FINE TUNING OF FUZZY CONTROLLERS FOR VIBRATION SUPPRESSION OF SMART PLATES USING PARTICLE SWARM OPTIMIZATION

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Abstract. *In the present investigation, an optimization algorithm inspired by nature is used for the fine-tuning of the parameters of a fuzzy controller used for the vibration suppression of a smart composite plate. More specifically, the particle swarm optimization method is chosen. This method is a population based optimization algorithm. It is a totally stochastic technique that simulates the movement of particles towards the optimum solution. The tuned controllers, which resulted from the optimization process, are tested for a wide range of different external loadings in order to examine the comprehensiveness of the proposed method in various excitation cases. The final results are compared with the ones from previous investigations of our team.*

1 INTRODUCTION

Piezoelectric components can be used as sensors and/or actuators in smart laminate composite structures for dynamic analysis and control, among other applications including static analysis energy harvesting etc., due to their ability to measure and smooth out vibrations of structures, caused by external loadings.

In previous investigations of our team, piezoelectric sensors and actuators were used for the vibration suppression and control of smart structures, such as beams and plates. The control strategy, which applied in these works, incorporated Mamdani-type fuzzy controllers [1], [2] and [3] and Sugeno-type neuro-fuzzy controllers [4], [5] trained through the Adaptive Neuro Fuzzy Inference System (ANFIS) within the MATLAB environment.

Initially, the parameters of the controllers where chosen from the literature and applied to the control strategy using the trial and error method. The next step involved the use of optimization tools [6], [7] in order to achieve better results regarding the vibration suppression of each structure.

In the present paper, the vibration suppression of plates using fuzzy control strategy is considered. Namely, the plate model considered is described by the Mindlin plate theory. The model is discretized using the finite element method and the control strategy is based on fuzzy controllers. This type of control is based on a set of linguistic rules that combine the membership functions, that is, the membership percentage of input variables to the final decision (output). For this purpose, fuzzy inference techniques are considered.

An optimization algorithm inspired by nature is used for the fine-tuning of the parameters of the fuzzy controllers. More specifically, the particle swarm optimization method is chosen. This method is a population based optimization algorithm. It is a totally stochastic technique that simulates the movement of particles i.e. the flying motion of a flock of birds, of a swarm of insects etc. In similar manner, the let say “flock” or “swarm” of possible solutions “flies” towards the optimum solution.

Particle swarm optimization is widely used in various applications of different scientific sectors, as it is considered to be one of the most promising algorithms inspired by nature. This kind of optimization methods is very popular because of their simplicity and their adaptiveness in many different problems.

The tuned fuzzy controllers, which resulted from the optimization process, are tested for a wide range of different external loadings in order to examine the comprehensiveness of the proposed method in various excitation cases. The final results are compared with the ones from previous investigations of our team.

2 STRUCTURAL DYNAMICS AND CONTROL

2.1 The smart composite plate

Consider a cantilever plate with two piezoelectric layers bonded symmetrically on both surfaces of the host structure. The bond between two layers is assumed to be perfect, so that the displacements remain continuous across the bond. The top surface serves as sensor, while the bottom one serves as actuator. The poling direction of the actuator is along the *z*-axis. An electric field E_z is applied along the poling direction of the actuator by applying a voltage *V* between the upper and lower electrodes of the actuator, with $E_z=V/h_p$. Because of the piezoelectric properties of the piezo layers, the actuator will perform in both x and y directions and therefore, induce deformation of the whole structure [8], [9].

The plate is discretized using the finite element method based on shear deformation theory. Four-node bilinear isoparametric elements with five degrees of freedom at every node were used. By using Hamilton's variational principle, the governing equations of motion of the piezoelectric composite plate in terms of the global coordinates are derived as follows [3]:

$$M \cdot \ddot{u} + C \cdot \dot{u} + K \cdot u = P + Z \tag{1}$$

where *M* is the mass matrix, *C* is the Rayleigh-damping matrix, *K* the stiffness matrix, *P* the loading vector and *Z* the control force vector. In addition, $u, \dot{u}$ and $\ddot{u}$ denote the global generalized displacement, the global velocity and the global acceleration respectively.

The main objective is to design control laws for the smart plate subjected to external induced vibrations. For this purpose, a fuzzy control system that was previously developed, is further tuned using a global optimization algorithm inspired by nature.

