Nonlinear Dynamics Based Sensors
A New Class of Devices for System Monitoring

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Abstract: Post-silicon materials like polymers and solution-based devices allow to design new types of sensors. On the other hand, the nonlinear dynamic behavior of a class of nonlinear circuits offers the possibility of conceiving devices where the nonlinearity of the circuit is exploited to realize new mechanisms or improve classical ones. In this PhD work we discuss the possibility of coupling a new class of materials with nonlinear dynamic circuits to design a new class of sensors. The results that are included are preliminary and cover a wide range of applications. In particular advanced sensors based equipment has been studied on an electromechanical system, in order to monitorize its vibrating behaviour to establish self organizing phenomenon to control the system.

1 STAGE OF THE RESEARCH

The research regards with the study and the characterization of a new class of sensors based on coupling the performances of new materials, like polymers, and the behaviour of nonlinear electronic circuits.

The proposal of using this sensors for monitoring complex self-organizing electromechanical systems is a second step of the research. At this time, the sensors have been realized and characterized.

The self-organizing electromechanical system has been realized by using different architectures.

Preliminary qualitative measurements have been performed.

2 OUTLINE OF OBJECTIVES

In this project the coupling between new materials and nonlinear circuits will be explored to design a new class of sensors.

The principle is to link the variation of a quantity detected by the material to the change of a parameter of a chaotic circuit, so that to exploit the parameter sensitivity of chaotic circuits.

A proof of concept will be given in this study, by using a type of innovative material/device, such as Clevios P HC V4, IPMC and water solution cells.

The principle will be demonstrated with a series of experiments that pave the way to a more intensive characterization of the devices proposed. The variation of a quantity, such as humidity, hydratation level or bending, will be here shown to lead to significant changes in the dynamical behaviours of the circuit (in particular, a Chua's circuit will be used), that is, the dynamical behaviour of the nonlinear system bifurcates as a result of the sensing (Fortuna, Frasca & Xibilia, 2009).

Although the principle may be applied to a variety of materials, it is particularly interesting when applied to newly conceived materials which as such may at a preliminary stage of development , or characterization, yet they can be successfully used with such approach.

Moreover, the proposed devices will be adopted for monitoring a complex electromechanical system, in order to make advanced studies in self-organizing complex systems.

3 RESEARCH PROBLEM

In this paper some qualitative preliminary results on a new class of a sensors (De Silva, 2007) whose core principle is based on the nonlinear dynamics of a class of electronic circuits are presented.

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In particular, polymeric materials have been considered. Our study is focused on the use of clevios-based sensors, Ionic Polymer Metal Composites (IPMCs), and solution-based systems to detect various physical quantities like displacement, humidity, concentration and so on.

The idea is to use the material as the electrical transducer and insert the electrical transducer into a nonlinear circuit. The effect of the coupling of these components with a nonlinear circuit like the Chua's circuit is that a variation of the dynamical attractor will be obtained as result of the change of the quantity to which the material is sensible.

Chaos has been already demonstrated to be helpful in improving the performance of sensors and other equipments, such as sonar sensors, mechanical systems and other devices (Fortuna, Frasca, & Rizzo, 2006): in this project, detection of the given quantity is made possible by the extreme sensitivity of the circuit to the variations of its parameters (Fortuna, Frasca, 2006).

In this study sensors based on water solutions, that have a behaviour that can be comparable with RC devices with frequency dependent component values and so are difficult to realize with classical components, are also reported.

The proposed sensors will be included in a complex electro mechanical system in order to study its self organizing behaviour.

4 STATE OF THE ART

In this Section three types of sensors are discussed.

The first one regards the clevios based sensors. Clevios is a conductive polymer. The clevios used (Clevios-P HC V4) is commercially available in a water colloidal suspension.

A layer of thickness of 100μm is coated on a surface and then treated in an oven at 80˚C for 50 minutes. Two different supports have been used: a glass support and a PVC foil. The first may be used to realize humidity, wet and PH sensors as the resistivity of clevios based materials is sensitive to these quantities.

Figure 1: The clevios based sensor (glass support).

The second type of device (those were the clevios is coated on flexible PVC foil) may be used to detect displacements. In this case, the clevios-based sensor is considered as an electrical bipole whose resistivity depends on the surface deformation.

