Applied Acoustics 134 (2018) 97–109

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Experimental characterization of air-borne sound sources via surface coupling

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ARTICLE INFO

Keywords:
Source characterization
Sound prediction
Surface coupling approach
Patch Impedance approach

ABSTRACT

The paper examines whether an advanced experimental method, the surface coupling method, could be used to intrinsically characterize a sound source. Such a characterization can be used in turn to predict sound radiation of the source into an arbitrary space. The surface coupling method considers the source as being made up of the physical source together with a part of the surrounding medium contained within an enveloping surface. The source is entirely characterized by two intrinsic descriptors measured across the interface surface – its blocked pressure and its surface impedance. In order to allow the use of a simple-shaped interface the identification of descriptors is done by the Patch Impedance approach. To demonstrate the principle of the surface coupling method a 1D experimental validation – prediction of sound radiated by a driver in a tube – is carried out first. The validation of the general 3D technique is then done by characterizing a 2-driver loudspeaker radiating into an irregular cavity. Both experiments confirm the feasibility of the sound prediction by experimental source characterization via surface coupling.

1. Introduction

One of the reasons to characterize the airborne noise of an operating source is to find out whether the noise level exceeds the values prescribed by norms or legislation. The characterization is usually done in terms of sound power level. The sound power is often taken to be invariant with the surrounding acoustical space. The power is fairly easy to measure, especially if an open space or a reverberant space is available. In either case the power level measurement reduces to measurement of sound pressure levels around the source. Sound power is a concept which is well accepted by manufacturers. A number of power measurement techniques are standardised, notably the popular semi free-field technique [1].

The relationship between the sound pressure and radiated power holds only statistically, within the simplified assumptions of Sabine acoustics, [2]. This relationship is usually enforced by frequency band averaging, and, in the case of a closed space, by additional spatial averaging. While the invariance of the averaged power appears to be a reasonable assumption where large spaces are concerned, it does not hold necessarily in a smaller space, such as an engine compartment or a transformer cabinet. In such confined spaces the radiated power becomes strongly affected by acoustical properties of the surroundings and the source characterization based on radiated sound power becomes environment-dependent.

A typical noise source may have a complex directivity pattern which cannot be taken into account by the knowledge of total radiated power. In [3] the authors have formulated a power-based "box-source" method which can account for the source directivity. The global source is in this case divided into five independent noise sources, each of which is characterized independently by a partial power obtained via ordinary sound power measurement.

If a prediction of noise output of a source into a given receiver space is required, a detailed intrinsic source characterization may be needed. Various source models or descriptors have been proposed to characterize a sound source in a detailed way. One of the most frequently used modelling technique is the Equivalent Source Method (ESM). The method was conceived by Cremer [4] and later developed mostly as a computation tool [5,6]. The sound field of the original source is obtained by a finite number of elementary sources, such as monopoles or dipoles. One of the drawbacks of this method is the impossibility to define the positions of the elementary sources from physical considerations. In [7] and [8] particular procedures were developed to identify suitable positions of equivalent sources.

However, as the simple sources are acoustically transparent, the diffraction of the sound field produced by the original source in an arbitrary environment cannot be reconstructed using such sources. This makes the equivalent source model depending on the space into which the source generates noise. Thus an equivalent volumeless source does

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https://doi.org/10.1016/j.apacoust.2018.01.007
Received 9 February 2017; Received in revised form 1 January 2018; Accepted 11 January 2018

not represent a correct model of a real source where the prediction of sound radiation in different acoustical environments is concerned. If the size of a real source is small compared to wavelength, the effects of diffraction may be neglected and the equivalent source model could then become an efficient tool. Good overall results were reported in [9–11] with the sources characterized by measurement in real environments.

As an alternative to equivalent source method, the source reconstruction method aims at identifying the vibration velocity across the boundary surface of the original source. If this is done correctly the sound radiation due to the original source in an arbitrary space can be predicted from the reconstructed surface velocity. One classical source reconstruction method is Near-field Acoustical Holography (NAH) introduced by Maynard [12]. It is mainly applied to sources of simple geometry, such as planar, cylindrical and spherical sources of known radiation solution [13–15]. Another classical reconstruction method is the Inverse Boundary Element Method (IBEM) which can deal with arbitrarily shaped sources [16–18]. However the source reconstruction method is restricted to vibratory sources only and cannot be applied to sources which do not produce sound by vibration, such as fans. Even the lightweight sources, the vibration of which depends on the radiation loading, cannot be characterized by this approach.

