Improvement of the relative sensitivity for obtaining a high performance piezoelectric sensor

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Improvement of the relative sensitivity for obtaining a high performance piezoelectric sensor

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Abstract

A piezoelectric sensor is a sensor using the piezoelectric effect in order to measure physical quantities such as pressure, acceleration, or any other physical quantity generating stresses or mechanical deformations through active materials (magnetic, electrical, thermal , mechanical...). In this paper, the operating principle of the piezoelectric sensor is defined in detail and it is translated to mathematical model (ie the modeling of this type of sensors). This developed model is related the accelerometer electrical parameters with their mechanical parameters, and simulation of this model allows to choose the appropriate damping rate of the sensor which minimizes measurement error and improves accuracy and sensitivity of this one. The proposal of a new relation links the relative frequency by the natural frequency of the piezoelectric accelerometer makes it possible to minimize the resonance phenomenon effect, to facilitate the suitable choice of the accelerometer and to protect it.

Keywords: *Measurement, Sensor, Frequency Accuracy.*

Introduction

Rotating machines are widely present in many industrial installations. The failures that can be encountered on a rotating machine are numerous. Given the importance of these rotating machines in certain devices, it is necessary to find out about their mechanical condition, in order to be able to take the appropriate decisions about their mechanical condition at the right time.

One of the means of monitoring the mechanical state of a rotating machine is the collection and analysis of its vibrations. Vibrations are an integral part of our universe. The slightest movement causes vibrations of varying amplitude and duration, from the slow oscillation of a suspension bridge excited by the wind to the shock generated on landing by an airplane, including the noise of the engines of our cars. This vibratory environment is felt by all the equipment we use in everyday life and can cause malfunctions going as far as the destruction of the material in question [1-2].

The moving parts generate vibrations and over time these vibrations degrade these parts, and the use of vibration analysis makes it possible to detect their fatigue and faults at an early stage [3-6].

In recent years, piezoelectric sensors have played a much different role from their conventional pressure sensing functions for test and measurement applications. Several research studies have been carried out to optimize the electrical performances of the piezoelectric sensor. [7-15]. On the other hand, in this paper; the piezoelectric sensor is chosen to study it, as well as to present their physical behavior in mathematical equations. the objectives of this work are:

- The appropriate choice of the depreciation rate
- Proposal of a formula which links the different parameters of this type of sensors (mechanical and electrical)
- Piezoelectric sensor performance improvements
- Reducing the effect of the resonance phenomenon by proposing a new relationship connects the relative frequency with the natural frequency of the piezoelectric accelerometer.

2. Piezoelectric technology

A piezoelectric material is a material across which an electric field forms when a force is applied to its ends. Likewise if a voltage is applied across the same material, it deforms. The first effect is called the direct piezoelectric effect and the second inverse piezoelectric effect (Fig1). These effects were discovered by Pierre and Jacques Curie in 1880 [16].

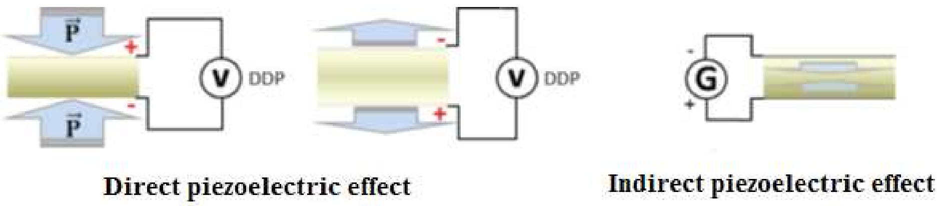

Fig.1. Direct and indirect piezoelectric effects.

Piezoelectric materials are particularly numerous. The best known is probably quartz, still used today in watches to generate clock pulses. But it is synthetic ceramics, PZTs, which are currently most widely used in industry.

Many natural crystals exhibit piezoelectric properties. We can cite quartz, topaz, tourmaline, berlinite (AlPO4) or sugar. In practice, the materials used for the manufacture of the various systems are synthetic materials which can be classified according to their crystallographic structure or their chemical composition.

4. Sensor modeling

In general, the vibration sensor is considered as a system made up of a mass, a spring and a shock absorber.