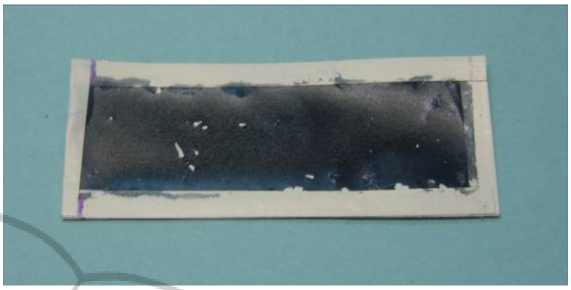


Figure 2: The clevios based sensor (PVC support).

The second type of sensor is realized by using Ionic Polymer Metal Composites (IPMCs). These materials belong to the class of wet electro-active polymers.

They are made of an ionic polymer membrane covered on both sides with Platinum, which realizes the two electrodes of the device. IPMCs operate with low voltage signals, are very light, and have both actuator and sensor characteristics.

Figure 3: IPMC sensor.

They are used after being cut in strips. If an electric field is applied across the thickness of a strip, it undergoes a broad bending deformation. Viceversa, by bending a strip of IPMC, a voltage arises between the two metallic electrodes.

Hence, IPMCs can operate as motion actuators or sensors. Instead, in this work, we exploit the dependence of the resistivity of IPMC on the hydration of the membrane to realize a humidity sensor.

Another proposed device is based on the resistivity change of a water solution. The device consists of four copper filaments on a plexiglass substrate which are electrically connected in two pairs (the two top ones and the two bottom ones).

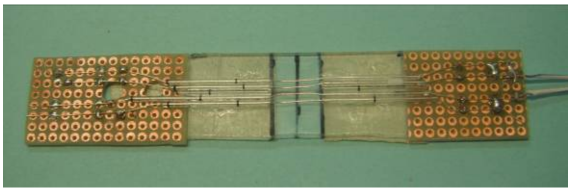


Figure 4: Water solution based sensor.

The space between the filaments hosts a small quantity of a water solution so that the value of the resistance measured at the two terminals of the device is made dependent on the quantity of water.

Figure 1 shows the first clevios-based device. It is realized on a rigid glass support, the sensor area has a length equal to 70mm and width equal to 22mm.

Figure 2 shows the second clevios-based device. This is realized on a PVC (3M Temflex 1500) of thickness equal to 0.3mm. The active area of the sensor measures 55mm x 15mm.

Figure 3 shows the IPMC strip used. The size is 44mm x 9mm. The IPMC material has been realized with the procedure detailed in Arena et al.(2006).

Figure 4 shows the last device. It is realized by fixing four copper wires on a plexiglass support (of thickness 2mm). Each wire has diameter equal to 0.22mm. The distance between each pair of wires is 1.5mm. The wires are isolated by glass microtubules with the only exception of a window of 10mm of length which constitutes the active area of the sensor.

5 METHODOLOGY

In this Section we briefly describe some experiments to show the proof of concept of the coupling of new materials and nonlinear circuits.

As discussed in Section 4, all the devices illustrated can be viewed as two terminals devices. The principle with which they have been coupled to the nonlinear circuit is common for all the devices.

Starting from the Chua's circuit (Madan, 1993), we identify one resistor of the circuit as the bifurcation parameter. In particular, without any loss of generality, we have taken into account the so-called CNN-based implementation of the Chua's circuit (Fortuna, Frasca & Xibilia, 2009), whose electrical scheme is shown in Fig. 5, and identified as bifurcation parameter the resistor R_6.

