Extension of acoustic holography for tire noise investigations

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Summary: Nearfield Acoustic Holography is a useful tool for source identification, but less appropriate for sources of complex geometries such as tires. An inverse BEM method has been developed to overcome the limitations of NAH and verified on an electroacoustic tire mock-up. The method seems to be correct both qualitatively and quantitatively, if appropriately selected measurement points are used.

INTRODUCTION

The identification of noise generation mechanisms inherent in tire/road interaction phenomena requires sophisticated instrumentation and measuring techniques. Due to the nature of the problem the application of conventional vibration sensors is largely limited, hence those methods making use of acoustic sensing are of primary importance. Nearfield Acoustic Holography (NAH, [1, 2]) is one of these techniques, used more extensively nowadays as microphone array instrumentation has become more affordable. Another set of microphone array methods makes use of time delays between the microphone signals, such as the Source Probability Function measurement which is based on cross-correlation functions [3]. Other useful techniques are the so called Airborne Source Quantification (ASQ) method [4] and a whole group of inverse FRF methods [5, 6], originally developed for excitation force identification in pure mechanical systems [7,8].

This paper reports on an inverse FRF method which makes use of numerically calculated transfer functions between the radiating, i.e. source, surface and the sensing, also called measurement or holography surface. The technique, originally proposed by Mas *et al.* [9], can be considered as a generalization of the acoustic holography technique. Unlike NAH though, it is not burdened by the limitation that both the source and the measurement surface must be plane or of some other elementary shape, which is of vital importance from the tire analyst's point of view. Its close relationship with the Boundary Element Method implies that it is more correct to denote it as an inverse BE method (I-BEM).

THEORY

The Boundary Element Method is a standard sound radiation prediction method, routinely used in tire development as well [10]. The governing equation of the radiation problem of a general vibrating surface can be described in its discrete form as

$$[A]\{p_s(x)\} - [B]\{v_s(x)\} = \{p(y)\} \qquad (1)$$

relating the sound pressure p_S and particle velocity v_S in any arbitrary node x along the source surface mesh to any arbitrary point y outside of the surface through the influence matrices $[A]$ and $[B]$.

The problem can be solved in two consecutive steps. At first one assumes that point y is selected inside the source surface, in its close vicinity. Then Eq. (1) becomes

$$[A]\{p_s\} = [B]\{v_s\} \qquad (2)$$

and the resulting system of equation can be solved, provided that either surface pressures or surface velocities are known as prescribed boundary conditions for any arbitrary node.

Secondly, if point y is selected in the farfield, the resulting radiated pressure p_r can be obtained from

$$[a]\{p_s\}+[b]\{v_s\} = \{p_r \qquad (3)$$

where the matrices $[a]$ and $[b]$ describe the participation of the various nodes in the radiated field and can therefore be referred to as contribution matrices.

The inversion of the method can easily be deduced from Eqs. (2) and (3):

$$\{p_m\} = \left[[a][A]^{-1}[B] + [b]\right]\{v_s\} = [c]\{v_s\} \quad (4)$$

and then

$$\{v_s\} = [c]^{-1}\{p_m\} \quad (5)$$

where p_m stands for the measured pressure, determined along measurement points of an arbitrary measurement surface. The matrix $[c]$ can be denoted as the transfer matrix of the system and $\{v_s\}$ is the vector of sought surface velocities.

The solution of Eq. (4) in principle rather straightforward, provided that the number of microphone positions along the measurement surface is greater than, or equal to, the number of elements on the source surface, and that matrix $[c]$ is not singular.

A BRIEF COMPARISON OF VARIOUS METHODS

As already mentioned, the most significant difference between the inverse BEM method and Nearfield Acoustic Holography is that I-BEM is not restricted to plane (or cylindrical, or spherical) source and measurement surfaces. Another drawback of NAH is that the hologram mesh or microphone array must be equidistant, in order to enable one to apply spatial FFT. Even though these restrictions do not hold for I-BEM, it will be shown below that the selection of the measurement surface and the spacing of the source and measurement mesh is rather critical from the calculation accuracy point of view.

I-BEM and ASQ are more closely related, with the only essential difference that the transfer matrix is determined for I-BEM numerically rather than experimentally. As one can expect, so are the problems and inaccuracies of both methods too.

