In-melt electromagnetic forces at MHD-stirring with the non-sine supply

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The crucial task in production of multi-component alloys is a development and study of MHD-stirring conditions which make it possible to achieve new process effects such as microinhomogeneous homogenization or MHD-resonance. One of the advanced ways to provide such stirring conditions is the supply of the non-sine periodic current of the given waveform to inductor coils. The paper presents the results of numerical simulation of a magnetohydrodynamic stirrer with non-sinusoidal power supply. The analysis of the behavior of electromagnetic forces at various power supply parameters is carried out. A comparative analysis of the obtained results with the characteristics of the MHD stirrer with a sinusoidal power supply system is carried out.

1. Introduction

At the time the area of metallurgical products’ application is heavily expanded. This is the case, for example, of aluminium alloy products which are nowadays widely used in the aircraft industry, in additive technologies and in other spheres. Therewith MHD-stirers are one of the most effective way to increase the metallurgical equipment efficiency [1]. Thus the in-furnace MHD-stirring of a molten metal presents a widely occurring technology for the modern metallurgical production. MHD-stirers allow automation of homogenization, decreasing the preparation time and power consumed to produce the good-quality alloys [2, 3].

The crucial task in production of multi-component alloys is a development and study of MHD-stirring conditions which make it possible to achieve new process effects such as microinhomogeneous homogenization or MHD-resonance [4]. One of the advanced ways to provide such stirring conditions is the supply of the non-sine periodic current of the given waveform to inductor coils.

A number of the studies of non-sine pulse EM fields’ efficiency in the molten metal stirrers have been conducted up to date. To sum up, MHD-stirers of non-sine supply can be divided into two groups. The first group includes stirrers where the supply current waveform presents sequential pulses of sine current modulated by the frequency much less than the basic one. Stirrers with industrial mains frequency are supplied in such a way. The second group includes stirrers where the supply current waveform presents the non-sine periodic function of the given waveform. The supply current may be as the single-pole or alternating square-wave pulses and triangular pulses. Low-frequency stirrers (0.5 - 5 Hz) are supplied in such a way.

A number of computational and experimental studies have been conducted for different MHD-stirers of the first group [4-6]. These works revealed a certain advantage of sequential modulated sine pulses supplied. The work [4] showed that such supply allows the so-called MHD resonance which leads to more intensive heat and mass transfer in melt.

As regards the MHD-stirers with the non-sine periodic supply current of the given waveform, the electromagnetic and hydrodynamic processes underwent the theoretical researches for some simple systems [7, 8]. The work [9] showed that non-sine supply of MHD-stirrer inductor with the current waveform being nearly square at the constant amplitude makes it possible to increase the integral EM force applied to the melt. Still it is evident that in this case the real power loss in the inductor will also increase as the effective mains current will actually get bigger. The work [10] includes computational studies of EM forces’ distribution in melt with the inductor being supplied with non-sine periodic rectangular voltage with various duty factor.
However, with such type of supply the current waveform may be corrected by altering only the coil parameters (turns, geometry, resistance) which is a hard-to-implement task. Therewith the up-to-date current supplies actually allow generating the output current of various waveforms [11] whereby control of the force applied to melt is possible. This work includes computational study of spatial and time-and-frequency distribution of EM forces in MF-influenced melt such magnetic field being generated by the MHD-stirrer inductor supplied with non-sine currents of the given waveform.

2. Statement of the Problem

2.1. Electromagnetic field equation and boundary conditions

Two-phase MHD-stirrer with intersecting winding produced by RPC MAGNETIC HYDRODYNAMICS, LLC, has been studied [12]. The below assumptions are accepted in computational modelling:

1. The problem is to be 2D considered;
2. Physical properties of areas are assumed to be constant;
3. Coils’ sections are simulated with no discretion by individual turns;
4. Magnetic permeability of a magnetic core is taken as constant based on the properties of the material selected;
5. Motion of melt particles is disregarded when solving the EM problem.