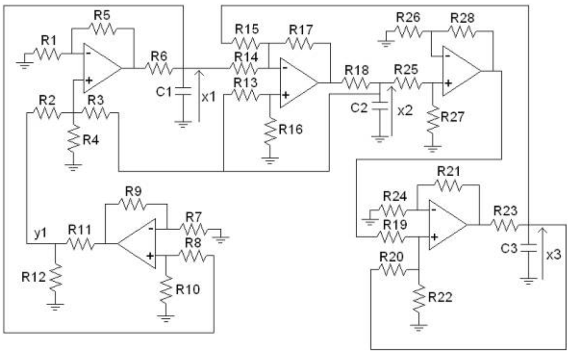


Figure 5: Electrical scheme of the CNN-based implementation of the Chua's circuit. The following components have been used: $R_1=4k\Omega$, $R_2=13.3k\Omega$, $R_3=5.6k\Omega$, $R_4=20k\Omega$, $R_5=20k\Omega$, R_6 fixed from experiment to experiment as the sensor device, $R_7=112k\Omega$, $R_8=112k\Omega$, $R_9=1M\Omega$, $R_{10}=1M\Omega$, $R_{11}=12.1k\Omega$, $R_{12}=1k\Omega$, $R_{13}=51.1k\Omega$, $R_{14}=100k\Omega$, $R_{15}=100k\Omega$, $R_{16}=100k\Omega$, $R_{17}=100k\Omega$, $R_{18}=1k\Omega$, $R_{19}=8.2k\Omega$, $R_{20}=100k\Omega$, $R_{21}=100k\Omega$, $R_{22}=7.8k\Omega$, $R_{23}=1k\Omega$, $C_1=C_2=C_3=100nF$.
The power supply has been fixed to ±9V.

The circuit obeys to the dimensionless equations:

$$\begin{aligned}\dot{x} &= \alpha[y-h(x)]\\ \dot{y} &= x-y+z\\ \dot{z} &= -\beta y\end{aligned} \qquad (1)$$

where $\beta = 14.286$ and h(x) represents the nonlinearity of the system:

$$h(x) = m_1x + 0.5(m_0 - m_1)(|x+1| - |x-1|) \qquad (2)$$

with: $m_0 = -1/7$ and $m_1 = 2/7$
and

$$x = x_1, \quad y = x_2, \quad z = x_3 \qquad (3)$$

being the state variables.

For the sake of brevity, we refer to Fortuna et al. (2009) for a more detailed discussion on the Chua's circuit and the CNN-based implementation reported in Fig. 5.

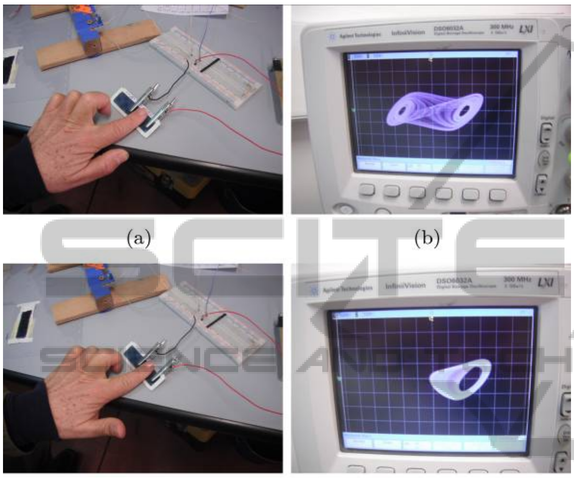
Here, we briefly mention that α is a key bifurcation parameter and it is related to the component values by:

$$\alpha = \frac{R_5 R_{12}}{R_8 R_6} \qquad (4)$$

We have thus kept constant R_3, R_5 and R_{18} and in place of the R_6 we have connected each of the sensors described in Section 4.

In some cases, where the typical values of resistance given by the device are out of the range of the operating conditions of the Chua's circuit, a resistor indicated in the following as R_p, has been also connected in parallel to the device with respect to them.

The first experiment refers to the use of the clevios based sensor of Fig. 1. This is a sensor realized by coating the clevios on a rigid support. The two terminals of this device have been connected to the Chua's circuit and the experimentally obtained attractors for two different operating conditions of the sensor have been reported in Fig. 6.


(a) (b)

(c) (d)

Figure 6: Wet detection experiment. (a) A dry finger is applied to the sensor. (b) Attractor corresponding to the experimental condition of dry finger. (c) A wet finger is applied to the sensor. (d) Attractor corresponding to the experimental condition of wet finger.

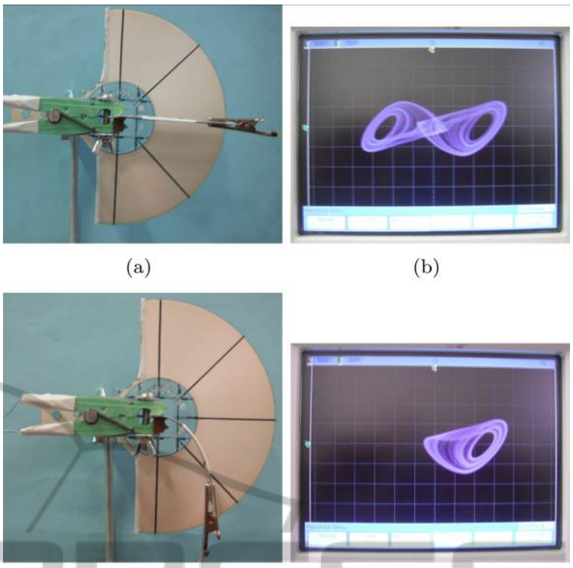
Figure 6(a) shows the sensor where a dry finger has been applied in the active area. The corresponding attractor is shown in Fig. 6(b). It is the well-known Chua's double scroll attractor.

