Acoustic Characterization of Retrofit Vertical Duct Soundproof Enclosure for Portable Mini-Generators

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Abstract

Environmental noise pollution from electric power generators has become seemingly intractable in most developing countries due to the epileptic power supply. Families as well as corporate organizations now rely on these standby generators for their daily electricity needs. The concern of this paper was the characterization of the developed vertical duct soundproof acoustic enclosure on mitigating the noise produced by portable mini generators. A total of six acoustic parallelepiped boxes were produced using chopped strand E-glass fiber mat reinforced composite panels with polyurethane foam inner lining. The generator noise spectra with and without the enclosure were obtained for comparative analysis. The sound pressure level of the generator noise at each enclosure height was also measured. It was found out that the noise level reduced by 12.8 dBA when the sound pressure levels at both conditions were taken and compared at optimal enclosure height (1600 mm). The result from exhaust ducting showed that exhaust duct projection, channeling out the fumes, did not significantly impact the enclosure insertion loss. The enclosure and the generator were also found to be in stable, acceptable thermal conditions while operating at rated load with a maximum temperature of 39 °C measured inside the enclosure. This eliminates the need for artificial cooling and its consequent power drain.

Keywords: vertical duct, acoustic enclosure, portable mini-generator noise, passive control, polymer composite

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1. Introduction

An unwanted sound or a sound out of place can be described as noise. Hence, noise is a form of sound that has attributes. Noise is the result of pressure variations or oscillations in air generated by a vibrating surface or turbulent fluid flow. There are numerous sources of noise including generators. The response of the human ear to sound or noise depends both on the sound frequency and pressure level. The human ear can perceive the noise frequencies within the range of 15 Hz and 20,000 Hz (Hansen, 2001). Generator noise contains frequencies that fall within this range, which caused numerous problems and altercations within homes and neighborhoods.

The boost in social development engendered by globalization, urbanization, population growth, and competitive lifestyle put enormous pressure on many government-provided social and economic infrastructures in many developing countries. The sustenance of social development outburst comes with the need for adequate electric power supply among others. Unfortunately, the public power supply capacity does not always match the ever-increasing demand for electricity. Due to the loss in power supply, individuals, organizations and some service providers utilize portable generators in powering their homes, offices and establishments. There are also mini generators that are commonly used in small offices, shops, barbering salons and market stalls for similar purposes.

Though these generators play a key role in the life of the people from developing countries, they cause enormous noise pollution in the environment and hazard to both the user and the occupants of the immediate neighborhood. The petrol-fueled mini generator produces both noise and lethal carbon monoxide emission claiming many lives. The sound pressure level of these generator sets is usually above 80 dBA and often found in clusters, causing huge environmental noise pollution. The environmental noise source contribution from generator is between 10.3 to 23.5% in Nigeria – second to the moving vehicle noise (Oloruntoba *et al.*, 2012). Noise, coming from different sources, has emerged as the leading environmental nuisance that engenders public complaints according World Health Organization (WHO) European Region (WHO, 2018). Noise is also one of the major causes of speech communication distortions and masking. Noises within the same frequency as the communication sound frequency will produce acoustic masking on the message signal. This is most pronounced if the difference in the sound pressure levels is below 10 dB resulting in loss of speech intelligibility. In the event of exposure to noises range from 78-80 dB, the acoustic threshold is increased causing temporal hard of hearing. Noise has contributed to the cause of some physiological disorders and psychological traumas including stresses, irritations, discomforts, metabolic disorders, irrational behaviors, work accidents and reduced worker output (International Labour Organization [ILO], 1979). In extreme cases, noise can cause depression and deafness.

The perceptibility of sound is always dependent on the signal to noise ratio (Operation Noise Manual, 2005). Unfortunately, the background noise caused by portable mini generators during the day and night in many residential areas, schools, hospital, and other establishments has gone out of proportion; hence, the demand to be investigated. The human ears are particularly sensitive to sound frequencies range from 1000 to 4000 Hz, and are less sensitive outside this range (Bloxsom, 2013). It is also said that sound most damaging to the range of hearing necessary to understand speech is between 500 Hz and 2000 Hz. According to WHO (2018) guidelines for community noise, less than 30 dBA is recommended in bedrooms during the night for a good sleep quality and less than 35 dBA in classrooms to allow conducive teaching and learning conditions. The WHO (2018) guidelines for noise at night recommend less than 40 dBA of annual average (L_{night}) outside the bedrooms to prevent adverse health effects, recognizing sleep as a biological necessity; and disturbed sleep is associated with several health consequences. New Jersey Noise Control Council (2017) recommended that owners and operators of standby generators should limit the duration of use and respect night time hours by turning off their standby generators when majority of the people is sleeping between 10:00 PM and 7:00 AM. Using the standby generators intermittently during the day will limit the exposure of neighbors to continuous noise source.

