Calculation of steering system parameters of a military training aircraft

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Abstract: *The mechanical-hydraulic steering system of a military training aircraft is a technical problem for specialized engineers and it must be investigated and solved in a scientific manner using theoretical knowledge, calculus programs such as Mathcad, and CAD applications for design such as CATIA V5 which allows the preservation of practical experience and favors its dissemination for future similar calculation. The scope of this calculus is to demonstrate that the active moment developed by the two hydraulic cylinders is always bigger than the resisting moment opposing the steering action of the nose landing gear wheel generated by the frictional forces between the wheel and the running way.*

Key Words: *mechanical-hydraulic steering system, calculation of the parameters, military training aircraft*

1. THE KINEMATICS OF THE MECHANICAL-HYDRAULIC STEERING SYSTEM

The steering system of the nose landing gear and the nose landing gear itself is presented in numerous papers [1 – 8]. The steering device for the military training aircraft IAR 99NG is operated by two hydraulic cylinders (left and right) that are interchangeable. The two actuator hydraulic cylinders work in tandem to steer the rotating subassembly of the nose landing gear: one cylinder extends and the other compresses, after which the rollers are reversed [5], as shown in Figure 1.

Initially, the two hydraulic cylinders are in a neutral position (steering angle is zero) and they have a neutral length of 223.5 mm. Steering angles of $\pm 45^{o}$ and constructive geometric data are shown in Figure 1.

The end of the rod of each hydraulic cylinder, named the front end, (the center of the ball joint, as shown in Figure 2 moves on a circle with a radius of 70 mm, and the opposite end of each hydraulic cylinder, named rear end, moves on a circle with a radius of 115.6 mm).

When the steering angle is $+ 45^{o}$ (maximum right steering) the hydraulic cylinder on the left has an extended length of 270.9 mm, and the hydraulic cylinder on the right has a retracted length of 171.9 mm. If the steering angle is -45^{o} (maximum left steering) the hydraulic cylinder on the left has a retracted length of 171.9 mm, and the hydraulic cylinder on the right has an extended length of 270.9 mm.

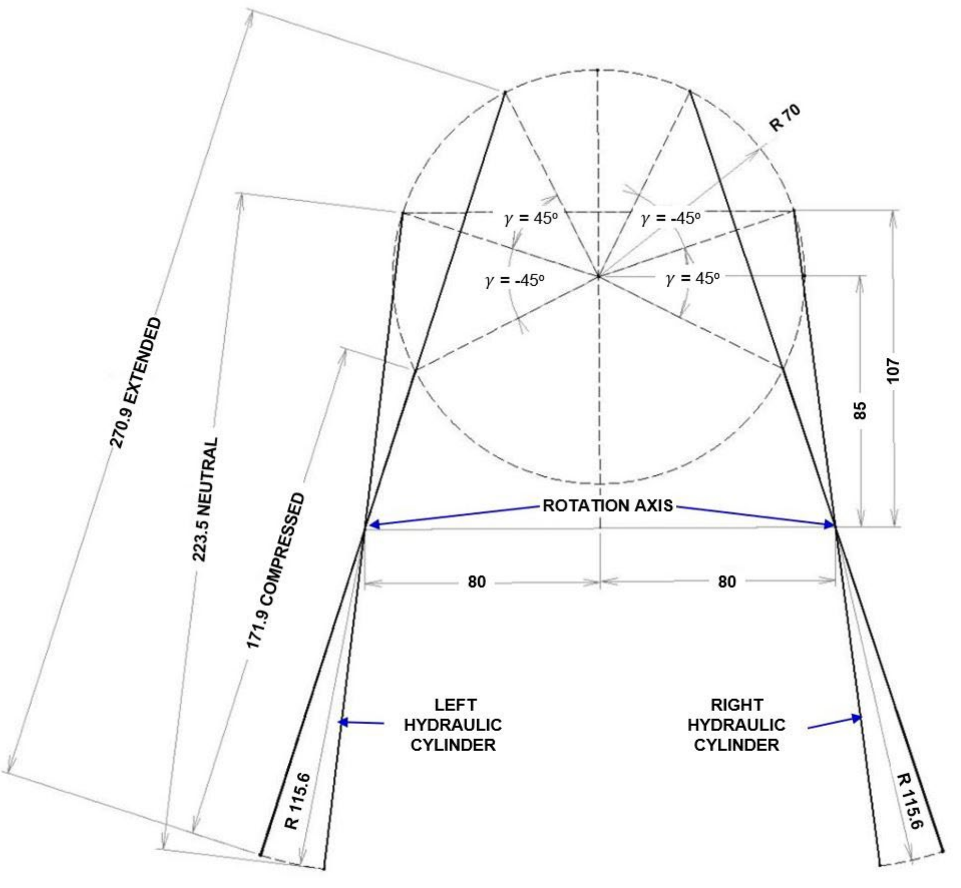

Fig. 1 Kinematics of the actuation of the steering device with two hydraulic cylinders

