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SOUND INTENSITY VECTOR FIELDS IN RELATION TO DIFFERENT REFERENCE SIGNALS

Örjan Johansson

Acoustics Group, Division of Environment Technology, Luleå University of Technology, 971 87 Luleå, Sweden, Orjan.Johansson@arb.luth.se

Abstract

3D-intensity measurements may be used for source localisation. There is, however, a complex relation between the near field intensity estimate and the sound pressure in the far field. Another complication is that the intensity field near a complex structure may be a combination of direct radiation and interference from coherent secondary sources. This is of particular interest when measuring in narrow bands because almost no frequency smearing effect occurs. In this paper, the multivariate technique partial least squares (PLS) regression, is applied for evaluating and interpreting intensity measurements in narrow bands in relation to different reference signals, such as sound pressure in the far field. The PLS method allows correlation in both the frequency and spatial domains. The method is tested and validated experimentally, by studies of a complex but controlled source model with partially correlated sources, in anechoic condition. It is concluded that a decomposition of the intensity vector field in so called principal components enhances the identification of inherent noise sources. The possibility of modelling the intensity vector field in relation to different reference signals reveals a better understanding of the relationship between the partly coherent near field and a specific position in the far field.

1. INTRODUCTION

In noise control and sound quality analysis a common problem is to locate the sources of sound radiation. A further problem is to establish the relation between sources of sound radiation and the hearing sensation. For source location, 3D-intensity measurements may be used as a straightforward method. In reality, however, there is a complex relation between the near field intensity estimate and the sound pressure level in the far field. Another complication is that the intensity from a complex structure like a diesel engine may be a combination of direct radiation and interference from coherent secondary sources [1]. Interference is of particular interest when measuring in narrow bands because almost no frequency smearing effect occurs. On the other hand, the information contained in spectral data of high resolution is needed for a clear description of the sound radiation, especially for correlation with narrow band vibration patterns.

Several studies of source location have been presented, for example: 1) selective intensity [2], 2) near field acoustic holography (NAH) [3], 3) spatial transformation of the sound field

(STSF) [4], 4) broad band acoustic holography using intensity measurements (BAHIM) [5], and 5) the principles of reciprocity [6]. In general, the main drawback for all the methods mentioned is that a complex measurement and/or calculation procedure is required.

The aim of this study is to define a model that describes a relationship between near field intensity measurements and a number of reference sound pressure signals in the far field. The modelling is based on a multivariate statistical method denoted as partial least squares regression (PLS), which is similar to principal component analysis (PCA) [7, 8]. The PLS is an approach to regression analysis, where the improvement in the fit is balanced against the increase in model uncertainties. A useful feature of both PCA and PLS is the ability to analyse correlated measurement data in both frequency and spatial domain. Another advantage is that the measurement data is decomposed in principal components which may be related to independent phenomena in the sound field.

To enable verification of PLS, a model experiment was performed. The model contains a number of loudspeakers covered by a complex aluminium enclosure. The enclosure is acoustically excited by near-field recorded engine noise (partly coherent). The objectives are: (1) to decompose the intensity vector field in independent components and thereby identify inherent noise sources (2) to obtain intensity vector estimate in relation to different reference positions. (3) to see in what extent partly coherent sources can be separated.

2. PARTIAL LEAST SQUARES REGRESSION

The theory and algorithms for both PCA and PLS rely on the Heisenberg principle of mathematical modelling and have been described in detail in the literature [7, 8, 9]. The calculation of PCA and PLS models was carried out by the software SIMCA-S 2.1 (Umetri AB, Umeå, Sweden). MATLAB was used for further processing of the multivariate model for transformation back to spectra in acoustic units.