Noise control can either be active or passive. Active control is a recently adapted technique, whereby a secondary sound source such as a loudspeaker is used to interfere destructively with the noise from a transmitting source. It is currently limited to low frequency noises and expensive to install. Passive control is more conventional and cheaper to install. It uses sound-absorbing and attenuating enclosure to reduce the noise to the environment, and utilizes vibration absorbers or damper to mitigate structural transmission. It works well at high frequencies (Krishna and Wegrzyn, 1999; Saif, 2007). Hence, this control is the choice of this paper. Generator noise emanates mainly from the engine, armature shaft bearings, cooling fan and vibrations of mechanical metal attachments. In the case of the portable mini generator, it is most difficult to identify the sources of the noise from a far field. The noise from this type of generator is treated as a point source and considered as a full-scale complete enclosure.

As of this time, attention has been focused on the reduction of noise produced by big diesel engine electricity generators and little has been done for the small generators utilized by the majority. This is understandable as big generators serve large populations with considerable high power output suitable for big organizations and well-off people. Unfortunately, there is a sense of indifference on the part of portable mini generator users to apply any form of enclosure due to its unavailability. Ironically, small generators with high-pitched noise are found in almost every family within the low- and middle-income class in most developing countries (Hammad *et al*., 2013; Okpighe, 2015). Therefore, the majority is at high risk to health hazards. The regulatory agencies, saddled with the responsibilities of checkmating noise pollution, are also not keen at enforcing the noise limit regulations, which could have stimulated public consciousness. It becomes imperative to investigate the acoustic characteristics of the noise produced by this popular set of portable mini generators and study the mitigating measures towards providing a suitable acoustic enclosure.

Noise mitigation can be implemented both at the source and the path between the source and the receiver. Factors influencing the choice of noise control method include acoustical, mechanical, practical and economic considerations (Tandon *et al*., 1998). To avoid noise, people would ordinarily move away from the source, which means increasing the distance between the source and the receiver. The most effective method of noise control is to reduce the noise at source, for instance, by isolating the noise source in separate premises or a sound-proofed enclosure (ILO, 1979). An enclosure, the choice of this paper, is more or less an arranged barrier to house a noise source from a generator. Hence, noise reduction is understood as an effective physical measure for quantifying the capability of acoustical enclosures that attenuate noise. Sound waves lose energy if they pass through a medium that absorbs the wave. The medium converts the wave’s acoustic energy into heat and gets weakened. Thus, the performance of an acoustic enclosure depends on the characteristics of the material construction and configuration. For a single-layered thin plate barriers, the noise insulation characteristics depend on its density, flexural modulus and dimensions, the sound wave incident angle to the plate and the loss factor (Gužas *et al*., 2008). As the barrier height increases or gets nearer to the source or the receiver, the efficiency of the noise attenuation capability also increases. Gries (2004) discussed noise control solutions for standby power generators and recommended that the generator noise level and spectra baseline data should be obtained and dominant noise sources be ascertained. This is to enable adaptation of appropriate control measures for a particular power generator to avoid one-size-fits-all design approach. This would also allow the control solution to be tailored to optimally contain the dominant noise sources and address the significant noise transmission paths.

In less than 25 kW standby generator noise baseline spectrum, the dominant frequencies were found to be present at 250-315 Hz third octaves low frequencies and 1250-2000 Hz third octaves high frequencies caused by engine and exhaust noise, and airflow, fan and alternator noise, respectively. In heavy-duty diesel engine generator sets, Ju *et al*. (2004) noted that the sound pressure level is most pronounced at the frequency level of 500 Hz. Contributions of the two frequency components of 125 and 250 Hz were little. Tandon *et al*. (1998) observed that the sound pressure spectra of the sides of a portable generator set, driven by kerosene engine, with rated alternating current power output of 800 VA and rated frequency of 50 Hz indicated high noise level mainly in the frequency range 265 to 555 Hz. The absorption coefficients of absorbent materials have also been found to be frequency-dependent. The absorption coefficient of glass wool is over 0.9 within the measurement frequency bands of 5-10 kHz, while well-vanished wood material is 0.05 (Liu and Lu, 2010). Bloxsom (2013) noted that low frequency noise is the most difficult to attenuate, which can be best controlled by the use of rigid barriers having substantial mass. High frequency noise can be controlled by the use of acoustic foams and other types of sound-absorbing materials. Used extensively in outdoor enclosures, acoustic insulation sound-absorbing acoustic foam is effective at controlling high frequency noise. In indoor installations, it can reduce noise when used to line air ducts or utilized as a wall or ceiling covering.

In the mini electricity generators, the convection airflow that provides combustion and cooling also propagates the generator noise. If the air is deflected frequently before it exits the enclosure, the energy of the noise can be reduced by good diffusion (Central Power Systems & Services [CPSS], 2013). When the radiated noise of a generator engine and other vibrating attachments are promptly trapped by impervious massive layers of wall material, the trapped sound is destructively absorbed by the inner liner of the porous sound absorber (Rahmad and Ahmad, 2018). The effectiveness of the enclosure is, therefore, largely dependent on its wall thickness and the absorbing layers in which performance is a function of the sound wavelength. Long wavelengths with low frequencies require thicker enclosure wall and vice versa (Cuesta and Cobo, 2001). Karuppiah and Ramiah (2017) observed that most materials that are efficient at sound absorption are soft and fluffy with many air spaces to entrap and weaken sound waves after several reflections. Askhedkar *et al*. (2016) simulated the variation of sound pressure level (SPL) with diesel generator load, mild steel sheet canopy thickness, polyurethane absorber thickness and absorber density, and indicated nonlinear relationships. Akhaze and John (2016) fabricated a soundproof device for 950 W rated portable generator using medium-density fireboard and polyurethane foam absorber. They reported an insertion loss of 8.68 dB at 3.50 m away from the generator. Ghorbani *et al*. (2016) conducted an experimental study on the noise emission and reduction of natural gas-fuelled small generator set using both partial and full enclosure with wood and steel panels at increasing load conditions. Parvathi and Gopalakrishnan (2003) carried out an experimental assessment and control of indoor and near-field noise levels from a portable power generator by employing anti-vibration mounts and various enclosure panel configurations.

