25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-1991
EXPERIMENTS IN FILTERED X-LMS ALGORITHM FOR ACTIVE NOISE CONTROL IN DUCTS

Renan Roberto Benitz da Silva[1]
Herbert Martins Gomes[2]
[1,2]Universidade Federal do Rio Grande do Sul. Programa de Pós-Graduação em Engenharia Mecânica, Av. Sarmento Leite, 425, sala 202, 2º. Andar, 90050-170, Porto Alegre, RS, Brazil.
e-mail: renan.benitz@ufrgs.br[1], herbert@mecanica.ufrgs.br[2]

Abstract. *Prolonged exposure to noise can cause problems related to hearing health, resulting in a deficit in attention and eventually work accidents. Ducts are important means of ventilation in the industry, even though they are also means of low-frequency airborne noise propagation. This article evaluates an active noise control system in ducts in order to actively attenuate the level of noise produced by a source. An experimental apparatus is developed as the initial prototype for a test rig of active noise control. A code was developed in MATLAB software language for microphone signal acquisition and speaker active control. In the end, noise graphs in frequency band spectrum with and without the active control system are presented. The proposed control system was able to attenuate sound pressure levels with a different performance that depend on the type of noise being controlled (multi-tone frequencies or narrow-band white noise).*

Keywords: *Active Control; Noise; Duct; Filtered X-LMS Control*

1. INTRODUCTION

As early as 1954 Beranek (1954) stated that there was an urgent need to solve the problem of noise created by airplanes, particularly jet planes, which threatened to render unfeasible the welfare of houses and buildings in regions and neighborhoods near airports (Beranek, 1954). The literature also indicates that environments such as oilrigs, refrigerated environments, ships, heliports, among others, are places where noise levels that can be uncomfortable or harmful to hearing health. For high noise levels, standards, such as OSHA Noise regulations, Brazilian standard NR-15 (2014), NIOSH(1998), ACGIH (2003) or ISO 9612 (2009), specifies maximum noise limits and exposure times so they do not affect hearing health (Elliot and Darlington, 1985). Among the various ways of reducing noise (attenuation of noise at source, attenuation of noise in the path to the listener and attenuation of noise directly at the receiver), passive control as well as active control has been extensively employed. Economically, the passive control is quite attractive; however, it has limitations on the maximum levels of attenuation and on the frequency bands that it can attenuate. Active control has the advantage of being able to attenuate, in general, higher levels in cases the passive control is not effective. However, being active, its cost may be prohibitive depending on the application. Then, it remains for the active control to be used in situations where it is indeed necessary, even if at a high cost.

The presence of ducts in industrial plants to enable ventilation or exhaustion results in an unwanted sound signal that can cause discomfort of health issues to workers and people living in the neighborhood of factories. As explained by Hansen et al. (2007) apud Oliveira (2010) this noise is generated by the passage of the exhaust blades by fixed elements of the structure, being a narrow band noise (or pure tone) with presence of harmonics. There is also a broadband aerodynamic signal generated in regions of turbulent flow and vortices (Hansen et al., 2007, Oliveira, 2010). Finally, there is still noise of mechanical origin, emitted by vibrations of electrical/combustions engines, structural components and blades. Most of the energy of this signal is present in the 0 to 500 Hz frequency range, where Active Noise Control (ANR) systems are more efficient. Oliveira (2010) in his work implemented a mono-channel ANR system and obtained a significant attenuation, in specific conditions, up to 35 dB.

This work evaluates an active noise control system in ducts in order to attenuate the noise level produced by a noise source. The purpose is to achieve attenuation of the noise, in a certain frequency range in a duct using microphones and speakers. Low frequency noise levels are hard to attenuate passively with the use of acoustic absorber materials. According to the literature of Lessa (2010) and Gontijo (2006), the active control allows a greater attenuation of the noise level in this low frequency band than the traditional passive control (Lessa, 2010, Gontijo, 2006). The Filtered-X LMS algorithm is used for noise control with well-defined frequencies and for noise with different frequency bands.

This problem is under intense investigation for the control of noise in ventilation ducts, as well as in the control of internal noise in aircraft and automobiles.

2. ACTIVE NOISE CONTROL – ANC

There are two main methods of noise control: Passive Control and Active Control. They differentiate themselves by the necessity or not of the energy necessary to control the noise. The advantages and disadvantages of each of these are diverse and depend on the problem of peculiarities of the type of noise to be attenuated. The Passive control does not use energy to attenuate the noise level. Its project can be based on: (*i*) design of sound-absorbing materials, (*ii*) architecture of environments for propagation control, (*iii*) barriers, enclosures, (*iv*) reduction of vibration in machines by means of damping adjustments, (*v*) layout arrangement of machines and even use of personal protective equipment.