In order to intrinsically characterize both vibratory and non-vibratory sound sources, the source characterization method via surface coupling has been proposed [19]. With the help of an interface surface enveloping the physical source, the source characterization is achieved by identifying two intrinsic source descriptors: its blocked pressure and its surface impedance. Any targeted acoustical space could then be characterized by an equivalent receiver descriptor – the surface impedance of the receiver – which is defined via the same interface surface. Then the sound radiation in the receiver space can be predicted using the identified source and receiver descriptors. The authors demonstrated the approach using a spherical interface surface and developing the sound field into spherical harmonics.

A spherical interface surface is unsuitable for experimental work. In [20] an alternative suitable for use with flat interface surfaces was proposed: the source descriptors are identified by the Patch Impedance approach. The patch approach segments the interface surface into patches. The pressure and velocity responses averaged across each patch are thereafter used to define the blocked pressure and the surface impedance. In order to adapt the surface coupling approach to the concept of acoustical impedance the analysis has to be carried out in frequency domain. If the sound created by the source is not of deterministic nature but remains stationary, the blocked pressure - and thus the predicted radiated sound - will be given in terms of the corresponding power spectra.

Using a rectangular interface surface, the sound prediction in a parallepipedic room was simulated in [20]. The results prove that the sound prediction could be achieved by patch source characterization even if the interface surface is of simple geometry. Aiming at future industrial applications, Du [21] has analyzed the influence of the patch size on the sound prediction. It has been found by error analysis that the optimal patch size, 1/3 of sound wavelength, ensures an acceptable sound prediction.

The present paper will review the principle of source characterization via surface coupling and the way to identify the source descriptors using Patch Impedance approach. To demonstrate the principle, a 1D experiment will be done: the source descriptors of a loudspeaker driver will be identified by measurements and its sound radiation in a straight tube will be predicted. To check the feasibility of the general technique of patch approach, an experimental validation on a 3D set-up will be carried out: the source descriptors of a home loudspeaker will be identified and the sound radiation by the loudspeaker in an irregular cavity will be predicted. It is worth mentioning that in both 1D and 3D cases the source is affected by its radiation loading, i.e. the vibration of either of the two sources is not independent of the surrounding space. This makes the present method applicable to cases to which the techniques of source velocity reconstruction are inapplicable.

2. Source characterization via enveloping surface

This section will shortly review the principle of source characterization via surface coupling, including the concept of source descriptors and the procedure of sound prediction.

2.1. Principle

A virtual interface surface S is defined to enable coupling between the physical source and an external receiver space. The physical source, the interface surface and the medium between them compose a specific space, named 'Source space'. The source space can be fully characterized by two descriptors defined across the interface surface: its blocked pressure p_b and its source impedance Z_s. Assuming harmonic time dependent of angular frequency ω, the blocked pressure can be represented as a product of a surface-dependent complex amplitude P_b and a harmonically varying time factor: $p_b(\mathbf{r},t) = P_b(\mathbf{r})e^{j\omega t}$. The frequency-dependent source impedance across the interface surface S will be defined as the ratio between the complex amplitude of sound pressure at S and the complex amplitude of the driving volume velocity across S. The blocked pressure P_b is the sound pressure response across the interface surface resulting from the operation of the physical source when the interface surface is fully blocked. The source impedance Z_s is the impedance of the interface surface when the physical source is switched off.

To predict the sound radiation of the physical source in a targeted acoustical environment the interface surface identical to that of the source space is defined in the receiving acoustical environment. Thus a receiver space corresponding to the source space is created; it represents the portion of the receiving acoustical environment outside the virtual interface surface. In other words, coupling the source and receiver spaces through their common interface surfaces yields the entire system, i.e. the acoustical environment with the physical source installed inside. The impedance of the interface surface in the receiver space is named receiver impedance, which is a receiver descriptor denoted by Z_r.

With the source and receiver descriptors identified, the volume velocity Q_c across the interface surface in the receiver space can be obtained by [20]

$$Q_c = (Z_s + Z_r)^{-1}P_b \tag{1}$$

The sound radiation in the receiver space can be then predicted by applying the volume velocity Q_c to the interface surface and computing the response in the receiver space due to this velocity. This means that the interface surface with the volume velocity Q_c acts as an equivalent source driving the receiver space. Once the coupling velocity Q_c has been identified the pressure response P_r at a receiving point r in the receiver space can be obtained by

$$P_r = Z_{rc}Q_c \tag{2}$$

where Z_{rc} is the transfer function between the sound pressure at the receiving point and the volume velocity of the interface surface.

In brief, the sound prediction of a physical source in an arbitrary acoustical environment could be fulfilled through the following process:

- Characterization of physical source: identify blocked pressure P_b and source impedance Z_s across an interface surface enveloping the physical source.
- Characterization of receiver space, i.e., acoustical environment: identify receiver impedance with the same interface surface defined in the acoustical environment. This can be done in principle by computation as well as by measurement.
- Sound prediction in receiver space: apply the volume velocity Q_c