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Survey of Noise Suppression Systems for Engine Generator Sets

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Abstract

The U.S. Army Communications & Electronics Command (CECOM) Research Development & Engineering (RD&E) is developing a new standard family of medium-sized mobile power systems. Noise reduction from the levels in current such equipment is required to meet the specifications. Brookhaven national laboratory (BNL) was tasked to assess the status of noise suppression technologies to achieve this. The report summarizes the results of a preliminary market survey of noise suppression technologies and a background review of diesel engine noise. Recommendations are made for a design strategy and for some specific steps to be followed.

1.0 Introduction

This report is the result of a study undertaken for the U.S. Army Communications & Electronics Command (CECOM) Research Development & Engineering (RD&E) center with Mr. E.A. Nawrocki as the program manager. The work contributes to the Advanced Medium-Sized Mobile Power System (AMMPS) program under CECOM. The work was conducted by personnel at the Brookhaven National Laboratory (BNL) in close cooperation with Mr. Nawrocki and with Ms. S. N. Matthews of CECOM.

The objective of the AMMPS program is to develop a new standard family of medium-sized (5-60 kW) mobile power systems for Force XXI and the Army After Next. There are major components to the AMMPS program that includes a study to choose the basic engine generators set design. This study was done to survey the commercially available active/passive noise and vibration control technologies that could be applicable to these engine generator designs. While the design choice has not been finalized yet, the direction from CECOM suggested that the engine, which would be the major source of the noise, was likely to be a diesel engine. Hence, this study was conducted assuming primarily that a generic diesel engine driven generator would be the mobile power system. A brief review on gas turbine noise is also included.

2.0 Methodology

The following methodology was used to obtain information for the study. A search of the literature was conducted to assess the state of the art of silencing of diesel engine generator sets primarily and to a limited extent of gas turbine sets. The literature on reciprocating (diesel and gasoline) engines as sources of noise is quite extensive and will only be referred to here in a limited fashion. The published literature on power gas turbines is mostly on large turbines, as the development of microturbine driven generators is quite recent. As the prime mover noise is likely to 'drown' the noise from the generator, we have not attempted to review the generator as a noise source. The goal of reducing the noise signature at a distance from these sources can obviously be approached through reducing it at the source, through 'passive control' by interposing absorbing material between and through destructive interference using 'active control'. An understanding of noise production from the source will be useful in all these areas of noise reduction. This is provided in a concise manner from a review of the relevant literature here. A review of the technologies of passive and active control will also be presented from the literature review. A number of publications that deal with the subject matter of the brief review are listed in appendix 1.

A market survey was conducted using several sources. An announcement (see appendix 2) was placed in the Commerce Business Daily (CBD) requesting information. In addition, a copy of the announcement was mailed with a letter requesting information to about seventy companies that were identified through searches on the web and in published sources. The list of companies and organizations that responded to these two requests for information are given in appendix 3. The responses received in the market survey are also reviewed below.

3.0 Literature Review

This review will be divided into sections on the sources of noise, and on passive and active controls.

3.1 Sources of noise

Most of the discussion will be on the noise characteristics of the diesel engine as this is considered to be the most likely prime mover. There will be a brief discussion of the gas turbine.

3.1.1 Diesel Engines

Diesel engine noise can be said to arise broadly from three sources. These are engine airflow interactions, combustion noise and mechanical noise. The air flowing through the cylinders at a frequency set by the valves opening and closing generate noise primarily by tones at the firing frequency and harmonics. This is added to by interactions with flow passage changes and by the rotating compressor and turbine vanes of the turbocharger, if one is used. If an external fan is used as in the case of an air cooled engine or to remove the heat from a liquid cooled engine in a radiator, additional air flow noises occur due to the fan operation and the flow of the air over the fins etc. The combustion noise is the result of the rate of change in gas pressure due to combustion and is therefore dependent on the type of injection and combustion system. The mechanical noises arise, as the name implies from the valve train, gears, etceteras. The engine structure vibrates in response to the oscillatory gas pressure forces and inertial forces of the piston, connecting rod and crank mechanism and generates noise. Figure 1 from the early paper by Priede [1] shows the predominance of the exhaust noise in an unsilenced diesel engine. Line /b/ shows that the next important noise source is the inlet, but only in the frequency range below about 1000 Herz. The figure illustrates also the wide frequency range over which significant noise output is present. The main cause of this noise is the combustion in the cylinders and hence the exhaust noise, for example, is dominated by tones at the firing frequency and its harmonics. The firing frequency is one for every two revolutions of the engine for a four-stroke cycle per cylinder and hence is given by multiplying the number of cylinders by half the rotation rate. For example, for a 4-cylinder engine running at 3600 RPM, the fundamental tone is at 120 Herz. This indicates that a significant part of the noise spectrum will be at a fairly low frequency, which is typically harder to control than noise at higher frequencies.

