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Predicting Optical Properties of an Objective Lens with Aid of Optimization by Synthesis Approach and Simulink Environment

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Abstract: In the present research design and simulate magnetic electron lens using optimization by synthesis approach has been achieved. The research in this study may be divided into two parts. The first one is the design part that including the reconstruction process of the polepieces where a mathematical target function has been used to approximate the distribution of the axial magnetic scalar potential of the symmetrical double polepiece magnetic lens and with the aid of Simulink environment in MATLAB, the target function and its related axial functions have been determined through out of built-up a Simulink Model for each function. By using the analytical solution of Laplace's equation and the distribution of the potential, the polepiece shape of the magnetic lens has been reconstructed according to a specific values of the optimization parameters that affect the design process. The second part is the evaluation of the objective properties of the electron lens that achieved by solving the paraxial ray equation of the electron beam and calculating the aberration coefficients. In addition, a comparison between the present model and the solenoid field model has been achieved. Results of the present research have shown clearly that the followed synthesis optimization approach using Simulink environment in MATLAB is a powerful approach to determine the design of magnetic lenses and can be used to investigate and synthesize other electron-optical devices.

Key words: Electron optics, magnetic lenses, synthesis approach, Simulink, MATLAB, synthesize

INTRODUCTION

The main function of electron lenses is to prepare images of object by sorting charged particles according to their points of exit from the object and their convergence to corresponding points of the images. Accordingly, problems such as the transport of electron beams and beam concentration at small targets or channels cannot be solved without electron lenses. Generally, electron lenses are components of almost all other electron-optical devices (Tsimring, 2007). However, electron lenses are considered the major components of the imaging system in the transmission electron microscope. Objective lens is the most important lens among the other lenses of imaging system, since, it is the first lens that produces the first magnification step from an electron distribution at an Angstrom dimension to an image with 10 nm details (Wentao, 2009).

The most important aberrations that limit the resolution of electron-optical devices are called spherical and chromatic aberrations (Egerton, 2005). However, the main important defects that limit the performance of Conventional Transmission Electron Microscope (CTEM) are the spherical aberration, chromatic aberration, defocus and axial astigmatism (Jawad *et al*., 2012).

Generally, performance of electron optical system depends on the quality of lenses. Widely used electrostatic and magnetic lenses are rotationally symmetric (Scherzer's theorem) but limited machining precision of electrodes and polepieces cases small perturbations from ideal shape. These perturbations induce parasitic fields which affect the optical properties of the lens. Aberrations corresponding to mechanical imperfections are usually, called parasitic aberrations (Horak, 2015).

The present study deals with design of magnetic electron objective lens using optimization by

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synthesis approach with the aid of Simulink, determine the first-order properties and third-order aberrations under zero magnification mode.

MATERIALS AND METHODS

Synthesis approach of magnetic lens: In the field of electron optics, design of any electron-optical device (electrostatic lens, magnetic lens, deflector, etc.,) may be carried out with the aid of analytical or synthesis optimization procedure. The analytical procedure is considered as a tool for the conventional design of the electron-optical device, see for example (Munro, 1971; Szilagyi, 1988). However, in the present research, optimization by synthesis approach has been followed to synthesize and simulate symmetrical double polepiece magnetic lens. In this approach, there are sequential various steps may be followed to design an electron lens. Firstly, the axial magnetic scalar potential distribution along the optical axis (i.e., region of the lens) represented by the following target function (Rashid, 2011):

$$V(z)=\left(\frac{(V_2\text{-}V_1)d}{2\pi S}\right)\left[\begin{array}{l}\frac{(2z+S)}{d}\tan^{-1}\left(\frac{2z+S}{d}\right)\text{-}\\ \frac{(2z\text{-}S)}{d}\tan^{-1}\left(\frac{2z\text{-}S}{d}\right)+\left(\frac{(V_1+V_2)}{2}\right)\end{array}\right]\quad(1)$$

Where:

V_1 and V_2 = The potential values at the object and image sides of the lens

d and S = Geometrical design parameters which approximately represent the bore radius and the air-gap width, respectively

