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Noise source characterisation using patch impedance technique

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A novel approach of an environment-independent sound source characterisation is discussed. The source is defined via a suitable enveloping interface surface by its blocked sound pressure and its surface impedance. Both the blocked pressure and the impedance is made discrete using the averaging patch concept. Such a definition avoids singularity of point acoustic impedance and is suitable for numerical as well as experimental implementation. The characterisation of a source by the patch concept allows for the acoustical sub-structuring, which in turn enables the prediction of the sound field created by the source coupled to an arbitrary environment. Numerical simulations are presented which demonstrate the feasibility of the approach. It is hoped that the proposed approach can serve as a tool for noise synthesis of complex equipment incorporating noise sources.

1 Introduction

Characterisation of noise sources is an application area which is getting an increasing importance with respect to the practice of noise control. Usually a noise source is very difficult to caracterise by computation. Measurements can potentially offer a reliable characterisation, providing the precautions are taken to make sure the results are free from the influence of the surrounding space.

A source of noise usually emits noise directly in air but also indirectly, via structure-borne and fluid borne paths. While the characterisation methods of structure-borne sources, e.g. [1-7], and sources in ducts and waveguides; e.g. [8-14], have been dealt with to a fairly large depth, the general air-borne noise characterisation has received less attention, probably because the measurement of air-borne noise looks as a self-evident task.

Where the synthesis of noise is concerned, the source needs to be characterised in such a way to allow for the coupling with its surroundings. Usual noise measurement procedures are not adapted to such a characterisation. In particular, the sound power of a source is not a quantity which can be used for an intrinsic source characterisation with respect to its integration into a given sourroundings. Not only the sound power does depend on the sourroundings, contrary to what is ignored by many, but it also provides no information on the spatial directivity of the source.

A meaningful characterisation of an air-borne noise source can be accomplished using a theorem given in [15]. It states that the sound field of a system composed of two subsystems, one driven, the other passive, coupled through an interface surface can be represented as the sum of two simpler field components. The first component is the field with the interface surface blocked. This field creates a particular blocked sound pressure at the interface. The second component is the field of the coupled subsystems under the sole action of the blocked pressure of the first component.

Based on this result, a particular characterisation technique for air-borne noise sources has been conceived in [16]. It consists in defining the source in terms of an enveloping spherical surface. In order to be used, this technique requires a particular spherical chamber which represents a fairly severe practical constraint. This paper examines possibilities of formulating an alternative source characterisation procedure which could be achieved with moderate experimental effort.

2 Patch substructuring

If a noise source has to be characterised by some acoustical descriptor in a surroundings-independent way, any further use of such a descriptor has to go via a substructuring phase such that the sound field created by the source in a given environment could be predicted.

Substructuring is a well-known technique [17-18]. It is widely applied to vibration modelling of built-up systems. It can be used either as a computational or a measurement approach. In either of the cases the idea is to subdivide the entire mechanical system into several subsystems, identify the properties of each subsystem on its own and finally synthesise the behaviour of the assembly by respecting the continuity conditions at the subsystem interfaces.

In order to satisfy the continuity conditions, the concept of mechanical mobility is used providing the system behaves in a linear fashion. Alternatively the concept of mechanical impedance can be used, the two being fully equivalent [19].

As a rule, the interaction between subsystems will not be a local one, implying that a force by which one subsystem acts on the adjacent one will affect all coupling areas. The synthesis can be thus most conveniently done using a matrix formulation of subsystem coupling. This means that the substructuring approach will be well suited to cases where the subsystems are coupled via a discrete number of point connections. While a point connection is a theoretical concept which is never strictly valid, it can be applied with a fair degree of accuracy to mechanical systems, at lower frequencies where the structural wavelength is significantly larger than the coupling size.

The coupling of acoustical subsystems is conceptually far more difficult unless the acoustical state is uniform across the coupling area, as it is e.g. in waveguides in plane wave conditions. In acoustical modelling a point impedance or a point mobility represents a singularity which cannot be dealt with numerically in a straightforward manner. The air-borne characterisation method described in [16] uses a spherical surface as an interface where the source characteristics are given by surface functions: the spherical harmonics. While such a formulation certainly removes the singularity obstacle, it requires a specialist's knowledge which may make it unsuitable for wider use.