There are numerous considerations in enclosure design for noise beyond levels such as airflow, exhaust, site and weather protection requirements and thermal management that contributed to the relative success of various noise control solutions (Gries, 2004). In a survey of noise suppression technologies and a background review of diesel engine noise to meet the requirements of the U.S. army new standard family of medium-sized mobile power systems, the key requirement for noise emission from these generator sets is at a level of 65 dBA across the audible spectrum at 7 m from the box. Also, the suppression technology applied should have minimum impact on engine performance. The construction materials should withstand ambient temperatures between -45 °C to 60 °C at any possible humidity (Krishna and Wegrzyn, 1999). The enclosure should be sufficiently rugged and portable permitting quick setup and minimum maintenance requirement. Hammad *et al*. (2013) presented a study on the selection of appropriate noise suppressant materials suitable for the generator canopy as well as effective heat transfer methodology to ensure stable generator operations. They proposed the use of steel panels and rock wool noise absorbers for the full enclosure model with fan cooling. Kuku *et al*. (2012) reported that full enclosure fabricated from panels made of plywood and a combination of sawdust, ground glass and perforated foam drastically reduced the noise of a 950 W portable home generator. However, they did not discuss the required airflow and heat management. Mushiri *et al*. (2017) also used polyurethane foam, plywood, sawdust, and ground glass to design enclosure walls. They employed copper coil and glycol/water coolant as a heat exchanger for effective heat transfer out of the enclosure.

Noise can also be ducted out or destroyed within a tunnel. Larsen *et al*. (2017) noted that except from air vents and other openings, the acoustic sound produced by the underground train in the tunnel is effectively trapped inside the tunnel. Air-handling ducts that carry noise were also lagged with sound-absorbing insulation and aluminum sheeting to reduce noise. Liu and Lu (2009; 2010) separately studied the attenuation inside long enclosures due to different tunnel branching configurations and reported positive effects on sound level attenuation, early decay and reverberation time. Ju *et al*. (2004) also applied ventilation duct silencers for fresh air intake and outflow of noise and heated air away from the receiver location. The present paper explores the duct mitigation measure to the generator noise by ducting out the combustion and the cooling air carrier of the noise after the interaction with the engine.

2. Methodology

2.1 Design Considerations

Some major design considerations were made during the fabrication of the enclosure. These include noise reduction system that can duct away the noise and materials that can absorb sound energy effectively. Materials sound absorption properties were obtained from secondary sources (Table 1) that were used in the fabrication of the acoustic enclosure.

Table 1. Sound absorption coefficient of some popularly used materials (Department of Occupational Safety and Health, 2005)

	Frequency (Hz)					
	125	250	500	1000	2000	4000
Polyurethane foam (2”)	0.35	0.51	0.82	0.98	0.97	0.95
Rock wool	0.54	0.74	0.93	0.95	0.95	0.95
Oil palm fiber	0.20	0.30	0.61	0.91	0.81	0.96
Coconut coir fiber	0.19	0.21	0.44	0.64	0.74	0.76
Hard backed fibrous glass (2”)	0.20	0.55	0.89	0.97	0.83	0.79
Wood	0.15	0.11	0.10	0.07	0.06	0.07

The lightweight of the enclosure was considered necessary as the structure was expected to be a makeshift that can be easily dismantled, assembled, and relocated. High strength to weight ratio also informed the choice of paneling material. Heat control, exhaust emission removal, and the space up and around the generator inside the enclosure were enough to allow the free flow of air by natural convection. A secondary duct was also provided for the removal of exhaust emission. The location of the duct was positioned in such a way that the exhaust pipe opening was centrally close to the duct. This was to enable the forced exhaust emission to push through the secondary duct out of the enclosure without contaminating the fresh air intake of the engine that would have otherwise lowered the efficiency of the engine combustion. Knowing that the class of generators involved are low power supplies, natural convection was considered to avoid extracting the power from the generator to drive artificial cooling forced convection accessories. The overall dimension of the generator was considered by providing a suitable cross-sectional dimension of the acoustic enclosure. Because the SPL of generator noise is more in the low frequency region and to avoid acoustic resonances caused by standing waves between the enclosure panel and the generator, the space in-between was just enough to enable free convection and easy removal of the generator from the enclosure. A straight vertical duct was used for the enclosure to avoid heat pockets and noise reverberations from the corners. The standing wave frequency (Equation 1) is given by (Tandon *et al*., 1998).

$$f = \frac{c}{2d} \tag{1}$$

where:

c = speed of sound (ms^{-1})
= $20.05\sqrt{T}$
T = temperature (313 K)
d = distance between source (generator) and panel

An average distance of 0.13 m between the generator and the panel gave 1364 Hz, which is within high frequency region of the generator noise. Thus, an inner lining of polyurethane foam was adopted to destroy the standing wave through absorption, reduction of the noise amplitude and raising the wave frequency.

