THE INDUCTANCE OF MATRIX EDDY-CURRENT TRANSDUCERS CALCULATION OF MOVINGS

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Railroad track width defines safety of transport traffic. Rails are of large length and subjected to dynamic and climatic impacts. Data on their state for train traffic management systems are acquired by means of diagnostic track test cars performing combined computer railway diagnostics using electromechanical scanning systems.

Electromagnetic testing methods are applied in different branches of industry for contactless measurement of movements and geometrical parameters of articles of complex shape. For simultaneous monitoring of the large number of factors, it is reasonable to use array method of eddy-current testing, which makes it possible to implement the multi-point testing. Herewith, it is necessary to locate over tested surface not less than $n_{op} = b_r/b_m$ probes, where: b_r – is width of the railhead top, while b_m – is width of single overlay probe (OP). Application of eddy-current array probe (ECAP) presupposes several electromagnetic field exciters in the form of magnetically coupled unit modules – inductance coils – located in space over test object (TO). Reliable operation of probes is possible when they are installed over TO with maximal safety gap $h_{z\,r}$.

ECAP's developed by ASEA-Brown Boveri are known. They represent transformer probes on a soft substrate. OP's are installed so that their mutual influence is minimal. In this case, possibility of testing mutually related factors is restricted.

Problem of the development of ECAP with unilateral acess to TO for contactless testing vertical h_z and horizontal h_y components of movements, as well as width b_r of TO is considered taking into account peculiarities of the TO profile. Increase of the number of tested factors leads to proportional increase of the number of ECAP modules and embarrasses their location over TO surface of restricted dimensions. It is necessary to use integral technologies allowing thin-film ECAP designs to be obtained. It is implemented easily by single-layer laying of current element conductors on the surface of strap magnetic conductor with thickness of several micrometers [1].

This problem is resolved using screened orthogonal probes. Varying relationship of $l\times b$, $l\times d$, $b\times d$ areas defining OP electromagnetic field in the given direction, it is possible to implement poly-varience of sensititvity-to-tested factor ratios. Length $l_m \approx D_E$ of the coil magnetic core defines long-range action of exciting electromagnetic field of a probe. Length of a rail exceeds considerably l_m; therefore, given variation range $h_{z\,max}$ of gaps between the rolling surface of rail and probes is implemented easily.

Multi-point testing of geometrical factors pre-determines application of modular principle for circuit-design arrangement of orthogonal OP's that makes it possible:

1. to arrange variable or periodic structure of exciting electromagnetic field basing on the testing tasks and peculiarities of article shape;
2. to improve testing performance through selection of the rational number of unified modules of orthogonal OP's and testing zones;
3. to obtain increased $K_т$ and D_E of every OP with regard to tested factor;
4. to use integral technology for production of orthogonal OP coil with magnetic conductor;
5. to locate OP in slots of single conductive housing for localization of electromagnetic field within the testing zone and reduction of error due mutual influence of spatial movement components and other factors like temperature;
6. to obtain new characteristics of probes extending functional capabilities of testing means.

Application of modular principle in ECAP design allows spatial selection of influencing factors to be implemented due to the increased number of OP's $n_y = b_ш/b_м$, while their location within the conductive housing of a device screens the OP, thus localizing electromagnetic field within the test zone, and reduces effect of external fields on measurement errors. OP's are located in a plane and form discrete bus with common electromagnetic field providing high D_E value.

Determination of magnetic fluxes of ECAP modules is complicated by the three-dimensional nature of electromagnetic field and requires determination of boundaries of the structurally unrestricted quazi-stationary fields of cophasal current elements (CE), which renders difficult application of known software products (ANSYS, Elcut and others), intended for calculation of two-dimensional fields.

Eddy-current probe in the form of conductor $b_{ш}\to\infty$ possesses with elementary topology. If current direction coincides with *Y* axis, lines of force of plane-parallel field in the *X0Z* plane represent the clump of circles defining tubes of exciting magnetic flux. In *Y0Z* plane, projections of the lines of force define the range D_E of field action, while their angular position is assumed to be the zero direction $\varphi_u = 0$. Cross-section of the CE magnetic flux is defined by its length $b_м$ and long-range action of the field: $S_м = b_м D_E$.

