ОБОРУДОВАНИЕ ДЛЯ ПРОИЗВОДСТВА И РЕМОНТА СРЕДСТВ ТРАНСПОРТА. СЕРВИСНОЕ ОБСЛУЖИВАНИЕ И ТЕХНИЧЕСКИЙ ОСМОТР АВТОМОБИЛЕЙ

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ELECTROMAGNETIC PROCESSES IN THE MAGNETIC-PULSE STRAIGHTENING TOOL - INDUCTOR SYSTEM WITH AN AZIMUTH GAP

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Abstract. *Investigations of the spatial distribution of the eddy currents are excited by field of flat circular single-turn inductor system with nonmagnetic perfectly conducting metal objects were carried out. We constructed volumetric epures of the amplitude-spatial distribution of total current density where the total current was induced. The obtained correlations of the radial distribution of induced current azimuthal component and the azimuthal distribution of induced current radial component were compared with the calculation data. It is proved that violation of the single-turn inductor system axial symmetry gives rise to the induced current radial component.*

Key worlds: *straightening, induction system, electromagnetic processes.*

ЕЛЕКТРОМАГНІТНІ ПРОЦЕСИ В ІНСТРУМЕНТІ МАГНІТНО-ІМПУЛЬСНОГО РИХТУВАННЯ – ІНДУКТОРНА СИСТЕМА С АЗИМУТАЛЬНИМ РОЗРІЗОМ

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Анотація. *Проведено дослідження розподілу вихрових струмів, що індукуються полем плоского кругового витка в індукторних системах. Побудовано об'ємні епюри розподілу щільності повного струму, наведеного витком. Обґрунтовано, що порушення аксіальної симетрії виток індукторної системи призводить до появи радіальної складової індукованого струму.*

Ключові слова: *рихтовка, індукторна система, електромагнітні процеси.*

ЭЛЕКТРОМАГНИТНЫЕ ПРОЦЕССЫ В ИНСТРУМЕНТЕ МАГНИТНО-ИМПУЛЬСНОЙ РИХТОВКИ – ИНДУКТОРНАЯ СИСТЕМА С АЗИМУТАЛЬНЫМ РАЗРЕЗОМ

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Аннотация. *Проведены исследования распределения вихревых токов, возбуждаемых полем плоского кругового витка в индукторных системах. Построены объёмные эпюры распределения плотности полного тока, наведенного витком. Обосновано, что нарушение аксиальной симметрии витка индукторной системы приводит к появлению радиальной составляющей индуцированного тока.*

Ключевые слова: *рихтовка, индукторная система, электромагнитные процессы.*

Introduction

Magnetic-pulse complexes (systems) for straightening and restoration of vehicle body elements consist of two main parts: the power source (magnetic pulse installation) and tool (inductor system). The power source provides generation of the necessary current impulse into the tool, which, in turn, performs the necessary repair operation [1-4].

The widespread tools of magnetic-pulse straightening (Electrical Magnetic Metal Forming) are flat single-turn solenoids. In the known publications on electrodynamic calculations flat single-turn solenoids are presented as closed circle contours what makes it possible to introduce the axial symmetry condition and significantly simplify the solution of the problem of the isolated single-turn inductor field on the metal object surface [5-8].

In reality, the single-turn inductor isn't closed circular contour, due to its consistent incorporating in the power source circuit. In other words, as a magnetic-pulse method tool we use single-turn inductor with a gap or open circular contour. Clearly, the violation of the axial symmetry of the field source (inductor) form leads to a distortion of force action on the processed object. This can explain many failures on application of electromagnetic fields in solving of the urgent technology challenges.

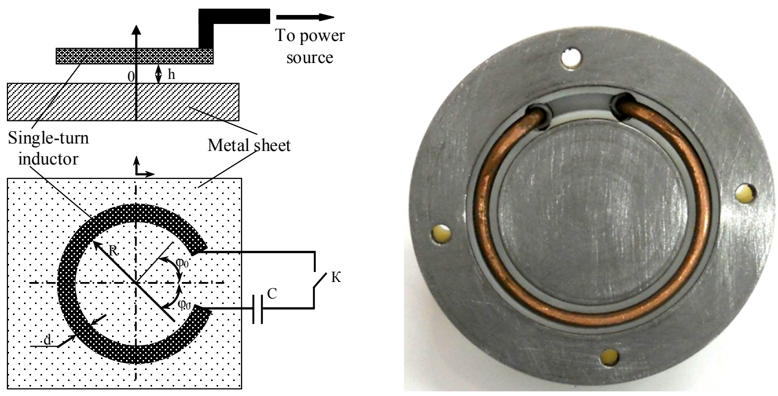
Theoretical analysis of electromagnetic processes in inductor system is described in the papers [1, 7, 9-12]. Here, we performed an analytic solution of the corresponding electrodynamic problem by the classical method.

