CALCULATION OF STATIC CHARACTERISTICS OF LINEAR STEP MOTORS FOR CONTROL ROD DRIVES OF NUCLEAR REACTORS - AN APPROXIMATE APPROACH

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ABSTRACT

This paper describes an approximate method for calculating the static characteristics of linear step motors (LSM), being developed for control rod drives (CRD) in large nuclear reactors. The static characteristic of such a LSM which is given by the variation of electromagnetic force with armature displacement determines the motor performance in its standing and dynamic modes. The approximate method of calculation of these characteristics is based on the permeance analysis method applied to the phase magnetic circuit of LSM. This is a simple, fast and efficient analytical approach which gives satisfactory results for small stator currents and weak iron saturation, typical to the standing mode of operation of LSM. The method is validated by comparing theoretical results with experimental ones.

INTRODUCTION

Despite the Chernobyl accident, the contribution of atomic power plants in the total output of electric energy in many countries around the world is still rising. This intensive development of atomic energy and the tendency to increse the unit power output of reactors set the complex task of ensuring their safe, reliable and economic exploitation. This is accomplished by ensuring controllability of energy output locally as well as globally over the entire volume of the reactor core by suitably designing the CRD of nuclear reactors. Basically, it consists of movable control rods, made of neutron absorbing materials in the form of individual rods or group of rods (cassettes, clusters, etc.) and a driving mechanism to move them inside the reactor core [1-3]. The key element of this driving mechanism is the electric motor, upon the rational selection and reliable fuctioning of which, to a great extent depend the safety and reliability of the entire power plant. In recent years countries like Russia, USA, France, Germany and Italy are developing linear and discrete electromagnetic driving mechanisms for CRD with passive armature linear step motors [1-3]. These CRD with LSM are fast, highly reliable due to the simplicity of kinematics and accurate in the fixation of control rods.

One of the vital performance characteristics of LSM is the static characteristic which gives the variation of electromagnetic force produced by the motor with armature displacement. It determines motor performance in its standing (when the armature with controls rods attached to it is held at a fixed position by electromagnetic force) and dynamic (when the armature is moved by sequential excitation of stator windings) modes of operation. In order to design reliable and economically viable CRD with LSM it is important to be able to calculate and evaluate their static characteristics. Although rotating step motors are well covered in literature, there are a few published papers which concern linear step motors [4, 5]. Two methods, approximate and accurate have been developed [6, 7] for the calculation of static characteristics of LSM. The approximate method, described in this paper is based on the permeance analysis approach [5, 8] and gives satisfactory results for small stator currents and low iron saturation. This is quite useful for the fast evaluation of motor performance at the earlier stages of their CAD without needing the computationally intensive modelling of magnetic fields by the finite element method on which the accurate method is based. The approximate method was used to calculate the static characteristics of LSM designed by the researchers at "Ijorcki Javod" (St. Petersburg, Russia) for CRD (namely, linear synchronous electromagnetic drive, LSED) of large pressurised water reactors with electrical power output of 1000 MW (VVER-1000) and more [9, 10]. Some of the the results are compared with experimental ones to establish the validity of the adopted approximate approach.

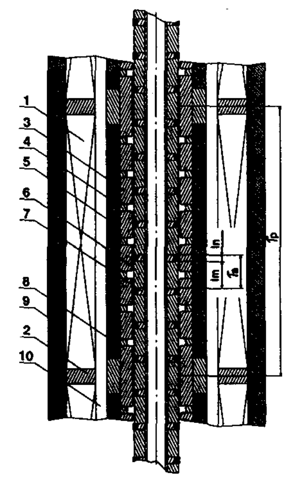

Figure 1. Longitudinal section of a phase of the LSM

CONSTRUCTIVE FEATURES AND THE GEOMETRIC PARAMETERS OF A LSM

Figure 1 shows the longitudinal section of one of the phases of the 4-phase LSM designed at "Ijorcki Javod". It consists of the stator with cylindrical dc winding (1), poles (2) and ring elements in the form of alternately arranged magnetic (3) and nonmagnetic (4) sleeves. The hermetically sealed cylinder (5) of the stator is made of nonmagnetic material (except the magnetic shunts under the poles) and withstands the high pressure inside the reactor vessel. The armature, in the form of a thin-wall hollow cylinder is made up of alternately arranged magnetic (6) and nonmagnetic (7) sleeves. These nonmagnetic sleeves are made up of the inner nonmagnetic ring and the outer ring made of antifriction material and acts as slide bearings. The height (length) of end (interphase) magnetic sleeves (8) of stator is higher than the height of those situated in between them (for example, 3). The outer casing of the motor (9) is made of magnetic material and acts as

