Measurement of the frequency and angular responses of loudspeaker systems using radiation modes

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ABSTRACT

In this paper, the "radiation mode" (RM) method is applied to the measurement of the frequency response and directivity pattern of two loudspeaker systems. This approach is based on solving the discretized Helmholtz equation on the source boundaries to obtain an efficient expansion suitable to represent any field radiated by a source. Bookshelf and column systems have been tested. Results obtained with the proposed method are then compared to the ones given by two other methods: measurement in an anechoic room and boundary element computation based on the scanning of the membrane velocity. Results show a good agreement between the different methods. Pros and cons of the different approaches are then discussed as well as the possibility to use the "radiation mode" method in non-anechoic rooms.

1 Introduction

Accurate measurements of the frequency response and even more directivity pattern of loudspeaker systems can be time consuming and very difficult to achieve without a specific equipment. Performing free-field acoustic pressure measurements requires anechoic conditions that are barely affordable, especially at lower frequencies. For instance, anechoic room are very expensive and outdoor measurements are cumbersome (see [1] for more details). An alternative to direct pressure measurements consists in measuring the velocity field on the speaker membrane and the box, to be used as the input data for numerical radiation computations. This allows to obtain exhaustive spatial information but requires a large amount of data to get reliable results at higher frequencies, and the results may be very sensitive to the loudspeaker mesh. Moreover, the velocity field must be measured contactless, *eg* by a scanning laser vibrometer which price is still quite high. Conversely, estimation of the radiated pressure may be obtained easily at lower frequencies by computing the velocity of the loudspeaker diaphragm through the "Thiele/Small" electroacoustic model [2]. This is however limited to the "piston" behavior of the membrane, excluding medium and higher frequencies, and giving no reliable information about directivity.

In this paper, we propose a method combining a limited number of cheap pressure measurements with an affordable numeric tool, allowing to estimate both frequency and angular responses over a wide frequency range. This method relies on the independent radiation solutions (usually called "radiation modes") of the source. They are computed numerically and used as an expansion series, whose coefficients are identified from pressure measurements in the vicinity of the source. The "radiation modes" (RM) series can be truncated to its most efficient terms, resulting to a short expansion which can be identified using a small number of measurements.

This approach is briefly described in section 2. Two examples are then presented. The first one, a classical "bookshelf" design is presented in section 3. It allows to illustrate the use of the "radiation modes" method and compares it to other methods. A second example, based on a "column" design, is considered in section 4. It allows to point out some limitations of the proposed approach. Section 5 gives a summary of the pro's and con's of the current method, and its potential improvements.

2 Radiation modes (RM) method

The "radiation modes" (RM) method is inspired by the IBEM-NAH technique regularized by SVD proposed by Veronesi and Maynard [3]. It has recently been suggested as a measurement method of the noise radiated by large transformers in power substations, where usual measurements are quite unconvenient [4]. It has then been proposed for measuring a small loudspeaker box, including a first comparison with measurements [5]. As more details may be found in these references, the method is only briefly described thereafter.

2.1 BEM pressure Computation

The pressure radiated by a vibrating object of surface S can be calculated from the following integral formulation [6, 7]:

$$p(\mathbf{x}) = \int\limits_S \left(\frac{\partial G}{\partial n}(\mathbf{x}-\mathbf{x}_s)\, p_s - G(\mathbf{x}-\mathbf{x}_s)\frac{\partial p_s}{\partial n} \right) dS \quad (1)$$

where $\mathbf{x}$ is the location of a point anywhere outside S, $\mathbf{x_s}$ is the location of an element dS of S, $p_s = p(\mathbf{x}_s)$ is the parietal pressure at $\mathbf{x}_s$ and ∂n denotes the normal derivative on dS. Assuming the $e^{-j\omega t}$ time convention, the Green function in the 3D space G is

$$G(\mathbf{x}-\mathbf{x_s}) = \frac{1}{4\pi}\frac{e^{jk|\mathbf{x}-\mathbf{x_s}|}}{|\mathbf{x}-\mathbf{x_s}|}$$

