Diesel Engines and the Environment - Noise

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Introduction

Nowadays, more and more consideration is being given to environmental issues. Our efforts in this field have already led to our being awarded the Danish Environmental Prize for developing a plant for removing the poisonous nitric oxides from exhaust gases.

Formerly, noise was considered a necessary, but harmless, evil. Today, excessive noise is considered a form of pollution which, in the long run, may cause permanently reduced hearing. As a consequence, authorities now demand that noise levels are kept below certain specified limits.

One of the first countries to introduce a standard for noise limits was the Federal Republic of Germany which, in 1968, issued a code regarding the noise levels permitted on its ships. Today, there are numerous national and international codes which both recommend, and demand, maximum permissible noise levels in the various parts of a ship.

The greater demand for noise limitation in the maritime area has, of course, aroused wide interest. Consequently, greater demands are now made on the engine designer to provide more detailed and precise information regarding the various types of noise emission from the engine.

After a brief definition of what noise actually is, this paper will attempt to clarify 'noise' as applied to MAN B&W's two-stroke engines, and will then go on to discuss the primary noise sources and types of engine-related noise emissions, noise level limitation, and the current situation in relation to noise.

What is Noise?

A popular definition of noise is 'an undesirable sound'. To what extent a sound can be characterised as noise is, of course, a personal evaluation. However, if the sound level is so high as to be damaging to health, it will normally be considered by one and all as undesirable and, therefore, as noise.

Sound is the result of mechanical vibrations occurring in an elastic medium, e.g. air. When the air starts to pulsate, the variations in air pressure will spread from the source through the transfer of energy from molecule to molecule. The more energy transferred, the higher the sound level.

Intensity of Sound

The physical intensity of sound, I – which expresses the volume of the sound – is defined as the energy emitted per second, per m^2 of a surface which is at right angles to the direction of propagation of the sound wave, as shown in Table 1 and Fig. 1.

Intensity of sound

$$I = pu = \rho c u^2$$

and if we use $k = \sqrt{\rho c}$, the corresponding mean effective sound pressure (p) and the pulsation velocity (u) may be stated as follows:

$$p = k \times \sqrt{I} \quad \text{and} \quad u = \frac{1}{k} \times \sqrt{I}$$

where,

I	= Intensity of sound	(W/m^2)
p	= Mean effective sound pressure	(N/m^2)
u	= Mean effective pulsation velocity	(m/s)
c	= Velocity of sound in medium (air)	(m/s)
ρ	= Specific mass of medium (air)	(kg/m^3)
k	$= \sqrt{\rho c} \cong \sqrt{1.2 \times 340} = 20$ at normal ambient air temperature.	

Reference for sound levels

Reference sound intensity

$$I_o = 10^{-12}\ \text{W/m}^2$$

Given a sound intensity $I_o = 10^{-12}$ W/m^2 and using the above formulas, we can state the corresponding reference mean effective sound pressure (p_o) and mean effective pulsation velocity (u_o) as follows:

Reference sound pressure level

$$p_o = 20 \times \sqrt{10^{-12}} = 2 \times 10^{-5}\ \text{Pa (Pascal = N/m}^2\text{)}$$

Reference velocity level

$$u_o = \frac{1}{20} \times \sqrt{10^{-12}} = 5 \times 10^{-8}\ \text{m/s}$$

Table 1: Sound wave formulas

Sound Level Measurement Units

The International Standards Organisation (ISO) has determined the following reference values for acoustics:

Reference for sound intensity:
$I_o = 10^{-12}$ W/m^2

Reference for sound pressure:
$p_o = 2 \times 10^{-5}$ Pa

Reference for vibration velocity:
$u_o = 2 \times 10^{-9}$ m/s

The above-mentioned intensity and pressure reference values represent sound intensity and sound pressure at the lowest levels perceptible to the human ear.

As the ear is not particularly sensitive and is just able to discern that a sound has doubled in intensity, a linear division of the intensity would be impractical. For this reason, decibel (dB) has been introduced as a unit for measuring sound.

This unit is logarithmic and is defined as 10 times the logarithmic relationship between the actual intensity of the sound and the reference value:

Sound intensity level (dB):
$L_I = 10 \times \mathrm{Log}_{10}\,(I/I_o)$

re $I_o = 10^{-12}$ W/m^2

As sound pressure squared corresponds to the intensity of the sound, the following corresponding values are valid when we use sound pressure as a basis:

Sound pressure level (dB):
$L_p = 20 \times \mathrm{Log}_{10}\,(p/p_o)$
re $p_o = 2 \times 10^{-5}$ Pa

Normally, it is the sound pressure level which is measured, and when nothing else is given, it will be re 2×10^{-5} Pa.

On the basis of the above, a sound intensity of 10^{-12} W/m^2 corresponds to a sound level of 0 dB, and a sound intensity of 1 W/m^2 corresponds to a sound level of 120 dB. Incidentally, 120 dB is the level at which the ear begins to feel pain – normal conversation is usually conducted at around 55 dB.

