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High Frequency calibration of MEMS microphones using spherical *N*-waves

S. Ollivier[1,a),b)], C. Desjouy[1], P.Y. Yuldashev[1,2], A. Koumela[3], E. Salze[1], M. Karzova[1,2], L. Rufer[3] and Ph. Blanc-Benon[1]

[1] *Laboratoire de Mécanique des Fluides et d'Acoustique, École Centrale de Lyon, 36, avenue Guy de Collongue, 69134 Écully cedex, France*
[2] *Faculty of Physics, Moscow State University, Russia*
[3] *Tima Laboratory (CNRS UMR 5509), Grenoble, France*

a) Corresponding author: sebastien.ollivier@univ-lyon1.fr
b) URL: http://acoustique.ec-lyon.fr

Abstract. In the context of the scientific program SIMMIC supported by the French National Agency for Research (SIMI 9, ANR 2010 BLANC 0905 03), new wide band MEMS piezoresistive microphones have been designed and fabricated for weak shock wave measurements. The fabricated microphones have a high frequency resonance between 300 to 800 kHz depending on the membrane size. In order to characterize the frequency response of the fabricated sensors up to 1 MHz, new calibration methods based on an N-wave source were designed and tested. Short duration spherical N-waves can be generated by an electric spark source. To estimated a constant sensitivity coefficient, a known method is based on the estimation of the peak pressure from the lengthening of N-waves induced by non linear propagation. However, to obtain the sensitivity as a function of frequency, the output voltage must be compared to the incident pressure waveform, which must be accurately characterized. Taking advantage of recent works on the characterization of pressure N-waves generated by an electric spark source by means of optical methods, two calibration methods have been designed to obtain the frequency response. A method based on the comparison with pressure waveforms deduced from the analysis of schlieren images allowed to estimate the frequency response. A second method, based on a Mach-Zender optical interferometer, was found to be the best method to estimate the sensitivity of microphones up to 1 MHz. The methods were first tested by calibrating standard 1/8 inch condenser microphones. Then, frequency responses of different MEMS microphones prototypes were characterized to test different sensor designs. Results show that using a spark source and optical methods it is possible to calibrate sensors in the frequency range 10 kHz-1 MHz. The new calibration methods were used to improve the design of new high frequency MEMS pressure sensors.

INTRODUCTION

This communication is dedicated to the calibration of microphones and pressure sensors in the range 10 kHz-1 MHz. The motivation comes from previous experimental studies by the present authors on the propagation of shockwave [1, 2, 3, 4]. These works were based on an electric spark source, which is a convenient device to generate short duration pressure "N-waves" to study the propagation of shockwaves at laboratory scale with turbulence or ground effects [2, 3, 4, 5, 6, 7]. In the case of a spark source with 20 mm gap between the electrodes driven with a 20 kilovolts power supply, the generated "*N*-waves" have the following characteristics at about 20 cm from the source : duration ~50 μs, front shock rise time < 1 μs, overpressure ~1000 Pa, and have energy beyond 1 MHz [1]. Those characteristics are beyond the frequency range of microphones, and at some tens of centimeters the pressure level is too low for most pressure shockwave sensors. At frequencies higher than 100 kHz, it has been observed that the mounting of the sensors and the resonance of their membrane have a great influence on the output signal, which is distorted compared to the incident pressure waveform [3]. This has motivated the development of optical methods to measure weak shock waves [8, 9], and a research program to design, fabricate, and characterize MEMS microphones with resonance frequency higher than 500 kHz [10, 11]. Hereafter are summarized the methods used to estimate the frequency response of MEMS microphones.

Recent Developments in Nonlinear Acoustics
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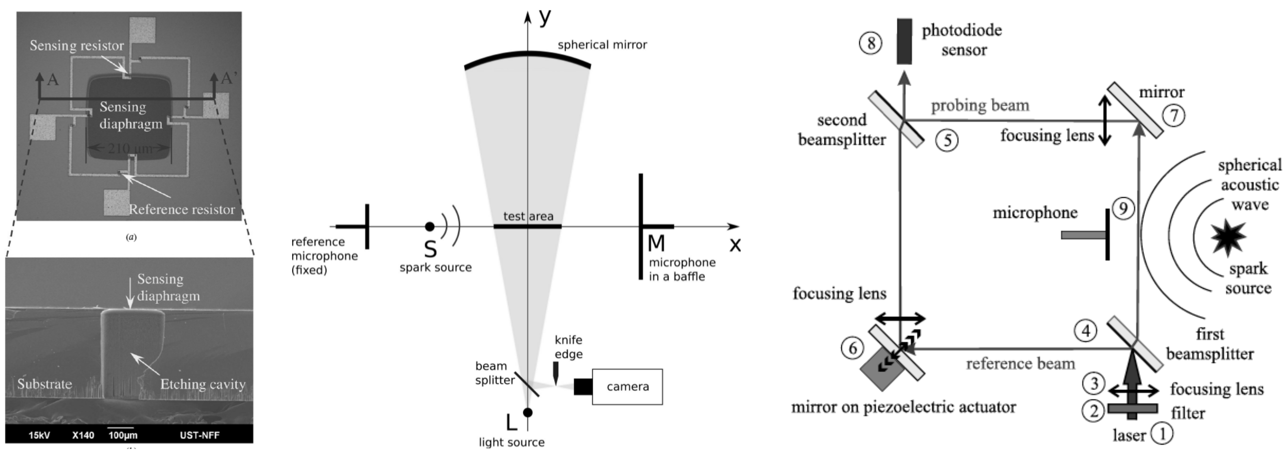