It should be mentioned that this mathematical formula has been used to represent the distribution of the electrostatic potential of einzel lens by Rashid (2011). Fortunately, it is found that this formula may represent the distribution of the magnetic scalar potential of the double polepiece magnetic lens. Hence, by using the equation ($B_z(z) = -\mu_0\, dV(z)/dz$) with Eq. 1, the imaging axial magnetic field distribution can be determined from the following Eq. 2:

$$B_z(z)=\frac{(V_2\text{-}V_1)d\mu_0}{2\pi S}=$$

$$\left[\begin{array}{l}\frac{2(2z+S)}{d^2+(2z+(S))^2}+\frac{2}{d}\tan^{-1}\left(\frac{2z+S}{d}\right)\text{-}\\ \frac{2(2z\text{-}2)}{d^2+(2z\text{-}(S))^2}\text{-}\frac{2}{d}\tan^{-1}\left(\frac{2z\text{-}S}{d}\right)\end{array}\right]\quad(2)$$

The research in present study may be divided into two parts: the first one is the predicting of the reconstructed polepiece shape of the lens that produces the suggested it's imaging field or potential distribution. This part can be carried out by using the synthesis approach depending on the determined axial potential Eq. 1 and its second derivative V" (z) deducing by the following Eq. 3 (Szilagyi, 1985):

$$R(z)=2\left[\frac{V(z)\text{-}V_p}{V''(z)}\right]^{1/2}\quad(3)$$

where, V_p is the potential at the farthest point on the polepiece from center of the gap and equals to NI/2 if the lens is symmetric where NI is the excitation of lens, R(z) is the radial height of the reconstructed polepiece. The second derivative of the potential V(z) can be calculated with aid of relation ($V''(z) = -B'_z(z)/\mu_0$) which is given by Eq. 4:

$$V''(z)=\frac{(V_2\text{-}V_1)d}{2\pi S}$$

$$\left[\left(\begin{array}{l}\frac{4d^2+4(2z+S)^2\text{-}8(2z+S)^2}{\left(d^2+(2z+S)^2\right)^2}+\frac{4}{d^2\left(1+\left(\frac{2z+S}{d}\right)^2\right)}\text{-}\\ \frac{4d^2+4(2z\text{-}S)^2\text{-}8(2z\text{-}S)^2}{\left(d^2\text{-}(2z\text{-}S)^2\right)^2}\text{-}\frac{4}{d^2\left(1+\left(\frac{2z\text{-}S}{d}\right)^2\right)}\end{array}\right)\right]\quad(4)$$

It should be mentioned that, the first part of the research can be carried out with the aid of Simulink in MATLAB instead of using algorithms and conventional computer programs in MATLAB or any other softwares. The second part of the present research including calculations the first-order properties and third-order aberrations of the electron lens under consideration.

Determination of electron beam trajectories and aberrations: The paraxial trajectories of the electron beam passing through a rotationally symmetric magnetic lens can be determined by solving the paraxial ray equation given by Hawkes and Kasper (1989):

$$r''(z)+\frac{e}{8\,mV_r}B_z^2(z)r(z)=0\quad(5)$$

where, V_r is the relativistically corrected accelerating voltage which is given by $V_r = V_a(1+0.978\times10^{-6}V_a)$ where, V_a is the applied voltage with e/m is the charge-to-mass quotient of the electron. This equation which is a second-order linear homogeneous differential equation is of more importance in the field of the geometrical charged particle optics.

The spherical and chromatic aberration coefficients of rotationally symmetric magnetic lens can be calculated from the following two integrals (El-Kareh and El-Kareh, 1970):

$$C_s=\frac{\eta}{128V_r}\int_{z_o}^{z_i}\begin{bmatrix}\frac{3\eta}{V_r}B_z^4(z)r_\alpha^4(z)+8B_z^{'4}(z)r_\alpha^4(z)- \\ 8B_z^2(z)r_\alpha^4(z)r_\alpha^{'2}(z)\end{bmatrix}dz \tag{6}$$

$$C_s=\frac{\eta}{8V_r}\int_{z_o}^{z_i}B_z^2(z)r_\alpha^2(z)dz \tag{7}$$

Where:

$r_{.}$ = The solution of the paraxial ray equation

$B_z(z)$ = The axial magnetic field distribution

And the primes indicate differentiation with respect to z with , is the charge to mass quotient of electron. Also, z_0 and z_i are the object and image planes, respectively.

RESULTS AND DISCUSSION

Polepiece profile with aid of Simulink: In the synthesis approach followed in the present study the target axial potential function and the related other axial functions are determined with the aid of Simulink which is an attendant application to MATLAB and with the aid of this application scientific and engineering problems can be constructed. However, Fig. 1a shows the for iterator subsystem Simulink Model that generates the axial magnetic scalar potential distribution depending on Eq. 1 whereas the structure of the for iterator subsystem Simulink blocks is shown in Fig. 1b which includes the process of producing the axial potential V(z) of the lens. Also, by using Eq. 2 and the direct Simulink method, Fig. 2 shows the model that simulates the magnetic field distribution of the double polepiece magnetic lens.