The concept of sound reduction by active noise control (ANC) was established by the German physicist Paul Lueg (1936), who patented the idea in the USA. In the Active Control there is energy spend for the reduction of noise based on the concept of wave cancellation. Among the existing control strategies, the most used are the control with Feedback and the Feedforward control, and this method adopted in the present work. In the anticipative control, there are two microphones, one that measures the noise and another that measures the effects of noise summation with the generated anti-noise. Thus, the anticipative control strategy consists of a simple reference sensor, usually a microphone, a secondary noise-generating source, usually a speaker, and an error microphone to evaluate the effectiveness of the control. The reference signal measured by the primary microphone is processed in the controller so that it generates the anti-signal to be transmitted to the cancellation speaker, or secondary source. The control logic should take into account the controller processing delays, and the transfer functions of the primary paths (from noise source to microphone error) and secondary path (from control speaker to error microphone). Figure 1 shows a sketch on how the anticipative control works in noise attenuation in ducts.

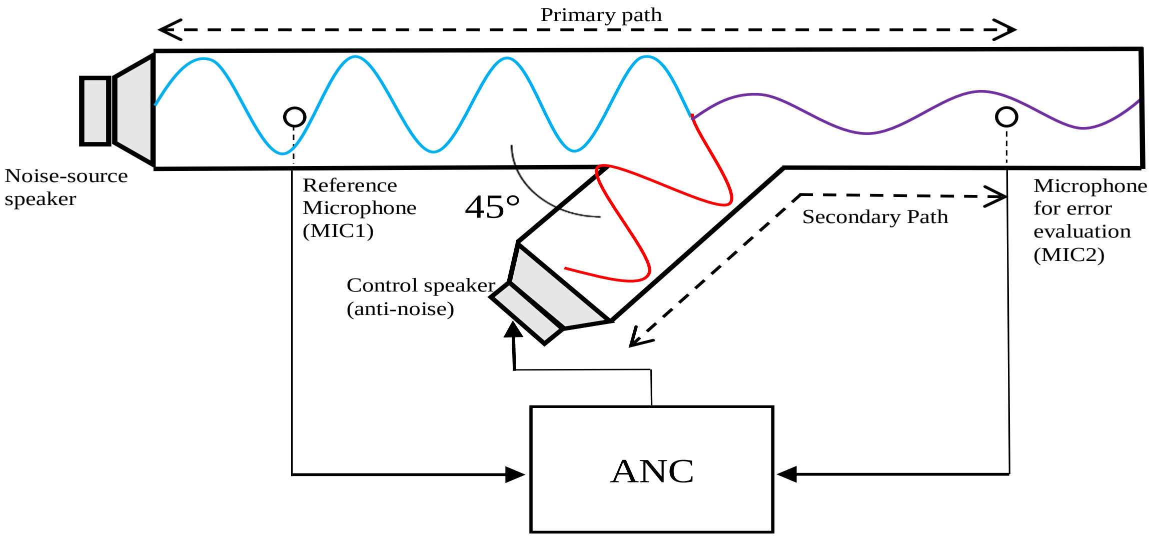

Figure 1. Active Noise Control System in a Duct (Feedforward).

3. THEORETICAL BASIS

The sound pressure level (*SPL*) is evaluated on a logarithmic scale which represents a comparison expressed as the ratio between the mean square value of the sound pressure signal history and a standard reference (minimum audible pressure fluctuation, p_0=20 μPa), Gerges (2000). For a point-like source emitting noise at a certain power *PWL* (dB), in all directions and without any interference, the sound pressure level *SPL* (dB) at a certain distance from this source can be calculated by:

$$SPL = PWL_{point} + 10\log\frac{Q}{4\pi r^2}\ [\text{dB}], \quad (1)$$

where *r* is the distance to the source, *Q* is the percentage of the effective area crossed by sound (Q = 1, spherical propagation). For point-like sources where there is a perfect screen, the value of Q becomes 2 (half of the area), by joining two planes, *Q* = 4, three planes, *Q* = 8, and so on. In the case of ducts, waves propagate approximately flat, and so *Q* = 0 and therefore by equation (1),

$SPL = PWL_{point}$ [dB], (2)

In this way, it can be seen that, theoretically, there would be no loss and the noise propagates without attenuation for long distances. In practice, other phenomena attenuate noise at long distances in ducts caused by the curves of the ducts, air outlets, obstacles or cross section reductions of the duct.

The cutoff frequency of a duct defines the limit for propagation of flat waves (fundamental mode). According to Elliot (2001), when the excitation frequency of the system becomes high, its wavelength becomes comparable with the dimensions of its cross section, consequently, not only plane waves propagate within the duct, but also high order modes.

