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A UNIFIED APPROACH TO COMPARE ACTIVE VIBRATION CONTROL PERFORMANCES AND ITS APPLICATION IN A MUSEAL CONTEXT

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ABSTRACT

The literature on active control, which has developed abundantly since the last 20 years, suffers from a lack of methodologies to compare the performance of different proposed algorithms. More precisely, the criteria introduced to evaluate them are often specific to their field of application, which makes them unsuitable for objective comparison with other algorithms. This work proposes a unified method which intensively compares algorithm performances. It relies on the definition of application-independent descriptors that reflect performances in the time domain both for transient and steady regimes. This evaluation method adapts to the user's needs by letting him choose the signals on which the algorithms are tested and by allowing him to adjust the weight of descriptors in the final score. The method is used to compare two feed-forward adaptive control algorithms for vibration cancellation: the FxLMS and an adaptive algorithm using the Youla-Kučera parametrisation. Test signals are extracted from an experimental test bench, designed to mimic a museum stand, consisting of a cantilever beam driven at one end with a vibration shaker and controlled at the other end with an actuator. The results show through several examples how the choice of descriptors' weight can be influenced by the user's needs and can affect the final score assigned to the algorithms.

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1. INTRODUCTION

This article introduces the basis of a benchmark designed to objectively assess active control performances. In here, active control refers to the technology that has been designed to cancel an unwanted vibration created by a disturbance source, thanks to an electronic system that creates an anti-vibration of equal amplitude and opposite phase [1]. It can be either acoustics noise cancellation in the case of sound waves or active control of structures in the case of waves propagation through solid materials. Moreover, it can be either feedfoward control when a well correlated signal with the disturbance source is available, or feedback when only the information of the target sensor is used. Finally, the benchmark is designed for adaptive algorithms, which use real-time information to update the controller. This article will only face the case of SISO (Single Input Single Output) active control.

Since the booming of papers about active control in the 80s and the proposition of the so-called FxLMS by Burgess [2], hundreds of active adaptive control algorithm have been developed [3, 4]. However, this growth has not been followed by the development of tools to objectively assess, and so to compare, algorithm performances. Most of the time, when a new algorithm is proposed, its performances are compared to references algorithms, following a paper-specific protocol. The discrepancy of protocols make it very complicated to consciously choose an algorithm when facing a new situation.

First, depending on the active control application, different features might be privileged: convergence time, global reduction, robustness to source variation, low complexity, low spillover (or waterbed effect)... Unfortunately, most article evaluate only some of these descriptors. Also, the methodology to extract these features is often only partially covered. Thus, the descriptors introduced in most publications only allow for a qualitative assessment of the performance of control algorithms, but not for a quantitative comparison.

The need for a robust benchmark of active control technology was first mentioned in 2003 [5]. To the knowledge of the authors only one article provide a large scale benchmark, in the case of active vibration control with feedback adaptive algorithms [6].

The purpose of the following work is not to propose a definitive method to get an complete benchmark, but to start a reflection on how such a benchmark must be built. First, methods to extract performance descriptors are introduced. Then, an application of this benchmark in a museal context is discussed.

2. PERFORMANCE DESCRIPTORS

The descriptors introduced in this section are designed to assess performances when the disturbance signals are stationary. Even though a complete benchmark must tackle the problem of nonstationnary perturbations, this case will not be treated in this article.

2.1 Notations

A very simple and reduced active control structure is introduced in Figure 1. The purpose of the control device is to minimize the error signal $e(n)$, measured at a specific position thanks to a so called error transducer. This signal is the sum of the disturbance $d(n)$ with the contribution of the electronic system $y(n)$, equal to the command $u(n)$ filtered by $\boldsymbol{H}$, the transfer function including the electrical response of the actuator and the physical path between the actuator and the error transducer. The command is defined by filtering a measured reference $x(n)$ with a time-varying control filter $\boldsymbol{W}(n)$.

In the following $e_{open}(n)$ will represent the open-loop error, i.e. when the active device is disabled ($\boldsymbol{W}(n) = 0$, thus $u(n) = 0$), while $e_{close}(n)$ will represent the controlled signal in closed loop, i.e. when the active device is turned on. Signals are all treated as digital signal, and $e(n)$ represents the value of the n-th samples of the signal e. The control device is assumed to be turned on at sample $n = 0$, and the recording stops at sample $n = n_{last}$. The sampling frequency is noted f_s.

