



# A First Order Phase Transition and Self-organizing States in Single-domain Ferromagnet

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## Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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## ABSTRACT

Analytical consideration of uni-axial single-domain ferromagnet during the first order phase transition induced by a magnetic field is performed. Field is directed along the symmetry axis antiparallel to initial magnetization direction. For samples of the flat shape, besides the known change of the magnetization direction on 180°, at definite relations between values of magnetic field, the magnetization and the anisotropy of a crystal, there is continuous spectrum of states with intermediate magnetization directions. In these states, a precession frequency  $\omega = 0$ . For samples of spherical shape, a process of the phase transition does not depend on the demagnetization field. At addition action of high frequency field perpendicular to the main magnetic field, there are dynamic equilibrium states, i.e. "self-organizing states" of ferromagnet, when the entropy increase connected with dissipation is compensated by the negative entropy flow due to the periodic field. It is shown that under these conditions, by varying the frequency of the periodic field, we can control the self-organising system, i.e. decrease or increase the system energy and, correspondingly, change the direction of magnetisation in ferromagnet.

**Keywords:** Ferromagnet; Magnetic field; Periodic magnetic field; First-order phase transition; Self-organizing system.

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### 1. INTRODUCTION

A very large number of phenomena and processes are known, which can be classified as "self-organizing systems" or "dissipative structures" [1-4]. Processes belonging to this category are, for example, sounding of wind and stringed musical instruments, a whistle sound, existence of proteins, development of plants, functioning of animals and humans. Generally, the life itself in all its forms is an example of such "self-organizing systems". It may seem surprising that, unlike nature, the man himself was able to invent so limited number of such systems. This could include such examples that can be reproduced on the laboratory table: the chemical "Belousov-Zhabotinsky reaction" [5,6], "Benar cells" at liquid boiling [7]. Precessing ball solitons during the magnetic phase transition in ferromagnet could also be considered as "classical" self-organizing system or self-organizing states (SOS) [8]. Some of these systems are structures periodic in space or in time. Others are more complex. But the common feature of all these processes is that the loss of energy in the system associated with dissipation, is fully offset by the influx of energy from external sources, i.e. inflow of entropy due to the dissipation is compensated by the negative flow of entropy due to the coupling to an external source.

Similar system existing at the expense of compensation of dissipation loss of energy by the influx of energy from external sources (SOS), is considered in this paper.

It should be noted that the effects of SOS the self-organizing states, after the works [1-3], been actively studied in the subsequent years. We note here only a few works related to the effect of the so-called self-organized criticality (SOC) [9-19], with the appropriate addition of a list of references.

In this article, the SOS arising at the first order phase transition in uni-axial single-domain ferromagnet under the action of a magnetic field directed along the symmetry axis are considered.

At first, in the second part of this article, peculiarities of the first-order phase transition in a single-domain ferromagnet has been analyzed. The sole purpose of the single-domain condition for this article is to exclude extraneous sources of nucleation of a new phase, such as domain walls or external boundaries of the crystal. (For example,  $2\pi$ -degree boundaries themselves are

nuclei of a new phase.) In such conditions, the phase transition under the action of the magnetic field is determined by the process of coherent magnetization change.

In the third part of the article, the changes in the phase transition of ferromagnet under the action of additional high frequency magnetic field perpendicular to the main field have been considered. In such conditions, SOS of ferromagnet arise. Features of these states have been investigated.

### 2. PHASE TRANSITION IN SINGLE-DOMAIN FERROMAGNET

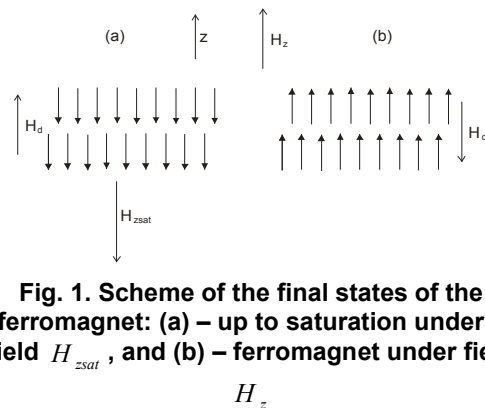
Analysis scheme of ferromagnetic is presented in Fig. 1. Initially, the sample is magnetized to saturation along the direction (-z) – see in Fig. 1(a). For this it is necessary that the applied field  $H_{dsat} < 0$  was in absolute value greater than arising in the sample the demagnetizing field, i.e.  $|H_{zsat}| > H_d$ . Fig. 1(b) shows the ferromagnet magnetized to saturation along the axis (z) under the action of the field  $H_z > |H_d|$ . Thus, Fig. 1 corresponds to the final states of the ferromagnet. In a given article the process of (a) → (b) transition is analyzed.

