The influence of external radiation on the Josephson junction + nanomagnet system

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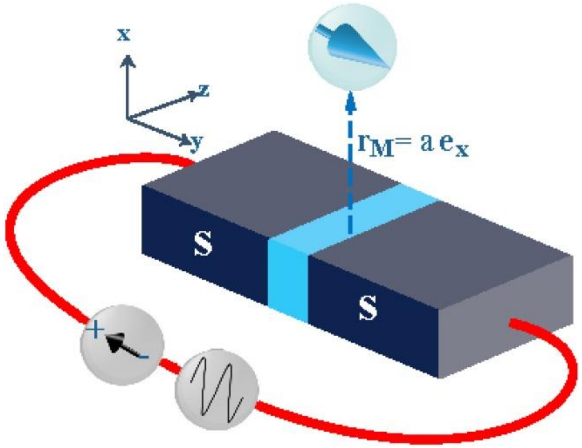
System of nanomagnet + Josephson junction



The dynamics of magnetic moment can be described by Landau-Lifshiz-Gilbert (LLG) equation

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{H}_{eff} \times \mathbf{M} + \frac{\alpha}{M_0}\left(\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right)$$

Effective magnetic field acting on the nanomagnet

$$h_x = 0,$$
$$\boxed{h_y = m_y,} \longrightarrow \text{Easy axis}$$
$$h_z = \boxed{\tilde{h}_z - \delta\epsilon k \dot{m}_z} \longrightarrow \text{AC Magnetic field generated by the Josephson junction}$$

where

$$\tilde{h}_z = \epsilon[\sin(V\tau - km_z + \frac{A}{\Omega}\sin(\Omega\tau)) + (V + A\cos(\Omega\tau) - \beta_c A\Omega\sin(\Omega\tau))]$$

$k = (2\pi/\Phi_0)\mu_0 M_s l/a\sqrt{l^2 + a^2}$ ⟶ Coupling parameter

l ⟶ Length of the JJ

a ⟶ Distance between nanomagnet and JJ

$\epsilon = Gk, \; G = \epsilon_J/K_{an}v$ ⟶ Josephson to magnetic energy ratio

○ Yu. M. Shukrinov, M. Nashaat, I. R. Rahmonov, and K. V. Kulikov, JETP Letters, 110, 3, 160-165 (2019)

Stability position in the case without periodic drive

LLG equations in spherical form are given by:

$$\dot{\theta} = -\frac{\Omega_F}{(1+\alpha^2)}\frac{\sin\theta}{\left(1+\frac{\Omega_F\alpha\epsilon k}{1+\alpha^2}\sin^2\theta\right)}\left[\alpha\tilde{h}_z - \sin\phi(\cos\phi + \alpha\cos\theta\sin\phi)\right],$$

$$\dot{\phi} = \frac{\Omega_F}{\alpha^2+1}\frac{1}{1+\frac{\alpha\epsilon k\Omega_F\sin^2\theta}{\alpha^2+1}}\left[\tilde{h}_z - \left(-\sin^2\theta\cos\phi\epsilon k\Omega_F + \sin\phi\cos\theta - \alpha\cos\phi\right)\sin(\phi)\right]$$

When *V* and *Ω* is much greater than the characteristic times of the variation of θ and *ϕ*, the Kapitsa pendulum forms. To study this, we use the notations

$$\theta \equiv \Theta + \xi \qquad \text{and} \qquad \phi \equiv \Phi + \zeta$$

Here, Θ and Φ describe the "slower" motion, relevant on longer time scales, whereas the variables *ξ* and *ζ* describe the "fast" oscillations of the system. Taking into account that

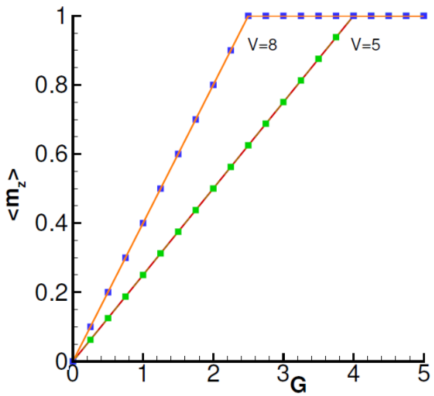
$$\sin[Vt - k\cos\Theta + \frac{A}{\Omega}\sin(\Omega t)] = \sum_{m=-\infty}^{\infty}\text{sign}^m(m)J_{|m|}\left(\frac{A}{\Omega}\right)\sin[(V+m\Omega)t - k\cos\Theta],$$

$$\cos[Vt - k\cos\Theta + \frac{A}{\Omega}\sin(\Omega t)] = \sum_{m=-\infty}^{\infty}\text{sign}^m(m)J_{|m|}\left(\frac{A}{\Omega}\right)\cos[(V+m\Omega)t - k\cos\Theta].$$

We obtain for *A* = 0 the stability position of the magnetic moment which is given by:

$$\Phi = \pi/2 \qquad \text{or} \qquad \Phi = 3\pi/2.$$

$$\langle m_z\rangle = \cos\Theta = \epsilon\delta V + \frac{\alpha\epsilon^2 k\sin^4\Theta\Omega_F}{2V(1+\alpha^2+\delta\alpha\epsilon k\sin^2\Theta\,\Omega_F)^2}$$



