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5aNSa7. Reproduction of sound source directionality in reduced scale model
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The study of acoustic phenomena through reduced scale models is a useful tool for predicting the acoustic performance of closed and outdoor environments. When using reduced scale models, begins a process of constructive adequacy details of the study environment and sound source characteristics, reproducing its level and directionality. It is presented in this paper, a study on the reproduction of sound source directionality with application in outdoor reduced scale model. The sound source is an electric power converting substation. The directionality of this source was calculated using sound pressure levels measured, in 1/3 octave frequency bands between 50 Hz and 12.5 kHz, in twenty-four points positioned on a circle located around of the sound source. The sound was recorded in a point outside the circle for later playback. For playback of the sound signal, the noise was emitted in each monitoring direction, considering in each one the directionality through the signal equalization. The reduced scale used in the model was 1:5 and, based on this, it was transposed the frequencies of the signal. It was concluded that the sound source used in the reduced scale can be an efficient tool for reproduction of the directionality characteristics of the source.

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Introduction

The study of phenomena of sound propagation in reduced scale has been used both for evaluating propagation in closed (JEON et al., 2008) and outdoor environments (HOROSHENKOV; HOTHERSALL; ATTENBOROUGH, 1996). Arizmendi (1980) emphasizes that experiments with reduced models demonstrated empirically that these are excellent systems to obtain precise information on future acoustic properties in an environment, even before having it built.

The reduced scale models are developed from numerous simplifications including texture of the materials used and expected variation of pressure and temperature gradients. From the delimitation of the boundary conditions and monitoring influential parameters on the propagation of waves, it is possible to obtain very realistic predictions of the sound behavior of environments. It is therefore an estimate of the prototype conditions from observations of models.

As Arizmendi (1980), when the sound propagation occurs in both, prototype and model, with similar paths and there is a constant ratio between the measured quantities during propagation in all the homologous points, of the acoustic point of view can be defined as similar the designed environment (prototype), and the model. Therefore it is essential to establish the geometric similarity between the model and the designed environment.

Due to the testing situation and reproduction of the actual situation, all tests of reduced scale models regarding closed environments are performed in controlled environments. Regarding the models that reproduce outdoor propagation situations, it is observed the establishment of a test procedure for researchers. These models are also tested in controlled environments: the anechoic or semi-anechoic chambers.

It is observed that are rare the applications of reduced scale models tested outdoor. This is due to the large number of influential variables and the difficulty of controlling them in an open environment. This fact explains the predominant choice of tests in anechoic and semi-anechoic chambers for reproduce outdoor situations. However, the possibility of performing such tests in outdoor environment exists. To this must be considered the around model, the controlling of influential variables and the need to apply corrections due to the simplifications adopted during the construction of the model.

It is presented in this paper a study on the reproduction of sound source directionality with implementation in an outdoor reduced scale model. The sound source under investigation is characterized by emission of noise with directionality varied in function of frequency band and intense at low frequencies.

Object of study

The object of study approached in this work is an electric power converting substation installed in Brazil. It makes the conversion from direct current to alternating current by eight converters connected to twenty-four converter transformers. Part of the energy is generated at 50Hz and therefore is also made conversion to 60Hz as Brazil consumes power at this frequency.

Among the equipment installed at the converter substation, converters and converter transformers are the largest noise generators, which is more intense at low frequencies.

Method

The research method adopted consisted of four stages namely: characterization of the sound source; determination of reduced scale; reproduction of the sound source in reduced scale; construction, testing and validation of reduced scale model.

Characterization of the sound source

As this is an electric power converting substation, the object of study is composed of numerous devices noise generators. To obtain a sample of the noise generated, it was monitored only a group of devices, which were selected because of the type of noise generated and the operating mode of the substation.

It was considered that the devices which generate low frequency noise would be the focus of study due to the greater ability of this type of noise propagates over longer distances and cause discomfort in the neighborhood. As regards the operating mode, are considered the equipment that works in connection with one transmission line. From there, was established monitoring area.
The noise measurement was conducted in order to characterize the directionality of the sound source. It was established a circumference around the equipment of interest whose center coincided in plant with the geometric center of such equipment. On the circumference were marked monitoring points in order to contemplate points in alignment with the equipment and points between them. This procedure allowed to measure differences in perceived sound level when making the pathway on the monitoring circumference. In these points we collected data of sound pressure level as a function of frequency bands in 1/3 octave from 50Hz to 12.5kHz.

