Bifurcations in Josephson junction coupled to the nanomagnet

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In this study, we consider voltage biased Josephson junction coupled to nanomagnet. We investigate the period doubling bifurcation due to interplay between superconducting phase and magnetization in Josephson junction. We use the variation of Josephson to magnetic energy ratio as our control parameter. Several precession motions are observed, such as chaos, bistabity, and multiperiodic orbits, in the ferromagnetic resonance region.

Introduction

Molecular nanomagnets [1–3] are good candidates for qubit realization, due to their long magnetization relation time [4–6]. Hybrid structures, such as the nanomagnet coupled to Josephson junction (NM-JJ), are also important contenders for the development of spintronic devices [7, 8]. The magnetic nanoparticle can be described by the Landau–Lifshitz-Gilbert equation [9], while, the Josephson junction, can be described by the resistively and capacitively shunted Josephson junction (RCSJ) model [10]. We investigate the magnetization bifurcations and chaos which appear in this system due to interplay of superconductivity and magnetism, and calculate the bifurcation diagrams.

Model

We consider voltage biased Josephson junction with length l coupled to a nonomagnet with magnetic moment $\mathbf{M} = (M_x;\ M_y;\ M_z)$ located at distance $\mathbf{r}_M = a\mathbf{e}_x$ from the center of the junction as shown in Fig.1a.

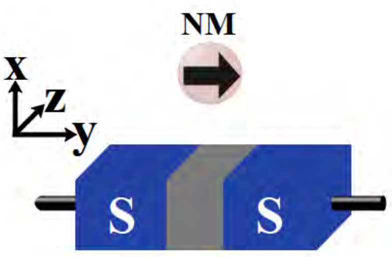

Fig. 1. Schematic diagram of the system of JJ-NM with the system geometry [10]

The total system of Landau-Lifshitz-Gilbert-Josephson equations to be used in our numerical studies in normalized units is given by [8, 11]:

$$\frac{dm_x}{d\tau}=\frac{\Omega_F}{(1+\alpha^2)}\left[h_y\left(m_z-\alpha m_x m_y\right)-h_z\left(\alpha m_x m_z+m_y\right)\right]$$
$$\frac{dm_y}{d\tau}=\frac{\Omega_F}{(1+\alpha^2)}\left[h_z\left(m_x-\alpha m_y m_z\right)+\alpha h_y\left(m_x^2+m_z^2\right)\right]$$
$$\frac{dm_z}{d\tau}=\frac{\Omega_F}{(1+\alpha^2)D}\left[\alpha\tilde{h}_z\left(m_x^2+m_y^2\right)-h_y\left(m_x+\alpha m_y m_z\right)\right]$$
$$D=1+\frac{\Omega_J\alpha\tau k}{1+\alpha^2}\left(m_x^2+m_y^2\right), \qquad (1)$$

where h_y, h_z are the components of the effective fieldin the y- and z-direction respectively (here h_x=0). The effective field components are given by:

$$h_y=m_y$$
$$h_z=\tilde{h}_z-\tau k\frac{dm_z}{dt} \qquad \tilde{h}_z=\tau[\sin(\Omega_J t-km_z)+\Omega_J], (2)$$

where Ω_J is the Josephson frequency normalized to the characteristic frequency of JJ, $\epsilon = Gk$, where k play the role of the coupling in the proposed system [7,11], $G=E_J/(K_{an}V)$ is the ratio between Josephson energy (E_J) and anisotropic energy, K_{an} is an anisotropic constant, V is the volume of ferromagnetic F layer, α is a phenomenological damping constant, $\mathbf{m_i} = \mathbf{M_i}/M_0$ for i = x, y, z, $M_0 = ||M||$, and Ω_F is the ferromagnetic resonance (FMR) frequency normalized to the characteristic frequency of JJ. Here, we consider $\Omega_F = 1$, $k = 0.05$, and $\alpha = 0.1$. We have chosen the Josephson to magnetic energy ratio G and the Josephson frequency Ω_J as control parameters.

