Dynamics of inductors for heating of the metal under deformation

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Abstract. Current issues of creating powerful systems for hot sheet rolling with induction heating application in mechanical engineering and metallurgy were discussed. Electrodynamic and vibroacoustic problems occurring due to the induction heating of objects with complex shapes, particularly the slabs heating prior to rolling, were analysed. The numerical mathematical model using the method of related contours and the principle of virtual displacements is recommended for electrodynamic calculations. For the numerical solution of the vibrational problem, it is reasonable to use the finite element method (FEM). In general, for calculating the distribution forces, the law of Biot-Savart-Laplace method providing the determination of the current density of the skin layer in slab was used. The form of the optimal design of the inductor based on maximum hardness was synthesized while researching the vibrodynamic model of the system “inductor-metal” which provided allowable sound level meeting all established sanitary standards.

1. Introduction

In the case of induction heating of bodies with rapidly changing surface curvature, which primarily include slabs [1, 2, 3], a problem occurs that is determined by the fact that electromagnetic processes in the system "inductor-metal" are characterized by not only the release of heat energy in the work piece but also in the inductor [4, 5]. In this case, it is also necessary to consider the density of the electromagnetic field and its associated electrodynamics efforts. Electrodynamics forces in the melting furnaces can improve the mixing of the liquid metal, but during induction heating for the deformation, the mechanical manifestation of electromagnetic energy plays a very negative role, due to the occurrence the problem of resistance of inductor against vibration arising under the electrodynamics forces [6, 7, 8]. This problem is especially actual for the induction heating of rectangular billets, particularly made of non-magnetic metals. This phenomenon can be used in the production for obtaining of artificial vibrations with a view to their beneficial use, for example, when exposed to the molding sand [9]. In design of inductors for heating of cylindrical billets there are no conditions for the occurrence of significant vibrations (circular cross section has a high natural stiffness) and in the inductors of rectangular shape it is necessary to take into account the low stability of the straight sections of the windings of the inductor. Moreover, the problem is not the mechanical strength of the copper pipe of the inductor, since the resulting bending stresses are much less than acceptable for copper, but the vibration and accompanying noise, which, if not to accept special measures greatly exceed sanitary norms for industrial buildings [10, 11, 12, 13].
2. Statement of the problem
In most cases, there is a problem related to dynamic properties of inductors designed for heating of large billets of rectangular shape, for example, slabs, whose weight is measured in tons. The resolution of this problem is possible by creating a vibration-resistant induction heating systems (ELIS), on the basis of the study of electrodynamics and related vibroacoustic processes. It is advisable carry out Electrodynamics calculations with the numerical mathematical model built using the related contours and displacements principle. Thus, the task of optimal design [14,15] of inductors, robust against the vibration and noise, is based on the study of electrodynamics and associated vibroacoustic processes. According to the criterion of reduced costs, construct of the inductor, while ensuring acceptable level of vibration and of noise must have a minimum cost. It is equivalent to minimizing its weight of the given composite materials for the vibration-resistant sheath of the inductor. Attempts intuitive approach to the selection of the best forms of shell of minimum volume because of a non-obviousness optimal design lead to contradictory and sometimes erroneous results. It is therefore appropriate to formulate and solve the optimization problem for the shape of the shell of the inductor. For this purpose it is necessary to choose the decisive optimization criterion, to build a simplified, idealized model of the inductor, and with the consideration real structural constraints formalize the conditions for its optimality, and develop an efficient optimization algorithm that allows getting the concrete results. The criterion of optimization it is advisable to take the rigidity of the inductor that is the equivalent of frequency of own oscillations. The accuracy of the theoretical research is confirmed by the patents [16, 17, 18].

3. Theory

3.1. Electromagnetic problem
If to base on the plane-parallel magnetic field model, then for the given case it is better to solve internal electrodynamics problem in 2D space for body’s crosssection:

$$\frac{d^2 H(x,y)}{dx^2} + \frac{d^2 H(x,y)}{dy^2} = \hat{k}^2 H(x,y)$$  \(1\)

$$\hat{H}(x,y)_{li} = H_o,$$  \(2\)

$$x \in [0,b], \quad y \in [0,d], \quad \hat{k} = (j+1) \frac{1}{\Delta_\gamma}$$  \(3\)