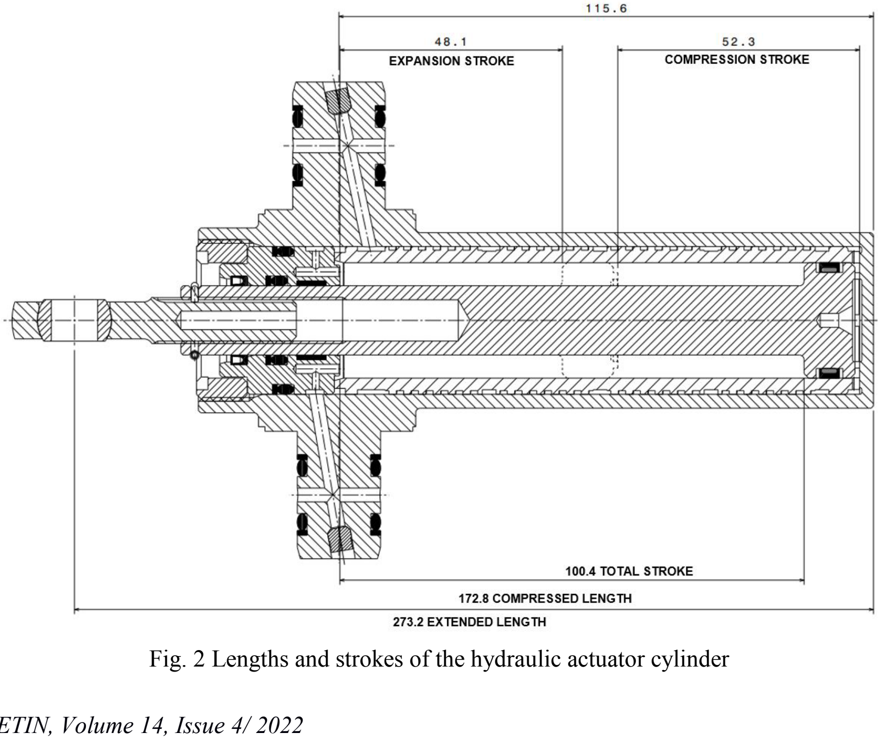

Fig. 2 Lengths and strokes of the hydraulic actuator cylinder

Consequently, the working stroke of the extension is 270.9 - 223.5 = 47.4 mm which is less than the maximum stroke of extension, which means that at the front end of the cylinder there will remain a reserve stroke of 48, 8 - 48.1 = 0.7 mm. The working travel of the hydraulic cylinder rod retraction is 223.5 - 171.9 = 51.6 mm, which means that a reserve stroke of 52.3 - 51.6 = 0,7 mm will remain at the rear end of the cylinder.

End-of-stroke reserves are required to avoid physical contact between the piston and the hydraulic cylinder ends. During this time, the lack of reserves at the end of the stroke would generate damage to parts that would have physical contact at the end of the stroke.

2. CALCULATION OF HYDRAULIC AND MECHANICAL PARAMETERS

The results of the hydraulic parameters calculation are presented in table 1.

Table 1. Calculation of hydraulic parameters

Parameter	Value
The pressure drop on load Δp_S	13.8 MPa
The pressure drop on the two hydraulic cylinders Δp_C	6.9 MPa
Nominal pressure p_n	20.7 MPa
Total volumic flow Q (100%)	16666.7 mm^3/s
Flow coefficient C_D	0.07452 [Ns^2/mm^8]
Flow rate per load Q_s	13.608 [mm^3/s]
The nominal outer diameter of the piston d_c	25 mm
Large piston surface A_1	490.62 mm^2
The nominal outer diameter of the hydraulic cylinder rod d_t	15 mm
The annular surface of the piston A_2	314 mm^2