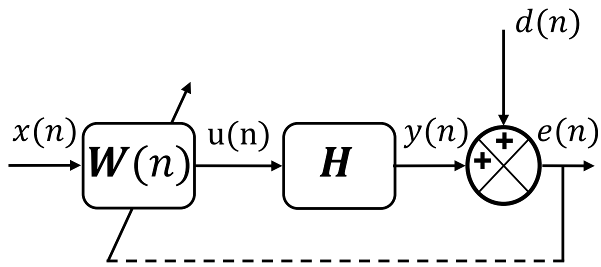

Figure 1. Reduced active control block diagram. $x(n)$ $u(n)$, $y(n)$, $d(n)$ and $e(n)$ represent respectively the measured reference, the control signal, the contribution of the control device, the disturbance signal and the error signal. The control filter is $\boldsymbol{W}(n)$, while $\boldsymbol{H}$ represents the secondary path.

In the following, the operator $\mathrm{rms}\,()$ represents the root mean square:

$$\mathrm{rms}(e(1:N)) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} e(n)^2} \quad (1)$$

2.2 Static descriptor: Global Reduction GR

Static descriptors are performance indicators used to estimate the control performance once the steady state has been reached. They can represents both time domain or frequency domain behaviors. Here, only the global reduction, which is a time domain descriptors, will be introduced. The search for frequency domain descriptors will be the treated in future works.

The **global reduction** (GR), which represents the attenuation in terms of energy, is computed by:

$$\mathrm{GR} = 20\log_{10}\left(\frac{\mathrm{rms}\left(e_{open}(n_{last} - 3f_s : n_{last})\right)}{\mathrm{rms}\left(e_{close}(n_{last} - 3f_s : n_{last})\right)}\right) \quad (2)$$

By definition, this descriptor only applies to signals which reached their steady state for more than 3 seconds. A preliminary study performed by the author on test signals pointed out that computing the root mean square over three seconds of signals is enough to significantly reduce the influence of white noise randomness.

2.3 Dynamic descriptor: Convergence Time CT

Dynamic descriptors are performance indicators used to estimate the control performance when a change in the control condition occurs. Here, only the convergence time will be presented.

The proposed algorithm is divided in two parts. The first algorithm starts with the extraction of an envelope $E_N(n)$ which represents the energy reduction over a window of length N

$$E_N(n) = \frac{\mathrm{rms}\left(e_{close}(n-N;n)\right)}{\mathrm{rms}\left(e_{open}(n-N:n)\right)} \tag{3}$$

Then this envelope is fitted with a decreasing exponential function $f(n)$ of the form:

$$f(n) = (1-r) \times \exp\left(\frac{-n}{\tau_N}\right) + r \tag{4}$$

where r and τ_N, respectively corresponding to the final value and the convergence of the envelope, are deduced from an optimization procedure. On our experimental test bench (see section 3), we observe that τ_N has a linear and increasing dependence with N, beyond a threshold value of N, usually around $N = 1000$. In addition, the intercept of this linear fit, which is by definition not depending on the window length, corresponds to the convergence time that an exponentially decreasing envelope would have in the absence of noise. We propose to use this value, which does not depend on any parameter of the algorithm, as a definition of the convergence time (Figure 2). In practice, to find the threshold value of N above the one the function $f(N) = \tau_N$ is linear, a first linear fit is performed with all N. Then the lowest value of N are successively removed until the Pearson correlation coefficient of the linear fit becomes higher than 0.99.