Equation 1 may be extended to the surface S, thus relating the pressure on S to its derivative, *ie* to the normal component of the vibration pattern over the object surface. There is no closed-form solution for this integral equation, but it can be solved numerically by discretizing the source surface with an adequate mesh of the surface S. A simple way is to assume that the pressures and velocities are constant over each mesh element, so the formulation 1 may be reduced to the following matrix form [8, 9] :

$$\frac{1}{2}\mathbf{p_s} = \mathbf{M}\mathbf{q_s} - \mathbf{D}\mathbf{p_s} \quad (2)$$

where $\mathbf{q_s}$ is the discretization of the normal component of the vibration pattern over S. The pressure over S can then be expressed as $\mathbf{p_s} = \mathbf{Z}\mathbf{q_s}$, where the impedance matrix $\mathbf{Z}$ is computed as:

$$\mathbf{Z} = \left[\frac{1}{2}\mathbf{I} + \mathbf{D}\right]^{-1}\mathbf{M} \quad (3)$$

where $\mathbf{I}$ is an identity matrix. Most of the computational effort is here devoted first to compute the singular integrals over elements when building the matrices $\mathbf{M}$ and $\mathbf{D}$, and then for the inversion required by eq. 3.

Classically, a discretized version of equation 1 then allows to compute the pressure at locations $\mathbf{x}$ from the pressure p_s on elements dS. This is straightforward as it involves no singularity, and is the result provided by most commercial BEM computer codes.

2.2 Expansion of the impedance matrix

For expressing the "radiation modes", we start from the impedance matrix $\mathbf{Z}$ defined by eq. 3, which is independent of the actual vibration pattern. It may be expanded trough a singular value decomposition (SVD). Each resulting singular vector corresponds to a separate radiation problem - hence the name "radiation modes" (RM). In general, all terms of the $\mathbf{Z}$ matrix have complex values, and the expansion requires a huge number of terms. The present approach assumes that the pressure measurements as well as the reconstructed pressure are in the far-field, where only the propagative terms are significant. These pressures then only depend on the real part of the surface impedance. Its imaginary part describes the evanescent field close to the object, which can be neglected further away. The "radiation modes" can therefore be calculated by SVD of the real part only of the impedance matrix :

$$\Re(\mathbf{Z}) = \mathbf{U}\Sigma\mathbf{V}^* \tag{4}$$

where **U** and **V** are sets of vectors corresponding to the pressure and the volume velocity of each element respectively, and Σ is a diagonal matrix composed of positive real values that represent the radiation efficiencies of each "mode".

Most SVD algorithms compute the singular vectors in decreasing order of importance, allowing to truncate easily the series by keeping only the most efficients radiating modes. Moreover, the number of efficient terms is much lower when expanding the real part of **Z**, especially at lower and medium frequencies. This is the key to the small number of terms required by the "radiation modes" method when all pressures are considered in far-field. Practically, the required distance is rather small compared to the dimensions of the source [10], which allows to make pressure measurements in the vicinity of the loudspeaker.

2.3 Expansion coefficients

The truncated "radiation modes" (RM) series may be used to expand the pressure field radiated by the loudspeaker at any location around the source. This requires however to determine the coefficients associated to each RM, which should be done from pressure measurements for the sake of simplicity and lower cost. The RM build a basis of the vector space that span the pressure or volumic velocity over *S*, but has no such property for the pressures outside *S*. Their coefficients may however be determined through an inverse problem using the transfer matrix $\mathbf{H_i}$ relating the RM patterns over *S* (considered as vibration patterns) to the corresponding pressure at the identification locations around the source. The simplest way to obtain the coefficients $\mathbf{d_i}$ associated to each term of the decomposition is thus by using the Moore-Penrose pseudoinverse of $\mathbf{H_i}$:

$$\mathbf{d_i} = \frac{\mathbf{H_i^*}}{\parallel \mathbf{H_i} \parallel^2}\mathbf{p_i} \tag{5}$$

where $\mathbf{p_i}$ is the pressure measured at some arbitrary locations around the source. Using the pseudoinverse requires very little computation time, but may lead to unaccurate results when the condition number of $\mathbf{H_i}$ is large, as it amplifies even small errors of the measurements $\mathbf{p_i}$. A simple regularization method consists in truncating the expansion to the *N* the most efficient RM, where *N* is chosen according to the desired accuracy (*eg* by keeping, say, 98% of the cumulated efficiency in matrix Σ). Equation 5 is thus restricted to rank *N* when computing $\mathbf{d_i}$.

