

Experimental design of an active vibration control device used to protect cultural heritage objects.

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ABSTRACT

While light, temperature and humidity on cultural heritage objects are drastically controlled to ensure better conservation, it is not the case of the vibrations and their impact on the objects have received little consideration. Most of the proposed solutions to protect objects from vibrations suffer from a lack of adaptability and poor performances in the lower frequency range. To tackle this issue, the development of a new kind of protection devices based on active control is proposed. The main challenge is to respect the cultural heritage ethics: non intrusiveness and reversibility. To adapt to a wide variety of cultural heritage objects, the proposed solution aims to minimise the vibrations

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of a museum's shelf in real time. A replica of museum's shelf is excited by a vibration exciter and a feedforward control configuration, with a reference signal measured on the shelf structure and actuators and error sensors placed on the shelf plate, is used to cancel vibrations of the plate. This bench offers the opportunity to experiment multiple PAA (parameter adaptation algorithms) for which a parameter analysis can be performed. A comparative study based on criterions such as amplitude attenuation and time convergence is performed to find an optimised control configuration.

1. CONTEXT

While cultural heritage community is particularly concerned about phenomena which can alter object's integrity, it is surprising to notice that only poor consideration has been given to vibrations. If hygrometry studies were already published in 1952 [1], the first article mentioning vibrations in a cultural heritage context was published only in 1991 [2]. However, vibration fatigue represents a real threat to cultural objects. A consequence of this phenomenon can be seen in Figure 1, which points out the cracks that appeared on a mural painting after a building renovation.

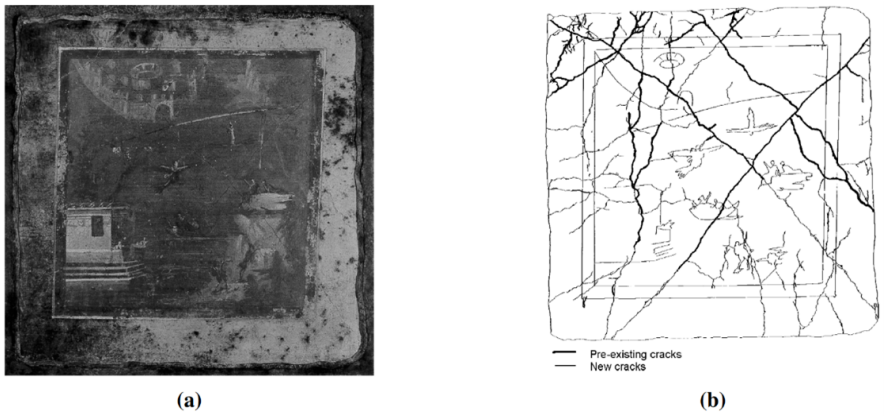


Figure 1: Picture (a) and drawing (b) showing cracks that appeared during construction works on the mural painting "The fall of Icarus". Reproduced from Thickett, D. "Vibration damage levels for museum objects" (2002) [3].

In the domain of cultural heritage, sources of vibrations are numerous and diversified. In museums, curators have to deal with public transports, loud music, construction works and even visitors that create vibrations because of their steps. Within the partners of the project, curators of the Musée des Arts Décoratifs are really concerned about the music played from powerful loudspeakers in the museum's nave during fashion shows. The floor of the Musée du Quai Branly Jacques Chirac is so flexible that vibrations due to visitor steps which are suspected to damage painted barks. When objects have to be moved for a special exhibition or to be relocated, the threat created by vibrations is quite high. This situation is faced by the Musée du Louvre, which relocates its Antique collection reserve out of Paris, and Musée de la Musique which frequently lends instruments. For all these reasons, curators started to work with researchers from engineering sciences to find solutions for specific vibrations issues [4–6]. However, even if the results were promising, none of the proposed solutions has been adopted on a large scale by the cultural heritage community. From the curator's point of view, this can be explained by the lack of adaptability of the solutions which, designed for a specific situation, can not always be re-employed for another museum object or context. Another common flaw of these solutions is the lack of performance when it comes to protect the objects against low frequency vibrations. Because they are all based on passive absorbers, physical constraints limit their efficiency in the low frequency range.