To analyse magnetic phase transition in the ferromagnet with uni-axial anisotropy, we use the Landau–Lifshitz equation [20] in the Gilbert form:

$$\frac{\partial \mathbf{m}}{\partial t} = \gamma \mathbf{m} \times \frac{\partial W}{\partial \mathbf{m}} + \kappa \left( \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} \right) \quad (\kappa > 0) \quad (1)$$

and the following expression for the density of energy:

$$W = \frac{K_1}{2} |m_{\perp}|^2 - m_z H_z + E_d \cdot \quad (2)$$



**Fig. 1. Scheme of the final states of the ferromagnet: (a) – up to saturation under a field  $H_{zsat}$ , and (b) – ferromagnet under field  $H_z$**

$H_z$  is an external magnetic field directed along the anisotropy axis  $Z$  ( $H_z > 0$ );  $K_1 > 0$ ,  $\gamma = 2\mu_B/\hbar$ ;  $\mathbf{m}$  is a non-dimensional vector of ferromagnetism equal (in the absolute value) to 1,  $m_\perp = m_x + im_y$ , initial magnetization is along the (-z) direction, in present paper  $m_z = \pm\sqrt{1-|m_\perp|^2}$ ;  $E_d$  is energy of demagnetization for the sample. We consider only two cases: Sample of the flat shape, moreover, the thickness of such sample is much smaller than the dimensions in other directions and the symmetry axis is perpendicular to the plane of a sample; in the second case the sample is of the spherical form.

## 2.1 Sample of the Flat Shape

In this case the energy of demagnetization is

$$E_d = 4\pi M_0 m_z^2 \quad (3)$$

where  $M_0$  is the magnetization of a crystal. In such case, equation (1) can be written as:

$$i\frac{\partial m_\perp}{\partial \tau} = -hm_\perp - (1-2h_d)m_z m_\perp + \kappa\left(m_\perp\frac{\partial m_z}{\partial \tau} - m_z\frac{\partial m_\perp}{\partial \tau}\right) \quad (4)$$

Here the differentiation is carried out with respect to the dimensionless time  $\tau = 2\mu_B K_1 \hbar^{-1} t$ ;  $h = H_z/K_1$ ; parameter of demagnetization field  $h_d = 4\pi M_0/K_1$ .

The solutions of Eq. (4) have the following form:

$$m_\perp(\tau) = p(\tau)e^{i\omega(\tau)\tau} \quad (5)$$

From (4), the equations, which define the correspondence between  $m_z$  and  $\omega$  and the time changes of these parameters are the following:

$$(1-2h_d)m_z + h = \omega(1+\kappa^2), \quad (6)$$

(here  $\kappa^2 \ll 1$ , therefore we neglect this value.)

$$\frac{dm_z}{d\tau} = \kappa\omega(1-m_z^2) \quad (7)$$

For the energy density relative to initial state we have:

$$e_{fl} = (1-2h_d)\frac{(1-m_z^2)}{2} - h(1+m_z), \quad (8)$$

and

$$\frac{de}{d\tau} = -\kappa\omega^2(1-m_z^2) \quad (9)$$

In what follows we consider the process of changing of parameters of a ferromagnet in the transition from the initial state when  $m_z = -1$ . In this process, the energy decreases, respectively  $m_z$  increases from the initial value, and precession frequency also changes. The character of changes in a ferromagnet during the phase transition depends strongly on the shape of the sample.

In Figs. 2 for the sample of flat form, limit values of main parameters are given as functions of  $h_d$  value for different values of acting field  $h$ . Initial energy is  $e_1 = 0$ , final energy is  $e_2$ . Correspondingly, we have initial  $m_{z1} = -1$  and final  $m_{z2}$ , initial  $\omega_1$  and final  $\omega_2$ . These limiting values are determined from equations (6) and (8).

If  $h > 0$ , there are two ranges for limit values of the parameters. In the first of them, a completed reorientation (CR) takes place if

$$0 \leq h \leq (2h_d - 1): m_{z2} = +1, \omega_1 = h - (1 - 2h_d), \omega_2 = h + (1 - 2h_d), e_2 = -2h. \quad (10)$$

In the second range, the transitions into intermediate states, where  $m_{z2} < (+1)$ , occur if

$$h \geq (2h_d - 1): m_{z2} = -h/(1-2h_d), \omega_1 = h - (1-2h_d), \omega_2 = 0, e_2 = \frac{(1-h-2h_d)^2}{2(1-2h_d)} \quad (11)$$

If  $h \leq 0$ , there is not completed phase reorientation, but only the transitions into intermediate states. In latter case, the limit parameters, as in (11), are the following:

$$\begin{aligned} m_{z2} &= -h/(1-2h_d), \quad \omega_1 = h - (1-2h_d), \\ \omega_2 &= 0, \quad e_2 = \frac{(1-h-2h_d)^2}{2(1-2h_d)} \end{aligned} \quad (12)$$

As can be seen, for a given value of a field, completed phase reorientation occurs only at sufficiently small value of  $h_d$ . At a higher value of  $h_d$ , the final value  $\omega_2 = 0$  and as can be seen in these Figs. 2, the values  $m_{z2} < (+1)$ . The field value becomes insufficient to overcome the demagnetizing fields. Fig. 2(e) corresponds to  $h = 0$ , i.e. when the field  $H_{zsat} < 0$ , which magnetizes the sample to saturation, is simply removed. In this case  $m_{z2} = 0$ . In this case the magnetization in final state is perpendicular to the axis of anisotropy.

