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NONLINEAR SOURCE CHARACTERISATION TECHNIQUES FOR IC-ENGINES

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A source characterization model for IC-engines, which can take weakly nonlinear source properties into account, is developed in the paper. It is based on so called polyharmonic distortion modeling, used for nonlinear characterization of microwave systems. Comparisons are made with the results from linear source models and another previously published weakly nonlinear source model. The results show that the new nonlinear impedance matrix model gives improvements in the prediction of sound pressure levels in the exhaust system

1. Introduction

Linear frequency domain prediction codes are frequently used for calculation of low frequency sound transmission in and sound radiation from IC-engine exhaust and intake systems. To calculate insertion loss of mufflers or the level of radiated sound, information about the engine as an acoustic source is needed. The source model often used in the low frequency plane wave range is the linear time invariant 1-port model[1,2]. The acoustic source data is obtained from experimental tests or from 1-D CFD codes describing the engine gas exchange process[3-5.] Multi-load methods and especially the two-load method are most commonly used to extract the source data. The IC-engine is a high level acoustic source and in most cases not completely linear. Linearity tests to check how well the experimental data fits a linear source model have been developed[6]. It is of interest to have models taking weak non-linearity into account while still maintaining a simple method for interfacing the source model with a linear frequency domain model for the attached exhaust or intake system. Some years ago a model which can consider weakly non-linear sources was presented[7] which gave an improvement over the traditional two-load technique for determining source data from experiments. It is however fairly complicated to implement and has not been used a lot. In this paper an alternative technique based on so called polyharmonic distortion modeling, used for nonlinear characterization of microwave systems[8-10] is proposed and tested. Comparisons are made with the results from linear source models and the previously published weakly nonlinear source model.

2. Source models

This section describes the source models used. The already published models are described briefly while the new model is described in some more detail. Figure 1 shows the test geometry discussed. We will assume that the travelling pressure wave amplitudes in the positive coordinate direction p_+ and in the negative coordinate direction p_- can be obtained either from multi-transducer measurements or from numerical simulation as described in[1-5]. We will use so called multi-load methods[1,2] to determine the source data. These require that measurements or simulations have been made for a number of different loads characterized by their reflection coefficients (R_L) or normalized impedance (Z_L)

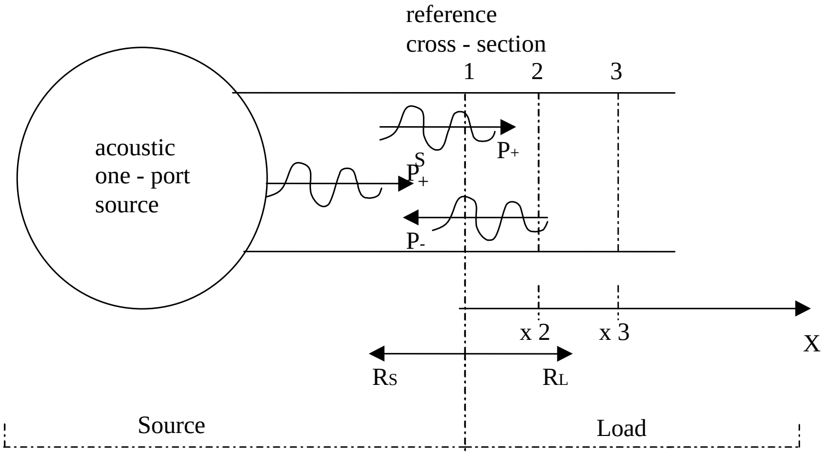

Figure1. An in-duct source modelled as an acoustic one-port

2.1 Linear one-port model

In the linear one-port model the source is characterized by two parameters: the source strength and the source reflection coefficient or source impedance. In the reflection coefficient formulation we have

$$p_+ = R_S p_- + p_+^S , \tag{1}$$

where R_S is the source reflection coefficient and p_+^S is the source strength. The source reflection coefficient will tell us how much that is reflected back when an acoustic plane wave is incident on the source and the source strength will tell us the generated sound pressure for a reflection free termination. In the literature the source model for one-ports is often expressed in terms of source strength (p_S) and normalized source impedance (Z_S),

