EVALUATION OF PARAMETERS IN THE COMPRESSED AIR NOISE

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Abstract. *The use of compressed air for cleaning and drying parts is very common in any industrial park. Furthermore, the noise levels measured in the operator's ear easily reaches values above 100 dB (A). In this work a methodology is presented based on response surface to study the effect of the parameters number of holes (with the same open area) and pressure has on the sound pressure levels SPL measured in the environment. The methodology used was Box-Behnke Methodology with Using Analysis of variance (ANOVA,) the best fitted model was the quadratic one. The angle of the plane generated by the RMS shows that the number of holes has more influence in noise levels generated by the pressure than the number of holes in the discharge area. Numerically, there is an average decrease of 6 dB(A) when increases the number of holes of 1 to 16 and a decrease of 8.6 dB(A) when decreases the pressure of 7 to 3 bar.*

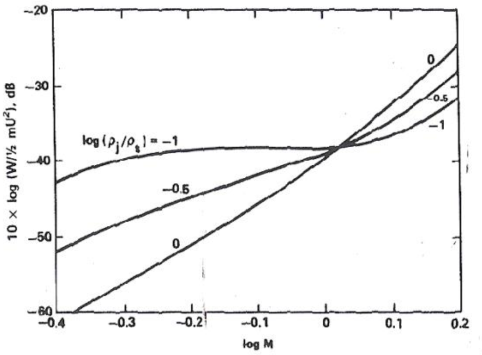
Keywords*: jet noise, response surface, noise control*

1. INTRODUCTION

Pneumatic systems are very useful in industries and they have a multiplicity of functions related to mass or energy transfer in a productive process, especially when it's necessary moderated effort to high velocities, clean environments or when the environment is hostile or flammable.

The discharge to the atmosphere of large volumes of gas at high pressures is one of the main sources found in the industrial plants. These are derived from the relief valves that discharging fluid at high velocity to air or to a lower pressure environment generates noise associated with different thermo-fluids mechanisms that act simultaneously. The industrial compressed air noise is considerate the second source responsible for the high rate of hearing loss, once that the main source is caused by the impact of machinery and tools. (Gerges, 2000).

The sound generated by high-speed jets is usually associated with several different active sources working simultaneously. Jet mixing noise, caused by the turbulent mixing of the jet with the ambient medium, and the imperfectly expanded supersonic jet's shock-associated noise, produced by the convection of turbulence through shock cells in the jet, is the principal components of the radiation. The properties of sound sources in real jets differ considerably from those on the idealized models. The dependence of $W/\frac{1}{2}mU^2$ on the jet Mach number $M = U/c$ and on the density ratio p_j/p_s, where c is the ambient sound speed and p_j, p_s are the densities (kg/m^3) of the fully expanded jet and the ambient atmosphere, respectively, is illustrated in Fig. 1. For M lower than about 1.05 the sound power increases as p_j/p_s decreases (i.e., as the jet temperature increases). For higher Mach numbers, the sound power levels decreases. (Beranek, 1992).



Source: Beranek, L. L.; "Noise and vibration control engineering: Principles and applications" John Wiley & Sons, Inc. Canada. 1992.

Figure 1. Ten times the logarithm of the acoustic power ratio of jet mixing noise to the mechanical stream power as a function of the fully expanded jet Mach number $M = U/c$ for different values of p_j/p_s.

Many works were developed to reduce the noise, which proposes changes in compressed air nozzles. Paliath (2006) used, in his work, computational aeroacoustics and parallel computers to conduct a study of flow-induced noise from different jet nozzle geometries, that includes a study of the effect of different nozzle geometries such as axisymmetric/non-axisymmetric and planar/non-planar exits on the far field noise predictions.

Peterson (1981) developed a patent to low noise air nozzle, which generates a minimum level of sound, once that most nozzles, even of the quiet type, have an open orifice of substantial cross sectional area so that a large volume of high pressure air is delivered by each nozzle. As the high velocity air jet impinges on and mixes with the relatively still ambient air, turbulence is set up which produces objectionable noise.

