WORKBOOK
AERODYNAMIC OF AIRCRAFT

LUBLIN 2014

KAPITAŁ LUDZKI
NARODOWA STRATEGIA SPÓJNOŚCI

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First edition

1. LOADING THE AREA OF THE DISC OF A ROTOR AND LOADING THE POWER

Basic characteristics of the model of a helicopter include so called loading of the area of a disc of a rotor p and loading of the power area q. The loading of the area of the disc of a rotor is the relation of the total weight of the whole model of a helicopter to the area of the disc of a bearing rotor, namely the area swept by the blades of the rotor. Thus, the loading of the area of the disc of a rotor p will be expressed with the following formula:

$$p = \frac{G}{S} = \frac{G}{\pi * R^2} \quad [kG/m^2] \qquad (1)$$

with whereas:

G – weight of the model [kG]

S – area of the disc of a rotor [m^2]

R – radiant of the rotor [m]

π = 3,14

The loading of the power q is the relation of the weight of the whole model of a helicopter to the power of the shaft of the bearing rotor, expressed with the formula:

$$q = \frac{G}{N} \quad [kG/KM] \qquad (2)$$

where:

G – weight of the model [kG]

N – power of the shaft of the rotor [KM]

One should emphasize exactly that N shall mean the power supplied to the bearing rotor, and not the power of a driver engine. In further considerations and calculations, it will be discussed broader. The pattern (3) defines so called unit sequence of a bearing rotor, namely developed with the power 1 KM, collected by the rotor:

$$q = \frac{T}{N} \quad [kG/KM] \qquad (3)$$

where:

T – pull of the rotor [kG]

One may write down the formula and the formula is correct, as in the hinge the weight of the model G must be balanced by the pull of the T rotor, whereas in the remaining conditions of the flight, the T pull is almost equal to the weight of the G model: T = G. Practically the unit pull q defines how many kilograms of weight, a given rotor in the hinge is able to hold with the power 1 KM (drawing 1).

Unit loading of the area swept p and unit loading of the power q are connected with a joint interdependence defining so called index of bearing rotor quality E on the sea level:

$$E = q\sqrt{p} \quad (4)$$

While making exact calculations of the achievements of the model one may use the formula (5) containing the index Δ, which includes the level above sea level:

$$E = q\sqrt{\frac{p}{\Delta}} \quad (5)$$

The values of indices Δ for different levels above sea level:

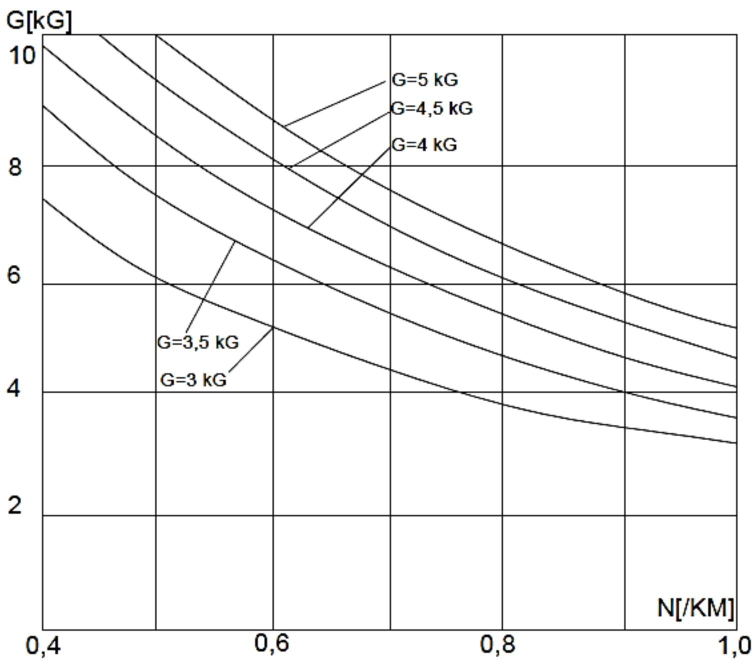
H[m]	0	250	500	75	1000
Δ	1,000	0,976	0,953	0,930	0,907