With due account of the assumptions taken, the equation of the magnetic vector potential for the computational domain is written as follows [13, 14]

\[ \Delta A = \mu \gamma \frac{\partial A}{\partial t}, \]  

(1)

where \( A \) is a magnetic vector potential; \( \mu \) is an absolute magnetic permeability; \( \gamma \) is a specific electric conductivity; \( t \) is time.

Dirichlet condition is applied to the normal component of the vector potential and Neumann condition is applied to the tangential component at the boundaries of the computational domain.

\[ A_n = 0; \quad \frac{\partial A_t}{\partial n} = 0. \]  

(2,3)

2.2. Numerical setup

The total MMF in each coil section is set as the loading source. The waveform of MMF in coils is a trapezoidal alternating function which parameters are set by the rise/fall time \( t_{front} \) and by the time of the MMF being constant \( t_{const} \). The MMF waveform depends on the non-dimensional parameter \( \hat{t} = 2t_{front}/T \) which is indicative of the current rise time to the peak value. Let’s say that this value is a waveform parameter. Thus, parameters of the MMF curve are found as below

\[ t_{front} = \hat{t} \frac{T}{2}; \quad t_{const} = \frac{T}{2} - t_{front} \]  

(3,4)

Therefore, when \( \hat{t} \to 0 \), MMF waveform represents bidirectional square pulses and, when \( \hat{t} \to 1 \), it represents triangular pulses. For meaningful comparison the peak MMF value varies with \( \hat{t} \) so that the effective value remains constant

\[ I_m n_{sec} = I_m n_{sec} \sqrt{\frac{3}{3 - 2 \hat{t}}}, \]  

(5)

where \( I_m \) is a base current amplitude; \( n_{sec} \) is a number of turns at the coil section; \( I_m \) is an amplitude of the non-sine supply.

Picture 1 shows the diagram of the instantaneous current in the coil conductor \( I_m \) for various waveform values.
Picture 1. Diagram of the instantaneous current in the coil conductors for various waveform values.

Picture 2 shows the sketch of the computational domain with the key geometrical and physical parameters and the finite element grid. The computational domain includes melt 1, magnetic core 2, two-phase coil 3 and ambient air 4. The finite element mesh is automatically built with Maxwell facilities based on the adaptive algorithms [15]. Table 1 presents the main geometrical and power parameters of the computational model. Other geometrical dimensions are in parametric relations with the main ones. Thus, the depth of a tooth is automatically computed based on the number of coil sections and the gap in-between them.

Conductivity $\gamma$ is given in [S/m]
Table 1. The main model parameters

| Geometrical parameters [m]            |       |
|--------------------------------------|-------|
| Pole pitch, \( \tau_{ind} \)        | 1.1   |
| Nonmagnetic gap, \( \Delta_{nm} \)  | 0.4   |
| Bath depth, \( H_{melt} \)          | 0.95  |
| Bath length, \( L_{melt} \)         | 6.2   |
| Height of the magnetic core yoke, \( h_{yoke} \) | 0.275 |
| Width of the end tooth, \( w_e \)    | 0.278 |
| Width of the middle tooth, \( w_m \) | 0.419 |
| Gap between the coil sections, \( \Delta_{sec} \) | 0.022 |

| Power parameters:                  |       |
|------------------------------------|-------|
| Frequency, [Hz]                    | 0.5, 1, 1.5 |
| Base current in conductor, [A]     | 224   |
| Phase shift between the coils’ currents, [deg] | 90 |

3. Results and discussion

3.1. Integral parameters
When studying MHD-stirrers’ parameters, the tangential component of EM force is of the prime interest as this component is responsible for the heat-and-mass transfer within the furnace. When the inductor coil is supplied with sine current, it is reasonable to take the force magnitude as the base value in order to compare the influence of the supply current waveform on the electromagnetic force \( F_{\text{sin}} \).