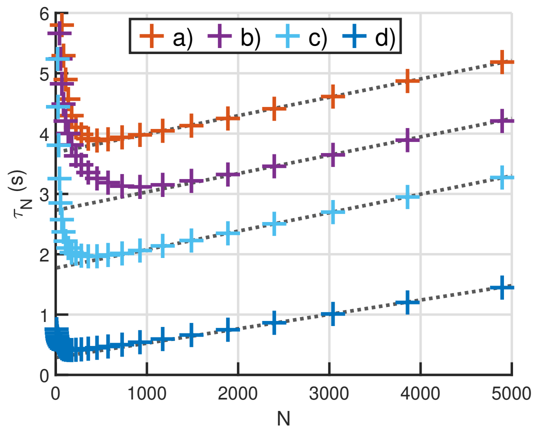

Figure 2. Convergence time of the envelope τ_N in function of N for different experimental controlled error signals. These signals are obtained using four experimental conditions (a b, c and d), which differ according to the algorithm, the position of the reference, the disturbance signal, etc. The grey dashed lines represent linear fit of the curves, excluding the first points.

2.4 Combining the descriptors

The proposed descriptors quantify independent performances of the control algorithm. Its evaluation requires a weighting of these descriptors values, which depends on the control application. In the following, a systematic method of weighting is proposed, consisting of answering three questions for each descriptor:

1. What is the lowest acceptable value $D_{i_{min}}$ for the descriptor D_i ?
2. Which value $D_{i_{max}}$ for the descriptor D_i is considered to be fully satisfactory?
3. How important is this descriptor compared to the other ones?

Q1 & Q2 aim to convert each descriptor value into a satisfaction index expressed as a percentage. Then these indexes are weighted according to the values given by the answer to Q3.

As instance, let's imagine a user decides to set the Global Reduction parameters such as the lowest value equals $GR_{min} = 10$ dB, the fully satisfactory value equals $GR_{max} = 30$ dB. Then, the satisfaction index related to the global reduction μ_{GR} is computed such as:

$$\begin{cases} \mu_{GR} = 1 & \text{when} \quad GR > 30 \\ \mu_{GR} = 0 & \text{when} \quad GR < 10 \\ \mu_{GR} = \frac{GR-10}{30-10} & \text{otherwise} \end{cases} \tag{5}$$

Finally, all satisfactory indexes are combined to get a global index performance:

$$I = \frac{\sum_i \mu_{D_i} \times w_{D_i}}{\sum_i w_{D_i}} \tag{6}$$

where D_i represents a descriptor and w_{D_i} is the associated weight defined by the user at Q 3.

2.4.1 Defining Test signals

As descriptors must be computed from controlled signal, it is necessary to define the test signals used as disturbance signal. Descriptors are indeed strongly influenced by properties of test signals such as bandwidth, amplitude, center frequency, stationarity.... As it is expected that every change within these parameters will result in different control performances, the test signals must be chosen carefully.

In some cases, the sources can be fully determined and it is possible to reproduce them only with a few test signals. In other situations however, the encountered sources are diverse and test signals which are representative of these sources must be carefully designed.

3. APPLICATION

In this section, an experimental application of the benchmark is described. The test bench, composed of a cantilever beam, and equipped with two sensors and one actuator, cf. Fig.3, is a mockup of stand used in museum to display artworks (jewelries, coins or other lights objects are often exposed to the tip of spikes). Two control algorithms are implemented to cancel out the vibrations of the stand, and their performances are compared.

3.1 Protocol

3.1.1 Control Algorithms

The first algorithm is the well known FxLMS algorithm [2]. The second one uses the Youla-Kuçera parametrisation, and has been intensively studied by Landau et al. [7]. The Youla-Kučera parametrisation used in this article is the simplest version, with a scalar adaptation gain, a finite impulse response filter as control filter, and no central regulator (called YKFIR in [8]). It will be noted as FIRYK in the rest of the article. Presentation of the control algorithms are out of the scope of this article and readers seeking for further information can refer to the above references.

3.1.2 Test Bench

The cantilever beam is made out of wood, is 200 mm long (from clamp to tip), 35 mm large and 19mm thick. It is excited at its fixed extremity with a vibration exciter, driven by signals designed to have similar properties to the signals measured *in situ*. The control system is composed of two accelerometers ((Bruel& Kjær, type 4374), with their charge conditioning amplifier (Brüel & Kjær, type 2635), an audio actuator (PUI Audio, ASX05404-HD-R), and a controller (dSpace MicrolabBox DS 1202). The first accelerometer is placed 1 cm away from the vibration exciter to get an image of the incoming disturbance. The second one is fixed at 4 cm from the other extremity with the actuator, where the object is to be placed, to measure the residual error. A drawing and a picture of the test bench are available Figures 3 and 4.

