Development of a large experimental acoustic transmission loss test bench suitable for large marine diesel exhaust system components

David R. Bowden

Maritime Division, Defence Science and Technology Group, Western Australia, Australia

ABSTRACT

The noise levels for large capacity marine diesel engines must meet legislative requirements as a minimum and may also have additional constraints on level and spectral content. The limited availability of test facilities and low production volumes for this class of engine / installation means that exhaust system testing and development is generally limited to confirmation testing. To address this development constraint, the Defence Science and Technology Group (DSTG) has developed an experimental test bench to measure the acoustic transmission loss performance of exhaust system components representative of large marine diesel engines. This study describes the test bench design, development, instrumentation, data acquisition and data processing techniques. This capability operates at room temperature and zero flow independently of the engine and engine installation and with excitation provided by a low frequency loudspeaker. The acoustic transmission loss was calculated using the four microphone method (two microphones before the test element and two after) and the three microphone method (two microphones before and one after). The performance of the facility was compared with computer simulation.

1. INTRODUCTION

Large capacity diesel engines are used in marine, rail and off-highway applications as propulsion engines, in diesel electric propulsion, and with generators for electrical power generation. The airborne noise levels of these installations must meet legislative requirements as a minimum and in some applications meet additional constraints on level and spectral content. Noise tests on such large diesel engines are rare except for confirmation testing due to the limited physical access when installed, limited availability of acoustic quality engine test facilities, low production volumes, high costs of operation and limited availability of the vehicle / vessel. Additionally mufflers for large diesel engines are large, heavy, expensive to manufacture, difficult to modify and cumbersome to manoeuvre.

Experimental verification and development of system acoustic performance is time consuming, expensive and requires dedicated test facilities (Martyr and Plint (2012); Blair, 1999). This has driven the emergence of mathematical modelling, including software simulation, which is quicker, cheaper and more flexible with respect to test parameters and test configurations (Ricardo, 2016; Amphlett et al., 2011; Munjal, 1998; Munjal, 2013; Tao and Seybert, 2003; Williamson and Chuter, 2002). As reported in 2015 (Bowden and Forrest, 2015), the Defence Science and Technology Group (DSTG) has developed a computer model based on Ricardo WAVE™ software capable of predicting the acoustic response and flow performance of an exhaust system representative of a large marine diesel. This computer model was validated with published test data and on-engine test data (Ibid.).

To provide further validation, increase confidence in the modelling capability and overcome many of the above development constraints, DSTG has developed an experimental laboratory test bench to measure the acoustic transmission loss performance of exhaust system components representative of large marine diesel engines. Transmission loss was selected as the preferred parameter to characterise acoustic performance as it is independent of the upstream and downstream systems which may vary depending upon the installation. This test bench operates independently of the engine and engine installation with excitation provided by a low frequency loudspeaker. The facility operates at room temperature and with zero flow.

This study describes the test bench design, instrumentation, data acquisition, development, data processing techniques and validation process.

2. EXPERIMENTAL TRANSMISSION LOSS TEST BENCH

This section describes the test bench, instrumentation and test parameters used.

2.1 Overview

The experimental test bench is designed to measure the acoustic transmission loss at room temperature and zero gas flow of large marine diesel exhaust mufflers. This marine muffler category is very different from automotive mufflers as exemplified by the subject muffler which is shown in Figure 1. This muffler is a twin expansion chamber muffler with extended inlet and extended outlet and weighs 450 kilograms.

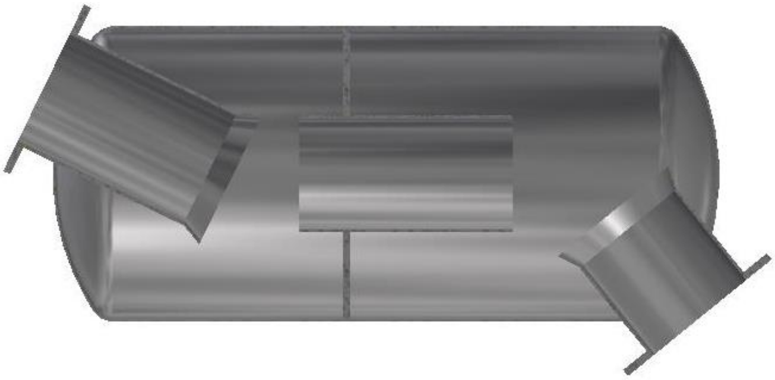


Figure 1: Subject large marine diesel muffler

The test bench is shown in Figures 2 and 3 and is approximately nine metres long.

