ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Murat Can ÖZDEN

IMPROVING OF CRAWLER EXCAVATOR CABINET ACOUSTIC ISOLATION WITH SYNTHETIC SOUND BARRIER AND POLYETHYLENE INSULATIONS MATERIALS

DEPARTMENT OF AUTOMOTIVE ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 04/ 02 /2019

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ABSTRACT

MSc THESIS

IMPROVING OF CRAWLER EXCAVATOR CABINET ACOUSTIC ISOLATION WITH SYNTHETIC SOUND BARRIER AND POLYETHYLENE INSULATIONS MATERIALS

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In this thesis, the sound level of a crawler excavator with a weight of 30 tons was determined and it was aimed to reduce the sound isolations in the cabin and the sound absorbers in the outside environment. Within the scope of the research, the openings that would affect acoustic isolation of excavator cabin were determined. Solutions suitable for these openings were developed. As a result of the tests, the highest decibel values of the excavator operating conditions, the frequency range corresponding to this value were determined. Appropriate isolation and sound absorbers were determined for these frequency ranges. Synthetic sound barrier is mounted on the cabin floor and polyethylene sound isolations are mounted on the cabin frame.as a result, the cabin noise level has been reduced by 3-5 dB Thus, a more comfortable and quiet operator area was obtained for the excavator.

Key Words: Crawler Excavator, Acoustic, Isolation, Absorber, Sound Pressure Level

ÖZ

YÜKSEK LİSANS TEZİ

PALETLİ EKSKAVATÖR KABİN AKUSTİĞİNİN SENTETİK SES BARİYERİ VE POLİETİLEN İZOLASYONLARLA GELİŞTİRİLMESİ

Murat Can ÖZDEN

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Bu tez çalışmasında stadartlara uygun test koşullarında 30 ton ağırlaga sahip bir paletli ekskavatörün kabin içi ses seviyesi belirlenmiş ve kabin içi izolasyon ve dış ortam ses emiciler ile ses seviyesinin azaltılması amaçlandı.Araştırma kapsamında öncelikle ekskavatör kabinin akustik izolasyonunu etkileyecek açıklıklar tespit edildi.Bu açıklıklara uygun çözüm yöntemleri geliştirildi. Testler sonucunda ekskavatörün çalışma şartlarındaki en yüksek desibel değerleri ve bu değerlerin karşılık geldiği frekans aralığı tespit edildi. Bu frekans aralıklarına uygun izolasyon ve ses emiciler belirlendi. Kabin tabanına sentetik ses bariyeri ve kabin karkasına polietilen ses izolasyonları montajlandı.Sonuç olarak kabin içi ses seviyesinde yakalaşık 3-5 dB azalma elde edilmiştir. Böylece ekskavatör için daha konforlu ve sessiz bir operatör mahali elde edilmiştir.

Anahtar Kelimeler: Paletli Ekskavatör,Akustik,İzolasyon,Yalıtım,Ses Basınç Seviyesi

GENİŞLETİLMİŞ ÖZET

Bu tez çalışmasında 30 ton paletli bir ekskavatörün kabin akustiği iyileştirme çalışması yürütülmüştür.Bu çalışma kapsamında kabin içerisindeki sese ek olarak ekskavatörün ses kaynaklarının dış kabin dışına yaydıkları ses basınç değerlerinde de iyileştirme çalışması yürütülmüştür.

Tez içeriği olarak başlangıç kısmında iş makinası sektörünün ülke ekonomileri üzerindeki etkileri üzerine durulmuştur ayrıca iş makinası sektöründeki kabin akustiği konularının neden önem arz ettiği hususunda da bilgiler verilmiştir.Tezin devam Eden bölümlerin akustik blimin temel kavramlarından bahsedilmiştir.Bu kavramlar tez içerisinde sık sık kullanımına başvurulacak kavramlardır.

Akustik konusunda başlıca ses tanımı, decibel, frekans, ses basınç seviyesi gibi tezin içerisinde kullanılacak ve sonuçlarda irdelenecek parametreler açıklanmıştır.Tezin materyal ve metod kısmında ise tez içersinde kullanılacak olan materyallerin ve yöntemlerin açıklamaları yapılmıştır.Materyaller kısmı tez çalışmasında kullanılacak izolasyon malzemeleri özellikleriyle beraber verilmiştir.Bu malzemeler ses emiciler ve ses yansıtıcılar olarak iki kategoride verilmiştir.Diğer kullanılacak malzemeler olarak ise test ekipmanları olan ses ölçer, data toplayıcılar ve sis testinde kullanılacak sis makinası belirtilmiştir.

Tez çalışmasının test aşamasında kullanılacak olan ekskavatör yine materyal kısmında detaylı olarak anlatılmıştır.Bu kısımda ekskavatörün çalışma prensipleri ve üzerinde bulunan komponentler işlevleri ile birlikte detayladırılmıştır.Metod kısmında ise tez çalışmasında kullanılacak olan test kriterlerinin açıklamaları yapılmıştır.Bu tez çalışmasında test çalışmalarının kriterleri TS ISO 6395 standardı kullanılmıştır.Bu standart iş makinası üreticilerinin uymasını gerektiren iş makinası ses emisyon değerlerini belirleyen bir standarttır.Bu standart makinanın dış ortamından belirtilen uzaklıklardan alınan ses basınç değerlerinin hesaplanması ve raporlanmasını içermektedir.

Tezin önceki kısımlarında belirtilen test koşulları ve materyaller test makinasına uygulanmıştır.Uygulama öncesi izolasyon malzemelerinin montajlanmadığı makinadan ölçümler alınmıştır.Bu ölçümler sayesinde ekskavatördeki ses kaynakları belirlenmiştir.Belirlenen ses kaynaklarının uygun bölgelerine eskavatörün çalışma şartlarına uygun olacak izolasyon ve yalıtım malzemeleri seçilmiştir.

Eskavatörün dış kısmının izolasyon ve yalıtım malzemeleriyle montajlanması sonrası kabin içi izolasyon çalışmasına başlanmıştır. Kabin içerisindeki izolasyon ve yalıtım malzemelerinin montajına başlamadan kabin içerisindeki alanı tam halde dış ortamdan izole edilebilmesi adına kabine sis testi yapılmıştır.Bu teste kabin tüm montaj parçaları montajlanmış halde 10 dakika boyunca bir sis testine tabi tutulmuştur.Bu test sonrasında ise kabin etrafındaki açıklıklar belirlenmiş ve bu bölgelere imkanlar doğrultusuda önlemler alınmıştır.

Ekskavatör kabinin açıklıkları giderildikten sonra kabin içerisine trim iç yüzeylerine yalıtım malzemesi ve kabin tabanına ise yüksek yoğunluklu ses bariyeri montajlanmıştır.Tamamlanan montaj sonrasında standartta belirtilen doğrultuda testler yapılmış ve sonuçlar alınmıştır.Test sonrasında elde edilen sonuçlar incelendiğinde kabin içi ses seviyesinde yakalaşık 3-5 dB azalma elde edilmiştir. Böylece ekskavatör için daha konforlu ve sessiz bir operatör mahali elde edilmiştir.

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LIST OF ABBREVIATIONS AND NOMENCLATURE

LIN	: The Linear (LIN) Weighting On Sound-Level Meter
SPL	: Sound Pressure Level
FBN	: Fluid borne Noise
TPA	: Transfer Path Analysis
AI	: Articulation Index
MBD	: Multi Body Dynamics
BEM	: Boundary Element Method
VINS	: Vehicle İnterior Noise Simulation
TL	: Transmission Loss
$L_{pA,T}$	: Average Energy of A-Weighted Sound Pressure
L_{pAi}	: A Weighted Sound Pressure Level, Derived from Microphone Position
SIP	: Seat Point Index
L_{WA}	: A-Weighted Sound Power Level

1. INTRODUCTION

The construction sector has an important place in the economies of the countries. The sector includes many civilization titles such as urbanization, transportation, energy and mining projects etc. Construction equipment are critical mission for the progress and completion of such projects. In other words, the means by which construction equipment are used in the reconstruction of the infrastructure and superstructure of a country, which are important contributors to the financial and societal augmentation of that country. There are several construction equipment used on today's projects such as excavators, loaders, bull dozers, motor graders, trenchers, etc. The equipment vary depending on the application, for instance, while backhoe loader are used digging and loading operations, graders are used obtain smooth surfaces. Excavators used in excavations and loading operations are divided into two main types considering the difference of drive elements. Crawler excavators travel process thanks to two endless tracks, while wheel excavators provide this process with four wheel.

The crawler excavator will be the main element of noise optimization in this thesis, can be seen in Figure 1.1. Excavators are one of the most preferred machines in the construction equipment sector due to their high digging capabilities, high tonnage lift capabilities and grade ability. These features of excavators are the characteristic of their large size components, such as diesel engine, cooling pack and hydraulic pump and motors. However, these large-scale components can also become high-decibel sound sources during excavator operation. Considering that the operators spent their hours in excavator cabin during excavation, the noise levels of excavators comes into question.

Figure 1.1. Crawler Excavator (M S T M300 LC)

Legislations of earth-moving machinery have started to push lately guidelines to secure operator's health. The legislations include directives that specify the level of excavator's noise and limit them to a certain decibel values. Manufactures of constructions machinery must admit the requirements of ISO 6393 directive in this respect. This legislation is taken into consideration to noise decibel improvement projects implemented by manufactures.

Sound and vibration studies are one of the branches of vehicle technology that has been the subject of research and development most of the time. Acoustics within the scope of this issue has always kept the subject of importance. Also acoustic has always been associated with vehicle reliability and durability due to its relationship with vibration, although it is always associated with comfort. Today, the concept of comfort in vehicles is in front of many parameters of vehicles. Naturally, the basis of this reason lies in the demands of the customer. The same customer demands are conveyed to excavator and construction machine design teams as design requests. Design teams carry out research and development activities in order to create a quieter and comfortable operator area in line with these demands.

In this study, acoustical research of an excavator cabin in line with the same demands. In the scope of this study, excavator external ambient sound levels will be determined according to the standard and this sound level will be scale down by selecting suitable isolation and sound absorbers. For the excavator whose external sound level has been reduced, the main target is to reduce the internal sound level of the cabin by means of a high-density sound barrier to be used from the floor of the cabin.

2. FUNDAMENTALS OF SOUND AND NOISE

Sound is such a widespread components of each day life that we uncommon comprehend all its functions. It fulfills delightful experimentation such as listening to music or spoken communication with other people. It can warm us, for instance with the ringing of a cellular phone, or a weeping hooter. Sound also allow us to make high grade assessment and identification, the grinding valves of a car, a creak of wheel. Yet, too oftentimes in our present community, sound irritates us. Many sounds are distasteful or unsolicited these are named noise. Nevertheless, the grade of vexation is not attached to not only on the quality of the sound, but also our approach against it. The take –off sound of the new jet plane can be considered harmless and pleasant by the design engineer, but it can be disturbing by the residents living around the take – off runway. But it doesn't need to be loud to disturb the sound. A squeaky floor, a scratch or dripping tap in a recording, can be as disturbing as a loud thunder. Worst of all, sound can detriment and demolish. A sonic boom can crush windows and waggle stucco of walls. But the most misfortune incident is when sound damages the sensitive mechanism designed to receive it – the human ear.

Measurements provide precise amounts of identifying and evaluating sounds. Sound measurements additionally allow touchy, scientific analysis of irritating sounds. However, because of the psychological distinction between individuals, we must state that the degree of discomfort is not measured scientifically for a particular person. But still the measurements provide a practical method of comparing disturbing sounds under different conditions.

Sound measurements also provide crisp evidence that a sound can damage auditory perception and allow corrective action to be taken. The degree of hearing impairment can be determined by audiometry, which measures the hearing response of the person. For this reason, sound measurements are a crucial part of auditory protection programs.

Eventually, sound measurement and analysis is a critical diagnostic tool for noise reduction applications ranging from airports, factories, apartments and recording studios. The noise measurement techniques are a tool that can help to improve the quality of our lives, given the contributions of our experiences. (Brüel & Kjær, 1984)

2.1. Sound

Sound is from air in vibration. The ears may be damaged from severe amplitude or level. One of the areas where the silence is demanded is the vehicle cabins. This desired silence is considered within the scope of the vehicle's internal acoustics. Reduction of echo time and back noise is one of the most substantial factors of in-vehicle acoustics.

The whole of the unsolicited sounds that are accepted as environmental pollution is describe as noise. The noise pollution has become a matter of concern to society more and more day by day. Ultrasonic and acoustic emissions are another two subjects in this respect. The noise produced by the materials when they are connected are called acoustic emissions. For instance, the sounds in vehicles are often very short, and in fact these sounds are shock waves that occur when the vehicle chassis panel boundaries are deformed along the slip planes. Ultrasonic is the generation of vibration over the human level of hearing (i.e. greater than 20 kHz). These ultrasonic vibrations are used to test materials, weld plastic, view the interior of the soft trim body structure, and detect vehicle cab noise.

Sound is defined as a periodic method (at least functional level in the environment). The transformation connection between sound wavelength and frequency is shown in Fig. 2.1. Sound includes energy transport. Sound propagation can energy transfer, but it does not cause material to move. Particles are excited to release about normal resting positions in their environment, but not swept along with the sound. To give the example, air molecules in the mouth of a speaker do not demand the listener to find ways to hear the speaker's voice. (WANG, X., 2010)

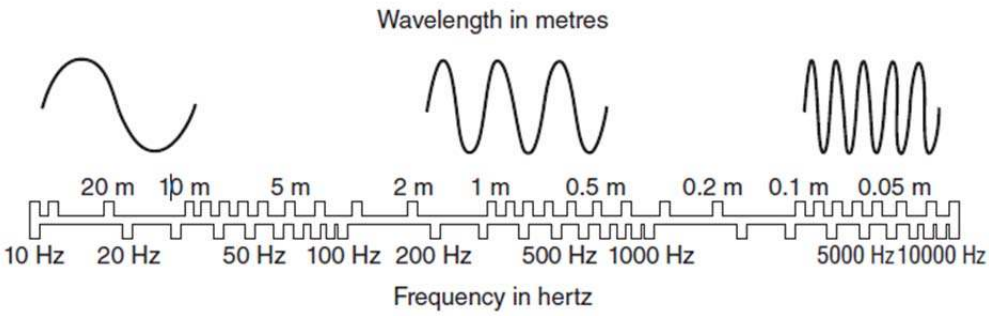


Figure 2.1. Wavelength of Sound (Brüel & Kjær, 1988)

So that they can oscillate around the normal resting positions of the particles, both resilient and inertial, so that a displaced particle that applies a restoring force on it will exceed the original resting position.

The speed of sound in air, *c*, rising with temperature. The speed of sound in air also lessening with altitude. Table 2.1 illustrates how the speed of sound varies with altitude, temperature and pressure.

Table 2.1. Altitude and the speed of sound. (Brüel & Kjær, 1988)

Altitude (m)	Temperature (K)	Pressure(Standard Atmospheres)	Air density (kg/m^3)	Speed (m/s)
0	288	1	1,225	340,3
1000	281	0,887	1,1117	336,4
10000	223	0,262	0,4135	299,5

Based on a low density medium in a high density environment sound propagates more quickly. A pressure variation in the air, most of the sound we hear is. It is a longitudinal compressive wave. Air moves through every moving, vibrating, oscillating, or vibrating object. A type of mechanical energy emitted from the source, sound. In air, sound progresses at 344 m/s at normative temperature and pressure. Density falls at a distance according to the law of inverse square; in other words, when the distance is doubled, the loss of air density in the air is 4 times. In this case it is assumed, under free space conditions, without barrier or other blocking objects.

In steel, sound travels at 5060 m/s, and inverse square law is not valid. It would be about 15 times faster than sound progress in steel. The sound energy is not spread evenly in all directions in the metal material, but is limited to a degree within metal boundaries. The sound energy is related to the metal way, but the sound reduction in the air is fairly fast. In solids or liquids, attenuation is much lower. Table 2.2 shows the media type and the speed of sound.

Sound has a source, a path and a receiver. Clearly three of these should be identified to solve the noise problems. The source and the receiver are usually straight forward. The greatest difficulty arises in defining the path, which is one of the points where noise control methods are most often applied. Sound has a very low level of energy intensity. Sound energy is generally measured in Pico watts. Extreme sensitivity of the human ear balance with this energies in extremely small quantities. The sensitivity of modern electronic sensors is almost proportional to this human sensitivity.

Table 2.2. Media type and the speed of sound.

Medium	Speed (m/s)
Water (fresh)	1481
Water (salt)	1500
Concrete	3100
Steel	6100

If it is placed in the free space or if there is a barrier in the sound path, the part corresponding to the voice is reflected, the part is absorbed and the remaining part is transmitted through the object or obstacle. (WANG, X., 2010)

2.2. Frequency and Sound Pressure Level

The human ear cannot reply homogeneously to sounds at all frequencies. The humans are insensitive to low-frequency sounds (below about 20 Hz) and high frequency sounds (above about 20,000 Hz), and are most precision to sounds around 2000 Hz. Human hearing response varies by age. The typical human hearing reaction is showed in Fig. 2.2.

To compensate for this, the "A" weighting response of a sound level measuring device adjusts the response of the metric to approach the reflections of the human ear. The linear (LIN) weighting on the sound-level meter is no weighting at all. The raw signal from the microfilm passes through the unmodified LIN character. Thus, the 'A' weighting feature can be used to adjust the amplitude measurements to approximate the applied human hearing sensitivity. However, when conducting a research study using frequency analysis, therefore, LIN weight is suitable because there is no need to modify any part of the spectrum. (WANG, X., 2010)

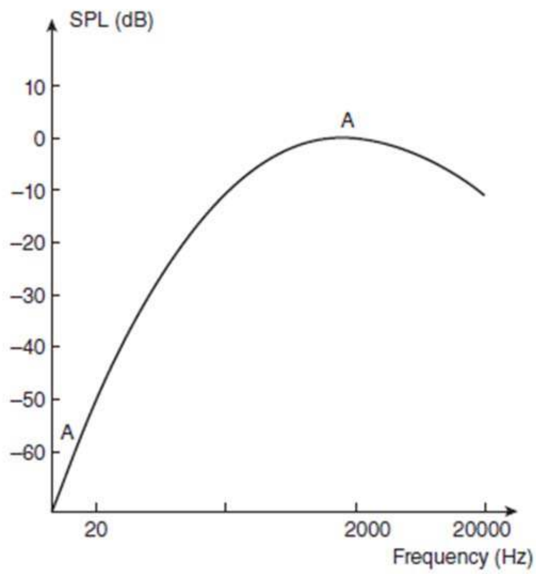


Figure 2.2. Human Hearing Response (Brüel & Kjær, 1984)

Figure 2.3 shows the A, B, C and D weighting sound pressure level (SPL) graph. As formerly mentioned, “A" weighting network aggravates the signal in a manner approaching the human hearing response (as shown in Fig. 2.2). Corresponds to the weighting of 'A', the inverted equilibrium contour at low SPL values. Represents the weighting of 'B', the contour of middle SPLs, and the ‘C’ weighting to an equal noise outline at high SPLs. ‘D’ weighting is used for aircraft noise measurements. The widely used 'A' weight is proportional to the nominal evaluation. But the weighting of B and C are not proportional to subjective tests.