Challen [2] has summarized in Figure 2, typical ranges of engine noise from different kinds of engines. DI refers to direct injection and IDI refers to indirect injection engines. The first conclusion to be drawn from this is that the noise radiated from the different combustion systems ranks as follows:

DI > Turbocharged DI > IDI at the same speed

The second conclusion is that for all the engine types, noise increases strongly with engine speed. Hence, from the noise point of view, it is preferable to generate the required power at as low a speed as feasible. For example, this could be accomplished by using turbocharging or by increasing the number of cylinders. Of course, these alternatives would lead to increased weight; which could be partly compensated by reduction in the requirements for suppression measures.

Priede [3] has quantified such results in the expression:

$$I \sim N^n B^5$$

Where I is the intensity of sound power radiated, N is the engine speed and B is the cylinder bore. The exponent of speed n varies from 2.5 to 4.5 depending on the type of combustion system.

Thien [4], Figure 3, summarizes for one diesel engine the noise radiated by different parts of the engine structure. These are parts that cannot be isolated easily from the vibrating forces. Air-borne noise from this and other structural sources will have to be contained to the extent possible by the enclosure around the engine generator set.

3.1.2 Gas Turbines

The most significant sources of noise in a gas turbine are the intake, the exhaust and the accessories. Figure 4 from a paper by Cummins Jr. [5] shows the octave band sound power levels from an unsilenced 15 MW turbine. The intake noise is predominantly in the high frequencies and is generated by the compressor. Hence, it includes dominant tones from the blade passing frequency as well. The exhaust noise is predominantly in the low-to mid-frequency range and can contain the tones from the turbine blade passing frequency as well. The noise levels for a microturbine, which is of interest in the present application, will be lower with a shift towards higher frequencies because of the smaller physical dimensions.

4.0 Noise Reduction

It is obviously most desirable to reduce the noise produced by the source. This can be achieved, for example, by choosing the lowest speed diesel engine available for the required power output. This is constrained by the allowable weight and size. New low noise, vibration and harshness (NVH) designs might be in the offing as suggested by Ratliff [6]. As the combustion pressure rise is a major source of the noise generation, beneficial modifications to it through changes to the injection process might become part of new designs.

If the source is given, the options for noise control, in an application such as under consideration here, can be broadly divided into two categories, namely Passive Control and Active Control. Broadly speaking, Passive Control consists of the use of sound absorbing and attenuating enclosures to reduce the noise radiated into the environment and the use of vibration absorbers/dampers to reduce structural transmission. Active Control is a technique of more recent practicality, in which a secondary source of sound such as a loudspeaker is used to interfere destructively with the noise from the original

source. Even more recently, active control of vibrating surfaces has been suggested. These will be discussed in a little more detail below.

4.1 Passive Control

This can include a range of measures taken to reduce the transmission and radiation of noise. These include, passive mufflers for the intake and exhaust, vibration-isolating mounts for the engine, dampening of surfaces subject to vibration such as oil pan covers and finally enclosures that cover the engine generator set partially or completely. Mufflers and silencers for reducing the inlet and exhaust noise have been practical for a long time. Typically over 20 decibel reductions in the sound pressure levels can be achieved with well designed silencers. A drawback in their use is the additional pressure drop that occurs and attempts to reduce this are constantly being made. An alternative design given by a respondent to the market survey is described below and the use of an active noise control system is another approach. Challen [2] indicates some of the methods used to reduce the noise radiated by the vibration of various covers in the engine.

Tree [7] and Thien [4] indicate some of the steps involved in the design and construction of enclosures. They also stress the importance of sealing of even small holes such as are needed to connect services to the engine and of preventing the enclosure from reverberating. As Tree indicates, using enclosures could lead to several of the following disadvantages: 1) increasing cooling requirements, 2) reducing access to the engine, 3) increasing the bulk and weight and 4) increase the possibility of fire. The recent publication of Tandon et al [8] is an excellent documentation of the detailed approach to noise reduction of a portable gasoline engine generator set of 800 watts capacity. The noise sources in the engine were identified and the passive control measures taken, including a partial enclosure, helped to achieve a maximum noise reduction of about 8.5 dBA. Figure 5 from Thien [4] below shows the potential for noise reduction by the use of an enclosure; the experimental enclosure gave a 21decibel reduction in the noise from a 4-cylinder, watercooled 34 kW diesel engine. As this was an experimental enclosure, it shows the potential noise reduction from using a carefully constructed enclosure. Practical enclosures for the present application may need to compromise from considerations of weight, mobility, ruggedness, cost etc.

