Exhaust noise – a new measurement technology in duct

Mr Claes-Göran Johansson	MSc,Sen. Scient. Acoustics ABB Corp.Research, Västerås Sweden, claes-goran.johansson@se.abb.com
Mr Kari Saine	MSc, Wärtsilä Finland Ltd, Engine Technology, Vaasa Finland , kari.saine@wartsila.com
Mr Petter Johansson	Consultant, Ztreme Engineering, Gothenburg Sweden petter.johansson@ztreme.com
Prof. Mats Åbom	The Royal Institute of Technology, Stockholm Sweden matsabom@kth.se

1. Abstract / Background

The noise emission from large internal combustion engines, from 500 kW to 20 MW, is inherently difficult to predict with a high degree of confidence. How the actual noise field propagates within a complex exhaust gas system and how to measure exhaust noise where the gas flow in the duct could be as high as 50 m/s and temperature about 450 degree. This translates to increased cost for silencer over-sizing or added costs associated with an exhaust gas system that fails to meet the required noise signature.
This paper deals with a new and verified hot gas (< 600 C) in-situ noise measurement technology called SESAM (Silencer & Exhaust System Acoustic Measurement). It makes it possible to accurately measure source strength and specific insertion loss of the various components in the exhaust train behind large 2 or 4 stroke diesels and power plant gas turbine. Also these measurements can be carried out easy way under field conditions with this portable system.
When designing an exhaust system for diesel engine it is most important to have a correct source spectrum for the engine and the noise requirement raised by the final customer in order to do the precision design for the attenuation in the system. In the past the source spectrum of diesel engines always has been an issue of large uncertainty due to the fact that no general reliable measurement procedure exists.
The paper presents the practical induct SESAM technology and discusses measurement results versus the time consuming and less accurate classic method. The system was tested at Wärtsilä Vaasa factory with real engine exhaust environmental. Also the loadspeaker was used as a sound source.

2. Measurements setup

The purpose of the SESAM-test was to perform the measurements with both loudspeaker and an engine. In both cases noise levels were measured inside the duct and after open duct by the classical method. All the measurements were performed at Wärtsilä Vaasa factory during last year, 2004. Below a general layout of the measurements is presented.
The length between duct inlet (in the test cell) and the open duct (on the roof) is 16,9m and has 4 bends, each with 90 degree, see photo 1 and 2. The induct measurement holes are located 6,9 to 10,9 meters from the inlet.
On the roof the system was opened up and a 2meter duct (photo 2) was removed. At this point the classical method for sound power measurement was done. Induct measurements was done before this open duct as well as after the silencer (then with closed duct again). The classical method was first calibrated (Qcorr) with a loudspeaker source to minimize the influence of the surroundings at the open duct. Measurements were performed with the diesel engine

running at different loads. After disconnecting the engine a special loudspeaker source was applied to the duct inlet and similar measurements was performed at cold conditions.