TABLE 1 -Geometric parameters of LSM used in linear synchronous electromagnetic drives

Parameters	LSED	LSED-4
1. Internal diameter of the armature cylinder Dci, mm	23	23
2. Internal diameter of armature magneitic sleeves Dai, mm	30	30.1
3. External diameter of armature magnetic sleeves Dae, mm	49	54.7
4. Internal diameter of stator magnetic sleeves Dsi, mm	50	56.2
5. External diameter of stator magneitc sleeves Dse, mm	76	76
6. Internal diameter of the cylindrical cooling duct Dc, mm	no duct	94
7. Internal diameter of stator poles Dp, mm	98	110
8. Width of stator poles bp, mm	16	16
9. Airgap between stator and armature δ, mm	0.5	0.75
10. Width of the cooling duct δc, mm	--	16
11. Thickness of the hermetically sealed cylinder of stator δs, mm	11	9
12. Height (length) of magnetic sleeves lm, mm	29	25
13. Height (length) of nonmagnetic sleeves ln, mm	7	7
14. Height (length) of end magnetic sleeves of stator lmi, mm	92	81
15. Number of phases in stator m	4	4
16. Number of nonmagnetic sleeves of stator per phase n	8	9

the outer magnetic circuit. The hollow cylindrical duct (10) in between the hermetically sealed cylinder (5) and stator windings (1) is meant for the circulation of water, cooling these windings. In reactors VVER-1000 the motor is designed to be mounted vertically on the lid of the reactor vessel. In case of power failure in the stator windings this ensures the armature with control rods to fall freely into the reactor core towards lowering its reactivity. Table 1 gives some of the geometric parameters of the LSM (shown in Figures 1 and 2) designed for two LSED. Some of the main design parameters of the motor are: armature step $\tau_a = lm + ln$ and discrete step $\tau_d = \tau_a/m$. Discrete step τ_d gives the armature displacement for unit voltage pulse in the stator winding. The height of the end magnetic sleeves of stator is chosen in such a way as to create a misalignment between stator and armature magnetic sleeves of adjacent phases. That is $lmi = lm \pm \tau_d + k\tau_a = lm + \tau_a(k \pm 1/m)$, where $k = 0, 1, 2$. For lmi in Figure 2 $k = 1$ and "+" sign is used before 1/m. Phase step τ_p (Figure 2) is given by the height of a phase, $\tau_p = n\tau_a + lm - ln = \tau_a(n + k \pm 1/m)$.

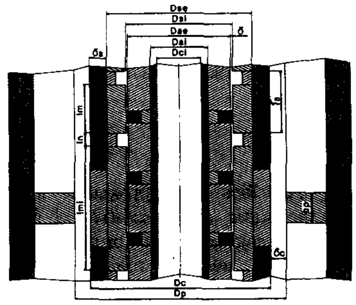

Figure 2. Various geometric parameters of the LSM

WORKING PRINCIPLE AND THE STATIC CHARACTERISTIC OF THE LSM

With each voltage pulse current in the stator winding produces mmf F that gives rise to the magnetic flux $\Phi = F/R(x) = FP(x)$, where R(x) and $P(x) = 1/R(x)$ are phase reluctance and permeance respectively. Armature movement changes the mutual alignments of stator and armature magnetic sleeves resulting in the change of reluctance R(x) and magnetic field energy $W(x) = F\Phi/2 = F^2/2R(x) = F^2P(x)/2$. These changes in energy W(x) give rise to electromagnetic force F(x) acting on the armature -

$$F(x) = \frac{dW(x)}{dx} = \frac{F^2}{2}\frac{d}{dx}\left(\frac{1}{R(x)}\right) = \frac{F^2}{2}\frac{dP(x)}{dx} \qquad (1)$$

where x is the coordinate of armature displacement which characterises mutual alignments of stator and armature magnetic sleeves. Force F(x) acts in such a direction as to increase field energy W(x) and hence permeance P(x). With armature movement, P(x) and so the force F(x) change periodically with a period of τ_a so that $F(x+\tau_a) = F(x)$. Figure 3 shows how F(x) changes with coordinate x for a given phase. This is