The pressure field can then be expressed anywhere in far-field as the superposition of these *N* most efficient radiation modes, weighted by their coefficients $\mathbf{d_{i_N}}$:

$$p_c = \mathbf{H_c}\mathbf{d_{i_N}} \tag{6}$$

where $\mathbf{H_c}$ is the transfer matrix relating the RM patterns over *S* to the corresponding pressures at the target locations, similarly to $\mathbf{H_i}$.

Although the above equations may seem somewhat complicated at first glance, they involve only very classical algebra, which may be implemented using available computer libraries. For this work the "radiation modes" and their corresponding $\mathbf{H_i}$ + $\mathbf{H_c}$ matrices were computed using a custom BEM code developed at LMA, dedicated to field expansion ("FELIN" : Field ELement INdependence). Although not optimized for speed, it requires typically a few minutes computation time using a current PC. A similar option in commercial software should run faster.

2.4 Dealing with wide frequency ranges

A major drawback of BEM methods is that almost all computations must be performed for each frequency. Wide-band measurements thus imply a high computation cost - especially if a good frequency resolution is desirable. Moreover, the mesh should be optimized for each frequency, or at least by frequency bands. Commercial BEM code may implement interpolation techniques [11], or fast multipoles techniques [12], but this leads to a much more complex code.

In the RM approach considered here, a simpler way to deal with numerous frequencies is to use the "nesting property" which allows computing expansion coefficients at a given frequency while using a RM series computed at a higher frequency [13]. It is thus possible to compute RM's at a limited set of frequencies evenly spaced over the required frequency band, although computing expansion coefficients with a much better resolution. Figure 1 depicts the estimation of the pressure radiated by the bookshelf speaker system (which will be described in the section 3). The pressure estimated by computing coefficients between RM's frequencies (green dashed curve) allows a good accuracy comparing to measurement (black curve) and to the pressure estimated in the RM's frequencies only (red dashed/circle curve), although this does not significantly increase the CPU time.

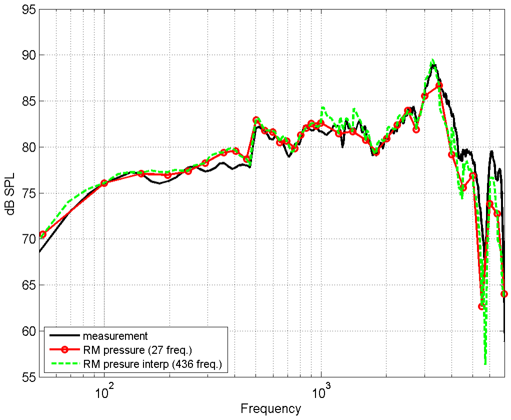


Fig. 1: Wide band computations : at RM frequencies only (red); expansion between RM frequencies (green)

3 Example 1 : bookshelf loudspeaker

As a first example, we consider here a custom made bookshelf enclosure (42 × 24 × 34 cm) equipped with a Monocor SPH-8M-8 boomer of nominal diameter 22 cm (see figure 2, left).

This enclosure is a coarse mock-up which lacks the two- or three-way setup typical of such a system, and does neither feature a port. It was built from 22 mm thick medium density fiberwood with internal bracing, to minimize any parasitic vibration of its walls. This configuration was designed for maximal accuracy when measuring its vibration pattern.

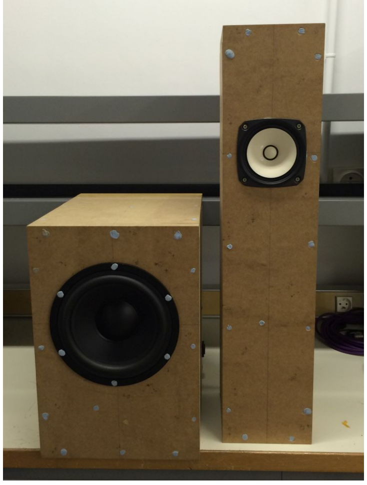


Fig. 2: Bookshelf and column speaker systems

3.1 Measurements

The membrane velocity was measured using a Polytech PSV500 H scanning vibrometer at 1713 nodes distributed as 24 concentric circles over the diaphragm. The maximum spacing between measurements over the diaphragm was about 5 mm. In order to grasp enough details of the actual vibration pattern for accurate BEM computations, the nodes density was reinforced at zones with more elaborate geometry (suspension, dust cap).