The finite element model is shown in the following figure:

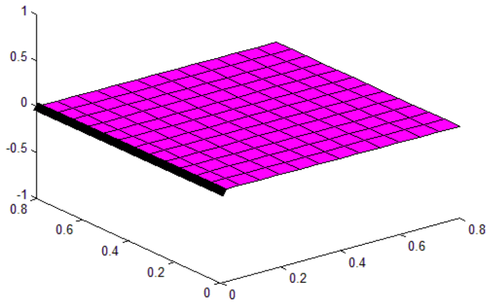

Figure 1.The plate model

2.2 The fuzzy controller

The initial fuzzy system is shown in Figure 2. It is developed completely using the fuzzy toolbox [1] of MATLAB. The control scheme consists of a Mamdani-type controller with two inputs and one output. The inputs of the controller are the displacement and the velocity and the output that it returns is the control force.

The membership functions used are of triangular and trapezoidal shape both for inputs and the output. The schematic representation of these functions is shown in Figure 3. The inference system use logical operations based on a set of if-then rules. This rule-based system includes a set of 15 rules with weights equal to unity and are connected using the AND-type operator. These rules are shown in Table 1.

The implication method is set to minimum and the aggregation one is set to maximum. As defuzzification method are chosen the mean of maximum and the centroid method.

Displacement / Velocity	Far up	Close up	Equilibrium	Close down	Far down
Up	Max	Med+	Low+	Null	Low-
Null	Med+	Low+	Null	Low-	Med-
Down	High+	Null	Low+	Med-	Min

Table 1: Fuzzy inference rules (e.g. if displacement is far up and velocity is up then the control force is max)

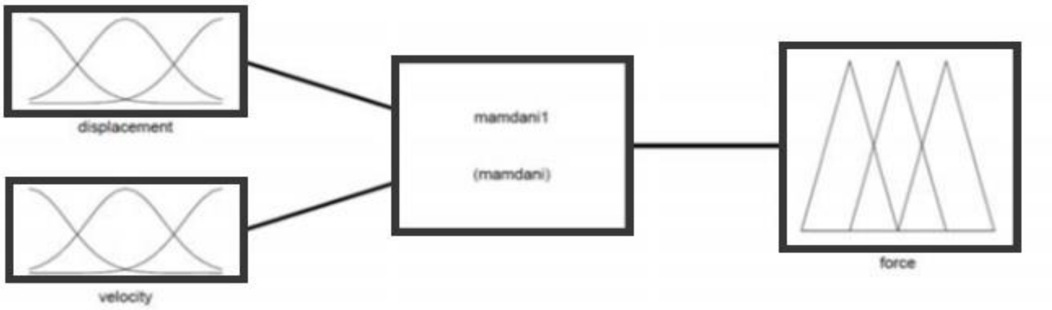

Figure 2. Mamdani fuzzy inference system

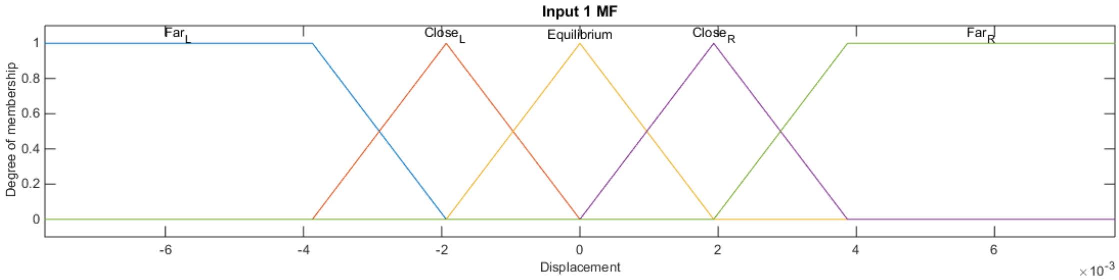

Figure 3. Membership functions of displacement (input 1)

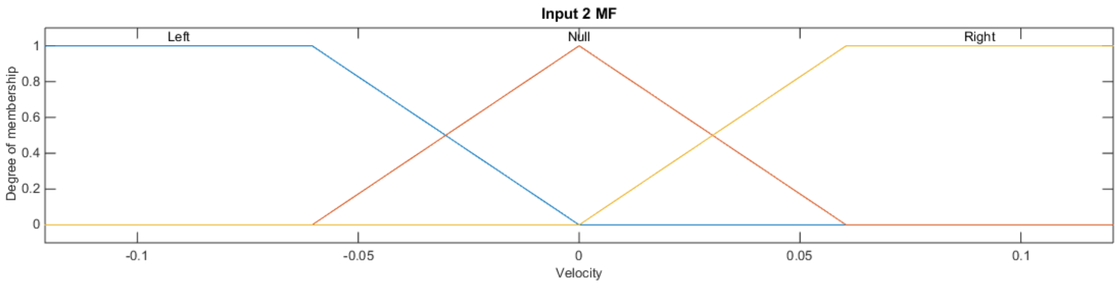

Figure 4. Membership functions of velocity (input 2)

