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System of design calculation of linear electromagnet without the stop (part 1)*

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Abstract. **The developed system allows to calculate and design a linear electromagnet without the stop with or without an external magnetic wire, with anchor of any shape (cylinder, ball, etc.) and with different cross-sectional areas.**

Keywords: **calculate, project, linear electromagnet, winding, magnetic wire, anchor, electromagnetic force.**

Introduction

On the base of the linear electromagnet without the stop (LEWS), various electro engineered transmitters and linear engines are made, which transform electric energy into mechanical work providing the needed linear movement of the anchor without any intermediate bodies. They are used in such technological systems, where a high amplitude of oscillation (e.g. in drills, presses, pumps, mills, oscillators, etc) or uninterrupted movement with linear acceleration (e.g. in linear accelerators, etc.) is needed.

Fig. 1. illustrates the structure and letter notations of the main measures of LEWS, where 1 is the control winding (CW), 2 is the ferromagnetic anchor, and 3 is the outer ferromagnetic wire. The anchor can be of any shape, for instance, cylinder (as in the picture), ball, etc. and can have different cross-sectional areas.

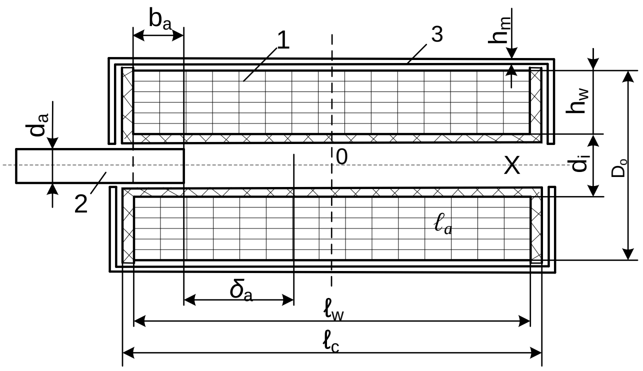

Fig. 1. The structure of the LEWS and letter notations of the main dimensions

The goal of the work is to calculate and design a LEWS accordant with the preliminary starting data.

The example of the calculation and design system of cylindrical anchor is presented.

Problem settings and method justification

The following was accepted as preliminary starting data for calculation and design of the LEWS:

- anchor diameter d_a, *m*;
- a step of the anchor δ_a, *m*;
- ancor length in CW b_a, *m*;
- power source voltage of CW U_n, *V*;
- starting dimension of the electromagnetic dragging force P_e, *N*;
- maximal temperature of the working environment t_w, *°C*;
- time index of the electromagnet's working regime α;
- presence of the external magnetic wire,
- saturation induction value of the external magnetic wire B_{Sm}, *Tl*.

1. Selection of the geometric dimentions of the CW:

- length $\ell_w \approx 2b_a+\delta_a$;
- height $h_w=\ell_w/K_w$, where K_w is the window index of the CW, K_w=1…30;
- inner diameter $d_i=d_a+2\Delta_f+2\Delta_a$, where Δ_f is the frame width of the CW, Δ_a is the air distance between the anchor and the frame,
- outer diameter $D_o=d_i+2h_w$,
- middle diameter and radius $d_a=d_i+h_w$, $r_a=d_a/2$,
- length of the frame `$\ell_f=\ell_w+2\Delta_f$.

2. The value of the calculated F_c magnet moving force (MMF) of the CW is being determined

$$F_c=K_s F'_c, \qquad (1)$$

where K_s is an index according to MMF supply: K_s =1,1…2,0, F'_c [1]

$$F'_c=\sqrt{\frac{2\theta_{ov}K_f K_t \ell_w^3}{\rho_t K_w}}, \qquad (2)$$

θ_{ov} is the amount of overheating $\theta_{ov}=t_m-t_s$, t_m is the permitted maximal working temperature of the copper wire, ρ_t is the specific resistance of the copper, K_f is the loading index of the CW K_f=0,3...0,6, K_t is the heat emission index according to θ_{ov}.

3. The induction value of the magnetic field in a specific point of b_a of the anchor with X axis is being determined.

In order to increase the preciseness of calculations b_a is divided into parts considering the features of the anchor.

In case of the cylinder, to make the calculations simpler b_a is divided into n equal parts $\Delta_{ai}=b_a/n$ (Fig. 2).

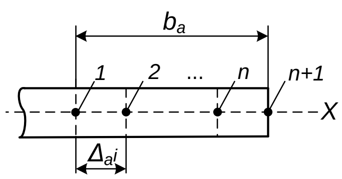

Fig. 2. The division of b_a into n parts

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On the endpoints of each Δ_{ai} parts the induction of magnetic field created by the CW (without a magnet) is calculated by the following formula [2];

$$B'_{0i}=\mu_0\frac{F_c}{2\ell_w}\left[\frac{0{,}5\ell_w-X_i}{\sqrt{r_a^2+(0{,}5\ell_w-X_i)^2}}+\frac{0{,}5\ell_w+X_i}{\sqrt{r_a^2+(0{,}5\ell_w+X_i)^2}}\right], \quad (3)$$

where μ_0 is the magnetic constant $\mu_0=4\pi 10^{-7}Hn/m$, X_1 is the distance between i-th point and CW's 0 center of the symmetricity axis (Fig. 1) $X_1=(\ell_w/2)-(i-1)\Delta_{wi}$, i is the number of the point $i=1...(n+1)$.