When a wet finger is applied to the sensor, as in Fig. 6(c), the attractor in Fig. 6(d), that is, the so-called single scroll attractor, is obtained. The different dynamical behaviours obtained allow to easily distinguish the different operating conditions of the sensor.

The value of the resistance of the clevios based sensor in dry conditions is 97kΩ, this is outside the typical range of values used for R_6 in the Chua's circuit. Therefore, in this experiment, a parallel resistor of value equal to $R_p = 375\Omega$ has been used.

In the second experiment the sensor based on clevios deposition on a flexible support is considered. The experiment is illustrated in Fig. 7.

When the sensor is in the horizontal position (Fig. 7(a)), the attractor obtained is the Chua's double scroll attractor (Fig. 7(b)).


(a) (b)

(c) (d)

Figure 7: Deformation detection experiment. (a) Clevios-based sensor in the horizontal position. (b) Attractor corresponding to the experimental condition of horizontal position. (c) Deformed position for the clevios-based sensor. (d) Attractor corresponding to the experimental condition of wet finger.

In correspondence of a bending with an angle of 45° (Fig. 7(c)), the Chua's single scroll attractor is obtained (Fig. 7(d)).

In this experiment R_p has been fixed as R_p=447Ω. The resistance of the clevios device changes from 4965Ω in the horizontal position to 5530Ω when bended.

The experiment based on the use of an IPMC strip is illustrated in Fig. 8, through different frames of a video recording the attractor obtained on the oscilloscope.

At time t = 0 (Fig. 7(a)) a limit cycle periodic attractor is evident. When the IPMC membrane is hydrated by inserting it in a small container filled of water (this takes a few seconds after the beginning of the experiment), the attractor changes. Due to the presence of equivalent resistive and capacitive effects in the membrane, a switching dynamics emerges. The dynamics is characterized by oscillations which spiral towards one of the two unstable equilibrium points of the circuit.

Before reaching the equilibrium, the trajectory suddenly jumps to the other lobe and starts again spiralling, this time towards the other equilibrium. This repeats until the membrane becomes again wet. In Fig. 7(b)-(f) we show the trajectory observed in the oscilloscope up to 3 minutes after the hydratation. The phenomenon maintains for about

15 minutes. In this experiment R_p has been fixed to $R_p = 413\Omega$.

In the fourth experiment the sensor shown in Fig. 4 is used. It has been directly substituted to the R_6 resistor without inserting further parallel resistor.

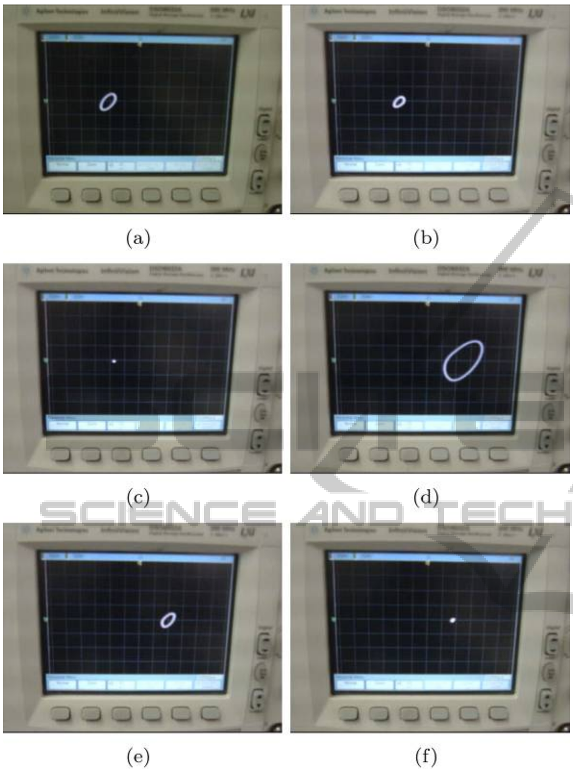

(a) (b) (c) (d) (e) (f)

Figure 8: IPMC hydratation sensor experiment. (a) t = 0s; (b) t = 60s; (c) t = 105s; (d) t = 120s; (e) t = 150s; (f) t = 180s.

