ICSV14

Cairns • Australia

9-12 July, 2007

14th International Congress on Sound & Vibration

RECENT ADVANCES IN IC-ENGINE ACOUSTIC SOURCE CHARACTERISATION

Hans Bodén

The Marcus Wallenberg Laboratory for Sound and Vibration Research,
Aeronautical and Vehicle Engineering Department, KTH,
SE-10044, Stockholm, Sweden
hansbod@kth.se

Abstract

This paper summarizes work performed at KTH over the years on source characterization for IC-engine exhaust and intake systems. An overview is made of recent advances in experimental and simulation methods for determination of acoustic source data. These include a source model which can consider weakly non-linear sources and application of 1-D CFD codes for extracting source data. Examples are presented for both exhaust and intake systems and for different types of engines. The results show that reasonably accurate results can be obtained using 1-D CFD codes to extract acoustic source data and that the newly developed non-linear multi-load technique has got advantages over the traditional two-load technique for determining source data from experiments.

1. INTRODUCTION

Linear frequency domain prediction codes are 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 used in the low frequency plane wave range is the linear time invariant 1-port model. The acoustic source data is usually obtained from experimental tests where multi-load methods and especially the two-load method are most commonly used. These tests are time consuming and expensive. It would therefore be of interest to extract the acoustic source data from existing 1-D CFD codes describing the engine gas exchange process. The objective of the work presented in this paper was development of source models with low level of complexity, which can be used in linear acoustic calculation codes. Source models of different level of complexity have therefore been tested on different types of engines. The models tested include: the well-known linear time invariant model and different formulations of linear time variant models and a non-linear model. The techniques used to extract the source data from the experimental or simulated data are indirect or multi-load methods [1, 2].

2. SOURCE MODELS AND SOURCE CHARACTERISATION TECHNIQUES

In developing source models the aim is to produce the most simple model which is able to provide acceptable results. The models can be classified as linear time-invariant, linear time varying, hybrid and non-linear models, in order of increasing complexity. The source is described by the physical quantities via which it interacts with the outside world. In the review papers [1, 2] on the subject source models applicable for different types of sources are discussed. For internal combustion engines it is usually sufficient to consider 1-D models for the sound propagation in the main exhaust pipes. The main question is whether a linear time-invariant source model can be used or if time-variance and non-linearity must be considered.

2.1 Linear time-invariant one-port source models

If only plane waves are considered in the duct system the simplest model that can be used to describe the source is the linear time-invariant frequency domain one-port model. In the frequency domain an acoustic one-port can be completely described by two complex parameters: the source strength (P_S) and normalized source impedance (Z_S). The behaviour of the one-port can in the frequency domain, be described by

$$P_S \cdot Z - P \cdot Z_S = P \cdot Z \, , \tag{1}$$

where P is the acoustic pressure and Z the normalized load impedance at the source cross section. Equation (1) has got two complex unknowns, which means that it can be solved if we have at least two complex equations. This is the so-called two-load method [1, 2]. If we use n acoustic loads we get an over-determined system which can be of advantage to reduce the effects of measurement errors and non-linearity. Alternatively the one-port model can be expressed as a volume velocity source. Both models should give the same result for Z_{S} *if* the source is really linear and time-invariant. If this is not the case a difference in the result can be expected. Evaluation data using both models is therefore a possible way for detecting non-linearity. Further linearity tests will be discussed in section 3.

2.2 Linear time varying source models

When determining the passive acoustic data, i.e., the source impedance of an IC-engine it is assumed that it does not change with time. If the machine in action is studied it is observed that pistons and valves move. One can therefore in principle expect that even the passive acoustic properties should be time-varying. In mathematical terms this means that the source is described by linear differential equations with time-varying coefficients. The time variation in the coefficients is normally caused by the periodic motion of the machine and will therefore be periodic. Using such a model for the machine the problem can be solved either in the time domain or in the frequency domain. A frequency domain linear time-varying source model was developed by Wang [3, 4] for an internal combustion engine inlet system. By assuming that the variables and the coefficients have periodic time dependence, so that they can be expanded in Fourier series, a frequency domain model for the source can be deduced. Here the source strength is replaced by a vector containing the data for each frequency component, and the source impedance is replaced by a matrix which also describes the coupling between different frequency components which can occur at the source. Bodén [5, 6] has presented measurement methods for determining the source data for such a model. The methods used are similar to the *multi-load* methods used for time-invariant 1-port sources. No major advantage of using these methods for applications on IC-engines have however been found [7].

