Five dB noise reduction for large medium speed diesel engines

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Abstract

Engine noise has becoming more and more important over years. Especially for maritime industry, the International Convention for the Safety of Life at Sea (SOLAS) launched new noise regulation since July 2014, which demands a maximum acceptable sound pressure level of 110 dB at any individual measurement position in the machinery space. Wärtsilä has a decade of experience on large medium speed diesel engine noise and vibration research and development. Today's Wärtsilä is capable to technically reduce the engine noise level by 5 dB without any insulation panel even with increased engine power and higher fuel efficiency. This paper will explain in detail both the structure-borne noise and air-borne noise from an engine, from the source of excitation, transmission path and the structure noise radiation. Major noisy engine components that contributes the engine room noise level will be addressed, from both theoretical and experimental point of view. This paper will also explain the methodology of noise reduction on different engine noise sources. In the end, other important factors that matter with final engine room noise level will be pointed out.

Introduction

Wärtsilä is a global leader in advanced technologies and complete lifecycle solutions for the marine and energy markets. One of its major products is large medium speed engines for shipyards and power plants. The engines being mentioned in this paper refer to W32 type, which has cylinder bore of 32 cm in diameter. Depending on different cylinder configurations ranging from 6 to 20, the weight of W32 in-line engines ranges 30-50 tons and V engines ranges 50-90 tons. At full load the engine output is 580 kW per cylinder and nominal speed is 720 or 750 rpm. At operating conditions, such massive machinery can produce significant amount of noise that may easily damage hearing within seconds if no hearing protection is used.

The main driving force for research of engine noise reduction is from relevant regulations. For the power plants there are various local occupational health and safety related and environment related regulations. For maritime industry the regulations are mainly from IMO (International Maritime Organization). With the increasing awareness of safety and comfort, the importance of noise has increased dramatically in the past 20 years. In July 2014, IMO has adopted regulation II-1/3-12 of the International Convention for the Safety of Life at Sea (SOLAS) 1974 as amended, concerning protection against noise. The new regulation has become mandatory and it requires a maximum of 110 dB at every individual measurement location 1 m away from the engine surface. This new regulation is much stricter comparing to the old one and it may pose great challenges to shipyards.

Wärtsilä started research work in engine noise and vibration since 1990s. The manpower in the engine acoustics has increased from one to nowadays seven [1]. The noise research area covers not only engine noise itself, but also exhaust noise, environmental noise and personnel daily noise exposure. Latest relevant papers can be found [2-5]. The pace of development of engine noise reduction solutions has speeded up in the past decade, with great amount of research projects in cooperation with various institutes, mainly in Scandinavian countries. Today's Wärtsilä is capable of reduce engine noise by more than 5 dB without any insulation panels, even though the engine output has increased by 16%. This has made Wärtsilä extremely competitive in the market where nowadays customers intend to select a manufacture with quieter engines. Meanwhile, shipyards are expected to take the leading role and responsibility of engine room acoustical design which will significantly influence the resulted engine room noise level.

Measurement Techniques

The SOLAS regulation on machinery room noise requires maximum 110 dB as sound pressure level, which will not only depend on the engine sound power but also the on-site room acoustical properties. As engine manufacture, Wärtsilä is responsible for the engine sound power, which is a unique property of the product.

In order to deliver reliable data, the instruments used in Wärtislä for standardized sound power reporting meet the requirements of the IEC 1043 and the measurement procedure is based on ISO 9614 "Acoustics – Determination of sound power levels of noise sources using sound intensity" - Part 2 "Measurement by scanning". Concerning the measurement uncertainty and accuracy, the "Engineering grade" (grade 2) defined in ISO 9614 Part 2 is used. The method of measuring the component of sound intensity normal to a measurement surface which is chosen so as to enclose the engine of which the sound power level is to be determined is specified in-house. Surface integration of the intensity component normal to the measurement surface is approximated by subdividing the measurement surface into contiguous segments, and scanning the intensity probe over each segment along a continuous path which covers the extent of the segment. To standardise sound intensity measurement, the engine to be measured is divided into partial sources. Moreover, in most cases the measurements are on purpose of research aiming at localizing the sound sources of an engine, a partial source should be in turn divided into even smaller measurement segments which can completely encloses the engine, Figure 1.