However, any theoretical studies have to be experimentally tested for compliance with described processes. The reliability degree of the obtained results is determined via the measurements of the studied phenomenon basic characteristics.

Work objective is to study the spatial distribution of the eddy currents induced by field of the open flat circular single-turn inductor in the inductor systems - magnetic-pulse straightening tools with nonmagnetic perfectly conducting metals.

The calculation model of the inductor system

The calculation model of the considered system with a perfectly conducting metal (massive conductor) in accordance with the paper [11, 12] and its physical implementation is shown in Fig. 1, where $\vec{e}_r, \vec{e}_\varphi, \vec{e}_z$ are the unit vectors in the cylindrical coordinate system.



a) b)

Fig. 1. The open flat single-turn inductor over the massive metal sheet:
a – is the calculation model; b – is the physical model

The experimental scheme is shown in Fig. 2, where a – is the single-turn inductor without a gap; b – is the single-turn inductor with the gap of 90^0. The current-conducting wires of electrical terminals of the current pulse generator that connected to the single-turn inductors are perpendicular to their plane. The scheme shows the marked lines along which the tangential and azimuthal components of magnetic field intensity were measured via inductance-type transducer (mutually perpendicular axes XX and YY). Transducers of this type are traditionally used in the measurements of pulsed fields and currents. They were described in detail in the papers [13, 14].

The current pulse source was the complex for simulation and modeling of processes in the Electrical Magnetic Metal Forming tools that were described on the Laboratory of the Electromagnetic Technologies of Kharkov National Automobile and Highway University website [3]. This generator has the following specifications: the supply voltage U_c = 220 V; the charge voltage of capacitor U_{ch} = 650 V; the capacitor capacitance of the complex C = 33 μF; the repetition frequency of the discharge pulses f_p = 20 Hz; the own frequency of the discharge pulse f_o = 30 kHz; the peak value of the pulse current, while working on a short-circuit terminal I = 3 kA; the own inductance L = 850 nH; the discharge pulse – is damped sinusoid.

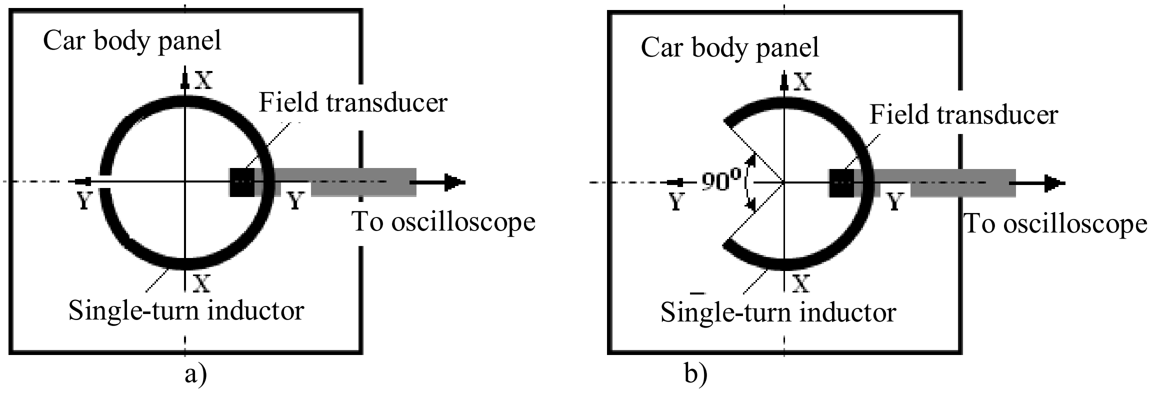


Fig. 2. Experimental scheme, current-conducting wires of the connecting of the single-turn inductors to the current pulse generator: a – is the single-turn inductor without a gap; b – is the single-turn inductor with the gap (90°)

