Analysis of the Process of Energy Transformation in Magnetohydrodynamic Stirrer of Liquid Metals with Nonsinusoidal Current

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***Abstract* - This article describes the electromagnetic field analytical model of magnetohydrodynamic (MHD) stirrer with nonsinusoidal current, built with the account of the longitudinal edge effect. The solution is obtained in the form of a Fourier series in a comprehensive way. Differential and integral properties of the system have been defined. There have been received differential and integral characteristics, which are the basis for building the power supply source and control systems for the liquid metal stirring process.**

Keywords – Magnetohydrodynamics, liquid metals stirring, analytical calculation, nonsinusoidal periodic voltage, Fourier series transformation.

I. INTRODUCTION

IN RECENT YEARS there have increased production and consumption of aluminum-based alloys. The technology of multicomponent alloys preparation implements an important operation, which is the homogenization of chemical composition and temperature of the melt (liquid metal) in the full volume of the alloying furnace bath [1]. The use of MHD stirrers enables to automate the homogenization process, to reduce the preparation time and decrease the power consumed for the production of high-quality alloys [2-5].

Normally, the power of MHD stirrer is supplied through the low frequency sinusoidal voltage [2, 3]. However, currently, the development of power conversion equipment raises interest to the use of non-sinusoidal periodic voltage as power source for MHD stirrer. The non-sinusoidal voltage can take the form of a single-pole rectangular pulses, alternating rectangular pulses, triangular pulses or a sequence of pulses of a sinusoidal voltage.

Currently, a number of studies have been completed on the effectiveness of using the non-sinusoidal pulse electromagnetic fields in the units designed for liquid metal stirring. In [6, 7] there have been carried out numerical and experimental studies on the heat transfer of conductive liquid in low frequency pulse periodic electromagnetic field. In addition, a number of works are dedicated to the numerical [8, 9] and experimental [10, 11] study into ingot solidification process as exposed to the pulse periodic magnetic field.

These works showed a specific advantage of using non-sinusoidal periodic fields in the units designed for the electromagnetic stirring of melt. However, no theoretical study of the energy conversion process and the nature of electromagnetic fields distribution has been performed.

This paper presents the analytical solution to the problem of the electromagnetic field distribution in MHD stirrer with nonsinusoidal periodic current, taking into account the longitudinal edge effect and the discrete distribution of linear current load. There have been identified differential and integral characteristics, which are the basis for building the power supply source and control systems.

II. PROBLEM STATEMENT

The sketch of the holding furnace with MHD stirrer installed under the bath bottom is presented in Fig. 1.

Fig. 1 displays: 1 is alloying furnace bath; 2 is liquid metal (melt); 3 is electric heaters; 4 os polyphase winding of the inductor; 5 is inductor core;

The length of the core $L = 2\rho\tau_{ind}$, where ρ is the number of poles pairs; τ_{ind} is a polar pitch.

When the multiphase (m-number of phases) winding is connected to the source of periodic sinusoidal or non-sinusoidal voltage the inductor generates a travelling magnetic field. The speed of movement of the magnetic induction amplitude in the direction of the axis x is equal to $u_1 = 2\tau f$, where f is the current frequency in the winding of the inductor. Exposed to the travelling magnetic field, the melt starts to move with speed u also in the direction of the axis x performing the stirring of melt.

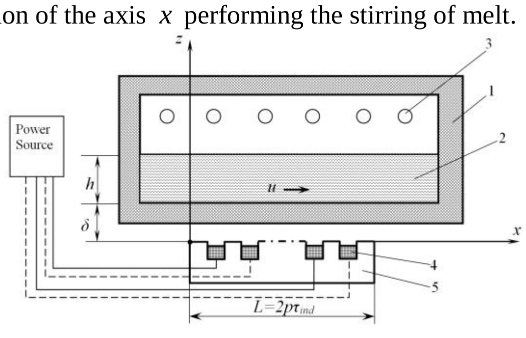

Fig. 1. Sketch - alloying furnace with MHD stirrer

Having adopted similar [4] assumptions, we obtain the design model of the MHD stirrer presented in Fig. 2.

