Dynamics of Magnetization in an Array of Three-Layer Nanodiscs

V A Orlov[1,2], G S Patrin[1,2] and I N Orlova[3]

[1]Siberian Federal University, Krasnoyarsk 660041, Russia
[2]Kirensky Institute of Physics Krasnoyarsk Scientific Center Russian Academy of Sciences Siberian Branch Krasnoyarsk 660036, Russia
[3]Krasnoyarsk State Pedagogical University after V.P. Astafev Krasnoyarsk 660049, Russia

E-mail: vingtr@yandex.ru

Abstract. The paper studies associated motion of magnetic vortices in a triple-layer FM/NM/FM disc array. The connection of magnetic layers' magnetization inside of one disc and between the discs is assured by magnetostatic interaction. The frequencies of magnetic vortex resonant motion have been calculated analytically and resonant curves for the arrays with different alternation of magnetic vortex polarity and chirality have been constructed. It has been shown that despite of a small value of the core magnetic moments, taking their interaction into account leads to a small but significant splitting of the resonant frequency.

1. Introduction

The interest to low-dimensional objects with a magnetization structure in the form of vortex structures is caused by the perspectives of constructing various spintronics devices on their basis [1, 2, 3]. The magnetization stability of nano-elements and their arrays is useful to create reliable data storage devices on their basis. At the same time it is important to be able to encode bits of information by both the polarity of the vortex central part (the core) $p = \pm 1$, and its chirality $q = \pm 1$ (twisting the magnetization vector clockwise or counterclockwise).

Naturally, multi-layer nano-elements, where each layer is characterized by its own combination $\{p, q\}$, have even more states that allows increasing the storage density orders of magnitude more. This also explains the occurrence of the detailed experimental and theoretical research devoted to multi-layer and single-layer nano-structures in recent years [4, 5, 6, 7, 8, 9, 10].

In relatively tightly packed arrays of elements the interaction of various origin between the elements' magnetic subsystems turns out to be significant (magnetostatic [11, 12], exchange, RKKY etc.). One of the energetically favorable ways to change the magnetic condition of the elements is the vortex transition into the resonant motion regime with a subsequent pulsed remagnetization of the core (change in the polarity) at the edge of the element. This process is carried out by means of an alternating magnetic field applied parallelly to the plane of the element. An isolated single-layer ferromagnetic disc has a single resonance frequency, depending on the constant magnetic field applied perpendicularly to the plane of the disc [13]. In the presence of inter-disc interaction in the array of discs, magnetic collective oscillations are similar to magnetostatic waves with the corresponding dispersion laws [14, 15] and the removal of resonance frequencies' degeneration for the arrays of discs with different formula combinations

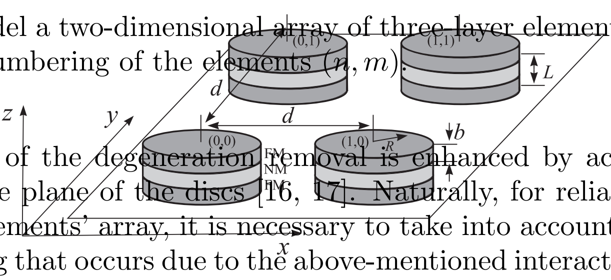

Figure 1. The model a two-dimensional array of three-layer elements with a coordinate system and the accepted numbering of the elements (n, m).

$\{p, q\}$. The degree of the degeneration removal is enhanced by activating the magnetic field perpendicular to the plane of the discs [16, 17]. Naturally, for reliable control of the magnetic state of the nano-elements' array, it is necessary to take into account the effect of the resonance frequencies' splitting that occurs due to the above-mentioned interactions, in multilayer discs and their arrays included. In particular, in two-layer discs it is necessary to take the magnetostatic interaction of the layers into account [18, 19, 20, 21, 22, 23]. The aim of this paper is to investigate the effect of the interaction between the magnetic layers in the array of nanodiscs on the magnetization dynamics taking the vortex core magnetic moment into account.