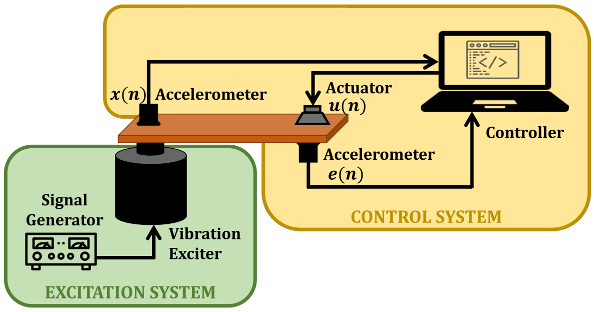

Figure 3. Drawing of the test bench used during experiments.

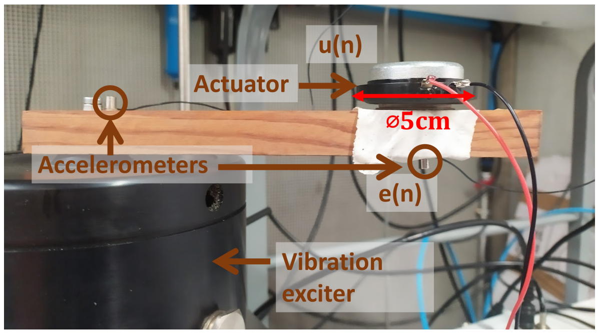

Figure 4. Photo of the test bench used during experiments.

3.1.3 Test signals

The characteristics of the test signals used as a disturbance source are selected from previous measurements found in the literature [9, 10] or recorded by the authors. Since the spectral content of the sources ranges from 10 Hz to 370 Hz, and the cutoff frequency of the actuator is around 70 Hz, the frequency band of interest is chosen to be 70-370 Hz. It is then decided to divide this band into three distinct sub-bands (70-170 Hz; 170-270 Hz and 270-370

Hz), as sources frequency bandwidth is usually around 100 Hz. To assess performances of the control system in the worst case (the broader the bandwidth, the lower the performances are expected [11]), a fourth signal covering the full bandwidth of interest is created. To create the test signals, a pseudo random binary sequence is filtered by a 20th order pass-band filter whose cutoff frequencies are chosen accordingly to the ones given above.

3.1.4 Test procedure

The sampling frequency of the controlled system is set to 2500 Hz. The test signals are designed to be 65 seconds long. Prior to each recording, the amplitude of the source is varied until the amplitude of the acceleration at the position of the error sensor is around 2mm/s^2. This value has been chosen because it is the maximum acceleration measured *in situ* by the authors and it represents a limit from which damage to cultural objects has been noticed [12].

For every test signal, the vibration shaker is driven while the active control is disabled for the whole duration, to record first the error sensor signal in the absence of control. Then, a second measurement is performed: the active control, which is initially disabled, is now activated after 5 seconds. The error sensor signal is recorded from this instant, considered at the origin of time.

3.1.5 Benchmark set

Table 1. Four different sets used to compute the benchmark performance index I.

		GR (dB)	CT (s)
Set 1	$D_{i_{min}}$	12	X
	$D_{i_{max}}$	18	X
	w_{D_i}	1	X
Set 2	$D_{i_{min}}$	12	0.5
	$D_{i_{max}}$	18	3
	w_{D_i}	1	1
Set 3	$D_{i_{min}}$	12	0
	$D_{i_{max}}$	18	1
	w_{D_i}	1	1
Set 4	$D_{i_{min}}$	12	0
	$D_{i_{max}}$	18	1
	w_{D_i}	1	3

Four different benchmark sets, including different values for $D_{i_{min}}$, $D_{i_{max}}$, and w_{D_i} for the descriptors GR and CT, are proposed to evaluate the control performances (see Table 1). The first one only focuses on static performances. One can imagine that this kind of set is used when sources are stationary, therefore dynamic performances are not that important and only performances in steady state matter. The second set includes the convergence time which is a relevant descriptor when the disturbance source is not stationary. The third set is a variation of the second one, but this time expectations related to convergence time are higher. This set can be used when the source show fast variation, thus it is necessary to have a fast adaptation algorithm. Finally, the last set is the same as the third with one difference: the weight given to the convergence time is increased, what means the user gives priority to the convergence time descriptor over the global reduction descriptor.

