Where, q(x, t) represents the sound source, P(x, t) represent pressure field, X is the space variable, c represents the speed of sound, t is the time variable, and r2 is the Laplacian.

$$\frac{1}{c^2}\frac{\delta^2[P(x,t)]}{\delta t^2} - \nabla^2[P(x,t)] = q(x,t) \quad (1)$$

Outside the space domain, if it is assumed that the sound source q(x, t) is null, it could be achieved while an external signal is opposite to q(x, t), ideally in amplitude and frequency. Nevertheless, due to many factors such as computing cost, robustness and short time response of sensors/actuators (microphones/loudspeakers), the objective is probably difficult to achieve. Otherwise, it is consequently necessary to analyse strategies with estimation "E ", error analysis "e" (as dependence of desired signal "d" and measured signal "m"), as it was made in this work through costing function "J", in discrete time "n".

$$J(n) = \left(E\left(d(n) - m(n)\right)\right)^2 \quad (2)$$

2.1 Adaptive FXLMS algorithm

For analysis made in this work, an adaptive FXLMS algorithm was evaluated because many successful results were obtained by this kind of algorithm, in which it is frequently to estimate weights "W" to be adapted every instant "n" in the input signal "X" in order to get an optimal error. Motor noise are usually a mixing of harmonic functions, no matter whether it is an "Electrical Motor or Diesel Motor" and of course changes produced in their amplitudes and frequencies are due to some specific characteristics through their physical parameters as well as the energy sources involved (such as combustion or some kind of electrical/mechanical energy transformation). It means that physical parameters can change as a consequence of external physical conditions, therefore, changes could produce an unsuitable adjustment during control. For this reason, it is possible to solve it by control strategies (with high computing time disadvantages) or through analysis using systems identification algorithm, such as classic FXLMS (owing to good recurrence in the main algorithm). However, as the costing function can be adapted by its "weights", the solution can be enhanced as it was probed in this work, achieving a general algorithm for motors in operating range from 40 dB to 90 dB and motor speed from 500 RPM to 3000 RPM.

In figure 2, it is shown a representation of the costing function curve that has changes dependences which means that through derivative of "J" with respect to the weight "w" is possible to find a minimal value around "J" [5], [6].

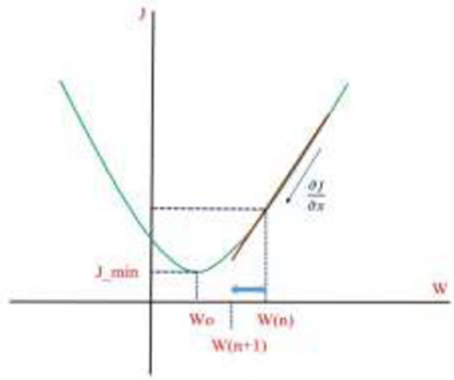

Fig. 1. Costing function representation for ANC analysis an adaptive effect of weights

It means that in the classic FXLMS algorithm (as it is represented in following equation) for the secondary path "S" (that is looking the reflection effect after sending the antinoise signal) every adaptive coefficient "w" can be adjusted in a better way in order to get the optimal error. Notwithstanding, it is good proposal to start predictive criterion, while it could be necessary as function of costing function.

$$e(n) = d(n) - S(n) * [w^T(n)\, X(n)] \quad (3)$$

2.2 Hybrid Controller

With the main objective to get the noise cancellation, the main control is designed through a hybrid configuration between feedback/ feedforward distribution [1], as the one depicted in figure 3 where "x" is the input noise signal and "d" is the desired signal obtained after to cross the physical space "P" (which is known as primary path). The block "LMS" is the Least Mean Square (function in algorithm connotation) in which the adaptive weights are contained to get the adaptive noise cancellation. This is achieved through the right matrices in adaptive coefficients "A and "C" which depends on the feedback and feedforward configuration controlling the error through the secondary path effect "S" for every instant "n".