2. The model and equation of magnetization motion

Let's consider the model of the nano-elements' array shown in 1. Each element has a shape of a disc with a radius of R and it is a three-layer system: two ferromagnetic layers separated by a non-magnetic layer. The thickness of the magnetic layers is b, the distance between their middle lines is L. The distance between the centers of the elements is d. Let the ratio b/R be such that a stable vortex state of magnetization occurs in the magnetic layers. We are interested in the magnetization motion in the elements of the array when it is placed in an alternating magnetic field parallel to the plane of the sample.

The calculations are based on the representation ideology of Landau-Lifshitz equation through collective variables [24, 25]. The speed and coordinates of the magnetic vortex center - the core - act as such variables. In the core, the magnetization is highly inhomogeneous and in the center it is directed perpendicular to the surface of the magnet.

The state of the vortex magnetization is traditionally given by two parameters $p = \pm 1$ and $q = \pm 1$ ($\{p, q\}$). The sign of polarity is given conditionally: along or against the normal line to the surface of the tape. The sign of chirality is also conditional: the rotation of magnetization in a vortex is clockwise or counterclockwise. Often, it is convenient to use the value $\pi_T = pq$ to set the magnetic state of vortices. The motion nature of the core displaced from the center of the disc is as if the core-quasiparticle is affected by the gyroscopic force $\mathbf{F}_G = \mathbf{G} \times \mathbf{v}$ [25]. Here $\mathbf{G}$ – is a gyrovector, $\mathbf{v}$ is the core velocity. The value of the gyrovector is determined by $\mathbf{G} = \mathbf{k}\pi_T(2\pi M_S b/\gamma)(1 - ph)$, where $\mathbf{k}$ is a single vector along the axis perpendicular to the disc plane, b is thickness of a magnet, γ is a gyromagnetic ratio, M_S is saturation magnetization, $h = H/(\mu_0 M_S)$ is a dimensionless field applied perpendicular to the plane of the magnet (along or against the magnetization in the core center) [26].

The equation of the core motion is convenient to be described by Thiele's equation:

$$\mathbf{G} \times \mathbf{v} - D\mathbf{v} - \nabla W = 0. \tag{1}$$

Here $\mathbf{v}$ is a core velocity, $D = -\alpha\,(\pi M_S b/\gamma)\,(2 + \ln{(R/\delta_0)})$ is an effective viscous friction coefficient, α is a parameter of the material decay, $\delta_0 \approx 10$ nm is a core characteristics radius [26]. The third term in the left part of the equation (1) is responsible for the effective conservative forces acting on the vortex core in the layer as on a quasi-particle. These forces include the returning force (it occurs when the core is displaced from the center of the disc), the force of interaction with the magnetization of the neighboring layer and the magnetizations of the other discs and the effective force that has an effect on the core due to the interaction of the vortex magnetization with the external magnetic field. Thus, for the energy W can be formulated in the following way: $W = W_M(\mathbf{r}_1, \mathbf{r}_2) + W_H + W_B$. Here $W_M(\mathbf{r}_1, \mathbf{r}_2)$ is the energy of interaction between magnetic moments of the disc ferromagnetic layers, W_H is Zeeman energy, W_B is the energy associated with the demagnetization fields which increases with the core displacement from the center of the element. The position of the vortex centers is given by the radius vectors $\mathbf{r}_1$ and $\mathbf{r}_2$. Let us consider each of the energy terms in more details. For Zeeman energy we formulate: $W_H = -\mathbf{M}(\mathbf{H}_0 + \mathbf{H}(t))$. Here $\mathbf{M}$ is a disc magnetic moment, $\mathbf{H}_0$ is a constant field perpendicular to the surface of the layers, $\mathbf{H}(t)$ is a varying magnetic field incorporated in the layers' plane. The value $W_M(\mathbf{r}_1, \mathbf{r}_2)$ is reformulated in dipole approximation:

$$W_M(\mathbf{r}_1, \mathbf{r}_2) = \frac{\mu_0}{4\pi}\left(\frac{\mathbf{M}_1\mathbf{M}_2}{|\mathbf{r}_1 - \mathbf{r}_2|^3} - 3\frac{(\mathbf{M}_1\mathbf{r}_1)(\mathbf{M}_2\mathbf{r}_2)}{|\mathbf{r}_1 - \mathbf{r}_2|^5}\right). \qquad (2)$$

Here $\mathbf{M}_1$ and $\mathbf{M}_2$ are magnetic moments of the interacting discs, μ_0 is a magnetic constant. The total magnetic moment of a layer can be considered as the sum of the core moment $\mathbf{M}_C$ (on figure it is directed to us or from us) and the effective moment of the vortex $\mathbf{M}_v$ (it lies in the plane of the layer and is shown by large white arrows): $\mathbf{M} = \mathbf{M}_C + \mathbf{M}_v$.