$$P(x,y,\frac{b}{\Delta_\gamma},\beta) = \frac{1}{\gamma} \gamma (\hat{E}_x\hat{E}_x + \hat{E}_y\hat{E}_y)$$  \(4\)

$$\hat{E}_x = \frac{1}{\gamma} \frac{d\hat{H}(x,y)}{dy}, \quad \hat{E}_y = \frac{1}{\gamma} \frac{d\hat{H}(x,y)}{dx}$$  \(5\)

$$\beta = b \frac{d}{d}; \quad \xi = \frac{d}{\Delta_\gamma}$$  \(6\)

where \(E, H\) - are electric and magnetic field strengths; \(\mu, \mu_0\) - are relative and absolute permeability; \(\gamma\) - is the specific electrical conductivity; \(d, b\) - the thickness and width of the heated rectangular billet (slab); \(\Delta_\gamma\) - the current penetration depth in the slab.
3.2. Heat problem.

Using (4), internal sources of the electromagnetic power distribution were explored, as well as the influence of crosssection size and penetrating depth.

The results are shown on Figure 1, where the power density on the crosssection’s wide side center, on the surface, is equal to 1.

The variants, shown on Figure 1a, has the same parameters as the aluminum slabs heating on 50 Hz frequency with the thickness of 0.28-0.35 m. Figure 1b - the same, but in the case of titanium slabs.

![Figure 1](image1.png)

To make a long story short, the term, penetrating depth, isn’t suitable for halfbordered body (Shtainmetz formula). The power density changing is determined by $\xi$ as well as by $\beta$.

The Furies’ equation solving for exothermic rectangular prism (see (4)), made isotherm creation possible (Figure 2) for the same $\xi$ and $\beta$ as on Figure 1. The isotherm analysis shows that the temperature gradients kind is the same, to the electromagnetic sources distribution, and they are also determined by $\xi$ and $\beta$; with $\xi$ and $\beta$ lowing-negative.

![Figure 2](image2.png)

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3.3. Electrodynamics for ces in the "inductor - metal" system

Electromagnetic processes in the "inductor - metal" system are characterized by thermal power liberation as well as by electrodynamics forces affecting the resistance of an inductor to vibration and
noise in the process of induction heating for metal forming. Rectangular inductors are particularly sensitive to this problem, while inductors for heating of cylinders have a greater natural rigidity.

The task of optimization-based design of inductors, resistant to acoustic vibration, is set on the basis of electrodynamics and acoustic vibration processes analysis.

Force interaction in the "inductor - metal" system is expressed as

\[ f = \mu \mu_0 \nabla [E \cdot H] = -\frac{1}{2} \mu \mu_0 \text{grad} H^2 + \mu \mu_0 (\text{HV}) \bar{H} \]

(7)

where \( \mu, \mu_0 \) - are relative and absolute permeability's.

When the field is a plane-parallel one \((H=H_0)\), and the angular frequency of the harmonic current is \(\omega = 2\pi f\) the centrifugal pressure, uniformly distributed over the inner surface of the inductor, will be

\[ Q(\tau) = \frac{\mu_0}{4} H_0^2 (1 + \cos 2\omega \tau) \]

(8)

The value of the mean pressure, equal to the amplitude in this case, with the specific surface power \(P_s\) (W/m²) absorbed by a rectangular billet being taken into consideration, is derived from the formula

\[ Q_m = \frac{\mu_0}{4} 3.15 \cdot 10^{-4} \frac{P_s}{\sqrt{\rho \sigma} \cdot F(\beta, \zeta)} \]

(9)

where \(\rho\) - is the specific electrical resistivity; \(F(\beta, \zeta)\) -is the function, dependent on the ratio of the heated billet dimensions to the depth of its penetration, and tending to unit with the increment of the arguments.

Figure 3 shows the distribution of electrodynamics pressure, acting along \(x\)- and \(y\)-axes, with different depths of slab penetration in the inductor (9).

The model and the program devised allow determining forces in multiphase inductors. The design was executed for an inductor with the dimensions of 1.7*0.37*2.7 m and for a slab, with the cross section of 1.24*0.28 m and with various lengths. The pressure in the site of joint figure 4 is of great interest.