In case of magnetically unloaded anchor in the CW, the inducton of magnetic field in the anchor's endpoints is being calculated as follows [3]:

$$B_{0i}\approx 3B'_{0i}. \quad (4)$$

In case of external magnetic wire the induction of each point is calculates with the following formula

$$B_i=K_B B_{0i}, \quad (5)$$

where K_B is an index that conditions the induction, that determines the influence volume of the external magnetic wire on the magnetic induction value of the anchor, the amplitude of which depends on K_w, determined by $K_B=f(K_w)$ graph Fig. 3 [4].

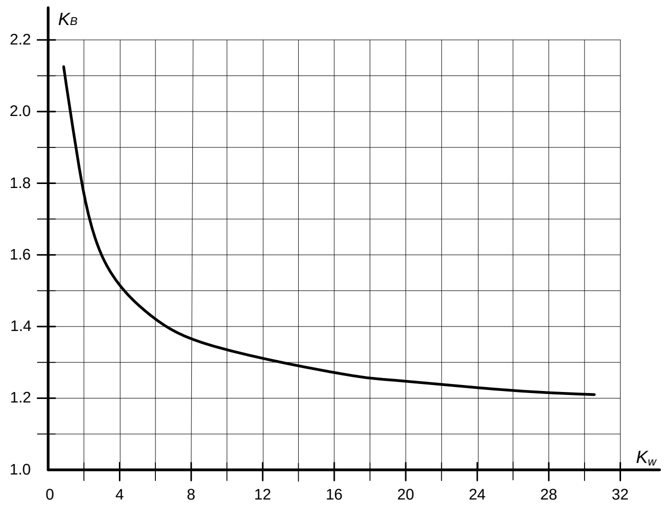


Fig. 3. $K_B=f(K_w)$ graphical dependance

In case of absence of the external magnetic wire $K_B=1$.

4. Determining the electromagnetic dragging force [5].

Specific electromagnetic cumulated dragging force, that impacts the ferromagnetic anchor through the X axis by the magnetic field, is calculated in the following way;

$$P_c=\sum_{i=1}^{n}P_{ix}\ , \quad (6)$$

where P_{ix} is the electromagnetic force that impacts i-th part of the anchor

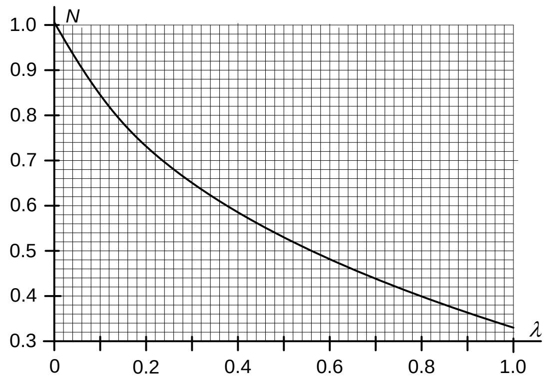
$$P_{ix}=V_{ai}B_{ai}\Delta B_i/\mu_0\Delta_{ai}N, \quad (7)$$

where V_{ai} is the volume of the i-th part of the anchor $V_{ai}=\pi d_a^2\Delta_{ai}/4$, B_{ai} is the mean amplitude of the magnetic field induction in the i-th part of the anchor $B_{ai}=0{,}5(B_i+B_{i+1})$, ΔB_i is the difference $\Delta B_i=B_{i+1}-B_i$, N is demagnetizing coefficient of the anchor, the value of which depends on λ coefficient of the anchor's part $\lambda=b_a/d_a$. N depends on λ and can be found using expression [3], or graphs in Fig. 4, when $\lambda<1$, and in Fig. 5 when $\lambda>1$ [4].

The following condition needs to be checked

$$0\le\frac{P_c-P_e}{P_e}\le\varepsilon_1, \quad (8)$$

where ε_1 is a certain positive value that reasons the relative mistake.



A.

Fig. 4. The relation of N and λ, when $\lambda<1$

If condition (8) is true the calculations can go one, else the chosen values or ℓ_w need to change and be calculated again.

5. The main parameters of the CW are being decided [1]:

- model of the copper wire, d_w diameter, S_w cross-sectional areas, δ_i width of the isolating layer;
- w quantity of the spins of the CW, active R_w resistance, I_w current, working F_w MMF, active P_w power.

The following condition needs to be checked

$$0\le\frac{F_w-F_c}{F_c}\le\varepsilon_2, \quad (9)$$

where ε_2 is a certain positive value that reasons the relative mistake.