The present approach uses the concept of an enveloping surface to define the borders of the source-subsystem, but returns to the classical concept of impedance. To remove the singularity problem the coupling surface is discretised into patches. The sound impedance is accordingly defined for a pair of patches as the ratio of the patch-averaged sound pressure of one patch and the patch-averaged normal particle velocity of the other patch. The patch concept has been alredy defined in [20]. The present approach will follow this definition.

According to [16] the source will be characterised by its blocked pressure p_b and its impedance Z_{SS}, both relative to the coupling surface selected for source characterisation. If the number of patches is N, p_b will be a $N\times1$ vector and Z_{SS} a $N\times N$ matrix. The surrounding reception space will be characterised using the same coupling surface by a $N \times N$ reception-space interface matrix Z_{RR}. In such a case the coupling pressure p_c reads [16]:

$$p_c = Z_{RR}\left(Z_{SS} + Z_{RR}\right)^{-1} p_b \tag{1}$$

Once the coupling pressure has been found, the sound pressure p_r at K points in the reception space can be found using the $K \times N$ reception impedance matrix Z_{AR}:

$$p_A = Z_{AR}\left(Z_{SS} + Z_{RR}\right)^{-1} p_b \tag{2}$$

Eqs. (1) and (2) are in the frequency domain, meaning that the application of these equations has to be made frequency by frequency.

3 The approach

3.1 Substructuring demo example

In order to illustrate the acoustical substructuring principle a simple analytical one-dimensional example is provided below.

The source is represented by a 2 chamber volume driven by an oscillating piston. Due to compressibility of the air in the volume the source is of neither volume nor pressure type. The receiver is a straight 1m tube, closed at the outer end by a layer of mineral wool.

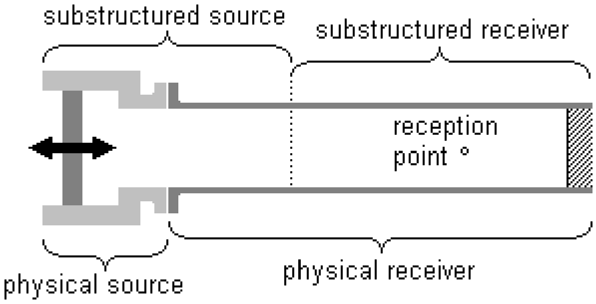

Fig. 1 The demonstration example.

In this example the lengths of the two source chambers are 0.1 and 0.12 m respectively, the second one having the surface of the cross section reduced by 30% with respect to the first one. The length of the receiver tube is 1m. The fluid in the system is air at 20°C.

The pressure at a reception point, placed 0.26m from the tube end, is obtained at first by a direct computation of the assembled system source-receiver, and then by a multi-step substructuring procedure via an interfacing surface placed at 0.31m from the tube opening.

Fig. 1 shows the moduli of the impedances of the physical components of the system and its substructured subsystems. The subsystems obtained by substructuring are seen to have properties which are significantly different from those of the physical components. The two computations produce nevertheless identical results, i.e. the reception pressure. The latter is seen on Fig. 2, along with the blocked pressure of the substructured source and the coupling pressure acting on the receiver subsystem. It thus follows that the notion of the source and the receiver used for substructuring is not physical but rather circumstantial. Of course, the interfacing surface between subsystems may coincide with the original interface between the physical components. However, such an interface will rarely be a surface of simple enough shape, while an interface exterior to the physical source can be made simple and thus preferred for practical reasons.

