OPTIMIZATION OF DISLOCATION OF MAGNETS IN A MAGNETIC SEPARATOR

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Abstract

Performance of magnetic separator is known to depend significantly on dislocation of magnets in its work-space. In this paper, we first formulate the mathematical relations that describe the magnetic field of the separator. The theoretical model is then exploited to optimize the structural parameters of the dislocation of magnets with respect to the price/performance objective function. Finally, numerical solution of the optimization problem for two types of separator is presented.

1 Introduction

Magnetic separators are bulky, expensive and individually designed industrial devices whose performance seems to be quite sensitive to the quality of their design. For example, the efficiency of the separator may be affected by the dislocation of the magnets in its work-space. Since there are often only very little additional costs on the part of a producer that are necessary to implement an improved design, there seems to be a good chance to improve the price/performance ratio of a magnetic separator by means of application of modern optimization methods.

Let us briefly describe an electromagnetic separator and some simplifications accepted throughout the paper. The liquid containing fine-grained substrat flows through the magnetic field that forces the ferromagnetic particles to separate from the medium. Most separators are drum-shaped (Fig. 1), so that one of the main parts of the separator is the large cylinder with a system of magnets fixed on its surface. In practice, the cylinder radius is much greater than the magnets. Since the curvature of the surface is relatively small, it seems acceptable to substitute the active part of the cylindrical drum by the planar region to simplify our computations. The magnets shaped as rectangular parallelepipeds are located so that

- their equal edges are parallel,
- the distribution is (in some sense) periodic,

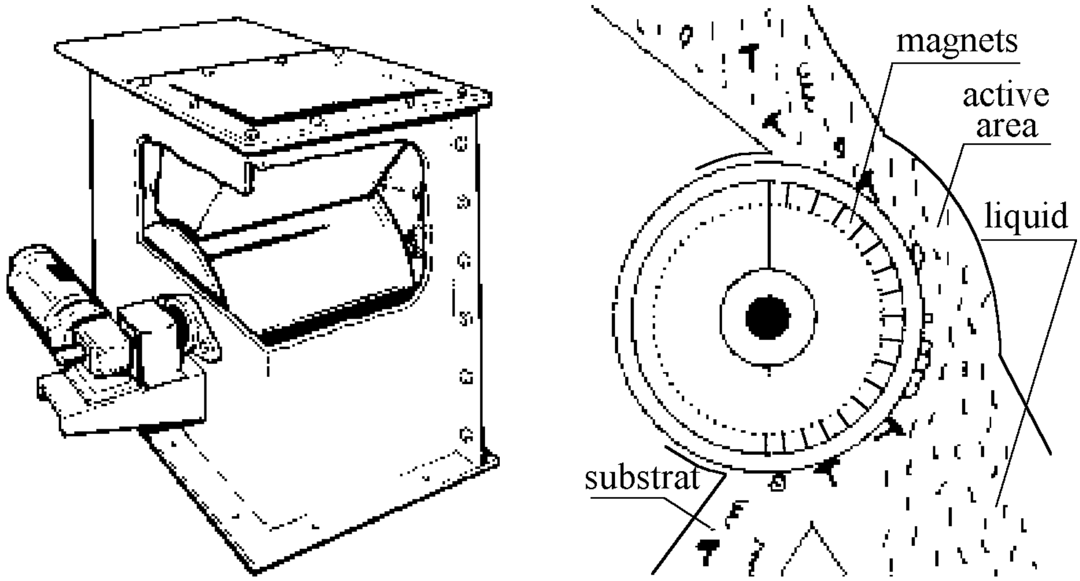


Figure 1: Magnetic separator (left) and cross-section of drum (right)

- there are gaps between magnets.

Under these restrictions, the characteristic parameters of a configuration are dimensions of the magnets and gaps. These will be our design variables for optimization.

The starting point of our study is the research report [1], where a basic mathematical model of separator was presented. After reviewing the basic equations, we proceed to relations that are important for numerical implementation of the basic model, including closed form of the components of the magnetic flux density corresponding to the sides of the magnet and description of the dislocation of the magnets. Then we define design parameters and an objective function. Using modern optimization methods, we obtain values of optimal design parameters for the two types of TMV magnetic separators. Some results of mathematical modelling of these separators appeared in [4].