Note that for multi-domain sample, zero magnetic field corresponds to the state, when the magnetic moments of domains are directed with equal probability along or against the anisotropy axis and averaged  $m_z = 0$ , as  $m_{z2}$  in our case.

If the current field is negative, i.e.  $h < 0$ , the value  $m_{z2} < 0$ , as is shown in Fig. 2(f).

So there are continuous spectrum of intermediate states, as though frozen states of a ferromagnet. System tends in each of these "frozen states" (FS) asymptotically, wherein the precession frequency  $\omega \rightarrow 0$ .

In Fig. 3, in dependence of the critical field on the parameter of demagnetization field, the boundaries of considered above areas are shown.

Note that the expressions (10), (11) and (12) are also valid for the phase transition in the case of a ferromagnet with the easy magnetization plane, i.e. at  $K_1 < 0$ .

Let us consider the time dependence of parameters during the phase transition. In correspondence with equations (6) and (7), the time dependence of  $m_z$  can be obtained:

$$\tau = \frac{1}{\kappa} \int_{m_{z0}}^{m_z} \frac{dm_z}{(1-m_z^2)[h + (1-2h_d)m_z]} \quad (13)$$

In Figs. 4, the time dependences of main parameters for flat sample are presented, according to (13) and (6), (8). In all these and in subsequent examples, the dissipation parameter is  $\kappa = 5 \times 10^{-4}$ . These time changes correctly correspond to dependences of the type shown in Figs. 2.

For a given  $h_d$  value, a minimum field, in which a change in orientation occurs, is:  $h_{\min} = 1 - 2h_d$ . If for flat sample  $h_d = 1.2566$ , i.e.  $M_0/K_1 = 0.1$ , this field equals to  $h_{\min} = -1.513274$  (an approach to this value can be seen in Fig. 4(d)).

In Fig. 5, field dependences of energy and  $m_{zFS}$  parameter of FS for flat sample at  $h_d = 1.2566$  are presented.