To reconstruct the pressure with the "radiation modes" method, 90 arbitrary points $\simeq$ 20 cm away from the enclosure surface were chosen from preliminary simulations. Their exact locations did not seem important, provided there are measurements all around the enclosure with roughly the same distances between them.

Pressure measurements were performed in the LAUM anechoic room (figure 3). Its size is 4.9 × 3.9 × 3.6 m between wedge tips, with a cut-off frequency around 70 Hz. Some fixed structure elements surrounding the setup were covered with lining material to avoid corrupting the measurements by an eventual parasitic diffracted field. A grating had to be left for the operator's access, and was partially covered with absorbing material during each measurement.

Pressure were recorded by moving a single microphone along all locations, thus avoiding any calibration issue. Far-field measurements were performed for the purpose of comparison between all methods: they involved 37

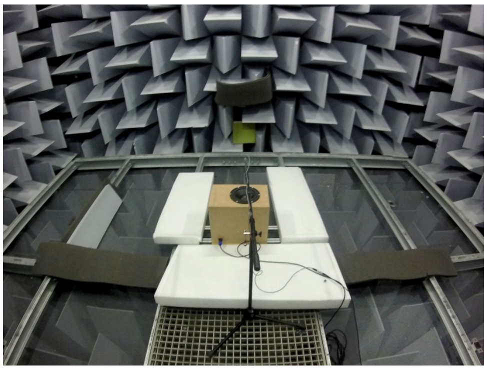


Fig. 3: Pressure measurements in the anechoic room, LAUM

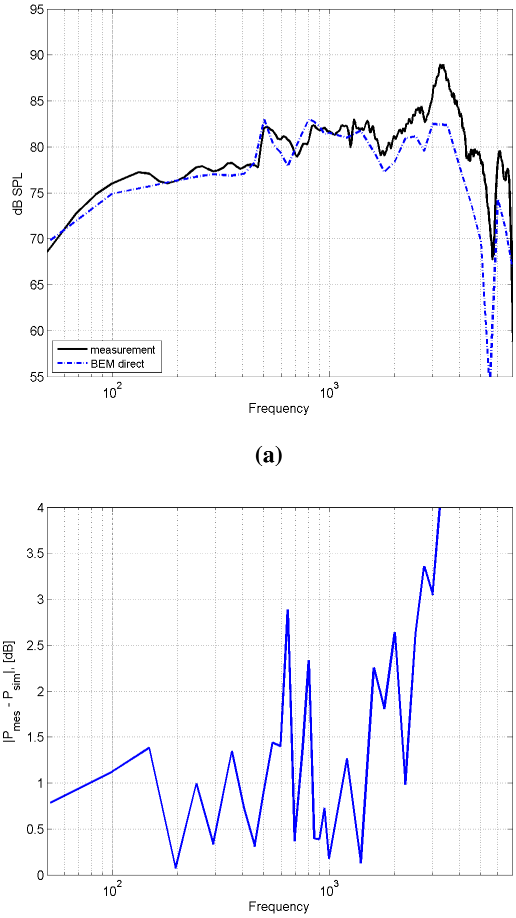
locations evenly placed on a circle around the box, in a plane including the loudspeaker axis and centered in the middle of the box. The circle radius was fixed to 1.19 m, so that the on-axis distance from the box front wall is 1 m.

For locations close to the enclosure, a positioning tool has been designed to allow fast and accurate positioning: a lightweight microphone support was fitted on the enclosure and moved over it. For that purpose, each wall (except the rear one) was in turn set horizontally, facing upward. This setup ensured a well-known distance between the enclosure walls and the measurement points.

3.2 Simulation using a BEM model

As a first step, we used our BEM code to compute the pressures at the same locations as the measurements. For that purpose, the vibration pattern $\mathbf{q_s}$ was obtained from the velocities measured over the membrane using the Polytec®vibrometer, assuming a rigid (non-vibrating) boundary over the remainder of the enclosure. The loudspeaker system was discretized as a mesh featuring 8512 triangular elements. The largest element size of this mesh is about 2 cm, which normally limits the validity of the simulation to frequencies below 1.7 kHz (based on the author's experience, a minimum of 10 elements per wavelength is required for such a direct BEM model).