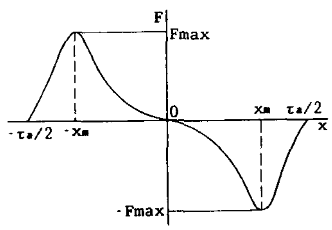

Figure 3. Static characteristic of the LSM

the static characteristic of the LSM shown in Figure 1. $x = 0$ in Figure 3 corresponds to a certain armature position when the central line through stator nonmagnetic sleeve aligns with that of the armature magnetic sleeve. F(x) attains its maximum for $x = x_m$ when the armature and stator magnetic sleeve corners align opposite to each other and dW/dx becomes maximum. $x=0$ corresponds to maximum values of permeance P(x) and field energy W(x) and hence $F(x)=dW(x)/dx=0$; $F(x)=0$ also for $x=\pm\tau_a/2$ when the magnetic sleeves of stator and armature are positioned opposite to each other and P(x) and W(x) have minimum values. Figure 4 shows static characteristics of all 4 phases of the LSM which are

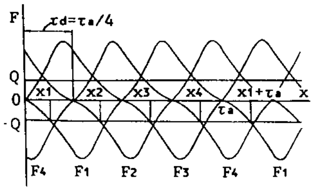

Figure 4. Static characteristics of all four phases of the LSM

shifted in space by discrete step τ_d. This is because the height of end magnetic sleeves of stator are different from the height of those situated in between them. For a given armature position this creates different alignments of magnetic sleeves for different phases. F_1, F_2, F_3 and F_4 in Figure 4 correspond to electromagnetic forces produced by phases 1, 2, 3 and 4 respectively. To move the armature, phase windings are sequentially excited from pulse voltage source. If, for example only phase 1 is excited due to the total force P_1+Q (Q is the force due to the weights of armature and control rods) the armature will take the equilibrium position corresponding to $x=x_1$ (Figure 4) for which $P_1+Q=0$. Now, if phase 1 is switched off and phase 2 is excited due to the force P_2+Q armature will move to the new position for which $x=x_2=x_1+\tau_d$. In this way armature is moved, each time by a distance of the discrete step τ_d by sequentially exciting the phase windings in the order 1-2-3-4-1-2-... . By reversing this order the armature can be made to move in the opposite direction.

CALCULATION OF THE STATIC CHARACTERISTIC OF THE LSM

Magnetic Circuit of a Phase of the LSM

As can be seen from equation (1) to calculate the electromagnetic force F(x) it is necessary to determine the equivalent phase reluctance R(x) or permeance P(x). For approximate calculation of F(x) this is done by analysing the complex magnetic circuit of the LSM shown in Figure 5 which shows the probable flux paths through various parts of stator and armature. The total flux Φ can be divided into stator and armature components Φ_s, Φ_a and the effective flux Φ_e which crosses the airgap. Thus $\Phi=\Phi_s+\Phi_a+\Phi_e$. Apart from these fluxes there can be, in principle leakage flux the lines of which take path entirely or partially through the air or nonmagnetic parts of the stator. The amount of such flux is small compared with the main flux Φ and can, therefore be neglected. Figure 5 also shows the reluctances due to the flux paths Φ_s, Φ_a and Φ_e which constitute the phase reluctance R. It consists of the reluctances of the outer casing Rc, poles Rp, nonmagnetic path between the poles and end magnetic sleeves of stator Rpe and inner magnetic circuit Ric: $R=Rc+2Rp+2Rpe+Ric$. Due to the large cross sectional areas of the outer casing and the poles their reluctances are considered negligibly small and $Rc=Rp=0$. Reluctance Rpe consists of the reluctances of the hermetically sealed cylinder Rsc