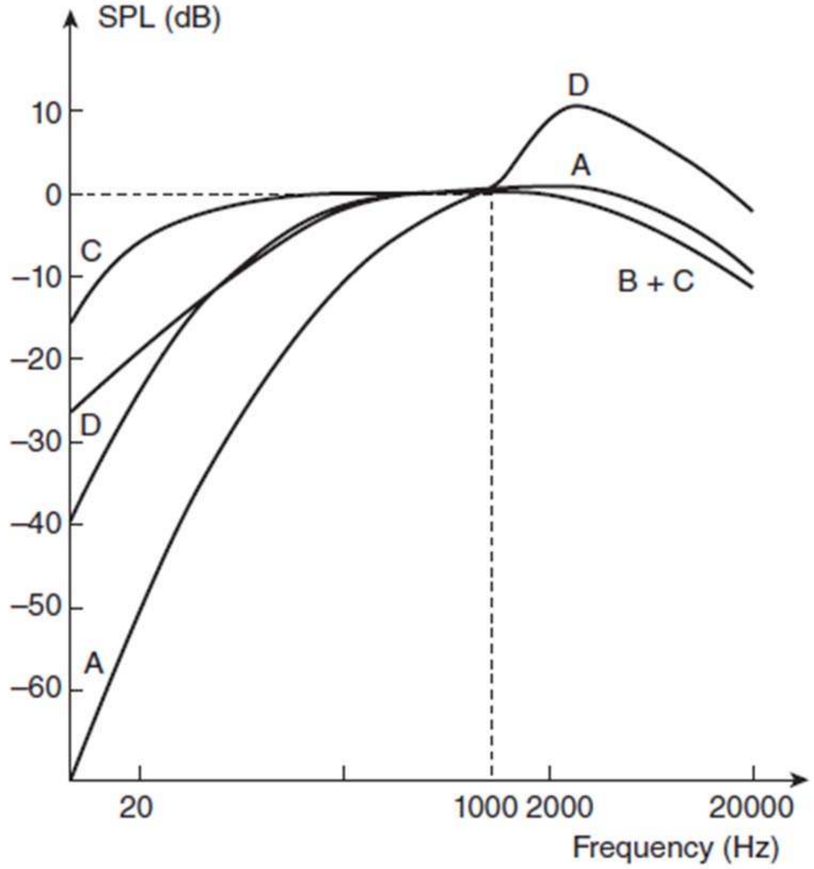


Figure 2.3. Weighting Curves for Sound-Level Meters (Brüel & Kjær, 1984)

2.3. Decibel Scales

Sound levels are widely identify in terms of the sound power (W) output of noise sources and the sound pressure (Pa) amplitude at a given area. However, because of the extended power range and the sound pressure amplitude that can be encountered, the decibel scales (dB) are useful.

Table 2.3 illustrates that machines with a sound power output range of 0.001 to 1000 W (a factor of one million times) and the human voice has a power output in the range of 0.000 000 001 to 0.001 W (also a factor of one million times).

Table 2.3. Typical sound power levels for different sources. (Brüel & Kjær, 1984)

Source	Sound power output (W)
Saturn rocket	25–40 million
Military jet engine with afterburner	100 000
Turbojet engine	1000–10 000
Propeller airliner with four engines	100–1000
75-piece orchestra	10–1000
Small aircraft engine	1–10
Piano	0.1–1
Car alarm	0.1
Hi-fi	0.01
Moving car	0.001–0.01
Fan	0.001
Person shouting	0.0001–0.001
Conversational voice	0.000 01
Whispering voice	0.000 000 001

The relationship of the pressure amplitudes between 0.0002 and 20 Pa is shown in Table 2.4 considering the daily noise environments. The sound pressure amplitudes in this range can be perceived by the human ear.

Table 2.4. Typical sound pressure levels for different sources (WANG, X., 2010)

Environment	Sound pressure amplitude (Pa)	Description
100 m from Saturn rocket	200	Ear pain threshold
At front of rock concert	20	Potentially damaging
Noisiest factory	2	Harmful
Next to road or railway	0,2	Noisy
Busy restaurant	0,02	Medium hearing
Quiet suburban street	0,002	Quiet
Recording studio	0,0002	Very quiet

They are often described using the decibel scale, to facilitate the availability of sound levels:

$$L = 10\log_{10}\left[\frac{X}{X_{ref}}\right] \text{ dB} \tag{2.1}$$

where:

$$X = X_{ref}\,\frac{10^{L/10}}{10} \tag{2.2}$$

The sound pressure level (L_P) is described as the ratio of the squared sound pressure amplitude to the threshold of hearing:

$$L_P = 10\log_{10}\left[\frac{p^2}{{p^2}_{ref}}\right] = 20\log_{10}\left[\frac{p}{p_{ref}}\right] \text{ dB} \tag{2.3}$$

where $p_{ref} = 20 \times 10^{-6}$ Pa.

Considering this range, it is observed that daily noise environments will fall within the range of 0-120 dB sound pressure levels. Attribute study pressures associated with internal combustion engines are listed below by comparison method:

- Peak cylinder pressure ≈ 60 bar ≈ 230 dB.
- Exhaust pressure wave ≈0.8 bar ≈192 dB
- Intake pressure wave ≈0.2 bar ≈ 180 dB.

The sound power level (L_w) is described as the ratio of the sound power to a reference power of 10^{-12}W :

$$L_w = 10\log_{10}\left[\frac{W}{W_{ref}}\right] \text{dB} \tag{2.4}$$

where:

$$W_{ref} = 10^{-12} \text{ W} \tag{2.5}$$

Considering the above mentioned values, the daily machines produce 70-160 dB sound power, and under normal conditions, human sound can produce 30-70 dB sound power. When the sound levels of two or more machines or sound sources are measured and the total sound pressure level (SPL) of the machines during operation is determined, the sound levels are collected and the total sound level is obtained. However, decibels cannot be added directly together because of the logarithmic scale. (WANG, X., 2010)

2.4. Vehicle Noise

When the vehicle generates power to accelerate, some of that power turns into sound power and spreads to the air during transmission, while some of it is in use and during production. The fractions of the current vehicle power converted to acoustic power are often too small. However, it is necessary to have some acoustic power to get a loud sound source.

The noise produced during vehicle work is examined in two categories; the noise transmitted in the air is called the noise in the air (airborne), and the noise emitted in the vehicle chassis is called the noise originating from the structure (structure-borne). There are two types of noise – broadband and narrowband, or pure tones. The broadband noise can be desirable or inappropriate depending on the frequency content, amplitude and structure-borne versus airborne content. The pure tones are almost always unpleasant.

In addition, resonances that lead to pure tones are examined in two types: structural or acoustic. Determining and correcting structural resonance is both easy. By matching the length of a channel with the wavelength of the objectionable tone with the method of an acoustic resonance. (WANG, X., 2010)

2.4.1. Airborne Sound

Even a simple air way is enough for sound to circulate comfortably in the air. For this reason, it is possible to pass sound even through high sound-proof barriers. For instance, a metal plate with a hole of only 13 percent of the overall area can transmit 97 percent of the sound. Furthermore, increasing and decreasing the mass of the metal block will have no effect on the transmission of sound. A good sound stream can be spread through a solid wall that is invisible to the eye cracks and diaphragms because air leaks are not capable of preventing transmission loss. Analogically, any flanking path will permit sound to travel around a barrier, toughly compromising its transmission loss. For instance, sound can easily travel from room to room through a traditional plenum or air retention channels.

A crack under a door or a wall penetration established by a loosely fitting electrical outlet box can compromise the insulating characteristics of an otherwise excellent partition. Air impermeability is critical for the isolation of airborne noises. In this context, the doors and windows of the settlement units should be avoided as much as possible, the walls of the apartments should be painted at all possible points and the holes and leak points should be sealed with sealing materials. Similarly, gaskets made of rubber material can be used in doors and other leakage zones. Even a robust design can be compromised by sloppy construction that will lead to degraded transmission loss below the design intention. (EVEREST and POLHMAN, 2009)

A random noise is created by a physical mechanism and then propagated. The physical mechanism could be:

- Hot displacement of fluid mass or volume (loudspeaker, exhaust tailpipe)
- Inconstant combustion (engine, furnace, boiler)
- Inconstant fluid transport (flow noise)
- Floating force on a fluid (fans, wires in a flow)
- Floating shear force (shear layer noise in a jet).

2.4.1.1 Airborne Noise Transmission Paths

The air, which is an acoustic transmission pathway, is different in other known transmission pathways. An example of a motor that works as a simple noise source is shown. If we assume the engine as an acoustic sound source (if the sound is caused by vibrations in the engine body), then the noise will be emitted in the air, the holes in the car chassis and the panels will help to dissipate it. At advanced levels, acoustic propagation will also include structural vibrations in the chassis, but the sound will still continue through the air (the noise outside the panel vibrates and produces noise inside the panel passenger compartment).Considering the arguments mentioned above, the airborne noise reduction focuses on the acoustic path, (special attention should be paid to prevent holes and leaks),on the structure (acoustic and vibration isolation should also work) and on acoustic absorption inner the cabin (this can also be done for structural noise, but common acoustic materials perform better in a high frequency range where noise prevails over the air).(WANG, X., 2010)

2.4.2. Structure-Borne Sound

Sound propagate very efficiency (with little attenuation) through dense materials, including such building materials as concrete and steel. Structure-borne noise such as vibration from outside traffic or HVAC (heating, ventilating, and air-conditioning) units, or even the effect of footsteps in a distant part of a building can easily reach an acoustically delicate room. Structure-borne vibrations can propagate walls and floors to vibrate, re-radiating energy airborne noise. Undesirable sounds can invade a room by mechanical transmission through solid structural members such as wood, steel, concrete, or masonry. Structure-borne noise is thus most adequately controlled at the source of the noise. Massive, rigid partitions such as concrete walls are most helpful for attenuating airborne noise, but offer little resistance to structure-borne noise. On the other hand, lightweight materials offer little protection versus airborne noise, but can be used to decouple factors of structures, and are thus effective against structure borne noise. (EVEREST and POLHMAN, 2009)

A random noise generated by structural reactions is actually created by the forces fluctuating and separated from the structure by sound radiation. The collaborative indirect sound sources on vehicles are:

- Casing vibration
- Bearing noise
- Electric motor or generator noise
- Belt, chain or gear drives
- Internal combustion engine structural noise.

2.4.2.1. Structure-Borne Noise Transmission Paths

The structure - borne is actually a vibration transmission pathway that is propagated by panels located in the structure of the cabin of noise. In a simple example, the vehicle engines work as a source of noise and vibration during the vehicle operation, the vibration energy emitted by the engine will be transferred to the vehicle chassis by means of wedges used in motor & chassis connections, and then the vibration will be transferred from the vehicle body to the passenger department panels. The vibration in the panels of the car body will be transmitted as energy to the air cavity inside the cabin and will turn into noise perceived by passengers. Structural-borne noise focuses mostly on the structure and isolation of the vibration considering the formation and progression of the vibrations mentioned above. In this instance the engine mounts play a significant role in the attenuation of the level of vibration, the vehicle structure should have a low hypersensitivity to the forces coming from the mounts, and the panels should have a low radiation efficiency and possibly be damped to minimize their levels of vibration. (WANG, X., 2010)

2.5. Noise in Hydraulic Systems

The power transmission and control provided by a pressurized fluid is becoming more and more prevalent in every branch of the industry. The hydraulic system has been the preferred power transmission source for most industrial and mobile equipment due to its advantages such as power density, compactness and rapid response. Fluid power systems have an extensive range of applications which include industrial, off-road vehicles, automotive systems, and aircraft. But, one of the main challenges with the hydraulic systems is the noise generated by them. The health and safety problems relating to noise have been recognized for many years and legislation is now placing clear demands on manufacturers to minimize noise levels. (EDGE, 1999)

2.5.1. Fluid borne Noise (FBN)

Among the positive displacement pumps, highest degree of FBN are generated by axial piston pumps and lowest degree by screw pumps and in between these lie the external gear pump and vane pump. An axial piston pump has a fixed number of displacement chambers arranged in a circular pattern dissimilar from each other by an angular pitch equal to:

$$\emptyset = \frac{360}{n} \tag{2.6}$$

Where n is the number of displacement chambers.

When emptying a specific volume of liquid in each chamber, discharge at the pump outlet is made up of all discharges in individual chambers. The discontinuity in the stream between adjoining rooms causes a kinematic flow fluctuation. It can be easily determined given the width of kinematic fluctuation, the size of the pump and the number of displacement chambers. Kinematic fluctuation is the main cause of fluid induced noise. Kinematic fluctuations are a conceptual value. The actual flow fluctuation in the pump output is much greater than the conceptual value, because kinematic fluctuation is combined with the compressibility element resulting from fluid compressibility. These ripples (also referred as flow pulsations) generated at the pump are transferred through the pipe or flexible hose connected to the pump and travel to all parts of the hydraulic circuit.

2.5.2. Structure borne Noise in Hydraulic Systems

In swash plate type pumps, the main sources of the structure-borne noise are the fluctuating forces and moments of the swash plate. These fluctuating forces originate as a result of the fluctuating pressure inside the displacement chamber. As the displacing components move from suction stroke to discharge stroke, the pressure varies accordingly from few bars to few hundred bars. These pressure changes are reflected on the displacement components (in this case, piston) as forces and these force are exerted on the swash plate causing the swash plate to vibrate. This vibration of the swash plate is the central cause of structure borne noise. There are other elements in the system which also vibrate and lead to structure borne noise, but the swash is the main contributor. (EDGE, 1999)

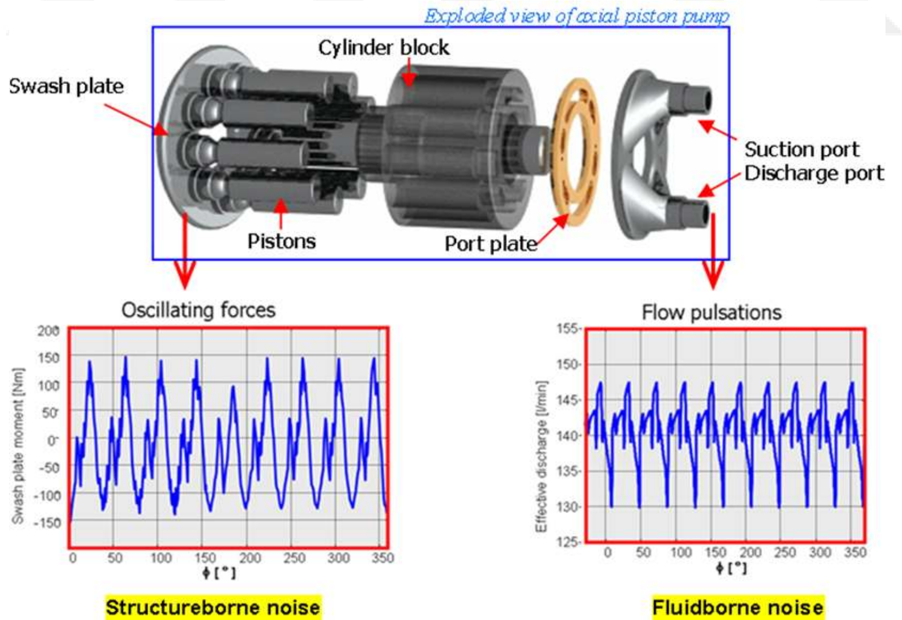


Figure 2.4. An Exploded View of Axial Piston Pump and Flow Pulsations and Oscillating forces on Swash Plate. (EDGE, 1999)

3. LITERATURE REVIEW

In his study, Panza (2015) has described about noise mapping techniques which acoustical holography, transfer path analysis (TPA), order tracking that are considered the most appropriate experimental techniques to analyze and detect NVH sources in a vehicle. Focused on noise sources and transfer path analysis within the vehicle, which is the main objective of the experimental techniques of NVH studies in the study. In addition, he has included in his work on structural measurement techniques, experimental modal analysis, operational modal analysis and deflection analysis. Another important factor to consider in the study is the quality of noise. Some of the most frequently used sound quality and psychoacoustic metrics for user's perception in a vehicle are articulation index (AI), loudness and sharpness. Explanations of these samples with sound quality measurements and measurement methods unit and formulas are explained. The sharpness is another important measure that takes into account the frequency content of the noise that has included study, it is defined as the ratio between the high frequency noise level and the overall level; it is not related to sound intensity, but it is high for metallic noise components that are generally considered annoying. It is stated in this study that the results of many experimental techniques which can be used in the studies of determining vehicle noise and vibration characteristics which are used as a result today are revealed.