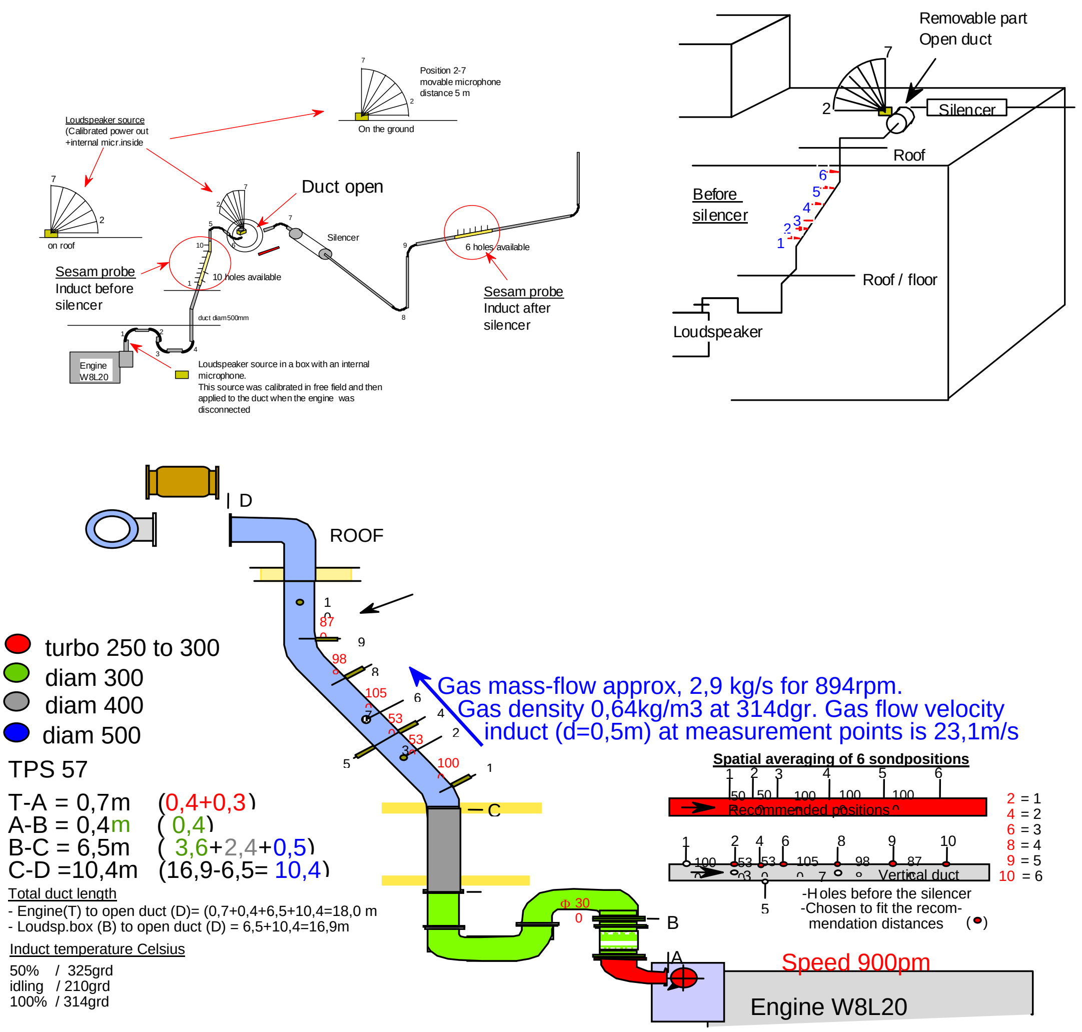


Fig 1. Overview first part of the exhaust duct system. Details regarding the exhaust system attached to engine W8L20 and important data for the evaluation of the induct measurements.

3. Induct – versus Classic method with loudspeaker at the inlet of the duct

Comparing injected sound power with measured power in the duct - using the measurement probe – will primarily indicate if the bends contribute with attenuation. If so it would only be expected above 500 Hz. The duct itself has minor attenuation because of the short length (<10m).

First measurement – classic measurement of sound pressure level (on the roof) calculated to sound power radiated at 90 degree angle at the open duct.
Second measurement- six flush measurements averaged to induct sound power and adjusted for end reflection and directivity radiated at 90 degree angle at the open duct.