In this case, the displacement is expressed as follows:

$$z(t) = x(t) - y(t) \quad (1)$$

To model this system, we apply Newton's second law as shown in Equation 2:

$$\sum F = m\gamma = mp^2 z \quad (2)$$

Where: p is the Laplace coefficient

We then obtain the following formula:

$$mp^2 z + cpz + kz = -mp^2 y \quad (3)$$

Where: m is the mass, c is the friction coefficient, k is the elasticity coefficient, y is the absolute motion and p^2y is the absolute acceleration.

The simplification of equation 3, gives the expression of displacement z as a function of the sensor natural frequency, the damping rate and the relative frequency of the vibratory movement as shown below (Equation 4) [17]:

$$z = \frac{y\omega^2}{\omega_0^2 \sqrt{\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega_0}\right)^2}} \quad (4)$$

With: ω_0: natural frequency of sensor, ξ: damping rate, ω: vibratory movement relative frequency

The sensitivity of the piezoelectric sensor is expressed by:

$$S = \frac{d.C}{\sqrt{1+(\frac{\omega_C}{\omega})^2}} \cdot \frac{1/\omega_0^2}{\sqrt{(1-\frac{\omega^2}{\omega_0^2})^2+(2.\zeta.\frac{\omega}{\omega_0})^2}} \quad (5)$$

The sensor relative sensitivity is expressed as follows:

$$S_r = \frac{S}{S_m} \quad (6)$$

Where:

$$S_m = \frac{d.C}{\omega_0^2} \quad (7)$$

So:

$$S_r = \frac{1}{\sqrt{1+\left(\frac{\omega_C}{\omega}\right)^2}} . \frac{1}{\sqrt{\left(1-\frac{\omega^2}{\omega_0^2}\right)^2 + (2.\zeta.\frac{\omega}{\omega_0})^2}} \quad (8)$$

From the two equations (4 and 8), we can express an equation of the relative sensitivity as a function of the motion displacement [14]:

$$S_r = \frac{1}{\sqrt{1+\left(\frac{\omega_C}{\omega}\right)^2}} . \frac{z\omega_0^2}{Y\omega^2} \quad (9)$$

The measurement error of the piezoelectric sensor is given by the following equation [14]:

$$E = \frac{1}{\sqrt{\left(1-(\omega/\omega_n)^2\right)^2 + (2\zeta\omega/\omega_n)^2}} - 1 \quad (10)$$

The relative sensitivity as a function of the measurement error of the sensor is expressed by the following new formula:

$$Sr = \frac{1}{\sqrt{1+\left(\frac{\omega_C}{\omega}\right)^2}} . (E+1) \quad (12)$$

The cutoff pulse ω_C can be expressed by the following formula:

$$\omega_C = \frac{\omega}{\tan\delta} \quad (13)$$

The following table shows the parameters of the piezoelectric material PZT (PZ27) (see table.1) [17].

Table.1. PZT (PZ27) piezoelectric material parameters

Parameters	Value	Unit
Accelerometer internal impedance (C)	7835 at 1Khz	pf
Piezoelectric constant (d)	500	pC/N
tan δ	15.85	10^{-3}

5. Simulation results

The parameters of the piezoelectric sensor used for simulation of the developed model are natural frequency of the sensor = 10000Hz, damping rate =0.6, 0.63, 0.65, 0.68 and 0.7, relative frequency varies from 0 to 4200Hz and amplitude of the movement =0.5 mm.

Table 2 and figure 2 show the displacement of the movement (z) as a function of the relative frequency variation and for various values of the sensor damping rate:

Table.2. Displacement results

	Displacement (mm)				
Frequency (Hz)	ζ = 0.6	ζ = 0.63	ζ = 0.65	ζ = 0.68	ζ = 0.7
0	0	0	0	0	0
300	0.0005	0.0005	0.0005	0.0005	0.0005
600	0.0018	0.0018	0.0018	0.0018	0.0018
900	0.0041	0.0041	0.0041	0.0041	0.0041
1200	0.0072	0.0072	0.0072	0.0072	0.0072
1500	0.0113	0.0113	0.0113	0.0113	0.0113
1800	0.0163	0.0163	0.0163	0.0162	0.0162
2100	0.0223	0.0222	0.0222	0.0221	0.0220
2400	0.0292	0.0291	0.0290	0.0289	0.0288
2700	0.0371	0.0369	0.0368	0.0366	0.0364
3000	0.0460	0.0457	0.0455	0.0451	0.0449
3300	0.0558	0.0554	0.0551	0.0546	0.0542
3600	0.0667	0.0660	0.0656	0.0649	0.0644
3900	0.0785	0.0776	0.0770	0.0760	0.0754
4200	0.0913	0.0901	0.0893	0.0880	0.0872