3.2 Preliminary Results

3.2.1 Descriptors

Global reduction obtained for both FxLMS and FIRYK is shown in Figures 5, and convergence time is shown in Figure 6. In each diagram, one vertical bar evaluates a performance of the algorithm for one of the four test signals used, whose spectral content is reminded in the inset box

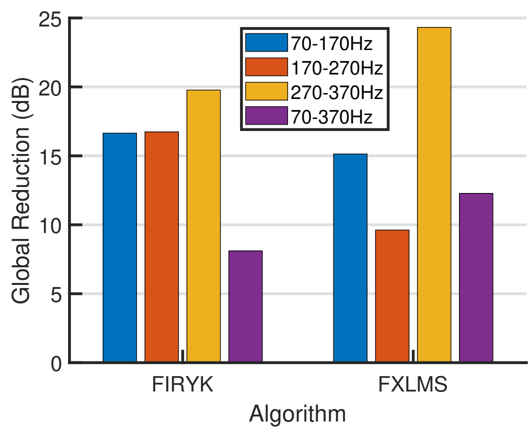

Figure 5. Global Reduction Results. The colours stands for the different test signals described in section 3.1.3.

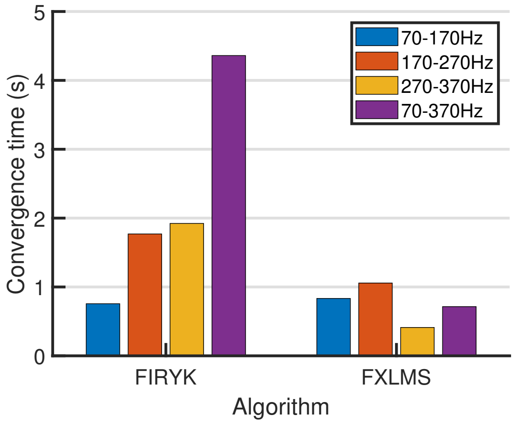

Figure 6. Convergence time.The colours stands for the different test signals described in section 3.1.3.

3.2.2 Benchmark Performances Index

Performances index I, computed for every proposed set in Table 1, are available in Table 2. One can see that regarding performances in stationary sources (Set 1), FIRYK must be chosen. However, in cultural heritage condition, most of sources are not stationary. In this case, it might be interesting to look at the second set, which gives equal importance to static and dynamic descriptors. For these benchmark parameters, the FxLMS definitely outperforms the FIRYK. In cultural heritage context, some sources can vary very quickly, both regarding temporal and frequency aspects, so more demanding convergence time parameters can be used (Set 3 vs. Set 2). In this case, the FIRYK appears to be better, even though both algorithms are probably not appropriated as they show poor global performance index. Finally, increasing the weight of the convergence time (Set 4) seems to increase the relevance of using FxLMS, thanks to its better capacity to adapt.

As a conclusion, these different sets show how performances parameters can influence the global performance index, as both a change in the min/max values or in the related weight can have a strong impact and change the final choice. Therefore, these parameters must be set carefully to match the user's requirements.

4. CONCLUSION

In this article, a method to objectively and quantitatively assess control performance has been proposed. This method relies on the extraction of time performance descriptors, which reflect specific properties of controlled signals, both in dynamic and static behavior. Then, parameters' weighting allows the user to tune the benchmark parameters according to his own needs and quantitatively compare several algorithms for a specific application. An application to a museum control condition has been proposed to compare performances of two algorithms (FxLMS and FIRYK). Results show that depending on the user requirements, performance indexes can vary a lot and does not always consider the same algorithm as the best. Future work will address the relevance of using frequency descriptors to help discriminate the two algorithms performances.

Table 2. Benchmark performance indexes obtained for different sets.

	FxLMS	FIRYK
Set 1	39.2%	64.1%
Set 2	64.1%	54.8%
Set 3	32.6%	35.1%
Set 4	29.3%	20.6%

5. STATEMENTS AND DECLARATIONS

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