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Assessment of magnetoelastic resonance parameters retrieval for sensor applications

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ABSTRACT

Magnetoelastic resonance sensors have been widely used for several sensing applications, as their resonance behavior is very sensitive to different external factors and they can be operated remotely. Nevertheless, under some working conditions, such as when the sensor signal is low, has considerable noise, or the medium viscosity causes damping of the signal, the accuracy in obtaining the parameters that characterize the resonance response of these sensors by direct methods can decrease. The aim of this work is to improve the performance of magnetoelastic sensors through the use of numerical fittings of the resonance curves to obtain accurately the resonance parameters used for detection. The capability of these numerical fittings to retrieve the parameters when signals present different levels of noise is evaluated, and the accuracy of this fitting method is compared with the precision of classical direct methods.

1. Introduction

Magnetoelastic resonance sensors are usually made of amorphous ribbon-shaped ferromagnetic alloys [1]. Due to the strong coupling between the magnetic and mechanical properties of these materials, elastic waves can be excited in them by the application of an alternating magnetic field. And conversely, mechanical vibrations change the magnetic state of the material and thus, can be magnetically detected. At specific frequencies of excitation, determined by the physical dimensions and elastic properties of the material, the phenomenon of magnetoelastic resonance occurs in these materials. The resonance frequencies are given by:

$$f_n = \frac{n}{2L}\sqrt{\frac{E}{\rho}} \tag{1}$$

where L corresponds to the length of the ribbon, ρ to its density, E is the Young modulus of the material, and n indicates the resonance mode, being $n = 1$ the fundamental resonance frequency (f_r). This resonance behavior is highly sensitive to different external parameters, which can be used to design several sensing devices [2,3]. Magnetoelastic sensors have been used to measure liquid viscosity and density [4], several environmental parameters such as humidity or temperature [5], pH [6], to detect nanoparticles [7], and to detect and monitor chemical and biological agents [8–11]. Usually, the shift of the resonance frequency of these sensors (f_r) under the effect of the external parameter is used for sensing purposes; however, other parameters that characterize the resonance curves are also sensitive to external factors, e.g., the coupling parameter k, or the quality factor Q (which accounts for the sharpness of the resonance peak). These parameters also have information about the resonance and the effect that the element to be detected has on it, and can also be used for monitoring the changes in the sensor signal [12]. There are some direct methods to obtain these parameters: f_r is taken as the frequency corresponding to the maximum amplitude of the signal, the quality factor is calculated as $Q = f_r/\Delta f$ (being Δf the Full Width at Half Maximum (FWHM)), and the coupling parameter is calculated from the resonance and anti-resonance frequencies as $k^2 = \pi^2/8\left(1-(f_r/f_a)^2\right)$ [13]. Nevertheless, when the sensor signal presents noise or a lot of damping (for example, when measurements are carried out in liquid media), obtaining the parameters that define the resonance by direct methods may not be accurate. In the present work, we propose the performance of numerical fittings of the whole magnetoelastic resonance curves to an analytical expression that describes the resonance behavior in order to obtain the governing parameters of this resonance signal accurately, even when noise is present, or the signal has poor quality. The ability of the fittings to retrieve the parameters is compared to the performance of direct method calculations and

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evaluated for different levels of noise in the resonance signal.

2. Methodology

The frequency response of the magnetoelastic sensor can be described with the following expression [12,14]:

$$\chi(\omega) = \chi_0\left[1 - \frac{8k^2}{\pi^2}\frac{1}{1-\omega_r^2/\omega^2 + jQ^{-1}\omega_r/\omega}\right] \quad (2)$$

where $\omega_r = 2\pi f_r$ is the resonance frequency, k is the coupling parameter, Q the quality factor and χ_0 the susceptibility at $\omega = 0$. Numerical fittings were carried out with a non-linear least-squares fitting of the data to expression (2) using MATLAB®. ω_r, k^2 and Q were the fitted parameters (which are the governing parameters of the resonance), and χ_0 was normalized to 1.

