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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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7 on the measurement of its velocity by scanning its surface using a laser vi-
8 brometer. The possibility to measure the acoustic velocity in the air using
9 a membrane has been investigated in a previous work [1], and the theory of
10 membrane-based holography is proposed in a second paper [2]. The main dif-
11 ficulty of the approach is that the membrane modifies the sound field : the
12 membrane velocity (equal for continuity reasons to the normal acoustic ve-
13 locity) is not equal to the normal acoustic velocity that would have existed
14 without it. The aim of the previous works was to show the possibility to cor-
15 rect the membrane velocity to virtually remove its mass, for a plane wave in
16 normal incidence [1] or for any kind of wave [2]. The aim of the present study
17 is to show the possibility to obtain acoustic pressures from membrane velocity
18 measurements. Although it has been shown in [5] [4] that velocity-to-velocity
19 NAH is more robust than pressure-to-velocity NAH, the assessment of acous-
20 tic pressure holograms remains necessary to compute the acoustic intensity
21 through the membrane, or to compare it with some microphone measure-
22 ments.

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

29 1 Theory of membrane-based holography

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

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

35 z being the direction normal to the measurement plane, with $k_{nx} = 2\pi n/L_x$,
36 $k_{my} = 2\pi m/L_y$, and n, m positive or negative integers varying between limits
37 defined by the spatial resolution, and L_x and L_y dimensions of the measure-
38 ment surface.

39

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

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

50

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

56

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

57 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 ($k_{nx}^2 +$
 58 $k_{my}^2 < k_0^2$ or ($k_{nx}^2 + k_{my}^2 > k_0^2$, μ is the mass per unit area of the membrane, ρ
 59 the air density, and \tilde{V}_{nm}^z the (n, m) component of the corrected velocity. It is
 60 important to note that this correction does not take into account the possible
 61 multiple reflections between the source and the membrane ; this explains that
 62 the minimization of the membrane mass remains crucial as stated and illus-
 63 trated in [1], even with this correcting term.

64

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

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

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

75 **2 Experimental validation**

76 *2.1 Experimental setup*

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

89 *2.2 Effect of the k-space averaging of the velocity-to-pressure operator*

90 The pressure obtained using the velocity-to-pressure operator given in Eq. (3)
 91 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-

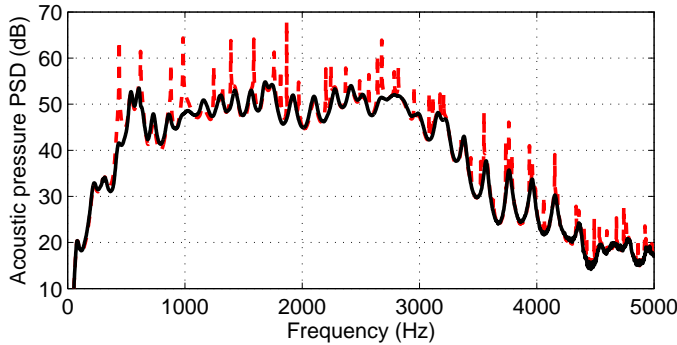


Fig. 1. Averaged acoustic pressure identified using the measured membrane velocity,
 using the non averaged (- - -) and averaged (—) velocity-to-pressure operator .

92
 93 The effect of the k-space averaging operation is clear in Figure 1. The result of the
 94 non-averaged transformation exhibits strong non-physical peaks at several fre-
 95 quencies, overestimating by more than 10dB the pressure obtained using the
 96 averaged operator. This peaks can be said "non-physical" firstly because they
 97 do not appear on microphone measurements, and, moreover, because their
 98 frequencies depend on the size of zero padding (or extrapolation) used before
 99 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.

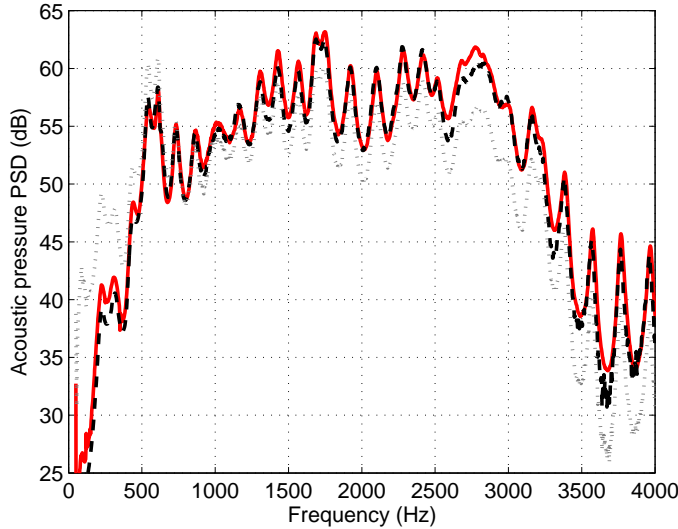


Fig. 2. Acoustic data averaged over 3 positions. Microphone acoustic pressure (—),
 membrane velocity $\ast \rho c$ (...) and membrane-based acoustic pressure (- - -) .

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

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

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