Panda (2016) aimed of his study is to provide a dip into of literature on the analysis techniques and validation methods used to address NVH subject in power-train systems, and also it covers the analysis procedures on present and future tendency. Intended at this study, showing the development of power-train NVH analysis, present practice and proposed recent ways to deal with forecast, process of characterization and reduction of low and mid frequency noise in the automotive industry. In the study of the subject was discussed description and examples of finite element analysis methods used in power transmission systems. NVH analysis can be implement using 3D FEA analysis, 1D analysis and Multi body dynamic analysis. Frequently used procedures in the power-train NVH necessity, takes quite a long time due to detailed FE model prerequisite of a complex system like power-train, are power-train bending analysis, power-train forced response analysis and power-train mount vibration analysis. In the study, development in resolving vehicle NVH issues using analytical and experimental tool was taken into consideration under 3 main headings; power-train bending induced vehicle NVH concerns at high RPM, exhaust modes induced - idle boom vibrations, regular vehicle speed moaning noise and driveshaft modes and axle gear mesh force induced axle whimper noise. Another analysis procedure can be used for NVH analysis is transfer path analysis (TPA) has been on the subjected in study. This procedure gives net knowledge on which structural path propagate how much noise. The Multi Body Dynamics (MBD) model is another subject included in the work. As the FEA analysis can't model the large deviation at bushings, hinges and joints, MBD analysis has been preferable for studying these dynamics. According to the conclusions of new challenge in system level NVH analysis of a power-train system and different analysis techniques need to be evolved to address requirement. The required steps for an integrated coupled flex-body MBD simulation is listed as follows:

- Structure the detailed MBD model
- Set up appropriate connection between components and subsystems, define flex-body parameters
- Implement the suitable loads and boundary conditions
- Amalgamate 1D models using co-simulation
- Transference the surface vibrations to BEM model
- BEM analysis
- Results: SPL, Radiation efficiency

In Balaban (2010) study, a tractor with a four-cylinder diesel engine is focused on determining noise sources. Using sound power level determination methods, spectral analysis of noise data and sound intensity measurement techniques, the collects data from the tractor's front right, front grille and front left sections. Balaban (2010) explained the methods of active and passive noise control systems and gave examples about these studies. The study emphasizes the importance of vibration isolation in noise control. The noise sources were identified as cooling fan exhaust pipe muffler and engine within the information obtained in the data of the tractor in operation. In the improvement study, the cooling fan was chosen to have a higher blade angle to reduce the flow induced noise. In addition, new helical gear sets are used in order to reduce the noise level for drive train noise level. In addition, an isolation element is used between the exhaust pipe and the mounting platform, and the sound intensity measurement is also reduced. Using the noise intensity measurement and noise control techniques, Balaban (2010) provided a 3 dB improvement in the pass-by noise level and the operator's ear noise level of the tractor. The engine silencer can be analyzed acoustically with the help of suitable software and future work may include exhaust pipes and silencers was highlighted at the end of the study.

Eisele et al (2005), application of vehicle interior noise simulation (VINS) in the vehicle NVH growth process was described in their research. A case study on a minivan was used to indicate the benefit of the VINS technique. With the major structure-borne and airborne noise paths included, a good relationship between simulated and measured noise was achieved. The VINS technique allows the separation of the interior noise into the individualistic noise shares for root cause specification and subsequent problem resolution. The case study highlighted the effect of a stiffened roll restrictor and the simulation result was approved through a vehicle interior noise measurement. The effect of control arm bushing modifications on the interior noise was also conjectural. At study, forthcoming efforts will be aimed at modeling power train stimulations analytically, and substituting the modules which were primarily empirically determined. In this way, the synchronization tool for non-simultaneous excitation measurements can also be used for analytically reproduced signals.

Lumnitzer and Bilova (2011) conducted a research on advanced techniques used to determine the acoustic character of noise absorbers. The purpose of this study is to determine the acoustic parameters of sound absorbing materials and to define these parameters. The methods of determining these parameters were defined in the ongoing sections of the study. Acoustic parameters are listed as follows:

- Sound absorption coefficient
- Sound pressure reflection
- Sound pressure etc.

In addition, critical material properties that affect absorption performance in the study are listed as ongoing list.

Material properties:

- Density
- Porosity
- Tortuosity

System properties:

- Total thickness and surface
- Presence of membrane
- Presence of layers, including skin.

In this study, impedance tube method, which is one of the classical measurement methods, was described with figures and formulas. The history and principles of the method were mentioned in detail. The advantages of this method are accurate and speed. Another classical type of measurement, Alpha cabin test technique is also included in the study. The conditions, room sizes and how the sound absorption coefficients of the sample insulation material were determined were explained in detail.

The micro flown technique described as advanced measurement technique within the scope of the study is explained at the end of the study. The Microflown technique to detect impedance, absorption and reflection makes use of a Microflown particle velocity sensor and a sound pressure microphone. Both sensors are mounted in the mini probe that is positioned close to the material with a sound source positioned at a certain distance. The sound pressure and acoustic particle velocity are measured right at the surface of the material. The impedance can be derived from the ratio of sound pressure and particle velocity. From this, the material reflection and absorption can be calculated. The disadvantages of classical techniques and advantages of micro flow technique are listed as follows as the final declaration of the study:

- The disadvantage of the impedance tube is that the tube is suitable only at a 90 degree angle and the frequency limits are indicated.
- The disadvantage of the alfa cabin is the cost and the need for a large sample and test area.
- On the other hand, the advantages of microflow technique are the ability to measure in real time and show wide angle, frequency range.

Haverkamp (2000) conducted a research on solving the vehicle noise problem with the transmitted sound energy analysis. At the entrance of the study, loss of sound transmission is defined and information on the effects on sound control is given. In this study, sound transmission loss was visualized with defined figures and represented by formulas. It was noted main advantage of this method is that it is also applied to acoustics of buildings, the total power is stated to be measurable with a few microphones without full radiation direction knowledge. In the later parts of the study, the measurement of the loss of sound transmission on the components of the vehicle body was taken into consideration. In this section details the air-borne and structural borne excitations behavior of the vehicle dashboard. Modifications were made on the panels of the vehicle dashboard using damping layers. The result is a reduction of the sound radiation that the application of damping layers, here causing a total reduction of> 3dB. Another study has been done on the prevention of the noise of the airborne formed by the tires. The resonance effect can completely be reduced by insertion of absorbent material into the cavity. The results showed that application of material which is feasible for long term road conditions will solve the 230 Hz road noise problem. Finally, it is stated that measurement and analysis techniques can be used as a good tool in acoustical systems and very accurate results can be obtained when they are taken into consideration.

Esenboğa (2014) has conducted an improvement study on the development of thermal and acoustic insulation of a bus. In Esenboğa (2014) study, he made heat, noise and vibration detection on a 3-axle automobile and made the appropriate insulation selection in the light of the results. The basic principles of acoustics and vibration are explained at the beginning of the work. These explanations are supported by formulas. Esenboğa (2014) shares the phases of a vehicle design in the advanced parts of the run. This prospectus describes how the car's acoustics and vibrations are handled and how they are handled while the vehicle is being designed. In the study, the tests were done before and after the installation of the bus insulations and the results were compared. The result report of the operation indicated that the internal sound quality of the bus was increased.

It was stated that the thermal insulation on the engine exhaust was treated effectively with the isolation study. A bus with a reduced noise level of 3-5 dB is obtained.

4. MATERIAL AND METHOD

This thesis aimed to reduce the noise level of cabin interior the diesel hydraulic crawler excavator with the help of sound isolation and sound barriers for the cabin. In line with this objective, the first tests were carried out, the excavator's sound sources were determined, the cabin openings were determined and the appropriate sound isolation and sound absorbers were used.

4.1. Material

4.1.1. Acoustic Isolation Material

The effects of acoustic insulation in the engine compartment and the hydraulic pump used in the engine compartment, which are sound sources, together with the glass, adhesives and panels used in the cabin in order to determine the internal sound level of the excavator cabin are also very important. Besides, in this thesis, synthetic sound barrier will be used in the excavator cabin floor and the effect will be examined.

4.1.1.1. Closed-Cell Polyethylene Foam

Closed-cell, noise-ısolation polyethylene foam with low density. Particularly applicable for applications where contact with humidity is feasible. Applications; machine construction, heating/ventilation/AC systems, cabins, rail vehicles, sound conditioning, ship building (CELLOFOAM, 2017)

Table 4.1. Technical Data of Closed-Cell Polyethylene Foam

Technical Data	
Temperature Resistance	-50°c to +100°c
Thermal Conductivity / ISO 8301	≤ 0.082 W/(m.K) at -5°c
Density	25 kg/m³
Water Absorption	< 4% Vol.
Thermal Stability	24 hours < 3% at 70°c

Figure 4.1. Cross Section of Closed-Cell Polyethylene Foam.

Benefits:

- Remarkable resistance against chemicals
- Dirt-repellent and effortless to clean
- Very good stability and durability
- Good resistance against humidity, freezing temperatures and impurity
- Does not offer a substratum for the development of bacteria or mold
- Corrosion prevention of covered metal sheets
- Excellent performance values for low and medium frequencies
- Can be completely recycled using standard industrial procedure
- Thanks to its engineered structural characteristic, this foam reaches sound attenuation values that are generally only obtainable with much heavier acoustic materials.(CELLOFOAM,2017)

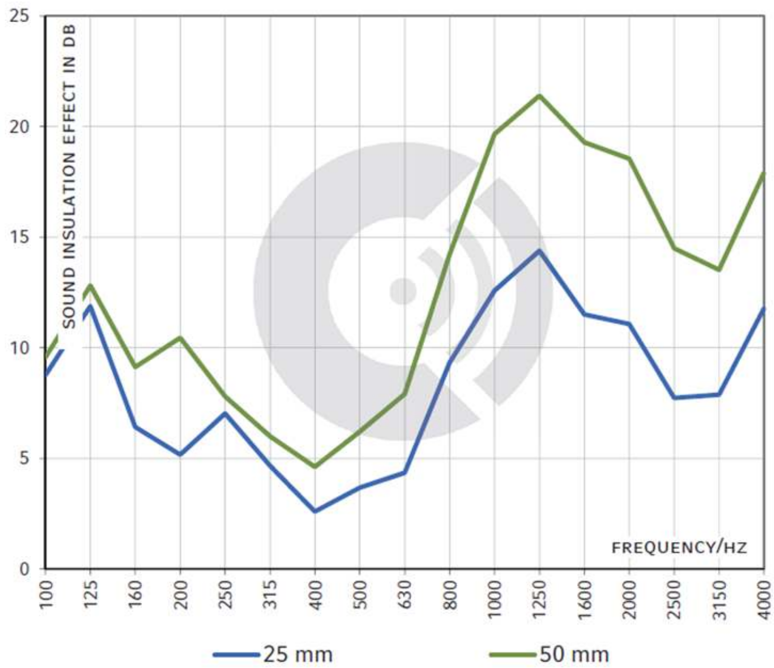


Figure 4.2. Sound Transmission Loss Graph of Closed-Cell Polyethylene Foam According Test Procedure to ISO 10140-2

4.1.1.2. Synthetic Sound Barrier

Heavy layers, comprise of a blend of synthetic materials on the basis of EPDM/EVA polymers, with compound of special flame-retardant minerals. Applications; house hold appliances, heating/ventilation/AC systems, machine construction (CELLOFOAM, 2017).

Table 4.2. Technical Data of Synthetic Sound Barrier

Technical Data	
Temperature Resistance	-50°c to +100°c, short-term up to +120°c
Thermal Conductivity / ISO 8301	≤ 0.147 W/(m.K) at 10°c
Weight	6 kg/m² ± 10%
Hardness / ISO 868	70 ± 5 Shore

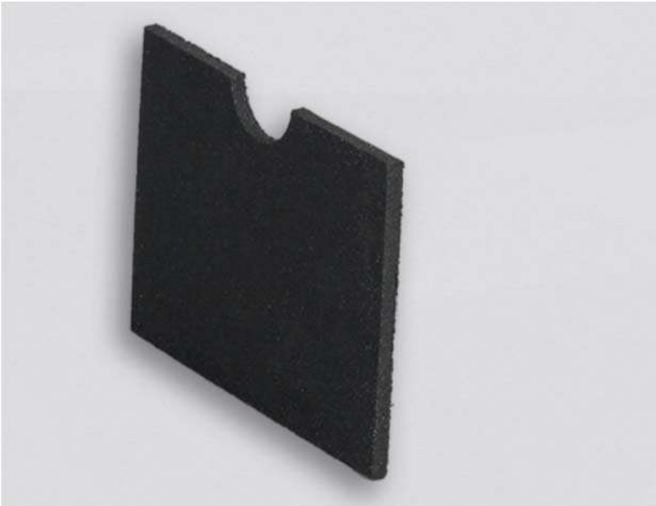


Figure 4.3. Cross Section of Synthetic Sound Barrier

Benefits:

- Remarkable sound insulation values
- Very good flammability properties
- Excellent temperature resistance than a bitumen layer
- Odorless even when warmed (in contrast to bitumen layers)
- Elastic, not sensitive to pressure, will not emit particles or cause smudges (CELLOFOAM,2017)

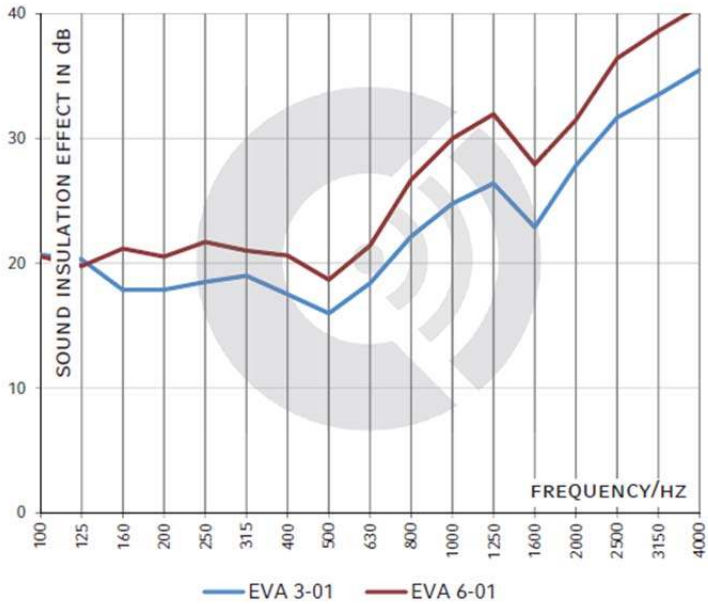


Figure 4.4. Sound Transmission Loss Graph Synthetic Sound Barrier According Test Procedure to ISO 10140-2

4.1.2. Acoustic Absorbent Material

Noise reduction solutions in a vehicle cabin it is the absorption of the energy of acoustic wave. This method is widely used in today's automotive industry. For the hydraulic crawler excavator model used in this thesis, sound absorbent materials were used and improvements were observed in the cooling pack department, air filter service cover and cabin trim zones.

4.1.2.1. Polyethylene Foam

Dark-gray polyethylene foam scores with very good chemical resistance contra carbon hydrides, alcohols as well as the fact that its water absorption is below 1 vol. % and high noise absorption property, remarkable temperature resistance and very good fire performance (CELLOFOAM, 2017)

Table 4.3. Technical Data of Polyethylene Foam

Technical Data	
Temperature Resistance	-50°c to +100°c
Thermal Conductivity / ISO 8301	≤ 0.035 W/(m.K) at -5°c
Density	28 kg/m³
Water Absorption	< 1% Vol.

Benefits:

- Remarkable thermal insulation effect
- High sound absorption characteristic
- No water sorption
- Excellent chemical resistance against carbon hydrides and alcohol
- Effortless to cut with a cardboard cutter. (CELLOFOAM,2017)

Figure 4.5. Cross Section of Polyethylene Foam

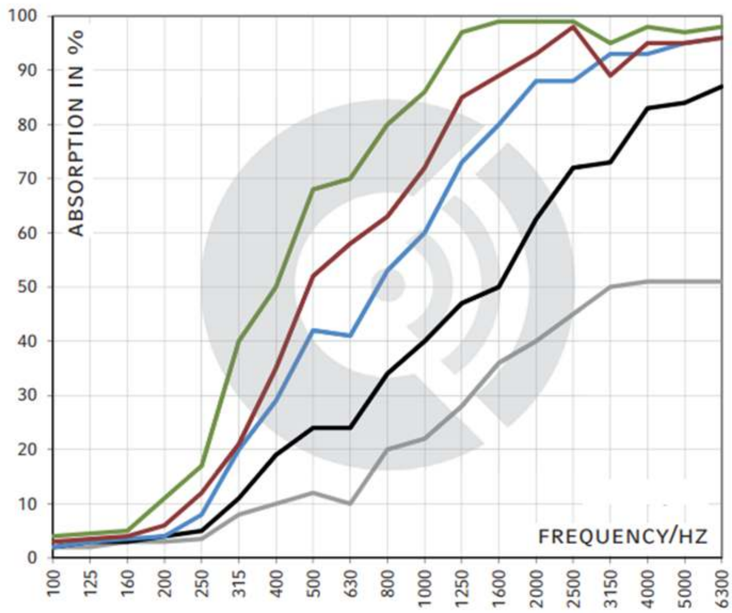


Figure 4.6. Sound Absorption Graph Polyethylene Foam According Impedance Tube / DIN 10 534-2

4.1.2.2. Oil and Water Repellent Polyester

Oil and water repellent polyester non-woven laminated the polyester scores with remarkable fire characteristic values and a surface that is impermeable to oil, water and fuels. Applications; machine construction, rail vehicles, shipbuilding (CELLOFOAM, 2017)

Table 4.4. Technical data of Oil and Water Repellent Polyester

Technical Data	
Temperature Resistance	-50°c to +100°c
Thermal Conductivity / ISO 8301	≤ 0.035 W/(m.K) at 10°c
Density	24 kg/m³
Water Absorption	< 2% Vol.
Tightness/ECE R-118.01	Diesel, oil and water coming into contact with the surface cannot seep into the non-woven.