The understanding of aerodynamic noise generation mechanisms is related to the investigation of Mach's number variation in the main flow, characterizing the flow in subsonic or supersonic; and the aerodynamic radiation types: monopole, dipole and quadrupole (Beranek, 1992). The sound radiation of a dipole occurs when a gas flow interacts with a body, producing non-stationary forces. The quadrupole source is used to model the resulting noise from viscous stress in a turbulent gas flow in the absence of interaction with solid bodies. The aerodynamics quadrupole sources consist in the dominant type of sources that has high subsonic velocities; and in turbulent jets. (Gerges, 2000).

The complexity of noise generation mechanisms implies the use of numerical and experimental models essential to the development of effective control devices. In most situations a chaotic and complex behavior of the flow prevails, involving phenomenon such as compressibility, turbulence and shock waves, relevant to subsonic and supersonic flows.

The Response Surface Method – RSM – is an optimization technique based on factorial design that was introduced by G.E.P. Box in the 1950s and since then it has been successfully used when it comes to modeling industries processes (Barros Neto *et al*., 2001). It is composed by planning and analysis of experiments, which seeks to relate responses with the quantitative factors levels that affect these responses (Box and Draper, 1987).

Duarte *et al.* (2010) studied the influence of the number of holes and the distance in the noise generated by a compressed air escape. They observed that the number of holes is more significant in the noise than the distance parameter. So, in this work, the parameter number of holes was maintained.

The objective of this work is to verify the influence of two parameters (number of holes and pressure) in the noise generated by a compressed air escape, using RSM, once it observed in literature that the radiated noise is very influenced by fluid velocity partner.

2. METHODOLOGY

This work consists in evaluating the influence of the number of holes and pressure loads parameters, related to the noise generated by compressed air leakage.

The proposed methodology uses an experimental design Box-Behnken based on response surface (RSM) cubic centered geometry with alfa being equal to 1 (Hines *et al.* 2006). Geometrically, the design is shown by Fig. 2.

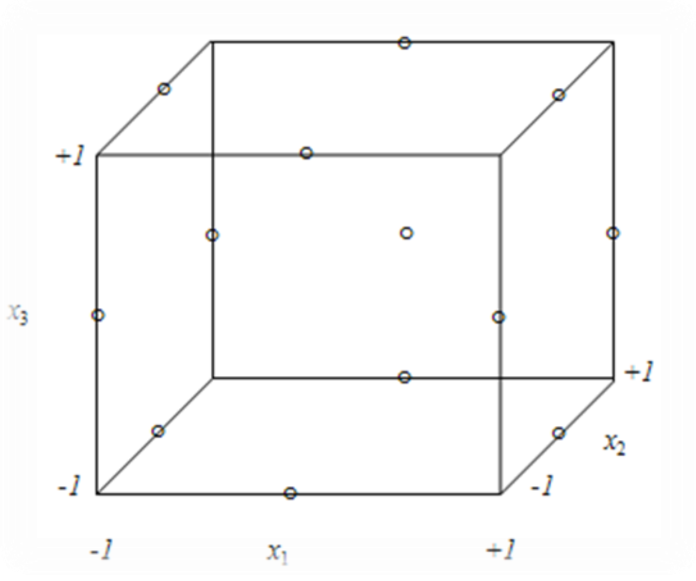


Figure 2. Geometrical representation of Box-Behnken's design.

To evaluate the experimental error, it has been made twelve (12) replications in the center point and one replication for the other levels.

3. EXPERIMENTAL PROCEEDURE

An experiment was executed to observe the air compressed noise behavior. The tubes were connected in a compressed air net and placed under a metallic table so that the generated noise was higher than the background noise.