The quality index of the bearing rotor δ may also be expressed by means of the formula p and q, to obtain the pattern (6), correct on the sea level:

$$\delta = \frac{q\sqrt{p}}{37},5 \quad (6)$$

On any heights of the flight l the pattern will be correct after including the index Δ:

$$\delta = \frac{q\sqrt{\frac{p}{\Delta}}}{37},5 \quad (7)$$

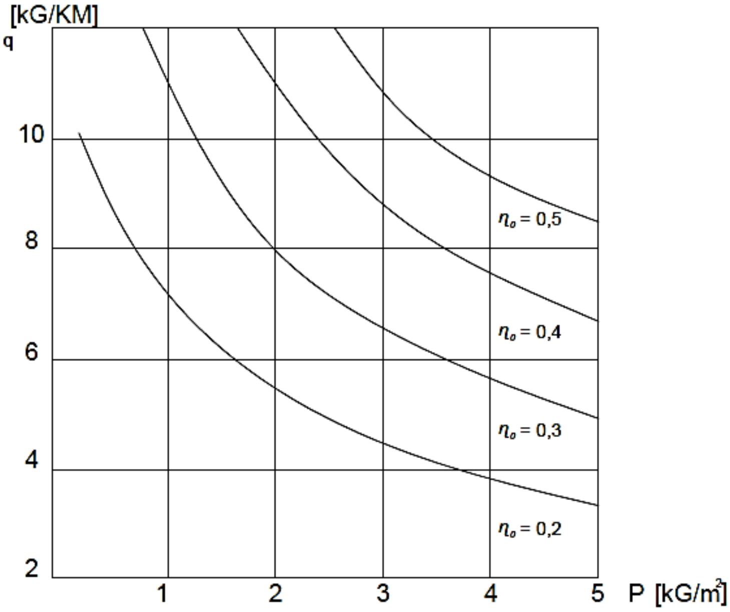


Drawing 1. Interdependence of power loading on the shaft of the rotor and weight of the model

or after including the patterns (4) or (5):

$$\delta = \frac{E}{37,5} \tag{8}$$

On the drawing 2 the outline of the course of changes in the index δ were presented depending on the loading of the area of the disc of the rotor p and loading of the power q. The outline corresponds to the pattern (6), i.e. the conditions on the sea level.



Drawing 2 The outline of changes depending on p and q for the conditions of the hinge is 5 kG, the area of the rotor area is - 3 m^2 , and the power collected by the rotor - 0,5 KM

2. THEORY OF ELEMENTARY PULLS

Our present considerations allowed only for approximate, initial defining basic characteristics of a rotor and a model, and did not give any idea about the methods of its designing. The application of elementary theories of pulls will allow for us to define more important features of the blades of a rotor, necessary to perform it.

In the considerations concerning the ideal rotor, to simplify we assumed that the velocities of an air stream along the whole radiant of the spade are equal. Then, for the real rotor we introduced an approximate value of $v_{i0\,śr}$. The theory of elementary pulls is not based on this type of assumptions, but introduces real velocities of the stream, occurring during the work of a bearing rotor.

Let us imagine that the spade of the rotor consists of a sufficient number of a „plaster" with respectively small thickness (drawing 3). Considering one of such "slices" - elements, we will obtain the profile set with reference to a define angle to the plane when the blades rotate. During the operation of the rotor, the profile moves with a progress velocity U equal to the multiple (ω*r), where ω – angle velocity of the rotor, whereas r – distance of "slice" from the centre of the rotor disc. At the same time, in case of a vertical movement, while lifting and falling, the profile performs the movement along the axis 0-0 with a velocity of V_0. Total vertical velocity of the air stream towards the profile V, will be equal to:

$$V_1 = V_0 + V_1 \quad [m/s] \qquad (9)$$

where:

V_0 - vertical velocity of the model - profile [m/s]

V_1 - induced velocity in the plane of the rotor disc [m/s]