2.2 Materials

E-glass fiber mat, polyester resin and curing agents, and laminates of chopped strand mat glass fiber-reinforced polymer composite were used for the outer part of the acoustic enclosure panels. Having good absorption qualities, the laminate serves as a noise damper. It is cheap (Agbo, 2019), noncorroding, easy to manufacture and resistant to water and moisture.

Polyurethane foam absorber material was used for the inner lining of the acoustic enclosure. This material is good at absorbing high frequency sound (Agbo, 2019). It is locally available and cheap compared to other synthetic absorbers. It is also resistant to fungal and insect attacks as opposed to natural-based absorber materials.

Rubber felt material was laid on the inside of the closed bottom of the first enclosure box where the generator was placed. This was for the easy cleaning of the enclosure floor and excellent vibration damping. Polyester resin, accelerator, catalyst, and fiber were also used for cold welding.

The tools utilized were mild steel sheet mold for lamination, grinding machine for cutting and masking tape material for keeping the panels in place during the cold welding.

The sound level meter used for SPL measurement was V&A VA8080 (Shanghai Yihua V&A Instrument Co., Ltd., China). A laptop computer installed with TrueRTA Real-Time Audio Spectrum Analyzer Software (version 3.5.6 [2014]), and a microphone was utilized.

The mini generator for testing is shown in Figure 1. It is a typical equipment found in many homes and neighborhoods in developing countries as a source of power supply. The specifications of the mini generator are the following: model - Tiger-TG950, rated power - 650 W, DC output - 12V/3.0A, AC output - 220 V/50 Hz, phase number - single-phase, fuel tank capacity - 4.2 l, gasoline/oil mixture ratio - 50:1, two-stroke cycle, reed valve, forced air-cooled single-cylinder, displacement - 63 cc, weight: 22 kg, and overall dimension: 380 x 320 x 330 mm.

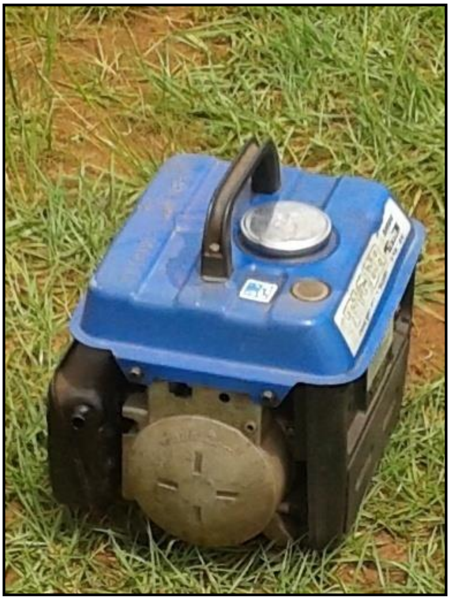

Figure 1. A portable mini generator popularly used in many homes and small shops

2.3 Methods

Composite laminates of 2 mm thickness were produced from chopped strand glass mat and unsaturated polyester resin using the wet lay-up technique. The chosen laminate thickness provides the structural strength (Agbo, 2019) and backing while augmenting the absorber foam material. The produced laminates were then cut into sizes using the grinding cutting machine. Twenty-four 600 mm x 400 mm rectangular panels were cut and used to form six parallelepiped boxes. One 600 mm x 600 mm square panel was cut and used to close the bottom of the first box, where the generator was placed. The dimensions were chosen considering the generator size in view, and allocated a side space just enough to allow accessibility while avoiding resonance from any standing wave. The rectangular cross-section box is simpler and cheap to produce though the inner corners might form small levels of heat pockets and secondary reverberations. The boxes' joints were cold welded using the resin and fiber mixture. The inner surfaces of the boxes were lined with a 20 mm polyurethane foam porous absorber (Mushiri *et al*., 2017). A marginal increase in the sound absorption coefficient with higher absorber thickness (ALRahman *et al*., 2013) was not justifiable economically. The inside bottom of the first box was additionally covered with a smooth rubber felt for the generator placement, stability and easy cleaning of any spilled oil or dirt.

A total of five 100 mm x 100 mm square cross-sectional pipe with lengths of 200 mm each were produced for the exhaust tunneling. One of the pipes was permanently fitted to the opening created on the first box for the generator exhaust while the others were used to adjust the tunnel length during the performance evaluation to determine the effect of the exhaust tunneling.

Figures 2 shows the designed and fabricated acoustic enclosure physical full scale models used to determine the appropriate height of the enclosure.

