Tomographic study of acoustic emission by parametric arrays for airborne sound

Holger Joost, Klaus D. Hinsch

Applied Optics, Institute of Physics, Carl von Ossietzky University, Oldenburg, Germany

mailto:holger.joost@uni-oldenburg.de

This study concerns extensions of TV-holography or Electronic Speckle Pattern Interferometry (ESPI) with sinusoidal reference wave modulation and phase shifting for acoustic challenges that require mapping of a 3D sound field with high spatial resolution.

1 Introduction

Parametric acoustic arrays are built to generate highly directional audio sound by nonlinear interaction of two ultrasonic waves differing in frequency by just the audio frequency to be generated [1]. To achieve high sound pressure levels such arrays are often composed of up to several hundred individual piezoelectric transducers of PZT, each of about 16 mm in diameter. For optimum performance it is required that these elements radiate in phase. Usually, however, they differ slightly in their resonance frequencies and as such radiate with differing phases. To control such effects and provide for active adjustments the resulting ultrasonic sound field near the array should be known. The small variations in the refractive index *n* of the air caused by the pressure fluctuations of a propagating sound wave can be used for optical monitoring. We have modified time-averaged Electronic Speckle Pattern Interferometry (ESPI - also called TV-holography) for this purpose.

2 Sound-mapping by ESPI

Let us briefly recall the basic technique as illustrated in Fig. 1. Primarily we measure the modulation in *n* integrated over the light path through the sound field. The field is generated in front of a rigid rough background wall and the light from a laser penetrates the field twice on its path to and from the wall to the detecting CCD-camera. A proper reference beam is split from the illumination beam, fed through a fiber and then superimposed in the optical configuration onto the object light. Both waves interfere to produce an image-plane hologram that is registered by the camera target. The system relies on time-averaging by the CCD and on electronic high-pass filtering and squaring of the video signal. The final image is stored in a computer memory. In time-average operation for sinusoidal phase modulation the image intensity versus the amplitude of the phase modulation is governed by the square of the zero-order Bessel function [2]. Since the changes in the refractive index in air are relatively small - a path of 5 cm in length through a sound field with a pressure level of 110 dB produces a phase modulation equivalent to a vibration amplitude of 1 nm - the sensitivity of the method is enhanced by shifting the operating point of the system to maximum slope by sinusoidal reference wave modulation with the sound frequency. By these means the system is phase sensitive and four 90° phase steps are applied to calculate the amplitude and phase distribution in the 3D field.

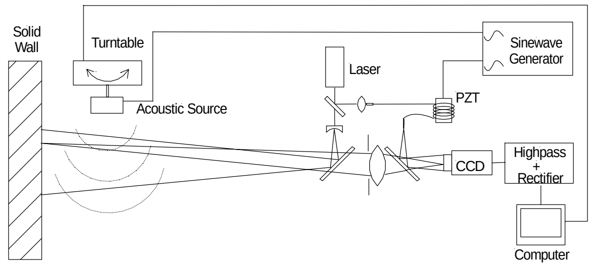

Fig. 1 *Schematic of ESPI set-up for the measurement of sound fields*

The measured light phase is the result of the integration of the change in refractive index along the projection path of the light through the sound field. In a 3D field we need many such projections with differing viewing directions through the sound field to invert for the sound distribution in space. For this purpose the sound source can be rotated around a horizontal axis parallel to the wall. In this way we obtain two-dimensional interferometric data for a set of 180 projection directions at 1° angular separation that are adjusted by a computer-controlled rotation stage.

Tomographic sound field mapping needs a special treatment, because it is different from ordinary tomography. Since the sound pressure amplitude is an oscillating quantity the integration along the projection path encounters contributions at differing phase settings and a direct inversion is not possible. Because of that, the integration has to be done separately for the real and imaginary parts of the modulation. This is done by a tomographic back-projection technique [2] especially adapted for an alternating field which allows to calculate phase and amplitude distributions in the 3D field.

3 Sound field radiated from an array of 37 ultrasonic transducers

The following study was made in a field produced by an array of 37 ultrasonic transducers (Fig. 2). Each transducer element allows changing the relative phase of the sound radiated by adjustment of its longitudinal position. The 3D sound field data is handled by a visualization-software that provides arbitrary planar cuts in space.