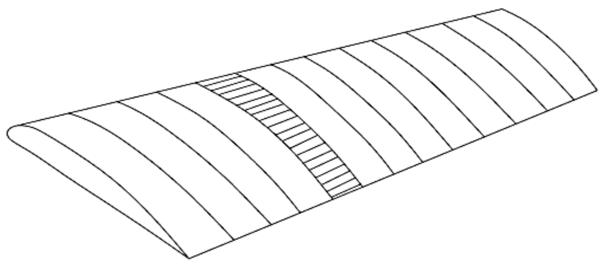
While marking on the drawing 4 the vertical velocity of the air influencing the profile by means of the vector (ω*r) directed contrary to the movement of the spade and adding both velocities we will obtain total velocity of the air flowing the profile W_1 :

$$W_1 = \sqrt{(\omega * r)^2 + V_1^2} \quad [m/s] \qquad (10)$$

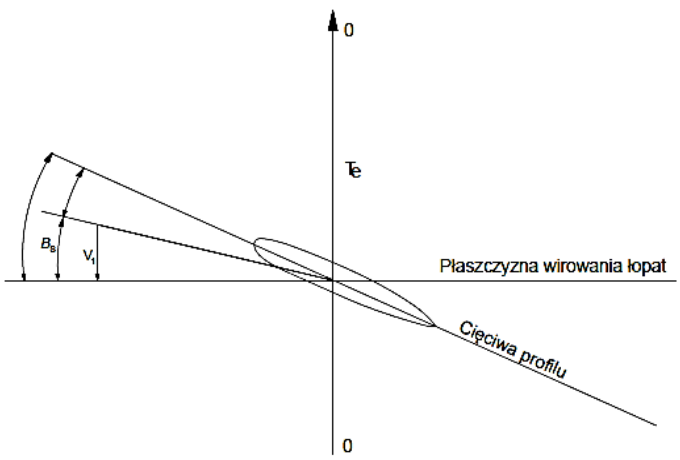
As the value of V_1^2 is very small in comparison to $(\omega * r)^2$, we can successfully admit that :

$$W_1 = \sqrt{(\omega * r)^2} = \omega * r \quad [m/s]$$

(11)



Drawing 3. Division of a bearing spade into elements



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Drawing 4. Characteristic angles and velocities occurring on the profile of the bearing spade

The angle β_e , contained between the air velocity direction W_1 and the plane of the rotor, called the relative flow angle. With sufficient exactness we can express it with a formula:

$$\beta_e = \frac{V_1}{\omega * \mathbf{r}} \quad \text{[rad]} \tag{12}$$

The value of the angle expressed in radians may be easily recalculated into the value in degrees, by multiplying by the common index amounting to 57,3:

$$\beta_e = 57{,}3 \frac{V_1}{\omega * \mathbf{r}} \quad [°] \tag{13}$$

The angle α_e , contained between the chord of the profile and the air direction flow, is the angle of attacking the element of the spade and in accordance with the drawing 4 it is:

$$\alpha_e = \varphi_e - \beta_e \quad \text{[rad]} \tag{14}$$

or

$$\alpha_e = \varphi_e - 57{,}3 \frac{V_1}{\omega * \mathbf{r}} \quad [°] \tag{15}$$

As we can see, on each separated sections (elements) of the spade, the air flows with a velocity of W_1 under the angle α_e . So this is obvious, that on each of these elements the elementary force will be created ΔP_z . It is also obvious that the total bearing force of the spade consists of the sum of these elementary bearing forces. In accordance with the principles of aerodynamics we can write:

$$\Delta P_z = C_{ze} \frac{\rho * W_1^2}{2} * S_e \quad \text{[kG]} \tag{16}$$

where:

ΔP_z - bearing force operating on the element of the spade

C_{ze} - index of the bearing force of the element of the spade – area of the spade element [m^2]

Taking into account that $W_1 = \omega * \mathbf{r}$ and assuming that the bearing force is approximately equal to the pull force, we will have:

$$T_e = C_{ze} \frac{\rho(\omega * r)^2}{2} * S_e \quad \text{[kG]} \tag{17}$$

In accordance with what we said previously, after summing all elementary pulls on one spade we can calculate the total pull of the bearing rotor having k spades:

$$\text{T} = \text{k}(T_{e1} + T_{e2} + \ldots T_{en}) = \text{k} * \sum \square * T_e \tag{18}$$

