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Design of intelligent control strategies using a magnetorheological damper for span structure

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Abstract. This paper focuses on the design of an intelligent control system. The used techniques are based on Neuro Fuzzy approaches applied to a magnetorheological damper in order to reduce the vibrations over footbridges; it has been applied to the Science Museum Footbridge of Valladolid, particularly. A model of the footbridge and of the damper has been built using different simulation tools, and a successful comparison with the real footbridge and the real damper has been carried out. This simulated model has allowed the reproduction of the behaviour of the footbridge and damper when a pedestrian walks across the footbridge. Once it is determined that the simulation results are similar to real data, the control system is introduced into the model. In this sense, different strategies based on Neuro Fuzzy systems have been studied. In fact, an ANFIS (Artificial Neuro Fuzzy Inference System) method has also been used, in addition to an alternative Neuro Fuzzy approach. Several trials have been carried out, using both techniques, obtaining satisfactory results after using these techniques.

Keywords: vibration; magnetorheological; control; footbridge; neuro fuzzy; ANFIS

1. Introduction

Nowadays engineering structures tend to be lighter and more flexible. Because of this, structures such as towers, buildings or footbridge are more susceptible of suffering vibrations. Footbridges are particularly subjected to external disturbances every day. According to several studies (Zivanovic *et al.* 2005), the vibrations are generally produced by pedestrians who might

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induce a footbridge response near to the resonance. Therefore, it is necessary to incorporate a device to these kinds of structures in order to protect them from damaging sources. In this work the external source that generates vibrations are pedestrians going across the footbridge.

There are several techniques capable of reducing the vibrations produced over engineering structures (Jansen *et al.* 1999) (Miller *et al.* 1988). The most traditional one is to use a passive one, usually consisted of a spring and a damper. The advantage of these systems is that no computer or external power source is needed. However, once the passive device is installed, its properties cannot be adaptable. This fact is an important constraint since it does not allow any adaptation of its parameters to changes of vibration signals. On the other side, the active control techniques lack this disadvantage while they also are very well considered owing to their adaptability properties. Actually, it provides a high control performance in a wide frequency range. However, its high power requirement and expensive hardware make their commercial adoption difficult.

In recent years, the semi active methods have been under use (Dong *et al.* 2010) (Yagit and Yuksek 2001) (Haibo and Jian 2009) since they offer a relatively low cost and reliable solutions. They are usually composed of a passive spring in parallel with a controlled damper. This allows the provision of further vibration reduction suffered by the structures since the damping properties can be adapted to each situation.

In this work a Magnetorheological (MR) damper is used as isolation device in order to reduce the vibrations suffered by the footbridge. These devices use controllable fluids composed by micron sized, magnetically polarisable particles dispersed in a fluid. Their properties are changed when a magnetic field is applied, since particles are stood in chains form modifying the fluid´s behaviour. This particular technology shows a fast response to the magnetic field. Thus, it is very convenient in control tasks, given the fact that it allows for a broad bandwidth in addition to the compact size of the actuator device. In spite of these advantages, its inherent nonlinear hysteresis nature and its dynamic uncertainty makes it difficult to find an adequate control strategy.

The current work is presented in several sections. In section 2 the MR damper and its mathematical model based on Bouc Wen model are shown. Section 3 shows the footbridge used in this study, along with the mechanical model of the footbridge and the MR damper implemented in Simmechanics (Simulink®). The control strategies are explained in section 4 and finally, the obtained results and conclusions are presented in section 5 and section 6, respectively.

2. Magnetorheological damper modelling

There are many mechanical models that can be used to predict the response of a MR damper (Spencer *et al.* 1996). Although there are more up to date models, in this paper the one used is composed of a Bouc Wen model in parallel with a damper (Yoshioka *et al.* 2002), as it is shown in Fig. 1. It was decided to employ this model since the available parameters make its behaviour accurate enough.

The equations that represent this Magnetorheological damper model are presented below.

The force in this system is provided by

$$F = C_0 \dot{x} + \alpha(t) z \tag{1}$$

where the evolutionary variable z is governed by

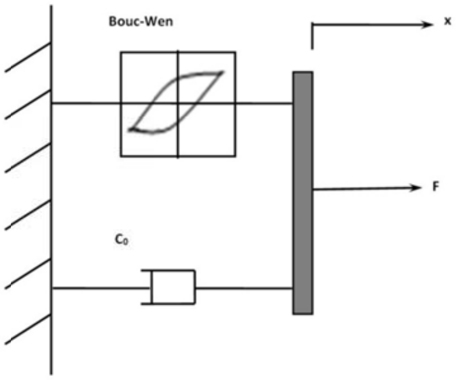


Fig. 1 Magnetorheological damper model

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^{n} + A\dot{x} \quad or \quad \dot{z} = \left(A - |z|^{n}\left(\gamma\,\mathrm{sgn}(\dot{x}z) + \beta\right)\right)\dot{x} \tag{2}$$