2. THE PROPOSED SOLUTION

In order to tackle the issues mentioned above, this work proposes to develop a low frequency anti-vibration device based on the principle of active control. Discussions with cultural institutes involved in the project helped us to understand their requirements specification regarding protection systems. In addition to respecting ethics standards dictated by the International Council Of Museums, the proposed solution must be versatile enough to cover a wide range of situations, easy and fast to install, and must not interfere too much with the museography. To meet all these requirements, the chosen solution is conceived as an extension of object's stand. Sensors and actuators are fixed to the stand and protect it from vibrating with the help of an active control system. From a vibrational point of view, the system must be effective in protecting cultural heritage objects against low frequency vibrations, usually between ten to a few hundred hertz, as vibrations sources measured in museums are usually in this range [3, 7]. While passive solutions struggle to attenuate low frequencies, active control is particularly relevant to tackle this issue. Furthermore, as sources encountered in cultural heritage context usually vary with time, the control algorithm must include an adaptive part. Finally, the frequency bandwidth of vibrations has to be taken in consideration to choose an appropriate control strategy. Against narrow band vibrations, both feedback and feedforward approaches can be used, while broadband vibrations necessitate a feed-forward approach [8]. As both situations can be faced in real situations, a feedforward approach is chosen.

3. PARAMETRIZED ADAPTIVE FEEDFORWARD COMPENSATORS

As stated above, the control algorithm must be adaptive and feedforward. One famous algorithm that meets these requirements is the Filtered-X Least Mean Square (FXLMS) [9]. Its principle is recalled in Figure 2, in the case of a single input-single output configuration. A primary disturbance is recorded by a reference sensor $x(t)$. The contribution of this disturbance to the error sensor $e(t)$ is $d(t)$. The transfer function between $x(t)$ and $d(t)$ is called the primary path F. To cancel the disturbance at the error sensor position, an actuator receives a command $u(t)$ defined by the control filter W. The contribution of the actuator to the error sensor $e(t)$ is $y(t)$. The transfer function between $u(t)$ and $y(t)$ is called the secondary path H, and its numerical estimation is $\hat{H}$.
The purpose of the FxLMS algorithm is to find the control filter W that cancels the error $e(t)$. For every new sample, a new set of coefficients is computed for the control filter W, using a recursive equation, this last being derived from a criterion of minimisation. In the case of the FXLMS, W is sought as a finite impulse response filter and the minimisation criterion is the mean of the quadratic error. In practice, the FxLMS can be summarised in three steps (for more details, see the reference [9]):

1. Record the new values of $x(t)$ and $e(t)$;
2. Compute and apply the command $u(t)$;
3. Update the control filter W from the recursive equation:

$$W(t+1) = W(t) + \alpha \hat{H} X(t) e(t) \tag{1}$$

where α is a gain defined by the user and $X(t)^T = [x(t), x(t-1), ..., x(t-n+1)]$, with n the length of the control filter

The structure of the FXLMS algorithm can be generalised to define a broader category of control algorithms: the parameterized adaptive feedforward compensators [10]. It is then possible to choose infinite impulse response structures for W, or even more complex structures. Further, it is possible to change the criterion of minimisation, replacing the LMS in Figure 2 by a new Parameter Adaptation Algorithm. As a consequence, the derivation outcomes a new recursive equation of W. These changes offer the opportunity to test multiple configurations. Finally, a comparative study based on criterions such as amplitude attenuation and time convergence can be performed.

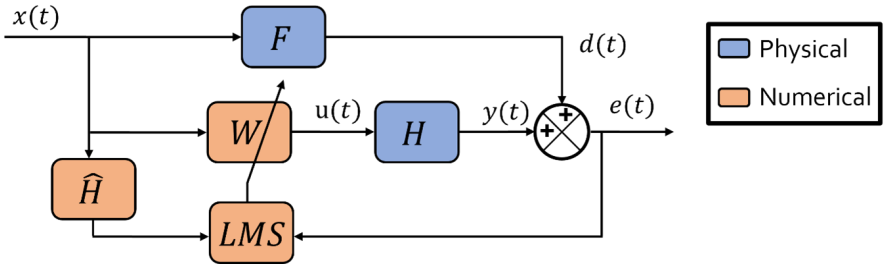


Figure 2: Block diagram of the FXLMS algorithm. $x(t)$ represents the reference signal and $e(t)$ is the error signal. F and H are respectively the primary and secondary path, while $\hat{H}$ is the estimation of the secondary path. W is the control filter, updated at every new time sample following a Least Mean Square (LMS) optimisation.

