Noise reduction of a portable gas generator set using an acoustic enclosure

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Abstract: The present experimental study has been conducted to evaluate the effect of different developed acoustic enclosures on the noise emission of a small generator set fuelled by natural gas. The sound signals of generator without enclosure and covered by developed enclosures were measured in front of the generator exhaust at five electric loading conditions (0%, 25%, 50%, 75% and 100% load). The sound signal was measured according to SAE J1074 test procedure. The recorded digital sound signals were converted to frequency domain using Fast Fourier Transform (FFT) algorithm. The results revealed that the simple enclosure (SE) and modified enclosures were effective to attenuate the generator noise at frequencies greater than 800 Hz and 250 Hz, respectively. The acoustic performance in attenuating the generator noise for the semi-covered modified enclosure (SME) and fully covered modified enclosure (FME) was better than for the SE enclosure. The acoustic performance of all enclosures was reduced with increasing the generator load especially at full load condition. The results of analysis of variance (ANOVA) showed that the generator loading condition, the enclosure setup mode and their interaction had a significant effect ($P<0.01$) on the generator A-weighted overall sound. The results of Duncan's multiple range tests showed that covering the generator with different types of enclosures reduced significantly ($P<0.01$) the generator sound level (93.2 dB(A)) to 88.4 dB(A) for SE, 87.2 dB(A) for SME and 86.1 dB(A) for FME. They also revealed that the generator sound increased significantly ($P<0.01$) with increasing the generator electric load.

Keywords: acoustic, enclosure, generator set, natural gas, noise emission

Citation: Ghorbani, Z., S. R. Hassan-Beygi, and B. Ghobadian. 2016. Noise reduction of a portable gas generator set using an acoustic enclosure. Agricultural Engineering International: CIGR Journal, 18(3):159-170.

1 Introduction

Portable engine driven generators are used as main electric power supplying in shops, greenhouses, offices and homes in cities, especially when there is a break in power supply. They are also used for electricity supply of buildings in some rural areas with electric outage problems. However, their noise is loud and can cause inconvenience to nearby people. Exposure to high noise levels can also cause temporary or permanent hearing loss, mental and nervous discomforts, loss of working efficiency and increased the risk of hazards (Crocker, 2007).

Some international organizations have developed regulations in order to restrict human noise exposure duration due to the threats of noise. The National Institute for Occupational Safety and Health (NIOSH) and International Organization for Standardization (ISO) define exposure to a 85 dB (A) noise level for 8 h/day or exposure to 88 dB (A) noise level for 4 h/day as one noise dose (NIOSH, 1998; ISO-1999, 2013). European directive established the minimal security level at the equivalent noise exposure limit to 80 dB (A) for an 8 h working day (DIRECTIVE 2003/10/EC). Humans may be exposed to more than one noise dose per day. Therefore, some developed countries are conducting noise reduction and control programs in order to reduce noise levels to 75 dB (A) (Hassan-Beygi et al., 2009).

Noise can be controlled by modifying the acoustic transmission path between the source of noise and receiver. Acoustic enclosure is one of the effective means to control the transmission path of sound. It can limit the power of outward sound of noise source using

Received date: 2016-02-20 **Accepted date:** 2016-06-20

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absorbers and dampers. Cobo et al. (1998) used passive control to reduce a generator noise within a rectangular steel box, which was lined with absorbing materials. Lai et al. (1999) and Be'cot and Sgard (2006) investigated the use of classical passive absorbing materials and poro-elastic and meso-heterogeneous porous materials for sound control in enclosures, respectively. The acoustical performance of an enclosure was evaluated with the amount of trapped noise radiated by the sound source. The enclosure walls should be thick in order to absorb the sound signal with low frequency (high wavelength).

The design of an enclosure could be evaluated from acoustic and thermal point of views (Ju et al., 2004). The transmission paths from the source to the receiver should be determined and ordered in relative importance in order to design an acoustic enclosure for a noise source. The enclosure wall is one of the most important transmission paths. It may also have permanent openings for ventilation, inspection, passing materials and could include a door in order to access to noise source. The enclosure door must close against rubber seals (being airtight).

Literature survey revealed that there is limited information concerning passive noise control of portable generator sets driven by small natural gas spark ignition engines using acoustic enclosures. Therefore, the aim of this study was to reduce the noise of a small power generator set driven by a small spark ignition engine fuelled by natural gas at different electric loads using an acoustic enclosure.

2 Materials and methods

2.1 Generator

The portable generator used in this study was equipped with a single cylinder, four-stroke, spark ignition, air-cooled engine fuelled by natural gas. Its important specifications are given in Table 1. The muffler on the generator installed by the manufacturer was reactive type (large diameter was 202 mm, small diameter was 118 mm, length was 230 mm, inlet and outlet pipe diameters were 22 mm and 28 mm, respectively) (Figure 1).