2 Coil model of magnet

2.1 Equivalent current loop

First we aim to derive the formula for magnetic flux density $\vec{B}(\vec{r})$ of rectangular magnet as the sum of contributions of its four sides. We introduce the coordinate system as in Fig.1 and identify the magnet axis with z-axis. As in report [1], we base our considerations on the concept of the equivalent current loop.

It is well known that the external field of a permanent magnet has the same structure as the field of the current loop representing infinitely thin mantle of the magnet. We can express the magnetic flux density upon one side of the magnet

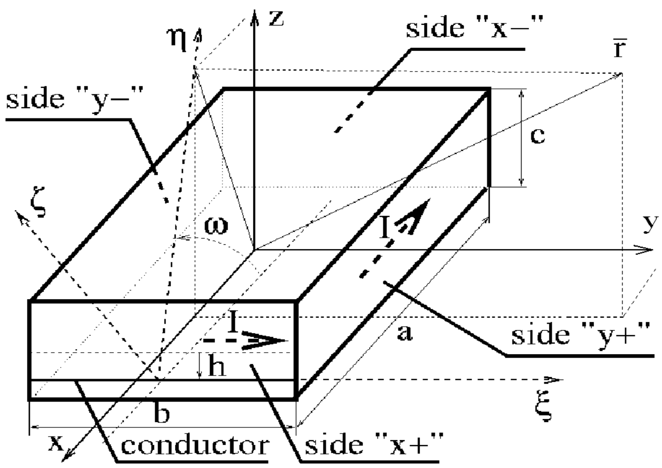


Figure 2: Coil model of magnet

as the superposition of contributions from individual line conductors that form the whole mantle. To this end, we start from the Biot-Savart law [2]

$$d\vec{B} = \frac{\mu I}{4\pi}\frac{d\vec{l} \times \vec{r'}}{|\vec{r'}|^3},$$

where I is the current and μ is the permeability. Further, $\vec{r} = (x, y, z)$ is the radius-vector of arbitrary point, $\vec{r'} = \vec{r} - \vec{l}$.

In particular, we express the magnetic flux density from the line conductor placed in the fictitious (ξ, η)-plane (see Fig.2): the conductor of the length l lies on the ξ-axis, so that $\vec{l} = (\xi, 0, 0)$ and its middle-point is located in the origin. The current is oriented in positive direction. The rearranged expression has the form

$$\vec{B}_l(\vec{r}) = \frac{\mu I}{4\pi}\int_L \frac{d\vec{l} \times (\vec{r} - \vec{l})}{|\vec{r} - \vec{l}|^3} d\vec{l} = \vec{k} y \frac{\mu I}{4\pi}\int_{-l/2}^{l/2} \frac{d\xi}{\sqrt{((x-\xi)^2 + y^2)^3}}.$$

with $\vec{k} = (0, 0, 1)$ and $y \neq 0$, so that the magnetic flux density outside the given line conductor is

$$\vec{B}_l(\vec{r}, l) = \vec{k}.\frac{\mu I}{4\pi y}.\left(\frac{l - 2x}{\sqrt{(l-2x)^2 + 4y^2}} + \frac{l + 2x}{\sqrt{(l+2x)^2 + 4y^2}}\right). \qquad (1)$$

2.2 Local and global coordinates

The following consideration aims to obtain the contribution of arbitrary side of the magnet in the form (1). Let us show in more detail how to get the magnetic flux density that corresponds to the side perpendicular to the positive part of the x-axis (related symbols are denoted by the superscript $x+$). To this purpose we introduce two usefull transformations.

The first mapping $\mathcal{L} : \mathrm{R}^3 \mapsto \mathrm{R}^3$ converts the global coordinates of a point into its local coordinates in the plane containing this point and the line conductor that is determined by the variable h as in the Fig.2:

$$\mathcal{L}^{(x+)}(\vec{r}) = \mathcal{L}^{(x+)}(x,y,z) = \left[\mathcal{T}_{x,-\frac{a}{2}} \circ \mathcal{T}_{z,h} \circ \mathcal{R}_{z,-\frac{\pi}{2}} \circ \mathcal{R}_{x,-\omega}\right](x,y,z),$$

where $\mathcal{T}_{o,d}$ is the translation d along the axis o and $\mathcal{R}_{o,\omega}$ is the rotation around the same axis in the positive direction by a given angle ω. The symbol $\circ$ is used for composition of mappings, and

$$\sin\omega = \frac{z+h}{\sqrt{(z+h)^2 + (a/2-x)^2}}.$$

After performing suggested operations, we get

$$\mathcal{L}^{(x+)}(x,y,z) = \left(y, \sqrt{(z+h)^2 + (a/2-x)^2}, 0\right). \tag{2}$$