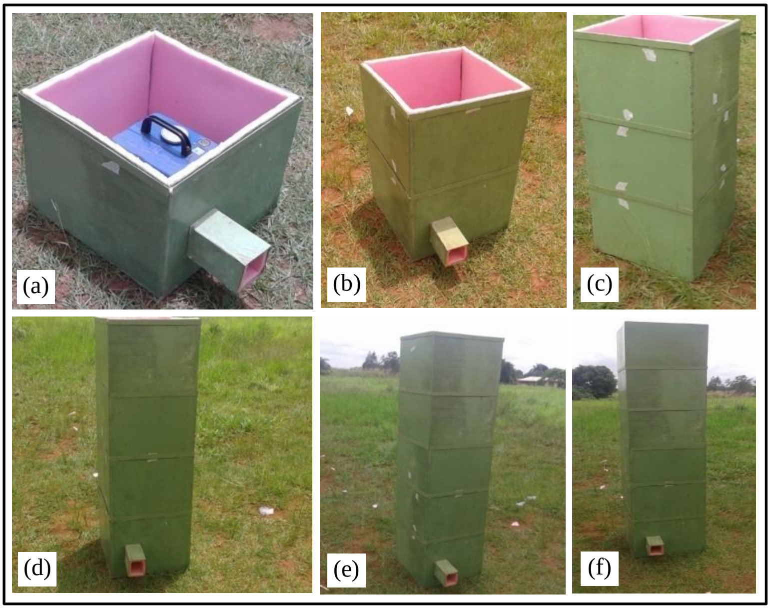

Figure 2. The developed acoustic enclosure boxes: stack height 400 mm (a), stack height 800 mm (b), stack height 1200 mm (c), stack height 1600 mm (d), stack height 2000 mm (e), and stack height 2400 mm (f)

The optimal height of the acoustic enclosure was obtained by placing the generator inside the first box and taking readings of the SPL in dBA using the sound level meter according to the International Standard Organization (ISO) standard 8528-10 measurement standard and evaluation (Marazza, 2016). Subsequently, the height of the enclosure was adjusted by stacking the boxes one after the other while taking readings at each level of change in height. The experiment was stopped when an increase in height did not produce any significant change in the sound pressure level. The measurements were also carried out while adjusting the exhaust tunnel length to determine its effect on the SPL. The tests were carried out in an open anechoic field with a measured background noise of 53 dBA.

Figure 3 shows the setup for the data collection of the generator noise spectrum using the TrueRTA Real-Time Audio Spectrum Analyzer Software installed on a laptop.

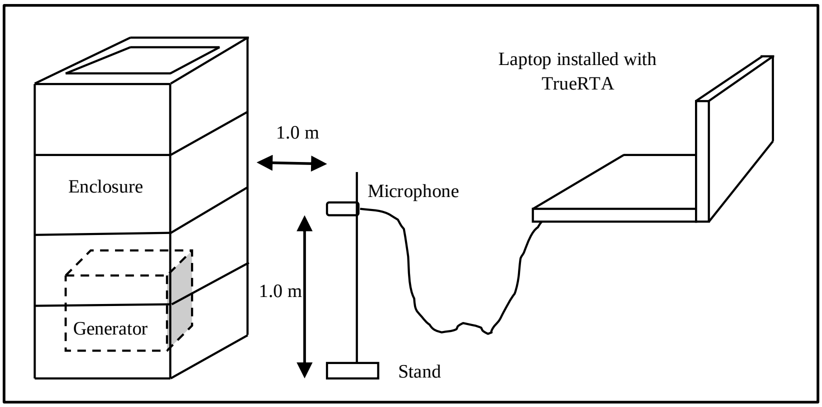

Figure 3. Setup for the generator noise spectrum data collection

The microphone was positioned with the help of a stand at a distance of 1.0 and 1.0 m up from the ground to avoid near-source and reflection effects, respectively. The measurements of the generator noise spectrum were carried out for both the absence of enclosure and the presence of the generator inside an enclosure. The settings of the analyzer included input/output sampling frequency at 44.1 kHz, frequency bandwidth fast fourier transformation size at 4 k, number of averages at 1, peak hold on, one-octave frequency bands and SPL mode. The steady-state temperature of the generator ambient was also taken while increasing the enclosure height. The data generated were presented using the necessary computer software tools.

3. Results and Discussion

Figure 4 shows the generator noise spectra obtained using the real-time audio spectrum analyzer software application.

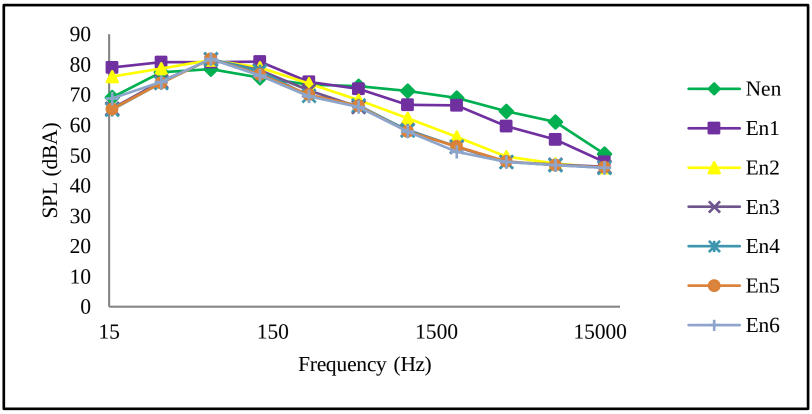

Figure 4. Real-time generator noise spectrum from exported data, Nen = without or no enclosure, En1 = with one enclosure box, En2 = with two enclosure boxes, etc.

