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Characterization of noise emitted by a power tiller through geostatistics

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ABSTRACT: Noise is one of the harmful and stressful physical agents present in the workplace. Research performed with geostatistics to adjust the semivariogram of tractor noise were performed using the Gaussian and spherical model. In this way, the aim was to map the spatial variability of the noise emitted by a power tiller through the sine wave model, besides testing other fitting methods, in order to identify health zones for the workers. The experiment was performed with an agricultural power tiller (10.3 kW) placed in a working regime (1500 rpm), coupled to a brushcutter, and a digital sound level meter to collect noises in points distributed along a regular grid sampling of 2.0×2.0 m around the tractor. The spatial dependence of noise was analyzed through semivariogram fitting by different methods and by the wave model to obtain the spatial distribution map interpolated by kriging. It was possible to characterize the structure and the magnitude of the spatial dependence of the noise levels emitted by the tractor, as well as to map the spatial distribution. A maximum noise level of 96.5 dB was observed close to the tractor engine, a value above the limit of 85.0 dB for 8 h of daily exposure (NR-15). Thus, the use of ear protectors is recommended for both the tractor driver and the professionals who support agricultural operation within a radius of 6 m from the emitting source under the conditions studied.

Key words: acoustic comfort, agricultural mechanization, spatial variability, ergonomics, sine wave model

Caracterização do ruído emitido por um trator de rabiça por meio da geoestatística

RESUMO: O ruído é um dos agentes físicos nocivos e estressantes presente no ambiente de trabalho. Pesquisas realizadas com a geoestatística para ajuste de semivariograma de ruído de tratores foram feitas por meio do modelo gaussiano e esférico. Dessa forma, objetivou-se mapear a variabilidade espacial do ruído emitido por um trator de rabiça, por meio do modelo de onda senoidal e testando outros métodos de ajuste, visando identificar zonas de salubridade para os trabalhadores. O experimento foi desenvolvido com um trator de rabiça agrícola (10.3 kW) colocado em regime de trabalho (1500 rpm), acoplado a uma roçadora, e um decibelímetro digital para a coleta dos ruídos em pontos distribuídos numa malha amostral regular de 2.0×2.0 m ao redor do trator. A dependência espacial do ruído foi analisada por meio de ajuste de semivariograma por diferentes métodos e pelo modelo wave para obtenção do mapa de distribuição espacial interpolados por krigagem. Foi possível caracterizar a estrutura e a magnitude da dependência espacial dos níveis de ruído emitidos pelo trator, bem como realizar o mapeamento da distribuição espacial. Observou-se valor máximo de nível de ruído de 96.5 dB próximo ao trator, valor acima do limite permitido de 85.0 dB para 8 h de exposição diária (NR-15). Assim, o uso de protetores auriculares é recomendado tanto para o tratorista quanto para os profissionais que dão suporte à operação agrícola em um raio de 6 m da fonte emissora, nas condições estudadas.

Palavras-chave: conforto acústico, mecanização agrícola, variabilidade espacial, ergonomia, modelo de onda senoidal



INTRODUCTION

The use of power tiller as an energy source is often used in family farming and can be a tool to optimize work. Due to the small size and low power of the power tiller, between 7.35 and 14.71 kW, these are widely used in small properties and in rugged relief regions (Veiga et al., 2015). However, machines and equipment can provide unhealthy conditions in their operations.

Agricultural work when aided by agricultural machinery exposes the worker to agents harmful to their health and physical integrity, such as: noise from the engines and implements, vibration, gases and dust particles, among other agents (Poje et al., 2016). This exposure to high noise levels emitted by machines can lead to hearing loss and can cause stress, affecting worker performance and workplace efficiency (Alves et al., 2011).

Regarding agricultural machinery, the Regulatory Standard (NR-15) (MTE, 2017) foresees additional of insalubrity to workers who are exposed to continuous or intermittent noise, heat, vibrations, chemical agents and dust. For continuous or intermittent noise, the NR-15 states that exposure to noise levels above 115.0 dB is not permitted for individuals not adequately protected. Furthermore, this standard establishes the time in which a person may be exposed to each level of noise.