The levels used for the pressure were 3, 5 and 7 bar, respectively, which, normalized in the range [-1 +1] was -1, 0 e +1. To guarantee the levels it was used a pressure regulating valve shown in the Fig. 3.

Figure 3. Pressure regulating valve used in this work.

To the factor number of holes were user three configurations of tubes with 1, 4, and 16 holes, which resulted in the normalized levels of -1, 0.6 and +1, respectively. The diameters and number of holes were chosen to guarantee a total open area of 31.67 mm², for each configuration. In Fig. 4 was shown the three PVC tubes, with the respective holes, used in this experiment.

Figure 4. Tubes used in this work.

To measure the Sound Pressure Levels (SPL), it was used an acquisition system composed by a microphone PCB 377B02 SN 107158, a pre-amplifier PCB 426E01 SN 010411, a coaxial cable, an acquisition data National Instruments USB-9162 and a notebook. Each signal data was measured for 20 seconds, with a sample frequency of 16384 Hz in three different specific measured points. The analyzed result corresponds to the average result.

The experiments were realized on a randomly order, in agreement with the sequence shown on Tab. 1. In this table, it is also shown the number of holes and the pressure value normalized for each one of the 14 treatments.

Table 1. Normalized treatments.

Treatment	Holes	Pressure
1	1	1
2	-1	-1
3	0,6	0
4	0,6	0
5	1	-1
6	0,6	1
7	-1	1
8	-1	0
9	0,6	0
10	1	0
11	0,6	0
12	0,6	0
13	0,6	-1
14	0,6	0

4. RESULTS AND DISCUSSION

The modeling, in RSM, is made by adjusting the simple models to the responses obtained with factorial planning (Barros Neto *et al.*, 2001). The models are simple and limited by the degree of freedom of the experimental design.

In this work, the system has nine (9) degrees of freedom. Therefore, a cubic model can't be used. So, quadratic and linear models were admitted for analysis. The responses can be estimated using the Eq. (1), Eq. (2) and Eq. (3) receptivity. In Eq. (2) can be observed an interaction in quadratic terms.

$$\hat{y} = f_0 + f_1x_1 + f_2x_2 + f_3x_1x_2 + f_4x_1^2 + f_5x_2^2 \tag{1}$$

$$\hat{y} = f_0 + f_1x_1 + f_2x_2 + f_3x_1x_2 + f_4x_1^2x_2 + f_5x_2^2x_1 \tag{2}$$

$$\hat{y} = f_0 + f_1x_1 + f_2x_2 + f_3x_1x_2 \tag{3}$$

Where f_0, f_1 ... f_5 are the models parameters and e x_1 e x_2 representing the parametric factors.

The parameters were obtained by Least Square Method (LSM). Then, the values of SPL can be estimated using the Eq. (4) and Eq. (5) to the quadratic models or the Eq. (6) to the linear one.

$$\hat{y} = 80.28 - 1.02x_1 + 4.35x_2 - 3.87x_1x_2 - 5.56x_1^2 + 0.12x_2^2 \tag{4}$$

$$\hat{y} = 76.38 + 0.38x_1 + 3.32x_2 - 3.72x_1x_2 + 1.27x_1^2x_2 - 0.68x_2^2x_1 \tag{5}$$

$$\hat{y} = 76.47 - 0.02x_1 + 4.35x_2 - 3.87x_1x_2 \tag{6}$$

Where $\hat{y}$ is the value of the SPL predicted by the model.

If the SPL obtained experimentaly is y, then the observed residue is calculated using Eq. (7).

$$e = y - \hat{y} \tag{7}$$

For the quadratic models, the calculated residues were 15.77 and 81.62. For the linear one, the residue is 85.19.