2.3 Non-linear source models

Non-linear models describing the engine gas exchange process are well developed and a number of commercial one-dimensional CFD codes are available. They are primarily intended for prediction of engine performance characteristics but could in principle be used for extracting also acoustic information since they provide time varying pressures and velocities in the exhaust and intake system. In the present paper such codes have been used to perform simulated measurements and to extract data using the techniques described in sections 2.1 and 2.2.

A method extending linear time-invariant models to include non-linear effects has recently been published [8]. The time domain representation of the source model with non-linear term is described by

$$\int z_S(\tau)q(t-\tau)d\tau + \int h_S(\tau)b(t-\tau)d\tau = p_S(t) - p(t)\,, \qquad (2)$$

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 section 4 it has been assumed that $b(t) = q^3(t)$ which is the first higher order series expansion term obtained for the pressure drop over an orifice. In the frequency domain (2) can be formulated as

$$P_S Z_0 Z - P Z_0 Z_S - H_S B = P Z_0 Z \qquad (3)$$

where (H_S) and (B) are the Fourier transforms of ($h_S(t)$) and ($b(t)$). This equation has compared to (1) 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.

3. LINEARITY TESTS

In order to be able to choose an appropriate source model it is important to have methods to determine if measured or simulated engine data fits a linear source model. First indicators of possible non-linearity can be studied. It is possible to look at the real part of the source impedance evaluated using the linear time-invariant techniques described in section 2.1. This resistance must be positive for a linear passive system. Negative resistances may be an indication of non-linearity. Another possibility is to evaluate data using both the pressure source and the velocity source formulations as mentioned in section 2.1. If the same source impedance is not obtained using both formulations this could also indicate a non-linear source. Linearity tests for in-direct or multi-load methods were proposed by Bodén and Albertsson [9]. The idea behind the tests is to verify that the source data (P_S, Z_S) are unchanged under acoustic load variations. If the linearity test indicates non-linear behavior, the use of non-linear or hybrid methods is a natural step.

If we assume that we have a problem with m complex unknowns and make n measurements the over-determined equation system for determining the unknowns $\mathbf{x}$ can be written in the following way

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{b} \tag{4}$$

where $\mathbf{A}$ is a $(n \times m)$ matrix, $\mathbf{x}$ is a $(m \times 1)$ vector and $\mathbf{b}$ is a $(n \times 1)$ vector. The idea is now to formulate tests, i.e. linearity coefficients, which can tell us if the measured data in $\mathbf{A}$ and $\mathbf{b}$ are consistent with the linear relationship (4). The number of measurements, n in (4), has to be larger than m for the linearity coefficients to be meaningful. If n equals m the linearity coefficients will always indicate a linear relationship. A linearity coefficient, which is similar to the coherence function be defined as

$$\gamma = \mathbf{x}^{-1} \cdot \mathbf{x} = \mathbf{b}^{-1} \cdot \mathbf{A} \cdot \mathbf{A}^{-1} \cdot \mathbf{b}\,, \tag{5}$$

where $\mathbf{x}^{-1}$ is interpreted as the pseudo-inverse of $\mathbf{x}$. This linearity coefficient will have a value in the interval $0 \le \gamma \le 1$, where the upper limit represents a perfect linear relationship. A drawback with such a test is that it is also sensitive to random errors. In [9] techniques to determine if a value lower than 1 is caused by non-linearities or random noise are discussed.

To increase the sensitivity of the linearity test, the right hand side in the equation $\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$ can be normalized to a unity vector, which means that every row in the equation system $\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$ is divided by the corresponding right hand side.

4. RESULTS AND DISCUSSION

In this section examples of results from exhaust and intake systems for different types of engines are given.

4.1 Four cylinder Otto engine exhaust

This section presents results from experimental tests on a four cylinder personal car petrol engine without turbo. The source data is based on tests using 15 different side-branches as acoustic loads. Figure 1 shows linearity tests indicating some at least weak source non-linearity. The same conclusion can be drawn from studying the source impedance evaluated using the pressure source model and the velocity source model shown in Figure 2 and 3. A perfectly linear source would have given the same result for both models. The comparison between measured pressure in the exhaust system and predictions using the linear pressure source model, the linear velocity source model and the non-linear model of section 2.3 shows that the non-linear model gives a better prediction in this weakly non-linear case.