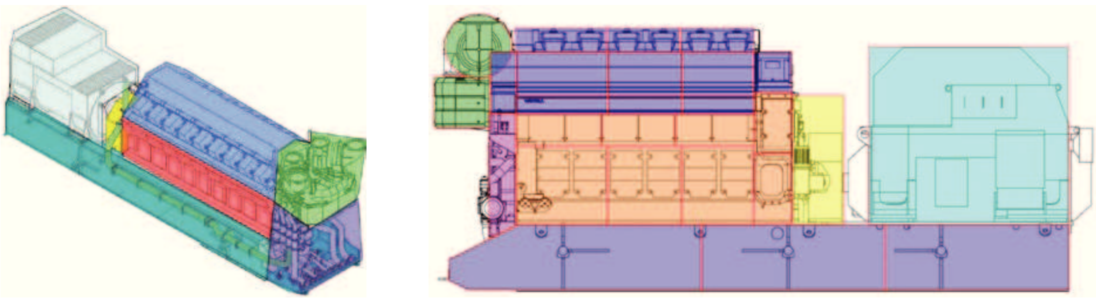

Figure 1: Left, partial sources division on a Wärtsilä V engine; Right, example of detail measurement segments for sound intensity scanning for a Wärtsilä in-line engine.

With increasing knowledge gained through standard sound intensity measurements, there have been more and more need for sound source localization for engine product in Wärtsilä. Scan and paint (S&P) technology has drawn Wärtsilä's attention for this purpose. Comparing to traditional sound intensity probe which consists of two microphones, the S&P probe consists of one microphone and one velocity sensor, Figure 2.

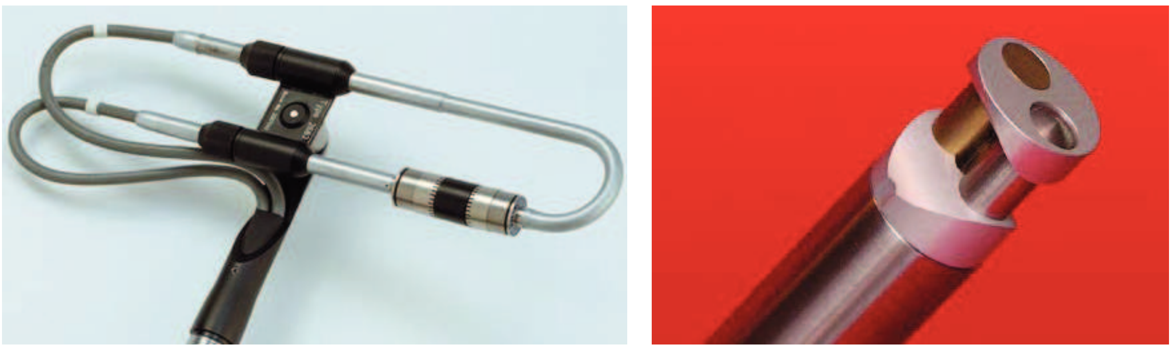

Figure 2: Left, example of traditional sound intensity probe composed by two microphones; Right, example of S&P probe composed by one microphone and one particle velocity sensor.

The S&P probe is supposed to be used at near field for sound source localization, and at further distance for sound intensity identification. As a relatively new technology in the market, the device was assessed by Wärtsilä in cooperation with VTT (Technical Research Centre of Finland) in 2015. Measurements were carried out on the top part of a Wärtsilä in-line engine by both the traditional probe and S&P probe. The results are demonstrated in Figure 3.