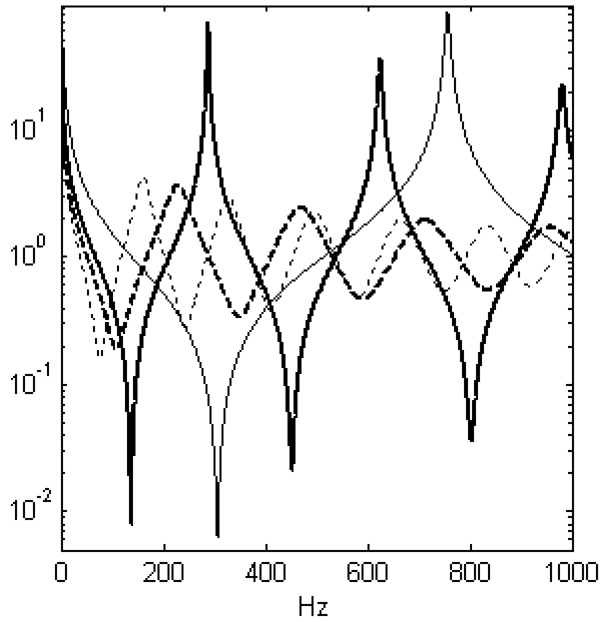

Fig.2 Impedances of the subsystems.
Full line: source, dashed line: receiver. Thin lines: original subsystems. Thick lines: substructured subsystems.

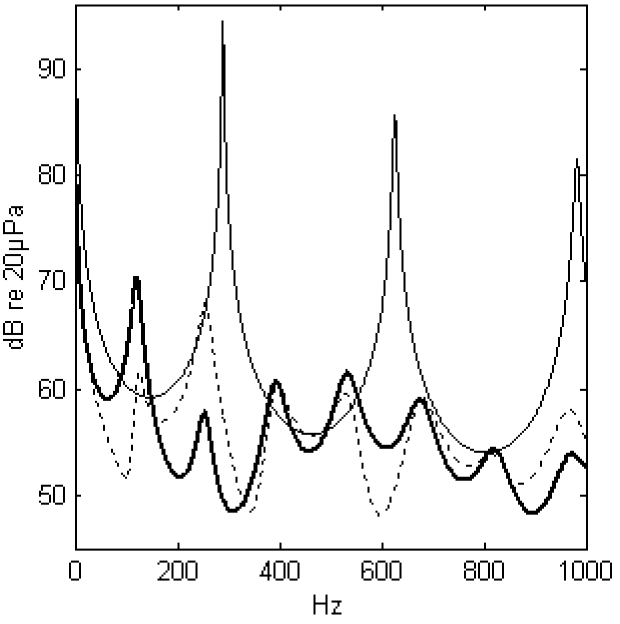

Fig. 3 The acoustical pressure in the system.
Thin line: blocked pressure of the source subsystem.
Dashed line: coupling pressure. Thick line: pressure at the reception point.

3.2 Numerical 3D analysis

A more realistic case will be considered next. The source was taken as vibrating box with round top. The enveloping interface surface was cylindric with a flat top, Fig. 5. The reception space was a room of the size 1.8m x 1m x 1m.

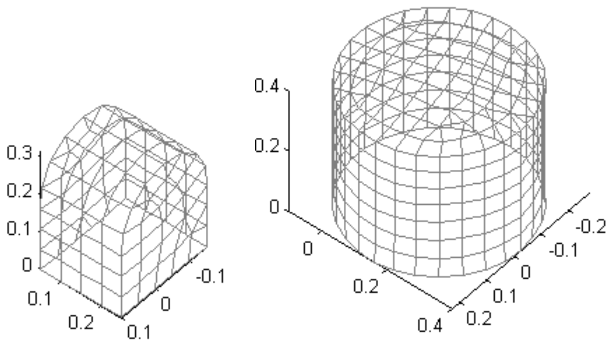

Fig. 4 Source geometry showing radiating patches (left) and interface surface showing coupling patches (right).

For the purpose of comparative analysis the sound pressure in several receiver points located in the reception space was computed first directly and then by patch substructuring, using a finite element code. The spatial averaging across the patches was achieved by a numerical technique based on Helmholtz equation and modal basis of the cavity with rigid walls. Pressure mode shapes have been extracted up to 2kHz and procedure presented in [20] has been used.