3.1 Active Noise Control Filtered-X LMS (Feedforward)

The classic closed-loop feedback LMS control only supports one error sensor (microphone 2) which feeds the control logic, which triggers the actuator (speaker 2) (Nunez, 2005, Haykin, 1986). The introduction of impulse response $S(z)$ to evaluate the secondary path followed by the sound and generated by the controller and emitted by the actuator to the error microphone, cause in the classic LMS algorithm with adjustable filter coefficients $W(z)$, an instability in the control system (Elliott et al., 1985). An alternative to circumvent this instability is the use of a Filtered-X LMS proposed by Widrow in 1981 (Widrow et al., 1981). Research literature shows improvements in performance of noise cancelation for the filtered-X LMS algorithm in this type of application compared to the standard LMS algorithm, assuming the general case of undermodelling of the unknown system response (Mayyas and Aboulnasr, 2002). Figure 2 shows the block diagram for the Filtered-X LMS algorithm for noise control. $x(n)$ is the controller's reference input signal (from microphone 1, noise source), n means the discrete time instants, $d(n)$ is the sound signal from the noise source after the primary path, and $y(n)$ is the sound signal measure by the microphone 2 after the secondary path (sent by sent by speaker 2). $e(z)$ is the error signal (measured by microphone 2), $W(z)$ represents the weights of the digital filter (linear filter), $P(z)$ is the impulsive response between the noise source and the error microphone (primary path), $S(z)$ is the impulsive response between the actuator (control speaker) and the error microphone (secondary path). Finally, $\hat{S}(z)$ is an estimation of the impulse response (transfer function) between the actuator (speaker 2) and the error microphone (secondary path).

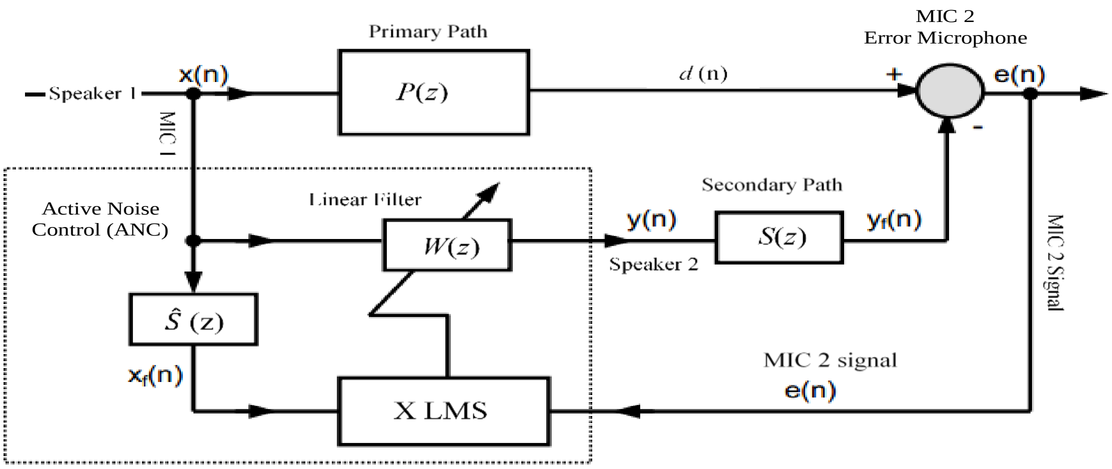

Figure 2. Block diagram for the Filtered-X LMS (Feedforward) control (Modified from Nunez, 2005 and Bjarnason, 1995).

In a simplified way, the error $e(n)$ is evaluated from the convolution of the impulse response of the secondary path $S(z)$ and the weights of the digital filter $W(z)$ by:

$$e(n) = d(n) - s(n) * [W^T(n).x(n)] \,, \tag{3}$$

where w(n) are the elements of the vector, is the reference signal vector at the instant n, $x(n) = [x(0)_n, \dots x(n - M + 1)_n]^T$, * means the convolution between the time signal and the weight vector and represents the order of the digital filter. Assuming an error function to be minimized of the type $E(n) = \mu[e^2(n)]$ and taking a gradient descending algorithm for minimization, then the correction of the weights of the filter $W(z)$ is defined as:

$$w(n+1) = w(n) - [\mu(n)/2]\nabla E(n), \tag{4}$$

where $\mu(n)$is an adaptive step factor and $\nabla E(n)$is the gradient of the error function. Several techniques may be used to evaluate this gradient so, using the gradient of the instantaneous quadratic mean error, we derive the error equation with respect to $w(n)$ that results:

$$\nabla E(n) = -2[s(n) * x(n)].e(n), \quad (5)$$

Briefly, the steps for the Filtered-X LMS algorithm is described in the pseudocode indicated in Table 1.

Table 1 - Pseudocode of the Filtered-X LMS algorithm (modified from Nunez, 2005 and Bjarnason, 1995).

Step 1: Initialization:
Filter coefficients: $w(k)_0$=0, M+1 coefficients;
Signal Power recursive evaluation for: $\sigma^2(0)$=1;
Step 2: Measurement of $x(n)$ and $e(n)$ by MIC1 and MIC2;
Step 3: Definition of parameter $\alpha$for signal power recursive evaluation;
Step 4: Evaluation of FIR filter output:

$$y(n) = \sum_{k=1}^{M-1} w(k)_n \, x(n-k),$$

Step 5: Evaluation of filtered input:

$$x(n) = \sum_{k=1}^{M-1} \hat{s}(k)_n \, x(n-k),$$

Step 6: Signal Power recursive evaluation:

$$\sigma^2(n) = \alpha x_f(n) + (1-\alpha)\sigma^2(n-1)$$

Step 7: Evaluate the adaptation step:

$$\mu(n) = 0.1/(M+1)\sigma^2(n)$$

Step 8: Update weighting coefficients:

$$w(k)_{n+1} = w(k)_n - \mu(n).e(n).x_f(n-k)$$

Step 9: Update variable n=n+1 and return to step 2:

4. MATERIALS AND METHODS

A computer sound card Realtek ALC662 was choosing for the experiments as the data acquisition and control system. Tt has a 16-bit resolution with ±1.5 V input and output limits. This A/D board has 4 input channels and 4 output channels and a sampling rate for sending and acquiring signals up to 96000 Hz. Electret microphones (AOM-6738L, PuiAudio) were used as sensors. This type of sensor is widely used because it is not so sensitive to external vibration and humidity, and it can be purchased by affordable values, which makes the best choice for the developed control system. For the frequency range of interest (low and medium frequencies), the microphones have relatively flat and constant sensitivity. As actuators for the control signal it was used two triaxis speakers, both 5" Selenium (5TR5A). They have 8Ω of impedance and is rated as 12 W RMS. Ducts of PVC of 150 mm (diameter) and a Y joint (45 °) of same diameter were used for the test bench. Figure 3 indicates how the parts of the test bench are interconnected and how the system was assembled in order to evaluate the performance of the Filtered-X LMS ANC in for the analyzed cases of multi frequencies, narrow and broadband noise.

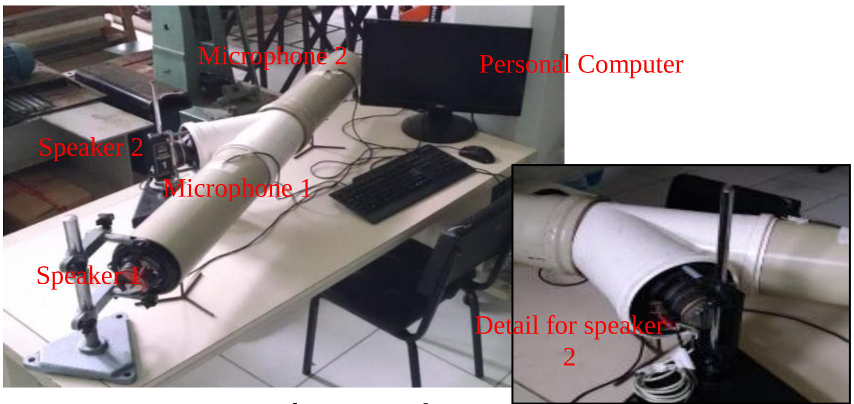

Figure 3 - Test rig for ANC in ducts.

5. RESULTS

5.1 Narrowband frequency noise attenuation - white noise (300 - 800Hz)

A narrowband uniform noise in the frequency range of 300Hz and 800Hz was tested with the ANC. This frequency range was choosen because it is in the range of values of difficult attenuation by passive control by acoustic insulation. Figure 4 and Figure 5 show the spectra in octave bands, the FFT plot and the SPL value for the noises measured before and after the application of the ANC. For this case, the performance of the control did not attain good results, reducing noise from 105,0dB (L) to 103,0dB (L) in the total sound pressure level SPL.

Figure 6 shows the SPL (dB) in frequency domain (Hz), where Channel 1 (red curve) represents the original noise (to be controlled) and Channel 2 (blue curve) overlaps the corresponding curve for the controlled noise. The attenuations by frequency bands are presented in Table 2, with the active control deactivated and activated.

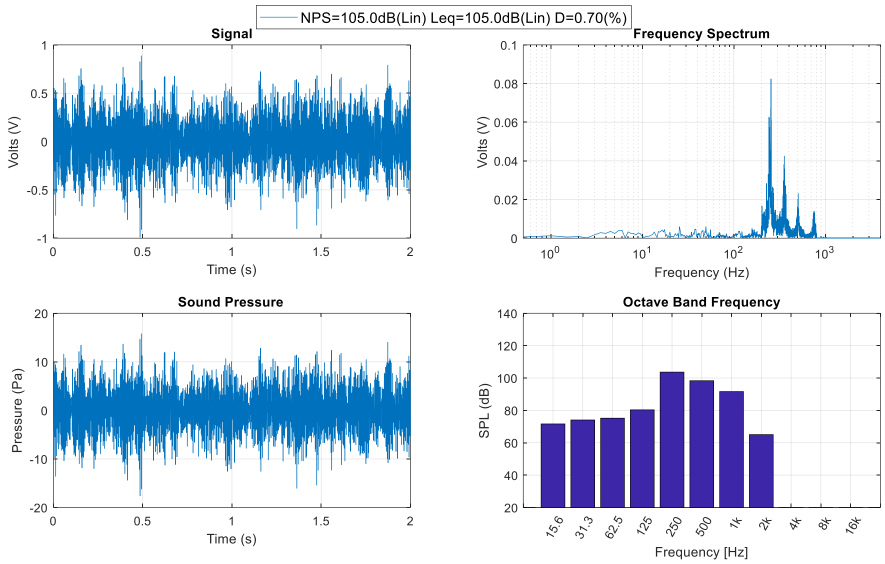

Figure 4 - Noise spectra in octave bands before control (white noise).

