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Enhanced Semiactive Multimodal Damping Control

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Abstract— The vibrations control using the piezoelectric elements is an area interesting many industrial sectors. Within this framework, we propose an improved control technique based semi-active method; it is modal SSDI-MAX for modal synchronized switch damping on inductor MAX. This technique developed recently and based on a modal observer to provide the moments of inversion is improved in this paper. The performances of the improved observer are analysed and the results show well that a light modification with same energy used can increase damping performances.

***Keywords*— Vibration control; SSDI; SSDI-MAX; LQG observer; Neuro-fuzzy controller.**

I. Introduction

The effects importance of the vibrations and the impact on the life of the structures and the wellbeing of the individuals as well as their omnipresence have strongly motivated researchers to develop several active and passive method in order to control the vibrations damping; for that, many methods of vibrations damping via the piezoelectric materials can be used. Among these methods, the passive control, which consists in connecting the piezoelectric element to a passive circuit (R, RL) [1] [2]. However, active control is one technique which aims at imposing a force or a displacement in certain points of the system to be controlled, in function in particular of the measured state or the history of this one [3] [4]. The disadvantages of this later method are the origin of the semi-active control methods development. This strategy is an innovative alternative to active control. It is a technique which carries out a nonlinear treatment of the voltage generated by the piezoelectric elements, without need for a great quantity of external energy (moreover it can be self-supplied). Among the semi-active methods, there is that one baptized modal SSDI for Synchronized Switch Damping on Inductor and its improvement modal SSDI-MAX.

Modal SSDI is developed in the first time by Harari and Al. in 2009 [5]. It consists in combining the advantages of the two methods semi-active and active. To be done, a modal model is proposed and basing on this model, a modal observer is developed to rebuild the modal coordinates of the system. In this manner, control can be targeted on the energy modes.

The performances of the modal strategy are substantially related to the performances of the observer used. Since, the inversions are made with the extreme of the modal displacements given by this observer.

In this work, we present the performances of SSDI-MAX modal technique applied to control the vibrations of an intelligent structure. To be done, we initially will describe the modal model of the selected intelligent structure. Then the definition and the installation of the improved modal observer are examined. The SSDI-max strategy is then defined and implemented.

II. Modeling of the Intelligent Structure

A. Modeling

The electromechanical behavior of an intelligent structure (instrumented of piezoelectric elements) is given by the following equations: [5]

$$m\ddot{\delta}+c\,\dot{\delta}+k^{E}\delta=-\alpha V+\beta F \tag{1}$$

$$I=\alpha^{t}\dot{\delta}-C_{0}\dot{V} \tag{2}$$

With δ is the vector of displacement, *m, C* and k^E are respectively the matrices of mass, damping and rigidity when the piezoelectric patches are in short-circuit. α is the electromechanical matrix of coupling, *V* is a voltage vector of the piezoelectric patch, *I* is the electrical current vector, and C_0 is the diagonal matrix of patches capacitances. *F* is the force applied to the system.

Carrying out the change of variable according to:

$$\delta=\phi q \tag{3}$$

Where ϕ is the mode matrix of the structure limited to *n* modes and *q* is the vector of modal displacement of the structure. Equations (1) and (2) become:

$$M\,\ddot{q}+C\,\dot{q}+K^{E}q=-\theta V+\beta F \tag{4}$$

$$I=\theta^{t}\dot{q}-C_{0}\dot{V} \tag{5}$$

With $\theta=\phi^{t}.\alpha$ is the modal matrix of electromechanical coupling of size [n, i]. *M, C,* K^E are respectively the modal matrices of the mass, damping and rigidity.

The equation (2) is standardized in order to have:

$$M=I_{d};\ C=2\,diag\,(\xi)\,diag\,(\omega^{D});\ K^{E}=diag\left(\left(\omega^{E}\right)^{2}\right)$$

With: ξ is the vector of modal damping, ω^E is the vector of the frequency in short-circuit and ω^D the vector of frequency in open circuit.