The second mapping $\mathcal{G} : \mathrm{R}^3 \mapsto \mathrm{R}^3$ transfers a vector of magnetic flux density $\vec{B}$ from the plane where it was calculated back to the global coordinate system:

$$\mathcal{G}^{(x+)}(\vec{B}) = \left[\mathcal{R}_{x,\omega} \circ \mathcal{R}_{z,-\frac{\pi}{2}}\right](B_x, B_y, B_z) =$$

$$= \left(\frac{B_z(z+h) - B_y(\frac{a}{2}-x)}{\sqrt{(z+h)^2 + (a/2-x)^2}}, B_x, \frac{B_y(z+h) + B_z(\frac{a}{2}-x)}{\sqrt{(z+h)^2 + (a/2-x)^2}}\right). \tag{3}$$

2.3 Magnetic flux density in coil model

Now let us return to the reasoning of the previous paragraph to establish the magnetic flux density corresponding to the whole side of the magnet. Formally, we carry out the integration of (1) over the whole side height c using (2) and (3):

$$\vec{B}^{(x+)}(\vec{r},\vec{s}) = \int_{-c/2}^{c/2} \mathcal{G}\left[\vec{B}_l(\mathcal{L}^{(x+)}(\vec{r}), b))\right] dh, \tag{4}$$

where $\vec{s} = (a,b,c)$. This integration yields three components of the vector $\vec{B}^{(x+)}$ in the closed form:

$$B_x^{(x+)}(\vec{r},\vec{s}) = \frac{\mu I}{4\pi}\left\{\mathrm{sgn}\left(y-\frac{b}{2}\right).\ln\frac{\sigma(a,2y,c).(|y-\frac{b}{2}| + \sigma(a,b,-c))}{\sigma(a,2y,-c).(|y-\frac{b}{2}| + \sigma(a,b,c))} - \right.$$

$$\left. - \quad \mathrm{sgn}\left(y+\frac{b}{2}\right).\ln\frac{\sigma(a,2y,c).(|y+\frac{b}{2}| + \sigma(a,-b,-c))}{\sigma(a,2y,-c).(|y+\frac{b}{2}| + \sigma(a,-b,c))}\right\}, \tag{5}$$

$$B_y^{(x+)}(\vec{r},\vec{s}) = 0\,, \tag{6}$$

$$B_z^{(x+)}(\vec{r},\vec{s}) \;=\; \frac{\mu I}{4\pi}.\mathrm{sgn}\left(x-\frac{a}{2}\right).\left\{\mathrm{sgn}\left(y-\frac{b}{2}\right).f_1(\vec{r},\vec{s}) - \mathrm{sgn}\left(y+\frac{b}{2}\right).f_2(\vec{r},\vec{s})\right\}\,, \tag{7}$$

where

$$f_1 = \arctan\frac{\left|x-\frac{a}{2}\right|.\left|y-\frac{b}{2}\right|.\left[\left(z+\frac{c}{2}\right).\sigma(a,b,c)-\left(z-\frac{c}{2}\right).\sigma(a,b,-c)\right]}{\left(x-\frac{a}{2}\right)^2.\sigma(a,b,c).\sigma(a,b,-c)+\left(y-\frac{b}{2}\right)^2.\left(z-\frac{c}{2}\right).\left(z+\frac{c}{2}\right)}\,,$$

$$f_2 = \arctan\frac{\left|x-\frac{a}{2}\right|.\left|y+\frac{b}{2}\right|.\left[\left(z+\frac{c}{2}\right).\sigma(a,-b,c)-\left(z-\frac{c}{2}\right).\sigma(a,-b,-c)\right]}{\left(x-\frac{a}{2}\right)^2.\sigma(a,-b,c).\sigma(a,-b,-c)+\left(y+\frac{b}{2}\right)^2.\left(z-\frac{c}{2}\right).\left(z+\frac{c}{2}\right)}\,.$$

Here we use $\sigma(a,b,c) = \left|\vec{r}-\frac{\vec{s}}{2}\right|$ with the Euclidean norm of the vector $\vec{r}-\frac{\vec{s}}{2}$. Note that the signs of the components of $\vec{s}$ vary by sides.