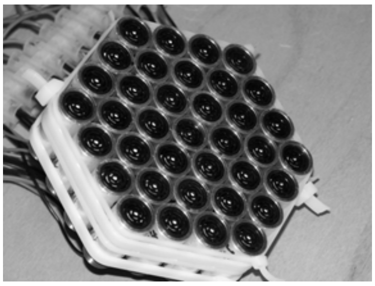

Fig. 2 *Sound source consisting of 37 piezoelectric transducers of 16 mm diameter each*

The kind of data and the utilization for sound field optimization is shown in a few illustrations. For Fig. 3 let us begin with the array of transducers assembled as they came. The figure contains phase and amplitude of the backprojected field for a plane parallel to the transducer array and directly above it and a plane perpendicular to the array. Fig. 3a presents the saw-tooth representation of the acoustic phase in the sound field slightly above the transducers. The positions of the individual transducers in the cluster are clearly visible from the structures in the phase-value image. Obviously the transducers radiate with differing phases. As a consequence, the amplitude distribution in Fig. 3b shows large fluctuations.

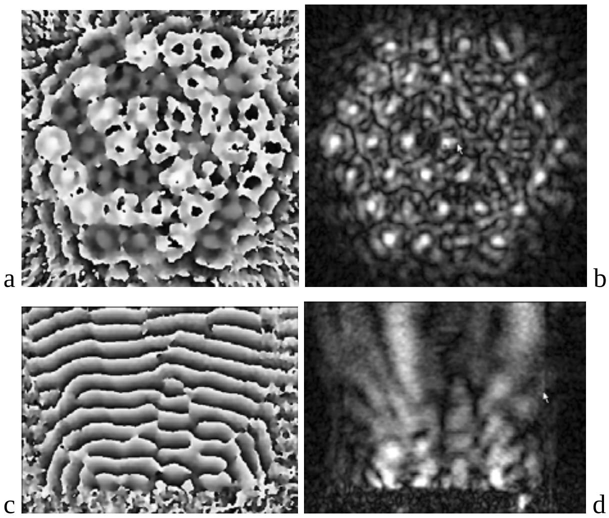

Fig. 3 *Tomographic analysis of 38.5-kHz ultrasound field above an array of 37 piezoelectric transducers, assembled without correction of their phases. a and b: phase and amplitude in a plane parallel to the array and directly above it. c and d: in a plane perpendicular to the array and through the centers of the lower row of transducers*

The situation is also demonstrated in the data from a cut perpendicular to the array in Fig. 3c (phase) and Fig. 3d (amplitude). This cut passes through the centers of the lower row of four transducers. This structure is also evident in the irregularities of the phase and the amplitude distribution.

This data was used for a first phase adjustment of the transducers. Fig. 4 gives the corresponding results. In Fig. 4a the phases of all transducers are well matched. One should not be irritated by the many changes from black to white – the saw-tooth representation of the phase shows jumps from black to white when the phase passes 2π. The amplitude above the array in Fig. 4b is also much more balanced. The same holds for the amplitude in the perpendicular plane (Fig. 4d). In addition, the phase distribution in Fig. 4c demonstrates an extended region of nicely parallel fringes indicating a well-defined plane-parallel wave.

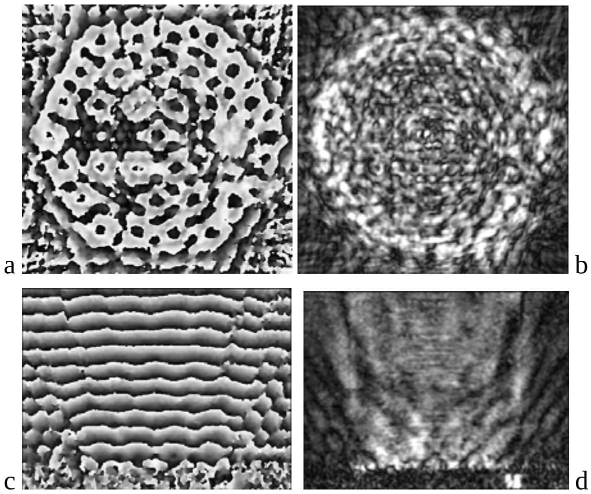

Fig. 4 *Tomographic analysis of 38.5-kHz ultrasound field as in Fig. 4, however after a first correction of the transducers' phases*

By this adjustment the beam angle in the radiation pattern of the nonlinearly generated audio sound was narrowed from about 30° to less than 10°.

4 Acknowledgements

We thank V. Mellert for the acoustical expertise that he dedicated to the present study and M. Schellenberg for his engaged contribution in developing Matlab routines. We also acknowledge financial support by DFG.

References

[1] P.J. Westervelt, "Parametric Acoustic Array", J.Acoust.Soc.Am. **35:** 535-537 (1963)

[2] C.M. Vest, *Holographic Interferometry*, p.180, John Wiley, New York (1979)

[3] M. Espeland, O.J. Løkberg, R. Rustad: "Full field tomographic reconstruction of sound fields using TV holography" J.Acoust.Soc.Am. **98:** 280-287 (1995)