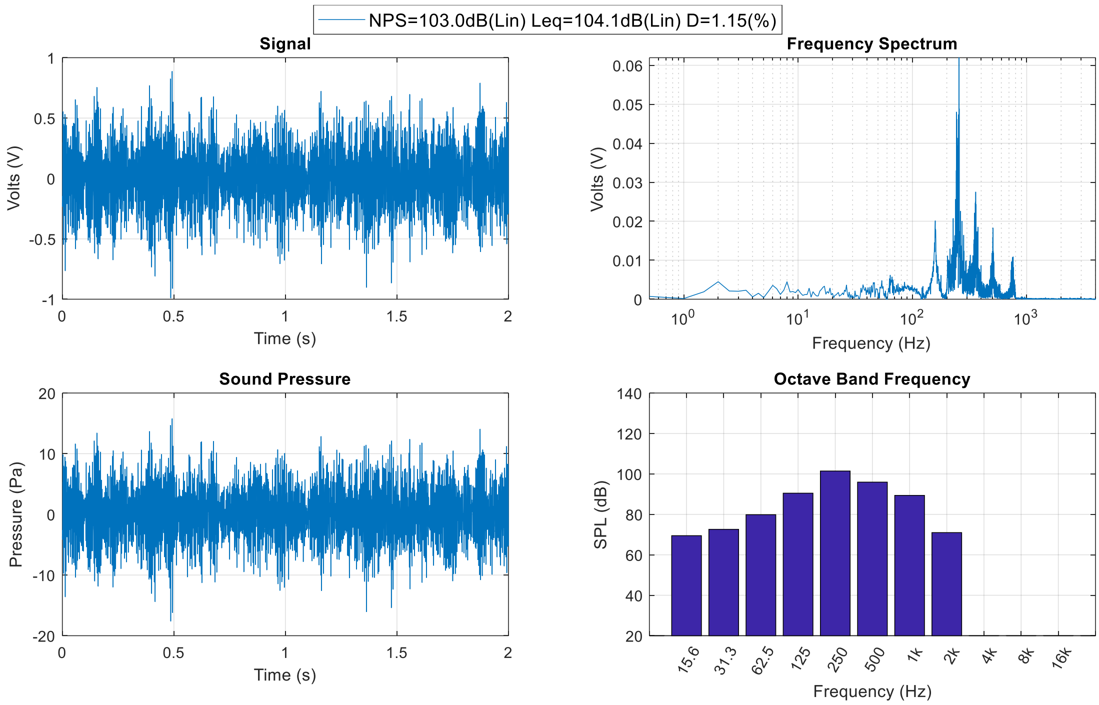

Figure 5 - Noise spectra in octave bands after control (white noise).

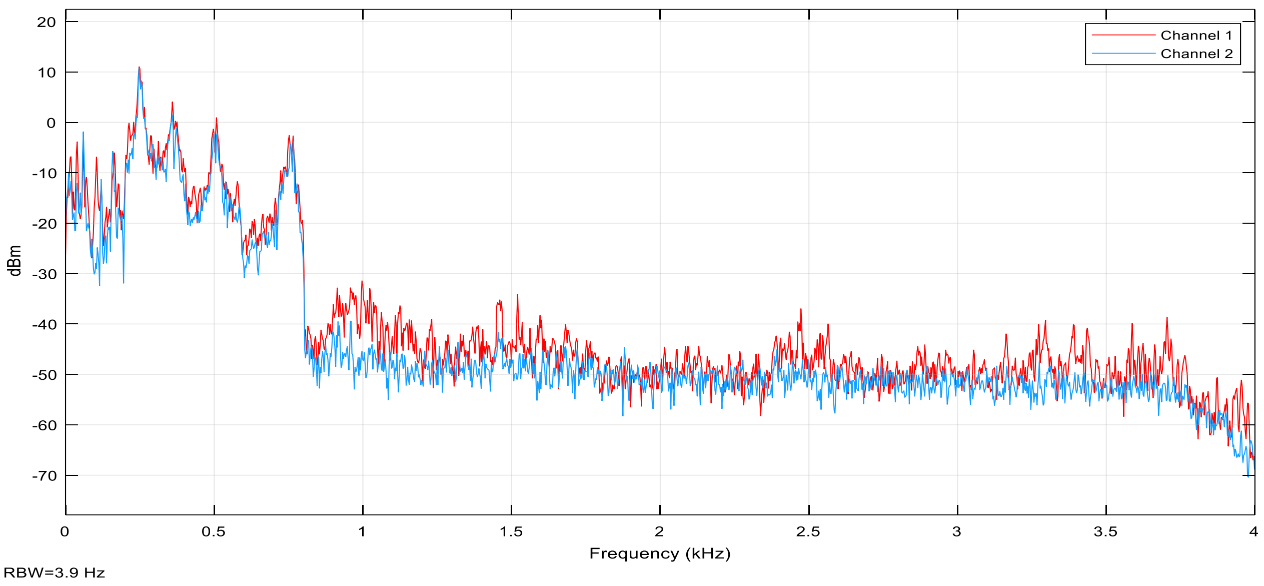

Figure 6 - Frequency spectrums before (Channel 1) and after (Channel 2) of the CAR performance in the tests with white noise.