Benefits:

- No long-term humidity keeping
- Remarkable protection against water splashes
- In vibration tests, the fiber composite showed no tendency to break up
- The aluminum foil prevents the material against the penetration of liquids, ensuring that the materials meets the highest hygiene requirements
- Does not provide a substrate for mold and fungal growth
- Remarkable sound absorption values

Figure 4.7. Cross Section of Oil and Water Repellent Polyester

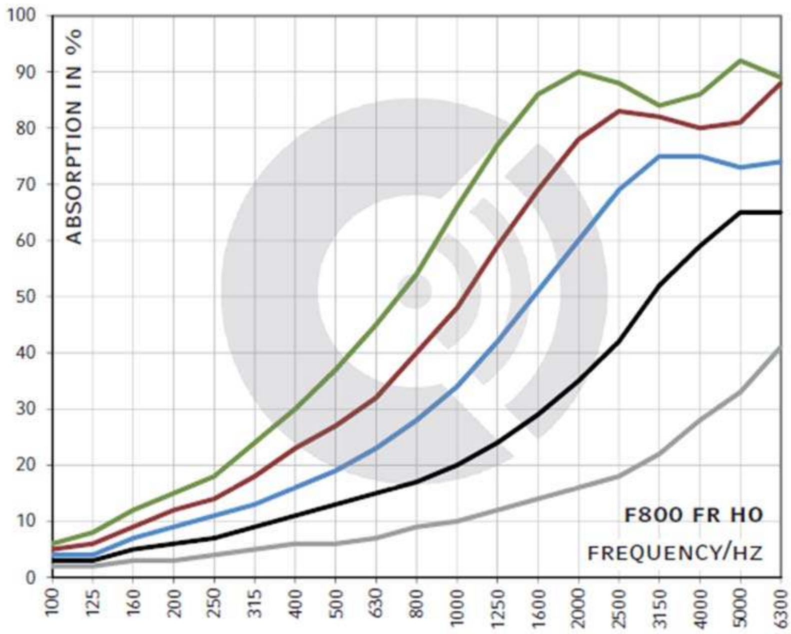


Figure 4.8. Sound Absorption Graph Oil and Water Repellent Polyester According Impedance Tube / DIN 10 534-2

4.1.2.3. Pur-Ether Foam

Dark grey, robust pur-ether foam, laminated with a sound-absorbing black non-woven. Ether foams are suitable for utilization involving relatively high humidity levels. Applications; machine construction, heating/ventilation/AC systems, cabins, rail vehicles, sound conditioning, shipbuilding. (CELLOFOAM, 2017)

Table 4.5. Technical Data of Pur-Ether Foam

Technical Data	
Temperature Resistance	-50°c to +100°c
Thermal Conductivity / ISO 8301	≤ 0.040 W/(m.K) at -5°c
Density	23 kg/m³

Benefits:

- Oil-/water-repellent and mechanically tremendously robust surface layer
- Visually appealing robust design
- Suitable for utilization with relatively high humidity levels, where ether foam has a better ageing resistance than ester foam.
- Straightforward to cut with a cardboard cutter.(CELLOFOAM,2017)

Figure 4.9. Cross Section of Pur-Ether Foam

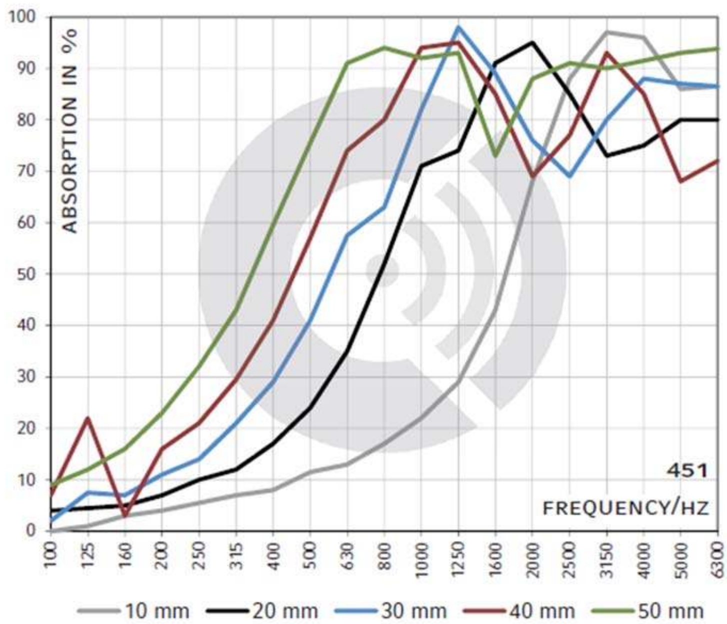


Figure 4.10. Sound Absorption Graph Pur-Ether Foam According Impedance Tube / DIN 10 534-2

4.1.2.4. Cross-Linked Polyethylene Foam

Dark grey, cross-linked polyethylene foam with closed-cell structure. Thickness: 20mm.

Table 4.6. Technical Data of Cross-Linked Polyethylene Foam

Technical Data	
Temperature Resistance	-50°c to +100°c
Thermal Conductivity / ISO 8301	≤ 0.036 W/(m.K) at 10°c
Weight	33kg/m² ± 10%
Hardness / ISO 868	54± 5 Shore
Tensile Strength / ISO 1926	min. 174 kPa
Water Absorption	< 1% Vol.

Figure 4.11. Cross Section of Cross-Linked Polyethylene Foam

4.1.3. Test Equipment

4.1.3.1. Dewesoft Data Acquisition

Dewesoft A43 data collector is a high-performance laptop. Dewesoft ensuresreal time sound level calculations according to the international standards. Any combine of frequency and time weighting can be calculated. The statistical values are calculated over the whole range or with the usual specific entered block size.The invariable percentage band filters work in real-time (true octave) and provide 1/1, 1/3, 1/6, 1/12, 1/24 band octave spectrum. With the array statistic matehmatics it’s easy to extract min/max/avg values over the total spectrum or a specific frequency range. Plugin supports the sound power measurements according to ISO 3741, ISO 3744 and ISO 3745. The microphone positions are calculated by the software, depending on the Size of the sound source and configuration.

Figure 4.12. Dewesoft Data Acquisition Systems Material Examples

Since the main focus of Dewesoft is on data acquisition and storage, it has comprehensive support for exporting the data to other file formats for post processing. It has opportunity of choose different export file types, use scripting for direct reporting and export raw, reduced or angle based data. Dewesoft offers templates with Flexpro, MS Excel and Famos. These templates allow you to prepare the reports once and execute them after Dewesoft data export. In this way you can automate report generation and facilitate the measurement process. (DEWESOFT, 2017)

4.1.3.2. Integrating Sound Level Meter

The sound level meter is the instrument that measures the sound level. Generally, it is made up by a microphone, the sound sensitive element, by an amplifier, by a signal processing entity and by a reading and data display entity. The microphone transforms the sound signal into a corresponding electrical signal. The sensitivity of microphones for level measurements does not depend on the sound signal frequency. The option of the type of microphone is generally based on the condenser type that grants remarkable features like accuracy, stability and reliability. The amplifier is essential to bring the electrical signal to a measurable amplitude and to strengthen the signal to allow cable transmission. The processing entity takes care of calculating all measuring parameters essential to characterize a sound event. In this thesis, Delta Ohm brand HD-2010 model sound level meter will be used.

The Delta Ohm HD-2010 is an integrating portable sound level meter performing statistical analyses. The instrument has been designed compound price competitiveness and simplicity of use. Attention has been paid to the possibility of updating the instrument, and the it can be integrated, at any time, with other options like data logger to extend its application range.

The Delta Ohm is an integrating sound level meter and analyzer suitable for the following applications:

- Assessment of the environmental noise level,
- Occupational noise measurements at the work-area
- Measurement at the work-area,
- Selection of personal protective materials,
- Manufacturing quality control,
- Measurement of machine noise.
- Environmental noise monitoring,
- Analysis of sound events,
- Complete statistical analysis with percentiles calculation
  (DELTA OHM, 2012)

Figure 4.13. Delta Ohm UD-2010 Sound Level Meter

4.1.3.3. Fog Machine

Before testing, fog machine is used in order to observe the openings of excavator cabin and to take precautions for openings. With the fog machine, it is possible to determine the cabin frame openings, wick assembly defects and cabin floor openings easily. In this thesis, the antari brand W-508 series remote control fog machine will be used.

Figure 4.14. Antari W-508 Fog Machine

4.1.4. The Test Crawler Excavator

Excavator is a hydraulic machine used in generally construction industry. However, it is also used in different sectors such as forestry and mining. The excavator is moving with wheels or pallets on undercarriage. Excavators have counterweight mounted on the rear part of the upper chassis, which give the excavator additional lifting capability and force for digging. In addition, excavators balance during swinging and digging with this counterweight. Thus it can take easy and reliable maneuvers at the time of operation. Diesel engines are generally used as power generators in the excavators used today. But in the near future, diesel engines will be replaced by fuel cells are believed to be.

Hydraulic system is driven by a hydraulic pump which gives the ability to move the excavator components. This hydraulic pump is mechanically connected to diesel engines. The main function of the excavator engine is to drive the hydraulic pumps that provide oil at a high pressure to the slew motor, rams, track-motors, and several accessories. Excavator's mobility is achieved by hydro-motors which are installed in the under-chassis. The hydro-motors move with the high pressure oil they receive from the hydraulic pump to the pallets.

The excavators are equipped in the upper frame with engine, oil and fuel tanks, cabin, air filters, exhaust, electrical equipment, cooling units and also hydraulic components. As hydraulic equipment, a hydraulic pump for pumping hydraulic oil to the hydraulic systems, a hydraulic control valve for controlling the direction and pressure of the oil in the hydraulic system, one swing-motor providing independent rotation of the lower and upper chassis, and a hydraulic connection between the upper-chassis and the undercarriage. A swing bearing is used to allow the lower and upper chassis mounts to move independently of each other.

The front attachment group consists of boom, arm and usually buckets. Mostly, the boom can move only up and down, or in additional so shift towards the left and right of the machine. An arm is attached to the boom end that imparts the force for digging into the ground. A bucket is fixed at the arm end for carrying the soil. In addition, there are numerous other categories of attachments with the excavator that are used, for boring, crushing, lifting, and ripping. In addition to the mentioned, there is a cabin where the excavator movements are controlled and the operator is positioned. Figure 4.15 and Table 4.16 show the components of a typical excavator.

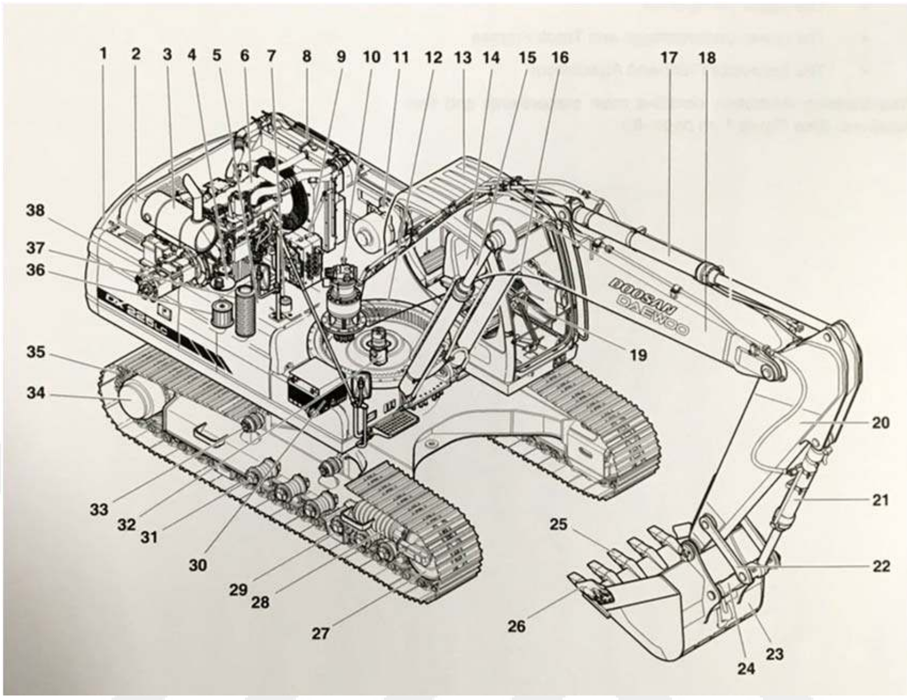


Figure 4.15. Component Visuals of a Typical Crawler Excavator (Doosan Service Manuel, 2014)

In this thesis, hydraulic crawler excavator was used that have water cooled,4-stroke,6-cylinder,direct injection diesel engine, 2 variable displacement, axial piston pump., maximum pump flow is 268 liters / minute. In addition, there is a pilot pump with gear type 30 liter/ minute flow rate feeding pilot system. Working weight of excavator is 31500 kilos. Excavator hydraulic work pressure is 350000kPa.Table 4.7Table 4.8 and Table 4.9 transfer technical information about the M300 LC excavator.

Table 4.7. List of Components a Typical Crawler Excavator

Reference Number	Description	Reference Number	Description
1	Counterweight	20	Arm
2	Hood	21	Bucket Cylinder
3	Muffler	22	Guide Link
4	Hydraulic Oil Tank	23	Bucket
5	Fuel Tank	24	Push Link
6	Engine	25	Tooth Point
7	Fuel Tank Fill Cap	26	Side Cutter
8	Radiator and Oil Cooler	27	Idler
9	Control Valves	28	Track Adjuster
10	Swing Motor	29	Track Guide
11	Air Cleaner	30	Battery
12	Swing Bearing	31	Lower Roller
13	Cabin	32	Center Joint
14	Seat	33	Upper Roller
15	Boom Cylinder	34	Travel Motor
16	Work Level Controls	35	Track Link and Shoe
17	Arm Cylinder	36	Suction Filter
18	Boom	37	Return Filter
19	Travel Lever	38	Pumps

Table 4.8. List of Working Pressure of Test Excavator

Working Pressures	kPa
Standard Operation Pressure	350000
Track Pressure	330000
Swing Pressure	285000
Pilot	30000

Table 4.9. List of Engine Specification of Test Excavator

Engine Specification	Description
Brand	Deutz
Model	DEUTZ L06 2V
Cylinder Number	6
Diameter x Stroke	108x130 mm
Volume	7.150 cc
Maximum Power	160 kW / 214 HP (2000 rpm)
Maximum Torque	952 Nm (1500 rpm)

Table 4.10. List of Track and Brakes Specification of Test Excavator

Track and Brakes Specification	Description
Type	Hydrostatic
Track Motor	2 Speed Step/Axial Piston
Track Speed	3.1 / 4,8 km/h
Climbing Capability	35° (70%)

4.2. Method

4.2.1. Determination of Appropriate Acoustic Materials

As mentioned in the first parts of the thesis, there are two types of noise sources in an excavator, airborne and structure-borne noise. Control of airborne noise can be achieved in two ways; sound isolation and sound absorption of excavator cabin.

The first action is to avert acoustically energy outside the cabin from entering the cabin, whereas, the second acts to the reduction and absorption of acoustic energy remaining in the operator compartment. In this thesis, acoustic materials of prototype machines were selected considering these two main headings.

The sound isolation capability of a given partition is very significant for airborne noise transmission in a vehicle as most of the acoustic sources are outer to the cabin: a good level of isolations then a good starting point to reduce the interior noise. This acoustic isolation capability of the structures is measured by the description of the sound transmission loss (TL):

$$TL(\beta, f) = 10\, log \frac{W_{in}(\beta,f)}{W_{out}(\beta,f)} \tag{4.1}$$

β is the angle of incidence of the sound wave over the surface of the given partition
f is the frequency of the considered sound wave
W_{in} is the sound power incident at the source side
W_{out} is the sound power radiated at the opposite side of the partition.
(WANG, X., 2010)

Another significant description for characterization of an acoustic material is the energy absorption coefficient (α) which is defined as the ratio between the absorbed acoustic energy and the whole incident acoustic energy. In all the reflections of acoustic waves on a surface the energy is partly reflected and partially absorbed by the material, and this coefficient represents the feature of the material to absorb the acoustic energy. The value α = 1 means that all the energy is absorbed, so there are no reflected waves by the surface; a value α = 0 means that there is perfect reflection, without any loss of energy.

The coefficient α depends on the material characteristic and the thicknesses of all the layers applied on the surface (absorbing materials, air gaps, etc.).Also, α is generally a function of the frequency and the angle of incidence of the sound wave, as in the case of the TL.

Another significant property is the density of the material and its ‘porosity’ (Φ):

$$\Phi = \frac{V_a}{V_m} \tag{4.2}$$

where:

V_a is the volume of the air included in the material

V_m is the total volume of the material, including the air inside it.

The flow resistance is related to the porosity, the fibre diameter and these-called ‘structure factor’ or ‘tortuosity’, which depends on tortuous paths that the air has to follow crossing the material: it takes into account the effect of openings that are perpendicular to the dissemination direction of the sound wave.

Another parameter, significant only for materials with a consistent structure, is the ‘volume coefficient of elasticity of the skeleton’ (*Q*), which measures the compression stiffness of the material: it is measured using flat layer of material (with a thickness *d*) compressed with a force (*F*) that acts homogeneously on the entire surface of the material (of area *S*). The measurement of the thickness reduction (Δd) gives the coefficient *Q*:

$$Q = \frac{F}{S}\frac{d}{\Delta \mathrm{d}} \tag{4.3}$$

Another property of materials for noise control applications is the ‘loss factor’ (η), which is important for the reduction of the structure vibrations. It comes from the measurement of the complex Young modulus (*E*) of the material subjected to a dynamic load:

$$E = E' + iE'' \tag{4.4}$$

$$\eta = \tan \delta = \frac{E''}{E'} \tag{4.5}$$

where:

E' is the 'storage modulus' (real part of the complex Young modulus)

E'' is the 'loss modulus' (imaginary part of the complex Young modulus)

$\delta$is the phase angle.(WANG, X., 2010)

4.2.2. Cabin Fog Test

The excavator cabin is subjected to fog testing to determine the cavities in the cabin before measured the interior sound pressure level of the excavator cabin. The welding cavities in the cabin frame, the hydraulic hose transition region in the cabin floor, the electrical wiring transition region, the hose transition region of the air conditioning unit, the emptying of the travel valve in the cabin floor and the connections, as well as the glass mounting adhesives and mounting problems of the wicks used in doors and sunroofs can cause cabin openings.

It is crucial to determine these openings to identify how isolated cabin interior is from noise sources outside. The correct measurement will not be taken unless the cabin interior is healthy insulated from the outside environment. Otherwise, sound waves will continue to propagate through the gaps and insulation and sound absorbers placed inside the cabin will not be able to perform their functions.

In order to determine cabin openings, a fog test will be performed on a machine where all cabin interior trim materials have been assembled. The fog machine placed inside the cabin will be operated in the highest mode and the inside of the cabin will be fully filled with fog. Fully foggy cabin will be observed for 10 minutes, during this time fog will be detected through the cabin openings. The cavities will be closed with solutions such as gromes and sealing before noise testing. Thus, the possible problems to be experienced in the measurement of the internal sound pressure level in the cabin are hindered.

Figure 4.16. Test Equipment Installation for Excavator Cabin Fog Test

Figure 4.17. Test Equipment Installation for Excavator Cabin Fog Test

4.2.3. Determination of Sound Pressure Level -Dynamic Test Conditions

Sound propagation in air can be juxtapose to ripples on a pond. The ripples spread out homogeneously in all directions, decreasing in amplitude as they act further from the source. For sound in air, when the distance doubles, the amplitude drops by half which is a drop of 6 dB Thus, if you are at a position one meter from the source and act one meter further away from the source, the sound pressure level will reduce by 6 dB. If you act to 4 meters, it will reduce by 12 dB, 8 meters by 18 dB, and so on.

