Electron beam deflection control system of a welding and surface modification installation

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Abstract. In the present work, we examined the patterns of the electron beam motion when controlling the transverse with respect to the axis of the beam homogeneous magnetic field created by the coils of the deflection system the electron gun. During electron beam processes, the beam motion is determined by the process type (welding, surface modification, etc.), the technological mode, the design dimensions of the electron gun and the shape of the processed samples. The electron beam motion is defined by the cumulative action of two cosine-like control signals generated by a functional generator. The signal control is related to changing the amplitudes, frequencies and phases (phase differences) of the generated voltages. We realized the motion control by applying a graphical user interface developed by us and an Arduino Uno programmable microcontroller. The signals generated were calibrated using experimental data from the available functional generator. The free and precise motion on arbitrary trajectories determines the possible applications of an electron beam process to carrying out various scientific research tasks in material processing.

1. Introduction
Electron beams find numerous applications in research and industry as a concentrated-energy heat source. The electron-beam deep-penetration welding of materials in vacuum is the most widely used method in non-conventional technologies of joining machine parts [1-3]. The reasons for this are: formation of deep and narrow welds with good physical-mechanical properties with minimal structural changes and heat deformations of the welded parts, possibility for high-speed welding in automated technological processes, elimination in many cases of the need for subsequent mechanical and heat treatment, possibility of welding near thermally-unstable structural elements, lack of necessity of special welding electrodes, protective gases or fluxes, improved use of materials, energy saving, especially when thick-wall structures are processed, etc.

In the present work, we developed a graphical user interface to generate control signals for the electron beam deflection system of an electron beam welding, surface modification and evaporation installation. The electron beam is moved in different patterns as determined by the magnetic field formed by the deflection system, depending on the process performed and the shape and location of
the samples to be processed. The software application developed by us provides motion control along different trajectories at different velocities.

2. Electron beam deflection system

Figure 1 presents a schematic diagram of an electron beam gun, where the electron beam is generated, accelerated, directed, focused and deflected.

![Figure 1](image1.png)

**Figure 1.** Schematic presentation of an electron beam gun: 1 - cathode, 2 - anode, 3 - focusing system, 4 - deflection system; 5 - sample.

The deviation of the electron beam in two mutually perpendicular directions at angles of about 7-10 degrees is achieved by means of two pairs of deflecting coils (figure 2 [1]). It is assumed that each magnetic field is transversal to the beam axis and uniform within the beam deflection. The coils turns are usually wound in the form of a saddle. In order to obtain a uniform magnetic field, the main portion of the turns is wound at the ends of the coils.

The stationary model for the deflection distance is a particular solution of the dynamic equations of the electrons when the electric and magnetic field distributions are known. The relationship between the deflection distance along the axes Ox and Oy depends on the deflection coil currents $i_{x\text{defl}}$ and $i_{y\text{defl}}$ and at a constant value of the acceleration voltage $U_a$ can be calculated by [4-6]:

$$
\begin{align*}
x_{\text{defl}} & \approx \frac{e_o}{2m_e} \frac{k_b \mu_o d_{\text{defl}} I_b}{a \sqrt{U_{ac}}} n_i_{x\text{defl}} = 3.7266 \frac{k_b d_{\text{defl}} I_b}{a \sqrt{U_{ac}}} n_i_{x\text{defl}} \\
y_{\text{defl}} & \approx \frac{e_o}{2m_e} \frac{k_b \mu_o d_{\text{defl}} I_b}{a \sqrt{U_{ac}}} n_i_{y\text{defl}} = 3.7266 \frac{k_b d_{\text{defl}} I_b}{a \sqrt{U_{ac}}} n_i_{y\text{defl}}
\end{align*}
$$

where $e_o$ is the elementary charge, $m_e$ is the electron's stationary mass, $\mu_o$ is the vacuum permittivity, $k_b$ is the deflection coil configuration coefficient, $d_{\text{defl}}$ is the distance between the deflection coil and the processed material surface, $I_b$ is the coil length, $n$ is the number of turns, $a$ is the coil dispersion. The dynamic models of the deflection system are [4-6]:

$$
\begin{align*}
L_s \frac{d i_{x\text{defl}}}{dt} + R_s^x i_{x\text{defl}}(t) & = u_{x\text{defl}}(t) \\
L_s \frac{d i_{y\text{defl}}}{dt} + R_s^y i_{y\text{defl}}(t) & = u_{y\text{defl}}(t)
\end{align*}
$$

where $L_s$ is the coil equivalent inductivity and $R_s$ is its equivalent resistivity.
The use of a magnetic conductor reduces about twice the required amperage, but it can cause field distortion, which is unacceptable. At high frequencies, the magnet may be a ferrite or not present at all and, in addition, the inductance and the capacity of the coils begin affecting the non-linearity of the deflection. Therefore, the required voltage (and power) increases and it is desirable to reduce the number of coil turns \((n)\). It turns out that the product of the deflection angle and the frequency, at a constant power of the deflection source, is a good characteristic of the quality of the deflection system.

Typically, the magnetic deflection systems are outside the vacuum volume and the magnetic coils are separated from the vacuum space by a non-magnetic material – ceramics or glass, since the magnetic field frequencies are high. This prevents the generation of Foucault currents in the walls of the deflection systems’ separation tube or cone, which can reduce the penetration of the magnetic field and can become an additional source of nonlinearities.