The available moment relative to the rotation axis of the movable body of the nose landing gear M_D can be calculated as follows [5]:

$$M_D = F_1d_1 + F_2d_2 = \Delta p_s \cdot (A_1d_1 + A_2d_2) = (p_n - \Delta p_v) \cdot (A_1d_1 + A_2d_2) \tag{1}$$

or

$$M_D = p_n \cdot (A_1d_1 + A_2d_2) - C_D\omega_A^2 \cdot (A_1d_1 + A_2d_2)^3 \tag{2}$$

where ω_A is the angular speed, F_1, F_2, d_1, and d_2 are defined in figure 3. The units of measurement of physical quantities are:

$$C_D\left[\frac{Ns^2}{m^2}\right], \omega_A[s^{-1}], A[mm^2], d[mm] \text{ and } p_n\left[\frac{N}{mm^2}\right].$$

Using those above units of measurement, it results:

$$M_D = 10^{-2} \cdot (A_1d_1 + A_2d_2) \tag{3}$$

To calculate the dynamic parameters, the equation of motion of the mobile assembly of the nose landing gear is used [9]:

$$I_o\frac{d\omega_A}{dt} = M_T - M_D \tag{4}$$

where $I_o[Nms^2]$ is the moment of inertia of the rotating subassembly of the nose landing gear to its axis of rotation [9].

The angular acceleration of the rotating subassembly of the nose landing gear ε_A is calculated by the following equation:

$$\frac{d\omega_A}{dt} = \varepsilon_A \tag{5}$$

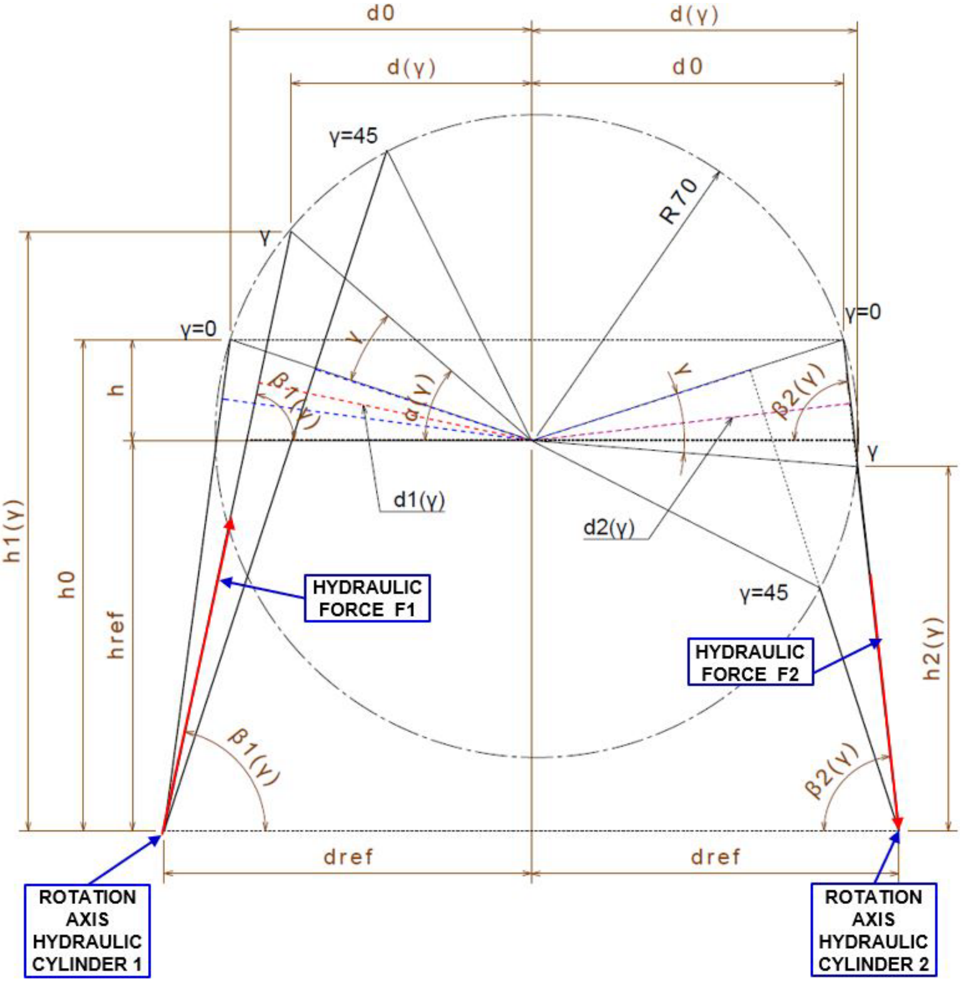

Fig. 3 Calculation scheme for the arms of hydraulic forces d1(γ) and d2(γ)

