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Resonant Dynamics of the Domain Walls in Multilayer Ferromagnetic Structure

Evgeniy G. Ekomasov[a], Azamat M. Gumerov[b *], Ramil R. Murtazin[c], Roman V. Kudryavtsev, Andrey E. Ekomasov and Natalya N. Abakumova

Bashkir State University, Russia, 450076, Ufa, Z. Validi St., 32

[a]ekomasoveg@gmail.com, [b]bgu@bk.ru, [c]murtazinrr@mail.ru

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Abstract. The domain walls dynamics and generation and evolution of magnetic inhomogeneities of soliton type, emerging in a thin flat layer with the parameters of the magnetic anisotropy, which are different from other two thick layers of the five-layer ferromagnetic structure, were investigated.

Introduction

Multilayer magnetic structures have been widely studied recently in connection with the opportunity of their practical application [1]. Frequently, these are periodically alternating layers of two materials, including nanoscale, with different physical properties. There are two approaches, used when studying the dynamics of linear and nonlinear waves of magnetization, which propagate perpendicularly to layers. In the first approach, often used to study the dynamics of spin waves, to describe the dynamics of magnetization in a layer, the Landau–Lifschitz equation is used with constant material parameters; in this case the fulfillment of certain boundary conditions is required at the layers interfaces [2]. In the second approach, the presence of layers that differ from each other in values of one or several magnetic parameters is taken into account via the spatial modulation of the magnetic parameters of the material (see, e.g., [3, 4]). The presence of local and periodic one-dimensional spatial modulation of the magnetic parameters of material (SMMP) influences on the propagation, spectrum, and damping of spin waves, and the high-frequency properties. Under certain conditions, the study of the one-dimensional dynamics of domain walls (DWs) leads to the problem (interesting from a mathematical point of view) of finding a solution to an equation of the sine-Gordon type with variable coefficients, which is important for many fields of contemporary physics [5]. Due to the complexity of the problem, the researchers considered, as a rule, the modulation of only individual parameters of the magnetic system. One often took into account, for example, the magnetic anisotropy modulations for the case of two- and three-layer magnetic, and the problems were studied both with analytical and numerical methods [6–7]. There was shown that the presence of a thin layer with the parameters of the magnetic anisotropy, less than in neighboring layers, may lead, for example, to the appearance of the nucleus of a new magnetic phase, to new dynamic effects. In this paper we investigated excitation conditions of localized high-amplitude nonlinear magnetic waves of soliton and breather types in five-layer ferromagnetic.

DW Dynamics and magnetic breathers excitation

Let us consider a five-layer ferromagnetic structure that consists of three thick identical layers separated by two thin layers with a different value of the anisotropy parameters, which we assume to be functions of the coordinate x oriented perpendicular to the interface between the layers. We will further study the dynamics of a DW lying in the plane yz. Usually, when solving dynamic problems, it is suitable to go to spherical coordinates of the normalized magnetization vector $\mathbf{m}$ ($\sin\varphi, \cos\varphi \sin\theta, \cos\varphi \cos\theta$), where $0 \le \theta \le 2\pi$ – is the angle in the plane yz between the direction of the vector of the magnetic moment and easy axis (axis Oz); $-\pi/2 < \varphi < \pi/2$ – is the angle that describes the deviation of $\mathbf{m}$ from the DW plane. We assume that there is no damping in the system. Taking into account the energy density of the exchange interaction, anisotropy and $\varphi << 1$ [1], one-dimensional equation of motion for the magnetization in the angular variables can be represented in the following dimensionless form [6]:

$$\frac{\partial^2\theta}{\partial x^2}-\frac{\partial^2\theta}{\partial t^2}-\frac{1}{2}K(x)\sin 2\theta=0 \tag{1}$$

where, $K(x) = K(x) / K_0$ are the functions that define the spatial modulation of the anisotropy constant; K_0 are the parameters of anisotropy in thick layers. Coordinates and time in equation (1) are dimensionless. And their normalization was done analogous to the study [6]. Equation (1) with $K(x) = 1$ passes into the well-known sine-Gordon equation [5]. To further investigate the problem we use the following form of the function $K(x)$ [8]:

$$K(x)=\begin{cases}1, & x<x_1,\ x_1+W<x<x_1+W+d,\ x>x_1+2W+d\\ 1-\Delta K, & x_1\le x\le x_1+W,\ x_1+W+d\le x\le x_1+2W+d\end{cases} \tag{2}$$

i.e. two identical thin layers arranged at a predetermined distance d from each other, W – width of each thin layer. When $\Delta K > 0$ thin layer is a potential well for moving DW, and when $\Delta K < 0$ — a potential barrier.