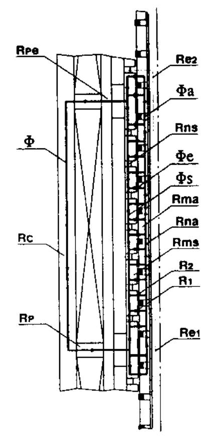

Figure 5. Magnetic circuit of a phase of the LSM

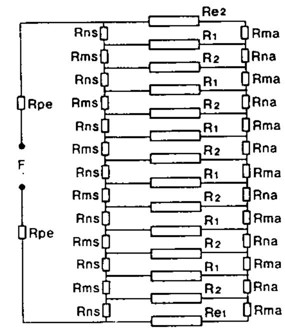

Figure 6. Equivalent circuit of a phase of the LSM

and the cooling duct Rcw and can be approximately calculated using $Rpe=Rcw+Rsc=\delta_c/\mu_0 Sc+\delta_s/\mu Ss$ where Sc and Ss are the effective areas which the total flux crosses in the cooling duct and hermetically sealed cylinder respectively; μ is the permeability. Effective areas $Sc=\pi(Dp+Dc)bpe/2$, $Ss=\pi(Dc+Dse)bpe/2$ where the effective pole width $bpe=bp+\delta_c+\delta_s$ in the presence of magnetic shunts and $bpe=bp+\delta_c$ in the absence of magnetic shunts in the hermetically sealed cylinder. The main difficulty is associated with the calculation of the reluctance Ric which consists of the airgap reluctances R_1, R_2, reluctances due to end magnetic sleeves of stator Re_1, Re_2 and the reluctances of the magnetic Rms, Rma and nonmagnetic Rns, Rna sleeves of stator and armature respectively. All these reluctances are functions of armature displacement x and need to be determined beforehand in order to calculate the phase reluctance R (or P). In the approximate method described in this paper given the above reluctances, R or P is calculated from the electric circuit analogue of the phase magnetic circuit shown in Figure 6. It takes into account complex flux distribution in the inner magnetic circuit of the LSM.

Approximate Calculation of Permeances of the Airgap and Nonmagnetic Sleeves of Stator and Armature

The approximate calculation of permeances of the airgap P_1, P_2 and nonmagnetic sleeves of stator and armature Pns, Pna is based on the plotting of flux paths graphically or numerically in the airgap and nonmagnetic sleeves. Alternatively, this may be done by assuming probable flux paths for various armature positions x. For these, it is assumed that the flux distribution in the above regions of the inner magnetic circuit does not depend on the saturation of stator and armature magnetic sleeves. After plotting the respective flux paths permeances are calculated analytically for various x. The results of such calculations for the 4-phase LSM used in LSED are shown in Figures 7 and 8. Due to the symmetry in flux distribution in the inner magnetic circuit it is sufficient to consider $0 \le x \le \tau_a/2$. Figure 7 shows the variation of permeances P_1 and P_2 with armature displacement x which reflect the complex nature of flux distribution in the airgap for various positions of the armature. The constant redistribution of flux components Φ_s, Φ_a and Φ_e with armature displacement x in the nonmagnetic sleeves is evident from the variation of permeances Pns and Pna shown in Figure 8.

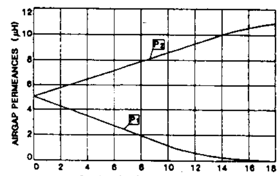

Figure 7. Variation of airgap permeances P_1 and P_2 with armature displacement x

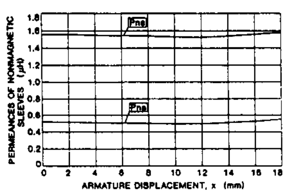

Figure 8. Variation of nonmagnetic sleeve permeances of stator (Pns) and armature (Pna) with x

Calculation of Permeances Between the Armature and End Magnetic Sleeves of Stator

As said earlier the height of end magnetic sleeves of stator lmi is different from that of other magnetic sleeves of stator and armature. This causes different flux distributions in the regions of end magnetic sleeves (shown schematically in Figure 9) for various

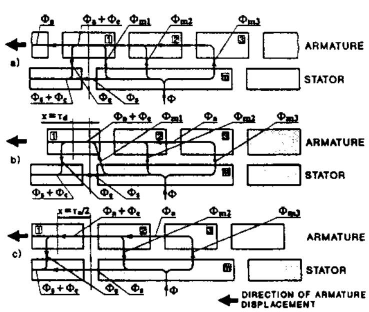

Figure 9. Flux distribution in the region of the first end magnetic sleeve used for the calculation of P_{e1}

armature positions x. The total flux Φ in the end magnetic sleeve m branches out into components Φ_s which shunts through the stator sleeves, and $\Phi_s + \Phi_e = \Phi_{m1} + \Phi_{m2} + \Phi_{m3}$ which crosses the airgap taking three parallel paths before entering the armature sleeves. From Figures 5 and 6 permeance $P_{e1} = 1/R_{e1}$ is defined as the permeance between the end magnetic sleeve m and the armature magnetic sleeve closest to it (marked 1 in Figure 9) through which the flux $\Phi_s + \Phi_e$ flows. As shown in Figure 9 armature magnetic sleeves marked 2 and 3 also take part in conducting this flux. Considering all these the magnetic circuit shown in Figure 9 may be represented by the equivalent circuit shown in Figure 10 which is used to calculate the permeance P_{e1}. For

