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Magnetostochastic resonance under colored noise condition

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Stochastic resonance (SR) is an amplification of the system output in correspondence of well-defined finite values of the noise strength that is injected into the system [Gammaitoni *et al.*, Rev. Mod. Phys. **70**, 223 (1998), Grigorenko *et al.*, IEEE Trans. Magn. **31**, 2491 (1995), Mantegna *et al.*, J. Appl. Phys. **97**, 10E519 (2005)]. In order to clarify the influence of a colored noise, in this paper magnetostochastic resonance (MSR) in magnetic systems described by the dynamic Preisach model is numerically investigated in the presence of colored noise. It is shown that noise spectrum affects MSR, white noise, 1/f and 1/f^2 noise induce in magnetic systems described by the dynamic Preisach model MSR, the maximum level of signal-to-noise ratio (SNR) obtained by using white noise but 1/f noise presented a range where SNR value is higher than the case of white noise; maximum signal amplification is obtained for white noise. © *2012 American Institute of Physics*. [doi:10.1063/1.3680083]

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INTRODUCTION

Stochastic resonance (SR) is a well-known phenomenon characterized by an amplification of the system response for certain finite values of the noise strength injected into the system.[1,2] In particular, the signal-to-noise ratio (SNR) and the signal amplification show nonmonotonic behaviors with a maximum as a function of the noise intensity. SR has been experimentally observed[3] in many physical systems and also in magnetic systems.[4] 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) for bistable systems, but no theoretical approach has been developed to describe SR in systems that present a magnetic-like hysteresis area (i.e., an entire area of accessible states, which is surrounded by a major loop). This effect is usually named magnetic stochastic resonance (MSR). MSR has been numerically described using both the classical Preisach model (CPM) and dynamic Preisach model (DPM).[5,6] In these investigations real noise has been numerically simulated. Real noise has a frequency spectrum that depends on various factors, however in theoretical analysis some standardized models are used. The typical models are named white and colored noise: white noise is a random process with a flat power spectrum density and colored noise is a process with a power spectrum density that has a frequency dependence. In all the above-recalled approaches, MSR has been investigated in white noise condition. SR in the presence of colored noise has been investigated only in bistable systems and no attempt to include colored noise in magnetic systems has yet been done.

In order to clarify the influence of the type of noise in magnetic systems, in this paper MSR in magnetic systems described by DPM is numerically investigated under colored noise condition. The colored noise models used assume a 1/f and 1/f^2 dependency on frequency. The use of DPM allows one to study the features of the SR in connection with the dynamic features of the magnetic systems and various types of noise.[7,8,10]

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THE DYNAMIC PREISACH MODEL

DPM was introduced to grasp dynamic characteristics of magnetic materials. A complete description of the model can be found in Ref. 9. In the following, only the details important for the comprehension of this paper will be outlined.

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

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

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

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

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.

THE NUMERICAL APPROACH

In this paper, the external magnetic field (h_{ext}) applied to a magnetic material has two components, one small sinusoidal component added to a colored noise component:

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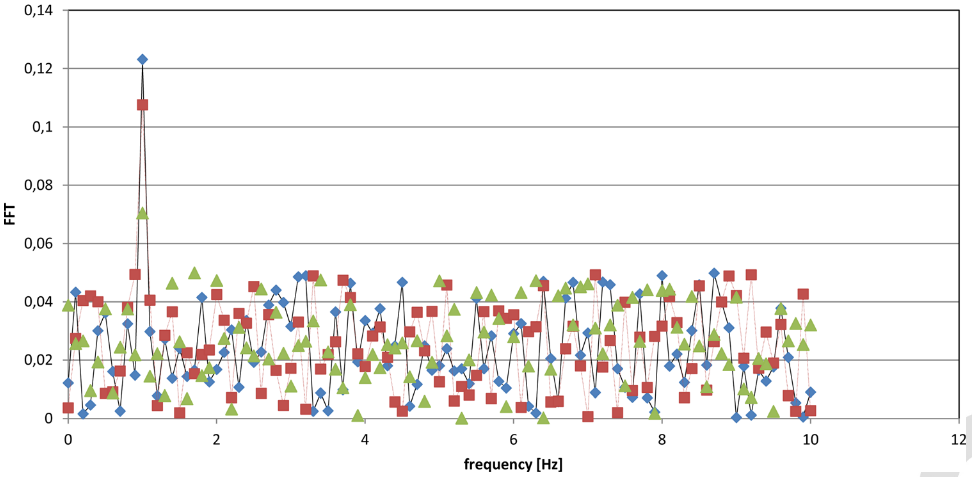

FIG. 1. (Color online) FFT of the output of the system. Diamonds represent white noise, squares 1/f noise, and triangles $1/f^2$ noise.