## 2.2 Sample of a Spherical Shape

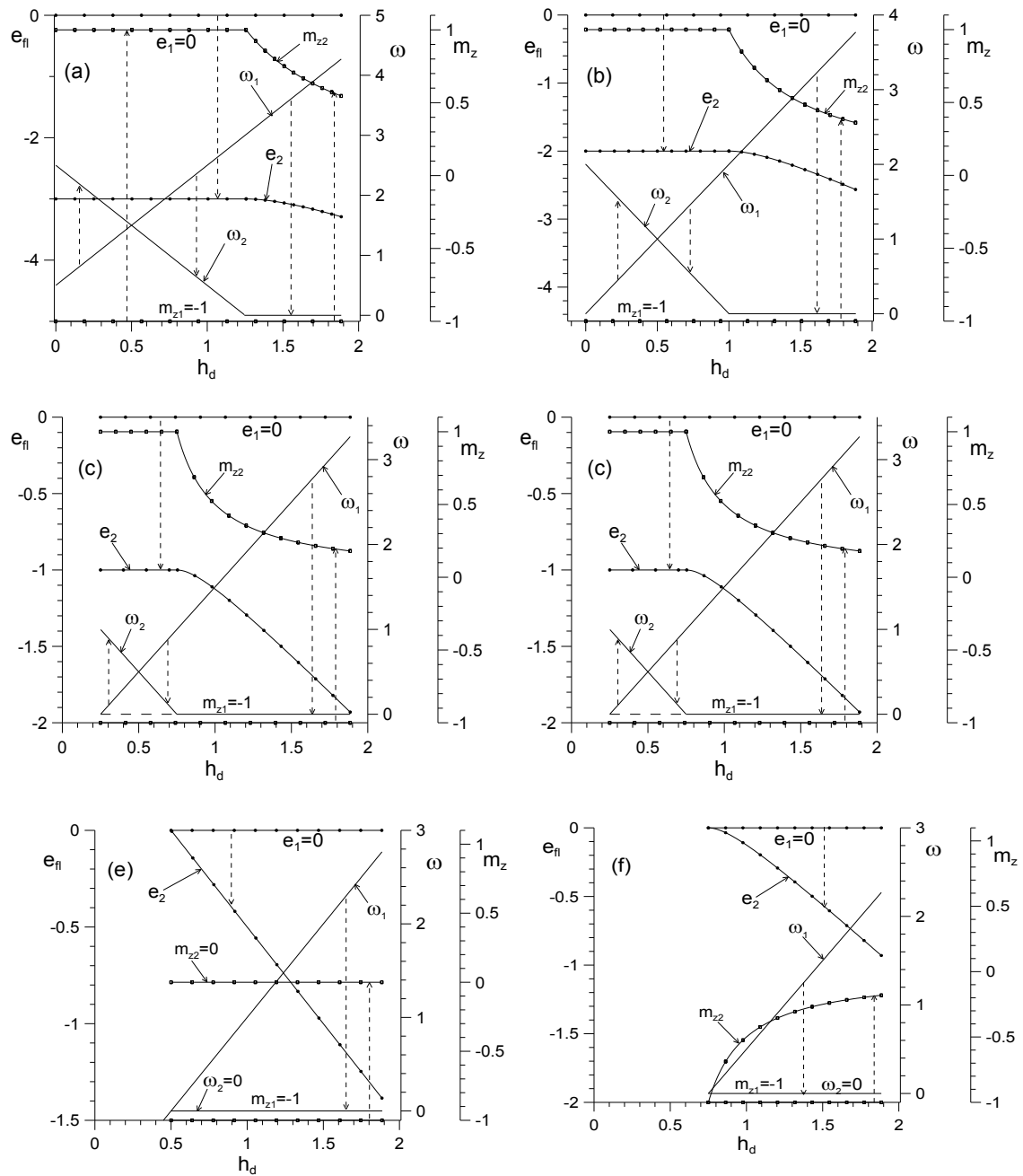
In this case

$$E_d = N_{dz}M_0m_z^2 + N_{d\perp}M_0|m_{\perp}|^2 = \frac{4\pi}{3}M_0, \quad (14)$$

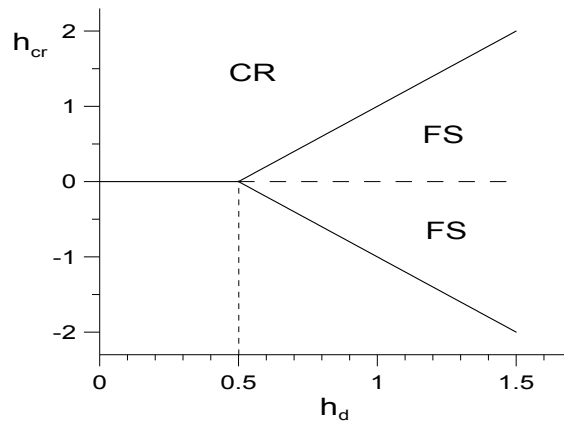
i.e. for spherical shape of the sample, the parameters  $m_z$ ,  $\omega$  and  $e$  and their time changes do not depend on the  $h_d$  value, but the value of energy contains a constant component

$\left( + \frac{4\pi M_0}{3K_1} \right)$ . Therefore, instead of (6) and (8), we have the following:

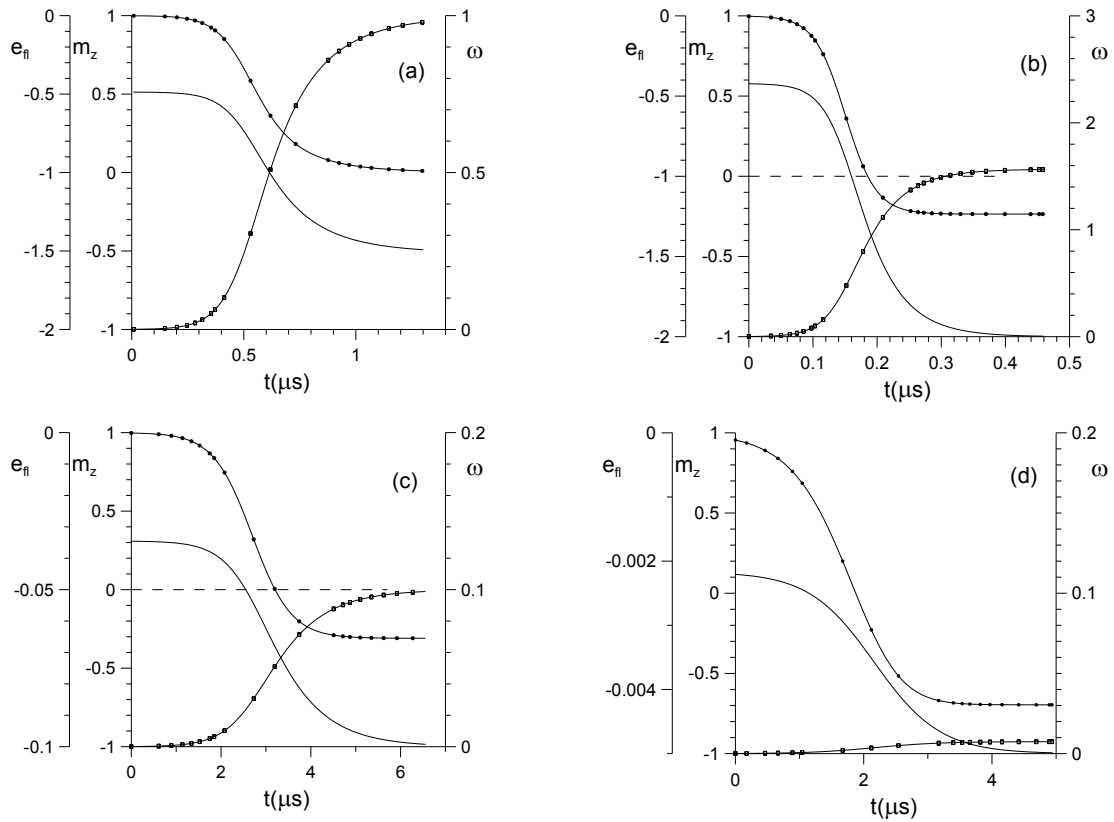
$$m_z + h = \omega(1 + \kappa^2) \quad (\kappa^2 \ll 1), \quad (15)$$