When using geostatistics for semivariographic analysis of noise, a data oscillation is observed due to the physical characteristic of the noise, because it is a sound wave. There are periodic models for this type of behavior that best fit these types of phenomena (Webster & Oliver, 2007).

It should be emphasized that most of the studies that evaluated the noise produced by agricultural machines using geostatistics conformed to the Gaussian model (Pimenta Junior et al., 2012; Yanagi Junior et al., 2012; Missio et al., 2015; Spadim et al., 2015). Ferraz et al. (2013) analyzed the noise of portable coffee harvesters and assembled the spherical model. The probable causes of non-detection of a periodic structure for the semivariogram of these authors are sample grid, environmental effects and experimental design.

Based on the above, the objective of present study was to evaluate the spatial variability of the noise emitted by a power tiller through the sine wave model and to test other methods of assembly through geostatistics for the observation and definition of health zones for the operators and workers involved in operations.

MATERIAL AND METHODS

The experiment was conducted at the Technical College of the Federal Rural University of Rio de Janeiro (CTUR), Seropédica, RJ, Brazil (22° 47' S; 43° 40' W; 22 m) in April of 2013. A power tiller coupled to a brushcutter with a nominal power of 10.3 kW and a rotation of 1500 rpm was used to drive the rotary brushcutter.

Noise levels were determined using sound level meters in the slow response circuit and "A" equalization, expressed in dB, being that the wind shield of this meter was used for all measurements. The noise level evaluations were performed

according to the methodology described in NBR 9999 (ABNT, 1987), in which the ambient temperature was between -5 and 30 °C and the air velocity was less than 5.0 m s⁻¹. On the day of the experiment, the wind speed and temperature were 2.6 m s⁻¹ and 26 °C, respectively, meeting the standard requirements.

The readings were performed at the average height of the operator's ear, at points distributed in a regular grid sampling of 2.0 x 2.0 m, totaling 121 sampling points, around the operating agricultural machine. A spatial coordinate was measured in meters where the center point (0, 0) corresponded to the place where the agricultural machine remained in operation during the entire collection. The center point (0, 0) corresponds to the operator seat.

The spatial dependence of the noise produced by the operating power tiller was analyzed through a classic and robust semivariogram fitting. The classic semivariogram was estimated by the Eq. 1:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{\substack{v(x_i, x_j) \\ |x_i - x_j| = h}} [Z(x_i) - Z(x_j)]^2 \quad (1)$$

where:

N(h) - number of experimental pairs of observations separated by the distance h; and,

Z(x_i) and Z(x_j) - random variables at the locations x_i and x_j.

The semivariogram is represented by the graph $\gamma(h)$ versus h. With the adjustment of a mathematical model to the calculated values of $\gamma(h)$, the coefficients of the theoretical model were estimated for the semivariogram. They are: nugget effect (C₀); sill (C₀ + C₁) and range, as described by Yanagi Junior et al. (2012).

According to Cressie & Hawkins (1980), the robust estimator of semivariogram values is less susceptible to the influence of mass data values than the classic estimator. Thus, the robust estimator is described by Eq. 2:

$$\hat{\gamma}(h) = \frac{1}{2} \frac{\left[N(h)^{-1} \sum_{N(h)} \sqrt{|Z(x+h) - Z(x)|} \right]^4}{0.457 + \frac{0.494}{N(h)}} \quad (2)$$

where:

N(h) - number of experimental pairs of observations; and,
Z(x), Z(x+h) - separated by a distance h.

This estimator assumes that the differences Z(x+h) - Z(x) are distributed normally for all pairs (x+h, x).

The fitting of semivariograms methods was chosen as a function of Ordinary Least Squares (OLS) and Weighted Least Squares (WLS), estimated by classic and robust mode. The wave model was tested for all methods (Webster & Oliver, 2007) Eq. 3, totaling four semivariograms for the variable under study.

$$\hat{\gamma}(h) = C_0^2 + \frac{a}{h} \text{sen} \left(\frac{h}{a} \right)^4 \quad (3)$$

where:

C₀ - nugget effect;

- a - range; and,
- h - distance between samples.

A third degree polynomial was used to remove the trend that might interfere with the spatial dependence of data, and thus fitted the semivariograms to the residuals and later added the residuals with the tendency to obtain the final map.