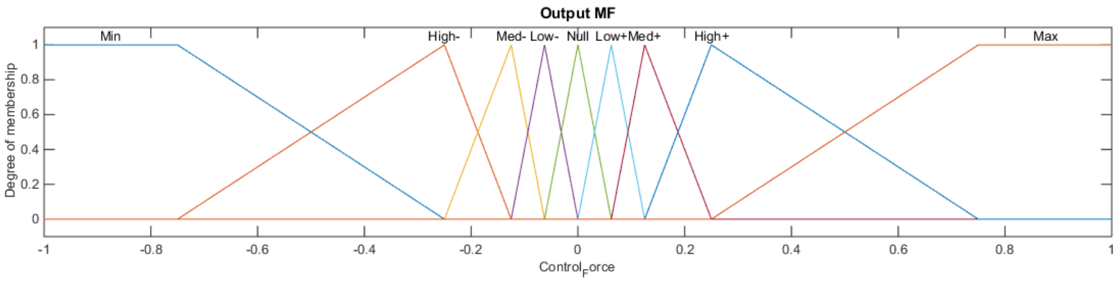

Figure 5. Membership functions of control force (output)

2.3 Structural dynamics

Based on the formulation described above, the equations (1) are used for dynamic response of the plate. The damping matrix C is given by:

$$C = 0.01 \cdot (M + K) \tag{2}$$

The loading P is given by:

$$P = P_0 \cdot sin(\omega \cdot t) \tag{3}$$

where P_0 is the loading's width and ω is the loading's frequency.

For the integration of the differential equations of motion (1), the Houbolt numerical integration method was chosen. Houbolt factors were set to:

$$\beta = 0.25, \gamma = 0.5 \tag{4}$$

The integration time was set to 3 seconds, while the time step *Δt* was chosen equal to 0.001 seconds.

Integration constants are given as:

$$c_1 = \frac{1}{\beta \cdot (\Delta t)^2}, c_2 = \frac{1}{\beta \cdot \Delta t}, c_3 = \frac{1}{2\beta}, c_4 = \frac{\gamma}{\beta \cdot \Delta t}, c_5 = \frac{\gamma}{\beta}, c_6 = \Delta t\left(\frac{\gamma}{2\beta} - 1\right) \tag{5}$$

The controller returns a control force Z(t) in each time-step (t) of the integration, taking as inputs the displacement u and the velocity $\dot{u}$. The total force, that is the control force plus the external loading, gives the next step's (t + Δt) values of displacement and velocity.

3 FINE TUNING OF THE CONTROLLER

In previous investigations [1], [2], [3], [5] fuzzy controllers gave very satisfactory results in terms of vibration suppression and in terms of displacement. However, velocities and accelerations were very high and definitely a burden for the structure and the controllers.

For this reason the tuning of the controller's parameters is necessary. In this investigation the particle swarm optimization method is chosen.

3.1 Particle Swarm Optimization (PSO)

Particle Swarm Optimization method is a population based optimization algorithm inspired by nature. It is a totally stochastic technique, as genetic algorithms and other similar optimization methods. This algorithm simulates the movement of particles i.e. the flying motion of a flock of birds or of a swarm of insects, the shoaling or schooling of a group of fish etc. In similar manner, the swarm of possible solutions "flies" towards the optimum solution.

Particle swarm optimization is widely used in various applications of different scientific sectors, as it is considered to be one of the most promising algorithms inspired by nature. This kind of optimization methods is very popular because of their simplicity and their adaptiveness in many different problems.

The algorithm used in the present paper is included in the optimization toolbox package of MATLAB. The parameters of the algorithm were chosen with the trial and error method, taking into account the size of the problem, the computational cost and the desired accuracy.

Namely, the inertia range was set to [0.1, 1.1], the maximum number of iterations to 50, the self-adjustment and the social-adjustment parameters of the algorithm to 1.49, the stall iteration limit was set to 10 iterations and the swarm size was chosen to be 4 particles.

3.2 The optimization problem

The objective is the maximization of the percentage of the vibration reduction in terms of displacement, thus to minimize the total oscillation of the plate in terms of displacement. This maximization problem consists of the maximization of the quotient of the ratio of the difference between the maximum displacement before and after control to the maximum displacement before control.

The design variables x_1, x_2 and x_3 of the algorithm are the coefficients that adjust the range of the membership functions of the three fuzzy variables (two inputs and one output) of the fuzzy controller.

The initial controller's ranges were set to [-0.0077, 0.0077] for the displacement and to [-0.1209, 0.1209] for the velocity respectively. The values 0.0077and 0.1209 were the maximum displacement and the maximum velocity respectively and were calculated solving the dynamic system without control. The initial ranges for the force were set to [-1, 1]. However, we shared it to three different points, that is, the range changed to [-1/3, 1/3].