When the sensing area is dry, the attractor is a stable equilibrium point (Fig. 9(a)). On the contrary, when a small quantity of water (or even a wet finger) is placed in the active area of the sensor, the circuit begins to oscillate as shown in Fig. 9(b).

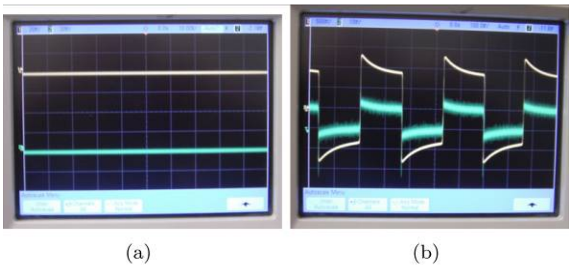

(a) (b)

Figure 9: Experiment based on the sensor of Fig. 4:
(a) attractor obtained for an experimental dry condition; (b) waveforms corresponding to wet experimental conditions.

6 EXPECTED OUTCOME

The core of PhD Thesis is the possibility of having a global real time behaviour monitoring of a complex electromechanical equipment.

The system has been conceived in order to study experimentally the effect of self-organizing phenomena in coupled electromechanical devices.

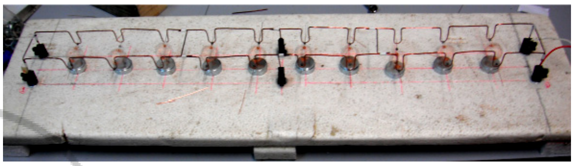


Figure 10: The electromechanical structure built on a flexible metallic support with the coils. The white base is made of polystyrene foam in order to absorb all external vibrations. Immediately below the flexible structure magnets are placed.

The project consists in the study of self organizing structures that allows the synchronization of a set of single coils. The possibility of synchronizing mechanical systems by using mechanical coupling has been proposed by Ditto et al. (1995). In that, a study has been proved numerically how mechanical random dissymmetry does favourite the synchronization of simple pendula.

In the proposed study, instead of pendula, coils that are directly coupled by a flexible support, have been considered. The irregularity of the coils movements generate a random forcing signals for the mechanical structures.

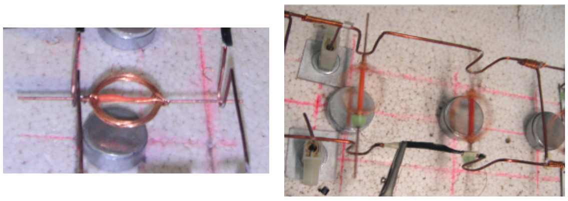


Figure 11: The detail of the coil with its insertion point on the flexible support.

What we want to prove consists in studying experimentally the phenomenon and to propose several suitable architectures where the irregular movements of the coils should produce a self organizing phenomenon in order both to have a regularization in the angular speed coils and in the control of the global mechanical structure.

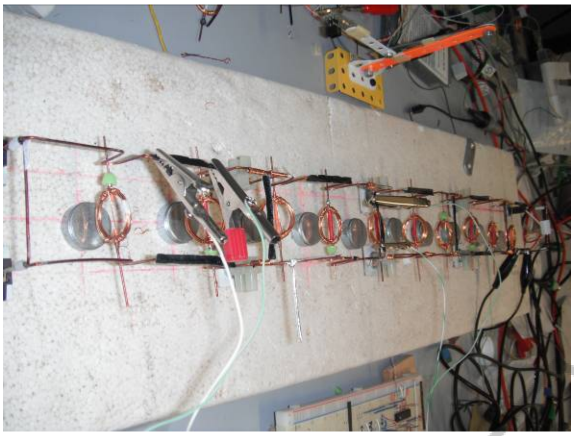


Figure 12: The complete electromechanical structure, with coils, magnets and the clevios based vibration sensors positioned on some sections of the structure.

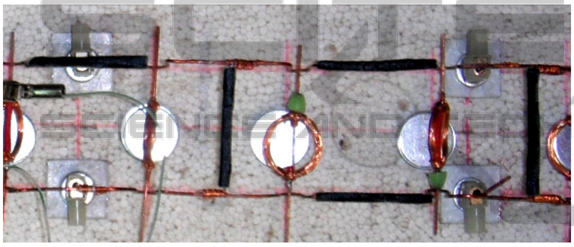


Figure 13: The particular of the elettromechanical support with, in black, the clevios based vibration sensors positioned on some branches of the structure.