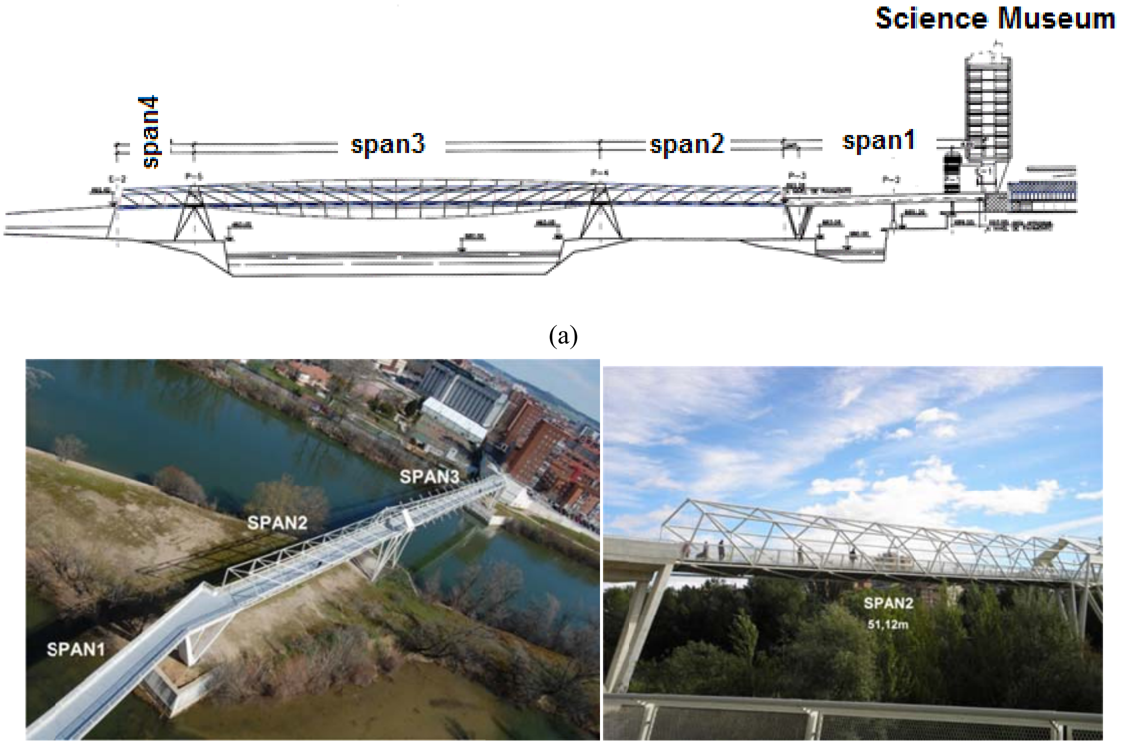
Since the MR fluid is directly dependent on the magnetic field, the parameter is assumed to be as a function of the applied voltage as shown in Eq. (3).

$$\alpha(t) = -\left(\alpha(t) - p_1 v(t) - p_2\right)\eta \tag{3}$$

The parameters for this MR damper model (Ramallo *et al.* 2004) are A=1, n=1, $\beta=\gamma=58.662*10^4$ m^{-2}, $C_0=33.27$ Ns/m, $\eta=2\pi 11$ rad/s, $p_1=3111.7*10^2$ N/m/V y $p_2=161.47*10^2$ N/m.

3. Footbridge description and mechanical model

The studied structure, Fig. 2(a), is a footbridge (Valladolid, Spain) over the Pisuerga River that links the “Science Museum” with the city (Gómez 2004). It is a 234 m long truss structure composed of four spans: three made of tubular steel bars (hexagonal cross section) and one made of white concrete, span1. Span2 is 51.12 m long, span3 is 111.31 m long, and span4 is 28.30 m long, the latter being much shorter and stiffer. The main span3, is prestressed by an external cabling system with two functions: aesthetical and structural (the two frames connected by means of tubular ribs maintain the shape of the cables and make stiffer the pedestrian area). Span2, Fig. 2(b), represents a typical lightweight structure sensitive to dynamic excitations produced by pedestrians. Hereunder the term footbridge will be utilized for the sake of simplicity, to make reference to Span2. The Finite Element Mode was used to find the main modal parameters (Casado *et al.* 2008) and eventually the model was updated (Casado *et al.* 2013) by means of operational modal analysis. Its natural frequencies, damping ratios, modal shapes of the lower vibration modes, frequency response functions at the point of maximum amplitude are obtained to identify thus its modal properties. Also, the Frequency Response Function was evaluated at the point of maximum amplitude to identify its modal properties (Span2).



(a)

(b) (c)

Fig. 2 Photograph of the Science Museum Footbridge of Valladolid where the studied section is marked with a double arrow

The simulating platform Simulink/Simmechanics provided by Matlab is applied in order to build the mechanical model. This model includes both the footbridge and the MR damper. The design followed in the construction of this model is a semi active TMD (Ji *et al.* 2005) and it is shown in Fig. 3. These systems attempt to reduce the dynamic response of a structure that is symbolized by M1 and a spring damper (K1 C1). This is achieved with a body (M2), a passive spring K2 and an adaptive damper C, when an external force (Fp) is applied. The optimisation of the TMD parameters was carried out using a methodology based on the design of an H∞ static output feedback controller (Poncela and Schmitendorf 1998). This method is just used to optimise the stiffness and damping of the TMD. The parameters obtained are summarized in Table1.

Table 1 Parameters of TMD semi active model

Mass (Kg)	Spring (N/m)	Damper (Ns/m)
M1= 18000	K1= 8458053.58	C1=4682.2
M2= 183.1	K2=86536.7	C(t)

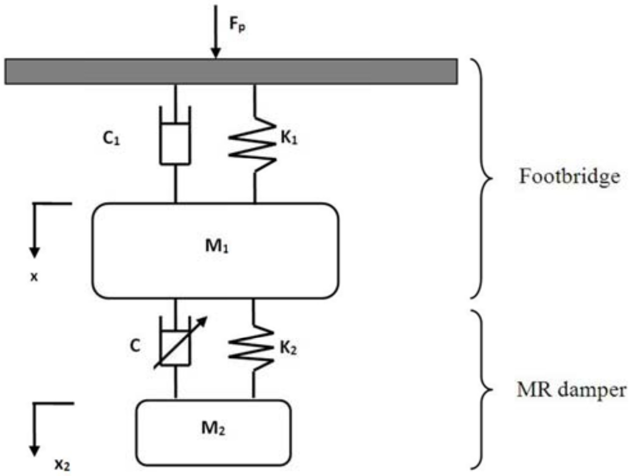


Fig. 3 Semi-active TMD

The equations showed in section 2 that represent the MR damper behaviour have been implemented in Simulink. Fig. 4 shows these equations where the system inputs are $\dot{x}$ (xp in Fig. 4), the displacement suffered by the structure, and ν, the MR damper voltage. This set of equations represents variable C behaviour as showed in Fig. 3.

