Physica B 435 (2014) 66–70

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

A comparison between advanced time–frequency analyses of non-stationary magnetization dynamics in spin-torque oscillators

Giulio Siracusano [a,*], Aurelio La Corte [b]

[a] Department of Electronic Engineering, Industrial Chemistry and Engineering, University of Messina, C. di Dio, S. Agata, 98166 Messina, Italy
[b] Department of Electrical, Electronic and Informatic Engineering, University of Catania, Viale Andrea Doria, 6-95125 Catania, Italy

ARTICLE INFO

Available online 30 August 2013

Keywords:
Hilbert–Huang Transform
Empirical Mode Decomposition
Spin-torque oscillator
Wavelet
Mode-mixing

ABSTRACT

We report re`sults of different time–frequency analyses (Wavelet and Hilbert–Huang Transform (HHT)) of voltage measurements related to a spin-torque oscillator working in a regime of non-stationary dynamics. Our results indicate that the Wavelet analysis identifies the non-stationary magnetization dynamics revealing the existence of intermittent and independent excited modes while the HHT is able to accurately extract the time domain traces of each independent mode. Overall performance indicates a route for a complete characterization of time–frequency domain data of a STO, pointing out that the combined Wavelet-HHT methodology developed is general and can be also used for a variety of other different scenarios.

1. Introduction

It has been discovered how a spin-polarized current flowing throw a nanomagnet can excite several different types of magnetization dynamics [1,2]. Such phenomenon has powered research on the applied spintronic technology which have been studied extensively both theoretically and experimentally [3–7]. Frequency [3] and time [7] domain measurements of magnetoresistance signal show strong non-linear and non-stationary behavior, for instance transition between static magnetic states and different steady-state precessions characterized by uniform and non-uniform magnetization patterns. In addition, the frequency, the linewidth, and the microwave output power of the precessions show strong dependence on external field and current [8,9].

In particular, exchange bias nanoscale spin-valves with a Py-free layer ($Py=Ni_{80}Fe_{20}$) of elliptical cross-sectional area exhibit dynamics with series of frequency jumps, as function of bias current, between stationary nonlinear modes with different spatial distribution [10,11].

As can be noted, those measurements also show a non-stationary magnetization dynamics related to nanosecond switching between a dynamical mode and a static magnetic configuration or between different dynamical modes [11]. In the latter case, this non-stationary regime is characterized by a spectrum with two well-defined peaks in frequency, and it is observed before that large-amplitude magnetic precession is excited [10].

In [12], we demonstrated how a continuous wavelet analysis (WA) is able to systematically reveal the non-stationary regime of experimental time-domain data [11]. We also predicted that, by combining micromagnetic simulations and WA, the excited modes of a spin-torque oscillator (STO) show together to a frequency modulation [13] a nanosecond intermittent disappearing and reappearing of the instantaneous microwave output power. In our present work, we introduce the use of the HHT (Hilbert–Huang Transform) in order to extract these modal components.

Concerning the same kind of devices, experimental data published in Ref. [11] show that non-stationary magnetization dynamics is driven before of the large-amplitude magnetization precession. In particular, for $I=4.5$ mA and $H=600$ Oe, the power spectrum of the real-time voltage signal (for a signal of 20 ns see Fig. 6(e) in Ref. [11]), captured via microwave single-shot storage-oscilloscope at which frequency jumps have been observed as shown in Fig. 6(a) of Ref. [11], reveals two excited modes P1 and P2 (where $f_{P1}=3.9$ GHz and $f_{P2}=4.6$ GHz). The origin of such dynamics has been studied in our previous work [11] and a tool for computing the MWS (Micromagnetic Wavelet Scalogram) has been presented to systematically give information of the excitations in the time–frequency space.

In the present work, we propose the use of an emerging technique in order to extract independent modal information from the time domain signal. Our technique applied to the voltage signal $x(t)$ of the STO demonstrates that can completely characterize the origin of the excited modes, furnishing information which is complementary to the one of the WA.

2. Description of the experimental setup

The experimental framework is the same as depicted in Ref. [10] and is composed by a magnetic multilayer consisting of Cu (80 nm)/$Ir_{20}Mn_{80}$ (8 nm)/Py (4 nm)/Cu (8 nm)/Py (4 nm)/Cu

* Corresponding author. Tel.: +39 340 7123548; fax: +39 090 8967948.
E-mail address: giuliosiracusano@gmail.com (G. Siracusano).

0921-4526/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physb.2013.07.034

(20 nm)/Pt (30 nm) onto an oxidized Si wafer (Py=$Ni_{80}Fe_{20}$). Measurements are shown in the voltage trace of Fig. 6(c) of Ref. [11] and have been performed under the bias conditions (applied current $I=4.5$ mA and under $H=600$ Oe), while the sampling frequency was 20 GHz.

3. Theory

3.1. Wavelet analysis

In our study, in order to identify the non-stationary behavior of the STO, we adopted the Wavelet-based method developed in Ref. [14], in particular we computed the MWS of $x(t)$, using $f_B=50, f_C=1$ with $N=40$ as the scale set $\{s_i\}_{i=1,\dots,N}$ dimension for the wavelet transform. The use of this WA allows to characterize a signal in the time–frequency space and to study eventual non-stationary behaviors.