From the sound spectra monitored was calculated the directionality of the source for each spectrum frequency bands in 1/3 octave from 50Hz to 12.5kHz. This calculation was made by comparing the levels measured for a given frequency in each monitoring point, with the maximum sound level obtained at that frequency. The highest noise level became the reference level of an omnidirectional sound source and, for this, was calculated the difference of sound pressure level in each direction, obtaining directivity. Was conducted the recording of the acoustic signal to be subsequently electronically worked and used at the reproduction of the sound source in reduced scale model. The location of the recording point was influenced by the need of absence of electrical interference in the recording equipment.

**Determination of reduced scale**

To determine the reduced scale were taken into consideration the frequency range of used equipment for data collection of sound pressure level, the area available for testing, the material on the substation floor and the sound source height.

The equipment used in measurements of sound pressure level in reduced scale model was also used for *in situ* measurements. This was set to collect data of sound pressure level as a function of frequency bands in 1/3 octave, from 50 Hz to 12.5 kHz. Work with reduced scale model makes the upper limit frequency of equipment capacity to capture data a limiter. This is because as the scale decreases, increases the frequency of interest in order to maintain the correlation between reduced model and the actual size. It was necessary evaluate the reduced scale that would fit better to the real situation, considering the frequencies whose sound pressure levels monitored were higher, which are the frequencies of interest in the research.

Also in relation to the equipment used to collect data of sound pressure level, it was considered, in determining the reduced scale, the height at which the microphone was positioned at the reduced scale tests. This height is conditioned by the height of the sound pressure level meter *in situ*.

With respect to the available area for reduced scale tests, it was established the need for a space without vertical obstructions near, with levels of background noise that not interfere during testing, and with smooth pavement to facilitating the reproduction of pavement roughness observed in the real situation.

**Reproduction of the sound source in reduced scale**

Due to the amount of detail of noise generating equipment and difficulty in reproducing them in reduced scale, the set of sound sources distributed in the monitoring area was replaced by a single source. This source, used to reproduce the noise signal on reduced scale model should be able of emitting noise with its characteristics of directionality preserved.

It was determined in accordance with the reduction scale adopted, the range of frequencies at which the sound source used should respond. It was made a study of the ability of the sound sources available on the market considering the reproduction of directionality of the source.

The height of the sound source in reduced scale was calculated from the height of the actual sound source considering the reduction scale adopted.

**Construction, testing and validation of reduced scale model**

In reduced scale model, the sound source was installed at a point equivalent in plant to the geometric center of the noise generating equipment of interest. Its height was conditioned by the height of the sound source in actual size and the reduction scale adopted. The direction of the sound source in reduced scale varied according to the emitted noise in order to reproduce the directionality of the noise monitored *in situ*. The monitoring points were located on a circumference surrounding the sound source with radius equivalent to the actual size considering the reduction scale. Were monitored at each point the sound pressure levels as a function of frequency bands in 1/3 octave covering the frequencies of interest from the application of the scale factor. From these data, was calculated the directionality of the sound source on a reduced scale through the same procedure used to calculate the actual
directivity of the sound source. The validation was achieved by comparing the directivity calculated from measurements in situ and directionality calculated from measurements in reduced scale model.

Results and analysis

Presents the results obtained at each step of the methodology and the respective analyzes.

Characterization of the sound source

Among the equipment installed at the substation, as informed by management of substation, converters and converter transformers are devices that generate most intense noise in the low and mid frequencies, spreading more easily in the vicinity of the substation. It was established as a focus of study the noise generated by converters and converter transformers.

Each two converters installed in the converter substation form a Pole that works connected to six converter transformers. This one was established as being the portion of interest of the sound source for its characterization.

To determine the directionality of the sound source analyzed, measuring points were established on a circumference of radius equal to fifty meters around the six converter transformers. The circumference had its center coinciding with the center point between the converter transformers. It was respected a minimum distance of five meters between the measurement points and the converter transformers and between the measurement points and converters to prevent magnetic interference in the measurement system. The converters, although work connected to converter transformers, were not included in the monitoring area because are installed inside buildings, being considered enclosed equipment.

Were determined twenty-four monitoring points. Four of these points were located five meters from each corner of the set of converter transformers at an angle of 45° with the normal of each face of the set. Ten points were located on lines perpendicular to the faces of converter transformers facing circumference. These lines were extended to the circumference and were centered in relation to the face of the equipment. Finally, were marked ten points intermediate between those previously mentioned. These in order to better characterize the source directionality. Figure 1 presents a sketch of the monitoring points.

![FIGURE 1. Sketch of monitoring points - area of converter transformers.](image-url)

In the twenty-four points were collected data of sound pressure level as a function of frequency in 1/3 octave from 50 Hz to 12.5 kHz. Was used a sound pressure level meter brand Brüel & Kjær®, model 2238, with a ½" microphone. At each point the meter was positioned two meters tall. The measurement time at each point was determined by selecting the optimal mode device. In this mode the meter calculates the time required to collect data.
at each frequency. Throughout the measurement it was used the wind screen. Figure 2 shows the graphic of sound pressure level as a function of frequency at all evaluated points. The highest sound pressure levels occurred at frequencies of 125Hz and 400Hz.

