Sound Source - Visualization and – Quantification of stationary and moving Sources for Aircrafts & Railbound Vehicles

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Introduction

Bombardier uses microphone arrays for the localisation ('Ortung') of airplane and train sound sources. Extended use of the array for wind tunnel measurements, sound power measurements of stationary sources and effective source-separation (e.g. wheel/track) demands a more accurate quantification of source position and absolute 'source strength'. Bombardier utilizes already current quantitative evaluations e.g. for source ranking. Traditional post-processing of array results do not show the 'true' source distribution, but the convolution of *source* and *array response functions*. Plausibility considerations show that convolution - despite optimized microphone positions- is the most influential error source for a more accurate quantitative analysis as well as for the interpretation and therefore for efficient noise control procedures. The area of microphone-array-techniques is characterized by a wide variety of hard- and software, that are used for very different objectives. Therefore all important factors of influence that may lead to an amplitude variation (e.g. type of microphones, spatial resolution or calibration) need to be considered. In the following, only intermediate results of the still ongoing investigation will be shown.

Sound (Source) Visualization

At the present time, the following hypothesis can be stated: the emerging of acoustics as science by Chladni and Young at the beginning of the nineteen century required sound visualization as a basis for quantification of sound variables and parameters.
The perception of visualized sound is not similar to or in easy agreement with standard visual experience. How do we know, whether we see the source clearly, in an undistorted way and in its original dimensions of importance? To ensure an objective view, we need to develop objective techniques and criteria for sound image quality assessment. A priori knowledge or reasoning is generally not sufficient and we will certainly need additional tools and extraneous information.

Sources & additional Tools

A generic example of sources are the three plates of Stenzel (1939):

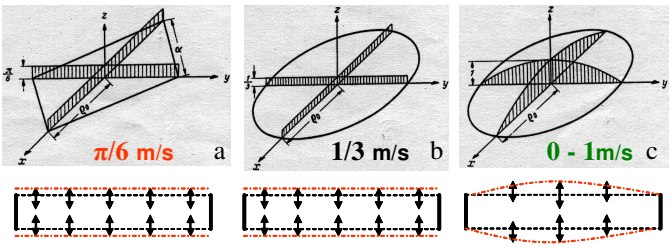

Figure 1: Three vibrating plates with different particle velocity, but same volume velocity (Source: Stenzel 1939 [1])

The square plate (ca. 0.08 m) vibrating with a particle velocity v of π/6 m/s (**a**), both disks (diameter $2r_0 \approx 0.11$ m) vibrating with v= 1/3 m/s (**b**), and 0 - 1 m/s ($v = (1-r^2/r_0^2)^2$) (**c**). Plate thickness is always 3 mm. For the simulation, the TD-(Time-Domain)-BEM-software of M. Stütz (TFH-Berlin) is used [2], which can be used for moving sources as well. **What is expected to be the visualization result for an excitation frequency of 800 Hz** (a deterministic sinusoidal signal; no noise field applied; λ ≈ 0.43 m) **in 1 m distance?** The plate dimensions are in every direction small compared to λ (Helmholtz no. < 1) and the measurement distance is ca. 2.4 λ. **Figure 2** shows very similar results for all three plates due to the excitation (same volume velocity!) and the measurement setup.

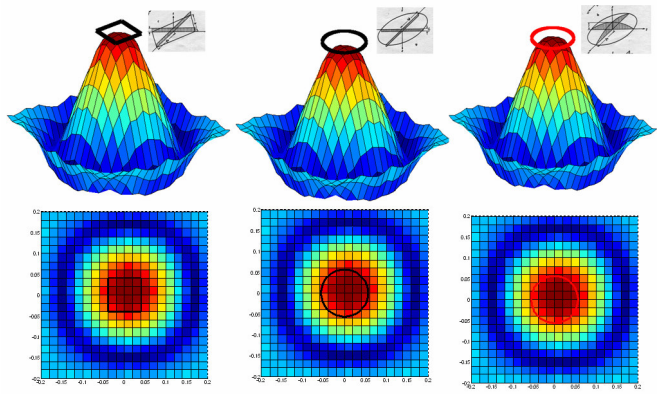

Figure 2: Results from standard array processing (array-100 mics 2 x 2 m, unnormalized, but identical scaling)