4. EXPERIMENTAL SETUP

The experimental tests are performed on the bench visible in Figure 3. One can see a museum shelf from Musée de la Musique, Paris, equipped with electronic components. Figure 4 shows a schematic representation of the picture to point out the different parts of the bench. The base of the shelf is excited vertically by a shaker driven by a signal generator. The signal generator can be used to send deterministic signals, filtered white noises or even signals recorded in situ (in Musée du Quai Branly Jacques Chirac, Musée des Arts décoratifs de Paris, Musée du Louvre and Muséum national d'Histoire naturelle), in order to reproduce vibration sources measured in museums. The reference accelerometer is fixed at the base of the shelf, on top of the vibration exciter. An audio actuator is used to control the shelf plate, where objects are supposed to be placed. The specification of the actuator gives a low frequency cut at around 60Hz. An accelerometer collocated with the actuator is used to get the error signal. Finally a control computer, in our case a MicrolabBox manufactured by the company dSpace, synchronises the acquisition of the signals, the command of the actuators, and the actualisation of the control filter.

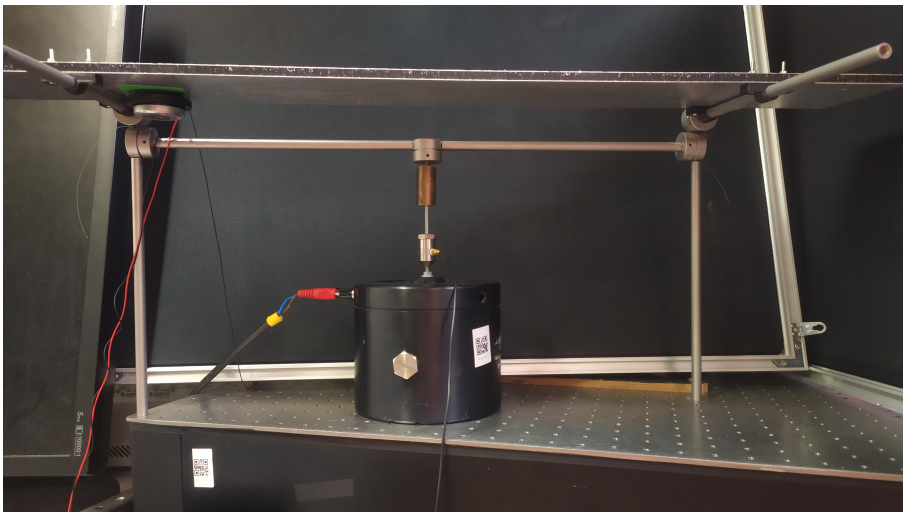


Figure 3: Picture of the experimental bench.

As stated previously, the energy of the sources measured in cultural heritage context is mainly distributed in the low frequencies. Because it is useless to control above around 500Hz and taking into account that a classical control recommendation is to take a sampling frequency five or six times higher than the maximum frequency to control, the tests are performed at a sampling frequency equal to 2500Hz.

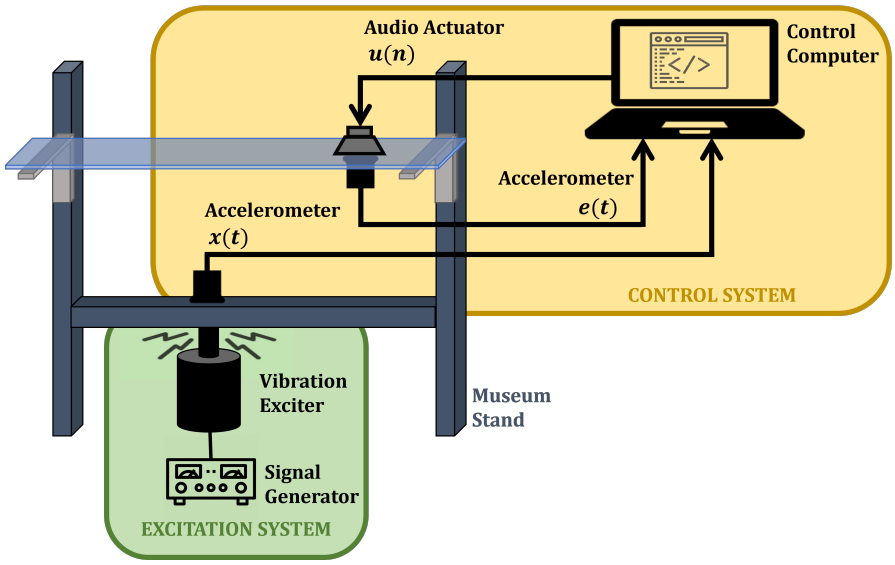


Figure 4: Schematic representation of the experimental bench.