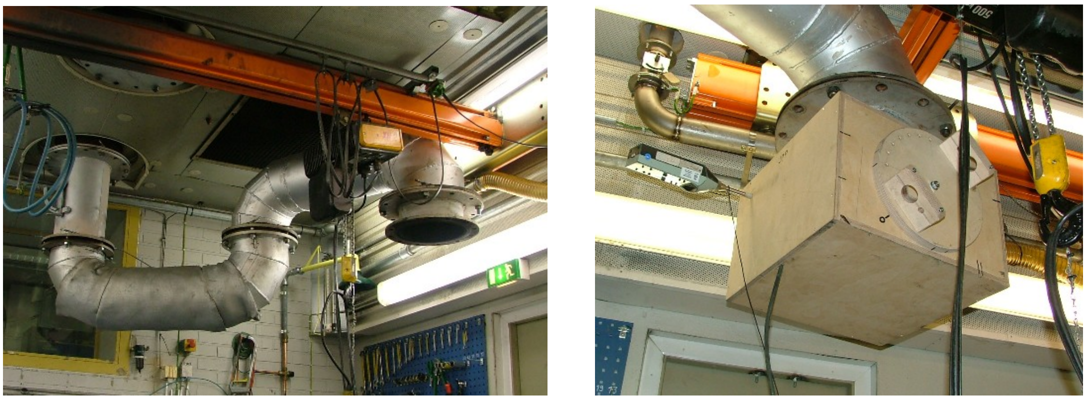


Photo 1. The loudspeaker box mounted for radiation into the duct. Injected sound power spectrum, first measured externally in free field and then corrected after mounting on duct.

The classic method to estimate the radiated sound power (Lw) from any type of sound source is standardized by enclosing the source within a fictive surface and then measure the sound pressure level (Lpi) at many points (n) on this surface. Normally the surface is half a hemisphere (Q=2) with the centre on a hard and sound reflecting ground. Position of the actual source should be at the centre. The radius (r) is normally chosen larger than the largest dimension of the source. After the average (Lp,average) from a measurement is calculated, the power (Lw) is found by logarithmic adding half of the hemisphere surface (10log 4π *r*r/2).

$$Lw = \overline{Lp} - 10\log Q + 10\log 4\pi r^2$$

$$\overline{Lp} = 10\log 1/n\ \Sigma\,(10^{Lp1/10} + 10^{Lpi/10} + \ldots + 10^{Lpn/10})$$

Lw = sound power level
n= number of measurement point
Lpi = sound pressure value at point (i)

$\overline{Lp}$ = logaritmic average for all points
10log Q = directivity = 2 for a half hemisphere
r = radius (m)

Measurement over a half hemisphere was not possible on the roof. This situation is very normal at engine manufacturers in general and causes problems to follow the classic acoustic standard. In fact only one direction could be used for significant measurements and in that direction 6 points was corrected and averaged, photo 2.

Photo 2. Surrounding at the roof.

The points had number (2-7) and the pole radius as an average seen from the open duct center was 5, 4 meter. Each measurement value (Lpi) was corrected with (10logQcorr, i).
The formula for the classic value of the sound power then became:

$$L_{w,\,classic} = 10\log 1/6 \sum_{i=2}^{i=7} \left(10^{\frac{(Lp - 10\log Q_{corr} - 10\log 4\pi r^2)_{i=2}}{10}} + \ldots + 10^{\frac{(Lp - 10\log Q_{corr} - 10\log 4\pi r^2)_{i=7}}{10}}\right)$$

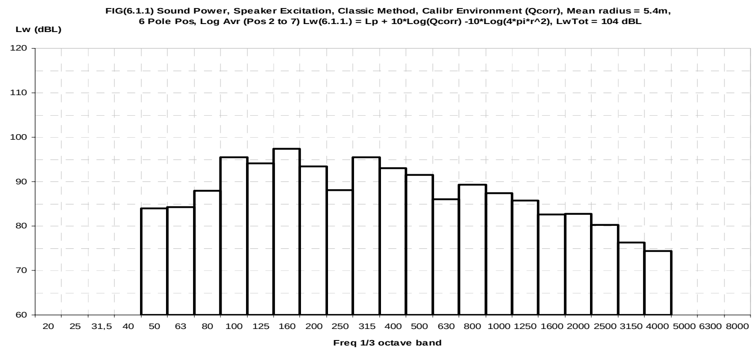


Fig 2. Sound Power, Speaker Excitation, Classic Method, Calibr. Environm. (Qcorr), LwTot = 104 dBL

4. Induct method to estimate the sound power radiated at the open duct

In order to find the radiated sound power at the open end of the duct - and be able to do the comparison with the classic method – the random spectrum in fig 3 has to be recalculated from flush measured sound pressure level to radiated sound power. This is done by corrections for duct area, multimode transition, end reflection and directivty (90 degree).