Two further important topics that are related to a proper description of sources shall be mentioned rather shortly: source uniqueness and the ubiquitous linear modeling of real sources: ‚The textbook situation in which a moving, small pulsating sphere is erroneously modeled by a convected monopole typifies the linear thinking that has so far clouded the picture.'[3] This refers inter alia to convective and diffractive effects determined by source variables and parameters difficult to be quantified.

Remarks about the Microphone Array Principle

The working principle of a Microphone Array can be interpreted and explained in several, very different ways (e.g. as a ‚acoustical camera' resp. lens or as constructive interference of phase shifted signals). The following two formulas demonstrate in a simple way (with few additional assumptions e.g. S/N is f or all microphones equal) three important points in relation to the variables AG – Array Gain – S/N-Ratio – directional pattern of Signal Field / directional pattern of Noise Field and B – directional Beampattern per unit solid angle [4]):

$$AG = 10\log 10\left(\frac{(S/N)_{\text{Array}}}{(S/N)_{\text{Single Element}}}\right)$$

$$AG = 10\log 10\left(\frac{\int_0^{4\pi} S(\alpha,\beta)B(\alpha,\beta)d\Omega \,/\, \int_0^{4\pi} N(\alpha,\beta)B(\alpha,\beta)d\Omega}{\int_0^{4\pi} S(\alpha,\beta)d\Omega \,/\, \int_0^{4\pi} N(\alpha,\beta)d\Omega}\right)$$

1. the enormous influence of the resulting directivity (based on the law of reciprocity the receivers resp. microphones can be replaced by sound sources);
2. the amplifying effect (the microphones maybe considered as sources and summed up energetically); and
3. the three decisive variables of influence (*Signal Field*, *Noise Field* -all sound sources not of interest- and *Beampattern*), which make use of the array so unique, that the same array (beampattern) in general delivers a different performance in different sound - and noise fields!

Finally, the equation does not consider the influence reverberation and scattering, which leads to a phase distortion due to repeated

reflections from different directions. This may be very important e.g. for measurements in a wind tunnel or in an unqualified room – purely anechoic or reverberating room. Any array performance is only unambiguous/definite with a description of these parameters.

'Single Source and Noise' Scenario 1: a distant source with non-dispersive propagating plane waves G_S and a number of statistically independent sources ('noise') surrounding the microphone array providing approximately equal pressure spectra G_D at all microphones. G_{xy} being the cross spectrum between microphones [4, 5].

'Single Source and Noise' Scenario 2: a distant source with non-dispersive propagating plane waves G_S; microphone and/or data acquisition and processing noise as statistically independent sources (noise contribution) for each physical channel G_N. The phase of Scenario2 (data acquisition noise) will not be changed, but the higher the ratio of diffuse noise to source G_D/G_S (Scenario1) the bigger the phase change.