Some general features of passive control should be noted. The technology, including the sound absorbing materials, has evolved over years of development so that it is relatively cheap and easy to apply. It is being extended to more effectively 'silence' engines, particularly in automotive applications. Clearly, a number of these developments will also be applicable to engine generator sets as well. One of the main difficulties with passive absorption is that its effectiveness drops off at low frequencies. As indicated above, it is possible that the fundamental tone may be of the order of 100 Herz or lower and at this frequency, passive control may not be very effective or could result in significant increase in weight. This has led to interest in other means of noise control, particularly active control, which is more easily implemented at low frequencies as described below.

4.2 Active Control

The prospect of active control and cancellation of noise has interested scientists and engineers since its original conception and patenting by P. Lueg in 1936. His basic idea was to superimpose a secondary acoustic wave to interact destructively with the primary noise and lead to lower sound pressure levels. This idea had to wait another fifty years for the advent of fast digital signal processing before becoming practical. This is because even the simple active control consisting of a microphone, the electronics and a loudspeaker requires adaptive control to compensate for slowly changing conditions. Adaptive control offers self-optimizing and tracking capabilities.

Today, active noise cancellation technology can be categorized as either as active noise control or as active vibration control. The former category describes a system that uses a secondary sound source to interfere destructively with unwanted sound from the primary source. The latter category describes a control system that uses secondary (control) vibrations to interfere destructively with the unwanted vibrations that are the sources of the noise. From a practical point of view, the generation of a stable destructive interference pattern is possible only at low frequencies of 500 Hertz or less and with slowly changing conditions. This restriction necessitates the combining of active control measures with passive control for broad band noise control. In the present application, this may not represent a serious problem, as, for example, Figure 5 shows passive control works best at frequencies above about 200 Hertz.

One successful application of active control is to transformer noise. Transformer noise is strongly tonal at the mains frequency (60 Hertz) and is annoying and pervasive. Application of active control can reduce the noise levels in the far field, which is typically beyond ten or more wavelengths from the source. 60 Hertz sound has a wavelength, under normal ambient conditions, of just under 6 meters. Two necessary conditions for noise reduction in the far field are that the generating source is physically smaller than the wavelength of the radiated sound and that the canceling source is located near the radiating source. When the size of the physical source is larger than the wavelength of the noise, only limited zones of cancellation can be achieved with a single loudspeaker. This is shown in figure 6 from Tokhi and Leitch [9], which shows regions of cancellation and reinforcing of the noise from a 15 MVA transformer when the loudspeaker is turned on. It can be seen that, while the level at 0° is lowered by about 15 dB, the level at 30° is increased by a similar amount.

In summary, active noise control that uses a loudspeaker to lower sound levels far from the noise source does not seem to be viable for the present application, as it can lead to increase of the noise levels over some regions. A better approach would be to use active control of the noise near the source. An example that is directly applicable to the engine generator set is that of controlling the noise from the engine exhaust using the technology developed by Walker Electronic Silencing, Inc. (See the review below).

Another successful application of active control is to headphones. Companies such as ANCT Inc., NCT Inc., and Koss Corporation sell headphones that use fixed analog controllers instead of adaptive control. They use a speaker inside the headphone to generate the appropriate canceling sound. They claim noise reductions of about 18 dB,

although independent tests seem to show about 8 to 10 dB. (Wang and Tse [10]). On the other hand, using adaptive active noise control can give over 40 dB reduction for a fixed frequency, narrow bandwidth noise and 8 to 10 dB for wide band noise, similar to the commercial headphones. This indicates that going to a wider band noise source makes the application of ANC less efficient. This application is different from the previous in that a loudspeaker is successful in canceling the noise at a local region, namely the ears. Such headphones may serve for personnel protection and the technical details of implementing the adaptive control strategy may be applicable in other cases, but the example is given here just to illustrate the successful application of ANC.