Equation (1) was solved numerically using the explicit integration scheme [7]. The discretization of the equation was carried out according to the standard five-point scheme of the “cross” type. The boundary conditions had the following form: $\theta(\pm\infty) = 0, \pi$; $\theta'(\pm\infty) = 0$. For our calculations, we use a uniform grid with a step ξ in the coordinate x: $\{x_i = \xi\cdot i,\ i = 0, \pm1, \ldots, \pm N_x\}$, and with a step τ in the time t: $\{t_n = \tau\cdot n,\ n = 0, 1, \ldots, N_t\}$ where N_x, N_t – are the numbers of grid points. By satisfying the convergence condition of the explicit scheme $\tau/\xi \le 0.25$, we calculated the angle θ at the subsequent instants of time. Then, for the domain wall structure at each instant of time, we calculated the main dynamic characteristics of the domain wall.

In the numerical experiments DW crosses the fields of thin layers. Among the options of the DW dynamics we observed the following: the DW "is captured" in the first narrow layer area or in the second narrow layer, the DW oscillates between them, is reflected in the opposite direction, or passes through both narrow layers area. In the last two cases in each narrow layer area the oscillating localized high-amplitude nonlinear waves of "breather" type are excited [5], which significantly affect the outcome of the DW scattering (fig. 1). Excited localized magnetic inhomogeneities represent four-kink multisoliton states. It is seen that there are in-phase, antiphase oscillations, beat cases and transition of two interacting magnetic breathers into one. Upon that, the beat case (fig. 1c) is the most common oscillations mode, and in-phase (fig. 1d) and antiphase (fig. 1b) oscillations occur only in special cases, and in these particular cases, the amplitude of localized waves practically does not depend on time. Thus, the link between magnetic breathers can fundamentally change the behavior of the system compared with the case of a three-layer structure with a single thin layer [7]. Magnetic breathers fluctuations are accompanied by the radiation of small-amplitude waves. Their excitation can take a significant portion of the DW initial energy. It is important, that the subsequent interaction with these localized waves underlies the mechanism of resonance effects (in the case of a single narrow layer, similar interactions may lead to the DW reflection from it [5, 9]).

We can also select the case when narrow layers are close enough to each other, then the energy required for the transition between them is low and the DW can oscillate between them. Besides, in such case a multisolitons condition, consisting of a DW and magnetic breather, may form. In this case, the DW geometric center does not reflect the complete status of the multisoliton generation. This area is allocated in fig. 2 as the capture area with multiple hopping from one narrow layer into the other. This diagram shows (numerically obtained) a complete analysis of possible DW dynamics scenarios depending on the initial DW velocity υ_0 and the distance between narrow layers d.