For the choice of semivariogram fitting methods, the cross-validation of data was considered according to the methodology used by Ferraz et al. (2012).

According to Isaaks & Srivastava (1989) and Mueller et al. (2004), cross-validation is the error estimation technique that allows comparing predicted values with the sampled ones. The sample value, at a certain location $Z(s_i)$, is temporarily discarded from the data set, and then a kriging prediction is performed on the location $Z(s_{(i)})$, using the remaining samples. Thereby, it is possible to extract some values very useful for choosing the method, such as the mean error (ME), the standard deviation of mean errors (SD_{ME}), the reduced mean error (RE), and the standard deviation of reduced mean errors (SD_{RE}).

The selection criteria based on cross-validation should find the value of ME and RE closest to zero, the value of SD_{ME} should be the lowest, and the value of SD_{RE} should be closest to one.

After the semivariogram fitting, the data were interpolated by universal kriging in order to allow visualizing spatial distribution patterns of the noise emitted by this agricultural machine.

The geostatistical analysis was performed using the R Development Core Team computer system (R Development Core Team, 2017), through the geoR package (Ribeiro Junior & Diggle, 2001). For the evaluation of health levels, the values recommended by NR 15 (MTE, 2017) were used. The layout of maps were generated by the free and open-source software QGIS version 2.14.15 (Quantum GIS Development Team, 2017).

RESULTS AND DISCUSSION

By analysing the minimum and maximum limits, the coefficient of variation and the average noise emitted by the power tiller (Table 1), a data variation is observed.

However, this analysis solely not allow stating where there is the highest or the lowest values of noise emitted by the tractor, thus requiring geostatistical studies.

Table 1. Descriptive statistics of noise emitted (dB) by a power tiller

Min	Max	x	Md	SD	Var	CV	K
73.5	96.5	80.10	79.30	4.47	19.95	5.6	1.27

Min - Minimum value of the variable; Max - Maximum value of the variable; x - Average; Md - Median; SD - Standard deviation; Var - Variance; CV - Coefficient of variation (%); K - Coefficient of kurtosis

Table 2. Estimated methods, models and parameters of the experimental semivariograms for the noise variables emitted by the power tiller

Method	Model	C_0	C_1	a	a'	ME	SD_{ME}	RE	SD_{RE}
OLS	Sine wave	0.21	5.53	1.83	5.46	0.01	0.86	0.01	1.64
WLS	Sine wave	0.30	5.48	1.81	5.43	0.01	0.86	0.01	1.38
Robust OLS	Sine wave	0.13	3.81	1.85	5.54	0.01	0.86	0.01	2.09
Robust WLS	Sine wave	0.16	3.82	1.84	5.52	0.01	0.86	0.01	1.90

C_0 - Nugget effect; C_1 - Contribution; $C_0 + C_1$ - Sill; a - Range; a' - Practical range; ME - Mean error; SD_{ME} - Standard deviation of mean error; RE - Reduced mean error; SD_{RE} - Standard deviation of reduced mean errors; OLS - Ordinary least squares; WLS - Weighted least squares

The semivariogram and its parameters (nugget effect, C_0 ; contribution, C_1 ; sill, C_0+C_1 ; range, a; and practical range, a') were obtained by fitting different wave model methods (Table 2).

According to Pyrcz & Deutsch (2003), the wave model is often used to indicate cycles or periodicity. Since the noise is a sound wave, such a model was very well adapted to the data, having a faithful fit to the cyclic behavior of the sound Figure 1.

In order to perform kriging, some semivariogram parameters must be estimated accurately. Otherwise, it will result in an ordinary kriging with estimation errors and erroneous information about the phenomenon (Ferreira et al., 2013). In this way, the wave model is the most suitable model for noise adjustment than other models, such as Gaussian and spherical, which may incur in estimation errors.

The best adjusted method was the weighted least square (WLS), in which the values of ME and RE were the closest to zero and the value of SD_{RE} was the closest to one (Table 2), according to the methodology proposed by Ferraz et al. (2012).

According to NR 15 (MTE, 2017), considering 8 h a day, a worker can be exposed only to 85.0 dB. When analysing Figure 2, it can be noted that the noise values emitted by the tractor around the operating agricultural machine were higher than those recommended by the standard, up to 7 m in the front, 5 m in the left side, 3 m in the rear and 7 m in the right side of the engine, where is located the engine exhaust.