This table show that the displacement has slightly varied with the damping rate variation.

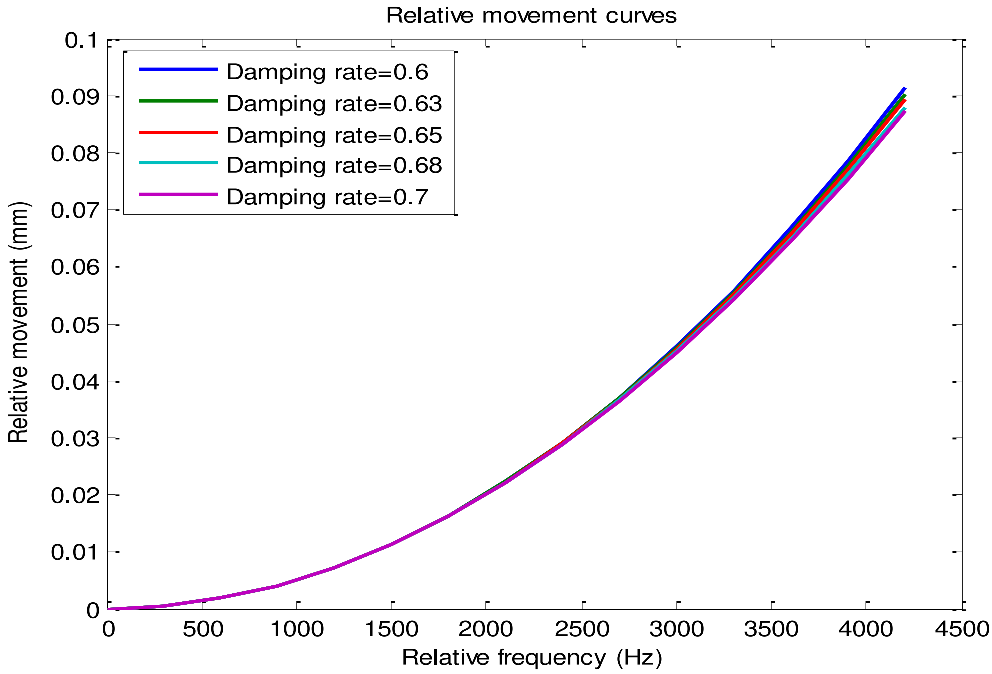

Fig.2. Displacement as a function of the relative frequency

There is a little difference between the five curves in figure 2, which implies the effect of the damping rate variation on the piezoelectric sensor measurement error.

For this purpose, the error equation is simulated to extract the appropriate damping rate to reduce it. The results are illustrate in Table 3 and Figure 3.

Table.3. Measurement error results

	Error (%)				
Frequency(Hz)	ζ = 0.6	ζ = 0.63	ζ = 0.65	ζ = 0.68	ζ = 0.7
0	0	0	0	0	0
300	0.03	0.02	0.01	0.01	0.005
600	0.10	0.07	0.06	0.03	0.01
900	0.22	0.16	0.12	0.06	0.01
1200	0.4	0.29	0.21	0.10	0.02
1500	0.61	0.44	0.33	0.14	0.02
1800	0.87	0.62	0.45	0.19	0.01
2100	1.16	0.82	0.59	0.24	-0.01
2400	1.48	1.04	0.73	0.27	-0.005
2700	1.82	1.26	0.88	0.28	-0.12
3000	2.18	1.48	1	0.27	-0.22
3300	2.55	1.69	1.11	0.23	-0.37
3600	2.91	1.88	1.19	0.14	-0.58
3900	3.25	2.04	1.22	-0.01	-0.84
4200	3.57	2.15	1.20	-0.23	-1.18

Table 3 present the measurement error results as a function of relative frequency for 5 damping rates.