The picture shows the dependence of the relative integral EM force on the waveform parameter. Thus, it is evident that when varying the supply current waveform from trapezoid to triangle with the effective value being the same, the integral value of the tangential force component will, at any time, be less if the inductor is sine supplied. Thereat the extreme value is observed in domain \( \tau \approx 0.6 \ldots 0.7 \) for all the frequencies reviewed. This is attributable to the fact that the harmonic content is best matched to the sine function under this waveform parameter. In addition to the above, the more current waveform edges are, the lower tangential EM force component is.

![Graph showing the dependence of the relative integral EM force on the form factor.](image1)

| 0.5 Hz | 1 Hz | 1.5 Hz |
|--------|------|-------|
| 0.5    | 1    | 1.5   |

![Graph showing the dependence of the relative normal EM force on the form factor.](image2)

| 0.5 Hz | 1 Hz | 1.5 Hz |
|--------|------|-------|
| 0.5    | 1    | 1.5   |

Therewith the integral value of the normal EM force component is slightly higher throughout the range \( \tilde{\tau} \) as compared with the inductor sine supply. Thus, with the frequency of 0.5 Hz, the integral normal EM force may increase by 5-7 percent when the inductor is supplied with trapezoidal current as compared with the sine supply. But the normal force component has no significant influence on the transient heat-and-mass transfer within the furnace. The work [16] states that the normal component provides only for the local vertical mass transfer with the general decrease of in-the-bath motion. On the other hand, such effect may be useful when installing an MHD-stirrer on the side wall of the furnace.

It also should be noted that the power consumed for coils’ and metal preheat will change when the supply parameters are changed. The picture shows dependence of the tangential EM force relation to the active power consumed for coils’ and metal preheat. Generally, the force-to-power increment is changed insignificantly throughout the reviewed range \( \tilde{\tau} \). It may just be noted that when current
approaches the rectangular waveform, the gain of the power consumed for preheat becomes more significant than the tangential EM force gain.

![Image](advanced_problems_of_electrotechnology.jpg)

**Picture 5.** Dependence of the tangential EM force relation to the active power consumed for coils’ and metal preheat on the waveform parameter.

3.2. *Spatial and time distributions of electromagnetic forces*

It is worth mentioning that in case of non-sine periodic inductor supply, the structure of the travelling magnetic field is disturbed whereby the spatial and time in-melt distribution of EM forces is much different from distribution of forces in case of the sine supply. Picture 6 shows the vector in-melt EMF distribution at different time with various inductor supply parameters (here $T$ is the supply current oscillation period). When the inductor is sine supplied, the wave of electromagnetic force glides along the bath length in the magnetic field direction. When the inductor is non-sine supplied, the spatial and time EMF distribution is disordered and characterized by its reversal in direction at different melt points. Besides that, it bears mentioning the occurrence of the strong normal EM force component in the middle part of the inductor such component being of the negative direction (vector to inductor). Such EMF behavior may have a disastrous effect on the integrity of the refractory lining.

![Image](advanced_problems_of_electrotechnology.jpg)

**Picture 6.** Vector in-melt distribution of EM forces over time under various inductor supply parameters.

Such spatial and time EMF in-melt distribution will generally have the adverse effect on the metal velocity, transient mass transfer and hence the mechanical efficiency. On the other hand, such pattern of changes opens up the potential for vibratory impacts in melt which, as stated above, also provides process advantages when producing multicomponent alloys. EMF at any point of the melt is known to be sinusoidally changed in time if an MHD-stirrer is also sine supplied. The work [4] revealed that EMF pulses allow intensifying the heat-and-mass transfer in melt by increasing the kinetic pulse energy. Low-frequency EMF sine waves lead to the periodic fluctuations of metal velocity which intensify elimination of microinhomogeneity by additional local acceleration and increased turbulent viscosity due to the components’ diffusion. Nevertheless low-frequency sine supply of the inductor does not provide for the sharp variation of the in-melt EM force whereat the amplitude of oscillations remains stable notwithstanding the supply parameters. Thus, such EMF behavior is advantageous which will ensure the mechanical impact on melt in order to remove microinhomogeneities.