5. PRELIMINARY RESULTS

To confirm the capacity of the parameterized adaptive feedforward compensators to effectively control vibrations in the test bench configuration, a first study is conducted. The control algorithm used is the FxLMS, the control filter is chosen with 100 coefficients, and the perturbation signal send to the vibration exciter is a withe noise filtered with a band-pass filter from 100 to 400Hz.

5.1. Identification of the secondary path

In order to update the state of the control filter, the FxLMS algorithm requires the knowledge of the secondary path (cf. equation 1). Therefore, prior to the control, it is necessary to get an identification of the secondary path. To do so, the procedure described by Landau in *Digital Control System: Design, Identification and Implementation* [11] is followed. The secondary path is searched as a recursive digital filter with n_a coefficients at the denominator, n_b coefficients at the numerator and a pure delay equal to d. The order estimation algorithm gives $n_a = 37$, $n_b = 35$ and $d = 1$. The algorithm used for the identification of the coefficients is an instrumental variable with auxiliary model [12]. The frequency response of the identification, visible in Figure 5, shows that the secondary path has a gain high enough and no zero in the frequency region of interest.

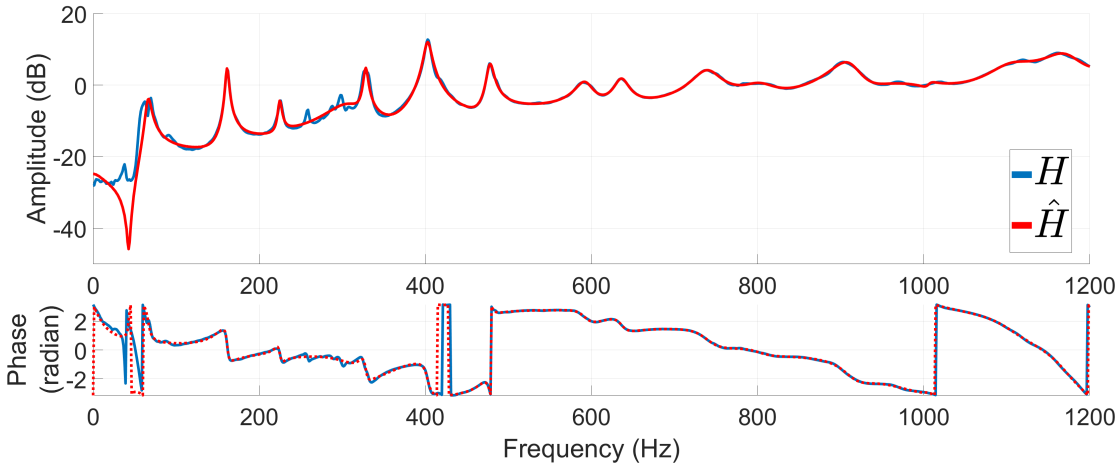


Figure 5: Frequency response of the secondary path H and of its identification ($\hat{H}$).

5.2. Control

The Figure 6 shows the effect of the control on the error signal. The first signal is recorded when no control is applied, while the second is recorded with a control activated after 4 seconds. During the first seconds, the two signals are obviously the same. When the control is activated, the amplitude of the error signal starts to decrease, what means the control is effective. The envelope extracted from the controlled signal clearly shows a transient state for a few seconds before reaching a stationary state. Once the stationary state has been reached, the total reduction is equal to $R = 8.2dB$, R being defined by the relation $R = 20\log\left(RMS\left(e_n\right)/RMS\left(e_c\right)\right)$ where e_n is the signal without control, e_c is the controlled signal and RMS stands for root mean square.