Figure 2 shows a couple of discs as an array element with a coordinate system. Next, we will use the following designations: $x_{n,m}$ and $y_{n,m}$ – the projection of the vortex core displacement from the center of the element $R_{n,m}$ in the projections on the coordinate axis. Then, for the vortex magnetic moment we can formulate: $\mathbf{M}_{v_{n,m}} = M_{v_{n,m}} q_{n,m}(-\mathbf{i}y_{n,m} + \mathbf{j}x_{n,m})/R_{n,m}$. The core magnetic moment is given by the equation: $\mathbf{M}_{C_{n,m}} = M_C p_{n,m}\mathbf{k}$.

It can be considered that any pair of elements participate in the following four interactions separately: "a vortex moment of the first disc/a vortex moment of the second disc" – W_{VV}, "a vortex moment of the first disc/core moment of the second disc" – W_{VC}, "a core moment of the first disc/a vortex moment of the second disc" – W_{CV} and "the core moment of the first disc / the core moment of the second disc" – W_{CC}. The sum of these values gives the total energy of the magnetostatic interaction: $W_M(\mathbf{r}_1, \mathbf{r}_2) = W_{VV} + W_{VC} + W_{CV} + W_{CC}$. Taking the selected designations into account, each of the terms in the magnetostatic energy of the interaction of the allocated disc and the disc with the number $\{n, m\}$ will be reformulated as:

$$W_{VV_{n,m}} = \frac{\mu_0 \chi_{0,0}\chi_{n,m} q_{0,0} q_{n,m}}{4\pi d^3\left(n^2 + m^2 + \left(\frac{\Delta z}{d}\right)^2\right)^{\frac{5}{2}}}\left[\left(-2n^2 + m^2 + \left(\frac{\Delta z}{d}\right)^2\right) y_{0,0}y_{n,m} + \right.$$
$$\left. + \left(-2m^2 + n^2 + \left(\frac{\Delta z}{d}\right)^2\right) x_{0,0}x_{n,m} + 3nm\left(y_{0,0}x_{n,m} + y_{n,m}x_{0,0}\right)\right]. \qquad (3)$$

Here Δz is the distance between magnetic discs on the axis z ($\Delta z = 0$ for the discs belonging to the same plane, $\Delta z = L$ for the discs in different layers (see figure 1)), $\chi_{0,0} = M_{v_{0,0}}/R_{0,0}$, $\chi_{n,m} = M_{v_{n,m}}/R_{n,m}$ – is the ratio of the vortex magnetic moment to the core rotation radius. It can be shown that the values χ are weakly dependent on the core displacement from the center of the disc (changes by no more than 15%). Similarly to (3), the values of $W_{CC_{n,m}}$, $W_{CV_{n,m}}$ and $W_{VC_{n,m}}$ are determined. For the total interaction energy we write down: $W_{M_{n,m}} = W_{VV_{n,m}} + W_{VC_{n,m}} + W_{CV_{n,m}} + W_{CC_{n,m}}$. For the Zeeman energy if the variable field is activated along the y, axis, we obtain: $W_{H_{n,m}} = -\chi_{n,m} q_{n,m} H(t) x_{n,m}$. Next, we assume that the field changes according to the law: $H(t) = H_M \exp(-i(\omega t + \delta))$. The core displacement