The relationship of equality between the resistance moment to steering M_R and the total moment M_T is as follows:

$$M_R = M_T[Nm] \tag{6}$$

and from equation (3) it successively results:

$$M_D - M_R = 10^{-2} \cdot (A_1 d_1 + A_2 d_2) \tag{7}$$

$$K_M = [10^{-2} \cdot p_n \cdot (A_1 d_1 + A_2 d_2) - M_T] \tag{8}$$

$$k = 10^{-2} \cdot C_D \tag{9}$$

and the equation of motion of the mobile assembly of the nose landing gear becomes:

$$I_o \frac{d\omega_A}{dt} = K_{\Delta t} - k \cdot \omega_A^2 \tag{10}$$

It is noted that:

$$d \cdot (K_{\Delta t} - k \cdot \omega_A^2) = -2 \cdot k \cdot \omega A \cdot d\omega A = -2 \cdot k \cdot \frac{d\omega}{dt} \cdot d\omega A = -2 \cdot k \cdot \frac{d\omega A}{dt} \cdot d\gamma \tag{11}$$

and the ratio *dω/dt* is expressed as follows:

$$\frac{d\omega A}{dt} = \frac{-1}{2 \cdot k \cdot \omega \cdot d\gamma} \cdot d \cdot (K_M - k \cdot \omega_A^2) \tag{12}$$

Substituting *dω/dt* in the equation of motion of the mobile assembly of the nose landing gear and after processing, result:

$$d\gamma = \frac{-I_0}{2k} \cdot \frac{d(K_M - k \cdot \omega A^2)}{(K_M - k \cdot \omega A^2)} \tag{13}$$

and by integration results:

$$\gamma = \frac{-I_0}{2k} \cdot ln(K_M - k\omega A^2) + C \tag{14}$$

where the integration constant C is determined from the condition $\gamma = 0$ when $\omega_A = 0$, so:

$$C = \frac{I_0}{2k} \cdot lnK_M \tag{15}$$

and the equation for the calculation of the steering angle becomes:

$$\gamma = \frac{I_0}{2k} \cdot \frac{lnK_M}{(K_M - k\omega^2)} \tag{16}$$

From equation (16) we can calculate ω_A, knowing K_M and k for each value of the steering angle γ:

$$\omega_A = \sqrt{\frac{K_M}{k}\left(1 - e^{\frac{-2k}{I_0} \cdot \gamma}\right)} \tag{17}$$

Next, the arms of the hydraulic forces $d_1(\gamma)$ for F_1 and $d_2(\gamma)$ for F_2 used in equations (1) and (2) must be calculated, as shown in figure 3.

The known initial data are: d_{ref} = 80 mm; h_{ref} = 85 mm; h_0 = 107 mm; $h = h_0 - h_{ref}$ = 22 mm; R = 70 mm. The steering angle γ takes values from 0 to 45°.

The distance d_0 is determined from the following equation:

$$d_o = \sqrt{(R^2 - h^2)} \quad [\text{mm}] \tag{18}$$

and α_o for ($\gamma = 0$) is calculated with the following equation:

$$\alpha_o = \arcsin\left({}^{h_o}/_{R}\right) \cdot {}^{180}/_{\pi} \quad [\text{angular degrees}] \tag{19}$$

The value of the angle $\alpha(\gamma)$ is determined according to the equation:

$$\alpha(\gamma) = \alpha_o + \gamma \quad [\text{angular degrees}] \tag{20}$$

The height h_o for ($\gamma = 0$) is calculated with the following equation:

$$h_o = h_{ref} + h \quad [mm], \tag{21}$$

and $h_1(\gamma)$ is determined from the equation that follows:

$$h_1(\gamma) = h_0 + R \cdot cos\left(\frac{\pi}{2} - \alpha(\gamma) \cdot \frac{\pi}{180}\right) \ [mm], \tag{22}$$

and $h_2(\gamma)$ is calculated with the following equation:

$$h_2(\gamma) = h_1(-\gamma) \ [mm], \tag{23}$$

The distance *d(γ)* is calculated with the relation below:

$$d(\gamma) = R \cdot sin\left(\frac{\pi}{2} - \alpha(\gamma) \cdot \frac{\pi}{180}\right) \ [mm], \tag{24}$$

and the angle $\beta(\gamma)$ with the following equation:

$$\beta(\gamma) = arctg\left(\frac{h(\gamma)}{d_{ref} - d(\gamma)}\right) \cdot \frac{180}{\pi} \ \text{[angular degrees]} \tag{25}$$