PLS is used to model the relation between two matrices **X** (*intensity spectra*) and **Y** (*sound pressure spectra*). PLS results in a decomposition of the original data matrices **X** and **Y** into a number (*N*) of orthogonal loading and score vectors, denoted as principal components), see Figure 1. A score vector related to **X**, describes the largest variance in the intensity data and thus the most dominating spectral distribution in the spatial domain. The corresponding loading vector describes the contribution from different positions and directions in relation to the score spectrum. Vector multiplication of a specific loading and score vector pair gives a matrix of principal component spectra. The extracted components are calculated as linear combinations of **X** and **Y** respectively to extract information in **X** which is relevant for predicting **Y**. The PLS model describes a subspace in **X** which is calculated to attain a maximum covariance with **Y.** This is unlike PCA where the model describes the space of largest variance in **X**. Using matrix notation, the final PLS model can be described as in equations 1 to 3. Equation (3) is frequently called the inner relation and relates the X and Y matrices to each other.

$$X = X_{avg.} + TP' + E, \tag{1}$$

$$Y = Y_{avg.} + UC' + F, \tag{2}$$

$$U = T + H, \tag{3}$$

where; X = sound intensity matrix, X_{avg} = mean value matrix of X, Y = reference sound pressure matrix, Y_{avg} = mean value matrix of Y, C = loading matrix for Y, U = score matrix for Y, F= residual matrix for Y, and H = residual for the inner relation.

Procedure for PLS regression:

(1) *Subtract the mean of every column from each element in the data matrices (mean centring).*

(2) *Calculate the first component by extracting the first loading and score vector pair from the mean centred data matrices by finding maximum covariance between Y and a subspace in X. The PLS algorithm is an iterative procedure, based on a singular value decomposition of the covariance matrix X'Y* [8].

(3) *Calculate residual matrices as the difference between the first principal component matrices and the original data matrices.*

(4) *Extract the loading and score vector pair of the second component from the first residual matrices.*

(5) *Repeat (3) and (4) until no more systematic variability remains in the residual matrices.*

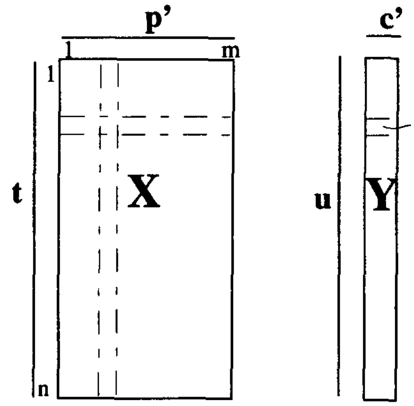


Figure 1. Procedure and data arrangement for PLS regression. The columns in the X matrix contains intensity spectra and the columns in the Y matrix contains reference pressure spectra. **p** and **c** indicate loading vectors, and **t** and **u** indicate score vectors.

For efficient interpretation of Equations 1 and 2, are a N number independent so called principal component intensity spectra (Equations 4 and 5) and principal component pressure spectra (Equation 6) defined.

$$\boldsymbol{TP'} = \sum_{q=1}^{N} \boldsymbol{t}_q \boldsymbol{p}_q' \ , \qquad (4)$$

where $\boldsymbol{t}_q$ is a principal component score vector and $\boldsymbol{p}_q$ is a principal component loading vector. Multiplication of these vectors results in a matrix of principal component intensity spectra ($\boldsymbol{X}_{PSq}$), see Equation 5. Each column in this matrix corresponds to a principal component intensity spectrum for a specific direction in a specific position in relation to the reference signals in **Y**. For a transformation back to original values, the first component matrix has to be corrected as the calculations of score and loading vectors are based on mean centred data.

$$\boldsymbol{X}_{PS_1} = \boldsymbol{X}_{avg} + \boldsymbol{t}_1 \boldsymbol{p}_1', \qquad \boldsymbol{X}_{PS_q} = \boldsymbol{t}_q \boldsymbol{p}_q' \qquad q = 2,3,\dots,N \qquad (5)$$

The intensity level in different positions and directions at a certain frequency (a row in $\boldsymbol{X}_{PSq}$), are visualised as principal intensity vector fields (PIV). The corresponding principal component reference pressure signals (PPS) are defined by Equation 6.