The various curves indicate the generator noise SPL at various frequencies. It can be observed that at very low frequencies (below 125 Hz), the enclosure was not effective at attenuating the generator noise as the SPL remained at a higher level. This may be attributed to the increased reverberation due to the enclosure. However, at higher frequencies (above 125 Hz and up to 16 kHz), there was a remarkable decrease in SPL with the generator inside the enclosure. The enclosure lining and the polymer composite panel must have absorbed and/or dampened the high frequency noise, while part of the noise drifted upwards with the associated dynamic insertion losses to a height where it becomes less noticeable. It is worthy to note that while the very low frequency noises were not attenuated, the high frequency noises within the range of human most sensitive frequencies were attenuated by up to 16 dBA. At very high frequencies (above 16 kHz), the generator noise seemed not to contain noises within that frequency as the curves for both the generator without the enclosure and with the enclosure tend to merge.

Figure 5 shows the second combined comparative real-time noise spectrum measurement from the software display. The curves follow a similar pattern can be seen in Figure 4, which confirms the behavior of the generator noise with and without the acoustic enclosure. The point of frequency-dependent attenuation is clearly shown to be 250 Hz.

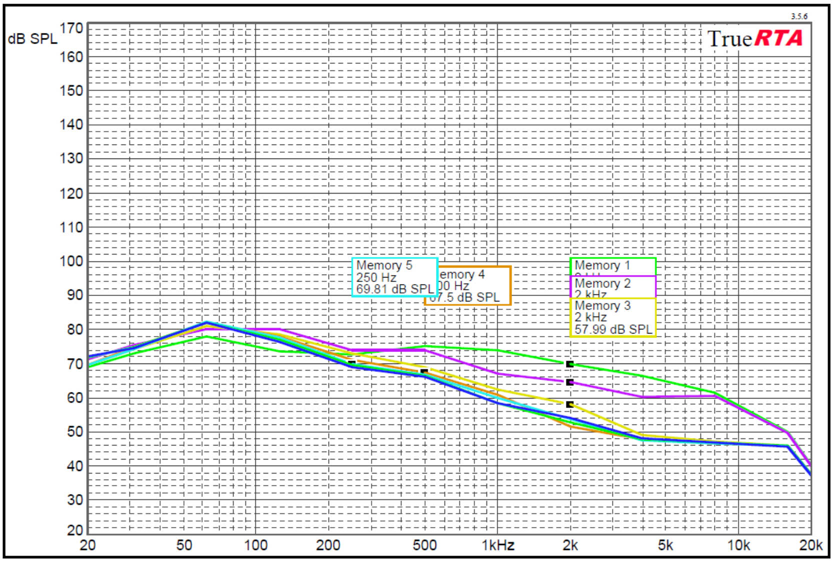

Figure 5. A combined comparative real-time generator noise spectrum as is, memory 1 = without enclosure, memory 2 = with one enclosure box, memory 3 = with two enclosure boxes, etc.

Figure 6 shows the comparative SPL (dBA) of the generator without the enclosure (zero acoustic enclosure height) and with the enclosure of various heights, as measured using a sound level meter.

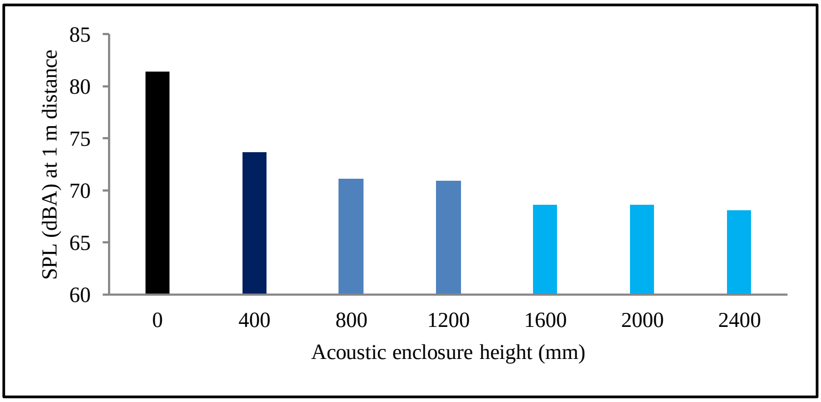

Figure 6. Comparative SPL at 1 m from the generator without enclosure (0 m) and with various enclosure heights

It was found that as the height of the enclosure is increased, the noise level decreased. Mainly, this may be due to the tunneling of the noise upwards over and above the line of sight of an individual within a few meters from the enclosure. The reduction in sound pressure level might also be partly due to the dynamic insertion loss as a result of an upward draft of hot air inside of the enclosure. Most of the sound energy may also have been absorbed by the polyurethane foam and others were blocked by the glass fiber mat reinforced composite laminates forming the enclosure's outside casing. It is found that the SPL of the generator is at the highest level without the enclosure given a value of 81.4 dBA, which can cause hearing impairment and other health disorders. There was a sharp drop in the sound pressure level to 73.7 dBA with the first enclosure and subsequent gradual reduction as the enclosure height was increased. This might be due to the blocking of the sound by the enclosure. The drop in SPL continued until a height of 1600 mm was reached with 68.6 dBA, which is below the threshold of hard of hearing. This gives a 12.8 dBA difference between the generator SPL without the enclosure and with the enclosure. Consequently, it lowered the loudness perception by more than half. At plus or minus 10 dBA to an SPL, the human ear perceives it twice or half as loud (Genesis Acoustics, 2015). It was observed that subsequent increases in height did not yield much significant drop to 68.1 dBA at 2400 mm. This may be that at 1600 mm height, the line of sight of the sound source from the vantage position of the listener (sound level meter position) has been completely blocked.

