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Active Noise Control in Ducts: Sensor Positioning Using FRF and FEM Analysis

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Abstract—Most studies of ANC are designed to tonal signal and discrete frequencies. One of the main difficulties of Active Noise Control (ANC) in Ducts is to develop a methodology that can achieve control in a wide frequency range due to fact that some specific frequencies are not so easy to control. This paper is conducted an experimental study to understand the reason of this issue. The main idea of this paper is to obtain the acoustical Frequency Response Function (FRF) among excitation point in several duct spots and conduct a study that correlates the influence of resonance and anti-resonance regions. In experimental procedure were used microphones as receiver's sensors and a micro-accelerometer attached to a loudspeaker to measure the excitation pressure field. After the selection of frequencies of interest, a mono-channel Broadband Feed forward method were used to noise control purpose. The results show that the frequency response position has a strong influence in ANC performance. It was also developed a study using Finite Element Methods (FEM) using ANSYS® software to compare the efficiency of the FRF analysis.

Index Terms: **Active Noise Control (ANC), Frequency Response Function (FRF).**

I. INTRODUCTION

High intensity noise are considered sound pollution and can cause several damage to human health. The transient noise, that means, noise with variable amplitude can provoke adverse reactions in humans since 35 dB(A). The noise effect above 70 dB(A) e for long time exposure can cause high blood pressure, stress, irritation, maniac-depressive excitation and heart attack, between another symptoms [1], [8], [10]. There are several kinds of noise that can be found at the environment. The first can be caused by turbulence, being totally random. This noise distributes energy equally trough a large frequencies bandwidth.

Examples of sound with low frequencies are airplane jets and a noise generated by an explosion. Another kind of noise is called straight bandwidth that can concentrate the most part of the energy in specific frequencies. This kind of noise can be found in rotate machines or repetitive machines, characterized by periodical behavior. Another example of noise generation is the radiation on from flush flow ducts, being a common noise source in industries, above all noise prevenient from valve control [5]. In many kinds of buildings, the ventilation is handled by a mechanical ventilation system. Such ventilation systems constitute a well-known source of broadband noise. As awareness of the negative effects that to low frequency noise can have on human well-being has increased, so too has the requirement for quieter ventilation installations. Traditionally, duct born noise is attenuated using passive resistive silencers. These passive silencers are silencers are valued for their ability to produce a high level of attenuation over a broad frequency range, however they tend to become large and bulky if designed for low frequency attenuation [3]. ANC system normally are used two kind of control strategies, Feed forward and Feedback. The basic difference between them is that in Feedback control is calculated only the error signal in the silence zone around the microphone. The Feed forward control uses a reference noise signal before it reaches the silence zone.

There is a third method that is the sum of Feed forward and Feedback in the same strategy, called hybrid. It is well known that cancelling broadband noise using active methods is much more complicated than those for narrowband noise [9]. Narasimhan conducted a study in a rectangular duct with fan where this was applied to mono-channel noise control. The results achieved were up to 32dB attenuation in narrowband and 12dB in broadband [6]. Oliveira, presented solutions for high-order acoustic waves in his PhD thesis. The author used a rectangular duct to eliminate the problem of high-order acoustic wave. It was applied a plaque in the middle of the duct to reduce the duct section by half. It Results two plane waves and the plane wave propagation has a greater facility of application of the ANC system. However when utilizes broadband it was found difficulties in some discrete frequencies to be controlled [7]. The main purpose of this paper is to understand why some frequencies the ANC does not reach a satisfactory control when working with large bandwidth. It is noticed that normally the system reach significant control (attenuation), occurring in some cases, intensity amplification, or even neutralization of the system.

II. STRUCTURE OF ACTIVE NOISE CONTROL

The basic principle of the Feed forward control is that the sound propagation delay between microphone and loud speaker offers sufficient time to calculate and activate the anti-noise, obtaining cancelation [4]. A simple scheme of Feed forward can be seen in figure 1.

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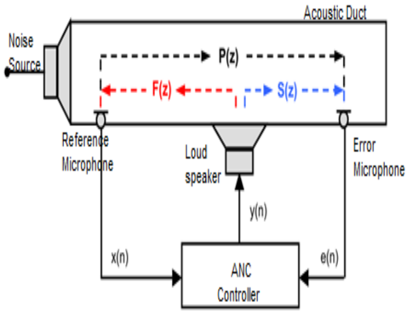


Fig.1: Broadband Feed forward (ANC Method) [5].