However, this is only true when there are no deflector or blocking objects in the sound transfer path. Such ideal circumstances are termed free-field conditions. With a hindrance in the sound path, part of the sound will be reflected, part absorbed and the remainder will be transmitted through the object. How much sound is reflected, absorbed or transmitted depends on the characteristic of the object, its size and the wavelength of the sound. Commonly, the object must be larger than one wavelength in order to considerably disturb the sound. (Brüel & Kjær, 1984)

The excavator has a diesel engine and hydraulic gear pump as sound sources. These two main elements are the main sound sources in the excavator. Noise is transmitted by air and by structure. However, the skeletal structure and service covers in the excavator design constitute an obstacle for the progression of the sound propagation.

In this thesis, the sound pressure level test conditions external of excavator will proceed in accordance with the conditions specified in TS ISO 6395. (Earth-moving machinery -Determination of sound power level -Dynamic test)

This standard covers a method of detecting noise emitted to the environment in terms of A-weighted sound power level when construction and excavation machines operate in dynamic experimental conditions.

As test conditions, moisture, air temperature, barometric pressure, vibration and magnetic field leakage are within the limits set by the manufacturer of the device.It is assumed that the ambient correction factor is less than or equal to 0.5 dB, and therefore neglected for the surface of the test site from a rigid reflective plane such as concrete or non-permeable asphalt, which has obstacles that do not reflect sound within the distance from the source at a distance equal to three times the radius of the In this case, the environment correction factor assumed to be equal to 0 dB.

The experiment site, which is limited to vertical projection of the microphones to the ground, is chosen from concrete or impermeable asphalt. The surface of the measurement to be used for the experiment is in the form of a hemisphere. The radius of the hemisphere is determined by the basic length of the excavator (*L*), as indicated in Figure 4.18.

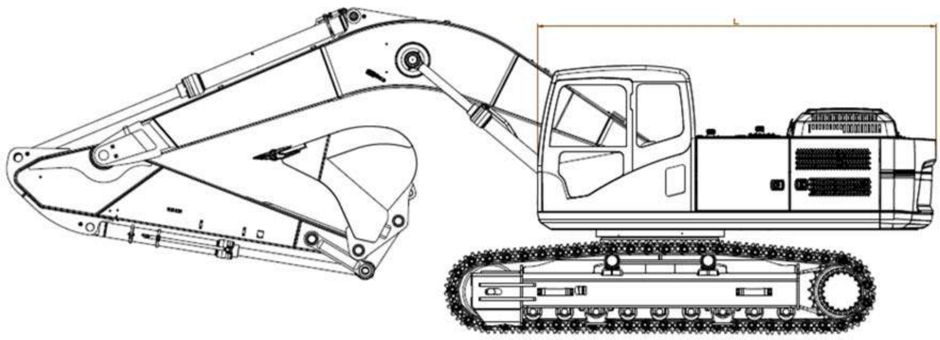


Figure 4.18. The Basic Length (*L*) of Excavator

The basic length of the machine to be subjected to experiment (*L*) is greater than or equal to 4 m, but less than 8 m, the half-diameter of the hemisphere was determined as 16 meters. As the center point of the hemisphere, the center of the swing bearing used in the combination of the upper and lower chassis, which is the center of the axis of the excavator swing, is selected. Six microphone measurement points were used throughout the test.Microphone positions and coordinates Figure 4. 19 and figure 4.20 are shown, and it is listed as in Table 4.10.

Table 4.11. Coordinates of Microphone Positions

Microphone Position	x/r	y/r	z
1	0,7	0,7	1,5 m
2	-0,7	0,7	1,5 m
3	-0,7	-0,7	1,5 m
4	0,7	-0,7	1,5 m
5	-0,27	0,65	0,71 r
6	0,27	-0,65	0,71 r

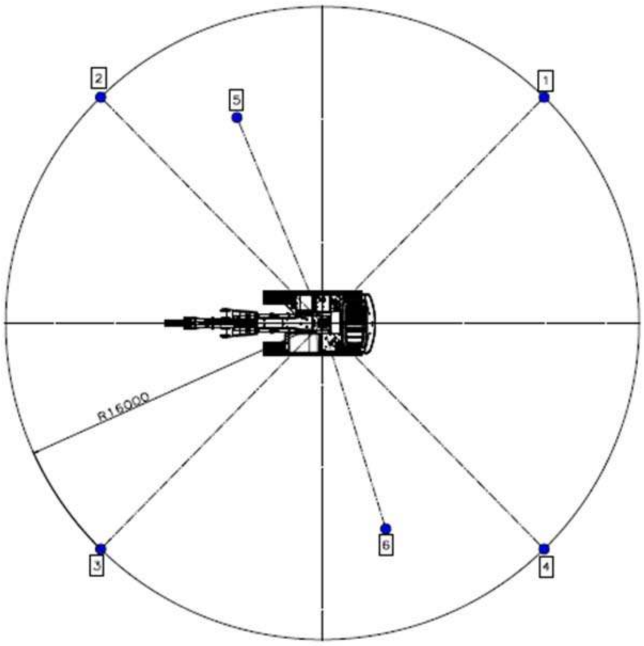


Figure 4.19. Microphone Layout on the Hemisphere

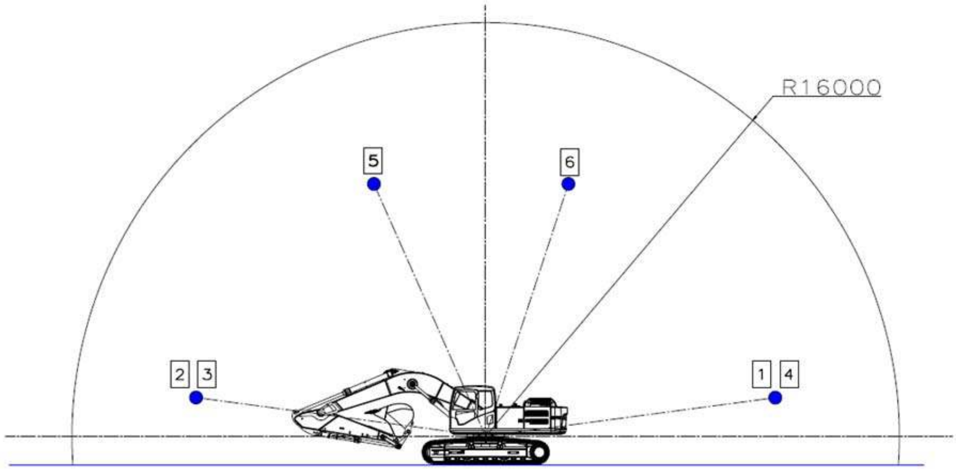


Figure 4.20. Microphone Layout on the Hemisphere (Vertical Position)

The positioning of the microphones was done with the aid of a tripod for 1, 2, 3 and 4 points and telescopic forklift for 5 and 6 points. The longitudinal axis of the machine is overlapped with the X-axis and rotated to the front (A) direction of the machine. The center point of the machine was determined as vertical on the center (C) of the sphere given in Figure 4.21.After the placement of the excavator was completed, pre-test preparations specified in the standard were completed:

- Signal installations such as forward warning horn or back maneuver Alarm have been disabled throughout the experiment.
- The machine is equipped with the equipment and add-ons determined by the machine manufacturer. The engine and hydraulic system are heated up to normal operating conditions as determined by the machine manufacturer.
- All liquid systems are filled within the range determined by the manufacturer.
- Motor rotation speed is set at maximum value without load as determined by the machine manufacturer.
- When the machine engine or hydraulic system is equipped with fans, it is operated throughout the experiment. Fan speed, specified by the machine manufacturer and adjusted fan constant variable speed is not less than 70 percent of the maximum operating speed, the fan speed is adjusted by the manufacturer.

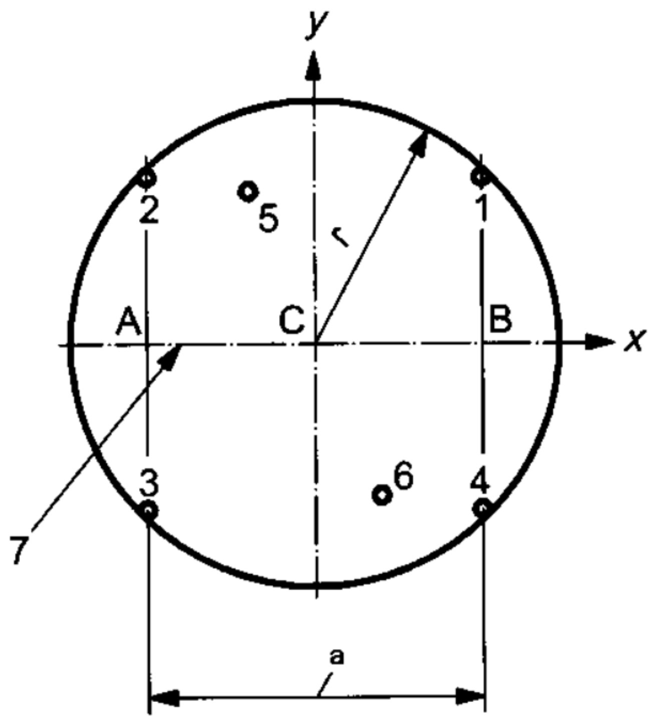


Figure 4.21. Excavator Movement Route

The machine has been operated at the highest motor speed (high idling) with hardware or add-ons (300 ± 50 mm) at the reduced carrying position and at the fixed forward and backward moving speed. Since the test machine is included in the class of hydrostatic driven machines, due to the difficulty of adjusting the ground speed controls for full motion rates, it is determined in the 3.5 km/h to 4 km/h range for crawler or steel wheeled machines. The sound pressure level is measured only when the machine is operating in the motion path between position A and position B in the middle point Figure 4.21.

In order to ensure that the machine movement is on the machine movement route on the Central Line of the experimental motion route, the operator has made routing corrections while moving along the experimental motion route.

The main machine cycle consists of three oscillations of 90 degrees to the left and back of the operator, with the dynamic cycle without moving materials, as indicated in Figure 4.21.Each oscillation must be from the X-axis to the Y-axis and behind the X-axis. A single cycle consists of three continuous oscillations to the left or back while the front end plug-in element moves along a specific sequence for each 90-degree oscillation and vice versa.

In addition to the main machine conversion, the operation cycle with the dynamic digger bucket plug is included in the experimental conditions. The aim of the dynamic cycle is to dig ditches and dump the material next to the trench. At the beginning of the cycle, the boom and arm should be set to position the bucket at 75% maximum with as close as possible to the ground surface as possible. Cutting edge of the ladle rotated forward position is determined at 60 ° angle to the test site.

First, the boom will be upgraded; the bucket will be retracted at the same time, keeping 50% of the boom and the arm movement distance on the ground. Then we would bend the bucket or go back. With boom upgrade, the lifting of the bucket and pulling back of the arm to simulate sufficient range (30% of the largest bucket lift height) in the required release against the edge of the canal. There will be a 90-degree oscillation to the left of the operator. During the oscillation boom is raised and the handle will be extended until the ladle reaches 60% of the maximum boom lift height. Then the arm won't curl until it reaches 75%. The cutter edge should rotate forward until it becomes vertical, but it will not curl. A return to working position will be made with a folded bucket and a lowered boom. In order to complete a dynamic cycle, the cycle will be repeated in order of more than two above.

A -weighted sound power level is determined in accordance with ISO 3744.For each mode of the study, the time-averaged A-weighted sound power level, as defined in the above paragraphs, will be measured at all microphone positions at least three times.

The A-weighted sound power level of the machine was calculated using the equation

4. 6 as L_{WA}decibel.

$$L_{WA} = L_{pA,T} - K_{1A} - K_{2A} + 10\log\left(\frac{S}{S_0}\right) \text{ dB} \tag{4.6}$$

where;

$L_{pA,T}$: Average energy of A-weighted sound pressure level on the measuring surface, as decibel (reference 20 µPa).

$$= 10\log\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0,1L_{pAi}}\right) dB \tag{4.7}$$

where;

L_{pAi} : A weighted sound pressure level, derived from the microphone position, as decibel (reference 20 µpa),

N: Total number of microphone locations (N = 6),

K_{1A} : Background noise correction factor,

K_{2A} : Environmental impact factor,

S: Sphere measuring surface area, m^2

S_0 : 1 m^2

$10\log\left(\frac{S}{S_0}\right)$,it was accepted as 20.0 dB for 4 m radius, 28.0 dB for 10 m radius and 32.1 dB for 16 m radius.

For the determination of the measurement results, the three groups of measurements obtained from each mic position will be calculated by the three A-weighted value of the sound pressure level. Like sound pressure levels and field calculation, all intermediate results will be expressed in the first decimal digit.

Determination of sound power level under dynamic conditions test on the excavator without isolation and prototype excavator that service covers and engine

department will be applied on the fully enclosed with sound absorbers and isolators.
(TS ISO 6395)

4.2.4. Determination of Emission Sound Pressure Level at Operator's Position

The sound package project of a vehicle requires knowledge of vehicle's acoustic targets, the basic noise sources in the vehicle, the transmission channel of the noise and the characteristics of the materials available in the market that can be used to improve the NVH performance: a robust design requires the use of applicable solutions in terms of materials, costs and performance. Not all the acoustics materials available in the market satisfy the requirements for a vehicle application (recyclable, flame resistance, cost, weight, etc.), likewise, design optimization of current vehicles is often.Performed in durable collaboration between materials suppliers and carmakers, and this allows for developing specific design for vehicle applications. The same applies to excavators whose controls are carried out inside the cabin. (WANG, X., 2010)

In this test, the values of the noise caused by the external noise sources of the excavator will be determined when the excavator operator reaches the ears. In addition, the effect of the high density sound barrier material on the noise level of the cabin interior will be observed in this thesis. In this thesis, the sound pressure level at operator's position will proceed in accordance with the conditions specified in TS ISO 6396. (Determination of emission sound pressure level at operator's position -Dynamic test condition)

This standard covers a method to determine the emission sound pressure level of the construction and excavation machine in the operator position, measured in terms of time-averaged A-weighted sound power level when working in dynamic test conditions. In these experimental conditions, the environmental conditions specified in ISO 6395 standard are valid. In experimental circumstance, the operator, which is defined as 1.7 m tall in height, will be used in accordance with the standards.

The operator must be in the driving position and the observers are not positioned within or near the cabin during the sound measurements. The operator will wear any abnormal sound absorption or noise measurements, a hat or scarf (other than the frame used to support the microphone or a protective sleeve used for safety reasons) is not equipped. The seat is set close to the middle of the horizontal and vertical position or as close as possible to this point, seat suspension is adjusted to operator weight.

The microphone is placed horizontally in the normal view of a person in the operator's neighborhood, taking into account the reference direction as indicated by the manufacturer. The control point for initial sound pressure level information is in a static state the microphone is 80 mm behind and parallel to the eye, 650 mm above the seat SIP point, while the machine is operating at the highest engine speed.

First, the microphone is placed on the left side of the operator head and then on the right side. Whichever side of the highest reading is obtained, it will be used for dynamic controls. If both initial sound pressure level controls are the same, the location on the right side will be used.

The microphone has been insulated from vibrations that may affect measurements. If the microphone is moved during the measurements, precautions have been taken to prevent the occurrence of acoustic noise (for example, the noise caused by the microphone friction against the operator wears) or electrical noise that may interfere with the measurements.

During the measurements doors and windows are closed and air conditioning and/or ventilation system is set up to work. Since they have more than one operating speed, the air conditioning system has been operated at the second speed for systems up to three speeds. Air conditioning and ventilation systems continued to work throughout the testing process. Microphone positions are shown in Figure 4.22 and figure 4.23 for all axes based on the SIP point of the seat. The time-averaged A-weighted emission sound pressure level at operator position as stated in the previous test procedure, the time-averaged A-weighted emission sound pressure level will be measured at microphone position at least three times.

If two of the three A-weighted values are not more than 1 dB, then the next measurements will not be passed. If so, measurements will continue until two values are obtained within a range of 1 dB between one value and another value. The time-averaged a-weighted emission pressure level will be reported as the arithmetic mean of the two highest values in each 1 dB range.

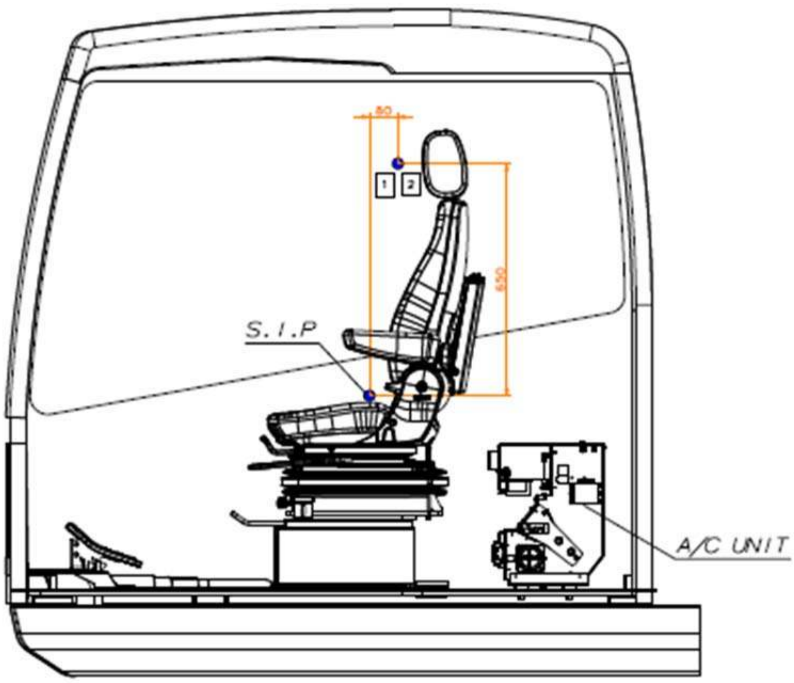


Figure 4.22. Microphone Layout in Excavator Cabin

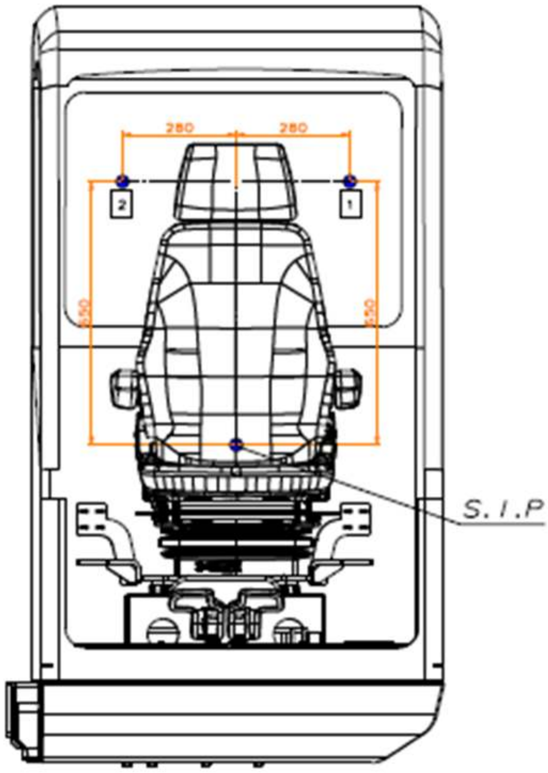


Figure 4.23. Microphone Layout in Excavator Cabin

4.2.5. Engine and Cooling Unit Department Insulation Installation

It is important that the noise sources, motor, fan and cooler unit area are masked with sound attenuators to reduce the sound level to be transmitted to the operator zone in the cabinet. For this purpose, the engine department is equipped with D2600 type polyethylene sound absorbers. The sound absorbers are mounted on the support plates assembled in the upper chassis of the engine room with the help of a builder and bolts. Figure 4.24 shows sound absorbers that have been installed in the engine department.