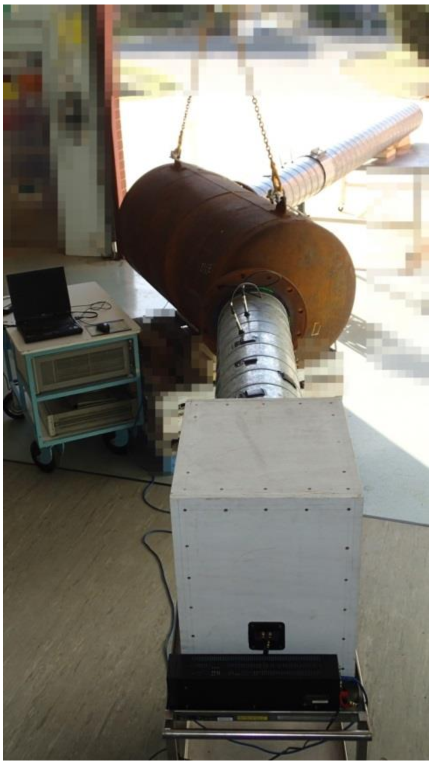


Figure 2: Transmission loss test bench, source end

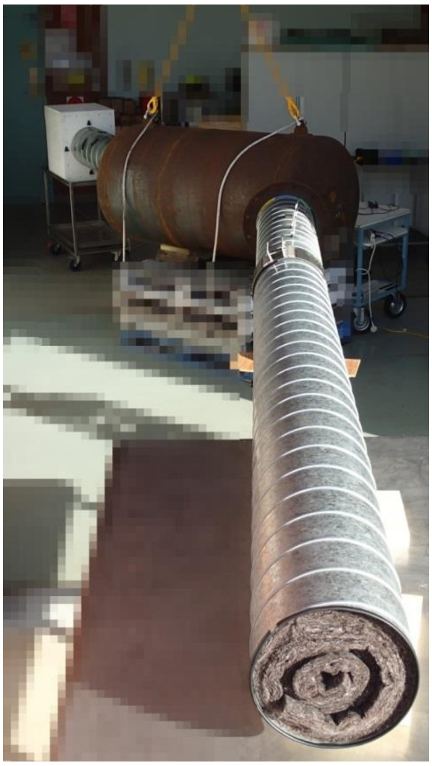


Figure 3: Transmission loss test bench, termination end

The test bench consists of:

- a 305 mm (12”) diameter subwoofer loudspeaker driver in a 126 litre non-vented enclosure,
- an upstream measurement duct 1.5 metres long,
- the test muffler,
- a downstream measurement duct 1.5 metres long, and
- an anechoic termination three metres long packed with Tontine Acousorb2™ material.

The measurement ducts and anechoic termination use galvanized steel round ducting of spiral-folded-seam construction with a nominal bore of 330 mm and 1 mm wall thickness.

2.2 Instrumentation

The loudspeaker is powered by a mono amplifier with the random excitation signal being provided by the sound source in the Hewlett Packard (HP) Spectrum Analyser. Two half inch microphones with integrated pre-amplifiers (PCB Model 378B02) are installed upstream of the test item and two similar microphones are installed downstream as shown in Figure 4. The microphones are installed nearly flush to the inside wall using elastomeric cable grommets. The HP Spectrum Analyser has four input and signal conditioning modules with 102.4 kHz bandwidth and a microphone calibrator is used for amplitude calibration. The microphones’ signals are averaged (25 samples) and processed in the frequency domain to give auto spectra, cross spectra and 1/3rd octave results.

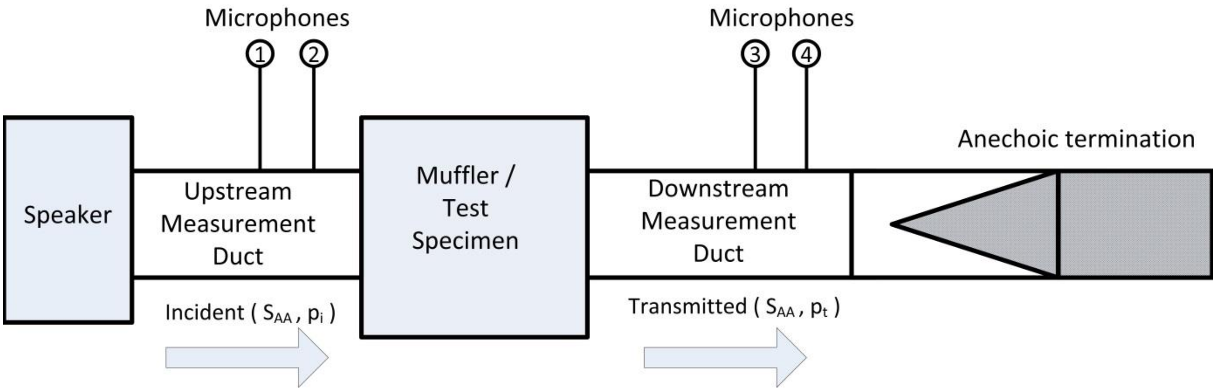


Figure 4: Schematic of transmission loss test bench

2.3 Test parameters

The nominal test conditions are zero flow, 101 kPa atmospheric pressure and 25 °C ambient temperature. Note that the ambient temperature and pressure are not controlled and variations may affect the results by changing the speed of sound. The test sound pressures are 120 dB which by plane wave theory equates to 50 mm/s particle velocity.