However, the outputs of the preceding two models are the distribution of potential and the imaging magnetic field plotted in Fig. 3. It should be mentioned that the red curve is the distribution of field gradient $B'_z(z)$ which can be determined from Eq. 4 multiblied by the free space permeability μ_0. Actually, the distribution of the axial functions showing in Fig. 3 are determined at the following values of the optimization parametes: S = d = 2 mm, V_1 = -250 A-t and V_2 = 250 A-t.

The final task of the inverse design problem or synthesis approach for the electron-optical devices is the reconstruction process of the polepiece or electrode that generates the optimum imaging field. However, by using the first two terms of the analytical solution of Laplace's equation for rotationally symmetric fields, i.e, Eq. 3 the polepiece shape of the magnetic lens can be reconstructed. Thus, depending on Eq. 1-4, Fig. 4 shows the Simulink Model that synthesize the polepiece profile of the magnetic electron lens. Accordingly, Fig. 5 shows the polepiece profile of the upper half of the symmetrical double polepiece magnetic lens that generates the imaging field plotted in Fig. 3.

Imaging field distribution: The present study concerns with calculation of the objective properties for symmetrical double polepiece magnetic lenses. Two types of field distributions will be considered according to the geometrical parameters that affect these distributions which including in the field mathematical formula. Thus, Fig. 6 shows these distribution fields where the left one illustrates magnetic field distributions with different axial bore radii when the air gap width S and the object, V_1 and image V_2 side potentials are kept constants at 1 mm, -250 A-t and 250 A-t, respectively, the right field curves are the magnetic field distributions with various air gap widths when d = 1 mm, V_1 = -250 A-t and V_2 = 250 A-t. It is noted that fields with different bore radii are slowly decreasing fields which are concide with real fields of the magnetic lenses, on the other hand, fields with different S values are sharply fields which are closer to the rectangular field shapes, especially, fields of large air gap widths. It should be mentioned that, the semi-rectangular fields that of different S values having hard edge which may represent the field of solenoid which is widely used in linear accelerators to obtain strong focusing of the charged particle beams.

However, if we compared the present fields with different S values with those of semi-Glaser bell shaped model that studied by Biswas (2013) given by the equation:

$$\left[B_z(z)=\frac{B_0}{1+(\frac{z}{a})^n}\right]$$

which is the general model for the solenoid's on axis magnetic fields where a is the axial distance of HWHM or just half-width for any order n in this model and B_0 is the peak maximum field, one can conclude that Biswas field reaches to the hard edge for n>80 while our present field becomes as a hard edge field for example at S = 5 mm, d = 0.1 mm and $|V_1|$ = V_2 = 400 A-t as shown in Fig. 7. It is noted that the half width of present model at these parameters is 2.501 mm which is used in Biswas Model with B_0 = 0.2010 T. However, it is clear that the two fields are approximately coincide one on another especially in the half width and peak maximum regions.