Table 2 - Comparison between noise by frequency bands, with active noise control deactivated and activated (third test - white noise).

Frequency Band	15.6 [Hz]	31.5 [Hz]	62.5 [Hz]	125 [Hz]	**250** [Hz]	500 [Hz]	1k [Hz]	2k [Hz]	Total [dB(L)]
Without control	71.62	74.07	75.18	80.33	103.70	98.32	91.63	65.05	105.0
X-LMS	69.46	72.59	79.84	90.47	101.40	95.93	89.37	70.98	103.0

For the three replication tests, an attenuation about 2.0 dB (L) was obtained for test 3, while an attenuation of 1.9 dB (L) was obtained for test 2 and test 1, resulting in a mean attenuation of 1.93dB (L) with a standard deviation of 0.5dB (L).

5.2 Multiple tone frequency noise attenuation in duct (235Hz, 672Hz and 842Hz)

In this example, the ANC was tested for a generated noise that contains three well-defined tone frequencies: 235Hz, 672Hz, and 842Hz. Again, these frequencies were chosen randomly taking into account they should be low frequencies that are difficult to be attenuate by passive control using acoustic insulation. In all experiments, the sound card sampling frequency was set to 48 kHz. Each scenario was replicated three times in order to quantify the uncertainty in the experiment. Figure 7 and Figure 8 shows the octave band spectrum for the measured noise by microphone 2 before and after the application of the ANC (first test from the 3 replications). In the same Figures 7 and 8, the magnitude spectrum of the measured signal, and the SPL value and noise Dose value (for human health evaluation) is presented for the replication. One can see that the amplitude value of the measured signal was reduced, in the 1st. frequency of 235Hz, from 0.2V to 0.12V. This corresponds, in the frequency band of 250Hz, to a noise attenuation in the order of 2.7dB (L). Figure. 9 shows the complete frequency spectrum of the measured signals with ANC activated and deactivated (Channel 1, red curve, represents the noise to be controlled and Channel 2, blue curve, represents the resulted noise and anti-noise from the ANC, measured by Microphone 2).

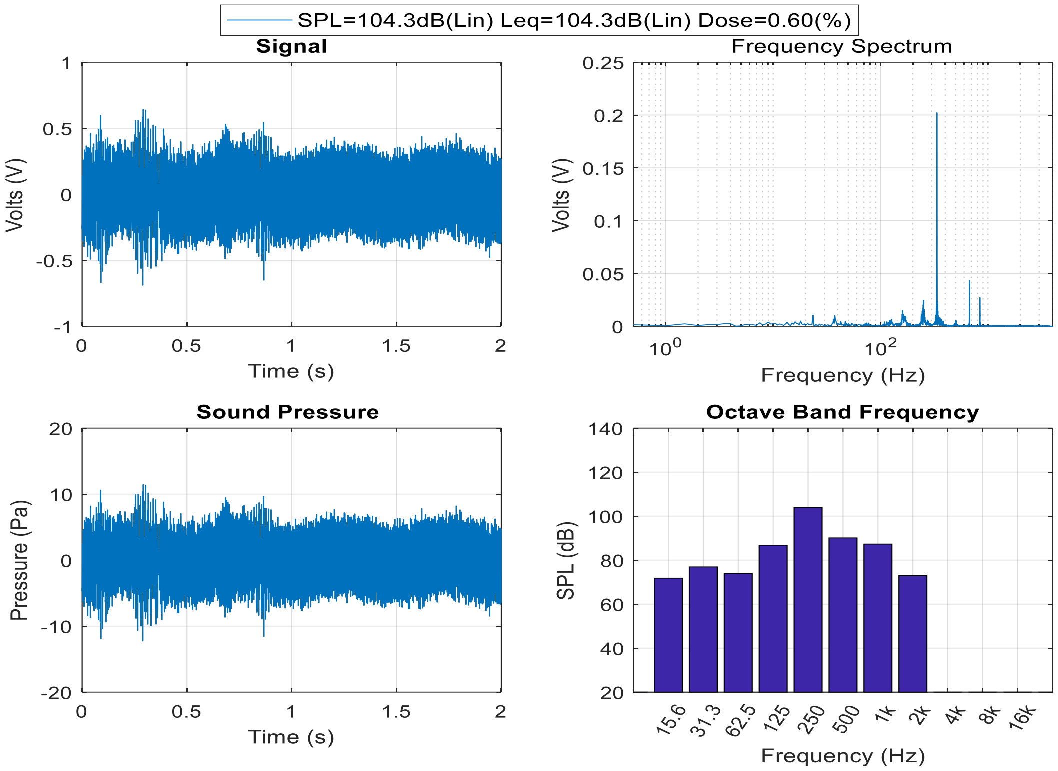

Figure 7. Measured signal, sound pressure level magnitude spectrum and octave band noise before ANC, in multiple frequency tests.