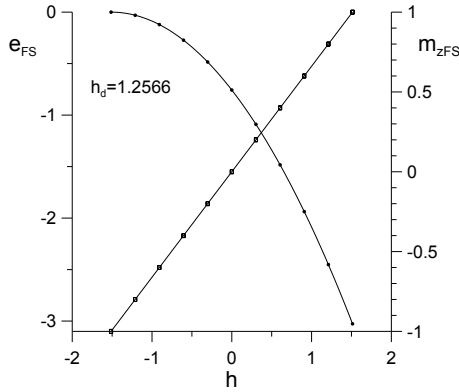
**Figs 2. Limit values of main parameters for flat sample vs demagnetisation field (energy is denoted by filled circles,  $m_z$  value – empty rectangle, frequency – continuous line): (a)  $h = 1.5$ , (b)  $h = 1$ , (c)  $h = 0.5$ , (d)  $h = 0.1$ , (e)  $h = 0$ , (f)  $h = -0.5$**



**Fig. 3.** The dependence of the critical field on the parameter of demagnetization field showing the boundaries between areas with different characters of the phase reconstruction in the case of the thin flat sample



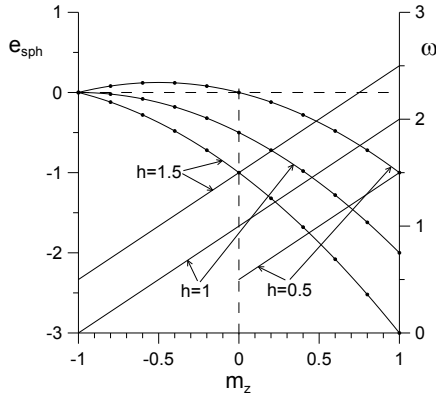
**Figs. 4.** The time dependences of  $e_{fl}$ ,  $m_z$  and  $\omega$  for flat sample: (a)  $h = 0.5$ ,  $h_d = 0.6283$  ( $M_0/K_1 = 0.05$ ); (b)  $h = 0.1$ ,  $h_d = 1.6336$  (**0.13**); (c)  $h = 0$ ,  $h_d = 0.5655$  (**0.045**); (d)  $h = -1.4$ ,  $h_d = 1.2566$  (**0.1**)



**Fig. 5. Field dependences of energy (full circles) and  $m_z$  parameter (empty rectangles) of FS for flat sample at  $h_d = 1.2566$ . Here, the frequency for all states is  $\omega \rightarrow 0$**

$$e_{sph} = \frac{(1-m_z^2)}{2} - h(1+m_z) \quad (16)$$

In Fig. 6, dependences of energy and frequency on  $m_z$  at three field values,  $h = 0.5, 1.0$  and  $1.5$ , for spherical sample are presented, in correspondence with (15) and (16). Of course, the transition from  $m_z = -1$  to  $m_z = +1$  is possible only if  $h \geq 1$ .



**Fig. 6. Dependences of energy and frequency on  $m_z$  at three field values for spherical sample**

In the case of spherical sample, according to (7) and (14):

$$\tau = \frac{1}{\kappa} \int_{m_{z0}}^{m_z} \frac{dm_z}{(1-m_z^2)(h+m_z)} \quad (17)$$

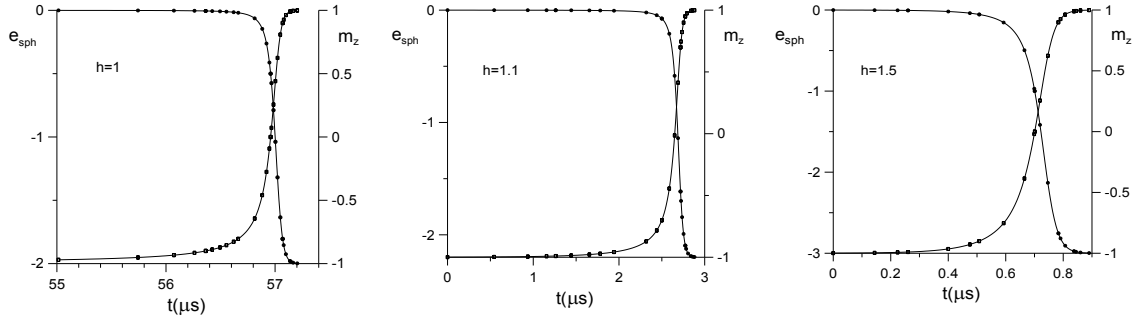
In Fig. 7, the time dependences of energy and  $m_z$  value are shown at  $h = 1, 1.1$  and  $1.5$  for spherical sample. In these cases the change of  $m_z$  is from  $(-0.999)$  to  $(+0.999)$ .