In order to include the index of the limit losses, elementary forces of pull T_e we will sum, starting from the radiant $r_{p,}$ and ending on the radiant $r_{k,}$. Due to this, only effective area S_{ef} of the rotor disc is included into calculation of the pull. Introducing the fulfillment index of the rotor disc σ and while making proper transformations we can obtain the formula for the pull index C_{Te} for one element of the spade, expressed with the aid of non-measurement values:

$$C_{Te} = C_{ze} * \sigma_e * \text{r}_e^{-2} \tag{19}$$

After summing elementary C_{Te} we will obtain the final value of the pull index for one whole spade. The same method may also be used to calculate the rotor moment index, summing elementary values C_{qe} calculated by means of the rotor:

C_{Qe} = $C_{ze}\cdot \bar{o}_e \cdot v_{1e} \cdot \acute{r} + C_{xpe} \cdot \bar{o}_e \cdot \acute{r}^3_e$ (20)

C_{Qe}= moment index acting on one element,

$\bar{o}_e$– fulfillment index of the rotor disc,

C_{ze}– index of the bearing force,

C_{xpe}– index of the profile resistance,

$\acute{r}_e$– relative radiant, on which the element is.

Elementary index of moment consists of two components, the first one defines the work intended for creation of a pull, the other – the work lost to overcome resistance, first of all the resistance of the profiles spades of the rotor. In order to calculate C_{Qe}, one should know the velocity V_1(for the flight with vertical velocity) or (the hinge). This is understandable as in the hinge the vertical velocity of the model $V_0 = 0$ and then $V_1 = v_i$ Velocity V_1 may be calculated while using one of the more important equations of aerodynamics of helicopters – so called continuance equation:

$$V_1 = \frac{V_0}{2} + \sqrt{\frac{V_0^2}{4} + \frac{1}{8} C_z * \sigma * r} \quad (21)$$

where:

V_1– total relative vertical velocity of air towards the rotor spade,

V_0– relative vertical velocity of the model.

One should explain here that the relative velocity (non-measurement) in a general sense is the relation of the basic velocity (i.e. in km/h or in m/s) to the multiple ω · r, namely to the peripheral velocities of the spades' endings:

$$V = \frac{V}{\omega * r} = \frac{V}{U} \quad (22)$$

As we said for the condition of the hinge of the model its vertical velocity is zero: $V_0 = 0$. As a result the relative velocity V_0 will be zero: $V_0 = 0$. In the situation, the continuance equation will be much simpler and will be s follows:

$$V_{10} = \sqrt{\frac{1}{8} C_z * \sigma * r} \quad (23)$$

In order to simplify the issue and allow to solve the tasks by numbers by means of the continuance equation, one may introduce a certain assumption, which will allow to separate from the equation the value unknown C_z, and introduce into the equation the angle of the spade setting φ_e known by assumption. Namely, we assume that:

$$C_z = A * \alpha \quad (24)$$

where:

C_z – index of the bearing force,

α – inclination of the curve $C_z = f(\propto °)$ Equal on average about 5,6 for the angle $\propto$ expressed in radians or 0,1 for the angle $\propto$ expressed in degrees.

For the angle $\propto$ we place for the continuance equation its expression in the following form:

$$\propto ° = \varphi° - 57{,}3\frac{V_1}{r} \quad (25)$$

and we obtain the continuance equation in a new form, suitable for practical calculations:

− With reference to the conditions of the flight of the vertical mode, when the vertical velocity is marked by V_0:

$$V_1 = \frac{V_0}{2} - \frac{A*\varphi}{16} + \sqrt{\left(\frac{V_0}{2} - \frac{A*\varphi}{16}\right) + \frac{A*\varphi}{8} * \varphi_e * r} \quad (26)$$

− With reference to the condition of the model hinge, when the vertical velocity of the model $V_0 = 0$

$$V_1 = \frac{A*\varphi}{16}\sqrt{\left(\frac{A*\varphi}{16}\right)^2 + \frac{A*\varphi}{8} * \varphi_e * r} \quad (27)$$

After introducing into the last pattern A = 5,6 and after expressing the angle φ_e in degrees and after making transformations, we will obtain the formula for the relative velocity V_{10} in a much simpler form:

$$V_{10} = 0{,}35{*}\sigma\left[-1 + \sqrt{1 + \frac{\varphi_e}{10_\sigma}}\right] \quad (28)$$

However one may not forget that introduction of the simplification in the form of constant inclination of the curve of the bearing force (A = const = 5,6) causes the creation of a certain error in calculations. The error will of course be increasing as the Reynolds number will reduce, at which the profiles of the spade operate, as then there is a significant difference in inclination of the curve of the bearing force, in relation to the assumed simplifying assumption. As a result, one may use for the more exact calculations the real values of the index of the bearing force C_z and the attacking angle $\propto °$. For that purpose the outlined method is used for solving the continuance equation, which will be described further on.