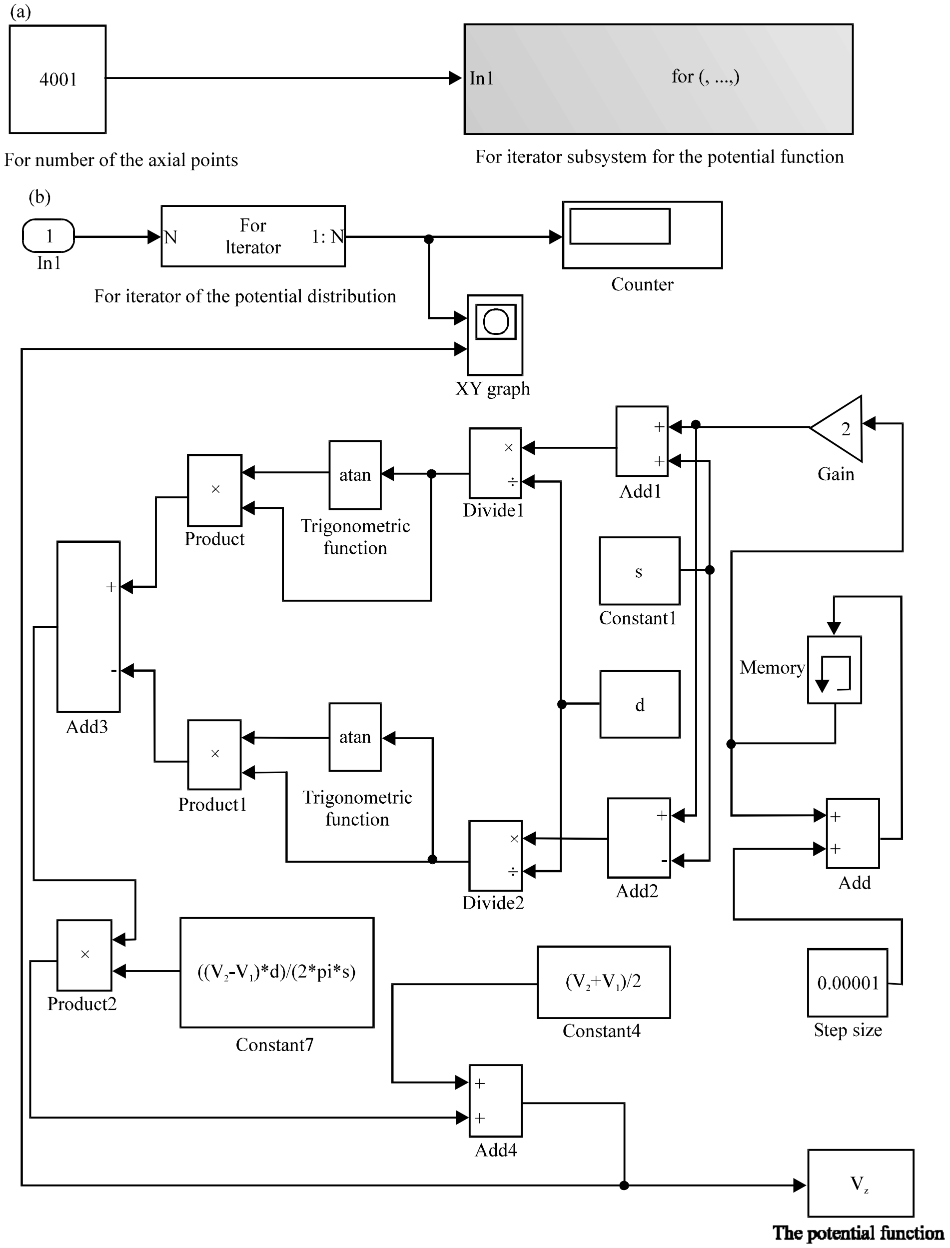

Fig. 1: a) For iterator subsystem for generation of the potential function and b) For iterator subsystem blocks of Fig. 1a

Properties of objective lens: The optimization parameters that more affect the imaging fields including the present field model are the axial bore radius and the air gap width of the polepieces, thus, the objective properties of the magnetic lens are evaluated under the effect of these parameters at constant object V_1 and image V_2 side potentials -250 A-t and 250 A-t, respectively. However, Fig. 8 shows the objective focal length f_o, chromatic C_c and spherical C_s aberration coefficients as a function to the excitation parameter ($NI/V_r^{1/2}$) for the small and large S and d values. It is noted that the properties of the objective lens enhanced for choosing small S and d values where these objective properties f_o, C_c and C_s, at $NI/V_r^{1/2} = 20$ when S = d = 1 mm are 0.3920 mm, 0.2749 mm and 0.2229 mm, respectively.

Comparison present model with solenoid model: Our present field model concides with the distribution of solenoid field distribution at small bore radius values and large air gap widths, thus, Fig. 9 shows the electron beam