At the so-called 'far-field', i.e. where no sound is reflected and where sound waves can be assumed to be propagated spherically, a doubling of the distance will reduce the intensity of the

Sound level - far-field law

Sound level at distance R_2 compared to distance R_1:

Reference sound intensity .... $I_o = 10^{-12}$ W/m^2
Sound intensity level (dB) at R_1 .... $L_1 = 10 \times \log_{10}(I_1/I_o)$
Area of a sphere:.......................... $A = 4\pi R^2$
Sound intensity at R_2 .... $I_2 = I_1 \times (R_1/R_2)^2$
Sound level at R_2.......................... $L_2 = L_1 - 20 \times \log_{10}(R_2/R_1)$

In general, the sound level will be reduced by 6 dB for each doubling of the distance from the noise source

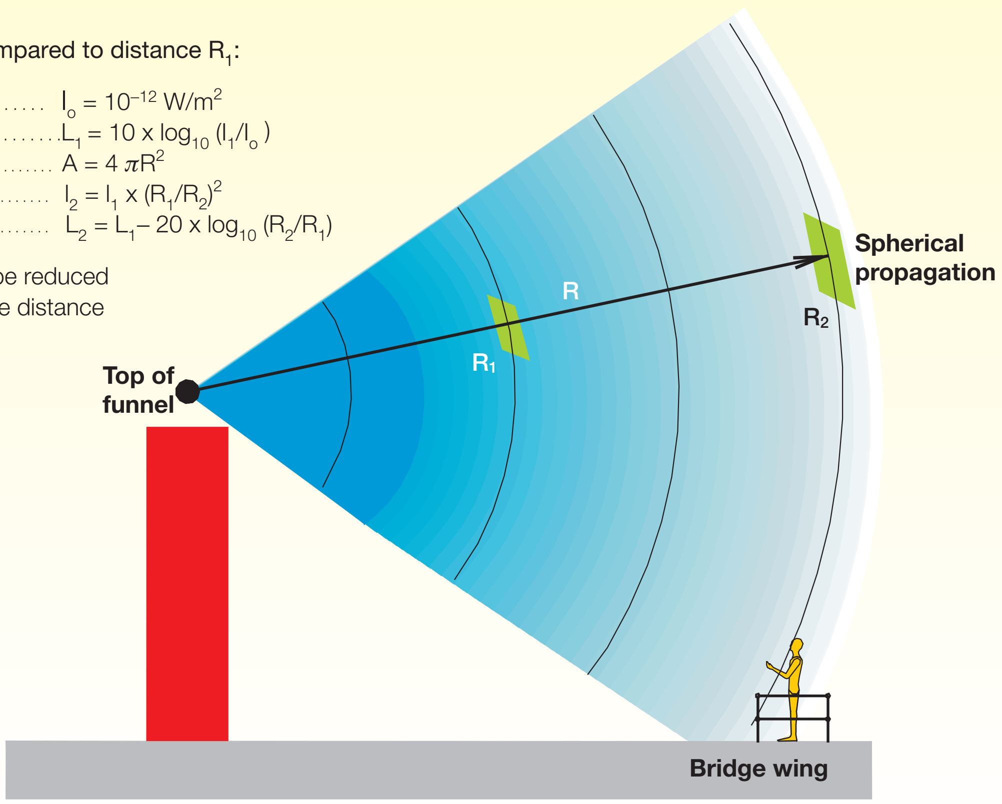

Fig. 1: Spherically propagated sound waves - far-field law. Distance R from noise source (point source assumed)

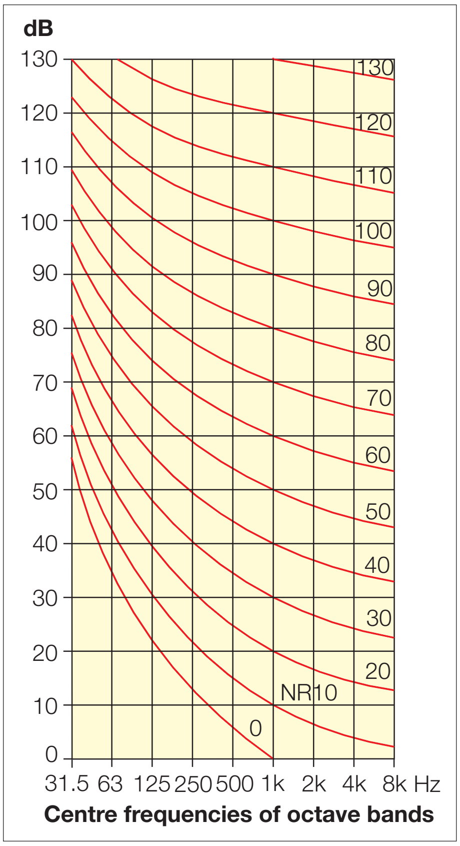

Fig. 2: ISO´s Noise Rating curves
Octave band pressure levels, re 2 x10^{-5} Pa

sound to 1/4, corresponding to a sound reduction of 6 dB, see Fig. 1.

Velocity level (dB):
In the same way, when using velocity level as a basis, we get
$L_V = 20 \times Log_{10} (u/u_o)$

1) re $u_o = 5 \times 10^{-8}$ m/s
used by MAN B&W Diesel in this paper and corresponds to the mentioned ISO reference figures I_o and p_o.

2) re $u_o = 10^{-9}$ m/s
used by ISO standard, and $u = 5 \times 10^{-8}$ m/s in this norm then corresponds to 34.0 dB.

Normally it is the velocity (sometimes the acceleration) level which is used when the vibrational energy transferred from the engine feet to the ship hull is measured.

The Influence of Sound Frequency

The sensitivity of the human ear is closely related to frequency (Hz = vibrations per second). Sensitivity is low at low frequencies, so it is often necessary to take measurements at different frequency ranges. Normally, these measurements are made in the so-called octave bands. The octave bands are intervals between two frequencies where the upper frequency is twice as high as the lower.