The tuning of these ranges is the object of the present investigation. The idea is to find the ranges of fuzzy inputs that maximize the vibration reduction. The design variables take values between 0 and 1, thus the range can be a percentage of the maximum values mentioned above. The optimization results are multiplied with the initial ranges yielding the new tuned ranges.

Particle swarm optimization have the advantage that needs lower computational power compared to other methods, like genetic optimization. On the contrary, it is more sensitive to local optima. In the present problem, strong local optima and/or non-convexity does not exist, making the use of the pso method suitable. Moreover, due to the simplicity of the optimization problem only a small number of iterations along with a small size of swarm were needed. However, the results were very satisfactory as will be shown below.

4 NUMERICAL RESULTS

The problem of the present investigation is the fine tuning of a fuzzy controller [1], [2] used for the vibration suppression of a cantilever laminated composite plate of dimensions 0.8 m × 0.8 m described in [3]. The plate consists of four composite layers and two outer piezoceramic layers and subject to sinusoidal loading. The material of the plate is T300/976 graphite-epoxy composite and the piezoceramic is PZT G1195N. The elastic moduli and the Poisson's ratios for the graphite-epoxy material and the piezoceramic are [3]: E_1=150.0 GPa, E_2=E_3=9.0 GPa, G_{12}=7.1 GPa, G_{23}=G_{13}=2.5 GPa, $v_{12} = v_{13} = v_{23}$=0.3 and $E_1^p = 63.0$ GPa, $E_2^p = E_3^p = 63.0$ GPa, $G_{12}^p = G_{23}^p = G_{13}^p$=24.2 GPa, $v_{12}^p = v_{23}^p = v_{13}^p = 0.3$.

The total thickness of the composite is h_c= 1 mm and each layer has the same thickness (0,025mm); the thickness of each PZT is h_p= 0.1 mm.

The structure is discretized using the finite elements method. Namely, it is divided into 144 square elements. The recurring system has 169 nodes with 5 degrees of freedom per node. The plate is fixed at the left side at nodes 1, 14, 27, 40, 53, 66, 79, 92, 105, 118, 131, 144 and 157 as denoted by the bold line in Figure 1.

In the present investigation, the loading was applied on three nodes. These nodes are 13, 91 and 169 and correspond to the upper corner, the middle point and the lower corner of the free side of the plate respectively, as shown in Figure 6(a). The position of control at node 91 is shown with blue arrow in Figure 6(b).

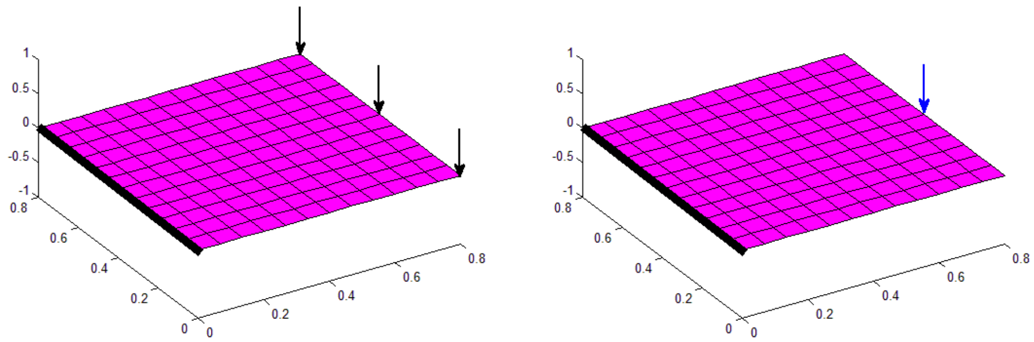

Figure 6. (a) The loading nodes and (b) the control node

The loading that is applied to each node is given by:

$$P = \frac{1}{3} sin(20t) \tag{6}$$

The vibration suppression of the smart plate before the optimization of the controller's parameters [3] was 71% for displacements and 31% for velocities. On the other hand the acceleration field increased by 167%.

One can observe that even if the reduction of displacement and velocity is significant, the appearance of higher accelerations is a burden for the structure, as well as for the sensors and actuators, since they lead to material fatique and discomfort problems. Thus, the optimization of the controller's parameters with use of particle swarm optimization method was studied.

In the present paper two different cases will be presented. The first one deals with the optimization of the inputs' (displacement and velocity) ranges of the fuzzy controller. In the second case the tuning of both inputs and output is performed.