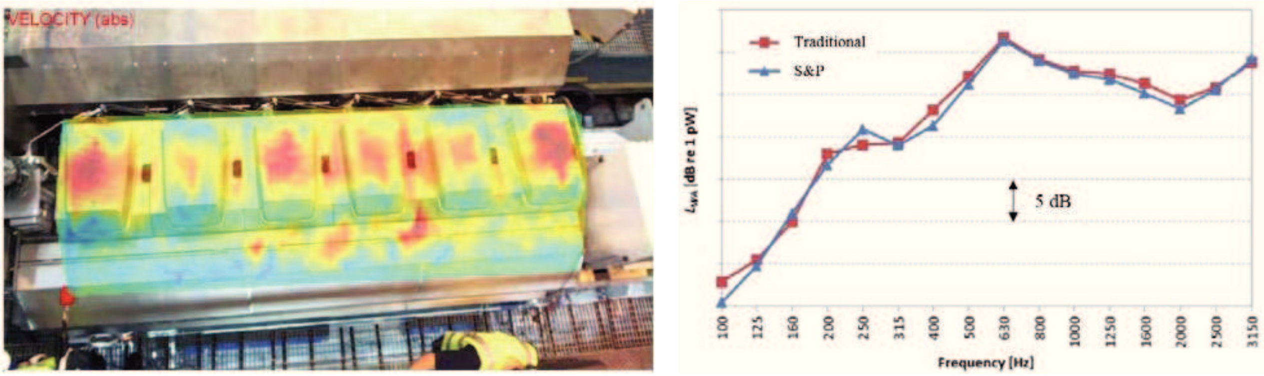

Figure 3: Left, particle velocity level of engine top part at a certain frequency band; Right, A-weighted sound power levels comparison between results from traditional and S&P probe**.**

It is found out that this new technology of measuring sound intensity by a probe consisting of one microphone and one velocity sensor is feasible to be used for noise localization and sound intensity measurement on large heavy duty medium speed engines at Wärtsilä.

Engine Mechanical Noise

Engine noise is complex in the way that there are multiple excitation mechanisms generate noise and vibration energy that transfers through all engine components giving rise to both structure-borne and airborne noise. The typical noise spectrum of a medium speed engine is similar to white noise, i.e. energy distributed in broadband, Figure 4.

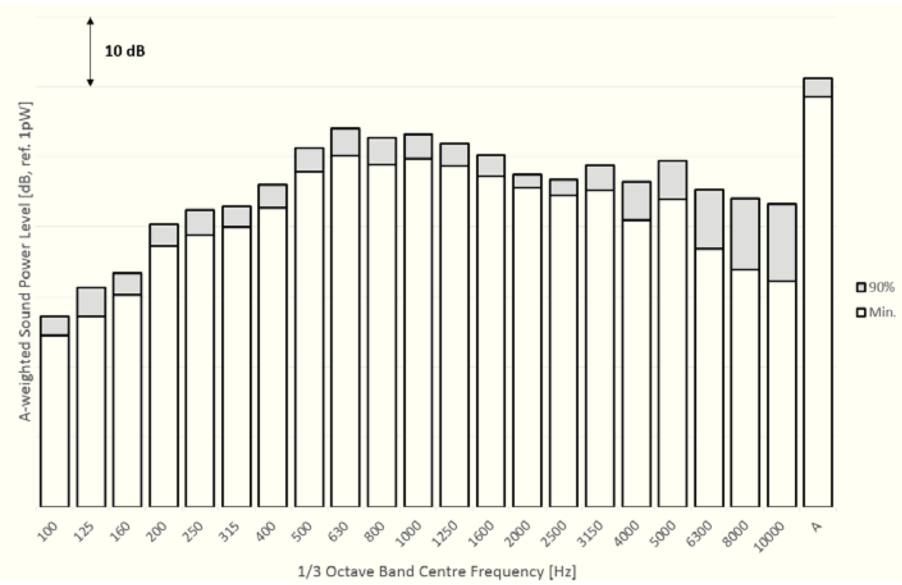

Figure 4: A-weighted sound power level of a certain type of Wärtsilä diesel engines. 90% of the measured engines have noise level within the grey area.