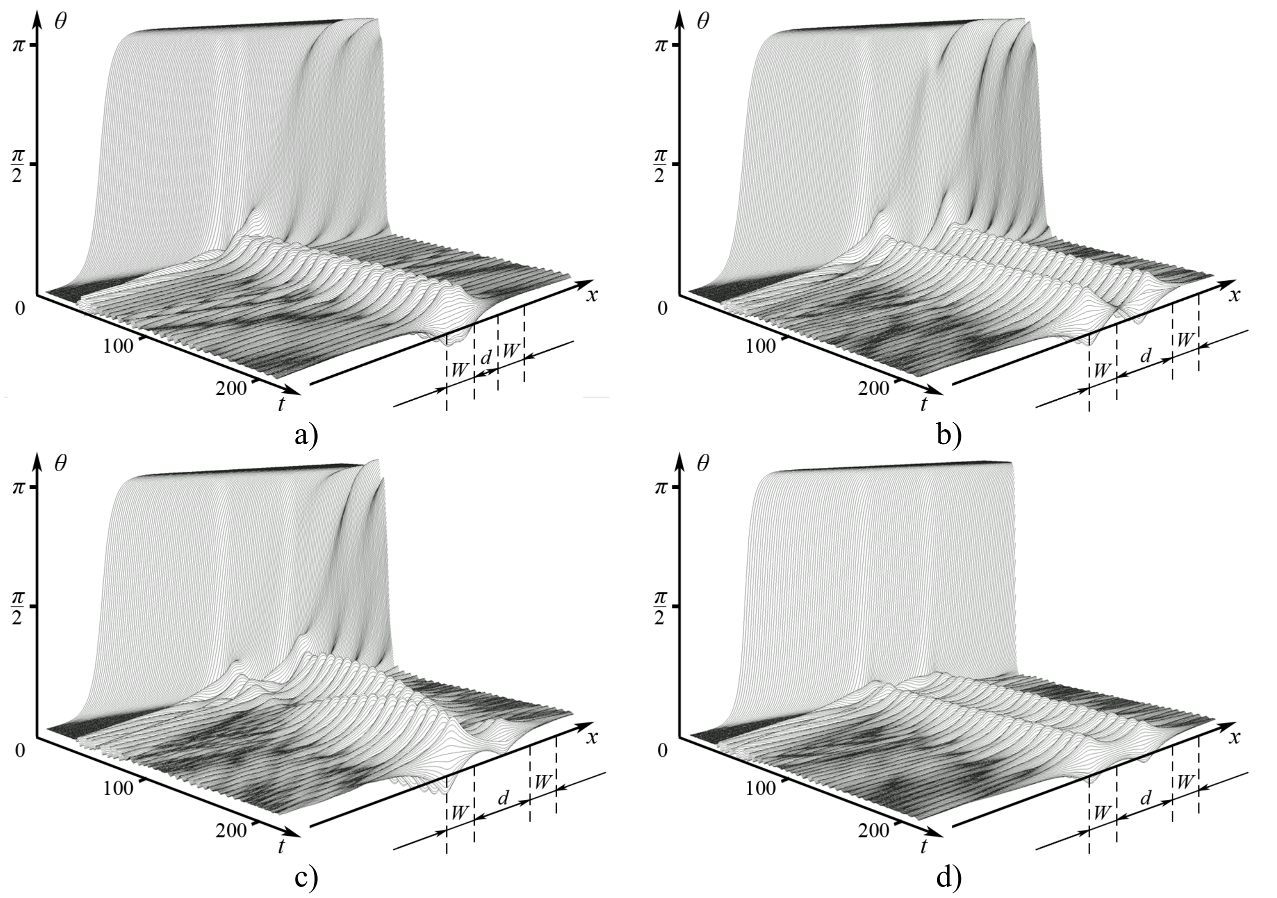

Fig.1. Excitation and evolution of the magnetic breathers in thin layers area as a result of the DW passage (with initial velocity υ_0) at $\Delta K = 1.2$, $W = 1$: a) $d = 0.75$, $\upsilon_0 = 0.6$, b) $d = 5$, $\upsilon_0 = 0.536$, c) $d = 5$, $\upsilon_0 = 0.64$, d) $d = 5$, $\upsilon_0 = 0.782$

Fig. 2 shows the presence of some critical distance d_{crit}, under which system behavior changes qualitatively. In case $d < d_{\text{crit}}$ two thin layers area can be generally regarded as an effective single layer. From fig. 2, where the horizontal line corresponds to the threshold velocity of the DW passage through a single thin layer – $\upsilon_{\min}^{one} = 0.245$, one can see, that at one point ($d = 0.84$) the threshold velocities, required for passage through both two and one thin layer with the same parameters ΔK and W, coincide. However, when $d > d_{\text{crit}}$ the diagram acquires a "petal" character: "capture" and "passage" areas start to alternate. The reason for such fundamentally new behavior, in our opinion, lies in the fact that the DW energy loss for the magnetic breather excitation depends on its initial velocity with a certain periodicity. And when those losses exceed certain value (as defined by narrow layer parameters), the remaining DW energy is not enough to "escape" from the attractive potential of the double narrow layer, and its "capture" takes place. Note that in some particular cases, in order to pass through the area of two identical narrow layers of the form (2) the DW requires kinetic energy smaller than for the passage of a single narrow layer area with the same parameter values ΔK and W. The area of the DW initial velocities, allowing to overcome the narrow layers (below the line $\upsilon_{\min}^{one} = 0.245$) is called a "quasitunneling" area (see fig. 2, Region *6*).