Most of methodologies, the controller is a digital filter due coefficients are modified (adaptive) according to a defined strategy. The error microphone measure the error signal (residual) $e(n)$, that is commonly used as a performance index, so the controller can use to adapt their coefficients. The block diagram of this scheme can be seen, considering Z transformation, in figure 2.

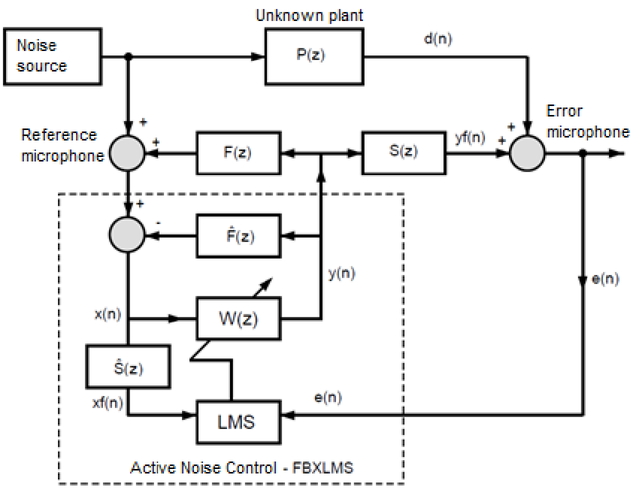


Fig.2: Broadband Feed forward (ANC) diagram. with FBXLMS [5].

The meaning of math signal and transfer function are:

$d(n)$≡ *Source signal in the error microphone.*

$e(n)$≡ *Error signal or residual.*

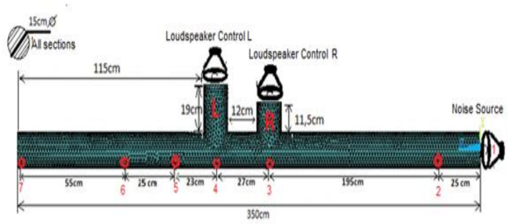
$x(n)$ ≡ *Reference (input) signal of the controller.*

$y(n)$ ≡ *Output signal of the controller.*

$P(z)$ ≡ *Transfer Function between noise source and error microphone (primary path)*

$G(z)$ ≡ *Transfer Function between noise source and reference microphone.*

$S(z)$ ≡ *Transfer Function between actuator sensor (loud speaker) and error microphone (Secondary path)*



$F(z)$ ≡ *Transfer function between actuator sensor (loud speaker) and reference microphone (feedback path).*

$W(z)$≡ *Transfer Function of the controller system (Digital Filter).*

Inside the controller system it was utilized filter FBXLMS so it was possible to estimate the feedback path $\hat{F}(z)$ and secondary path $\hat{S}(z)$ so the ANC system could be more stable. These estimative were performed simultaneously with off-line training techniques [2].

III. METHODOLOGY

The experimental bench as can be seen at figure 3 has several equipment's microphones model B&K 4957, PCB 352C22 micro-accelerometer located at loudspeaker membrane (noise source), control loudspeakers, DSpace model RTI1104 for system interface, signal conditioning model PCB 482A20, sound amplifier Stetsom CL500 and signal generator Standford Research Systems model DS360 "Ultra Low Distortion Function Generator" and a 12V DC car battery for the controller loud speakers.

Fig.3: Duct experimental built at the Laboratory of Acoustics and Vibration UFU.

The microphones in group of three were placed at the particular spots as shown in figure 4. Microphones where alternated at the spots positions e1, e2, e3, e4, and e5 (error microphones), while maintaining the microphone x (Reference Microphone) for comparison.

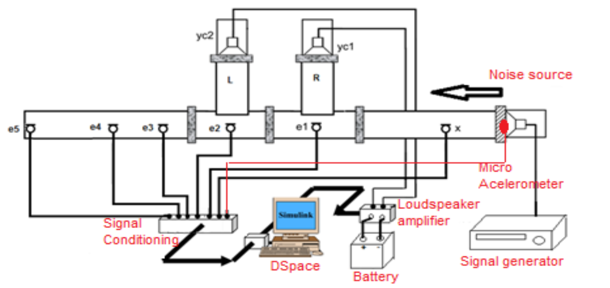


Fig.4: Installation diagram of experimental bench duct [5].