3. TEST BENCH DESIGN PARAMETERS

This section considers the key drivers influencing the physical layout of the test bench.

3.1 Frequency Range

A survey of large marine diesels was undertaken to determine the required frequency range for the test bench. Diesel generators typically run at 1500 rpm or 1800 rpm for power generation at 50 Hz or 60 Hz respectively. Using the cylinder firing rate (CFR) to give the lower limit and the fifth harmonic of the CFR to give the upper limit (Ricardo_Software, 2015), the required frequency range was therefore 75 Hz to 1000 Hz. As the acoustic performance of devices is generally wavelength / temperature dependent, these values were then corrected using the ratio of the speed of sounds based on a nominal exhaust temperature (430 °C) to give 25 °C equivalent frequencies of 50 Hz to 650 Hz. This gave a target range of 30 Hz to 700 Hz for the test facility.

3.2 Lateral Cut-on Frequencies

While the test bench and data processing assumes plane wave propagation there are transverse / lateral modes within the frequency range of interest. As the two microphone method assumes plane wave propagation, the first lateral cut-on frequency sets an upper limit for testing. The lateral cut-on frequencies can be calculated and for circular cross sections they are effectively equivalent to a half wave length across the corrected diameter. Using Equation 1 (Singh et al., 2008), the lateral cut-on frequencies for a 330 mm diameter duct and a 800 mm diameter muffler body / duct are 615 Hz and 253 Hz respectively at 25 °C.

$$f_c = 1.8412 * c/(2 * \pi * r) \tag{1}$$

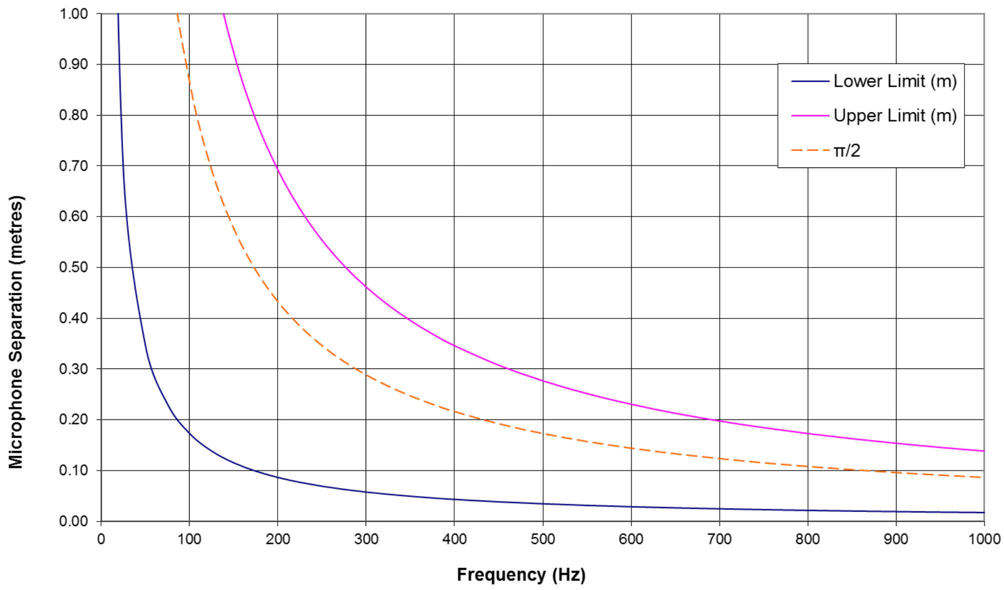
where r is the duct radius and c is the speed of sound

3.3 Microphone Spacing

The relative spacing of each microphone in the microphone pairs is critical in that it affects the effective frequency range and resultant measurement accuracy. There has been considerable work in this area and the following guidelines (Bodén and Åbom, 1986) were used. These are graphically represented in Figure 5:

- The optimum microphone spacing is achieved when $ks = \pi/2$, and
- The effective range is achieved at $0.1\pi < ks < .8\pi$

where k is wave number ($k = 2\pi f/c$), f is frequency and s is microphone spacing



It can be seen from Figure 5 that the two spacings chosen (200 mm and 500 mm) cover the required frequency range of 30 Hz to 700 Hz.

3.4 Length of Measurement ducts

Guidelines on the length of the measurement ducts and the microphone pair placements were available from a range of sources (ASTM, 2012; Bodén and Åbom, 1986). To promote plane wave propagation the length of the measurement ducts should be five to ten times its diameter. The test sections used are at the lower end of this range. To minimise the effects of attenuation along the duct, the microphone pairs should be close to the item being measured and this requirement is also satisfied.