A number of cases was covered, with variations in source excitation distribution and interface patch configurations. Shown here will be the results for 3 types of box vibration: uniform (pulsation), oscillation (the pairs of opposite sides vibrate in anti-phase, the top is immobile) and randomly distributed across the box surface. The case where all of the 282 interface patches are employed for the substructuring will be considered as a reference. In all other cases the number of interface patches will be reduced in order to assess the role of substructuring simplifications to the accuracy of synthesis results. Out of 9 reduced patch configurations analysed 3 will be shown with the number of patches equal to 5 (2% of total number), 20 (7%) and 71 (25%), Fig. 5.

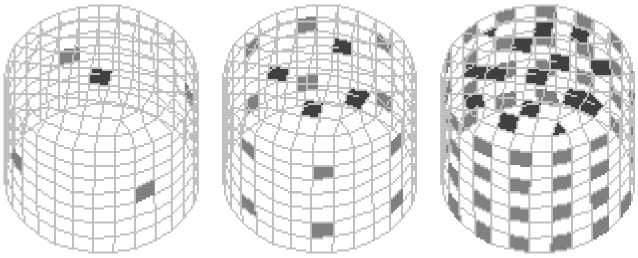

Fig. 5. Reduced patch configurations used for synthesis.

The comparison of narrowband pressure spectra at one of the reception points, created by the oscillating source, are shown on Fig. 6. The results for other analysed types of source vibrations and at other reception points are of similar nature and will not be shown in the narrowband format.

It can be seen that the matching between the substructuring synthesis and direct computation is rather poor at very low number of patches (5) but it gets acceptable even at a patch number as low as 20 - which involves 7% of the interfacing surface. Oddly enough, the matching is best when only 25% of the surface is involved, and then slighty drops when the whole surface is taken in account. This effect needs further examination.

It should be noted that the present comparisons show only the moduli of the computed sound pressure. The next plots will show the total difference between the two methods.

