# Capacitive Sensor Accuracy Optimisation by the Frequency Range Appropriate Choice

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# Abstract

Measuring rotating machine vibrations requires an electronic instrument called a vibration sensor. In this work, the vibration sensor with capacitive detection is chosen to measure the vibrations movement. In order to fulfill the objectives of reducing the measurement error and achieving high sensor accuracy, this sensor is modeled by the application of motion law. The results obtained by the developed model simulation showed that it was possible to extract a formula linked to relative frequency of the vibrating structure and to the capacitive sensor natural frequency, this makes it possible to reduce the measurement error and improve the capacitive sensor accuracy


# 1. Introduction

The field of sensors is in full evolution following rapid progression of technologies for manufacturing electronic components and more particularly the arrival on the industrial market of microsystems with mixed analog-digital signals, as well as the emergence of MEMS technologies (Micro-Electro -Mechanical-Systems) [1]. Accelerometers operate by the principle of measuring acceleration, measuring the force exerted on a test body, or the deformation that the latter generates on a structure. There are different techniques for measuring the displacement of the test object or for transforming the action of acceleration on the sensor into an electrical signal depending on its application (piezoelectricity, resonant structure, piezoresistivity, thermal, optical and capacitive) [1].

The vibration sensor is used to control the acceleration and speed of the vibrations. This type of vibration sensor is used in different measurement applications. Some areas of use are predictive maintenance of engines, fans, pumps, compressors and automobiles to enhance safety (airbag, active suspension, seat belt pretensioner, etc.) [2].

Capacitive detection is the most widely used method to date for accelerometers. The “test body” (term designating the part of the sensor sensitive to acceleration, the term “seismic mass” is also used) is a mobile electrode. A capacitance is formed between the test body and a fixed part of the system. Detection consists in evaluating during acceleration the variations in capacitance when the test body moves away or approaches the fixed element [2].

Several works were conducted in order to improve the physical characteristics and the performances of the capacitive sensor [3–8]. In this work, the modeling of the capacitive detection sensor aims to extract the formulas for acceleration and measurement error. The simulation of these formulas make possible to express a relation of the relative frequency in connection with of natural frequency of the capacitive sensor. The main purpose of this relationship is to determine the frequency margin.

# 2. Capacitive Detection Techniques

The capacitive accelerometer uses, as a principle for the detection of the displacement of the mass, the variation of the capacitance of a condenser to vary the distance between its armor.

In these accelerometers, the mass (made with a conductive material) constitutes an armature, while the other is formed on the fixed structure of the device, in the immediate vicinity of the mass. The mass is suspended from a relatively rigid elastic element (typically a membrane). A special circuit detects the capacitance of the capacitor thus formed, and generates an electrical signal proportional to the position of the ground (see Fig. 1).

There are two types of capacitive accelerometers [9]: 1) simple accelerometers which contain only one sensing element, which implies a single variable capacitance, 2) differential accelerometers which contain two sensing elements (i.e. two variable capacitors that make a capacitive half bridge as shown in Fig. 2).

## 3. Modelling Of Capacitive Sensor

In general, the capacitive sensor area can be expressed as follows:

$A= 2N \pi r x$ (1)

With:

N: the CNTs number on the electrode surface,

r: the radius of one carbon nano-tube,

x: electrode displacement,

Currently; for 1 $cm^2$, the surface density of the CNTs is equal to 109 tubes and their diameter is approximately equal to250 nm, as well as the electrodes area takes the value of 0.78 $cm^2$ [2]. Then formula (1) becomes:

$A= 612.6x$ (2)

The global capacitance of senoris given by the following expression [10]:

$C= \epsilon_0 \epsilon_r A/2d$ (3)

With:

$\epsilon_0$ : free space permittivity, $\epsilon_r$ : electrolyte relative permittivity and d : electrode-electrolyte separation.

