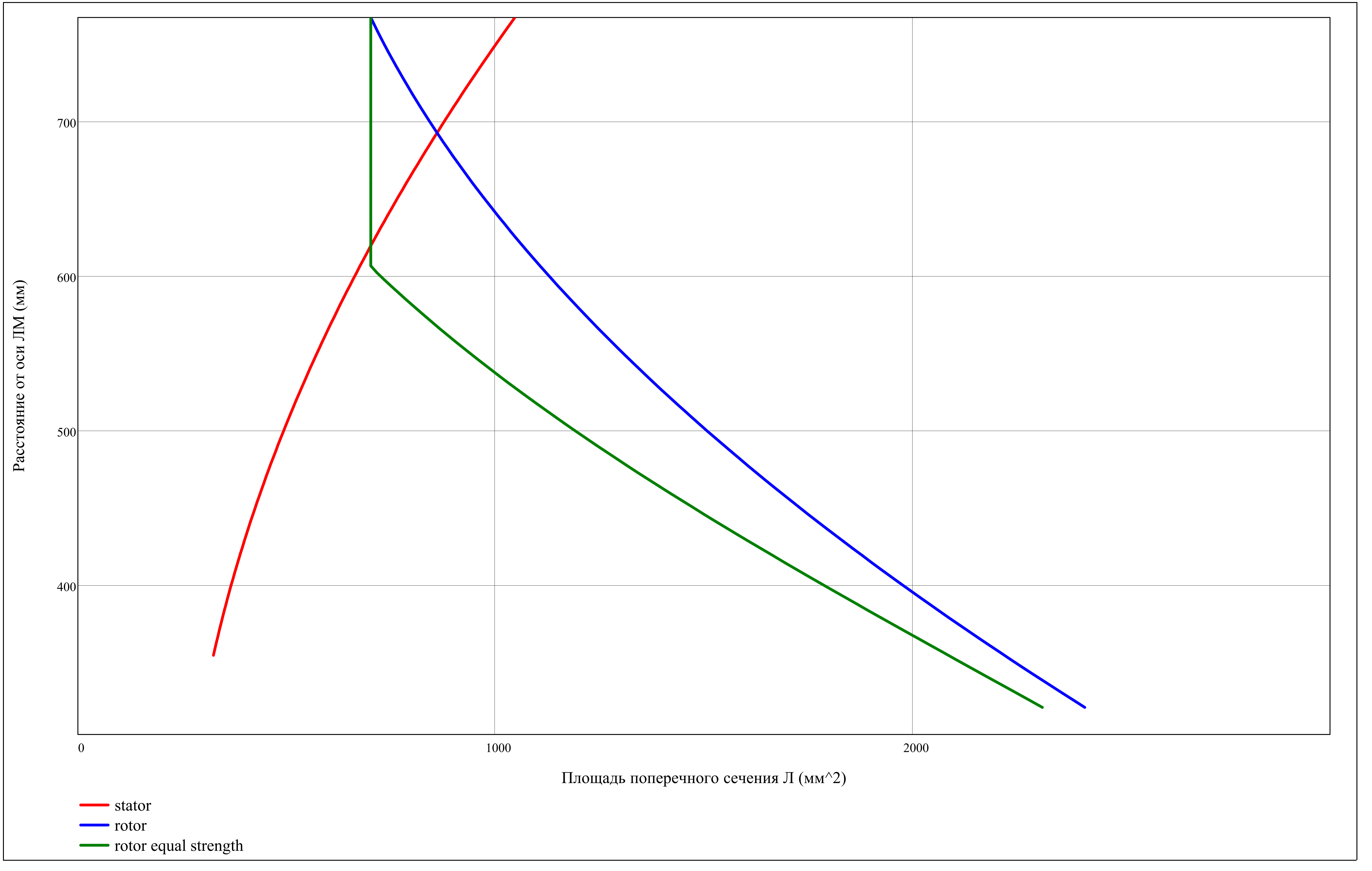
Дискретизация по высоте Л:

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

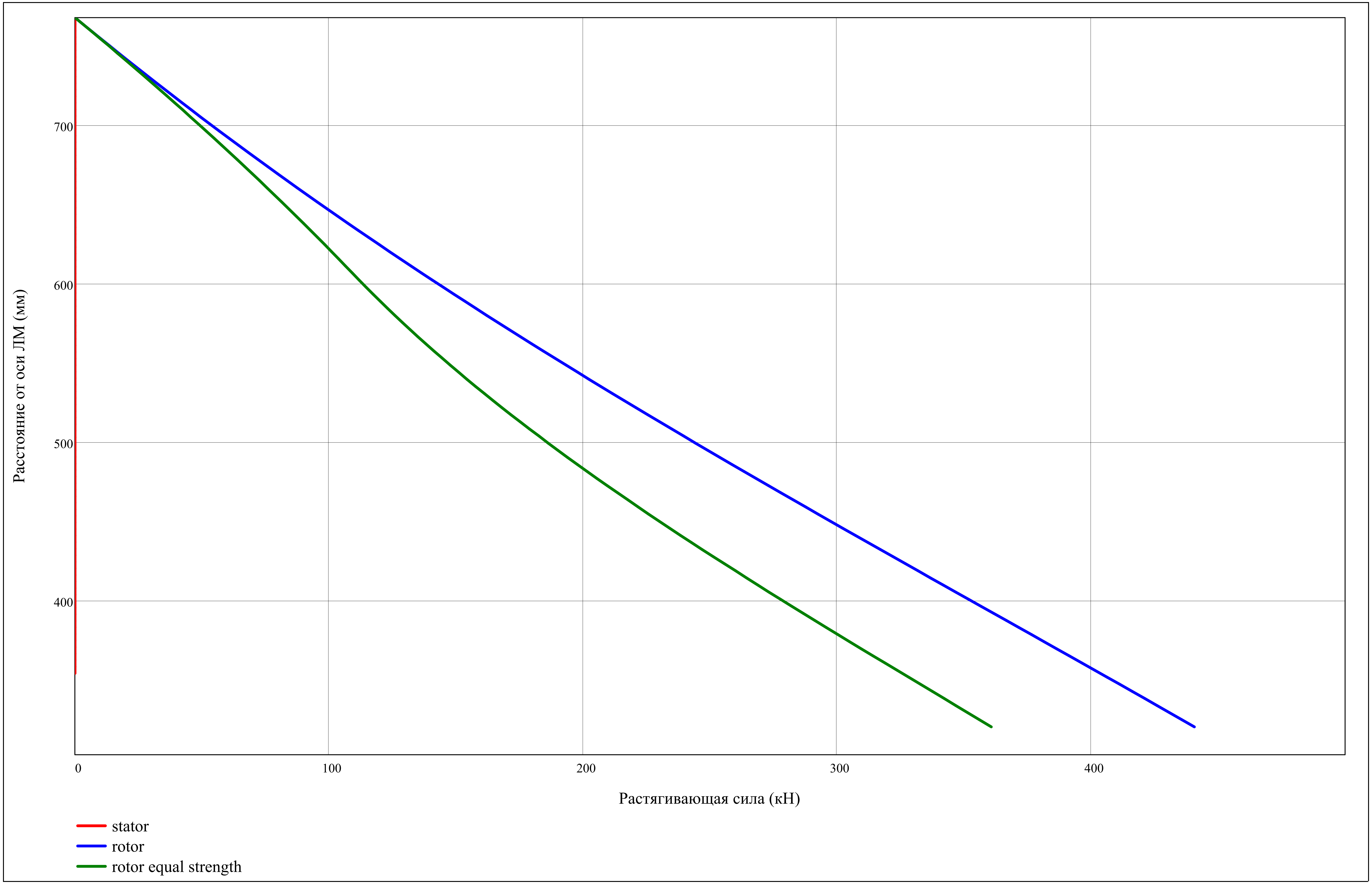
$$z_{rotor} := \left| \begin{array}{l} \operatorname{mean}\left(Rj_{1,1}, Rj_{2,1}\right), \operatorname{mean}\left(Rj_{1,1}, Rj_{2,1}\right) + \dfrac{\operatorname{mean}\left(Rj_{1,N_r}, Rj_{2,N_r}\right) - \operatorname{mean}\left(Rj_{1,1}, Rj_{2,1}\right)}{100} .. \operatorname{mean}\left(Rj_{1,N_r},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