3.4. Optimization-based design of an inductor resistant to vibration

An intuitive approach to the choice of the best possible form of a cover, protecting a small inductor against vibration, often results in errors.

\[ \text{Figure 3. Electrodynamics pressure at penetration (m):} \]
\[ 1 - 0.015; 2 - 0.035; 3 - 0.085; 4 - 0.185; 5 - 0.285; 6 - 0.385 \]

Thus the task to optimize the form of inductors cover by rigidity index or by its equivalent, i.e. internal vibration frequency is set.
For the mathematical formalization of the task, inductor (its broad side) is replaced by an ideal vibrator system in the form of a prismatic beam with stiffly fixed ends, its length being equal to the inductor’s width \((L)\), and its width being equal to the inductor’s length \((B)\). The above mentioned simplification is legitimate for the more 3 relationship of inductor’s window dimensions, when the difference between the bending moments at the edges of the inductor’s broad side and similar beam moments at the sites of fixation is as large as 14% or less, which, as a first approximation, allows to neglect the influence of the inductor’s narrow sides.

The thickness of the cover, protecting inductors against vibration “\(h\)”, and, if the inductor’s length “\(B\)” is set, then the area of its cross section are considered to be design parameters in the task of optimization. The equation of free cross section vibrations in the ideal construction is

\[
\frac{d^2}{dx^2} \left[ EI(x) \frac{d^2W(x)}{dx^2} \right] - p^2 \gamma F(x) W(x) = 0, \quad x \in [0, L] \tag{10}
\]

where \(E, I\) - is the modulus of elasticity and the moment of inertia of the inductor’s broad side crosssection; \(p\) - is the frequency of internal vibrations; \(\gamma\) - is the tightness of material.

Stretch values are introduced

\[
x = \frac{X}{L}, \quad \alpha(x) = \frac{F(X) L}{V}, \quad F(X) = Bh(X),
\]

\[
I(X) = a F^3(X), \quad a = \frac{1}{12} B^2, \quad \Lambda = \frac{p^2 \gamma L^6}{a EV^2}, \tag{11}
\]

where: \(V\) - is the volume of the cover; \(A\) - is the value, characterizing the internal vibration frequency.

In a stretch form the equation (10) becomes

\[
\left( \alpha^3(x) W''(x) \right)'' - \Lambda \alpha(x) W(x) = 0, \quad x \in [0, 1] \tag{12}
\]

with boundary conditions

\[
W(0) = W(1) = W'(0) = W'(1) = 0 \tag{13}
\]

Internal vibration frequency of an inductor is determined as follows
\[
\Delta = \int_0^1 \alpha(x)(W'(x))^2 \, dx \left( \int_0^1 \alpha(x)W^2(x) \, dx \right)^{-1}
\]  
(14)

It is required to maximize (14) by a real limitation of geometrical dimensions and the volume of the cover

\[
\int_0^1 \alpha(x) \, dx = 1; \quad \alpha(x) \geq \bar{\alpha}
\]  
(15)

where \(\alpha\) is a given minimum value.

The task is executed using the maximal principle device. The form of the optimal cover is shown in figure 5.

**Figure 5.** The form of optional cover at \(\alpha\):

1 - 0.3; 2 - 0.5; 3 - 0.7; 4 - 0.9

Optimal constructions resistant to vibration are 1.5 – 2.4 times as rigid versus similar conventional constructions and they provide noise abatement (4 - 6 dB) decreasing the specific consumption of materials to 15 - 20%.

### 3.5. Field tests

Field tests were conducted with inductors having commercial of 50 Hz while heating aluminum, titanium and steel slabs. Inductors’ capacity was up to 3000 kW. The coil was enclosed either in an epoxy or in a glass-reinforced plastic compound [19, 20]. In the process of titanium slabs heating, the level of noise was as high as 85 dB or less, while for steel slabs - 65 dB or less and for aluminum slab - 130 dB. When the last inductor was enclosed in a concrete cover of an optimal form (figure 6) the level of noise was reduced to 80 dB with the capacity of 2500 kW.

The field tests have proved the maximum error to be as 8% or less, which meets the requirements.

### 4. Conclusions

Algorithm and software are offered for the automatic design of induction installations to heat metal for pressurized processing. The optimal solutions are found from the condition of reaching extremum of a summated economic index of the work of the corresponding technological complex “heating - deformation”; they represent optimal regime, constructive, power and technological parameters of the induction heating system.

The developed system of automatic design fulfills the needed complex of electromagnetic, thermal, electrodynamics and vibro-acoustic calculations, supplies the selection of optimal constructive parameters.
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