Based on these results, the first quadratic model best describes the experiment in analysis. However, it is observed in the quadratic ones that the parameters $f_5$have little influence on the final response when compared with the others parameters. Thus, another quadratic model was analyzed, described by Eq. (8).

$$\hat{y} = f_0 + f_1x_1 + f_2x_2 + f_3x_1x_2 + f_4x_1^2x_2 + f_5x_1^2 \tag{8}$$

By the LSM the parameters are described in Eq. (9).

$$\hat{y} = 80.28 - 1.02x_1 + 3.32x_2 - 3.72x_1x_2 + 1.27x_1^2x_2 - 5.47x_1^2 \tag{9}$$

The observed residue is 14.19. So, the Eq. (9) represents the best SPL generated by the compressed air leakage over a metallic barrier.

So, the analysis is realized only to the last proposed model. Admitting a normal distribution, it possible get the confidence intervals of the coefficients, shown in Tab. 2.

Table 2. Confidence intervals of the coefficients.

Confidence Interval, with 90% of trust	
79.76	80.81
-1.32	-0.72
2.41	4.24
-4.09	-3.35
0.21	2.33
-6.16	-4.79

All the calculated coefficients are within their respective range, and thus are statistically significant.

The residue analysis is fundamental to evaluate the quality of the fit. In general, the common method to determinate the error is the analysis of variance (ANOVA). The results of the quadratic modeling are shown in the Tab. 3.

Table 3. Analysis of variance to the model of Eq. (8), using the Tab. 1.

Variation Source	Quadratic Sum	No of D.F.	Mean Square
Regression	358.51	5	71.70
Residues	14.19	22	0.64
Lack of fit	1.71	3	0.57
Experimental error	12.48	19	0.66
Total	372.70	27	-
% of explained variation		96.19%	
% maximum variation explained		96.65%	

In addition to the percentages of variation explained and the consistent maximum explainable variation, the value of MQ_R/MQ_r is equal to 112.03 and adopting a confidence interval of 90% attending the hypothesis that the model is satisfactory and the $F_{0.9,5,22}$ equals to 2.12, the model is highly significant.

A detailed examination of Tab. 3 justifies the choice of the model. The reason MQ_{faj}/MQ_{ep} has a value of 0.86, which is lower than $F_{0.9,3,19}$ that equals to 2.39 is that the hypothesis is accepted and the adjusted model describes adequately the response surface on the analyzed region.

The Eq. (8) defines the plane represented in perspective by Fig. 5, and the levels curves in Fig. 6.

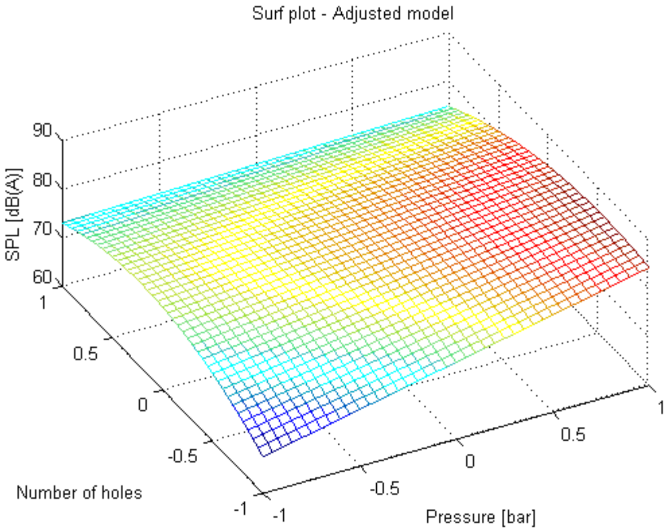


Figure 5. Plane of the RSM.