Obtained results can be used to derive the contribution from any side of the permanent magnet. If we put $i = (x-),\ (y+),\ \text{or}\ (y-)$, then

$$\vec{B}^i = \mathcal{S}^i\left[\vec{B}^{(x+)}\left(\left(\mathcal{S}^i\right)^{-1}(\vec{r},\vec{s}^i)\right)\right]\,. \tag{8}$$

For example, the contribution of the side transversal to the positive y-axis is given by

$$i=(y+),\quad \mathcal{S}^i = R_{z,\frac{\pi}{2}},\quad \left(\mathcal{S}^i\right)^{-1} = R_{z,-\frac{\pi}{2}},\quad \vec{s}^i = (b,a,c)\,.$$

Resulting magnetic flux density of the whole permanent magnet is the sum

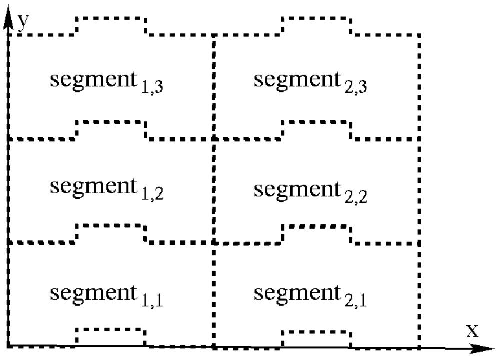
$$\vec{B}(\vec{r},\vec{s}) = \vec{B}^{(x+)} + \vec{B}^{(x-)} + \vec{B}^{(y+)} + \vec{B}^{(y-)}\,. \tag{9}$$

The transform (8) allows us to rewrite the components of $\vec{B}$ in terms of the vector $\vec{B}^{(x+)}$:

$$B_x(\vec{r},\vec{s}) = B_x^{(x+)}(x,y,z,a,b,c) - B_x^{(x+)}(-x,-y,z,a,b,c)\,, \tag{10}$$

$$B_y(\vec{r},\vec{s}) = B_x^{(x+)}(y,-x,z,a,b,c) - B_x^{(x+)}(-y,x,z,b,a,c)\,, \tag{11}$$

$$\begin{aligned} B_z(\vec{r},\vec{s}) = {} & B_z^{(x+)}(x,y,z,a,b,c) + B_z^{(x+)}(y,-x,z,a,b,c) + \\ & + B_z^{(x+)}(-x,-y,z,a,b,c) + B_z^{(x+)}(-y,x,z,b,a,c)\,. \end{aligned} \tag{12}$$



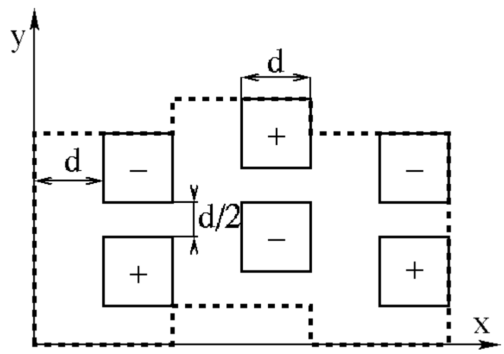


Figure 3: System of segments (left), magnets within a segment (right)

3 Dislocation of magnets

Having the coil model of the individual magnet, we can proceed to get the global magnetic field of the separator. We obtain it rather easily by superposition of the contributions of the magnets. Of course, the resulting magnetic field will depend on the dislocation of the magnets that we try to optimize.

To avoid unnecessary generality, we suppose all the magnets to be of the same size. This assumption agrees with the common practice motivated by the effort to reduce the production costs. The most general configuration could be identified by a set of vectors $\{(x, y, m) \in \mathrm{R} \times \mathrm{R} \times \{-1, 1\}\}$ whose first two entries x, y correspond to the coordinates of the center of gravity in the plane of the drum, while m defines the magnet orientation (N-S or S-N). However, a practical separator design has rather regular dislocation of magnets, so we shall restrict our attention to the latter case.