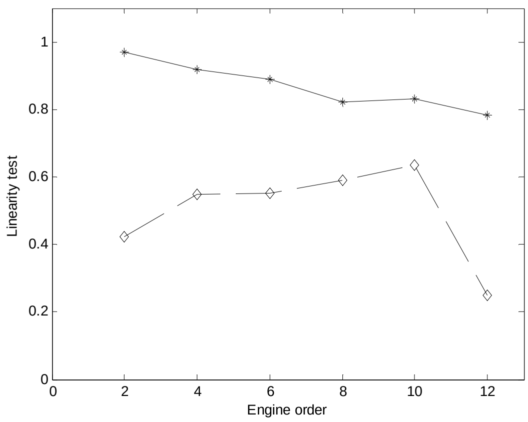

Figure 1. Linearity tests as a function of engine orders: linearity test according to (5) (——) and normalized linearity test (- - - -).

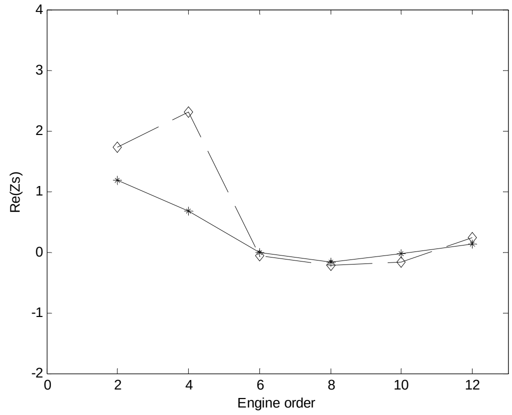

Figure 2. Real part of normalized source impedance: pressure source (——) and velocity source (- - - -).

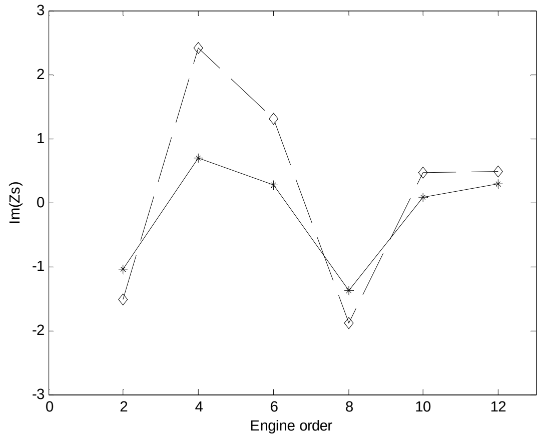

Figure 3. Imaginary part of normalized source impedance: pressure source (——) and velocity source (- - - -).

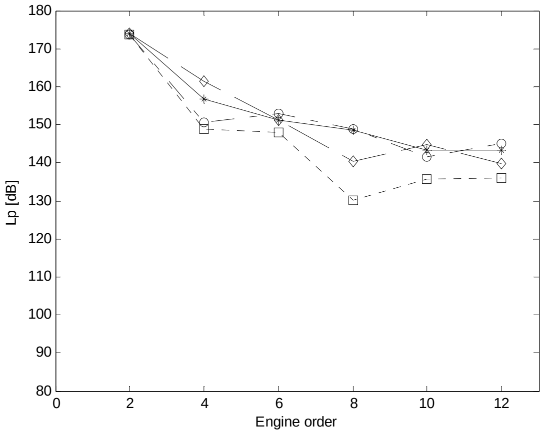

Figure 4. Sound pressure level in exhaust system: measured (——), predicted linear pressure source model(– – –), predicted linear velocity source model (- - - -) and predicted non-linear source model (- · - ·).

4.2 Six cylinder Diesel engine exhaust

This section presents results from experimental tests on a six cylinder truck diesel engine with a turbo [7, 10]. The source data is based on tests using 10 different side-branches as acoustic loads. Figure 5 shows linearity tests indicating reasonably linear source behaviour at lower engine harmonics. Figure 6 shows a comparison between pressures predicted using source data obtained from 1-D CFD (AVL-BOOST) simulations and measured in the exhaust system. Figure 7 shows a comparison between pressure predicted using source data obtained with different formulations of time-variant source models discussed in section 2.2 and measured in the exhaust system. The results show that the linear time-variant source model gives a quite large scatter in the results. Figure 8 shows a comparison between pressure predicted from source data, obtained from experimental data using the linear and non-linear source model according to section 2.3, and measured in the exhaust system. The results show that a linear model was sufficient for this engine and that good prediction results could be obtained.