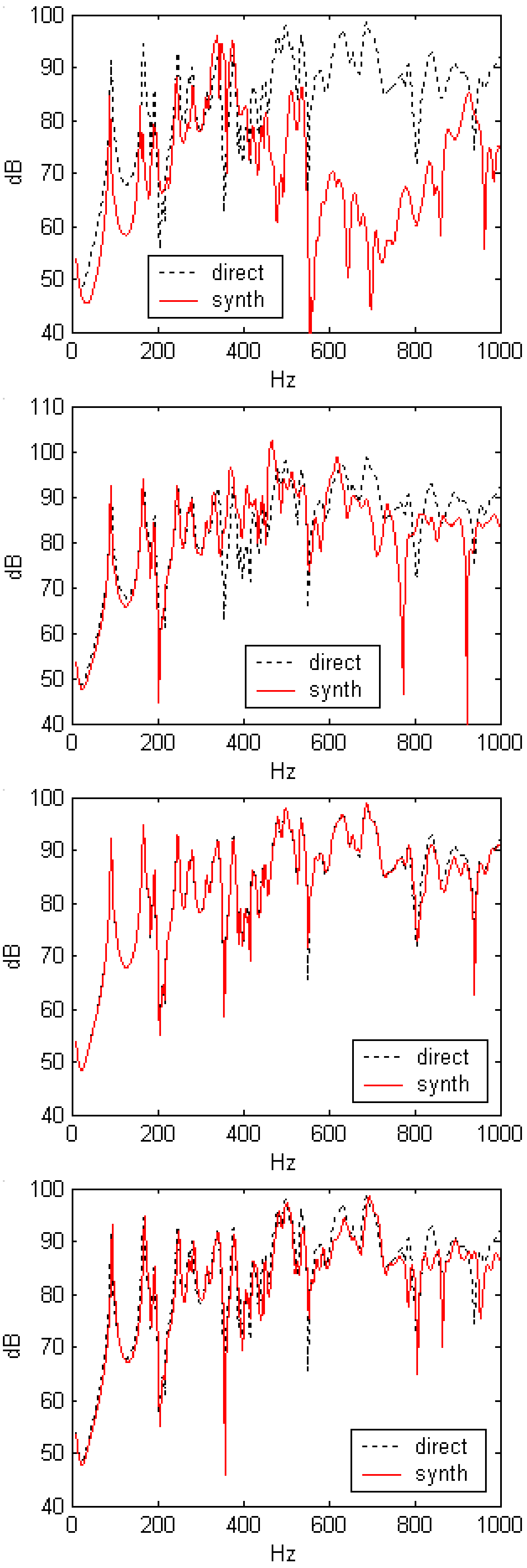

Fig. 6 Comparison of pressure spectra at the reception point. Full line: patch substructuring method; dashed line: direct computation. Interface patch configuration from top: 5 patches, 20 patches, 71 patch, all patches.

3.3 Substructuring error

The relative error of substructuring will be shown next. This error will be here defined at the absolute value of the difference between the values of (complex) sound pressure p obtained by substructuring and the pressure p_0 obtained directly, divided by the absolute value of p_0. For easier comparison the error will be averaged in octave frequency bands (denoted by triangular brackets):

$$\varepsilon=\sqrt{\frac{\left\langle\left|p-p_0\right|^2\right\rangle}{\left\langle\left|p_0\right|^2\right\rangle}} \qquad (3)$$

The averaged relative errors for the 3 source types and 4 of patch interface cases are shown on the plots below.

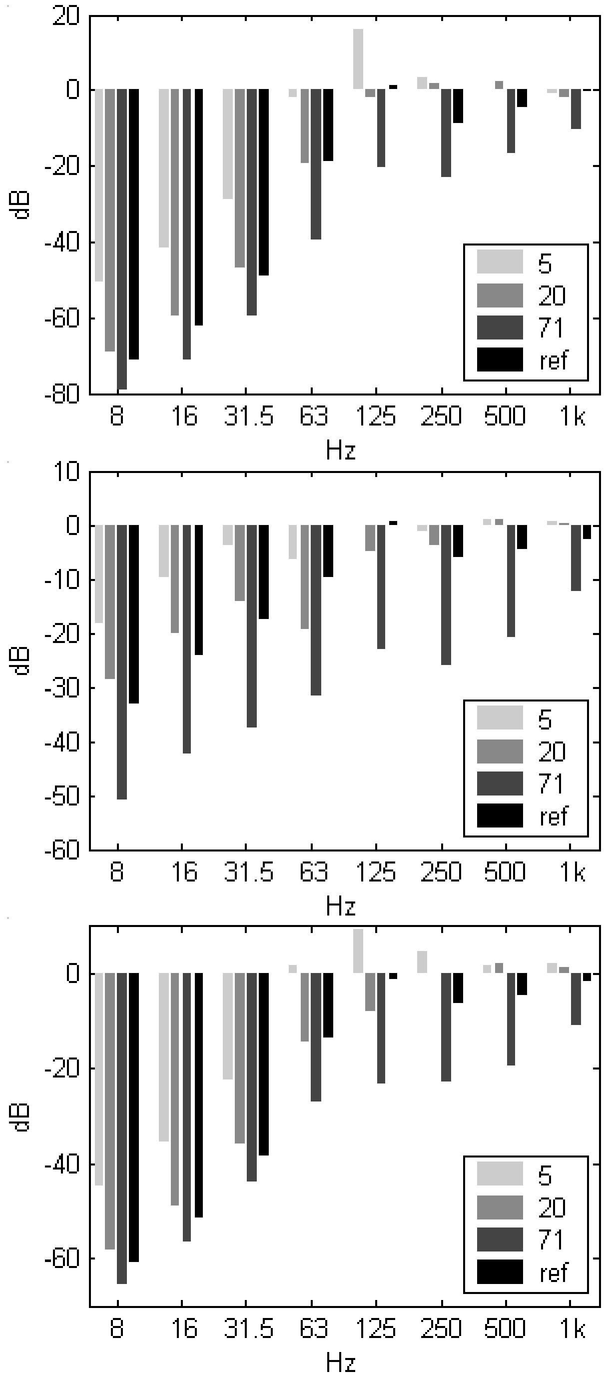

Fig. 7. Relative octave-band averaged substructuring error. Top: pulsating source, middle: oscillating source, bottom: randomly vibrating source.