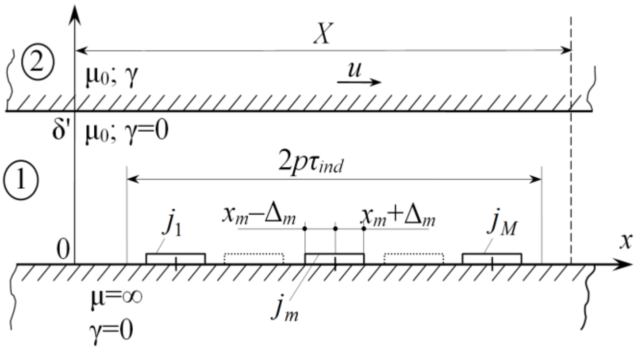

Fig. 2. Design model of MHD stirrer

Linear current density in the current sheet is defined as follows

$$j_m(t) = \frac{W_m \cdot i_m(t)}{2\varDelta_m},$$

where $i_m(t)$; W_m is the instantaneous current and a turning number in m th seam.

To obtain a travelling magnetic field in the inductor it is required to install in the inductor two or more windings that are supplied from the source with the same shape, frequency and voltages, phase-shifted relative to each other. Suppose that the inductor has M seams and linear current load of each subsequent phase is phase-shifted relative to linear current load of the previous seam by the angle *T/M*. Then, for the m th seam the linear current load will be determined in the range of

$$t_m - \frac{T}{2} \prec t \prec t_m + \frac{T}{2},$$

where

$$t_m = \frac{T}{2} + \frac{T}{M}(m-1).$$

Thus, linear current density in the mth seam is defined as follows

$$j_m(t) = \begin{cases} A - 2Ae^{-\frac{\left(t-\left(t_m - \frac{T}{2}\right)\right)}{\tau}}; \; t_m - \frac{T}{2} \prec t \prec t_m \\ -A + 2Ae^{-\frac{(t-t_m)}{\tau}}; \quad t_m \prec t \prec t_m + \frac{T}{2} \end{cases}.$$

Here

$$A = J - 2Je^{-\frac{T}{2\tau}};$$
$$\tau = L / R;$$
$$J = \frac{U}{R} \cdot \frac{W}{2\varDelta};$$

where *J* is an amplitude of linear current density, *A/m*; T - period, *s*; *L* is the inductivity, *H; R* is the copper resistance, Ω; U is the voltage amplitude, V; W -number of turns in the seam; $2\varDelta$ is the width of current sheet, *m*.

Figure 3 displays graphs of voltage and linear current density at various τ.

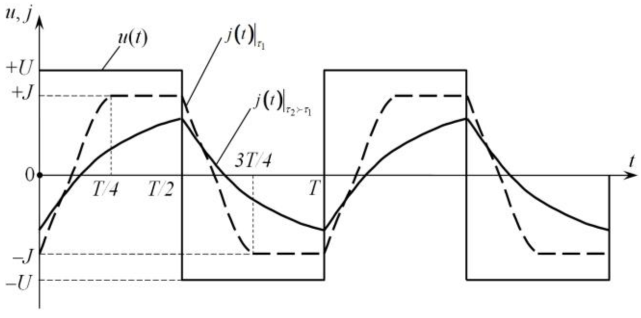

Fig. 3 Graphs of instantaneous value of voltage and current linear density

III. THEORY

A. Electromagnetic field equations and boundary condition

This model of electric- and magnetic -fields vector have the following elements:

$$\overline{E}(z,x,t) = \overline{e}_y E_y; \overline{H}_{1,2}(z,x,t) = \overline{e}_x H_{x1,2} + \overline{e}_z H_{z1,2}.$$