Table 1 Generator set specifications

Generator	Description
Manufacture	Green power CO.
Number of cylinder	One
Voltage and Frequency	220/390 V & 50 Hz
Bore × stroke	64 mm × 88 mm
Displacement volume	389 cm^3
Running power	3.2 kW
Engine rotation speed	3600 r/min

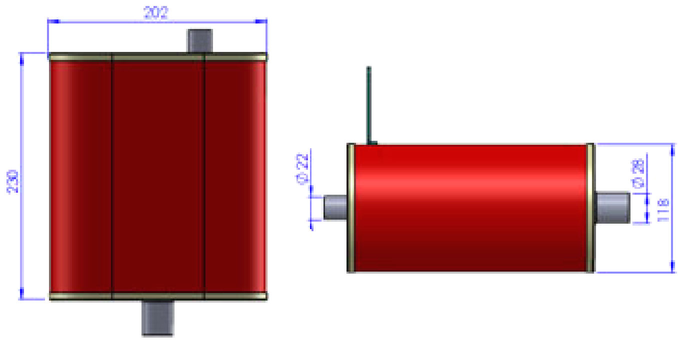
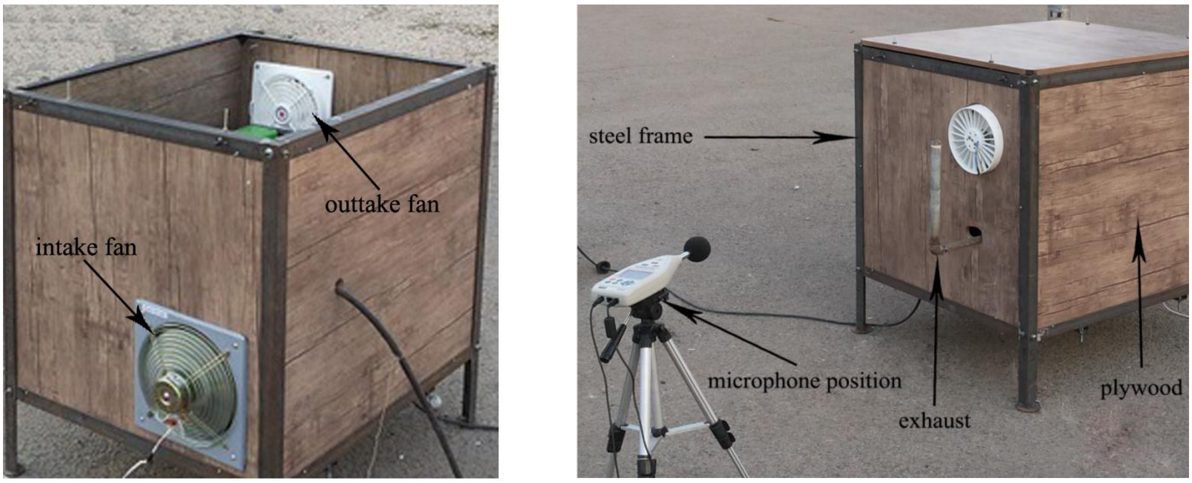


Figure 1 The generator engine reactive muffler dimensions, mm

2.2 Enclosures

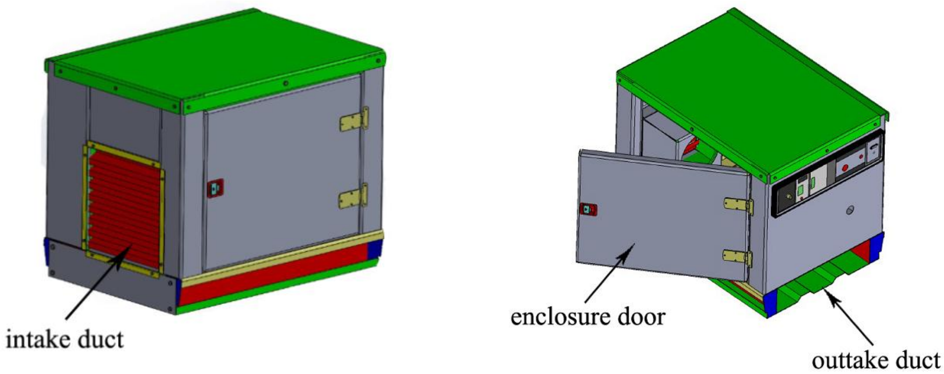
A simple enclosure, SE, was developed using 20 mm thickness plywood with dimensions of 1000×950×800 mm^3, which was installed on a steel frame (Figure 2). Its weight was 700 N. A silent centrifugal fan (300 mm diameter, 1400 r/min, with the air capacity of 860 m^3/h and 60 dB noise) was installed next to the engine intake duct in order to provide enough flow of air for cooling and combustion. Many holes with 8 mm diameter were drilled with uniform distribution on the bottom plate of the enclosure in order to discharge air from the enclosure. Another silent fan (200 mm diameter, 1800 r/min, 270 m^3/h air capacity and 57 dB noise) was installed next to the engine exhaust to improve the depletion of air from the enclosure. An air gap layer with about 250 mm thickness was provided between the enclosure walls and the generator.