The current pulse source was the complex for simulation and modeling of processes in the Electrical Magnetic Metal Forming tools that were described on the Laboratory of the Electromagnetic Technologies of Kharkov National Automobile and Highway University website [3]. This generator has the following specifications: the supply voltage U_c = 220 V; the charge voltage of capacitor U_{ch} = 650 V; the capacitor capacitance of the complex C = 33 μF; the repetition frequency of the discharge pulses f_p = 20 Hz; the own frequency of the discharge pulse f_o = 30 kHz; the peak value of the pulse current, while working on a short-circuit terminal I = 3 kA; the own inductance L = 850 nH; the discharge pulse – is damped sinusoid.

The current pulses from the generator is supplied via current-conducting wires (copper wire, section of 2 мм^2), that located at the angle of 90^0 to the plane of the single-turn inductor. The current-conducting wires connected to the single-turn inductor in the gap area, in other words, the discharge circuit parameters consisted of own parameters of the generator and inductor with a gap with current-conducting wires are connected to it.

As a perfectly conducting object there was the copper plate in thickness d = 0,01m. The distance from to the single-turn inductor to the copper plate plane was h = 0,0025 m. At the operational frequency f =30 kHz, the effective depth of field penetration will be equal to Δ = 0,000375 m. If we accept this value as an amendment to the distance between the single-turn inductor and the plate (h+Δ) = 0,002875 m, the plate metal can be considered perfectly conducting. In this case, on the surface of the study object (copper plate) tangential component of the modulus of magnetic field intensity vector is equal to the modulus of induced current azimuthal component density vector. The modulus of the intensity vector azimuthal component is equal to the radial component of the excited current density vector. In the polar system of coordinates, in that calculation model this means that $H_r = j_\varphi$ and $H_\varphi = j_r$.

We record obtained analytical expressions for the components of the induced current density vector similar to the papers [11, 12]:

a) the azimuthal component is normalized to the maximum,

$$j_\varphi\left(\frac{r}{R},\varphi\right)=\sum_{n=0}^{\infty}F_n(\varphi_0)\cos(n\varphi)\left[\int_0^{\infty}f_n(x)\left(J_{n-1}\times\right.\right.$$
$$\left.\left.\times\left(x\frac{r}{R}\right)-J_{n+1}\left(x\frac{r}{R}\right)\right)e^{-x\frac{h}{R}}\,dx\right] \qquad (1)$$

b) the radial component is normalized to the maximum,

$$j_r(\frac{r}{R},\varphi)=\sum_{n=1}^{\infty} n\cdot F_n(\varphi_0)\cdot \sin(n\,\varphi)\times$$
$$\times\left[\int_0^{\infty} f_n(x)\cdot\frac{J_n\left(x\frac{r}{R}\right)}{\left(\frac{r}{R}\right)}\cdot\frac{e^{-x\cdot\frac{h}{R}}}{x}dx\right], \quad (2)$$

where

$$F_n(\varphi_0)=\begin{cases}\left(-\dfrac{2\cdot\sin(n\cdot\varphi_0)}{\pi\cdot n}\right), & n\neq 0,\\ \left(1-\dfrac{\varphi_0}{\pi}\right), & n=0,\end{cases}$$

$$f_n(x)=\frac{x}{4}\cdot\left[J_{n-1}(x)-J_{n+1}(x)\right].$$

x – is the integration variable

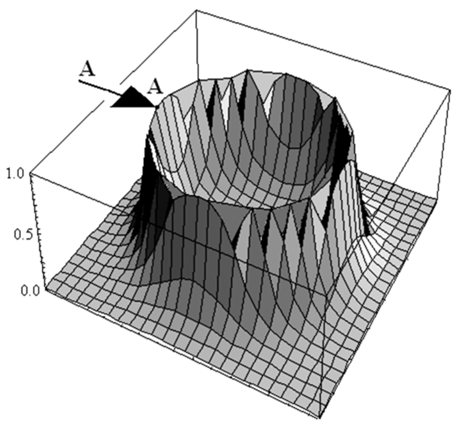
The distribution of the induced currents

We perform the calculations of amplitude-spatial distribution of eddy currents that were induced by the open flat circular single-turn inductor in a perfectly conducting metal object for the permanent air gap that equal *h/R*. The variation of this quantity and study of its influence are not interesting. Because of the role of this system parameter is insignificantly by a priori physical considerations.