Example 1

Calculate the index C_r of the model rotor in hinge. The rotor has two spades, and their dimensions were provided on the drawing 5. Geometrical twisting of the spade $\Delta_\varphi = 0°$, the angle of setting the spade in the hinge $\varphi = 10°$, inclination of the curve of the bearing force A = 5,6.

1) We calculate the fulfillment index of the rotor disc:

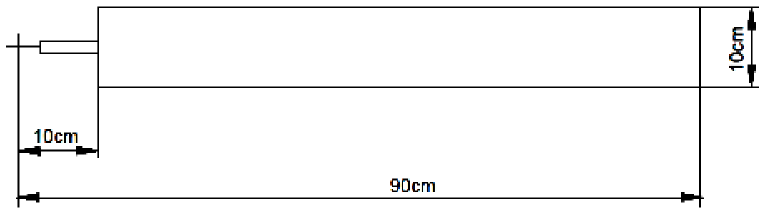
$$\sigma = k\frac{b}{\pi * r} = 2\frac{0{,}1}{3{,}14 * 0{,}9} = 0{,}071 \quad (29)$$

2) We divide the spade into elements, establishing the following cross-sections:

r=0,1; 0,25; 0,4; 0,7, 0,85, 1,0

3) We calculate relative velocity v_{10} for particular cross-sections in accordance with the formula (27):

$$V_{10} = 0{,}35 * \sigma \left[-1 + \sqrt{1 + \frac{\varphi_\sigma}{10_\sigma}}\right] \qquad (30)$$



Drawing 5. Scheme of the bearing spade

For the formula: and σ=0,071 We will obtain a working formula in the form of:

$$v_{10} = 0{,}02485 \left[-1 + \sqrt{1 + 14{,}1 * r}\right] \qquad (31)$$

While placing into the working formula next values r we calculate values v_{10} corresponding to them and we write them down:

r=	0,1	0,25	0,4	0,55	0,7	0,85	1,0
v_{10} =	0,0136	0,0278	0,0390	0,0487	0,0570	0,0647	0,0714

4) we calculate the attacking angle of the spade in particular subsequent cross-sections of the spade in accordance with the formula

$$\propto = \varphi - 57{,}3 \frac{v_{io}}{r} \qquad (32)$$

for r=0,1

$$\propto_{0.1} = 10° - 57{,}3 \frac{0{,}0136}{0{,}1} = 10° - 7{,}8° = 2{,}2°$$

for r=0,25

$$\propto_{0,25} = 10° - 57{,}3 \frac{0{,}0278}{0{,}25} = 10° - 6{,}4° = 3{,}6°$$

And in the same way for all other values of a relative radiant r. We match the results in the table:

r=	0,1	0.25	0,4	0,55	0,7	0,85	1,0
v_{iw}=	0.0136	0,0278	0,0390	0,0487	0,0570	0,0647	0,0714
$\propto$ =	2,2°	3,6°	4,4°	5,0°	5,3°	5,7°	5,9°

5) In accordance with the assumption of the pattern (23) we define the index of the of the bearing force C_z for particular elements of the spade:

$$C_{ze} = A * \propto = 0{,}1 \propto ° \qquad (33)$$

$C_{z0,1} = 0{,}1 * 2{,}2° = 0{,}22$
$C_{z0,25} = 0{,}1 * 3{,}6° = 0{,}36$

Similarly we calculate C_z for the remaining attacking angles $\propto$ corresponding to next radiuses r. We place the results in the table:

r= 0,1	0.25	0,4	0,55	0,7	0,85	1,0	
$\propto$ =	2,2°	3,6°	4,4°	5,0°	5,3°	5,7°	5,9°
C_{ze} =	0,22	0,36	0,44	0,50	0,53	0,57	0,59