Finally, the hydraulic force arm F_1, denoted $d_1(\gamma)$ is calculated with the following equation:

$$d_1(\gamma) = R \cdot sin\left(\pi - \alpha(\gamma) \cdot \frac{\pi}{180} - \beta(\gamma) \cdot \frac{\pi}{180}\right) \ [mm], \tag{26}$$

and the hydraulic force arm F_2, denoted $d_2(\gamma)$ is calculated using equation:

$$d_2(\gamma) = d_1(-\gamma) \ [mm] \tag{27}$$

Therefore, the value of the angular velocity of the rotating subassembly of the previous landing gear ω_A is now known, as a function of the steering angle γ, for the range ±45° and the parameters K_M (8) and k (9), calculated above.

3. CALCULATION AND PRESENTATION OF FUNCTIONAL PARAMETERS

At the beginning, the geometric parameters shown in Figure 1 are calculated as explained in equations (18) ... (27) [5], using the Mathcad application.

In table 2, the values of parameters $h_1(\gamma)$ and $h_2(\gamma)$ are presented, depending on the variation of the steering angle $\gamma = 0 ... 45°$, calculated with equations (22) and (23).

Table 2. Values of parameters $h_1(\gamma)$ and $h_2(\gamma)$

γ [deg.]	$h_1(\gamma)$ [mm]	$h_2(\gamma)$ [mm]
0	107	107
1	108.156	105.837
2	109.306	104.667
3	110.448	103.492
4	111.582	102.311
5	112.708	101.125
6	113.826	99.933
7	114.935	98.737
8	116.034	97.537
9	117.125	96.334
10	118.205	95.126
11	119.276	93.916
12	120.336	92.703
13	121.385	91.487

14	122.423	90.27
15	123.45	89.051
16	124.465	87.831
17	125.468	86.61
18	126.458	85.388
19	127.436	84.166
20	128.401	82.945
21	129.353	81.724
22	130.292	80.504
23	131.216	79.286
24	132.127	78.069
25	133.023	76.855
26	133.905	75.642
27	134.771	74.433
28	135.623	73.227
29	136.459	72.025
30	137.279	70.826
31	138.084	69.632
32	138.872	68.442
33	139.644	67.258
34	140.399	66.079
35	141.137	64.905
36	141.858	63.738
37	142.562	62.578
38	143.249	61.424
39	143.917	60.277
40	144.568	59.138
41	145.201	58.007
42	145.815	56.883
43	146.411	55.769
44	146.988	54.663
45	147.546	53.567

The graphical representation of parameters $h_1(\gamma)$ and $h_2(\gamma)$, depending on the steering angle $\gamma = 0 \ldots 45^o$, is presented in figure 4.

