ACOUSTIC SOURCE DATA FOR MEDIUM SPEED IC-ENGINES

Antti Hynninen[1)], Raimo Turunen[1)], Mats Åbom[2)], Hans Bodén[2)]

[1)]VTT Technical Research Centre of Finland
P.O. Box 1000 FI-02044 VTT, Finland
e-mail: antti.hynninen@vtt.fi

[2)]KTH CCGEx, Marcus Wallenberg Laboratory
SE-10044 Stockholm, Sweden

1 INTRODUCTION

The noise generation of a fluid machine e.g. internal combustion engine (IC-engine), pump, compressor, fan, etc. can be divided into the acoustic source and transmission path. Knowledge of the acoustic source characteristics of IC-engines is of great importance when designing the exhaust duct system and its components to withstand the resulting dynamic loads and to reduce the exhaust noise emission.

Medium speed IC-engines are used in large electrical generators, ship propulsion systems and mechanical drive applications such as large compressors and pumps. The rotation speed of a medium speed IC-engine is typically from 300 to 1000 rpm whereas high-speed IC-engines used to power e.g. trucks, buses and cars usually run at 1000 rpm or more.

Number of studies has been published earlier on the low frequency in-duct exhaust noise of high speed engines. The acoustic source data of a six cylinder turbo-charged truck diesel engine exhaust system has been determined in the papers by Bodén et al. [1] and Fairbrother et al. [2]. The source data of a four-cylinder passenger car petrol engine exhaust system and six cylinder truck diesel intake system were studied in the paper by Bodén [3]. The acoustic source data of a six cylinder passenger car petrol engine intake system was studied in the thesis by Knutsson [4].

The goal of the present study is to investigate the medium speed IC-engine acoustic source characteristics numerically and experimentally not only in the low frequency - plane wave range but also in the high frequency range.

2 METHODS

The low frequency - plane wave range acoustic source characteristics of a medium speed IC-engine were obtained by simulating the acoustic multi-load method measurements. A commercial one-dimensional process simulation software GT-Power [5] was used to solve the nonlinear set of partial differential equations describing the gas dynamics of the IC-engine. The simulation model of the IC-engine was validated with engine performance and cylinder pressure measurements. The measured acoustic pressure $\hat{p}$ and acoustic load impedance $\hat{\zeta}_L$ of the exhaust piping was used to estimate the accuracy of the simulated low frequency - plane wave range source data, i.e. source pressure $\hat{p}_s$ and source impedance $\hat{\zeta}_s$.

The high frequency range was included in the acoustic power estimation using spatial averaging methods. The source data was estimated by averaging the measured auto- and cross-spectra and assuming negligible reflections and a semi-diffuse field. In the high frequency range measurements, the acoustic pressures were measured from several points in the same measurement section of the exhaust duct. The sound powers achieved with different methods were compared.

2.1 Acoustic power estimation using wave decomposition

According to Neise et al. [6] the time averaged downstream acoustic power can be estimated by summing over the cut-on modes as

$$\overline{W}_{+} = \frac{1}{Z_0} \sum_{n=0}^{N} \varepsilon_n \tilde{p}_{n+}^2, \tag{1}$$

where $Z_0 = \rho c/A$ is the characteristic impedance for a propagating plane wave in a duct with cross sectional area A filled with gas of density ρ, c is the speed of sound in the gas mixture, ε_n is a weighting factor for each mode, $\tilde{p}_n$ is the root mean square of the acoustic pressure, n is the mode number and $+$ denotes propagation to downstream direction.

To obtain downstream acoustic power in the plane wave range $\overline{W}_{0+}$, the so called wave decomposition was done by using the two microphone method presented e.g. by Chung and Blaser [7]. The acoustical load impedance $\hat{\zeta}_L$ of the exhaust piping was derived according to the wave decomposition formulation presented by Bodén and Åbom [8].

If we use simulated acoustic source pressure $\hat{p}_s$ and simulated acoustic source impedance $\hat{\zeta}_s$ together with the measured load impedance $\hat{\zeta}_L$ we get the acoustic "simulated" pressure as

$$\hat{p}_0' = \frac{\hat{p}_s \hat{\zeta}_L}{\hat{\zeta}_s + \hat{\zeta}_L}. \tag{2}$$

Using this we get the "simulated" downstream acoustic power in the plane wave range $\overline{W}_{0+}'$.