A first comparison is shown by figure 4a, representing the sound pressure level (SPL) in dB at 1 m on the axis of the loudspeaker. The difference between the BEM computation (blue curve) and the measured pressure (black curve) is emphasized by figure 4b.



(a)

(b)

Fig. 4: (**a**): On-axis SPL : measurement (black) and BEM computation (dash/dot blue)
(**b**): Difference between measured and computed SPL in dB

The frequency resolution of the BEM computation has been kept to a minimum because of the CPU time involved. It already allows to see that the computation results are quite close to the pressure measurements up to about 1.5 kHz (typically 1.5 dB discrepancy). For higher frequencies a refined mesh would anyway be needed. The main trends are however reasonably described up to about 5 kHz, but with a much lower accuracy.

We feel that a great part of the computation inaccuracy results from difficulties to focus the vibrometer laser over the black surface of the loudspeaker diaphragm, although it is claimed to be adequate for such situations. This is an additional drawback of such a method : it requires numerous accelerations measurements, several of which must be repeated depending of unpredictible optical conditions.

3.3 Estimation using the "alpha" method

One classical way to mix a model with measurements is the so-called "alpha" method. Its principle is to use a simple model to compute on-axis response $P_{sim}(R_1)$ at a short distance ($R_1 = 20$ cm in our example), measure the actual pressure $P_{mes}(R_1)$ at the same distance, and use this measurement to estimate the pressure $P_{est}(R_2)$ further away ($R_2 = 1$ m in our example). A correction ratio α can be determined as :

$$\alpha = \frac{P_{mes}(R_1)}{P_{sim}(R_1)}$$

This requires a single measurement in the vicinity of the loudspeaker, avoiding the use of a large measurement room. The estimation at distance R_2 is then obtained from the simulation $P_{sim}(R_2)$ at the same location :

$$P_{est}(R_2) = \alpha P_{sim}(R_2)$$

In the case of a monopole in free-field, this is equivalent to applying a $\alpha = R_1/R_2$ factor. Considering the finite size of the diaphragm greatly improves the initial simulation; this is simple by considering a piston over an infinite baffle. Many simulation tools already provide such a simulation, usually coupled with the Thiele/Small model of the loudspeaker. Dealing with the finite size of the enclosure requires switching to a BEM model, either keeping the piston assumption, or considering the actual (measured) velocity.

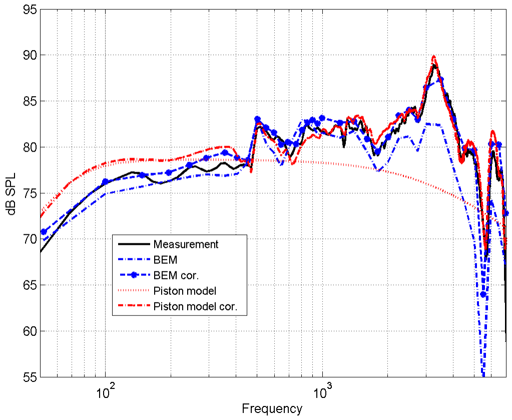


Fig. 5: Pressure radiated : measurement (black); piston model (dotted red); corrected piston (dashed red); BEM model (dash/dot blue); corrected BEM (dashed + markers blue)

Figure 5 shows two examples of the "alpha" method. The measured pressure at 1 m is the black curve. The "piston+infinite baffle" simulation corresponds to the red curves; the dotted one is the bare simulation, and the dashed one the simulation corrected by α. The blue curves use the full BEM model described in section 2.1. Note that the frequency resolution is lower, but could be improved. The dash/dotted curve is the direct BEM simulation using the measured velocity (same as figure 4). The dashed curve with markers is an "hybrid BEM/alpha" method, where BEM results computed from velocity measurements are corrected from a pressure measurement.

This example shows that the "alpha" method seems quite efficient for on-axis measurements. Spatial behaviour depends on the underlying model : it only improves the axial response. Good spatial results require BEM computation, exhaustive velocity measurements, and at least one near-field pressure. This seems to be the best we can get from a BEM model, whose robustness is greatly improved by the single pressure measurement. This motivated our interest for the RM method, which can somewhat be considered as a generalization of the "alpha" method for 3D estimation.