4. DATA FLOW

A HP 3567A Spectrum Analyser was used for data acquisition and frequency analysis. HP software (HP35639A Data Viewer) was used to convert HP Standard Data Format (SDF) files (*.dat) to Matlab data files (*.mat). Matlab scripts were then used to calculate wave decomposition, transmission loss and power reflection coefficient. The data flow and processing was initially validated by using a plain duct in lieu of a muffler. Additional validation was achieved by feeding a single signal from one microphone on an acoustic microphone calibrator to all four channels with the calibrations manipulated to give an artificial transmission loss across a "virtual" muffler.

5. WAVE DECOMPOSITION

The four microphones can each only measure the total acoustic pressure at their respective locations. This total pressure is a summation of forward and backward travelling waves as illustrated in Figure 6. This is especially so before the test item (microphones 1 and 2) due to the reflection of sound back towards the source. In contrast the anechoic termination eliminates any reflection after the test item (microphones 3 and 4). If the anechoic termination is effective then microphones 3 and 4 will have identical amplitude signals. The loudspeaker output is assumed to be stationary with the loudspeaker being non-reflective to backwards travelling waves.

As the acoustic transmission loss of the test item is defined as the ratio of the transmitted power versus the incident power, it is necessary to separate the forward travelling (incident) wave from the reflected (backwards travelling) waves. Wave decomposition techniques have been derived to separate the total acoustic signals measured at two arbitrary locations into incident and reflected values (Chung and Blaser, 1980a; Chung and Blaser, 1980b; Seybert, 1988; Tao and Seybert, 2003). Note that the algorithms fail when the microphone spacings are multiples of half wavelength, e.g. 346 Hz at 25 °C for a 500 mm microphone spacing. The incident (forward travelling) spectra are then used to calculate the incident sound pressure before and after the test item which can then be used to calculate the acoustic transmission loss. Because of the anechoic termination, the incident spectra after the test item can be derived directly from microphone 3 or 4. The ratio of the incident and reflected spectra after the test item can be used to evaluate the effectiveness of the anechoic termination.

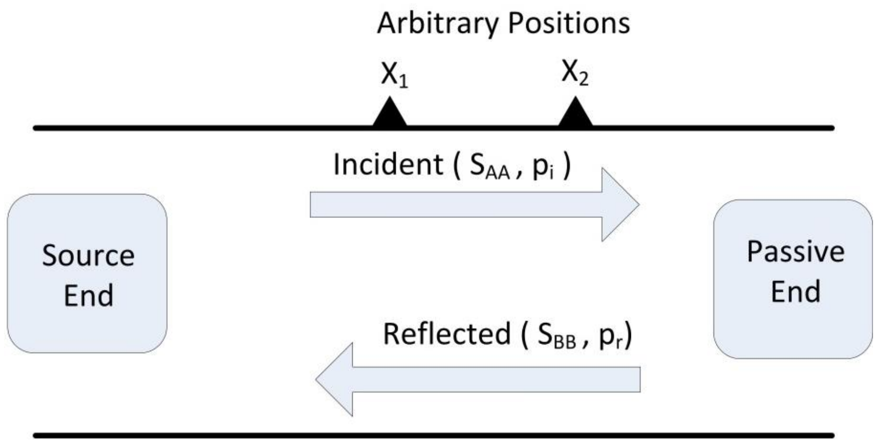


Figure 6: Plain wave decomposition within a duct

The wave decomposition is calculated using Equations 2,3,4 and 5 (Seybert, 1988; Tao and Seybert, 2003):

Incident wave spectra (S_{AA})

$$S_{AA} = [S_{11} + S_{22} - 2C_{12} \cos\ k(x_1 - x_2) + 2Q_{12} sin\, k(x_1 - x_2)]/4sin^2 k(x_1 - x_2) \quad (2)$$

Reflected wave spectra S_{BB}

$$S_{BB} = [S_{11} + S_{22} - 2C_{12} coskx(x_1 - x_2) - 2Q_{12} sink(x_1 - x_2)]/4sin^2 k(x_1 - x_2) \quad (3)$$

Amplitude of the incident wave sound (p_i)

$$p_i = \sqrt{S_{AA}} \tag{4}$$

Amplitude of the reflected wave sound pressure (p_r)

$$p_r = \sqrt{S_{BB}} \tag{5}$$

The transmission loss calculation is calculated using Equation 6 (Tao and Seybert, 2003):

$$Transmission\ Loss\ = 20\log_{10}(p_i/p_t) + 10\log_{10}(S_i/S_0) \tag{6}$$

The effectiveness of the anechoic termination (power reflection coefficient) is calculated using Equation 7 (Seybert, 1988):

$$\alpha_0(f) = S_{BB}(f)/S_{AA}(f) \tag{7}$$

where:

$S_{AA(f)}$ is the incident wave spectra
$S_{BB(f)}$ is the reflected wave spectra
$S_{11}(f)$ is the auto spectra at (arbitrary) point x_1
$S_{22}(f)$ is the auto spectra at (arbitrary) point x_2
$C_{12}(f)$ is the real part of the cross spectrum between points x_1 and x_2
$Q_{12}(f)$ is the imaginary part of the cross spectrum between points x_1 and x_2
x_1 is the distance to an arbitrary point from a reference position
x_2 is the distance to an arbitrary point from a reference position
$(x_1 - x_2)$ is the microphone spacing
p_i is the amplitude of the incident wave sound pressure
p_r is the amplitude of the reflected wave sound pressure
$p_t$is the amplitude of the transmitted wave sound pressure (incident wave sound pressure after the test item)
S_i is the area of the area of the inlet tube area
S_0 is the area of the area of the outlet tube area
$\alpha_0(f)$ is the power reflection coefficient

6. RESULTS and DISCUSSION

The results from the development of the test bench are discussed under the following sub-headings.

6.1 Loudspeaker Performance

Two different 305 mm diameter (12”) loudspeaker drivers in a 127 litre enclosure were characterised with a microphone at 1.5 metres from the loudspeaker front face. In free radiation above a hard surface, the Dayton Audio driver was distortion free from 30 Hz to 1000 Hz and was therefore used in preference to the “generic” driver which had distortion below 50 Hz. Note that the loudspeaker output spectra was not linear across the full frequency range and this may be an area of potential improvement especially when in duct performance is considered.

6.2 Anechoic Termination

The anechoic termination was evaluated using two plain measurement ducts in series coupled to the anechoic termination. The effectiveness of the termination is shown in Figure 7 with near zero reflection above 80 Hz. At the lower end target 30 Hz, the reflection is less than 15 %. The high value at 345 Hz is an aberration due to the half wavelength calculation effect discussed earlier.

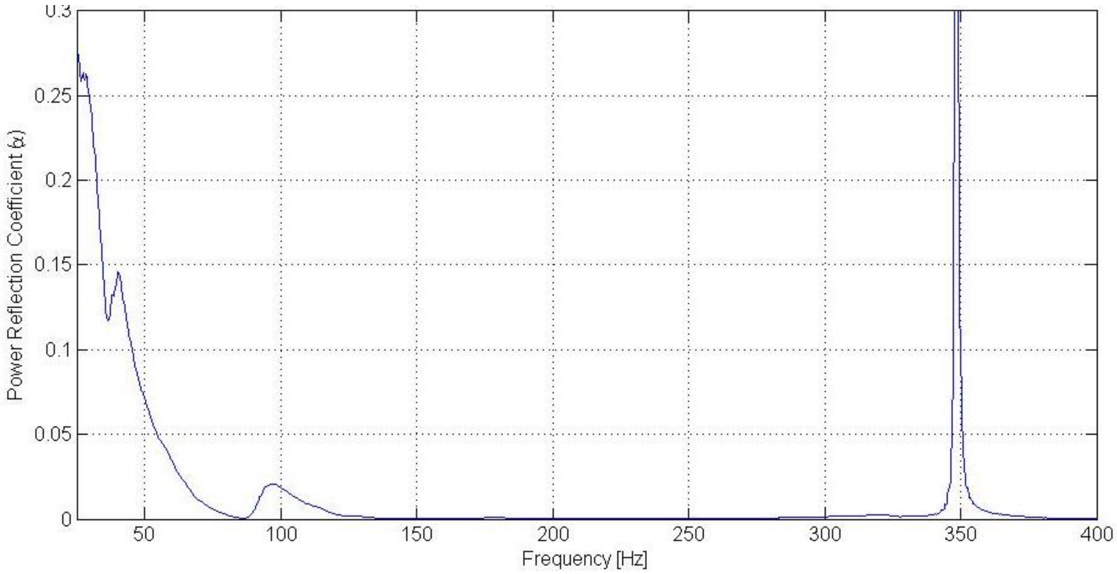


Figure 7: Effectiveness of anechoic termination (Power Reflection Coefficient)

6.3 Microphone matching

Differences in amplitude and phase between the microphones will induce errors in the calculated results and some sources recommend a measured microphone correction while others recommend interchanging of microphones (ASTM, 2012; Chung and Blaser, 1980b; Seybert and Ross, 1977). The amplitude and phase matching of the four microphones was evaluated using a single measurement duct coupled to the anechoic termination. All microphones were located at the same distance from the loudspeaker and spaced around the circumference of the duct. The matching was excellent up to at least 550 and 600 Hz as shown in Figures 8 and 9 respectively and obviated the need to use corrections or position interchanging. This is as expected for the low-frequency response of high quality microphones of the same model. The matching above 550 / 600 Hz could not be ascertained due to the interference of lateral modes in the measurement set-up.

