07

Inductive characteristic of a spintronic nanooscillator

© E.S. Papoyan[1], L.A. Tsyrulnikova[1,2], A.R. Safin[1,2]

[1] National Research University „Moscow Power Engineering Institute", Moscow, Russia
[2] Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, Russia
E-mail: mila.tsyrulnikova@gmail.com

Received October 3, 2025
Revised October 28, 2025
Accepted November 10, 2025

The inductive characteristic of a spintronic nanooscillator with easy plane magnetization of the free layer is analyzed based on a small-signal equivalent circuit of the oscillatory system. The dependence of effective inductance on current strength is determined, and inductive characteristics for different magnitudes of the external magnetic field are plotted. It is demonstrated that the slope of the inductive characteristic of the spintronic nanooscillator increases with increasing magnitude of the external magnetic field. The presented results may be used in the design of radio engineering models of spintronic generators and the development of new hardware components for modern radio electronics.

Keywords: spintronic nanooscillator, magnetization precession, inductance, radio electronic model, small-signal mode.

DOI: 10.61011/TPL.2026.03.63057.20514

The progress in modern radio electronics is characterized by a steady trend toward miniaturization of devices, reduction of their energy consumption, and increase in operating speed [1]. Research in the field of spintronics aimed at producing new energy-efficient hardware components is becoming especially relevant in this context [2–5]. A nanoscale spintronic oscillator (SO), which combines the functions of generating microwave oscillations and wide-range frequency tuning by electric current and magnetic field, is one of the key elements of spintronics. Engineering analysis and the development of radio engineering SO models will help formulate methods for calculating circuits with spintronic components [6–9]. The implementation of this approach should enable integrated design of spintronic devices and facilitate their subsequent commercialization. An equivalent electrical circuit of a spintronic oscillator in the form of a nonlinear oscillatory circuit with losses and current and voltage sources, which characterize the action of spin torque compensating for inherent damping, was obtained in [7,8]. At the same time, the oscillatory system parameters need to depend on voltages and currents of the corresponding elements (capacitance and inductance coil) for SO equivalent circuits to be used directly in SPICE (Simulation Program with Integrated Circuit Emphasis) modeling. The aim of the present study is to determine and analyze the current dependence of inductance of an oscillatory circuit with easy plane magnetization of the free layer in the small-signal mode.

The SO dynamics is characterized by the Landau–Lifshitz–Gilbert–Slonczewski equation for the magnetization vector of the free layer [7,8], the trajectory of which corresponds to the precession of a spinning top. The oscillatory system of the SO free layer may be presented in the form of an equivalent LC circuit (Fig. 1, a) with a nonlinear dependence of inductance and capacitance on the azimuthal angle of precession of the magnetization vector (Fig. 1, b). The expression relating differential inductance L of the oscillatory circuit to azimuthal angle φ for a free layer of the easy plane (EP) type takes the following form [7]:

$$L(\varphi) = \frac{Z_s}{\gamma} \frac{1}{B_{e,x}\cos\varphi + B_{e,y}\sin\varphi + B_a\cos 2\varphi}, \qquad (1)$$

where γ is the gyromagnetic ratio; $B_{e,x}$, $B_{e,y}$ are the projections of the external magnetic field onto directions x, y; B_a is the effective anisotropy field along axis x; φ is the azimuthal angle of magnetization direction; $Z_s = \left(\frac{\hbar}{e}\right)^2 \frac{\gamma}{M_s V_s}$ is the characteristic quantity (resistance) associated with conversion of spin units into electrical ones; M_s is the saturation magnetization; V_s is the free ferromagnetic layer volume; $\hbar$ is the reduced Planck constant; and e is the elementary charge. Current flowing through the inductance is also related to the parameters of

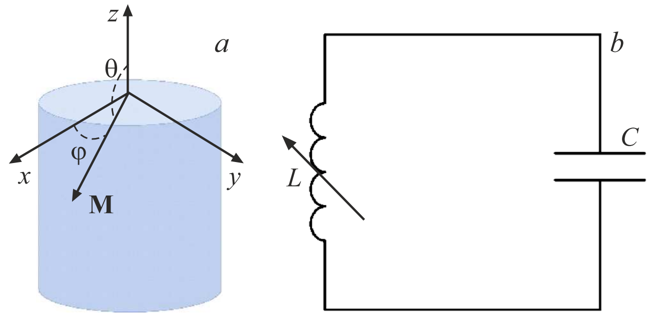

Figure 1. Spintronic nanooscillator (a) and equivalent circuit (b) of its oscillatory system.

precession of the magnetization vector:

$$I_L(\varphi) \approx \frac{\gamma\hbar}{eZ_s}\left[B_{e,x}\sin\varphi - B_{e,y}\cos\varphi + \frac{1}{2}B_a\sin 2\varphi\right]. \quad (2)$$

Expressions (1), (2) are periodic nonlinear functions of azimuthal angle φ. In the EP geometry, the magnetization vector precesses in the xy plane, the polar angle is $\theta = \pi/2$, and the equilibrium magnetization vector (ground state) is directed along the x axis. The expression for capacitance of the equivalent SO oscillatory circuit (Fig. 1) in the EP geometry is virtually independent of angle φ and takes the following form [7]:

$$C \approx \frac{1}{\gamma B_d Z_s}, \quad (3)$$

where B_d is the anisotropy field along the hard axis. Since the capacitance of the equivalent SO circuit is related to the precession of the magnetization vector primarily through polar angle θ, the capacitance may be considered constant in the EP case, and the nonlinear SO properties are manifested in inductance $L(\varphi)$, which is reminiscent of the properties of a Josephson junction [10].