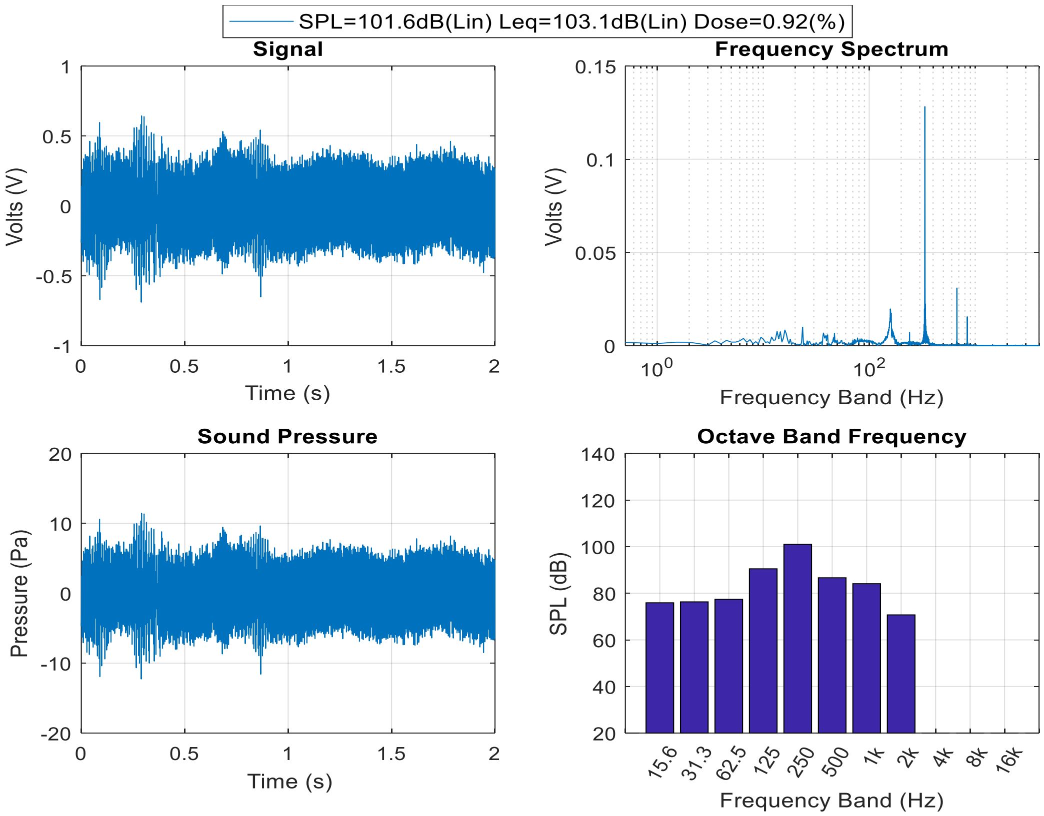

Figure 8. Measured signal, sound pressure level magnitude spectrum and octave band noise after ANC, in multiple frequency tests.

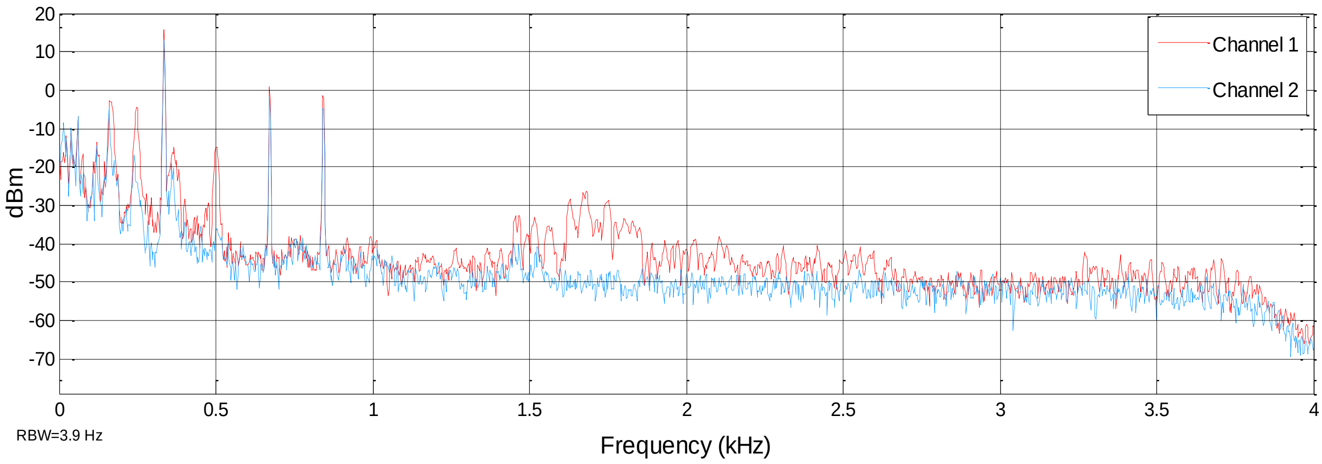

Figure 9 Magnitude frequency spectrum before (Channel 1) and after (Channel 2) ANC, in multiple discrete frequency tests.