$$Z \cdot p = Z_L \cdot p_S - Z_S \cdot p , \tag{2}$$

where p_S is the source pressure, p is acoustic pressure and Z_S is the normalised source impedance. The source impedance represents the acoustic impedance seen from the reference cross-section towards the source and the source strength represents the pressure generated for a blocked output. It is also possible to formulate the source model in Eq. (2) as a volume velocity source

$$p = Z_0 Z_L \cdot q_S - \frac{Z}{Z_S} \cdot p , \tag{3}$$

where q_S is the source strength in terms of the volume flow obtained for a completely open termination and Z_0 is the characteristic impedance of the medium.

2.2 Nonlinear frequency response function model

The time domain representation of the source model with non-linear term was in[7] described by

$$\int z_S(\tau) q(t-\tau) d\tau + \int h_S(\tau) b(t-\tau) d\tau = p_S(t) - p(t) , \tag{4}$$

where ($p(t)$) and ($q(t)$) denote the pressure and volume velocity at the source cross section, ($z_S(t)$) is the time domain representation of the source impedance, ($p_S(t)$) is the source strength, (b(t)) is the non-linear input and ($h_S(t)$) is the source data coefficient for the non-linear part. When applying this technique in[8] it was assumed that $b(t) = q^3(t)$ which is the first higher order series expansion term obtained for the pressure drop over an orifice. This assumption will also be used here. In the frequency domain Eq. (3) can be formulated as

$$Z \cdot p = Z_L \cdot p_S - Z_S \cdot p - H_S \cdot B = Z_L \cdot p \tag{5}$$

where (H_S) and (B) are the Fourier transforms of ($h_S(t)$) and ($b(t)$). This equation has compared to Eq. (2) a third complex unknown (H_S), which means that now at least three acoustic loads will have to be used in order to solve the equation and to obtain the source data.

2.3 Nonlinear scattering matrix model

In this section expressions for the acoustic source data starting from the polyharmonic distortion (PHD) theory[8-10] will be introduced for a source according to Fig. 1. The PHD approach describes nonlinear scattering and transmission properties when a system is excited with discrete tone or harmonic excitation. It has here been adapted to the case that the system also has an active source part. The PHD model is an approximation, which involves linearization using three main assumptions. The first assumption is that the system studied is time-invariant. This implies that applying an arbitrary delay to the input signals in our case the incident p_+-waves, always results in exactly the same time delay for the output signals, the scattered p_--waves. Time-invariance means that the system properties do not change with time. One could imagine that for a non-linear system where the system properties depend on the level of excitation there is a variation of system properties over the acoustic cycle. The second assumption is that the functions describing the system are non-analytic because of the nonlinear system properties. In general, when the sample under test becomes nonlinear, the superposition principle is no longer valid. The third assumption is that there is only one dominant large-signal input component present ($p_+(f)$) whereas all other harmonic input components are relatively small. In this case, we will be able to use the superposition principle for the relatively small input components. This harmonic superposition assumption is the key to the development of the PHD model. Using these assumptions leads to a source model

$$\begin{aligned} p_+(nf) = {} & p^s_{n+} + X_{n1}(|p_-(f)|)\cdot e^{j(n-1)\phi(p_-(f))}\cdot p_-(f) + X_{n2}(|p_-(f)|)\cdot e^{j(n-2)\phi(p_-(f))}\cdot p_-(2f) \\ & + \Xi_{n2}(|p_-(f)|)\cdot e^{j(n+2)\phi(p_-(f))}\cdot p^*_-(2f) + X_{n3}(|p_-(f)|)\cdot e^{j(n-3)\phi(p_-(f))}\cdot p_-(3f) \\ & + \Xi_{n3}(|p_-(f)|)\cdot e^{j(n+3)\phi(p_-(f))}\cdot p^*_-(3f) + ... \end{aligned} , \tag{6}$$