$$\boldsymbol{Y}_{PS_1} = \boldsymbol{Y}_{avg} + \boldsymbol{t}_1 \boldsymbol{c}_1', \qquad \boldsymbol{Y}_{PS_q} = \boldsymbol{t}_q \boldsymbol{c}_q' \qquad q = 2,3,\dots,N \qquad (6)$$

3. EXPERIMENTAL PROCEDURES

A noise source model (Figure 2a) enabled acoustic excitation of a timing transmission cover (TTC) in cast aluminium. The TTC was bolted to a 35 mm thick steel plate which was softly connected to a box of chipboard, that contains three loudspeakers. The loudspeakers were fed with near-field recorded engine noise at two different positions on an engine, which resulted in two partly coherent signals, see Figure 2c. The A loudspeaker (Figure 2a) was fed by a signal recorded close to the fuel pump. The B and C loudspeakers were out of phase and fed by a signal recorded close to the oil sump.

Three different measurements were carried out, the first using only A excitation and the second using BC excitation and finally an ABC excitation was performed. The measurement results due to ABC excitation were analysed with PLS and the other two cases were used to validate the multivariate calculations.

The acoustic measurements were carried out in anechoic conditions in the frequency range 400 - 4000 Hz with a resolution of 4 Hz. The sound intensity [1] was measured by a robot controlled 3D-probe (B&K 0447), see Figure 2. The intensity was measured by scanning the probe with a speed of less than 0.1 m/s [10] over each sub-area (0.01 m^2) in a plane grid (6x7). Each intensity spectrum is an average based on 60 independent samples, determined at a distance of 10 cm from the structure. The averaging time and scanning speed were adjusted to cover each sub-area equally. The probe was calibrated using an acoustic coupler B& K 3541 and the residual pressure intensity index [11] varied from 26-32 dB in the observed frequency range. The reference microphones were positioned 1 m apart and 1 m from the source. The reference sound pressure spectra were measured before and after the intensity measurement with the robot removed. To validate the intensity measurements the vibration behaviour of the TTC was determined by operational deflection shape (ODS) estimation [12].

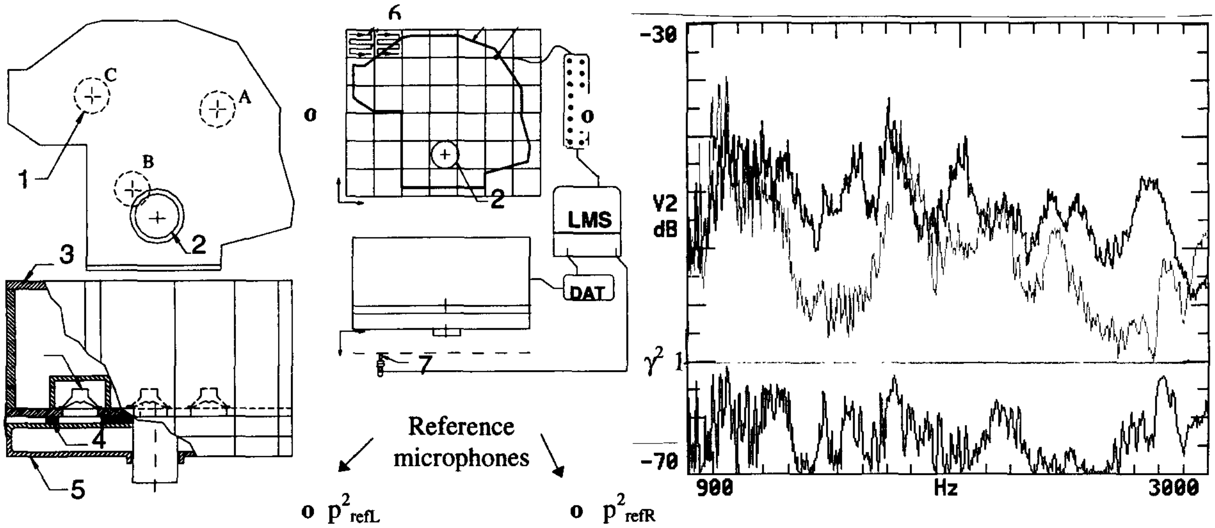


Figure 2. Experimental set-up and noise source model. 1: Loudspeaker. 2: Hub (simulation of crankshaft). 3: Box of chipboard. 4: Steel plate. 5: TTC cover. **b)** Experimental set-up: 6. Scanning scheme, 7. 3D-intensity probe. **c)** The voltage level of the excitation signals and the coherence(γ^2) between them, black =A, grey = BC.