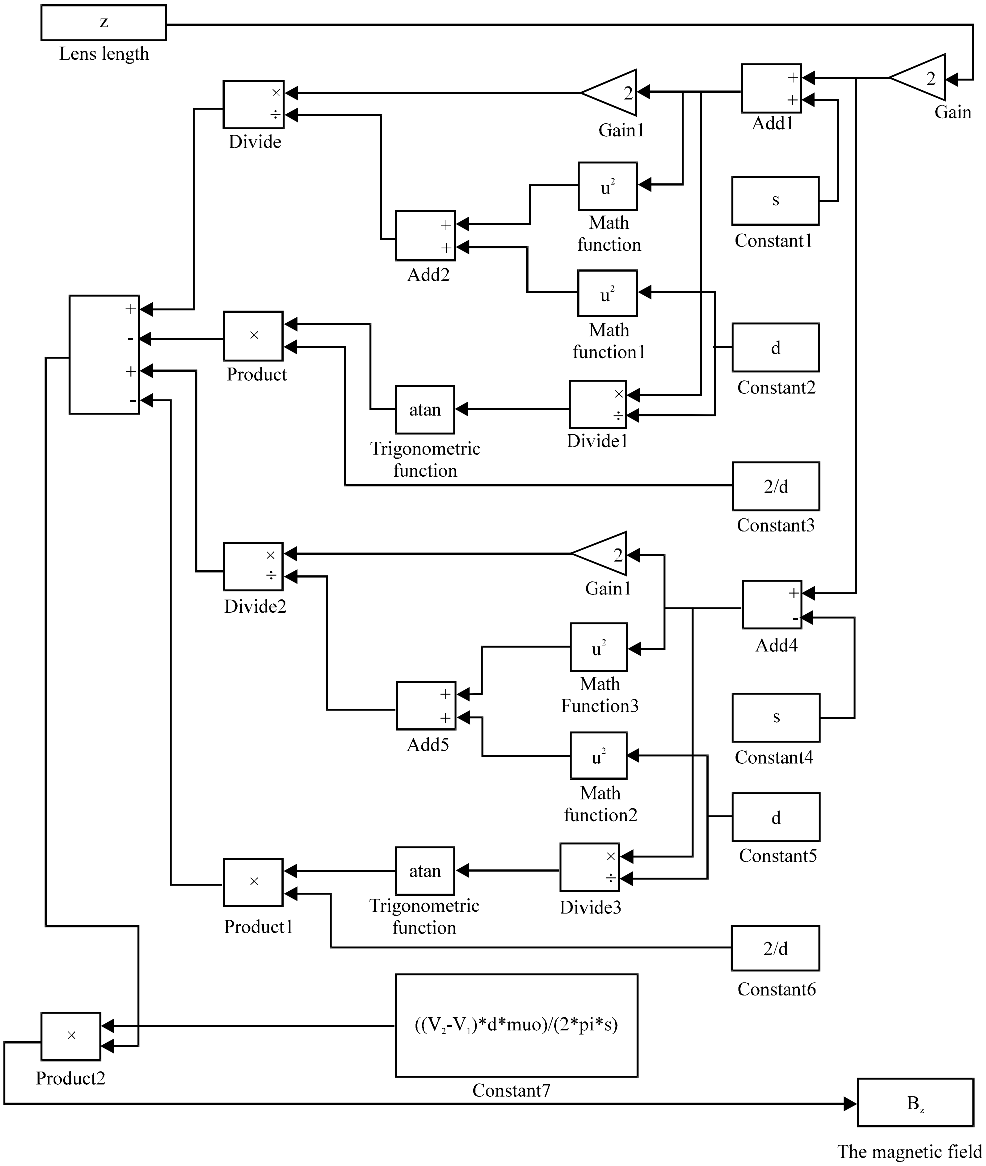

Fig. 2: Simulink Model for the imaging field function $B_z(z)$

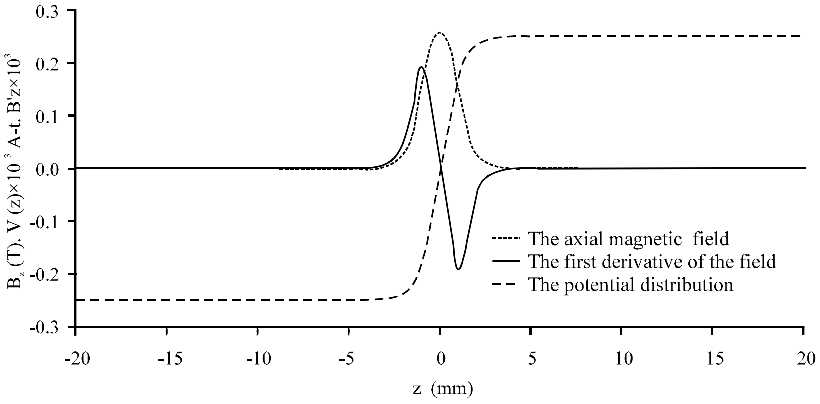

Fig. 3: The axial distribution of the potential, imaging field and its gradient at S = d = 2 mm, V_1 = -250A-t and V_2 = 2 0A-t