2.2 Acoustic power estimation using spatial averaging

Assuming the reflection coefficients to be negligible, the sum of downstream modal acoustic pressures in Eq. (1) can be estimated as

$$\sum_{n=0}^{N} \varepsilon_n \tilde{p}_{n+}^2 = \eta \langle \tilde{p}^2 \rangle, \tag{3}$$

where η is the frequency range weighting factor and $\langle \tilde{p}^2 \rangle$ is the spatial average of the squared rms-pressures. If we assume a semi-diffuse field, the frequency range weighting

Figure 1: The test engine, Wärtsilä Vasa 4R32 in VTT engine laboratory.

factor $\eta = 1$ for the plane wave range and $\eta = 1/2$ after the first cut-on frequency as stated in the paper by Joseph et al. [9].

Finally using Eq. (1), the downstream acoustic power can be estimated with spatial averaging of the acoustic pressures as

$$\overline{W}_{S+} = \frac{\eta \langle \tilde{p}^2 \rangle}{Z_0}, \tag{4}$$

where subscript S denotes for spatial averaging method.

3 THE STUDIED IC-ENGINE

The test engine studied is a Wärtsilä Vasa 4R32. The inline four-cylinder engine operates with constant speed of 750 rpm, producing 1640 kW power. The cylinder bore is 320 mm and stroke 350 mm. The engine weights 20.3 tons (with liquids, but without flywheel). The test engine presented in Fig. 1 is located in the VTT engine laboratory in Otaniemi, Espoo Finland.

4 MEASUREMENTS

To derive the downstream acoustic powers in the plane-wave range $\overline{W}_{0+}$ and $\overline{W}'_{0+}$, the acoustic load impedance of the exhaust piping $\hat{\zeta}_L$ as well as the downstream acoustic pressures in the exhaust pipe $\hat{p}_{0+}$ were measured using two-microphone method.

The pressure was measured using six measurement points in the exhaust pipe after the turbocharger. Four pressure transducers were used in the first measurement section. In this measurement section, the four pressure transducers were mounted evenly around the pipe (measurement points 1 to 4 in Fig. 2). In the other sections, sections 2 and 3, only one pressure transducer was used at each section (measurement points 5 and 6 in Fig. 2). The measurement points and measurement sections are presented in Fig. 2.

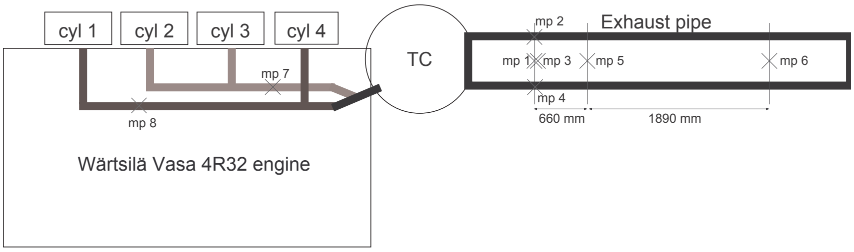

Figure 2: The measurement point locations for pressure transducers in the exhaust manifold and exhaust pipe.

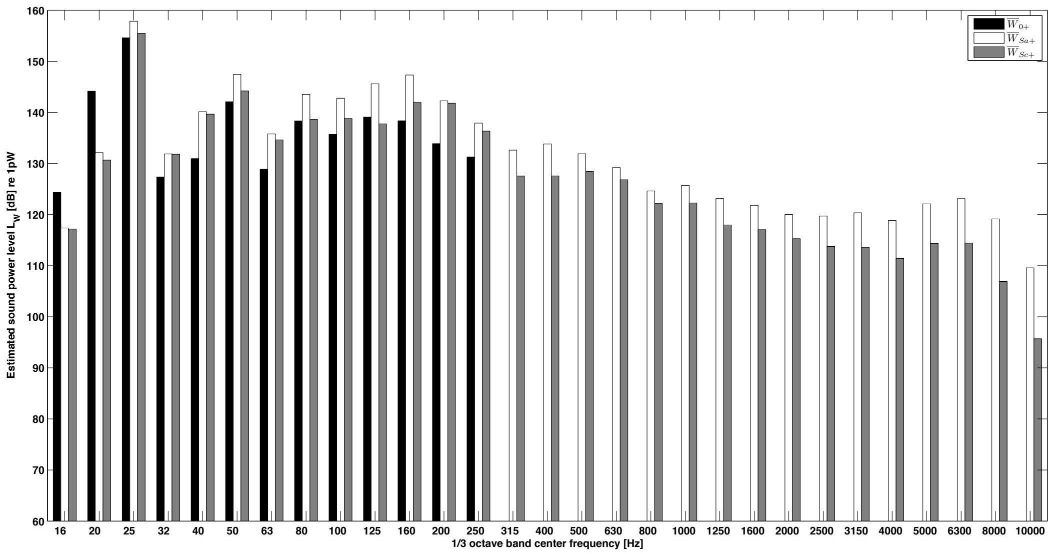

Figure 3: The downstream acoustic power levels determined at the full engine load. The plane-wave range part $\overline{W}_{0+}$ based on wave decomposition, $\overline{W}_{Sa+}$ and $\overline{W}_{Sc+}$ achieved by averaging the auto- and cross spectra.