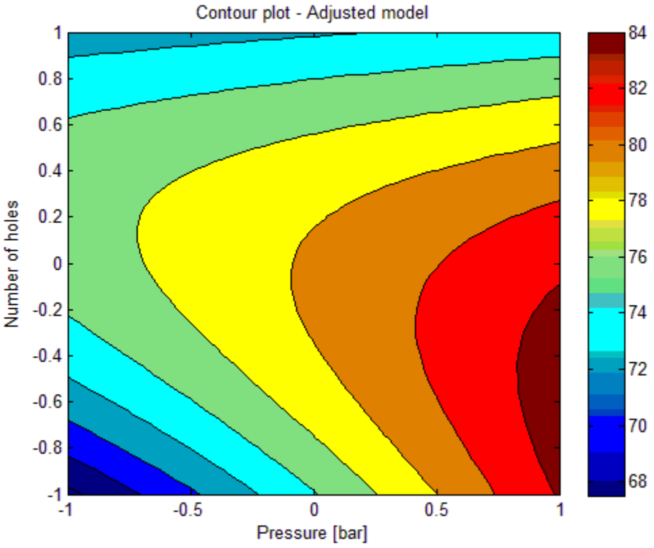


Figure 6. Levels curves of RMS.

Analysing the figures, it can be observed that as higher it is the number of holes and lower pressure is, lower is the value of SPL (dBA). Numericaly, it has an average decrease of 6 dB(A) when the number of holes increases of 1 to 16 and a decreases of 8.6 dB(A) to reduce the pressure of 7 to 3 bar. Note that in low pressure the factor number of holes didn't significantly influence the result, which was more influential for medium and high pressures.

Figure 7 illustrate the frequency spectrum in 1/3 octave bands to the configuration of 7 bar with all levels of number of holes.

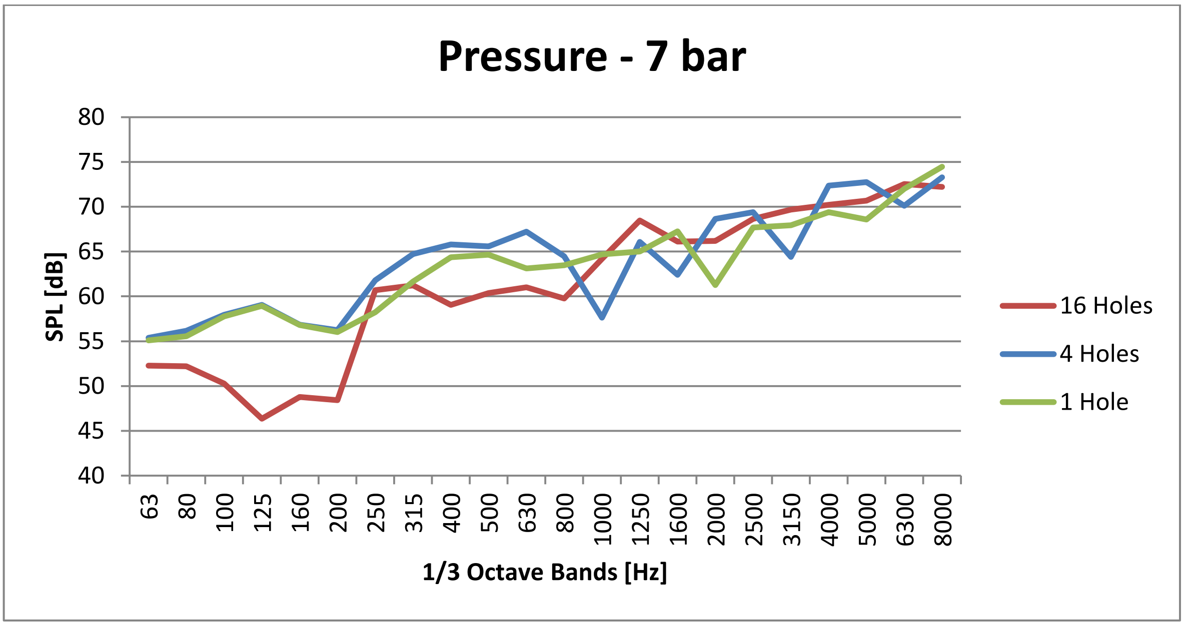


Figure 7. Frequency spectrum in 1/3 octave bands to 7 bar of pressure at the levels of number of holes.