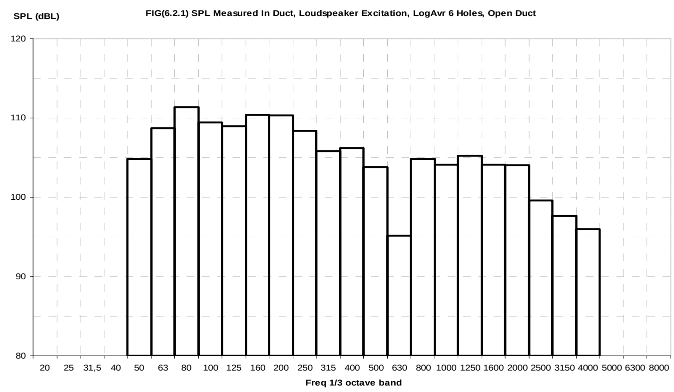


Fig 3. SPL Measured In Duct, Loudspeaker Excitation, LogAvr 6 Holes

Comparing with the classic method can be seen in fig 4 and the deviation between the two results in fig 5.
Totally for the induct method <u>106, 2 dBL</u> and the classic method <u>104 dBL.</u> The 2 dB difference is acceptable and induct method also should show the highest value because that method covers the power more efficient inside the duct. The classic method - in our case usable with 6 points in only one direction– could never cover all radiated power accurately.

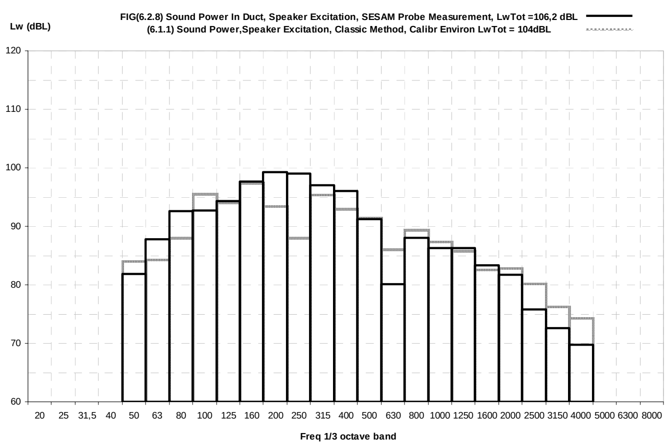


Fig 4. Sound Power in Duct, Speaker Excitation, SESAM Probe Measurement
compared to Classic Method

Individually per 1/3 octave band the difference is <5dB except for 250 and 630 Hz.
Normally sound predictions from models are forgiving in the sense that large deviations on the 1/3 octave level averages out and the total value comes close. This happens when the deviations are spread “symmetrically” around the correct value.

The geometrical size of the surrounding ducts on the roof are close to ½ a wavelength at 250 Hz and consequently a strong influence could be expected on the directivity field in the classic measurement.

At 630 Hz the injected sound spectrum from the loudspeaker had the lowest input and problems with the background influence is believed to be the reason for the deviation.

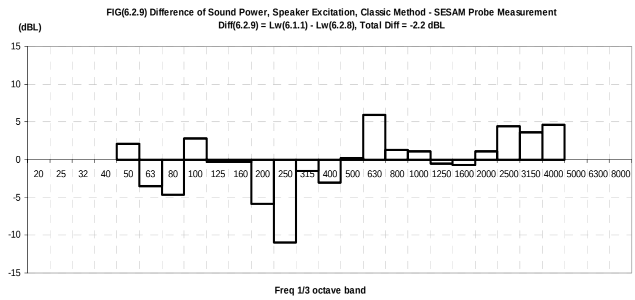


Fig 5. Difference of Sound Power, Speaker Excitation, Classic Method - SESAM Probe Measurement