3.4 Simulation of the RM method

We consider now a simulation of the RM method : in this section the pressure is estimated at 1 m on the axis of the loudspeaker using the RM method and identification pressures computed by BEM simulation. This allows to assess the basic principle of the method, avoiding any measurement problem as all pressure data are computed from a single dataset through the same BEM model. The result is presented on figure 6.

Figure 6 shows a very good agreement between the target pressure (black curve) and the calculated one (red

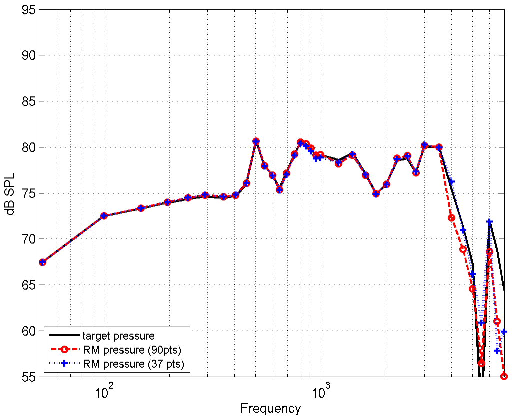


Fig. 6: Simulation of the pressure radiated by the bookshelf enclosure by the "radiation modes" method

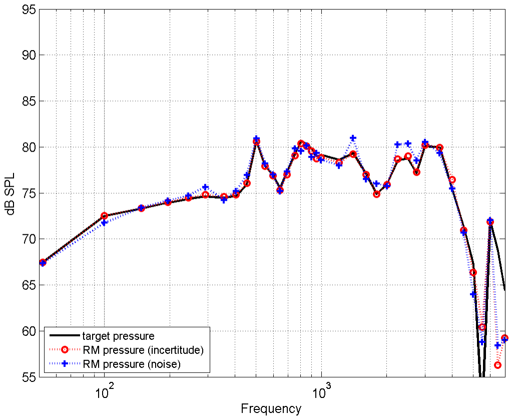


Fig. 7: Influence of measurement errors on the "radiation modes" method : 5 mm location error (red / circles); 30 % noise (blue / crosses)

dotted curve). This curve was obtained using all the 90 locations selected for "the virtual pressure measurements" (red dotted curve with round markers), but the number of these locations can be significantly reduced while keeping a very good accuracy. We found that 37 locations are sufficient for practical purposes (blue dotted curve with cross markers in figure 6).

Obviously this result is quite optimistic as actual measurements involve many errors. Therefore, two additional simulations were performed, still with 37 identification locations:

- 5 mm error was introduced into the identification locations (red circles on figure 7);
- 30 % random noise was introduced into the "virtual measurements" (blue crosses on figure 7).

Figure 7 shows that a 5 mm position has a marginal influence on the RM identification accuracy, but the method appears to be more sensitive to additive noise.

3.5 Estimation using RM and nearby measurements

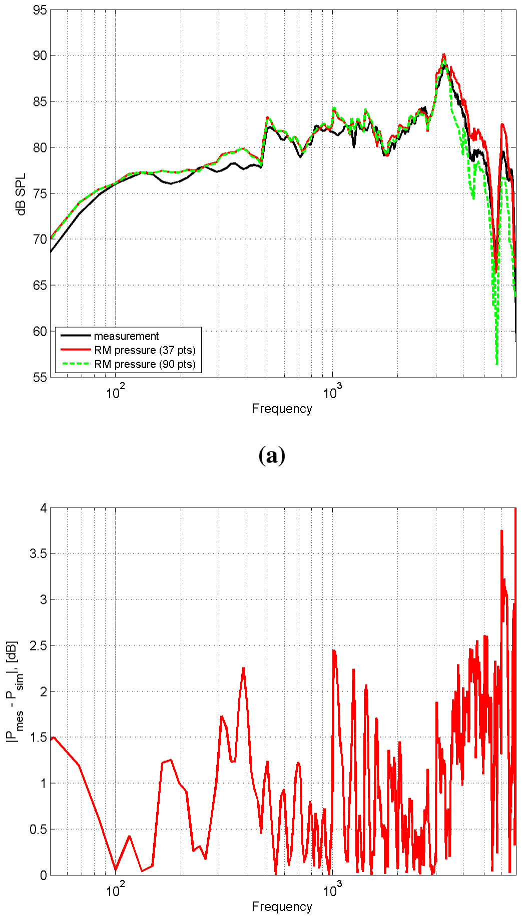
The RM series coefficients are now identified from actual nearby pressure measurements, and the resulting estimation of pressure is compared to the actual far-field pressure measurements. This is shown by figure 8a and the difference between measured (black) and calculated (red/dotted blue) SPL in dB is emphasized by figure 8b.