It is also observed that in the center map, where is the operator, the noise level measured was 91 dB (Figure 2), with the red coloration. According to the values recommended by

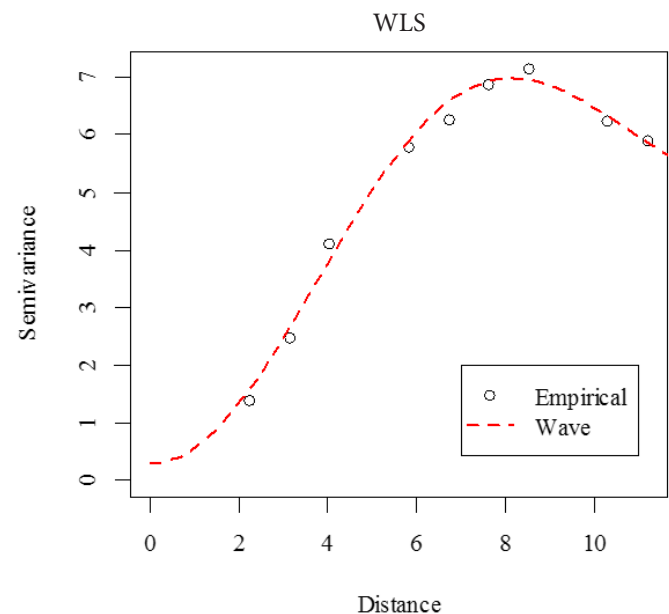


Figure 1. Semivariogram of the noise emitted by the power tiller fitted by the sine wave model

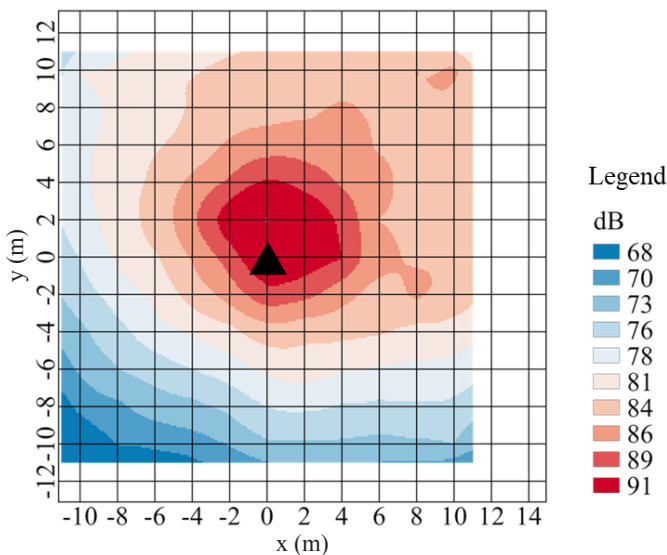


Figure 2. Spatial distribution map of the noise emitted by the power tiller

NR 15 (MTE, 2017), for this noise level, the allowable daily exposure limit is 3 h without the use of ear protection devices during its execution.

The maximum noise value, 96.5 dB (Table 1), was observed at point (0, 2), which was the measured near the tractor engine (source of noise), represented by the red color in the map. Under these conditions, according to the standard NR 15 (MTE, 2017), the worker only could be exposed to this noise up to 1 h and 45 min daily.

Studying some models of tractors, Gonçalves et al. (2013) found that for an 8 h working day the noise levels of the tractors were above the level allowed by NR 15. Baesso et al. (2015) evaluated 12 tractors of different models and concluded that tractors without a closed cabin had noise levels close to the operator's ear above the levels allowed by NR 15, being necessary the use of ear protectors. Studies performed by Rinaldi et al. (2008), Alves et al. (2011) and Nascimento et al. (2013) also concluded that farm machinery noise levels were above tolerance limits, being needed to take measures to reduce or eliminate the risk which the workers were exposed in the agricultural operations.