4. RESULTS AND DISCUSSION

The development of the PLS model was based on a logarithmic transformation of the absolute values of the pressure and intensity spectra during the calculation procedure. The intensity vector components sign information were stored in a sign matrix and afterwards added to the analysed data. The use of a logarithmic transform reduces the influence from otherwise dominating frequencies and by that a better model was obtained. The logarithmic values were only used when extracting the principal components, all other calculations, e.g. when calculating the residual matrices, were based on linear values.

The results of sound pressure, sound intensity and ODS measurements, are presented together with the results of PLS regression. The PLS regression resulted in five significant principal components, which describe 88 % of the variance in the reference sound pressure spectra (1^{st}: 78%, 2^{nd}: 3.3%, 3^{rd}: 4.1%, 4^{th}: 1.4% and 5^{th}: 1.2%). The first step in the analysis is to make a comparison between the sound pressure measurements due to ABC excitation and the principal pressure spectra (PPS), see Figure 3. To judge weather a component is relevant to describe the variance of a specific reference spectra, a condition of less then 10 dB difference between the PPS and measured data is used. The idea is that the reference signals can be described by a proper combination of the PPS shown in Figure 3.

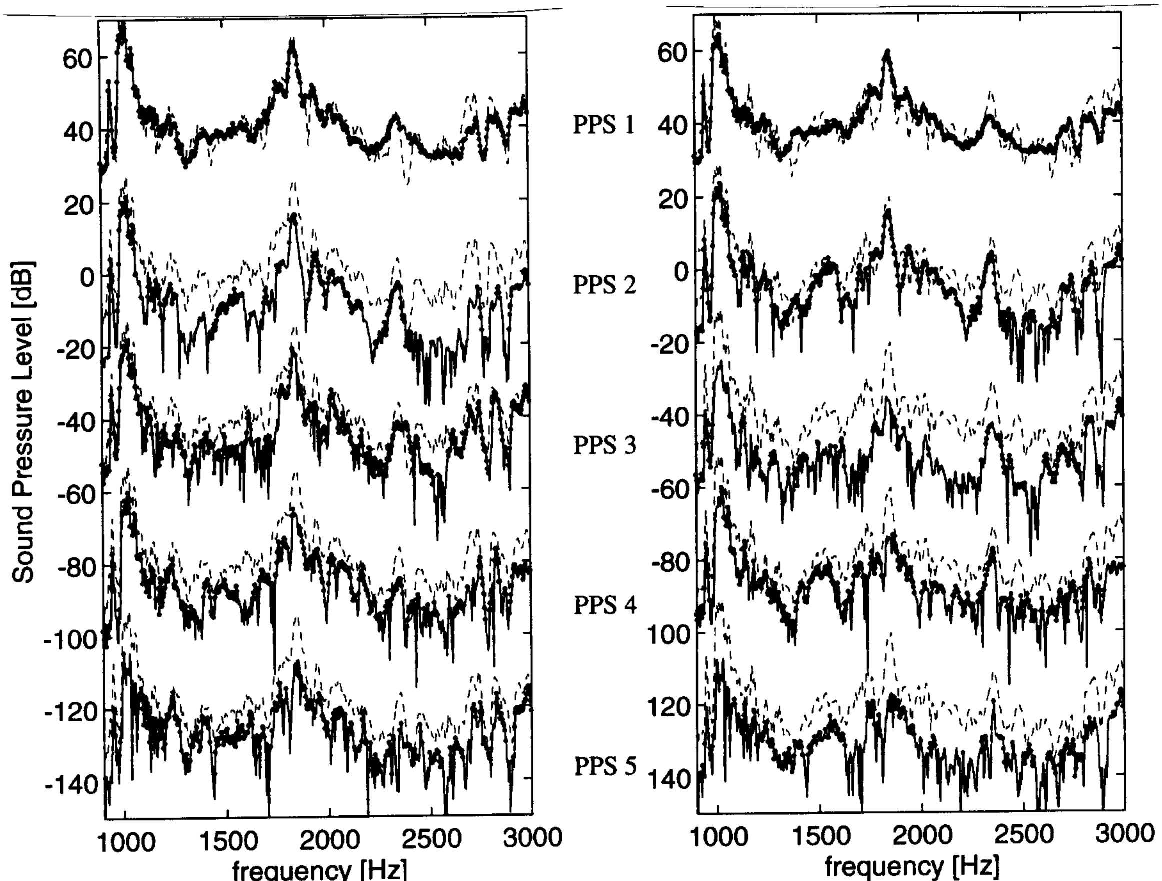


Figure 3 Sound pressure spectra due to ABC excitation (----) compared with PPS 1 to 5 (—). Level differences less then 10 dB between the PPS and the measurement results are marked with a dot. The PPS are separated with 40 dB and all are compared with the reference sound pressure level. **a)** left position **b)** right position.

Figure 4 shows the reference sound pressure level in both right and left positions, due to A, BC and ABC excitations, compared with the most proper PPS combinations. The differences between the sound pressure spectra in left and right position, especially at 1852 Hz, 1948 Hz, 2352 Hz and 2700-2750 Hz, indicate acoustic interference due to a multiple-pole radiation behaviour. This can also be seen in the PLS model, where the left sound pressure spectrum can be described by combining PPS 1, 3, 4 and 5. The right spectrum, on the other hand, can be described by PPS 1, 2, 4 and 5.

A description of the phenomena related to BC excitation is expected to be found in the lower order PPS, since it is the dominating source. Phenomena related to A excitation are therefore expected to be represented by higher order principal components. It can be seen that the results due to BC excitation are well described by PPS 1 & 3 (left) and PPS 1 & 2 (right). In case of A excitation the most proper combination is PPS 1, 4 & 5 (left) and PPS 2, 4 & 5 (right). The spectrum due to A excitation is not very well described by the model, except at the frequencies where A is the important source, e.g. the important frequency 2352 Hz.

In a normal measurement situation, however, the information about the excitation sources is not available. To determine if a principal component describes a physically independent phenomena, a more detailed analysis of the narrow band data is required. For this purpose, the PPS are combined to give the best possible estimate of the reference sound pressure spectrum around the frequencies of interest. The combinations of principal components for a certain frequency are then interpreted by observing the corresponding principal intensity vector field (PIV). The following analysis are concentrated on the frequencies 1024, 1852 and 2756 Hz, where BC excitation dominates, and at 2352 Hz, where A is the important source.