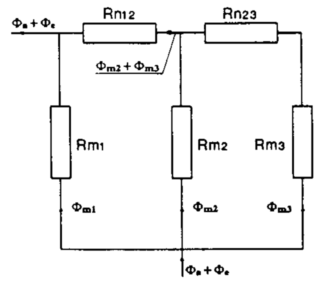

Figure 10. Equivalent circuit for the calculation of permeance P_{e1}

this it is assumed that the reluctances of magnetic sleeves 2 and 3 are negligibly small since a very small amount of flux passes through them and, therefore their flux density is considerably smaller than the saturation density. The following symbols are used in Figure 10: R_{n12}, R_{n23} - reluctances of nonmagnetic sleeves between 1, 2 and 2, 3 respectively (Figure 9); R_{m1}, R_{m2}, R_{m3} - airgap reluctances between m and 1, 2 , 3 respectively. It may be assumed that $R_{n12} = R_{n23} = R_{na} = 1/P_{na}$ and $R_{m1} = R_1 = 1/P_1$. Reluctances R_{m2} and R_{m3} are calculated from the following :

$$R_{m2} = \frac{\delta}{\pi \mu_0 l_m (D_{ae} + D_{si})/2} \tag{2}$$

$$R_{m3} = \begin{cases} \dfrac{\delta}{\pi \mu_0 (l_m - \tau_d + x)(D_{ae} + D_{si})/2}, & 0 \le x \le \tau_d \\ R_{m2} & \tau_d \le x \le \tau_a/2 \end{cases} \tag{3}$$

The variation of R_{m3} with armature displacement x is taken into account in equation (3). Knowing the above reluctances P_{e1} is calculated from the equivalent circuit in Figure 10 using -

$$P_{e1} = P_1 + \frac{1}{\dfrac{1}{\dfrac{1}{R_{m2}} + \dfrac{1}{R_{m3} + R_{na}}} + R_{na}} \tag{4}$$

Permeance due to the second end magnetic sleeve P_{e2} is calculated by considering the flux distribution in that region (see Figure 11). From the above this gives :

$$P_{e2} = P_2 + \frac{1}{\dfrac{1}{\dfrac{1}{R_{m2}} + \dfrac{1}{R_{m3} + R_{na}}} + R_{na}} \tag{5}$$

In equation (5) the reluctance Rm_3 is different from that given by equation (3) and is determined by taking

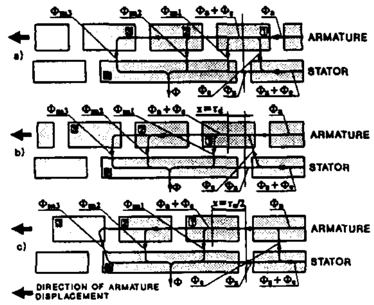

Figure 11. Flux distribution in the region of the second end magnetic sleeve used for the calculation of Pe_2

into account the variation of airgap reluctance with x between the magnetic sleeves m and 3 shown in Figure 11. Thus,

$$Rm_3 = \frac{\delta}{\pi\mu_0(lm-\tau_d-x)(Dae+Dsi)/2} \qquad (6)$$

Iterative Calculation of the Reluctances of Magnetic Sleeves, Fluxes and Equivalent Phase Permeance