Let us consider the small-signal model of the oscillatory SO characteristic with azimuthal angle φ varying near zero. This is fitting for a wide range of scenarios: natural oscillations of the SO magnetization near the equilibrium position in the problem of detection of microwave oscillations, nonlinear ferromagnetic resonance, etc. In this approximation, the trigonometric functions in (1), (2) may be expanded in a Taylor series about $\varphi \approx 0$. Expressions (1) and (2) then take the form

$$L(\varphi) = \frac{Z_s}{\gamma}\frac{1}{B_{e,x} + B_{e,y}\varphi + B_a}, \quad (4)$$

$$I_L(\varphi) \approx \frac{\gamma\hbar}{eZ_s}\left[B_{e,x}\varphi - B_{e,y} + B_a\varphi\right]. \quad (5)$$

Dependence $L(\varphi)$ in the general case (1) is represented by the solid curve in Fig. 2, *a*, while small-signal approximation (4) is represented by the dashed line. It can be seen that the inductance in the general case increases with φ; as the external magnetic field grows stronger, both the inductance and the slope of the characteristic decrease. Dependence I_L is presented in Fig. 2, *b* both in the general case (2) (solid curve) and in small-signal approximation (5) (dashed line). It is evident that the current through the inductance increases with φ and that the inductive current decreases as the external magnetic field grows stronger. As was expected, the small-signal approximation matches the general case at small φ angles for both the $L(\varphi)$ dependence (Fig. 2, *a*) and the $I_L(\varphi)$ dependence (Fig. 2, *b*).

Thus, the inductance in the approximation linear in φ (in the small-signal mode) may be presented as a function of current flowing through it:

$$L(I_L) = \frac{Z_s}{\gamma}\frac{1}{B_{e,x} + B_{e,y}\left[I_L + \frac{\gamma\hbar}{eZ_s}B_{e,y} \Big/ \frac{\gamma\hbar}{eZ_s}\left(B_{e,x} + B_a\right)\right] + B_a}. \quad (6)$$

Expression (6) makes it clear that $L(I_L)$ has a hyperbolic character and decreases with increasing current through inductance L. It is evident from Fig. 3 that the coil inductance decreases with increasing current, which corresponds to an increase in frequency of natural oscillations of the coil with an increase in current through it. With an increase in magnitude of the constant magnetic field, the slope of the inductive characteristic increases, and the required value of inductance of the coil is reached due to a weaker current flow through it.

Thus, a model of the equivalent oscillatory circuit of a spintronic oscillator was studied. Expressions for the inductance and current through it as functions of the