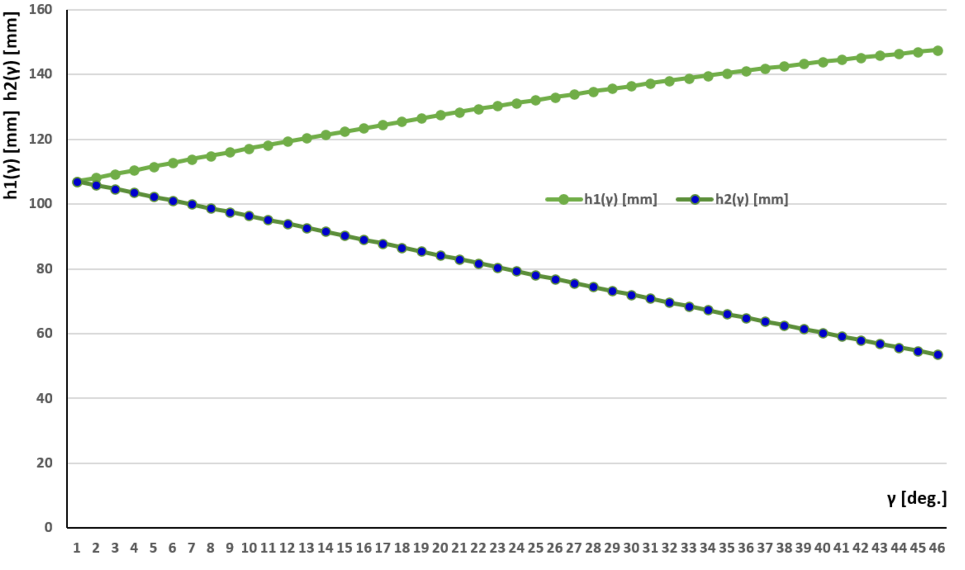

Fig. 4 Graphical representation of the parameters $h_1(\gamma)$ and $h_2(\gamma)$

The arms of the hydraulic forces F_1 and F_2, (figure 1), denoted $d_1(\gamma)$, and $d_2(\gamma)$, respectively, are calculated with equations (26) and (27), depending on the variation of the steering angle $\gamma = 0 \ldots 45^o$, as shown in Table 3.

Table 3. Values of parameters $d_1(\gamma)$ and $d_2(\gamma)$

γ [deg.]	**$d_1(\gamma)$ [mm]**	**$d_2(\gamma)$ [mm]**
0	68.69	68.69
1	68.477	68.889
2	68.251	69.073
3	68.011	69.242
4	67.759	69.396
5	67.494	69.534
6	67.216	69.655
7	66.927	69.759
8	66.627	69.846
9	66.315	69.914
10	65.993	69.962
11	65.659	69.991
12	65.316	70
13	64.962	69.987
14	64.599	69.952
15	64.225	69.893
16	63.843	69.811
17	63.451	69.703
18	63.05	69.569
19	62.641	69.407
20	62.222	69.217
21	61.796	68.997
22	61.361	68.745
23	60.918	68.461
24	60.467	68.142
25	60.008	67.787
26	59.542	67.395
27	59.068	66.963
28	58.587	66.489
29	58.098	65.972
30	57.603	65.409
31	57.101	64.799
32	56.592	64.138
33	56.076	63.424
34	55.554	62.655
35	55.026	61.828
36	54.491	60.94
37	53.95	59.989
38	53.403	58.971
39	52.85	57.883
40	52.291	56.723
41	51.726	55.487
42	51.156	54.173
43	50.58	52.778
44	49.999	51.297
45	49.413	49.73

The graphical representation of parameters $d_1(\gamma)$ and $d_2(\gamma)$ depending on the variation of the steering angle $\gamma = 0 \ldots 45^o$ is presented in figure 5.

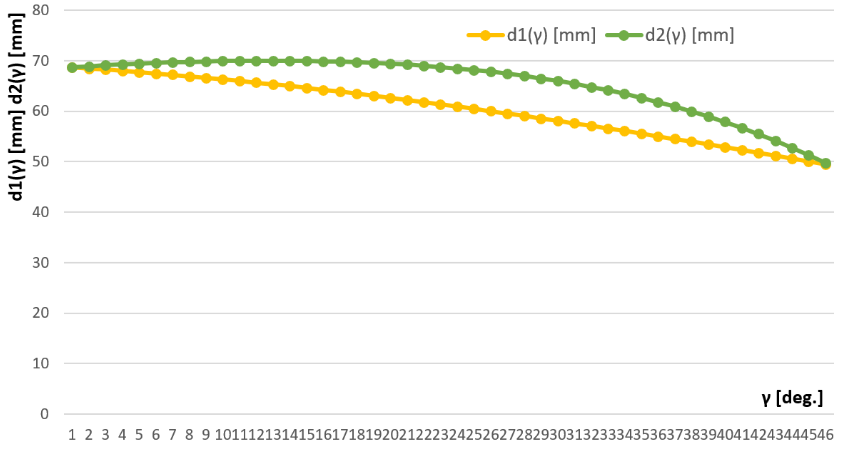

Fig. 5 Graphical representation of parameters $d_1(\gamma)$ and $d_2(\gamma)$

From equations (1) ... (5) it results:

- Δp_c = 6,9 MPa, pressure drop on each of the two hydraulic cylinders;
- Δp_{sR} = 13,8 MPa, pressure drop on the recommended load;
- C_D = 0,07452 [$Ns^2/\ mm^8$] flow coefficient;
- Q_s = 13,608 [mm^3/s] load flow;
- A_1 = 490,625 mm^2 large piston surface;
- A_2 = 314 mm^2 the annular surface between the piston and the hydraulic cylinder rod.

