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Magnetic stochastic resonance in systems described by dynamic Preisach model

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Abstract

In this paper, dynamic Preisach model is applied to investigate magnetic stochastic resonance. It is shown that magnetic systems described by dynamic Preisach model presents magnetic stochastic resonance. The resonance in the power amplification disappears if the frequency of the input signal is greater than characteristic frequency of the system introduced by dynamic Preisach model and the resonance in signal to noise ratio is strongly reduced under the same condition. Finally, frequency and phase locking phenomenon is detected under resonance condition.

Keywords: Hysteresis; Dynamic Preisach model; Stochastic resonance; Magnetic devices; Electric machines

1. Introduction

Stochastic resonance (SR) is generally considered as an amplification of the system response for certain finite values of the noise strength that is pumped into the system [1,2]. In particular, the signal to noise ratio (SNR) and the signal amplification show a maximum as a function of the noise intensity. It is generally accepted that a system should be bistable and non-linear in order to present SR.

SR has been experimentally observed (for a review see Ref. [3]) in many physical systems and also in magnetic systems. The occurrence of SR in magnetic systems is remarkable because it demonstrates that SR can occur not only in bistable systems but also in systems that are multistable. Some theoretical approaches have been developed to describe SR (for a theory of SR in magnetic systems see Ref. [4] and for a review see Ref. [3]) they usually assume that the system is bistable and that there is a hysteresis in the switching between one state and the other, but no theoretical approach is able to describe SR in systems that present a magnetic-like hysteresis area (i.e. an entire area of accessible states, that is surrounded by a major loop), in this paper this effect will be called magnetic stochastic resonance (MSR). MSR has been numerically described by using the Classical Preisach Model (CPM) [5].

Moreover, as far as magnetic-like systems are concerned, both the available theoretical and the numerical descriptions of SR do not include the dynamic features of the system and they assume that the typical relaxation time of the system is negligible. However, this is clearly a rough approximation.

In order to clarify the influence of the dynamic features of the system, in this paper MSR in magnetic systems described by dynamic Preisach model (DPM) is numerically investigated. The use of DPM allows to study the features of the SR in connection with the dynamic features of the magnetic systems. More particularly, in this paper it is shown that:

– magnetic systems described by DPM presents SR;
– the resonance in the power amplification disappears if the frequency of the input signal is greater than characteristic frequency of the system introduced by DPM and SR in SNR is strongly reduced under the same condition;
– frequency and phase locking phenomenon is detected under resonance condition.

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2. The DPM

DPM was introduced to describe dynamic features of the magnetic systems. A full description of the model can be found in Ref. [6]. Below, only the features important for the comprehension of this paper will be outlined.

In DPM, the magnetization $M(t)$ at the generic time t is given by the equation

$$M(t) = M_s \int_0^{\infty} dh_c \int_{-\infty}^{\infty} p(h_c, h_u)\phi(h_c, h_u, t)dh_u, \quad (1)$$

where M_s is the saturation magnetization, $p(h_c, h_u)$ is the Preisach Model density function and $\phi(h_c, h_u, t)$ describes the state of each elementary Preisach Model loop at the time t. $\phi(h_c, h_u, t)$ varies according to

$$\frac{\partial\varphi(h_u, h_c, t)}{\partial t} = \begin{cases} k[H(t) - (h_u + h_c)], & \text{if} \quad H(t) < (h_u + h_c) \\ k[H(t) - (h_u - h_c)], & \text{if} \quad H(t) < (h_u - h_c) \end{cases}, \quad (2)$$

where k is an unknown parameter. The Dynamic Model becomes equivalent to CPM if the parameter k becomes infinite, because, in this case, the function $\varphi(h_c, h_u, t)$ can assume only the values -1 and $+1$. The parameter k quantifies the finite rate of the switching of the hysterons of DPM.