where we have a linear combination of the input amplitudes and their corresponding complex conjugates denoted by p^*. The phase of the large harmonic input signal is here arbitrarily chosen as a reference for all harmonics. If we do not make the assumption that the system is non-analytic we get

$$\begin{aligned} p_+(nf) = {} & p^s_{n+} + X_{n1}(|p_-(f)|)\cdot e^{j(n-1)\phi(p_-(f))} + X_{n2}(|p_-(f)|)\cdot e^{j(n-2)\phi(p_-(f))}\cdot p_-(2f) \\ & + X_{n3}(|p_-(f)|)\cdot e^{j(n-3)\phi(p_-(f))}\cdot p_-(3f) + ... \end{aligned} . \tag{7}$$

One assumption which has been used with success for application to perforates is that the nonlinear energy transfer only goes from lower to higher frequencies and not the other way around. Using this Eq. (7) can be simplified to

$$p_+(nf) = p_{n+}^s + \sum_{i=1}^{n} X_{ni}\left(\left|p_-(f)\right|\right) \cdot e^{j(n-i)\phi(p_-(f))} \cdot p_-(if) = \\ p_{n+}^s + + \sum_{i=1}^{n} S_{ni}\left(\left|p_-(f)\right|\right) \cdot p_-(if) \quad . \tag{8}$$

It is furthermore reasonable to assume that nonlinear energy transfer only occurs to integer multiples of a certain frequency so that only components in the sum in Eq. (8) where *n/i* is an integer should be retained.

2.4 Nonlinear impedance matrix model

In order to more easily compare the results to the outcome of Eq. (2) and Eq. (5) it is possible to reformulate the nonlinear scattering matrix result in Eq. (8) to a nonlinear impedance matrix model

$$Z_L(nf) \cdot p(nf) = .Z_L(nf) \cdot p_{n+}^s \cdot \frac{2}{1 - S_{nn}\left(\left|p_-(f)\right|\right)} - \frac{1 + S_{nn}\left(\left|p_-(f)\right|\right)}{1 - S_{nn}\left(\left|p_-(f)\right|\right)} \cdot p(nf) + \\ + \sum_{i=1}^{n-1} \frac{Z_L(nf)}{Z_L(if)} \cdot \left(Z_L(if) - 1\right) \cdot \frac{S_{ni}\left(\left|p_-(f)\right|\right)}{1 - S_{nn}\left(\left|p_-(f)\right|\right)} \cdot p(if) = \\ Z_L(nf) \cdot p_n^s - Z_{nn}^s\left(\left|p_-(f)\right|\right) \cdot p(nf) + \sum_{i=1}^{n-1} \frac{Z_L(nf)}{Z_L(if)} \cdot \left(Z_L(if) - 1\right) \cdot Z_{ni}^s\left(\left|p_-(f)\right|\right) \cdot p(if) \quad . \tag{9}$$

3. Experimental results and discussion

Comparisons of results obtained using models according to Eqs. (2), (5) and (9) will be presented. The experimental results are taken from multi load tests on IC-engines from[1-8]. To determine the linear one-port data in Eq. (2) data for two acoustic loads are needed, while the model in Eq. (5) requires data for three loads. The number of loads needed for the nonlinear impedance matrix model in Eq. (9) depends on the number of components included in the sum from 1 to *n*-1. As discussed in section 2.3 only terms for which *n/i* is an integer should be included so the number of loads required will vary with *n*. Measurements were made for more acoustic loads than needed which give the possibility for some over-determination, and can be used to improve the quality of the results. It is also possible to formulate linearity tests[6] and a normalised residual to show how well the data fits the modes.

3.1 Four cylinder Otto engine

Results for a four cylinder Otto engine[11] are presented. Experiments were performed using 20 different loads consisting of side branches of different lengths. Figure 2 shows an example of source data and linearity tests[7] obtained using models according to Eqs. (2), (5) and (9). It can be seen that all three models give similar source strength while there is some difference in the source impedance. The real part of the source impedance becomes negative for engine orders 4 and 8, which could be an indication of non-linearity. The linearity test, which show how well the measured data fits the models, gives a slightly higher value when using the two models including “nonlinear” terms.