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All dimensions are displayed at figure 5.

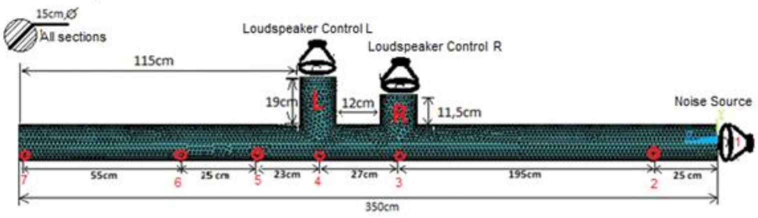

Fig.5: Duct dimensions, actuator and receiver sensors positions [5].

The FRFs – with a frequency resolution of 0.5 Hz – was obtained using the H1 estimator with an overlap of 50%, 400 averaged and Hanning window. The H1estimator technique considers the existence of associated random noiseonly the response signal. The FRF is calculated from the average ofsamples for each frequency (ω) according to equation (1) [5]:

$$H(\omega) = \frac{S_{xf}(\omega)}{S_{ff}(\omega)} \qquad (1)$$

Were:

$H(\omega)$ – *FRF;*
$S_{xf}(\omega)$ – *Excitation auto-spectrum* [(X(ω)·F(ω)*)];
$S_{ff}(\omega)$ – *Response excitation cross-spectrum* [F(ω)· F(ω)*];
F(ω) – *Excitation Spectrum*
X(ω) – *Response Spectrum*
()* – *Conjugate a complex number*

In title of example in figure 6 is showed the FRF21 (reference microphone at point 2) in red and FRF61 (control microphone at point 6) in blue. In this figure is possible to see various resonance and anti-resonance regions for two microphones positions.

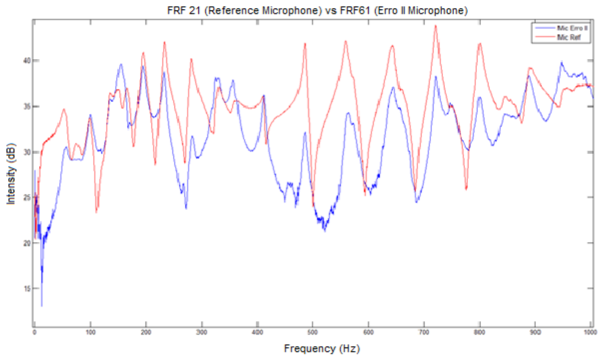

Fig.6: FRF Reference Microphone (Red) compared with the FRF Microphone Control R (Blue) [5].

From these results, it was possible to identify the frequencies that are located in the resonance regions and anti-resonance duct and so to use them in the ANC experimental procedure. The experimental study aimed to understand if these regions of resonance and anti-resonance are making the control system stable or instable [5]. It was developed a 3D duct for FEM studies, actually it was used to guarantee that our methods was reliable as the software showed to us. The figure 7 shows the prototype used in real scale 1:1.

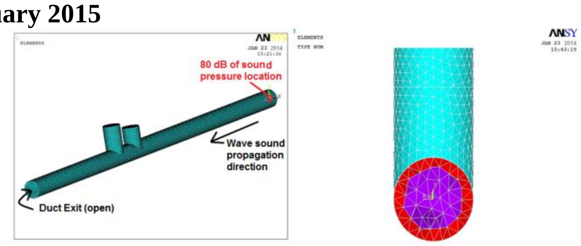

Fig.7: Duct designed for FEM study [5].

Just for comparing meters it was analyzed the experimental FRF from reference microphone (position 2 at figure 5) with the Finite Element Method FRF it can be seen that both results were very similar according to figure 8 and 9 respectively.