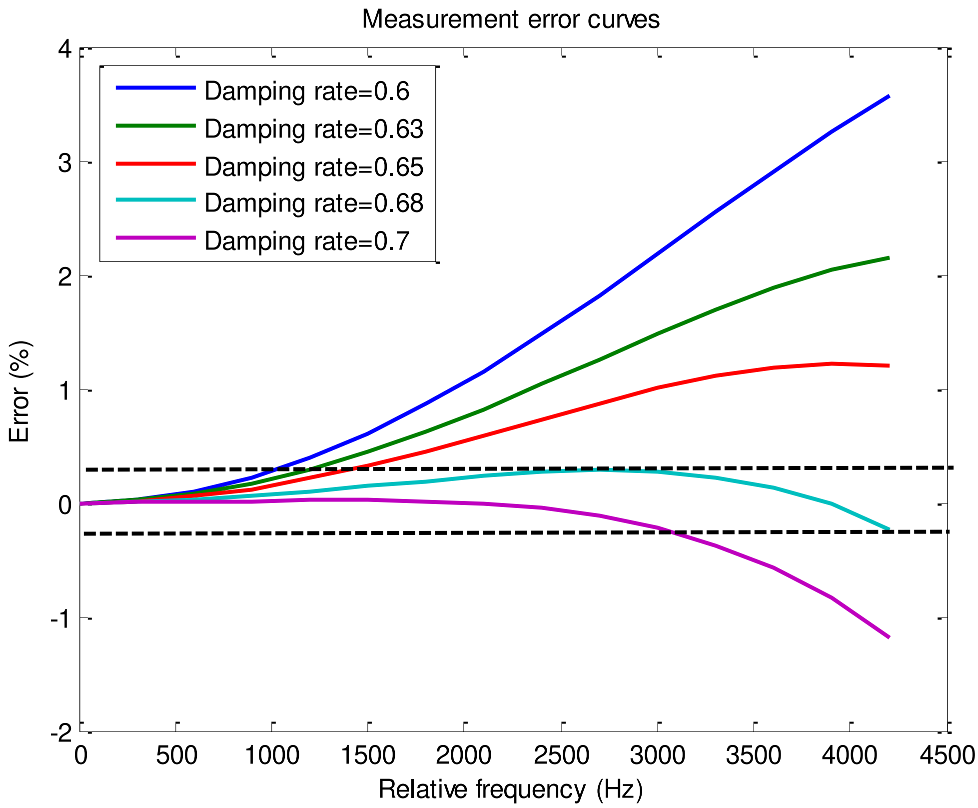

Fig.3. Error as a function of relative frequency for 5 values of damping rate

We notice from these results that:

- For a variation of the relative frequency from 0 to 4200Hz and a choice of the damping rate of 0.6, the measurement error does not exceed a value which equals 3.57%.

- For a variation of the relative frequency from 0 to 4200Hz and a choice of the damping rate of 0.63, the measurement error does not exceed a value which equals 2.15%.
- For a variation of the relative frequency from 0 to 4200Hz and a choice of the damping rate of 0.65, the measurement error does not exceed a value which equals 1.2%.
- For a variation of the relative frequency from 0 to 4200Hz and a choice of the damping rate of 0.68, the measurement error does not exceed a value which equals 0.28%.
- For a variation of the relative frequency from 0 to 4200Hz and a choice of the damping rate of 0.7, the measurement error does not exceed a value which equals 1.18%.

The damping rate suitable for the piezoelectric sensor according to table 3 and figure 3 to minimize the measurement error to a value equal to 0.28% is to 0.68.