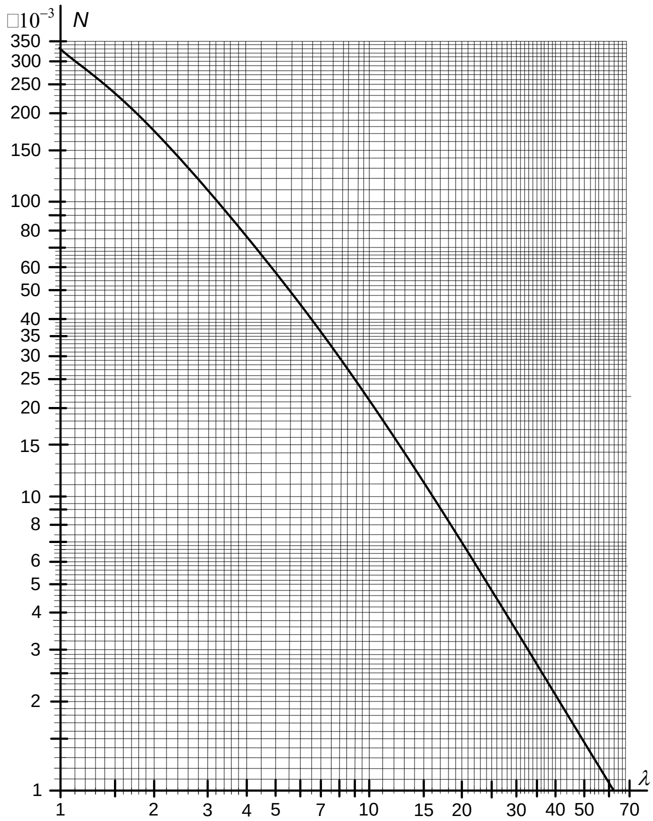


Fig. 5. The relation of N and λ, when $\lambda>1$

If condition (9) is true the calculations can go one, else changing the value of d_w the calculation is repeated. In the extreme case, ℓ_w or other values can change.

6. Checking the heating mode of the CW.

The calculated overheating of the CW is being determined [1]

$$\theta_c = \frac{\alpha P_w}{K_T S_c}, \qquad (10)$$

where S_c is the cooling surface $S_c=\pi[\ell_w(D_o+d_i)+0,5(D_o^2-d_i^2)]$.

The following condition needs to be checked

$$\theta_c \le \theta_{ov}. \qquad (11)$$

If the condition (11) is true the calculations and design are finished, else the calculations need to be repeated after changing ℓ_w or K_w.

If the value of θ_c is notably smaller than θ_{ov}, means that h_w height of the winding is greater than needed: in that case, re-calculation can be done by changing only the value of h_w.

7. The weight of the CW copper is calculated

$$Q_c=\beta_c V_c, \qquad (12)$$

where β_c is the specific weight of the copper, V_c is the volume of the copper in the CW $V_c=\pi S_c w d_a$.

8. Choosing the parameters of the external magnetic wire:
- the diameter $D_m \ge D_o$;
- the thickness

$$h_m \ge \mu_0 K_B \frac{d_i^2 F_w}{2 D_m B_{Sm} \ell_w}. \qquad (13)$$

The results of the research

The main preliminary data for the calculations and design of the LEWS were d_a=13*mm*, δ_a=20*mm*, b_a=10*mm*, U_n=110*V*, P_e=0,9*N*, t_w=30°*C*, α=0,5, with the external magnetic wire, B_{Sm}=2*Tl*.

The chosen values were K_w=2, Δ_a=0,5*mm*, Δ_f=0,5*mm*, *n*=1, k_s=1,1, ε_1=0,05, ε_2=0,15.

As a result of the working process we got the following output data: ℓ_w=40*mm*, h_w=20*mm*, d_i=15*mm*, D_{ov}=55*mm*, d_a=35*mm*, ℓ_c=41*mm*, θ_{ov}=75^0*C*, F_c=1040*A*, P_e=0,9641*N*, d_c=0,17*mm*, *w*=8320, R_w=805,6*Ohm*, I_w=0,136*A*, F_w=1131*A*, P_w=14,9*Vatt*, θ_c=53^0*C*, Q_c=0,186*kg*, h_m=0,06*mm*.

Conclusion

The developed system allows to calculate and design a linear electromagnet without the stop with or without an external magnetic wire, with anchor of any shape (cylinder, ball, etc.) and with different cross-sectional areas. It can be used in educational, engineering and research procedures.

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Система проектирования и расчета линейного электромагнита без стопа (часть 1)

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***Аннотация*. Разработанная система позволяет рассчитать и спроектировать линейный электромагнит без стопа с внешним магнитопроводом или без него, с любым видом якоря (цилиндр, шар и т.д.) и с различными площадями поперечного сечения.**

***Ключевые слова*: расчет, проект, линейный электромагнит, обмотка, магнитопровод, якорь, электромагнитная сила.**

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