As can be seen from Figure 4, the dominating frequency range is about 500 – 2k Hz. In this frequency range most of the noise is caused by engine mechanical excitations. From experience, combustion noise is not so important for a large diesel engine because it has relatively low frequency ranges, i.e. below 500Hz, and especially when the engine runs on full load other noise sources will dominate. At higher frequencies above 3k Hz, typically there is turbocharger tonal noise, which can reach over 130 dB at 1 m distance if no silencer is applied.

Typically, a diesel engine is noisier than a gas engine. Figure 5 shows an example of a Wärtsilä dual-fuel gen-set noise levels on diesel and gas modes.

Figure 5: A-weighted sound power levels of a certain type of Wärtsilä dual-fuel gen-set running on diesel and gas modes.

The total noise level of diesel mode is about 4 dB higher than gas mode. The main difference exists in the mechanical noise frequency range, i.e. 500 – 2k Hz. This is due to the fuel injection process of the diesel mode. When the cam drives the fuel injection pump, high torsional vibration will be generated on the camshaft. This torsional vibration will cause gear teeth impact in the gear train. The energy generated by gear teeth impact will transfer via shaft bearings to engine block and attached structures, thus radiates noise. This phenomenon has been investigated earlier at Wärtsilä in cooperation with KTH (Royal Institute of Technology) and Lloyd's Register ODS [6]. To illustrate the gear teeth impact, the shaft torques were measured and demonstrated in Figure 6.

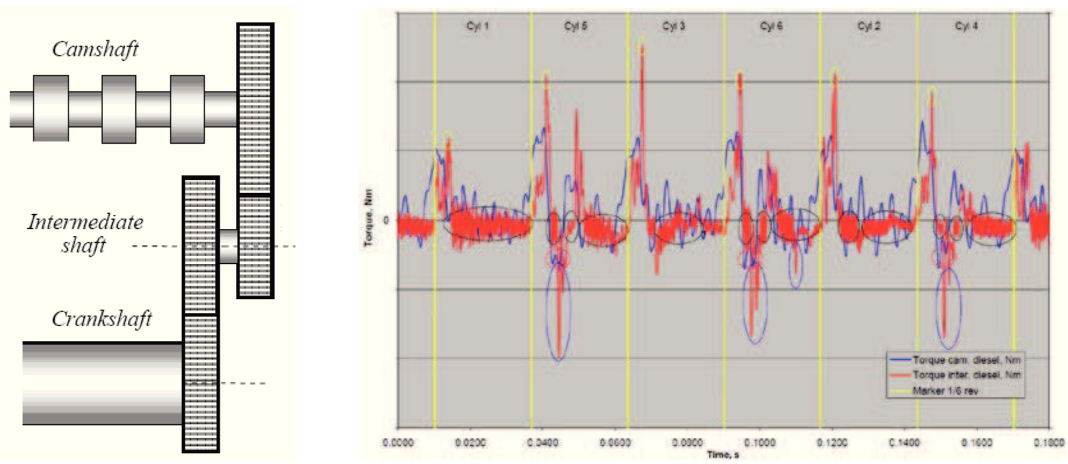

Figure 6: Camshaft and intermediate shaft torques measured on a Wärtsilä in-line engine with 6 cylinders. Red – intermediate shaft; Blue – camshaft.

Yellow ovals mark the fuel injection moment for each cylinder. One may also notice that there are sharp negative peaks in the torque measurement results. These peaks marked by blue and red ovals indicate that the gear teeth of the mesh between camshaft and intermediate shaft have traveled through its backlash and are impacting with each other on the non-working flank. Before and after gear impacts a loss of contact between the teeth occurs, marked by black ovals.

The gear impacts are more severe during the fuel injection process of the cylinders that locate far away from the gear train than the ones near the gear train. This is because to drive fuel pumps that are far from the gear train the camshaft needs to be twisted more in angular displacement, thus more potential energy is stored during and will be released after fuel injection process, causing more severe gear impacts phenomenon.