A diesel engine produces a fairly wide bandwidth noise (Figure 1) and would make a difficult case for overall active control. A variable speed engine would compound this problem by fast changes in this radiated noise in amplitude and spectral distribution and would make it even more difficult. Solutions may lie in future research.

Active Vibration Control (AVC) is less well developed it would seem. The basic idea is to control the vibration that generates the noise. For example, the enclosure around an engine generator set will be vibrating in response to the noise source inside and this will generate noise by setting in vibratory motion the air around it. Chatel presents a method for increasing the noise suppression of an engine enclosure by using internal loudspeakers to control the vibration of the panels forming the enclosure appropriately. Two of the organizations that responded to the market survey suggested different approaches to vibration control. They are discussed briefly below. However, no practical systems that are commercial and of potential application to the engine generator sets were identified. This technology has the potential, but needs to be examined in more detail before recommendations can be made as to its applicability in the time frame of interest.

5.0 Results of the Market Survey

The responses to the survey fall into three broad groups. The first includes those that offer a more or less complete engine-generator system. Clearly, these systems will not meet all the specifications as presently desired by CECOM, such as variable speed operation. The second group offers noise-reducing components, including sound barrier materials, sound absorbent materials, and exhaust silencers. The third is more in the nature of a 'white paper' and is primarily, though not exclusively, concerned with active noise control. In the following, the individual responses in the group order mentioned above are discussed briefly.

5.1 Group 1: Total Systems

There were three responses that fell into this group. As mentioned above, the systems that are offered by these companies will not meet probably, all the requirements of CECOM. However, they offer one set of sources for the procurement effort.

Alturdyne: The company produces a range of diesel engine generator sets for both commercial and Government customers within the power range that the present program

is considering. They also offer gas turbine driven generator sets of 90 kW and 125kW capacity. They also claim to have supplied (to the U.S. Army) 60 kW sets using a turbocharged diesel engine with a noise level of 65dBA at 25 feet, which seems to meet one of the key requirements in the present program. While the location and status of these sets could not be determined, it may be useful to do so.

The noise control is achieved through passive means. There is data on size and weight for some of the diesel and turbine sets. It is not obvious that the diesel engines can meet the ambient temperature requirements set in the CBD announcement. There is no cost data reported. Presumably, the purchase costs of the sets bought by the Army are available. No maintenance or life cycle data is included.

Fischer Panda Generators, Inc.: The company has water cooled designs that are used for auxiliary power in vehicles and also offers marine diesel generators. They are installed in sound reducing enclosures and claim less than 55dBA at 7 meters when using “super silent” sound proof capsule.

The noise control is achieved through passive means and a sound proof enclosure. There is data given on overall size and weight of the different power sets. There is no data on the limits on ambient temperatures for operation. Total prices for the complete sets are given. No maintenance or life cycle data is included.

Intermodal Equipment Solutions Int'l LLC: The company offers 15kW to 22 kW gensets that are meant to be mounted on cargo containers. No data is given on their noise levels.

5.2 Group 2: Components

The largest number of responses fell into this group. They will be discussed individually below.

Boeing Company: This was an unexpected response and came after a telephone call from the principal engineer. Boeing has recently installed a 100 kW turbocharged diesel engine generator in the aft cargo bay of a Boeing 737 airplane. One of the requirements was to keep the speech interference level below 65 dB in the cabin above. In this installation, the exhaust noise was not a concern and the requirement was met by an intake muffler and an engine enclosure. Boeing's response includes some proprietary data from this installation and a proposal that they will be able to design and deliver an optimized system to meet the specified requirements. Their approach suggests the use of both passive mufflers and active noise control for the intake and exhaust. It also includes vibration isolating mounts and a noise reducing enclosure. They indicate, rightly it would seem, that further information is needed to estimate cost and weight etc. As their design was for an airborne system, it would be logical to think that low weight might have been a consideration. This group at Boeing has obviously the expertise to design a noise suppression system for a diesel generator and the experience with one uncommon installation at least.

Floyd Manufacturing: The company manufactures specialized enclosures for packaged generator power systems. The response consists of a brochure and a report from Diesel & Gas Turbine Worldwide on the successful effort to reduce the untreated noise level of

112 dBA from a 480 kW diesel engine to a level of 55dBA at 4.6 meters. The enclosure includes sound baffles constructed from a dense material within a perforated aluminum framework and a sound-insulating wall around the generator set. A special baffle design was used for the air intake and radiator exhaust areas and a silencer with a catalytic converter (to reduce pollutant emissions) was used in the exhaust. While this engine is significantly larger than one of interest to CECOM, some features of the design could be applicable. There is no cost or weight data given.