Stability position under external drive

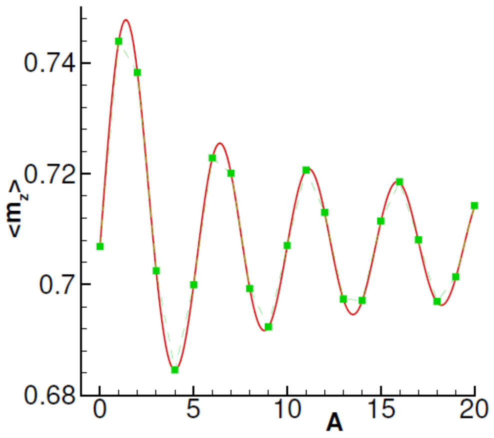
In the 0th order of approximation we have terms that oscillate with frequencies $V + m\Omega$. If there is a negative integer m_0, such that $V + m_0\Omega = 0$, then we obtain

$$\dot{\Theta}_0 = \frac{\Omega_F}{1+\alpha^2+\alpha\delta\epsilon k\Omega_F\sin^2\Theta}\Big\{(\alpha\sin\Phi\cos\Theta+\cos\Phi)\sin\Theta\sin\Phi$$
$$-\alpha\epsilon\sin\Theta\left[\delta V-\mathrm{sign}^{m_0}(m_0)J_{m_0}\left(\frac{A}{\Omega}\right)\sin(km_z)\right]\Big\},$$

$$\dot{\Phi}_0 = \frac{\Omega_F}{1+\alpha^2+\alpha\delta\epsilon k\Omega_F\sin^2\Theta}\Big\{(\delta\epsilon k\Omega_F\sin^2\Theta\cos\Phi-\cos\Theta\sin\Phi+\alpha\cos\Phi)\sin\Phi$$
$$+\epsilon\left[\delta V-\mathrm{sign}^{m_0}(m_0)J_{m_0}\left(\frac{A}{\Omega}\right)\sin(km_z)\right]\Big\},$$

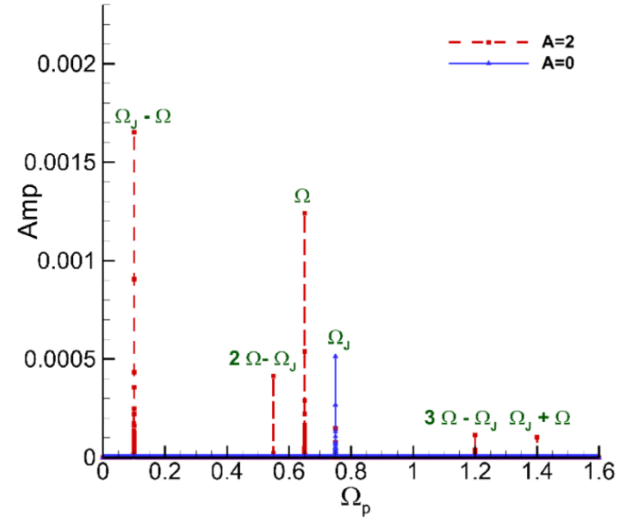
As in the case $A = 0$, the equation $\dot{\Theta} = \dot{\Phi} = 0$ lead to $\Phi = \pi/2 \text{ or } 3\pi/2$ and the equation for Θ:

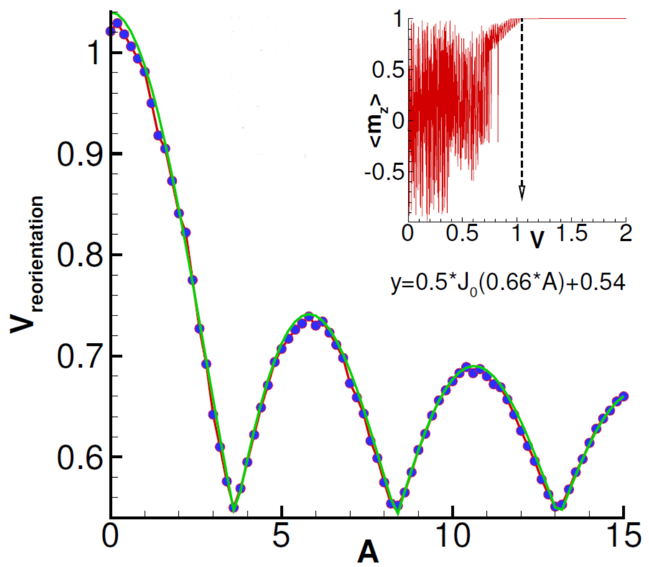
$$\cos\Theta = \epsilon\delta V - \epsilon\,\mathrm{sign}^{m_0}(m_0)J_{m_0}\left(\frac{A}{\Omega}\right)\sin(k\cos\Theta)$$



Influence of external radiation

The presence of the terms that oscillate in time may be emphasized by the FFT of $m_z(t)$. The oscillating frequencies should be $|nV + m\Omega|$, where n,m are integers and $n \geq 0$.





The applied external periodic drive also affects the voltage of complete reorientation V_r, which indicates the stabilization of the magnetic moment dynamics (see inset). The numerical data is well fitted by the Bessel function $0.5J(A/\Omega)+0.54$ shown by green solid line

Summary

- We obtained an analytical expressions to describe the movement of the stability position in the *yz* plane and had a very good agreement with the direct numerical simulations.

- It was shown that the average value of magnetic moment component m_z as a function of amplitude of external drive demonstrate Bessel behavior.

- We emphasis that influence of external periodic drive on the Kapitsa-like pendulum effects on the orders of magnitude more pronounced when the Josephson frequency V is equal to integer number of external drive frequencies Ω ($V + m_0\Omega = 0$). Otherwise, it is very small and the Kapitsa-like pendulum effects come mainly from the Josephson oscillations.

- We also shown that the voltage of complete reorientation depend as the Bessel function on the external drive amplitude.

Thank you for attention.