(a) (b)

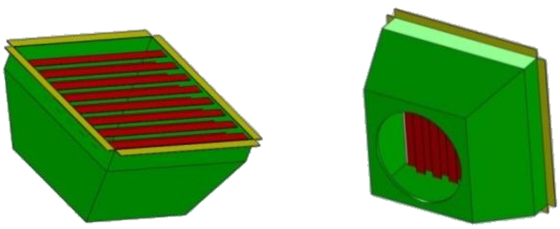
Figure 2 The developed simple enclosure (a) without upper panel and (b) complete

The developed simple enclosure was heavy and its transportation was difficult. Therefore, another enclosure was fabricated using 2 mm thickness steel plate (St 37 steel). The inner walls of the enclosure were lined with absorbing materials, elastomeric foam (kaiflex, Kiamann group) with 50 mm thickness and absorption coefficient of 0.45, in order to control noise emission of the generator. The dimensions of enclosure were 930×670×750 mm^3 and its weight was 400 N (Figure 3). The developed lighter steel enclosure was called modified enclosure. A silent centrifugal fan (200 mm diameter, 3000 r/min speed, air supply of 900 m^3/h and 52 dB noise) was used for sufficient supply of cooling air. The fan was installed in an intake duct (Figure 4). An air gap layer was provided between generator surfaces and enclosure walls. The gap thickness was about 300 mm in height and 150 mm in other sides. The intake duct concentrated air flow on the generator for having greater temperature reduction. The heated air was discharged from outtake duct, which was placed at the bottom of the enclosure.



(a) (b)

Figure 3 The developed modified enclosure (a) closed door (fully covered modified enclosure, FME) and (b) open door (semi covered modified enclosure, SME)



(a) (b)

Figure 4 The developed intake duct (a) front view and (b) rear view

2.3 Acoustic performance of enclosures

The acoustic performances of enclosures were evaluated as the difference between the sound pressure levels in the exhaust side of the generator set with and without enclosures. The acoustic performances of simple enclosure (SE), modified enclosure in closed door mode (fully covered modified enclosure, FME) and in open door mode (semi covered modified enclosure, SME) were evaluated. In fact, the sound pressure levels of generator in SE, SME and FME modes were compared with the sound pressure levels of generator without enclosure, WE mode.

2.4 Instrumentation and signal processing

The instruments used for sound signal measurement consisted of a HT 157 sound level meter along with its microphone, a HP Pavilion lap-top computer, a Testo anemometer and a Lutron digital thermometer. The specifications of the instruments are given in Table 2. Cool Edit Pro software was installed on the computer to acquire and store sound pressure signals. The output analogue voltage of sound level meter was connected to the computer sound card through a shield cable and connector. According to Nyquist criteria, in order to correct conversion of analogue signals to digital ones, data sampling rate must be at least twice as of the maximum frequency (Oppenheim et al., 1989). Since the human audible frequency range is 20 to 20,000 Hz, 48,000 Hz sampling rate was used. The digital time domain sound signals of generator were stored with 16-bit resolution and wave format (.wav) on lap-top hard disk. The duration of measurements for each test run was 12 s. Three windows with about 2 s duration of the nearly uniform digital sound signal were selected using the rectangular window function. There was no overlap between consecutive windows.

Table 2 Specifications of the used instruments

Name of the instrument	Resolution	Range/Capacity	Sensitivity	Model
Sound level meter	0.1 dB	24-140 dB	-	HT 157-class 1-Italy
Prepolarized condenser microphone		10 Hz-20 kHz	50 mV Pa^{-1}	
Hot wire anemometer	0.1 m/s	0.9-35 m/s	-	Testo Germany
Digital thermometer	0.1 ℃	-10 to 50 ℃	-	Lutron AM-4220

The sound level meter was calibrated with its portable calibrator (HT 151 with 94 dB, equal to 1 Pascal, and 1 kHz ± 1% operating frequency) before and after sound measurements. The results of calibration were in the permissible range of sound level meter. The recorded time domain sound signals were converted to frequency domain signals through a developed Fast Fourier Transform (FFT) algorithm using MATLAB software with resolution of 0.36 Hz. The narrow band frequency domain sound signals were obtained using this program. The frequency domain sound signals were converted to dB scale using Equation 1. The narrow band frequency domain sound signals were further processed to obtain 1/3rd octave frequency band. The 1/3rd octave frequency domain sound signals were A-weighted and overall A-weighted sound level calculated with Equation 2 using a developed computer sub-routine program (Raichel, 2006):

$$L_p = 20\log(\frac{P}{P_0})$$

$$L_A = 10\log(\sum_{i=1}^{n} 10^{\frac{L_{pi}}{10}})$$

where, L_p is sound pressure level, dB; P is root mean square sound pressure, Pa; P_0 is reference pressure, 20×10^{-6} Pa; L_A is overall A-weighted sound level, dB(A); and Lp_i is sound pressure level at band-center frequency of 1/3rd octave frequency bands, dB(A).