Electric-field vector E_y satisfies the functions of equations [4] (index "y" is omitted):

in area 1, $0 \le z \le \delta'$

$$\frac{\partial^2 E_1}{\partial z^2} + \frac{\partial^2 E_1}{\partial x^2} = 0; \quad (1)$$

in area 2

$$\frac{\partial^2 E_1}{\partial z^2} + \frac{\partial^2 E_1}{\partial x^2} - \mu_0 \gamma \frac{\partial E_2}{\partial t} - \mu_0 \gamma u \frac{\partial^2 E_2}{\partial x} = 0; \quad (2)$$

where γ is specific electrical conductivity of melt, $Ohm^{-1} \cdot m^{-1}$; u is the speed of melt movement, m/s; $\mu_0 = 4\pi \cdot 10^{-7}$ *H/m*; t is time, *s*.

Below are the area boundary conditions that are found true:

$$\frac{\partial E_1}{\partial z}(0,x,t) = \begin{cases} \mu_0 \frac{\partial j_m}{\partial t}, \; x_m - \varDelta_m \prec x \prec x_m + \varDelta_m \\ 0 \end{cases}; \quad (3)$$

$$E_1(\delta',x,t) = E_2(\delta',x,t); \quad (4)$$

$$\frac{\partial E_1}{\partial z}(\delta',x,t) = \frac{\partial E_2}{\partial z}(\delta',x,t); \quad (5)$$

$$E_2(\infty,x,t) = 0. \quad (6)$$

B. Solving electromagnetic field equations

The required functions $E_{1,2}(z,x,t)$ are periodical in time t with the period T, thus, the solutions shall be searched as Fourier series of a complex form [12]

$$E_{1,2}(z,x,t)=\sum_{k=-\infty}^{k=+\infty} E_{1,2k}(z,x)\,e^{i\zeta_k t}, \quad (7)$$

where

$$E_{1,2k}(z,x)=\frac{1}{T}\int_0^T E_{1,2}(z,x,t)\,e^{-i\zeta_k t}\partial t\,; \quad (8)$$

$$\zeta_k=\frac{2k\pi}{T}.$$

We convert the differential equations (1), (2) and the boundary conditions (3) to (6) in compliance with (7) and (8). We multiply these expressions by function $\frac{1}{T}e^{-i\zeta_k t}$ and integrate the resulting expressions by t from 0 to T, in the result we obtain

$$\frac{\partial^2 E_{1k}}{\partial z^2}+\frac{\partial^2 E_{1k}}{\partial x^2}=0\,; \quad (9)$$

$$\frac{\partial^2 E_{2k}}{\partial z^2}+\frac{\partial^2 E_{2k}}{\partial x^2}-i\zeta_k\mu_0\gamma E_{2k}-\mu_0\gamma u\frac{\partial E_2}{\partial x}=0\,; \quad (10)$$

$$\frac{\partial E_{1k}}{\partial z}(0,x)=\begin{cases}\psi_{km}, & x_m-\Delta_m \prec x \prec x_m+\Delta_m\\ 0\end{cases}\,; \quad (11)$$

$$E_{1k}(\delta',x)=E_{2k}(\delta',x)\,; \quad (12)$$

$$\frac{\partial E_{1k}}{\partial z}(\delta',x)=\frac{\partial E_{2k}}{\partial z}(\delta',x)\,; \quad (13)$$

$$E_{2k}(\infty,x)=0\,. \quad (14)$$

Here

$$\psi_{km}=i\mu_0\zeta_k J\sum_{m=1}^{M}\left(I_{km1}+I_{km2}\right);$$

where

$$I_{km1}=i\frac{A}{2k\pi}\left(e^{-i\zeta_k t_m}-e^{-i\zeta_k\left(t_m-\frac{T}{2}\right)}\right)+ +\frac{2Ae^{\frac{t_m-T/2}{\tau}}}{\left(\frac{T}{\tau}+i2k\pi\right)}\left(e^{-t_m\left(\frac{1}{\tau}+i\xi_k\right)}-e^{-\left(t_m-\frac{T}{2}\right)\left(\frac{1}{\tau}+i\xi_k\right)}\right);$$