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

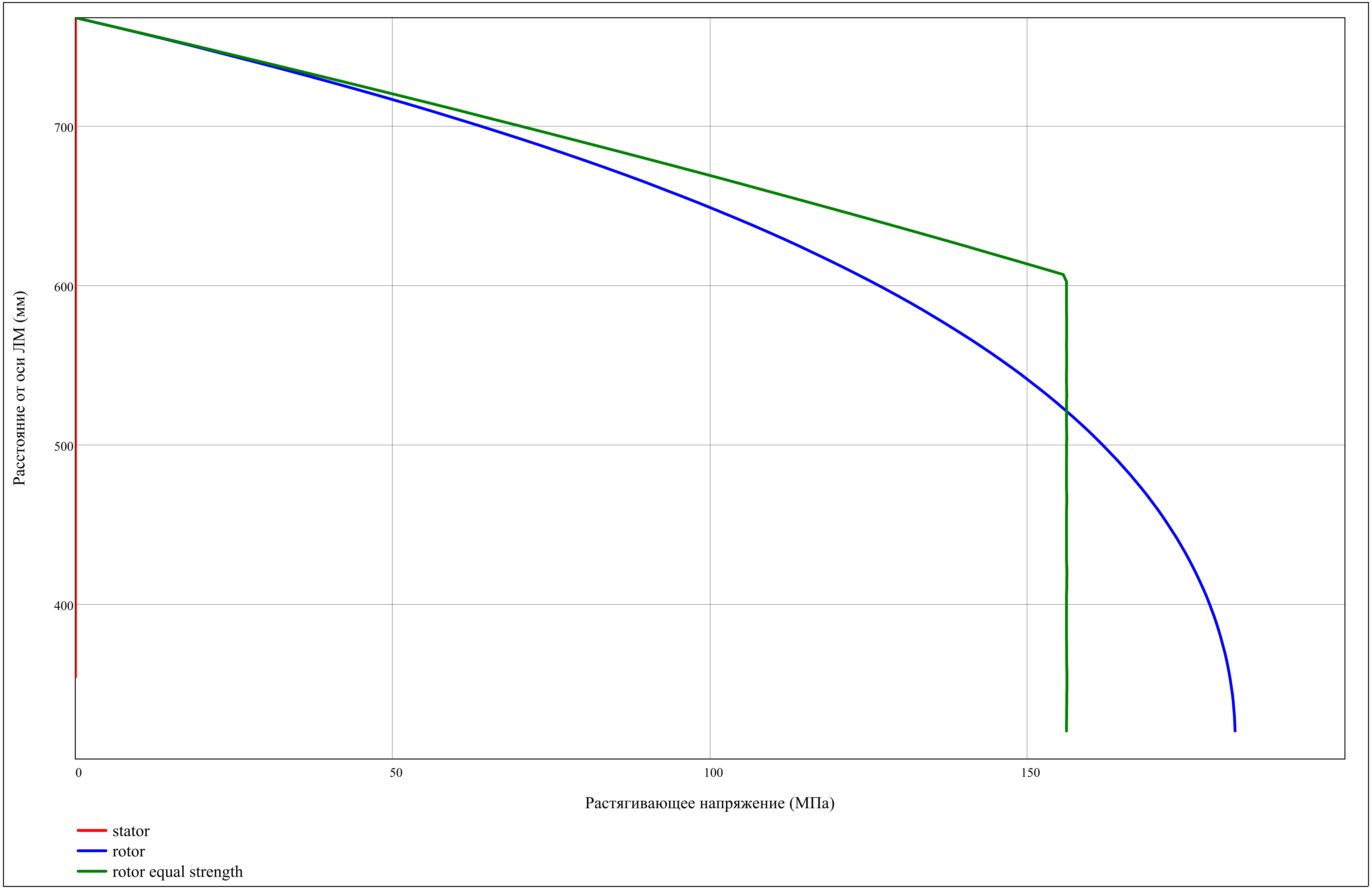
Результаты расчета на прочность Л

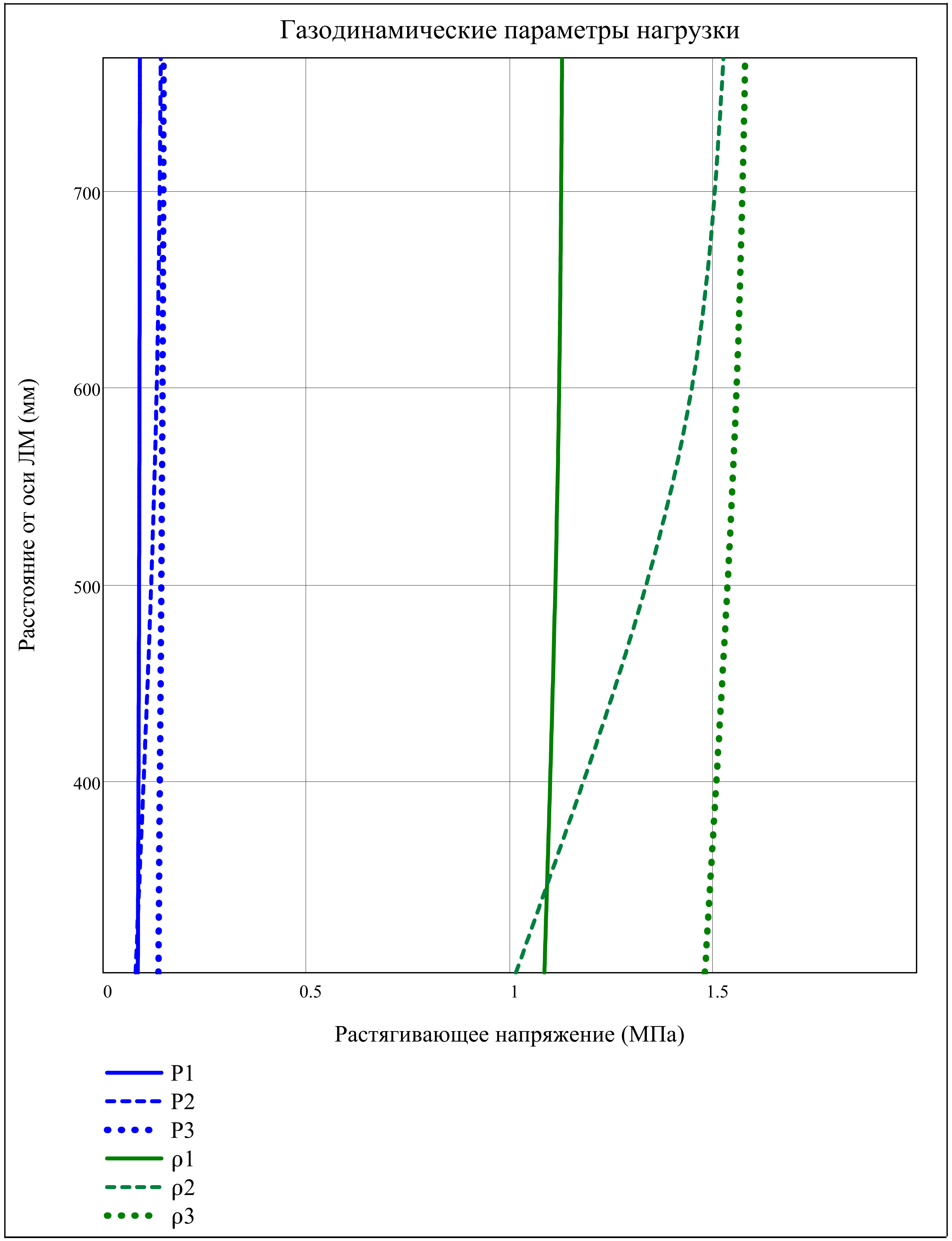


700
600
500
400
Расстояние от оси ЛМ (мм)
0
1000
2000
Площадь поперечного сечения Л (мм^2)
stator
rotor
rotor equal strength

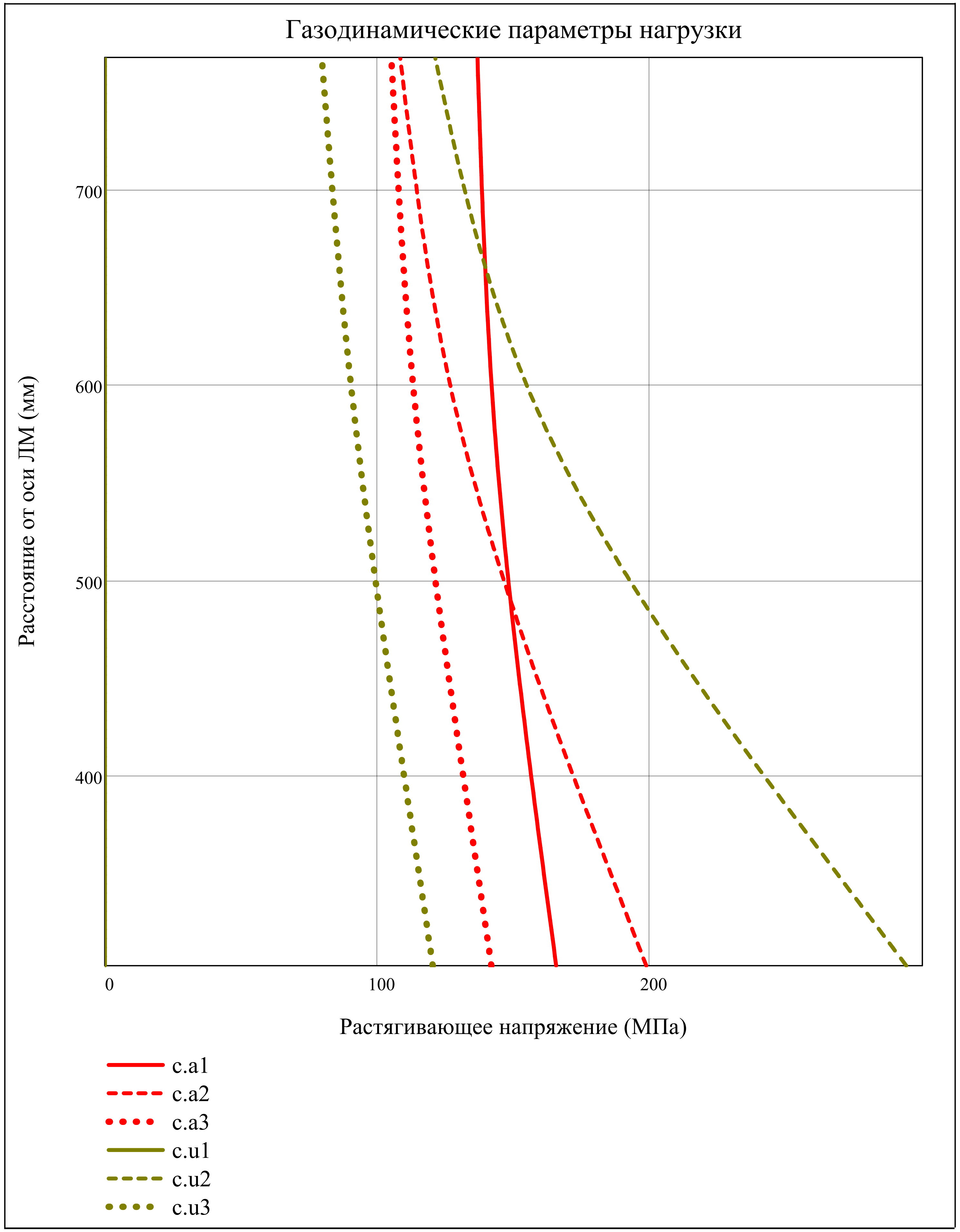


700
600
500
400
Расстояние от оси ЛМ (мм)
0
100
200
300
400
Растягивающая сила (кН)
stator
rotor
rotor equal strength