4.1 Tuning of the ranges of both inputs and output

In this tuning scenario, we tried to optimize the parameters of both inputs and of the output of the fuzzy inference system. This means that the ranges of the membership function of displacement and velocity, as well as of the control force have changed.

The particle swarm optimization algorithm returns the new ranges as follows. As for the two inputs of the controller, the new ranges were a percentage of 34.04% of the maximum displacement and 25.51% of the maximum velocity respectively. The range for the output variable was chosen to be at the 95.93% of the maximum force width.

The recurring membership functions, which occurred from the optimization process, are shown in the following figures.

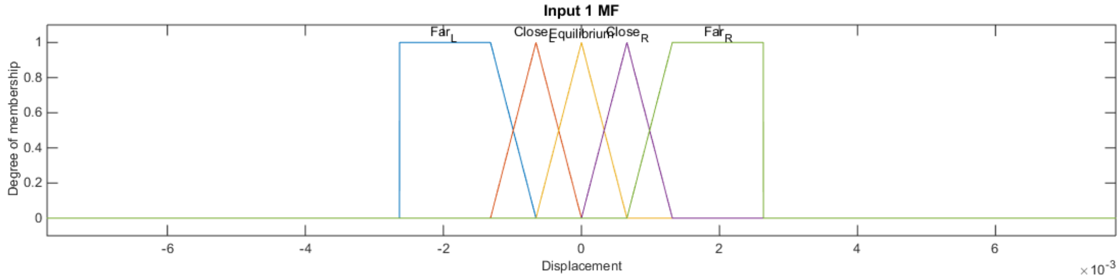

Figure 7. Membership functions of displacement (input 1) after optimization of inputs and output

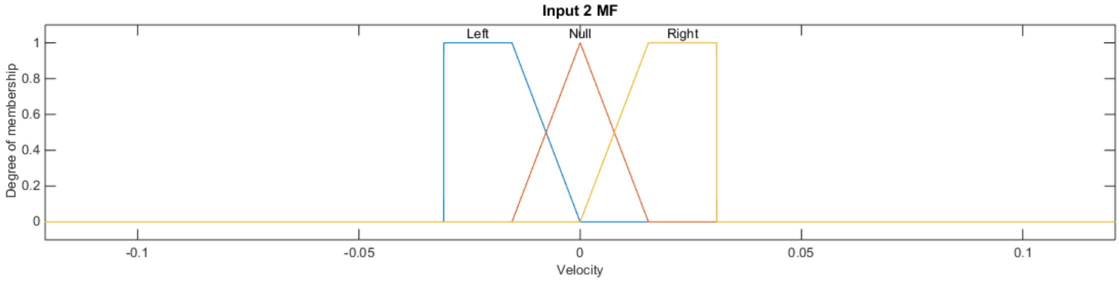

Figure 8. Membership functions of velocity (input 2) after optimization of inputs and output

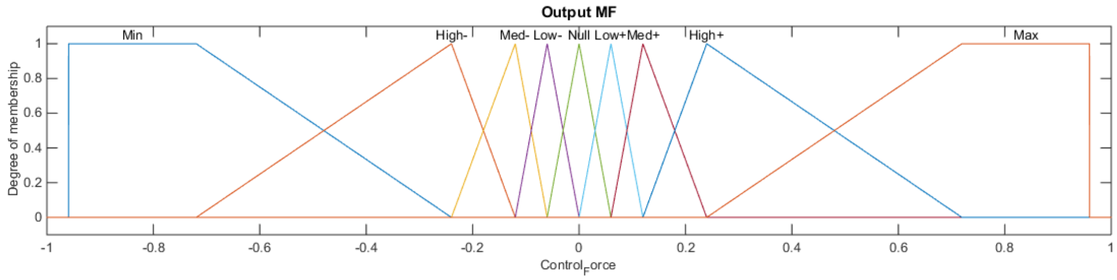

Figure 9. Membership functions of control force (output) after optimization of inputs and output

The new optimized fuzzy controller reduced oscillations by 90.59% for displacement in relation to the controller without optimization. The velocity reduced by only 79.78%, while acceleration increased to 115.72%. This increase of the acceleration is problem that demands further tuning of the fuzzy controller. Schematically, these numerical results are shown in the following figures. Another fact here is that the control force, shown in figure 11, is also very high.