2.5 Measurements

The sound measurement site was prepared and managed according to SAE J1074 sound measurement standard. It was a flat open space, free from obstacles and effects of signboards, buildings and hillsides for at least 15 m from the center line of generator (Figure 5).

The wind speed was lower than 4.4 m/s, which met the standard requirements. The background noise of the test site was in the range of 62.5-65 dB. The microphone was located horizontally at height of the generator engine exhaust tail and 1 m away from the center line of generator and pointed perpendicular to the center line of the generator. The initial sound measurement showed that the generator sound had the maximum value in the exhaust side. Therefore, the sound of generator was only measured at this position.

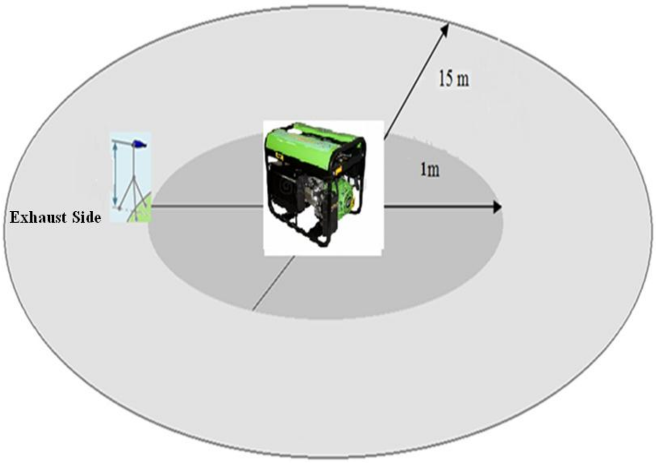


Figure 5 The schematic diagram of the sound measurement test site

The selected variables in this study were five levels of generator electric load (0%, 25%, 50%, 75% and 100%) and four types of enclosure setup (without enclosure (WE), simple enclosure (SE), semi covered modified enclosure (SME) and fully covered modified enclosure (FME).

In order to apply electric load on the generator, a resistor bank with maximum power of 5000 W was developed using nine 500 W electric heater elements, two 200 W and one 100 W Cooper Lighting Halogens (Figure 6). An electric switch was considered for each element to control the generator electric load in the desirable level.

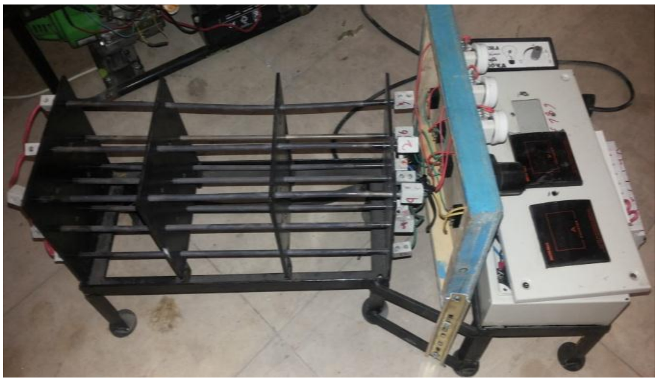
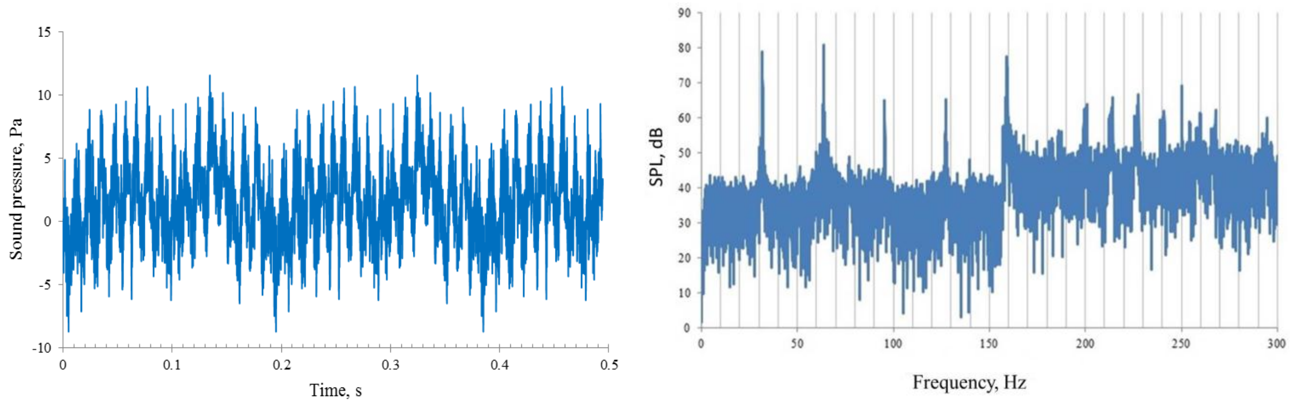


Figure 6 The developed resistor bank

The effects of generator electric load and type of enclosure parameters, independent variables, on the overall A-weighted sound emitted from generator, dependent variable, were analyzed using the two factors completely randomized design. Further, the Duncan's multiple range test was used to compare the mean values of generator noise. Common letters were used when no significant difference at 1% probability level ($P>0.01$) was found between the mean values. All the experiments were replicated three times and mean values were reported.