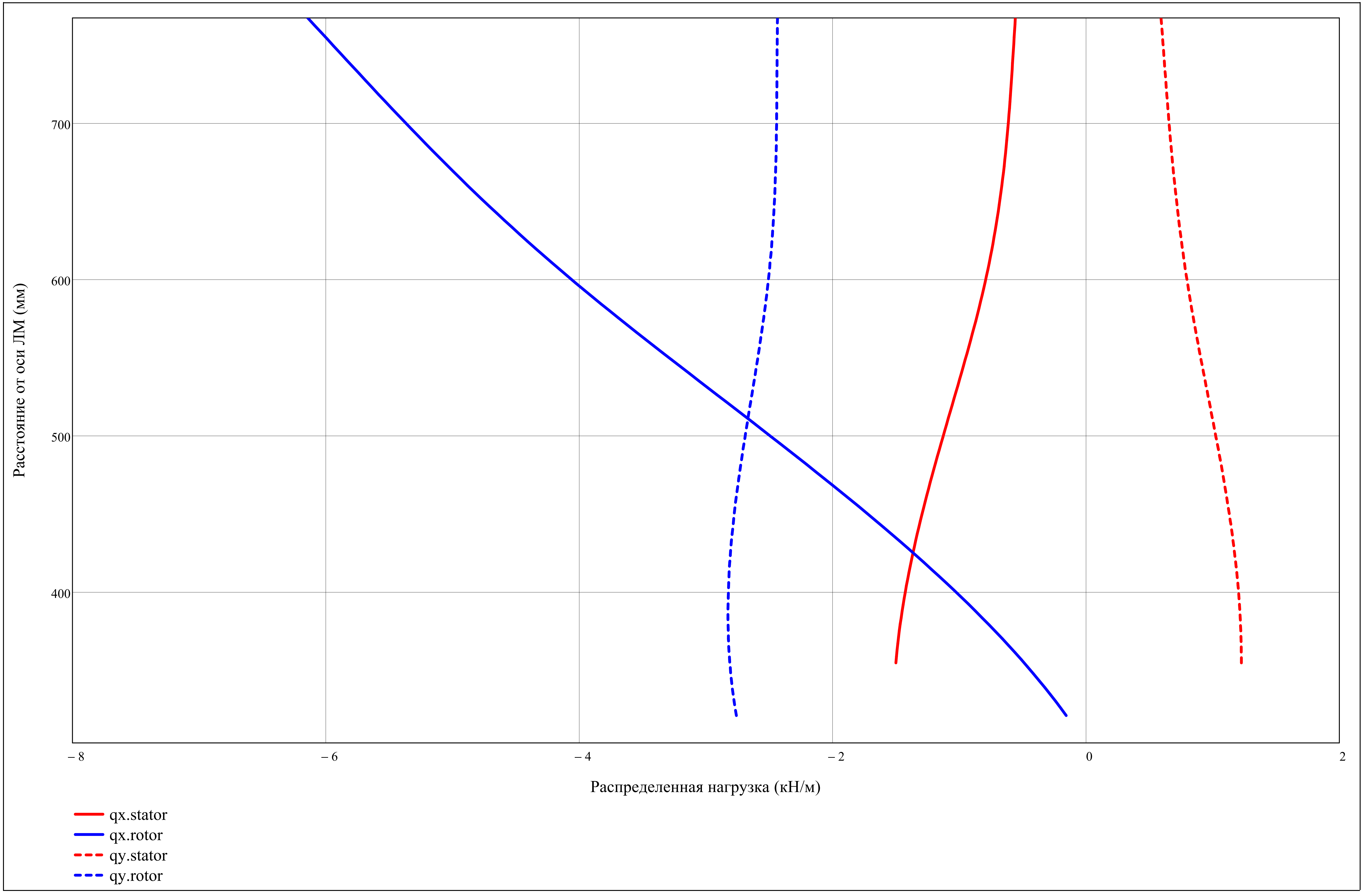

Расстояние от оси ЛМ (мм)
700
600
500
400
0
50
100
150
Растягивающее напряжение (МПа)
stator
rotor
rotor equal strength