$$I_{km2}=-\left[i\frac{A}{2k\pi}\left(e^{-i\zeta_k\left(t_m+\frac{T}{2}\right)}-e^{-i\xi_k t_m}\right)+ +\frac{2Ae^{\frac{t_m}{\tau}}}{\left(\frac{T}{\tau}+i2k\pi\right)}\left(e^{-\left(\frac{1}{\tau}+i\zeta_k\right)\left(t_m+\frac{T}{2}\right)}-e^{-t_m\left(\frac{1}{\tau}+i\xi_k\right)}\right)\right].$$

Assuming that the required functions are periodical also in the coordinate x with the period X, we can have the following

$$E_{1,2k(z,x)}=\sum_{n=-\infty}^{n=+\infty} E_{1,2kn}(z)\,e^{i\xi_n x}, \quad (15)$$

where

$$E_{1,2kn}=\frac{1}{X}\int_0^X E_{1,2kn}(z,x)\,e^{-i\xi_n x}\partial x\,; \quad (16)$$

$$\xi_n=\frac{2n\pi}{X}.$$

Similarly, we convert equations (9), (10) and the boundary conditions (11) to (14) in compliance with (15) and (16), in the result we obtain

$$\frac{d^2E_{1kn}}{dz^2}-\xi_n^2E_{1kn}=0\,; \quad (17)$$

$$\frac{d^2E_{2kn}}{dz^2}-\phi_{kn}^2E_{2kn}=0\,; \quad (18)$$

$$\frac{dE_{1kn}}{dz}(0)=\psi_{kn}\,; \quad (19)$$

$$E_{2kn}(\infty)=0\,; \quad (20)$$

$$E_{1kn}(\delta')=E_{2kn}(\delta')\,; \quad (21)$$

$$\frac{dE_{1kn}}{dz}(\delta')=\frac{dE_{2kn}}{dz}(\delta')\,; \quad (22)$$

where

$$\phi_{kn}^2=\xi_n^2+i\zeta_k\mu_0\gamma+i\mu_0\gamma u\xi_n\,;$$

$$\psi_{kn}=i\frac{2\mu_0\zeta_k J}{X\ \xi_n}N_{kn}\,;$$

$$N_{kn}=\sum_{m=1}^{M}\left(\hat{I}_{km1}+\hat{I}_{km2}\right)\sin\left(\xi_n\Delta_m\right)e^{-i\xi_n x_m}\,;$$

Common solutions and are as follows

$$E_{1kn}=C_1e^{\xi_n z}+C_2e^{-\xi_n z}\,; \quad (23)$$

$$E_{2kn}=C_3e^{\phi_{kn}z}+C_4e^{-\phi_{kn}z}\,. \quad (24)$$

Having defined constant integrations $C_1\div C_4$ from the boundary conditions (19) to (22) and having input them in (23) and (24), we make some simple transformations and obtain

$$E_{1kn}(z)=-\frac{\psi_{kn}}{\xi_n}\frac{G_{kn}(z)}{Q_{kn}}\,;$$

$$E_{2kn}(z)=-\psi_{kn}\frac{e^{\phi_{kn}(\delta-z)}}{Q_{kn}}\,.$$

Here

$$G_{kn}(z)=\xi_n ch\xi_n(z-\delta')-\phi_{kn}sh\xi_n(z-\delta')\,;$$

$$Q_{kn}=\xi_n sh\xi_n\delta'+\phi_{kn}ch\xi_n\delta'\,.$$

Given (7) and (15), we apply Euler formula and determine the real part. We obtain the following for area 1

$$E_1(z,x,t) = -\frac{4\mu_o XJ}{\pi T}\sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\frac{k}{n^2}D_{kn}(z)\times$$
$$\times\cos(\zeta_k t + \xi_n x + \beta_{kn})$$