In table 1, the dimensions and characteristics of the structural design are shown:

Table 1

The detailed structure design

| Parameters | Value |
|---|---|
| Chip width | 5 cm |
| Chip length | 7 cm |
| d | 1 nm |
| $\epsilon_0$ | 8.8549 $*10^{-12}$ F/m |
| $\epsilon$ | 1 |
| Spring constant (K) | 531N/m |
| The maximum capacitance | 135.5 μF |
| The movable electrode surface | 200$mm^2$ |

After replacing equation 2 in equation 3 and taking the values of dimensions and characteristics from Table 1, we obtain the following formula:

$C= 2.71x$ (4)

The modeling of the mechanical part of the capacitive sensor is made by applying Newton's second law of motion, which is given as follows [10]:

$\sum F = m\gamma = m\, d^2x/dt^2$ (5)

The modelization detail is given by the work [10], and the developed model of displacement according to the mechanical parameters of the capacitive accelerometer is as follows:

$x = \omega^2 y / \omega_n^2 [(1 - (\omega/ \omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2]^{1/2}$ (6)

Where:

x: displacement of vibratory movement

ω: relative frequency

$\omega_n$: naturel frequency

ζ: damping rate

Thefollowing equation is obtained by replacing equation(6) in equation (4):

$C= 2.71\, \omega^2 y / \omega_n^2 [(1 - (\omega/ \omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2]^{1/2}$ (7)

The acceleration measured by the capacitive sensor is expressed as follows:

$a=\omega^2 y$ (8)

$a=\omega_n^2 C [(1 - (\omega/\omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2]^{1/2} /2.71$ (9)

To ensure better accuracy of the capacitive sensor, it must minimize the measurement error. To achieve this objective, the measurement error is expressed as a function of the frequency margin by the following relation and the appropriate choice of the latter minimizes this error.

$E=[(d^2x/dt^2)/(d^2y/dt^2)]-1=[1/(1-(\omega/\omega_n)^2)^2+(2\zeta\omega/\omega_n)^2]^{1/2}- 1$ (10)

The simulation of this equation makes it possible to minimize the measurement error by the appropriate choice of the frequency margin and thus to improve the measurement precision.

## 4. Choice Of The Frequency Margin To Avoid The Effect Of The Resonance Phenomenon

If the relative frequency of vibratory movements approaches the natural frequency of the capacitive sensor, the resonance phenomenon begins to appear. To reduce the effect of this phenomenon, he must determine the appropriate frequency margin for this sensor. For this purpose, a formula between the natural frequency of the capacitive sensor and the relative frequency will extract later.

In the following, a variation of the relative frequency up to the natural frequency of the capacitive accelerometer ($\omega n$ = 1000Hz) and the simulation parameters are shown in the following table (table 2):

Table 2

Capacitive sensor parameters for simulation

| Parameters | Values |
|---|---|
| $\omega_0$ (Hz) | 1000 |
| y (mm) | 0.15 |
| $\zeta$ | 0.65 |
| $\omega$ (Hz) | 0 to 1000 |

The following table and figures will show the results obtained from the simulation of the developed model (see table 3, figure 3 and figure 4):

Table 3

Simulation results of displacement and measurement error for capacitive sensor in the resonance case

| Frequency (Hz) | Displacement (mm) | Error % |
|---|---|---|
| 0 | 0 | 0 |
| 50 | 0.0004 | 0.04 |
| 100 | 0.0015 | 0.15 |
| 150 | 0.0034 | 0.33 |
| 200 | 0.0060 | 0.54 |
| 250 | 0.0094 | 0.78 |
| 300 | 0.0136 | 1.00 |
| 350 | 0.0186 | 1.17 |
| 400 | 0.0243 | 1.22 |
| 450 | 0.0307 | 1.11 |
| 500 | 0.0378 | 0.76 |
| 550 | 0.0454 | 0.11 |
| 600 | 0.0535 | -0.89 |
| 650 | 0.0619 | -2.30 |
| 700 | 0.0705 | -4.14 |
| 750 | 0.0790 | -6.42 |
| 800 | 0.0872 | -9.14 |
| 850 | 0.0951 | -12.23 |
| 900 | 0.1025 | -15.64 |
| 950 | 0.1093 | -19.28 |
| 1000 | 0.1154 | -23.08 |

In the resonance case, the results of Table 3 of displacement as a function of the relative frequency illustrate that the capacitive accelerometer became less precise and less reliable.

The two figures 3 and 4 show the displacement and the measurement error as a function of the relative frequency variation from 0 up to 1000Hz, in the case of the relative frequency = 1000 Hz, i.e. equal to the natural frequency of the accelerometer (case of resonance), the error increases and the presision decreases.

The effect of the resonance phenomenon can be reduced by the appropriate choice of the frequency margin of the capacitive accelerometer. Table 3 illustrates to limit the measurement error to a value not exceeding 1%, the relative frequency must be less than or equal to 300 Hz. The frequency ratio can be expressed as follows:

$\omega_{max/}\omega_n$= 300/1000 = 3/10=0.3 → $\omega_{max\,=}0.3\omega_n$ (11)

This relationship makes it easy to extract the sensor frequency range through their natural frequency.