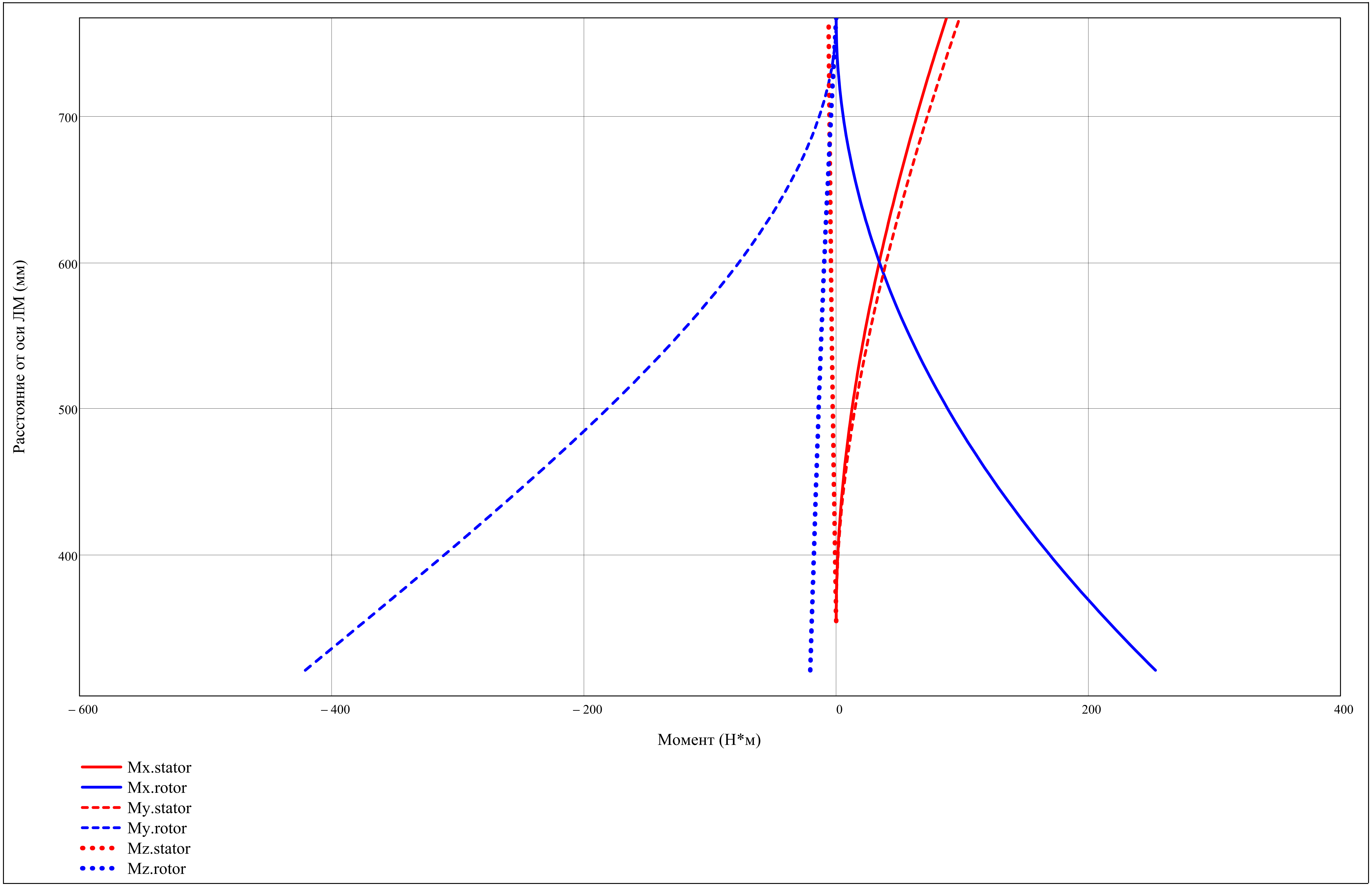
Газодинамические параметры нагрузки

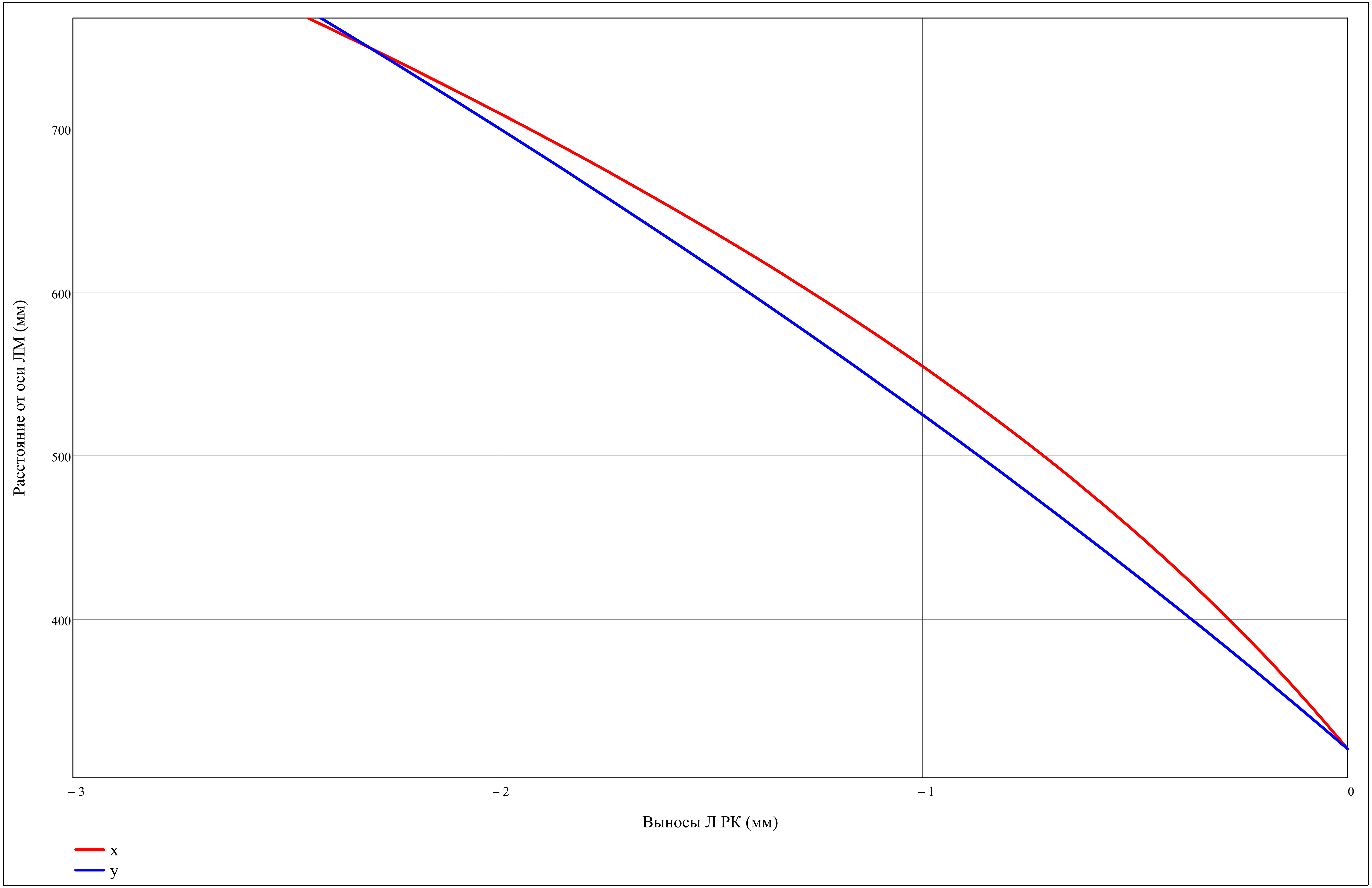


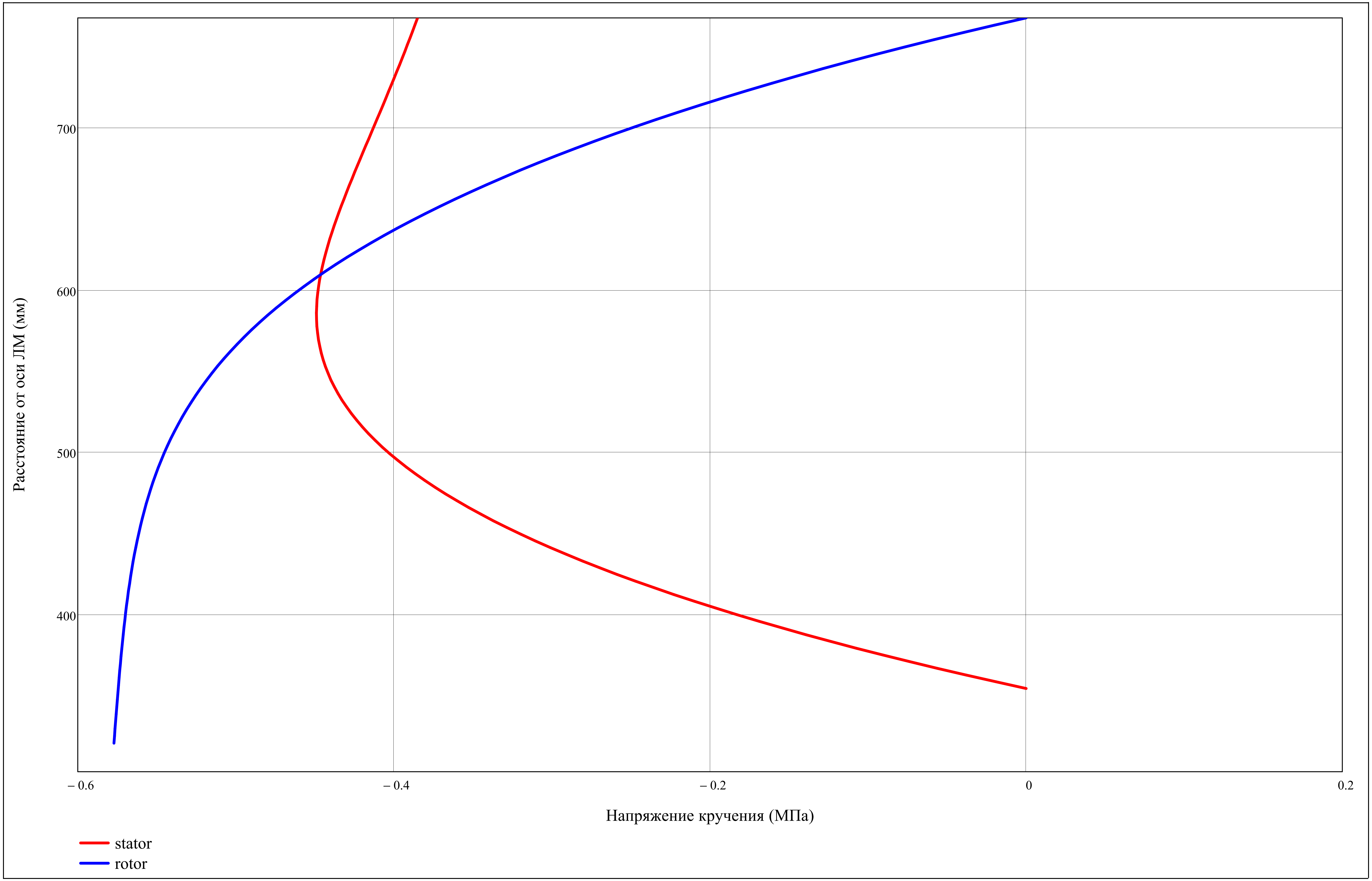
Газодинамические параметры нагрузки



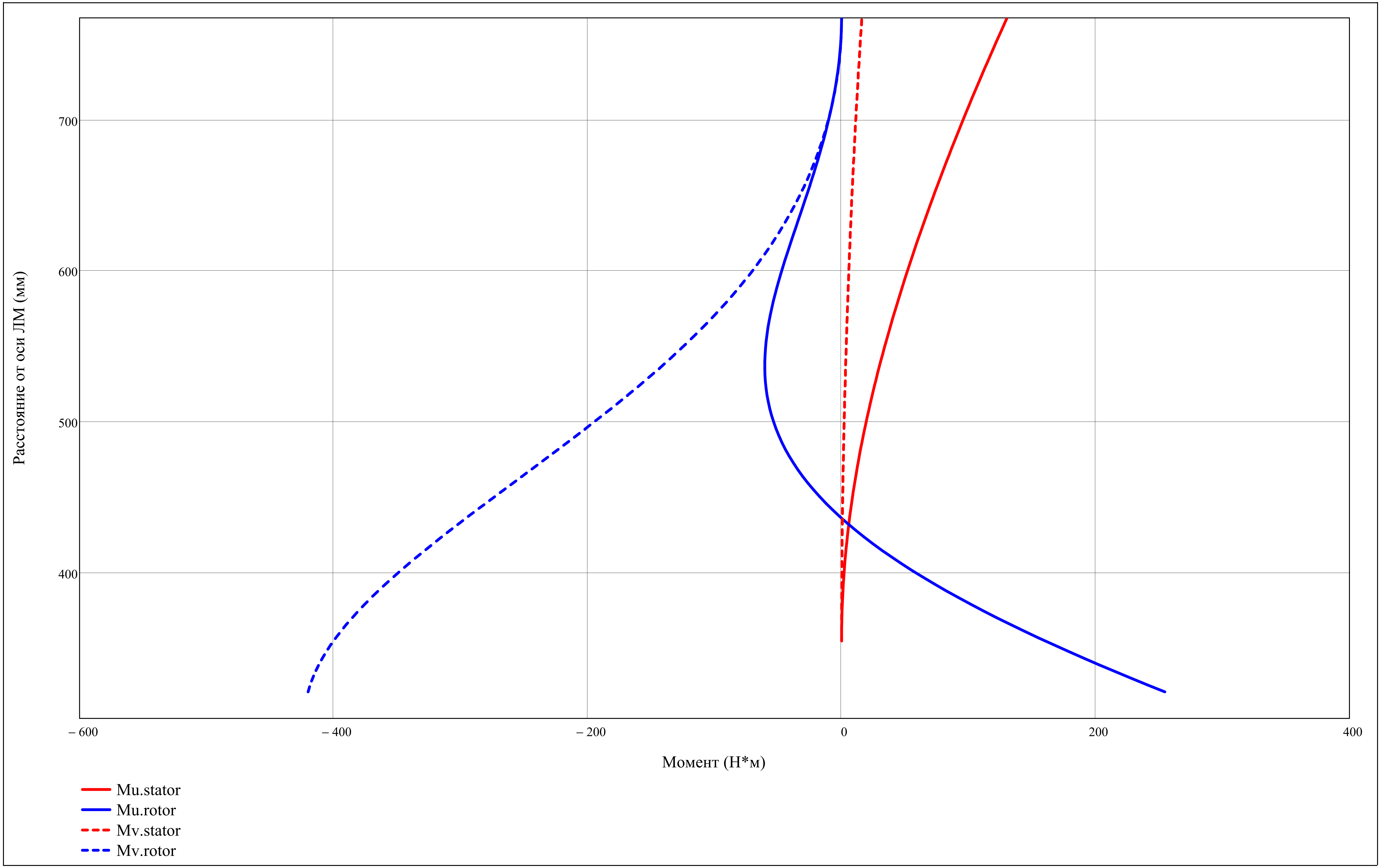
Расстояние от оси ЛМ (мм)
700
600
500
400
– 8
– 6
– 4
– 2
0
2
Распределенная нагрузка (кН/м)
qx.stator
qx.rotor
qy.stator
qy.rotor


Расстояние от оси ЛМ (мм)
700
600
500
400
– 600
– 400
– 200
0
200
400
Момент (Н*м)
Mx.stator
Mx.rotor
My.stator
My.rotor
Mz.stator
Mz.rotor