We investigate h_{y-av} and h_{z-av} as functions of G and Ω_J and create 2-D maps, which are demonstrated in Fig. 2(a and b). Fig. 2(a) shows that the average of h_y has a non-zero values only at $G < 20\pi$ and around the FMR condition ($\Omega_J \approx \Omega_F$), while the average of h_z smoothly increasing with the increasing in G and Ω_J (see Fig.2(b)). We note that the condition $h_{y-av} = 0$ indicates the complete reorientation of the magnetic moment, while the negative values of h_{y-av} indicates the re versal of the easy axis [11, 12]. The reorientation features at $\Omega_J >> \Omega_F$ have been investigated in Refs. [10]. Here, we investigate the regions of the non-zero values of h_{y-av} which appear at small Ω_J ($\Omega_J < 2$). The system in this region is influenced by the irregular oscillations of $h_y(t)$, which can be a cause of a chaotic dynamic of the nanomagnet [11].

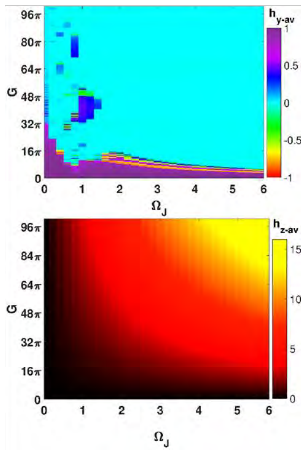

Fig. 2. (a) The average value of $hy{-}av$, (b) the aver- age value of $hz{-}av$ as functions of G and ΩJ

Changes of the oscillatory behaviors according to the increases of Ω_J can be seen in Fig.3. By increasing Ω_J the motion orbit is shrinked. In addition to this, the Poincar´e sections for $\Omega_J = 1$ shows that by increasing G, a transition from P2 to P4 motion (see Fig.2 (a) and (b)) take place. However, an inverse transition occurs where P4 to P2 motion occurs (see Fig.2 (c) and (d)).

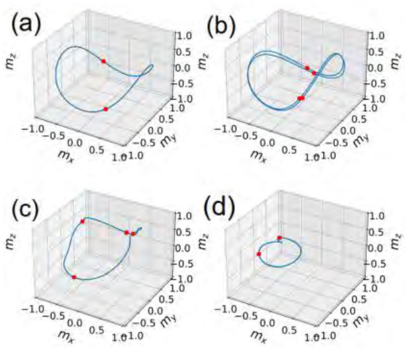

Fig. 3. The effect of ΩJ on orbits of the motion of the magnetization (blue curves) and corresponding Poincar´e sections (red dots) at different values of G at ΩJ = 1: (a) for G = 7, and (b) for G = 8. The same for (c), and (d) but for ΩJ = 1.5

Figure. 4 represent that the motion of the magnetization at G=10 is chaotic. Each time the magnetization passes through a region, its trajectory is changing, opening up new loops on the Bloch sphere (See Fig.3(b-e)).

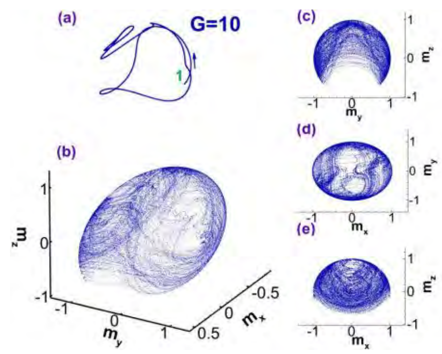

Fig. 4. Shows the trajectory of motion in 3D and 2D plan, indicating the chaotic feature of the system at G=10 and Ω_J=*1* . (a) represent the initial starting point. (b) Bloch sphere for the magnetization. (c-d) represent the 2D zy-, xy- and zx- planes

In summary, we show the transformations between different types of motions of the system and the magnetization may exhibit chaotic, and multiperiodic orbits motion depending of the Josephson junction parameters.

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