3. The numerical approach

In this paper, it is assumed that the external magnetic field (h_{ext}) applied to a magnetic material consisted of two components, one small sinuisodal component added to a Gaussian noise component:

$$h_{ext} = H_s \sin t + D(t), \quad (3)$$

where t is the time and D is the Gaussian noise. D was generated by a suitable Gaussian generator in which the root mean square was controllable. The frequency of the sinusoidal component was kept constant at the value of 1 in all the numerical simulations here presented and the dynamic features of the system were changed by letting k vary. The value of h_{ext} was computed at several time steps. As a result, the time evolution of the magnetization of the system could be computed by inserting Eq. (3) in DPM (Eqs. (1) and (2)). A Lorentzian Preisach distribution function was used in Eq. (1). Its expression is given in Ref. [5]. The Lorentzian function is identified by two parameters σ_c and H_0. σ_c was set equal to 0.1 and H_0 to 1. This distribution generates a major loop of the static hysteresis that has a coercive field equal to 1 (see Ref. [5]).

The magnetization was computed by discretizing the integral in Eq. (1) on a suitable grid. The grid on the Preisach plane is rectangular with $0 \leqslant h_c \leqslant 4$ and $-3 \leqslant h_u \leqslant 3$ and it is made by a maximum of 1000×1000 points and the set of differential equations in Eq. (2) were solved by standard numerical techniques.

The Fast Fourier Transforms (FFT) of the magnetization was computed and the value of the component of the FFT for the frequency of the signal was used to compute the SNR and the power amplification.

The SNR was calculated by

$$\mathrm{SNR} = 10 \log_{10}\left(\frac{P_1}{N_1}\right) \quad (4)$$

and the power amplification as

$$\eta = 2\left(\frac{|M_1|}{M_s}\right)^2, \quad (5)$$

where P_1 is the output signal power level obtained from the FFT of the resulting magnetization at the frequency of the sinusoidal component, N_1 is the noise level obtained from the same FFT at the frequency of the sinusoidal component, M_1 is the component of the FFT at the frequency of the sinusoidal component and M_s is the amplitude of the magnetization obtained with no noise pumped in the system.

The SNR, the power amplification and the behavior of the magnetization for several H_s and D as a function of the parameter k have been computed.

In Fig. 1, the FFT of the time varying magnetization for an amplitude of $H_s = 0.5$ in the case of presence of noise with a value of $H_{rms} = 0.8$ and for $k = 1000$ is shown. The FFT of the time varying magnetization for an amplitude of $H_s = 0.5$ in the case of absence of noise has a maximum value that is much smaller (1/1000) than the one presented in Fig. 1. That means that the addiction of noise enhances the signal. This, together with the non-monotonic behavior of both SNR and η, is the fingerprint of SR. Moreover, for $H_s = 0.5$ and $H_{rms} = 0.8$ but for $k = 0.01$ the maximum in FFT was strongly reduced (1/2000) and no SR occurred.

Fig. 2 shows SNR as a function of H_{rms} for various values of k at $H_s = 0.5$. The variation of k implies the modification of the dynamic features of the system. In particular the reduction of k from a high value (1000) to a small one (0.001) implies that the frequency of the input signal is much lower in the characteristic frequency of the system in the first case (and therefore CPM is applicable) and much higher in the second case. It can be seen how for values of k less than 1, SNR presents a maximum value almost equal to the minimum one. However, it seems that there is still a non-monotonic behavior of SNR.

As a result, these data indicate that the occurrence of SR is negatively affected if the frequency of the signal gets close or becomes higher than the characteristic frequency of the system. This behavior has been experimentally reported in Ref. [7] in a non-magnetic system, even though in that case the maximum frequency of the signal was lower than the characteristic frequency of the system.

Fig. 3 shows η (dB) as a function of H_{rms} for various values of k at $H_s = 0.5$. It can be seen how for values of k less than 1, η does not present any SR. It is worth saying that the absolute value of M_1 in the case of low ks becomes much less (three order of magnitudes) than the