The Simulink block, together with the Bouc Wen equations, is included with the rest of components that model the footbridge in order to build the semi active TMD. Fig. 5 presents the Simulink/Simmechanics environment with the elements constituting the semi active TMD.

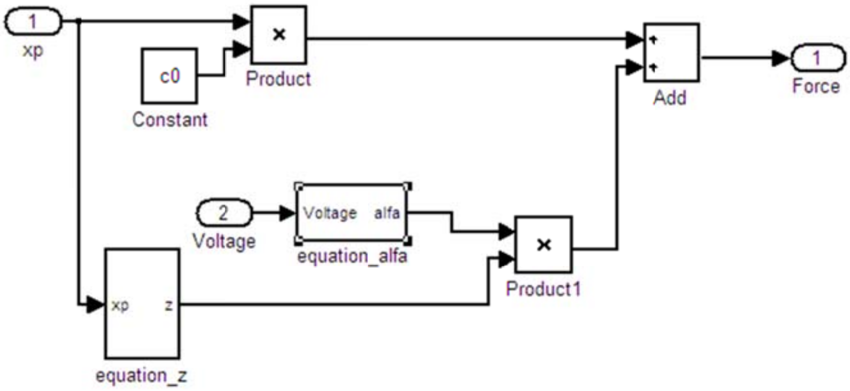


Fig. 4 Modelling of MR damper in Simulink

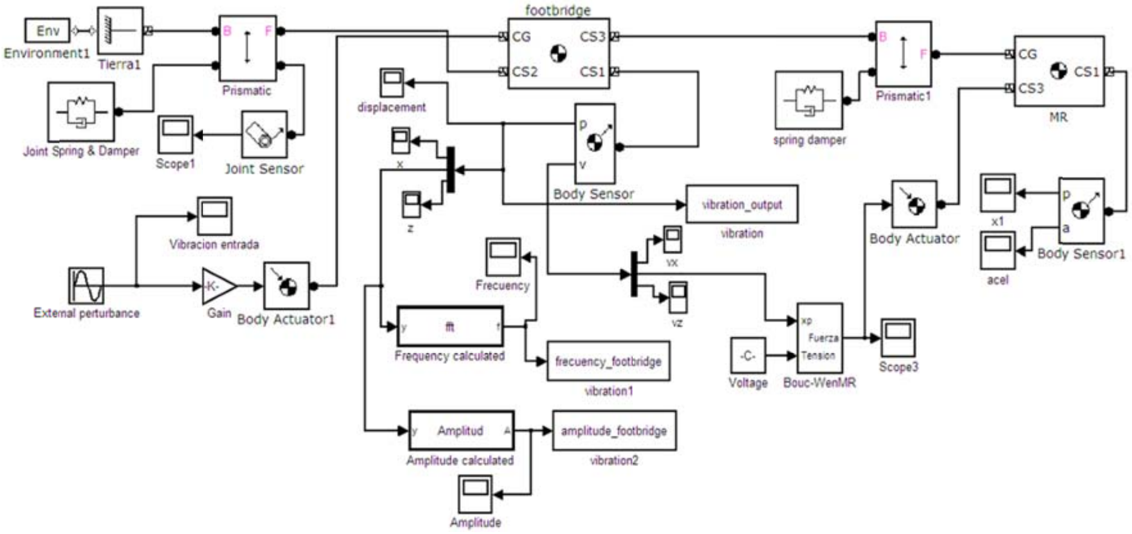


Fig. 5 Semi active TMD model in Simulink/Simmechanics

Once the TMD model was built it was necessary to check the model. With this purpose a comparison between the real footbridge behaviour and the simulated one was realized. Given the fact that footbridge behaviour depends on the voltage MR damper, it was decided to fix it in a middle value, 1.1 watt particularly. This choice allowed to make a test more efficiently since making real experiments is complicated. This comparison consists of introducing an external force generated by a pedestrian and analysing if the simulated footbridge behaves as the real one. Several trials were conducted. In fact, a pedestrian weighing 100 Kg jumping with a frequency of 3.5 Hz over the footbridge was considered. Forces near 670N of standard deviation with peaks of 2000N are generated in this case. These forces cause a vibration around of 1.6mm over the footbridge and a vibration of around 16 mm over the MR damper.

Once the real behaviour is known the force was introduced into the simulation environment in order to compare the results with the previous ones. The simulated model produces a vibration in the footbridge of 1.5 mm of standard deviation and a vibration over the MR damper of 18.5 mm of standard deviation, keeping the voltage fixed at 1.1watt. As it could be checked, these results are quite similar to the real behaviour. Thus, it could be argued that the simulated semi active TMD mimics the behaviour of the real system satisfactorily.

4. Semi active control strategies

The design of the proposed control system is based on the adaptability of the MR damper to disturbances suffered by the footbridge. This means that depending on the external disturbance, the necessary voltage to the MR damper will be different in order to reduce the footbridge vibration as much as possible. The inherent non linear hysteresis nature and the dynamic uncertainty of the semi active actuator make think that an intelligent control system is an adequate choice in order to relate both parameters. Note that the voltage that will be introduced depends on the vibrations suffered over the footbridge.