Here

$$D_{kn} = \left| i\frac{G_{kn}(z)}{Q_{kn}}N_{kn}\right|;\ \beta_{kn} = \arg\left(i\frac{G_{kn}(z)}{Q_{kn}}N_{kn}\right).$$

C. Differential and integral properties

Maxwell equation allows to define the vertical component of magnetic induction

$$B_{z1}(z,x,t) = \int\frac{\partial E_1(z,x,t)}{\partial x}\partial t = $$
$$= -\frac{4\mu_o J}{\pi}\sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\frac{1}{n}D_{kn}(z)\cos(\zeta_k t + \xi_n x + \beta_{kn}).$$

Instantaneous electromagnetic (EM) power generated in the inductor winding is equal to

$$P(t) = -l\sum_{m=1}^{M}\int_{x_m-\Delta_m}^{x_m+\Delta_m}E_1(0,x,t)\, j_m(t)\partial x = $$
$$= \frac{4\mu_0 X^2 l J^2}{\pi^2 T}\sum_{k=1}^{\infty}k\sum_{n=1}^{\infty}\frac{1}{n^3}D_{kn}(0)C_{kn}(t),$$

where

$$C_{kn}(t) = \sum_{m=1}^{M}\hat{j}(t)\int_{x_m-\Delta_m}^{x_m+\Delta_m}\cos(\zeta_k t + \xi_n x + \beta_{kn})\partial x = $$
$$= \sum_{m=1}^{M}\hat{j}_m(t)\sin(\xi_n\Delta_m)\cos(\zeta_k t + \alpha_{knm})$$

where

$$\hat{j}(t) = j(t)/J;\ \alpha_{knm} = \xi_n x_m + \beta_{kn}.$$

Instantaneous EM force acting on the winding of the inductor is defined by expression

$$f(t) = -l\sum_{m=1}^{M}\int_{x_m-\Delta_m}^{x_m+\Delta_m}B_{z1}(0,x,t)\, j_m(t)\partial x = $$
$$= \frac{4\mu_0 l\, X\, J^2}{\pi^2}\sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\frac{1}{n^2}D_{kn}(0)C_{kn}(t).$$

We find the average values for the period of EM force and power in the relative units, taking the following as basic values

$$P_b = \frac{4\mu_0\tau^2 l\, J^2}{\pi^2 T};\ F_b = \frac{4\mu_0 l\,\tau\, J^2}{\pi^2}.$$

The average EM power and force for the period are

$$\hat{P}_{em} = \sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\frac{k}{n^3}\hat{D}_{kn}(0)K_{kn};\ \hat{F}_{em} = \sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\frac{1}{n^2}\hat{D}_{kn}(0)K_{kn}.$$

Here

$$K_{kn} = \sum_{m=1}^{M}\sin(\xi_n\Delta_m)\left(V_{knm}^{(1)} + V_{knm}^{(2)}\right);$$

$$V_{knm}^{(1)} = \frac{1}{T}\int_{t_m-\frac{T}{2}}^{t_m}\hat{j}(t)\cos(\zeta_k t + \alpha_{knm})\partial t;$$

$$V_{knm}^{(2)} = \frac{1}{T}\int_{t_m}^{t_m+\frac{T}{2}}\hat{j}(t)\cos(\zeta_k t + \alpha_{knm})\partial t;$$

$$\hat{G}_{kn}(z) = \frac{2n}{\hat{X}}ch\left[\frac{2n}{\hat{X}}(z-\delta')\right] - \hat{\varphi}_{kn}sh\left[\frac{2n}{\hat{X}}(z-\delta')\right]$$

$$\hat{Q}_{kn} = \frac{2n}{\hat{X}}sh\left(\frac{2n}{\hat{X}}\delta'\right) + \hat{\varphi}_{kn}ch\left(\frac{2n}{\hat{X}}\delta'\right);$$