In order to evaluate the accuracy in obtaining the governing resonance parameters, the procedure was as follows (Fig. 1): First, theoretical curves were generated using expression (2) and a given value for each parameter (Fig. 1(a)); then white Gaussian noise was added to the generated data (Fig. 1(b)); finally the main resonance parameters selected in the first step were retrieved from the noisy curves by using two different procedures: the direct method calculations (as indicated in black, in Fig. 1(a)), and the numerical fittings of the curves to expression (2) (Fig. 1(c)). The accuracy in the recovery of the parameters obtained by each procedure was compared and analyzed as a function of the level of noise added to the signal. Fig. 2 shows the effect that the values of Q and k have on the sensor signal. As it can be seen, Q parameter accounts for the sharpness of the resonance peak (the relation between the amplitude and the width of the peak). As Q increases, the signal amplitude is more significant, and the peak is sharper (Fig. 2(a)). The coupling parameter k also affects the resonance amplitude and determines the anti-resonance frequency and the drop of the susceptibility at high frequencies (Fig. 2(b)).

The study was performed for different combinations of Q and k^2 values, with Q ranging between 5 and 20, and k^2 between 0.5 and 0.9, as it appears in Fig. 2. The performance of both methods was tested for different *SNR* values: 10, 20, 30, 40 and 50.

3. Results

An example of the retrieval of the resonance parameters is shown in Fig. 3. Fig. 3(a) shows the recovered values of the parameter Q (when it has a value of $Q = 10$) for different values of k^2 and different values of the signal-to-noise ratio (*SNR*). Fig. 3(b) shows the recovered values of k^2 when it has a value of $k^2 = 0.8$, for different Q and *SNR* values. The values retrieved from the numerical fittings of the noisy curves are depicted in blue in Fig. 3, whereas the values calculated from direct methods are represented in black.

As seen in Fig. 3, the values retrieved from the numerical fitting to expression (2) are more accurate than those calculated through direct methods, especially when *SNR* has a low value and the noise is significant compared to the signal amplitude. In those cases, the error in determining the parameters through direct calculation can be considerable. Table 1 shows an example of the values of the key resonance parameters obtained from the fitting compared with those obtained by direct methods. In Table 1 it can be seen that fits retrieve the theoretical values of the parameters in a more reliable way.

In order to evaluate the accuracy of each method in the determination of the parameters, the error relative to the theoretical value (%) was analyzed (Table 2, Table 3 and Table 4).

As compiled in Tables 2, 3 and 4, the accuracy in the retrieval of the parameters was clearly greater in all cases when numerical fits were used compared to the results calculated by direct methods. This improvement is, in general, more noticeable as the quality factor and the