Octave band frequencies, which are named according to their geometrical average frequencies, 31.5, 63, 125, 250, etc. up to 16,000 Hz, are specified by ISO. The audible frequency range for young people with undamaged hearing is around 20-20,000 Hz.

As a result of the ear's varying sensitivity to combinations of different frequencies and sound levels, ISO has introduced special noise curves, and ISO's 'Noise Rating' curve sheet is very often used, see Fig. 2.

The groups of curves shown correspond, more or less, to the hearing characteristics of the ear with the sound level of the 1000 Hz octave band used as a reference. As an example, curve NR 60 shows that the sensitivity of the ear to 60 dB in the 1000 Hz octave band roughly corresponds to its sensitivity to 75 dB in the 125 Hz octave band.

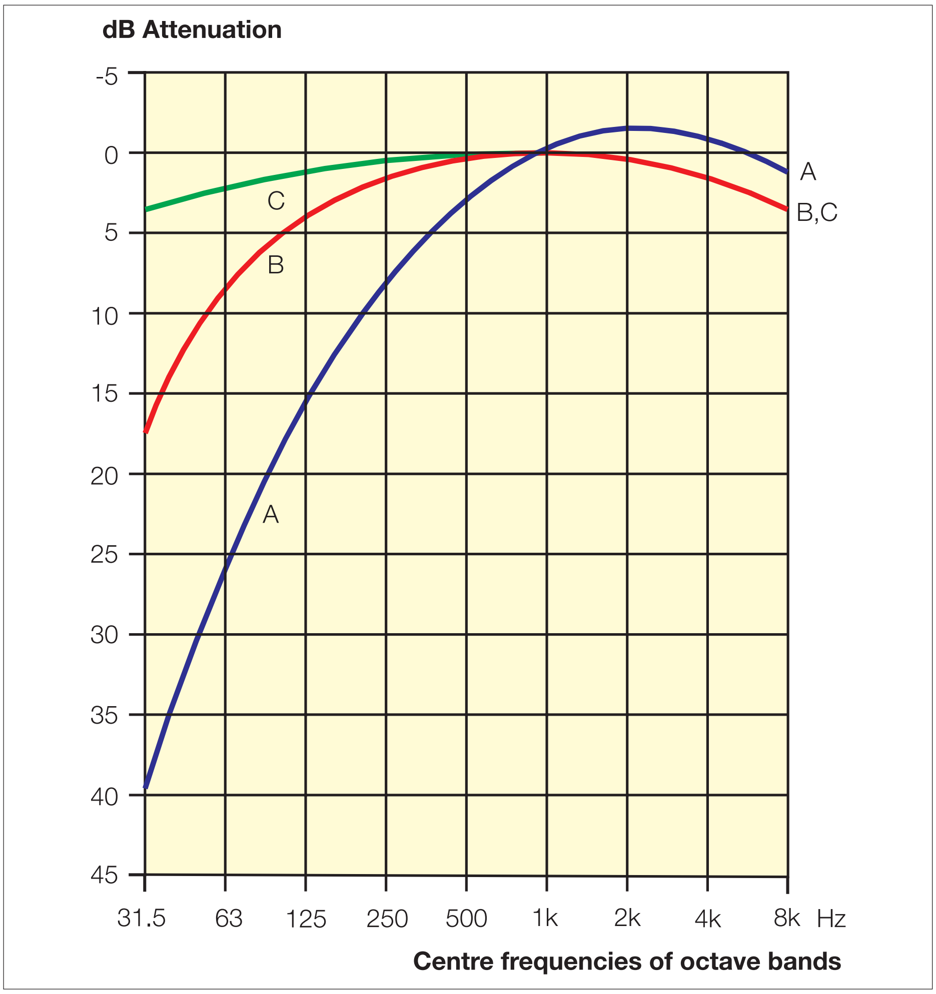

Fig. 3: Filtering (weighting) curves for sound level meters

If the sound pressure levels of the various octave bands for a given noise measurement are drawn-in on the curve sheet, the octave band with the highest NR-figure will give the resulting NR noise level for the measurement and, at the same time, show which frequency range(s) should be attenuated.

Another, simpler, method of compensating for the ear's subjective perception is the use of sound level meters fitted with internationally standardised frequency weighting curves, i.e. electrical filtering curves, the so-called A, B, C, and now (for aeroplanes) also D filters. See Fig. 3.

In principle, to compensate for the frequency-dependent sensitivity of the ear at various loudness levels, weighting curves A, B and C correct the actual linear (un-weighted) noise levels in relation to 1000 Hz corresponding to, respectively, the average 'Noise Rating' curves NR 0-55 for A, NR 55-85 for B, and higher than NR 85 for C.

In particular, the A filter is often used to give the final results of a sound measurement as a single value. The measured A-weighted value, designated dB(A), is also regularly used, even in cases where the sound level is high and a B or C-weighting curve would have been more appropriate.

A sound level obtained by linear measurement, i.e. without any correction for the sensitivity of the ear, is designated dB(Lin).