6) On the basis of the pattern (19) we calculate elementary values of the pull index C_{Te} corresponding to the next relative radiuses *r*:

$C_{Te} = C_{ze} * \sigma * r^2$ (34)

$C_{T0,1} = 0{,}22 * 0{,}071 * 0.01 = 0{,}000156$

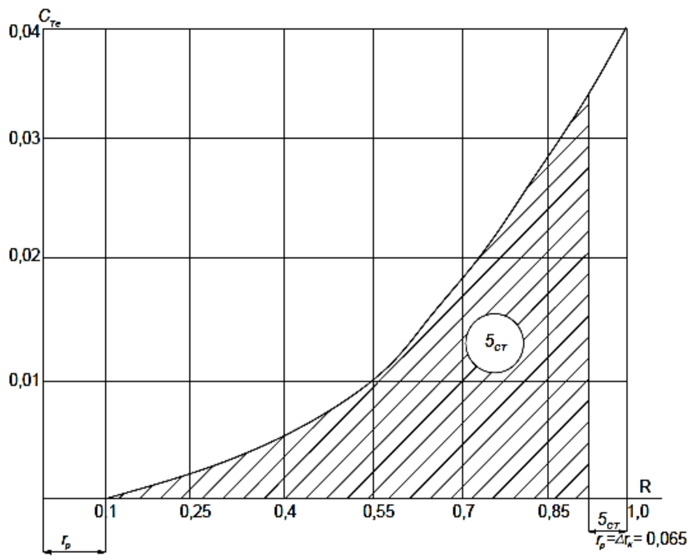
$C_{T0,25} =$ 0,36*3,071*0,0625=0,00161

Etc. and we place them in the table:

r= 0,1	0.25	0,4	0,55	0,7	0,85	1,0	
C_{ze} =	0,22	0,36	0,44	0,50	0,53	0,57	0,59
C_{Te} =	0,000156	0,00161	0,005	0,0106	0,0185	0,0288	0,0418

7) We sum elementary values of the pull index C_{Te} on the whole range of the spade by means of the so called outlined (graphic) integration. For that purpose, we build the scheme of the curve created by connecting the points with coordinates C_{Te} i r_e calculated so far.

On the vertical axis of the system we place next values C_{Te}, and on the horizontal axis the values of relative radiuses r for which C_{Te}. was calculated. Particular points of a diagram are connected in order to facilitate with simple sections and we obtain a ready outline of the function $C_{Te} = f(r)$ for one spade (drawing 6).



Drawing 6. Outline of the function $C_{Te} = f(r)$

In order to include limit losses, on the outline we must mark these sections of the spade which do not participate in creation of a pull. The section r_p does not create a pull equal to 0,1. The value of Δ_{r_k} whereas is calculated from the following formula, correct for the spades with rectangular endings:

$\Delta_{r_k} = b_k * C_{z1,0}$ (35)

where:

Δ_{r_k} – section of the ending of the spade expressed without measurements, not creating the pull,

b_k – relative value of the chord of the spade at its ending,

$C_{z1,0}$ – value of the index of the bearing force on the radius r=1,0 i.e. at the end of the spade (see p. 6 of the example).

As it is known, b_k can be easily marked from the interdependence:

$$b_k = \frac{b_k}{R} = \frac{0,1m}{0,9m} = \frac{1}{9}$$

Thus:

$\Delta_{r_k} =$

The obtained value Δ_{r_k} we place on the diagram on the horizontal axis from the end of the spade to the left, namely from $r_e = R = 1,0$

Then, we calculate the limited area with the horizontal axis with the system, the outline of the function $C_{Te} = f(r)$ and vertical lines introduced from the points r_p i $(R - \Delta_{r_k})$ of the horizontal axis. For that purpose, we calculate the areas of all trapezoids, from which the area under the outlines consists, using the known formula for the area of the trapezoid:

S= h(a+b) $[\mathbf{cm^2}]$

Remembering that *h* means the height of the trapezoid whereas *a* and *b* are the lengths of the parallel sides (basis of the trapezoid). In our example, the area under the outline is approximately equal to:

r≈21 cm^2

8) We calculate so called index of the scale of the outline, i.e. the number expressing how many units of a given value on the system axis fall per one centimeter of the axis. For this vertical axis, on which placed the value C_{Te} the index is:

K_{CT} =0,005 $[C_{Te}/cm]$

It means that per one centimeter of the vertical axis the value C_{Te} equal to 0,005 falls. Respectively, we have for the horizontal axis:

K_r =0,1 $[r/cm]$

9) The pull index is calculated as follows:

$C_T = K_{CT} * K_r * S_{CT}$ = 0,005*0,1*21≈0,01

Example 2

Calculate the pull index C_T of the rotor model in the hinge, assuming as the basis the outline and dimensions of the spades as in the previous example (drawing 7), however, the spades have the line form $\Delta_\varphi = 6°$, and the setting angle of the spade on the radius *r* = 1,0 is $\varphi_{1,0} = 10°$

1) We calculate the fulfillment index:

$$\sigma = k\frac{b}{\pi * R} = 2\frac{0{,}1}{3{,}14 * 0{,}9} = 0{,}071$$

We divide the spade into cross-sections in accordance with relative radiuses:

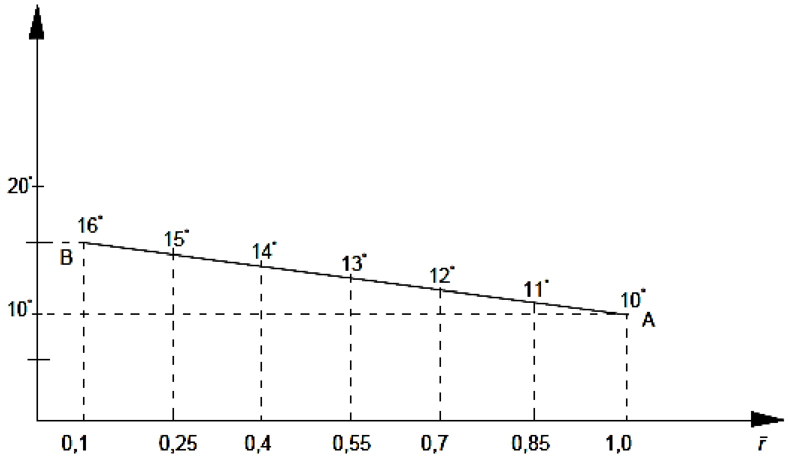
r= 0,1; 0,25; 0,4; 0,55; 0,7; 0,85; 1,0

3) We define the angles of setting the spade on particular relative radiuses r. For that purpose we prepare a diagram, on which we mark the angle of spade setting φ on the vertical axis. In accordance with the assumption of the example we mark on the outline in the first row, the starting point *A* corresponding to the angle $\varphi_e = 10°$ and lying in r=1,0 from the beginning of the system (end of the spade). Then, we outline the straight line with the angle to the horizontal line so that the difference φ_e between the point *A* and *B* was equal to twisting $\Delta_\varphi = 6°$. Thus, the setting angle at the beginning of the spade will be 10 +6 = 16

In this way we obtained the geometrical characteristics of the spade (see drawing 7). We read from the geometrical characteristics of the spade the setting angles of the spade on particular cross-sections, respectively to the relative radiuses r and we enter them into the collective table.

4) We calculate relative velocity v_{i0} for the next relative radiuses r in accordance with the formula:

$$v_{i0} = 0{,}35 * \sigma\left[-1 + \sqrt{1 + \frac{\varphi_e * r}{10_\sigma}}\right] \qquad (36)$$



Drawing 7. Geometrical characteristics of the spade

Placing for φ the values defined on the basis of the geometrical characteristics of the spade (p. 3 of the example) and for r next relative radiuses:

$$v_{10}=0{,}35*0{,}071\left[-1+\sqrt{\frac{16*0{,}1}{10*0{,}071}}\right]=0{,}02485\left[-1+\sqrt{1+1{,}41*16*0{,}1}\right]=0{,}02$$

etc.

The values v_{i0} obtained in this way for the next r are entered into the table.