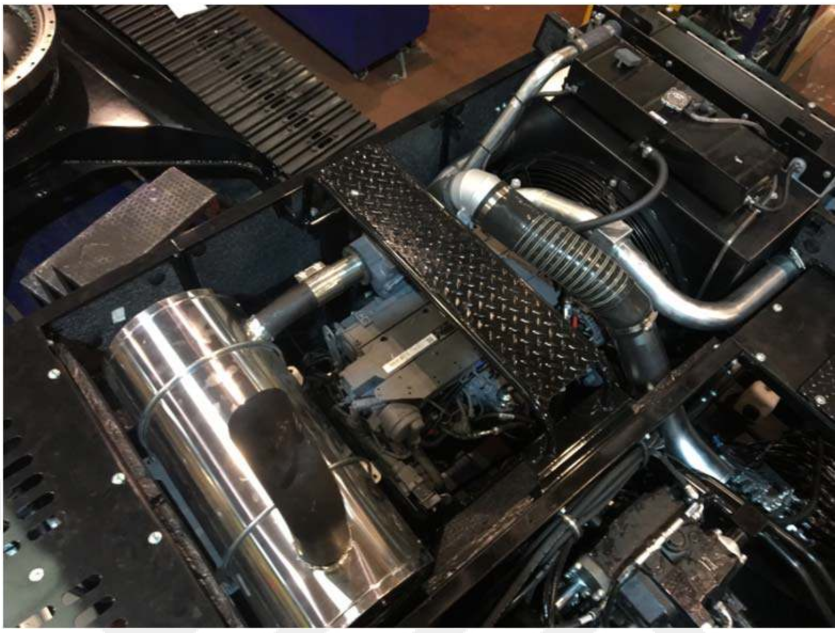


Figure 4.24. The Engine Room Where Polyethylene Sound Absorbers are Installed Visual

4.2.6. Excavator Cabinet Internal and External Sound Insulation Installation

It is requisite to isolate the cabin from the outside very well in order to obtain a quieter operator space. Sound absorbers and reflectors shall be installed on the prototype machine cabin, under the cabin floor which provides the connection to the upper chassis, on the inner cabin floor and under the trim, in order to obtain this isolated environment. In this context. The polyethylene sound absorber is mounted on the outer surface of the prototype excavator's cabin floor where the effect of the isolations will be tested. Sound absorber has the same lines as the cabinet base design.

It only has discharge in areas with electrical cords, hydraulic hose transitions and component connection holes. Grommet and adhesive will be applied in these transition areas and in the holes to ensure the environment inside the isolated cabin. Figure 4.25 shows the mounting of the cabinet base outer sound absorber.

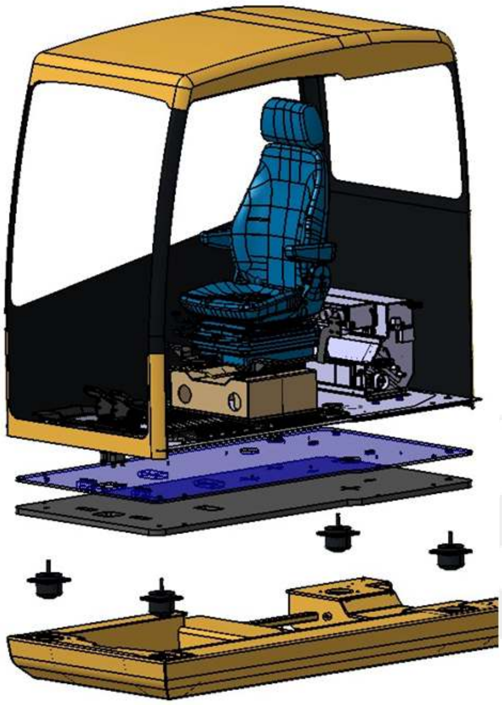


Figure 4.25. Mounting of Cabinet Base Outer Sound Absorber.

Figure 4.26. Mounting of Cabinet Base Outer Sound Absorber.

High-density synthetic sound barrier will be applied to the base area from inside the cabin. This barrier, which is not easy to form due to its high density, is manufactured to match the cabinet dimensions. The vacancies in the cab floor base were added to the barrier. The sound barrier is mounted on the base plate of the cab with the aid of a metal-plastic type adhesive. Figure 4.26 shows the mounting of the cabinet base synthetic sound barrier.

It is also important to isolate the cabin base and provide insulation to the cabin carcass as well as sound absorbers in order to provide an effective isolation space inside the cabin. In order to isolate the inside of the cabin from the outside, trim undercarriages and cabin carcasses are wrapped with polyester isolations. Due to the form of the pressed sheets found in the main case of the cabin, it has been noted that the insulation material to be used in these areas is an easy-to-form isolation.

Figure 4.27. Polyester Insulation Coating Unfinished Cabin Carcass Visual

Figure 4.28. Visualization of Finished Cabin Carcass with Isolation

5. RESULTS AND DISCUSSION

5.1. The Cabin Fog Test Results

Before excavator dynamic cycle external and cabin operator position sound pressure level tests, in order to observe the openings in the cabin, the excavator cabin was tested with fog. During the test, the cabin was subjected to high pressure fog as shown in Figure 5.1.During the cab fog test points of leakage of the pressurized fog were detected. As a result of the first observation, leaks were found at the bottom of the mounting areas of the operator rest pads in the cabin, shown in Figure 5.2.The other point where the leakage is detected is the transition area of the electrical installations passing through the cabin.

Figure 5.1. Excavator Cabin Fog Test

Figure 5.2. Leaking Fog Through Pedal Valve and Operator Foot Restraint Area

Figure 5.3. Leaking Fog Through Pollen Filtration Zone & Air Conditioning Unit Fresh Air Intake Zone

Seepage was also detected from the grille of the fresh air intake area (pollen filter area) of the air conditioner unit by increasing the pressure in the cabin, shown in Figure 5.3 a small amount of fog leaks were detected from the glues of the cabin door glass and and the door lock compartment, towards the end of the test.

After the test various precautions were taken before the sound pressure level test was started in the areas where leakage was detected. Some of the precautions are listed as follows:

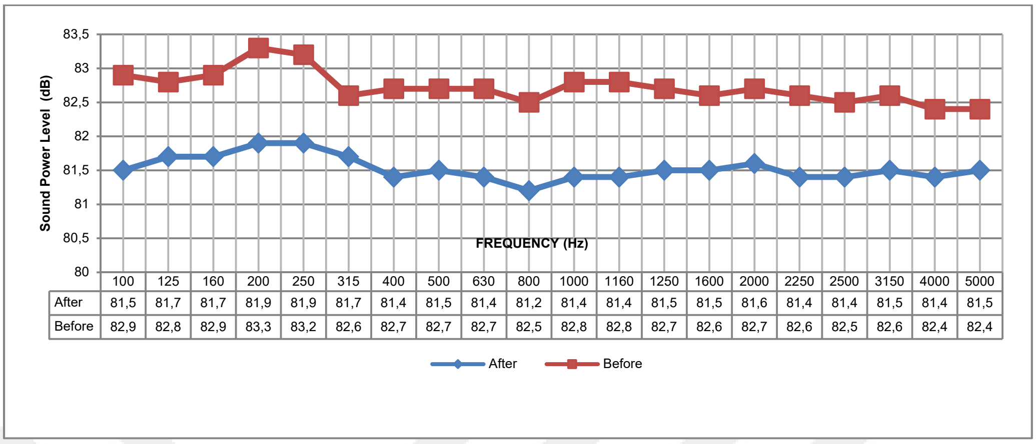
- Sealant is applied to the pad mounting areas where leakage is detected. Also, grommet is designed in the pedal valve area and it is mounted under the cabin mop.
- A rubber grommet is designed in the transition area of the electrical installation. After the grommet cable passes, the insulation is ensured by closing the openings in the hole.
- Pollen filter assembly area is designed with a transition bracket from metal material to provide the connection between the air conditioning unit and the pollen filter. This bracket will prevent leakage from the pollen filter to the air conditioning unit. In addition, an adhesive is used to prevent possible openings in bracket mounting.

5.2. Test Results of Sound Power Level -Dynamic Test Conditions

The external environment data have been obtained by using the techniques of TS ISO 6395. Techniques and formulas used in obtaining the data are given in Chapter 4. Tests were carried out in the excavator with engine compartment and service covers insulation and in the excavator without insulation. Comparative values of the resulting test data are given in figures.

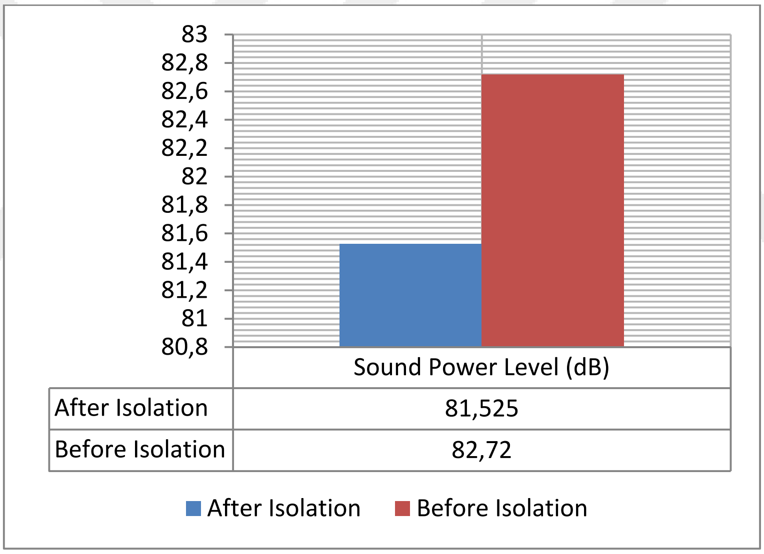
Figure 5.4. Figure in the Test Moment When Receiving Sound Values from Points Specified on the Vehicle

Figure 5.5. Figure in the Test Moment When Receiving Sound Values from Points Specified on the Vehicle



	100	125	160	200	250	315	400	500	630	800	1000	1160	1250	1600	2000	2250	2500	3150	4000	5000
After	81,5	81,7	81,7	81,9	81,9	81,7	81,4	81,5	81,4	81,2	81,4	81,4	81,5	81,5	81,6	81,4	81,4	81,5	81,4	81,5
Before	82,9	82,8	82,9	83,3	83,2	82,6	82,7	82,7	82,7	82,5	82,8	82,8	82,7	82,6	82,7	82,6	82,5	82,6	82,4	82,4

Figure 5.6. Point 1 L_{WA} Test Results (Outside Excavator)



	Sound Power Level (dB)
After Isolation	81,525
Before Isolation	82,72

Figure 5.7. Mean Values of Test Results (L_{WA}) for Point 1(Outside Excavator)

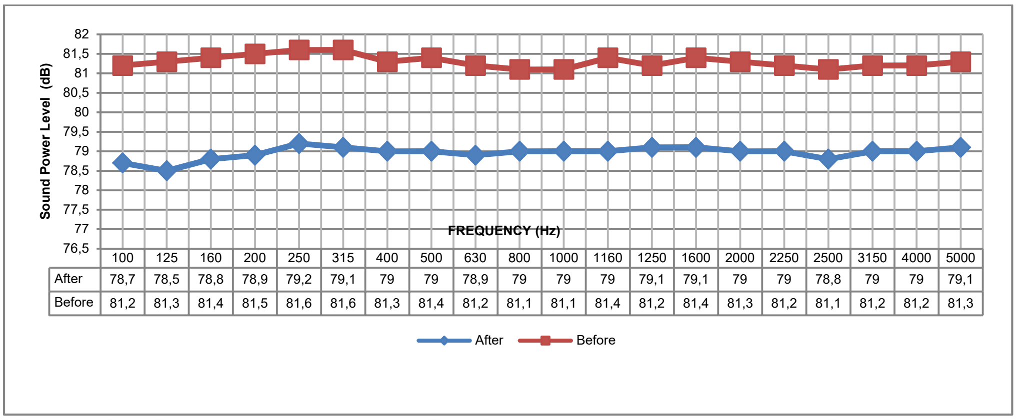


Figure 5.8. Point 2 L_{WA} Test Results (Outside Excavator)

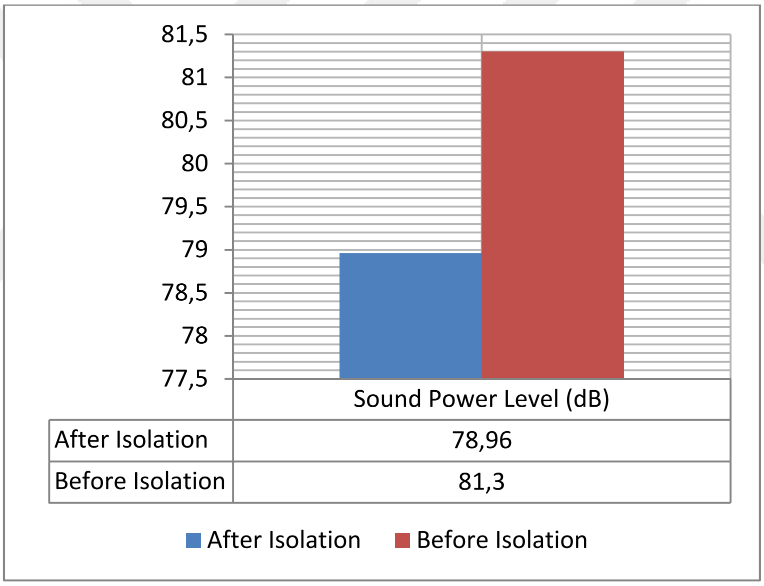


Figure 5.9. Mean Values of Test Results (L_{WA}) for Point 2 (Outside Excavator)

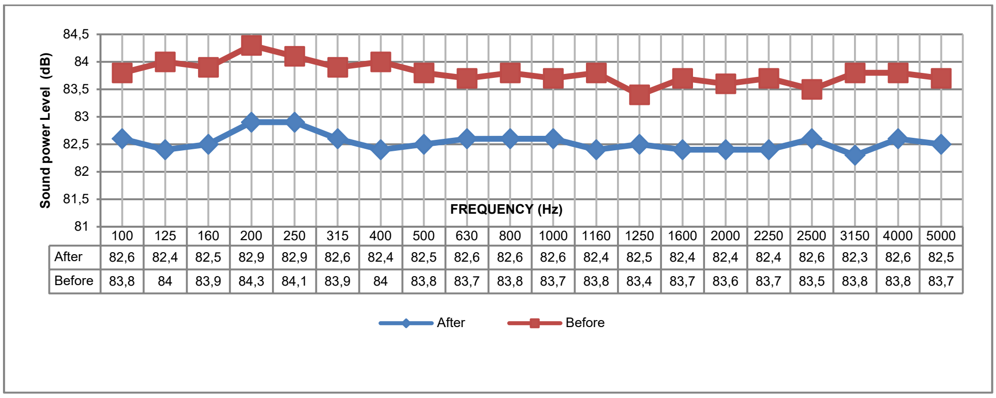


Figure 5.10. Point 3 L_{WA} Test Results (Outside Excavator)

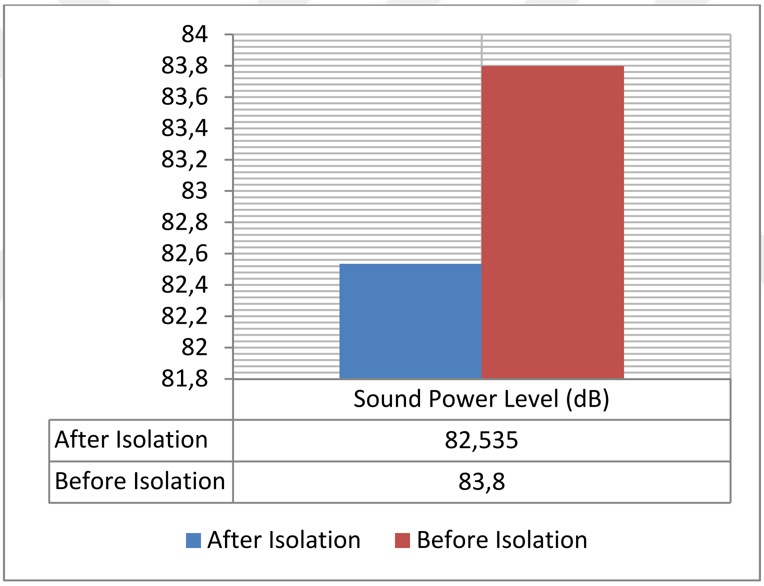


Figure 5.11. Mean Values of Test Results (L_{WA}) for Point 3 (Outside Excavator)