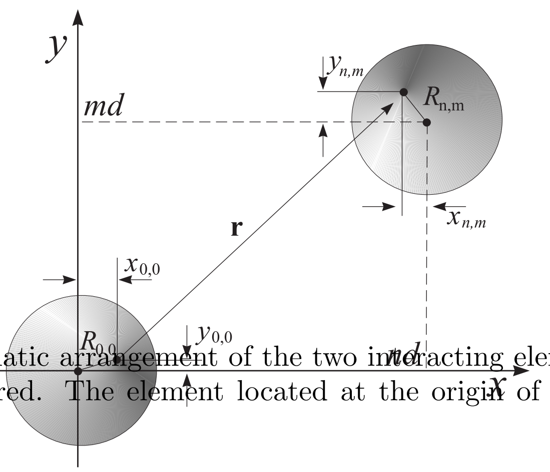

Figure 2. A schematic arrangement of the two interacting elements of the array. Using n and m discs are numbered. The element located at the origin of the coordinates is numbered as $[0, 0]$.

increases demagnetization energy W_B, as a result, there is a quasi-elastic returning force. For this energy let's use the equation: $W_{B_{n,m}} = \kappa R_{n,m}^2/2$. Here $\kappa = 40\pi M_S^2 b^2/(9R)$ [26, 27].

Then we can write Thiel equation system (1) for the disc located at the origin of the coordinates (with the number $\{0, 0\}$) in the projections to the coordinate system:

$$\begin{cases} -G_{0,0}v_{y_{0,0}} - Dv_{x_{0,0}} - \kappa x_{0,0} + \chi_{0,0}q_{0,0}H(t) - \\ -\frac{\partial}{\partial x_{0,0}} \sum\limits_n \sum\limits_m W_{M_{n,m}} = 0, \\ G_{0,0}v_{x_{0,0}} - Dv_{y_{0,0}} - \kappa y_{0,0} - \frac{\partial}{\partial y_{0,0}} \sum\limits_n \sum\limits_m W_{M_{n,m}} = 0. \end{cases} \quad (4)$$

We obtain similar pairs of equations for all elements of the array. For a complete description of the nature of the vortex core motion the equations for all elements should be combined into a single system. In general, it is not possible to obtain a solution. Therefore, we further consider some of the most interesting specific cases of the vortex polarities and chiralities' distribution in different discs.

3. Magnetic resonance in special cases

Let us consider the following model of a three-layer discs array where ferromagnetic layers belonging to the same disc have the same values p and q (let's call it "Model A"'). But the nearest neighbors can have different polarities and/or chiralities. This structure resembles a chess one, where discs of one type are located on white fields, and discs of another type another - on black ones.

It is natural to assume that the magnetization motion laws for the layers of the same type are the same and may differ only in addition to the phase, depending on the coordinates of the disc. Therefore, we choose the following equations as a trial solution. For the upper layers of the discs of the first type (see figure 1): $x(\mathbf{r}_{n,m}, t) = x_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t))$, $y(\mathbf{r}_{n,m}, t) = ipqy_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t))$. For the upper layers of the discs of the second type: $X(\mathbf{r}_{n,m}, t) = X_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t))$, $Y(\mathbf{r}_{n,m}, t) = iPQY_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t))$. Similarly, for the lower layers: $x'(\mathbf{r}_{n,m}, t) = x'_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t + \phi_0))$, $y'(\mathbf{r}_{n,m}, t) = ipqy'_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t + \phi_0))$, $X'(\mathbf{r}_{n,m}, t) = X'_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t + \phi_0))$, $Y'(\mathbf{r}_{n,m}, t) = iPQY'_0 \exp(i(\mathbf{k}\mathbf{r}_{n,m} - \omega t + \phi_0))$. Here ϕ_0 is a phase shift of the laws for the motion of the cores that belong to different layers, i – is an