Fig. 5 illustrates the measurement error of the capacitive sensor as a function of the variation of the vibrations relative frequency during normal operation, ie the choice of the frequency margin by the use of equation 11 developed.

From this curve, it can be seen that the measurement error does not exceed 1%, which implies that this choice improves the measurement accuracy of the sensor.

## 5. Conclusion

From this work, it can be concluded that the capacitive sensor is based on the variation in capacitance between the two electrodes, this variation makes possible the measurement of vibratory movement acceleration. The modeling of the sensor operating principle gives a mathematical model of the displacement and the measurement error as a function of the vibrating structure movement relative frequency. In the case of the resonance phenomenon, the simulation of the developed model showed that the vibration sensor loses its performance (increase in the measurement error). In order to reduce the effect of this phenomenon, a relationship of the frequency ratio is proposed. This relationship has made possible to choose a frequency range suitable for the capacitive sensor.

## Declarations

# a. Funding

Not applicable

# b. Conflicts of interest/Competing interests

The authors declare that they have no competing interests

# c. Availability of data and material

Not applicable

# d. Code availability

Not applicable

# e. Ethics approval

Not applicable

# f. Consent to participate

Not applicable

# g. Consent for publication

Not applicable

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# Figures

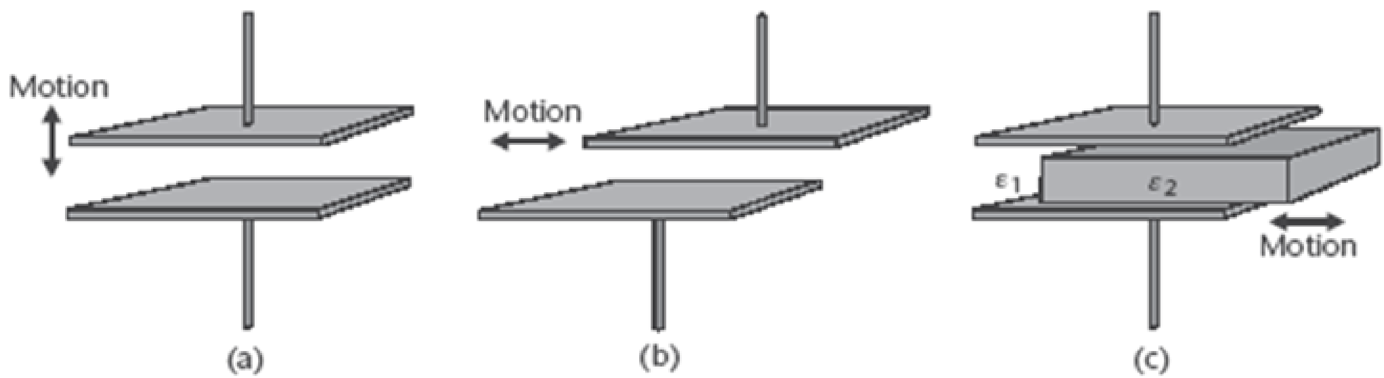


**Figure 1**

Detection by capacitive displacement: (a) flat mobile, (b) with variable section, and (c) dielectric mobile [1].