Three-dimensionality of magnetic fields of ECAP modules pre-determines the necessity of elaboration of new numerical calculation methods of their inductance [2]. For calculation of ECAP module inductance, method of sections is used. It consists in that closed circuit is divided into individual sections (segments of linear conductor of infinitely thin cross-section) — current elements (CE). It is convenient to consider magnetic fluxes of the every CE as an aggregate of elementary magnetic tubes of small cross-section; field density *H* within this cross-section can be considered as constant. Density *H* of the tube magnetic field in cross-section $\Delta S_м = \Delta b_м \times \Delta h_z$ is determined by integration of the equation of Biot-Savart-Laplace $d\vec{H} = I_к d\vec{b}_м \times h_0 / 4\pi|h|^3$ for the CE $I_к d\vec{b}_м$ remoted at the distance *h* from the point of field determination $\vec{H}$, where: Δb_s, Δh_z – is width and height of the elementary tube of magnetic flux. Determination of boundaries of the structurally unrestricted quazi-stationary fields of cophasal CE's is substantiated [3]. Magnetic flux defining the initial inductance of a module is calculated by summing magnetic fluxes of elementary tubes. Numerical calculation of $L_н$ is performed by summing magnetic fluxes of tubes $\Phi_{i_s} = \mu H_{i_s} \Delta S_м$ created by *i*-th CE and magnetic fluxes of tubes $\Phi_{ij_м} = \mu H_{ij_м} \Delta S_м$ created by *j*-th CE and covering *i*-th CE:

$$L_н = \sum_1^{n_x} \left(\sum_1^{m_{z_i}} \sum_1^{m_{y_i}} \Phi_{i_s} + \sum_1^{n_x n_y} \sum_1^{m_{z_{ij}}} \sum_1^{m_{y_{ij}}} \Phi_{ij_м} \right) \Big/ I_к ,$$

where: n_x, n_y – is number of CE's of the discrete current bus in the direction of *X* and *Y* axes; m_z, m_y – is number of magnetic flux tubes in the direction of *Z* and *Y* axes. Operational inductance L_p is defined as $L_p = L_н - L_{вн}$, where: $L_{вн}$ – is variation of ECAP modules inductance due to influence of eddy-current fields ($-L_{вн}$) on the TO surface and variation of cross-sections of magnetic fluxes of free CE's ($+L_{вн}$).

Discussed approach to calculation of inductance of strongly coupled electromagnetic probes is implemented in simulation program for fields of discrete current bus used to obtain characteristics $L_{вн} = f(h_z, h_y, \varphi_x)$ demonstrating that linear location of probes makes it possible to obtain various sensitivies to tested factors providing spatial selection of geometrical parameters of a rail.

To verify the trustworthiness of obtained theoretical results, computerized laboratory bench was created to determine charactericties of ECAP modules. Bench includes instrumental microscope MMI-1, ECAP, electronic unit to form output signals and software for their automatic processing. OP models are fixed on the MMI-1 sample table so that tested surface $X_r 0_r Y_r$ is located in parallel with ECAP working surface, while probe center coincides with table rotation axis Z_c. Initial TO positioning - $h_y = 0$, $h_z = h_{z\,н}$, $\varphi_x = 0$ – is ensured by aligning of coordinate axes of ECAP and TO. Electronic unit forming output voltages performs conversion of the analog signal of ECAP modules into digital form and transmits measuring voltages phasor into computer.

Obtained characteristics $L_{вн}/L_{вн\,m} = f(h_y, h_z)$ of strongly coupled ECAP modules differ significantly from characteristics of weakly coupled modules. Analysis of characteristics of strongly coupled ECAP modules demonstrates that Анализ характеристик сильносвязанных модулей МВП показывает, что для преобразователей, находящихся за пределами ОК, $L_p > L_н$ ($+L_{вн}$). Данный результат можно объяснить тем, что компенсация возбуждающих полей закрытых модулей МВП полями вихревых токов ОК при $h_z \to 0$ уменьшает их магнитный поток, что снижает давление на магнитный поток соседнего открытого модуля. При этом сильное увеличение сечения $S_м$ магнитного потока открытого модуля приводит к росту его L_p ($+L_{вн}$), что позволяет сделать вывод о доминирующем влиянии изменений $S_м$ на величину L_p и необходимости определения границ конструктивно неограниченных квазистационарных полей синфазных ТЭ.

Сравнение теоретических и экспериментальных характеристик модулей МВП показало их удовлетворительное совпадение, что свидетельствует о достоверности полученных результатов.

Проведёный в ходе исследований сравнительный анализ известных систем контроля перемещений и геометрических параметров верха головки железнодорожного рельса в загрязнённой среде показывает перспективность разработки и применения матричных вихретоковых преобразователей в устройствах многофакторного экспресс-контроля железнодорожной колеи. Выделенные контролируемые факторы характеризуют состояние рельса в колее. Разработана математическая модель для численных расчётов электромагнитных полей матричных преобразователей, реализованных на дискретных токовых элементах. В отличие от известных моделей расчёт индуктивностей выполнен на основе оценки границ сечений конструктивно неограниченных магнитных потоков сильносвязанных преобразователей.

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