While separating the voltages of the actuators and the sensors, I_s and V_s respectively, and when the sensor voltage is supervised by a voltage amplifier (whose intensity of the sensor is null). equations (4) and (5) become:

$$M\ddot{q}+C\dot{q}+K^E q=-\theta_a V_a-\theta_s V_s+\beta F \quad (6)$$

$$\theta_s^t q-C_{0s}V_s=0 \quad (7)$$

By substitution of (8) in (7) we find:

$$M\ddot{q}+C\dot{q}+\left(K^E+\theta_s\left(C_{0s}\right)^{-1}\theta_s^t\right)q=-\theta_a V_a+\beta F \quad (8)$$

The system of linear equations (6) and (7) can be written in the form:

$$\begin{cases}\dot{x}=Ax+Bu\\ y=Cx\end{cases} \qquad x=\begin{bmatrix}q\\ \dot{q}\end{bmatrix} \quad (9)$$

$U=\left[\,F,\ V_a\right]$ is the control vector; $y=\left[q,\ \dot{q},\ Vs\right]$ is the output vector, *A*, *B*, *C* are the state matrices:

$$A=\begin{bmatrix}0 & I_d\\ -M^{-1}\left(K^E+\theta_s C_{0s}^{-1}\theta_s^t\right) & -M^{-1}C\end{bmatrix}$$

$$B=\begin{bmatrix}0 & \\ +M^{-1}\beta & -M^{-1}\theta_a\end{bmatrix},\ C=\begin{pmatrix}I_d & 0\\ 0 & I_d\\ C_{0s}^{-1}\theta_s^t & 0\end{pmatrix}$$

V_a is calculated by the following relation:

$$V_a=C_{0a}^{-1}\,\theta_a^t q$$

C_{0a} and C_{0s} are the capacity matrices of actuators and sensors respectively.

The structure used in the following simulations is that proposed by T Richard in [6] and [7].

B. Smart structure definition:

The intelligent structure used in simulation is a steel plate fixed on the four sides and equipped with four piezoelectric inserts PZT P188. (Fig.1).Its dimensions and its physical properties are given in tables I and II. This structure was identified according to the model describes previously. The procedure of measurement and identification of the parameters is described in detail in [6].

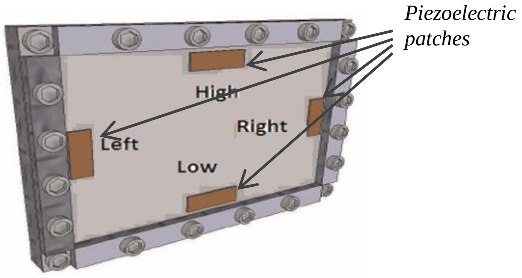


Fig.1. Protective panel structure used in the simulations.
The plate is clamped on all four sides. Each four piezoelectric elements are $12\times 4\ cm^2$ and 600 µm thick. [6]

TABLE I
CHARACTERISTICS OF THE PLATE. [6]

Parameter	Real value
Length	0.6 m
Width	0.4m
Thickness	1 mm
Young modulus	210 GPa
Poisson ratio	0.345
Density	7500 Kg/m3

TABLE III
CHARACTERISTICS OF PZT P189 PIEZOELECTRIC PATCHES. [6]

Property	Symbol	Real value
density	ρ	$7650 Kg*m^3$
Compliances CC	s_{11}^E s_{12}^E s_{13}^E s_{33}^E	$10.66\times10^{-12}\ Pa^{-1}$ $-3.34\times10^{-12}\ Pa^{-1}$ $-4.52\times10^{-12}\ Pa^{-1}$ $13.25\times10^{-12}\ Pa^{-1}$
permittivity	ε_{33}^1	$10.17\ nF.m^{-1}$
Piezoelectric coefficient	d_{11}	$-108\ pC.N^{-1}$

III. THE SSDI CONTROL

The SSDI control (Synchronized Switch Damping on Inductor) consists in using an electronic switch controlled during brief moments in a synchronous way with the vibration. When the voltage of the piezoelectric elements is extreme, the switch connects the piezoelectric elements to an electric circuit composed of an inductance which drives to reverse the voltage (This inversion is made possible by the capacity C_0 of the piezoelectric elements and the inductance L which forms an oscillating electric circuit). This inversion induces a mechanical force of sign opposed at the speed, thus creating the desired damping [8], [9] and [10].