4.1 Downstream acoustic power estimations

The downstream acoustic power in the plane-wave range $\overline{W}_{0+}$ as well as the sound powers derived with auto and cross spectra $\overline{W}_{Sa+}$ and $\overline{W}_{Sc+}$ are presented in Fig. 3. Using the averaging with auto spectra the measured pressures from measurement points 1, 5 and 6 were used for the low frequency range and measurement points 1 to 6 for frequency range from the first non-plane wave cut-on frequency onwards. Averaging with cross spectra, the measured cross spectrum from measurement point 1 to 2, 1 to 5 and 1 to 6 were used for the low frequency range and all the measured cross spectra were used for frequency range from the first non-plane wave cut-on frequency onwards.

5 SIMULATIONS

In this study a validated engine model was used in the acoustical multi-load method simulations to determine the acoustic source data of a four-cylinder medium speed IC-engine exhaust system. By using simulated acoustic source data together with the mea-

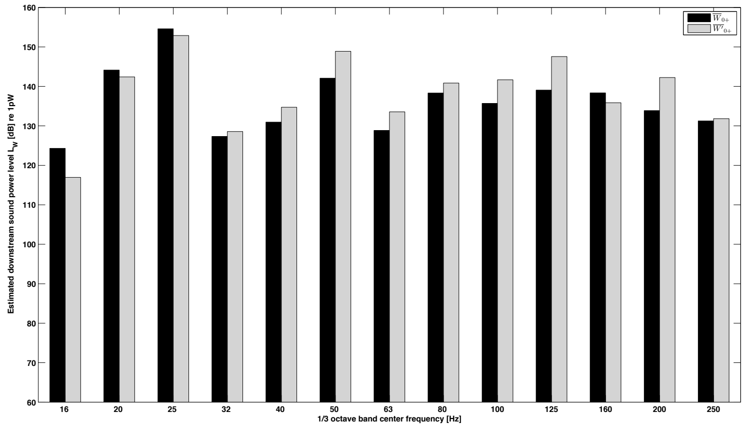

Figure 4: The measured induct sound power level $\overline{W}_{0+}$ and simulated induct sound power level $\overline{W}'_{0+}$ in the low frequency range at the full engine load.

sured acoustic load, the "simulated" downstream acoustic power in the plane wave range $\overline{W}'_{0+}$ was derived.

5.1 Source data simulations

The acoustical loads needed in the multi-load method were constructed by adding side branches to the exhaust piping model after the turbo charger. In the simulation a total of ten different acoustical loads were used. The length of a side branch pipe was varied between approximately 0.8 and 11 m.

5.2 Downstream acoustic power simulations

The measured and "simulated" induct downstream sound powers $\overline{W}_{0+}$ and $\overline{W}'_{0+}$ for the low frequency - plane wave range are presented in Fig. 4.

6 CONCLUSIONS

The goal of the present study was to investigate the medium speed IC-engine acoustic source characteristics numerically and experimentally not only in the low frequency - plane wave range but also in the high frequency range.

In this study the possibility to extract the acoustic source data for an exhaust system of a medium speed IC-engine using one-dimensional process simulation software has been tested. It was shown that the low frequency - plane-wave range induct exhaust noise of a medium speed IC-engine can be predicted reasonable accurately by using the GT-Power software. To predict the high frequency range noise, some other methods than the one-dimensional process simulation used in this study must be developed.

The high frequency range was included in the experimental acoustic power estimation using spatial averaging methods. The source data was estimated by averaging the measured auto- and cross-spectra and assuming negligible reflections and a semi-diffuse field. The sound power levels were higher when using the measured acoustic pressure auto spectra than the levels when using the measured acoustic pressure cross spectra. Estimating the downstream acoustic power by using the measured acoustic pressure cross spectra gave fairly similar results as the sound power estimation based on wave decomposition at the main engine cycle harmonics. According to this study, using the simple cross spectra averaging method instead of two microphone method to estimate the in-duct downstream acoustic power of medium speed IC-engine exhaust noise seems promising. To estimate the accuracy of the averaging methods used in the high frequency range, more experimental and numerical studies are necessary.

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