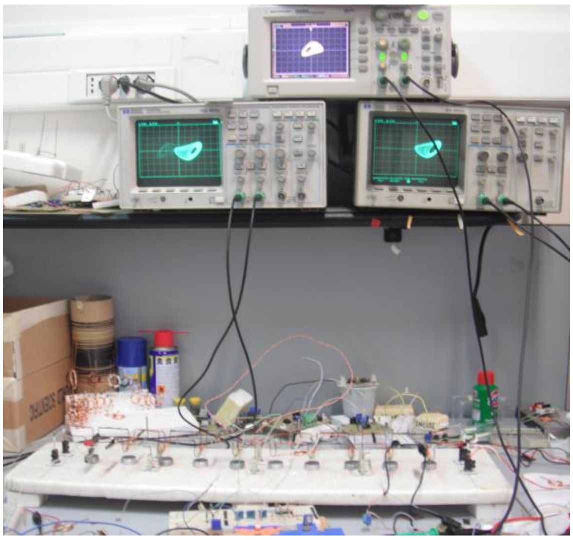


Figure 14: An overview of the complete system connected to three Chua's circuits.

In order to achieve the previous task, a qualitative vibrating measurement system is studied in order to have a global behaviour of the system's vibrations. This should be made considering distributed sensors in the various beams of the structure. The adopted sensors surface have been made by clevios based sensors.

Each sensor that responds dynamically as a variation of ohmic resistance to the vibration is coupled to a chaotic device. That does change attractor when the vibration does occur.

An overview of the complete system connected to three Chua's circuits, and the corresponding dynamic responses, is shown in fig. 15.

The intermittency of the vibrating coils and his frequency spectrum are detected by the strange attractor shape changing and can be quantified by the intermittency condition of each attractor.

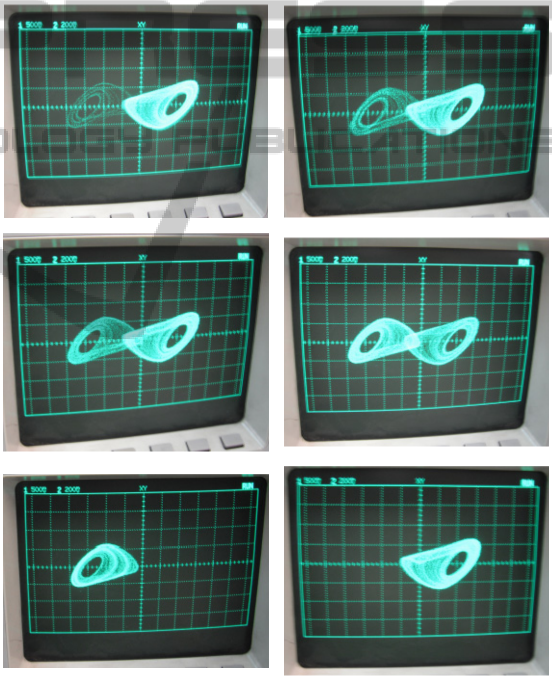


Figure 15: The intermittency of a strange attractor in response to the vibrations of the structure transduced by one of clevios based sensors.

In Fig. 15 the variations of the shape of the so-called single scroll attractor, are shown. The different dynamical behaviours obtained allows to easily distinguish the different operating conditions of one of the clevios based sensors placed on the flexible structure.

The complexity of the dynamics of the electromechanical system is more appreciated if other sensors are connected to as many Chua's circuits.

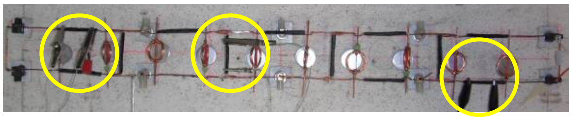


Figure 16: The position of the clevios based sensors on the electromechanical structure connected to Chua's circuits are shown.