IV. SSDI – MAX CONTROL

A. *Modal SSDI strategy*

The strategy of control SSDI is adequately used for excitation signals with single frequency. In the wide band case of excitation, the method reaches its limits. These ones are due to the many inversions of voltage having too small amplitudes. The significant number of inversions does not make it possible consequently to maximize the actuator voltage that involves a weak damping.

Moreover, this technique does not make it possible to target control on certain modes of the structure. On the other hand, the localization of the action of control on the energy modes would make it possible to improve the effectiveness of control.

With an aim of improving these disadvantages, modal method SSDI was developed [6]. In order to target certain modes by control, the method suggested consists in reversing the actuator voltage when the displacement of the targeted mode is extreme. The Fig.2 presents the voltage of the

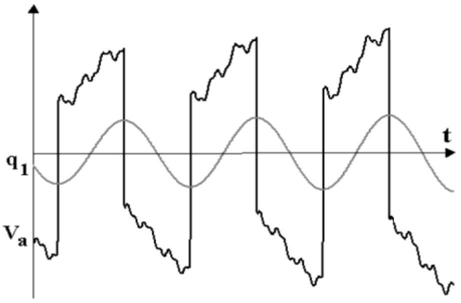


Fig.2. Wave form of the voltage, where V_a is the piezoelectric actuator voltage and q_1 is the corresponding first modal displacement. [5]

piezoelectric actuator V_a related to modal displacement q_I.The inversion of the voltage when selected modal displacement is extreme is not possible only if the modal displacement is available, but this last not being accessible directly via measurements, it is therefore necessary to estimate it. In this way, a modal observer is used [11]. Thus, modal SSDI is the association of the SSDI control to a modal observer (Fig.3).

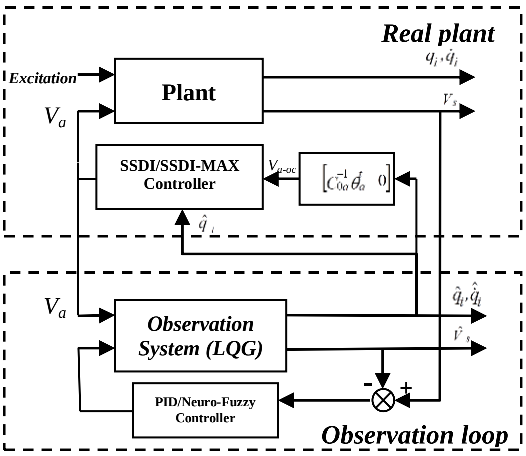


Fig.3. Modal SSDI/SSDI- MAX control architecture.

B. Modal observer

The modal observer used in this work consists in deriving from the measurement voltages V_s, modal coordinate qi making it possible to trigger the commutation device. This loop of observation will estimate at the same time the state space vector and the voltages of the sensor.

Therefore the equation of control in closed loop is given by:

$$\dot{\hat{x}} = A\hat{x} + BV_a - L(V_s - \hat{V}_s)$$

The matrix of gain L must be selected so that the error on the state is stable and disappears quickly with a great dynamics; faster than the structure itself. To calculate this matrix, method LQG was chosen.

LQG Technique only does not guarantee the good properties. In order to ensure an adequate stability of the system and to improve the global performances, the solution [12] consisted in adding an external loop implementing a regulator PID (proportional–integral–derivative.).

The implementations of estimator LQG and regulator PID are given in detail in [12] and [13].

C. Improvement of the observer architecture

With an aim of improving the performances of the observer used, regulator PID in architecture is replaced by a fuzzy-neural regulator.

In Neuro-fuzzy control, the neural networks are used to design membership functions of fuzzy systems that are employed to control the systems. This idea was proposed by Takagi and Hayashi [14].

The development cycle of the Neuro-fuzzy model (ANFIS) can be summarized in: data-gathering and analysis, the choice of neural network architecture and the training using the data.