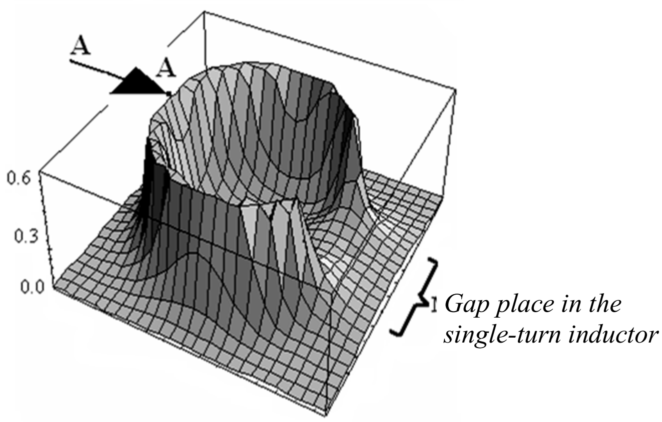
The particular interest for practice, first of all, is attracted by the influence estimates of the gap size in open flat circular single-turn inductor on the induced current amplitude and distribution.

As shown in Fig. 1, the gap size is defined in terms of the azimuthal angle $2\varphi_0$.

The measurement results and the calculated data that were determined by the formulas (1) and (2) were shown in the volumetric epures (Fig. 3), as well as in the two-dimensional graphic dependencies (Fig. 4–6). Data presentations like this clearly presented the density distributions of the induced eddy currents in the spatial coordinates, with specification of the amplitudes in relative units that is normalized to the corresponding maximums.



a)



b)

Fig. 3. The volumetric epures of amplitude-spatial distribution of the total current density, where the total current is induced by the single-turn inductor: a – is the single-turn inductor without a gap; b – is the single-turn inductor with the gap of 90°

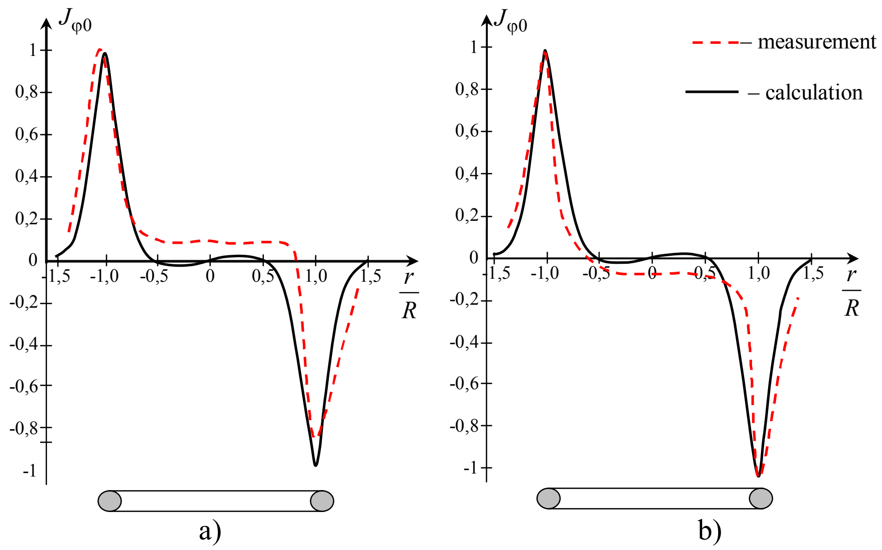


Fig. 4. The radial distribution of the azimuthal component of the current, that is induced in the copper plate metal, on the XX axis: a – is the single-turn inductor without a gap; b - is the single-turn inductor with the gap of 90^0