Before designing the control algorithm, it is necessary to create a reference table with the most adequate voltage values in order to achieve a minimum structure movement. The parameters which should be taken under consideration in order to be controller inputs should be characteristic values of the structure movement. In fact, the amplitude value of the vibration signal, the frequencies and amplitudes of its Fast Fourier Transform (FFT) and the current voltage applied to the TMD damper have been taken into consideration. The decision of including the voltage, both as input and output, is because the vibration footbridge also depends on the voltage applied at this time. That is, the output voltage chosen in a $(k+1)^{th}$ instant will be function of the voltage in the k^{th} instant, as well as the signal amplitude, frequency and FFT amplitude of the footbridge. In Fig. 6 a controller diagram with its inputs and it output is shown. It is important to point out that the chosen inputs can be obtained or measured directly over the structure. In other words, the amplitude value is measured by an accelerometer located on the footbridge, whereas the collected signal is used to obtain the dominant frequency and the amplitude of the dominant frequency by applying a FFT transform. Finally, as it was explained above the current voltage is used as one of the inputs. It is necessary to clarify that the MR voltage is taken as zero at the first time. Therefore, V1 will be obtained establishing V0=0. Once V1 is obtained as the most adequate voltage to minimize the footbridge movement, the process will be repeated each 0.5s. In fact, V2 is obtained, considering V1 as the applied voltage at a previous instant and so on.

In order to build the reference table it is firstly necessary to introduce an external perturbance and then to measure previous parameters over the footbridge. The external force levels are known experimentally, therefore, the frequencies and amplitudes of the disturbance signals that will be used are in that range. Considering this dependency, an iterative process is carried out with the semi active TMD model. In this way, the dominant frequency, the amplitude and the FFT amplitude are measured over the structure depending on MR voltage on the previous instant for each frequency and amplitude value of the input disturbance, with the voltage applied over the MR being modified for each case. With the purpose of deciding the most adequate voltage value, a criterion function is defined. This function will choose the voltage value that produces a minimum structure movement around the equilibrium position. It is necessary to point out that the maximum value of voltage is 2 V due to the input range of the MR actuator.

Once the reference table is built, it gives the best voltage value based on the footbridge movement. At this point, it is necessary to devise an intelligent control system in order to relate all variables pointed out in Fig. 6 in an adequate way.

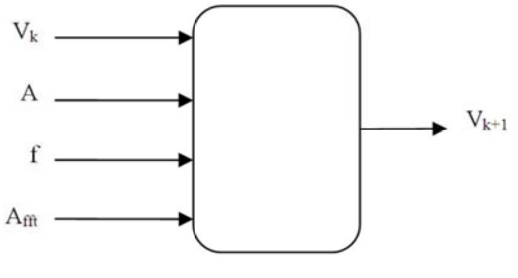


Fig. 6 Controller diagram with inputs and output

4.1 Intelligent control based on ANFIS

Particularly in this work, an ANFIS system is proposed as first study method (Marichal *et al.* 2009) (Jang 1993). It was decided to use this technique because it has been widely implemented and there are available tools in Matlab, which allows to integrate this method with the simulated model of TMD. It is an Artificial Intelligence technique based on training. In this method, based on a set of known input data and their corresponding outputs, the system interprets a new set of input data according to a set of rules, and provides an output value. The set of inputs used in this work consists of the frequency, the amplitude of the structure movement, the FFT amplitude and the MR voltage in the measurement instant [f A Afft vk], and the set of output is the corresponding voltage value [vk+1] that will be applied over the MR damper. The used ANFIS architecture is shown in Fig. 7, where can be seen a five layer system with four inputs, each one with two membership functions, and an output. The first and fourth layers have adaptive nodes, that is, their parameters could change during the training phase.

The first step is to choose the number and type of membership functions (MF) for each input, and to determine their membership degree values. As it was said previously, four inputs and two Generalized Bell MFs were chosen for each input. In the first layer each node has an output defined as

$$O_{A,i} = \mu_{A,i}(v_k);\, O_{B,i} = \mu_{B,i}(A);\, O_{C,i} = \mu_{C,i}(f);\, O_{D,i} = \mu_{D,i}(A_{fft}); \quad i = 1,2 \tag{4}$$

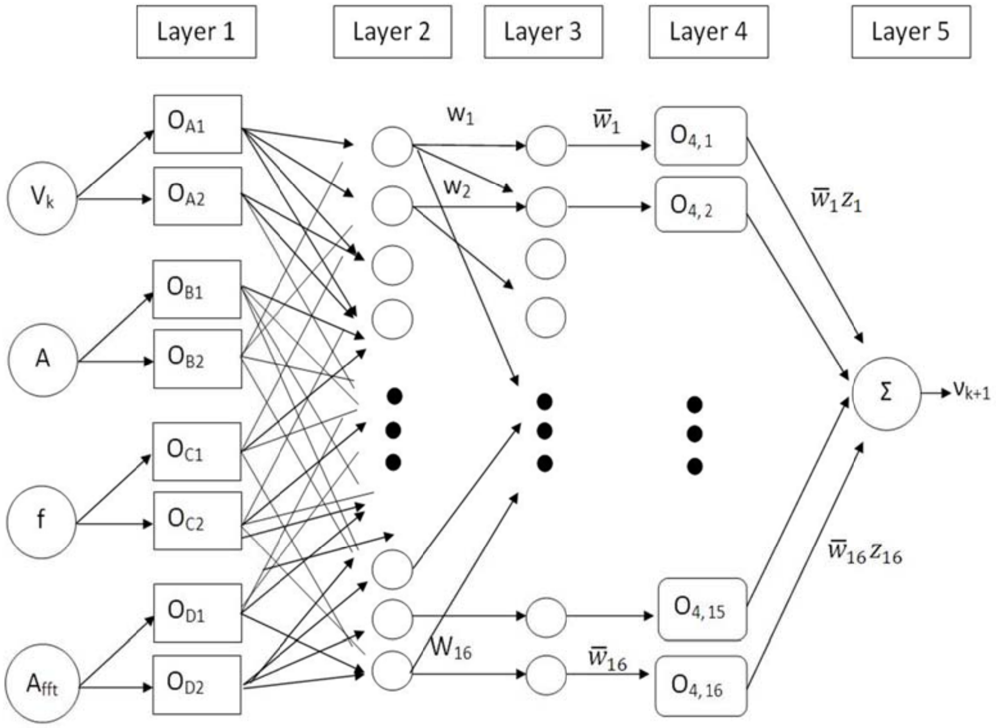


Fig. 7 Architecture ANFIS

In the second layer the fuzzy operator is applied, therefore the input signals are multiplied and the result represents the weight of each rule.