In this work, the training data base for the ANFIS model is learned from the simulation model and the chosen Neuro-fuzzy network architecture is given in Fig 4. It comprises two input variables and three membership functions.

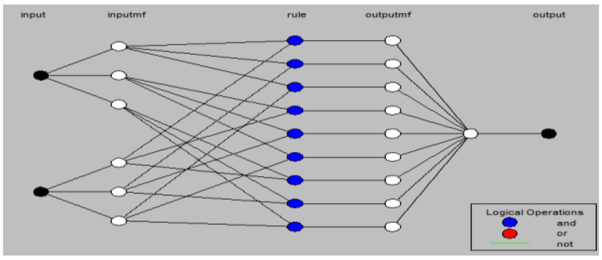


Fig.4. Neuro-fuzzy network architecture

The fuzzy controller which consists of two inputs; the error (*e*) which is $(V_s - \hat{V}_s)$ and the change in error (*de*) and one output is defined by the following membership functions:

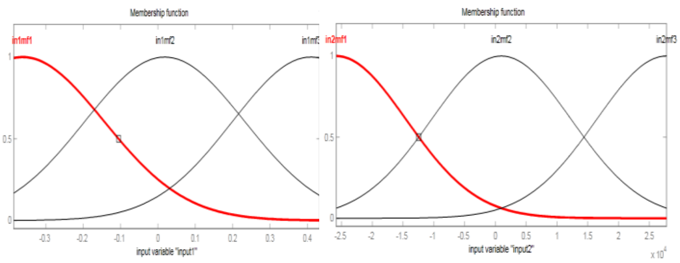


Fig.5. Fuzzy controller membership functions: (left) inputs1 (e) and (right) input2 (de)

The controller output is calculated using the equation : $y = a.x_1 + b.x_2 + c$ .With y is the output, x_1 is the input1 (e) and x_2 is the input2 (*de*) and coefficients *a, b* and *c* are given for the nine output membership functions in table III.

TABLE IIII
COEFFICIENTS *A*, *B* AND *C*.

[a b c] for the nine membership functions
[127.6 -3.493e-005 -2.253]
[132.1 -1.381e-005 0.1343]
[131.7 -1.472e-005 0.7989]
[129.4 7.673e-006 0.4491]
[132.1 8.453e-006 -0.06528]
[132 1.847e-005 -0.3501]
[93.69 -0.0008193 -1.83]
[136.1 -0.0001929 -0.4182]
[127.9 -0.000232 6.853]

D. Observer performances

Simulations were made for the structure model presented by using three patches like sensors and the other left in open circuit. Consequently, no control of the vibrations is carried out. The excitation is a pulse square force of 50µs and normalized amplitude.

In order to compare the two various configurations of observers, the real and the estimate of the modal coordinate q_i are compared.

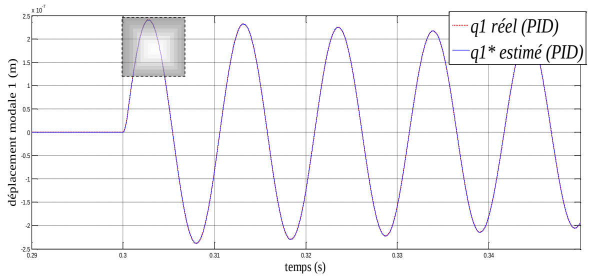


Fig 6 Real (red) and estimated (blue) modal coordinates for mode 1 and using the LQG + PID method without control.

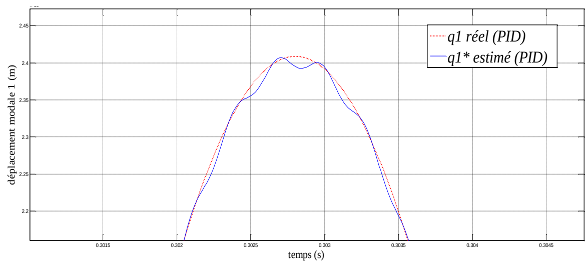


Fig 7 Real (red) and estimated (blue) modal coordinates for mode 1 and using the LQG + PID method without control (increased seen of the gray area.).