![Figure 2. Noise spectrum of the noise measured at monitoring points.](image)

From the measured data of sound pressure level, it was calculated the directionality of the noise propagated. The difference of sound pressure level of the measured point relative to the reference level was calculated for each frequency of 1/3 octave between 50Hz and 12.5kHz and represents the directionality of the source at that frequency.

**Determination of reduced scale**

With regard to equipment used to collect data on reduced scale model, was used the same equipment available for in situ measurements. The meter is brand Brüel & Kjær® Model 2238 Mediator, with a ½” microphone and filter in 1/3 octave, from 50 Hz to 12.5kHz. Considering the frequency at which the highest sound pressure levels were measured, 125Hz and 400Hz, it is understood that the limits on frequency of data collecting of the meter used are large and allow working with reduction scales up to 1:30. If it were adopted to 1:30 scale, the frequency 400Hz corresponds in scale, the frequency of 12kHz. However, despite a frequency of 400Hz be highlighted in this study, one cannot ignore the analysis of the higher frequencies. Therefore, one must adopt a reduction scale with which the model has a size greater than 1:30 scale model. This scale was determined according to the other conditioning factors, namely the equipment height and the available area for tests.

The height of the equipment was determined from the height of the equipment used in measurement in situ, when it was available a microphone holder two meters height. According to ISO 10847:1997, while monitoring acoustic parameters, the microphone must be at least one meter and twenty centimeters above the ground. Analyzing this value and relating it to the height of the equipment during measurements in situ, it was found that one option would be to work with a reduction scale of 1:5. The height of the microphone on a reduced scale would be equal 0.40 m (forty centimeters), which would meet the minimum of twenty-four centimeters from the ground imposed by the standard (the reduction scale 1:5 applied to the minimum height one meter and twenty centimeters).

Regarding the area available for testing on a reduced scale, was searched an area without near vertical obstructions and with levels of background noise that do not mask the noise used in the test. It was chosen an area in the western part of the campus of the State University of Maringá, city of Maringá, Paraná State, where was available an sports court, on which the tests were conducted.

The tests were performed on the court, as this presents cementitious pavement without significant roughness. This characteristic was desirable because part of the pavement of the converting substation is asphalt. Thus, it was necessary to have a smooth pavement which on the reduction scale had equivalent roughness to substation pavement.

The sports court used to perform the tests is twenty-three meters wide by forty-three meters long. The radius of monitoring circumference in converter substation is fifty meters. Therefore, the scale 1:5 allowed dispose the monitoring points on a circumference with radius equal to ten meters, adjusting to the available space.
Reproduction of the sound source in reduced scale

As already mentioned, the sound source discussed in this study consists of six converter transformers. The sound source was monitored as to its directionality having as reference a point located in plant in the geometric center of the six transformers. Was used for the reproduction of noise a point source positioned in the reference point because of the difficulty of reproducing in reduced scale geometric details of the equipment. Furthermore, when characterizing the directionality of a sound source, are monitored the sound pressure levels at points located on a circumference in its surrounding and thus the source is observed as a point source.

There is no commercially available sound box for the noise emission considering the characteristics of directionality of the sound source. Therefore, it was decided to issue the noise in each monitored direction, considering in each one its directionality. Therefore, the noise recorded in the converter substation was equalized for each of the 24 (twenty four) monitoring directions according to the directionality calculated. It was used the software Wavelab®, version 6.1.

Still using the software Wavelab®, it was applied the scaling factor for each noise signal equalized. Considering the reduction scale 1:5, were increased twenty-eight semitones in order to keep the relationship with frequency.

The monitoring of sound pressure level data was made as function of frequency in bands of 1/3 octave from 50Hz to 12.5kHz. After applying the reduction scale 1:5 in the noise signal, these frequencies became equivalent to 250Hz and 62.5 kHz. As the equipment used for measurements on reduced scale model has 12.5kHz as the upper limit in frequency of data capture, the sound source used in the model must respond from 250Hz to 12.5 kHz.

Among the commercially available loudspeakers, it was identified as suitable for the tests the model F6 brand Bravox S/A. This loudspeaker is characterized as full-range and has diffuser for acute. The response curve of the loudspeaker does not change significantly in the frequency range monitored in reduced scale model. As recommended by the manufacturer for a sealed box is required volume of twelve liters.

Construction, testing and validation of reduced scale model

The height of the sound source was calculated from the height of the converter transformers. These are six meters tall and there is no specific point noise generator in their structures. It was established that the loudspeaker of the sound source used should be positioned at a height equivalent to the converter transformers height. In the scale 1:5 the height of a converter transformer is equal to one meter and twenty centimeters, and thus the average height is equal to sixty centimeters.