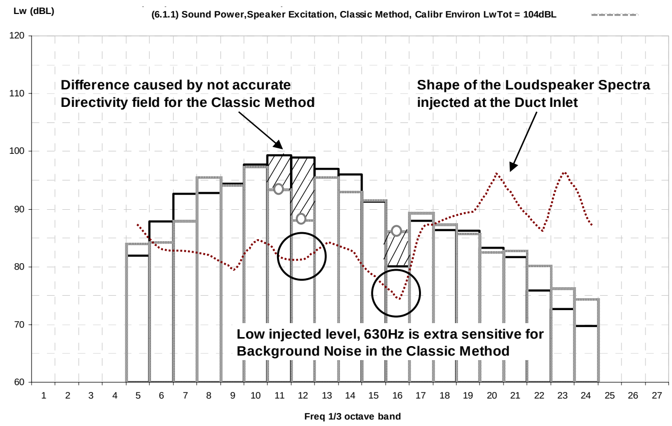


Fig 6. At 630 Hz the sound power level is 86 dBL for the classic method. This power value corresponds to 86 – 10log2/4π 29,2 = 63 dBL sound pressure value which might have been caused by the background level on the roof.

5. Induct method – versus Classic method, diesel engine at load 100%

The analysis is similar with the exception that:
- the loudspeaker source is changed to engine W8L20
- a special spatial averaging method is used to improve the accuracy of the induct method.

Temperature in the exhaust gas is 315 Celsius degree and the flow speed 25 m/s at the probe positions. The engine is injecting much higher sound power level into the inlet duct in comparison with the loudspeaker and the spectrum is a line spectrum with many harmonics. The engine speed 900 rpm creates an ingnition frequency of 60 Hz. On the roof the duct is open and the duct between the engine and this opening is finite with a length of approximate 18 meter. This length and the duct temperature constitute duct resonances and standing wave phenomena's.

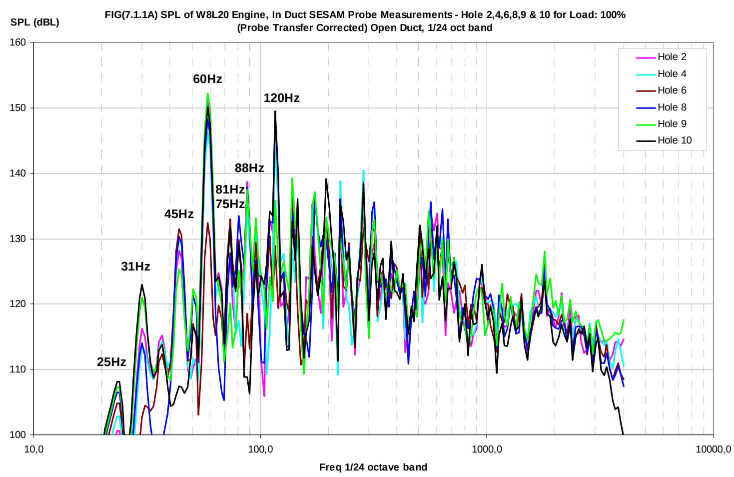


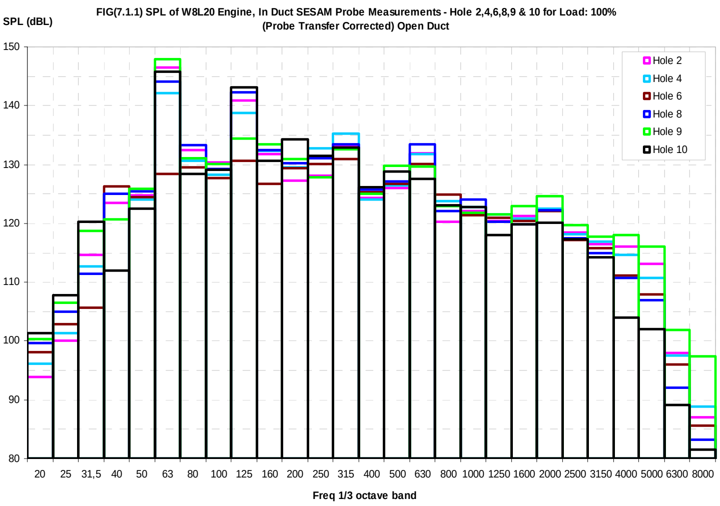
Fig 7. Illustration of duct resonances in the finite duct after the engine.