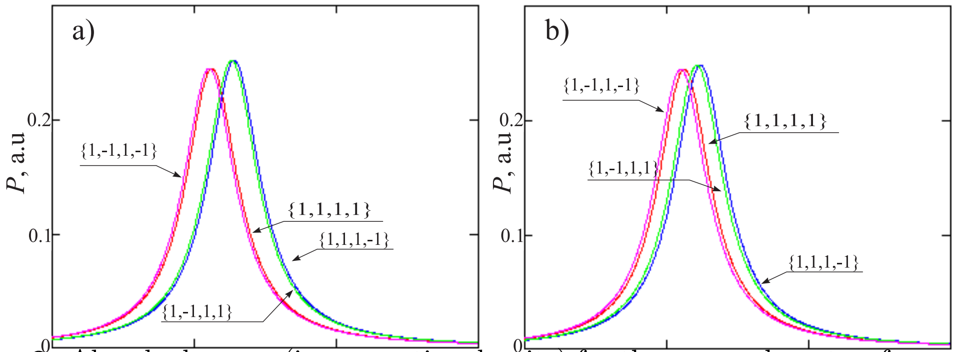

Figure 3. Absorbed power (in conventional units) for the array where two ferromagnetic layers of the same disc are of the same type - model A (figure a)). Figure b) shows the curves for the array where layers of the same disc are of different types - model B. In curly brackets there are combinations of polarities and chirality of magnetic layers $\{p, P, q, Q\}$.

imaginary unit, $\mathbf{k}$ is a wave vector, $x_{0n,m}$, $y_{0n,m}$, $X_{0n,m}$, $Y_{0n,m}$ are the maximum deviation of the vortex cores for the respective axes, p, P, q, Q are vortex polarities and chiralities of the first and second types of the layers respectively. After substituting the trial solution in the equation (4) for the discs of two types we obtain a solution for complex amplitudes and frequencies for normal modes ω. We argue similarly for the second case of the same "chess" distribution of polarity and chirality, but the layers of the same disc belong to different types (let's call it "Model B").

Let us consider the resonant properties of the array. To do this, we determine the total absorbed power of two array elements of two different types: $P(\omega) \sim D\omega^2 \left(|x_0|^2 + |y_0|^2 + |X_0|^2 + |Y_0|^2\right)$. Figure 3 shows the absorption curves based on the results of the solution (4) for the permalloy disc array in the long-wave limit ($\mathbf{k} = 0$) in the absence of a constant external field ($\mathbf{H}_0 = 0$). The array parameters are as follows: $b/R = 0.01$, $L/R = 4$, $d/R = 3$, the ratio of the core linear size to the radius of the disc δ_0/R=0.1. Permalloy magnetic parameters have been taken to draw the figures: $M_S = 800$ kA/m, $\alpha = 0.01$, $\gamma = 18$ MHz/Oe. Note that splitting of the resonance frequency in a) case is maximally manifested for the array where the discs differ by the sign of the parameter $\pi_T = pq$, but not separately by the signs of polarity or chirality. The difference between only polarities or chiralities in both cases does not lead to a noticeable additional removal of frequency degeneration. However, in b) case, the dipole interaction of the core magnetic moments plays a much larger role than in a) case.

The dependence of the frequency splitting value depending on the geometric parameters of the arrays such as the distance between the layers, the distance between the discs is of great interest. Figure 4 shows the difference of resonance frequencies depending on the distance between the ferromagnetic layers for a single disc, as a specific case $d/R \to \infty$. The figure proves the splitting associated with the difference of π_T decreases with the distance between the layers according to the law $\sim L^{-3}$, and the splitting due to the difference in the polarity of the cores according to the law $\sim L^{-5}$. This is explained by the corresponding dependences of the terms responsible for the interaction of the moments M_v and M_C between the layers in the energy $W_M(\mathbf{r}_1, \mathbf{r}_2)$ on L.

Figure 5 shows the dependence of $\Delta\omega_v$ on the distance between the layers in the disc and the distance between the disc centers of the considered array models. In model B there are such L and d ($L \approx d$), when the frequency splitting is minimal. A qualitative explanation for this may be as follows. Each magnetic layer is in a magnetic field created by its closest neighbors: the layer of its own disc and the layers of the neighboring discs. Moreover, at $L \approx d$ the effect of the neighboring discs' layers and the second layer of its own disc on a certain isolated magnetic