$$\varepsilon_1 = \frac{\gamma\mu_0\zeta_{k=1}\tau^2}{\pi^2} = \frac{2\gamma\mu_0\tau^2}{\pi T};\ s_1 = 1 - \frac{u}{2\tau}T;$$

$$\hat{\varphi}_{kn} = \sqrt{\left(\frac{2n}{\hat{X}}\right)^2 + i\varepsilon_1 - i\varepsilon_1\frac{2n}{\hat{X}}(1-s_1)};$$

$$\hat{X} = X/\tau.$$

IV. Discussion of Results

Fig. 4 shows the graph of instantaneous value distribution for the relative magnetic induction density within the slot ($\pi B_{z1}/4\mu_0 J$). Tooth and slot ripples emerge on the inductor surface, however, their manifestation on the melt surface is reducing. In addition, the non-sinusoidal supply voltage affects the dynamics of distribution for the travelling magnetic field but does not affect the nature of its distribution in the gap.

Fig. 5 shows the graphs of instantaneous EM force and power for the period. The force and power modify with a double frequency, but their form is not sinusoidal and is characterized by moments of sharp decline and increase in the amplitude. Such a character of EM force change makes it possible to generate the impulse mechanical effect in the melt, which allows to perform stirring and homogenization at the level of microinhomogeneities.

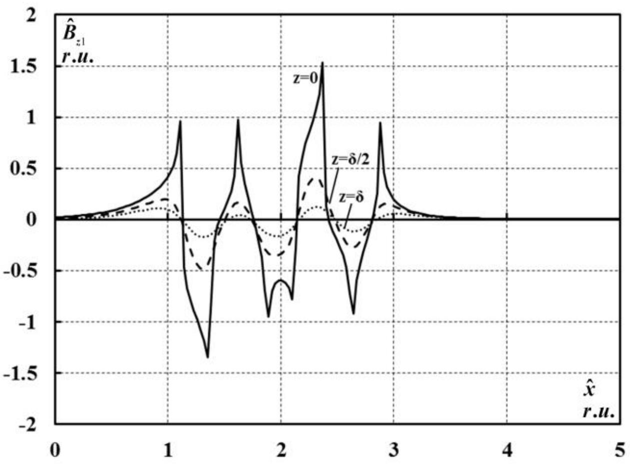

Fig. 4 Graph of distribution for the instantaneous relative magnetic induction in the gap taking into account the longitudinal edge effect for t=0, τ=0.05T, s=1, ε=3.6

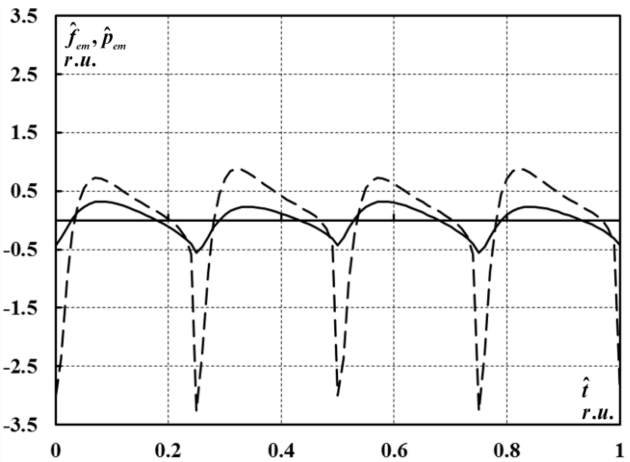

Fig. 5 Graph of instantaneous relative EM force (solid line) and power (dotted line) during the period taking into account the longitudinal edge effect τ=0.05T, s=1, ε=3.6

Fig. 6 and 7 give the relations of the average values for the period of EM power and force obtained from sliding at different values of Q factor ε. As can be seen from Figure 6, the non-sinusoidal nature of the supply voltage has a minor impact on the energy characteristic, while the curves shape is close in nature to the case of MHD stirrer with a classic sinusoidal power supply [4]. The nature of the mechanical characteristics curves in Fig. 7 differs substantially from the case of sinusoidal power supply. During the metal acceleration (s≤0.2), the EM force changes its direction at specific values of Q factor ε. This nature is due to the interaction of the induced current of moving melt with the higher harmonics of the inductor magnetic field.