The spatial averaging technique - over 6 holes at chosen distances for a known gas temperature – eliminates the problem with the unknown positions of standing waves inside the duct. From six spectrums measured with flush mounted probe one space averaged spectra is calculated.

First measurement - six flush measurements averaged to induct sound power.
Induct sound power adjusted for end reflection and directivity radiated at 90 degree angle at the open duct.
Second measurement - classic measurement of sound pressure level (on the roof) recalculated to sound power radiated at 90 degree angle at the open duct.

6. Spatial averaging of 6 induct measurements

Fig 8 shows the measured sound pressure levels for 6 different holes along the duct.



Notice the large deviations between the spectrums depending on the position of the probe. The standing wave pattern inside the duct has pressure maxima and pressure minima versus distance and frequency in such a way that an efficient averaging technique is needed to create <u>one</u> spectrum.

Fig 8. SPL of W8L20 Engine, Open Duct SESAM Probe Measurements – Hole 2, 4,6,8,9 & 10 for Load: 100%

7. Spatial averaging of the 6 hole induct measurement - result

Comparing normal logarithmic averaging with the spatial averaging very little deviation was found for this actual measurement, fig 9. A conclusion that this would also be the case for other measurements is not correct because the premises could be completely different. Fig 10 shows the spread in the measurements for each 1/ 3 – octave band (max/min) and the standard deviation of the measurement error versus the spatial average method (zero line).
Standard dev. = (square root((1/6) sum(i-te value – spatial value)Exp2)).

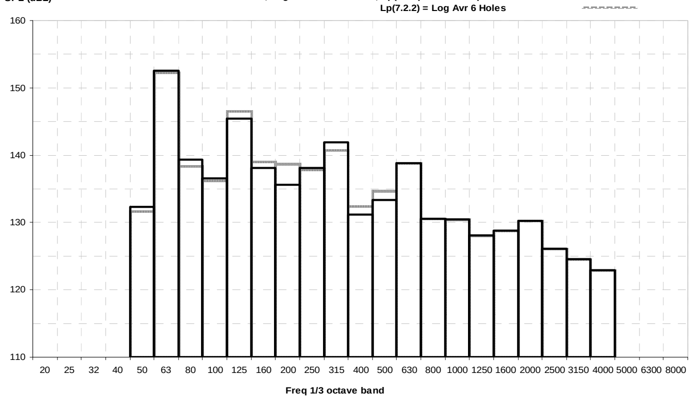


Fig 9. Induct Meas with SESAM Probe, Engine W8L20 at 100% Spatial RMS Method compared with Log Avr 6 Holes

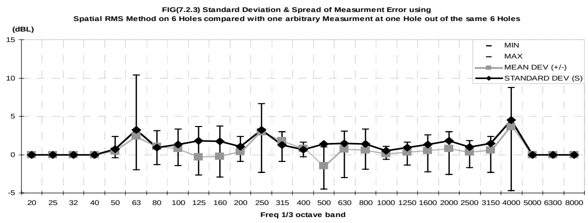
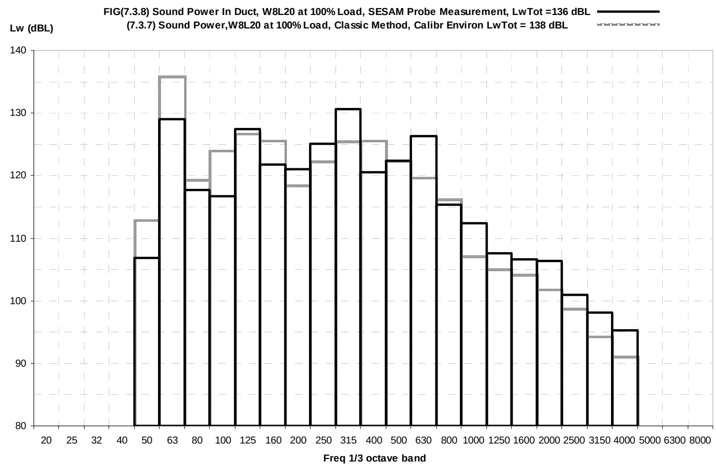


Fig 10. Standard Deviation & Spread of Measurement Error using one arbitrary hole in relation to the Spatial rms-method (with 6 holes)-the zero level.