Two bottom points (Picture 7) have been chosen to study the EMF behavior: point 1 is the middle point as relating to the inductor geometric symmetry (middle zone) and point 2 is in the area of the end inductor tooth (edge zone).
Picture 7. Points to study the EMF behavior in melt.

Picture 8 shows the instantaneous values of tangential EMF component at points 1 and 2 under various waveform parameter values. It can be seen that tangential EMF in the edge zone varies about the zero value which indicates that its period average in this zone is close to zero and, moreover, may be reverse in relation to the magnetic field direction. Such behavior of the tangential force component in the edge zone is attributed to the linear edge effect [17]. Tangential EMF component in the middle zone varies about some average value in the positive domain. Therewith the instantaneous EM force is close to the sine form when the waveform parameter is $\hat{\tau} \approx 0.4 \ldots 0.8$. With $\hat{\tau} = 0.2$ and $\hat{\tau} = 1$ the force is most suddenly changed, moreover, in case of triangular supply current the instantaneous tangential EM force also has the obvious triangular waveform.

$\hat{\tau} = 0.2$

$\hat{\tau} = 0.4$

$\hat{\tau} = 0.6$

$\hat{\tau} = 0.8$

$\hat{\tau} = 1$
Picture 8. Diagram of the instantaneous tangential EM force in the middle zone

Picture 9. Diagram of the instantaneous normal EM force in the edge zone

Picture 9 shows the instantaneous normal EMF component at points 1 and 2 under various waveform parameter values $\tilde{t}$. As regards the middle zone, normal force is most suddenly changed with $\tilde{t} = 0.2$. Beside the EMF behavior in time, the peak-to-peak force oscillations are also important for generation of the force impact required for the efficient homogenization and elimination of microinhomogeneities. The peak-to-peak EMF oscillations may be evaluated with the peak factor which corresponds to a peak-to-RMS relation

$$K_a = \frac{F_m}{F_{rms}}; \quad F_{rms} = \sqrt{\frac{\sum_{n=1}^{N} F_n^2}{N}},$$

where $F_m$ is the peak EMF value; $F_{rms}$ is the RMS value of EM force; $F_n$ is the instantaneous EMF for n time step; $N$ is a number time steps over the period.

In the present case let us consider the EMF change function without the average value being taken into account. It is known that in this case for sine function $K_a^{\sin} \approx 1.41$. Picture 10 shows the diagrams of the peak factor dependence on the waveform parameter at the middle and edge points. It is apparent that dependence of the peak factor on the form factor is alike for all the reviewed frequencies of non-sine supply current and, moreover, the frequency has slight effect on the peak factor.

Point 1

Point 2

$0.5 \text{ Hz}$  $1 \text{ Hz}$  $1.5 \text{ Hz}$  $K_a^{\sin}$
Picture 10. Dependence of the EMF peak factor on the form factor with various supply current frequencies.

The highest amplitude of tangential EMF component oscillation in the middle zone is ensured for the values \( \tau < 0.4 \) and \( \tau > 0.8 \), that is actually with almost rectangular supply current or triangular supply current. It is also noteworthy that peak oscillations of tangential force component within these values may be lower than when sine supplied. On the contrary, the highest amplitude of the normal component oscillations in the middle zone is provided at \( \tau \approx 0.4 \ldots 0.5 \).

Peak factor dependences for tangential and normal EMF component at Point 2 have no maximum. Peak oscillations of tangential component in this zone is increased as the current waveform approaches the squarewave. As regards the normal component, the peak oscillations are, on the contrary, increased as the supply current waveform approaches the triangle.