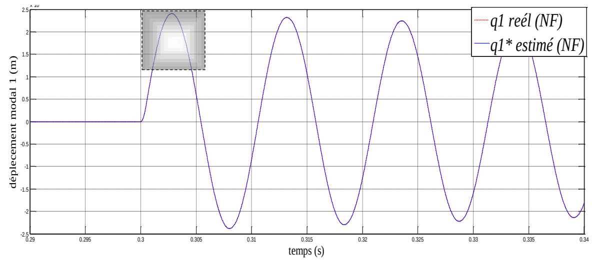


Fig 8 Real (red) and estimated (blue) modal coordinates for mode 1 and using the enhanced LQG + NF method without control.

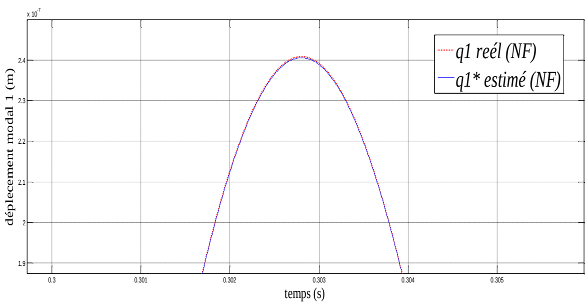


Fig 9 Real (red) and estimated (blue) modal coordinates for mode 1 and using the enhanced LQG + NF method without control (increased seen of the gray area.).

Figure 6 illustrates this comparison for the PID-based observer design; Figure 8 shows the same comparison in the case of the NF-based one. And finally, figures 7, 9 are an increased seen of the gray area of figures 6 and 8 respectively. It is clear that the best solution is the LQG + NF architecture, offering a quick and precise convergence.

Since this observer will intervene in dynamics, same

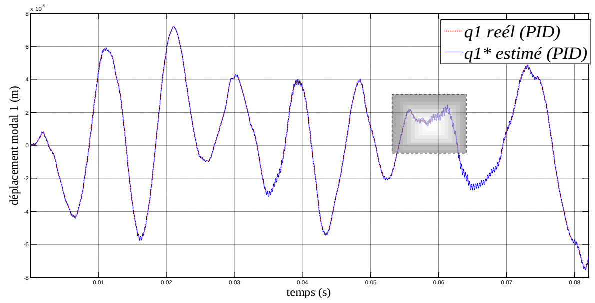


Fig.10.Real (red) and estimated (blue) modal coordinates for mode 1 and using the LQG + PID method with SSDI control.

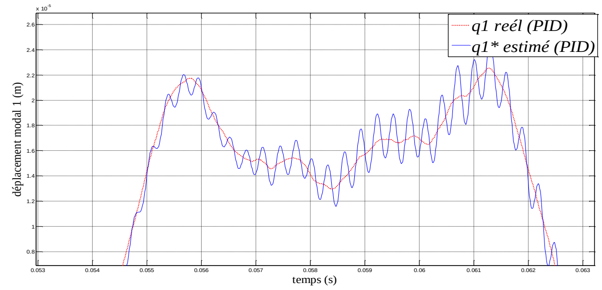


Fig.11.Real (red) and estimated (blue) modal coordinates for mode 1 and using the LQG + PID method with SSDI control (increased seen of the gray area.).

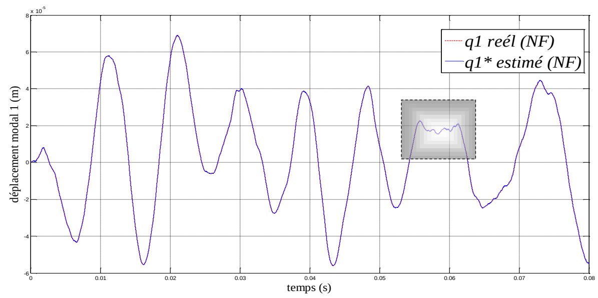


Fig.12.Real (red) and estimated (blue) modal coordinates for mode 1 and using the LQG + NF method with SSDI control.