The moment of inertia of the rotating subassembly of the nose landing gear relative to its axis of rotation is provided by the CATIA V5 design software:

- Io = 0,375 [kgm^2].

The friction moment that opposes the steering is the steering friction moment and it is calculated as:

$$M_T = \mathrm{M}_{rv} = 393{,}15\ [\mathrm{Nm}] \tag{28}$$

The value of the active torque for steering M_D calculated with equation (1) for Pn = 20.7MPa, the value of friction torque at steering M_{rv} and the angular velocity during steering ω_A (17) are shown in Table 4, depending on the variation of steering angle $\gamma = 0 \ldots 45°$.

It is very clear that the value of the calculated active torque is at least twice the value of the steering moment, both in Table 4 and in Figure 6.

Table 4. Values of the parameters $M_D(\gamma)$, M_{rv} and $\omega_A(\gamma)$

γ [deg.]	$M_D(\gamma)$ [Nm]	M_{rv} [Nm]	ω_A [rad/sec]	ω_A [deg./sec]
0	1.14E+03	393.15	0	0.0000
1	1.14E+03	393.15	0.30919	17.7243
2	1.14E+03	393.15	0.30964	17.7501
3	1.14E+03	393.15	0.31018	17.7810
4	1.14E+03	393.15	0.31082	17.8177
5	1.14E+03	393.15	0.31155	17.8596
6	1.14E+03	393.15	0.31239	17.9077
7	1.13E+03	393.15	0.31332	17.9610
8	1.13E+03	393.15	0.31436	18.0206
9	1.13E+03	393.15	0.3155	18.0860
10	1.13E+03	393.15	0.31674	18.1571
11	1.12E+03	393.15	0.3181	18.2350
12	1.12E+03	393.15	0.31956	18.3187

13	1.12E+03	393.15	0.32115	18.4099
14	1.11E+03	393.15	0.32285	18.5073
15	1.11E+03	393.15	0.32468	18.6122
16	1.10E+03	393.15	0.32663	18.7240
17	1.10E+03	393.15	0.32872	18.8438
18	1.09E+03	393.15	0.33096	18.9722
19	1.09E+03	393.15	0.33334	19.1087
20	1.08E+03	393.15	0.33588	19.2543
21	1.08E+03	393.15	0.33858	19.4090
22	1.07E+03	393.15	0.34146	19.5741
23	1.06E+03	393.15	0.34452	19.7496
24	1.06E+03	393.15	0.34777	19.9359
25	1.05E+03	393.15	0.35124	20.1348
26	1.04E+03	393.15	0.35493	20.3463
27	1.04E+03	393.15	0.35885	20.5710
28	1.03E+03	393.15	0.36304	20.8112
29	1.02E+03	393.15	0.36749	21.0663
30	1.01E+03	393.15	0.37224	21.3386
31	1.00E+03	393.15	0.37731	21.6292
32	991.621	393.15	0.38273	21.9399
33	981.745	393.15	0.38852	22.2718
34	971.443	393.15	0.39471	22.6267
35	960.7	393.15	0.40135	23.0073
36	949.498	393.15	0.40848	23.4161
37	937.82	393.15	0.41613	23.8546
38	925.647	393.15	0.42437	24.3269
39	912.963	393.15	0.43324	24.8354
40	899.747	393.15	0.44282	25.3846
41	885.982	393.15	0.45318	25.9785
42	871.65	393.15	0.4644	26.6217
43	856.731	393.15	0.47659	27.3204
44	841.208	393.15	0.48984	28.0800
45	825.064	393.15	0.50429	28.9083

The variation of the maximum active torque $M_D(\gamma)$ to perform the steering depending on the steering angle $\gamma = 0 \ldots 45^o$ and the value of the constant friction torque M_{rv} are shown in figure 6. The variation of the angular velocity during the steering $\omega_A(\gamma)$ expressed in radians per second and degrees per second, as a function of the steering angle $\gamma = 0 \ldots 45^o$ is shown in figure 7.