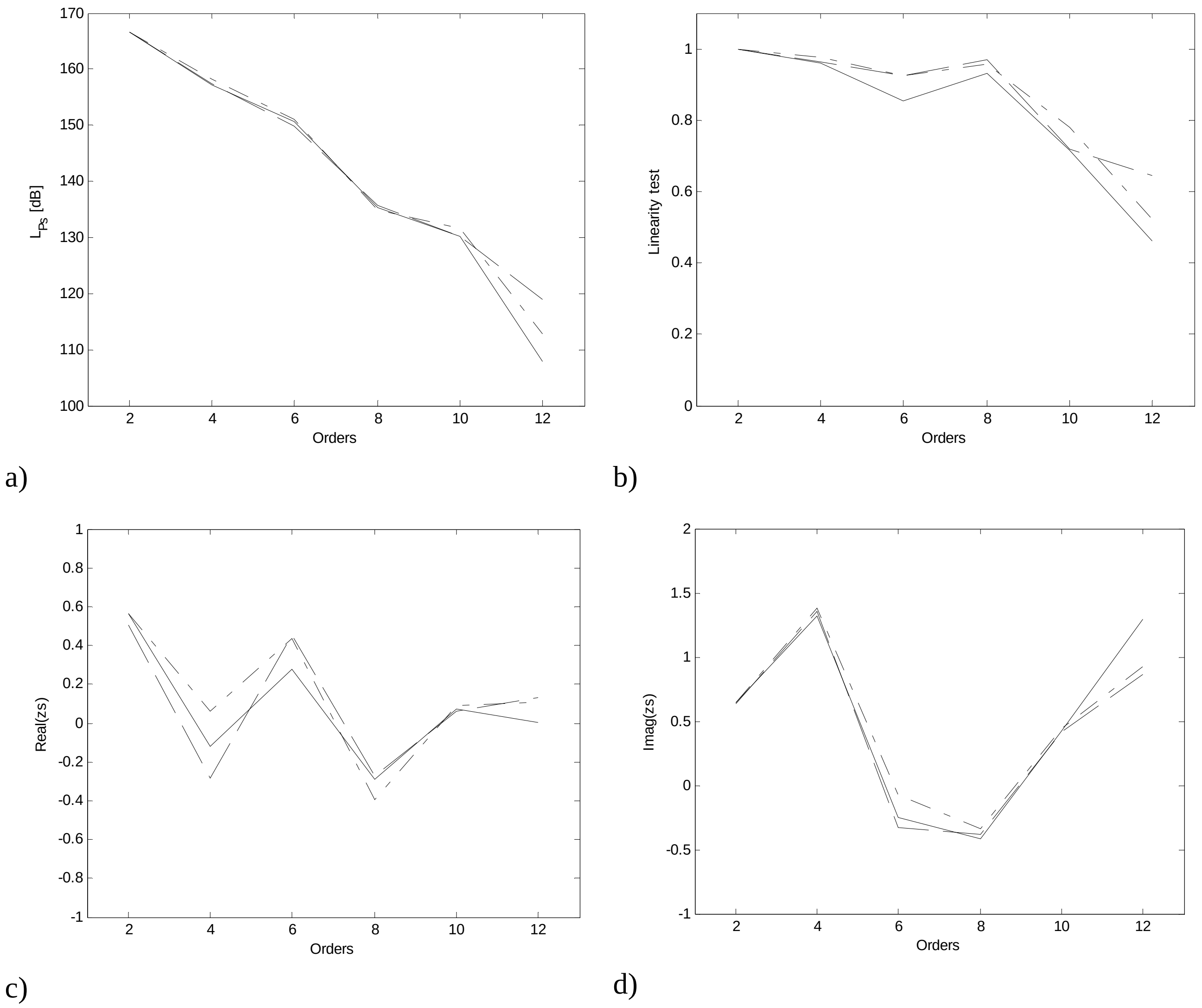

Figure 2. Source data and linearity test: full line – two load method, dashed line - nonlinear frequency response function model, dashed-dotted line – nonlinear impedance matrix model. a) Source strength, b) Linearity test[7], c) Real part of normalised source impedance, d) Imaginary part of normalised source impedance.