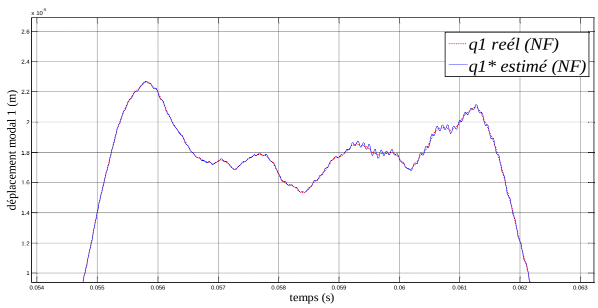


Fig.13.Real (red) and estimated (blue) modal coordinates for mode 1 and using the LQG + NF method with SSDI control (increased seen of the gray area)

simulations were made using now closed loop (using SSDI method). The excitation was a white noise. The real and the estimate of the modal coordinate qi are compared (Fig.10, 11, 12, 13). Figures illustrate that the proposed observer offers much better performances in both open loop and closed loop tests.

E. *The SSDI-MAX control*

The SSDI-max technique is an improvement of SSDI technique by the avoidance of commutation in local maxima. It consists in immediately delaying the moment spent to the extreme of following tension after the extreme of targeted modal coordinate. This process is illustrated in the Fig.14.

Therefore the algorithm of the strategy is summarized in: [13].

When a maximum of modal displacement appears, the window of time of limitation starts. Thus the signs of the voltage V_a and its derivative are considered during the window:

- If the voltage is positive and the derivative is negative, the switch trigger is immediate.
- If the voltage is positive and the derivative is positive, the system waits for the next maximum voltage. This delay is nevertheless limited by the time window.
- If the voltage is negative, the system waits for one of the above conditions.
- If no switching occurred and the end of the time window is reached, the switching is triggered.

This algorithm is antisymmetric if a minimum modal displacement is reached.

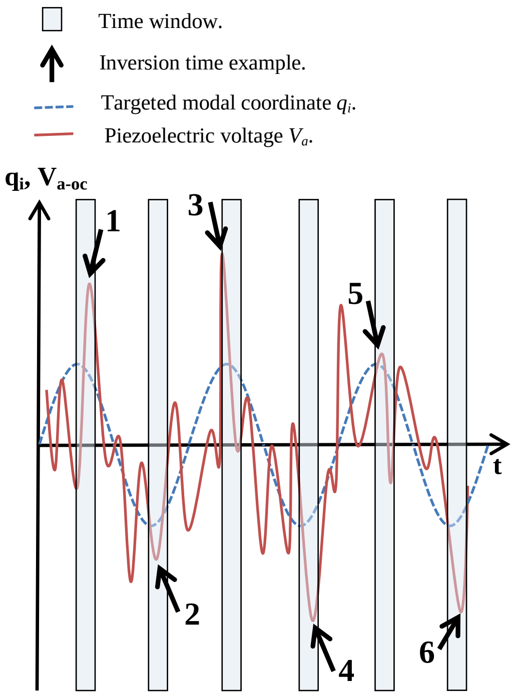


Fig.14. the SSDI-max strategy illustration: the definition of the switching moment according to the targeted modal coordinate, the piezoelectric actuator voltage in open circuit and the authorized maximum time. [13]

V. Simulation Results

Simulations are carried out by using the Matlab/SimulinkTM environment.

A. *Control of only one mode*

In this case, only one piezoelectric element is used like actuator. The three others are used as sensors to feed the observer. The strategy consists in targeting the first mode.

A.1. Sinusoidal excitation

In this case, the excitation is made up of the sum of four sinusoidal signals (frequencies of the four modes which are efficiently electromechanically coupled [12]).