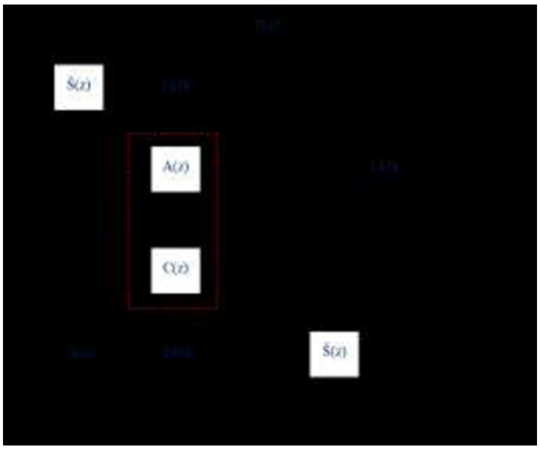

Fig 2. Hybrid block diagram scheme [3]

3 Simulations and Analysis

With all theoretical analysis described above, the algorithm was designed according to get noise cancellation for harmonic signals with changes in frequency domain as it is expected in motors noise evaluations. However, a simple classic search is always made by testing the opposite signal to the main noise signal. For this reason, in figure 4 is shown part of motor noise signal (Diesel motor - Energy Laboratory of PUCP) and antinoise signal that was achieved after sending the opposite signal to the space domain where the motor was located. The average noise was 90 dB at 1000 RPM (in figure 4 it is shown its equivalent in Voltage as it was obtained by microphones). The antinoise signal accomplished a cancellation of 10 dB approximately; it was because the motor did not increase speed. Therefore, computing time was enough in order to send the simple opposite signal. Nevertheless, when the motor speed changed, the error increased. For this reason, it is suggested to design an adaptive hybrid algorithm based in FXLM.

On the other hand, LMS is evaluated to adapt the main control algorithm. For this reason, expected results are shown in figure 5. A reduction of 50 dB (voltage equivalence) is achieved.

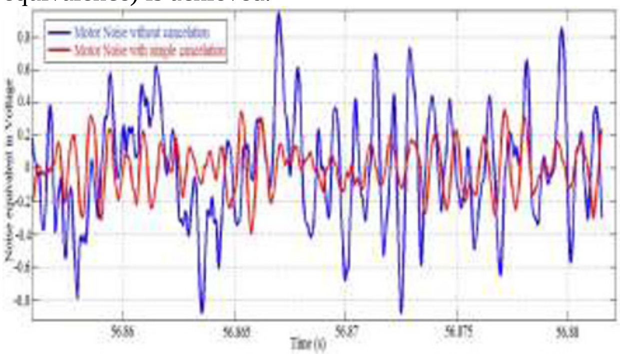

Fig. 3. Motor noise signal and simple noise cancellation based on ANC

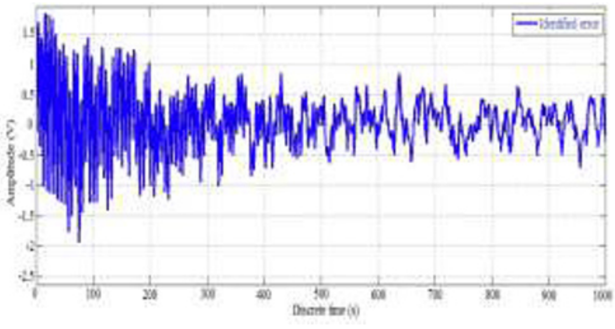

Fig. 4. LMS results

Evaluation was made positioning the antinoise source only around this physical space and the noise was attenuated. However, that is not usual while workers are around the room where the motor is operated. For that reason, all the physical space was analysed in order to get a better spatial noise cancellation, so that it was generalized a source "M" (as it is described in figure 6) that produce noise for every position "r". Also there are represented "m" antinoise sources "NC" which try to get desired noise cancellation at every instant "n".