Let us consider a dislocation that comprises equal segments as in Fig. 3 , so that it is described by a triple $C = \left(N^{(x)}, N^{(y)}, \mathrm{Q}\right)$, where $N^{(x)}$, $N^{(y)}$ denote numbers of segments along the x- or y-axis, respectively, and Q represents dislocation of magnets inside a chosen segment. Denoting by $n^{(x)}$, $n^{(y)}$ the number of magnets in both directions, we can define the arrangement $\mathrm{Q} = \left(\vec{d}^{(x)},\, \vec{d}^{(y)},\, s^{(x)},\, s^{(y)},\, \mathrm{M}\right)$. Here $\vec{d}^{(x)}$, $\vec{d}^{(y)}$ are vectors of dimensions $n^{(x)}$, $n^{(y)}$ that determine the gaps between the magnets, and $s^{(x)}$, $s^{(y)}$ determine the shift of even rows (columns) relative to the odd rows (columns). The matrix M of type $n^{(x)} \times n^{(y)}$ with elements 1 or -1 specifies the pole-orientation. For example, Fig. 3 shows the dislocation

$$C = (2, 3, \mathrm{Q}),\ \mathrm{Q} = \left((d, d, d),\, \left(\frac{d}{2}, \frac{d}{2}\right),\, 0,\, \frac{d}{2},\, \mathrm{M}\right),\ \mathrm{M} = \begin{pmatrix} 1 & -1 & 1 \\ -1 & 1 & -1 \end{pmatrix}^T .$$

The general formula for the total magnetic flux density of the planar separator is

$$\vec{B}(\vec{r}) = \sum_{i=1}^{N^{(x)}} \sum_{j=1}^{N^{(y)}} \vec{B}^{seg}(\vec{r} - \vec{u}_{i,j}^{seg})\,, \tag{13}$$

$$\vec{u}^{seg}_{i,j} = \left((i-1).\sum_{k=1}^{n^{(x)}} \left(a + d_k^{(x)}\right),\, (j-1).\sum_{k=1}^{n^{(y)}} \left(b + d_k^{(y)}\right),\, 0 \right)$$

$$\vec{B}^{seg}(\vec{r}) = \sum_{i=1}^{n^{(x)}} \sum_{j=1}^{n^{(y)}} \vec{B}^{mg}(\vec{r} - \vec{u}^{mg}_{i,j})\,, \tag{14}$$

$$\vec{u}^{mg}_{i,j} = \frac{1}{2}.\left(a + 2d_i^{(x)} + 2.\sum_{k=1}^{i-1} \left(a + d_k^{(x)}\right) + 2.\delta(j).s^{(x)},\; b + 2d_j^{(y)} + \right.$$

$$\left. +2.\sum_{k=1}^{j-1} \left(b + d_k^{(y)}\right) + 2.\delta(i).s^{(y)},\; 0 \right)\,,$$

where $\delta(i) = 1$ for even i and $\delta(i) = 0$ otherwise. The superscript *"seg"* stands for segment, similary *"mg"* for magnet.

4 Optimization

4.1 Objective function

An obvious optimization problem is to find the dislocation of the magnets that maximizes the output of the separator. From this point of view, it seems reasonable to maximize the total action of the magnetic field determined by the magnetic flux Φ. To simplify our computations, we only take into account the magnetic field in a plane S parallel to the pole-faces ($z = const.$) in the separation space:

$$\Phi = \int_S |\vec{B}.\vec{n}\,|dS = \int_S |B_z\,|dS\,. \tag{15}$$

Here we integrate the absolute value of the magnetic flux density. This is acceptable because the separated particles are very small.

Since there is no preferable level S for calculating of Φ, we shall use the mean value of the weighted sum for all the levels, i.e. the integral mean over the whole height H of the separation space

$$P = \frac{1}{H}\int_{c/2}^{c/2+H} w(z)\Phi(z)dz = \frac{1}{H}\int_{c/2}^{c/2+H} w(z) \int_{S(z)} |B_z(x,y,z)\,|dS\,dz\,, \tag{16}$$

where $w(z)$ is a weighting function that may specify the filling of the separation space.