LIMITATIONS AND IMPROVEMENT POSSIBILITIES OF THE I-BEM

It is known for all inverse methods that the accuracy of the method largely depends on the condition number of the transfer matrix, in this case $[c]$. As the condition number of the matrix increases, the obtained result $\{v_s\}$ is increasingly influenced by modeling and measurement errors. It was shown for plane measurement arrays analytically and experimentally [6], how the sensitivity to errors can optimally be controlled by selection of appropriate measurement points. We have performed simulation calculations with more complex measurement surfaces around various source models. It was established that those simple rules developed by Dumbacher *et al.* (equal source/measurement surface spacing, source and microphone points in line, source-microphone distance less than source point spacing) do hold for a wider variety of models and surfaces as well.

In some practical cases not all of these rules can be followed exactly. If the condition number of $[c]$ increases, a simple overdetermination of Eq. (4) and a standard least mean square solution is not sufficient to obtain meaningful results. In order to limit the computation error to practicable levels, some kind of regularization methods shall be resorted to. Two methods have been investigated: Tikhonov regularization and Truncated Singular Value Decomposition (TSVD) [11]. We have obtained better results for the solution of the I-BEM problem by using the TSVD method. Increasing the extent of regularization the solution becomes less sensitive to modeling/measurement errors, at a price of decreased spatial resolution.

PRACTICAL IMPLEMENTATION FOR TIRE NOISE INVESTIGATIONS

The practical implementation of the method is largely based on the vibroacoustic prediction software package SYSNOISE, embedded in MATLAB environment. Following the aforementioned rules, an appropriately matched discretized source model / measurement surface is to be defined first. The sound pressure field is scanned by a microphone array and the data processed by a multichannel measurement system. The influence and contribution matrices are calculated by SYSNOISE. Both the measured sound pressures and the required numerical matrices are imported into MATLAB through small interface programs. Eq. (4) is solved by means of a MATLAB program package [11] and the obtained results are eventually exported to SYSNOISE for visualization.

After having tested the method on small testing objects, the procedure was applied on the tire noise problem. A wooden mock-up with six built-in, independent loudspeakers was constructed and calibrated by means of a laser Doppler vibrometer. (Note that measurements on real tires under normal operating conditions are in progress during the preparation of this manuscript.) The mock-up was then placed in an anechoic chamber and the microphone array measurements repeated twice: placed app. 1.2 m above the absorbent floor (Fig. 1) and directly on a wooden floor plate, simulating road reflections (Fig. 2). The obtained source velocity distribution is given in Table (1) and in Figs. (3) and (4).