The RM pressure estimation computed from 90 arbitrary measurements at 20 cm from the enclosure (8a dashed green curve) leads to slightly lower discrepancies and a quite wider frequency range than the BEM direct calculation (compare with figure 4b). Moreover, reducing the number of measured locations to 37 (8a red curve) does not degrade significantly these performances.

However, a great care was necessary when performing the identification measurements. We observed that measurement noise has an obvious effect on estimation accuracy, emphasizing the concern about regularizing the inversion mentioned in section 2.3.

3.6 Directivity

Far-field on-axis measurements may be obtained by simple methods, so this sections illustrates how the RM method allows to get spatial informations. Figure 9 shows the directivity of the loudspeaker system, estimated at 805 Hz and 1398 Hz. The black curve are actual measurements in anechoic room, while the blue ones are obtained from the BEM simulation using the 1713 velocity measurements provided by the scanning vibrometer. The red curves are obtained with the RM methods, based on 37 pressure measurements in the vicinity of the enclosure.

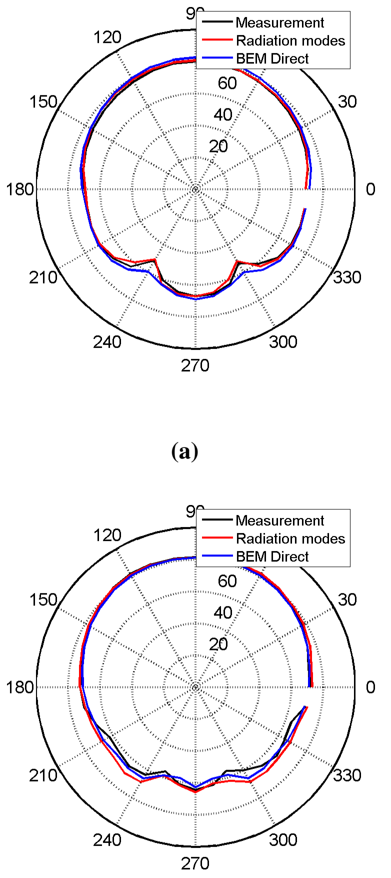


(a)

(b)

Fig. 8: (**a**): "Radiation modes" pressure reconstruction – black: measurement; red: reconstruction from 37 points; green: reconstruction from 90 points (**b**): Difference between measured and computed SPL in dB

At 805 Hz both the BEM simulation and the RM estimation agree well with the directivity measurement, but the RM estimation provides a slightly better accuracy at angles with minimum angular response. At 1398 Hz, the two methods provide similar results, still close to the actual measurements.



(a)

(b)

Fig. 9: "Radiation modes" directivity reconstruction: black: measurement; red: reconstruction from 37 measurements; blue: reconstruction from direct BEM computation using measured acceleration
(**a**): at 805 Hz; (**b**): at 1398 Hz

4 Example 2 : Column loudspeaker system

Some limitations of the RM methods in its present form are now illustrated by considering the second loudspeaker box shown by figure 2. It is the mock-up of a column enclosure (19 × 75 × 16 cm) loading a FE126En Fostex loudspeaker (diameter 9 cm). Construction details are the same as for the previous example.

The corresponding BEM model involves a mesh featuring 2889 elements whose largest element size is again about to 2 cm. Velocity measurements have been performed at 1106 membrane nodes (this smaller number results from the diaphragm size; measurement density is equivalent). For this second example, the white color of the loudspeaker diaphragm improves the laser focusing, leading to more reliable results.