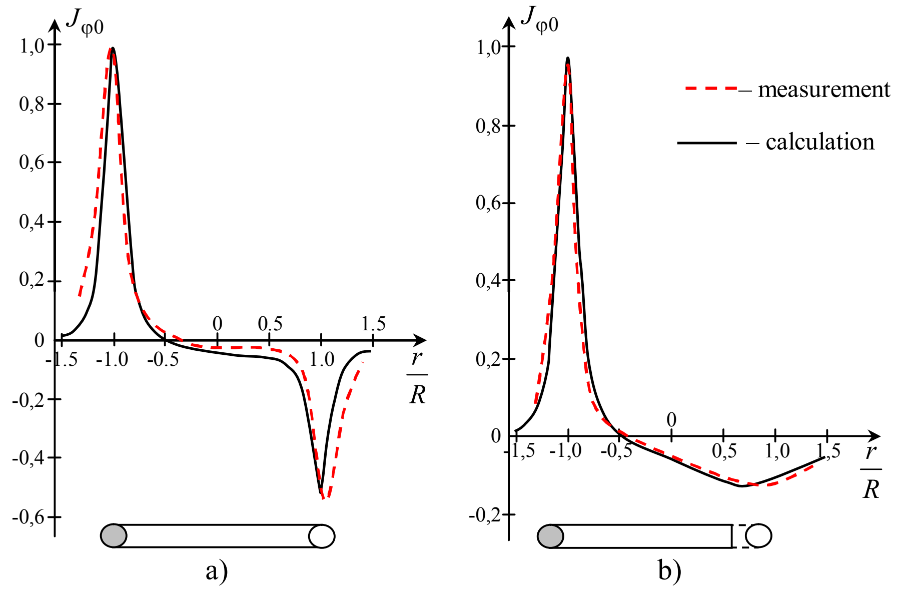


Fig. 5. The radial distribution of the azimuthal component of the current, that is induced in the copper plate metal, on the YY axis: a – is the single-turn inductor without a gap; b – is the single-turn inductor with the gap of 90^0

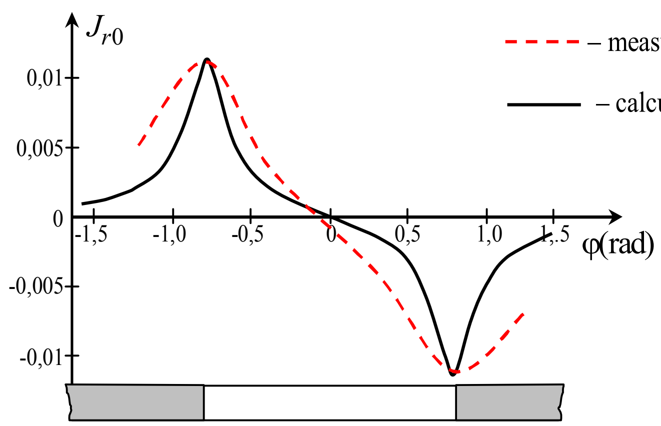


Fig. 6. The azimuthal distribution of the current radial component, where the current is induced in the copper plate metal by the single-turn inductor with the gap of 90^0

Analysis of the received results leads to the following conclusions

In the zone under the gap, in the single-turn inductor area there is the substantial uniformity violation of the induced current density spatial distribution (this follows from the comparison of the Fig. 3…5 both inside the gap zone and out) and the reduction of their amplitude values. It makes approximation of axial symmetry in the calculations of the single-turn inductor systems inadmissible.

The axial symmetry violation (single-turn inductor with a gap) is the reason for the induced current radial component appearance. The radial current spatial maximums are located close to the gap edges in the single-turn inductor and have a different signs that indicates about their flow in opposite directions.

In general, the comparison of the graphs of various components of the induced current density vector shows that the spatial shape of the induced total current is formed, mainly, by the contribution of the azimuthal component.

Within the formulated physical model it is apparent that with minimal electromagnetic coupling, when the single-turn inductor is perpendicular to the conductor plane or between them there is a sufficiently large distance or large gap, the induced current tends to zero. With the maximum connection if the planes of the single-turn inductor and the conductor are parallel, the distance between them tends to zero, if the gap is absent, the induced current value comes close to the excitatory current in the single-turn inductor, but is opposite in direction.

Conclusions

The experimental studies of the spatial distribution of eddy currents are induced by the open flat circular single-turn inductor field in the inductor systems are magnetic-pulse straightening tools with nonmagnetic perfectly conducting metals are carried out.

The studies were shown that:
– in the zone under the gap, in the single-turn inductor area there is the substantial uniformity violation of the induced current density spatial distribution. It makes the axial approximation in the calculations of the single-turn inductor systems for Electrical Magnetic Metal Forming inadmissible;
- the integral value of the induced current density vector is formed mainly by the contribute its azimuthal component.

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