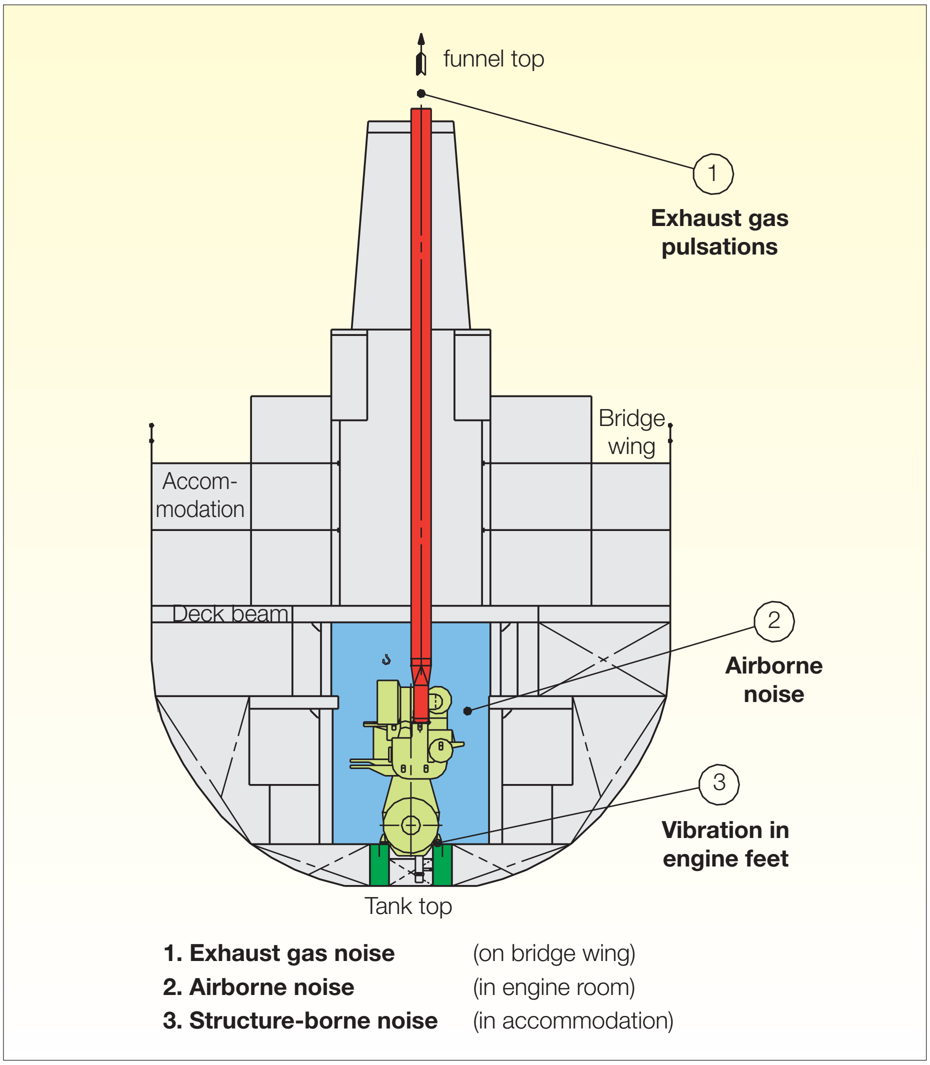

Fig. 4: Typical sources of engine noise

Primary Sources of Engine Noise

On the basis of engine noise measurements and frequency analyses, it can be ascertained that noise emissions from the two-stroke engine primarily originate from:

- The turbocharger, air and gas pulsations
- Exhaust valves
- Fuel oil injection systems

  and, to a certain extent,

- The chain drive.

The best way of reducing engine-related noise is, naturally, to reduce the vibrational energy at the source or, if this is neither feasible nor adequate, to attenuate the noise as close to its source as possible.

The different noise sources of the diesel engine, of which the primary ones are mentioned above, will, as a result, generate various types of noise emission to the environment. The types of engine-related noise emission will be discussed in the next section.

Two-Stroke Engine Noise Emissions

On the basis of theoretical calculations and actual measurements, we employ computer models – please refer to our paper: 'MAN B&W Computerised Engine Application System' – to provide our customers with data regarding the sound levels of the following engine-related noise emissions, which are typical of our two-stroke engines. See also Fig. 4:

1. **Exhaust gas noise** (gas pulsations)

2. **Airborne noise** (engine room noise)

3. **Structure-borne noise excitation** (vibration in engine feet)