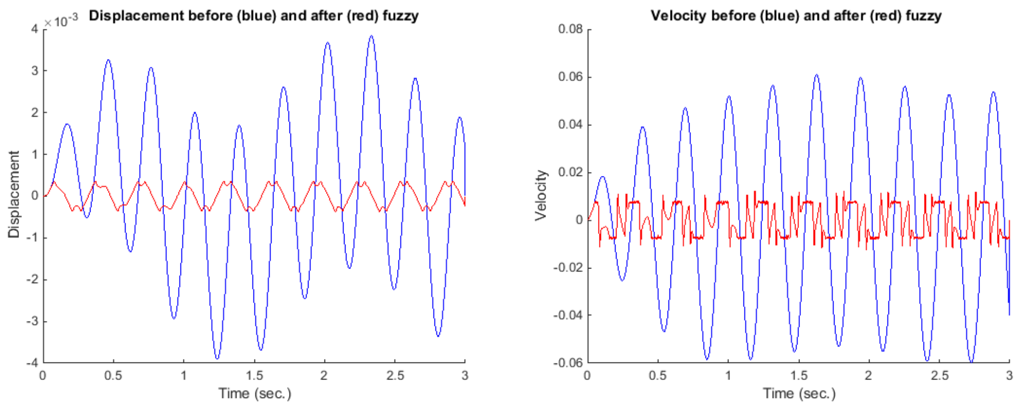

Figure 10. (a) Displacement and (b) Velocity at node 91 after optimization of inputs and output

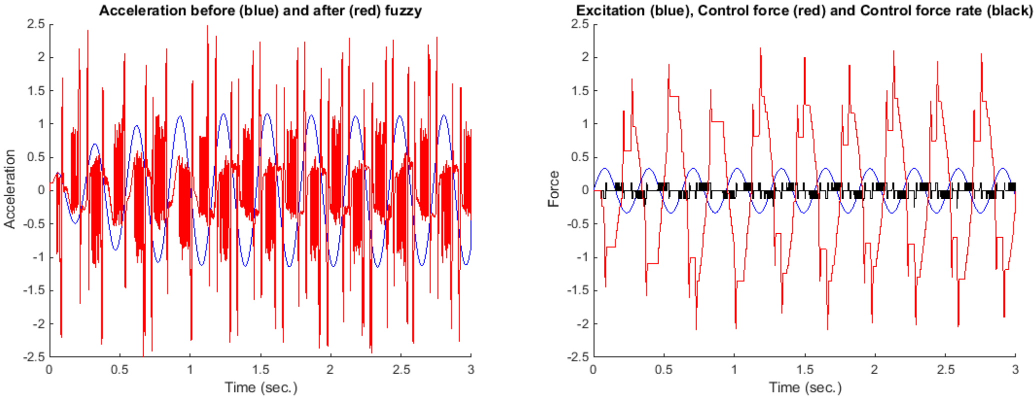

Figure 11. (a) Acceleration and (b) Forces at node 91 after optimization of inputs and output

4.2 Tuning of the ranges of the inputs

From the previous tuning scenario, one can easily observe that the membership functions of the output practically, remain unchanged, or changed slightly. Namely, the value of maximum control force that came from the optimization process was 0.96 instead of 1. For this reason we decided to simplify more the optimization problem, by trying to tune only the ranges of the fuzzy inputs. Thus the recurring optimization problem has only two design variables, that is, the range of the two inputs of the fuzzy system; the displacement and the velocity.

From the optimization process, the particle swarm algorithm provided the new ranges for the two inputs of the controllers as a percentage of 69% of the maximum displacement and 5.5% of the maximum velocity. The membership function of the output remained unchanged. The membership functions that occurred are shown in the following figures.

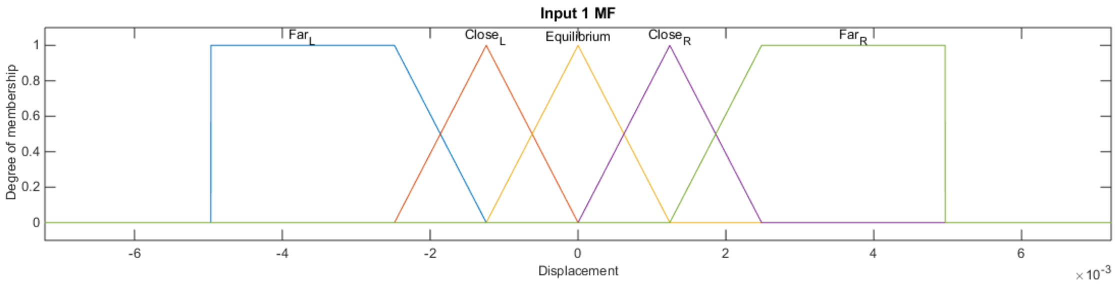

Figure 12. Membership functions of displacement (input 1) after optimization of inputs