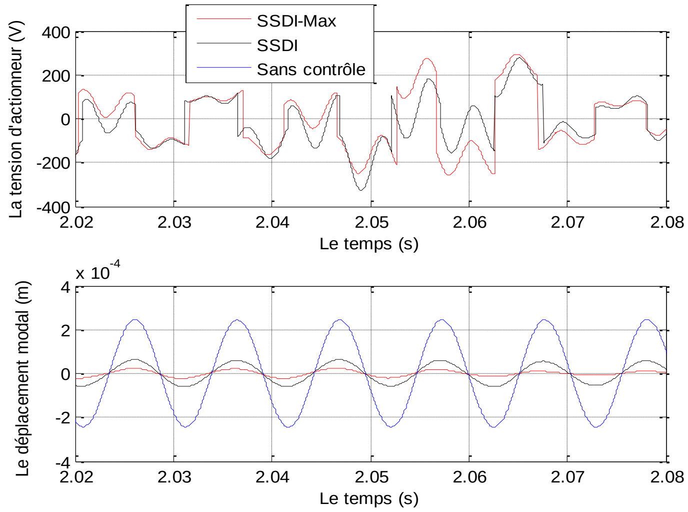


Fig.15. the piezoelectric actuator voltage and modal displacement for control of only one mode (mode 1). In the case of multi-sinusoidal excitation.

A.2. Pulse excitation.

The excitation is a pulse square of 50 µs

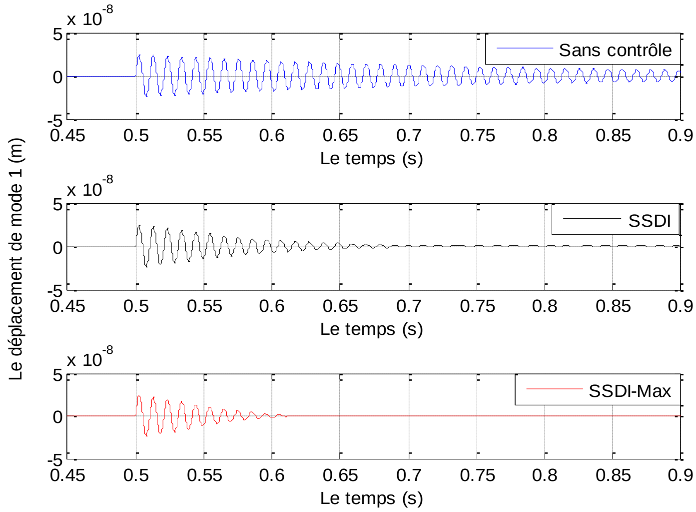
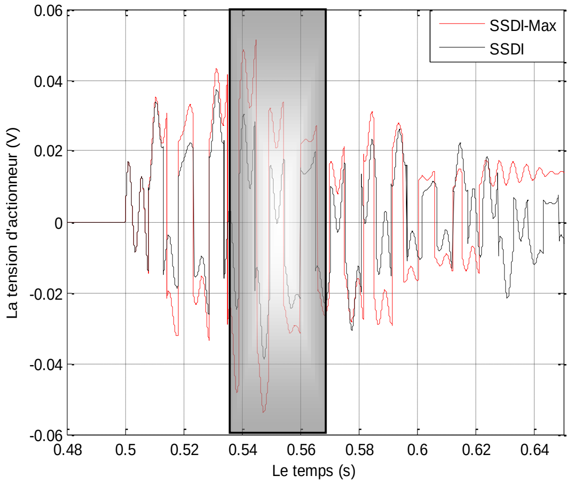


Fig.16.displacement simulation of mode 1 with the impulse excitation in the case of mode 1 targeted by control.



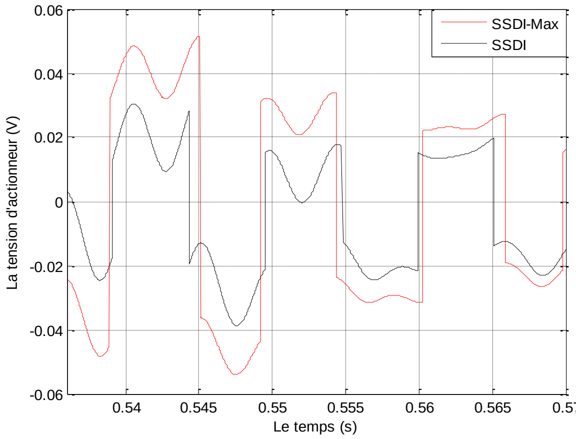


Fig.17. (Top) the actuator voltage simulation with an excitation by impulse in the case of mode 1 targeted by control (low) increased seen of the gray area.