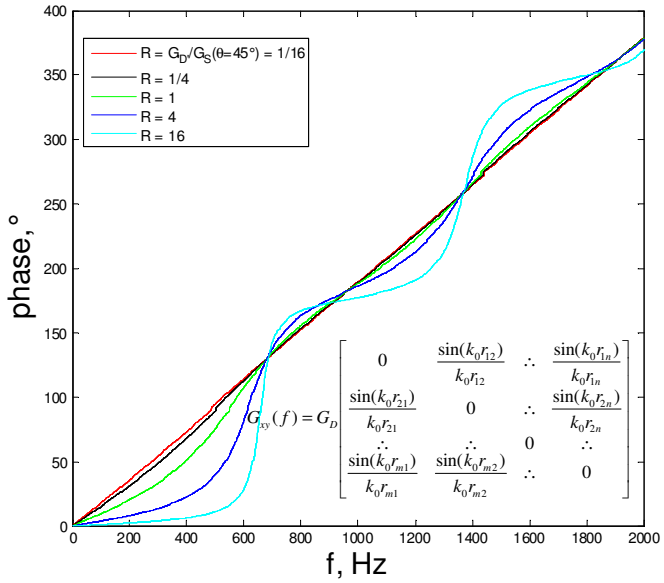

Figure 3: Phase for diffuse noise and plane wave (noise field of interest (microphone distance 0.25 m ;angle of incidence 45°, c_0=340 m/s, no flow)

Array Processing Methodology

Traditional quantitative single source analysis displayed as autopower-spectral mapping is at the source position a good estimation of the source spectrum. There are, in general, only standard measurement problems like *point source dimensions*, *output noise*, *data acquisition* or *processing noise* and *reverberation*. Processing only the main-lobe of a moved array would provide similar estimation results for multiple sources, but not being very practical. Integration methods like '**intensity scaling**' [8] or matched field processing (e.g. the parametric approach '**s**pectral **e**stimation **m**ethod' [9] are not usable for moving sources (airplane & train). From the physical point of view, a deconvolution of the array-response for stationary sources is the most consequential procedure: a literature example [7] is recalculated (see fig. 4) by the point-spread functions H_{fs}. (r distance, m mics-, f focus-pos., k wave-no.) and solving the following least square problem (BO beamforming output, σ pressure-amplitude squared):

$$H_{fs}(f) = \left| \sum_{m=1}^{M} \frac{r_{fm}}{r_{sm}} e^{-jk(r_{fm}-r_{sm})} \right|^2 ;$$

$$C(\sigma) = \sum_{f=1}^{F} \left(\sum_{s=1}^{F} H_{fs}\sigma - BO_f \right)^2$$

The next big step is a deconvolution for moving sources (e.g. by re-constructing the array response as function of movement and in-cluding the Doppler shifts [7]) - presumably - at the expense of in-creasing computational time and need of memory.

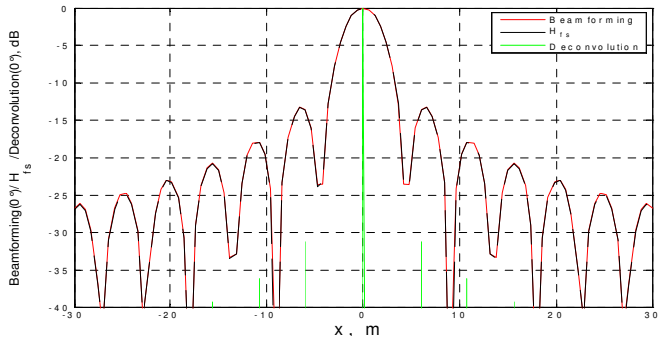

Figure 4: Deconvolution literature example [7] recalculated:101 mic-array; length 15 m; calculation distance 200 m (Beamf./Hfs/Deconv)

Old Tricks & Fields of Applications

Old tricks like the simultaneous use of slightly shifted double beams with different width or a simple change of polarity for reducing the beamwidth of loudspeaker arrays work for microphone arrays as well.

Conclusion

Computer simulations for quantifying or checking the *array-performance* should not only model microphone, data acquisition and/or processing noise as statistically independent sources, but use the 'real' acoustic noise and reverberation fields, particularly since it could lead to phase distortion.

The development of array-performance criteria (besides main/side lobe level, co-array) should be quantified, reproducible and examinable.

Deconvolution is currently the best physical choice to get useful quantified results with a high resolution, accuracy and ease of interpretation. With respect to expense and time consumption other methods need to be tested (e.g. Clean-C).

Increased understanding and aiding interpretation (explanation) of sources needs additional, computational tools (e.g. CFD, Time-Domain-BEM) as well extraneous information.

Literature

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