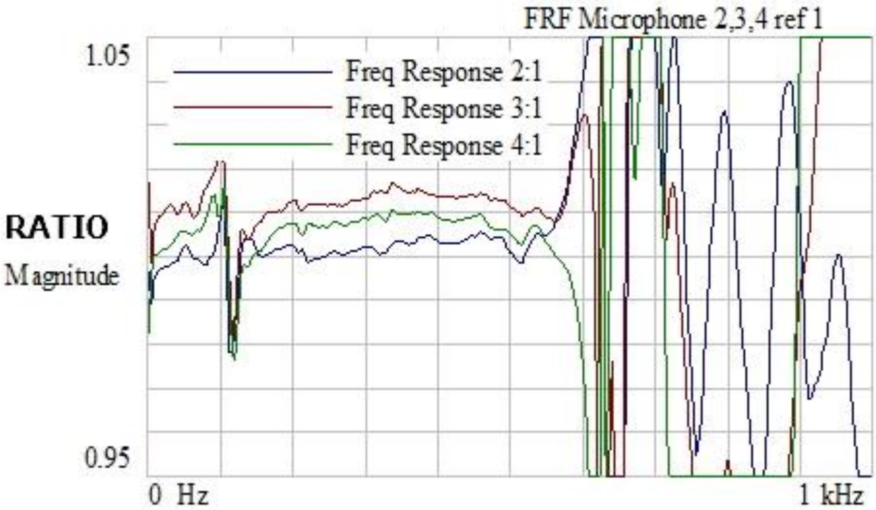


Figure 8: Amplitude comparison of microphones using frequency response function (FRF) relative to #1

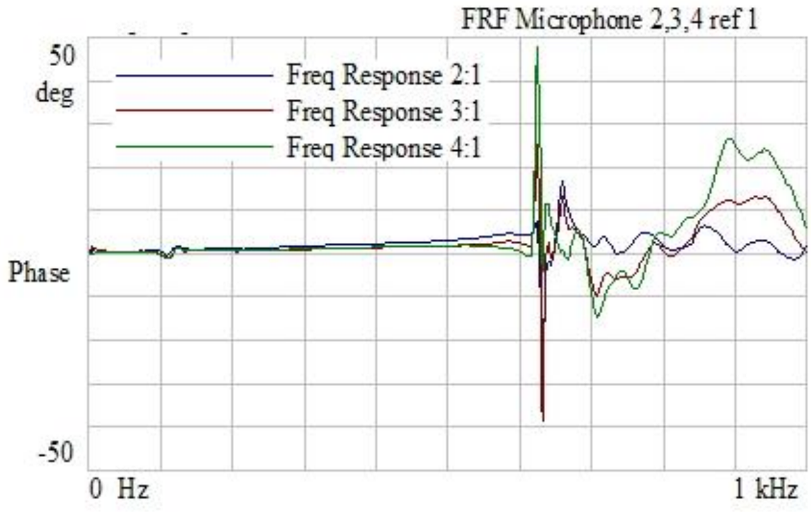


Figure 9: Phase comparison of microphones using frequency response function (FRF) relative to #1

Of particular interest were phase shifts and poor coherence at 625, 1030, 1300 and 1400 Hz indicating lateral modes. The values of these modes were confirmed using Bessel functions and the duct diameter (Eriksson, 1980). Note that the ambient test temperature of approximately 33 °C increased the measured lateral mode frequency to 625 Hz from the 615 Hz calculated previously at 25 °C. This lateral mode / cut-on frequency at 625 Hz effectively limits the test bench’s upper frequency to 600 Hz for plane wave propagation.

The muffler structure’s shell modes were measured using accelerometers and impact excitation. These did show a mode at 610 Hz but did not shown modes at the frequencies attributed to the aforementioned lateral modes.

6.4 Muffler Results

The test bench with the test muffler was set up and the background noise level was measured with the loudspeaker off but the microphones in place. The background noise level was 56 to 57 dB (relative to 20µPa). This is well below the operating sound pressure levels of approximately 120 dB and 107 dB before and after the test muffler respectively.

The muffler was then tested using two frequency ranges and the corresponding two microphone spacings and the data was processed with the Matlab code.

Figure 10 shows the measured auto spectra for the pair of microphones before the test muffler. The standing wave behaviour is very clear upstream of the muffler whereas there is no standing wave behaviour after the muffler due to the anechoic termination.