3 Results and discussion

The sound pressure signal in time domain and the respective narrow band frequency domain signal for the generator equipped with modified enclosure at full load in front of the engine exhaust are shown in Figure 7. It can be seen from the time domain part of this figure that the sound pressure varied in the range of -9.5 to 12 Pa and the sound peak was replicated every 33 ms.



(a) (b)

Figure 7 The sound signal for fully covered generator by modified enclosure in front of the generator exhaust at full load condition: (a) The time history and (b) Narrow band frequency domain signal

In other words, the needed time for completing one combustion cycle is about 33 ms. However, time domain signal did not show enough useful information about the required noise pollution concept. The narrow band frequency domain signal represented more useful information through depicting the noise intensity and frequency (Figure 7b). However, its un-smoothed nature made data comparison for different conditions so difficult especially at high frequency. Since 1/3rd of octave frequency band had smoother curve, it was selected for further processing.

Figure 8 shows the generator sound pressure level on 1/3rd octave frequency domain measured in front of the exhaust at different generator loading conditions for generator without enclosure (WE), covered with simple enclosure (SE), semi covered with modified enclosure (SME) and fully covered with modified enclosure (FME).

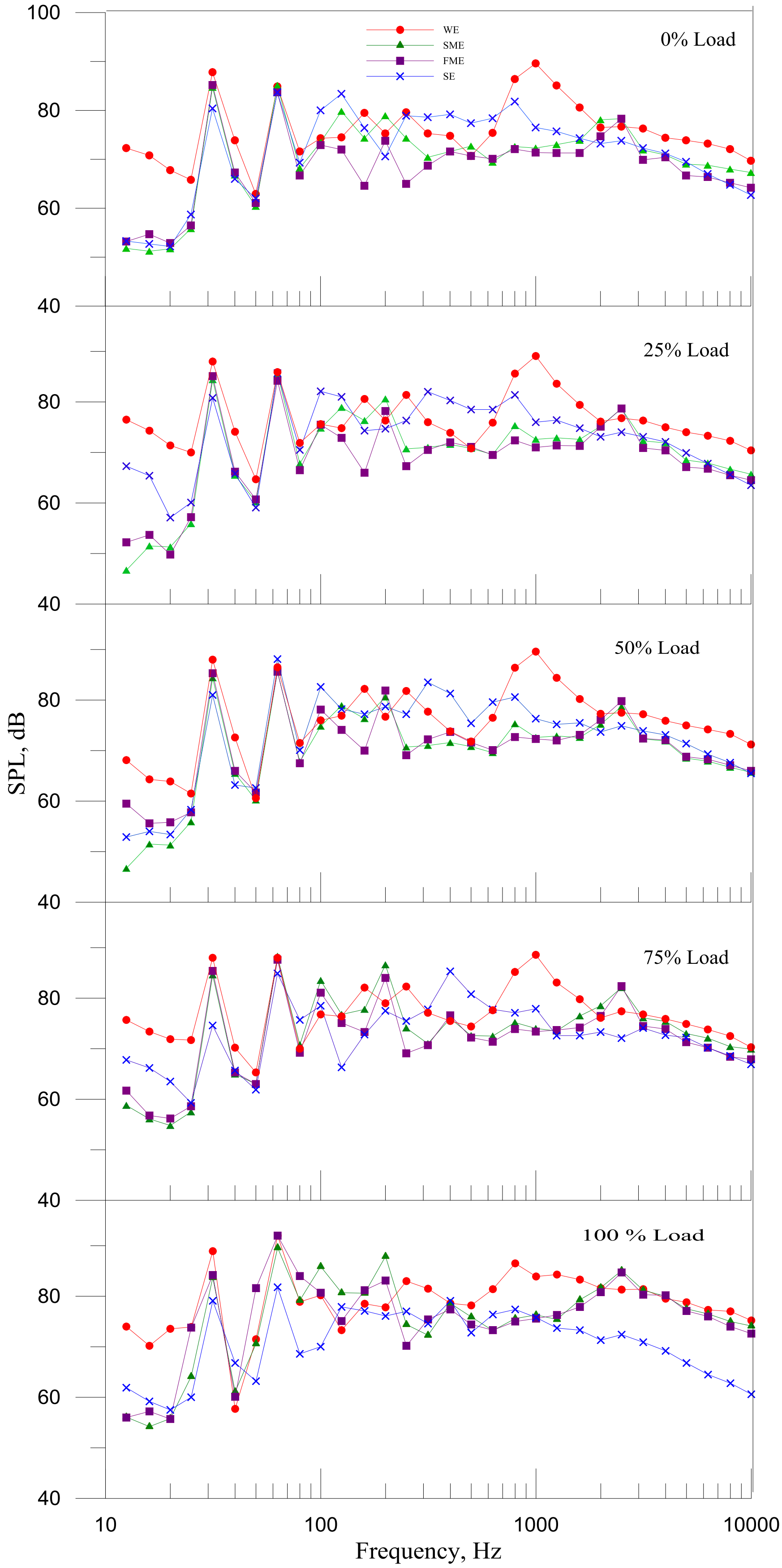


Figure 8 The 1/3rd octave sound pressure levels (SPL) of the generator for different conditions at (a) no load, (b) 25% load, (c) 50% load, (d) 75% load, and (e) full load