It is easy to see that the unconstrained maximization of P leads to large dimensions of magnets. To get reasonable designs, we include also the costs into the objective function. In practice, the separators work in series to achieve desired efficiency. Suppose that we need to get the total mean magnetic flux $P_{tot} = n.P$ with n

devices with the same power given by (16) and with the price p. Denoting $\varphi = n.p$, we obtain, because P_{tot} is constant, the objective function

$$\varphi = n.p = \frac{P_{tot}}{P}.p \sim \frac{p}{P}\,. \tag{17}$$

Furthermore, we assume that the price of the separator is the sum of certain fixed costs p_{fix} and of the price of the magnets. If p_{mg} is the price of 1 m^3 magnets, then we obtain (see previous paragraph for notation)

$$p = p_{fix} + N^{(x)}.N^{(y)}.n^{(x)}.n^{(y)}.V.p_{mg}\,, \tag{18}$$

where $V = a.b.c$ is the volume of a single magnet.

Now let us specify the formula for the magnetic flux. We shall take into account some natural restrictions on generality of dislocations, namely we assume that the magnets inside the segments are arranged into strips, in agreement with common practice. In particular, we shall consider the strips of magnets parallel to x-axis placed one next to the other, so that $s^{(y)} = 0$. Thus, the mean magnetic flux over a single segment can be calculated by (16) with the weighting function $w(z) = 1$ as

$$P_{n^{(x)},n^{(y)}} = \sum_{j=1}^{n^{(y)}} \int_{K^{(x)}}^{K^{\star(x)}} \int_{K_{j-1}^{(y)}}^{K_j^{\star(y)}} \int_{\frac{c}{2}}^{\frac{c}{2}+H} |B_z^{seg}(\vec{r}, \vec{s}, \vec{d}^{(x)}, \vec{d}^{(y)}, s^{(x)})|\, dz\, dy\, dx\,, \tag{19}$$

where

$$K^{(x)} = \delta(j).s^{(x)}\,, \quad K_{j-1}^{(y)} = \sum_{k=1}^{j-1} \left(b + d_k^{(y)}\right)\,, \tag{20}$$

$$K^{\star(x)} = K^{(x)} + \sum_{k=1}^{n^{(x)}} \left(a + d_k^{(x)}\right)\,, \quad K_j^{\star(y)} = K_j^{(y)} + d_j^{(y)}.$$

Finally, let D and L denote the width (in the x-direction) and the length (y-direction) of the area covered by magnets, respectively. Then

$$N^{(x)} = \frac{D}{\sum_{k=1}^{n^{(x)}} \left(a + d_k^{(x)}\right)}\,, \quad N^{(y)} = \frac{L}{K^{(y)}},$$

where $K^{(y)} = K_{n^{(y)}}^{(y)}$ by (20). Resulting cost functional, i. e. objective function (17), can be written as

$$\varphi = \frac{\frac{K^{(x)}.K^{(y)}}{D.L}.p_{fix} + n^{(x)}.n^{(y)}.V.p_{mg}}{P_{n^{(x)},n^{(y)}}}\,. \tag{21}$$

4.2 Design variables

A dislocation of the magnets in the separator is defined by the following information about the segments:

- gaps between the magnets in the x-direction: $\vec{d}^{(x)} = \left(d_1^{(x)}, \ldots, d_{n^{(x)}}^{(x)}\right)$,
- gaps between the magnets in the y-direction: $\vec{d}^{(y)} = \left(d_1^{(y)}, \ldots, d_{n^{(y)}}^{(y)}\right)$,
- height of the magnets c,
- configuration of the magnet polarity, i. e. the matrix M.

All the mentioned characteristics play the role of design variables in the optimization problem. We shall restrict our attention to the strip dislocation with the matrix

$$\mathrm{M} = \begin{pmatrix} -1 & -1 \\ 1 & 1 \end{pmatrix}. \tag{22}$$

Moreover, we assume

$$d_i^{(x)} = d^{(x)} = const., \quad d_j^{(y)} = d^{(y)} = const. \quad \text{for } i = 1, \ldots, n^{(x)},\ j = 1, \ldots, n^{(y)}.$$

Evidently, both the distances $d^{(x)}$, $d^{(y)}$ and the height of the magnet c are non-negative, so that we shall carry out the minimization with respect to these natural constraints, namely

$$d^{(x)} \geq 0, \quad d^{(y)} \geq 0, \quad c \geq 0\,. \tag{23}$$

Furthermore, due to the periodic structure of our dislocations, we may introduce the bound

$$|s^{(x)}| \leq a + d^{(x)}\,. \tag{24}$$

As the last constraint we take the lower bound on the ratio of the area of the pole faces to the whole area of the segment

$$\frac{a.b}{[a + d^{(x)}]\,.\,[b + d^{(y)}]} \quad \geq \quad q\,, \tag{25}$$

where q is a given value. This constraint may be used to imply reasonable limits on the gaps.