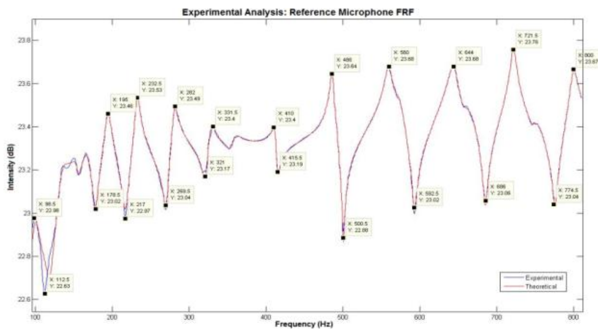

Fig.8: FRF Reference Microphone (Red Theoretical) compared with the Experimental FRF Reference Microphone (Blue) [5].

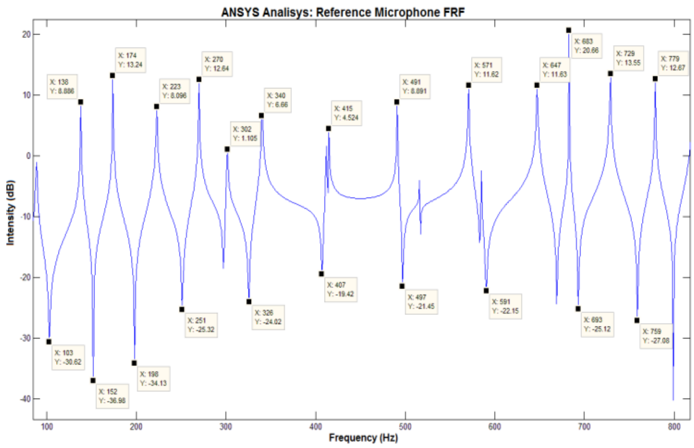

Fig.9: FRF Reference Microphone (Blue using FEM) [5].

These results may lead us to new approaches for further studies in ANC issues, when using more elaborated scheme for 3D projects, even for frequencies selection or microphone positioning.

IV. EXPERIMENTAL ANC RESULTS

Results are presented from data tables with discrete frequencies, attenuation in dB and description of the reading point, when the point is in resonance or anti-resonance of the FRF in question.The tables were separated by microphone (receiver sensor) and evaluated their behavior towards mitigating acquired. The table I is divided as follows:

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Table I: Model layout of the tables with the results of the ANC system

	ReferenceMicrophone	MicrophoneName	ANC
Frequencie (Hz)	Position in FRF	Position in FRF	Attenuation(dB)
The dominant frequencies that appear in the FRF of the reference microphone	Positioning the discrete frequency in the FRF reference microphone	Positioning the discrete frequency in the FRF Microphone N	dB value of the difference between dB and dB before after ANC.

All results take into consideration the frequencies acquired with the reference microphone FRF. The frequencies were selected from the graph harvested field experiment acoustic reference microphone (Figure 8). From these discrete frequencies, there was compared with the FRF of the other microphones (error microphones, 3-7 microphones according to figure 5). Ten trials were conducted with active noise control in 26 discrete frequencies that are presented at the first column of the table as exemplified in Table I [5]. At title of example it was chosen the following scheme of control, as shows figure 10:

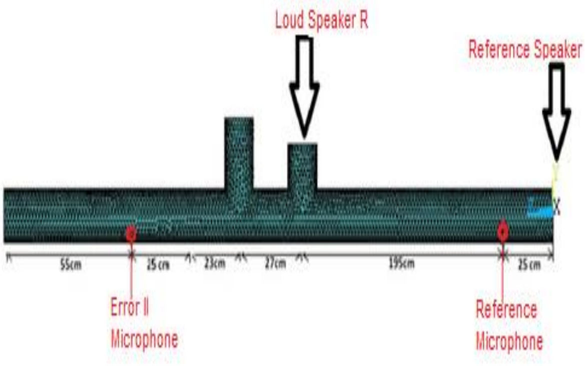

Fig.10: Experiment using Error II Microphone as receiver sensor and loud speaker R as actuator sensor [5].