It can be seen that the relative error increases considerably with increase in frequency. This is not surprising, taking that, at a fixed patch configuration, the number of patches per wavelength drop and the field gets less well represented. Once again, the substructuring using only 25% of available patches gives best results.

4 On virtual noise synthesis

One of the potential applications of substructuring for noise is the virtual noise synthesis. Individual characterisation of subsystems of an assembled system can allow for the global noise synthesis providing the substrucuring works properly.

It has been shown that a fairly reasonable noise synthesis of industrial products can be obtained by substructuring if the noise source is characterised rather rigorously in terms of its frequency content, while the noise transfer path can be at the same time described in an averaged (smoothed) sense [21]. The synthesis of noise which is of non-stationnary character will require an adequate phase information which also can be obtained by frequency smoothing [22].

The preceding results have shown that the noise spectrum modulus can be obtained by substructuring with a sufficient accuracy with a relatively low number of interface coupling points. The error analysis carried out in 3.3, which includes the phase error as well as the amplitude one, shows much higher overall error, coming undoubtfully from the loss of precise phase information.

The overall synthesis error, dominated by phase mismatch between the sound pressures obtained by substructuring and directly, is a consequence of the frequency-by-frequency error evaluation as seen from (3). Such an error assessment procedure may overestimate the impact of the mismatch on subjective evaluation of the synthesised noise. For example, if the error mismatch was strictly proportional to frequency, corresponding to a simple delay, the error evaluated by (3) would have certainly existed while it would produce no difference to the hearing. The quality of synthesised noise may be less affected by the mismatch in phase if the phase of synthesised signal matches globally the original one.

Fig. 8 shows the phase of the sound pressures obtained directly and by patch substructuring using 20 patches. One can see that the overall matching of the two is fairly good in the sense discussed previuosly.

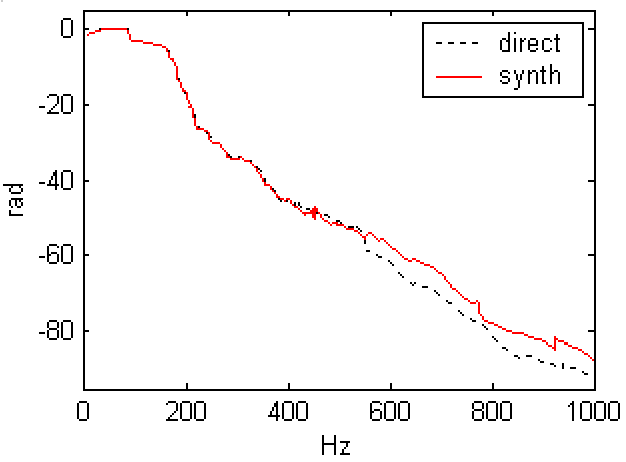

Fig. 8. Phase of sound pressure at the reception point: 20 interface patches.

The last finding was supported by listening tests where virtually no difference can be detected to sounds created by the direct and substructuring computation.

By reducing a number of interface patches, a particular type of acoustical substructuring can be achieved, where the subsystems are identified mostly by measurement while the synthesis is done by computation. Such a substructuring approach is suited to industrial applications, as it represents a form of virtual noise prototyping. Providing the number of interface patches is kept low, the blocked pressure of the source as well as the source and receiver impedances could be obtained by convenient robotised measurements. In this way the virtual noise synthesis based on realistic subsystem characteristics may become a reality.

5 Conclusion

It has been shown that the acoustical substructuring using the patch impedance concept works in cases where only a limited number of interface patches are employed. This fact may be of major importance for carrying out a particular type of substructuring suitable for virtual noise synthesis. Further investigations will be needed in order to fully assess the scope of this approach and its limitations.

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