$$w_i = \mu_{A,i}(v_k)\mu_{B,i}(A)\mu_{C,i}(f)\mu_{D,i}(A_{fft}); \quad i=1,2 \tag{5}$$

The Implication method is applied in the third layer and the output of each node corresponds to the standard weights, which is a number between 0 and 1.

$$\overline{w}_i = \frac{w_i}{\sum_{i=1}^{n} w_i}; \quad i=1,2 \tag{6}$$

The aggregation is presented in the fourth layer and it consists of the fuzzy sets that represent the outputs of each rule combined into a single fuzzy set.

$$O_{4,i} = \overline{w}_i z_i; \quad i=1,2 \tag{7}$$

Where zi corresponds to three fuzzy if then rules of Takagi Sugeno type which are

$$\textit{If } v_k \textit{ is } ?_{A_1}, A \textit{ is } ?_{B_1}, f \textit{ is } ?_{C_1} \textit{ and } A_{fft} \textit{ is } ?_{D_1} \textit{ then } z_1 = p_1 v_k + q_1 A + r_1 f + s_1 A_{fft} + t_1 \tag{8a}$$

$$\textit{If } v_k \textit{ is } ?_{A_2}, A \textit{ is } ?_{B_2}, f \textit{ is } ?_{C_2} \textit{ and } A_{fft} \textit{ is } ?_{D_2} \textit{ then } z_2 = p_2 v_k + q_2 A + r_2 f + s_2 A_{fft} + t_2 \tag{8b}$$

Where p_i, q_i, r_i, s_i, t_i are the consequent parameters.

Finally, the output system is obtained in the fifth layer. This value is a real number. In this case the voltage value in the (k+1) th instant.

$$v_{k+1} = \frac{\sum_{i=1}^{N} \overline{w}_i z_i}{\sum_{i=1}^{N} \overline{w}_i} \tag{9}$$

Once the ANFIS technique has been chosen, the system is trained using 70% of reference table data. The remaining 30% is kept back in order to test if the system has achieved the adequate degree of generalization. The next step is to include the trained ANFIS in the simulation environment as a Simulink block. This block needs the frequency and amplitude of the structure movement, FFT amplitude and MR voltage in the measurement instant, as inputs. Therefore, a method in order to calculate them is required. Because of that, a FFT block is added before the ANFIS block and after the block that measures the footbridge vibration. This block is in charge of obtaining the spectral composition using the Fast Fourier Transform. In the same way, a block that calculates the amplitude is put between both blocks. This block obtains the footbridge movement amplitude from the accelerometer located on the structure and provides the maximum value for each 0.5 seconds. With this diagram, the ANFIS analyzes the inputs in order to provide the adequate voltage at intervals of 0.5 seconds. Finally, the obtained voltage value is introduced in the MR block explained in section 4. It is important to point out that a saturation block has been situated after ANFIS block in order to guarantee that the provided values are in the range admitted by the manufacture. In Fig. 8 the model with the integrated ANFIS control strategy is shown.

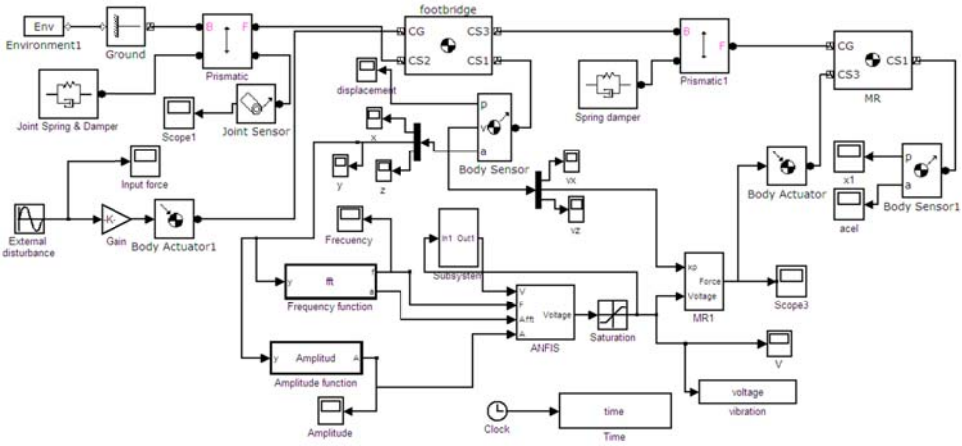
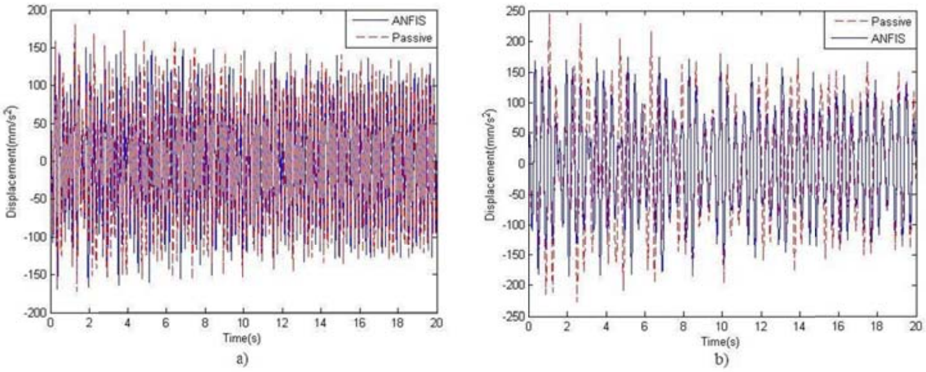


Fig. 8 Simulink model with ANFIS control technique

Several simulations were carried out considering an external disturbance as a block. The next step was to analyze the footbridge response under these vibrations and to study the performance of the intelligent control strategy based on the ANFIS. For that, firstly the system is subjected to a simulated external perturbance. These signals are generated taking into account that their parameters must be realistic, that is, their amplitude and frequency values are included into the range of data produced by pedestrians.