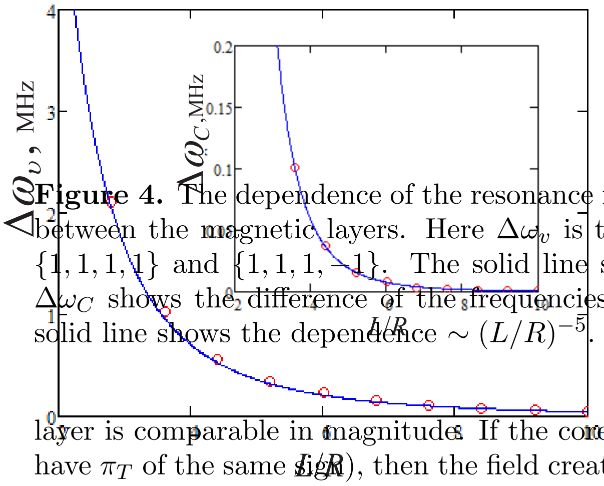

Figure 4. The dependence of the resonance frequency difference of a single disc on the distance between the magnetic layers. Here $\Delta\omega_v$ is the difference of the frequencies on the disc states $\{1,1,1,1\}$ and $\{1,1,1,-1\}$. The solid line shows the dependence $\sim (L/R)^{-3}$. The insertion $\Delta\omega_C$ shows the difference of the frequencies of the states $\{1,1,1,1\}$ and $\{1,-1,1,-1\}$. The solid line shows the dependence $\sim (L/R)^{-5}$.

layer is comparable in magnitude. If the cores of these layers rotate in the same direction (and have π_T of the same sign), then the field created by them in the center of the selected disc varies in a wide range, which leads to a shift in the resonance frequency in comparison with the case of non-interacting elements. If the cores of the nearest neighbors rotate in the opposite directions (this is possible only in model A and with different signs π_T), the resulting torque they created is small due to the compensation, and the frequency shift in this case compared to the frequency of the isolated layer is small. Therefore, according to figure 5 a), the difference between the frequencies of the states with the same and different neighbors' core rotation directions differs significantly and cannot coincide. In model B, the rotation direction of the nearest neighbors to the selected layer is always the same, so for any combination of polarity and chirality, when $L \approx d$ the resonance frequencies are comparable and the difference between them is close to zero and even changes sign. An important difference between models A and B is manifested in a significant difference in the splitting value (almost by an order of magnitude). But in any case, the effect of such a "thin" splitting due to the interaction of the core magnetic moments is much less than the effect of the interaction of the vortices' magnetic moments.

In the long-wave limit ($\mathbf{k} = 0$) and with $D/G \ll 1$ it is relatively easy to calculate the resonance frequencies. The frequencies of modes are determined from the zero determinant, built on the coefficients of the equation system (4). As a results we get the following equation:

$$\begin{aligned} \omega_{1,2}^2 = \frac{1}{2}\left(\kappa - s_{1x}\right)^2 \left(\frac{1}{G^2} + \frac{1}{G'^2}\right) + \frac{S_{1x}^2}{G^2 G'^2} \pm \\ \pm \left[\left(\frac{1}{2}\left(\kappa - s_{1x}\right)^2 \left(\frac{1}{G^2} + \frac{1}{G'^2}\right) + \frac{S_{1x}^2}{G^2 G'^2}\right)^2 - \frac{\left(\left(\kappa - s_{1x}\right)^2 - S_{1x}^2\right)^2}{G^2 G'^2}\right]^{\frac{1}{2}}. \end{aligned} \tag{5}$$

Here:

$$s_{1x} = \frac{\mu_0 \chi^2 d^2}{4\pi d^5}\left[\sum_{n\neq 0}\sum_{m\neq 0}\left(\frac{2m^2 - n^2}{(n^2+m^2)^{\frac{5}{2}}}\right) + \sum_{n}\sum_{m}\left(\frac{2m^2 - n^2 - l^2}{(n^2+m^2+l^2)^{\frac{5}{2}}}\right)\right], \tag{6}$$