4.3 Formulation of the optimization problem

If we sum up the reasoning of the previous section, we shall get the optimization problem to find

$$Min \quad \varphi\left(c, d^{(x)}, d^{(y)}, s^{(x)}\right) \tag{26}$$
$$subject\,to \quad (23), (24), (25).$$

The problem is fully specified when all the parameters of the model are known, in particular

- geometrical structure (dimensions of the magnet a, b, proportions of the active separation area D, L, H);
- the physical properties of the magnets (to determine a current I);
- economical data p_{fix}, p_{mg}.

Except the last values that may vary in time, all the other data may be obtained from commercial sources [8].

With respect to the recent analysis [5], we can expect that a (4×4)-segment with sixteen magnets will be sufficiently representative regarding whatever (greater) structure with the same dislocation. To define polarity of the magnets, we use the four matrices (22) in the configuration 2×2. Therefore, the reduced cost functional (21) may be written as

$$\varphi\left(c, d^{(x)}, d^{(y)}, s^{(x)}\right) = \frac{\frac{\left(a+d^{(x)}\right).\left(b+d^{(y)}\right)}{D.L}.p_{fix} + V.p_{mg}}{P_{4,4}}. \tag{27}$$

4.4 Numerical solution

The optimization problem (26) is obviously so complex that there is no chance to solve it by the classical analytical tools. However, it may be rather easily verified that both the objective function and the constraints are differenciable, so that we can use the standard methods of continuous optimization to obtain numerical solution of (26). The natural choice seems to be a variant of the sequential quadratic programming (SQP) method that does not require analytical formulas for the derivatives, but builds the second order information from previous iterations by the modified BFGS method [10].

The objective function was coded in MATLAB so that the integrals in $P_{4,4}$ were evaluated by means of the zero-order Newton-Cotes method [7]. The integration points were located in the regular grid that covered the magnets in 4×4-segment including the gaps. The numbers of mesh nodes in the directions x, y , z are denoted by $M^{(x)}$, $M^{(y)}$, $M^{(z)}$, respectively. Thus we obtained the discretized formula for the mean magnetic flux

$$P_{4,4} = \frac{\left(a + d^{(x)}\right)\left(b + d^{(y)}\right) H}{M^{(x)}.M^{(y)}.M^{(z)}} \sum_{i=1}^{4.M^{(x)}} \sum_{j=1}^{4.M^{(y)}} \sum_{k=1}^{M^{(z)}} |B_z^{seg}(\vec{r}_{i,j,k}, \vec{s}, d^{(x)}, d^{(y)}, s^{(x)})|.$$

Here $\vec{r}_{i,j,k} = (x_i, y_j, z_k)$, where the node coordinates are defined by

$$x_i = \left(i - \frac{1}{2}\right).\frac{a + d^{(x)}}{M^{(x)}} + \delta(t)s^{(x)} \quad \text{with} \quad t = \text{ceil}\left(\frac{y_j}{b + d_y}\right),$$

$$y_j = \left(j - \frac{1}{2}\right).\frac{b + d^{(y)}}{M^{(y)}}, \qquad z_k = \left(k - \frac{1}{2}\right).\frac{H}{M^{(z)}} + \frac{c}{2}.$$

The code for the objective function together with simple codes for the constraints were supplied to the programe from the Optimization TOOLBOX [6] which carried out the minimization.

We tried also to apply the genetic algorithms [3, 11] with similar results. Further research will include application of more general algorithms of the global optimization [12] together with alternative cost functions.

4.5 Examples and results

Described mathematical model was used to optimize the magnet dislocation for the separators TMV 500/650 and TMV 800/2400 [8]. The Table 1 shows their basic data. Since price parameters p_{fix}, p_{mg} vary depending on the type of magnets, we

Separator	D [m]	L [m]	H [m]	a [m]	b [m]	I [A]
TMV 500/650	0.690	0.888	0.191	0.150	0.200	400000
TMV 800/2400	2.200	1.416	0.189	0.150	0.200	400000

Table 1: The global characteristics of separators

solved the optimization problem for alternative values of p_{fix}/p_{mg}. We used $q = 0.5$ in (25) and $M^{(x)} = M^{(y)} = 8$, $M^{(z)} = 2$.