Using the loudspeaker model F6 brand Bravox S/A, it was built a sound box that satisfied those specifications height of the sound source. The speaker used as a sound source was not amplified, so it was connected to an amplifier and a mixer to make possible the issuance of the noise signal.

In the twenty-four points on the circumference surrounding the sound source the sound pressure levels were monitored as function of frequency in bands of 1/3 octave. For each sound box direction, the noise was emitted as the equalization performed to such direction and the noise signal was monitored at the point on the circumference to which the sound source was directed. At each point three measurements were made. It was also made the monitoring of background noise.

It was found that between 250 Hz and 2.5kHz background noise is at least 10dB lower than the noise analysis. From the frequency 2.5 kHz there is influence of background noise in the monitored data.

Using the sound pressure level data monitored as function of frequency, was calculated the directionality of the tested sound source on a reduced scale. To make the comparison of directionality calculated for the reduced scale model with directionality obtained for the actual situation, were constructed graphs in polar coordinates, overlapping the two directionality.

Are shown in Figure 3 the polar graphs illustrating the directionality of the source for frequencies in bands of 1/3 octave between 250Hz and 630Hz. The blue curves represent the results of reduced scale model, and curves in red, data about the real situation.
Analyzing Figure 3 it is observed that for frequencies in the bands of 1/3 octave between 250Hz and 630Hz cannot be established correlation between the actual sound source directivity and the directivity of the sound source used in the reduced model. The background noise does not cause interference for measurements at these frequencies. It is believed that the non validation of the directionality in these frequencies is due to the fact that these are frequencies with long wavelengths, which makes it harder to reproduce in reduced scale model, the directionality of the real situation. Furthermore, it is known that in the actual situation there may be points of cancellation or amplification of sound pressure level due to interference from various existent noise sources. In reduced scale model was used only one source, which excludes the possibility of sound canceling or amplification due to interference from other sound sources that were in the immediate surroundings of the test area. This phenomenon should be studied in greater detail so that it can be considered in the process of validating the results.

Are presented in Figure 4 polar graphs illustrating the directionality of the source for frequencies in bands of 1/3 octave between 800Hz and 4kHz. The blue curves represent the results of reduced scale model, and curves in red, data about the real situation.
In Figure 4, it is noted that for frequencies in bands of 1/3 octave between 800Hz and 4kHz were similarities in respect of the directionality obtained for the real situation and the reduced scale model.

Are shown in Figure 5 polar graphs illustrating the directionality of the source for frequencies in bands of 1/3 octave between 5 kHz and 12.5 kHz. The blue curves represent the results of reduced scale model, and curves in red, data about the real situation.

FIGURE 5. Directionality of the sound source – 5kHz, 6.3kHz, 8kHz, 10kHz, 12,5kHz (part 1).
FIGURE 5. Directionality of the sound source – 5kHz, 6.3kHz, 8kHz, 10kHz, 12.5kHz (part 2).

It is verified, by graphs of Figure 5, which from 5kHz there is no relationship between the directionalities, which may be explained by the interference of background noise, which for frequencies greater than 5kHz, has sound level that competes with sound level of noise generated. It is concluded that, for best results in the reproduction of directionality in reduced scale, one should perform the tests using the sound source with greater power, so that can be measured in the receiver, sound pressure levels that do not suffer masking due to the presence of background noise.

Final Remarks

The sound source characterization was performed by measuring the sound pressure level in situ, in order to characterize the directionality of the sound source. At this stage, when calculating the directionality of the source as a function of frequency in bands of 1/3 octave, it was noticed that the directionality characteristic is quite pronounced in some frequency bands. Moreover, the measured sound pressure levels remitted to the fact that the equipment in the converter substation, in particular converter transformers generate more intense noise at low frequencies.

The reproduction of the sound source in reduced scale involved the use of the software Wavelab® to work up the sound signal recorded in situ with respect to its directionality. This signal was reproduced in reduced scale model. Since there is no commercially available sound source capable of emitting noise with directional characteristics varied as a function of frequency, the reproduction of noise was made separately in each direction of interest used to characterize directionality, which was possible due to the creation of electronic filters with software Wavelab®.

Regarding the validation of directionality reproduced in reduced scale model, it was found that may occur influence of background noise, and the cancellation or amplification of sound signal due to simplifications adopted to construct the model. Among these simplifications stands out the fact that have been used a single sound source in the model to reproduce the effect of all sources influential on the actual situation. However, in general, it was noticed that there is reproduction of directionality characteristics with the method used to reproduce the sound source on a reduced scale.

REFERENCES