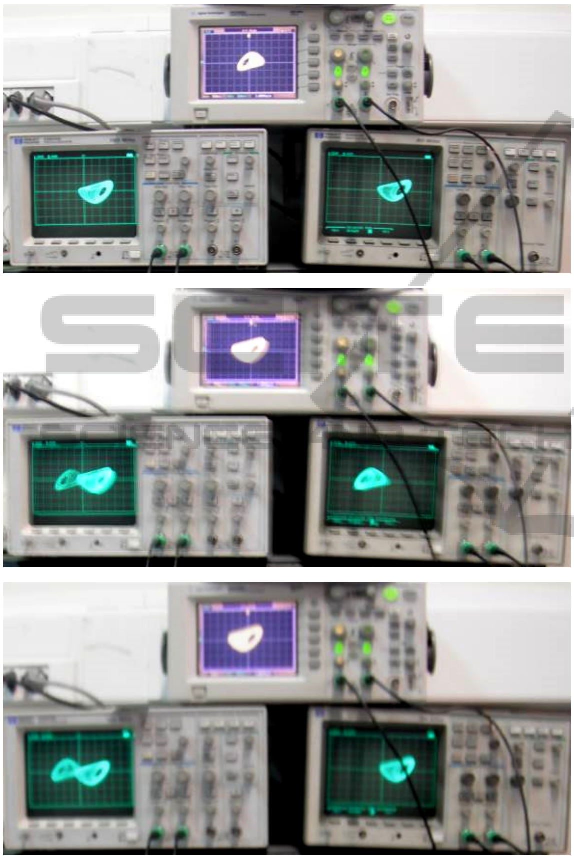


Figure 17: The intermittency of a strange attractor in response to the vibrations of the structure transduced by three clevios based sensors.

The observation of the dynamics of these non-linear circuits (which is conducted qualitatively by means of the variation of the shape of their strange attractors), highlights not only the interaction of the sensor with the structure, but also how the structure allows its elements interact between them.

Moreover, to have more sensors, in order to establish such a type of vibration, optical sensor have been considered in the mechanical structure.

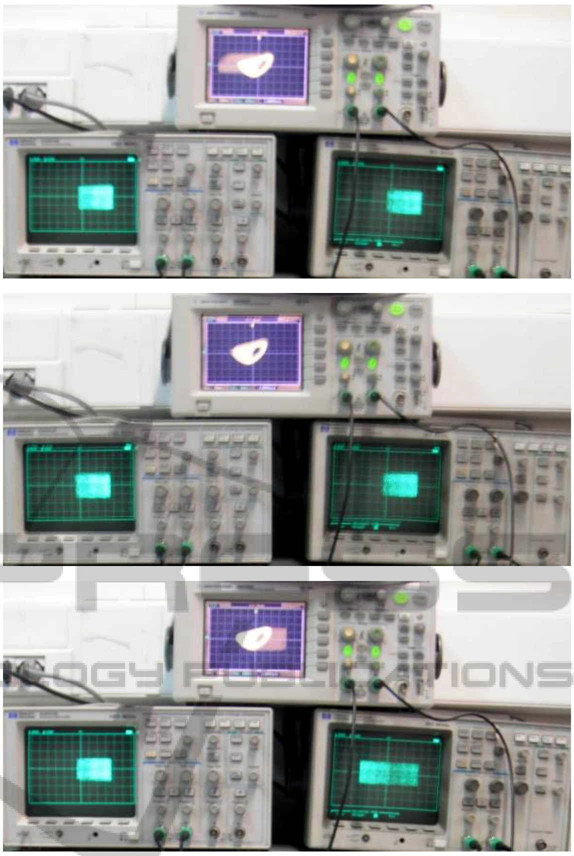


Figure 18: Intermittency behaviour and strange attractors.

(a) (b)

Figure 19: The optical sensors considered in the mechanical structure. In (b) the optical sensor estimate the oscillations on the vertical plane, in (a) the optical sensors estimate the oscillations on two normal planes.

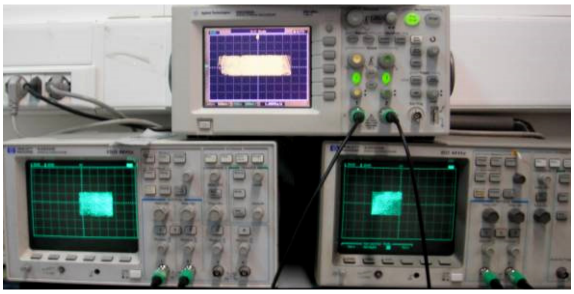


Figure 20: Intermittency behaviour and strange attractors for mutual interference vibrations.