It can be observed, in the configuration of 16 numbers of holes, a lower SPL value for lower frequencies and a few difference along the rest of the spectrum when compares all configurations. On the other hand, the curve of 4 holes has some SPL values lower when compared with the 1 hole configuration. But it can't be observed in the frequency spectrum.

To the configuration of 4 holes, Fig. 8 illustrates the frequency spectrum in 1/3 octave bands with the pressure values.

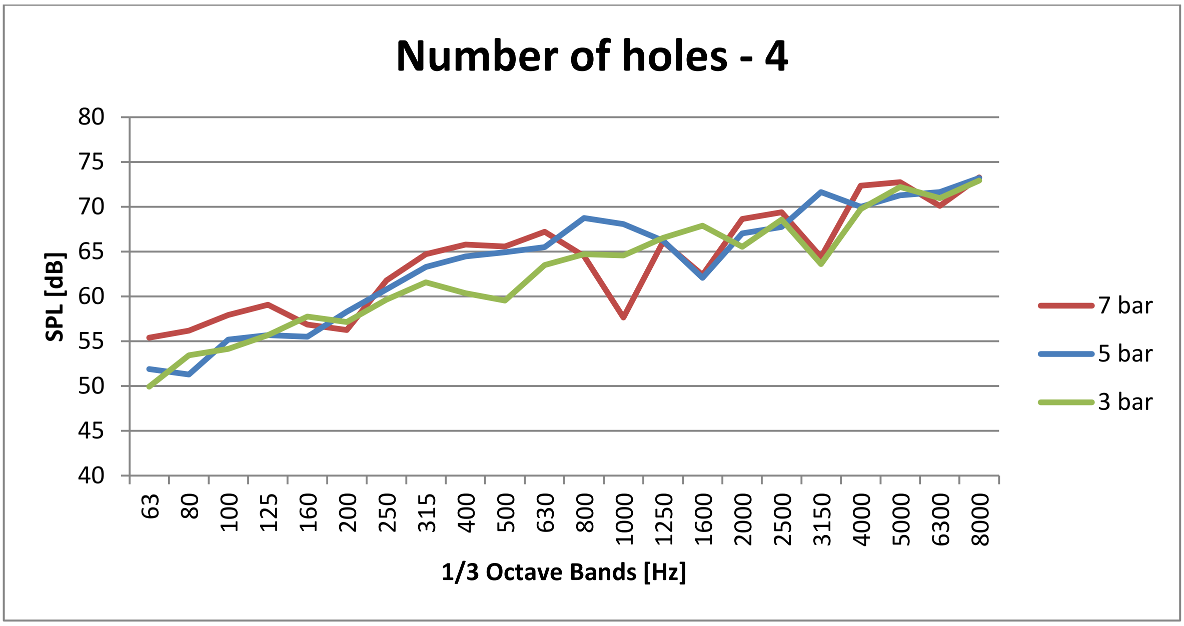


Figure 8. Frequency spectrum in 1/3 octave bands to 4 number of holes of pressure at the levels of pressure.

It can be observed in Fig. 8 the predominance of the higher values of SPL in the curve corresponding to 7 bar, mainly in lower frequencies. After, the lowest values are in the configuration of 3 bar.

5. CONCLUSIONS

The main conclusions of this work are:

- Statistically, the quadratic metamodel equate the behavior of SPL according the number of holes and the pressure in compressed air flow;
- The angle of the plane generated by the RMS shows that the number of holes has more influence in noise levels generated by the pressure than the number of holes in the discharge area. Numerically, there is an average decrease of 6 dB(A) when increases the number of holes of 1 to 16 and a decrease of 8.6 dB(A) when increase the pressure decreases from 7 to 3 bar;
- Using spectral analysis, the regions of low frequencies presented more changes between the studies configurations.

6. ACKNOWLEDGEMENTS

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