Gear train is considered as one of the most important mechanical noise sources of a large medium speed diesel engine. Other mechanical noise sources may include piston slap and valve train impacts etc. All mechanical excitations will give rise to the structure-borne noise of an engine.

Engine Structure-borne Noise

Structure-borne noise is defined as the noise radiated by a vibrating structure that has the energy with a major transfer path through structures. The structure-borne noise is considered to be more important than air-borne noise for Wärtsilä diesel engines.

Mechanical impacts and friction will give rise to structure vibration, generating noise. The amount of noise generated by a vibrating structure does not only depends on vibration magnitude, but also on air impedance and radiation efficiency. In general, the radiated sound power can be estimated as in equation (1).

$$P = \left\langle v^2 \right\rangle \rho c A \ \sigma \qquad \text{[W]} \qquad (1)$$

where $\left\langle v^2 \right\rangle$ is perpendicular mean square velocity of the surface, ρ is fluid density, c is speed of sound in fluid, A is area of the vibrating surface and σ is radiation efficiency.

The equation tells us that a less vibrating structure does not necessarily mean less noise radiation. The air impedance term which is air density by sound speed is typically a constant at certain environment, whereas the sound radiation efficiency makes the difference between noise and vibration. It is a measure of how effective a vibration gets translated into noise. Theoretically for a simply supported structure the radiation efficiency in logarithmic scale has the following pattern of curve in frequency domain, Figure 7.

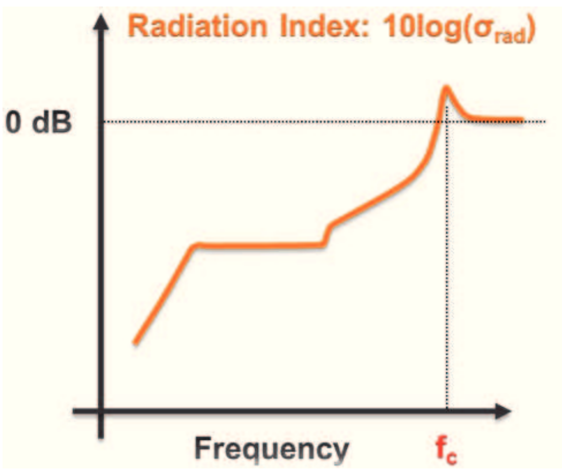

Figure 7: Demonstration of radiation index curve in frequency domain.

The radiation index is low in the low frequency ranges. It ramps up to a peak level at the critical frequency f_c, where the structural bending wave speed equals the sound speed resulting in the maximum efficiency of sound radiation. At the frequencies higher than the critical frequency, the radiation index stays flat. To have a structure with low radiation efficiency, the critical frequency f_c should be as high as possible. Theoretically, the critical frequency is proportional to the square root of mass and inversely proportional to the square root of bending stiffness of the structure. To mitigate broad band structure-borne noise, one of the most effective ways is to design the structure with low stiffness and high mass. When the stiffness is decreased, the low frequency vibration will increase. However at low frequency range the radiation efficiency is low, which means the structure is not effective in generating acoustical energy from its vibration. Furthermore, one may also consider increasing structural impedance mismatch by using different material layers so that the energy will dissipate at the contact surface.

One of the components that are effective in noise radiation is the engine side covers for crankcase and cam case. Wärtislä previously used cast aluminium as the side covers. Lately the covers have been updated to thin steel plate. Significant noise reduction is achieved, Figure 8.