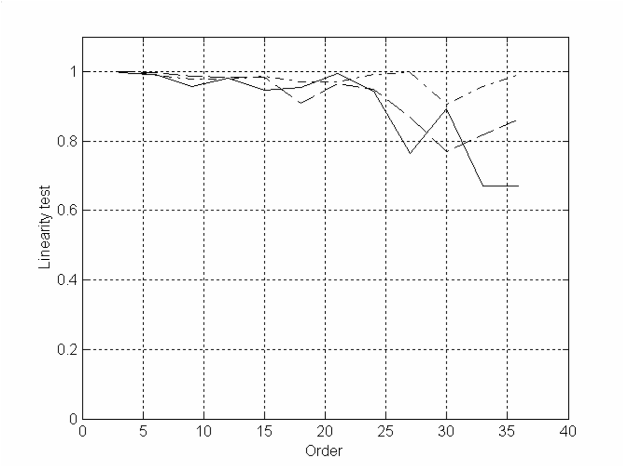

Figure 5. Linearity test according to (5) as a function of engine orders: full load (——), 50 % load (– – –), and 25 % load (–·–·–).

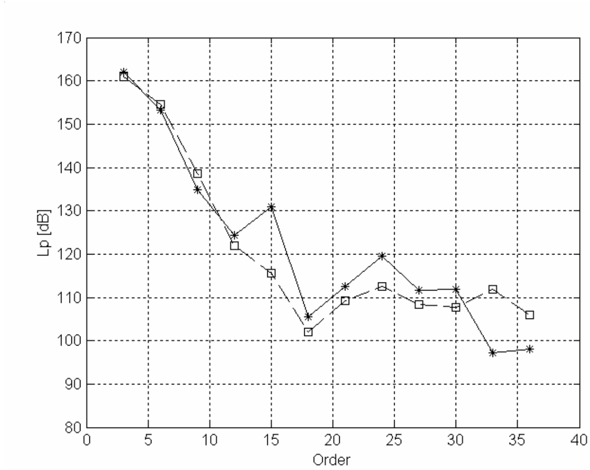

Figure 6. Sound pressure level in the exhaust system for acoustic load 6 and 1800 rpm full load: measured (——) and predicted using experimentally determined source data (- - - -).

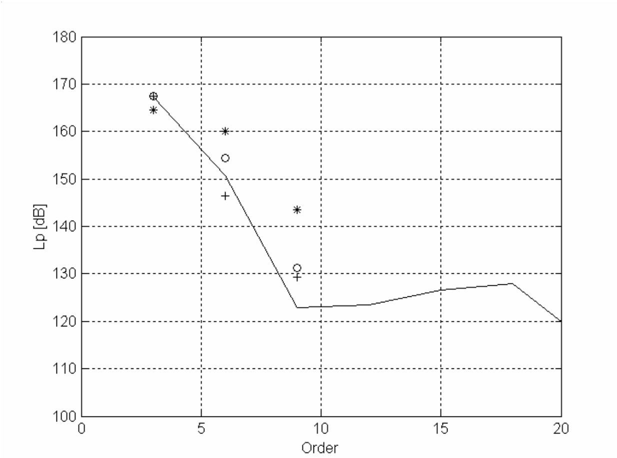

Figure 7. Sound pressure level in the exhaust system for acoustic load 12 and 1200 rpm 25% load.: measured (——) and predicted using time-variant source model (stars, plus and circles).

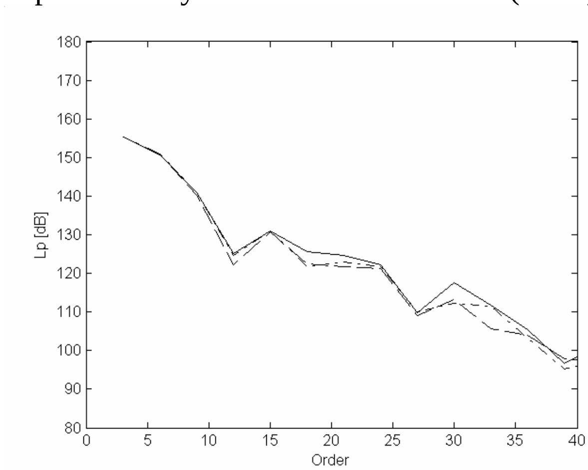

Figure 8. Sound pressure level in exhaust system: measured (——), predicted linear pressure source model (– – –), and predicted non-linear source model (–·–·–).