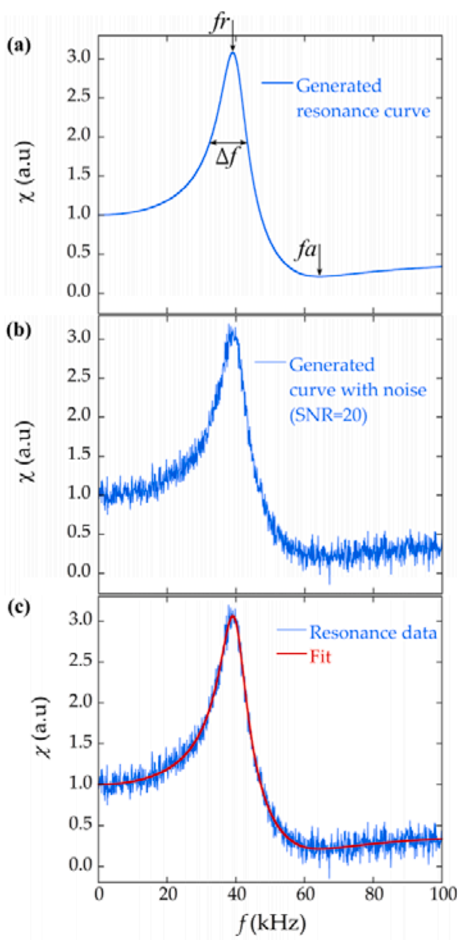

Fig. 1. **(a)** Generated magnetoelastic resonance curve with parameters: $\omega_r = 40$ kHz, $Q = 5$, $k^2 = 0.7$ and $\chi_0 = 1$. The procedure to obtain the parameters by direct methods (Δf, f_r, f_a) is indicated in black. **(b)** Generated resonance curve with added white noise, the signal to noise ratio (*SNR*) is, in this case, 20. **(c)** Numerical fitting to expression (2) of the data of the noisy resonance curve appearing in **(b)**.

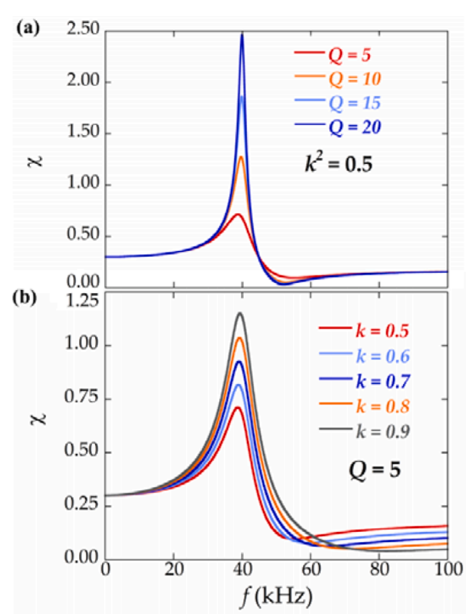

Fig. 2. Effect on the resonance signal of **(a)** the quality factor Q and **(b)** the coupling parameter k.

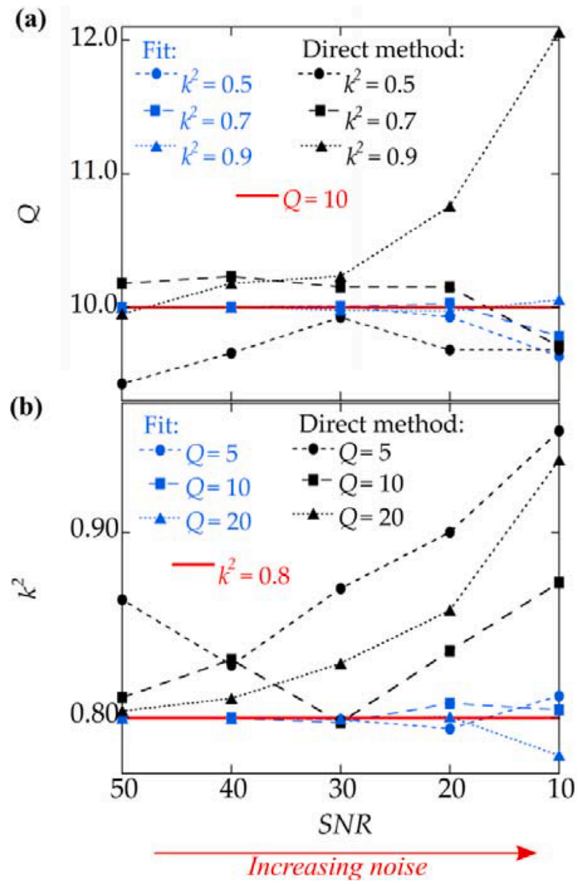

Fig. 3. Evaluation of the retrieval, as a function of *SNR*, of: **(a)** the quality factor (Q) for a value of $Q = 10$ and different values of the coupling parameter; and **(b)** the coupling parameter ($k^2 = 0.8$) and different values of the quality factor. Values obtained from the numerical fits are depicted in blue, and values calculated by direct methods are shown in black. The theoretical value to be retrieved is shown in red.