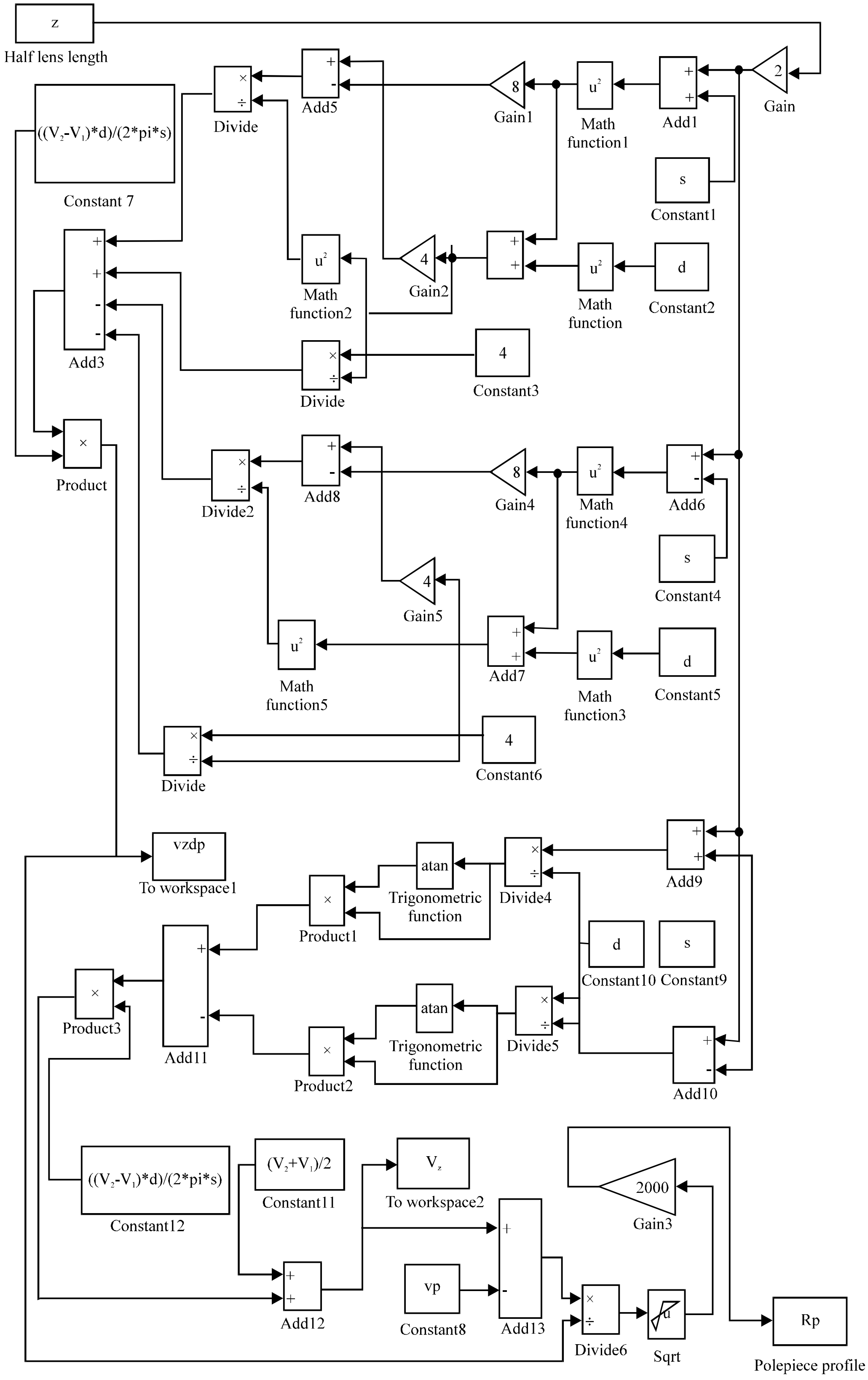

Fig. 4: Simulink Model for the polepiece profile

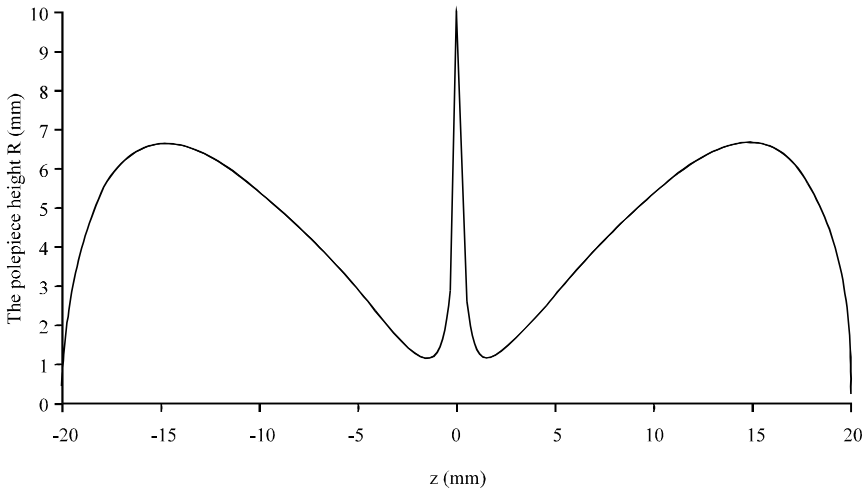

Fig. 5: The upper half pole piece profile for symmetrical magnetic lens; The polepiece height at S = d = 2 mm, V_1 = -250 A-t and V_2 = 250 A-t