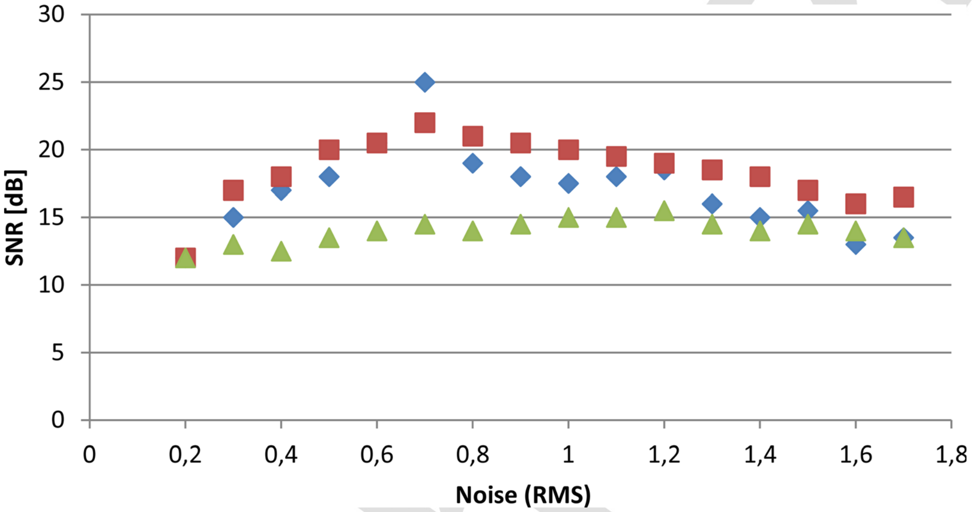

FIG. 2. (Color online) SNR vs noise intensity. Diamonds represent white noise, squares 1/f noise, and triangles $1/f^2$ noise. The maximum SNR is reached in the case of white noise but 1/f noise presents a broader maximum, and an area where SNR values are higher than white noise case.

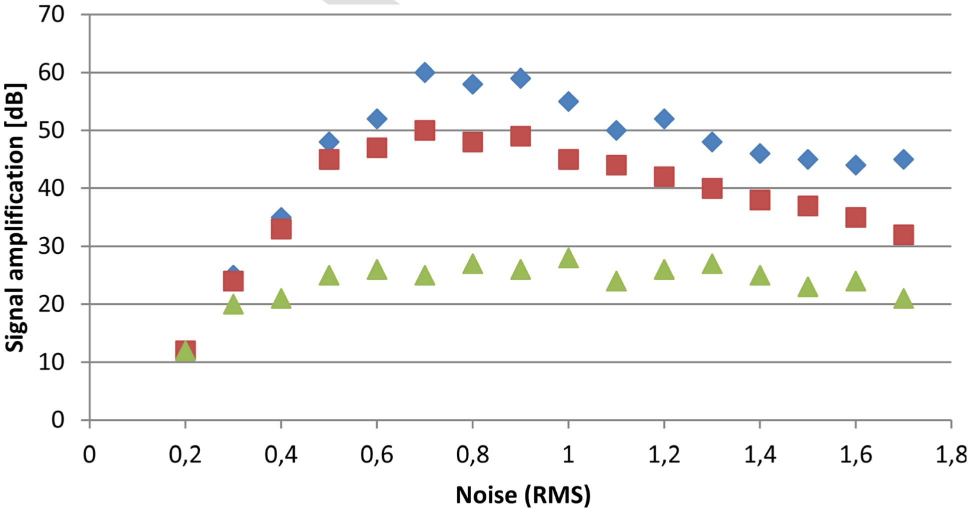

FIG. 3. (Color online) Signal amplification vs noise intensity. Diamonds represent white noise, squares 1/f noise, and triangles $1/f^2$ noise. The maximum signal amplification is reached in the case of white noise.

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

where t is the time and D is the colored noise. D was generated by a suitable generator in which the type of noise and its 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 in the DPM and the correlation time in the noise generator. 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 [Eq. (1) and (2)]. A Lorentzian Preisach distribution function was used in Eq. (1). Its expression is given in Ref. 5. The two parameters σ_c and H_0, which define the Lorentzian, were set equal to 0.1 and 1 respectively. 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 $0 \le h_c \le 4$ and $-3 \le h_u \le 3$ and it is made by at maximum 1000×1000 points and the set of differential equations in Eq. (2) were solved by standard numerical techniques.

To compute the SNR and the power amplification, the fast Fourier transforms (FFT) of the magnetization were computed and the value of the component of the FFT for the frequency of the signal was used.

The SNR was calculated as

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

and the power amplification as

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

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 and in correspondence of white, 1/f and 1/f^2 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 $H_{\text{rms}} = 0.8$ and for $k = 1000$ is shown for the three types of noise. The amplitude of the harmonic of the FFT of the time varying magnetization at the frequency of the applied signal for a signal amplitude of $H_s = 0.5$ in the case of absence of noise is much smaller (1/1000)[5] than the amplitude of the same harmonic when an external noise is applied. That means that the addiction of noise amplifies the harmonic value at the frequency of the signal. This, together with the nonmonotonic behavior of both SNR and η, is the fingerprint of SR. Figure 1 shows the amplification of the harmonic value at the frequency of the signal and how white noise guarantees the maximum signal amplification; 1/f noise amplification is 20% less than white noise and 1/f^2 amplification is 40% less.

In Fig. 2 SNR is shown as a function of H_{rms} for the three types of noise at $H_s = 0.5$.

The maximum SNR is obtained for white noise, but 1/f noise seems to have a broader range where it is larger than white noise. This is due to the fact that in 1/f noise the noise reduction plays a role in the SNR by enhancing its value for a broad range, this tendency is confirmed in the 1/f^2 case where noise reduction plays a role in a broader range than the 1/f case. In the 1/f^2 case the maximum in SNR is reached at a noise rms (root mean square) value higher than the other cases (a noise RMS equal to 1.2). In Fig. 3 η[dB] is shown as function of H_{rms} for the three types of noise at $H_s = 0.5$. Also in this case, white noise guarantees a higher signal amplification. However, in this case there is no range where 1/f noise presents a higher level of amplification. This is due to the fact that in signal amplification the level of noise is not included in the calculation.

CONCLUSIONS

In this paper, magnetostochastic resonance in the presence of colored noise has been investigated. It has been shown that:

(1) Noise spectrum affects MSR.
(2) White noise, 1/f and 1/f2 noise induce in magnetic systems described by the dynamic Preisach model MSR.
(3) Maximum level of SNR has been obtained by using white noise but 1/f noise presents a range where SNR value is higher than the case of white noise.
(4) Maximum signal amplification is obtained for white noise.

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