For WE mode, there were some peaks at 31.5, 63, 160, 250 and 1000 Hz frequencies at different loading conditions. The first peak was related to firing frequency of the engine (31.5 Hz). The second peak was observed at frequency of 63 Hz. Since the engine cylinder has two valves, the noise source at 63 Hz could be the strike for exhaust and intake valves and so it is exactly twice the firing frequency. As the engine is four-stroke, there are two piston blows in one combustion cycle, which could be another noise source. Mechanical components noise could originate from valve trains, timing drives, bearings and inertia forces causing piston slap (impact of piston on the cylinder wall, most notably when moving from top dead center to bottom dead center during expansion) (Giakoumis et al., 2011). The other peaks after the second one may be attributed to the harmonics of firing and mechanical components frequencies.

The 1/3rd octave frequency band of sound pressure level at different loading conditions revealed that the sound pressure level in SE mode compared with WE mode had greater values at the frequency ranges of 100-125 Hz and 315-630 Hz at loading conditions of 0% to 50%. With the increase in electric load to 75% and 100%, generator sound level increased at 400-630 Hz. The sound level increment in SE mode could be attributed to the fact that the inner walls of this enclosure were not lined with any absorbing material and collision of sound waves within this enclosure created reflected waves. However, by using this enclosure, the sound of generator was reduced in frequencies greater than 800 Hz. SE mode could reduce the sound pressure level of the generator in firing frequency at all loading conditions comparing to WE mode. However, at 63 Hz, this enclosure just was effective at higher engine loadings. For example, about 10 dB decrease in sound pressure level was found at 100% loading condition (Figure 8e).

The sound pressure level on 1/3rd octave frequency bands also showed that in SME mode, the sound level was decreased in the majority of the frequency bands in comparison with WE mode, and even SE mode. The noise attenuation of SME better than SE might be attributed to the use of steel walls lined with absorbing materials instead of wooden ones. However, at a few frequencies, the sound pressure level increased in SME mode. At loading conditions of 0% to 50%, the greater generator sound level was observed at 125, 200 and 2500 Hz. With further increase in electric load to 75% the greater sound level was observed at 100, 200, 2000 and 2500 Hz. At full load condition, the increase in sound level was observed at 100-200 Hz and frequencies greater than 2000 Hz. The greater sound level could be attributed to constructive interference of the reflected waves within the enclosure and unsuitable attenuation of these waves by absorbing materials. At full load condition, the resonance phenomenon of enclosure walls may be reason of the increase in sound at frequencies higher than 2000 Hz.

When generator operated in FME mode, the sound pressure level on 1/3rd octave frequency band was reduced in the majority of the frequency bands in comparison with WE mode and even with SE mode at all loading conditions except full load. At full load condition, the increase in sound level was observed at 80-200 Hz and at frequencies greater than 2000 Hz. Such increase could be attributed to the resonance and vibration of enclosure walls. The greater sound attenuation of FME than SE might be related to use of steel walls lined with absorbing materials instead of wooden walls. Comparing the 1/3rd octave frequency spectra of sound signals for FME and SME modes at different loading conditions revealed that the sound pressure levels for FME mode at some frequencies were smaller than SME mode. It could be related to more absorption of sound energy by absorbing material, which covered the generator set completely in FME mode.

In general, it can be seen from Figure 8 that using SE was effective in sound attenuation at frequencies greater than 800 Hz at different loading conditions. The SME and FME usage were effective in sound attenuation at frequencies greater than 250 Hz and at all loading conditions except full load. This is in agreement with other relevant studies, which used acoustic enclosures to reduce the noise emitted (Fuller et al., 2012; Cuesta and Cobo, 2001).

As depicted in different parts of Figure 8, the greatest sound pressure level was observed for WE mode. The sound pressure level of generator in WE mode was ranged in 57-92 dB at different loading conditions. For generator covered with SE, the maximum sound pressure level (88 dB) was observed in 63 Hz at 50% load. The sound pressure level in SME and FME modes ranged in 46.7-89.6 dB and in 49.8-92 dB, respectively.

Figure 9 shows the overall A-weighted generator sound versus its load for different enclosure setups. As depicted from this figure, the overall generator sound level increased when generator load increased. The trends were well explained by second order polynomials with high coefficient of determination. This is in accordance with Tandon et al. (1998) and Ghorbani et al. (2016) for portable generator set and with Priede (1975), Ghobadian (1994) and Seifi et al. (2016) for diesel engine. The overall generator sound in WE, SE, SME and FME modes ranged 91.5-93.5 dB(A), 86.4-91 dB(A), 85-91 dB(A) and 84-91 dB(A), respectively.