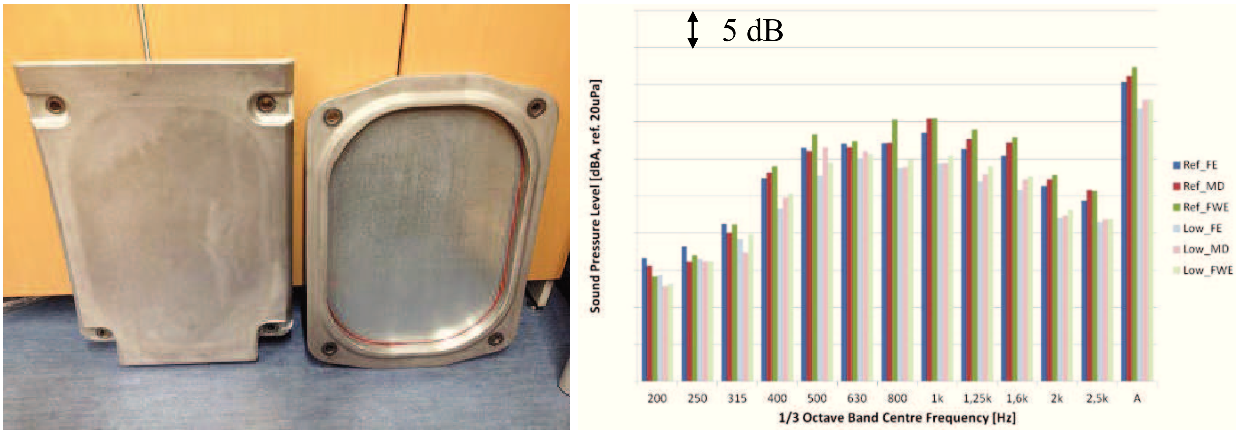

Figure 8: Left, cast aluminium and thin plate cover; Right, comparison of noise levels measured at 1 m distance away from the engine at free end (FE), middle part (MD) and flywheel end (FWE) between cast aluminium covers (Ref) and thin steel plate covers (Low).

The density of steel is about three times as high as the one of aluminium, and the thin steel plate has much lower stiffness than the cast aluminium. These facts have resulted in the critical frequency of the steel plate is much higher than the cast aluminium, thus the radiation efficiency of the steel plate is much lower than the cast aluminium. Furthermore, the new cover frame is still made by cast aluminium and only the plate is made by steel. This has increased the structural impedance mismatch so that some of the vibration energy from the engine block acting on the cover frame dissipates at the contact surface between the plate and the frame.

Looking into the spectra in Figure 8, the noise reduction can be seen along the engine body from free end to flywheel end and the reduction is in a broad band range where the radiated mechanical noise is high, i.e. 300 – 3k Hz. This result is from sound pressure measurements at 1 m distance away from the engine. Meanwhile the result from sound intensity measurements where the probe is approximately 10 cm away from the covers shows even more noise reduction.

One should be aware that before deciding to apply this methodology of reducing radiation efficiency by increasing the critical frequency in order to reduce the noise radiated by engine side covers, one needs to be sure that the major noise of the engine is structure-borne noise from the vibration of the structure instead of air-borne noise from cylinder combustion. Furthermore, if the major noise is obviously from the resonances of the side covers, the first thing one should consider is to damp the resonances or stiffen the structure in a proper way. [2]

Flow Noise in Engine Room

Besides the mechanical noise and combustion noise, the noise generated by strong flow from air wastegate or condensate drains of a large medium speed engine can be very high over 125 dB. The strong flow generated noise normally dominates at high frequencies broad band. Proper types of silencer need to be used for strong flow. From experience, various types of wool can be good high frequency noise absorption material. Most of the time it will not give too much pressure drop influencing the engine performance. Moreover, one should avoid using steel wire mesh for strong flow noise absorption because its noise reduction property is very poor, Figure 9.