The figures 15, 16 and 17 for the two types of excitation illustrate the increase in the piezoelectric actuator voltage generated V_a where the performances of damping are strongly dependent on this voltage. Moreover, it is clearly visible that a strong improvement of damping by using method SSDI- max is carried out.

VI. CONCLUSION

The performances of SSDI technique can be improved by using an algorithm which exploits the complexity of the form of the piezoelectric voltage in the wide band case (modal SSDI-MAX)

Though the setup of the modal SSDI-MAX is impossible without the presence of an observer for the reason that it is based on modal coordinates which are inaccessible by the measurement. Hence the performances of the modal strategy are substantially related to the performances of the observer used.

In this work, performances of the LQG observer were improved using a fuzzy-neural regulator. And it compared with a LQG+PID observer developed by CHERIF and Al [8]. It was shown that the proposed observer offers much better performances in both open and closed loop tests. The validation of this proposed work was done using numeric simulation (using the Matlab/SimulinkTM environment.) in the case of a clamped steel plate.

Prospect works aim at implanting and validating experimentally the proposed work.

REFERENCES

[1] R. L. Forward. « Electronic damping of vibrations in optical structures ». Applied Optics, 18(5): 690˝U697, 1979.

[2] N. W. Hagood and A. Von Flotow. « Damping of structural vibrations with piezoelectric materials and passive electrical networks ». Journal of Sound and Vibration, 146(2): 243–268, April 1991.

[3] C.H. Park and D.J. Inman. « Enhanced piezoelectric shunt design ». Shock and Vibration, 10 (2):127–133, 2003.

[4] A. J. Fleming and S. O. R. Moheimani. « Adaptive piezoelectric shunt damping ». IOP Smart Materials and Structures, 12: 36–48, 2003.

[5] Harari S, Richard C, and Gaudiller L., « New semi-active multi-modal vibration control using piezoceramic components ». Journal of Intelligent Material Systems and Structures, Vol. 20: 1603-1613. 2009.

[6] D. Guyomar, T. Richard and C. Richard. Sound wave transmission reduction through a plate using the piezoelectric Synchronised Switch Damping technique, Journal of Intelligent Material Systems and Structures, 2007

[7] S. Harari, C. Richard, and L. Gaudiller. Semi-active control of a targeted mode of smart structures submitted to multimodal excitation. In 9th International Conference on Motion and Vibration Control, Tech Univ Munchen, 2008.

[8] A. Chérif, C. Richard, D. Guyomar, S. Belkhiat, and M. Meddad «Simulation of multimodal vibration damping of a plate structure using a modal SSDI-Max technique». Journal of Intelligent Material Systems and Structures, Vol. 16: 1-16. 2012.

[9] S. Harari, C. Richard, and L. Gaudiller. New semi-active multi-modal vibration control using piezoceramic components. Journal of Intelligent Material Systems and Structures, In Press: 0, 2009.

[10] S. Harari, C. Richard, and L.Gaudiller. Multimodal control of smart structures based on semi-passive techniques and modal observer. Motion and Vibration Control: Selected Papers fromMOVIC 2008, 1:113–122, 2009.

[11] D. Luenberger. « An introduction to observers ». Automatic Control, IEEE Transactions on, 16(6):596–602, 1971.

[12] T. Richard, « Diminution du coefficient de transmission acoustique d'une paroi à l'aide d'amortisseurs piézoélectriques semi-passifs », thèse de doctorat de laboratoire de Génie Electrique et Ferroélectricité de l'INSA, 2007.

[13] A.CHERIF, «Optimisation du transformateur piézoélectrique. Application : contrôle semi-passive des vibrations.», thèse de doctorat de l'Université Ferhat Abbas – Sétif UFAS (Algérie) ,2012.

[14] H. Takagi, Fusion technology of fuzzy theory and neural networks - survey and future directions, in: Proc. First Int. Conf. on Fuzzy Logic & Neural Networks, 1990 1326.