5) We calculate the attacking angles for the next cross-sections of the spade in accordance with the formula:

$$\alpha_i=\varphi_e-57{,}3\frac{v_{i0}}{r}\quad [°]$$

Placing the next values φ_e from the geometrical characteristics values v_{i0} calculated in p. 4 of the example and proper values of the relative radius r:

$$\alpha_{0,1}=16°-57{,}3\frac{0{,}02}{0{,}1}=16°-11{,}5°=4{,}5°$$

The remaining values of the attacking angles α_e are obtained in the same way, and the results obtained are entered into the collective table.

6) In accordance with the assumption that:

$$C_z=A*\alpha=0{,}1*\alpha$$

We calculate the value of the index of the bearing force C_{ze} for the next radiuses r:

$$C_{z0,1}=0{,}1*4{,}5=0{,}45$$

$$C_{z0,25}=0{,}1*6{,}5=0{,}65$$

etc. We enter the results obtained into the table.

7) Elementary values of the pull index C_{Te} we calculate from the formula:

$$C_{Te}=C_{ze}*\sigma*r^2 \qquad (37)$$

Placing for C_{ze} values of the index of the bearing force calculated in p.6, for σ the calculated value of the fulfillment index of the rotor disc equal 0.071, and for r– next values of the relative radius:

$C_{T0,1}$ = 0,45*0,071*0,01=0,00032

$C_{T0,25}$ = 0,65*0,071*0,0625=0,00287

etc. We enter the results obtained into the table.

r	0,1	0.25	0,4	0,55	0,7	0,85	1,0
φ_e	16°	15°	14°	13°	12°	11°	10°
v_{i0}	0,020	0,037	0,049	0,058	0,064	0,069	0,072
α_e	4,5°	6,5°	7,0°	7,0°	6,8°	6,3°	5,9°
C_{ze}	0,45	0.65	0,70	0,70	0,68	0,63	0,59
C_{Te}	0,0003	0,0029	0,0079	0,0155	0,0237	0,0322	0,0418

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a) We prepare the outline of the function C_{Te} =f(r) in accordance with the guidelines contained in the example 6, on the basis of the data from the table (drawing 8).

b) We calculate the value Δ_{r_k} in order to include limit losses:

$$\Delta_{r_k} = \frac{b_k}{R} * C_{z0,1} = \frac{0,1}{0,9} * 0,59 = 0,066$$

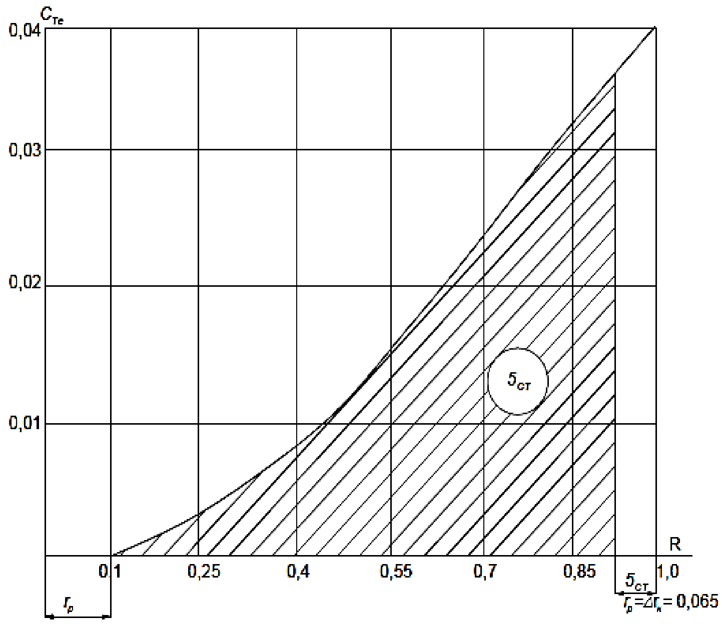
c) We calculate the area of the outline by means of simple figures limited with radiuses r_p: and r_k:

S_{CT} =26,0 cm^2

d) Indices of scale of the outline is calculated as in the example 6:

K_{CT} =0,005 $[C_1 Te/cm]$

K_r =0,1 [r/cm]



Drawing 8. Outline of the function $C_{Te} = f(r_e)$

e) We calculate the pull index C_T :

$C_T = K_{CT} * K_r * S_{CT} = 0,005 * 0,1 * 26 = 0,13$

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