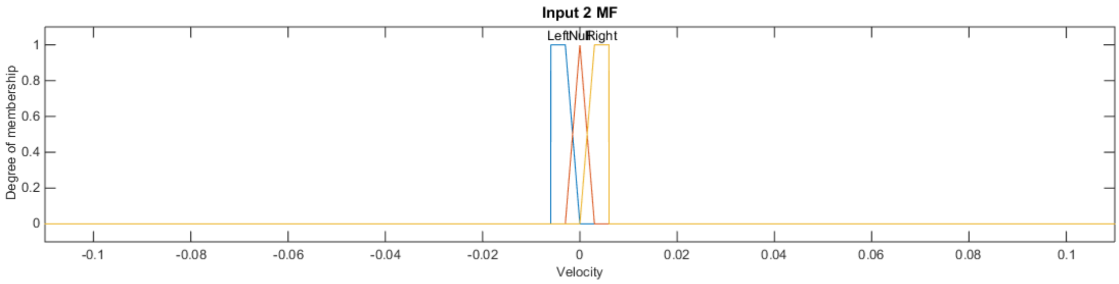

Figure 13. Membership functions of velocity (input 2) after optimization of inputs

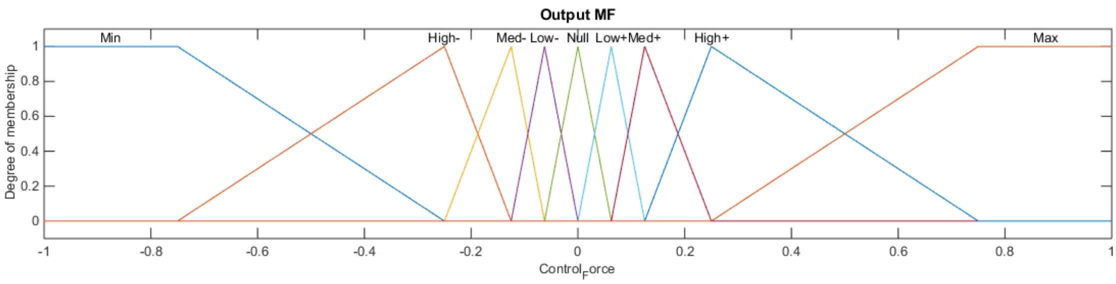

Figure 14. Membership functions of control force (output) after optimization of inputs

The control with these tuned ranges was very efficient in terms of displacement and velocity. The reduction of the displacement was 96.35%, while velocity reduced by 96.64%. However, the acceleration increased by 6,10%, which is much better than the 167%, that appeared before the tuning, although further refinement is possible.

These results are shown schematically in the following figures.

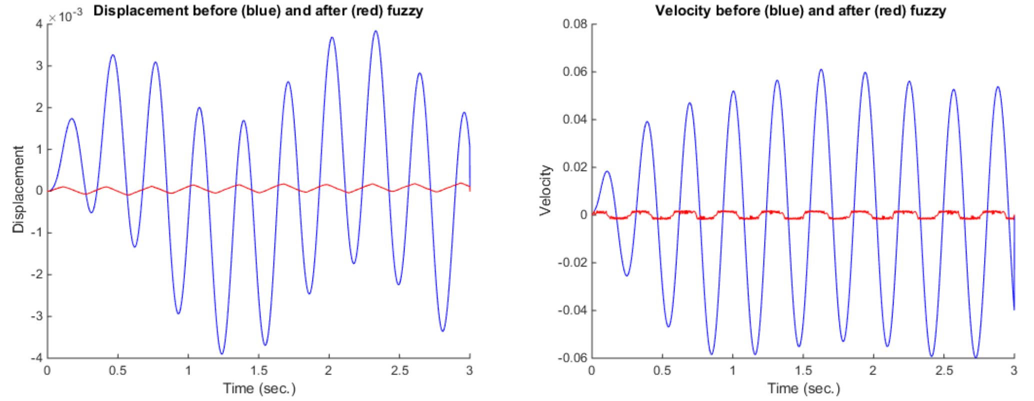

Figure 15. (a) Displacement and (b) Velocity at node 91 after optimization of inputs