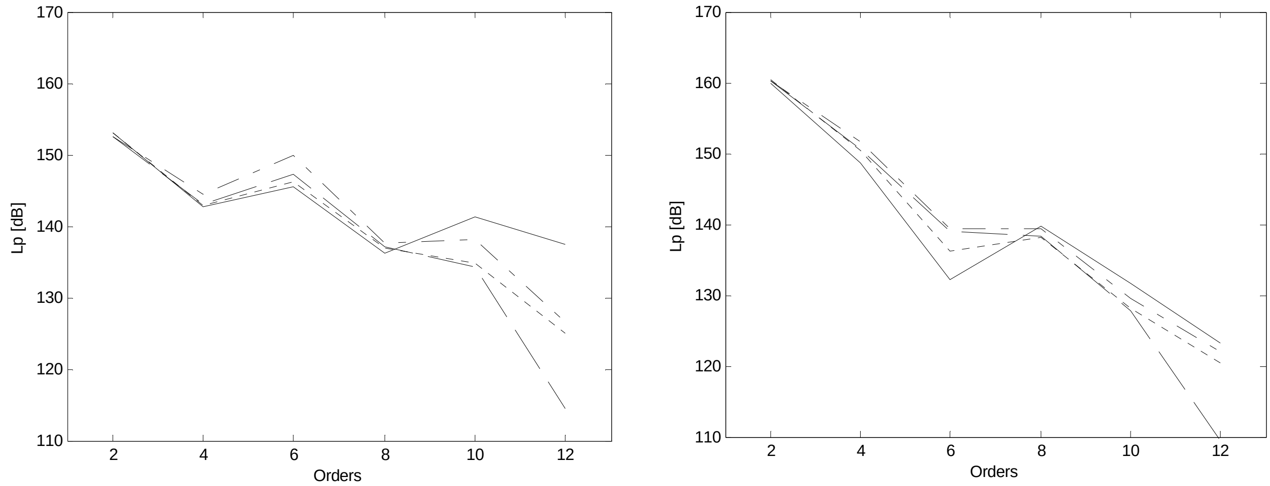

Figure 3. Sound pressure level in the exhaust system for two different acoustic loads: full line – measured, dashed line - two load method, dashed-dotted line – nonlinear frequency response function model, dotted line - nonlinear impedance matrix model.

Figure 3 shows a comparison between measured sound pressure level at the source cross section in the exhaust system and simulated results obtained using source data according to the three different models. Results are presented for two acoustic loads which were not included in the loads used to determine the source data. It can be seen that the nonlinear impedance matrix model gives an improvement of the prediction result compared to the linear two load model and for most engine orders also over the nonlinear frequency response function model.

3.2 Six cylinder diesel engine

Results for a six cylinder Diesel engine[3] are presented. Experiments were performed using 11 different loads consisting of side branches of different lengths.