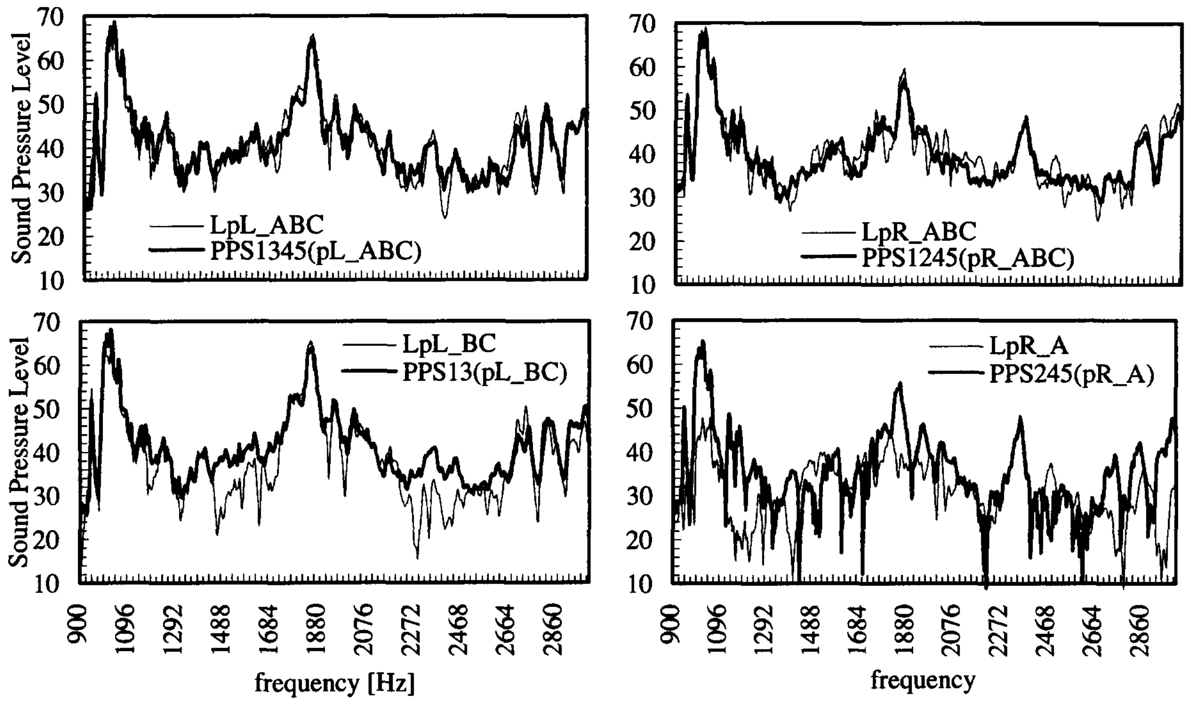


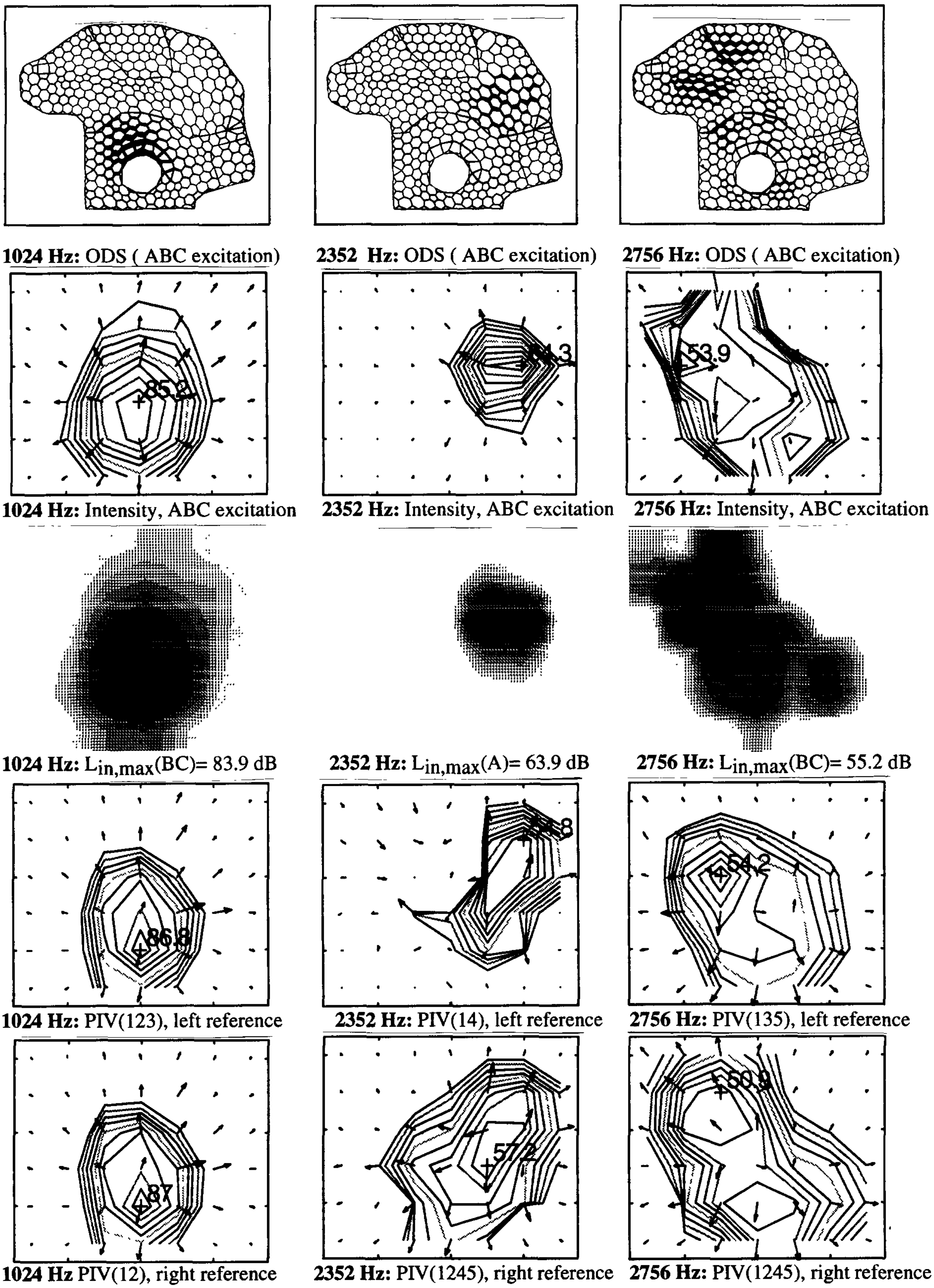
Figure 4. Comparison between the best possible PPS combinations and the measured sound pressure levels in the reference positions (LpL or LpR) due to different excitation signals.