Reorientation of the magnetization in single-domain ferromagnets under the action magnetic field pulses had been studied in many papers. These studies were conducted primarily in connection with the creation of high speed memory elements. We refer here just to a few articles related to the issues addressed in this paper: [21-27]. Single-domain ferromagnets (Stoner particles) on the basis of numerical solutions of Landau-Lifshitz were considered in those studies. The different directions of the external magnetic field was taken into account, but the symmetric case was not considered there, when the field is acting along the symmetry axis of the crystal with uniaxial symmetry. In addition, calculations were made at conditions corresponding to high values of dissipation parameter  $\kappa \approx 1$  in equation Landau-Lifshitz, i.e. in the area of Stoner-Wohlfarth limit [21]. In this region, the time by coherent switching takes a minimum value in the range close to  $10^{-9}$ s.

In the next part of this article, a particular case for the analysis of self-organizing states is considered, when the magnetic field is directed along the axis of anisotropy. Such geometry allows to enter the frequency of precession relatively to the axis of symmetry and enables an exact analytical consideration of the phase transition (as opposed to numerical calculations in [21-27]). Moreover, some features of reorientation (see above) not detected in [21-27] have appeared.

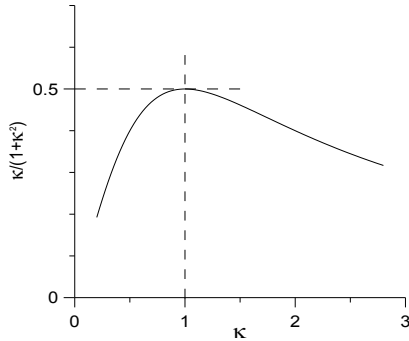
Comparing our results with [21-27], we see that by taking into account  $\kappa^2$  relative to a unit in the equation (15), we have instead of (17) the ratio (in this case for the spherical sample):

$$\tau = \left( \frac{1}{\kappa} + \kappa \right) \int_{m_{z0}}^{m_z} \frac{dm_z}{(1-m_z^2)(h+m_z)} \quad (18)$$



**Fig. 7. Time dependences of energy and  $m_z$  for spherical sample: (a)  $h = 1$ , (b)  $h = 1.1$ , (c)  $h = 1.5$ . All changes are from  $m_{z1} = -0.999$  to  $m_{z2} = +0.999$**

In Fig. 8, dependency of  $\kappa/(1+\kappa^2) \equiv \left(\kappa + \frac{1}{\kappa}\right)^{-1}$  on  $\kappa$  is shown. It can be seen that the rate of change of parameters of the ferromagnet, i.e. a speed of coherent switching is maximum at  $\kappa = 1$ , in corresponding with [21].



**Fig. 8. Dependency of effective parameter  $\kappa_{eff}$  of coherent switching on  $\kappa$**

Using the value  $\kappa_{eff} \equiv \frac{\kappa}{1+\kappa^2} = 0.5$  corresponding to the maximum speed, instead of the value  $\kappa = 0.5 \times 10^{-3}$  taken from magnetic resonance investigations, as it is in Fig. 4 and Fig. 7, we obtain the same curves for parameters variation but with the transformation  $t(\mu s) \rightarrow t(ns)$  of the timeline, i.e. in accordance with [21 - 27] about quick coherent switching in ferromagnets.

### 3. SELF-ORGANIZING STATES

Using an additional external high frequency magnetic field, we can fix the precession

frequency and thereby stabilize the intermediate states of the ferromagnet. If the added periodic field is perpendicular to a main field, and

$$\mathbf{H}_{\perp} = K_{\perp} h_{\perp} e^{i\omega_0 \tau}, \quad (19)$$

we can express the magnetic component of magnetization in the form

$$m_{\perp}(\tau) = p(\tau) e^{i(\omega_0 \tau - \beta(\tau))} \quad (20)$$

i.e. the precession phase of magnetic moments differs from the phase of periodic field. In this case, the equations for  $m_z$  in the case of flat sample take the following form:

$$\begin{aligned} \left(1 - n_z^2\right) \left[ (1 - 2h_d) m_z + h \left( \omega_0 - \frac{d\beta}{d\tau} \right) \right] = +\kappa \frac{dm_z}{d\tau} \\ + h_{\perp} m_z \sqrt{1 - n_z^2} \cos \beta \end{aligned} \quad (21)$$

$$\frac{dm_z}{d\tau} = \sqrt{1 - m_z^2} \left[ \kappa \sqrt{1 - m_z^2} \left( \omega_0 - \frac{d\beta}{d\tau} \right) - h_{\perp} \sin \beta \right] \quad (22)$$