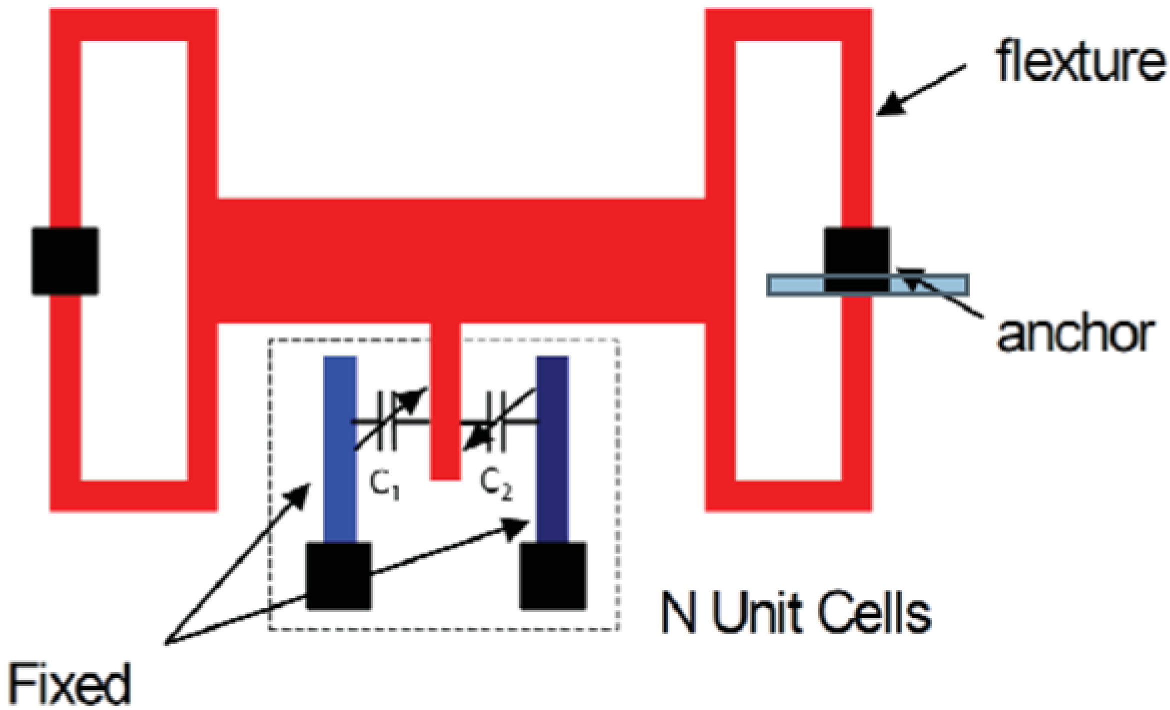


**Figure 2**

Differential capacitive sensor

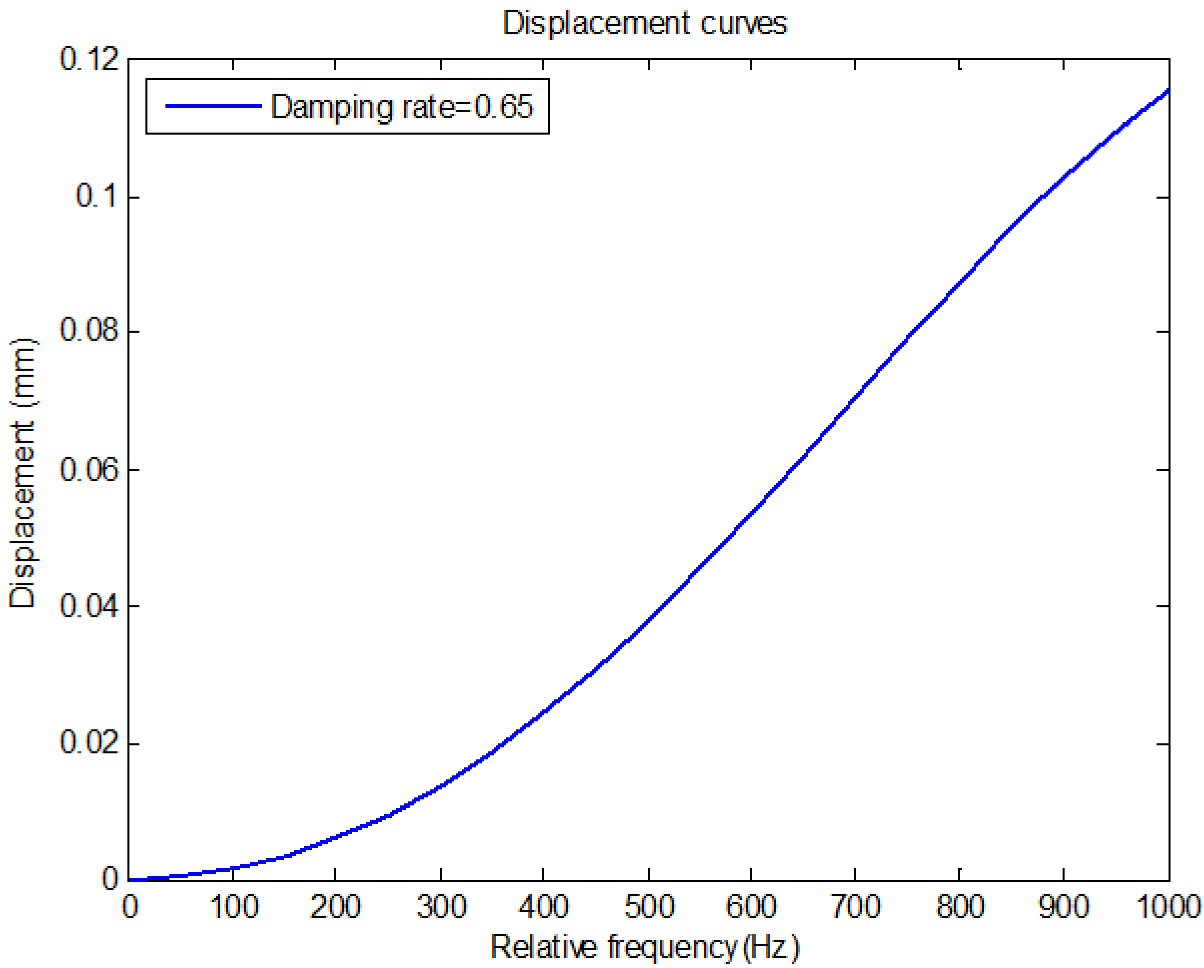