Freeberg Industrial Fabrication: This company claims experience with turbine engine enclosures and equipment to handle the intake and exhaust. The response also refers to the recent manufacture of five large diesel burning generator set enclosures for the Navy, although no details are offered apart from a photograph. Some 'typical' enclosure weights and costs are given, but are not applicable to the present project. The company's experience does not appear to be in the arena of small, mobile diesel generator sets.

Hi-Z Technology, Inc.: The company manufactures thermoelectric modules to convert low temperature waste heat directly to electricity. Data showing up to 1kW of power generated from the exhaust of a 14liter diesel engine generating 300 HP. The proposal is to use electric power, converted from the engine exhaust, for supplying the power required by an active noise control scheme. This suggestion, while interesting, is not directly relevant to the present project.

I.D.E. Processes Corporation: The response included the company brochure. The transmittal letter indicates that to respond properly detailed calculations will have to be performed and that the professional time required will have to be compensated. The company offers only custom designs and claims to have supplied silencer and noise suppression systems to the Navy and the Air Force. The brochure suggests experience in building noise suppression systems for large combustion turbine installations.

Inplant Enviro-Systems 2000 Ohio, Inc.: The company manufactures, according to the company literature, various components that are used to fabricate sound reducing enclosures. These include steel panels and enclosures for diesel generators, silencers, and vibration isolation mounts. No specific experience with diesel engine generators is given and most of the brochure illustrations deal with industrial machinery. Acoustical performance data in terms of transmission loss for one of their acoustical panels is included.

Phillips & Temro industries: The company offers engine exhaust silencers of multi-chamber design and a patented spiral design. Pressure loss and attenuation data are given for the different designs. Measurements when using the spiral silencer on a couple of diesel engines show attenuation values of around 30 dBA. The advantages of the spiral design claimed are reduction in size and weight and in the pressure loss when compared to a reactive silencer. No cost data is given.

Polymer Technologies: Polymer technologies manufactures a broad range of acoustical products used for noise absorption and vibration damping. Data sheets on the various

materials give physical properties and acoustical performance. These materials can be used in the construction of enclosures to increase sound absorption and also as barriers to reduce sound transmission. No cost data is given.

Quietflo Noise Control Division of Flaregas Corporation: They claimed to have served with noise pollution control equipment various customers including the U.S. Armed Services. They manufacture enclosures for engine generators and gas turbines. It is not obvious whether the power range covered is low enough to include the 5kW to 60 kW of interest here. The brochure does not give any size, weight or cost information.

Singer Safety Company: This response was the one that tried to be the most responsive to the CBD announcement. The company presently manufactures a variety of barrier products including barium sulfate loaded vinyl and absorber products such as polyurethane foam and fiberglass panels. In terms of future products, they include the use of silicone foams and fabrics, which may result in stronger, more durable and lighter products. Data sheets are given for a variety of their products and cost data are given including cost per dB reduction, which ranges between \$0.45 and \$0.75 per square foot of material. This cost would obviously be carried into the total cost based on the design of the enclosure.

Tenneco Automotive: Walker Electronic Silencing, Inc., a subsidiary of Tenneco, Inc., claims to be in the Active Noise Control field since 1990. They have developed active control silencers for the exhaust from engines used as prime and standby generators. In their description, it consists of six components: An engine speed sensor, a controller to calculate the 'anti-noise' signal, a power amplifier, the metal active enclosure, an error correction microphone and the absorptive silencer to reduce significant noise tones over 500 Hz. The available sizes could be useable in the largest of the contemplated power ranges after being modified to meet the CECOM requirements. Presently, it is claimed that approximately 1000 units are in the marketplace. Its use in a Waukesha 645 kW natural gas fired engine is said to have reduced the noise from 107 dBA to 79 dBA at 1 meter from the engine. Backpressure from this system was 3.55 inches, which is significantly less than the 20.55 inches with a traditional muffler. The response suggests additional weights of 0.3 lbs./dBA to 1.0 lbs./dBA and additional costs of about \$ 20/dBA to \$33/dBA. It is also suggested that potentially the engine intake could be silenced this way as well. Clearly, this company was responsive to the RFI and has had some practical success in active noise control of engine exhaust. Again, all indications are that the system has worked with a constant speed engine.