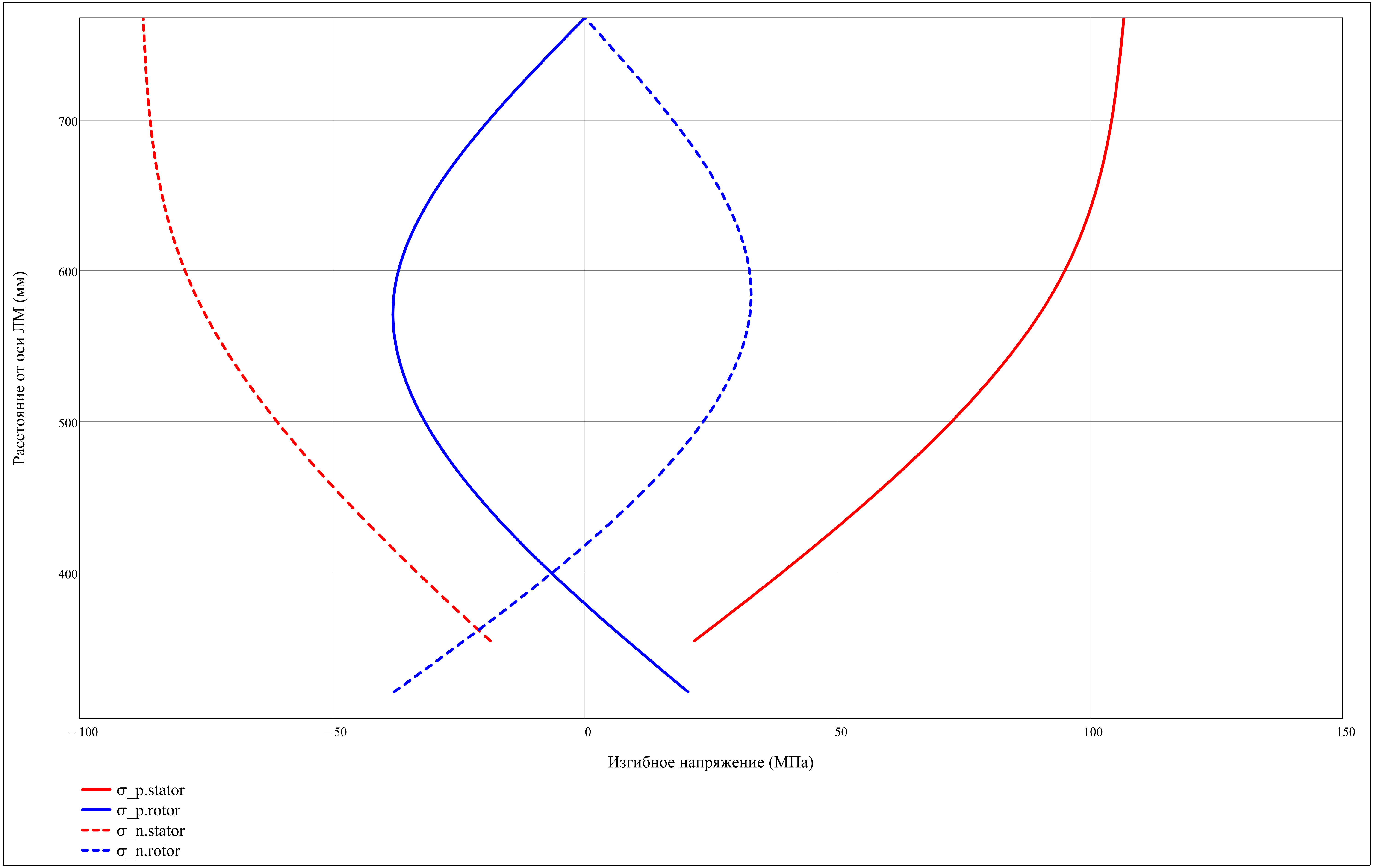

Расстояние от оси ЛМ (мм)
700
600
500
400
− 3
− 2
− 1
0
Выносы Л РК (мм)
x
y

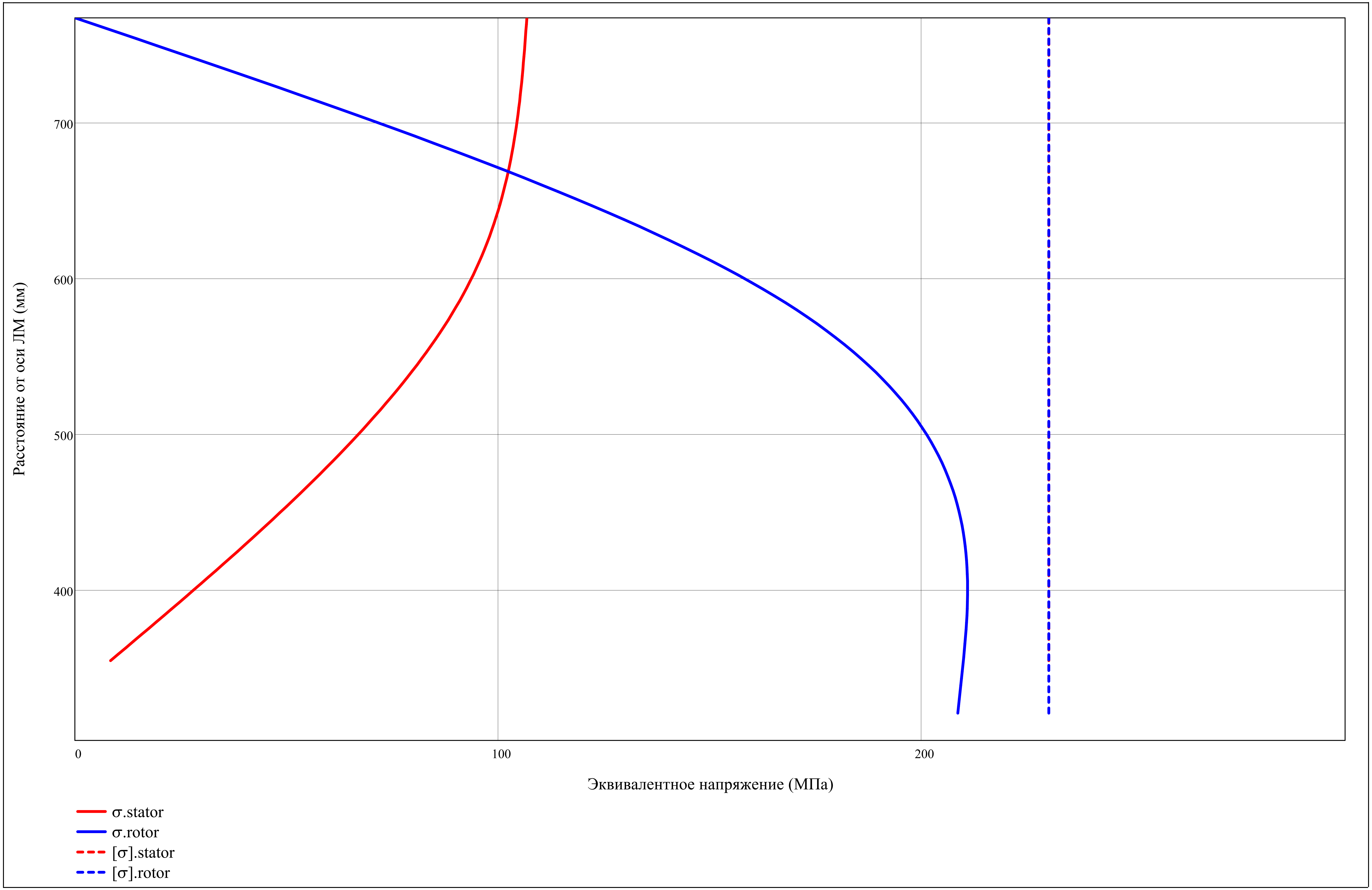


700
600
500
400
Расстояние от оси ЛМ (мм)
– 0.6
– 0.4
– 0.2
0
0.2
Напряжение кручения (МПа)
stator
rotor



700
600
500
400
Расстояние от оси ЛМ (мм)
– 600
– 400
– 200
0
200
400
Момент (Н*м)
Mu.stator
Mu.rotor
Mv.stator
Mv.rotor


Расстояние от оси ЛМ (мм)
700
600
500
400
– 100
– 50
0
50
100
150
Изгибное напряжение (МПа)
σ_p.stator
σ_p.rotor
σ_n.stator
σ_n.rotor


Расстояние от оси ЛМ (мм)
700
600
500
400
0
100
200
Эквивалентное напряжение (МПа)
σ.stator
σ.rotor
[σ].stator
[σ].rotor

$$\begin{pmatrix} \text{blade} \\ r \end{pmatrix} = \begin{pmatrix} \text{"rotor"} \\ 1 \end{pmatrix}$$

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	7.22	16.33
2	-59.37	-22.71
3	-0.17	2.70
4	65.31	-3.63

$\cdot 10^{-3}$

Изгибные напряжения (Па):

$$\begin{pmatrix} \sigma\_p_{rotor_{j,r}} & \sigma\_p_{stator_{j,r}} \\ \sigma\_n_{rotor_{j,r}} & \sigma\_n_{stator_{j,r}} \end{pmatrix} = \begin{pmatrix} 27 & 1 \\ -45 & -2 \end{pmatrix} \cdot 10^{6}$$

Эквивалентные напряжения (Па):

$$\begin{pmatrix} \sigma_{stator_{j,r}} \\ \sigma_{rotor_{j,r}} \end{pmatrix} = \begin{pmatrix} 1 \\ 209 \end{pmatrix} \cdot 10^{6}$$

Коэф. запаса:

$$\begin{pmatrix} \text{safety}_{stator_{j,r}} \\ \text{safety}_{rotor_{j,r}} \end{pmatrix} =$$

	1
1	175.344
2	1.100

$$\begin{pmatrix} v\_p \\ v\_n \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} v\_u_{rotor_{j,r}} \\ v\_l_{rotor_{j,r}} \end{pmatrix} & \text{if blade = "rotor"} \\ \begin{pmatrix} v\_u_{stator_{j,r}} \\ v\_l_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. =$$

	1
1	16.326
2	-22.714

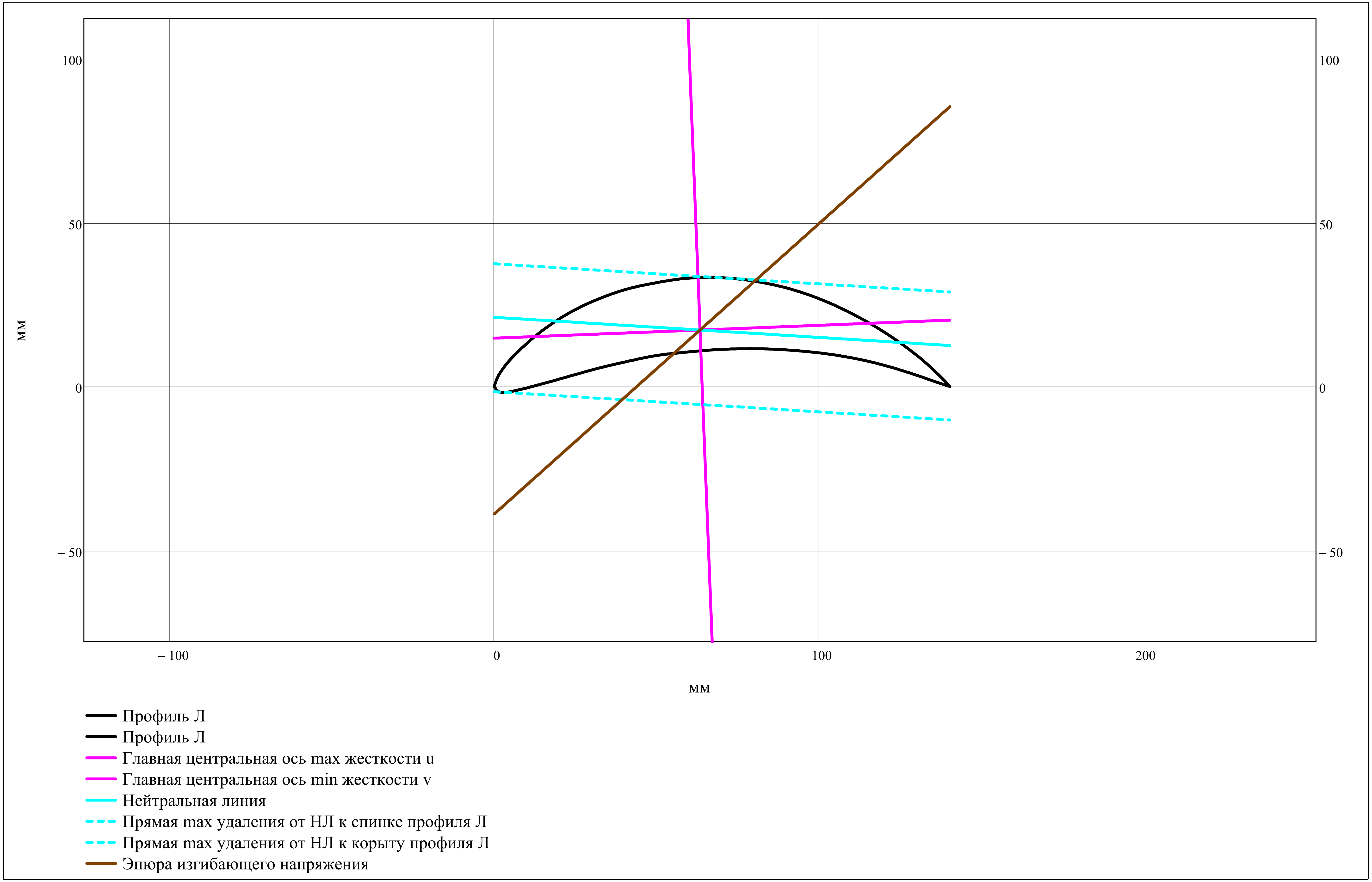
$\cdot 10^{-3}$

$$\begin{pmatrix} x0 \\ y0 \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} x0_{rotor_{j,r}} \\ y0_{rotor_{j,r}} \end{pmatrix} & \text{if blade = "rotor"} \\ \begin{pmatrix} x0_{stator_{j,r}} \\ y0_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. =$$