4. Conclusion
The influence of the waveform of the current supplying the MHD-stirrer inductor on the EMF behavior in melt has been assessed in this work. Several main conclusions can be made based on the findings:
1. When supply current waveform approaches the rectangle, the integral value of in-melt tangential force is decreased as compared with the value when the inductor is sine supplied.
2. The highest tangential EMF component is achieved when the inductor is supplied with trapezoidal current with the amplitude rise/fall time \( t_{\text{front}} \) being equal to approximately quarter-period.
3. As regards the non-sine current of the given waveform, it is expected that the transient mass transfer throughout the melt will decrease and hence the mechanical efficiency will also decrease. However the disordered spatial and time distribution of EM forces opens up the potential for the vibratory impact on the melt which may pose some process advantages for removal of microrinhomogeneities.
4. The most sudden change and the highest amplitude of EMF fluctuations are ensured when triangle or trapezoid current is supplied with the minimum amplitude rise/fall time that is at \( t_{\text{front}} \rightarrow 0 \).

5. References
[1] Baake, E., et al. "MHD technologies in metallurgy." Intensive Course Specific IV. Study guide, Publishing house of ETU, St. Petersburg 232 (2013).
[2] Fdhila R, Sand U and Eriksson JE, et al. 2016 A stirring history. ABB Review.,3:45-48.
[3] Timofeev V and Khatsayuk M. 2016 Theoretical design fundamentals for mhd stirrers for molten metals //Magnetohydrodynamics (0024-998X). – Vol. 52. – №. 4.
[4] Musaeva D, Ilin V and Baake E, et al. 2015 Numerical Simulation of the Melt Flow in an Induction Crucible Furnace Driven by a Lorentz Force Pulsed at Low Frequency. Magnetohydrodynamics.
[5] Eckert S, Nikritiyuk P and Rabiger D, et al. 2008 Efficient melt stirring using pulse sequences of a rotating magnetic field: Part I. Flow field in a liquid metal column. Metall Mater Trans B.
[6] Wang X. et al. 2009 A periodically reversed flow driven by a modulated traveling magnetic field: Part I. Experiments with GaInSn //Metallurgical and Materials Transactions B. – Vol. 40. – №. 1. – p. 82.
[7] Ma X, Yang Y and Wang B. 2009 Effect of pulsed magnetic field on superalloy melt //International Journal of Heat and Mass Transfer. – Vol. 52. – №. 23-24. – p. 5285-5292
[8] Guo-Jun C, Yong-Jie Z and Yuan-Sheng Y. 2013. Modelling the unsteady melt flow under a pulsed magnetic field //Chinese Physics B. – Vol. 22. – №. 12. – p. 124703

[9] Timofeev V, Lybzikov G and Khatsayuk M, et al. 2015. Magnetohydrodynamic stirrer liquid metal with a non-sinusoidal currents. Engineering & Technologies. 166-177

[10] Jia, Yonghui, et al. "Numerical study on action of HMF, PMF, DHMF, and DPMF on molten metal during electromagnetic casting." The International Journal of Advanced Manufacturing Technology 103.1-4 (2019): 201-217

[11] Patent RU 2680715
[12] web site: https://www.npcmgd.com/
[13] Landau, L. D. (Ed.). (2013). The classical theory of fields (Vol.2). Elsevier.
[14] Landau, L. D., Bell, J. S., Kearsley, M. J., Pitaevskii, L. P., Lifshitz, E. M., & Sykes, J. B. (2013). Electrodynamics of continuous media (Vol.8). Elsevier.
[15] Ansys Maxwell 15.0 User’s Guide 3D
[16] Maksimov, Aleksiy A., Maksim Y. Khatsayuk, and Viktor N. Timofeev. "Aspects of Energy Transformation and Energy Control Capabilities in Electric Machines with a Liquid-Metal Working Body." 2019 20th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM). IEEE, 2019.
[17] Yamamura S., Ito H., Ishulawa Y. Theories of the linear, induction motor and compensated linear induction motor //IEEE Transactions on Power Apparatus and Systems. – 1972. – №. 4. – C. 1700-1710

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