Fig. 9 shows the footbridge vibration using the ANFIS control policy versus a traditional passive technique under an instance of a particular simulated perturbance, where the MR voltage is kept fixed at an intermediate value. It can be seen in Fig. 9 (b)) that the ANFIS technique is capable of reducing the biggest peaks of the passive method. Nevertheless, Fig. 9 (a)) shows that the ANFIS hardly reduces the structure movement and both techniques have virtually the same behaviour.



a)

b)

Fig. 9 Comparison of footbridge acceleration under two different external disturbance with a passive control strategy and with the ANFIS technique

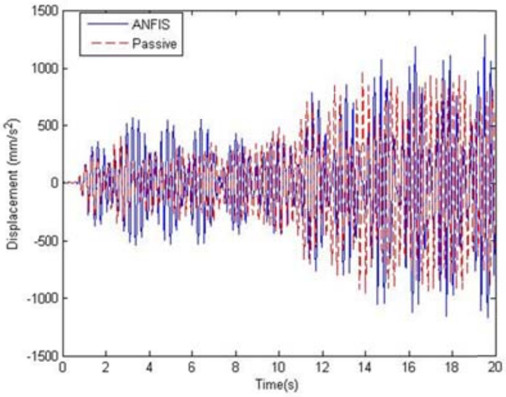


Fig. 10 Comparison of footbridge acceleration with a passive control strategy and with the ANFIS technique under a real perturbance

Although the ANFIS does not seem to reduce the structure movement for all simulated external perturbances, it has been decided to apply this technique to a real movement. Since it is possible to use laboratory instrumental to measure the force produced by a pedestrian, this real disturbance has been introduced in the simulation environment in order to check the ANFIS behaviour. Fig. 10 shows that the ANFIS behaves worse than a passive technique.

Although the ANFIS method has been applied satisfactorily to a wide variety of fields, in this range its behaviour is not as good as it was expected, therefore, it has been decided to test another intelligent approach. In section 4.2 an approach based on an alternative Neuro Fuzzy system has been considered.

4.2 Intelligent control based on NF

This method has a structure similar to Artificial Neural Network Fuzzy Inference System by Jang (Jang 1993) and it is an alternative technique proposed by Marichal *et al.* (Marichal *at al.* 2011) (Marichal *et al.* 2001). Fig. 11 shows that the proposed system could be seen as a typical Radial Basis Network including an additional layer between the input and output layer.

The first layer represents membership functions and it is composed by Radial Basis neuron where their inputs are the inputs to the Neuro Fuzzy System and the output nodes are expressed in the Eq. (10).

$$P_{ij} = exp\left(-\frac{\left(U_i - m_{ij}\right)^2}{\sigma_{ij}^2} \right) \qquad \begin{array}{l} j = 1,2,...,N_2 \\ i = 1,2,...,N_1 \end{array} \tag{10}$$

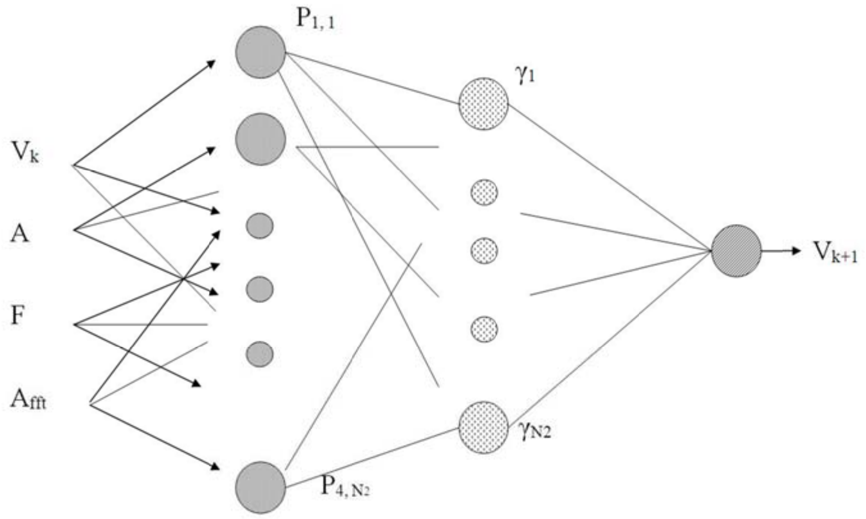


Fig. 11 Proposed Neuro Fuzzy architecture

Where

N_1 is the number of Neuro Fuzzy System inputs and N_2 is the number of nodes at the hidden layer.

U_i is the ith Input to the Neuro Fuzzy System.

m_{ij} is the centre of the membership function corresponding to ith input and the jth neuron of the hidden layer.

σ_{ij} is the width of the membership function corresponding to the ith input and the jth neuron of the hidden layer.

P_{ij} is the output of the Radial Basis neuron and give the degree of membership for ith input corresponding to jth neuron

The second layer represents the rule system and their outputs are calculated by:

$$\gamma_i = min\left|P_{1j,}P_{2j},\dots,P_{N_1 j}\right|\ j=1,\dots,N_2 \tag{11}$$

Finally, in the third layer the defuzzification is carried out, providing the Neuro Fuzzy output. It is composed by linear neurons which output is calculated by this expression

$$Y_k = \frac{\sum_j sv_{jk}\gamma_j}{\sum_j \gamma_j}\ j=1,\dots,N_2\ k=1,\dots,N_3 \tag{12}$$

Where N_3 is the output number of the Neuro Fuzzy system and sv_{jk} is the estimated value of kth output provided by jth node at the hidden layer.