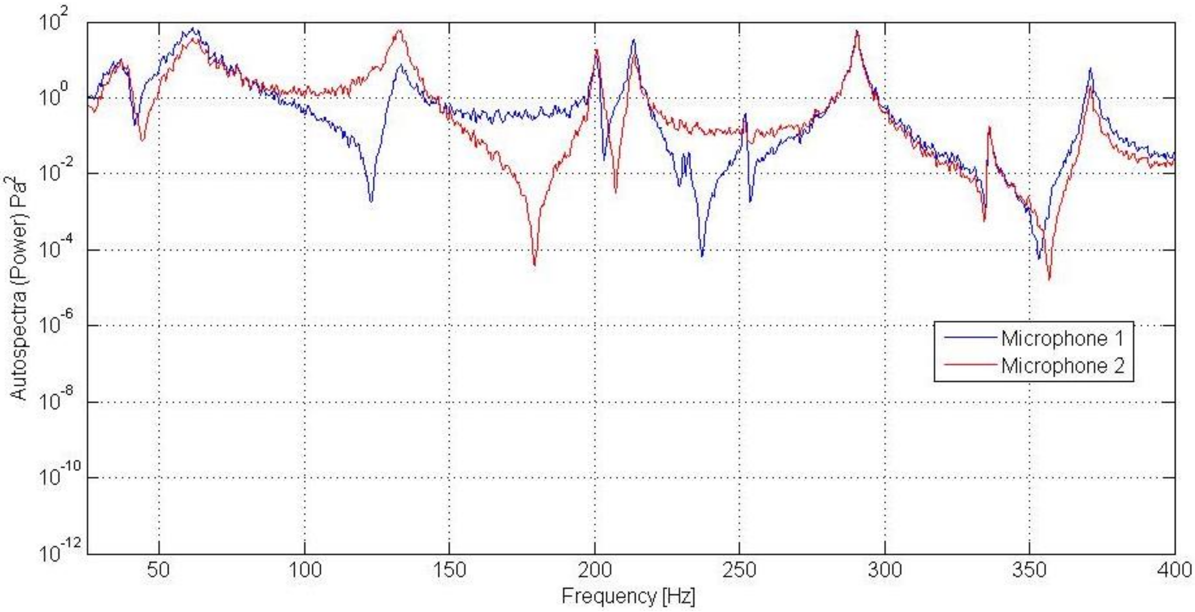


Figure 10: Measured auto spectra of Microphones 1 and 2 (Upstream of muffler)

Figure 11 shows the calculated incident and reflected auto spectra after the test muffler. The incident auto spectrum is greater than the reflected auto spectrum in both cases (as expected) with the difference being much greater after the muffler due again to the anechoic termination.

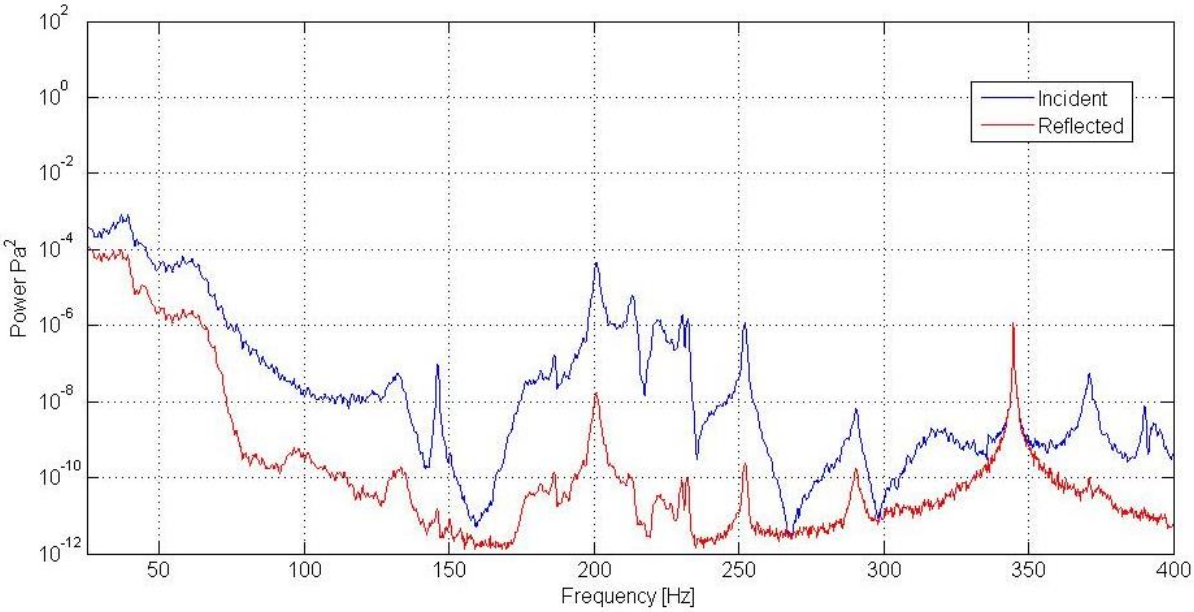


Figure 11: Calculated incident and reflected auto spectra after the muffler

Figure 12 shows the calculated acoustic transmission loss for the low frequency range. The transmission loss was also calculated using only one microphone after the muffler and this result is also included in Figure 12, labelled as the “three microphone” result. There is little difference between using two microphones or one after the muffler as expected with an effective anechoic termination.