Reluctances of magnetic sleeves of stator and armature Rms and Rma are determined iteratively which lies in the basis of the approximate method of calculation of phase reluctance R (or permeance P) and the static characteristics of LSM. For this, it is assumed that flux distributions in magnetic sleeves are uniform and, for a given alignment of stator and armature magnetic sleeves their permeabilities μ_s and μ_a depend only on the total flux passing through them and not on coordinate x. It is assumed that the variation of total flux in the magnetic sleeves with x determined by airgap flux Φ_e is linear. From this the average calculated flux components in stator and armature magnetic sleeves Φ_{sc} and Φ_{ac} are given by $\Phi_{sc}=\Phi_s+\Phi_e/2$ and $\Phi_{ac}=\Phi_a+\Phi_e/2$. The effective permeabilities μ_s and μ_a are calculated from the flux densities Bs and Ba determined by these flux components: $Bs=\Phi_{sc}/Sms$, $Ba=\Phi_{ac}/Sma$ where Sms and Sma are respectively the cross sectional areas of stator and armature magnetic sleeves. Now, from respective magnetisation curves $\mu_s=Bs/Hs$ and $\mu_a=Ba/Ha$ where Hs, Ha are field intensities correponding to Bs and Ba. Knowing μ_s and μ_a magnetic sleeve reluctances Rms and Rma are calculated: $Rms=lm/(\mu_s Sms)$ and $Rma=lm/(\mu_a Sma)$.

Knowing Rms, Rma and other reluctances phase reluctance R, total flux Φ and its components Φ_s, Φ_a and Φ_e could be calculated from the equivalent circuit shown in Figure 6. But it is not possible to do that directly since Rms and Rma themselves depend on the total flux Φ. For this reason the above calculation can be effectively done by successive iterations in which the flux components Φ_s, Φ_a and Φ_e are determined by solving the following set of equations of mmf balance for these flux paths (Figure 6):

$$\begin{aligned}
F &= \Phi Rpe + n\Phi_s Rns + (n-1)(\Phi_s+\Phi_e/2)Rms \\
F &= \Phi Rpe + (n-1)\Phi_a Rna + (\Phi_a+\Phi_e)(Re_1+Re_2) + \\
&\quad + n(\Phi_a+\Phi_e/2)Rma \qquad (7)\\
F &= \Phi Rpe + \Phi_e(n-1)(R_1+R_2) + (\Phi_a+\Phi_e)\times \\
&\quad \times(Re_1+Re_2) + n(\Phi_a+\Phi_e/2)Rma + \\
&\quad + (n-1)(\Phi_s+\Phi_e/2)Rms
\end{aligned}$$

For the iterative solution of (7) it is convenient to rewrite the equations in terms of flux components in the k-th iteration:

$$\begin{aligned}
\Phi_s^{(k)} &= Fic^{(k)}/Rs \\
\Phi a^{(k)} &= Fic^{(k)}/Ra \qquad (8)\\
\Phi_e^{(k)} &= Fic^{(k)}/Re
\end{aligned}$$

In the first iterarion (k = 1) the mmf drop in the inner magnetic cicuit Fic in equation (8) is taken as $Fic^{(1)}=(0.8\text{-}0.9)F$ and in successive iterations $Fic^{(k)}=F-\Phi^{(k)}Rpe$. Equivalent reluctances Rs, Ra and Re due to the flux paths Φ_s, Φ_a and Φ_e repectively are calculated in the first iteration by assuming that the reluctances of magnetic sleeves Rms = Rma = 0. This gives for k = 1

$$\begin{aligned}
Rs^{(1)} &= nRns \\
Ra^{(1)} &= (n-1)Rna + 2(Re_1+Re_2) \qquad (9)\\
Re^{(1)} &= (n-1)(R_1+R_2) + 2(Re_1+Re_2)
\end{aligned}$$

and in successive iterations-

$$\begin{aligned}
Rs^{(k)} &= nRns + (n-1)(1+\Phi_e^{(k-1)}/2\Phi_s^{(k-1)})Rms^{(k)} \\
Ra^{(k)} &= (n-1)Rna + (1+\Phi_e^{(k-1)}/\Phi_a^{(k-1)})(Re_1+Re_2) + \\
&\quad + n(1+\Phi_e^{(k-1)}/2\Phi_a^{(k-1)})Rma^{(k)} \qquad (10)\\
Re^{(k)} &= (n-1)(R_1+R_2) + (1+\Phi_e^{(k-1)}/\Phi_a^{(k-1)})\times \\
&\quad \times(Re_1+Re_2) + n(1+\Phi_e^{(k-1)}/2\Phi_a^{(k-1)})\times \\
&\quad \times Rma^{(k)} + (n-1)(1+\Phi_e^{(k-1)}/2\Phi_s^{(k-1)})Rms^{(k)}
\end{aligned}$$