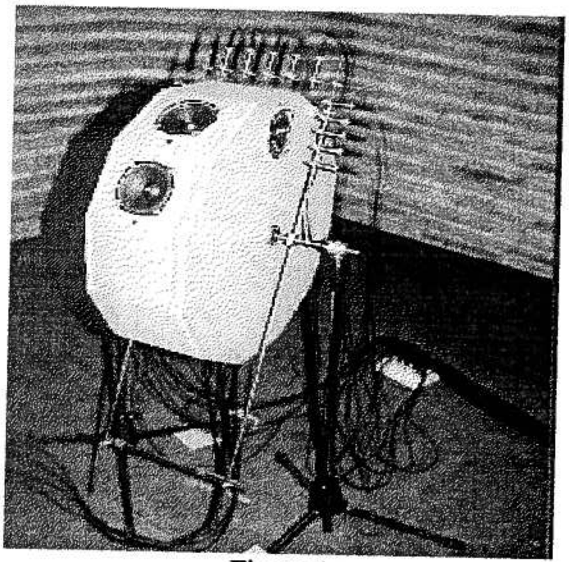
Figure 1

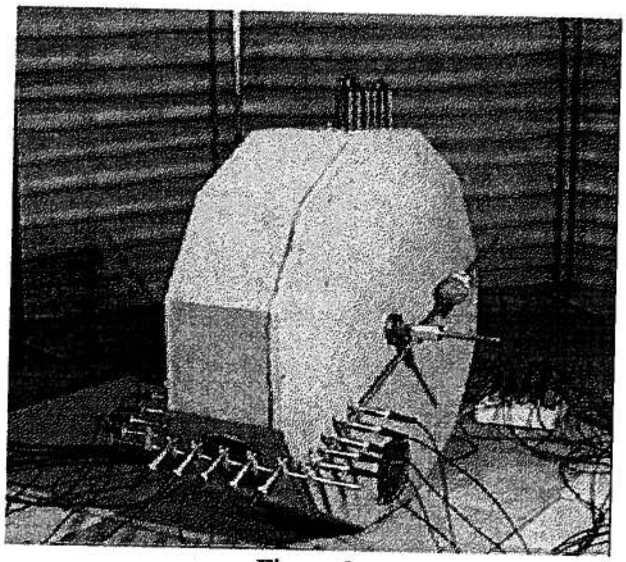
Figure 2

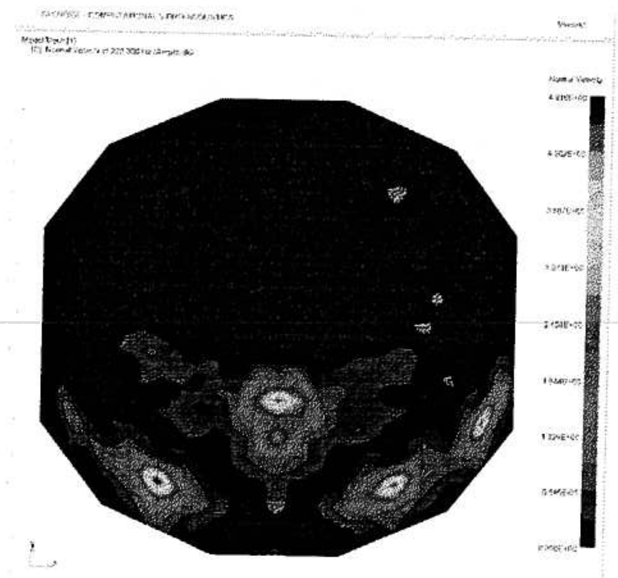
Figure 3

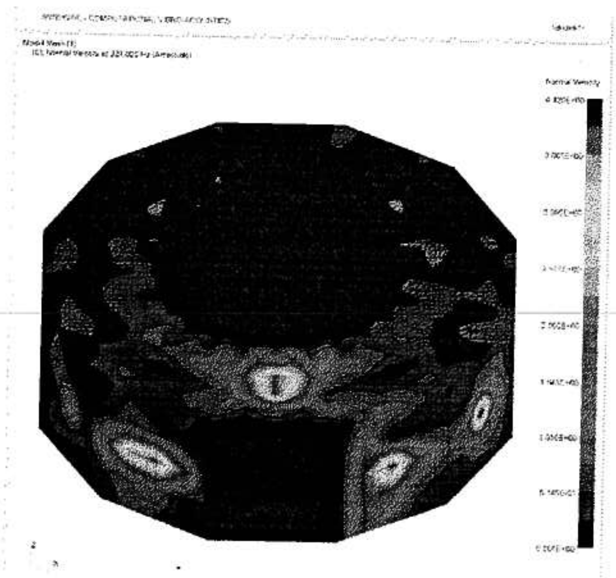
Figure 4

Loudspeaker	Measured and calculated volume velocities of the various loudspeakers for the non-reflective case [*100 cm^3/s]					
	220 Hz		480 Hz		700 Hz	
A	161.9	187.9	62.9	73.1	48.6	61.1
B	54.0	58.3	20.7	22.9	12.6	13.9
C	152.9	182.5	63.8	68.8	42.3	46.7
D	36.0	43.0	16.2	18.7	10.8	15.0
E	152.9	171.4	58.4	64.7	41.4	40.7
F	152.9	172.6	71.9	77.9	44.1	48.9

Table 1

As one can see, the obtained results are promising. Not only the radiating surfaces can be easily identified, but the measured results are correct in qualitative sense as well. It is worth noting that reasonable estimations could also be obtained for the reflective case in the vicinity of the contact patch, where the acoustic environment around the partial source is rather adverse.

CONCLUSION

The inverse BE method seems to be a viable alternative of NAH in those cases when the source is of complex shape. The obtained results enable the analyst to draw not only qualitative but quantitative conclusions too. In order to get meaningful results, an optimally matched source model / measurement point mesh surface, placed close to the source, is essential. Even this is the case, regularization methods to solve the inverse problem is usually required.

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