	1
1	63.459
2	17.233

$\cdot 10^{-3}$

$$\text{chord} = \left| \begin{array}{ll} \text{chord}_{rotor_{j,r}} & \text{if blade = "rotor"} \\ \text{chord}_{stator_{j,r}} & \text{if blade = "stator"} \end{array} \right. = 141 \cdot 10^{-3}$$


100
50
0
– 50
100
50
0
– 50
мм
– 100
0
100
200
мм
Профиль Л
Профиль Л
Главная центральная ось max жесткости u
Главная центральная ось min жесткости v
Нейтральная линия
Прямая max удаления от НЛ к спинке профиля Л
Прямая max удаления от НЛ к корыту профиля Л
Эпюра изгибающего напряжения

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

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	-3.27	5.98
2	82.74	-4.65
3	-1.52	4.13
4	-46.90	-3.46

$\cdot 10^{-3}$

Изгибные напряжения (Па):

$$\begin{pmatrix} \sigma\_p_{rotor_{j,r}} & \sigma\_p_{stator_{j,r}} \\ \sigma\_n_{rotor_{j,r}} & \sigma\_n_{stator_{j,r}} \end{pmatrix} = \begin{pmatrix} -38 & 92 \\ 33 & -77 \end{pmatrix} \cdot 10^{6}$$

Эквивалентные напряжения (Па):

$$\begin{pmatrix} \sigma_{stator_{j,r}} \\ \sigma_{rotor_{j,r}} \end{pmatrix} = \begin{pmatrix} 92 \\ 163 \end{pmatrix} \cdot 10^{6}$$

Коэф. запаса: $\begin{pmatrix} safety_{stator_{j,r}} \\ safety_{rotor_{j,r}} \end{pmatrix} =$

	1
1	2.491
2	1.415

$$\begin{pmatrix} v\_p \\ v\_n \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} v\_u_{rotor_{j,r}} \\ v\_l_{rotor_{j,r}} \end{pmatrix} & \text{if blade = "rotor"} \\ \begin{pmatrix} v\_u_{stator_{j,r}} \\ v\_l_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. =$$

	1
1	5.980
2	-4.647

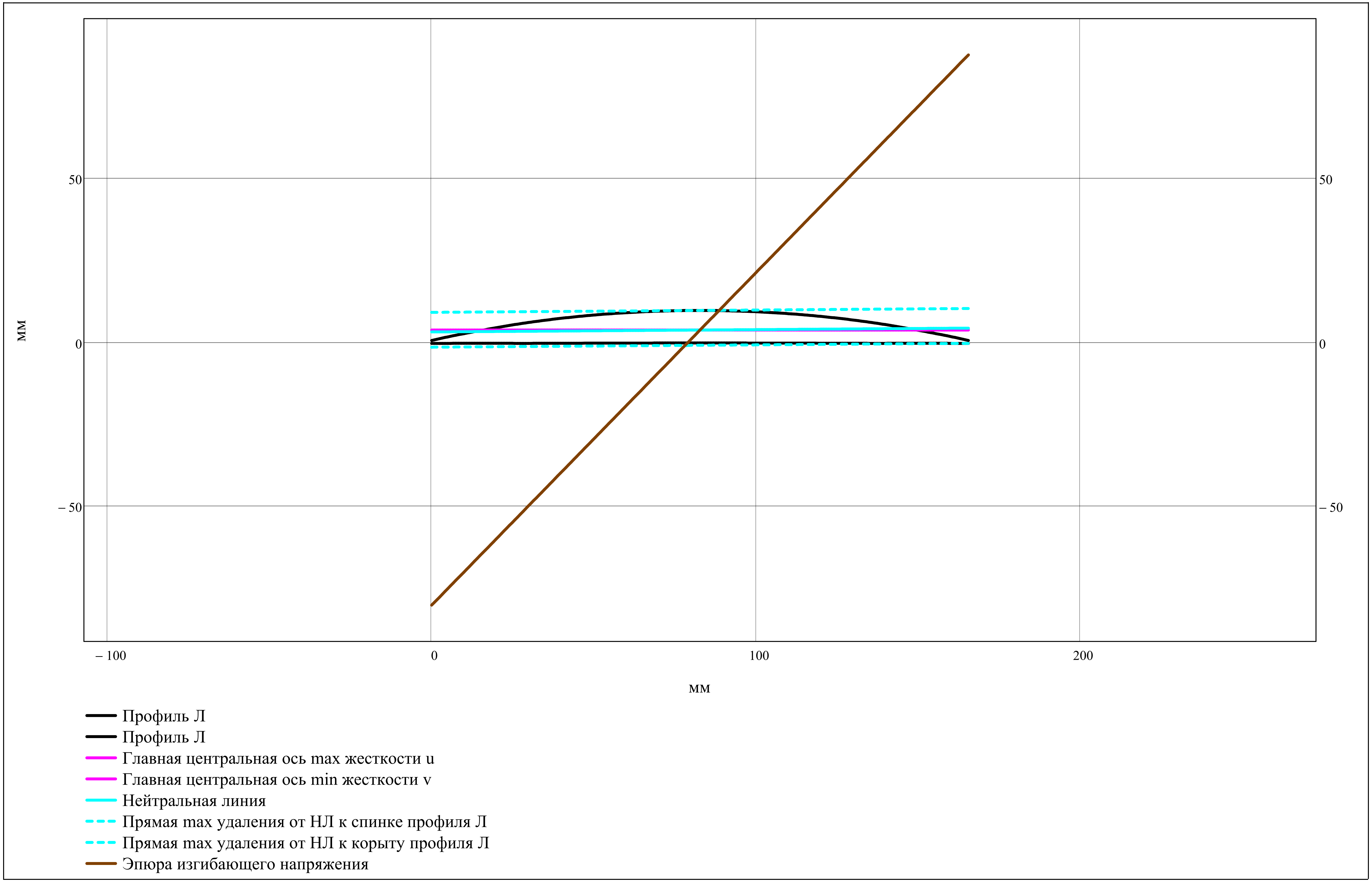
$\cdot 10^{-3}$

$$\begin{pmatrix} x0 \\ y0 \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} x0_{rotor_{j,r}} \\ y0_{rotor_{j,r}} \end{pmatrix} & \text{if blade = "rotor"} \\ \begin{pmatrix} x0_{stator_{j,r}} \\ y0_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. =$$

	1
1	82.768
2	3.616

$\cdot 10^{-3}$

$$chord = \left| \begin{array}{ll} chord_{rotor_{j,r}} & \text{if blade = "rotor"} \\ chord_{stator_{j,r}} & \text{if blade = "stator"} \end{array} \right. = 166 \cdot 10^{-3}$$


50
0
– 50
50
0
– 50
– 100
0
100
200
мм
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

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

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	-3.27	5.98
2	82.74	-4.65
3	-1.52	4.13
4	-46.90	-3.46

$\cdot 10^{-3}$

Изгибные напряжения (Па):

$$\begin{pmatrix} \sigma\_p_{rotor_{j,r}} & \sigma\_p_{stator_{j,r}} \\ \sigma\_n_{rotor_{j,r}} & \sigma\_n_{stator_{j,r}} \end{pmatrix} = \begin{pmatrix} -38 & 92 \\ 33 & -77 \end{pmatrix} \cdot 10^{6}$$

Эквивалентные напряжения (Па):

$$\begin{pmatrix} \sigma_{stator_{j,r}} \\ \sigma_{rotor_{j,r}} \end{pmatrix} = \begin{pmatrix} 92 \\ 163 \end{pmatrix} \cdot 10^{6}$$

Коэф. запаса: $\begin{pmatrix} safety_{stator_{j,r}} \\ safety_{rotor_{j,r}} \end{pmatrix} =$

	1
1	2.491
2	1.415

$$\begin{pmatrix} v\_p \\ v\_n \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} v\_u_{rotor_{j,r}} \\ v\_l_{rotor_{j,r}} \end{pmatrix} & \text{if } blade = \text{"rotor"} \\ \begin{pmatrix} v\_u_{stator_{j,r}} \\ v\_l_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. =$$