**Figure 3**

Displacement in the resonance case

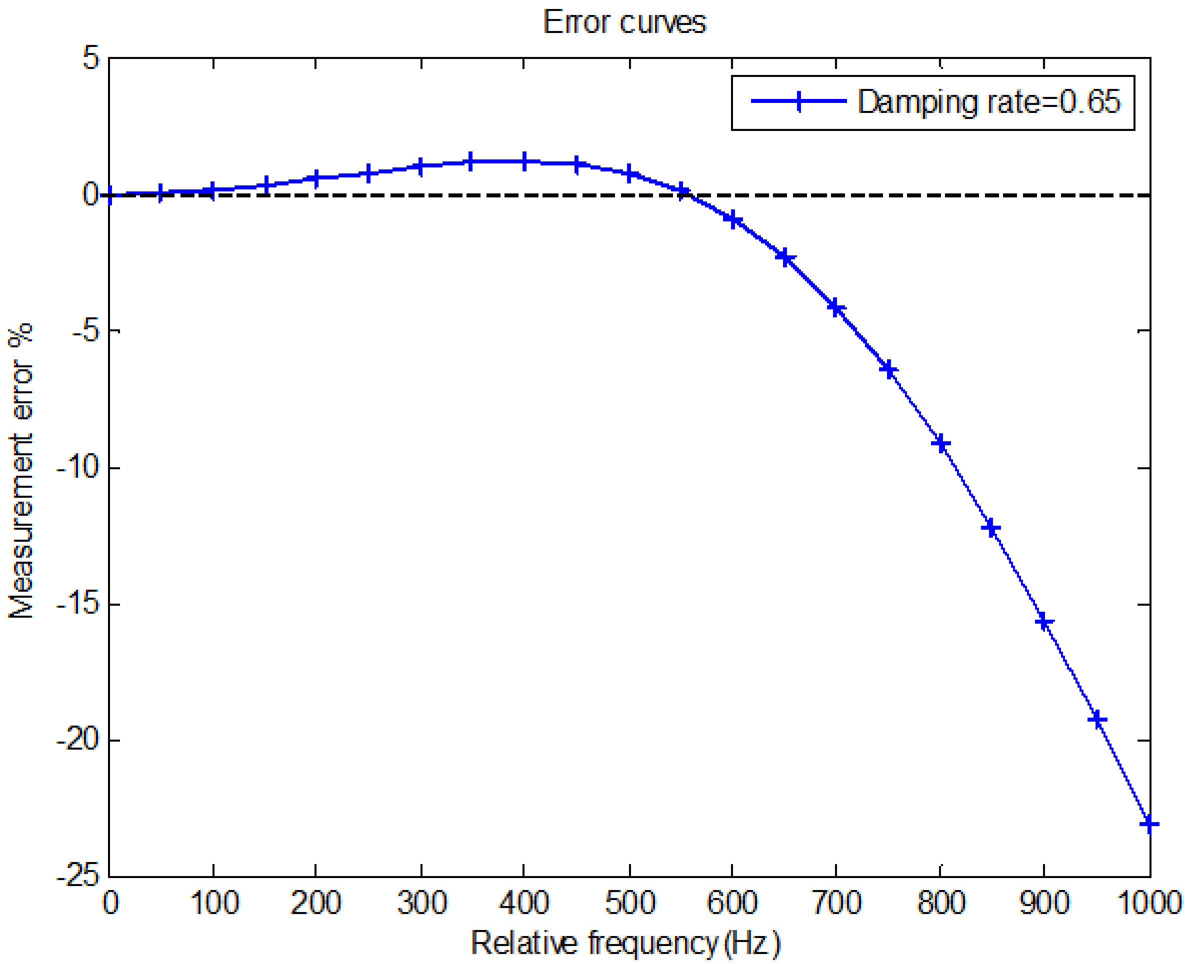


**Figure 4**

Measurement error in the resonance case