(a) (b) (c)

FIGURE 1. (a) Photograph of a 200 μm witdh MEMS microphone [10]; (b) Schlieren experimental arrangement [8]; (c) Mach-Zender interferometer [9]

HIGH FREQUENCY CALIBRATION METHODS

The acoustic source used to calibrated MEMS sensors is an electric spark source made of two tungstene electrodes separated by a 20 mm gap and driven by a 20 kilovolts supply. When an electric spark is generated, a spherical pressure shockwave with energy beyond 1 MHz and a waveform close to an N-wave is generated. The experimental arrangements include a computer-controlled linear stage in order to vary the distance r between the spark source and the microphone. Since no available reference microphone is able to measure up to 1 MHz, the waveforms were obtained using two optical methods. Both are based on fact that the pressure wave $p(r,t)$ induces locally a variation of the density, and therefore a variation of the local optical index n. If the pressure level is sufficiently high, the deviation of light can be observed.

A first optical measurement method of the pressure wave is based on an optical arrangement designed to record Schlieren images as described in reference [8] (Figure 1.b). Under the hypothesis of a spherical wavefront, average light intensity profiles were obtained from the Schlieren photographs. Then, performing inverse Abel transform, the pressure waveforms were estimated. Then a non linear propagation model based on an extended Burgers equation accounting for non linear effects, thermoviscous dissipation and molecular relaxation was applied to estimate the pressure wave at the microphone location. This method permits to obtain the incident pressure, from which the frequency response ofthe microphone can be obtained. However, the method does not permit to obtain the pressure level because the intensity profiles depends on the light intensity, on the sensitivity of the camera, and the setting of the optical system. To obtain the sensitivity, following W. Wright [6] the peak pressure level was estimated from the analysis of the the pulse lengthening with the distance, under the hypothesis of the dominating influence of non linear effects compared to dissipation. In the case of sperical N-waves, the duration (or half-duration) increases with the propagation distance r as :

$$T(r) = T_0\sqrt{1+\sigma_0\ln\left(\frac{r}{r_0}\right)} \quad \text{with} \quad \sigma_0 = (\gamma+1)r_0P_0/(2\gamma P_{atm}c_0T_0),$$

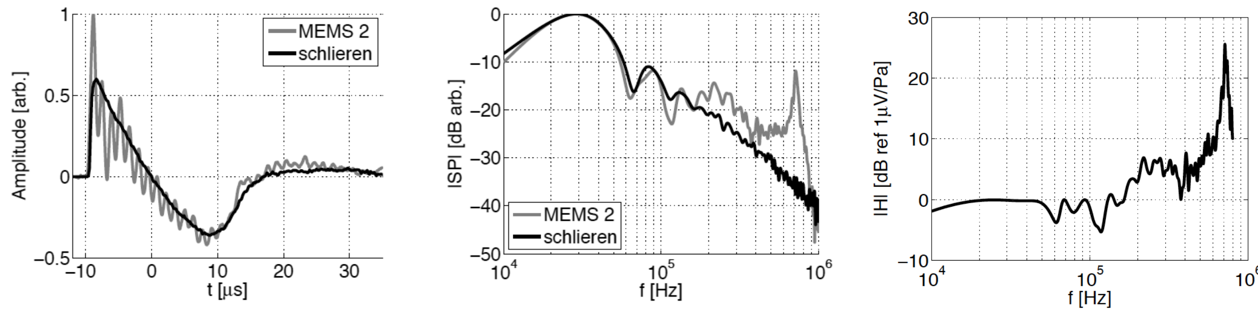
where r is the propagation distance from the source, r_0 an arbitrary reference position (chosen as the smaller distance), and P_0 and T_0 are respectively the peak overpressure and the wave duration at a distance r_0. Constant parameters γ, P_{atm} and c_0 are respectively the heat capacity ratio, the ambient atmospheric pressure and the ambient sound speed. The peak overpressure P_0 at a distance r_0 can be deduced from the lengthening of the pulse when the distance increases between two positions r_0 and r:

$$P_0 = \left(\frac{2\gamma P_{atm}c_0T_0}{(\gamma+1)r_0}\right)\left[\left(\frac{T(r)}{T_0}\right)^2-1\right]\ln\left(\frac{r}{r_0}\right)$$