	1
1	4.132
2	-3.463

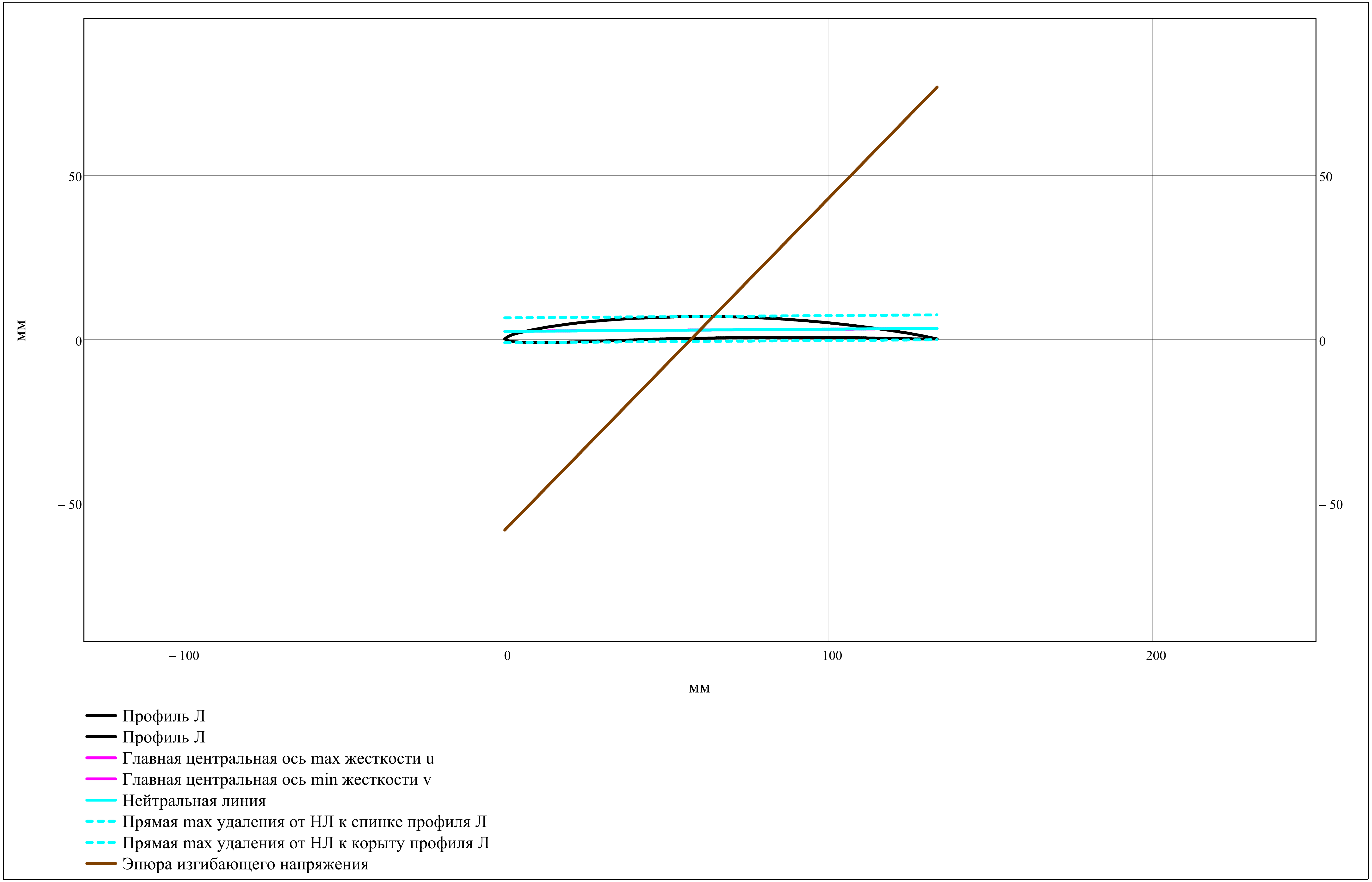
$\cdot 10^{-3}$

$$\begin{pmatrix} x0 \\ y0 \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} x0_{rotor_{j,r}} \\ y0_{rotor_{j,r}} \end{pmatrix} & \text{if } blade = \text{"rotor"} \\ \begin{pmatrix} x0_{stator_{j,r}} \\ y0_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. =$$

	1
1	60.200
2	2.720

$\cdot 10^{-3}$

$$chord = \left| \begin{array}{ll} chord_{rotor_{j,r}} & \text{if } blade = \text{"rotor"} \\ chord_{stator_{j,r}} & \text{if } blade = \text{"stator"} \end{array} \right. = 133 \cdot 10^{-3}$$


50
0
– 50
50
0
– 50
мм
– 100
0
100
200
мм
Профиль Л
Профиль Л
Главная центральная ось max жесткости u
Главная центральная ось min жесткости v
Нейтральная линия
Прямая max удаления от НЛ к спинке профиля Л
Прямая max удаления от НЛ к корыту профиля Л
Эпюра изгибающего напряжения

$$\begin{pmatrix} blade \\ r \end{pmatrix} = \begin{pmatrix} \text{"stator"} \\ 3 \end{pmatrix}$$

Наиболее удаленные точки от НЛ (мм):

$$\begin{pmatrix} u\_u_{rotor_{j,r}} & v\_u_{rotor_{j,r}} \\ u\_l_{rotor_{j,r}} & v\_l_{rotor_{j,r}} \\ u\_u_{stator_{j,r}} & v\_u_{stator_{j,r}} \\ u\_l_{stator_{j,r}} & v\_l_{stator_{j,r}} \end{pmatrix} = \text{[table]} \cdot 10^{-3}$$

	1	2
1	-0.31	91.33
2	-0.80	-91.33
3	-3.05	5.78
4	-40.30	-4.76

Изгибные напряжения (Па):

$$\begin{pmatrix} \sigma\_p_{rotor_{j,r}} & \sigma\_p_{stator_{j,r}} \\ \sigma\_n_{rotor_{j,r}} & \sigma\_n_{stator_{j,r}} \end{pmatrix} = \begin{pmatrix} 0 & 107 \\ 0 & -87 \end{pmatrix} \cdot 10^{6}$$

Эквивалентные напряжения (Па):

$$\begin{pmatrix} \sigma_{stator_{j,r}} \\ \sigma_{rotor_{j,r}} \end{pmatrix} = \begin{pmatrix} 107 \\ 0 \end{pmatrix} \cdot 10^{6}$$

Коэф. запаса: $\begin{pmatrix} safety_{stator_{j,r}} \\ safety_{rotor_{j,r}} \end{pmatrix} =$

	1
1	2.155
2	00000000000000000000000000000.0

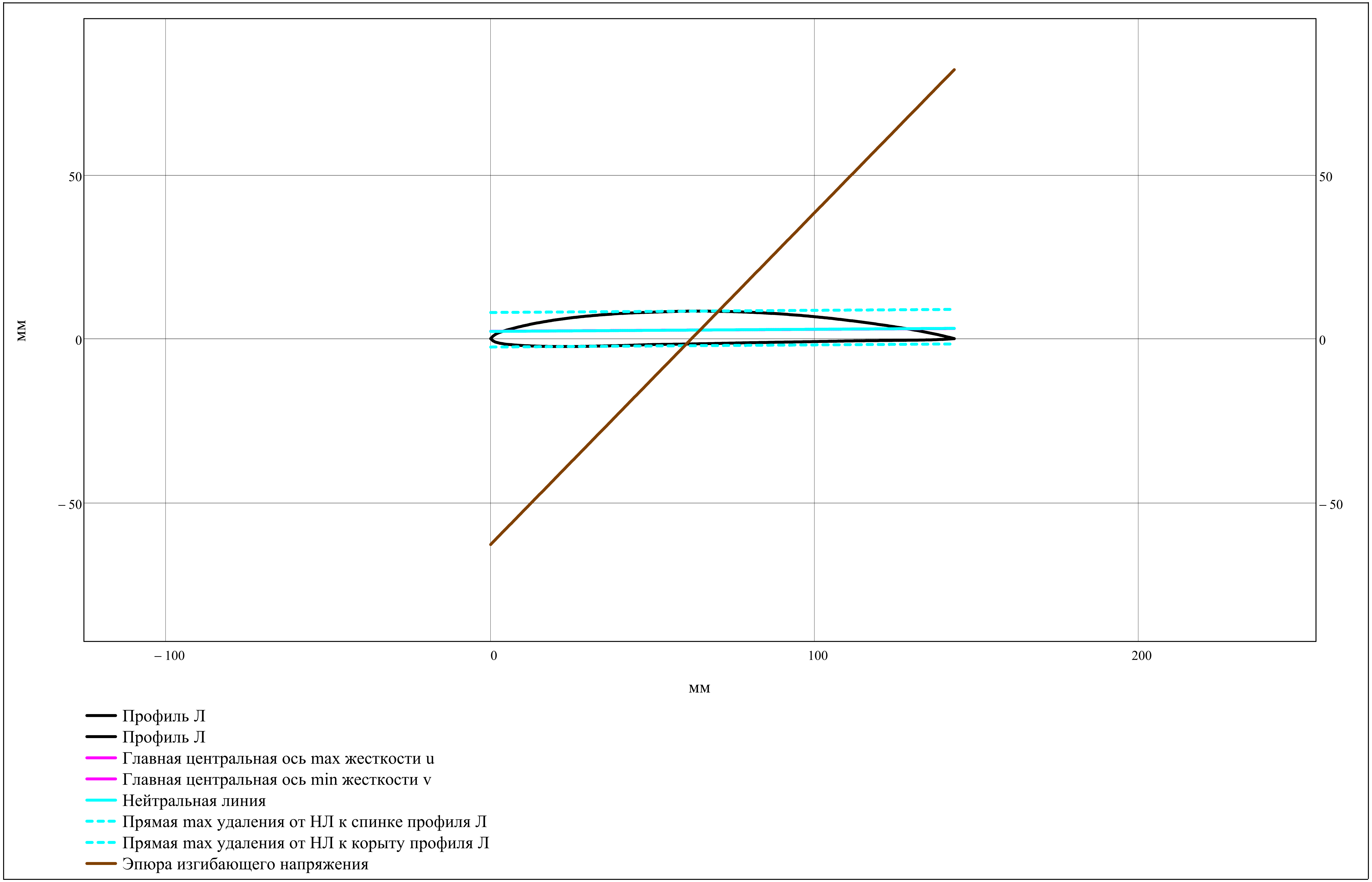
$$\begin{pmatrix} y\_p \\ y\_n \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} v\_u_{rotor_{j,r}} \\ v\_l_{rotor_{j,r}} \end{pmatrix} & \text{if } blade = \text{"rotor"} \\ \begin{pmatrix} v\_u_{stator_{j,r}} \\ v\_l_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. = \text{[table]} \cdot 10^{-3}$$

	1
1	5.778
2	-4.764

$$\begin{pmatrix} x0 \\ y0 \end{pmatrix} = \left| \begin{array}{ll} \begin{pmatrix} x0_{rotor_{j,r}} \\ y0_{rotor_{j,r}} \end{pmatrix} & \text{if } blade = \text{"rotor"} \\ \begin{pmatrix} x0_{stator_{j,r}} \\ y0_{stator_{j,r}} \end{pmatrix} & \text{otherwise} \end{array} \right. = \text{[table]} \cdot 10^{-3}$$

	1
1	64.573
2	2.637

$$chord = \left| \begin{array}{ll} chord_{rotor_{j,r}} & \text{if } blade = \text{"rotor"} \\ chord_{stator_{j,r}} & \text{if } blade = \text{"stator"} \end{array} \right. = 143 \cdot 10^{-3}$$



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	"ВТ23"								