United Process, Inc.: This company also manufactures foam and fiberglass absorbers, noise barriers and vibration dampers. They also engineer acoustical solutions and the examples given seem to be primarily in the industrial sector. No cost or performance data is given. Clearly, the company's material could be incorporated in the design of the noise abatement enclosure if appropriate.

5.3 Group 3: White Papers

The two responses are discussed below individually.

BBN Technologies: In a past contract with the U.S. Army mobility Equipment Research and Development Command, BBN had worked at reducing the acoustic detectability of an army 30kw diesel generator set. The white paper, using the results from this and other BBN work, spells out the technology options for acoustic suppression of primarily diesel generators. The sources of noise are quantified from the data taken in the previous work on the 30 kW set. Figure 6 is a summary of such data, wherein the 'Criterion' line sets the level required to be achieved through suppression measures in order to avoid detection. Figure 7 is an indication of what could be achieved in the reduction of noise from a 30 kW generator set. The various sources in the diesel engine are identified and the potential treatments, which can be passive, active, or a hybrid of the two, are indicated. BBN also draws on its experience in designing a treatment package for the U.S. Army 1.5 kW engine generator set to reduce acoustic and infrared detectability. The report also references an internal R&D project, where an active control system was used to enhance vibration isolation of a small diesel engine. This was achieved by using electromagnetic actuators to reduce the force transmitted by the mount, the actuators responding to a digital feedback of the signal of the force transmitted.

It must be noted that the work was done in the context of constant speed engines and the complications arising from variable speed operation are not specifically addressed.

SRI International: The application of active noise suppressors for quieting the structural vibration noise from the diesel engine is discussed in this paper. SRI has a patented device, which consists of three components; an accelerometer, a loudspeaker and a controller. The accelerometer measures the surface vibration and sends the signal to the controller. The controller generates a signal that drives the loudspeaker to generate sound of phase opposite to that from the vibrating surface. It is claimed that the noise reduction is broadband unlike some active noise controls that are tonal in their effect. It may also need less power than the approach used, such as in the BBN report discussed above, where actuators are used to reduce the mount vibrational motion.

The SRI concept for using this type of active noise control is illustrated in figure 8. The concept is to integrate the active noise suppressors into a tile, which acts as a passive suppressor. These tiles cover the enclosure surfaces around the engine generator set. The hybrid system will reduce both low and high frequency noises from the vibrating surface. It is reasonable to conclude that the SRI approach, while very intriguing, requires more development work to enable it to meet the demanding requirements of the tactical generation systems.

5.4 Discussion and Conclusions from Market Survey

A broad conclusion from an overview of the responses is that they are generally non-specific in terms of the information requested in the CBD announcement. This may be due to several reasons. One is that the specifications for the engine(s) including its noise

signature could not be spelled out in detail. A second reason might have to do with the uncertainty about the financial incentive, which would make it hard to justify the additional effort required for developing a conceptual design.

A number of companies seem to be able to supply a complete diesel engine generator set, albeit to their own specifications. There are also a sizable number who offer the expertise and the materials for building noise-suppressing enclosures. Only one company was found to offer active noise control, which had been designed for and installed in the engine exhaust. Clearly, active noise control is still not very common in this application at least. Overall, the market survey by itself did not provide new designs or enough information to configure new system designs.

6.0 Discussion and recommendations

This discussion will be limited to diesel engines as prime movers. It is obvious that the most favorable approach from the noise point of view is to use an engine that has the lowest noise level. This would generally entail an engine at the lowest speed for the power required. Of course, the lower speed engine is normally bulkier and heavier for the same power. Turbocharging would mitigate this by increasing the power density at the cost of some additional complexity. There are more recent developments in fuel injection that also promise potential reductions in noise. A fixed speed engine would furnish a constant (within reason) noise source and hence make the design of passive enclosures and particularly active noise control where practical at present (exhaust and intake systems) easier to implement. If variable speed operation is chosen, appropriate compromises should be made in the design depending on weighting criteria such as vulnerability (detection), operating time at different speeds, and personnel comfort/protection.

6.1 Matrix on Technologies

The following matrix is an attempt to describe the application of noise suppression technologies to the sources of noise from a diesel engine, such as might be chosen for the generator sets. A potential source, the turbocharger, is not included, as it is not certain whether one will be used. The market survey did not, at this stage, provide sufficient information to be more quantitative in the details of the matrix.