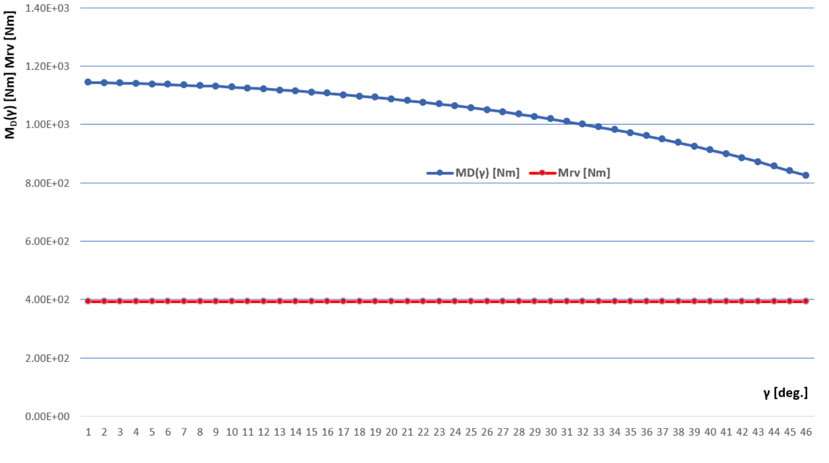

Fig. 6 Graphical representation of parameters $M_D(\gamma)$ and M_{rv}

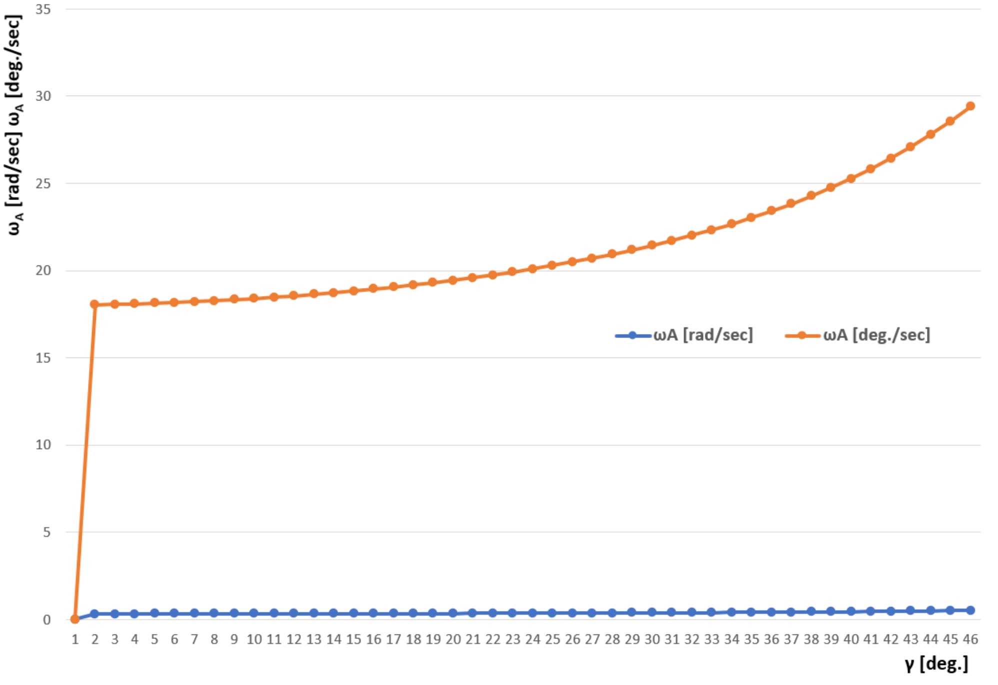

Fig. 7 Graphical representation of angular velocity $\omega_A(\gamma)$ expressed in radians per second and degrees per second

4. CONCLUSIONS

The method presented above contains the presentation of the kinematics of the mechanical-hydraulic steering system, calculation of the hydraulic actuation parameters, and calculation and graphical representation of functional parameters such as $h_1(\gamma)$ and $h_2(\gamma)$, the arms of hydraulic forces F_1 and F_2, denoted $d_1(\gamma)$, and $d_2(\gamma)$, the friction moment that opposes the steering $M_T = M_{rv}$, the value of the active torque for steering $M_D(\gamma)$, and the variation of the angular velocity during the steering $\omega_A(\gamma)$ expressed in radians per second and degrees per second.

It is very clear that the value of the calculated active torque for steering $M_D(\gamma)$ is at least twice the value of the steering moment that opposes the steering $M_T = M_{rv}$. The results presented above will be verified by experimental research soon.

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