Table 2 shows the variation in SPL as the distance increases from the generator inside the optimal height (1600 mm) enclosure. It can be observed that operating the generator with enclosure within a reasonable distance of 2 m away from the receiver, the noise SPL dropped from 68.6 to 64.2 dBA, which is within the required range for most regulatory bodies.

Table 2. Variation in SPL with respect to distance from the generator with 1600 mm height enclosure

	Distance (m)							
	1	2	3	6	9	12	18	24
	SPL (dBA)							
Without enclosure	81.4	78.2	73.4	69.2	64.5	61.5	60.3	56.5
With enclosure	68.6	64.2	62.4	57.3	56.3	55.9	53.5	52.1

Increasing the length of the enclosure exhaust tunnel projection beyond 200 mm did not improve the enclosure insertion loss. While increases in the height of the enclosure beyond 1600 mm did not substantially improve the effectiveness of the enclosure, it increased the temperature inside the enclosure to approximately 40 °C (Table 3).

Table 3. Temperature variation near the generator with the change in enclosure height

Height (mm)	0	400	800	1200	1600	2000	2400
Temperature inside enclosure (°C)	26.7	32.2	34.4	35.6	36.7	37.8	39.4

The maximum temperature attained within the enclosure when measured at the optimal height of 1600 mm was about 37 °C – way below 60 °C allowable temperature which guarantees safe operation. The temperature of the environment increased from 26.7 °C to about 28 °C due to the sunlight. The temperature of the surrounding environment approximates the temperature at zero height (without enclosure) around the generator.

4. Conclusion and Recommendation

A portable acoustic enclosure for mini generators was designed, fabricated and evaluated. The design of the enclosure considered the nature of the noise produced that served as the basis in choosing the materials, the size of the generator, the location of exhaust and intake ports to enable proper engine operation, and the weight of the enclosure to ensure portability. The noise frequency is a factor in deciding the type of inner lining absorption material and the outer paneling. In this study, it was observed that noise attenuation is frequency-dependent. The inside of the parallelepiped boxes was lined with polyurethane foam to absorb the high frequency noise, while the hard composite panel was to block and dampen out the low frequency noise.

The acoustic enclosure reduced the SPL of the generator to a manageable level of 64.2 dBA at 1 m away, which is acceptable by the regulatory bodies. The choice of glass fiber-reinforced composite with polyurethane foam lining ensured lightweight, medium and high frequency noise absorption, better damping, durability, and waterproofing. The noise of the generator was partly tunneled upwards to a height where its effect became unnoticeable by those who were nearby and at a distance. The thermal conditions of the generator can also be considered stable as no excessive temperature rise was recorded.

The insertion loss of the full acoustic enclosure was substantial at more than 12 dBA, thus, bringing down the loudness perception of generator noise at 1 m away by less than a half. Hence, it can help to minimize noise pollution from this type of generator. It is also worthy to mention that the generator can be operated at safe temperatures inside the enclosure providing protection and noise reduction. Since it is protected, the generator can be placed outside the immediate environment, without fear of damaging or losing it. In general, this developed enclosure could save people from the harmful effects of the generator noise and associated fumes causing death. Therefore, it is recommended that users of portable mini generators should buy a matching acoustic enclosure to ensure equanimity and good neighborliness within the community. Future works should consider the use of natural and recyclable materials for both the absorber and hardback panels to further reduce costs.

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6. References

Agbo, C.O.A. (2019). Adaptive design and performance evaluation of compact acoustic enclosure built with GFRP for portable mini-generators. Journal of Engineering Research and Reports, 7(3), 1-11. https://doi.org/10.9734/jerr/2019/v7i316972

Akhaze, M.N., & John, E. (2016). Development of a soundproof device for 950 Watt rated portable generators. Journal of Applied Science and Environmental Management, 20(1), 83-86. http://dx.doi.org/10.4314/jasem.v20i1.10

ALRahman, L.A., Raja I.R., & Rahman, R.A. (2013). Experimental study on natural fibers for green acoustic absorption materials. American Journal of Applied Sciences, 10(10), 1307-1314. doi:10.3844/ajassp.2013.1307.1314

Askhedkar, R.R., Modak, J.P., & Vanalkar, A.V. (2016). Formulation of a field data-based model to estimate the noise level in a diesel generator set with an acoustic enclosure. International Journal of Mechanical Engineering and Technology (IJMET), 7(3), 368-386.