Using this method to obtain the peak overpressure at r_0, a sensitivity coefficient can be calculated as $S = V_{max}(r_0)/P_0$ with $V_{max}(r_0)$ the peak ouput voltage at the distance r_0. This method was applied to characterize some MEMS microphones, however the measurement in two steps is not fully satisfying.

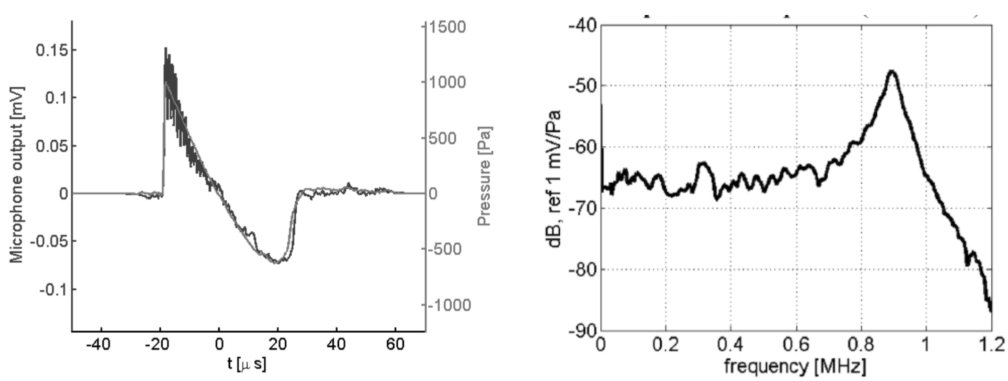
A second optical method, based on an optical Mach-Zender interferometer, has then been used. The experimental arrangement is described in details in reference [9]. It is similar to the one in reference [12]. A laser beam is splitted in two beams, one is a reference beam, the other being crossed by the pressure wave (Figure 1.c). The interference signal measured by a photodiode, depend on the variation of the optical index, and thus on the pressure waveform. A similar analysis of the interference signal as for the Schlieren images has been performed, based on the inverse Abel transform and the Gladstone-Dale relation [9]. Contrary to the previous Schlieren method, the interferometer allows to obtain the absolute pressure waveforms, and no additionnal measurement is needed. As for the Schlieren method, the propagation between the laser probe and the microphone membrane is taken into account using a non linear propagation model based on an extended Burgers equation. Comparing the microphone output signal and the pressure signal deduced from the optical interference, the microphone frequency response was the obtained.

RESULTS



(a) (b) (c)

FIGURE 2. Response of a MEMS microphone [10] obtained by comparison with the pressure estimated using the Schlieren method and the appropriate data analysis. (a) Time waveforms; (b) Amplitude spectra. Grey lines: MEMS output voltage; Black lines: pressure waveform from Schlieren images. (c) Frequency response of the MEMS microphone deduced from (b).



(a) (b)

FIGURE 3. Response of a MEMS microphone [10] obtained by comparison with the pressure estimated using the Mach-Zender interferometer method and the appropriate data analysis. (a) Time waveforms (Grey line: MEMS output voltage; Black line: pressure waveform); (b) Frequency response of the microphone for a 3 Volts supply voltage.

Results given in figure 2 concern the frequency response of a MEMS microphones obtained using the method based on the analysis of Schlieren photographs. Results are given as dimensionless amplitude curves. A resonance frequency of about 700 kHz was found. The sensitivity obtained by analyzing the increase of the positive half duration was of the order of 1 μV/Pa. The ability to measure the high frequency response was helpful to feed back the design and fabrication process since it was possible to compare the measured and the predicted response.

Figure 3 shows results of the calibration method based on the optical Mach-Zender interferometer and the appropriate data processing to obtain the pressure waveform. Results are given for another microphone. This method permitted to estimate the sensitivity as a function of the frequency. The resonance frequency of this microphone is of the order of 900 kHz.

CONCLUSION

Using a spark source and optical measurements, the frequency the response of pressure sensors can be obtained up to frequencies of the order of 1 MHz. The methods applies whatever the transduction principle, and whatever the mounting. The method based on a Mach-Zender interferometer is more convienient since it permits to obtain the pressure waveform. Further studies will include the estimation of the order of magnitude of the different sources of error.

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