Noise Source	Suppression Technology	State of technology	Cost	Advantages	Disadvantages
Intake	Passive (Silencer)	Commercial	Low	Current Technology	Weight, Variable Speed?
	Active Control	Commercial	High	Adaptable for Variable Speed	High cost?
Engine	Combustion Modification	Under Development	Not Known	Reduction at Source	
Engine Structure	Passive (Damping)	Commercial	Low	Current Technology	
	Active Vibration Control	Under Development	Not Known	Potentially Lighter	Cost?
Exhaust	Passive (Muffler)	Commercial	Low	Current Technology	Variable Speed?
	Active Control	Commercial	High	Adaptable for Variable Speed	High Cost?
Cooling Fan	Low Noise Design	Possibly Commercial	High	Source Noise Reduction	High Cost?
	Active Control	Under Development	Not Known, probably High		
Enclosure	Passive (Damping)	Commercial	Low	Current Technology	Variable Speed?
	Active Control	Under Development	Probably High		Cost?

6.2 Design Strategy

The following discussion is based on the results from the market survey and the literature review. One can start with a system configuration and specification with no constraints. Logically, the next step would be to seek an optimization of the system with appropriate constraints.

From the perspective of noise, which is our concern here, one has to set some requirements based on vulnerability (detectability) at a specified distance, and comfort/protection of operators and/or other personnel. It is not clear whether the requirement of 65 dBA at 7 meters that was in the CBD announcement reflects these

sufficiently. As BBN's white paper suggests, setting a detection criterion at a specific distance from the engine generator could result in a required maximum source noise level, which is a non-monotonic function of the frequency. This would, at the least suggest a frequency dependent limit for the source noise level if vulnerability is a key criterion.

Given the requirement on the source noise level, one would choose the lowest speed engine feasible to meet this requirement as closely as possible. Based on the difference between the engine noise level and the requirement, and from an assessment of the sources within the engine, appropriate technologies as identified in the matrix above can be implemented to close this gap. This would be an 'ideal' choice without regard to any constraints.

As an example, in the response to the survey, Fischer Panda lists generator sets up to 25 kW output that, with the 'sound capsule', have claimed noise levels of about 54 dBA at 7 meters. Some components such as the engine seem to be of foreign manufacture and it is not clear whether this poses a problem. The sets appear to be 'expensive', but they claim lower weights compared to the competition. This indicates that there are available sources of engine generator sets, which may meet the noise requirements as specified in the CBD announcement.

On the other hand, all of CECOM's requirements might not be met by this or other 'off-the-shelf' systems. The specifications, especially if they are enlarged to include criteria such as those above, will generate the constraints that will necessitate modifications to such systems. Other examples of such constraints could be maximum weight, maximum cost, and limit on fuel consumption and ability to operate in extreme environments. While these constraints might primarily affect the choosing of the engine, the generator and associated hardware, the choices with regard to the noise suppression systems will have an impact on meeting some at least of these constraints. Obviously, one would like to be able to find an optimum system subject to these constraints.

One could proceed in many ways to move towards the optimum system. It would seem that CECOM would like to use or adapt a commercial system, as clearly it would have cost benefits. This would require that a fairly detailed specification be developed and used as a basis for a response from commercial entities. The development of the specification could occur through the development of a conceptual design of the system, where, in the context of noise control for example, the application of the technologies in the matrix above would be made more specific and quantitative. This would be a team approach with inputs from all the groups dealing with the different aspects of the system.

6.3 Recommendations

The following recommendations are offered from the perspective of this study. They offer a basis, hopefully, for mutual discussion and arriving at a consensus on how to proceed.

1. A database of commercial capability that can match the needs of CECOM in this area has to be developed.

2. The benefits of Active Noise Control (ANC) and the potential of Active Vibration Control (AVC) and of the capabilities available to implement these techniques have to be analyzed.
3. A concept design could be developed to integrate the noise control strategy with the system and utilize this to develop the specifications for commercial procurement.

Figure 1. Octave Band Spectra of Diesel Engine Noise.

Figure 2. Typical Ranges of Engine Noise.

Figure 3. Noise Radiated by Engine Surfaces.

Figure 4. Unsilenced Octave Band Sound Power Level of a 15 MW Combustion Turbine.

Figure 5. Noise reduction from a watercooled diesel engine with an enclosure.

Figure 6. Noise Reduction of a 15 MVA transformer

Figure 7. Sources of Noise from the U.S. Army 30 kW Diesel generator

Figure 8. Noise Reduction Achieved for the Treated 30 kW Generator.