4.3 Six cylinder Diesel engine intake

This section presents results from experimental tests on a six cylinder personal car diesel engine with a turbo [11, 12]. The source data is based on tests using 6 different side-branches as acoustic loads. Figure 9 shows acoustic source data obtained from measurements and 1-D CFD (WAVE) simulations. It can be seen that a fairly good agreement is obtained. The linearity test indicates that a linear source model can be used for this engine. Figure 10 shows absolute value of normalized source impedance and linearity coefficient for the 6th engine order calculated from the pressure formulation and velocity source formulation. The results show a good agreement at most engine speeds. For engine speeds where there is a deviation there is also a value slightly lower than one for the linearity test indicating a weak non-linearity.

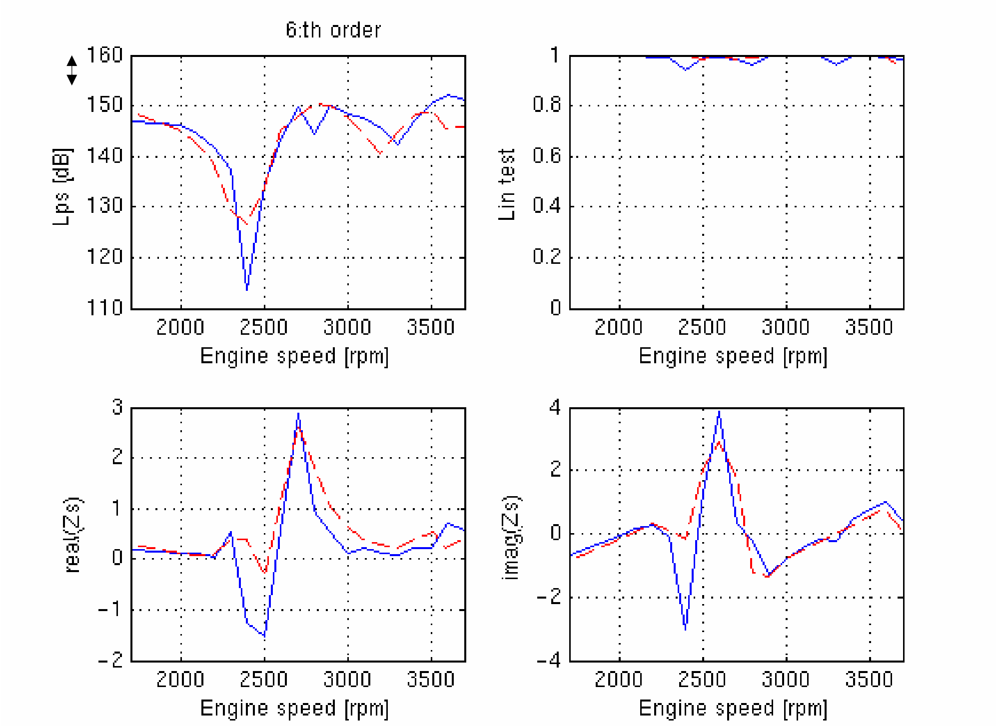

Figure 9. Source data as a function of engine speed obtained from measurements (full line) and WAVE calculations (dashed line) for 6:th engine order.