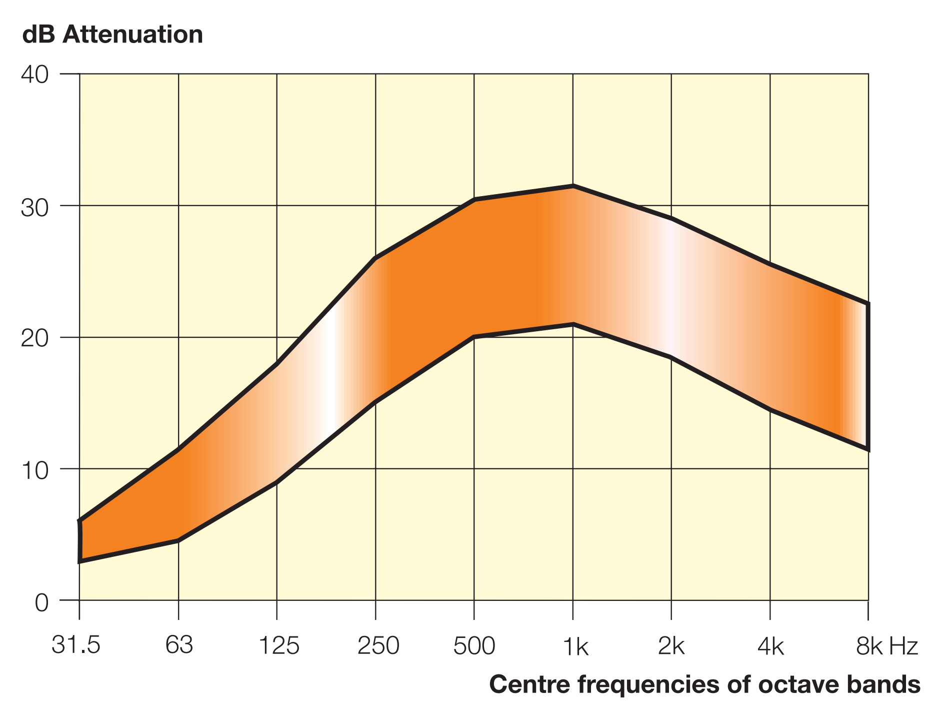

Fig. 5b: Typical noise attenuation for a 25 dB(A) absorption silencer

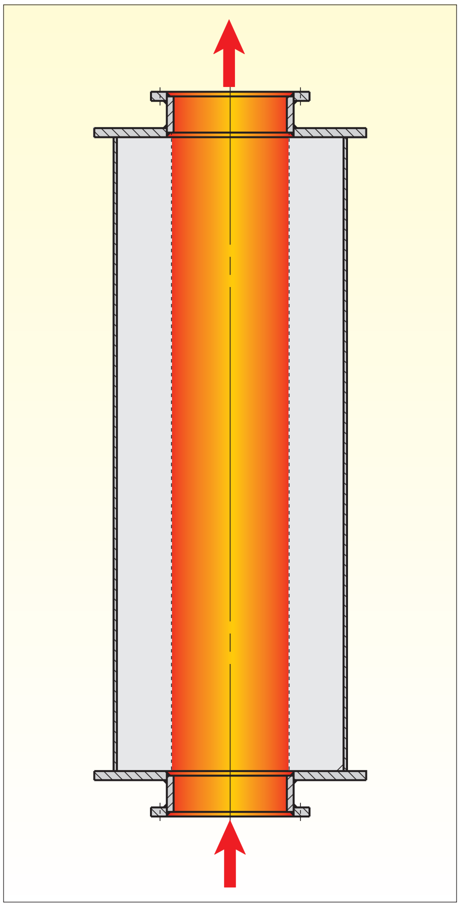

Fig. 5a: Absorption silencer

1. Exhaust gas noise

Our constant-pressure turbocharged two-stroke diesel engines are, unlike the former impulse turbocharged engines, equipped with a large exhaust gas receiver located between the gas outlets of the cylinders and the turbocharger(s).

Thanks to its ideal location, i.e. close to the noise source, this gas receiver also functions as an exhaust gas silencer, in particular attenuating the low-frequency gas pulsations.

Fig. 7a curve 1 shows a 6L80MC Mk 5 engine, running at nominal MCR, where the calculated octave band analysis of the exhaust gas noise from an exhaust gas system without boiler and without silencer has been drawn in.

The noise level calculation is based on a distance of 15 metres from the top of the funnel to the bridge wing. The curve sheet shows that the noise level in the octave band frequencies between 125 and 1,000 Hz is decisive for the total noise level of NR 81, and that the A-weighted sound level corresponds to 86 dB(A). The dB(A) figure is calculated by accumulating the intensities of the octave band sound levels, including the A-weighted attenuation, as shown in Fig. 3.

Fig. 7b shows the similarly calculated noise levels for a nominally rated 6S26MC Mk 6 engine where the distance from the funnel top to the bridge wing is 7 metres.

To keep noise below a maximum permissible level of, for example, 65 dB(A) on the bridge wing, a relatively voluminous 20-25 dB(A) exhaust gas silencer of the absorption type will normally be adequate, as this attenuates the dominant frequency ranges in question.

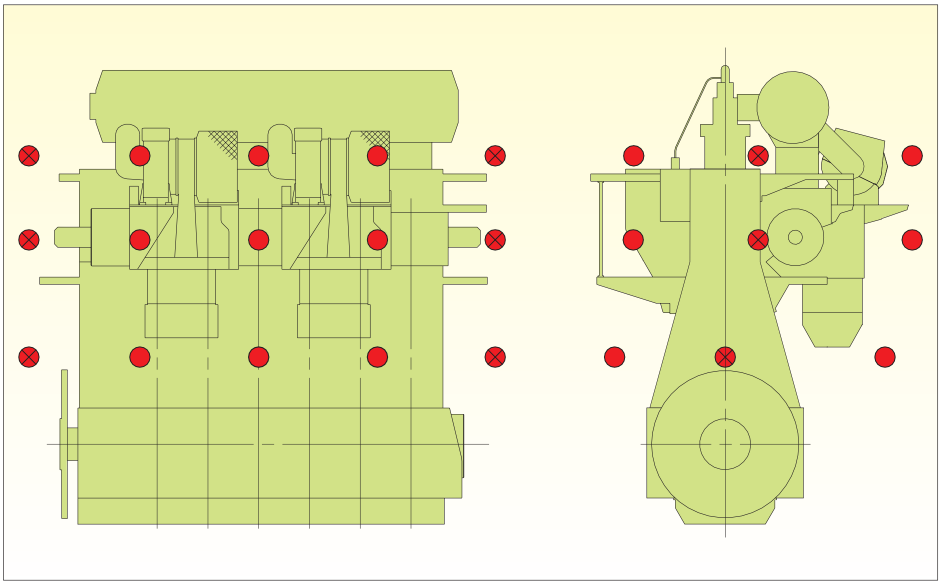

Fig. 6: Example of location of measuring points on a diesel engine in accordance with CIMAC's recommendations of measurement

As the exhaust gas arrangement itself (for example the exhaust gas boiler) can generate noise, we recommend that the exhaust gas silencer is inserted as close to the funnel top as possible.