Bloxsom, W. (2013). Sound Science: Understanding and implementing generator set noise control. Retrieved from https://www.csemag.com/articles/understanding-implementing-genset-noise-control/

Central Power Systems & Services. (2013). Sound attenuation of generator sets. Retrieved from https://cpower.com/PDF/InfoSheets/04.pdf

Cuesta, M., & Cobo, P. (2001). Optimization of an active control system to reduce the exhaust noise radiated by a small generator. Applied Acoustics, 62, 513-526. https://doi.org/10.1016/S0003-682X(00)00060-8

Department of Occupational Safety and Health. (2005). Guidelines for the control of occupational noise Malaysia. Retrieved from https://www.dosh.gov.my/index.php /legislation/guidelines/industrial-hygiene-1/1416-01-guidelines-for-control-of-occupational-noise-2005/file

Genesis Acoustics. (2015). Soundproofing and generators. Retrieved from https://www.genesisacoustics.co.za/downloads/file/pdf/soundproofing_of_generators _13Feb15.pdf

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

Gries, D. (2004). Noise control solutions for standby power generators. Indianapolis, Indiana: EAR Aearo Technologies LLC.

Gužas, D., Gailius, A., & Girnienė, I. (2008). Dependence of sound insulation of building constructions on the acoustic properties of materials. ULTRAGARSAS (ULTRASOUND), 63(1), 27-32.

Hammad, U., Aizaz, A., Kahn, A., & Qurehi, T. (2013). Design and development of a noise suppression system for domestic generators. European Scientific Journal, 4, 526-533

Hansen, C.H. (2001). Fundamentals of Acoustics. Occupational exposure to noise: evaluation, prevention, and control. World Health Organization. Retrieved from https://www.who.int/occupationalhealth/publications/noise.pdf

International Labour Organization (ILO). (1979). Introduction to work-study (3rd Ed.). Geneva, Switzerland: International Labour Office.

Ju, H.D., Lee, S.B., Jeong, W.B., & Lee, B.H. (2004). Design of an acoustic enclosure with duct silencers for the heavy-duty diesel engine generator set. Applied Acoustics, 65, 441-455. https://doi.org/10.1016/j.apacoust.2003.10.007

Karuppiah, T., & Ramiah, K.V.S. (2017). Testing various synthetic and natural fiber materials for soundproofing. Journal of Emerging Investigators, 1-5.

Krishna, C.R., & Wegrzyn, J.E. (1999). Survey of noise suppression systems for engine generator sets. Brookhaven National Laboratory (BNL). Retrieved from https://www.osti.gov/servlets/purl/752962

Kuku, R.O., Raji, N.A., & Bello, T. (2012). Development and performance evaluation of soundproof enclosure for portable generators. Research Journal of Applied Sciences, Engineering, and Technology, 4(16), 2600-2603.

Larsen, A., Markham, B., Zapfe, J., & Barnes, J. (2017). Noise control insights and guidelines. Retrieved from http://www.sandv.com/downloads/1701lars.pdf

Liu, J.C., & Lu, P.C. (2009). Study on sound propagation in a long enclosure with a vertical or inclined branch of different dimensions. Applied Acoustics, 70, 522-529. https://doi.org/10.1016/j.apacoust.2008.05.010

Liu, J.C., & Lu, P.C. (2010). Sound field prediction in a long enclosure with branches: A combined method. Applied Acoustics, 71, 306-314. https://doi.org/10.1016/j.apacoust.2009.11.002

Marazza, C. (2016). Noise and vibrations measurements and analysis in high power diesel generating sets (Thesis). Politecnico Milano 1863, Italy.

Mushiri, T., Madziro, N., & Mbohwa, C. (2017). Design of an optimum acoustic enclosure for an open frame diesel generator. Procedia Manufacturing, 8, 424-431. https://doi.org/10.1016/j.promfg.2017.02.054

New Jersey Noise Control Council. (2017). Portable & stationary emergency generator consumer Fact Sheet. Retrieved from https://www.nj.gov/dep/enforcement/docs/emergency_generator_consumer_fact_sheet.pdf

Okpighe, S.O. (2015). Review of noise suppression in package generators. Journal of Scientific Research & Reports, 5(5), 361-374.

Oloruntoba, E.O., Ademola, R.A., Sridhar, M.K.C., Agbola, S.A., Omokhodion, F.O., Ana, G.R.E.E., & Alabi, R.T. (2012). Urban environmental noise pollution and perceived health effects in Ibadan, Nigeria. African Journal of Biomedical Research, 15(2), 77-84.

Parvathi, K., & Gopalakrishnan, A.N. (2003). Studies on the control of noise from a portable power generator. Proceedings of the Third International Conference on Environment and Health, Chennai, India, 328-338.

Rahmad, R., & Ahmad Sukri, A.S. (2018). Sound absorption of palm coir fiber. Journal of Science and Technology, 10(4), 55-59.

Saif, M.A.G. (2007). Acoustical treatment of emergency power generators. Proceedings of the 14th International Congress on Sound & Vibration (ICSV14), Cairns, Australia, 513-520.

Tandon, N., Nakra, B.C., Ubhe, D.R., & Killa, N.K. (1998). Noise control of engine-driven portable generator set. Applied Acoustics, 55(4), 307-328. https://doi.org/10.1016/S0003-682X(98)00004-8

World Health Organization (WHO). (2018). Noise: data and statistics. Retrieved from http://www.euro.who.int/en/health-topics/environment-and-health/noise/data-and-statistics