Table 3. Comparison between noise by frequency bands, without and with the ANC (discrete frequency test).

Frequency Band	15.6 [Hz]	31.5 [Hz]	62.5 [Hz]	125 [Hz]	250 [Hz]	500 [Hz]	1k [Hz]	2k [Hz]	Total [dB(L)]
Without control	71.79	76.91	73.89	86.76	103.90	90.09	87.28	72.92	104.30
X-LMS	75.93	76.32	77.40	90.51	101.00	86.66	84.11	70.74	101.60

From Table 3, one can see that at 250Hz frequency band the attenuation was about 2.9dB (L). Briefly, for the three replication tests performed, a total value attenuation of 2.7dB (L) was obtained for test 6 and test 7, and 1.9dB (L) for test 8, resulting in a mean attenuation of 2.43dB (L) with a standard deviation of 0.57dB (L).

6. CONCLUSIONS

In the white noise test (narrowband frequency) the performance of the controller was not as good as expected, with a reduction of 2.0 dB (L) in this case and 2.7 dB (L) for the multiple tone frequency case. It is thought that this loss in efficiency was due to problems in the implementation of the test rig since there were unintended noise interferences from the external environment (the laboratory is near a main Avenue) and due to the lack acoustic insulation of the speaker-duct junction. As a proposal for future work, possible improvements in the test rig, detailed analysis of the used materials like pipe, microphones, speakers and the acoustic insulation may result in better attenuation. The length of the tube can also be taken into account in the improvements since resonance effects can be decreased. In previous reported works in the Literature, longer tubes presented better results for noise control. Attention should also be drawn to better estimation of secondary path transfer function S(z) since it will have a direct influence on the performance of the ANC.

7. REFERENCES

ACGIH. *Noise control*., 2003. 3rd edition, Emory e. Knowles iii, cih, csp editors.

Beranek, L. L., 1954. *Acoustics.* Mcgraw Hill Book Company Inc. 492p.

Bjarnason, E. 1995. “Analysis of the Filtered-X LMS Algorithm”. IEEE Transactions on Speech and Audio Processing, vol. 3, no. 6.

Elliot, S. J. and Darlington, P., 1985. “Adaptive cancellation of periodic, synchronously sampled interference”. IEEE Trans. Acoustics, Speech, Signal Processing, vol. 33, 715-717, DOI: 10.1109/TASSP.1985.1164596.

Gerges, S. N. Y., 2000. *Noise: fundamentals and control*. 2nd Ed. – Florianopolis: Ed. S.N.Y. Gerges.

Gontijo, W. A., 2006. “Implementation and performance evaluation of adaptive algorithms applied in active vibration control”. M.Sc. Dissertation in Electrical Engineering, Post-Graduation Program in Electrical Engineering, Federal University of Santa Catarina, Florianópolis, SC, 65p.

Hansen, C. H., Qiu, X., Petersen, C., Howard, C., Singh, S., 2007. “Active Noise and Vibration control system design considerations. Mechanics”, 26 (2), 37-46.

ISO 9612:2009. Acoustics. Determination of occupational noise exposure. Engineering method. International Organization for Standardization.

Lessa, E. M., 2010. “Active noise control in ventilation ducts on ships and offshore platforms”. Monography. Control and Automation Engineering, UFRJ, RJ, Brasil, 59p.

Mayyas, K., Aboulanasr, t., 2002. “Comparative study of the filtered-x LMS and LMS algorithms with under modeling conditions”. *International journal of modeling and simulation*, vol. 22, no. 3. DOI: 10.1080/02286203.2002.11442237

NR-15, Ministry of Labor and Employment, Ministerial Order No. 1.297, dated August 13, 2014, NR-15 Unhealthy Activities, Official Gazette of the Federative Republic of Brazil, Brasília, 6 July 1978. <http://www.mte.gov.br/legislacao/normas_regulamentadoras/nr_15.pdf>.

NIOSH 1910-95:1998. Occupational Noise Exposure. Criteria for a recommended Standard. The National Institute for Occupational Safety and Health.

Nunez, I. J. C., 2005. *The active control of noise in ducts: a theoretical-experimental study*. Ph.D. Thesis, PPG in Mechanical Engineering, federal University of Uberlandia.

Oliveira, E. L., 2010. *The active control of noise in ducts: a theoretical-experimental study*. Ph.D. thesis, PPG in Mechanical Engineering, Federal university of Uberlandia, 4p. (2010).

Vanset, f. Z. *Construction of an Acoustic Measurement System in One-third Octave Bands*. 15f. Monography. Dept. Of mechanical engineering, UFRGS, Porto Alegre, (2016).

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.