The most frequently used absorption silencer is a flow silencer, i.e. a pipe with sound-absorbing wall material (mineral or glass wool). Fig. 5a shows such a flow silencer which, apart from having good attenuating qualities in the high-frequency ranges can, by virtue of its size, also be used to attenuate some of the lower frequency ranges.

The typical noise attenuation achieved with such a silencer type is shown in Fig. 5b as a function of the octave band frequencies.

2. Airborne noise

Engine room noise is primarily generated by emissions from the individual engine components and their surfaces, which cause the air to pulsate.

The average engine noise levels measured, for example according to CIMAC's 'Recommendations for Measurements of the Overall Noise for Reciprocating Engines', or other similar standards, are used to express the typical airborne sound pressure level of the engine.

The calculated average sound level corresponds to the average value of sound intensity measured at different points around the engine. Measuring points are - depending on the engine size - located at two or three heights around the engine, and at a distance of approximately one metre from the engine surface. Along each side of the engine, the number of measuring points at each level must equal half the number of cylinders. Fig. 6 shows where these measuring points could be located.

In general, depending, of course, on the type of engine, the average airborne noise level of a nominally rated engine will be around 105 dB(A), whereas the maximum level measured around the engine, and normally near a turbocharger, will be about 110 dB(A), but higher for bigger engines and lower for smaller engines.

Fig. 7a curve 2 shows the average airborne noise level calculated for a nominally rated 6L80MC Mk 5 engine with a noise level of approximately NR 101 and 105 dB(A) for an engine with high efficiency turbochargers, (curve 2A) and approximately NR 98 and 103 dB(A) for an engine with conventional turbochargers (curve 2B). The difference in noise levels originates from the difference in noise emission from the turbo- chargers themselves. In general, the higher the turbocharger efficiency, the higher the noise emission from the turbocharger and the engine.

Fig. 7b shows the corresponding average airborne noise level calculations for a 6S26MC Mk 6 engine.

Because of the reverberations of sound in the engine room, the sound pressure based noise levels measured in the vessel may be 1-5 dB higher than the calculated sound intensity based noise levels.

Measurements show that the turbocharger noise has a dominant influence on the total average airborne noise level, an influence which has become greater and greater because of the increasingly efficient and high powered engines demanded by the shipyards and shipowners.

The maximum noise level measured near a turbocharger will normally be about 3-5 dB(A) higher than the average noise level of the engine, using the high figure for high efficiency turbochargers. Often it is the maximum noise level measured at an engine that has to meet the specified noise limit requirements.

Especially in large diesel engines, it may sometimes – to meet the noise limit requirements – be necessary to introduce additional noise reduction measures, see Table 2.

These measures may reduce the maximum noise levels by 3-5 dB(A) and sometimes more, depending on their extent.

It would be extremely difficult to meet stricter requirements with regard to maximum engine room noise levels of,

3. Structure-borne noise excitation

Vibrational energy in the engine is propagated, via the engine structure, to the engine bedplate flanges, i.e. the 'feet' of the engine. From here, the energy is transferred to the ship's tank top, and then outwards to the ship's structure, which starts to vibrate and thus emits noise.

Among the sources which can generate vibrational energy are the pulses caused by the combustion process of the engine and the reciprocating movement of the pistons.

The vibrational energy transferred between the contact surfaces of the engine bedplate and the ship is largely amplitude-dependent, so the velocity can normally be employed as a unit of measurement. Like the sound pressure level, the velocity is best expressed in dB, see also Table 1 and page 5:

Velocity level (dB):

$L_V = 20 \times Log_{10} (u/u_o)$

re $u_o = 5 \times 10^{-8}$ m/s

The reference velocity used corresponds to the previously used intensity and sound pressure reference values and