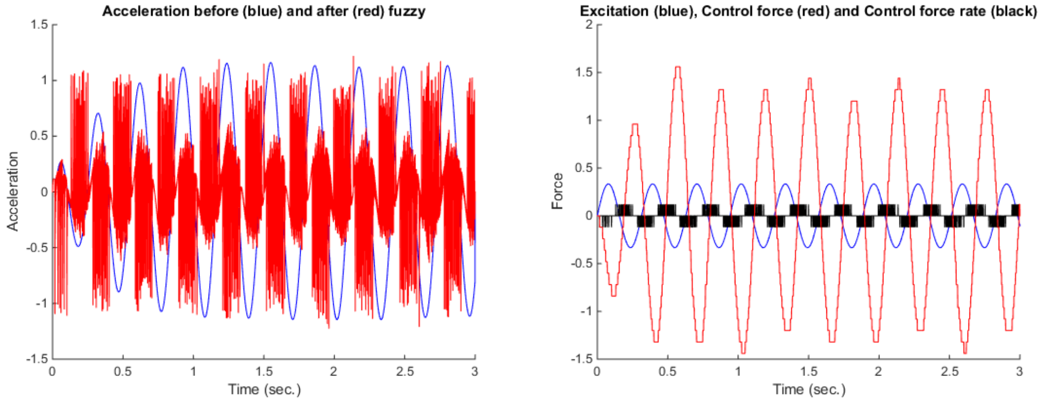

Figure 16. (a) Acceleration and (b) Forces at node 91 after optimization of inputs

As one can easily observe from the results above, the reduction of displacement and velocity is very sufficient and smooth as well. As for the acceleration, even if the results have improved significantly, they remain rough.

For this purpose we have done some further fine tuning by changing the defuzzification methods. The best results produced by the centroid method.

In this case, both displacement, velocity, and acceleration filed reduced significantly. Namely, the displacement reduced by 99.35%, the velocity by 98.98% and acceleration by 95.89%. Moreover, even if the control force needed for the suppression was higher than the excitation, its form is smooth enough as it is shown in the figure above. These results as shown schematically in the following figures.

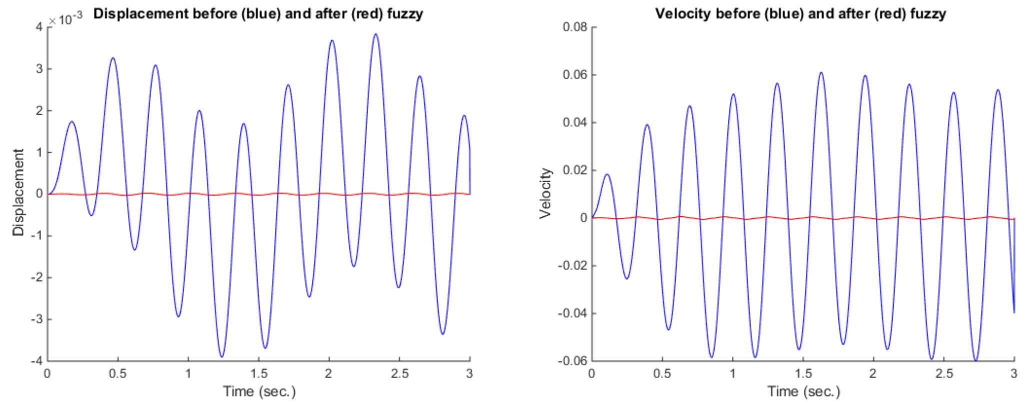

Figure 17. (a) Displacement and (b) Velocity at node 91 after optimization of inputs with centroid method

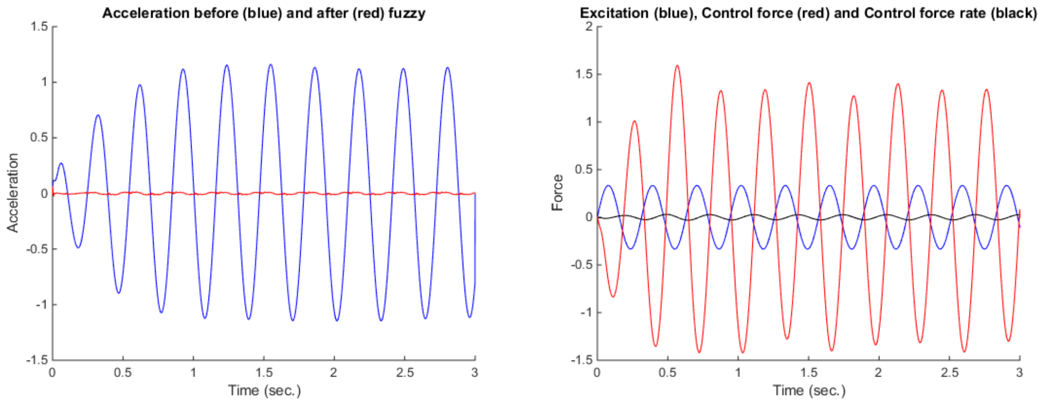

Figure 18. (a) Acceleration and (b) Forces at node 91 after optimization of inputs with centroid method

5 FUTURE WORK

As shown in the latter case, the vibration suppression was very satisfactory, for both displacement and velocity and even for acceleration. The results were smooth enough as well. A possible next step could be the use of neuro-fuzzy controllers or other optimization methods for even smoother results.

ACKNOWLEDGEMENTS

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