The analysis of the numerically obtained results suggests that the critical distance between the narrow layers d_{crit} divides the diagram into two regions characterized by strong and weak interaction between the localized nonlinear waves. The numerical results for the general case show that the nature of the emerging state of the system can be influenced by varying two parameters: the DW initial velocity - υ_0 and d. Since the localized waves are not initiated simultaneously, but after some time Δt_0, it can be assumed that υ_0 affects the initial phase difference of their oscillations. The results demonstrate qualitatively new effects of the magnetic material multilayer collective impact, which can be observed experimentally. For their experimental discovery in magnetic systems during the DW dynamics study (for example, by the high-speed photography [1]) one must be able to control the DW velocity value and the distance between layers.

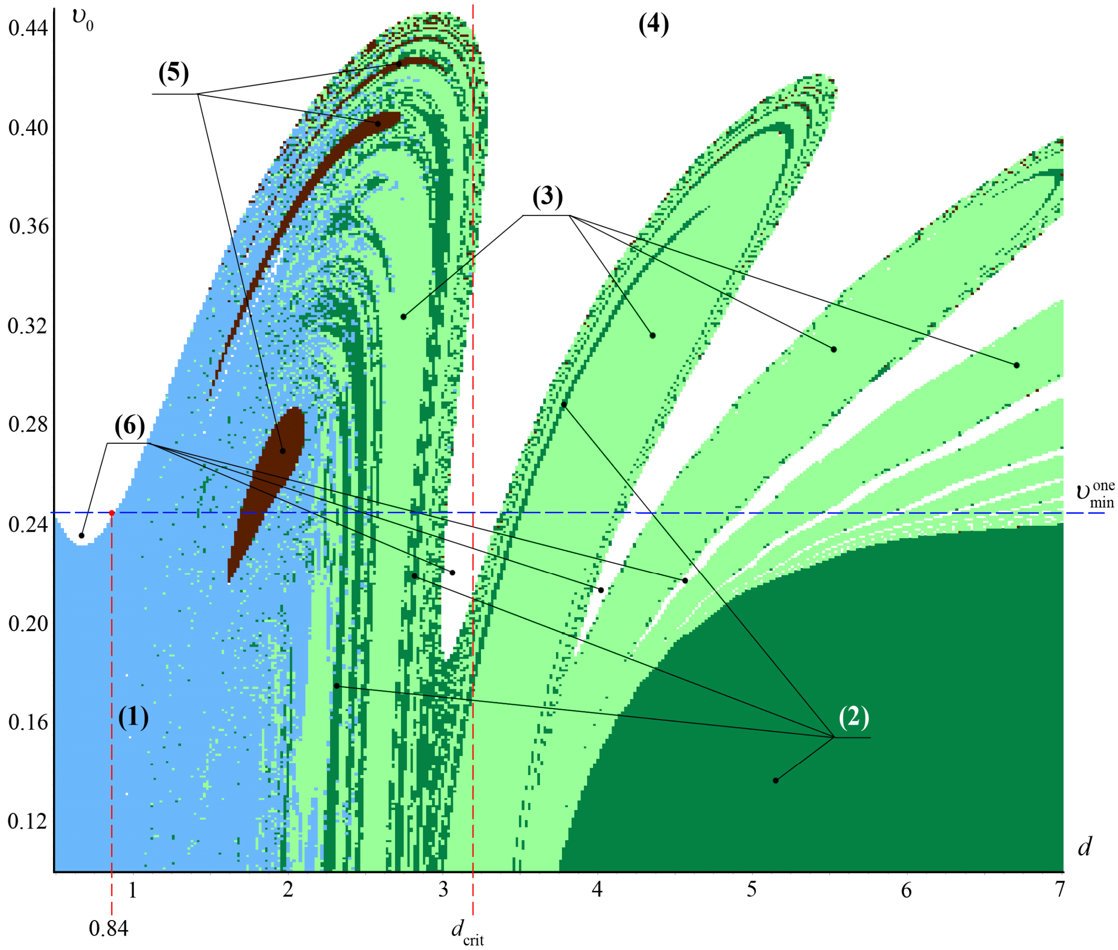

Fig.2. Diagram of possible scenarios of the DW dynamics depending on the initial velocity υ_0 and distance between narrow layers d at $\Delta K = 0.8$, W = 1. Diagram section: (1) – DW capture on one of the thin layers with multiple hopping from one into the other, (2) – capture on the first thin layer, (3) – capture on the second thin layer, (4) – passing of the DW through the area of both narrow layers, (5) – total DW reflection, (6) – "quasitunneling" area, part of the (4)

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