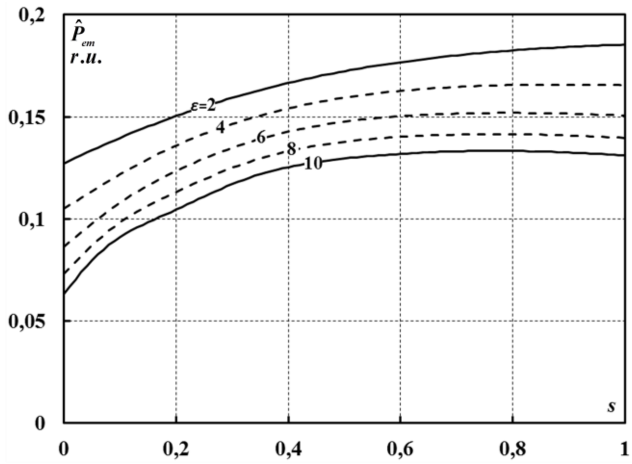

Fig. 6 Relation of relative EM power from sliding average for the period taking into account the longitudinal edge effect for τ=0.05T

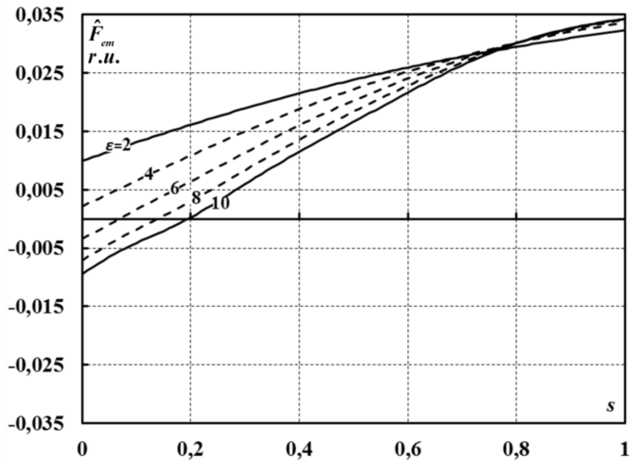

Fig. 7 Relation of relative EM force from sliding average for the period taking into account the longitudinal edge effect for τ=0.05T

VI. Findings and Conclusions

1. The 2D design model has been built to analyze the electromagnetic field and electromagnetic characteristics of MHD stirrer of liquid metal with non sinusoidal current.
2. The application of double integral conversions using Fourier series with complex coefficients enabled to obtain analytical expressions for electromagnetic fields vectors and electromagnetic characteristics of MHD stirrer.
3. The analysis has been completed on the magnetic induction distribution in the device gap, instantaneous EM power and force for the period non sinusoidal current. The results obtained can be used to eliminate inhomogeneities in the process of multi-component aluminum alloys production.
4. The obtained integral characteristics for power and force can be used to develop a power source and stirring process control systems.

ACKNOWLEDGEMENTS

This research has been completed with the financial support of the Russian Fund of Fundamental Research and the Government of Krasnoyarsk Territory within the framework of Research Project No. 18-48-242013 “Research into the impact of spatial and time-and-frequency distributions of electromagnetic forces in the melt on the nature of the MHD processes in liquid metal”.

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Prize winner of the contest held by the Krasnoyarsk City Mayor, the State Award of the Krasnoyarsk Territory, Award of the Strategic Research Fund “Siberian Club”, Award of the IFC Bank in scientific nominations, medal of All-Russian Exhibition of Scientific and Technical Creativity of Youth “For achievements in the scientific and technical creativity”.

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