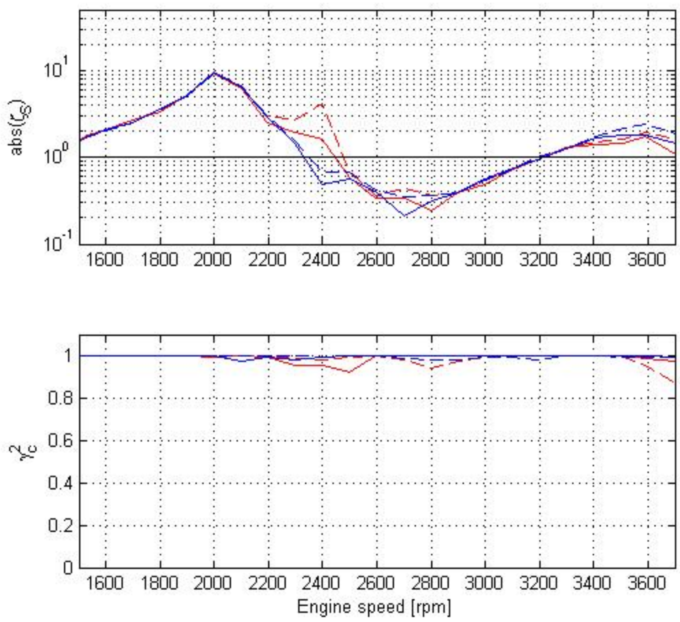

Figure 10. Absolute value of normalized source impedance and linearity coefficient for 6th engine order calculated from pressure formulation and velocity formulation. Pressure source formulation data is indicated by solid lines and velocity source formulation data by dashed lines. The red and blue curves come from two different sets of acoustic load data.

6. SUMMARY AND CONCLUSIONS

A number of different source models which can be used for describing IC-engines as sources of exhaust and intake noise have been discussed. Examples of results from experimental studies and 1-D CFD simulation studies have been used to illustrate how one can determine which type of source model that is appropriate for the engine under study. Especially interesting recent developments are the techniques for extracting acoustic source data from

1-D CFD calculations and the new non-linear multi-load technique for including weak non-linear effects in the source model. Obtaining source data from simulations saves time and money since expensive engine cell tests can be avoided. Better source characterisation results were obtained, using the new non-linear multi-load method compared to the two-load method, when the source under test exhibited non-linear behaviour. The new non-linear indirect source characterisation technique requires one additional acoustic load compared to the two-load technique. Since over-determination is anyway used in many cases the additional data would often be available. It has been shown that the new technique gives improved results compared to the two-load technique if the source is weakly non-linear. For cases when the source is linear and time-invariant the new technique gives the same result as the two-load technique. This means that there is no risk for increased errors when the source is linear and time-invariant which can happen if a linear time-varying source model is used. It can therefore be recommended that the new technique is used whenever sufficient data is available.

REFERENCES

[1] H. Bodén and M. Åbom, “Modelling of fluid machines as sources of sound in duct and pipe systems”, *Acta Acustica* **3**, 549-560 (1995).

[2] H. Bodén, “Characterization of fluid-borne sound sources and structure-borne sound sources”, *Proceedings of the 9th International Congress on Sound and Vibration* (ICSV9), 8-11 July 2002, Orlando, Florida, USA.

[3] W.M. Wang, “Matrix formulation in acoustic analysis of mechanically driven fluid systems” *Journal of the Acoustical Society of America*, **41**, 1418-1423 (1967).

[4] W.M. Wang, “Acoustical analysis of a multicylinder engine air induction system” *Journal of the Acoustical Society of America*, **42**, 1244-1249 (1967).

[5] H. Bodén, “The multiple load method for measuring the source characteristics of time-variant sources” *Journal of Sound and Vibration* **148**, 437-453 (1991).

[6] H. Bodén and F. Albertson, “Application of the multiple load method for non-linear sources” *Proceedings of the Seventh International Congres on Sound and Vibration,* 4-7 July 2000, Garmisch-Partenkirchen, Germany.

[7] H. Bodén, “Acoustic Source Characterisation for Diesel Engine Exhaust Systems”, *Proceedings of THIESEL 2004*, 8-10 September 2004, Valencia, Spain.

[8] H. Rämmal and H. Bodén “Modified multi-load method for non-linear sources”, *Journal of Sound and Vibration* **299**, 1094-1113 (2007).

[9] H Bodén, F Albertson, “Linearity tests for in-duct acoustic one-port sources”, *Journal of Sound and Vibration* **237,** 45-65(2000).

[10] H. Bodén , M. Tonsa and R. Fairbrother “On extraction of IC-engine linear acoustic source data from non-linear simulations” *Proceedings of the 11th International Congress on Sound and Vibration*, 5-8 July 2004, St. Petersburg, Russia.

[11] M. Knutsson and H. Bodén, “On extraction of IC-engine intake acoustic source data from non-linear simulations”, *Proceedings of SAE*,SAE 2007-01-2209

[12] M. Knutsson and H. Bodén, “IC-engine intake acoustic source data from non-linear simulations”, *Proceedings of the 12th International Congress on Sound and Vibration* (ICSV12), 11-14 July 2005, Lisbon, Portugal.