The simulation of the new expression of relative sensitivity is shown in table 4 and figure 4:

Table.4. Relative sensitivity results

	Relative sensitivity (mV/g)				
Frequency (Hz)	$\zeta = 0.6$	$\zeta = 0.63$	$\zeta = 0.65$	$\zeta = 0.68$	$\zeta = 0.7$
0	0.0159	0.0159	0.0159	0.0159	0.0159
300	0.0159	0.0159	0.0159	0.0159	0.0159
600	0.0159	0.0159	0.0159	0.0159	0.0159
900	0.0159	0.0159	0.0159	0.0159	0.0159
1200	0.0159	0.0159	0.0159	0.0159	0.0159
1500	0.0159	0.0159	0.0159	0.0159	0.0159
1800	0.0160	0.0159	0.0159	0.0159	0.0159
2100	0.0160	0.0160	0.0159	0.0159	0.0158
2400	0.0161	0.0160	0.0160	0.0159	0.0158
2700	0.0161	0.0160	0.0160	0.0159	0.0158
3000	0.0162	0.0161	0.0160	0.0159	0.0158
3300	0.0163	0.0161	0.0160	0.0159	0.0158
3600	0.0163	0.0161	0.0160	0.0159	0.0158
3900	0.0164	0.0162	0.0160	0.0158	0.0157
4200	0.0164	0.0162	0.0160	0.0158	0.0157

Table 4 show the relative sensitivity results as a function of the relative frequency for five values of the damping rate.

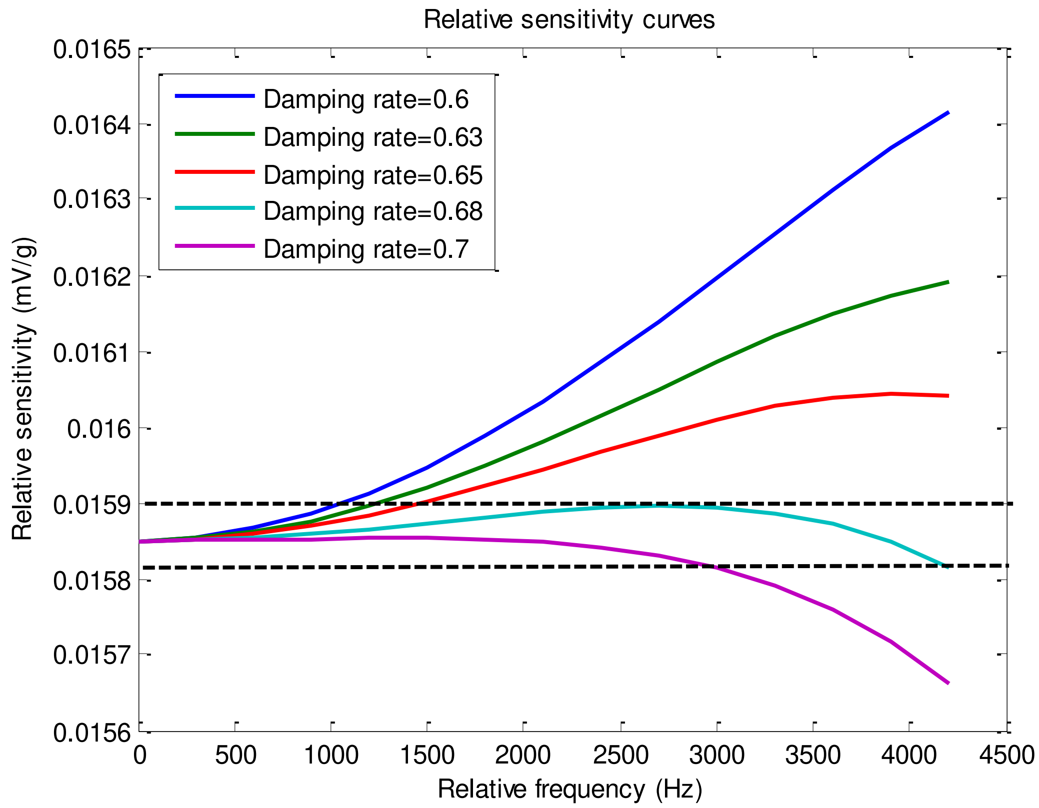

Fig.4. The accelerometer relative sensitivity as a function of relative frequency for various values of the damping rate

From the results obtained in the table 4 and the figure 4, we notice that:

- The relative sensitivity is equal to 0.0159 mV / g ± 0.5%, if the damping rate choice is equal to 0.6 and the relative frequency variation is from 0 to 4200Hz.
- The relative sensitivity is equal to 0.0159 mV / g ± 0.3% if the damping rate choice is equal to 0.63 and the relative frequency variation is from 0 to 4200Hz.
- The relative sensitivity is equal to 0.0159 mV / g ± 0.15%, if the damping rate choice is equal to 0.65 and the relative frequency variation is from 0 to 4200Hz.
- The relative sensitivity is equal to 0.0159 mV / g ± 0.1%, if the damping rate choice is equal to 0.68 and the relative frequency variation is from 0 to 4200Hz.
- The relative sensitivity is equal to 0.0159 mV / g ± 0.25%, if the damping rate choice is equal to 0.7 and the relative frequency variation is from 0 to 4200Hz.

We deduce that the damping rate which equals 0.68 makes it possible to obtain a constant sensitivity, which implies that the sensor is more sensitive and precise.

6. Influence of the resonance phenomenon on the accelerometer operation:

Vibrations are generally undesirable. Resonance is a phenomenon that presents itself in various aspects; it manifests by an amplification of the response or the vibrations amplitude of any system as a function of the excitation frequencies.

In piezoelectric accelerometers, if the relative frequency of the vibratory movement approaches of the sensor natural frequency; the phenomenon of resonance appears. To reduce the effect of this phenomenon, a relationship must be found between the relative frequency of movement and the accelerometer natural frequency, which allows the appropriate frequency margin to be determined for the piezoelectric accelerometer.

To simulate the piezoelectric accelerometer model in the presence of resonance phenomenon, it is necessary to vary the relative frequency from 0 up to 10,000 Hz knowing that the natural frequency of the accelerometer is equal to 10,000Hz. The simulation results of displacement and measurement error are presented in the following two figures (Fig.5 and Fig.6):