$\rho\_disk^T =$

	1
1	4570

$\sigma\_disk\_long^T =$

	1
1	230

$\cdot 10^6$

▲ Выбор материала Д

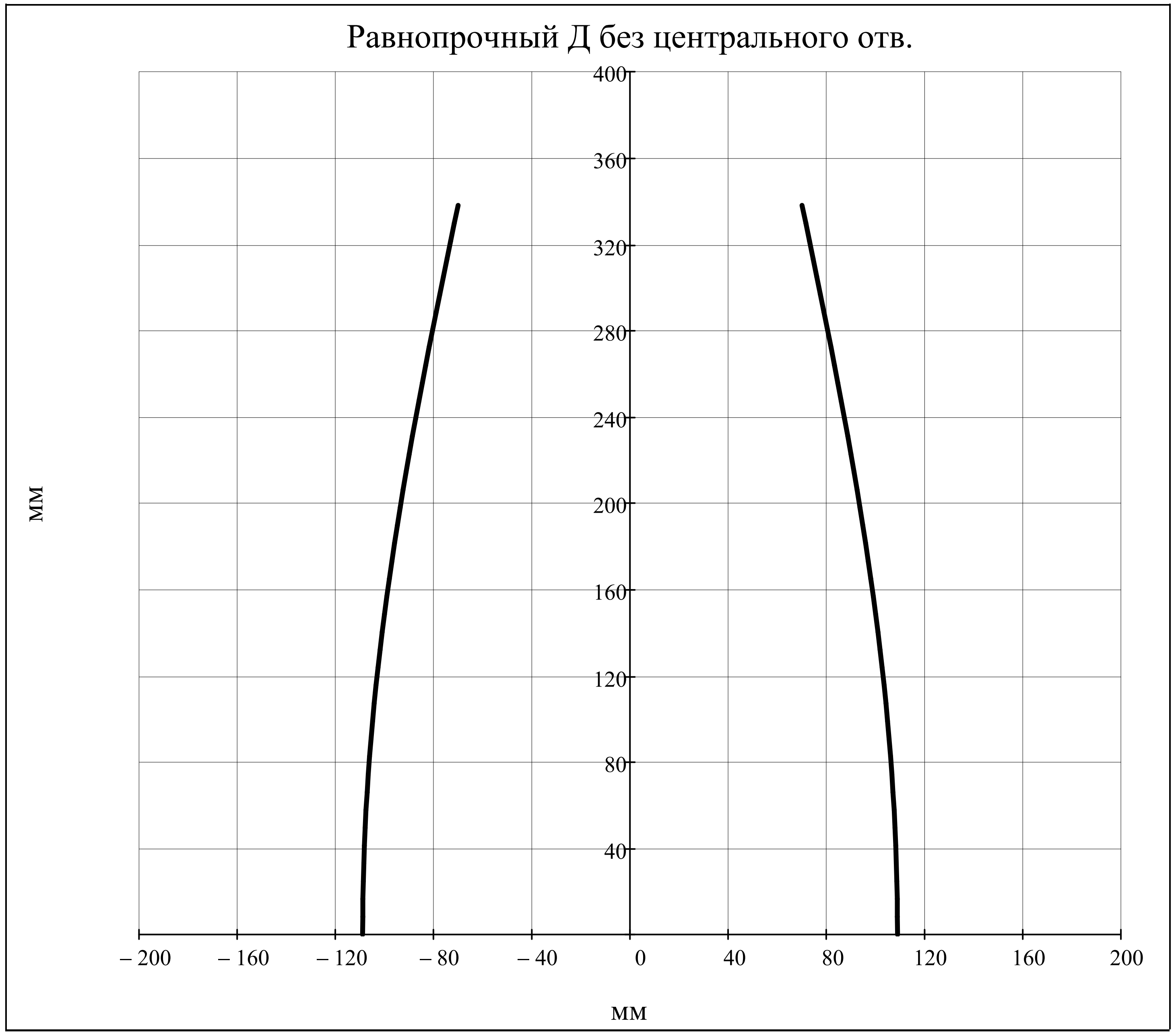
Рассматриваемая ступень:

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

▼ Профилирование равнопрочного Д без центрального отв.

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

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



▲ Профилирование равнопрочного Д без центрального отв.

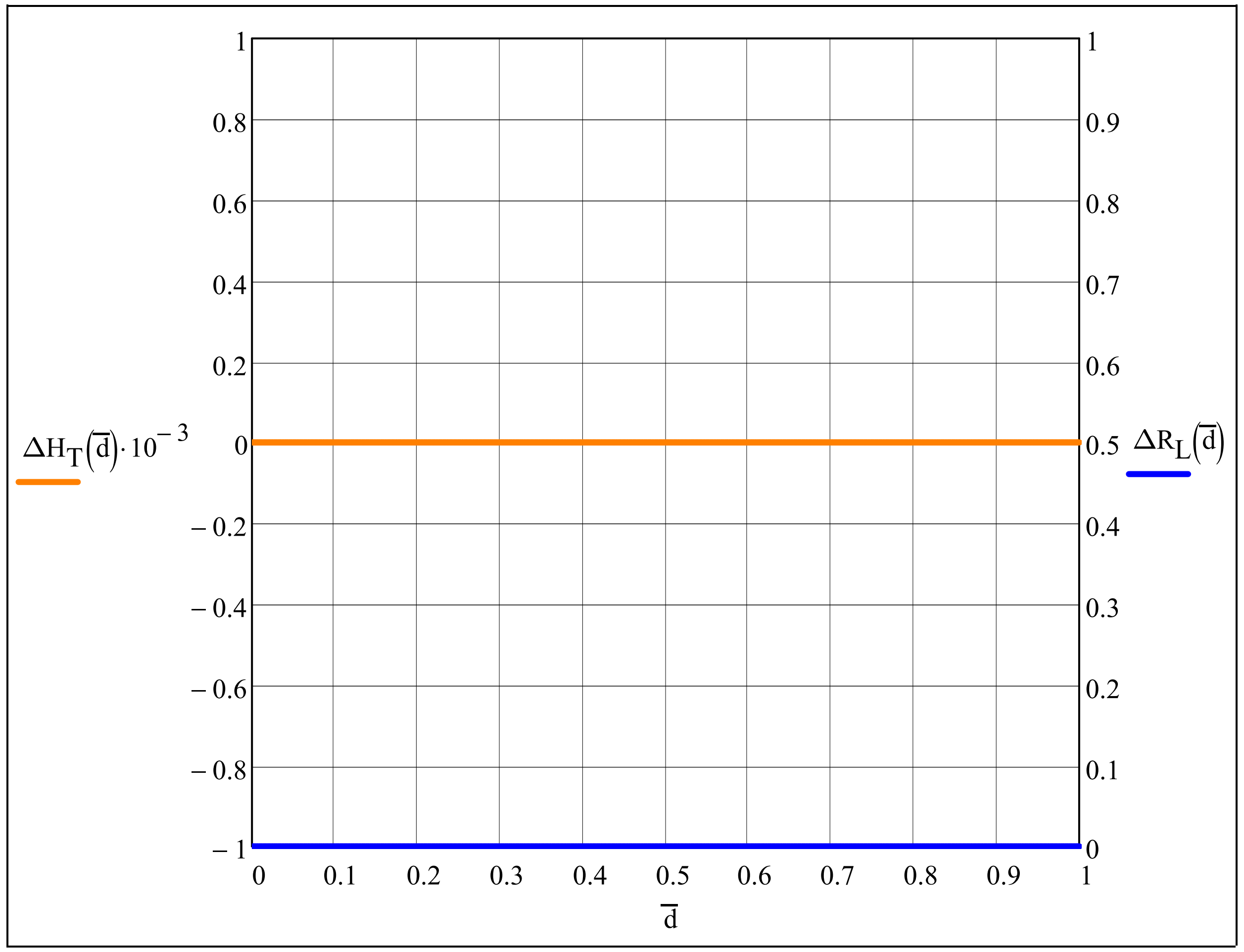
Max разница теор. напора ступени и реактивности от периферии к корню по высоте Л (Дж/кг) [16, с.118-119]:

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

$\Delta R_{Lmax} = 0.0$

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

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



$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 165.58 \\ 333.69 \\ 175.76 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 165.58 \\ 188.89 \\ 134.63 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 235.98 \\ 208.15 \\ 163.39 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 90.00 \\ 34.48 \\ 49.99 \end{pmatrix} \cdot {}^{\circ}$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 168.13 \\ 187.64 \\ 205.57 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 44.56 \\ 114.84 \\ 55.48 \end{pmatrix} \cdot {}^{\circ}$$

$$\varepsilon_{stator_{j,r}} = 15.52 \cdot {}^{\circ}$$

$$\varepsilon_{rotor_{j,r}} = 70.28 \cdot {}^{\circ}$$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 142.69 \\ 202.3 \\ 144.39 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 142.69 \\ 127.78 \\ 112.87 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 353.85 \\ 214.5 \\ 269.19 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 90 \\ 39.17 \\ 51.42 \end{pmatrix} \cdot ^{\circ}$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 323.8 \\ 329.11 \\ 334.43 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 23.78 \\ 36.56 \\ 24.79 \end{pmatrix} \cdot ^{\circ}$$

$$\varepsilon_{stator_{j,r}} = 12.25 \cdot ^{\circ}$$

$$\varepsilon_{rotor_{j,r}} = 12.78 \cdot ^{\circ}$$

$$\begin{pmatrix} c_{st(j,1),r} \\ c_{st(j,2),r} \\ c_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 136.69 \\ 162.54 \\ 131.80 \end{pmatrix}$$

$$\begin{pmatrix} c_{a_{st(j,1),r}} \\ c_{a_{st(j,2),r}} \\ c_{a_{st(j,3),r}} \end{pmatrix} = \begin{pmatrix} 136.69 \\ 108.33 \\ 105.08 \end{pmatrix}$$

$$\begin{pmatrix} w_{st(j,1),r} \\ w_{st(j,2),r} \\ w_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 447.33 \\ 323.44 \\ 361.97 \end{pmatrix}$$

$$\begin{pmatrix} \alpha_{st(j,1),r} \\ \alpha_{st(j,2),r} \\ \alpha_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 90 \\ 41.8 \\ 52.87 \end{pmatrix} \cdot °$$

$$\begin{pmatrix} u_{st(j,1),r} \\ u_{st(j,2),r} \\ u_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 425.94 \\ 425.94 \\ 425.94 \end{pmatrix}$$

$$\begin{pmatrix} \beta_{st(j,1),r} \\ \beta_{st(j,2),r} \\ \beta_{st(j,3),r} \end{pmatrix} = \begin{pmatrix} 17.79 \\ 19.57 \\ 16.88 \end{pmatrix} \cdot °$$

$$\varepsilon_{stator_{j,r}} = 11.07 \cdot °$$

$$\varepsilon_{rotor_{j,r}} = 1.78 \cdot °$$

MM

MM

$,z\big)$

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

$^{-3}$

7	8	9