The following analysis is divided in two parts, (1) independent or partly coherent sources and (2) decomposition of the sound field.

Detection of independent or partly coherent sources: To see in what extent independent sources can be detected, the PIV's at the frequencies 1024, 2352 and 2756 Hz are compared with the intensity and ODS measurements, see Figure 5. At *1024 Hz*, the left sound pressure level is described by combining PPS 1, 2 & 3, and the right signal is described by PPS 1 and 2. At *2352 Hz*, the left position is described by PPS 1 & 4, and the right position is described by PPS 1, 2, 4 & 5. The fact that 1024 Hz is described by components of lower order than 2352 Hz indicates that these two frequencies are independently excited. At *2756 Hz*, the situation is more complex since there is a great difference between the reference sound pressure levels. At this frequency the main difference between the principal components is related to the difference between left and right position. The left reference level is described by a combination of PPS 1, 3 & 5. The right reference is estimated by PPS 1, 2, 4 & 5.

In some cases, the PIV's are less detailed than the intensity measurement, which might be physically relevant since the PIV reflect the contribution to the far-field. The benefit of modelling the intensity field in relation to different reference positions is found at 2756 Hz, see Figure 5. The lower level in the right position is related to a PIV that looks like a dipole. The higher level in the left position is related to a PIV that shows a dominating pole. This result indicates that PLS regression gives a possibility to gain more information out of the measurement data.

Decomposition of the sound field: What information is found by a decomposition of the sound field? As an example, the most significant principal intensity vector fields at 1852 Hz are evaluated, see Figure 6. The comparison between ODS measurements and the PIV's indicates an enhanced possibility to detect sources of sound power radiation by a decomposition of the sound field. The best possible model of the intensity field at a specific frequency, independent of the reference signals, is found by adding all principal components.