It was observed, still in Figure 2, that the more distant the tractor, the more bluish the spots, signaling the noise level decrease, thus becoming more appropriate to the workers and not requiring the compulsory use of Personal Protective Equipment (PPE). However, the use of PPE is still recommended for all workers involved in this machine operation. The minimum noise value produced by this tractor was around 73.5 dB (Table 1) observed in point (4, -10), i.e., the farthest from the source, corroborating with results found by Magalhães et al. (2012); Pimenta Junior et al. (2012); Nascimento et al. (2013) and Missio et al. (2015).

It is also observed that the noise levels spread in the northeastern direction of the map, and although the measurements were according to the standard, this result may have been influenced by the wind, since the wind is a propagation way of the noise, thus being recommended research regarding the wind influence on noise levels.

High noise levels may compromise the health of the worker. According to Brisolin et al. (2012), these loud noise levels can cause physiological changes in heart rate and blood pressure, sleep disturbances, digestive, vestibular, neurological and behavioral disorders, such as irritation, fatigue, decreased productivity, noise intolerance, anxiety, depression and stress.

Fernandes & Morata (2002) studied machine noise levels and observed an extreme discomfort for the machine operator, where workers exposed to this risk complain of hearing loss and tinnitus, besides several other symptoms as headache, nervousness, and stomach problems.

According to Guida et al. (2014), noise is the main physical causative agent of Noise-Induced Hearing Loss (NIHL). NIHL also causes stress and impair an effective communication at work, leading to work related accidents (Leão & Dias, 2010).

The noise levels found in this study are above the legislation and exceed the standard limits, classified as unhealthy zones, in which up to 6 m in the front, 5 m in the right side, 4 m in the left side and 3 m in the rear of the power tiller, measures are recommended in order to reduce noise levels at source, or the operator and workers involved in the operations shall use the PPE in the whole 8 h working day, since this zone exceeded the tolerance limits, according to the standard (Figure 3).

It can be stated that apart a distancing radius of 6 m from the power tiller, the operators will be in the health zone for this machine and for these conditions.

In this way, the existence of an unhealthy situation is evident for the operator and the support worker to the agricultural operation, as presented in Figure 3, with red color. At some points, farther from the emitting source, values below 85.0 dB were identified, but already enough to generate stress situations.

To reduce such unhealthy effects, the ideal would be to reduce the noise source, according to Gonçalves et al. (2009). However, it is often tough to deploy a cabin, e.g., in power tiller due to their robustness, thus adopting prevention, comfort and safety measures, such as the use of PPE as well as awareness and training of operators and support workers on a continuous basis is mostly recommended. Two types of PPE recommended in this case: earmuffs and earplugs.

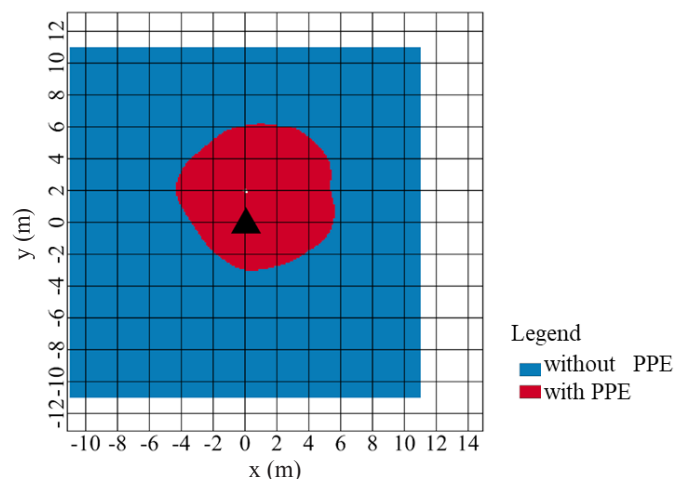


Figure 3. Map of unhealthy zones for operators involved in operations with the power tiller

CONCLUSIONS

1. It was possible to characterize the spatial structure of the noise emitted by a power tiller and to evaluate its variability through the wave semivariogram fitting model with the WLS method. It was possible to define the unhealthy zones.

2. Under the conditions studied, both the machine operator and people around the tractor within a 6 m radius from the emitting source are subject to the harmful health effects caused by noise exposure, since they exceeded the values recommended by the regulatory standard.

3. The use of ear protectors is recommended for both the power tiller operators and professionals who support the machine operation.

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