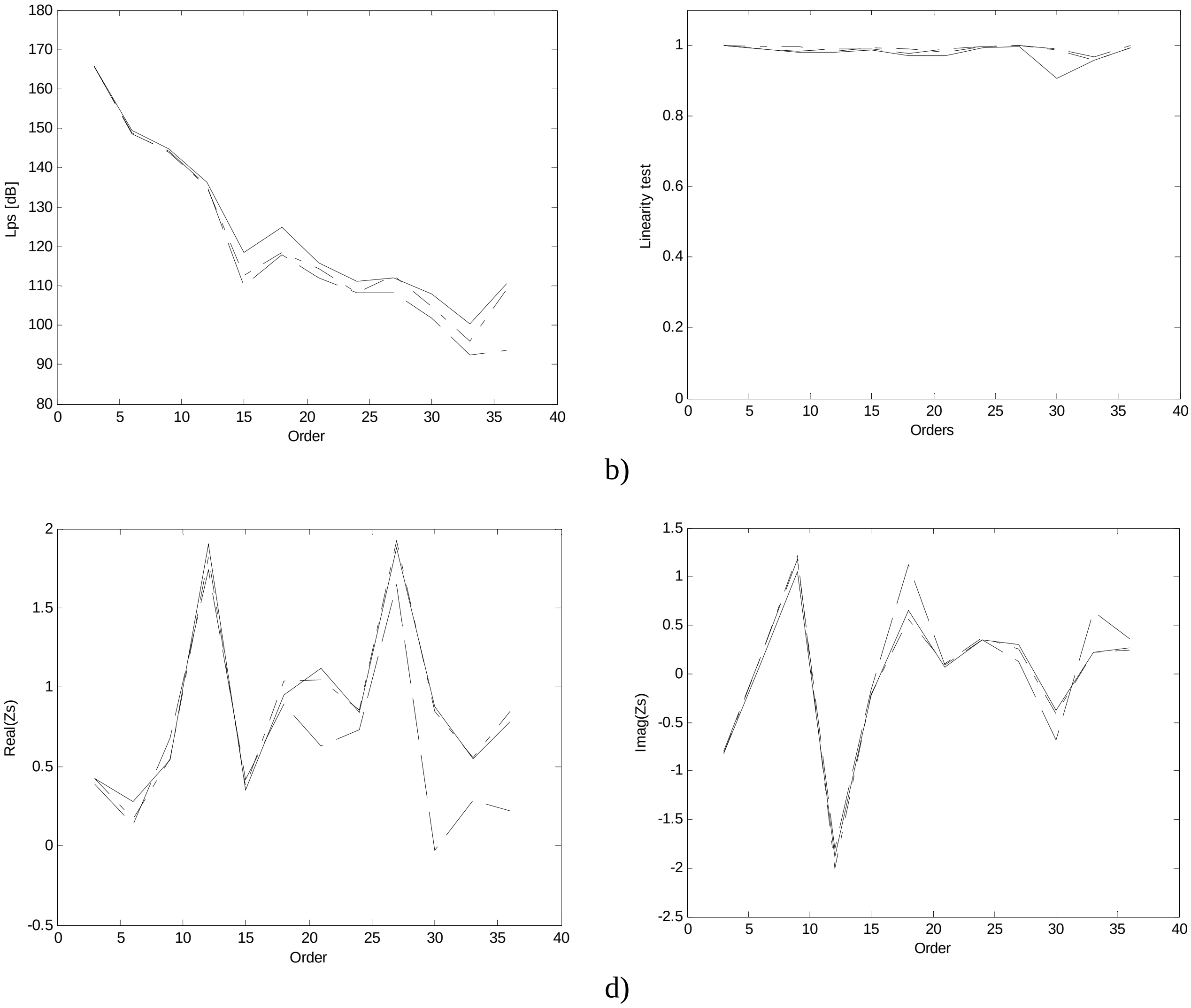

Figure 4. Source data and linearity test: full line – two load model, dashed line - nonlinear frequency response function model, dashed-dotted line – nonlinear impedance matrix model. a) Source strength, b) linearity test[7], c) Real part of normalised source impedance, d) Imaginary part of normalised source impedance.

Figure 4 shows an example, for one engine operating condition, of source data and linearity test[7] obtained using models according to Eqs. (2), (5) and (9). It can be seen that all three models give similar source data for lower engine orders while there is some difference at higher harmonics. The real part of the source impedance does not become negative with one exception for the nonlinear frequency response model. The linearity tests show that all three models give a good fit to the measured data, with only small improvements obtained by using the nonlinear models. Figure 5 shows a comparison between measured sound pressure level at the source cross section in the exhaust system and simulated results obtained using source data according to the three different models. Results are presented for one acoustic load, which was not included in the loads used to determine the source data, and two different operating conditions. It can be seen that the nonlinear impedance matrix model gives an improvement of the prediction result compared to the linear two load model and the nonlinear frequency response function model.