To sum up, the described Neuro Fuzzy depends on the centres of membership functions (m_{ij}), their widths (σ_{ij}) and the estimated output values (sv_{jk}). These parameters are obtained using a training algorithm divided into four phases.

In the first one is fixed $\sigma_{ij}=1$ and an algorithm based on the Kohonen network has been used in order to establish initial values to m_{ij} and sv_{jk}. The elements of the weight vectors of the self organizing map (Eq. (13)) correspond to centres of membership functions and the estimated output value.

$$w_j = \left(w_{1j},...,w_{N_1 j},...,w_{N_1+N_3,j}\right) j = 1,...,N_2 \tag{13}$$

The self organizing map inputs are

$$V = \left(U_1,...,U_{N_1}, YD_1,...,YD_{N_3}\right) \tag{14}$$

Where U_k are the Neuro Fuzzy inputs and YD_m are the desired outputs. The Eq. (15) is the applied rule in order to determine the winner node (x) and to update the weight in each Kohonen algorithm cycle.

$$\|W_x - V\|^2 = min_j \|W_j - V\|^2 \ j = 1,...,N_2 \tag{15}$$

The weights are updated by

$$W_j(t+1) = W_j(t) + lr_0\left(\frac{mc-t}{mc}\right) exp\left(-\frac{(j-x)^2}{\sigma^2}\right)(V - W_j(t)) \quad j = 1,...,N_2 \quad t = 1,...,mc \tag{16}$$

Where σ is the variance, x is the winner node, lr_0 is the index of initial learning and mc is the number of learning cycles. The three terms that multiply to lr_0 are in charge of updating the weight. The first term [(mc-t)/mc] diminishes the learning rate while the training is progressing. The term $exp(-(j-x)^2/\sigma^2)$ defines the neighbourhood of the winner node. Finally $(V-W_j(t))$ takes into account the difference between the input vector and the weight vector.

This phase concludes after providing input output pairs for mc training cycles. Each weight vector is related to a neuron of the hidden layer since this vector contains the centres of membership functions and the estimated output.

In the second phase the number of nodes at the hidden layer is optimized. Note that, these nodes represent the number of fuzzy rules.

Although the first phase achieves that a neuron of the hidden layer and its related ones, show a strong response to a input pattern, it is possible that two nodes provide similar responses to a similar patterns. This means that nodes of similar rules could have been created. For this reason the aim of this phase is to reduce the node set.

In the third phase, a first change of the width of membership functions is done.

An iterative process is carried out where σ is changed for every membership function. The final σ is chosen comparing the training pattern and the test one to the network that has been trained with the non supervised algorithm. The chosen value is which one that minimizes the error of its response.

Finally, in the last phase, the Neuro Fuzzy parameters (m_{ij} σ_{ij} sv_{jk}) are definitely fixed by the supervised training algorithm.

Particularly, the Least Mean Squares (LMS) (Widrow *et al.* 1971) algorithm is used and it is based on the Eq. (17).

$$E = \frac{1}{2}\sum_{k=1}^{N_3}(Y_k - \hat{y}_k)^2 \tag{17}$$

Where $\hat{y}_k$ is the kth desired output and Y_k is the kth Neuro Fuzzy output.

In order to determine the Neuro Fuzzy parameters the Eq. 18 is applied iteratively.

$$m(t+1) = m(t) - lr\frac{\partial E}{\partial m} \quad t = 1,\ldots,m_f \tag{18}$$

Where m(t) is the Neuro Fuzzy parameter value that will be determined in the iteration t, lr is the learning index and m_f is the cycles training number. Therefore, the partial derivative of the error function with respect to each parameter (m_{ij} σ_{ij} sv_{jk}) should be calculated in order to apply the LMS algorithm.

This Neuro Fuzzy system was used as it was depicted above. In this case, the 70% of reference table data has been used in the training stage, keeping the remaining 30% to test the generalization capability. After that, the trained Neuro Fuzzy system was included in the simulation environment as a Simulink block with the necessary inputs. The diagram of Fig. 12 shows how the Neuro Fuzzy system analyzes the inputs providing the adequate voltage at intervals of 0.5 seconds.

Several trials were carried out with the proposed intelligent control policy. Fig. 13 shows that this technique works considerably better than the ANFIS. It could be checked that the proposed method reduces the undesirable structure vibration in up to 100 mm/s2. Since the proposed Neuro Fuzzy system seems to behave suitably, it was tested under real perturbances like the previous method. The result is shown in Fig. 14, where it is possible to observe that this Neuro Fuzzy system keeps a more stable movement while it also reduces bigger peaks after the first ten seconds.

The resonance condition is the worst situation to submit the footbridge to. With the purpose of doing a final comparison, the structure will suffer this condition and both methods were applied. As it could be seen in Figs. 15 and 16 the structure suffers saturation when the external perturbance has a frequency of 3 Hz. Therefore, it is necessary to change the MR voltage in an adequate way. Both Figs. show that the movement has been considerably reduced, although it could be seen in Figs. 15 (b) and 16 (b) that the alternative Neuro Fuzzy system achieves a more significant reduction.