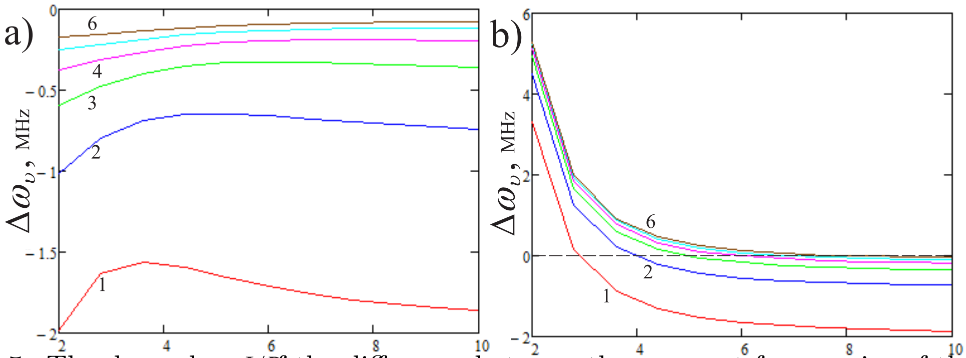

Figure 5. The dependence of the difference between the resonant frequencies of the disc array on the distance between the magnetic layers. Here the value $\Delta\omega_v$ is determined in the same way as in figure 4. The set of figures 1-6 are drawn for different d/R from 3 to 8 in increments of 1. Figure a) is drawn for model A, figure b) - for model B.

$$S_{1x} = \frac{\mu_0 q Q}{4\pi d^5} \sum_{n\neq 0} \sum_{m\neq 0} \left(\frac{\chi^2 d^2 (2m^2 - n^2)}{(n^2+m^2)^{\frac{5}{2}}} + \frac{M_C^2 (12n^2 - m^2)}{(n^2+m^2)^{\frac{7}{2}}} \right) +$$

$$+ \frac{\mu_0 p P}{4\pi d^5} \sum_{n} \sum_{m} \left(\frac{\chi^2 d^2 (2m^2 - n^2 - l^2)}{(n^2+m^2+l^2)^{\frac{5}{2}}} + \frac{3M_C^2 (18n^2 - m^2 - l^2)\left(n^2+m^2-4l^2\right)}{(n^2+m^2+l^2)^{\frac{9}{2}}} \right), \quad l = \frac{L}{d}. \tag{7}$$

The formula (5) is obtained in disregard of the dipole-dipole interaction of the core magnetic moments. Note that in the limit of $L/R \to \infty$ and $d/R \to \infty$ the interaction between the array elements is negligible ($s_{1x} = 0$, $S_{1x} = 0$), and the equation for the resonant frequencies take the obvious form: $\omega_1 = \kappa/G$, $\omega_2 = \kappa/G'$. This corresponds to two resonances of two sets of independent layers. In the absence of external constant field ($\mathbf{H}_0 = 0$) the gyrovectors' modules of the discs of different types are the same $G^2 = G'^2$. When the field is applied depending on the vortex core polarity the gyrovectors' values can increase or decrease. This leads to an additional removal of degeneration due to inequality $G^2 \neq G'^2$.

4. Conclusion

The analysis of the collective magnetization motion of interacting three-layer discs with the vortex structure showed that the removal of the resonance frequencies degeneration is mainly determined by the interaction of magnetic moments lying in the plane of the magnetic layers and arising from the displacement of the vortex core from the centers of the discs. The contribution of the dipole interaction of the vortex cores' magnetic moments is by an order of magnitude smaller and in most cases it can be neglected. An exception is the array where each disc has magnetic layers with different polarity and/or chirality values. In this model of the array with the comparable distances between the layers inside the disc and between the centers of the discs, the dipole-dipole interaction between the vortex cores' magnetic moments plays the main role in removing the degeneration of the resonant frequencies.

We note that in the array where the vortex cores of one disc layers rotate in opposite directions, the value of frequency splitting can be minimal at comparable distances between the magnetic layers inside of the disc and between the discs.

Acknowledgments

The reported study was funded by RFBR according to the research project no. 18-02-00161.