The total flux $\Phi^{(k)}$ in k-th iteration is calculated from its components determined in (k-1)-th iteration:

$$\Phi^{(k)} = \Phi_s^{(k-1)} + \Phi_a^{(k-1)} + \Phi_e^{(k-1)} \qquad (11)$$

In each iteration, starting from the 2nd before the calculation of reluctances $Rs^{(k)}$, $Ra^{(k)}$ and $Re^{(k)}$ in the k-th iteration magnetic sleeve reluctances $Rms^{(k)}$ and $Rma^{(k)}$ are calculated using the flux components $\Phi_s^{(k-1)}$, $\Phi_a^{(k-1)}$ and $\Phi_e^{(k-1)}$ determined in the (k-1)-th iteration. For this the procedure described at the beginning of this section for calculating Rms and Rma from μ_s and μ_a using the flux components Φ_{sc} and Φ_{ac} is used. However, theoretical experiments show that the above method for updating the permeabilities can diverge the iterative process. To avoid this and to accelerate convergence the permeabilities of magnetic sleeves are corrected in each k-th iteration using

$$\begin{aligned}
\mu_s^{(k)} &= q(Bs^{(k)}/Hs^{(k)} + (1-q)\mu_s^{(k-1)} \qquad (12)\\
\mu_a^{(k)} &= q(Ba^{(k)}/Ha^{(k)} + (1-q)\mu_a^{(k-1)}
\end{aligned}$$

where relaxation factor $0.5 \leq q \leq 0.8$ and initially $\mu_s^{(1)} = \mu_a^{(1)} = 100\mu_0$. The above iterative process is ended when the flux components in two successive iterations become very close. For this the following end condition can be used:

$$|\Phi_s^{(k)}/\Phi_s^{(k-1)}-1| + |\Phi_a^{(k)}/\Phi_a^{(k-1)}-1| + \\ + |\Phi_e^{(k)}/\Phi_e^{(k-1)}-1| + |\Phi^{(k)}/\Phi^{(k-1)}-1| \leq \varepsilon \quad (13)$$

where ε is the end factor determined by accuracy requirements. Thus, using the method described above the total flux $\Phi(x)$ is calculated for various armature displacements x from which phase permeance $P(x) = \Phi(x)/F$ is calculated. Finally, electromagnetic force F(x) is calculated as a function of x by differentiating $P(x) = f(x)$ using equation (1).

RESULTS AND DISCUSSIONS

Some of the results of above calculations for the 4-phase LSM used in LSED are presented in Figures 12 and 13. Figure 12 shows the variation of phase permeance with armature displacement for a small

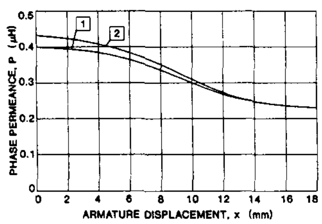

Figure 12. Variation of phase permeance P with armature displacement x: 1 - considering saturation effects, 2 - without considering saturation effects

stator current I = 5 A with (1 - Ps(x)) and without (2 - Puns(x)) saturation of magnetic sleeves taken into account. For Puns(x) it is assumed that $\mu_s = \mu_a = \infty$ and hence, Rms = Rma = 0. As can be seen from Figure 12 the effect of saturation on phase permeance for small stator current is not significant. Figure 13

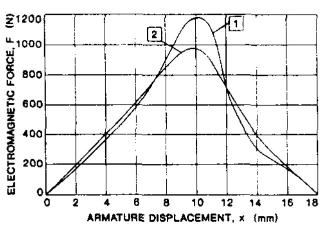

Figure 13. Static characteristics of the LSM: 1 - approximate method, 2 - experimental

shows the static characteristic of the LSM calculated by the approximate method (1) for I = 5 A and its comparison with the experimental characteristic (2) obtained from [10]. It shows, in general satisfactory agreement which validates the above described method. Maximum error of about 15% can be seen in the region of highest electromagnetic force for $x \approx 11$ mm. This is due to the approximate incorporation of iron saturation, especially the saturation of magnetic sleeve corners which takes place (even for small currents) for certain armature positions for which stator and armature magnetic sleeve corners align opposite to each other.

CONCLUSIONS

A method has been developed for the approximate calculation of static characteristics of linear step motors which gives satisfactory results for small currents and weak iron saturation. This is a simple and fast analytical technique which can be readily used at the early stages of CAD of these motors to generate, verify and evaluate initial designs.

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