From (8), we obtain expressions for energy density relative to the initial state, together with the energy of interaction with the periodic field (see, for example, [8]):

$$\begin{aligned} e_0 = (1 - 2h_d) \frac{(1 - m_z^2)}{2} - h(1 + m_z) - \\ h_{\perp} \sqrt{1 - m_z^2} \cos \beta \end{aligned} \quad (23)$$

and for the change of this energy connected with dissipation and the action of external periodic field:



$$\frac{de}{d\tau} = -\kappa \left[ \frac{1}{1-m_z^2} \left( \frac{dm_z}{d\tau} \right)^2 + \left( \omega_0 - \frac{d\beta}{d\tau} \right)^2 \right] + h_{\perp} \sqrt{1-m_z^2} \omega_0 \sin \beta \quad (24)$$

The equations (19) – (24) constitute a complete description of the system, including its time transformation. However, in the present paper we consider only dynamic equilibrium state of ferromagnet, i.e. when the decrease of energy caused by dissipation is compensated by energy flow from the external periodic field, i.e.  $de_0(\tau)/d\tau = 0$ . Furthermore, in this case  $dm_{z0}/d\tau = 0$  and  $d\beta_0/d\tau = 0$ . Therefore, for this equilibrium state of ferromagnet, i.e. for self-organizing state (SOS), we obtain the following expressions:

$$\frac{dm_z}{d\tau} = \sqrt{1-m_{z0}^2} (\kappa \omega_0 \sqrt{1-m_{z0}^2} - h_{\perp} \sin \beta_0) = 0, \quad (25)$$

$$\frac{de_0}{d\tau} = -\omega_0 \sqrt{1-m_{z0}^2} (\kappa \omega_0 \sqrt{1-m_{z0}^2} - h_{\perp} \sin \beta_0) = 0. \quad (26)$$

From these expressions, we obtain the relation:

$$\sin \beta_0 = (\kappa \omega_0 \sqrt{1-m_{z0}^2} / h_{\perp}). \quad (27)$$

Correspondingly, the corrected equation for SOS takes the following form (instead of (6)):

$$\sqrt{1-m_{z0}^2} [(1-2h_d)m_{z0} + h - \omega_0] = m_{z0} \sqrt{h_{\perp}^2 - \kappa^2 \omega_0^2 (1-m_{z0}^2)}. \quad (28)$$

From equations (25) and (26), it can also be seen that the energy compensation and consequently the origin of SOS is possible only if

$$h_{\perp} \geq h_{\perp \min} = \kappa \omega_0 \sqrt{1-m_{z0}^2}. \quad (29)$$

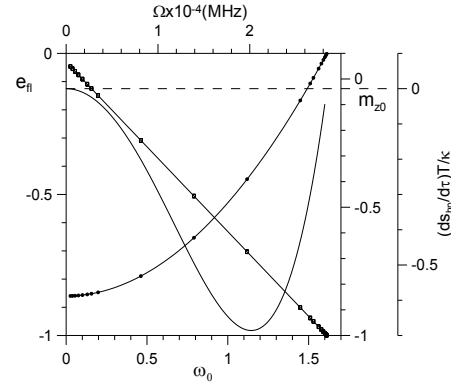
For such a system, the entropy increase connected with dissipation is compensated by the negative flow of the entropy, which is the result of external periodic field. It can be expressed as follows:

$$\frac{ds}{d\tau} = \frac{ds_{diss}}{d\tau} + \frac{ds_{h_{\perp}}}{d\tau} = 0, \quad (30)$$

Where

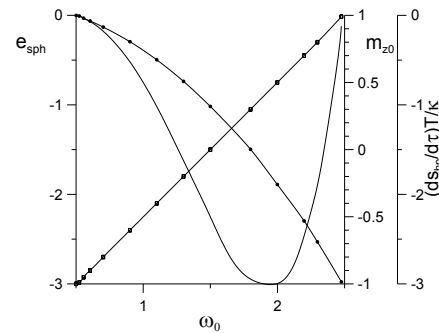
$$\frac{ds_{h_{\perp}}}{d\tau} = -\frac{ds_{diss}}{d\tau} = \frac{1}{T} \frac{de_{diss}}{d\tau} = -\frac{\kappa \omega_0^2}{T} (1-m_z^2) < 0 \quad (31)$$

Examples of the frequency dependences of energy, value of  $m_{z0}$  and the change in entropy for the flat and spherical samples in SOS at  $h_{\perp} = 2 \times 10^{-3}$  are presented in Fig. 9 and Fig. 10. It should be noted that in the examples shown, the quantities  $e_0(\omega_0)$  and  $m_{z0}(\omega_0)$  differ very little, not more than 1-2%, from such values in the absence of  $\mathbf{H}_{\perp}$  field.



**Fig. 9. The frequency dependences of energy,  $m_{z0}$  value and the negative flow of the entropy due the external periodic field in SOS for flat sample, at  $h = 0.1$ ,  $h_d = 1.2566$ ,  $h_{\perp} = 0.002$ . In this case maximum of  $m_{z0}$ , at  $\omega_0 = 0$ , equals approximately (+0.05)**

In Fig. 11, the frequency dependence of minimum amplitude of periodic field  $h_{\perp}$  for SOS in flat sample, according to (27), is shown.