1024 Hz: ODS (ABC excitation) **2352 Hz:** ODS (ABC excitation) **2756 Hz:** ODS (ABC excitation)

1024 Hz: Intensity, ABC excitation **2352 Hz:** Intensity, ABC excitation **2756 Hz:** Intensity, ABC excitation

1024 Hz: $L_{in,max}(BC)$= 83.9 dB **2352 Hz:** $L_{in,max}(A)$= 63.9 dB **2756 Hz:** $L_{in,max}(BC)$= 55.2 dB

1024 Hz: PIV(123), left reference **2352 Hz:** PIV(14), left reference **2756 Hz:** PIV(135), left reference

1024 Hz PIV(12), right reference **2352 Hz:** PIV(1245), right reference **2756 Hz:** PIV(1245), right reference

Figure 5. Intensity and ODS measurements compared to principal intensity vector fields (PIV). In the contour plots of the sound intensity level distributions, ΔL_{In}=1.0 dB. In case of A or BC excitation, only the normal intensity component is shown, and black indicates max intensity. Dark areas on the ODS measurements indicate high vibration amplitude.

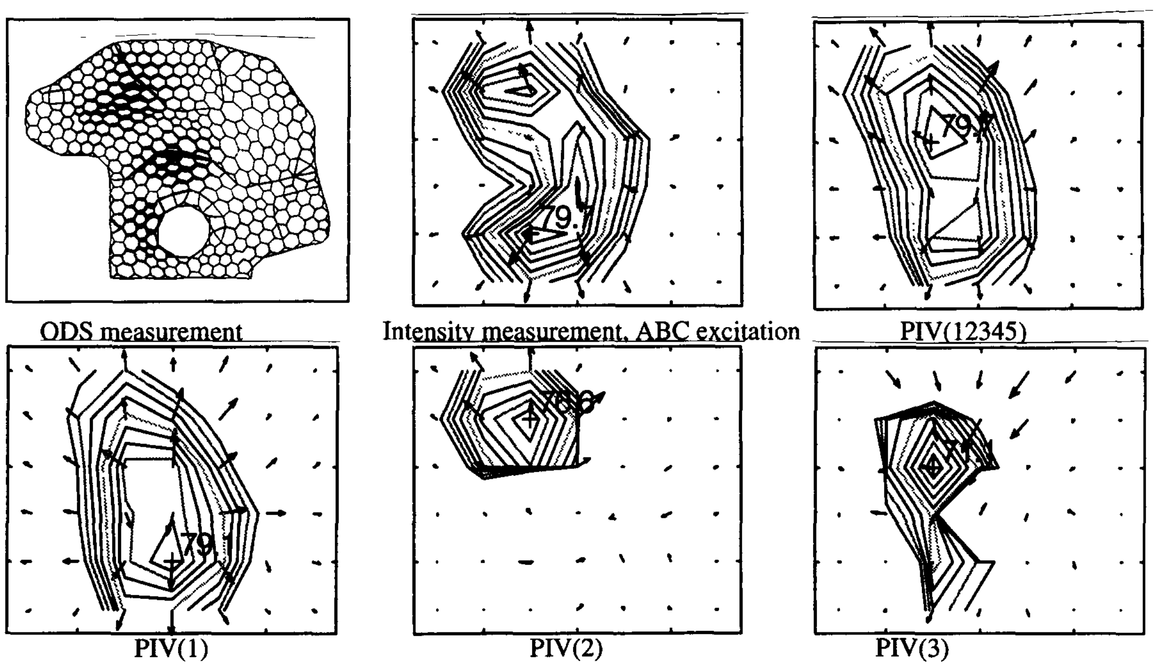


Figure 6 Principal intensity vector fields (PIV) at 1852 Hz compared with intensity and ODS measurement.

5. CONCLUSIONS

Partial least squares regression allows a decomposition of measurement data into a number of statistically independent spectra and models the near-field intensity contribution to a point in the far field. Describing the results by principal pressure spectra and corresponding principal intensity vector fields gives a quick, but detailed overview of the result. The results also indicate a method that facilitates finding important clues to real independent phenomena in the sound field. The PLS model was improved by using a logarithmic transformation of the measurement data.

6. REFERENCES

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