Figure 9. Concept of Generator with Active-Passive Noise Reducing Tiles.

Appendix 1

Announcement in the Commerce Business Daily

Noise Suppression Systems for Military (5 – 60 kW) Diesel Fuel Burning Generator Sets Noise Suppression systems for military generator sets for the 21st Century Battlefield. Request for Information (RFI), the US Army Communication and Electronics Command, R&D Center, Command and Control Directorate, Army Power Division, Power Generation Branch, Advanced Technology Power Source team is soliciting information from manufacturers who have the technology for reducing (suppressing) noise from engine-generator sets that start and operate on diesel or JP8. The engines shall be state of the art diesel fuel burning engines that are currently available and/or will be commercially available in the next two to three years. The generator sets are expected to be packaged in the usual way in a 'rectangular' box that is rugged for field operation. This will be the basis for the development of a new family of generator sets in the 5 to 60 kW ranges for application to the 21st Century Battlefield.

The key requirement for noise emission from these generator sets is for a level of 65 dBA across the audible spectrum at 7 meters from the box. Both passive and active control technologies are being considered to meet this requirement. The suppression technology will have to be applied to the intake and exhaust system of the engine with minimum impact on performance and to the noise emitted from the box. The design, materials used and the construction shall be such as to minimize additional weight and be able to withstand ambient temperatures between -50°F to + 140°F at any possible humidity. As the generator sets will be deployed in the field, the design and construction shall also be easily transportable, permit quick setup and be sufficiently rugged. The design shall also be such as to minimize maintenance and possess mean time between overhaul at least equal to that of the engine-generator system.

The performance specifications for the engine-generator system are not yet finalized, except for the power range, which is 5 to 60 kilowatts. Therefore, what is requested at this stage are:

1. a broad statement of capabilities,
2. a description of present technologies and of potential new or improved active and/or passive technologies that could become commercial within the next three years,
3. some indications of performance, such as weight increase per dBA reduction, impact on the performance of the engine/generator, maintenance and replacement characteristics where relevant, description of suppressant materials and an indication of the range of costs per dBA reduction of the different suppression techniques, and
4. sample cost data of existing, currently implemented active and/or passive noise systems.

The above information is to be sent to the following within 30 days of this announcement:

C.R.Krishna

Brookhaven National Laboratory

Building 526,

Upton, NY 11973-5000

Krishna@bnl.gov

Phone: 516-344-4025

The information will be supplanted by discussions and reviews. Subsequently, the CECOM RDE Center will initiate a process for the procurement of these systems.

Appendix 2.

References

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10. A. K. Wang and B. Tse, Adaptive Active Noise Control for Headphones Using the TMS320C30 DSP, SPRA 160, Texas Instruments, 1997.

Appendix 3

Companies that Responded

1. Alturdyne
8050 Armour Street
San Diego, CA 92111
2. Boeing Airplane Co.
Commercial Airplane group
3. Alturdyne Energy Systems
784 North Benson Road
Fairfield, CT 06430
4. Fischer Panda Generators, Inc.
1218 S.W. 1st Ave.
Ft. Lauderdale, Florida 33315
5. Floyd Manufacturing
2712 Wyoming Ave.
P.O.Box 7054
Norfolk, VA 23509-0054
6. Freeberg Industrial Fabrication
2874 Progress Place
Escondido, CA 92029
7. Hi-Z Technology, Inc.
7606 Miramar Road, Suite 7400
San Diego, CA 92126
8. I.D.E.
105 81st Avenue
Kew Gardens, NY 11415
9. IES 2000
3032 South Elmtree
St. Paris, OH 43072
10. IES Int'l LLC
703 King Street
Charleston, SC 29401

11. Philips & Temro industries inc.
9700 West 74th Street
Eden Prairie, MN 55344
12. Polymer Technologies Inc.
420 Corporate Blvd.
Newark, DE 19702
13. Quietflo Noise Control Division
Flaregas Corporation
100 Airport Executive Park
Nanuet, NY 10954
14. Singer Safety Company
2300 W. Logan Blvd.
Chicago, IL 60647
15. United Process, Inc.
P.O. Box 545
Agawam, MA 01001-0545
16. Walker Electronic Silencing, Inc.
1025, W. Nursery Road, Suite 100,
Linthicum, MD 21090

Organizations that Responded

17. BBN Technologies
70 Fawcett Street
Cambridge, MA 02138
18. SRI International
333 Ravenswood Ave
Menlo Park, CA 94025