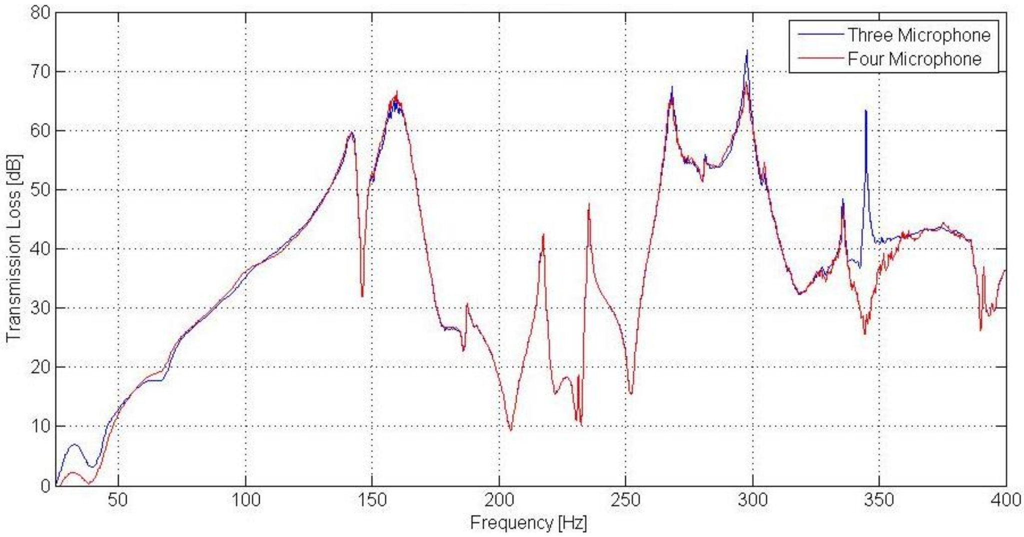


Figure 12: Muffler transmission loss - measured using three and four microphones

Ricardo™ Wave computer simulation was used for comparison and the results are shown in Figure 13. There is reasonable agreement in the variation of the magnitudes of the transmission loss, but additional work is required to explain the apparent frequency shifts. The frequencies at which the transmission losses occur are higher in the computer simulations than as measured on the experimental test bench. The computer simulation was originally validated using simple acoustic elements and then used to simulate more complex mufflers such as in Figure 1. So it is not clear if the variation is in the simulation or the experimental work or in both. One avenue to be explored is reverting to experimentally testing simplified test items whose acoustic performance is well documented, e.g. simple large single volume expansion chambers.

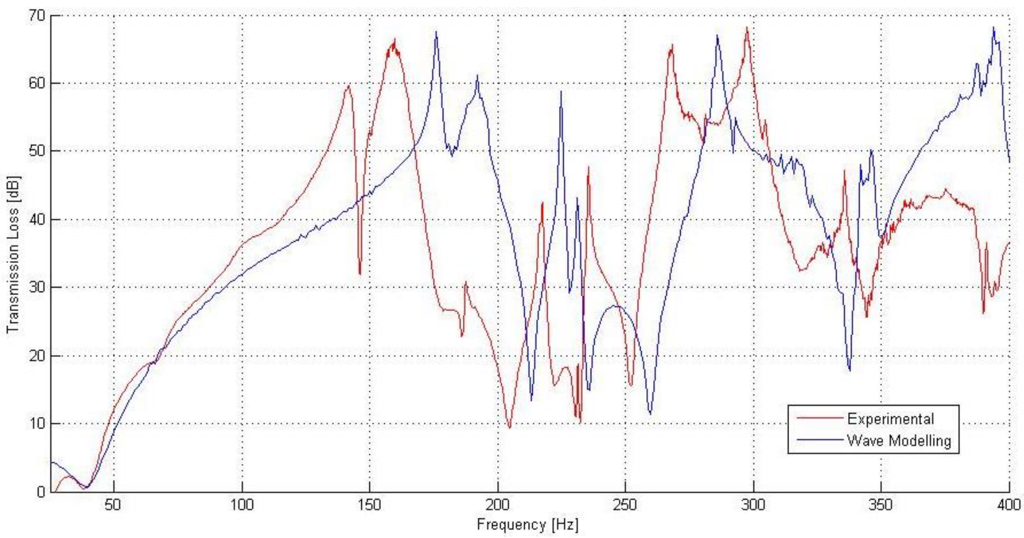


Figure 13: Comparison of measured and simulated muffler transmission loss

7. CONCLUSIONS

DSTG has developed an experimental facility capable of measuring the acoustic transmission loss of exhaust system components representative of a large marine diesel. The performance of this facility has been compared with computer simulations. There is reasonable agreement in the variation of the magnitudes of the transmission losses but frequency shifts are evident. The differences between measured and simulated transmission loss results need to be further investigated and the reasons identified.

It is expected that the experimental facility's performance can be further improved with development and optimisation of parameters including measurement duct lengths, microphone locations, data processing error analysis and tailored input spectra. The effective frequency range of the facility at room temperature is 30 Hz to 600 Hz due to the measurement duct's first cut-on frequency being at approximately 625 Hz.

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