8. Sound Power diesel engine - comparing induct method with classic method



Comparing with the classic method the deviation between the two results is shown in fig 11. Totally the induct method gave 136 dBL and the classic method gave 138 dBL.

Fig 11. Sound Power In Duct, W8L20 at 100% Load, SESAM Probe Measurement compared with Classic Method, Open Duct

Individually per 1/3 octave band the difference is < 6dB, fig 12, but the spread deviations averages down totally to 2dB. The 2 dB difference is acceptable but the induct method should show the highest total value because that method covers the power more efficiently inside the duct. However that is not seen in this engine measurement. The difference with the random noise loudspeaker test, see fig4, is the harmonic spectrum caused by the engine. To accurate capture distinct tones, with the classic method, would need a dramatically improvement of the precautions for the classic measurement. The reason for the high tone contributions at 63 and 100 Hz in the classic measurement is therefore caused by the bad acoustic environment on the roof in combination with an engine spectrum built by distinct tones and too few possible measurement points.

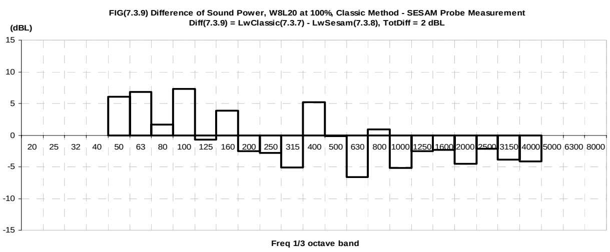


Fig 12. Difference of Sound Power, W8L20 at 100%, Open Duct Classic Method - SESAM Probe Measurement, Tot Diff = 2 dBL

9. CONCLUSION

All induct measurements with the probe technique gave fast and reliable results. The flexible and battery supported SESAM vest-system made it very easy to change between different measurement locations without extra time delays.

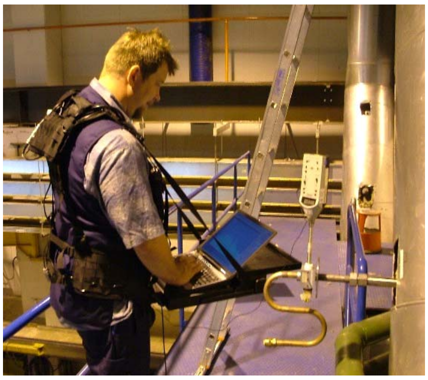


Photo 3. Induct measurements with SESAM

The classic method was performed at a realistic situation for an engine manufacturer. The acoustic precautions for the classic method were:
- problems with background noise
- not free field conditions
- disturbed near field
- too few measurement points and directions to cover a hemisphere surface

Sound power was injected with two different sources - a large loudspeaker (cold system without gas flow) and the engine W8L20 (hot system with gas flow). Comparing the two methods for the two different sources showed a total difference of < 2 dB. The induct method is easier and more accurate when two frequency independent constants are needed to calculate the induct sound power from only six flush mounted measurements. The classic method on the other hand needs 10 times more measurement points in free field, a frequency dependant directivity function, a frequency dependant end reflection function and ash-, break out-and bend attenuation corrections to achieve the same induct sound power.
The classic method can only be performed by opening up a duct system. The induct method on the other hand can be performed almost anywhere on an exhaust system.

Reference

CG.JOHANSSON, K.SAINE, P.JOHANSSON, M.ÅBOM: Exhaust Noise-a new novel in situ measurement technology in duct. *12th International conference sound and vibration 11-15.7.2005, Lisbon*.