References

[1] Allwood D A, Xiong G, Faulkner C C, Atkinson D, Petit D, Cowburn R P, 2005 *Science* **309** 1688

[2] Hayashi M, Thomas L, Moriya R, Rettner Ch, Parkin S S P, 2008 *Science* **320** 209

[3] Scholz W, Guslienko K Yu, Novosad V, Suess D, Schrefl T, Chantrell R W, Fidler J,2003 *JMMM* **266** 155

[4] Jung H, Lee K S, Jeong D E, Choi Y S, Yu Y S, Han D S, Vogel A, Bocklage L, Meier G, Im M Y, Fischer P, Kim S K, 2011 *Sci. Rep.* **59** 1

[5] Belanovsky A D, Locatelli N, Skirdkov P N, Abreu Araujo F, Zvezdin K A, Grollier J, Cros V, Zvezdin A K, 2013 *Appl. Phys. Lett.* **103** 122405

[6] Locatelli N, Ekomasov A E, Khvalkovskiy A V, Azamatov Sh A, Zvezdin K A, Grollier J, Ekomasov E G, Cros V, 2013 *Appl. Phys. Lett.* **102** 062401

[7] Stebliy M E, Jain S, Kolesnikov A G, Ognev A V, Samardak A S, Davydenko A V, Sukovatitcina E V, Chebotkevich L A, Ding J, Pearson J, Khovaylo V, Novosad V, 2017 *Sci. Rep.* **7** 1127

[8] Ekomasov A E, Stepanov S V, Zvezdin K A, Ekomasov E G, 2017 *Phys. Met. Metallogr.* **118** 328

[9] Jain S, Novosad V, Fradin F Y, Pearson J E, Bader S D, 2004 *Appl. Phys. Lett.* **104** 082409

[10] Stebliy M E, Kolesnikov A G, Davydenko A V, Ognev A V, Samardak A S, Chebotkevich L A, 2015 *J. Appl. Phys.* **117** 17B529

[11] Vogel A, Drews A, Kamionka T, Bolte M, Meier G, 2010 *Phys. Rev. Lett.* **105** 037201

[12] Lee K S, Jung H, Han D S, Kim S K, 2011 *J. Appl. Phys.* **110** 113903

[13] Loubens G, Riegler A, Pigeau B, Lochner F, Boust F, Guslienko K Yu, Hurdequint H, Molenkamp L W, Schmidt G, Slavin A N, Tiberkevich V S, Vukadinovic N, Klein O, 2009 *Phys. Rev. Lett.* **102** 177602

[14] Kim P D, Orlov V A, Rudenko R Yu, Prokopenko V S, Orlova I N, Zamai S S, 2015 *JETP letters* **101** 562

[15] Han D S, Vogel A, Jung H, Lee K S, Weigand M, Stoll H, Schutz G, Fischer P, Meier G, Kim S K, 2013 *Sci. Rep.* **3** 2262

[16] Barman A, Barman S, Kimura T, Fukuma Y, Otani Y, 2010 *J. Phys. D: Appl. Phys.* **43** 422001

[17] Kim P D, Orlov V A, Rudenko R Yu, Prokopenko V S, Orlova I N, Kobyakov A V,2017 *JMMM* **440** 171

[18] Guslienko K Yu, Buchanan K S, Bader S D, Novosad V, 2005 *Appl. Phys. Lett.* **86** 223112

[19] Cherepov S S, Koop B C, Galkin A Yu, Khymyn R S, Ivanov B A, Worledge D C, Korenivski V, 2012 *Phys. Rev. Lett.* **109** 097204

[20] Hanze M, Adolff C F, Schulte B, Moller J, Weigand M, Meier G, *Sci. Rep.* **6** 22402

[21] Holmgren E, Bondarenko A, Ivanov B A, Korenivski V, 2018 *Phys. Rev. B* **97** 094406

[22] Stepanov S V, Ekomasov A E, Zvezdin K A, Ekomasov E G, 2018 *Physics of the Solid State* **60** 1055

[23] Ekomasov A E, Stepanov S V, Ekomasov E G, 2016 *Letters on materials* **6(1)** 46

[24] Thiele A, 1973 *Phys. Rev. Lett.* **30** 230

[25] Zvezdin A K, Zvezdin K A, 2010 *Bulletin of the Lebedev Physics Institute* **37** 240

[26] Guslienko K Yu, Ivanov B A, Novosad V, Otani Y, Shima H, Fukamichi K, 2002 *J. of Appl. Phys.* **91** 8037

[27] Guslienko K Yu, Han X F, Keavney D J, Divan R, Bader S D, 2006 *Phys. Rev. Lett.* **96** 067205