3.2. Hilbert–Huang transform

HHT [15,16] is a recently developed method which has proven successful in the study of the nonlinear behavior of time series. By means of this technique, complex sets of non-linear, non-stationary data sets can be decomposed into a finite collection of individual characteristic oscillatory modes, named intrinsic mode functions (IMF), through a process known as Empirical Mode Decomposition (EMD). These IMFs have well defined instantaneous frequencies, and are assumed to represent the inherent oscillatory modes embedded in the original signal. HHT consists of two parts: Hilbert transform (HT) and EMD. Given a time-domain function $x(t)$, its Hilbert transform $y(t)=H\{x(t)\}$ is defined as $y(t)=\frac{P}{\pi}\int_{-\infty}^{\infty}\frac{x(s)}{t-s}\,ds$, where P is the Cauchy principal value. If $z(t)$ is the analytic signal associated to $x(t)$, we have, for all t, $z(t)=x(t)+iy(t)=A(t)e^{i\theta(t)}$, where $A(t)=\sqrt{x^2(t)+y^2(t)}$ and $\theta(t)=\arctan\left(\frac{y(t)}{x(t)}\right)$ are the instantaneous amplitude and phase associated to the signal, respectively. The instantaneous frequency $\omega(t)$ is defined as, $\omega(t)=d\theta(t)/dt$ while the instantaneous power, $P(t)=|A(t)|^2$, reflects how the power of the signal $x(t)$ varies with time. A generalization of the notion of such an analytic signal to a multi-component one is possible by using the EMD method which is described in Ref. [15].

It is an adaptive and efficient method to decompose nonlinear and non-stationary signals. EMD extracts a series of IMFs $c_i(t)$ from the analyzed signal by means of an iterative method which is known as *sifting* process [15,16]. If n ortogonal IMFs are obtained through EMD, then the original signal can be reconstructed by using the HT as in the following equation:

$$x(t)=\sum_{j=1}^{n}c_j(t)+r(t) \tag{1}$$

while the residue signal $r(t)$ is not an IMF. In terms of the Hilbert transform

$$x(t)=\mathrm{Re}[z(t)]\approx \mathrm{Re}\left[\sum_{j=1}^{n}A_j(t)\exp\left(i\int\omega_j(t)dt\right)\right] \tag{2}$$

where the residue $r(t)$ is ignored. Eq. (2) can be seen as a generalized form of the Fourier decomposition for $x(t)$ where both amplitude $A(t)$ and frequency $\omega(t)$ are functions of time. This principle insures that the instantaneous amplitude and frequency of each component of the resulting signal have physical meaning. Nevertheless, the original EMD fails to separate modes whose frequencies lie within an octave [17] and the mode-mixing [15,16] is common in IMFs, especially when excited dynamics give rise to modes with intermittent behavior, like the current trace $x(t)$. As noted in Refs. [16,18], intermittency is a major obstacle to the use of EMD on many signals and can be described as a component, at a particular time scale, either coming into existence or disappearing from a signal entirely. Since EMD locally separate the highest frequency component as the current IMF, intermittency in a signal causes that the frequency captured by a given IMF will jump as the intermittent component is active or not, disturbing overall filtering process. Assisted signals (also called as masking signals in some papers [19–21]) are the most accepted methods to improve the resolution capabilities in EMD. In this sense, we used a masking signal to solve the mode mixing problem when dealing with the optimal extraction of intermittent "high" and "low" modes. For each IMF affected by mode mixing, a mask signal $mask_j(t)$ is applied on EMD according to the method in Ref. [19] ($j=1,\dots,n$), with $f_1<f_2<\dots<f_n$, setting

$$mask_j(t)=M_j\ \sin\left(2\pi(f_j+f_{j-1})\right) \tag{3}$$

where $M_j=R_jA_j$, while R_j is a dimensionless amplification factor, A_j is the amplitude of frequency peak f_j obtained by the FFT spectrum. It is significant that, by means of this tool, we are able to distinguish the oscillation modes in the time domain for a better understanding of nonlinear dynamics which take place in our system.

4. Results and discussion

4.1. Combined wavelet and HHT-based analysis

Fig. 1(a) shows the time trace of the voltage signal $x(t)$ for a nanosecond window of 0–20 ns as in Fig. 6(c) of Ref. [11], whereas in the inset displays its normalized Fourier spectrum (equivalent to the plot in Fig. 6(e) of Ref. [11]) where the two peaks P1 and P2 ($f_{P1}=3.9$ GHz and $f_{P2}\approx 4.6$ GHz) can be identified, indicating the excitation of two modes for a wide nanosecond interval. The intensities of the two peaks are of the same order, suggesting that the excited modes are independent components of a mainly stationary signal. However, further numerical investigations will describe a completely different scenario.

In Fig. 1(b) we plot the MWS of $x(t)$ as in Fig. 2(b) of Ref. [12], confirming the existence of two non-stationary oscillation regimes, at f_{P1} for the "low" and f_{P2} for the "high" frequency mode, respectively. By means of MWS we are able to identify different regions of interest (ROIs) related to the existence of the former or the latter. There is no evidence of a time interval wherein both modes are simultaneously excited.

In particular, concerning the same figure, we see how the "low" mode exists in the time windows R1 [0–7 ns] and R2 [15–16 ns], while the "high" mode exists in R3 [8–9 ns], R4 [10–14 ns] and R5 [17–20 ns]. Results highlight the different inner nature of each modal component, both in terms of intensity-duration relationship of excitations and localization in time. In particular we observe that the "low" mode is less intermittent and has higher amplitude compared to the "high" mode [which will be confirmed in Fig. 2(b)], while, conversely, the latter has a lower amplitude [again, it is confirmed in Fig. 2(a)] but is more intermittent, owing a larger temporal presence.

In order to gain further insights into the spin-wave dynamics, we performed an additional time domain study by using the HHT on $x(t)$, applying the EMD to investigate the instantaneous properties of the signal. Fig. 2(a) shows a time-domain representation of "high" frequency and (b) "low" frequency harmonics obtained by HHT. Normalized Fourier spectrum plots are presented for "high" mode (inset of Fig. 2(a)) and "low" mode (inset of Fig. 2(b)),