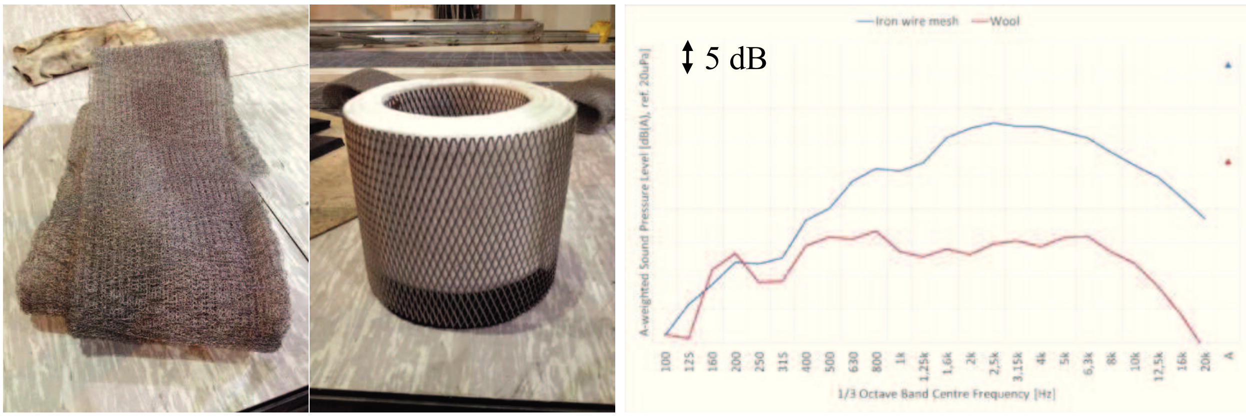

Figure 9: Noise level at 1 m distance away from the air wastegate silencer on a Wärtsilä engine with steel wire mesh and wool as the silencer absorption material.

As can be seen, the air wastegate flow caused noise starts to ramp up from 500 Hz and depending on how strong the flow is the noise spectrum will continue till very high frequencies in broad band. In this case the wool material has almost 15 dB better noise reduction performance than the steel wire mesh material. In order to fulfill SOLAS new noise regulation, all strong flow from air wastegate or condensate drains of a large medium speed engine must be properly silenced or lead to outside of the engine room.

Influence of Room Acoustics

The sound pressure level in the engine room depends on the engine sound power, measurement locations and the engine room properties. In the 2000s, Wärtsilä was in close cooperation with Lloyd's Register ODS, aiming at engine room noise reduction. Substantial research and measurements were carried out. It was concluded that the used prediction strategy can accurately model the noise from an engine in an engine room. The study investigated the influence of room volume and the absorption on the resulted SPL. The results are demonstrated in Table 1.

Room Volume (m^3)	Absorption	Reverberation time (s)	A-weighted L_p (dB)
1000	NO	~ 2	112
3000	NO	~ 3	108
1000	YES	~ 0.8	105
3000	YES	~ 1.3	104

Table 1: Simulated effect of volume and absorption on noise level in engine room

The absorption here refers to 60mm absorption material behind a perforated steel panel fully covering the 2 walls parallel to the engine. The ideal low noise engine room design is to have a large volume and enough absorption. For a small engine room, by adding absorption in the calculation, the noise level can be reduced by 7 dB (ideal case). Once there is enough absorption in the room, it seems that the volume influence to the noise is not so big anymore because the engine room is approaching the free field condition like an anechoic room. [7]

Summary

To reduce large medium speed diesel engine noise, one should take mechanical noise into serious consideration before focusing on the combustion noise. All mechanical impacts and friction can give rise to mechanical noise, e.g. piston slap, gear train and valve train impacts etc. In case of broad band noise when no obvious resonant peak can be found in the noise spectrum, one may want to study the vibro-acoustic behavior of the structures that radiating the noise. Typically by utilizing designs with low radiation efficiency, which requires high density and low stiffness, and increasing structural impedance mismatch between material layers can improve the noise radiation to a much lower level. Furthermore, all strong flow should be lead out from the engine room or properly silenced. Any strong flow leakage may result in dramatically high noise level in the room.

Wärtsilä has decades of experience in engine noise and vibration study. It is important for engine manufactures to have reliable and advance measurement instruments to know the engine noise behaviour thoroughly before deciding the most effective way to reduce the engine noise. With ever demanding and challenging market, in the past decade Wärtsilä medium speed diesel engines' output has increased by 20%, while the noise level has dropped significantly, e.g. at manoeuvring side, Figure 10, without adding any insulation panel that may complicate the maintenance work.