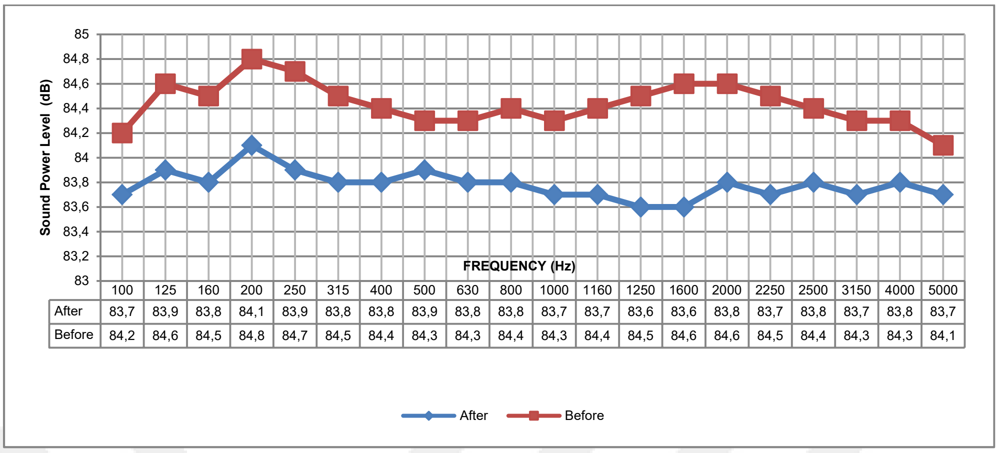


Figure 5.12. Point 4 L_{WA} Test Results (Outside Excavator)

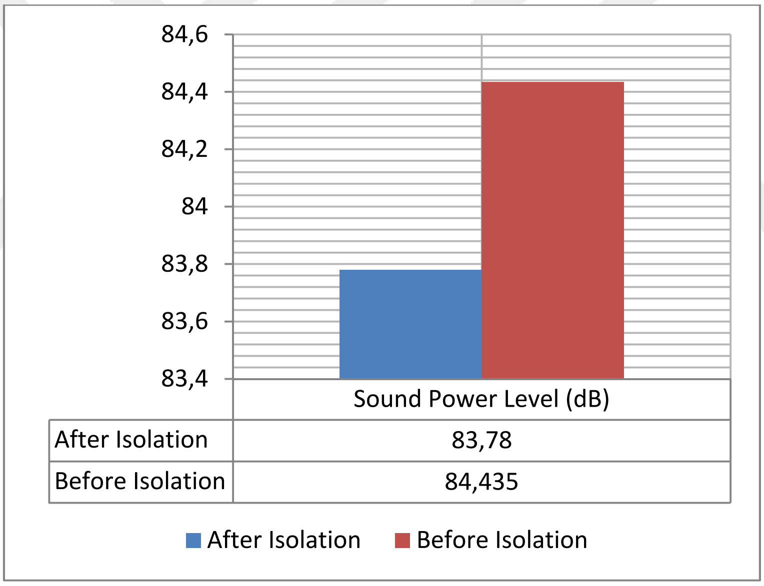


Figure 5.13. Mean Values of Test Results (L_{WA}) for Point 4 (Outside Excavator)

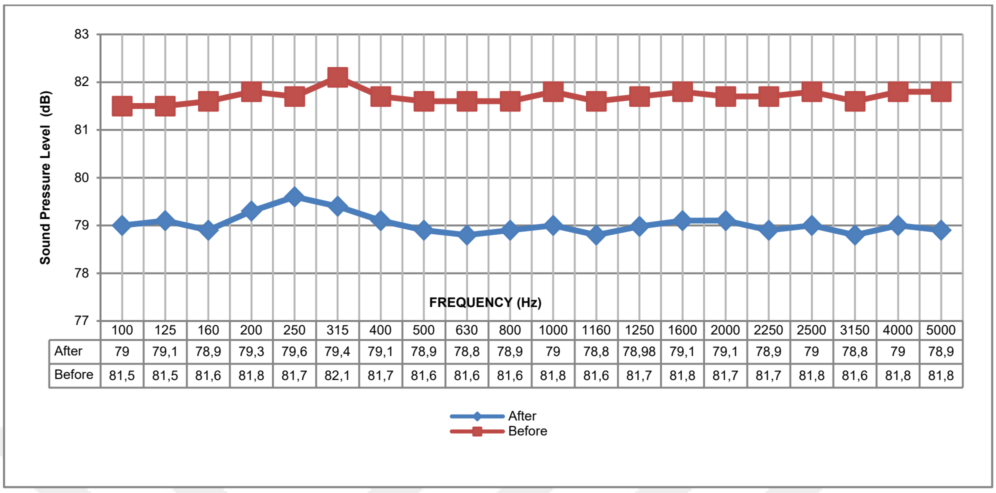


Figure 5.14. Point 5 L_{WA} Test Results (Outside Excavator)

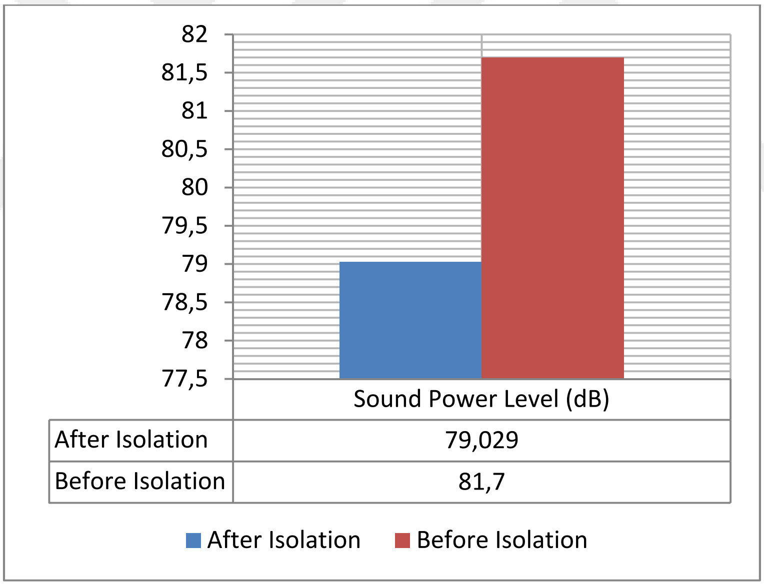


Figure 5.15. Mean Values of Test Results (L_{WA}) for Point 5 (Outside Excavator)

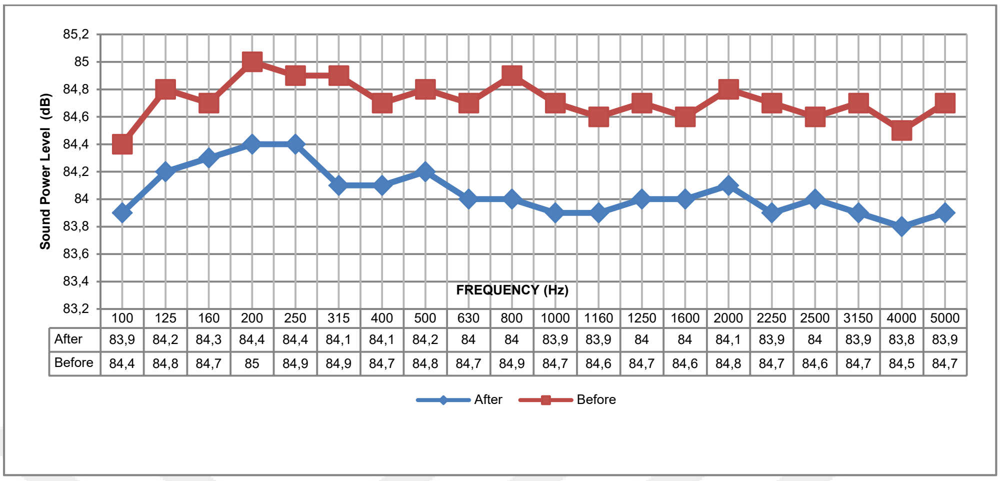


Figure 5.16. Point 6 L_{WA} Test Results (Outside Excavator)

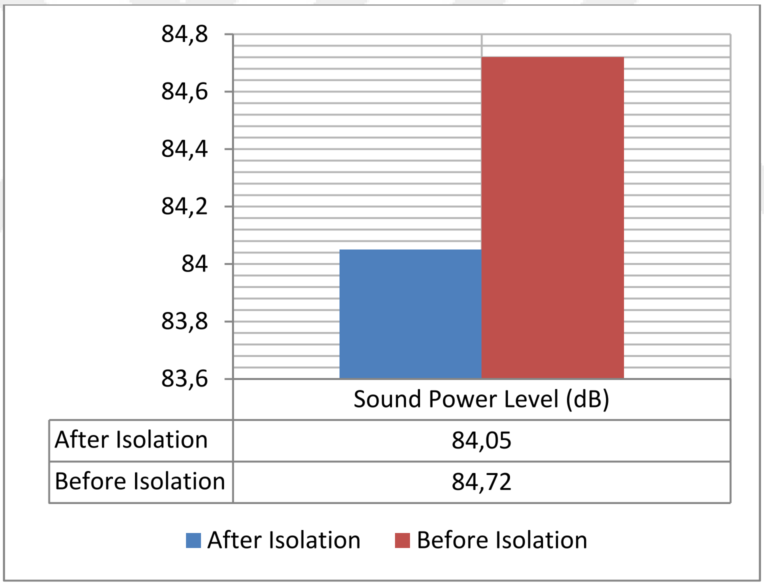


Figure 5.17. Mean Values of Test Results (L_{WA}) for Point 6 (Outside Excavator)

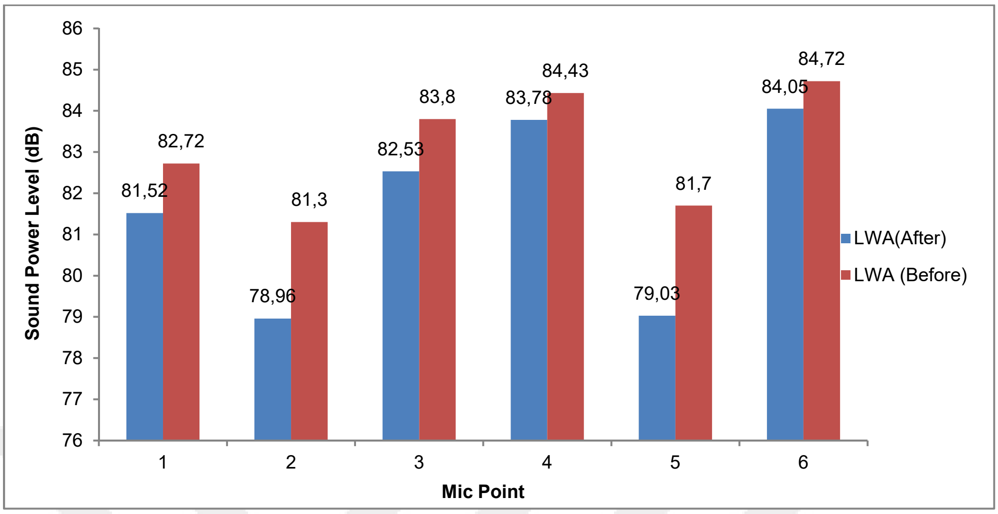


Figure 5.18. Test Data Comparison Chart of Audio Power Levels According to Microphone Positions

Table 5.1. Comparison Table of Dynamic Test Data

Microphone Point	L_{WA} (After)	L_{WA} (Before)
1	81,52	82,72
2	78,96	81,3
3	82,53	83,8
4	83,78	84,43
5	79,03	81,7
6	84,05	84,72

When the dynamic test results are examined, the highest dB value according to the point is observed in the 6th zone with 84.72 dB data in the non-isolation test.The decibel data of the same region in the isolated machine were determined as 84.05.The second highest value was observed at Point 4 with a value of 84.43 db. The decibel value of the same point in the isolated machine was determined as 83.78 dB at these points, the cooling unit fan can be shown as the cause of the high sound power level. There are grids for air flow on the service cover of the cooling unit zone. In order to avoid the airflow of these grilles, insulation or sound absorber has not been applied to this area. For this reason, the number 4 and 6 microphones that are close to this region have also been detected with the highest level of sound data. After these regions, the third highest level of sound power was detected at the point of 3 microphone area with the value 83, 8 dB before isolation, and after isolation 82,53 dB This point is followed by region number 1, which measures 82,72 dB without isolation and 81,52 dB with isolation test.The lowest sound power level 81.3 dB before isolation and 78,96 dB after isolation installation of the 2. microphone area was measured. The reason why this zone has the lowest level of decibel is the distance from excavator noise sources.

When examining the test data, it is possible to observe the effects of sound absorption and sound insulation on the engine room and service covers. The effects of these sound absorbers and insulation on the points and decibel reductions are shown in Table5.2 as below. Due to the design of the engine room and the machine, the placement of sound isolations and sound absorbers are concentrated in the engine & hydraulic pump region. Only sound absorbers can be placed on the air curtains located in the radiator hood between the engine and the coolant unit. For these reasons, effects of insulation and sound absorbers are observed less at microphone points near the cooler area, while this effect has been observed more in other regions.

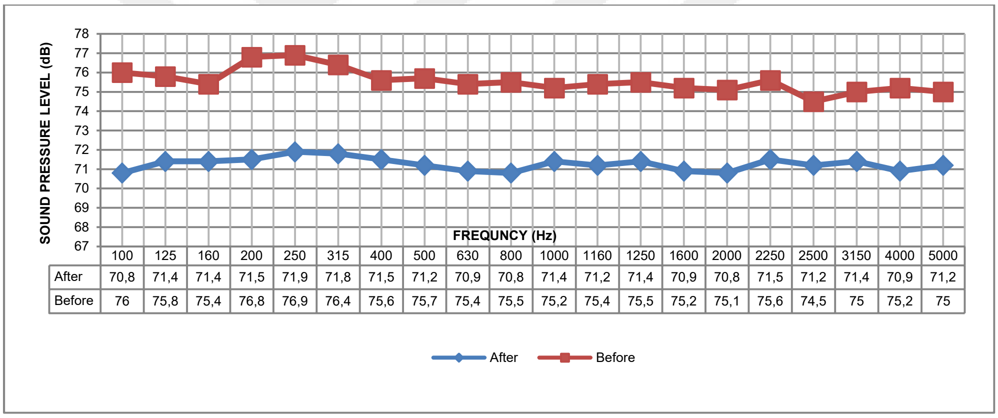
Table 5.2. Desibel Reductions According to Microphone Regions

Microphone Point	Decibel Reduction
1	1,2
2	2,34
3	1,27
4	0,65
5	2,67
6	0,67

5.3. Test Results of Sound Pressure Level at Operator's Position

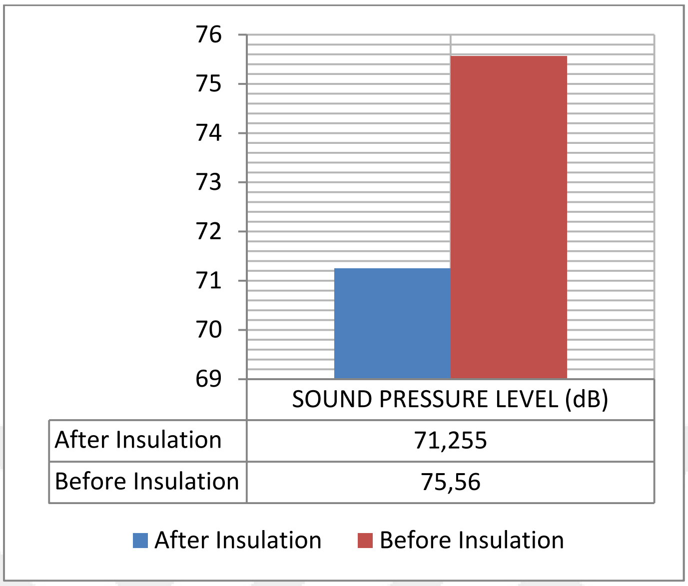
To determine the sound pressure level of the cabin inside, the test environment was set up to comply with the standard and the test data was taken. The tests were repeated three times to make sure that the test data were correct. The results of all three tests taken were averaged with the formulations specified in the standard and final data were obtained

Results for each point 1. Test was calledL_{pA1}, 2. Test was calledL_{pA2} , and the last test was calledL_{pA3}. The mean values of the data obtained for 20 seconds were taken from these tests and these results were obtained. This value is calledL_{pAT}. All of these terms are defined according to the standard.



