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Assessment of acoustic pressure holograms from membrane velocity measurements

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Abstract

The aim of this paper is to show experimentally the possibility to assess acoustic pressure holograms using a light membrane and a scanning laser vibrometer. The velocity of a light membrane placed in an acoustic field can be measured without contact by means of a laser vibrometer. The ideal membrane must be optically reflective, acoustically transparent (as light as possible), impermeable, and mounted without tension. The measured velocity is equal for continuity reasons to the normal acoustic velocity, but differs from the acoustic velocity without the membrane because the membrane is never completely transparent to acoustic waves. A mass effect can be taken into account to correct this difference. Then, the acoustic pressure holograms can be deduced from velocity holograms using the 2D Discrete Fourier Transform. An experimental validation is carried out, acoustic pressures identified from laser measurements are compared to microphone measurements, with a very satisfying match over a wide frequency range.

Key words:

1 Introduction

2 An acoustic pressure hologram is generally acquired by using a moving micro-
3 phone (with a reference sensor) or a microphone array. The aim of this paper
4 is to show experimentally the possibility to assess acoustic pressure holograms
5 using a light membrane and a scanning laser vibrometer. The technique is
6 based on the insertion of a light membrane in the studied acoustic field and

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on the measurement of its velocity by scanning its surface using a laser vibrometer. The possibility to measure the acoustic velocity in the air using a membrane has been investigated in a previous work [1], and the theory of membrane-based holography is proposed in a second paper [2]. The main difficulty of the approach is that the membrane modifies the sound field : the membrane velocity (equal for continuity reasons to the normal acoustic velocity) is not equal to the normal acoustic velocity that would have existed without it. The aim of the previous works was to show the possibility to correct the membrane velocity to virtually remove its mass, for a plane wave in normal incidence [1] or for any kind of wave [2]. The aim of the present study is to show the possibility to obtain acoustic pressures from membrane velocity measurements. Although it has been shown in [5] [4] that velocity-to-velocity NAH is more robust than pressure-to-velocity NAH, the assessment of acoustic pressure holograms remains necessary to compute the acoustic intensity through the membrane, or to compare it with some microphone measurements.

The first part of this work recalls the basic principles of membrane-based NAH, including the mass correction and the velocity to pressure transformation, which requires the use of an averaged k-space function. The second part is about the experimental validation : the acoustic pressure obtained by using membrane velocity measurements is compared to the acoustic pressure measured with a microphone in the same plane without the membrane.

1 Theory of membrane-based holography

The formulation of planar NAH based on acoustic velocity measurements [5] is similar to pressure-based NAH [6], and has been experimented thanks to recently developed acoustic velocity sensors [7]. The particle velocity is measured on the direction normal to the hologram plane, and its 2D Discrete Fourier Transform (DFT) allows the following expansion :

$$V^z(x, y, z, \omega) = \sum_n \sum_m V_{nm}^z(z, \omega) e^{jk_{nx}x} e^{jk_{my}y}, \quad (1)$$

z being the direction normal to the measurement plane, with $k_{nx} = 2\pi n/L_x$, $k_{my} = 2\pi m/L_y$, and n, m positive or negative integers varying between limits defined by the spatial resolution, and L_x and L_y dimensions of the measurement surface.

The use of the 2D DFT implies that the acoustic field is periodical in the x and y directions, a period corresponding to the measurement surface. This

induces non-physical discontinuities at the borders, generating artificial high wavenumbers. The classical solution to overcome this problem is to use spatial windows to zero edges of the measurement surface [8]. A more interesting approach is to find an extrapolation of the 2D acoustic field in order to extend the hologram [9], and to apply the spatial window to the extrapolated area, thus keeping the whole measured information intact (this is a kind of intelligent zero-padding : data is not extended by zeros but by physically pertinent values). The procedure is experimentally validated in [4].

The use of the membrane to assess the acoustic velocity is intrusive : the membrane itself modifies the sound field. Waves emitted by the source are indeed partially reflected by the membrane. However, these modifications can be corrected to obtain the acoustic velocity that would have existed without membrane (using a $e^{-j\omega t}$ time dependency):

$$\tilde{V}_{nm}^z(z, \omega) = V_{nm}^z(z, \omega) \left(1 - \frac{j\mu k_{nmz}}{2\rho} \right), \quad (2)$$

where $k_{nmz} = \sqrt{k_0^2 - k_{nx}^2 - k_{my}^2}$ or $j\sqrt{k_{nx}^2 + k_{my}^2 - k_0^2}$ for respectively $(k_{nx}^2 + k_{my}^2) < k_0^2$ or $(k_{nx}^2 + k_{my}^2) > k_0^2$, μ is the mass per unit area of the membrane, ρ the air density, and \tilde{V}_{nm}^z the (n, m) component of the corrected velocity. It is important to note that this correction does not take into account the possible multiple reflections between the source and the membrane ; this explains that the minimization of the membrane mass remains crucial as stated and illustrated in [1], even with this correcting term.

The velocity-to-pressure transformation, applying the Euler equation to the (n, m) component of the 2D DFT, is given by

$$P_{nm}(z, \omega) = \frac{\omega\rho}{k_{nmz}} V_{nm}^z(z, \omega) = G_{nm}(\omega) V_{nm}^z(z, \omega). \quad (3)$$

This operation is well-posed for high spatial frequencies, because of the division by the term k_{nmz} . Meanwhile, this division can induce a strong amplification when some components of the 2D DFT decomposition have wavenumbers in the vicinity of the acoustic wavenumber ($k_{nx}^2 + k_{my}^2 \approx k_0^2$). This can potentially induce a large bias error because the transformation is applied to a Discrete Fourier Transform of the velocity field. A solution, proposed in [10] and used in this work, is to compute an averaged expression of $G_{nm}(\omega)$ to avoid coincidence effects between the singularity and discretized wavenumbers of the 2D-DFT.