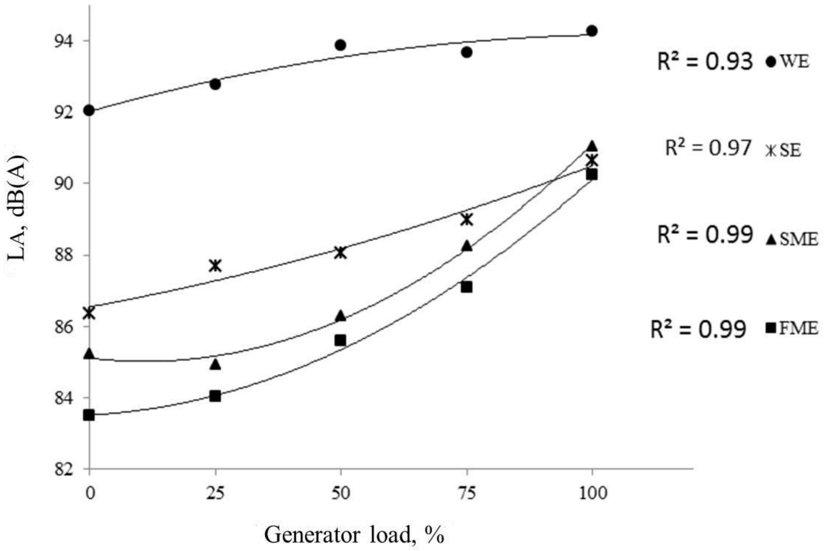


Figure 9 The overall generator sound for different setups at varying generator loading conditions

The acoustic performances of the different enclosures setups versus the generator loading conditions are shown in Figure 10. As illustrated in this Figure, covering the generator in the modified enclosure showed better acoustic performance than the simple enclosure. The best performance at all loading conditions was observed for FME mode. The acoustic performance of all the enclosure setups was reduced with increasing the generator load especially at full load condition. Furthermore, with increasing the generator load, the differences among the acoustic performances of SE with SME and FME modes were decreased and, at full load condition, no considerable difference was found. These trends could be verified by the results of generator sound in 1/3rd octave frequency band. The reduction of acoustic performance for the modified enclosure could be attributed to the vibrations of enclosure body, which showed unsuitable attenuation performance at some frequencies (as depicted in Figure 8e). The ranges of acoustic performance in SE, SME and FME modes are 7.37-3.04 dB(A), 8.04-2.68 dB(A) and 9.86-3.35 dB(A), respectively.

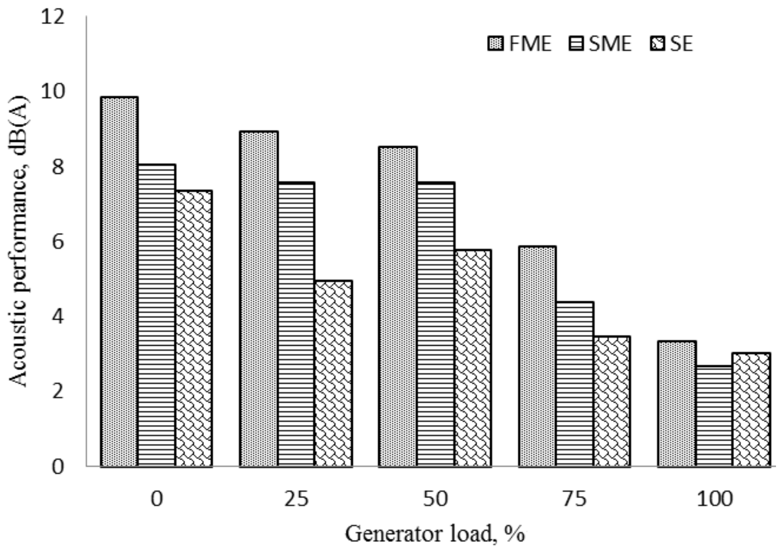


Figure 10 The acoustic performance of different enclosures at different generator loading conditions

Tandon et al. (1998) reported the sound pressure level reduction (maximum 8.5 dB(A)) by using an enclosure for a portable generator set driven by gasoline internal combustion engine. The results of the analysis of variance (ANOVA) on the A-weighted overall sound pressure levels are given in Table 4. As given in this Table, the generator loading condition, enclosure setup mode and their interaction had a significant effect ($P<0.01$) on the A-weighted generator overall sound. The results of Duncan's multiple range tests to compare mean values of the generator overall sound versus different enclosure modes and generator loading conditions are shown in Figure 11 and Figure 12, respectively. Each of these sound pressure levels in Figure 11 is the mean of overall A-weighted values at five loading conditions (0%-25%-50%-75%-100%) with three replications (the mean values of 15 data) and in Figure 12 it is the mean of overall A-weighted values at four enclosure modes (WE, SE, SME, FME) with three replications (the mean values of 12 data).