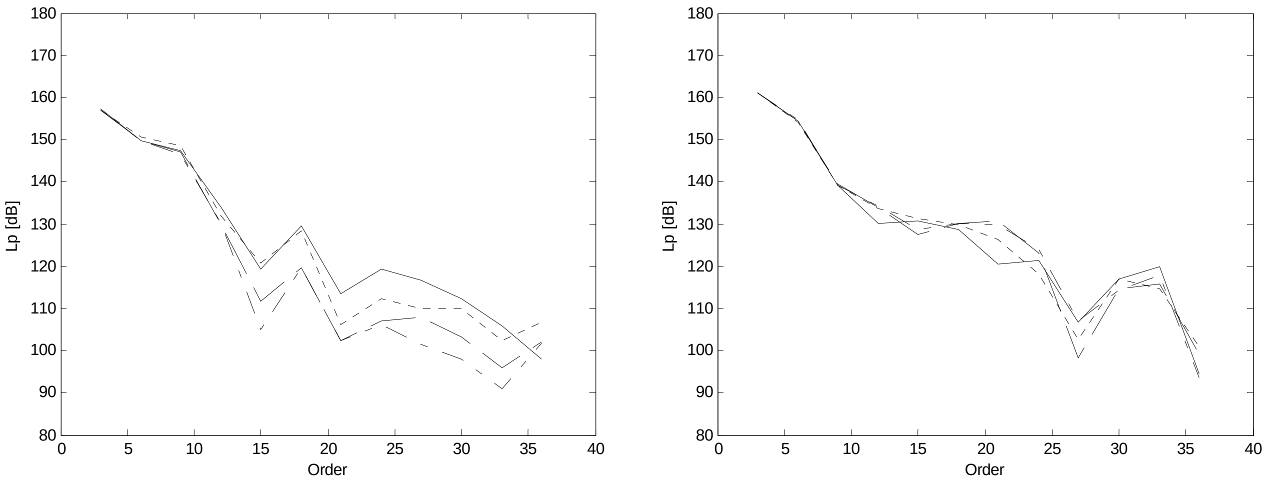

Figure 5. Sound pressure level in the exhaust system for two different engine operating conditions: full line – measured, dashed line - two load method, dashed-dotted line – nonlinear frequency response function model, dotted line - nonlinear impedance matrix model.

4. Summary and conclusions

A new source model intended to take weakly nonlinear source properties into account has been introduced. It is intended to be used for instance for IC-engines which are known to be high level sources of exhaust and intake system noise and not completely linear in character. The model takes it starting point in polyharmonic distortion models[8-10] used to characterize microwave systems. Through a series of simplifications a model which can be used when multi-load data for an engine is available has been developed. The results of using this model are compared to the results from the linear one-port model[1,2] and the nonlinear frequency response function model[7], which is also intended for weakly nonlinear sources. One of the differences between the two nonlinear models is that the new nonlinear impedance matrix model only considers nonlinear energy transfer from lower to higher harmonics and not the other way around. In the nonlinear frequency response function model one has to make an assumption about the character of the non-linearity, typically cubic or so-called square law with sign. Based on this a nonlinear term is deduced which does not in a direct way show the nonlinear energy transfer to higher harmonics. The three different models have been applied to measured data from a four cylinder Otto engine and a six cylinder Diesel engine. The results show that we get an improvement in the results when using the source data to predict the sound pressure level in the exhaust system by using both the models taking weak non-linearity into account. The new nonlinear impedance matrix model gives slightly better results than the nonlinear frequency response function model. It is also more straight-forward to use when acoustic multi-load data is available. It can also be used when extracting acoustic source data from numerical simulations[4-5] which is a current trend in exhaust system modelling.

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