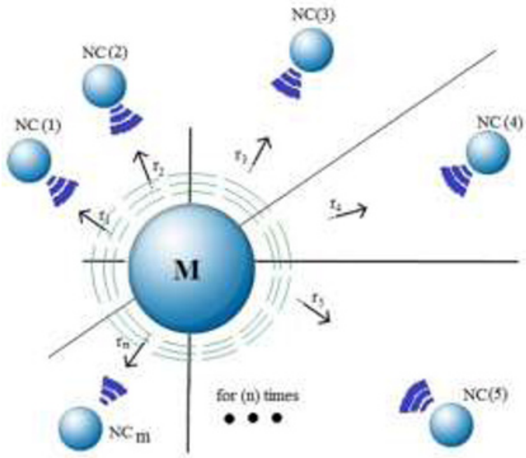

Fig. 6. 3D mathematical representation for ANC that is generalized for "n" antinoise sources.

Applying the adaptive algorithm:

$$e(n)_y = d(n)_y - S(n)_y \quad (4)$$

For every

$$S(n)_y = S(n)_i * [w^T(n)_i X(n)_i] \quad (5)$$

$$e(n)_y = \begin{pmatrix} e(n) \\ e(n) \\ \vdots \\ e(n) \end{pmatrix} \quad (6)$$

Then, after identifying the motor noise by LMS, it was possible to evaluate the 3D noise cancellation simulating 3 antinoise sources for the primary source. In average the expected noise reduction was between 50 dB to 52 dB as it is depicted in figure 7. However, it is suggested to use a controller which could be faster enough than the motor noise changes (as real time controllers).

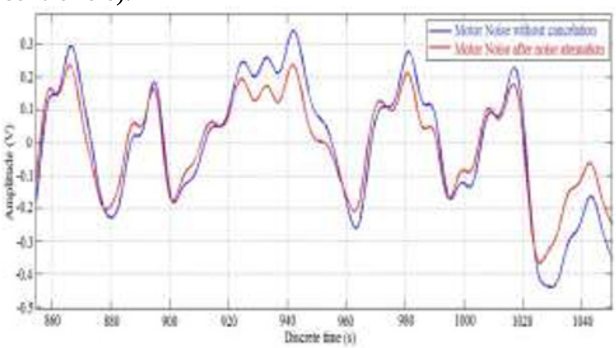

Fig. 5. Motor noise signal and noise cancellation based on LMS adaptive algorithm

4 Enhancement Proposal

From last results, through simulations and experiments, response time is an important factor to achieve noise cancellation. Moreover, to get enough time to solve task by the main controller such as adaptive cancellation logic. For this reason, it is proposed in this work to replace traditional actuators (loudspeakers) by sound emission based on nanostructures due to the fact that sensors and actuators based in high order nanostructures arrays provide faster response time and robustness. Figure 8 shows motor noise attenuated using ANC strategies and sensors/actuators based on nanostructures.

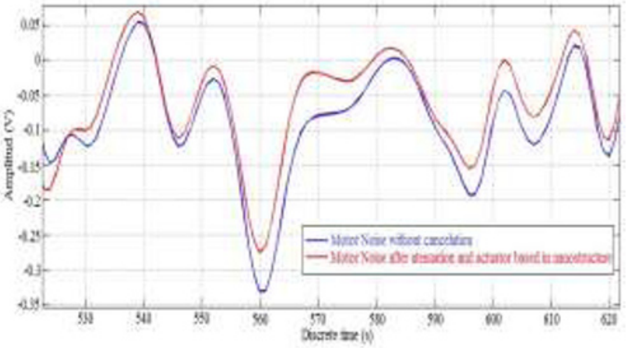

Fig. 6. Motor noise signal and cancellation considering nanostructure effect.

5 Conclusions

In this work, a hybrid-adaptive algorithm was evaluated in order to get noise cancellation that was produced by a diesel motor of 10 HP. Noise cancellation was achieved reducing noise from 80 dB to 37 dB.
It was analysed a 3D propagation ANC due to geometric dependence between sensors/actuators (microphones/loudspeakers) and noise source.
Through simulations, it was obtained that sound transmitter based on nanostructures produces faster responses to get optimal noise cancellation that also is a good support to achieve predictions.

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