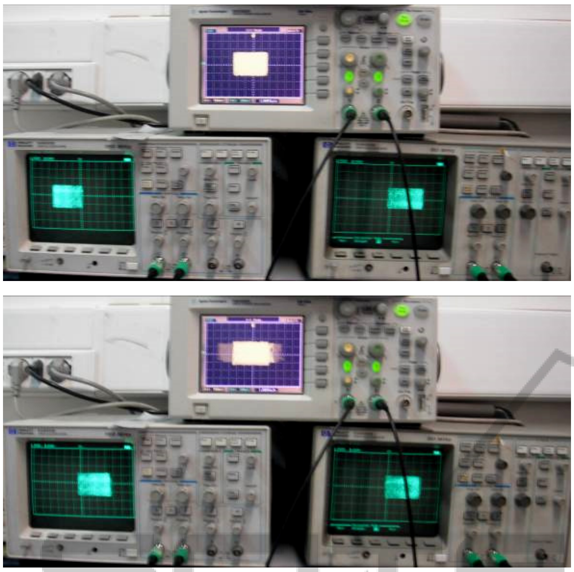
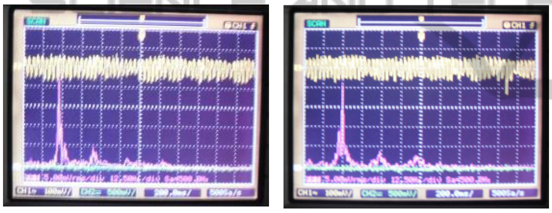


Figure 21: Intermittency behaviour and strange attractors for mutual interference vibrations. (cont.)



(a) (b)

Figure 22: The waveforms generated by the optical sensor for the oscillations in the vertical plane and its FFT at two different speed of rotation of the coils. The speed of rotation in (a) is greater than in (b).

In order to achieve also a global monitoring of the system, thermal measurement will be acquired.

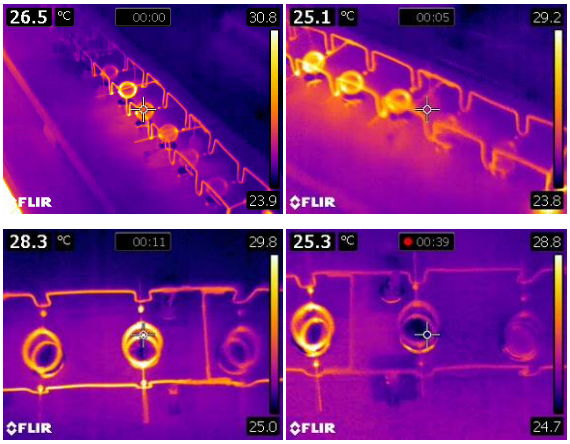


Figure 23: Thermal camera pictures of the structure. Higher temperatures can be observed in slower coils since higher currents flow into them.

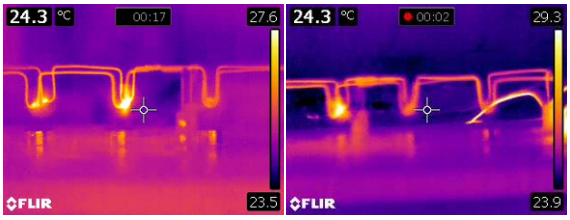


Figure 24: Thermal camera pictures of the structure. Higher temperatures can be observed in slower coils since higher currents flow into them. (cont.)

In this way a qualitative behaviour also from an electrical point of view can be achieved.

Even if each coil can be modelled by the following linear equations:

$$\begin{gathered} J^i \ddot{\vartheta}^i + b^i \dot{\vartheta}^i = K_t^i i_a^i(t) \\ L_a^i \frac{di_a^i}{dt} + i_a^i(t) R_a^i + K_e^i \dot{\vartheta}^i = v_a^i(t) \end{gathered} \tag{5}$$

where:

i : indicate the generic coil

J^i : Moment of inertia of the coil

ϑ^i : Angular position of the coil

b^i : Viscous friction coefficient

K_t^i : Coil torque constant

$i_a^i(t)$: Current coil

R_a^i : Coil's resistance

L_a^i : Coil's inductance

K_e^i : Coil electro magnetic force constant

$v_a^i(t)$: Voltage coil

nonlinear phenomenon can arise both locally and globally. This effect will be studied in order to achieve the self-organizing conditions.

In this way a global mathematical model can be proposed and a setup measurement equipment will be available.

The study will be performed for a large number of coils (about 100) and will be the cornerstone mechanical forced system that should be used for qualitative models of complex phenomena like earthquakes and mechanical vibrations in distributed forced mechanical equipments.

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