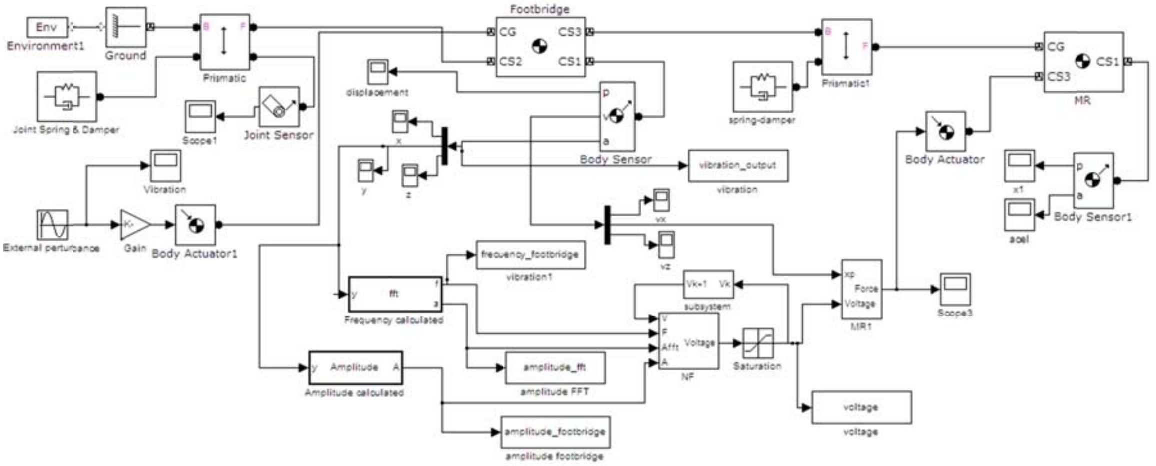


Fig. 12 Simulink model with Neuro Fuzzy control technique

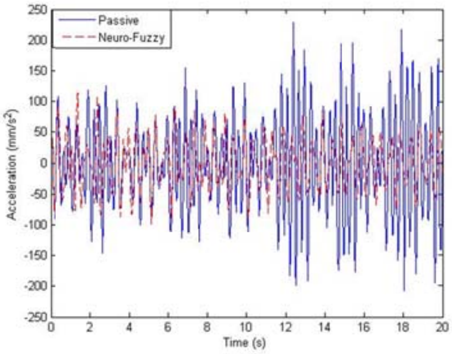


Fig. 13 Comparison of footbridge acceleration with a passive control strategy and with the proposed Neuro Fuzzy technique

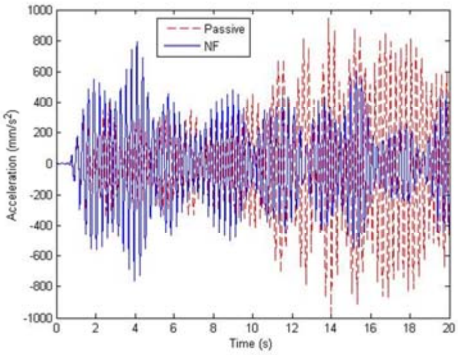


Fig. 14 Comparison of footbridge acceleration with a passive control strategy and with the proposed Neuro Fuzzy technique under a real perturbance

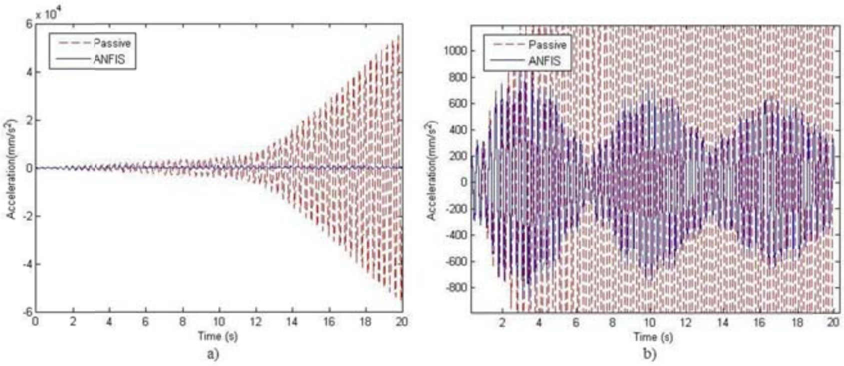


Fig. 15 (a) Comparison of footbridge acceleration with a passive control strategy and with the ANFIS technique under a perturbance near the resonance (b) Zoom of the a)

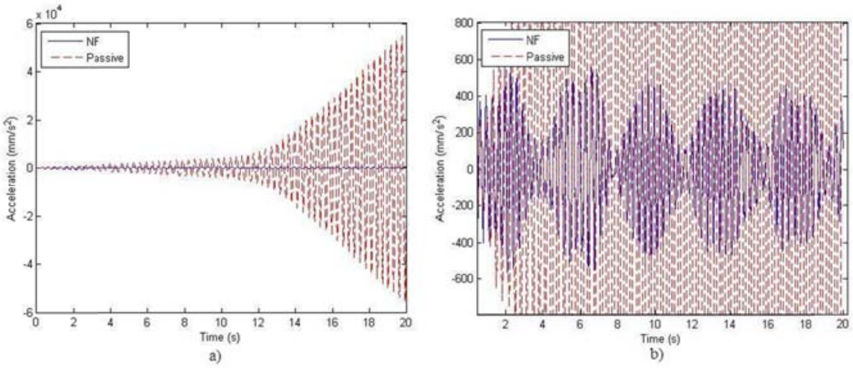


Fig. 16 (a) Comparison of footbridge acceleration with a passive control strategy and with the proposed Neuro Fuzzy technique under a perturbance near the resonance and (b) Zoom of the a)

5. Conclusions

In this work, a model of a footbridge with a Magnetorheological Damper based on a real footbridge was built. In particular, a tuned mass damper was utilized. The mechanical model has been compared with data extracted from the real structure, concluding that both real and simulated models have similar behaviours. Taking into account the simulated model, a study of the induced footbridge vibrations have been considered under a case in which the disturbances are close to the resonance conditions.

The proposed control methods have shown a considerable reduction of the undesirable vibrations suffered by the structure. Particularly, it has been proved that the proposed alternative Neuro Fuzzy system had a better response, reducing even more footbridge vibrations. It is important to remark that the proposed control system contributes notably to avoid structural damages.

A real signal caused by a pedestrian was introduced into the simulated environment in order to test the control system in a real situation. The results have proved that the proposed Neuro Fuzzy approach also reduces movement under real conditions.

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