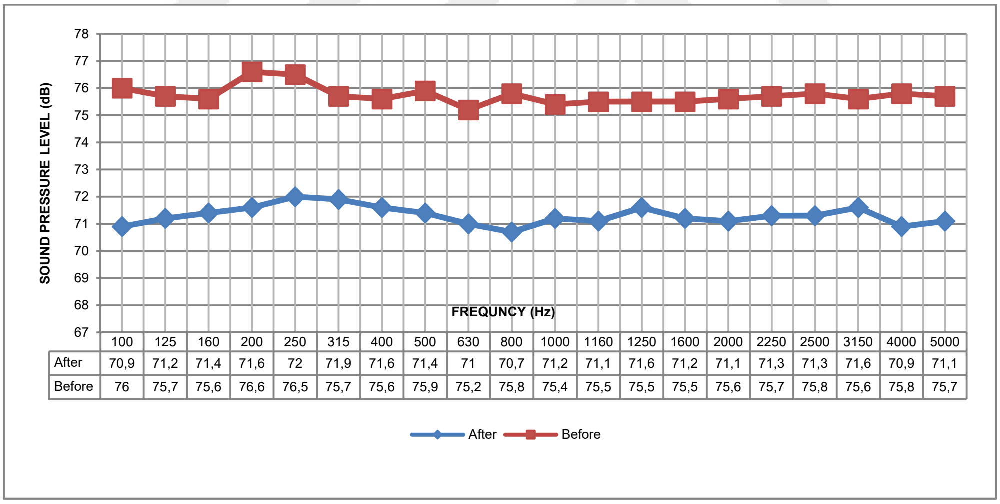
	100	125	160	200	250	315	400	500	630	800	1000	1160	1250	1600	2000	2250	2500	3150	4000	5000
After	70,8	71,4	71,4	71,5	71,9	71,8	71,5	71,2	70,9	70,8	71,4	71,2	71,4	70,9	70,8	71,5	71,2	71,4	70,9	71,2
Before	76	75,8	75,4	76,8	76,9	76,4	75,6	75,7	75,4	75,5	75,2	75,4	75,5	75,2	75,1	75,6	74,5	75	75,2	75

Figure 5.19. Point 1 L_{pA1} Test Results (Inside Cab) According to Scale A-Weighted SPL



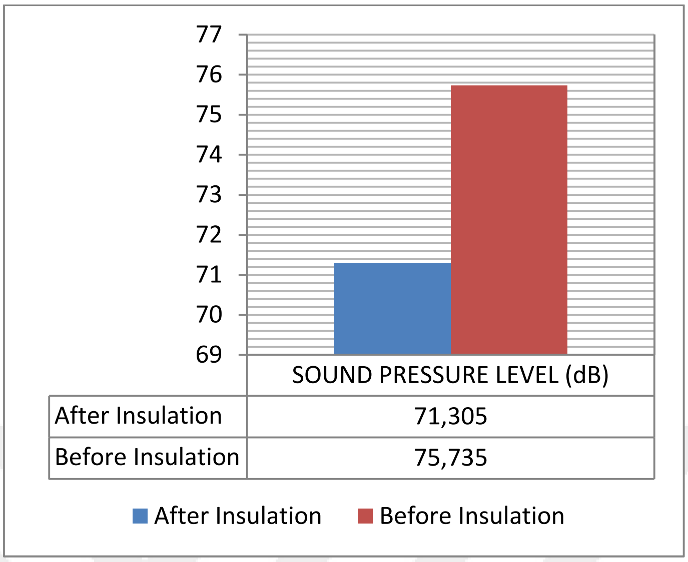
	SOUND PRESSURE LEVEL (dB)
After Insulation	71,255
Before Insulation	75,56

Figure 5.20. Mean Values of Test Results (L_{pA1}) for Point 1



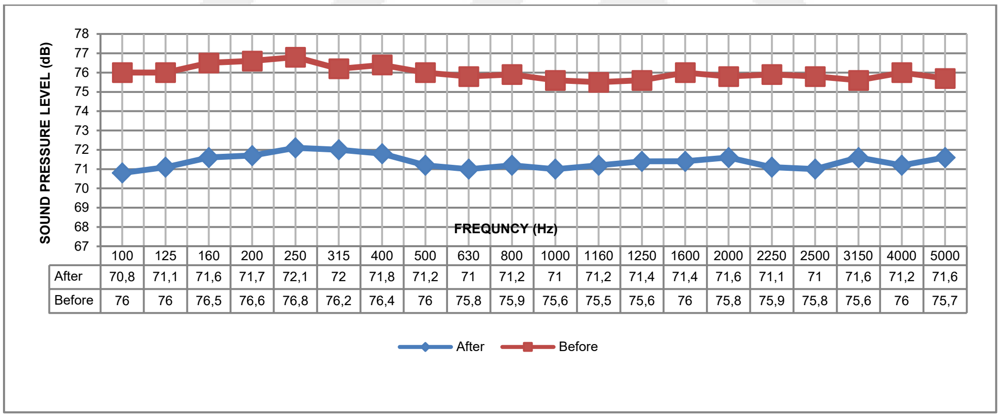
	100	125	160	200	250	315	400	500	630	800	1000	1160	1250	1600	2000	2250	2500	3150	4000	5000
After	70,9	71,2	71,4	71,6	72	71,9	71,6	71,4	71	70,7	71,2	71,1	71,6	71,2	71,1	71,3	71,3	71,6	70,9	71,1
Before	76	75,7	75,6	76,6	76,5	75,7	75,6	75,9	75,2	75,8	75,4	75,5	75,5	75,5	75,6	75,7	75,8	75,6	75,8	75,7

Figure 5.21. Point 1 L_{pA2} Test Results (Inside Cab) According to Scale A-Weighted SPL



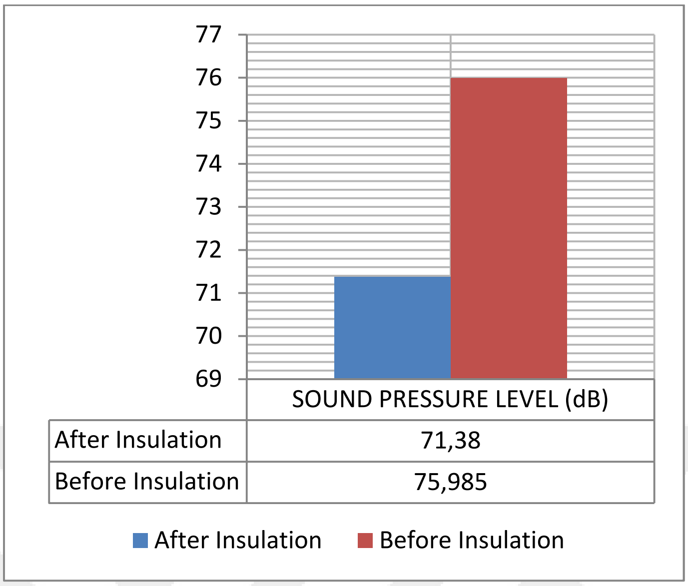
	SOUND PRESSURE LEVEL (dB)
After Insulation	71,305
Before Insulation	75,735

Figure 5.22. Mean Values of Test Results (L_{pA2}) for Point 1



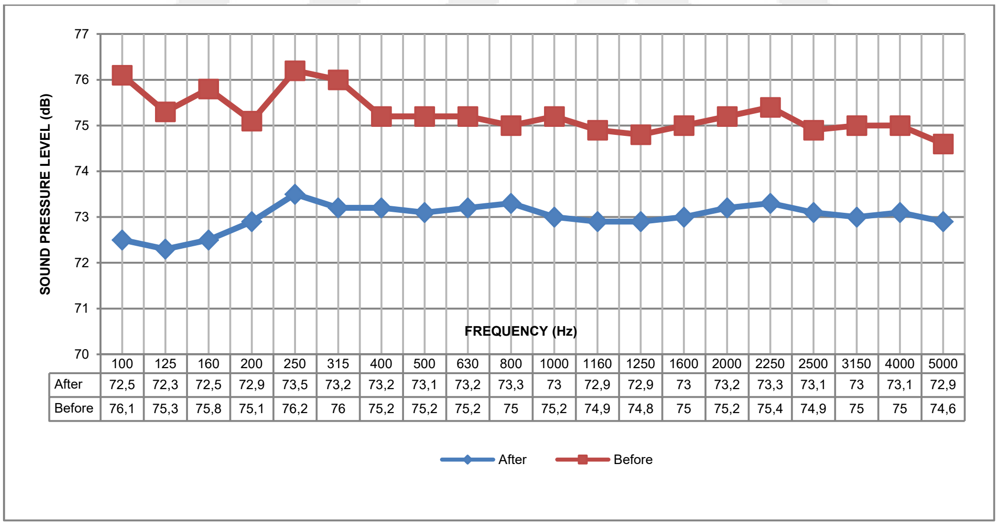
	100	125	160	200	250	315	400	500	630	800	1000	1160	1250	1600	2000	2250	2500	3150	4000	5000
After	70,8	71,1	71,6	71,7	72,1	72	71,8	71,2	71	71,2	71	71,2	71,4	71,4	71,6	71,1	71	71,6	71,2	71,6
Before	76	76	76,5	76,6	76,8	76,2	76,4	76	75,8	75,9	75,6	75,5	75,6	76	75,8	75,9	75,8	75,6	76	75,7

Figure 5.23. Point 1 L_{pA3} Test Results (Inside Cab) According to Scale A-Weighted SPL



	SOUND PRESSURE LEVEL (dB)
After Insulation	71,38
Before Insulation	75,985

Figure 5.24. Mean Values of Test Results (L_{pA3})for Point 2



	100	125	160	200	250	315	400	500	630	800	1000	1160	1250	1600	2000	2250	2500	3150	4000	5000
After	72,5	72,3	72,5	72,9	73,5	73,2	73,2	73,1	73,2	73,3	73	72,9	72,9	73	73,2	73,3	73,1	73	73,1	72,9
Before	76,1	75,3	75,8	75,1	76,2	76	75,2	75,2	75,2	75	75,2	74,9	74,8	75	75,2	75,4	74,9	75	75	74,6

Figure 5.25. Point 2L_{pA1} Test Results (Inside Cab) According to Scale A-Weighted SPL

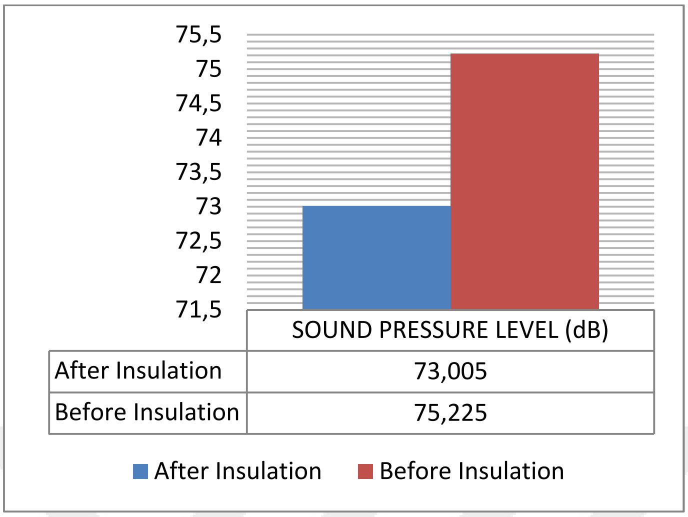


Figure 5.26. Mean Values of Test Results (L_{pA1})for Point 2

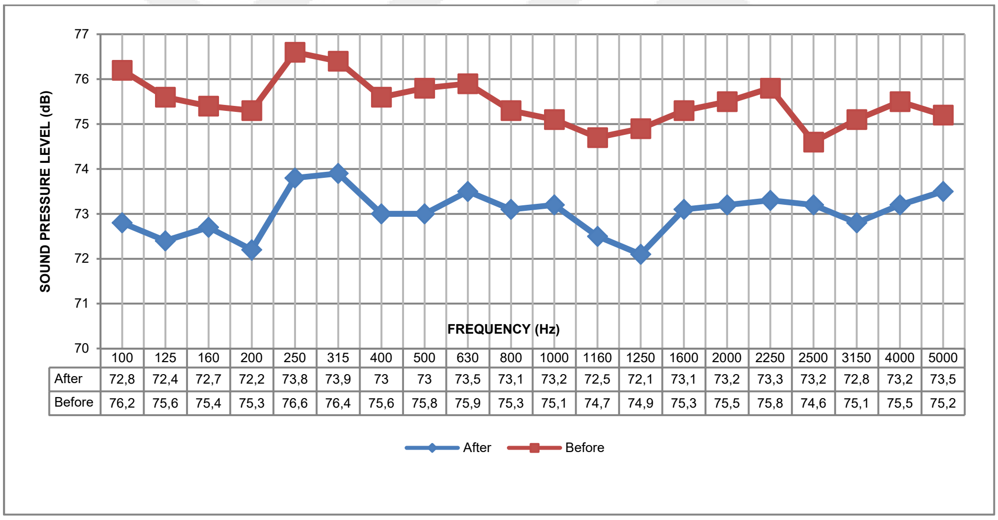


Figure 5.27. Point 2 L_{pA2} Test Results (Inside Cab) According to Scale A-Weighted SPL

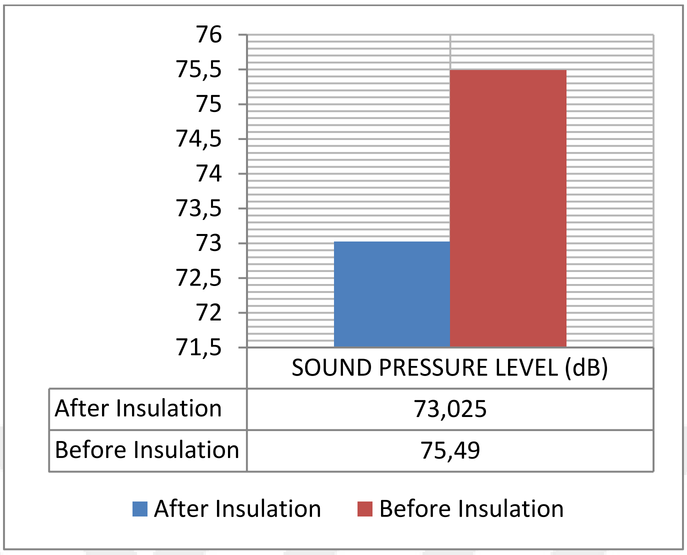


Figure 5.28. Mean Values of Test Results (L_{pA2})for Point 2

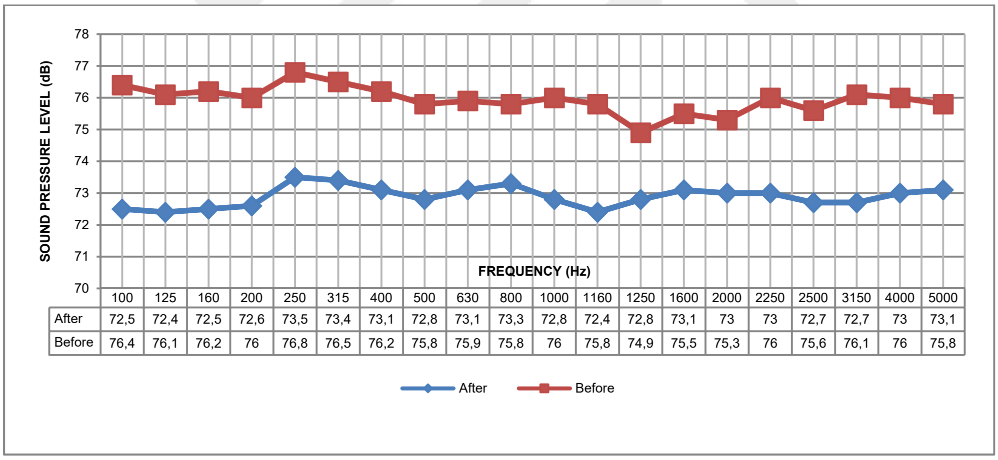


Figure 5.29. Point 2 L_{pA3} Test Results (Inside Cab) According to Scale A-Weighted SPL

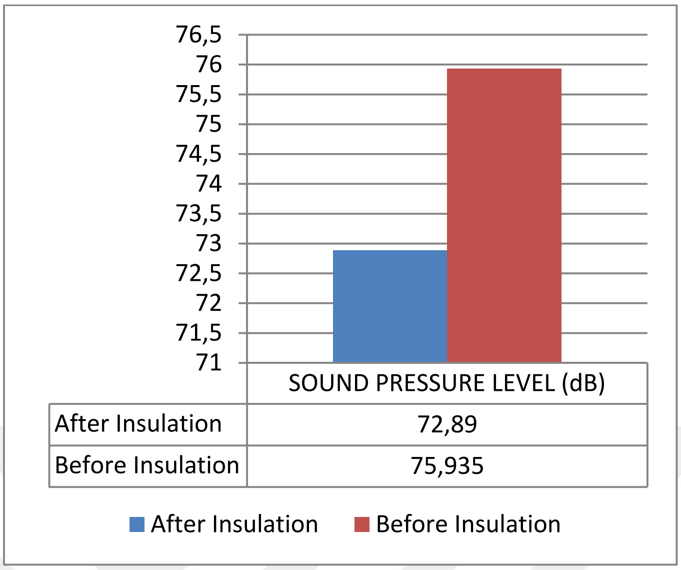


Figure 5.30. Mean Values of Test Results (L_{pA3})for Point 2

Table 5.3. Test Results for Point 1(Cabin)

Test Conditions	Microphone Position Point	L_{pA1}	L_{pA2}	L_{pA3}	L_{pAT}
After Insulation	Point 1	71,255	71,305	71,38	71,31
Before Insulation	Point 1	75,56	75,735	75,985	75,76

Table 5.4. Test Results for Point 2(Cabin)

Test Conditions	Microphone Position Point	L_{pA1}	L_{pA2}	L_{pA3}	L_{pAT}
After Insulation	Point 2	73,005	73,025	72,89	72,97
Before Insulation	Point 2	75,225	75,49	75,935	75,55

When the test results were evaluated, the average left ear level of the operator for the cabin was 75.5 dB before the isolation study and 72.9 dB after the isolation study. The results were 75.8 before the isolation study and 71.3 dB after the isolation study for the right ear alignment. A reduction of about 3-5 dB in sound level for the cabin was observed, taking into account the test results. The reduction values correspond to a reduction of about 3% to 6%.Also, since the test result graphs are examined, the peak dB value is also determined. These values are73.9-73.5 dB (after isolation), 76.2-76.8 dB (before isolation) for the left ear alignment and 71,9-72,1 dB (after isolation), 76,7 -76,9 dB (before isolation).

6. CONCLUSION

As a result of this thesis study, a hydraulic excavator with lower noise emission (outdoor) and quieter operator department (cabin) was obtained. When the test results are examined, the excavator has an average outdoor noise level of 1-2.7 dB .In the excavator interior volume level, on the average, a decrease of between 3-5 dB is achieved. When these reductions were examined, it was observed that the excavator, which applied isolation to the service cover areas, had a higher sound level reduction on the pump side. These results show that the polyethylene sound absorber and insulation placed in the service cover and engine chamber fulfill their functions. In the excavator cabin, the sound level reduction process started with the cabin fog test. Grommet and sealer were applied to the cabin openings detected in the test and the openings were closed. A high-density sound barrier is used on the floor of the cabin with its openings closed and a significant decrease in the internal sound level is achieved. These high-density sound barriers are not easily available in the cabin frame and trim parts because of their lack of form. For this reason, polyester sound insulation was used on cabinet frame and trim assembly. Consequently, the conclusions listed below for possible future studies may be considered as the gains of this study:

- Low density polyethylene sound absorber and insulators with closed cell structure in the regions where they are assembled for noise sources (diesel engine & hydraulic pump, etc.) which can emit high amplitude sound waves at low frequency values effectively benefit from sound loss.
- In order for the excavator cabinet to be acoustically isolated, the cabinet must be fully isolated from the outside environment. This isolation situation can be achieved through the proper closure of cabin openings. Determining and closing these openings is of most importance for cabin acoustics.

- The cabin structure can consist of parts that are not in a proper form. It is not possible to use a high-density sound barrier in these irregular form areas. For this reason, these areas can be easily formable polyester insulations for sound acoustics.
- As a result of the study, the most important part is to determine the impact of high density sound barriers on the cabin floor. These data show that the sound barriers influence sound acoustics effectively in flat areas of use. The use of high density sound barriers in the structure of the cabin floor will contribute positively to cabin acoustics in future excavator's cabin projects.

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