2 Experimental validation

2.1 Experimental setup

An experiment has been carried out to validate the theoretical developments proposed in the previous sections. The acoustic source, already used in previous work [2], is a compression driver coupled to a copper tube (22 mm diameter) with 3 openings. The resulting acoustic source is equivalent to 3 correlated monopoles in the frequency range of interest. A light membrane (height $0.5m \times$ width $0.35m$, $45g/sqm$) is placed at 5cm of the acoustic source, in a plane parallel to the one defined by the 3 openings of the studied source. The membrane is maintained by a frame, without tension. The velocity of the membrane is measured by using a scanning laser vibrometer, using a 16×24 scan grid (2cm resolution). The acoustic pressure in the same plane (without the membrane) is measured with a microphone at 3 positions, at 5cm in front of each source.

2.2 Effect of the k -space averaging of the velocity-to-pressure operator

The pressure obtained using the velocity-to-pressure operator given in Eq. (3) is drawn in Figure 1, averaged on the whole measurement grid (384 points), with and without the averaged expression of $G_{nm}(\omega)$. The regularization ef-

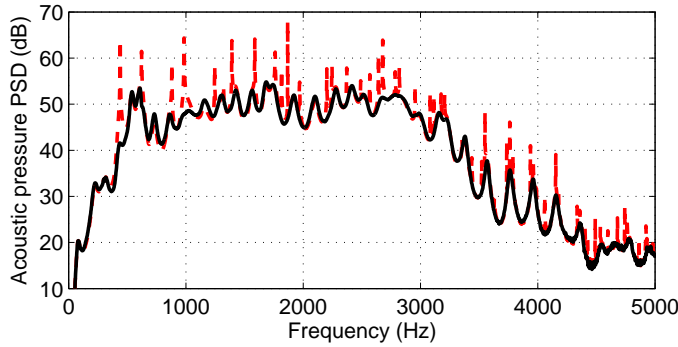


Fig. 1. Averaged acoustic pressure identified using the measured membrane velocity, using the non averaged (---) and averaged (—) velocity-to-pressure operator .

fect of the k -space averaging operation is clear in Figure 1. The result of the non-averaged transformation exhibits strong non-physical peaks at several frequencies, overestimating by more than 10dB the pressure obtained using the averaged operator. This peaks can be said "non-physical" firstly because they do not appear on microphone measurements, and, moreover, because their frequencies depend on the size of zero padding (or extrapolation) used before the spatial DFT.

101 The pressure identified from membrane velocity measurements and corrected
 102 using equation (2) is drawn in Figure 2 with the acoustic pressure measured
 without the membrane.

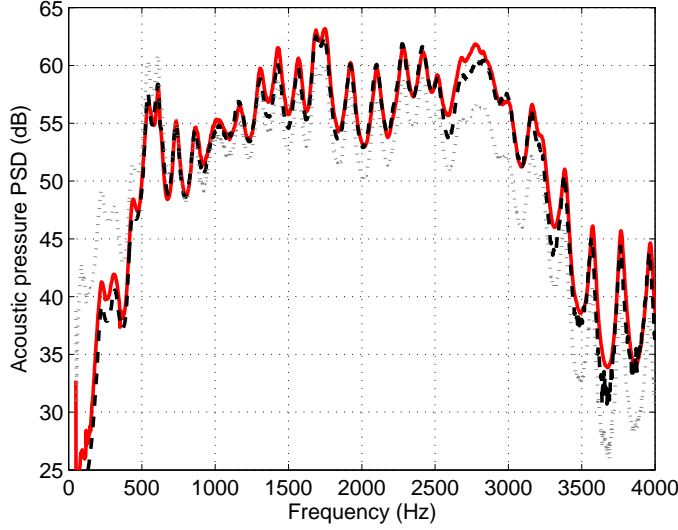


Fig. 2. Acoustic data averaged over 3 positions. Microphone acoustic pressure (—),
 membrane velocity $\times \rho c$ (...) and membrane-based acoustic pressure (- - -) .

103

104 The corrected pressure is very close to the measured acoustic pressure without
 105 the membrane, illustrating the possibility to virtually remove the membrane,
 106 and to precisely assess the acoustic pressure that would have been without it.
 107 The measured velocity, only corrected by the acoustic impedance of the plane
 108 wave ρc , is also given in the same figure, to show the combined effect of the
 109 velocity-to-pressure transformation and the mass correction. The velocity-to-
 110 pressure transformation and the mass correction are preponderant respectively
 111 in low and high frequency.

112 conclusion

113 This paper illustrates experimentally the possibility to use a scanning laser
 114 vibrometer and a light membrane to assess acoustic pressure holograms. Al-
 115 though the NAH velocity-to-pressure operation is known to be well-posed for
 116 high spatial frequencies, a special care has to be taken to treat a k-space
 117 singularity generating potentially large errors. A solution, proposed in the lit-
 118 erature for acoustic radiation computations, has been efficiently applied in

the present work, and experimental results show the necessity to implement it systematically. An experimental comparison with directly measured acoustic pressures validates the velocity-to-pressure transformation as well as the membrane mass correction over a wide frequency range. This validation is very encouraging and shows that the membrane approach is able to provide the acoustic pressure as well as the normal acoustic velocity, and consequently the acoustic power crossing the membrane, and all these quantities with the high spatial resolution that can be reached by a laser vibrometer.

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