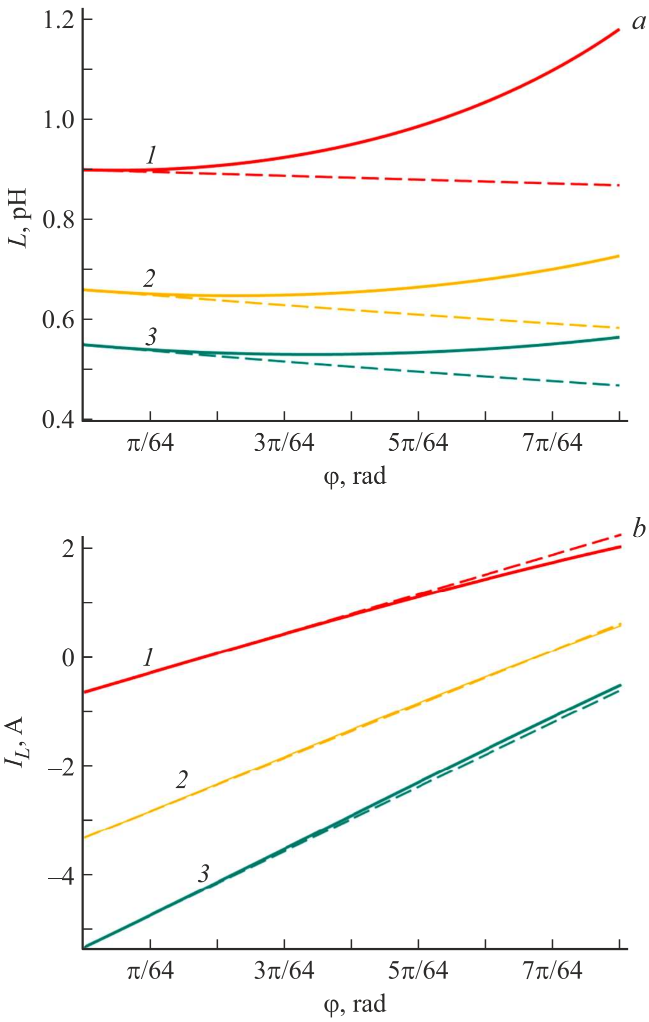

Figure 2. Dependences of the coil inductance (*a*) and the current through it (*b*) on the azimuthal angle in the general case (solid curves) and linearizations (dashed curves) at different external field magnitudes. *1* — $B_{e,x} = 0.1$ T, $B_{e,y} = 0.1$ T; *2* — $B_{e,x} = 0.5$ T, $B_{e,y} = 0.5$ T; *3* — $B_{e,x} = 0.8$ T, $B_{e,y} = 0.8$ T.

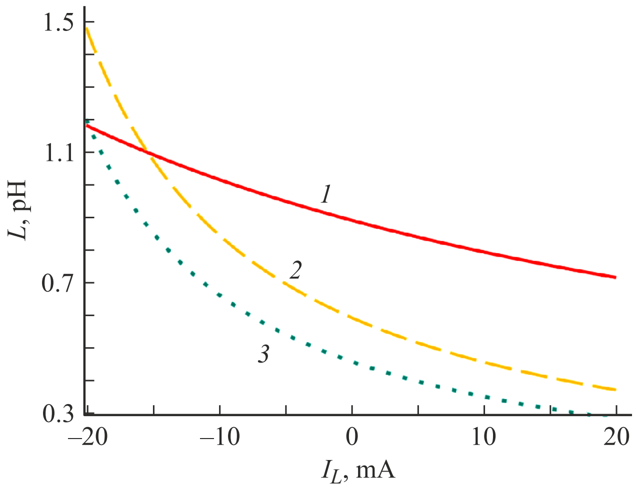

Figure 3. Dependence of the coil inductance on current passing through it at different external field magnitudes. *1* — $B_{e,x} = 0.1$ T, $B_{e,y} = 0.1$ T; *2* — $B_{e,x} = 0.5$ T, $B_{e,y} = 0.5$ T; *3* — $B_{e,x} = 0.8$ T, $B_{e,y} = 0.8$ T.

azimuthal angle of precession of the magnetization vector were obtained in the small-signal approximation in the easy plane geometry. Inductive characteristics were plotted for different magnitudes of the external magnetic field. It was demonstrated that the slope of the inductive characteristic of the spintronic oscillator increases with increasing magnitude of the external magnetic field. This research opens up opportunities for SPICE investigation of spintronic oscillators in the small-signal mode, which should enable the development of electronic devices with spintronic elements in the form of integrated units for further analysis.

Funding

This study was supported by the Russian Science Foundation (No. 25-79-20053).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A. Fert, Phys. Usp., **51** (12), 1336 (2008). https://ufn.ru/en/articles/2008/12/n/

[2] M. Zahedinejad, H. Mazraati, H. Fulara, J. Yue, S. Jiang, A.A. Awad, J. Åkerman, Appl. Phys. Lett., **112** (13), 132404 (2018). DOI: 10.1063/1.5022049

[3] T. Chen, R.K. Dumas, A. Eklund, P.K. Muduli, A. Houshang, A.A. Awad, P. Dürrenfeld, B.G. Malm, A. Rusu, J. Åkerman, Proc. IEEE, **104** (10), 1919 (2016). DOI: 10.1109/JPROC.2016.2554518

[4] O. Haas, B. Dufay, S. Saez, C. Dolabdjian, IEEE Sens. J., **20** (23), 14289 (2020). DOI: 10.1109/JSEN.2020.3008555

[5] A.A. Mitrofanov, A.R. Safin, N.N. Udalov, Tech. Phys. Lett., **40** (7), 571 (2014). DOI: 10.1134/S1063785014070074.

[6] A. Kumar, A. Litvinenko, N. Behera, A.A. Awad, R. Khymyn, J. Åkerman, in *Nanomagnets as dynamical systems: physics and applications*, ed. by S. Bandyopadhyay, A. Barman (Springer, Cham, 2024), p. 143–182. DOI: 10.1007/978-3-031-73191-4_5

[7] S. Louis, H. Bradley, V. Tyberkevych, *Equivalent electric model of a macrospin*, arXiv:2503.20811 [cond-mat.mes-hall] (2025). DOI: 10.48550/arXiv.2503.20811

[8] S. Louis, H. Bradley, A. Litvinenko, V. Tyberkevych, IEEE Magn. Lett., **16**, 4500305 (2025). DOI: 10.1109/LMAG.2025.3577475

[9] F. Vanderveken, V.S. Tiberkevich, G. Talmelli, B. Sorée, Sci. Rep., **12**, 3796 (2022). DOI: 10.1038/s41598-022-07625-2

[10] A. Barone, G. Paternó, *Physics and applications of the Josephson effect* (Wiley, N.Y., 1982).

Translated by D.Safin