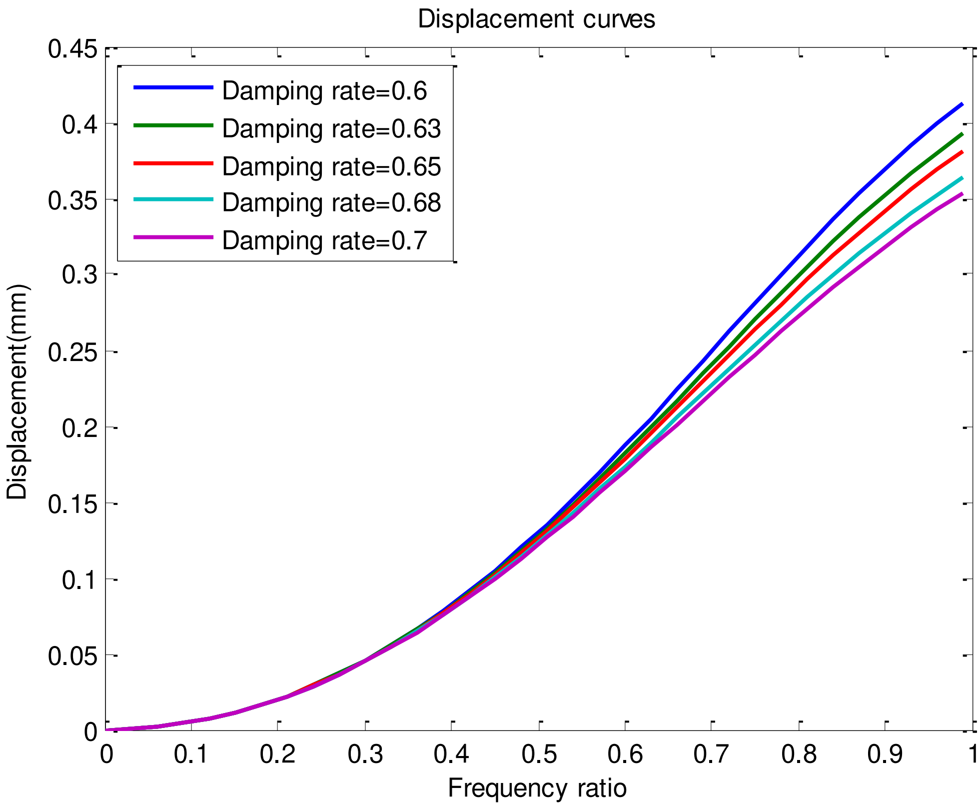

Fig.5. Displacement as a function of frequency ratio in the resonance phenomenon

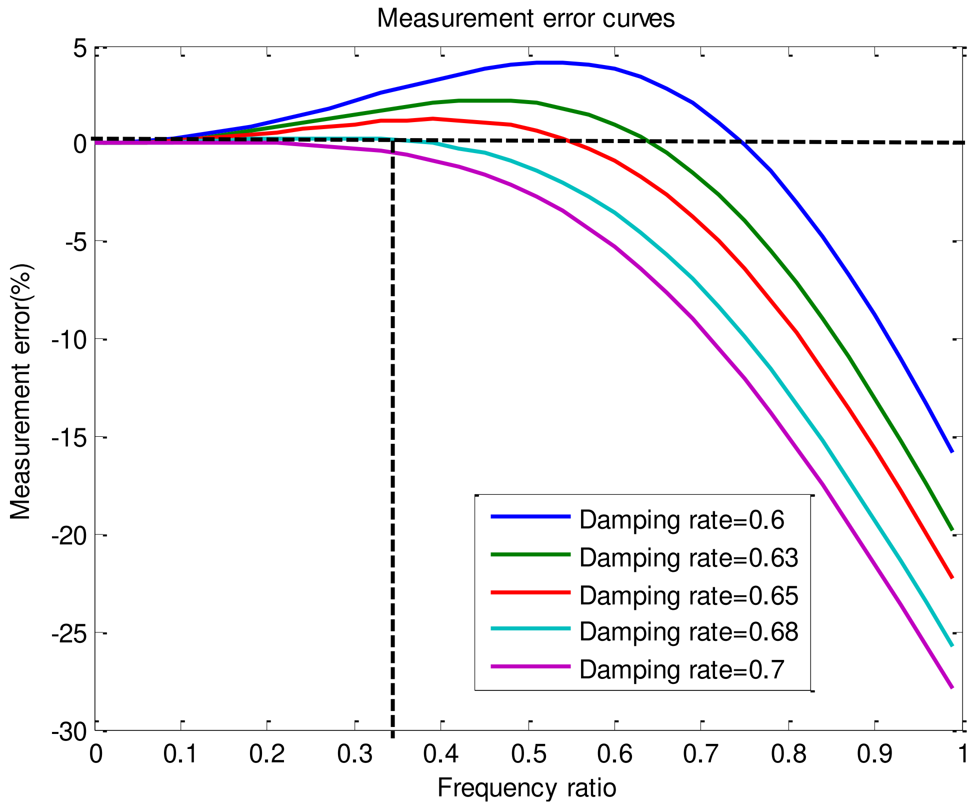

Fig.6. Measurement error as a function of frequency ratio in the resonance phenomenon

The results of Figure 5 and Figure 6 illustrate that the piezoelectric accelerometer loses their performance in the case where the relative frequency approaches to the natural frequency (the measurement error takes the maximum values). From figure (6), we see that the reduction in the effect of the resonance phenomenon and the measurement error of the accelerometer occurred if we take a frequency ratio less than or equal to 0.35 (as shown in relation (14)).

$$\frac{\omega}{\omega_0} \leq 0.35 \qquad (14)$$

Then the maximum relative frequency of the vibratory movement is given by the following relation:

$$\omega_{max} = 0.35\, \omega_0 \qquad (15)$$

This relation makes it possible to choose the suitable accelerometer and to protect it.

7. Conclusion

In this work, the piezoelectric sensor is studied to present their mathematical model of their operating principle, the model developed is an equation related to the displacement with the parameters of the piezoelectric sensor, as well as the new formula expresses the relative sensitivity as a function of different parameters of the sensor.

By simulation tests, this developed model is validated and the results obtained have shown that ζ=0.68 is chosen in order to minimize the measurement error to a value equal to 0.28%, increasing the precision to 99.72% and a relative sensitivity does not allow to exceed 0.62%. The proposed expression which relates the relative frequency of the vibratory movement as a function of the natural frequency of the piezoelectric accelerometer makes it possible to reduce the resonance phenomenon effect, to stabilize the accelerometer operation and to improve their performance.

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