Table 4 Analysis of variance of effective parameters on the A-weighted overall sound level of generator

Source of variations	DF	Mean square
Enclosure setup mode	3	146.25**
Loading condition	4	42.38**
Enclosure setup mode ×Loading condition	12	3.08**

Note: **stands for significant at 1% probability levels

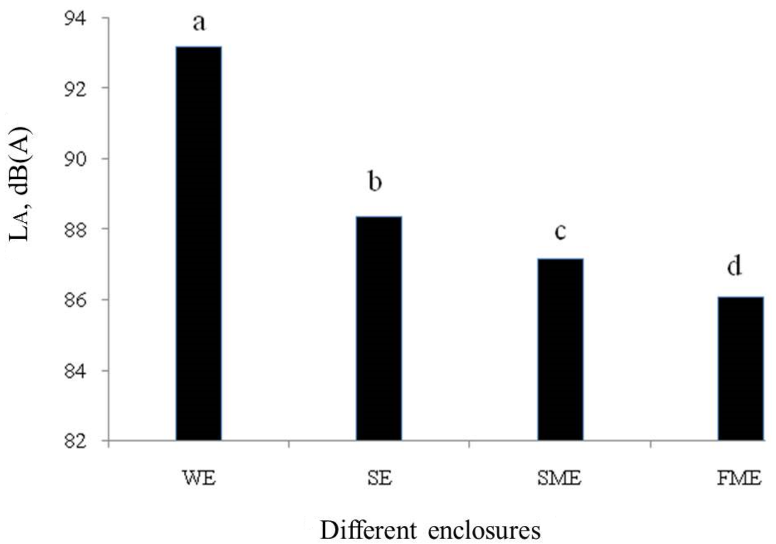


Figure 11 The effect of different enclosure setups on the A-weighted generator sound

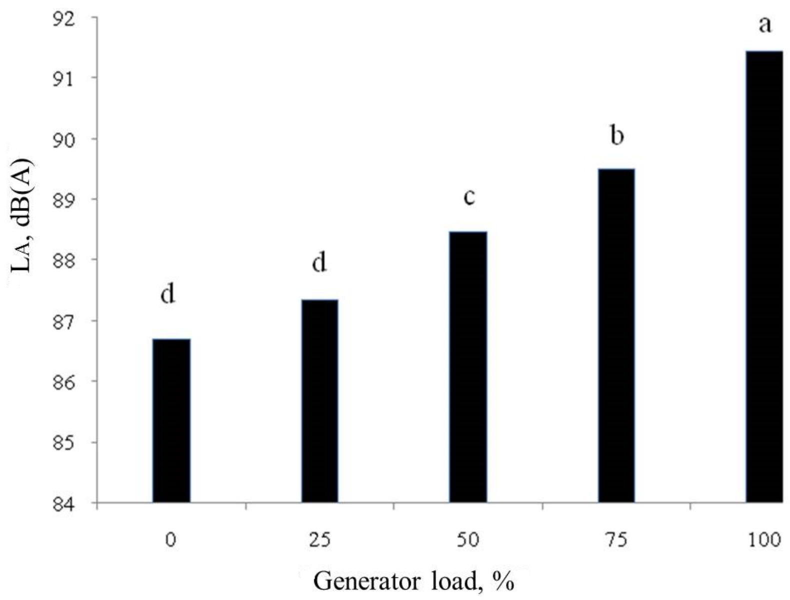


Figure 12 The effect of generator loading conditions on its A-weighted sound

As illustrated in Figure 11, the overall generator sound in WE mode reaches up to 93.2 dB(A) and was significantly ($P<0.01$) greater than other modes. Covering the generator with different types of enclosures reduced significantly the sound level to 88.4 dB(A) for SE, 87.2 dB(A) for SME and 86.1 dB(A) for FME mode.

It can be seen from Figure 12 that the mean values of overall generator sound increased significantly ($P<0.01$) when the generator load increased. The maximum and minimum generator sounds were found for its operation at 100% load and no-load conditions, respectively. However, there was no significant difference between the mean values of sound at no-load and 25% load conditions.

4 Conclusions

Important findings of this experimental endeavor are summarized as follows:

(1) The simple enclosure usage was effective at frequencies greater than 800 Hz at all loading conditions.

(2) The usage of modified enclosure was effective to attenuate the generator noise in the majority of the frequency bands greater than 250 Hz.

(3) The effects of enclosure type and generator load parameters were significant ($P<0.01$) on the overall A-weighted generator sound.

(4) The overall generator sound increased significantly ($P<0.01$) when increasing the generator electric load.

(5) The generator noise emission without enclosure was 93.2 dB (A). Covering the generator by SE, SME and FME reduced significantly ($P<0.01$) the overall A-weighted generator sound to 88.4 dB (A), 87.2 dB (A) and 86.1 dB (A), respectively.

(6) The maximum acoustic performance of enclosures was observed for FME at all loading conditions.

(7) At full load condition, the acoustic performance of SE is comparable with SME and FME modes, which could be related to the vibrations of the modified enclosure body.

Acknowledgements

The authors would like to express their appreciation to University of Tehran and Renewable Energy Research Institute authorities for their full support.

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