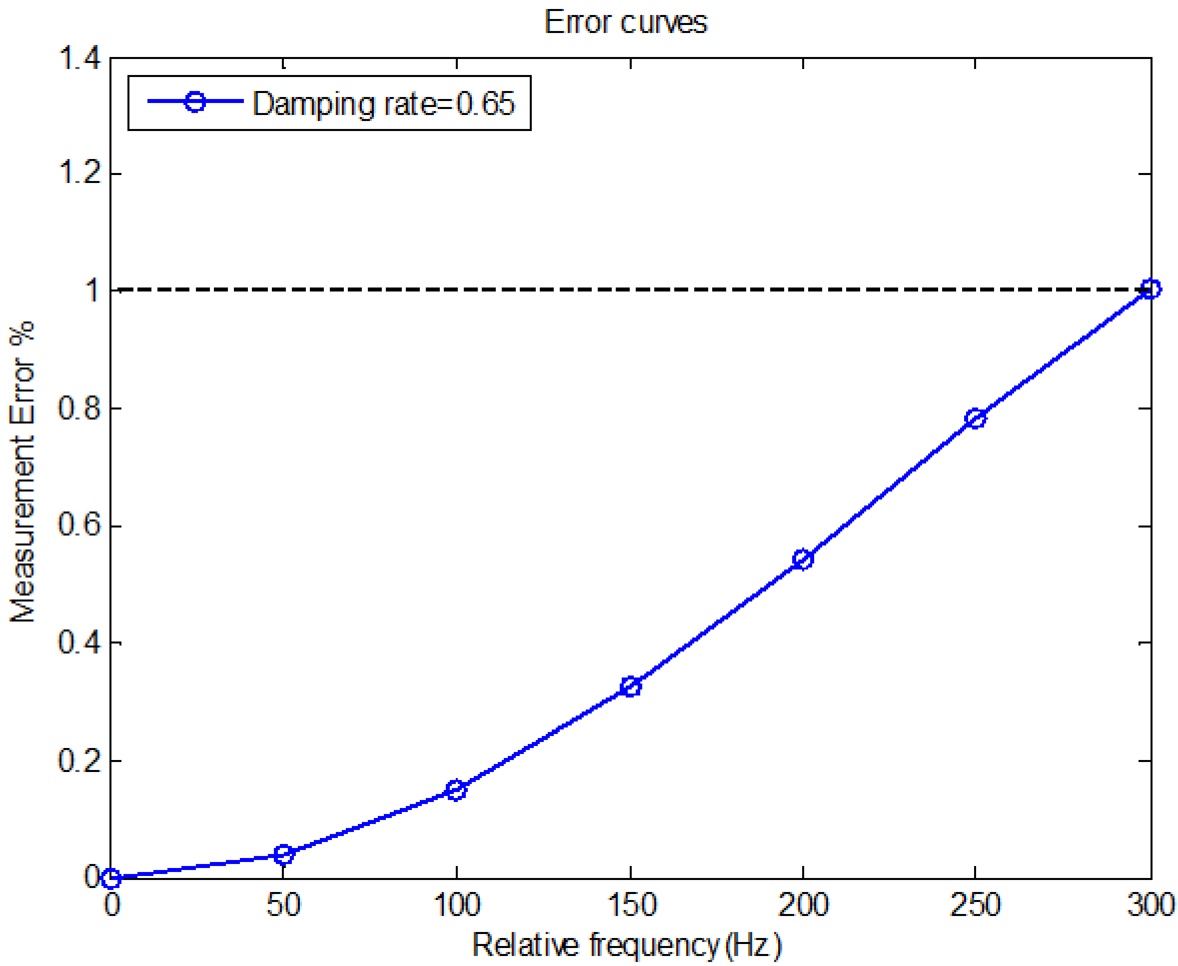


**Figure 5**

Measurement error in the normal operation of capacitive sensor