For the experiments with the loudspeaker R as control, microphone with the best results from the data collected was the microphone Error II according to Table II, attenuating 18 discrete frequencies [5]. In this context, note that the frequency response functions have a direct relationship with the proper functioning of the active noise control. Best results occur when the discrete frequency is in the region of resonance for both microphones reference microphone and error microphone. It was also observed that in some cases there has been amplification of the signal. This usually occurred when the frequency is found in regions of anti-resonance. Was obtained also some rare cases where it can be seen a bad result in the resonance region for both microphones (reference and error). When considering an overview of the results it can be realized that the functioning of ANC system is directly connected in positioning the microphones receivers and also directly correlated with function curves frequency response.

Loud Speaker R	Reference Microphone	Error II Microfone	ANC	
Frequency (Hz)	Position in FRF	Position in FRF	Attenuation (dB)	Noise Control
100.5	Resonance	Resonance	-6,2	Amplified
112	Anti-resonance	Anti-resonance	0	Neutral
136	Resonance	Slope of the curve	-1,2	Amplified
150	Resonance	Slope of the curve	-11	Amplified
156	Anti-resonance	Resonance	-4	Amplified
165.5	Resonance	Descent of the curve	6.2	Good Control
178	Anti-resonance	Anti-resonance	1.6	Weak Control
194.5	Resonance	Resonance	13.7	Good Control
217	Anti-resonance	Anti-resonance	1.2	Weak Control
233	Resonance	Resonance	2.2	Weak Control
269.3	Anti-resonance	Anti-resonance	0	Neutral
282	Resonance	Resonance	10.8	Good Control
318	Anti-resonance	Slope of the curve	1.6	Weak Control
331	Resonance	Resonance	11	Good Control
352.5	Anti-resonance	Slope of the curve	11.5	Good Control
410	Resonance	Resonance	0	Neutral
415.5	Anti-resonance	Descent of the curve	4,1	Weak Control
500	Anti-resonance	Descent of the curve	1.8	Weak Control
559	Resonance	Slope of the curve	1.8	Weak Control
592.5	Anti-resonance	Descent of the curve	0.9	Weak Control
642.5	Resonance	Resonance	5.5	Good Control
685	Anti-resonance	Anti-resonance	6.8	Unstable
721.5	Resonance	Resonance	9.8	Good Control
775.5	Anti-resonance	Anti-resonance	6.1	Weak Control
800	Resonance	Resonance	13	Good Control
Observation: The ARX convergence results for Primary Path is 77,25% and for Secondary Path is 79,56%.				

Table II: Results of the ANC system with the configuration Error II as receiver sensor (5) and using loudspeaker R as actuator sensor.

V. CONCLUSIONS

From the frequency response functions obtained in Item 3 it was possible to analyze the behavior of the acoustic wave inside the duct. Based on the reference microphone FRF checked the discrete frequencies that would be studied and then compared with the FRFs of error microphones (L Control, R Control, Error I, Error II and Exit). With the results presented in Item 4 we conclude that the best systems of Active Noise Control sets were presented:

- Loudspeaker L as actuator sensor (control) and microphone “Exit” as receiver sensor.
- Loudspeaker R as actuator sensor (control) and microphone “Error II” as receiver sensor.

We conclude that the receiver sensor (microphones) positioning and actuators sensors (speakers) are directly linked to the behavior of the ANC system. It can also be concluded that the frequency response functions might predict the behavior of the ANC system. This paper could demonstrate experimentally the "why" of the ANC system malfunction when expanding the frequency to a broadband control system. The response is due to some frequencies situated in the regions of anti-resonance. Therefore using FRFs it can be predicted the quality of the ANC system and from this statement, it is possible to work in positioning actuators and receivers sensors according to their frequency response functions, improving attenuation. So it can maximize the attenuation in a range for greater coverage compared to control tonal or narrowband ANC, obtained in previous works. In other hand, these issue can be avoided if the structural that is being analyzed by a FEM software before starting the experiments, as can be seen at figure 8 and 9 shows how much the FRF are similar between them. If the model used in software has a great reliability at the maximum details to the real experiment, results should be better than those presented in this paper. In other words, the FEM software should be able to predicted the positioning of the microphones only using a 3D model and using FRF analysis. Depending on the frequency in which the product has the problem, whether because of a fan or a cooling tower, compressor or whatever the device is, you can always analyze the frequency of the acoustic wave which it passes and overview their FRF at the desired spot.

VI. ACKNOWLEDGMENT

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