Separator	p_{fix}/p_{mg}	c_{opt} [m]	$d^{(x)}_{opt}$ [m]	$d^{(y)}_{opt}$ [m]	$s^{(x)}_{opt}$ [m]
TMV 500/650	10	0.5612	0.0316	0	0
	4	0.4050	0.0320	0	0
	1	0.2554	0.0329	0	0
TMV 800/2400	10	0.3176	0.0321	0	0
	4	0.2354	0.0326	0	0
	1	0.1461	0.0332	0	0

Table 2: Optimized parameters

Obtained results (see the Table 2) lead to the following conclusions:

- the size of gaps between the magnets of the same orientation decreases towards zero as well as the shift of odd rows;
- the optimal gaps between the strips of the magnets of different orientation are about 3 cm;
- the optimal dislocation has the form depicted in Fig. 4.

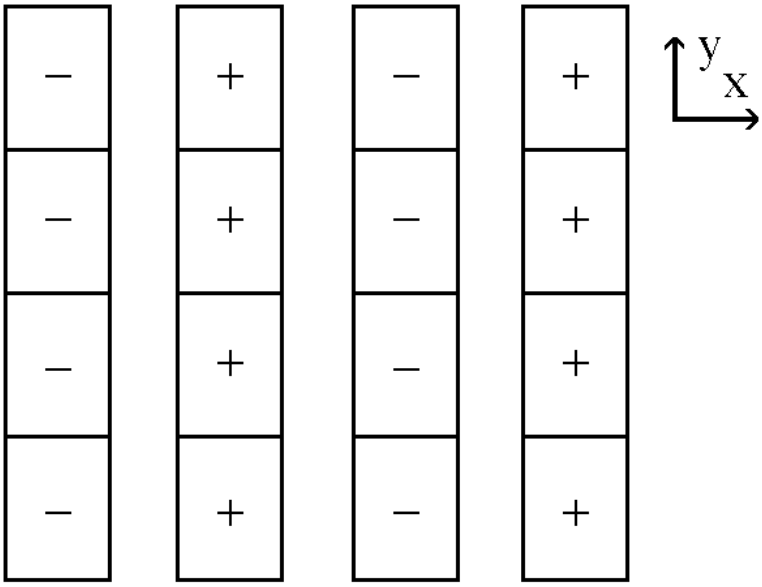


Figure 4: Optimized dislocation of the magnets in a separator

5 Acknowledgement

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References

[1] Homa, V. - Hytka, Z.: *The calculation of different variants of the magnetic field in magnetic crusher.* Research report HS 47/88, VŠB-TU Ostrava, October 1988 (in Czech)

[2] Haňka, L.: *Theory of Electromagnetic Field.* SNTL/Alfa, Praha 1982 (in Czech)

[3] Lukáš, D.: A Genetic Algorithm for Optimization of Continuous Functions and its Parallel Implementation, Student's Report, Department of Applied Mathematics, FEI VŠB-TU Ostrava 1998

[4] Lukáš, D.: *Modelling of Electromagnetic Field in the Separator with Permanent Magnets.* Proc. of 6th Student Conference VŠTEZ. JČMF, Praha 1998, pp. 62-71 (in Czech)

[5] Lukáš, D.: M.Sc. Thesis, FEI VŠB TU Ostrava, 1999 (in Czech)

[6] *MATLAB Optimization TOOLBOX User Manual.* The Mathworks, Inc., 1995

[7] Rektorys, K. et al *The Overview of Apllied Mathematics I.* Prometheus, Praha 1996 (in Czech)

[8] *Electromagnetic Cylinder Separators TMV.* The Catalogue of Bratislava Electrotechnic Works (BEZ), Bratislava 1983 (in Slovakian)

[9] *http://www.aamag.com/mdsep.htm*, Web Page of A & A Magnetics, Inc.

[10] Fletcher, R.: Practical Methods of Optimization, John Wiley and Sons, 2nd Edition, Chichester 1997.

[11] Michalewicz, Z.: *Genetic Algorithms*, Springer, Berlin 1996

[12] Horst, R. and Tuy, H.: *Global Optimization*, Springer, Berlin 1996