Table 1
Comparison between the parameters used to generate the theoretical curves, those retrieved through the numerical fit, and those calculated from direct methods when the signal has a level of noise corresponding to an $SNR = 20$.

	Theoretical	Calculated	Retrieved (Fit)
ω_r(kHz)	40.00	37.90	40.02
Q	5.00	4.35	4.95
k^2	0.70	0.84	0.69

coupling parameter take smaller values, and the peak has less quality and more damping. The reduction in the error when numerical fittings are used is more evident for the parameters Q and k^2, which are more sensitive to noise than ω_r.

4. Conclusions

In the present work, numerical fittings of the resonance curves of a magnetoelastic sensor were evaluated as a tool to retrieve the governing parameters of the resonance in order to improve the detection. This method has been demonstrated to be more accurate in obtaining the parameters that describe the resonance than the classical direct methods, in particular when signals have considerable noise or damping. This makes the use of these numerical fittings suitable for improving the detection with magnetoelastic sensors.

Table 2
Comparison of the relative error in the determination of the quality factor Q (relative to its theoretical value, in %) through both methods: calculated by the direct formula and retrieved from numerical fit. Results are shown for different values of the parameters and different values of *SNR*.

		Error in Q (%)	
	SNR	Calculated	Retrieved (Fit)
$Q = 5k^2 = 0.5\omega_r = 40$kHz	10	26.54	6.93
	30	20.42	0.16
	50	17.87	0.03
$Q = 5k^2 = 0.9\omega_r = 40$kHz	10	8.33	1.27
	30	3.46	0.29
	50	4.15	0.01
$Q = 20k^2 = 0.5\omega_r = 40$kHz	10	10.55	2.70
	30	5.00	0.09
	50	5.00	0.02
$Q = 20k^2 = 0.9\omega_r = 40$kHz	10	10.55	0.94
	30	5.00	0.09
	50	5.26	0.01

Table 3
Comparison of the error in the determination of k^2 (relative to its theoretical value, in %) through both methods: calculated by the direct formula and retrieved from numerical fit. Results are shown for different values of the parameters and different values of *SNR*.

		Error in k^2 (%)	
	SNR	Calculated	Retrieved (Fit)
$Q = 5k^2 = 0.5\omega_r = 40$kHz	10	46.06	2.64
	30	22.35	0.13
	50	26.96	0.04
$Q = 5k^2 = 0.9\omega_r = 40$kHz	10	5.30	2.39
	30	11.60	0.13
	50	5.12	0.01
$Q = 20k^2 = 0.5\omega_r = 40$kHz	10	10.69	3.01
	30	2.03	0.03
	50	3.13	0.00
$Q = 20k^2 = 0.9\omega_r = 40$kHz	10	1.39	1.11
	30	1.48	0.06
	50	0.49	0.01

Table 4
Comparison of the error in the determination of the resonance frequency ω_r (relative to its theoretical value, in %) through both methods: taken directly from the maximum and retrieved from numerical fit. Results are shown for different values of the parameters and different values of *SNR*.

		Error in ω_r (%)	
	SNR	Calculated	Retrieved (Fit)
$Q = 5k^2 = 0.5\omega_r = 40$kHz	10	4.50	0.12
	30	4.50	0.05
	50	3.50	0.00
$Q = 5k^2 = 0.9\omega_r = 40$kHz	10	2.50	0.42
	30	2.25	0.04
	50	1.75	0.00
$Q = 20k^2 = 0.5\omega_r = 40$kHz	10	0.50	0.05
	30	0.25	0.01
	50	0.25	0.00
$Q = 20k^2 = 0.9\omega_r = 40$kHz	10	0.50	0.03
	30	0.25	0.01
	50	0.00	0.00

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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