![Figure 3. Electron beam deflection system control.](image1)

![Figure 4. Deflection system control signals: amplitudes \(A = B = 450\) mV, period \(T = 10\) ms, frequency \(\omega = 628.32\) Hz.](image2)

The deflection control system developed is presented schematically in figure 3. The available functional generator and amplifier are replaced by a computer and an Arduino Uno programmable microcontroller. The electron beam motion is controlled by varying the parameters of the two voltage signals (figure 4) – amplitudes, frequencies and phases (phase differences). Currently, verification and correction of the exact beam position is performed by observation; the implementation is considered of an image capturing system [5-7] for automatic correction of the beam deflection.

3. Electron beam deflection control software and motion patterns

The electron beam motion is a result of the cumulative action of two sinusoidal control signals (voltage) fed to the deflection coils:

- Signal 1: \(X(t) = A(t)\sin[\omega t + \phi_x(t)]\),
- Signal 2: \(Y(t) = B(t)\sin[\omega t + \phi_y(t)]\),

where \(A\) is the amplitude of signal 1, \(B\) is the amplitude of the second signal, \(\omega\) is the frequency of the oscillations, and the phase difference \(\delta(t) = \phi_y(t) - \phi_x(t)\) is defined by the phases of the two signals (figure 4). The amplitudes, frequencies and phase differences of the two signals may be constant or may vary over time in a particular pattern. The period \(T\) (the time needed for one full turn of the electron beam) at a constant frequency is calculated as \(T = 2\pi/\omega\), and if the working time is \(T_0\), the number of turns is \(T_0/T\). The characteristics of the two signals affect the magnetic field generated and, consequently, the electron beam path. The electron beam deflection is limited by the electron gun design characteristics, by the sample surface treated and by the type of technological process, together with the physical processes taking place.
Figure 5. Electron beam deflection software.

Figure 5 presents the electron beam deflection control software developed. It allows one to select several motion patterns: line; several lines crossing at different angles, circle, ellipse spiral, spiral (ellipse), Lissajous figures, square rectangle and flower. It can be updated with other patterns. The parameters of the two signals can be set by the user, depending on the concrete electron beam process performed. The current coordinates of the overall effect of the two signals can be observed as values and a graph. The example shown represents a Lissajous figure with a frequency ratio of 6/8 and a phase difference $\delta = \pi/2$.

Figure 6. A spiral motion pattern –: a) Signal 1 and Signal 2 voltage as functions of time, b) voltage of Signal 1 vs. voltage of Signal 2.

Figure 6 presents another example of a motion pattern – spiral electron beam trajectory. The control signals parameters are: amplitude initial values $A_0 = 0.05$, $B_0 = 0.05$, increasing with at a step $s = 0.05$; frequency $\omega = 1$ Hz, working time $T_0 = 40$ s, period $T = 6.28$ s and phase difference $\delta = \pi/2$.

4. Conclusions
The electron beam welding is a complex process with many processing variables, which requires integration of interfaces for control of the processes on different levels through hierarchical equipment models, functional data and operation control models.

We developed software for electron beam deflection system control, implementing models for the characteristics of two control voltage signals — their amplitudes, frequencies, phases and phase differences. This is only one of the stages to realizing complete control of the electron beam settings,
including its formation, characterization, focusing and motion. The beam pattern used in each case depends on the process (welding, surface modification, evaporation etc.) and the shape of the processed samples. The graphical user interface developed can be integrated with more complex shape trajectories in different modes, electron beam spot tracking, electron beam focusing system control etc. The operation of the deflection system must also be coordinated with the operation of the manipulators in the vacuum chamber, with which the work-pieces are moved.

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References
[1] Mladenov 2009 Electron and ion technologies (Prof. Marin Drinov, Sofia, Bulgaria)
[2] Koleva E and Mladenov G 2011 Practical Aspects and Applications of Electron Beam Irradiation 95-133 ISBN: 978-81-7895-541-4
[3] Volker A, Uwe C, Dobeneck D, Krüssel T and Löwer T 2011 Electron Beam Welding, The fundamentals of a fascinating technology (Pro-beam AG & Co. KgaA)
[4] Chvertko A, Nazarenko O, Svyiatskiy A and Nekrasov A 1973 Equipment for electron beam welding (Naukova Dumka, Kiev)
[5] Oltean S, Grif, H and Duka A 2007 Proc. Int. Conf. Interdisciplinarity in Eng. Sci. (INTER-ENG) 1-6
[6] Oltean S and Abrudean M 2008 J. Control Eng. and Appl. Informatics 10/1 40-8
[7] Oltean S and Dulau M 2011 Proc. Int. Conf. Interdisciplinarity in Eng. Sci. (INTER-ENG) 20
[8] Koleva E, Mladenov G, Vuchkov I, Velev K, Lamond B and Petrova D 2012. Research and development of new materials on the base of recycling of reactive and refractory metals scrap through electron beam method ed Vutova K (IE-BAS, Sofia, Bulgaria) 30-7
[9] Trushnikov D, Koleva E, Mladenov G and Belenkiy V 2013 J. Material Proc. Technol. 213/9 1623–34
[10] Koleva E and Dzharov V 2016 Science, Engineering & Education 1/1