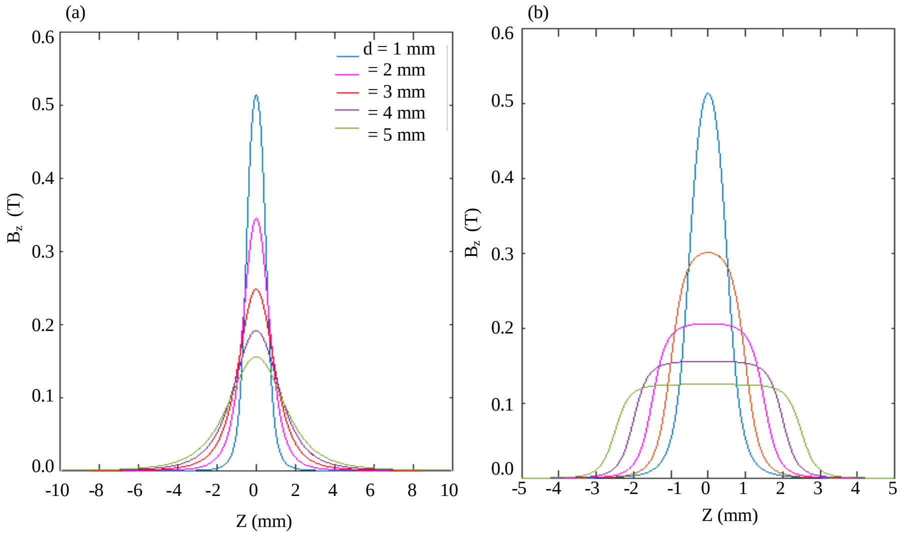

Fig. 6: The axial magnetic field distributions: on the left fields with different axial bore radii and fields on the right of different air gap widths

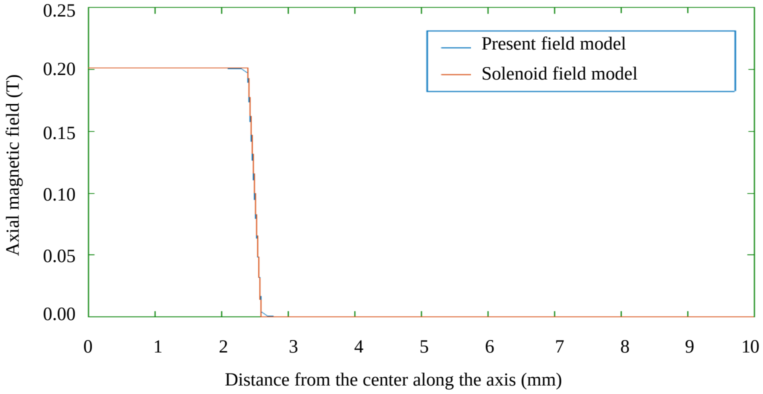

Fig. 7: Solenoid field model for n = 300, B_0 = 0.2010(T), a = 2.501 mm and present field model with S = 5 mm, d = 0.1 mm, V_1 = -400A-t and V_2 = 400A-t