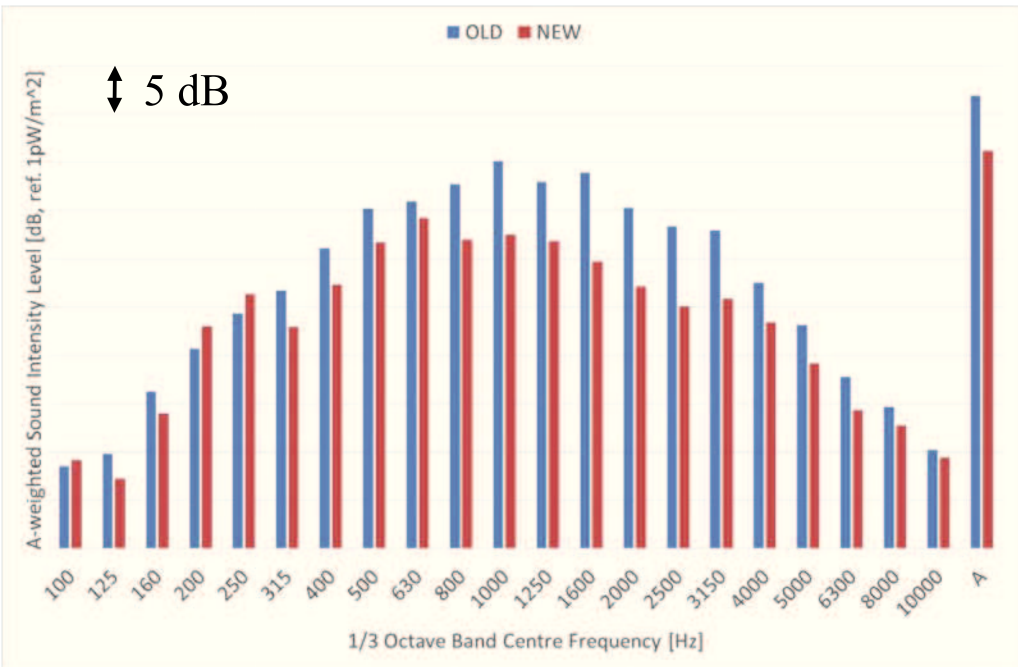

Figure 10: Manoeuvring side noise level comparison between old and new Wärtsilä 6L engines.

To fulfill SOLAS new noise regulation, efforts and responsibilities only from engine manufactures are not enough. Since engine room acoustics plays also an important role, the shipyards are expected to have a leading role in and responsibility for the engine room acoustical design.

References

[1] K. Saine, Z. Gao, E. Nousiainen, Two decades of noise research in Wärtsilä. Baltic Nordic Acoustic Meeting, Tallinn, 2014

[2] Z. Gao, K. Saine, S. Oksanen, SOLAS new noise regulation impact on engine noise reduction and engine room. CIMAC, Helsinki, 2016

[3] S. Oksanen, Z. Gao, J. Holmberg, J. Hartikainen, Optimized performance, design and manufacturing of compact silencer system for engine exhaust noise. CIMAC, Helsinki, 2016

[4] Z. Gao, S. Oksanen, K. Saine, J. Hartikainen, R. Hjort, Low frequency noise investigation and solution for a large diesel engine factory in the city. Internoise, San Francisco, 2015

[5] K. Saine, Z. Gao, A. Leskinen, R. Hjort, Long term noise measurements – Is Leq(A) run out of steam. Baltic Nordic Acoustic Meeting, Stockholm, 2016

[6] Z. Gao, K. Saine, M. Wollström, Gear noise analysis for a large diesel engine. ICSV, Krakow, 2009

[7] Z. Gao, K. Saine, Noise reduction for a large diesel engine. Baltic Nordic Acoustic Meeting, Stockholm, 2016