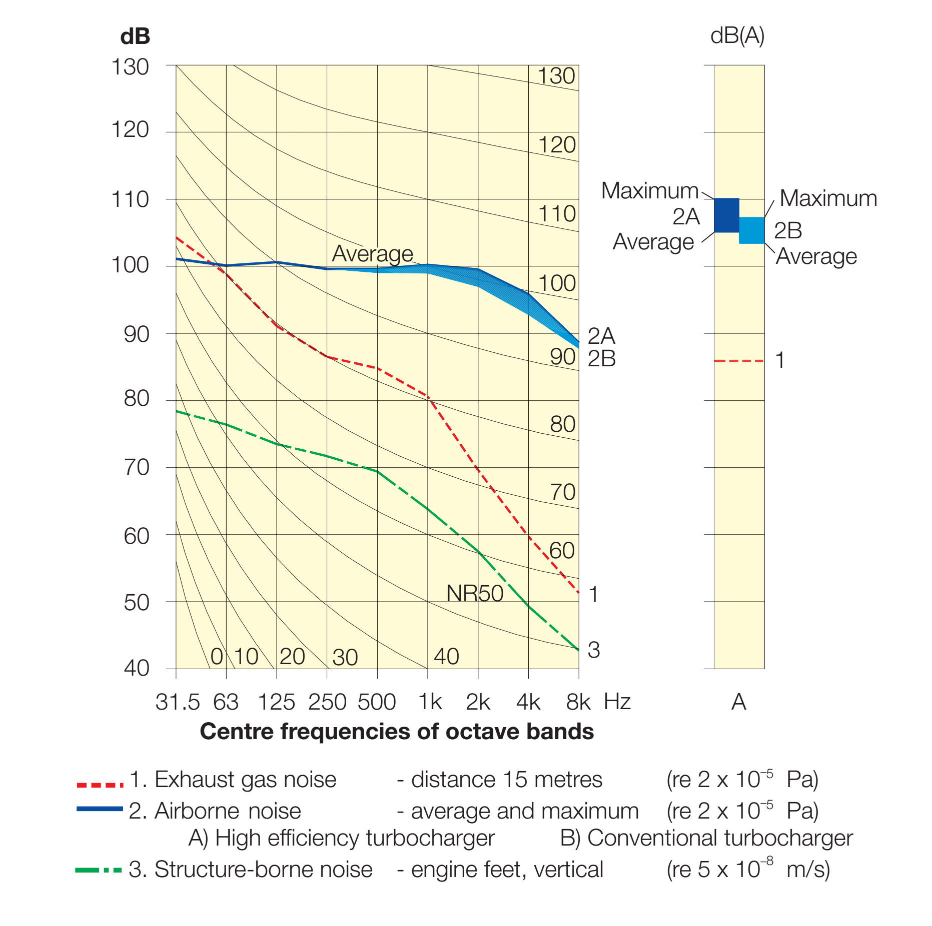

Fig. 7a: ISO´s NR curves and noise levels for a 6L80MC Mk 5 engine MCR: 20,580 kW at 93 r/min

for example, 105 dB(A) instead of 110 dB(A), especially in view of the influence of sound reverberations and the noise emitted by other machinery. The possibility of reducing the noise from an existing engine is greatly limited because, as previously mentioned, the noise stems from many different sources, and because the noise transmission paths – through which vibrational energy is transferred from one area to another through the engine – are numerous.

However, in principle, the transmission of airborne noise from the engine room to other locations, e.g. accommodation quarters, normally has no influence on the actual noise level in these locations.

1.	Helmholtz resonator lining in scavenge air pipe
2.	External insulation of scavenge air receiver
3.	External insulation of scavenge air cooler
4.	Additional absorption material at the engine and/or at the engine room walls (yard's responsibility)
5.	Additional turbocharger intake silencer attenuation (turbocharger maker's responsibility)
6.	Additional attenuation material at the turbocharger's inspection cover
7.	Low noise diffusor for turbocharger compressor, if available

Table 2: Additional noise reduction measures on diesel engines

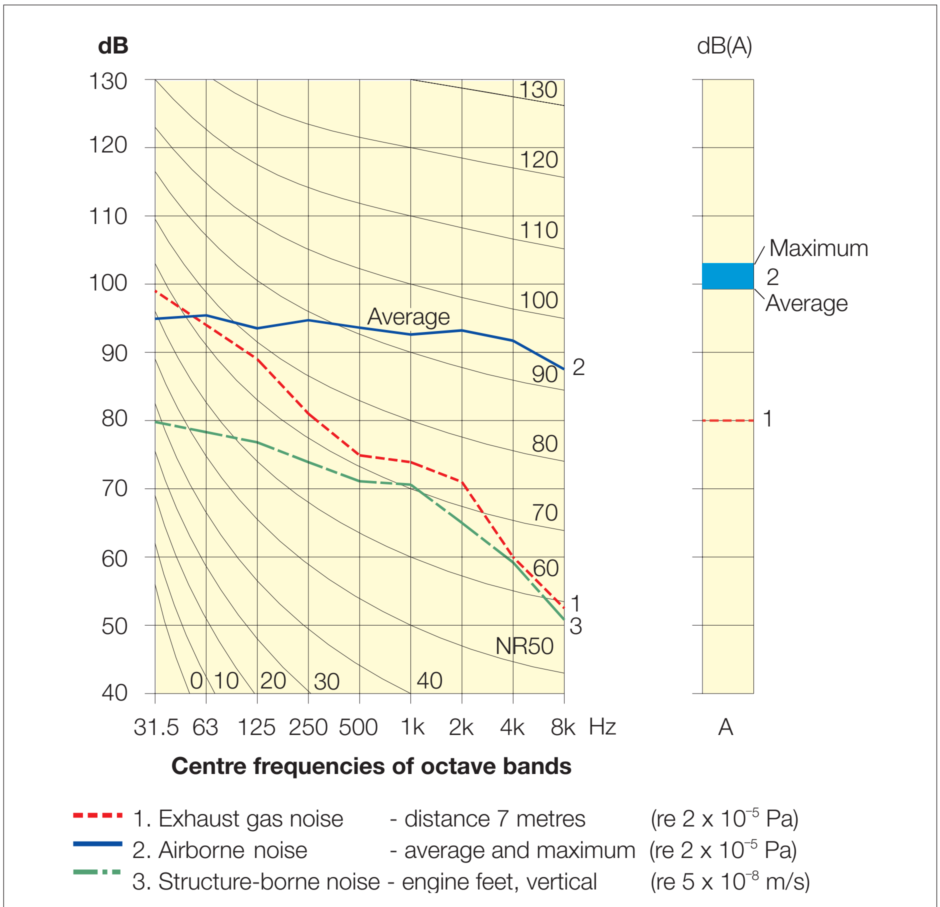

Fig. 7b: ISO's NR curves and noise levels for a 6S26MC Mk 6 engine MCR: 2,400 kW at 250 r/min

has therefore been selected by MAN B&W Diesel. However, according to the latest ISO Standard, as previously mentioned, the reference value 10^{-9} m/s is now used in this norm.