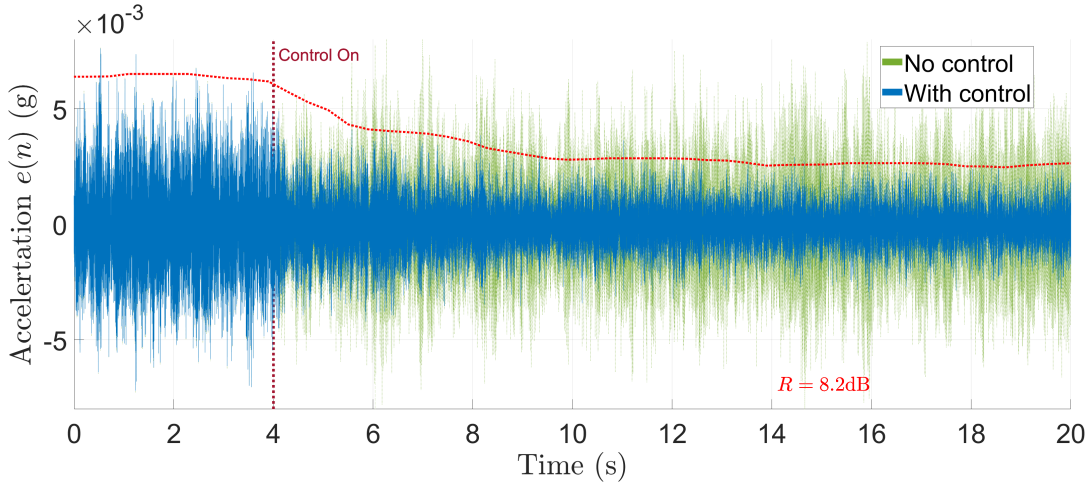


Figure 6

The Figure 7 compares the power spectral density of the error signal without control and the power spectral density of the control signal once the steady state has been reached. Even though most of the frequencies of the perturbation have been reduced, one can see that the algorithm failed to attenuate all of them. Furthermore, there is a slight amplification of the power of the signal for the frequencies above 400Hz, region where the disturbance signal only has a few energy.

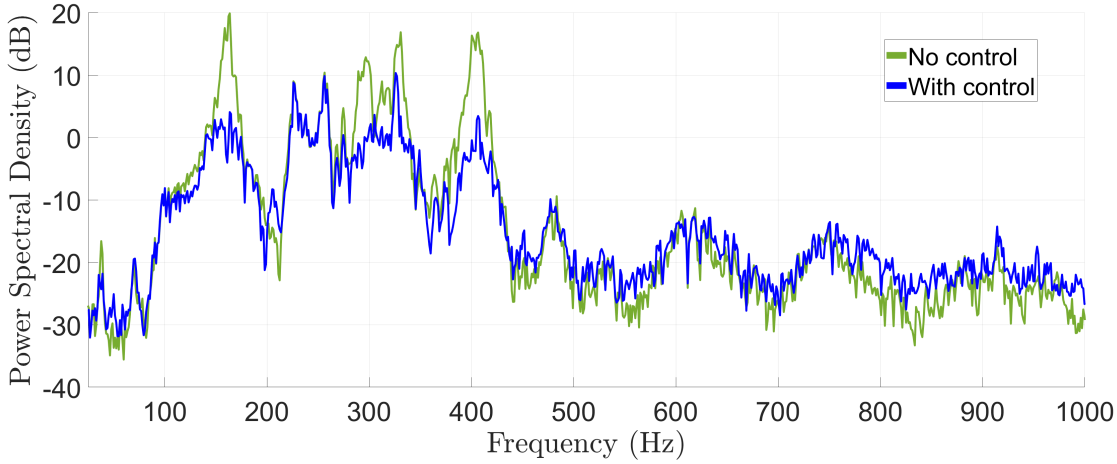


Figure 7

This preliminary study confirms that the FxLMS is able to reduce vibrations in the given control configuration. However, it suffers from a fairly long convergence time from the perspective of using it in cultural heritage domain. Moreover, a frequency analysis points out that the algorithm fails to control all the frequencies in the case of a broadband disturbance signal.

6. CONCLUSIONS

This paper points out the lack of effective systems to protect cultural objects against vibrations, and gives a brief overview of the context and objectives of the project. The solution we propose to avoid the flaws of previous protection systems is based on active control. The museum conditions encourage us to use parameterized adaptive feedforward compensators as control algorithms. For the test bench, a museum's shelf is excited with different kind of signal including signals measured *in situ*. A preliminary study shows that the control strategy chose to face the problem is effective, and points out ways of improvements. Others parameterised adaptive algorithms will be tested and the new results will be presented at the conference under the form of a comparative study.

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