**Fig. 10. The frequency dependences of energy,  $m_{z0}$  value and the negative flow of the entropy due the external periodic field in SOS for spherical sample, if  $h = 1.5$ ,  $h_{\perp} = 0.002$**

However, in addition to obtaining SOS, you can change these states. Assume that the precession frequency varies slowly enough. In this case, in Equations (24) - (27) instead of  $\omega_0$ , we have

$(\omega_0 + \frac{d\omega}{dt}t)$ , where  $\omega_0$  is the initial frequency.

We can in all equations simply replace  $(\omega_0 + \frac{d\omega}{dt}t)$  on  $\omega_0(t)$ . In result, we obtain the characteristics of self-organising state which depend on time, i.e.  $e_0(t)$ ,  $m_{z0}(t)$  and

$$\sin\beta_0(t) \cong \kappa\omega_0(t)h_{\perp}^{-1}\sqrt{1-\frac{(\omega_0(t)-h)^2}{(1-2h_d)^2}} \quad (32)$$

- in the case of flat sample, and

$$\sin\beta_0(t) \cong \kappa\omega_0(t)h_{\perp}^{-1}\sqrt{1-(\omega_0(t)-h)^2} \quad (33)$$

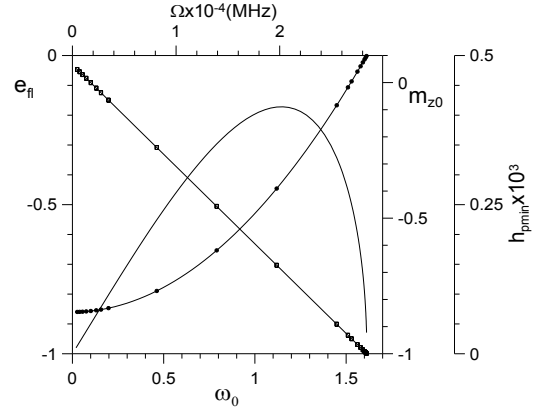
- for spherical sample.

and, correspondingly, the change of entropy depends on the time too, according to Fig. 9 and Fig. 10. As a result, changing the frequency of external field, and consequently the energy

$e_{\perp}(t) = h_{\perp}\sqrt{1-m_{z0}^2}\cos\beta_0$  too, we can control the self-organising system, and not only reduce the system energy, but also increase it, decreasing  $m_{z0}$  value and returning the ferromagnetic in direction to initial phase state.

Further, we can compare the soliton SOS described in [8] with those presented here. Precessing ball solitons of paper [8] may also occur at the first-order transition in a ferromagnet. But their origin is spontaneous and is connected with significant fluctuations in the system configuration. Moreover, the probability of such SOS is strongly dependent on the temperature and the distance from the bifurcation point, in which their energy relative to the initial state is zero.

The SOS presented here, in contrast to [8], are not localized in space, but distributed throughout all volume of the crystal; their appearance is not associated with fluctuations, they do not have a random, probability character, and do not depend on temperature.



**Fig. 11. The frequency dependences of energy,  $m_z$  value and minimum amplitude of periodic field  $h_{\perp}$  for SOS in the case of flat sample, at  $h = 0.1$ ,  $h_d = 1.2566$**

#### 4. CONCLUSION

1. A single-domain ferromagnet with uniaxial anisotropy at the first-order phase transition under the action of a magnetic field directed along the anisotropy axis has been considered. Analytical analysis of the entire process of phase transition is performed for two configurations of crystalline samples: a thin flat sample with the anisotropy axis perpendicular to the surface of the plane, and the spherical shape of the sample.
2. The two cases of phase reconstruction are significantly different. In the first case, the phase transition depends essentially on the relation between the sample magnetization and anisotropy of the crystal and thus of the demagnetisation field parameter. There are two areas for demagnetisation field parameter. In the first of these areas, a "full" phase reconstruction is carried out in the crystal, i.e. a change in the magnitude  $m_z$  from  $m_{z1} = -1$  to  $m_{z2} = +1$ . In the second area, "unfinished" phase reconstruction is carried out, i.e. a transition in "frozen states" (FS) where  $m_{z2} < 1$ . These states have a continuous spectrum, the precession frequency is  $\omega \rightarrow 0$  for each such state.
3. A phase transition for sample of spherical form is described in the same variables as

for flat sample, but in this case the process of transition does not depend on the demagnetization field. In spherical samples, FS does not arise.

4. At simultaneous action of high-frequency magnetic field perpendicular to the direction of the main field, a self-organizing state (SOS) of a ferromagnetic arises, in which the ferromagnetic is in dynamic equilibrium. In this equilibrium state, the entropy increase connected with dissipation is compensated by the negative flow of the entropy that is the result of external periodic field.
5. Relations between the main parameters of SOS, i.e. between the values of fields, energy, precession frequency, and the angle between ferromagnetism vector and the anisotropy axis, have been analysed.
6. Changing the frequency of the alternating field, and thereby, the flow of the entropy, can be a continuous method to change all parameters of SOS, including reduction or increase of the system energy.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

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