Figs. 7a and 7b (curve 3) also show the structure-borne noise excitation levels from a nominally rated 6L80MC Mk 5 and a 6S26MC Mk 6 engine, given as a vertical vibration velocity level in the engine feet.

When referring to 10^{-9} m/s instead of 5×10^{-8} m/s, the structure-borne noise levels shown should be 34.0 dB higher.

Incidentally, the vibration velocity level in a two-stroke engine is, on average, approximately 15-20 dB lower than in a four-stroke engine which, therefore, may sometimes have special vibration isolators (resilient mountings) built-in between the engine feet and the tank top of the ship. The structure-borne sound attenuation achieved is of some 15-20 dB, which means that the final result corresponds to the level of a solid-mounted two-stroke engine.

The above-mentioned vibration velocity levels in the diesel engine feet can, with the aid of empirical formulas, be used to calculate the excitation velocities and, thus, the sound pressure levels in the accommodation quarters. The shipyards, or their consultants, normally have these formulas at their disposal.

Noise Limits

Limits for the maximum sound pressure level are either defined specifically between owner/shipyard and engine builder, or indirectly by referring to national or international legislation on the subject. Many owners refer to the SBG (See-Berufsgenossenschaft) specifications or the IMO (International Maritime Organisation) recommendations. The IMO noise (sound pressure) limits for different ship spaces are listed in Table 3.

The appearance of national and international standards for noise levels in ships has, in general, resulted in a considerable reduction of the noise levels in newly-built ships, especially in the accommodation spaces.

Bridge wing – *Exhaust gas noise*

On the bridge wing, where it is the exhaust gas noise that predominates, there are certain limitations, as the bridge wing is regarded as a listening post. The requirement here, depending on the noise standard to be met, is a maximum of 60-70 dB(A), which can always be met by installing a suitable exhaust gas silencer.

It is often seen that ships built and registered in the Far East are not equipped with exhaust gas silencers, whereas ships built in Europe are normally equipped with silencers, in accordance with rules and regulations prevailing there.

The reason for omitting silencers is that, to save the cost of silencers, shipowners often do not specify compliance with rules required in Europe, for ships built in the Far East. Even if such ships are later on transferred to Europe, compliance with the rules is not required.

Engine room – Airborne noise

On the other hand, it is apparent that the above-mentioned general noise reductions have not been achieved in the engine room itself, where the airborne noise from the diesel engine dominates.

	dB(A)
Work spaces	
Machinery spaces (continuously manned) **	90
Machinery spaces (not continuously manned) **	**110**
Machinery control rooms	75
Workshops	85
Unspecified work spaces **	90
Navigation spaces	
Navigating bridge and chartrooms	65
Listening posts, including navigating bridge wings and windows	**70**
Radio rooms (with radio equipment operating but not producing audio signals)	60
Radar rooms	65
Accommodation spaces	
Cabins and hospital	60
Mess rooms	65
Recreation rooms	65
Open recreation areas	75
Offices	65

** Ear protectors should be used when the noise level is above 85 dB(A), and no individual's daily exposure duration should exceed four hours continuously or eight hours in total.

Table 3: IMO noise limits (sound pressure level)

The reason for this is that the acceptable noise limits for periodically manned engine rooms have, for many years, been set at around 110 dB(A), and the introduction of stricter requirements has not been realistic as the noise emission from a diesel engine has increased over the years because of the higher rated engines.

The unchanged noise limit thus in itself seems to have constituted a serious limitation for the engine builders. However, it is a recognised fact that a noise level of over 110 dB(A) can, in the long term, cause permanent damage to hearing, and therefore this limit cannot be expected to be eased, rather on the contrary.

This means that as engine designers – even though our engines generate no more noise than the engines of our competitors – we must, in future engine designs, pay particular attention to the airborne noise emitted by our engines.

Accommodation – *Structure-borne noise excitations*

The introduction of a 'floating floor' construction in the accommodation quarters has reduced the effect of the structure-borne noise excitation. Today, depending on the noise standard to be met, the noise limit requirements for accommodation are between 45 dB(A) and 65 dB(A), or lower, similar to those required in passenger ships. These noise requirements can, as a rule, be observed by taking adequate noise-attenuating precautions, e.g. the above-mentioned floating floor construction.

Conclusion

Generally, the noise emitted by the engine's exhaust gas, and the structure-borne noise excited by the engine, are so low that keeping within the noise requirements for the bridge wing and accommodation will not be a problem.

On the other hand, the airborne noise emitted from the engine in the engine room is so high that, in some cases, there is a risk that the noise limits for the engine room cannot be met, unless additional noise reduction measures are introduced.

In future, therefore, it must be expected that it will be very important, from a marketing point of view, to develop an engine with reduced airborne sound levels.