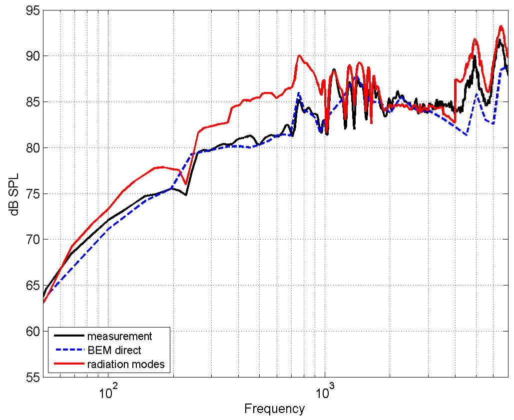


Fig. 10: Column enclosure on axis : measurements (black); BEM simulation (magenta); RM method (red)

Figure 10 presents on-axis measurements (black curve), compared to BEM simulation based on velocity measurements (magenta curve) and to estimation by the RM method (red curve). The BEM simulation seems to have almost the same performance than for the first example, with a somewhat wider frequency range.

Conversely, the RM method performance is here disappointing, with large discrepancies even at lower frequencies, although red curve in figure 10 is obtained from 88 pressure measurements at 30 cm away from the enclosure. It should however be noted that many "small scale" trends of the frequency response are present in the RM identifications, which seems biased by a superimposed "large-scale" parasitic term. This point is discussed in the next section.

5 Discussion

Loudspeaker measurements is a difficult task when a wide-range response is needed, especially at lower frequencies. Is is even more challenging if directivity data is mandatory, involving a great number of pressure measurements in 3D, especially at higher frequencies. Standards require to perform measurements in free-field, which is best approximated by an anechoic room. This is a very expensive equipment, especially for measurements at lower frequencies and in far-field. Our goal in this paper is to propose a method allowing to use pressure measurements close to the loudspeaker system, in order to estimate of the pressure radiated in far field. This method is also based on pressure measurements only, as this may be quite inexpensive.

When only the on-axis response is needed, cheap alternatives exists, such as the "alpha" method proposed in section 3.3. If more accuracy is needed, a BEM model using vibration measurements may be considered (see section 2.1, and the two previous methods may even be combined into a hybrid "BEM-alpha" method - at the cost of vibration and pressure measurements, combined with a wide-band BEM model.

If spatial information is needed, the BEM model may be used again, and gives satisfactory results provided an adequate mesh is used, and with a significant computational effort. The major part of the measurement cost is still the vibration measurement, as a huge volume of data is required to describe the small-scale patterns involved in the vibration of a loudspeaker diaphragm. Even if a scanning vibrometer is available, the measurement may not be that easy, depending of the finish of the diaphragm among many factors.

The RM method proposed here can be considered as a trade-off between accuracy and cost when spatial information is needed. Requiring a few pressure measurements but no vibration measurements, it may be quite fast if a modular microphone grid is used. Using the technique proposed in section 2.4, the BEM computation time is lower than a direct BEM computation. It gives reasonable accuracy all around a radiating object, providing high-resolution directivity data in 3D.

However, this method is not yet ready to use. All the required tools are almost a hand (only the RM option has to be added to usual BEM codes) and it seems already efficient for large industrial vibrating objects [4], but some work is still needed to adapt the method to loudspeaker systems, as illustrated by the example of section 4. The specificity of loudspeaker systems is that the radiating vibration pattern is almost restricted to very small parts of the object surface : loudspeaker diaphragms, ports, etc. The RM series described in section 2 is optimal to describe a vibration pattern evenly distributed over the whole surface of an object, but is much less efficient when a high local velocity contrast is involved. This is emphasized by our "column" and "bookshelf" examples, with respectively about 4.51 and 12.90 % of their surfaces actually vibrating.

The RM series could indeed be used "as is" by increasing its number of terms; this would however require a higher number of pressure measurements to be able to identify the expansion coefficients. Apart for the increased measurement cost, it would increase the condition number of the transfer matrix, requiring sophisticated regularization techniques - with a probable loss of robustness to noise. A better option seems to adapt the RM series, by limiting the spatial extent of the RM series to the radiating parts of the enclosure surfaces. This option is not a major upgrade, and we are now in the process of implementing it into our custom code.

We expect this option will allow to deal with our column loudspeaker system with the same performance level as the bookshelf one, and possibly improve results for both cases. It is also expected that the better condition number resulting from a more suited expansion series will improve the robustness of the RM method. This might relax the need for an anechoic room: a room with reasonable damping allows to perform good measurements in the vicinity of the loudspeaker system, as they benefit from the predominance of the direct field in the total measured pressure. However, this does not seem sufficient for accurate estimation with the RM method using overall RM series, except for very compact loudspeaker designs.

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