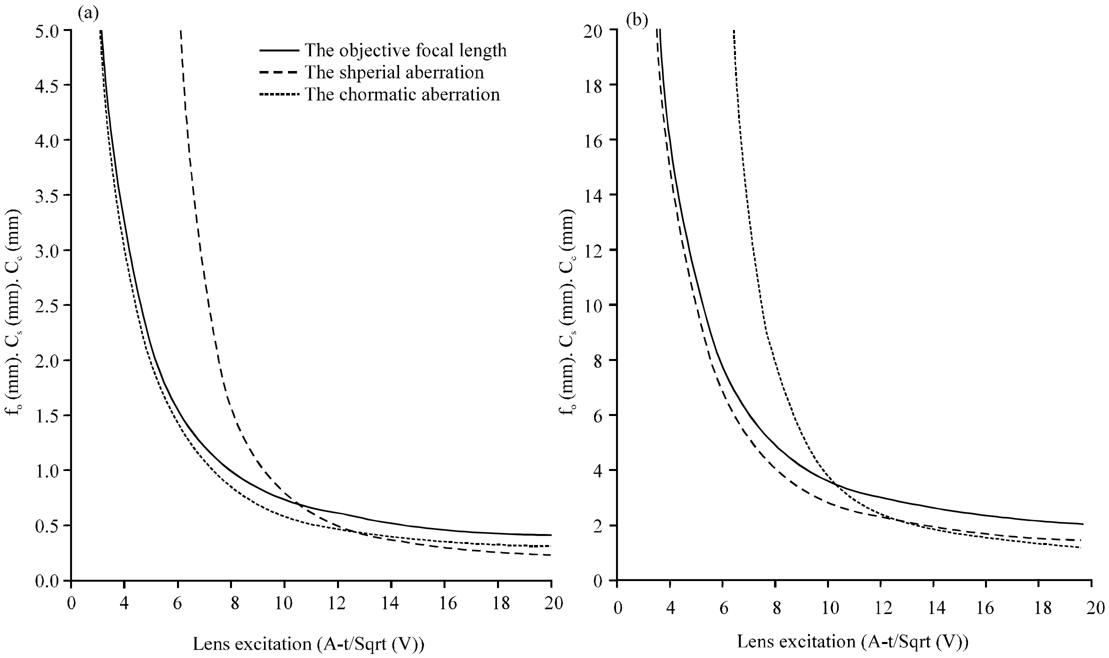

Fig. 8: The objective focal length f_0, spherical C_s and chromatic C_c aberration coefficients of imaging fields determined when a) The objective properties at V_1 = 250 A-t, V_2 = 250 A-t, S = d = 1 mm and b) The objective properties at S = d = 5 mm, V_1 = 250 A-t, V_2 = 250 A-t

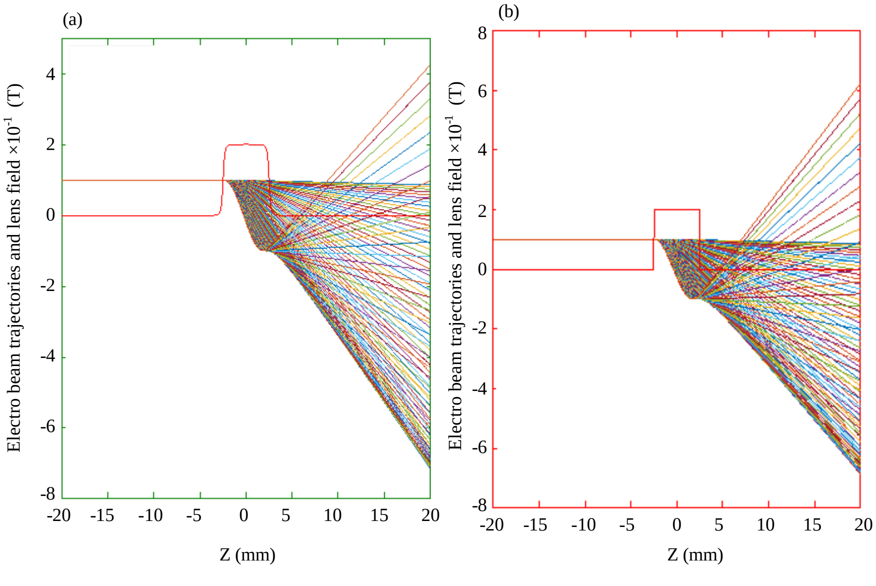

Fig. 9: Electron beam trajectories through: a) Present field model and b) Solenoid field model

trajectories and the field distributions of present model and solenoid model at S = 5 mm, d = 0.5 mm, V_1 = -400 A-t and V_2 = 400 A-t that evaluated on the range of the excitation parameter (Tsimring, 2007). It is noted that, the electron beam that passes through solenoid field distribution is of more slightly refractive from that passes in the present model, this is due to the more sharply solenoid field distribution.

CONCLUSION

From the results, one can be conclude that the present field model can be used to represent the solenoid magnets at large air gap widths and small bore radii and this model may be useful to approximate the permeant magnetic solenoids. Also, present field model may be convenient to approximate real fields of soft edge to hard edge transformation for large air gap widths to obtain analytical expression for spherical aberration coefficient in terms of its optimization parameters instead of solving the equation of motion. On the other hand, from the execution time point of view, the synthesis approach of an electron-optical devices with the aid Simulink is considered as an optimum environment tool.

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